

Hard probes in AA collisions

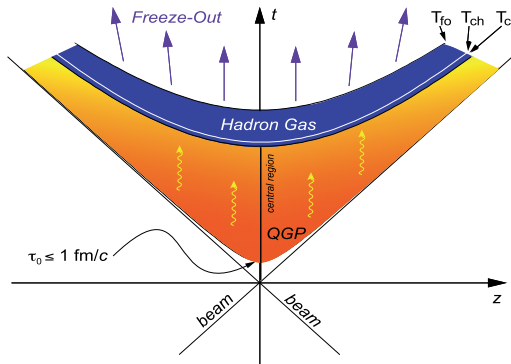
General overview and recent developments

Andrea Beraudo

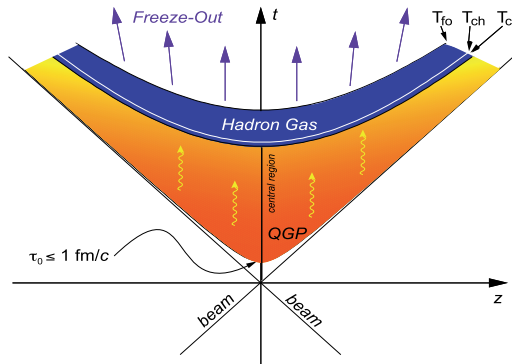
CERN, Theory Unit

Frascati, 18th January 2012

Heavy-ion collisions: a cartoon of space-time evolution

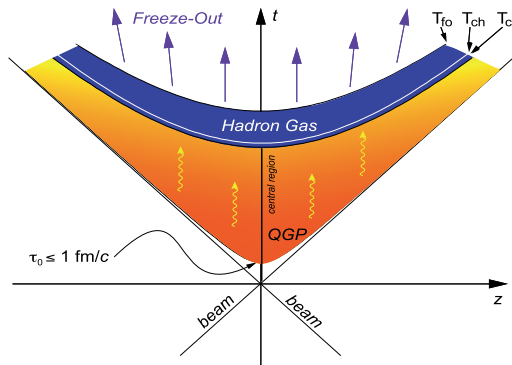


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- **Soft probes** (low- p_T hadrons): **collective behavior** of the *medium*;
- **Hard probes** (high- p_T particles, heavy quarks, quarkonia): produced in *hard pQCD processes* in the initial stage, allow to perform a **tomography of the medium**

Hard Probes

Particles whose production involves a *hard perturbative scale* (p_T , M), so that it occurs on a short time-scale ($\tau_{\text{hard}} \ll \tau_0$) and is supposed to be under good theoretical control. *Modification of their spectra and/or correlations in AA wrt pp* would be a signature of the formation of a *hot/dense medium*

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The challenge for a theorist is then:

- to give an accurate description of the **probe-medium interaction** (like evaluating $\hat{\sigma}_{\gamma^*p}$ in DIS);
- to exploit this knowledge to **extract information on medium properties** (T , dN_g/dy , transport coefficients...) through a comparison with experimental data (like getting PDFs in DIS).

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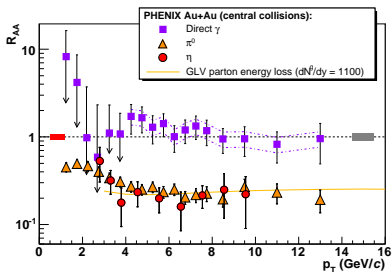
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- The standard theoretical framework: *parton energy-loss* due to medium-induced gluon radiation;
- The interplay between medium modification of color-flow and hadronization: relevance for the final hadron spectra;
- Heavy flavor: implementation of a relativistic Langevin equation, outcomes for charm and beauty spectra, and comparison with the experiment.

Some highlights

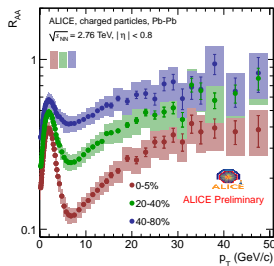
- Quenching of **single particle spectra** ($R_{AA}(p_T)$);
- Suppression of away-side **azimuthal correlation** ($dN/d\Delta\phi$);
- **γ -hadron** correlations;
- **Jet-quenching**:
 - **Inclusive jet spectra** (STAR);
 - **Dijet** imbalance (ATLAS and CMS).

Inclusive hadron spectra: the nuclear modification factor



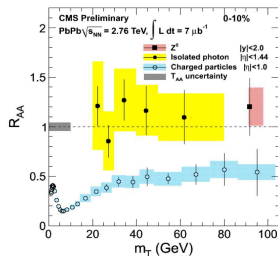
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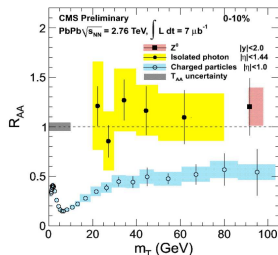
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Hard-photon $R_{AA} \approx 1$

- supports the Glauber picture (binary-collision scaling);
- entails that **quenching of inclusive hadron spectra** is a *final state effect due to in-medium energy loss*.

Some CAVEAT:

- At variance wrt e^+e^- collisions, in hadronic collisions one starts with a parton p_T -distribution ($\sim 1/p_T^\alpha$) so that **inclusive hadron spectrum** simply reflects *higher moments of FF*

$$\frac{dN^h}{dp_T} \sim \frac{1}{p_T^\alpha} \sum_f \int_0^1 dz z^{\alpha-1} D^{f \rightarrow h}(z)$$

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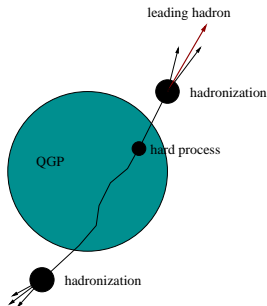
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- **Surface bias:**



Quenched spectrum does not reflect $\langle L_{\text{QGP}} \rangle$ crossed by partons distributed in the transverse plane according to $n_{\text{coll}}(\mathbf{x})$ scaling, but *due to its steeply falling shape* is biased by the *enhanced contribution of the ones produced close to the surface and losing a small amount of energy!*

Two-particle azimuthal correlations

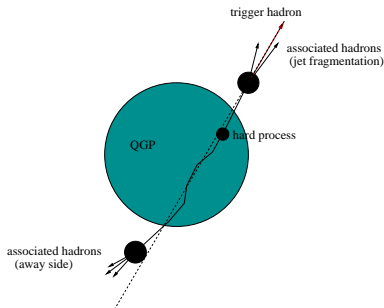
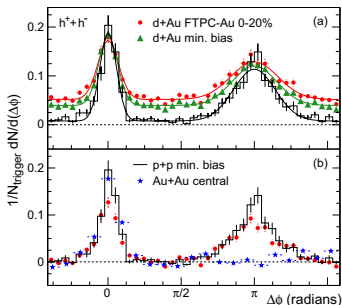
Given a high- p_T *trigger hadron* ($p_T^{\text{trig}} > p_T^{\text{hard}}$), one studies the azimuthal distribution of softer *associated hadrons* ($p_T^{\text{soft}} < p_T^{\text{ass}} < p_T^{\text{trig}}$):

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Some comments:

- Jet-like away-side peak present in p+p and d+Au, but completely quenched in Au+Au → **Suppression of back-to-back azimuthal correlations** in AA is a *final state effect* due to *parton energy loss* in the plasma!

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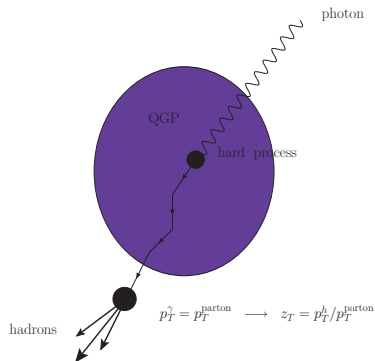
NB: higher harmonics (v_3) can give rise to non-trivial structures in the away-side peak!

γ -hadron correlations: generalities

For a given *trigger photon* (or Z !) one studies the *associated hadrons*.
Ideally the golden probe!

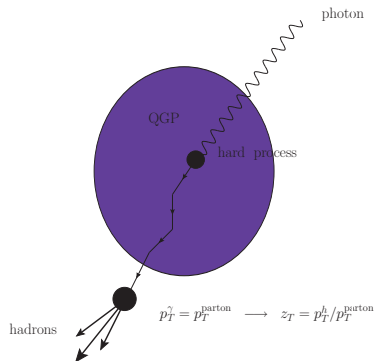
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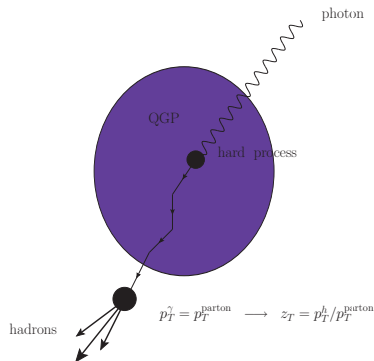
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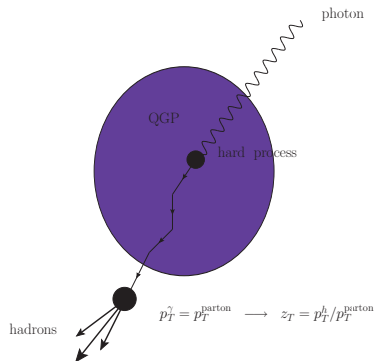
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- $gq \rightarrow \gamma q$ dominant over $q\bar{q} \rightarrow \gamma g \rightarrow$ knowledge of the **color charge** of the probe

γ -hadron correlations: results

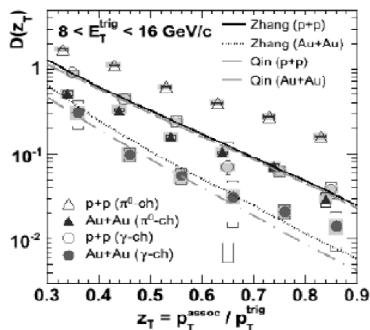
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$$D(z_T) \equiv \frac{1}{N_{\text{trig}}} \left. \frac{dN_{\text{ass}}^h}{dz_T} \right|_{z_T \equiv p_T^h / p_T^\gamma},$$

with the away-side hadron yield defined as:

$$N_{\text{ass}}^h \equiv \int_{\pi-0.63}^{\pi+0.63} d\Delta\phi \frac{dN^h}{d\Delta\phi}$$

STAR, Phys. Rev. C 82 (2010) 34909



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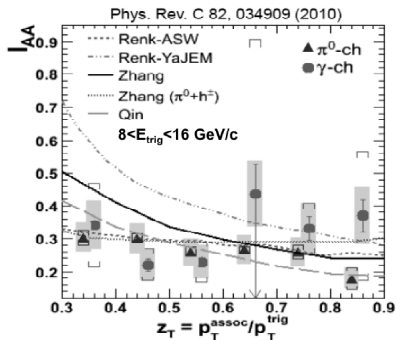
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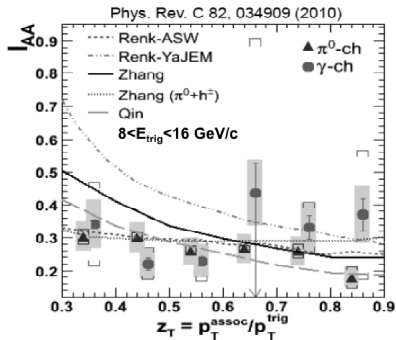
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Experimental data display a quenching of the fragmentation function!

Jets in AA collisions

- Jet reconstruction in heavy-ion environment: a challenge!

$$E_T^{\text{exp}} = E_T^{\text{jet}} + \rho(\pi R^2) \pm F$$

¹M. Cacciari *et al.* EPJC 71, 1539 (2011)

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$$\langle \rho \rangle \equiv \frac{\langle \Delta E_T^{\text{bkg}} \rangle}{\Delta \phi \Delta \eta} \approx 310 \text{ GeV}, \quad \langle \sigma \rangle \approx 20 \text{ GeV}$$

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Quenching of inclusive jet-spectra

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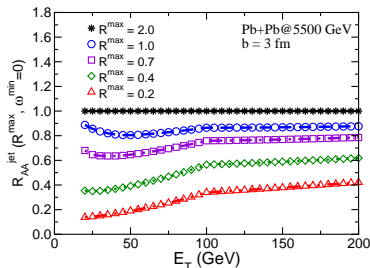
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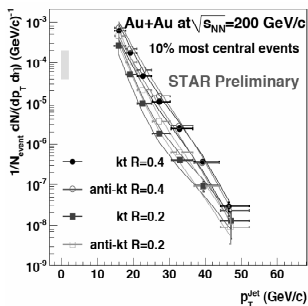


(I. Vitev *et al.* JHEP11 (2008) 093)

- For R^{max} large (and $\omega^{\text{min}} \rightarrow 0$) radiated gluon belongs to the jet $\rightarrow R_{AA}^{\text{jet}} \approx 1$;
- For $R^{\text{max}} \rightarrow 0$ radiated gluon is always lost $\rightarrow R_{AA}^{\text{jet}} \approx R_{AA}^{\text{hadron}}$

Inclusive jet spectra: results

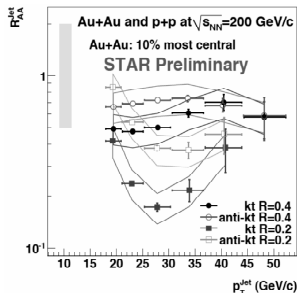
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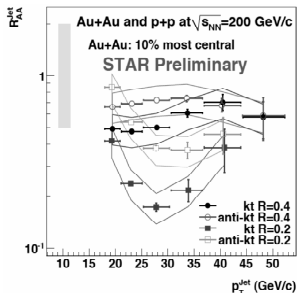


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 NB highest bin close to the kinematic limit ($E_{beam}=100A$ GeV)!

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Quenching of jets *milder* than the one of hadron spectra!

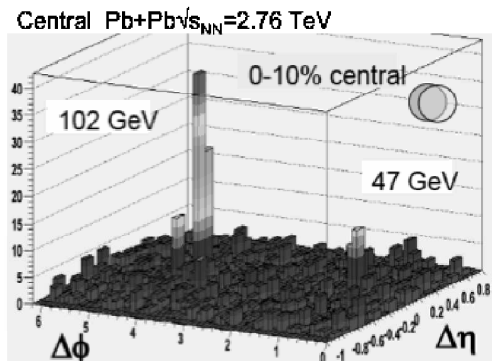
Part of the radiated gluons contribute to the E_T inside the jet-cone

Dijet imbalance at LHC: looking at the event display

An important fraction of events display a *huge mismatch* in E_T between the leading jet and its away-side partner

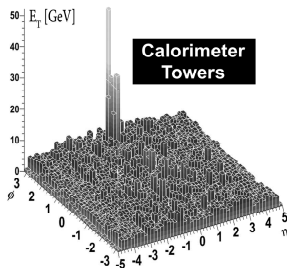
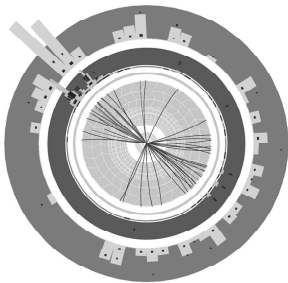
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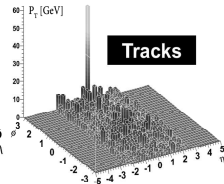


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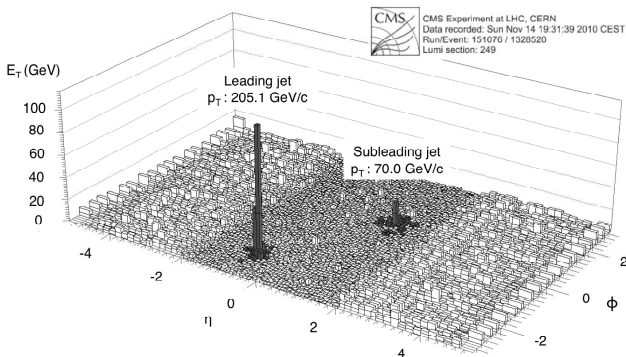
**ATLAS**

Run: 169045
Event: 1914004
Date: 2010-11-12
Time: 04:11:44 CET



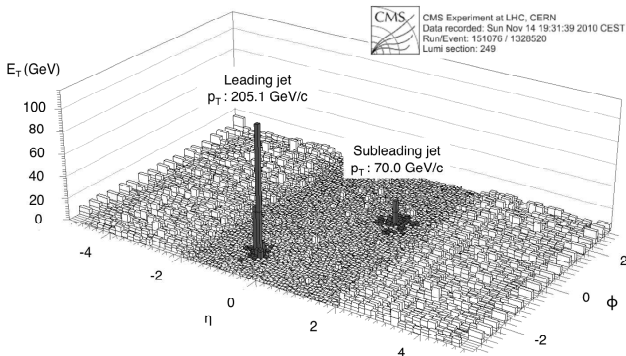
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Possible to observe event-by-event, without any analysis!

Dijet correlations: definitions

First analysis of dijet-imbalance in heavy-ion performed by ATLAS²:

- Define a sample of jet events with a *leading jet* with $E_{T_1} > 100$ GeV (1693 “jet-selected events”);

²PRL 105, 252303 (2010)

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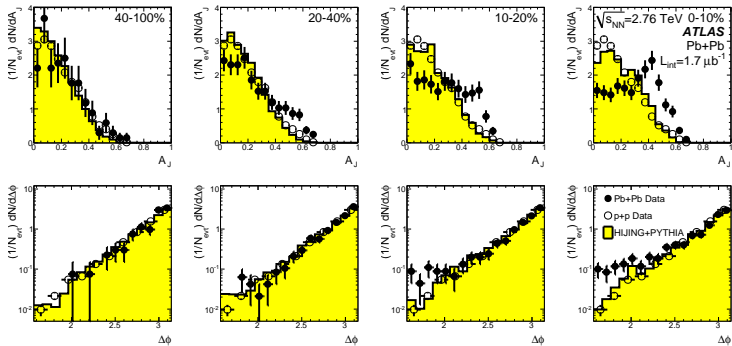
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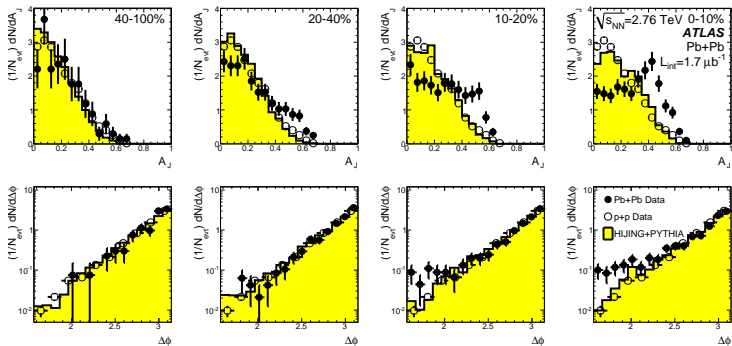
$$\frac{1}{N_{\text{jet ev.}}} \frac{dN}{dA_J}, \quad \frac{1}{N_{\text{jet ev.}}} \frac{dN}{d(\Delta\phi)}$$

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Dijet correlations: results

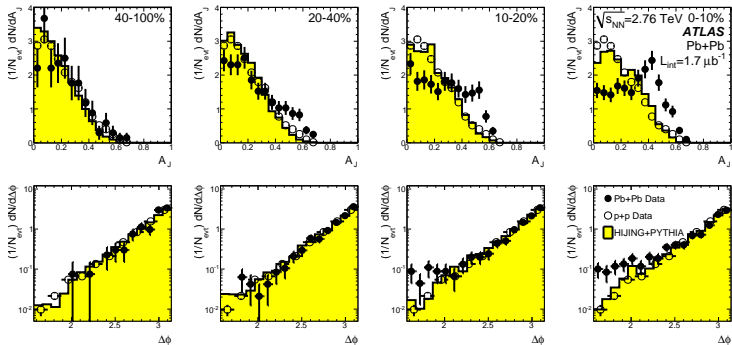


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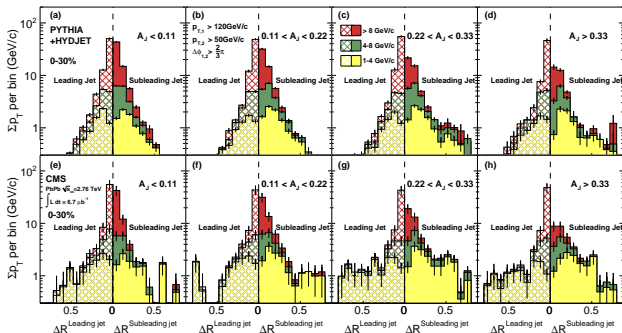
- Dijet **asymmetry** A_J enhanced wrt to p+p and increasing with centrality;
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Dijet correlations: adding tracking information

Tracks in a ring of radius $\Delta R \equiv \sqrt{\Delta\phi^2 + \Delta\eta^2}$ and width 0.08 *around the subleading-jet axis*:

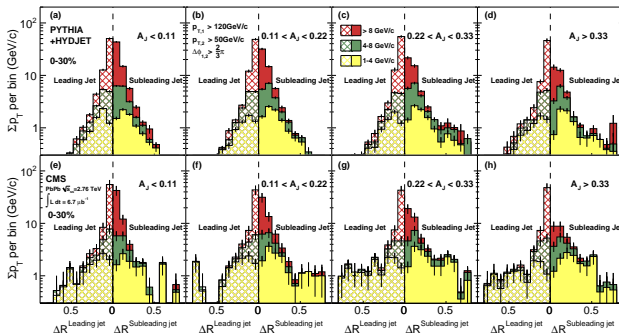
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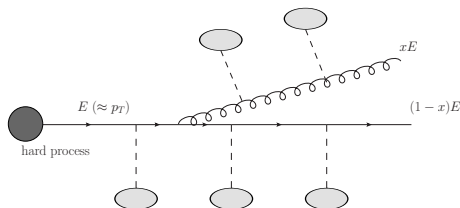


Increasing A_J a sizable fraction of energy around subleading jet carried by *soft* ($p_T < 4$ GeV) *tracks* with a *broad angular distribution*

The challenge:

Developing a rigorous theoretical setup for the study of the “jet”-medium interaction, providing a consistent description of the various observables

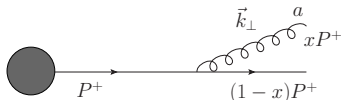
Physical interpretation of the data: *energy-loss at the parton level!*



- Interaction of the high- p_T parton with the *color field of the medium* induces the **radiation of** (mostly) *soft* ($\omega \ll E$) and *collinear* ($k_\perp \ll \omega$) **gluons**;
- Radiated gluon can further re-scatter in the medium (cumulated \mathbf{q}_\perp favor *decoherence* from the projectile).

Vacuum radiation by off-shell partons

A hard parton with $p_i \equiv [p_+, Q^2/2p_+, \mathbf{0}]$ loses its virtuality Q through gluon-radiation. In *light-cone coordinates*, with $p_{\pm} \equiv E \pm p_z/\sqrt{2}$:

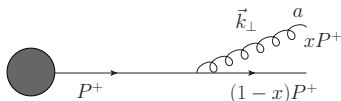


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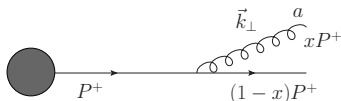
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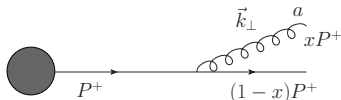
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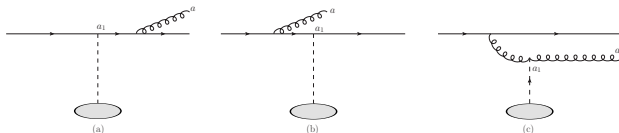
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- Time-scale (*formation time*) for gluon radiation:

$$\Delta t_{\text{rad}} \sim Q^{-1}(E/Q) \sim 2\omega/\mathbf{k}^2 \quad (x \approx \omega/E)$$

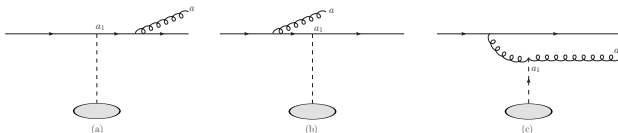
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- The single-inclusive gluon spectrum: the Gunion-Bertsch result

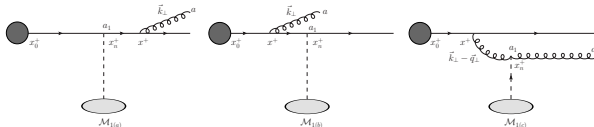
$$\omega \frac{dN_g^{\text{GB}}}{dkd\omega} = C_R \frac{\alpha_s}{\pi^2} \left(\frac{L}{\lambda_g^{\text{el}}} \right) \langle [\mathbf{K}_0 - \mathbf{K}_1]^2 \rangle = C_R \frac{\alpha_s}{\pi^2} \left(\frac{L}{\lambda_g^{\text{el}}} \right) \left\langle \frac{\mathbf{q}^2}{\mathbf{k}^2 (\mathbf{k} - \mathbf{q})^2} \right\rangle$$

where C_R is the *color charge* of the hard parton and:

$$\mathbf{K}_0 \equiv \frac{\mathbf{k}}{k^2}, \quad \mathbf{K}_1 \equiv \frac{\mathbf{k} - \mathbf{q}}{(\mathbf{k} - \mathbf{q})^2} \quad \text{and} \quad \langle \dots \rangle \equiv \int d\mathbf{q} \frac{1}{\sigma^{\text{el}}} \frac{d\sigma^{\text{el}}}{d\mathbf{q}}$$

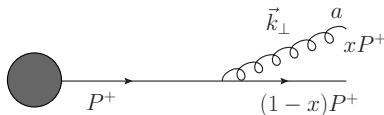
NB We work under the assumption $E \gg \omega \gg k_{\perp} \gg T$

The realistic case: hard parton *produced in the medium*



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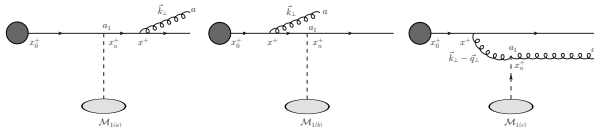


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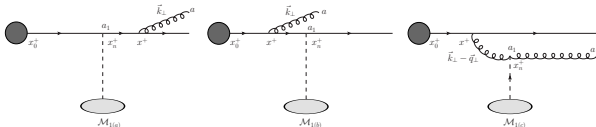


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- The *medium length* L introduces a scale to compare with the *gluon formation-time* t_{form} \longrightarrow non-trivial *interference effects*!
In the vacuum (no other scale!) $t_{\text{form}}^{\text{vac}} \equiv 2\omega/k^2$ played no role.

Evaluating the induced spectrum: opacity expansion

Gluon-spectrum $d\sigma^{\text{rad}}$ written as an *expansion in powers of (L/λ^{el})*

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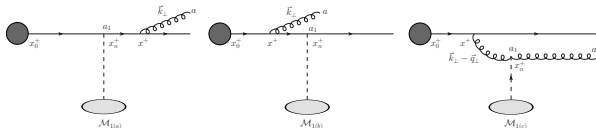
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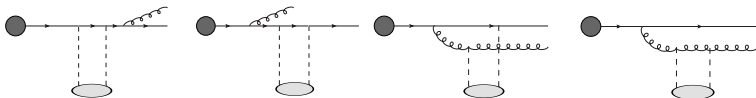
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$2\text{Re}\langle \mathcal{M}_2^{\text{virt}} \rangle \mathcal{M}_0^*$: reducing the contribution to the spectrum by vacuum radiation, involving *no color-exchange with the medium*

The induced spectrum: physical interpretation

$$\omega \frac{d\sigma^{\text{ind}}}{d\omega d\mathbf{k}} = d\sigma^{\text{hard}} C_R \frac{\alpha_s}{\pi^2} \left(\frac{L}{\lambda_g^{\text{el}}} \right) \left\langle [(\mathbf{K}_0 - \mathbf{K}_1)^2 + \mathbf{K}_1^2 - \mathbf{K}_0^2] \left(1 - \frac{\sin(\omega_1 L)}{\omega_1 L} \right) \right\rangle$$

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The full radiation spectrum can be organized as

$$d\sigma^{\text{rad}} = d\sigma^{\text{GB}} + d\sigma_{\text{gain}}^{\text{vac}} + d\sigma_{\text{loss}}^{\text{vac}}$$

where

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Gluon formation-time: physical meaning

Behavior of the induced spectrum depending on the *gluon formation-time*

$$t_{\text{form}} \equiv \omega_1^{-1} = 2\omega/(\mathbf{k} - \mathbf{q})^2$$

differing from the vacuum result $t_{\text{form}}^{\text{vac}} \equiv 2\omega/\mathbf{k}^2$, due to the **transverse \mathbf{q} -kick received from the medium**. Why such an expression?

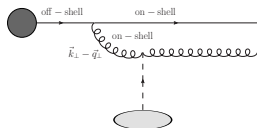
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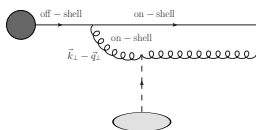
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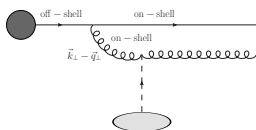
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→ if $t_{\text{form}} \geq L$ the process is suppressed!

Average energy loss

Integrating the lost energy ω over the inclusive gluon spectrum:

$$\langle \Delta E \rangle = \int d\omega \int d\mathbf{k} \, \omega \frac{dN_g^{\text{ind}}}{d\omega d\mathbf{k}} \sim \frac{C_R \alpha_s}{4} \left(\frac{\mu_D^2}{\lambda_g^{\text{el}}} \right) L^2 \ln \frac{E}{\mu_D}$$

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- μ_D : Debye screening mass of color interaction \sim *typical momentum exchanged in a collision*;

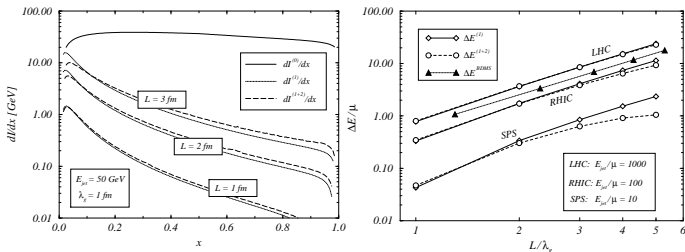
Average energy loss

Integrating the lost energy ω over the inclusive gluon spectrum:

$$\langle \Delta E \rangle = \int d\omega \int d\mathbf{k} \, \omega \frac{dN_g^{\text{ind}}}{d\omega d\mathbf{k}} \sim \frac{C_R \alpha_s}{4} \left(\frac{\mu_D^2}{\lambda_g^{\text{el}}} \right) L^2 \ln \frac{E}{\mu_D}$$

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Numerical results



(M. Gyulassy, P. Levai and I. Vitev, PRL 85, 5535 (2000))

- Vacuum-radiation rapidity flat (50% of jet energy!);
- Medium-induced energy-loss concentrated at small x

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- A more differential information (e.g. *exclusive* one, two... gluon spectrum) is desirable in order to deal with *more exclusive observables* (jet fragmentation, jet-shapes...);
- Ideally one would like to *follow a full parton-shower evolution in the plasma*, described by *modified Sudakov form factors*

$$\Delta(t, t_0) = \exp \left[- \int_{t_0}^t \frac{dt'}{t'} \int dz \frac{\alpha_s(t', z)}{2\pi} P(z, t') \right],$$

where *medium effects* are included as *corrections to the DGLAP splitting functions*:

$$P(z, t) = P^{\text{vac}}(z) + \Delta P(z, t)$$

As an evolution variable one can use the parton virtuality $t \equiv Q^2$

Evaluation of modified splitting functions

■ Vacuum-radiation spectrum

$$dN_g^{\text{vac}} = \frac{\alpha_s}{\pi^2} C_R \frac{dk^+}{k^+} \frac{d\mathbf{k}}{k^2} = \frac{\alpha_s}{2\pi} \left(\frac{2C_R}{x} \right) dx \frac{d\mathbf{k}^2}{k^2}$$

allows to identify the soft limit of $P^{\text{vac}}(z)$ (where $z=1-x$):

$$\frac{dN_g^{\text{vac}}}{dz d\mathbf{k}^2} \equiv \frac{\alpha_s}{2\pi} \frac{1}{k^2} P^{\text{vac}}(z), \quad \longrightarrow \quad P^{\text{vac}}(z) \underset{z \rightarrow 1}{\simeq} \frac{2C_R}{1-z}$$

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- Medium-corrections to the splitting function are then obtained through the matching with the induced radiation spectrum:

$$\Delta P(z, t) \simeq \frac{2\pi t}{\alpha_s} \frac{dN_g^{\text{ind}}}{dzdt}$$

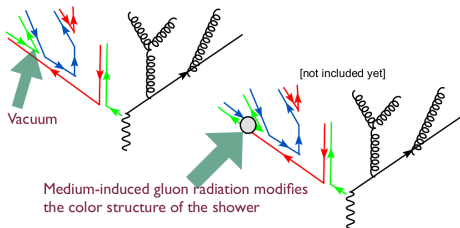
where $\mathbf{k}^2 = z(1-z)t$.

Caveat

Color connections in the medium

⇒ The interaction of the radiated gluon with the medium is given by color exchange

→ The color structure of the jet shower is modified



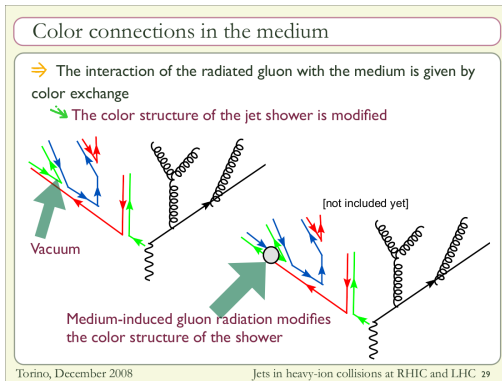
Torino, December 2008

Jets in heavy-ion collisions at RHIC and LHC 29

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³Fig. from C.A. Salgado lectures

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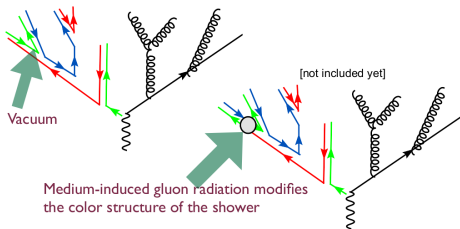
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Parton-medium interaction involves *color-exchange*³ which can affect

- correlation between subsequent emissions;
- color connections at the end of the evolution (hence *hadronization*)

³Fig. from C.A. Salgado lectures

...Hence the interest in studying
medium-modification of color-flow for
high- p_T probes⁴

- I will mainly focus on leading-hadron spectra...
- ...but the effects may be relevant for more differential observables (e.g. jet-fragmentation pattern)

⁴A.B., J.G.Milhano and U.A. Wiedemann, *J.Phys.G* G38 (2011) 124118 and [arXiv:1109.5025](#) [hep-ph] + *work in progress*

“Factorization” in AA collisions: medium-modified FFs

$$d\sigma_{\text{med}}^{AA \rightarrow h+X} = \sum_f d\sigma_{\text{vac}}^{AA \rightarrow f+X} \otimes \langle D_{\text{med}}^{f \rightarrow h}(z, \mu_F^2) \rangle_{AA}$$

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Underlying assumption

A high-energy parton with low-virtuality Q fragments *outside the medium*

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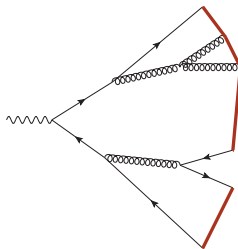
Does the above factorization hold *if the medium modifies the color flow?*

From partons to hadrons

The *final stage of any parton shower* has to be interfaced with some *hadronization routine*. Keeping track of color-flow one identifies *color-singlet objects* whose decay will give rise to hadrons

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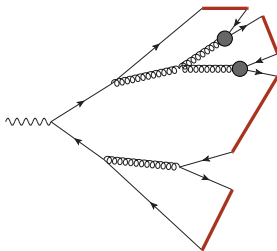
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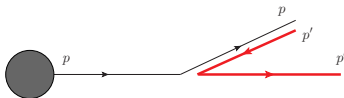
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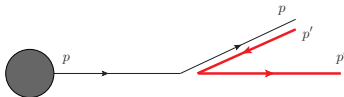
- In PYTHIA hadrons come from the fragmentation of *$q\bar{q}$ strings*, with gluons representing kinks along the string (Lund model);
- In HERWIG the shower is evolved up to a softer scale, *all gluons are forced to split in $q\bar{q}$ pair* (large- N_c !) and *singlet clusters* (usually of *low invariant mass*!) are thus identified.

Vacuum radiation: color flow



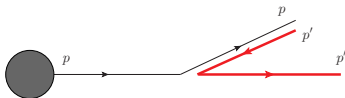
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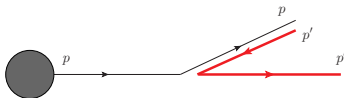


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- The **red lines** form the **color-singlet cluster** C_0 , with $p_0^C = p_f + k/2$:

$$\underbrace{p_+^{C_0} = \left(1 - \frac{x}{2}\right) p_+}_{\text{leading hadron}}, \quad s^{C_0} \equiv \left(p_f + \frac{\mathbf{k}}{2}\right)^2 = \frac{\mathbf{k}^2}{2x(1-x)} \equiv \frac{Q^2}{2}$$

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whose decay will give rise to the **leading hadron**;

- The second end-point of the gluon, color-connected with the rest of the event, will only contribute to the soft part of the spectrum

Medium-induced radiation: color flow

- **Reminder:** if the production of the hard parton occurs *inside the medium* the radiation spectrum is given by:

$$d\sigma^{\text{rad}} = d\sigma^{\text{vac}} + d\sigma^{\text{ind}}$$

The hard parton would radiate losing its virtuality also in the vacuum: only the *induced radiation* contributes to the energy-loss!

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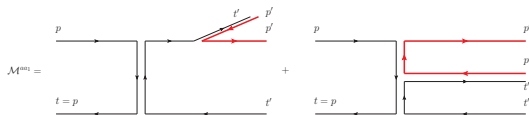
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$d\sigma_a^{\text{ind}}$: correction to vac. rad. to ensure probability conservation.

Quark projectile: color-flow analysis

- The aa_1 channel: leading hadron from cluster C_1 (in red)

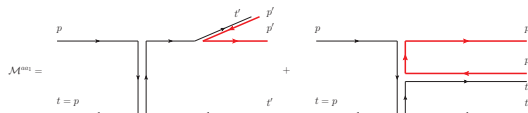


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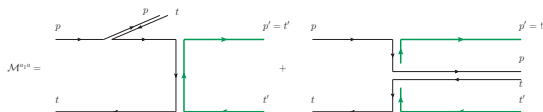
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- The a_1a channel: leading hadron from cluster \mathcal{C}_2 (in green)



$$p_+^{\mathcal{C}_2} \underset{\omega \gg T}{\sim} (1-x) p_+ (< p_+^{\mathcal{C}_1}!), \quad s^{\mathcal{C}_2} \equiv (p_f + t)^2 = 2p_f \cdot t \sim E T (\gg s^{\mathcal{C}_1})$$

where a medium particle has momentum components $\sim T$

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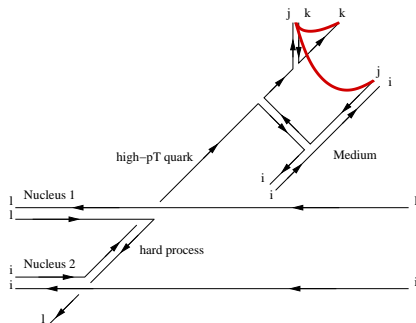
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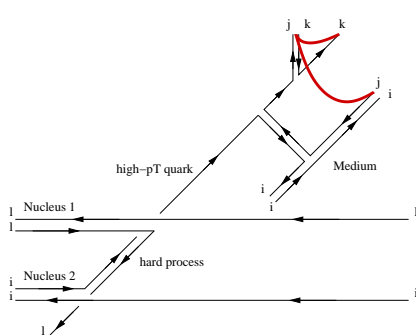
Cluster C_2 , already softer than C_1 , can have very large invariant mass and, before hadronization, fragment into sub-clusters. This will further soften the spectrum of hadrons produced in the a_1 color-channel!

Hadronization: string-fragmentation (PYTHIA)

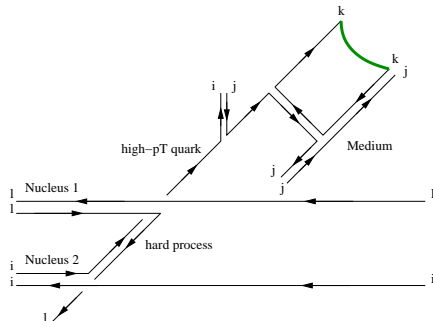


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Gluon color decohered: its energy is lost and cannot contribute to the leading hadron

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The presence of channels with the **leading projectile fragment color-connected with the medium** *always entails a softening of the hadron spectrum*

Color differential radiation spectrum

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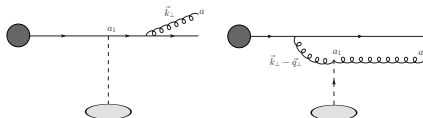
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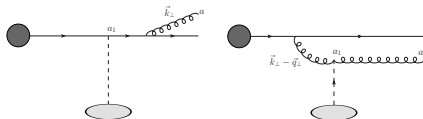
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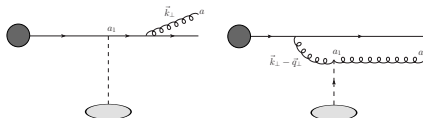


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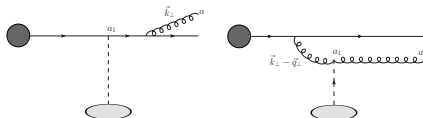
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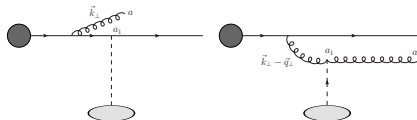
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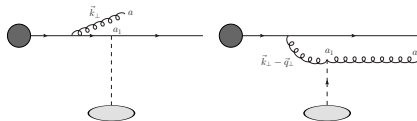
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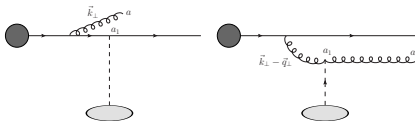


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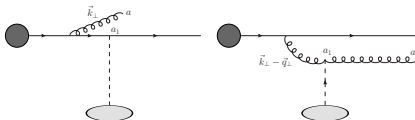
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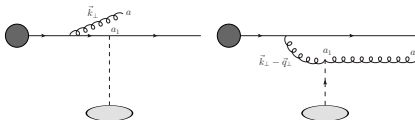
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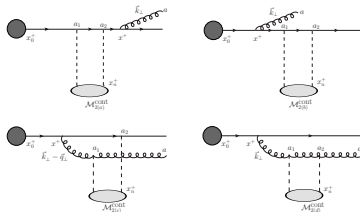
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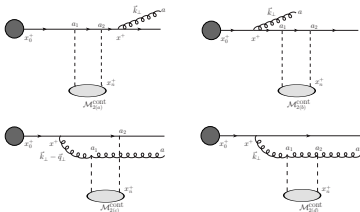
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The inclusive ($a + aa_1 + a_1a$) *induced* radiation-spectrum:

$$k^+ \frac{d\sigma^{\text{ind}}}{dk^+ d\mathbf{k}} \Big|_{\text{incoh.}} = d\sigma^{\text{hard}} C_R \frac{\alpha_s}{\pi^2} \left(\frac{L}{\lambda_g^{\text{el}}} \right) \langle (\mathbf{K}_0 - \mathbf{K}_1)^2 - \mathbf{K}_0^2 + \mathbf{K}_1^2 \rangle$$

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- The medium may simply provide a color-rotation, but *leading hadrons always arise from C_0/C_1 clusters: no effect on the spectrum!*

From partons to hadrons: modified color-flow effects

- **Incoherent limit** ($\omega_{0/1}L \gg 1$):
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Quenching of hadron spectra *not due to enhanced rate of gluon radiation*,
but to a *change of color-connections* of the hard parton in the medium

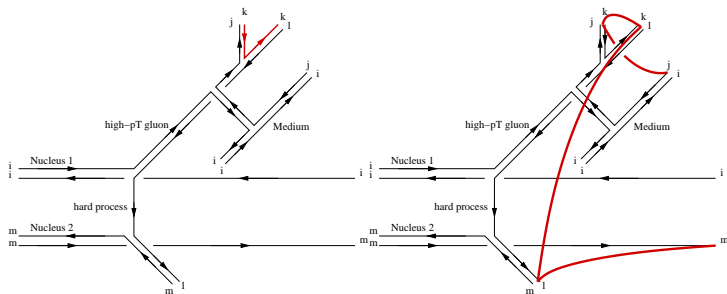
Further developments

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- The analysis can be in principle performed **for any number of elastic scatterings**: for $N=2$ in 4 of 5 color-channels the **leading fragment** is **connected with the medium**!

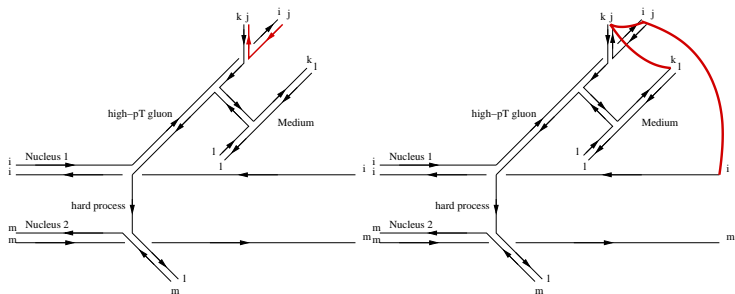
Gluon projectile: color channels



Only 4 color channels contribute in the soft ($\omega \ll E$) limit

- two with “vacuum-like” color-connections

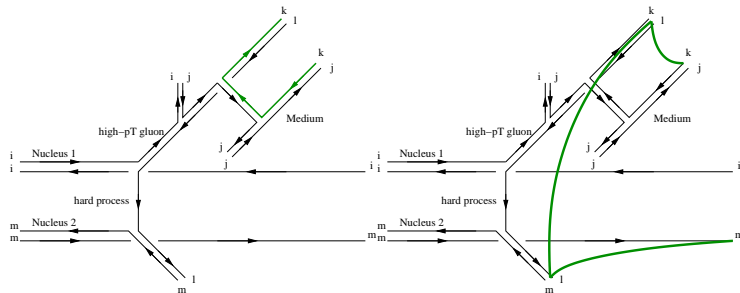
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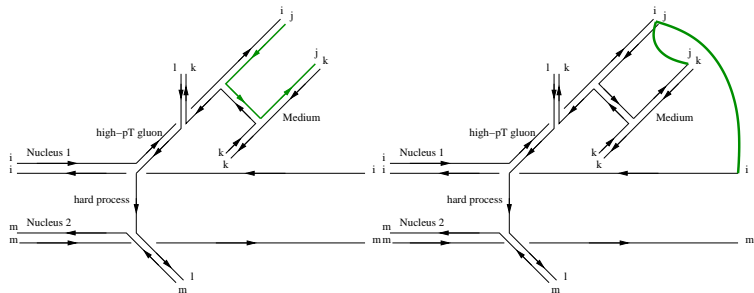
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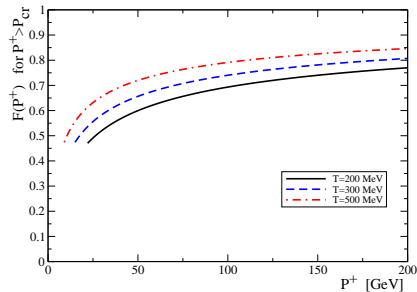
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- It is possible to supplement it with the further suppression arising from the parton-medium color-connection:

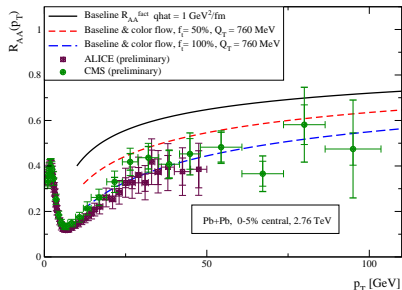
$$R_{AA}(p_T) \simeq (1 - f_t) R_{AA}^{\text{fact}}(p_T) + f_t F[\sqrt{2}(4/3)p_T] R_{AA}^{\text{fact}}(p_T)$$

- f_t : fraction of in-medium showers with the leading fragment color-connected with the medium
- F : suppression due to parton-medium color connection, leading to *high invariant-mass singlet clusters* \longrightarrow fission into lighter clusters responsible for *softening of the spectra*

Hadron- R_{AA} : numerical results



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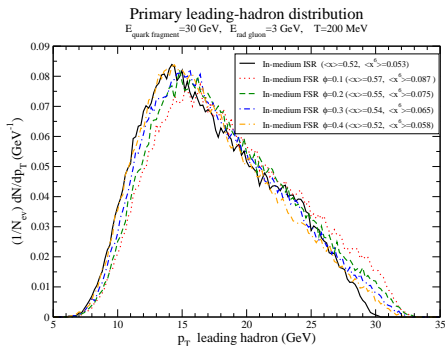
- Black line: parton e-loss \otimes vacuum fragmentation;
- Colored lines: parton e-loss \otimes fragm. with modified color-flow.

Hadron suppression could be reproduced with milder values of \hat{q}

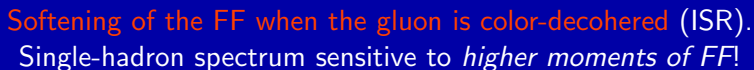
Hadronization à la PYTHIA

(work in progress)

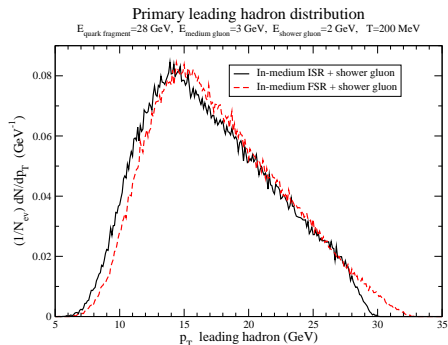
Leading-hadron distribution



When the gluon is color-decohered from the projectile (black curve) its energy is lost and does not contribute to the leading hadron



Medium-induced radiation + further branching



Effect not washed-out by possible radiation outside the medium

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Color-exchange with the medium leads to a **modification of the properties of *leading color-singlet clusters***

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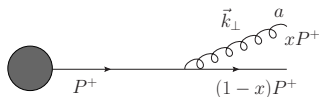
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Heavy flavor

Gluon radiation by a heavy quark



$$d\sigma^{\text{rad}} = d\sigma^{\text{hard}} \frac{\alpha_s}{\pi^2} C_F \frac{dx}{x} d\mathbf{k}_\perp \frac{\mathbf{k}_\perp^2}{[\mathbf{k}_\perp^2 + x^2 M^2]^2}$$

- Color charge C_F ($< C_A$) known;
- Reduction of the gluon formation time:

$$t_{\text{form}} = \frac{2\omega}{\mathbf{k}^2} \longrightarrow t_{\text{form}} = \frac{2\omega}{\mathbf{k}^2 + x^2 M^2}$$

Coherence effects less relevant!

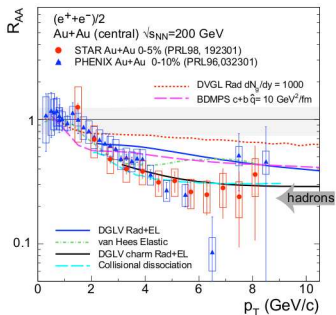
- Gluon radiation at angles $\theta < M/E$ is **suppressed** (*dead-cone effect!*)

Heavy quark energy loss versus RHIC data

- If soft-gluon radiation were the only energy loss mechanism, we would expect p_T spectra of heavy quark hadrons (and their decay electrons) much less quenched. Such expectation was wiped away by RHIC data!

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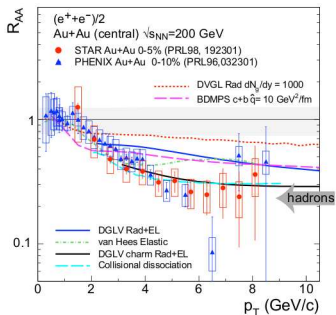
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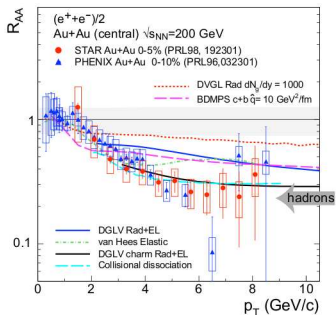
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- Indication of importance of collisional energy-loss for HQs

A possible tool to study the heavy-quark dynamics in the QGP: the relativistic Langevin equation

⁵W.M. Alberico *et al.*, EPJC 71, 1666 (2011) and QM2011 proceedings

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- The Langevin equation allows to follow the *relaxation to thermal equilibrium*.⁵

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Update of the HQ momentum in the plasma: the recipe

$$\frac{\Delta p^i}{\Delta t} = - \underbrace{\eta_D(p)p^i}_{\text{determ.}} + \underbrace{\xi^i(t)}_{\text{stochastic}} ,$$

with the properties of the noise encoded in

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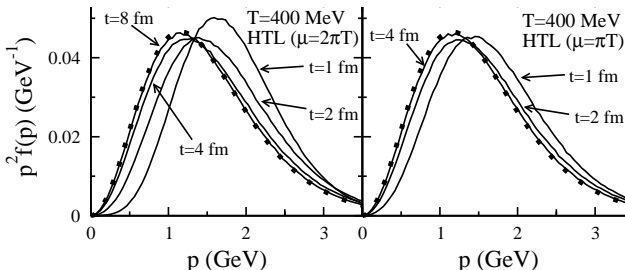
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$$\eta_D^{\text{Ito}}(p) = \frac{\kappa_L(p)}{2TE_p} - \frac{1}{E_p^2} \left[(1 - v^2) \frac{\partial \kappa_L(p)}{\partial v^2} + \frac{d-1}{2} \frac{\kappa_L(p) - \kappa_T(p)}{v^2} \right]$$

fixed in order to insure approach to equilibrium (**Einstein relation**):

Langevin \Leftrightarrow Fokker Planck with steady solution $\exp(-E_p/T)$

In a static medium...



For $t \gg 1/\eta_D$ one approaches a relativistic Maxwell-Jüttner distribution⁶

$$f_{MJ}(p) \equiv \frac{e^{-E_p/T}}{4\pi M^2 T K_2(M/T)}, \quad \text{with} \quad \int d^3p f_{MJ}(p) = 1$$

(Test with a sample of c quarks with $p_0 = 2 \text{ GeV}/c$)

⁶A.B., A. De Pace, W.M. Alberico and A. Molinari, NPA 831, 59 (2009)

In an expanding fluid...

The fields $u^\mu(x)$ and $T(x)$ are taken from the output of two longitudinally boost-invariant (“Hubble-law” longitudinal expansion $v_z = z/t$)

$$x^\mu = (\tau \cosh \eta, \mathbf{r}_\perp, \tau \sinh \eta) \quad \text{with} \quad \tau \equiv \sqrt{t^2 - z^2}$$

$$u^\mu = \bar{\gamma}_\perp (\cosh \eta, \bar{\mathbf{v}}_\perp, \sinh \eta) \quad \text{with} \quad \bar{\gamma} \equiv \frac{1}{\sqrt{1 - \bar{\mathbf{v}}_\perp^2}}$$

hydro codes⁷.

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- $u^\mu(x)$ used to perform the update each time in the fluid rest-frame;
- $T(x)$ allows to fix at each step the value of the transport coefficients.

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Evaluation of $\kappa_{T/L}(p)$

It's the stage where the various models differ!

We account for the effect of $2 \rightarrow 2$ collisions in the medium

⁸Similar strategy for the evaluation of dE/dx in S. Peigne and A. Peshier, Phys.Rev.D77:114017 (2008).

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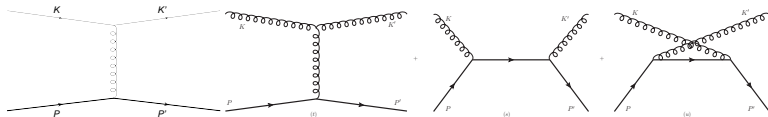
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- **hard collisions** ($|t| > |t|^*$): kinetic pQCD calculation
- **soft collisions** ($|t| < |t|^*$): Hard Thermal Loop approximation (*resummation of medium effects*)

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Transport coefficients $\kappa_{T/L}(p)$: hard contribution

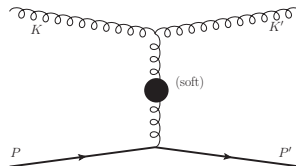
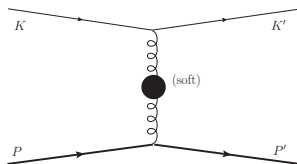


$$\kappa_T^{g/q(\text{hard})} = \frac{1}{2} \frac{1}{2E} \int_k \frac{n_{B/F}(k)}{2k} \int_{k'} \frac{1 \pm n_{B/F}(k')}{2k'} \int_{p'} \frac{1}{2E'} \theta(|t| - |t|^*) \times \\ \times (2\pi)^4 \delta^{(4)}(P + K - P' - K') |\overline{\mathcal{M}}_{g/q}(s, t)|^2 q_T^2$$

$$\kappa_L^{g/q(\text{hard})} = \frac{1}{2E} \int_k \frac{n_{B/F}(k)}{2k} \int_{k'} \frac{1 \pm n_{B/F}(k')}{2k'} \int_{p'} \frac{1}{2E'} \theta(|t| - |t|^*) \times \\ \times (2\pi)^4 \delta^{(4)}(P + K - P' - K') |\overline{\mathcal{M}}_{g/q}(s, t)|^2 q_L^2$$

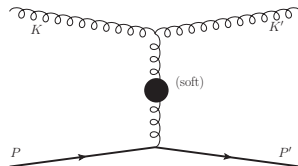
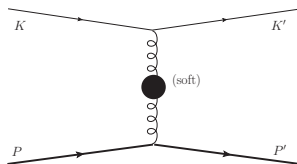
where: $(|t| \equiv q^2 - \omega^2)$

Transport coefficients $\kappa_{T/L}(p)$: soft contribution



When the exchanged 4-momentum is **soft** the **t-channel gluon** feels the **presence of the medium** and **requires resummation**.

Transport coefficients $\kappa_{T/L}(p)$: soft contribution



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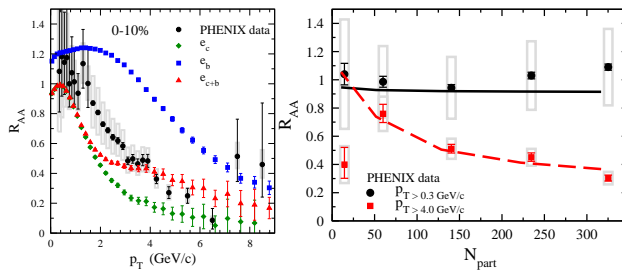
The **blob** represents the **dressed gluon propagator**, which has longitudinal and transverse components:

$$\Delta_L(z, q) = \frac{-1}{q^2 + \Pi_L(z, q)}, \quad \Delta_T(z, q) = \frac{-1}{z^2 - q^2 - \Pi_T(z, q)},$$

where *medium effects* are embedded in the **HTL gluon self-energy**.

Results for RHIC

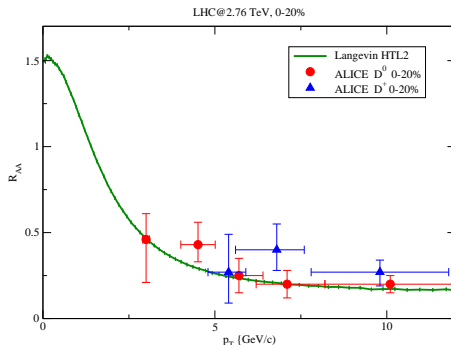
Heavy-flavor electrons: R_{AA}



- Left panel: $R_{AA}(p_T)$ in central events;
- Right panel: integrated R_{AA} vs centrality

Results for LHC (*work in progress!*)

D mesons vs ALICE results

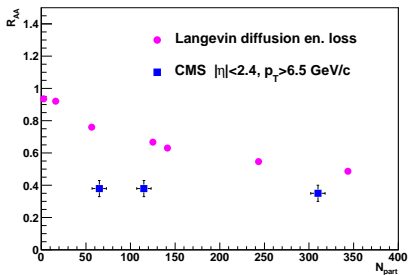


High- p_T D-meson suppression nicely reproduced

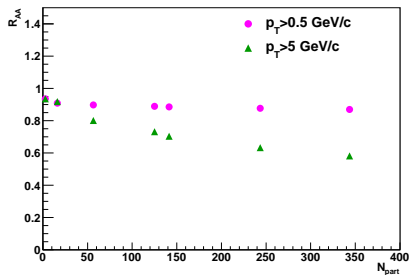
Results for LHC (*work in progress!*)

Displaced J/ψ vs CMS data and ALICE potentiality

non-prompt J/ψ in Pb-Pb coll. at $\sqrt{s_{NN}}=2.76$ TeV



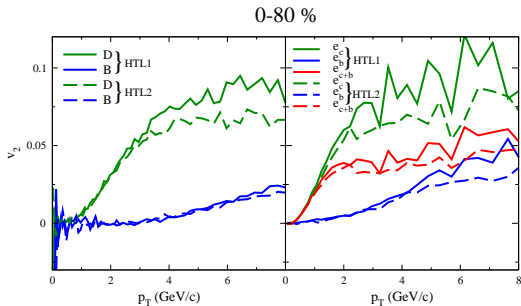
non-prompt J/ψ in Pb-Pb coll. at $\sqrt{s_{NN}}=2.76$ TeV, $|\eta| < 0.9$ (ALICE)



- Flat behavior of CMS result vs centrality a bit puzzling;
- ALICE capability to go to low- p_T of interest!

Results for LHC (*work in progress!*)

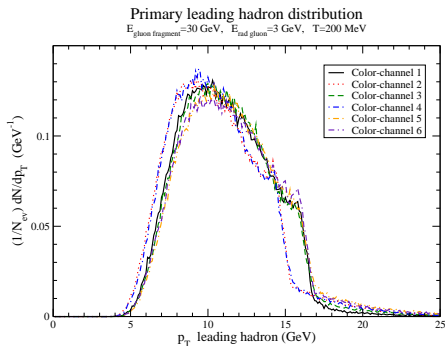
Elliptic flow



- Charm has a much larger elliptic flow with respect to RHIC
- Modest elliptic flow of bottom

Back-up slides

Gluon projectile: numerical results



Color-exchange effects present even in the case of a gluon-projectile