Perturbative vs non-perturbative aspects of jet quenching:

the role of color flow

Andrea Beraudo

CERN, Theory Unit

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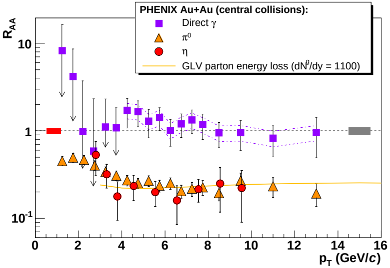
"Jet-quenching": the experimental evidence



From the *nuclear modification factor*...

$$R_{AA} \equiv \frac{\left(dN^h/dp_T\right)^{AA}}{\langle N_{\rm coll}\rangle \left(dN^h/dp_T\right)^{pp}}$$

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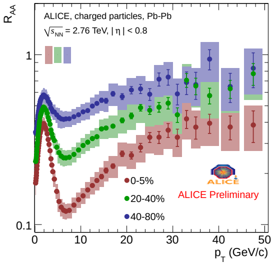

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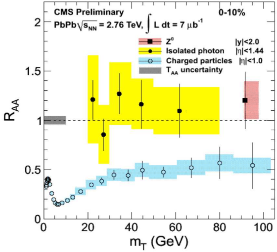

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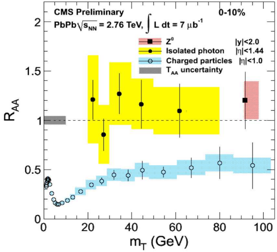

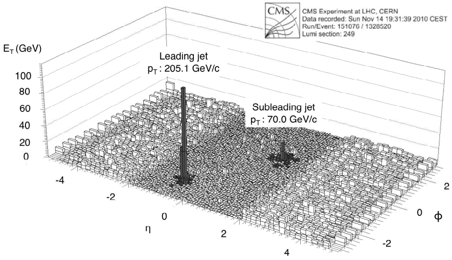

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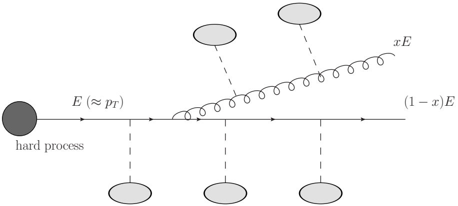
...to the *di-jet imbalance*

The challenge:

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

- Quenching of single particle spectra (R_{AA});
- Suppression of away-side azimuthal correlation ($dN/d\Delta\phi$);
- γ-hadron (now also γ-jet!) correlations;
- Jet-quenching:
  - Inclusive jet spectra (STAR @ RHIC and ATLAS @ LHC);
  - Di-jet imbalance (ATLAS and CMS @ LHC).
- ...

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).

Parton energy loss calculations available on the market

A whole zoo of acronyms, like

- BDMPS-Z (Multiple soft scatterings)
- DGLV (Opacity expansion)
- WHDG (Collisional + radiative E-loss)
- ASW (Path-integral)
- AMY (Thermal field theory)
- HT (Higher-Twist)
- ...and many others

differing in the way the rate of medium-induced gluon radiation is evaluated[1], but essentially based on the same conceptual setup, namely...

[1] For a review see e.g. ArXiv 1106.1106

"Factorization" in AA collisions: medium-modified FFs

$$
\begin{aligned}
d\sigma_{\rm med}^{AA\to h+X} &= \sum_f d\sigma_{\rm vac}^{AA\to f+X} \otimes \langle D_{\rm med}^{f\to h}(z,\mu_F^2)\rangle_{AA} \\
&= \sum_f \underbrace{d\sigma_{\rm vac}^{AA\to f+X}}_{pQCD} \otimes \underbrace{\langle P(\Delta E)\rangle_{AA}}_{\rm e.loss\ prob.} \otimes \underbrace{D_{\rm vac}^{f\to h}(z,\mu_F^2)}_{\mathrm{vacuumFF}\ (NP)}
\end{aligned}
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Vacuum FF applied to a parton with a degraded energy.

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Vacuum FF applied to a parton with a degraded energy. *Caveat*:

- Energy loss probability *usually* described by a Poisson distribution

$$P(\Delta E) = \sum_{n=0}^{\infty} \frac{e^{-\langle N_g \rangle}}{n!} \prod_{i=1}^{n} \left[\int d\omega_i \frac{dN_g}{d\omega_i}\right] \delta\left(\Delta E - \sum_{i=1}^{n} \omega_i\right),$$

assuming implicitly successive gluon emissions as uncorrelated;

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  assuming implicitly successive gluon emissions as uncorrelated;

- High-energy partons expected to fragment *outside the medium*

$$\Delta t_{\rm rest}^{\rm hadr} \sim 1/Q \quad \longrightarrow \quad \Delta t_{\rm lab}^{\rm hadr} \sim (E/Q)(1/Q) \underset{E\to\infty}{>>} \tau_{\rm QGP},$$

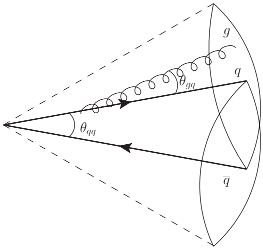
  although *the interaction with the medium can modify the color flow*!

Until very recently the problems of

- Correlations in multiple gluon radiation (i.e. angular ordering)
- Color-flow

essential for our understanding of QCD in the elementary collisions, simply ignored in "jet-quenching" studies

QCD radiation in the vacuum: angular ordering



Radiation pattern of a $q\bar{q}$ antenna
in the vacuum

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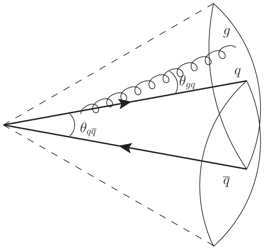


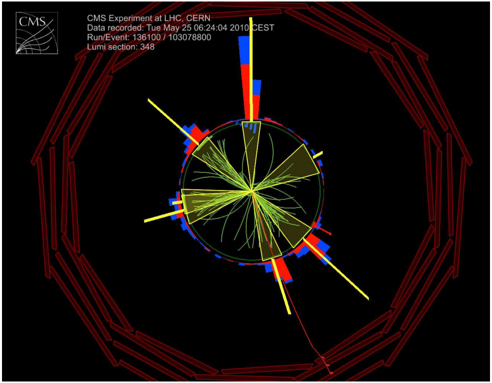
Radiation pattern of a $q\bar{q}$ antenna
in the vacuum

- Formation-time required for gluon radiation: $t_f = 2\omega/k_\perp^2 \sim 1/\omega\theta_{gq}^2$;
- Transverse wave-length of the gluon $\lambda_\perp \sim 1/k_\perp \sim 1/\omega\theta_{gq}$ ...
- ... must be sufficient to *resolve* the transverse separation $d_\perp = t_f\theta_{q\bar{q}}$ reached meanwhile by the pair:

$$1/\omega\theta_{gq} \sim \lambda_\perp < d_\perp \sim \theta_{q\bar{q}}/\omega\theta_{gq}^2$$

- Gluon forced to be radiated within the cone $\theta_{gq} < \theta_{q\bar{q}}$

Angular ordering in parton branching: jet production



Angular ordering of QCD radiation in the vacuum *at the basis of the development of collimated jets*

Angular ordering: Hump-backed Plateau

- In order to resolve the color charges of the antenna

$$\lambda_\perp < d_\perp = t_f\,\theta_{q\bar{q}} \quad \longrightarrow \quad 1/k_\perp < (2\omega/k_\perp^2)\,\theta_{q\bar{q}}$$

- The request $k_\perp > \Lambda_{\mathrm{QCD}}$ leads to the constraint $\omega > \Lambda_{\mathrm{QCD}}/\theta_{q\bar{q}}$

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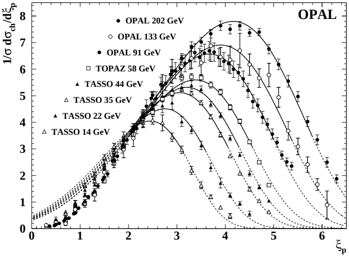
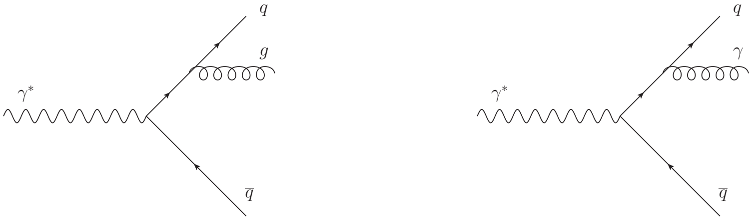


$$\xi \equiv -\ln\left(p^h/E^{\mathrm{jet}}\right)$$

(OPAL collab. – EPJC 27 (2003), 467)

Angular ordering responsible for the *suppression of soft-hadron production* in jet-fragmentation in the vacuum

Color-coherence in QCD: the string effect in e^+e^-



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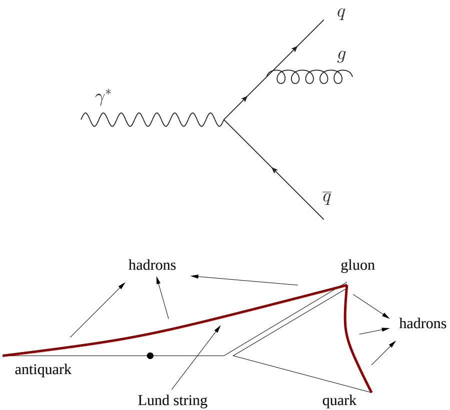

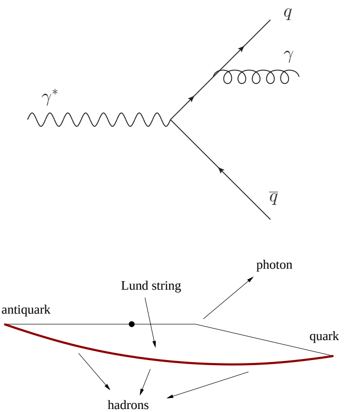

$e^+e^- \to q\bar{q}g$ vs $e^+e^- \to q\bar{q}\gamma$

Exactly the same kinematics, but *different color flow*

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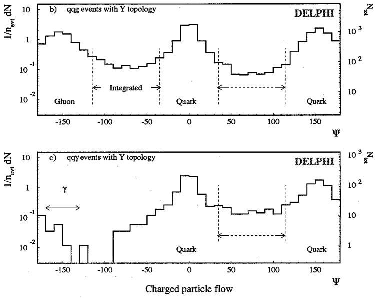

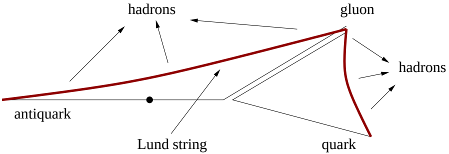

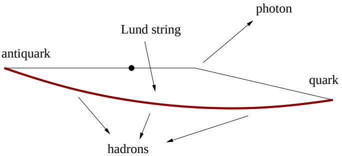

Depletion vs enhancement **of particle production within the $q - \overline{q}$ angle**

A first lesson

- Angular-ordering and color-flow essential to describe *basic qualitative predictions of QCD* in elementary collisions:
    - Development of collimated jets (the experimentally accessible observable closest to quarks and gluons);
    - *Intra-jet* coherence (soft-hadron suppression inside the jet-cone: Hump-backed Plateau);
    - *Inter-jet* coherence (angular pattern of soft particles outside the jets: string effect)

Without explaining the above effects could QCD have been promoted to be THE theory of strong interactions?

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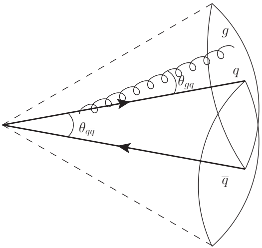
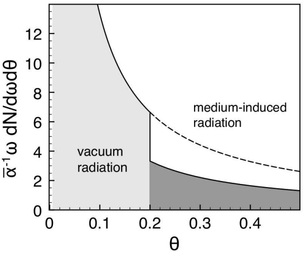
  Without explaining the above effects could QCD have been promoted to be THE theory of strong interactions?
- Hence the interest in studying how the above picture gets modified due to the interaction (i.e. *color-exchange*) with a medium

QCD-antenna radiation in the medium

- Problem analyzed in a series of papers: Y. Mehtar-Tani, C.A. Salgado and K. Tywoniuk, PRL 106 (2011) 122002, PLB 707 (2012) 156-159, JHEP 1204 (2012) 064...
- A plenary talk (by K. Tywoniuk) on this subject...

QCD radiation in the medium: *antiangular* ordering





The total (vacuum+medium) radiation spectrum reads

$$dN_{q,\gamma^*} = \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{\sin\theta\, d\theta}{1-\cos\theta} \left[\theta(\cos\theta - \cos\theta_{q\bar{q}}) + \Delta_{\rm med}\theta(\cos\theta_{q\bar{q}} - \cos\theta)\right]$$

- $\Delta_{\rm med}$ from 0 (no medium effect) to 1 (complete decoherence of the $q\bar{q}$ pair, radiating as two uncorrelated color charges)
- Soft divergence suggesting the possibility of resummation?

...Hence the interest in studying medium-modification of color-flow for high-p_T probes[2]

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

Essential ideas presented here in a $N = 1$ opacity calculation

[2] A.B, J.G.Milhano and U.A. Wiedemann, J. Phys. G G38 (2011) 124118 and Phys. Rev. C85 (2012) 031901 + arXiv:1204.4342 [hep-ph]

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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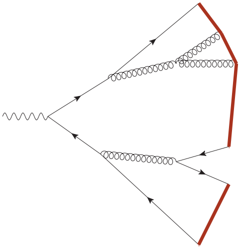

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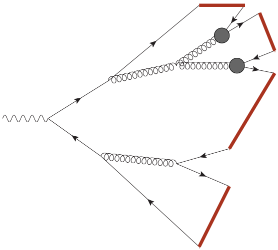
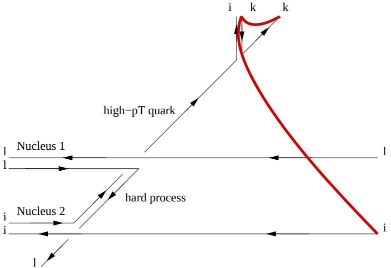


- In PYTHIA hadrons come from the fragmentation of *$q\bar{q}$ strings*, with gluons representing kinks along the string (Lund model);
- In HERWIG the shower is evolved up to a softer scale, all gluons are *forced to split* in $q\bar{q}$ pair (large-N_c!) and *singlet clusters* (usually of *low invariant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

Vacuum radiation: color flow (in large-N_c)



Final hadrons from the fragmentation of the Lund string (in red)

- First endpoint attached to the final quark fragment;
- Radiated gluon – *color connected* with the other daughter of the branching – belongs to the same string forming a kink on it;
- Second endpoint of the string here attached to the beam-remnant (very low p_T, very far in rapidity)

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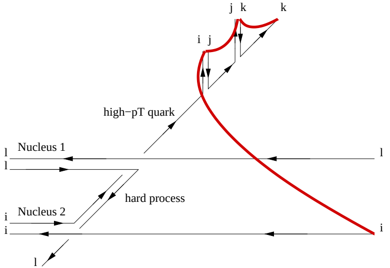

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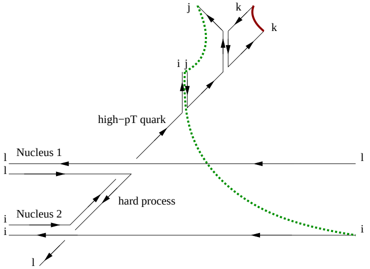
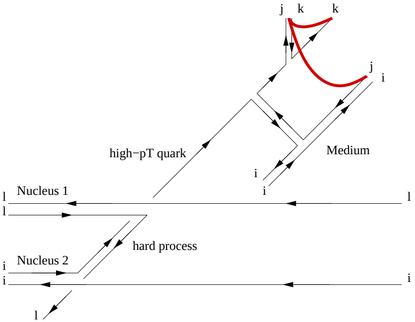


- Most of the radiated gluons in a shower remain color-connected with the projectile fragment;
- Only $g \to q\bar{q}$ splitting can break the color connection, BUT

$$P_{qg} \sim \left[z^2 + (1-z)^2\right] \quad vs \quad P_{qg} \sim \left[\frac{1-z}{z} + \frac{z}{1-z} + z(1-z)\right]$$

less likely: no soft (i.e. $z \to 1$) enhancement!

Medium-induced radiation: color-flow (+ Lund string)



Radiated gluon is part of the string fragmenting into the leading hadron

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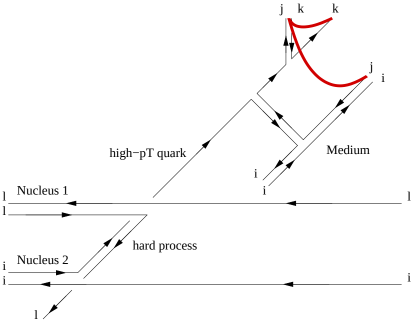

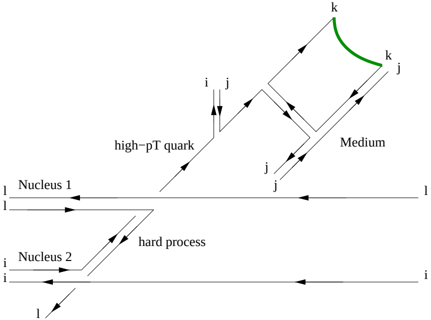

Radiated gluon is part of the string fragmenting into the leading hadron

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

Medium-induced radiation: color flow

- Reminder: if the the hard parton is produced *inside the medium*:

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

The hard parton would radiate losing virtuality also in the vacuum!

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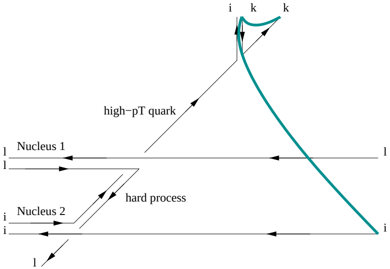

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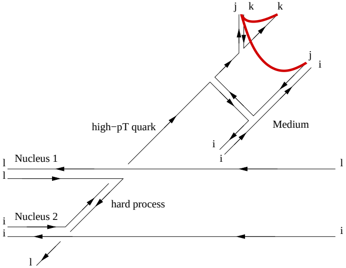

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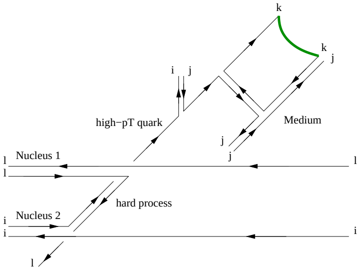

In the forthcoming slides:

- Evaluation of *color-differential* radiation spectrum: QCD-based result!
- Some numerical results: relying on the particular hadronization scheme

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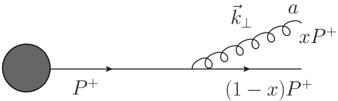
On top of the same amount of partonic energy loss, the presence of channels with the radiated gluon color decohered from the projectile fragment *always entails a softening of the hadron spectrum*

The basic ingredients

- Vacuum-radiation spectrum;
- (Gunion-Bertsch) induced spectrum

Vacuum radiation by off-shell partons

A hard parton with $p_i \equiv \left[p_+, Q^2/2p_+, \mathbf{0}\right]$ 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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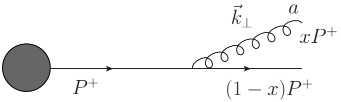

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- $k_\perp$ *vs* virtuality: $\mathbf{k}^2 = x\,(1-x)\,Q^2$;
- Radiation spectrum (our benchmark): IR and collinear divergent!

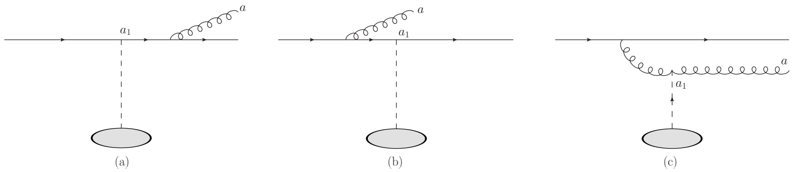
$$d\sigma^{\rm rad}_{\rm vac} = d\sigma^{\rm hard}\frac{\alpha_s}{\pi^2}C_R\frac{dk^+}{k^+}\frac{d\mathbf{k}}{\mathbf{k}^2}$$

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

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

Medium-induced radiation by on-shell partons

- On-shell partons propagating in a color field can radiated gluons.



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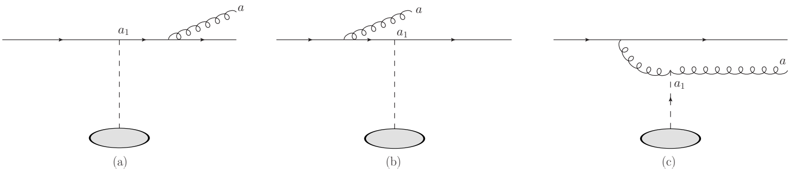


- The single-inclusive gluon spectrum: the Gunion-Bertsch result

$$x\frac{dN_g^{\mathrm{GB}}}{dx\,d\mathbf{k}} = C_R\frac{\alpha_s}{\pi^2}\left(\frac{L}{\lambda_g^{\mathrm{el}}}\right)\left\langle[\mathbf{K}_0-\mathbf{K}_1]^2\right\rangle = C_R\frac{\alpha_s}{\pi^2}\left(\frac{L}{\lambda_g^{\mathrm{el}}}\right)\left\langle\frac{\mathbf{q}^2}{\mathbf{k}^2(\mathbf{k}-\mathbf{q})^2}\right\rangle$$

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

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

Color differential radiation spectrum

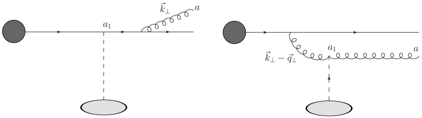
Its general expression is quite cumbersome due to the presence of different time-scales; however in order to get a physical insight it is sufficient to focus on some limiting regimes

Two time-scales for the *color-differential* spectrum

- $1/\omega_1 \equiv 2\omega/(\mathbf{k}-\mathbf{q})^2$: *initial* gluon-momentum;
- $1/\omega_0 \equiv 2\omega/\mathbf{k}^2$: *final* gluon-momentum.

Radiation spectrum: the incoherent limit ($t_f \ll L$)

The $\mathrm{aa_1}$ channel (gluon $\in$ leading string) gets contribution from the diagrams:



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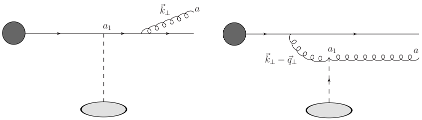

The radiation spectrum reads:

$$x\frac{d\sigma^{\mathrm{rad}}}{dxd\mathbf{k}}\Bigg|_{aa_1}^{\mathrm{incoh.}} = d\sigma^{\mathrm{hard}}\frac{C_F}{2}\frac{\alpha_s}{\pi^2}\left(\frac{L}{\lambda_g^{\mathrm{el}}}\right)\left[\left\langle(\mathbf{K}_0-\mathbf{K}_1)^2\right\rangle+\left\langle\mathbf{K}_1^2\right\rangle\right]$$

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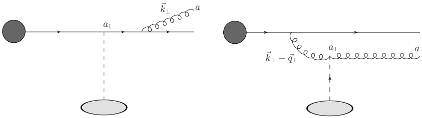


The radiation spectrum reads:

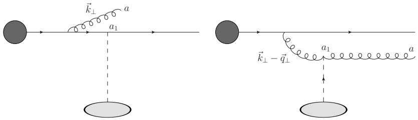
$$x\frac{d\sigma^{\rm rad}}{dxd\mathbf{k}}\bigg|_{aa_1}^{\rm incoh.} = d\sigma^{\rm hard}\frac{C_F}{2}\frac{\alpha_s}{\pi^2}\left(\frac{L}{\lambda_g^{\rm el}}\right)\left[\left\langle(\mathbf{K}_0-\mathbf{K}_1)^2\right\rangle + \langle\mathbf{K}_1^2\rangle\right]$$

Physical interpretation:

- $(C_F/2)\langle(\mathbf{K}_0-\mathbf{K}_1)^2\rangle$: 50% GB spectrum by *on-shell* quark (F);
- $(C_F/2)\langle\mathbf{K}_1^2\rangle$: 50% rescattered vac. rad. by *off-shell* quark (F).

Radiation spectrum: the incoherent limit ($t_f \ll L$)

The $\mathrm{a}_1\mathrm{a}$ channel (gluon decohered!) gets contribution from the diagrams:



The radiation spectrum reads ($C_F = C_A/2$ in the large-N_c limit!):

$$x\frac{d\sigma^{\mathrm{rad}}}{dx d\mathbf{k}}\bigg|_{a_1 a}^{\mathrm{incoh.}} = d\sigma^{\mathrm{hard}}\frac{\alpha_s}{\pi^2}\left[\left(\frac{L}{\lambda_g^{\mathrm{el}}}\right)\left(\frac{C_F}{2}\right)\left(\langle(\mathbf{K}_0-\mathbf{K}_1)^2\rangle+\langle\mathbf{K}_1^2\rangle\right)+\left(\frac{L}{\lambda_q^{\mathrm{el}}}\right)C_F\mathbf{K}_0^2\right]$$

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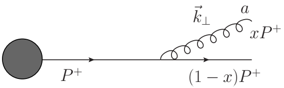
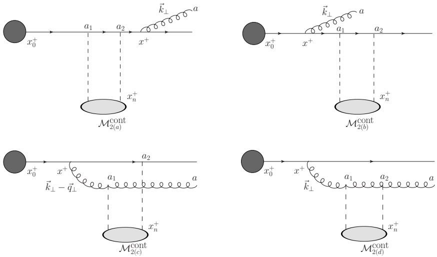
- $(C_F/2)\langle\mathbf{K}_1^2\rangle$: 50% rescattered vac. rad. by *off-shell* quark (F).
- $C_F\mathbf{K}_0^2$: vac. rad. by *off-shell* quark (F) + quark elastic scatt.;

Radiation spectrum: the incoherent limit ($t_f \ll L$)

The a channel (vacuum radiation + unitarity corrections):





$$x\frac{d\sigma^{\mathrm{rad}}}{dxd\mathbf{k}}\bigg|_a^{\mathrm{incoh.}} = x\frac{d\sigma^{\mathrm{rad}}}{dxd\mathbf{k}}\bigg|_{\mathrm{vac}} + d\sigma^{\mathrm{hard}}\frac{\alpha_s}{\pi^2}\left(\frac{L}{\lambda_g^{\mathrm{el}}}\right)\frac{C_F}{2}(-3\mathbf{K}_0^2)$$

The inclusive $(\mathrm{a} + \mathrm{aa}_1 + \mathrm{a}_1\mathrm{a})$ *induced* radiation-spectrum:

$$x\frac{d\sigma^{\mathrm{ind}}}{dxd\mathbf{k}}\bigg|^{\mathrm{incoh.}} = d\sigma^{\mathrm{hard}}C_F\frac{\alpha_s}{\pi^2}\left(\frac{L}{\lambda_g^{\mathrm{el}}}\right)\left\langle(\mathbf{K}_0-\mathbf{K}_1)^2-\mathbf{K}_0^2+\mathbf{K}_1^2\right\rangle$$

Induced radiation vs modified color-flow

A particular kinematic window $\omega_1 L \ll 1 \ll \omega_0 L$

$$d\sigma^{\rm ind}_{aa_1} \sim \mathbf{K}_0^2, \qquad d\sigma^{\rm ind}_{a_1 a} \sim 2\mathbf{K}_0^2, \qquad d\sigma^{\rm ind}_{a} \sim -3\mathbf{K}_0^2$$

- $d\sigma^{\rm ind} = 0$: NO medium-induced radiation;
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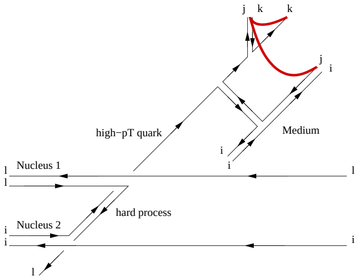
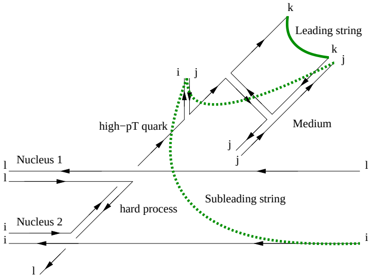
Quenching of the hadron spectra *not due to an enhanced rate of gluon radiation*, but to the *breaking of color-coherence* between the radiated gluon and the projectile fragment

Hadronization in the presence of medium-modified color flow

Hadronization à la PYTHIA

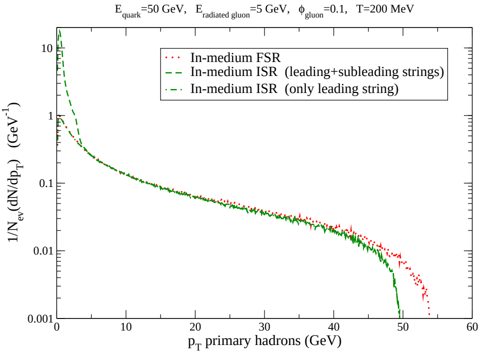


"Final State Radiation"
(gluon $\in$ leading string)
Gluon contributes to leading hadron



"Initial State Radiation"
(gluon decohered: lost!)
Gluon contributes to *enhanced soft multiplicity* from subleading string

Fragmentation function (I)



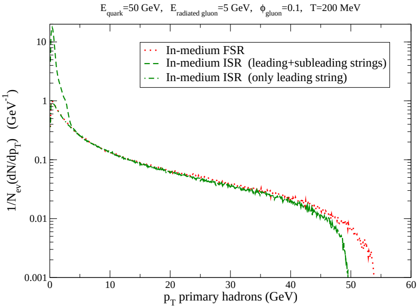
ISR characterized by:

- Depletion of hard tail of FF (gluon decohered!);
- Enhanced soft multiplicity from the subleading string

FF: higher order moments and hadron spectra

Starting from a steeply falling parton spectrum $\sim 1/p_T^n$ at the end of the shower evolution, single hadron spectrum sensitive to *higher moments* of FF:

$$dN^h/dp_T \sim \langle x^{n-1} \rangle / p_T^n$$



- Quenching of hard tail of FF affects higher moments: e.g.
  - FSR: $\langle x^6 \rangle \approx 0.078$;
  - ISR: $\langle x^6 \rangle_{\mathrm{lead}} \approx 0.052$

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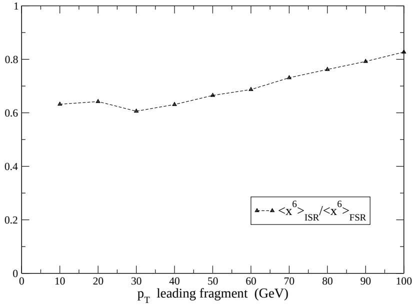

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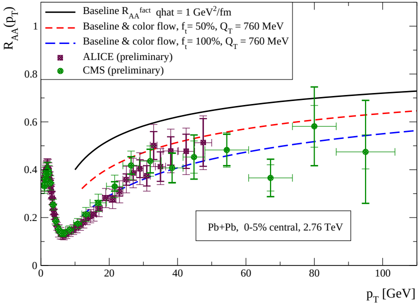

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In summary

- Relevance for jet observables;
- Relevance for single-hadron spectra;
- Relevance for info on medium properties;
- Robustness of the results

Relevance for jet observables

Some comments in the light of experimental results[3]:

- Vacuum-like fragmentation of strings of reduced energy (color-decoherence of radiated gluons), in agreement with no change of hard-FF ($p_T^{\rm track} > 4$ GeV) in Pb+Pb wrt p+p measured by CMS;
- Enhanced multplicity of soft particles from the decay of subleading strings (decohered gluons give rise to new strings!), in agreement with CMS observations;
- Broad angular distribution of soft hadrons around the-jet axis observed by CMS remains to be explained: larger amount of partonic rescattering (i.e. higher orders in opacity) probably required.

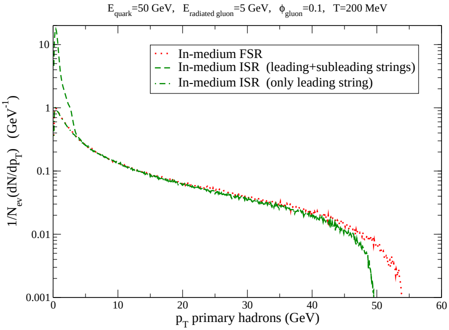
[3] CMS PAS HIN-11-004 and PRC 84, 024906 (2011)

Interplay with antiangular ordering

- Both color-decoherence mechanism would lead to an enhacement of soft particle multiplicity
  - Angular ordering responsible for depletion of soft gluon radiation in jet fragmentation in the vacuum. Antiangular ordering removes such a suppression: mechanism acting *at the partonic level*.
  - Color decoherence of radiated gluons would give rise to independent soft strings to fragment: mechanism acting *at the interface between partonic and hadronic world*.
- Antiangular ordering could be useful to interpret the *broadening of particle production around the jet-cone*

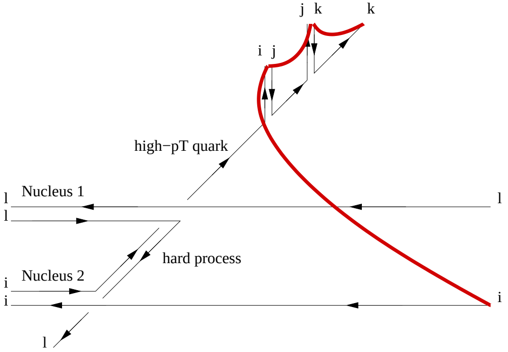
Relevance for single hadron spectrum

Depletion of hard tail of FF with color decoherence of radiated gluons contributes to the *quenching of single-hadron spectra* (R_{AA})



Relevance for info on medium properties

- Hadronization schemes developed to reproduce data from elementary collisions: a situation in which most of the radiated gluons are still color-connected with leading high-p_T fragment;



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- In the case of AA collisions a naive convolution

$$\text{Parton Energy loss} \otimes \text{Vacuum Fragmentation}$$

without accounting for the modified color-flow would result into a too hard hadron spectrum: fitting the experimental amount of quenching would require an overestimate of the energy loss at the partonic level;

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  without accounting for the modified color-flow would result into a too hard hadron spectrum: fitting the experimental amount of quenching would require an overestimate of the energy loss at the partonic level;

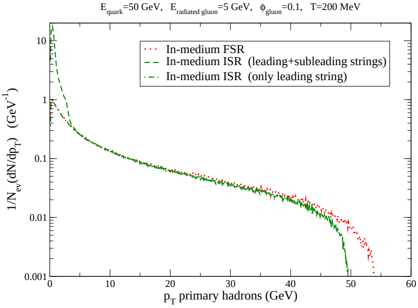
- Color-decoherence of radiated gluon might contribute to reproduce the observed high-p_T suppression with milder values of the medium transport coefficients (e.g. $\hat{q}$).

Robustness of the results

- Any interaction with the medium based on gluon-exchange entails a *modification of color connections*;
- Any hadronization model (string, cluster...) must start from color singlets identified following the color-flow at the partonic level. In particular any color-decohered gluon
  - will be lost for the purpose of leading hadron production;
  - will give rise to a *new independent color-singlet* enhancing soft-particle multiplicity

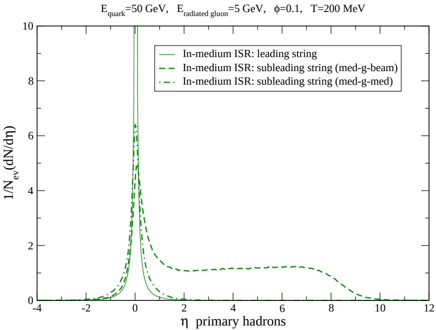
Back-up slides

Full fragmentation function (II)



- FSR: $\langle N_h \rangle \approx 5.4$ hadrons per event, mostly hard (3.9 with $p_T > 2$ GeV);
- ISR: contribution from *leading* and *subleading* strings
  - $\langle N_h \rangle_{\mathrm{lead}} \approx 5.2$ hadrons per event, 3.7 hard;
  - $\langle N_h \rangle_{\mathrm{sublead}} \approx 12.7$ hadrons per event, almost all soft (12 with $p_T < 2$ GeV)

ISR channel: rapidity distribution

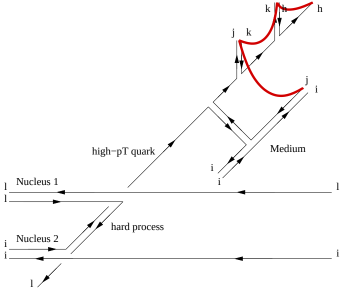


Subleading string linked to beam-remnant leads to rapidity-plateau

- $\langle N_h \rangle_{\mathrm{sublead}} = 12.7$ hadrons per event, but only 4 at $\eta < 1$;
- If both endpoints connected to medium particles: $\langle N_h \rangle_{\mathrm{sublead}}^{\mathrm{med-g-med}} = 3.7$ hadrons per event

Medium-induced radiation + further branching

In case of further showering outside the medium...



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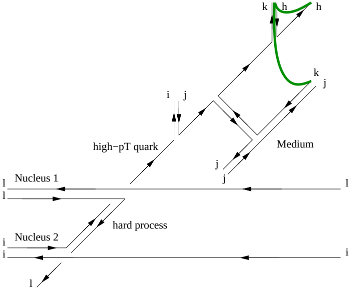
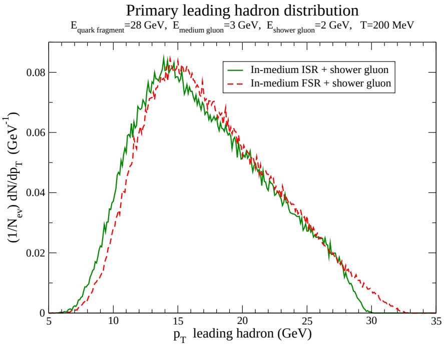


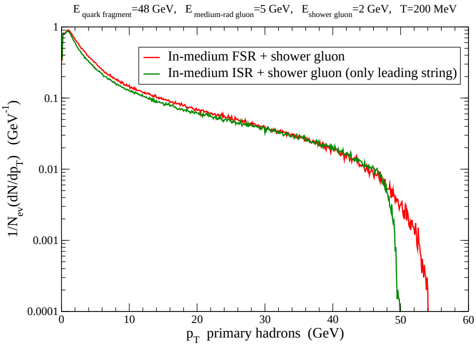
“Initial State Radiation”

Medium-induced radiation + further branching



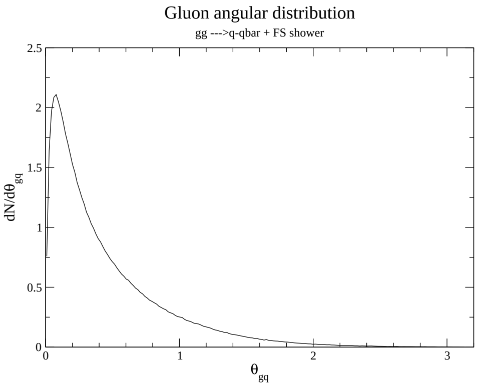
Effect not washed-out by possible radiation outside the medium

Medium-induced radiation + further branching



Effect not washed-out by possible radiation outside the medium

Parton-shower in the vacuum



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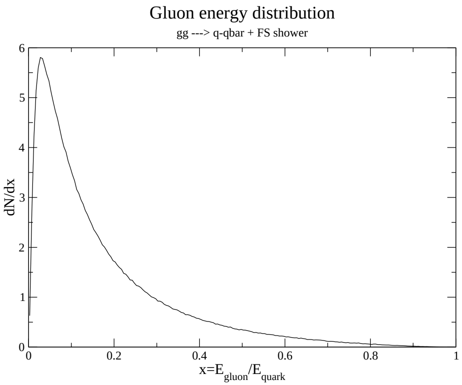
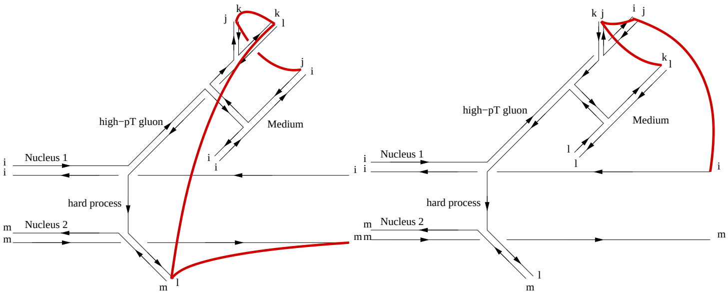


Gluon projectile: color channels



Only 4 color channels contribute in the soft ($\omega \ll E$) limit: the ones in which either its "q" or its "$\bar{q}$" line acts as a *spectator*

- two with "vacuum-like" color-connections

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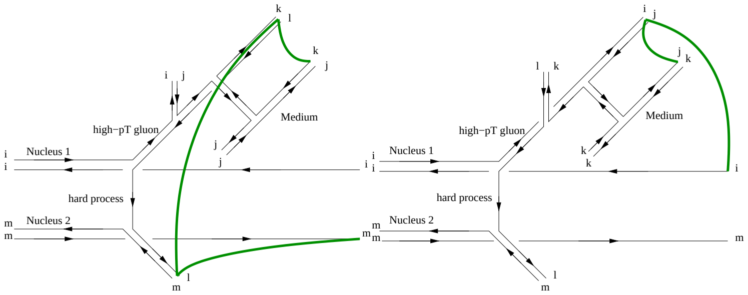

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- two with "vacuum-like" color-connections
- two with medium-induced "color-decoherence"