Parton energy loss in QCD matter

Konrad Tywoniuk

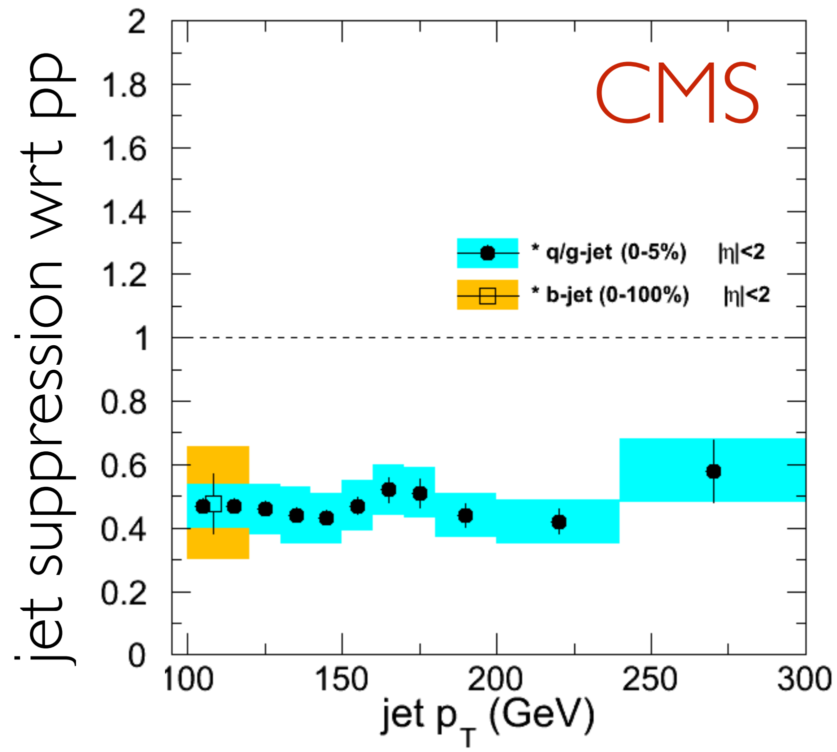
Thanks to: Yacine Mehtar-Tani & Jorge Casalderrey-Solana

Hard Probes 2016, 23-27 Sep 2016, Wuhan, China

Introduction

JETS IN HEAVY-IONS

- strong modifications
  - jet yields
  - dijet energy imbalance
  - intra-jet structure
  - correlations

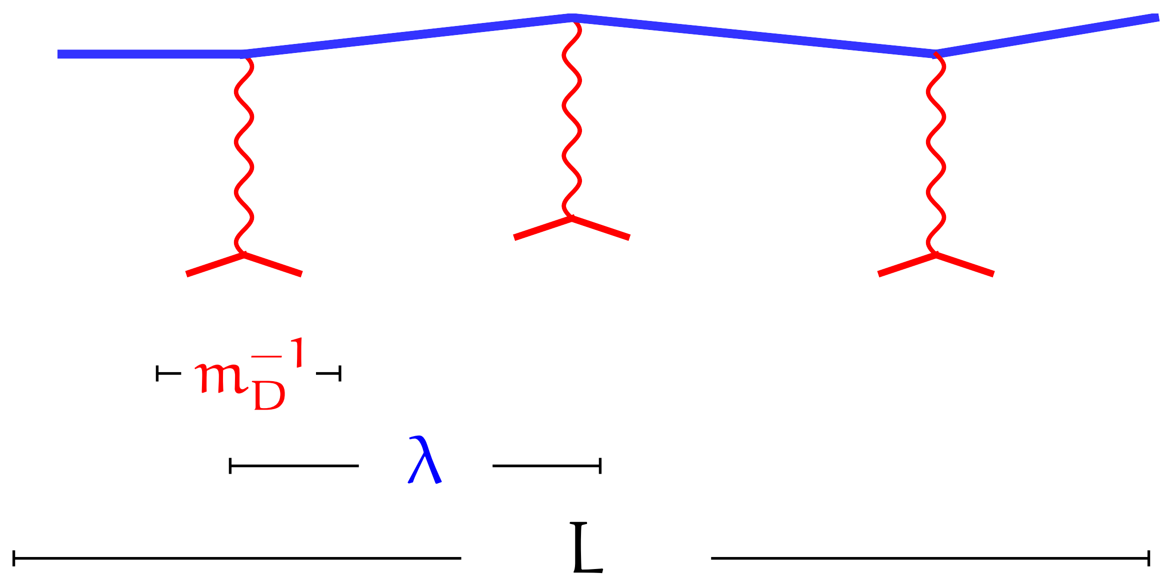


- hope: can be used as probes of the medium (jet tomography)
- transport coefficient $\hat{q}$ and geometry L

Medium effects

Momentum broadening

- $\langle k_T{}^2 \rangle \sim \hat{q} t$
- correlation length ≪ mean free path ≪ L

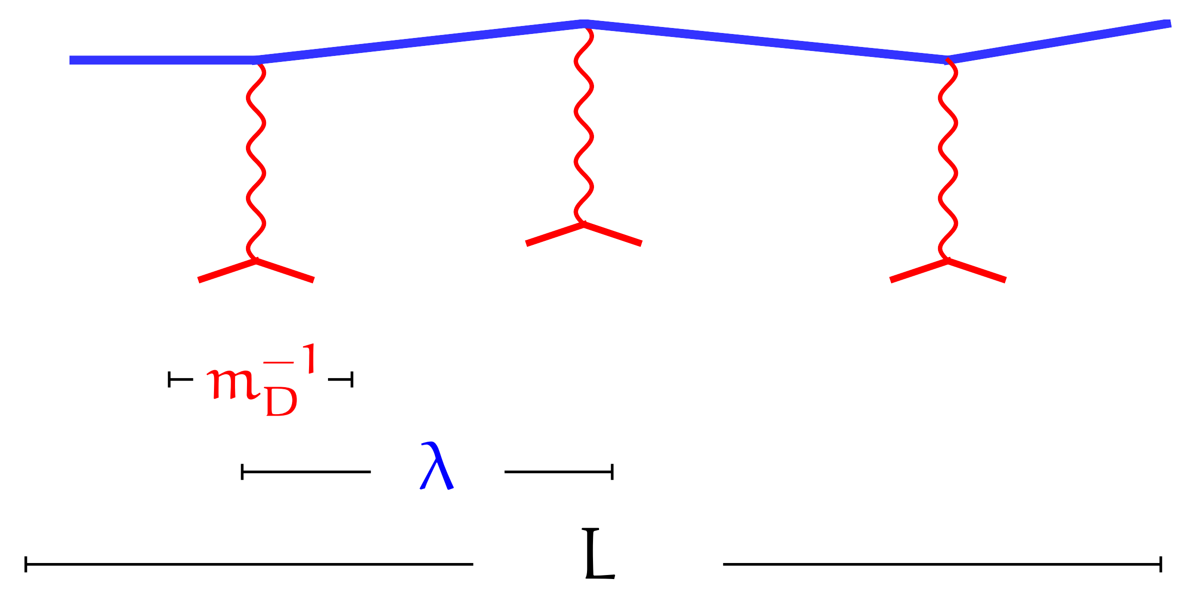


Baier, Dokshitzer, Mueller, Peigné, Schiff (1997-2000), Zakharov (1996), Wiedemann (2000), Gyulassy, Levai, Vitev (2000), Arnold, Moore, Yaffe (2001)

Medium effects

Momentum broadening

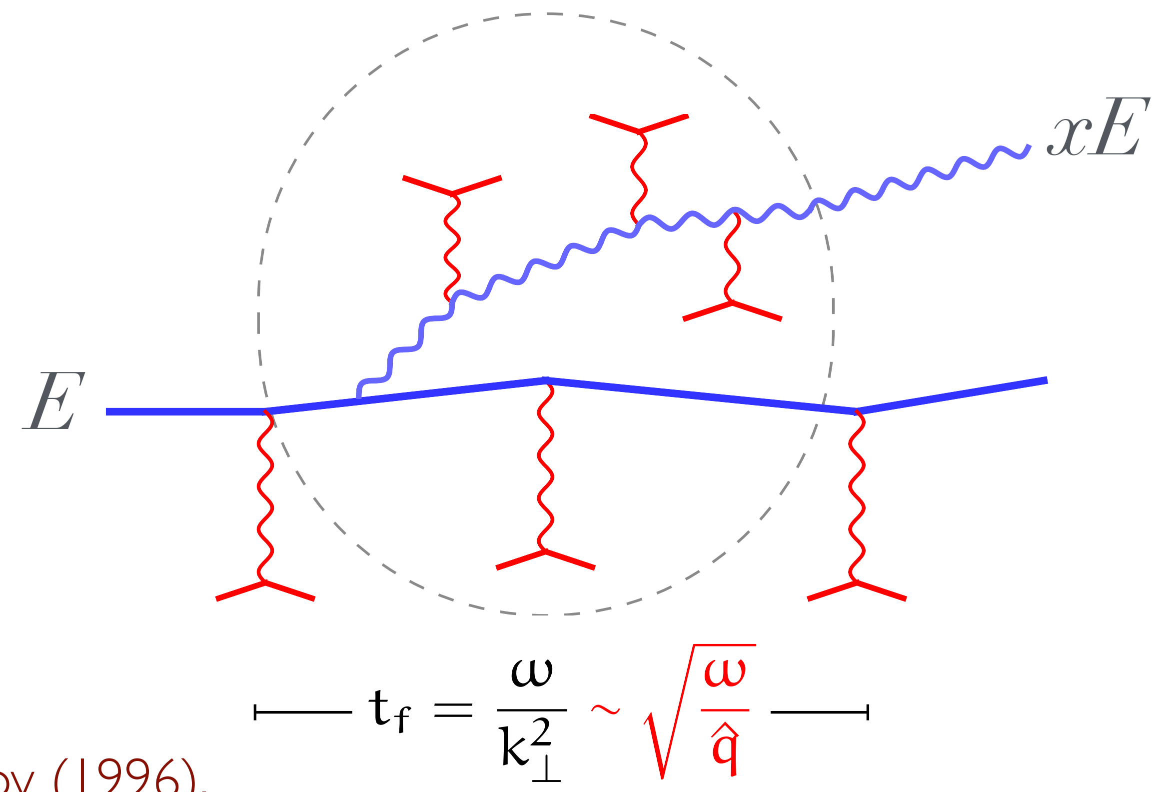
- $\langle k_T{}^2 \rangle \sim \hat{q} t$
- correlation length ≪ mean free path ≪ L



Medium-induced radiation

- energy spectrum
- energy loss: $\Delta E \sim \hat{q} L^2$

$$x \frac{\mathrm{d}I}{\mathrm{d}x} = \frac{\alpha_s\, L}{t_\mathrm{f}}$$



Baier, Dokshitzer, Mueller, Peigné, Schiff (1997-2000), Zakharov (1996), Wiedemann (2000), Gyulassy, Levai, Vitev (2000), Arnold, Moore, Yaffe (2001)

BDMPS-Z SPECTRUM

$\Rightarrow$ soft gluons are emitted rapidly and at large angles
hard emissions take time and are quasi-collinear

BDMPS-Z SPECTRUM

$\Rightarrow$ soft gluons are emitted rapidly and at large angles
hard emissions take time and are quasi-collinear

Scales:

$\omega_c = \hat{q}L^2$ hard scale, *rare* emissions, related to average energy loss

$\omega_s = \alpha_s^2 \hat{q}L^2$ *multiple* emissions, related to "typical" energy loss

$$x\frac{\mathrm{d}I}{\mathrm{d}x} = \alpha_s \sqrt{\frac{\omega_c}{xE}}$$

& suppressed as x^{-2}
$x > \omega_c/E$

BDMPS-Z SPECTRUM

$\Rightarrow$ soft gluons are emitted rapidly and at large angles
hard emissions take time and are quasi-collinear

Scales:

$\omega_c = \hat{q}L^2$ hard scale, *rare* emissions, related to average energy loss

$\omega_s = \alpha_s^2 \hat{q} L^2$ *multiple* emissions, related to "typical" energy loss

$$x \frac{\mathrm{d}I}{\mathrm{d}x} = \alpha_s \sqrt{\frac{\omega_c}{xE}}$$

& suppressed as x^{-2}
$x > \omega_c / E$

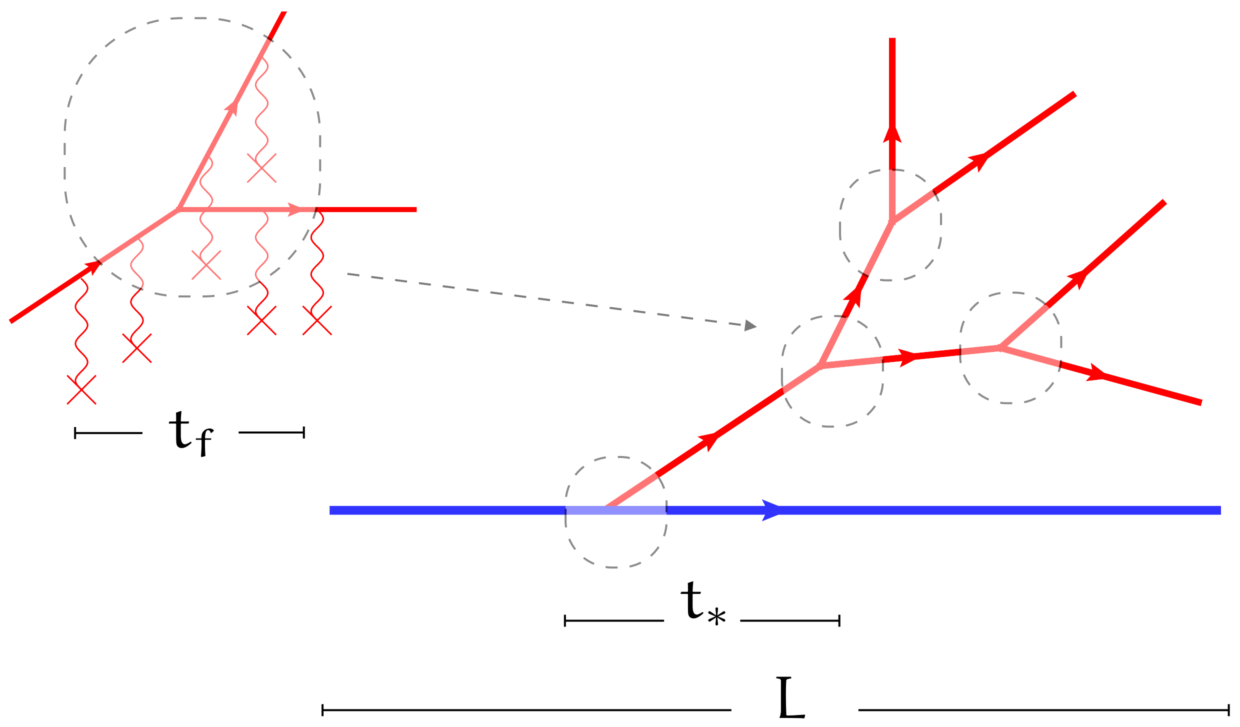
$\mathcal{N}$=1

$$t_\mathrm{f} = \frac{xE}{m_\mathrm{D}^2} \Rightarrow \theta = \frac{m_\mathrm{D}}{xE}$$

$$x \frac{\mathrm{d}I}{\mathrm{d}x} = \alpha_s \frac{L}{\lambda_\mathrm{mfp}}$$

& suppressed as x^{-1}
$x > m_\mathrm{D}^2 L / E$

IN-MEDIUM CASCADE

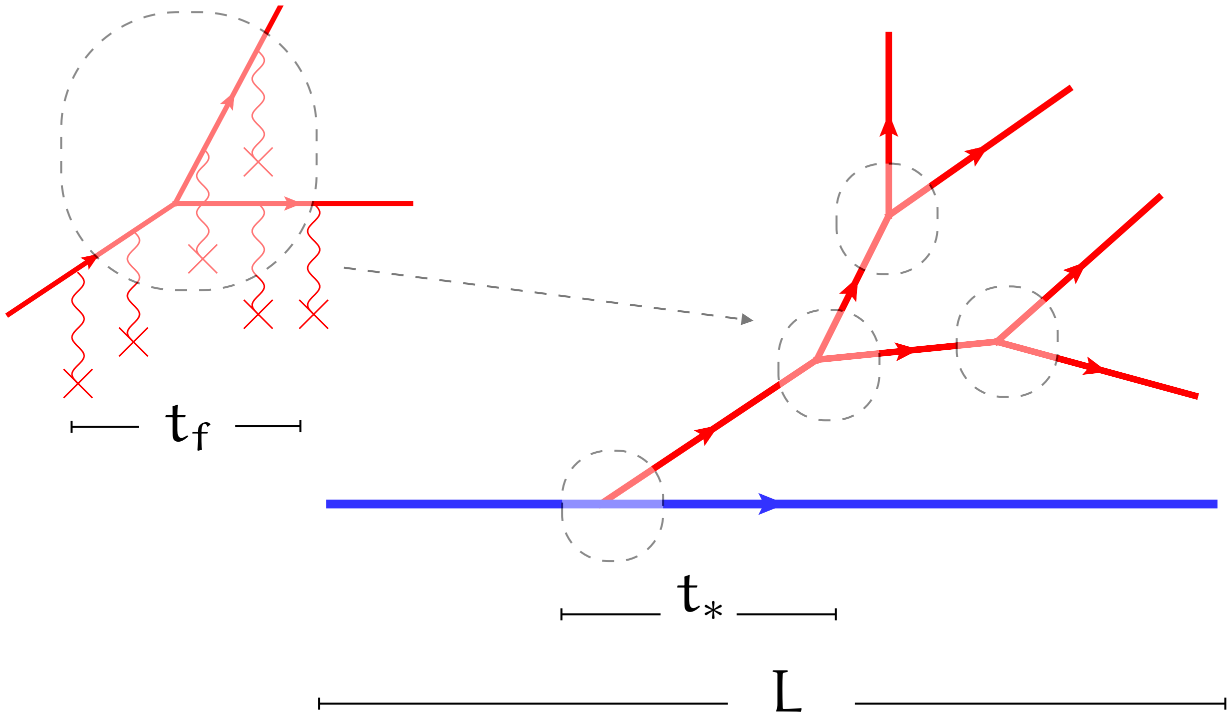


multiple emission regime

$$t_* \ll \frac{1}{\alpha_s} t_f$$

Baier, Mueller, Schiff, Son (2001), Jeon Moore (2003), Blaizot, Dominguez, Iancu, Mehtar-Tani (2014)

IN-MEDIUM CASCADE



multiple emission regime

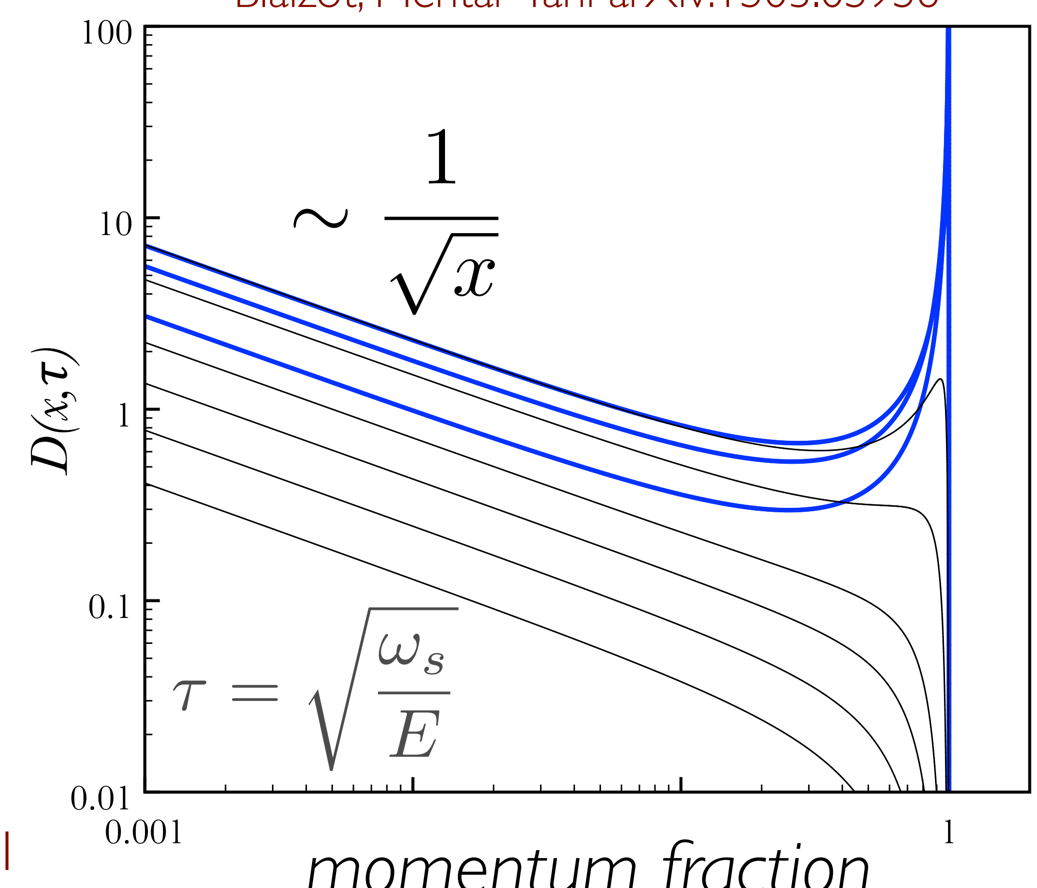
$$t_* \ll \frac{1}{\alpha_s} t_f$$

Baier, Mueller, Schiff, Son (2001), Jeon Moore (2003), Blaizot, Dominguez, Iancu, Mehtar-Tani (2014)

- probabilistic picture
- energy taken away from projectile into soft particles at large angles
- IR: thermalisation (bottom-up)
- multi-particle correlations

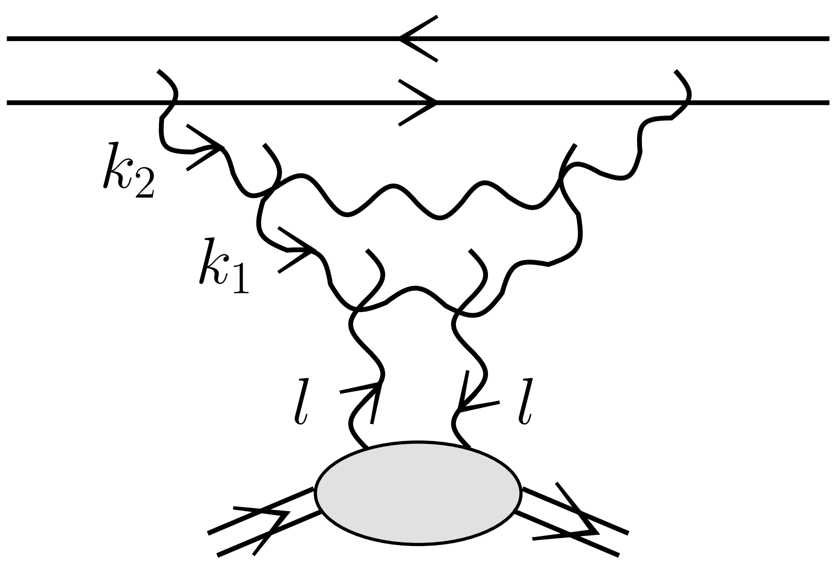
M. A. Escobedo - Sat 24/09 parallel

Blaizot, Mehtar-Tani arXiv:1503.05958



RENORMALIZATION OF $\hat{q}$

Liu, Mueller, Wu arXiv:1304.7677
Blaizot, Mehtar-Tani arXiv:1403.2323
Iancu arXiv:1403.1996



- strongly-ordered emissions
  - overlapping formation times
- resums corrections to $\hat{q}$
  - double-log contributions
- affects observables
  - transverse momentum broadening
  - energy loss

$$\langle p_\perp^2 \rangle = \frac{\alpha_s N_c}{4\pi} \hat{q} L \frac{1}{2!} \ln^2 \left(\frac{L}{l_0} \right)^2$$

$$\Delta E \sim L^{2+\gamma}$$

$$\gamma = 2\sqrt{\bar{\alpha}}$$

OUTSTANDING ISSUES

- corrections to probabilistic picture
  - coherence effects
  - multi-gluon emissions w/overlapping formation times

L. Apolinario - Sat 24/09 parallel
F. Dominguez - Sun 25/09 parallel

- vacuum+medium: how can we combine them?
  - novel tools: effective field theory (SCET)
  - interferences & ordering (MC prescription)
  - observables

I.Vitev - Mon 25/09 plenary

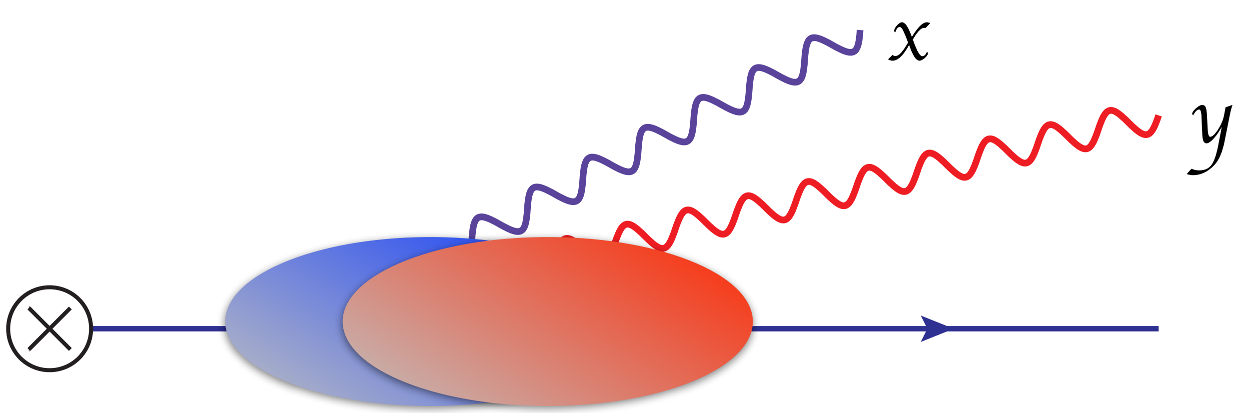
- modified hadronisation mechanism
- medium response
- medium modeling

D. Pablos - Sat 24/09 parallel
Y.Tachibana, N.-B. Chang - Sat 24/09 parallel

J. Casalderrey-Solana - Fri 23/09 plenary

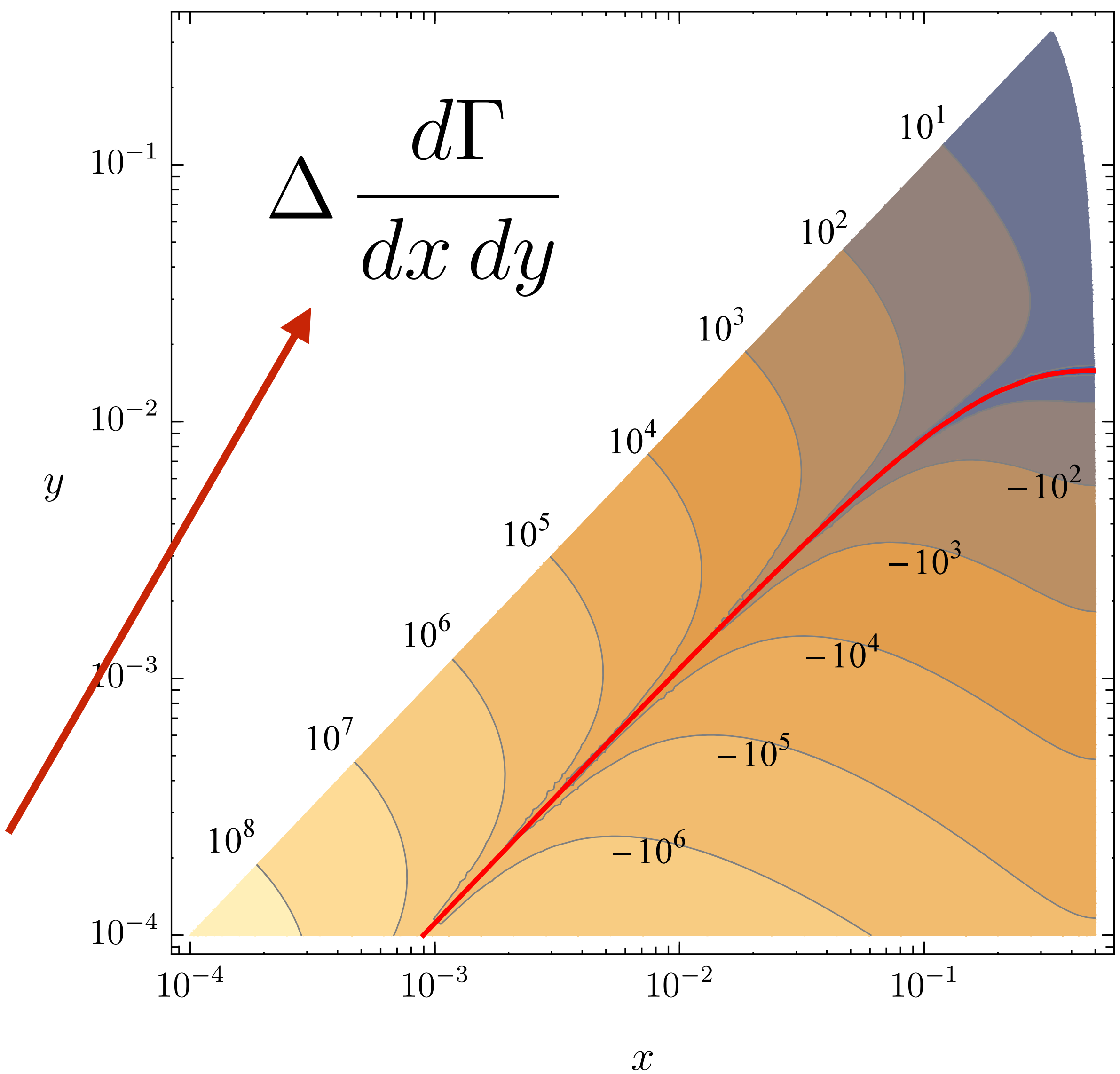
MULTI-GLUON PROCESSES

LPM effect in 2-gluon emissions



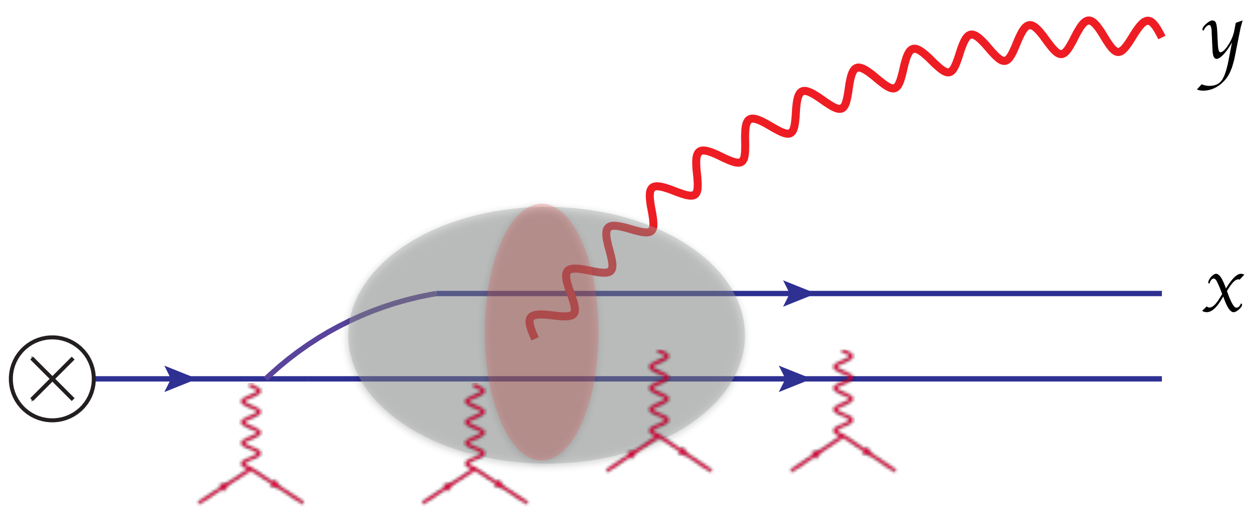
Arnold, Iqbal arXiv:1501.04964
Arnold, Chang, Iqbal arXiv:1605.07624, arXiv:1606.08853, arXiv:1608.05718

- one-to-three splitting (large-N_c, real diagrams, no angle)
- important accomplishment
- reproduces real contributions: absorbed in $\hat{q}$
- corrections to probabilistic picture
  - negative weights!



WHY NEGATIVE?

Arnold, Chang, Iqbal arXiv:1605.07624



- contribution arises from overlapping emissions
- instead of radiation from daughters of the splitting: radiation off total charge
- colour coherence in medium relates the decoherence time to the formation time

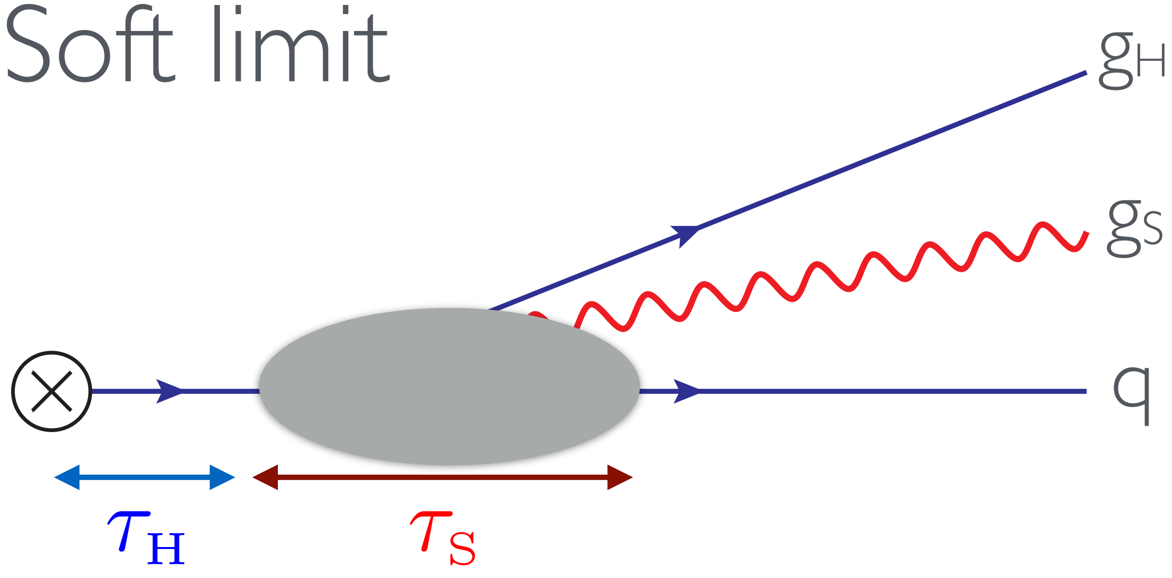
2-GLUON: INCLUDING ANGLE

Casalderrey-Solana, Pablos, KT arXiv:1512.07561

- two-gluon emission off a hard quark
  - $\mathcal{N}=1$ opacity
- one gluon is "hard", the "soft" can be medium-induced
- interested in the angular structure
  - comparable angles $\vartheta_{\mathcal{H}} \sim \vartheta_{S}$
- complicated expression: explore in detail two limits relevant for jet fragmentation studies

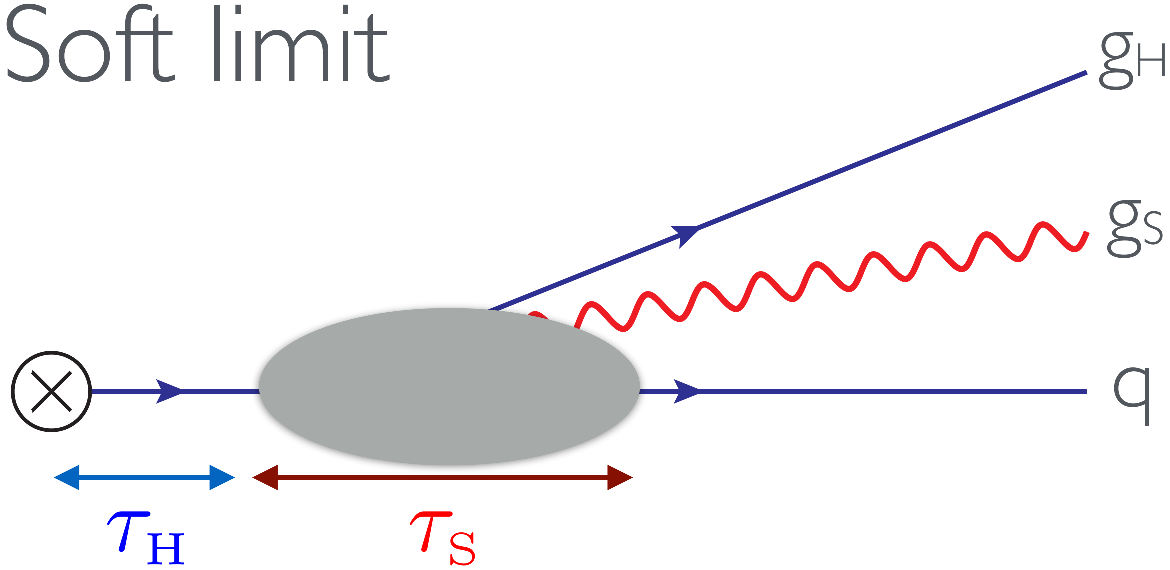
1 → 3 Splitting function, full kinematics   Fickinger, Ovanesyan, Vitev arXiv:1304.3497

Soft limit



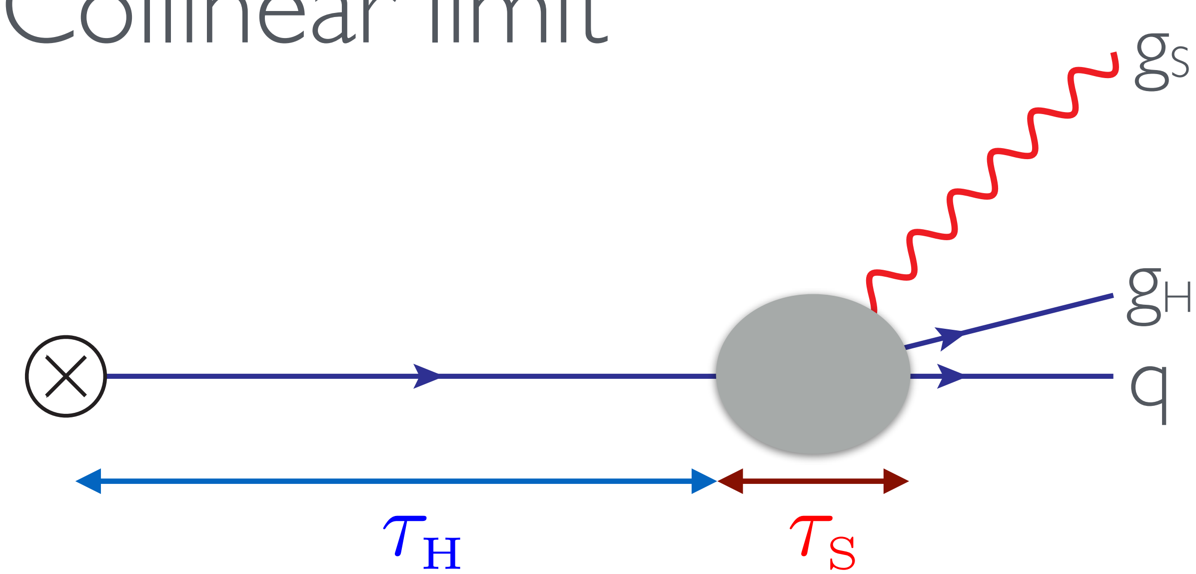
- g_H much *harder* than medium scale
- g_H formed with much *smaller* formation time than g_S
- forming a "dipole" early on

Soft limit



- g_H much *harder* than medium scale
- g_H formed with much *smaller* formation time than g_S
- forming a "dipole" early on

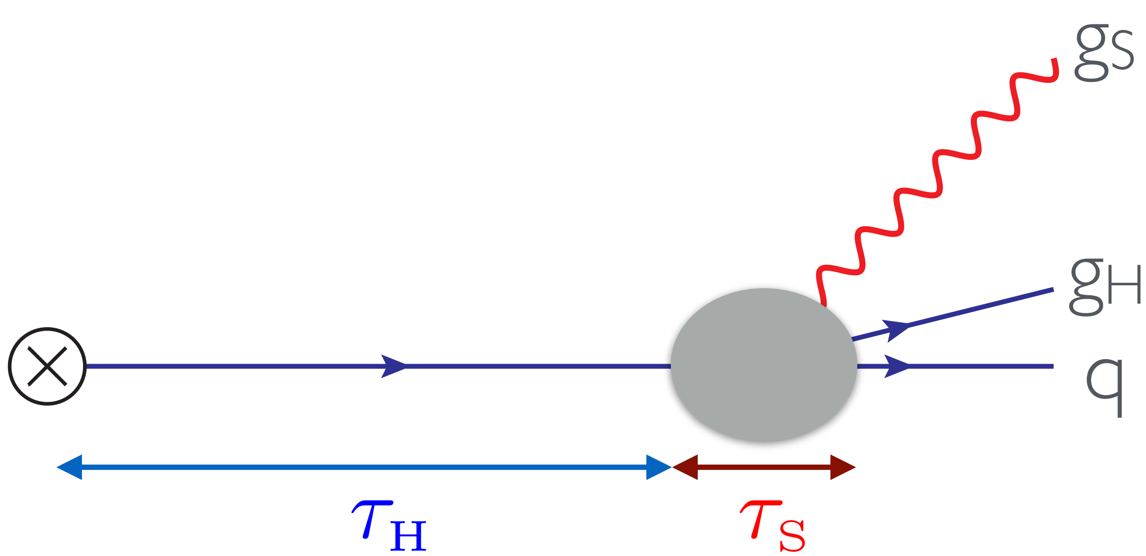
Collinear limit



- g_H much *softer* than medium scale
- g_H formed with much *longer* formation time than g_S
- "dipole" emerges after finite time

FINITE FORMATION TIME

Casalderrey-Solana, Pablos, KT arXiv:1512.07561



- completely resolved system
- soft gluon spectrum controlled by the formation time of hard gluon!
  - no emission before the hard gluon appears
- collinear limit: vacuum radiation off g_H suppressed due to angular ordering
  - finite resolution time in medium
  - radiation comes from an on-shell colour source!

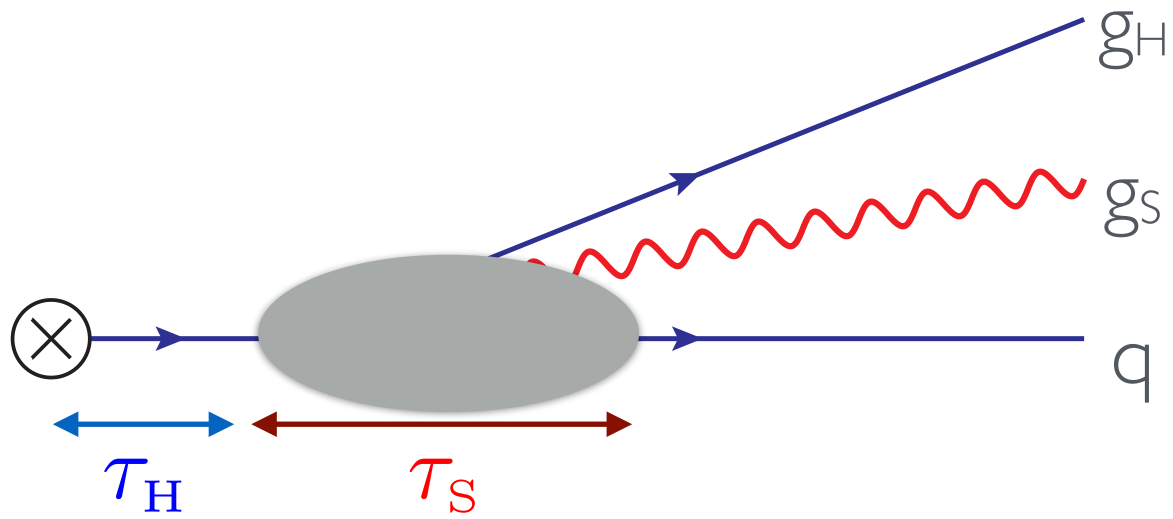
this limit insensitive to medium resolution scale

➡ need to study $z \sim r \rightarrow 0$ limit

P. Arnold et al. 2015-2016

SMALL FORMATION TIME

Casalderrey-Solana, Pablos, KT arXiv:1512.07561

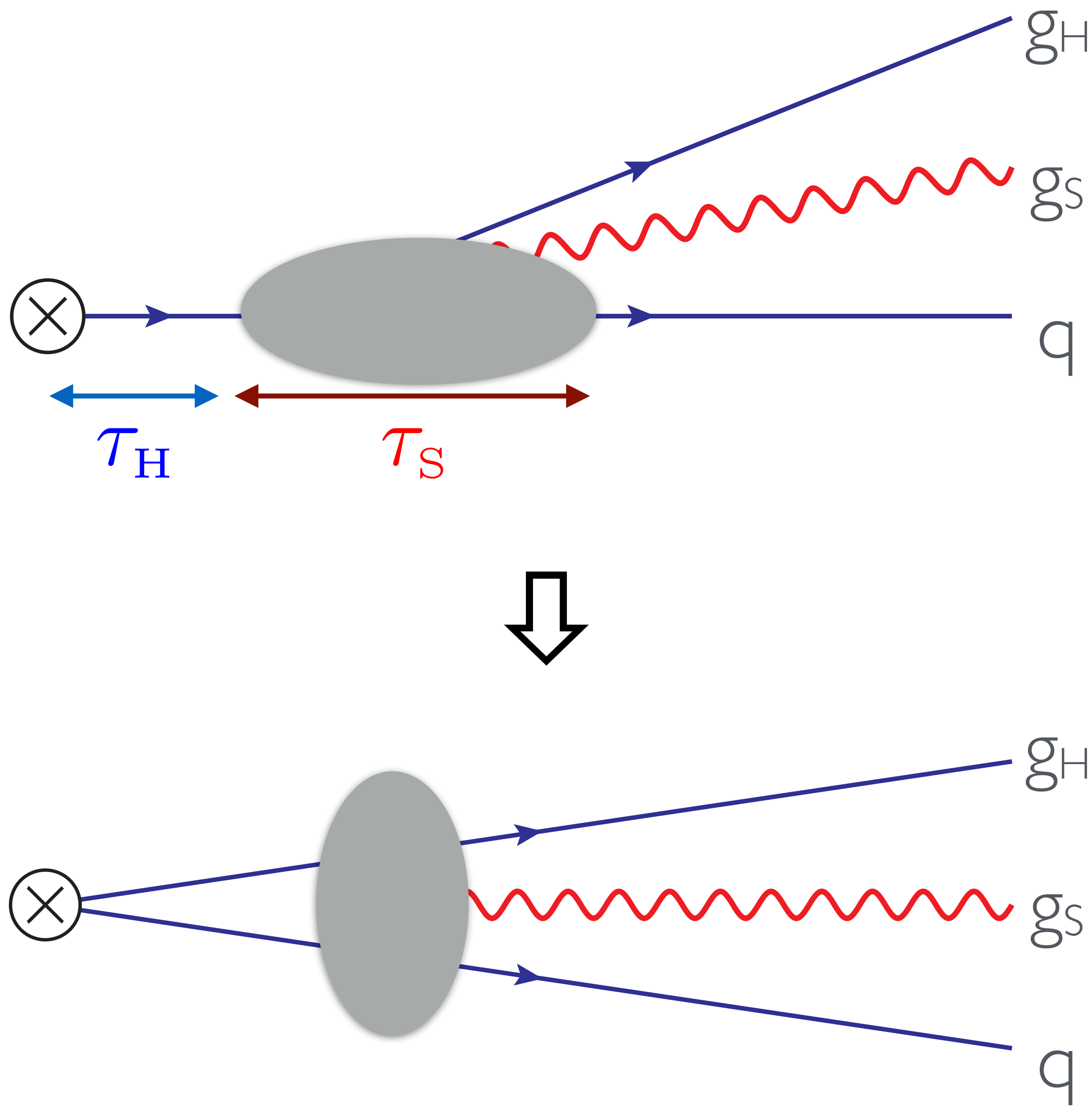


- double-inclusive is a product of
  - cross section for hard gluon
  - spectrum off quark-gluon system
- recover the antenna spectrum!
- hard scale analysis
  - compare the resolution scale of the medium to the opening angle of the jet

Mehtar-Tani, Salgado, KT PRL 106 (2011) 122002, PLB (2012), JHEP (2012)
Casalderrey-Solana, Iancu JHEP (2012)

SMALL FORMATION TIME

Casalderrey-Solana, Pablos, KT arXiv:1512.07561



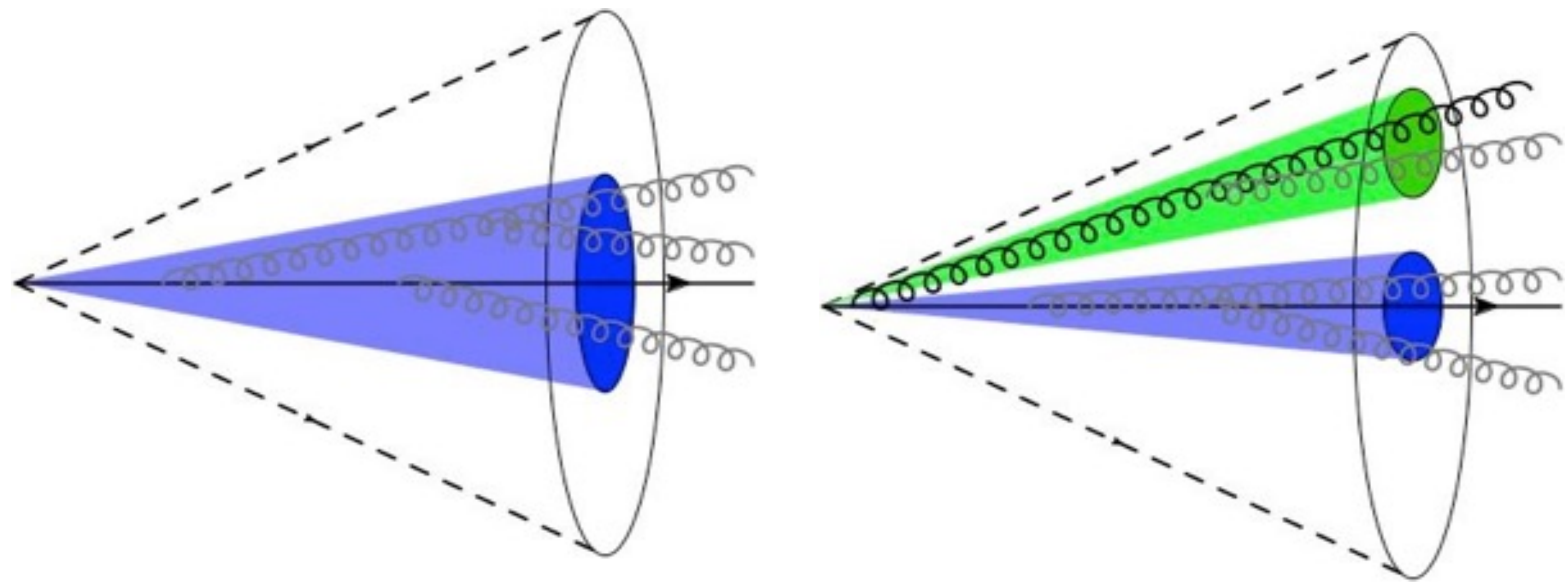
- double-inclusive is a product of
  - cross section for hard gluon
  - spectrum off quark-gluon system
- recover the antenna spectrum!
- hard scale analysis
  - compare the resolution scale of the medium to the opening angle of the jet

Mehtar-Tani, Salgado, KT PRL 106 (2011) 122002, PLB (2012), JHEP (2012)
Casalderrey-Solana, Iancu JHEP (2012)

NEW PICTURE OF JETS

Casalderrey-Solana Mehtar-Tani, Salgado, KT PLB 725 (2013) 357

number of medium-resolved substructures



energy loss	radiation as total charge	radiation as independent charges

- fragmentation within each substructure: vacuum-like
- clean theoretical limit: unresolved jet
  - study small deviations from this limit

Role of colour coherence firmly established

- antenna calculations
- two-gluon emission

Is coherence an $\mathcal{O}(1)$ effect?

JET SUBSTRUCTURE MEASUREMENTS

JETS AS PROBES OF QCD MATTER

Jet "tomography"

using jet observables to extract properties of the medium (geometry and local properties)

Caveats

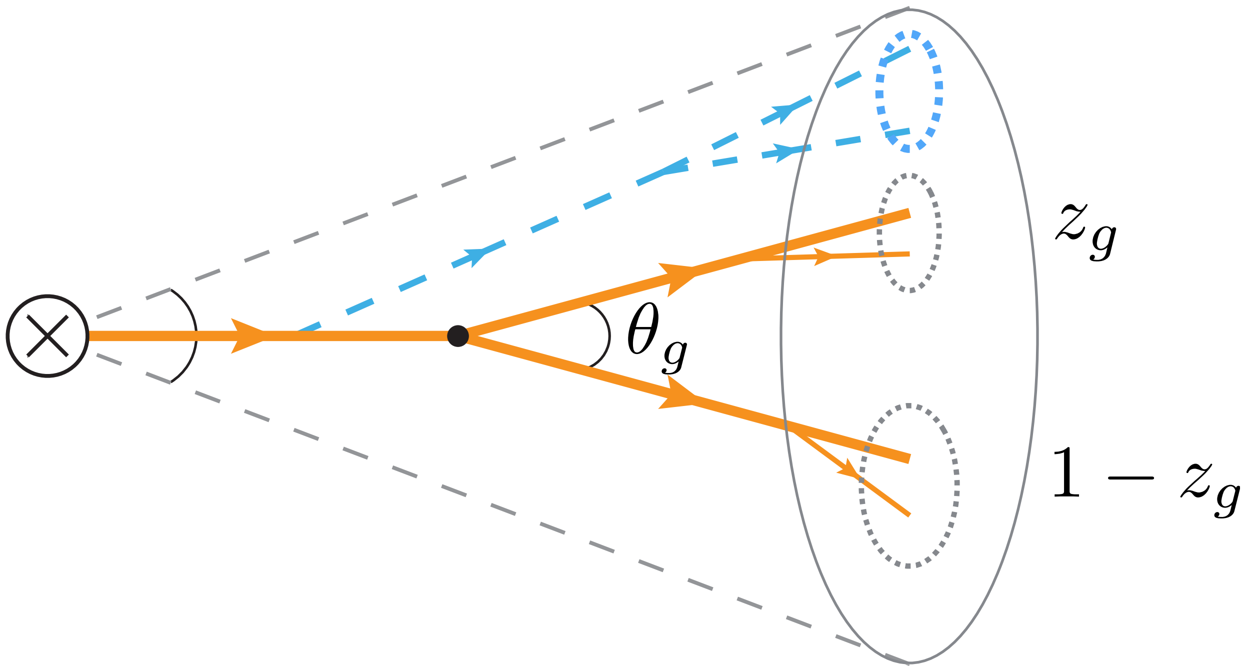
1. sensitive to accumulated effects
   - $w_1 \times$(elastic proc) + $w_2 \times$(inelastic proc)
   - qualitative features easily accommodated for by models with different assumptions and/or different path-length behaviour
2. depending on implementations of jet evolution
   - apply modifications before, after or during jet branching?
3. depending on details of underlying medium dynamics
   - medium response, etc.

Are there observables that are sensitive to the properties of the medium in a more *direct* way?

Can we measure *directly* a new & distinct contribution to the spectrum of final-state hadrons?

JET GROOMING

Larkoski, Marzani, Thaler PRD (2015); Larkoski, Marzani, Soyez, Thaler JHEP (2014)
M. Cacciari - Fri 23/09 plenary



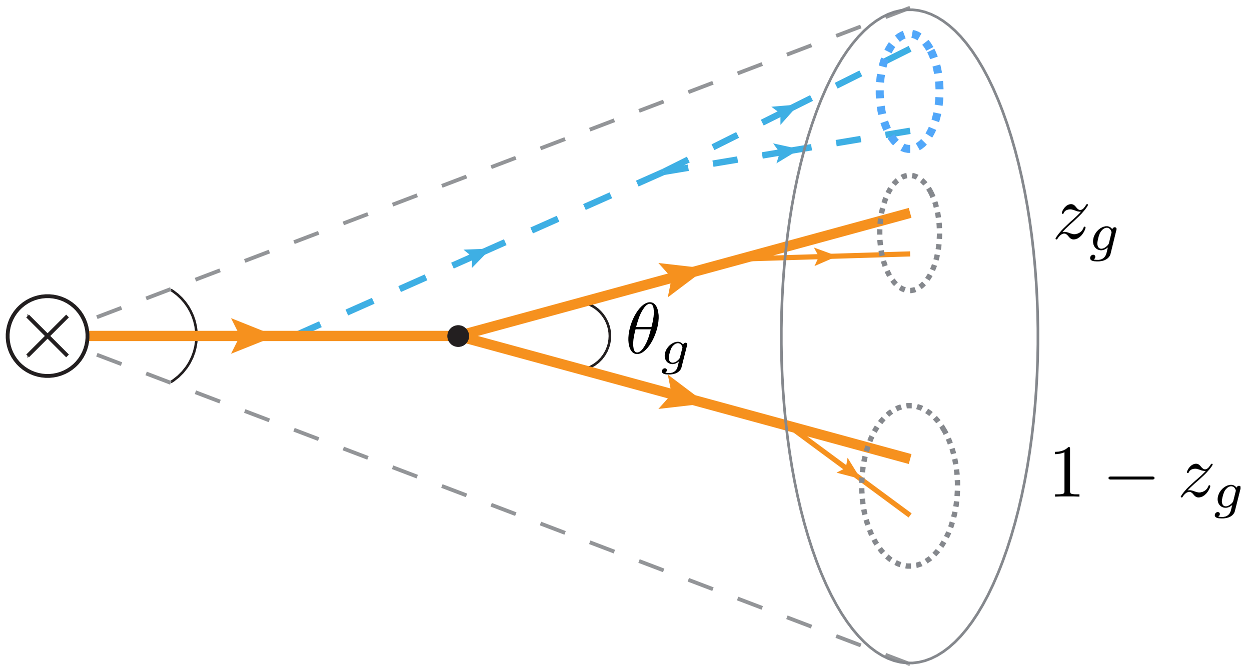
$$z > z_{\mathrm{cut}}\theta^{\beta}$$

Using "soft drop" procedure, we can clean the jet of soft "junk" & probe the first* perturbative QCD splitting

in an angular ordered tree.

JET GROOMING

Larkoski, Marzani, Thaler PRD (2015); Larkoski, Marzani, Soyez, Thaler JHEP (2014)
M. Cacciari - Fri 23/09 plenary



$$z > z_{\text{cut}}\theta^{\beta}$$

Using "soft drop" procedure, we can clean the jet of soft "junk" & probe the first* perturbative QCD splitting

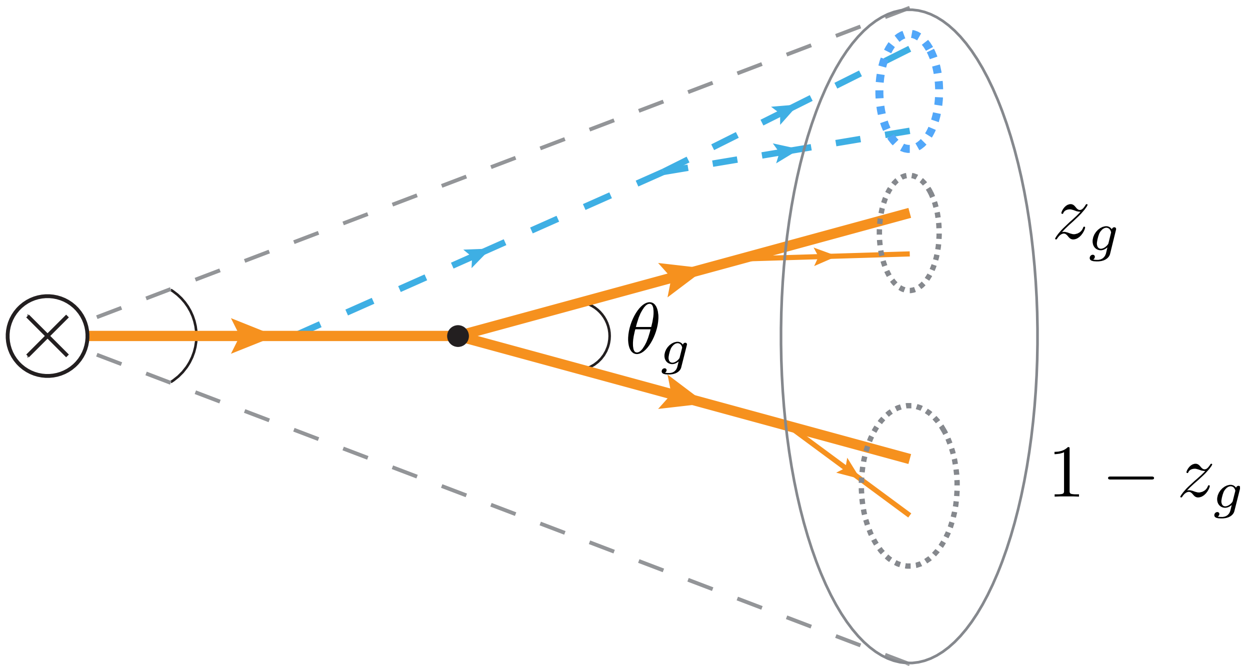
*in an angular ordered tree.

QCD splitting function:
(soft & collinear divergences)

$$\mathcal{P}^{\text{vac}}(z,\theta) = \alpha_s \frac{P_{gg}(z)}{\theta}$$

JET GROOMING

Larkoski, Marzani, Thaler PRD (2015); Larkoski, Marzani, Soyez, Thaler JHEP (2014)
M. Cacciari - Fri 23/09 plenary



$$z > z_{\rm cut}\theta^{\beta}$$

Using "soft drop" procedure, we can clean the jet of soft "junk" & probe the first* perturbative QCD splitting

*in an angular ordered tree.

QCD splitting function:
(soft & collinear divergences)

$$\mathcal{P}^{\rm vac}(z,\theta) = \alpha_s \frac{P_{gg}(z)}{\theta}$$

Probability:

$$p(z_g) = \int_0^{\theta_{\rm jet}} {\rm d}\theta\, \Delta(\theta_{\rm jet},\theta)\mathcal{P}^{\rm vac}(z_g,\theta)\Theta_{\rm cut}(z_g,\theta)$$

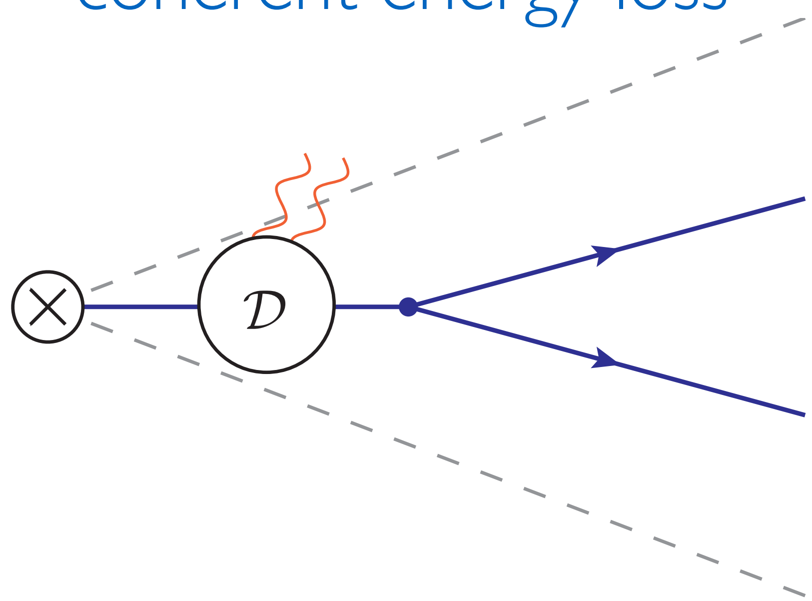
Sudakov form factor
accounts for groomed emissions

For β=0: splitting probability does not depend on α_s or flavour

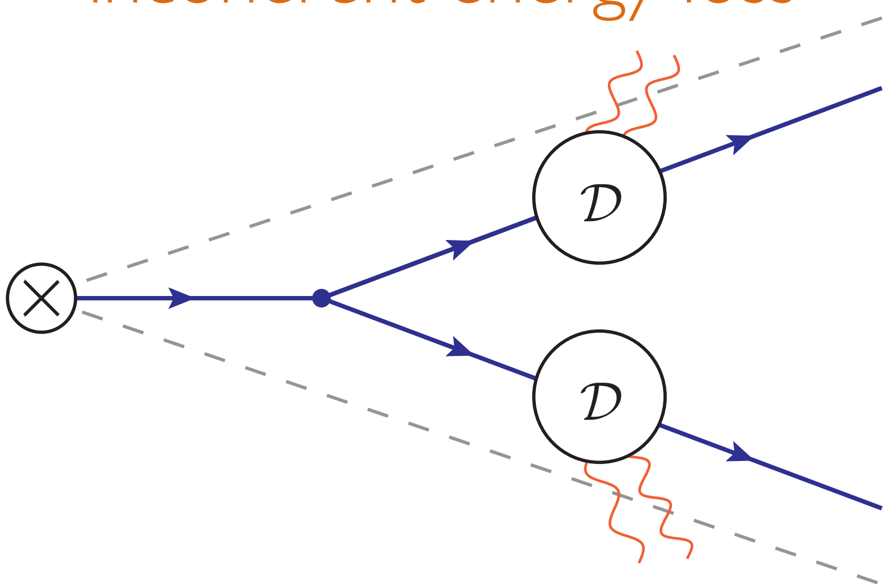
$$p(z_g) \sim 1/[z(1-z)]$$

LOOKING INTO THE JET CORE

Mehtar-Tani, KT 1609:xxxx



$$\mathrm{d}\sigma \sim \frac{\alpha_s}{z} Q(E_{\mathrm{jet}})$$



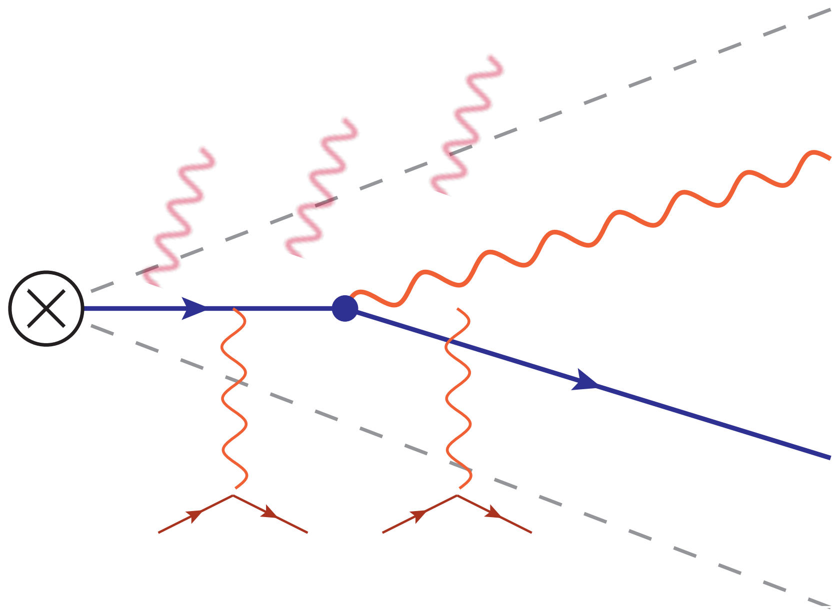
$$\mathrm{d}\sigma \sim \frac{\alpha_s}{z + z^*} Q^2(E_{\mathrm{jet}})$$

- internal structure of jet affected only if resolved
  - regularises infrared behaviour $z^* \sim \omega_s / E_{\mathrm{jet}}$
- e-loss: depends on the number of resolved jet substructures
  - coherence plays a crucial role!

quenching factor: $Q(E) = \frac{1}{\sigma} \int_\epsilon D(\epsilon) \mathrm{d}\sigma(E + \epsilon) \sim R_{AA}$

NOVEL RADIATIVE CONTRIBUTION

Mehtar-Tani, KT 1609:xxxx

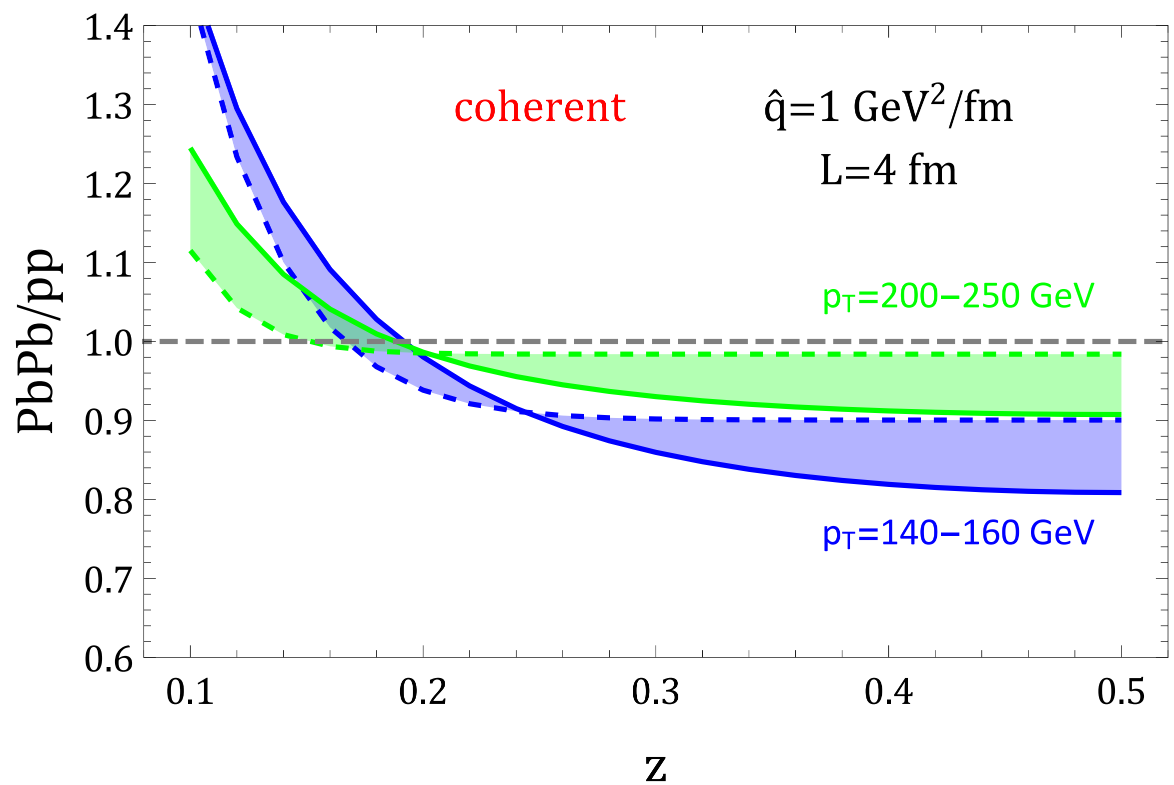


Medium-induced soft gluons:

$$\mathrm{d}\sigma_{\mathrm{LPM}} \sim \frac{\alpha_s}{z^{3/2}}\sqrt{\frac{\hat{q}L^2}{E_{\mathrm{jet}}}}$$

$\mathcal{N}=1$: $\mathrm{d}\sigma \sim z^{-2}E^{-1}$ for "hard" gluons

- add to vacuum: *rare emissions* of gluons due to interaction with the medium!
- have to take into account the limited angle due to momentum broadening
- multiple interactions: enhanced infrared energy range
  - $\mathcal{N}=1$: study the interplay!



YaJEM: K. Lapidus; JEWEL: R. Kunnawalkam Elayavalli - Sat 24/09 parallel
Vitev, Chien arXiv:1608.07283

Outlook

- lot of progress
  - multi-gluon/multi-leg calculations
  - convergence of tools & ideas
- probabilistic picture w/running transport coefficients
- importance of coherence effects
  - vacuum & medium
  - $\mathcal{O}(1)$ effect
- novel observables: jet substructure
  - potentially a *direct* probe of radiative mechanism in the medium
  - analytical tools & insight valuable for qualitative features

Thank you!

Backup

Grooming in medium

CMS Collaboration CMS-PAS-HIN-16-006

takes "physical meaning" due to interactions
- ➡ scanning formation times
- ➡ modified grooming angle and splitting fraction!

Angular range: $\vartheta_{\text{res}}=0.1 < \vartheta < \vartheta_{\text{jet}}=0.4$

typical vacuum radiation

$$t_{\text{f}} = \frac{1}{zE\theta^2}$$

~10-2-1.5 fm

$$t_{\text{f}} = \sqrt{\frac{zE}{\hat{q}}}$$

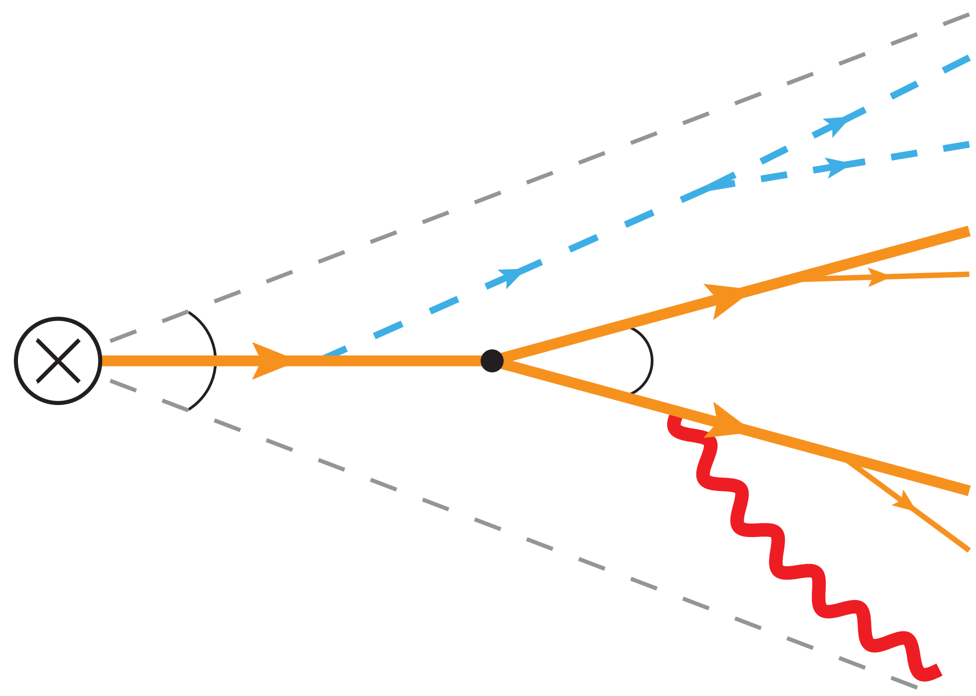
typical medium radiation

~0.5-2.5 fm

Med gluon can still broaden (inside the cone) $\theta = \sqrt{\hat{q}L}/\omega$

5 GeV < ω_{med} < 20 GeV

COMPLICATED SHOWER STRUCTURE



can probably only be accessed in MC

JEWEL: R. Kunnawalkam Elayavalli - Sat 24/09 parallel