“Jets” in heavy-ion collisions

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PHYSICAL REVIEW D VOLUME 34, NUMBER 9 1 NOVEMBER 1986

Jets in expanding quark-gluon plasmas

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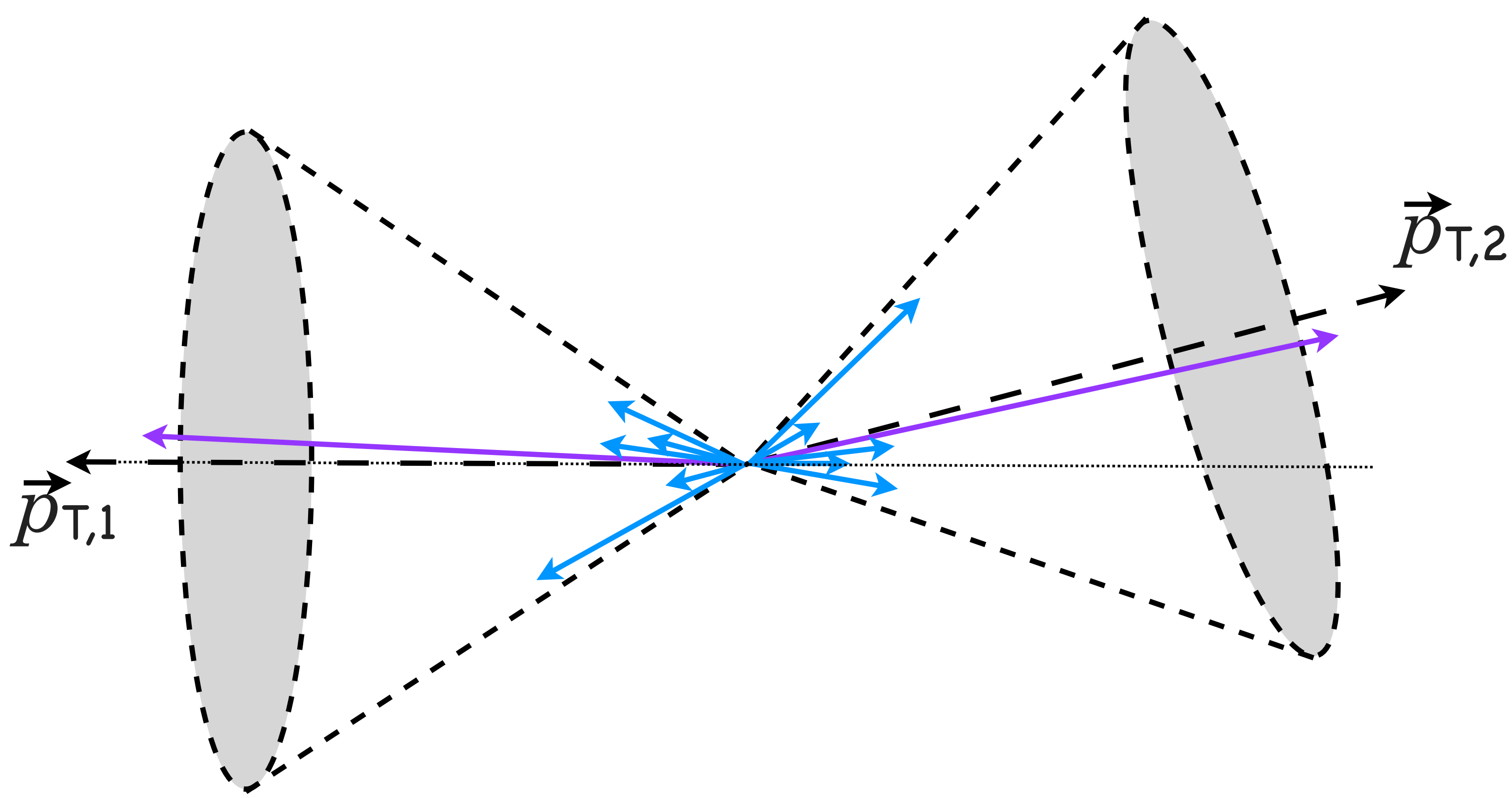
(Received 30 April 1986)

We study the transverse-momentum imbalance (acoplanarity) of a gluon jet propagating in an expanding quark-gluon plasma. (...)



"Jets" in heavy-ion collisions

- High (transverse) momentum particle in a QGP.
- Jet(?) in a QGP.
- Why am I using quotes and/or question marks.

Jets in heavy-ion collisions

Fermi National Accelerator Laboratory

FERMILAB-Pub-82/59-THY
August, 1982

Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

[...] a produced secondary high-p_T quark or gluon might lose tens of GeV of its initial transverse momentum while plowing through quark-gluon plasma produced in its local environment. High energy hadron jet experiments should be analysed ...

Jets in heavy-ion collisions

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Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

(unfortunately, effect overestimated by a factor ≈100)

J. D. BJORKEN
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[...] a produced secondary high-p_T quark or gluon might lose tens of GeV of its initial transverse momentum while plowing through quark-gluon plasma produced in its local environment. High energy hadron jet experiments should be analysed ...

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Jets in heavy-ion collisions

Experimentally, the first step in a jet study is the measurement of the yield / production cross-section of high-p_{T} particles.

~~Jets~~ in heavy-ion collisions

High-p_T particles

Experimentally, the first step in a jet study is the measurement of the yield / production cross-section of high-p_T particles.

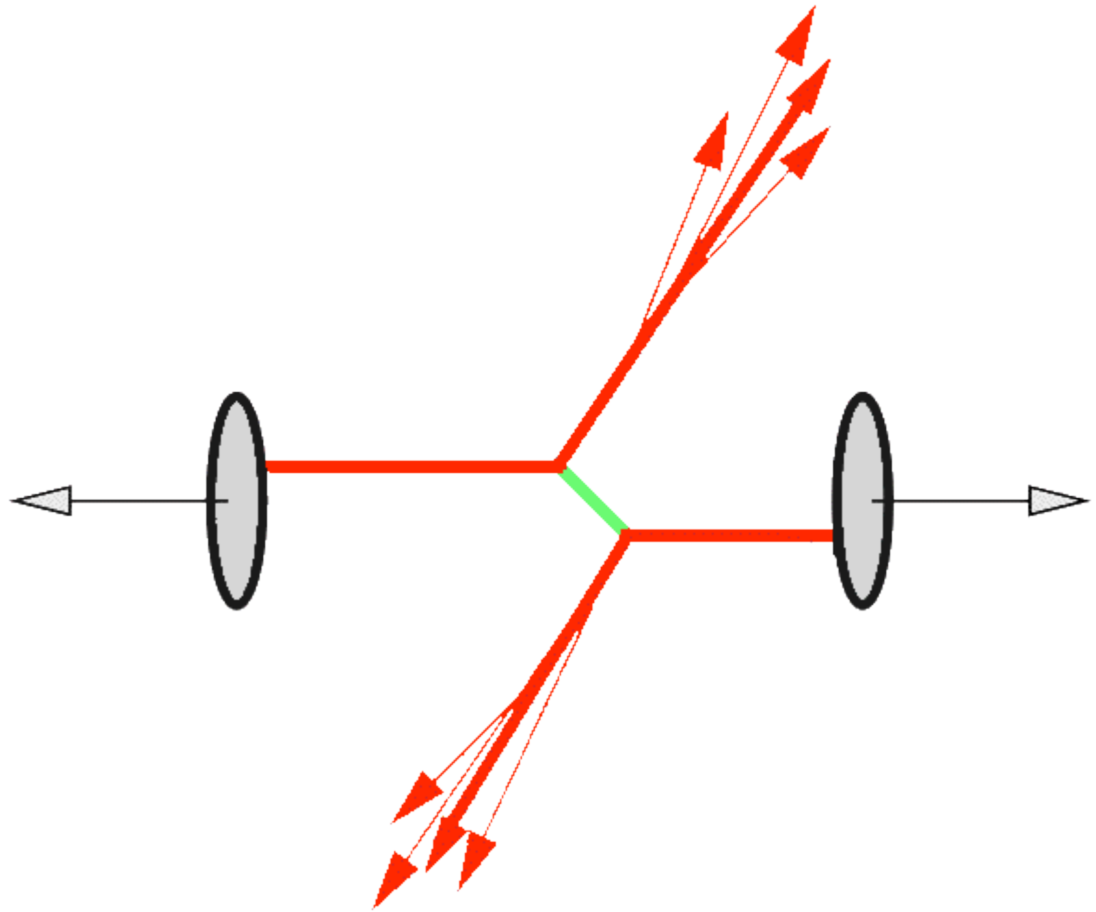
"Jet quenching": basic picture

A fast parton propagating through a dense medium will "lose" part of its energy-momentum.

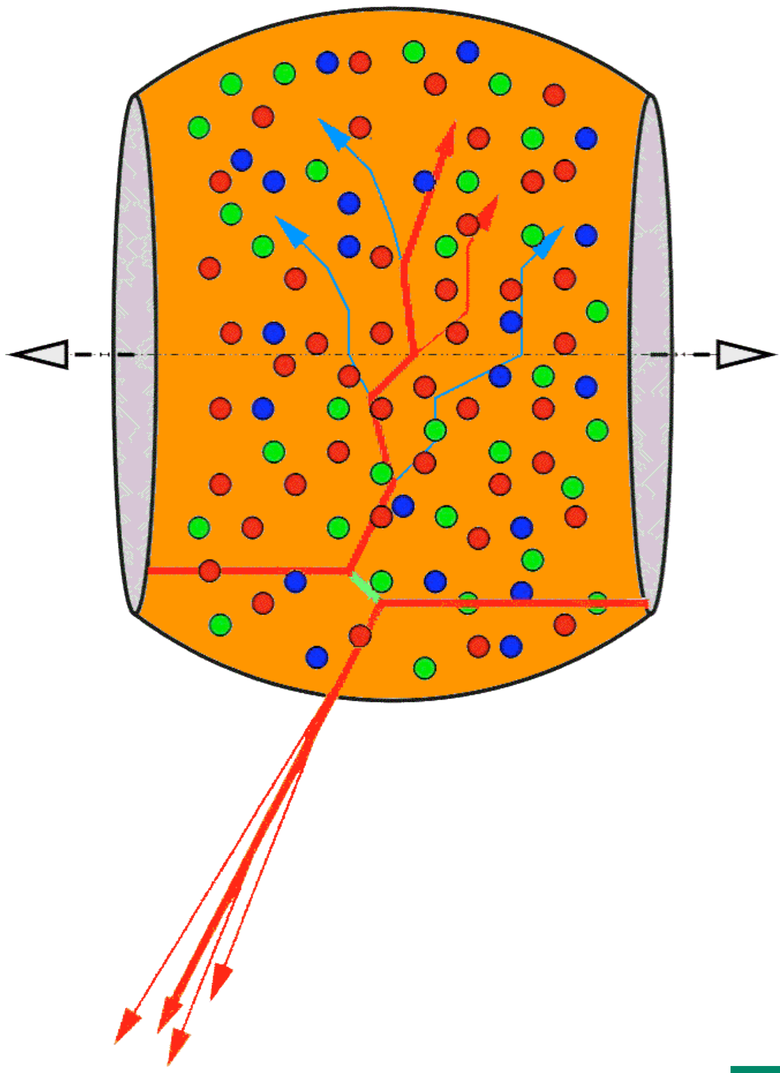
(cf. energy loss of electrically charged particles in matter: Bethe-Bloch formula...)

The resulting yield of high-p_T particles is reduced: "jet quenching".

in vacuum



in medium



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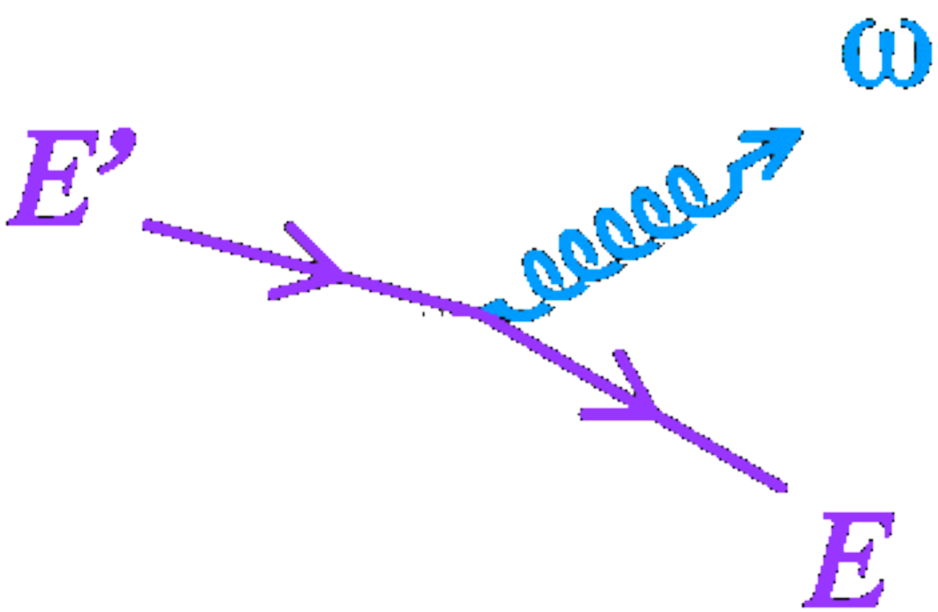
Jet quenching: underlying processes

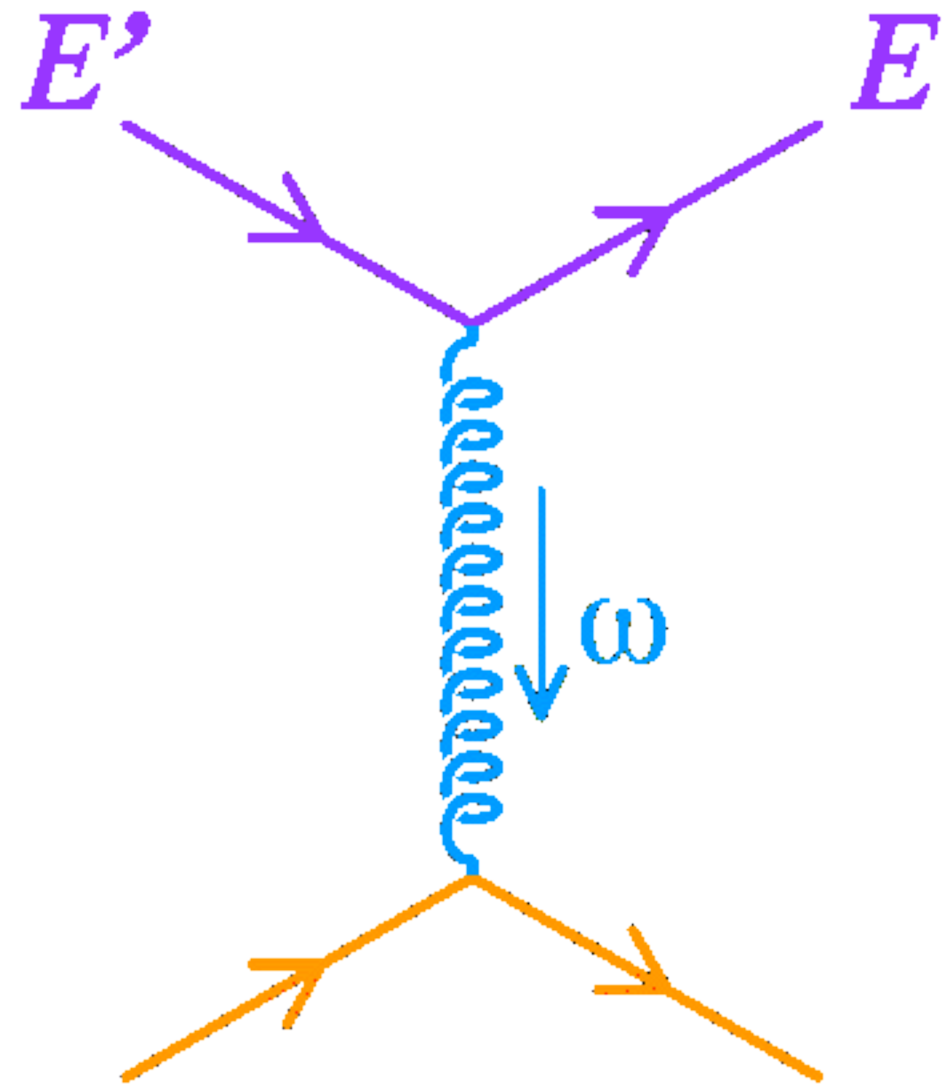
Two different processes lead to the loss of energy by a fast parton:

"radiative" process (Bremsstrahlung)



also "in vacuum" (DGLAP evolution), yet modified by the presence of a (colored) medium

"collisional" process

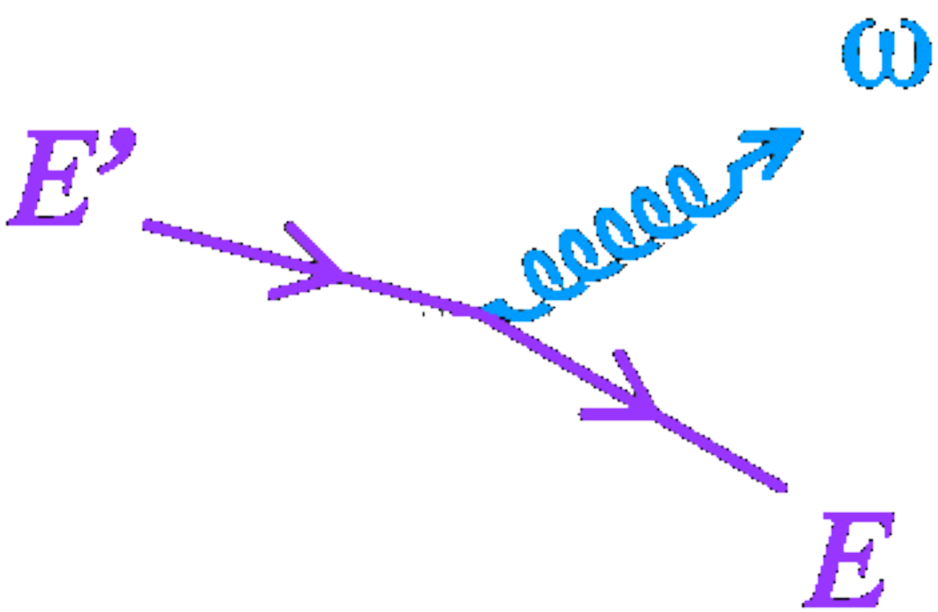


Jet quenching: underlying processes

Two different processes lead to the loss of energy by a fast parton:

inelastic

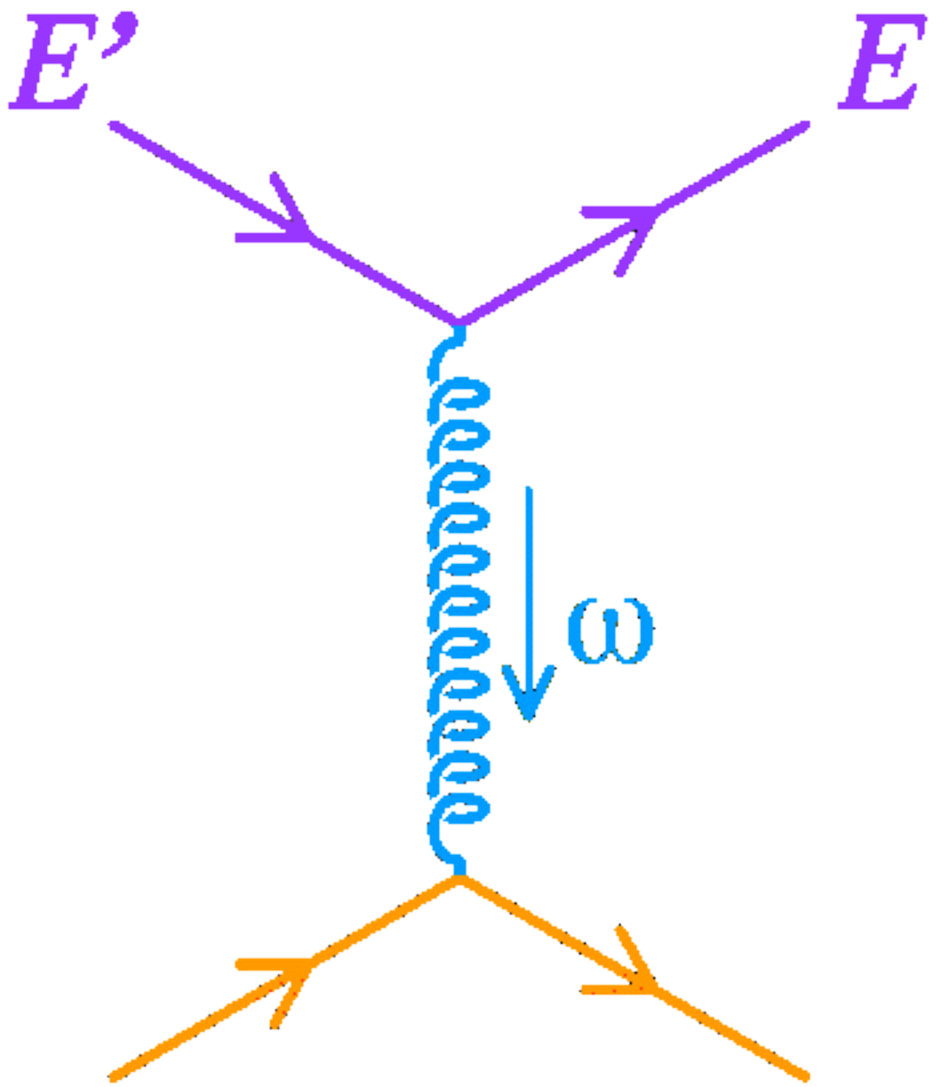
"~~radiative~~" process (Bremsstrahlung)



also "in vacuum" (DGLAP evolution), yet modified by the presence of a (colored) medium

elastic

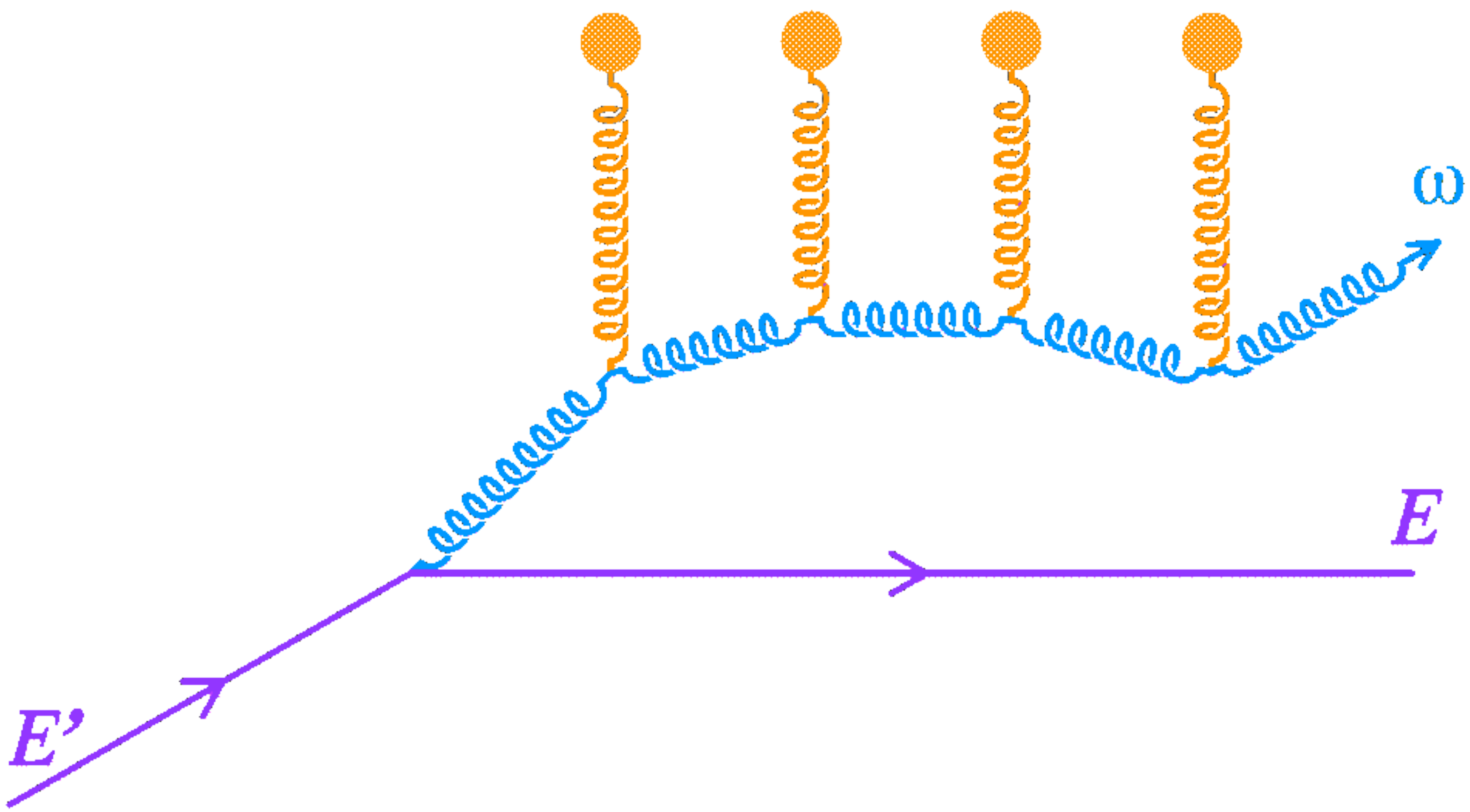
"~~collisional~~" process



Jet quenching: coherent gluonstrahlung

Landau-Pomeranchuk-Migdal effect: Multiple soft scattering limit

The propagating high-p_T parton traverses a **thick target**.



It radiates soft gluons, which scatter **coherently** on independent color charges in the medium, resulting in a medium-modified gluon spectrum.

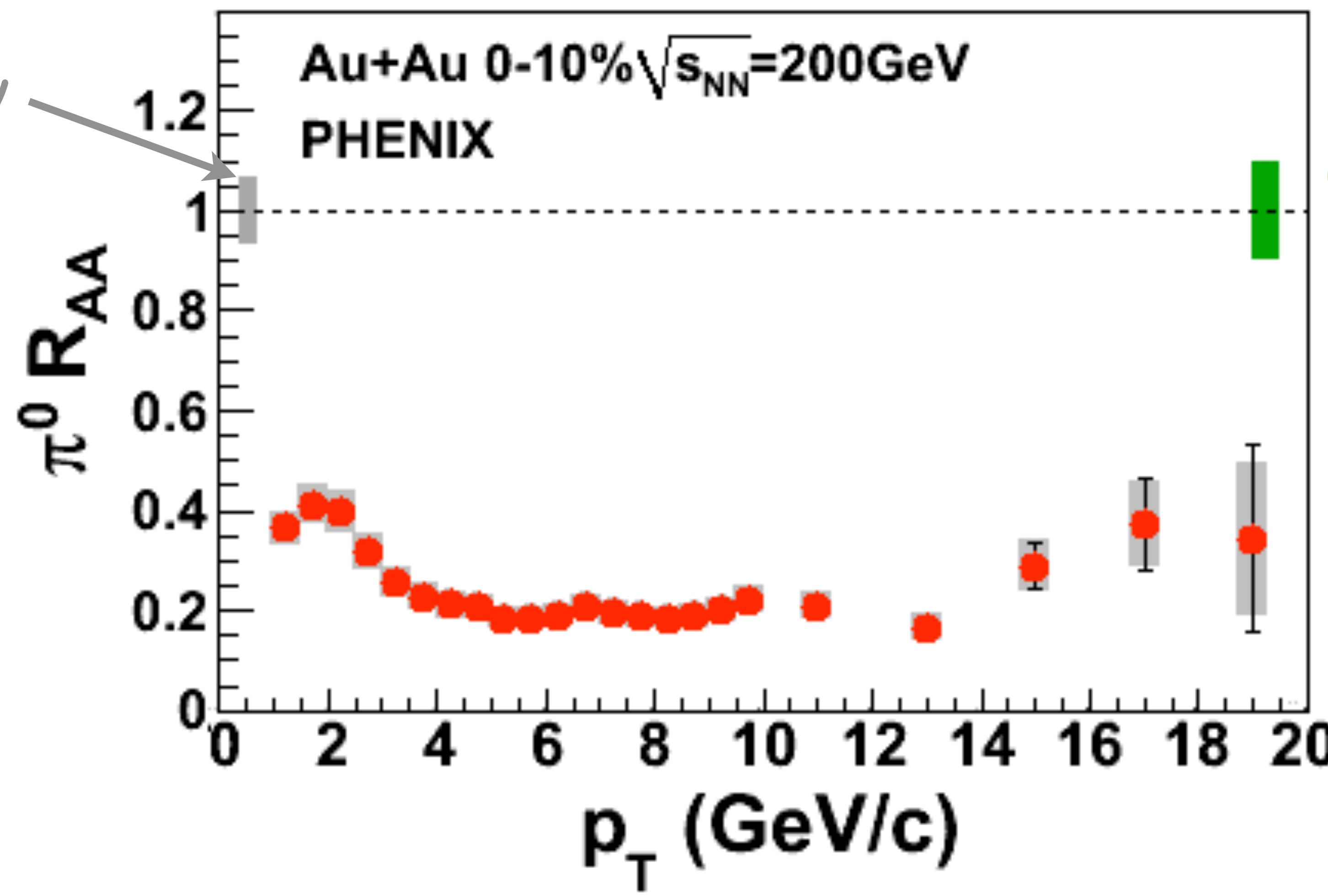
☞ transport coefficient $\hat{q}$

Baier, Dokshitzer, Mueller, Peigné, Schiff (BDMPS); Zakharov

"Jet quenching": experimental findings

$N_{\rm coll}$ uncertainty

$$\frac{1}{N_{\rm coll}}\frac{\frac{{\rm d}^2N_{AA}}{{\rm d}p_T\,{\rm d}y}}{\frac{{\rm d}^2N_{pp}}{{\rm d}p_T\,{\rm d}y}} \equiv$$

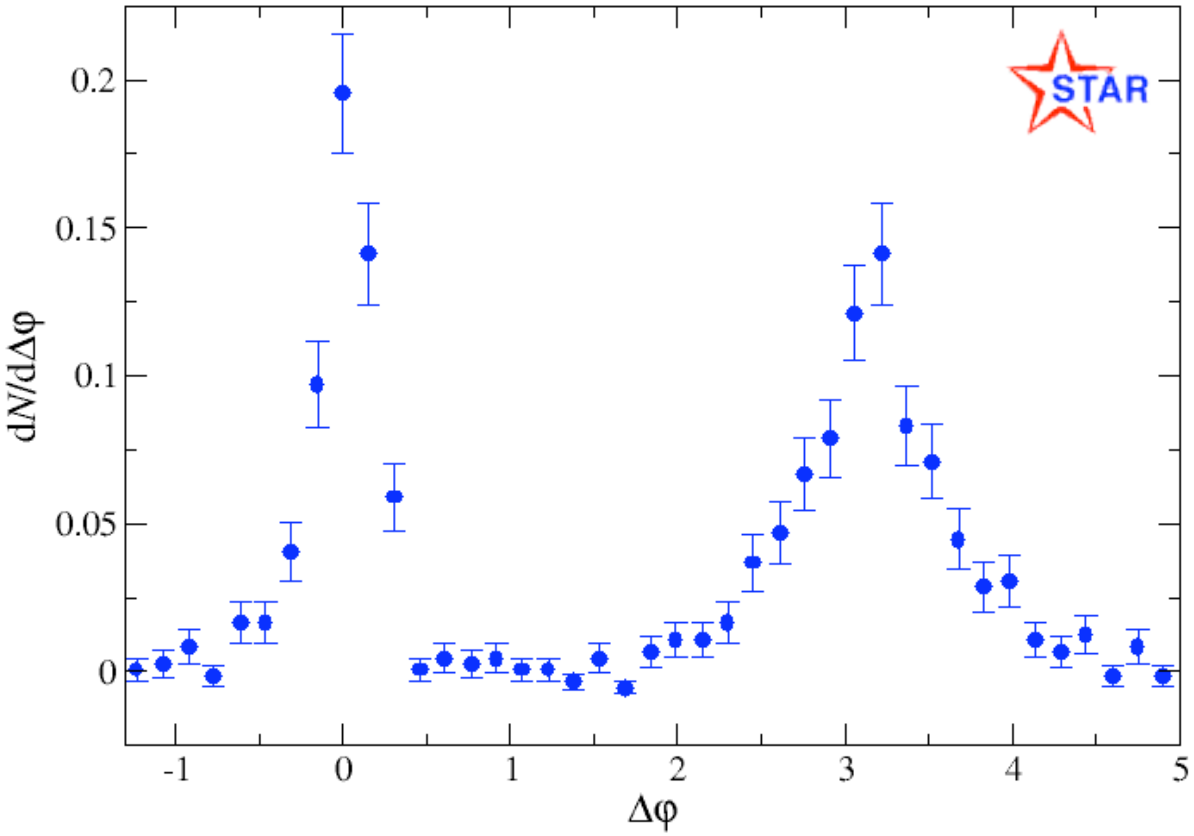


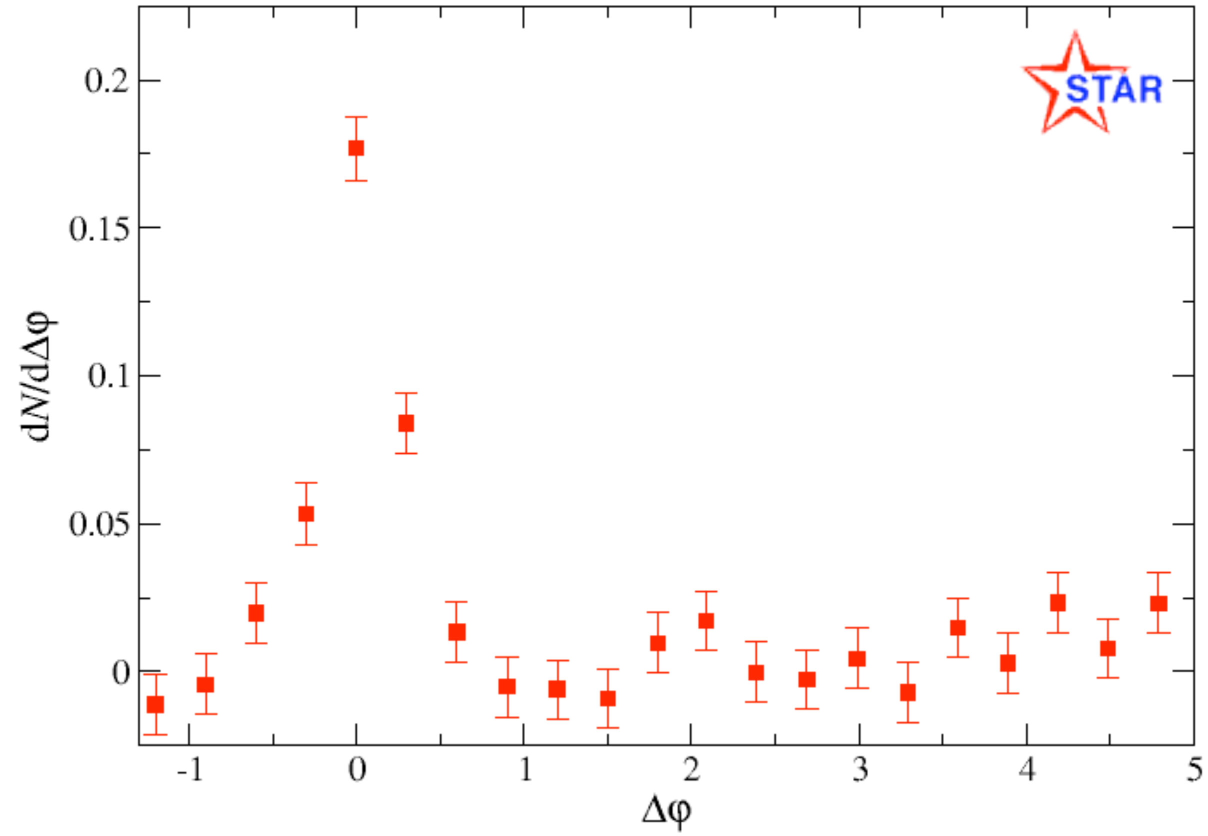
uncertainty on pp-normalization

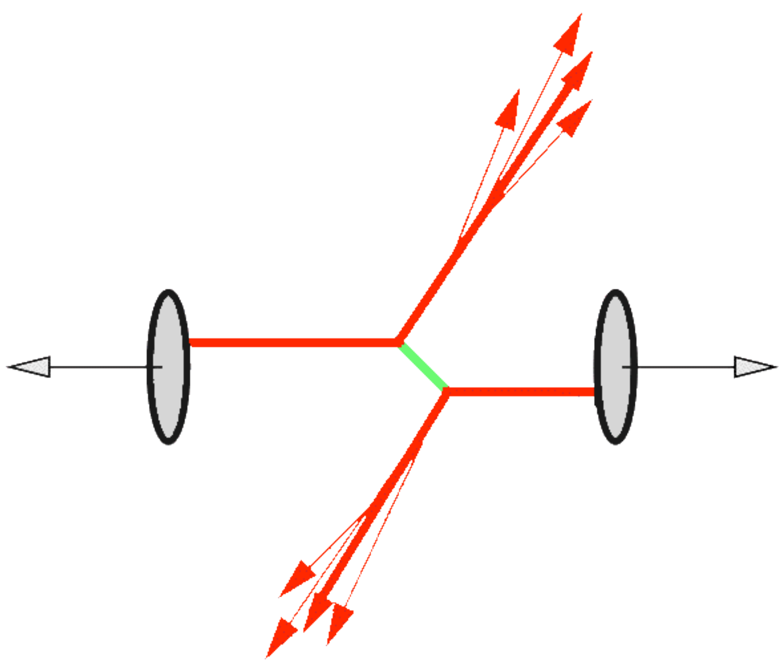
The yield of high-p_T hadrons is reduced by 80% in Au-Au collisions!

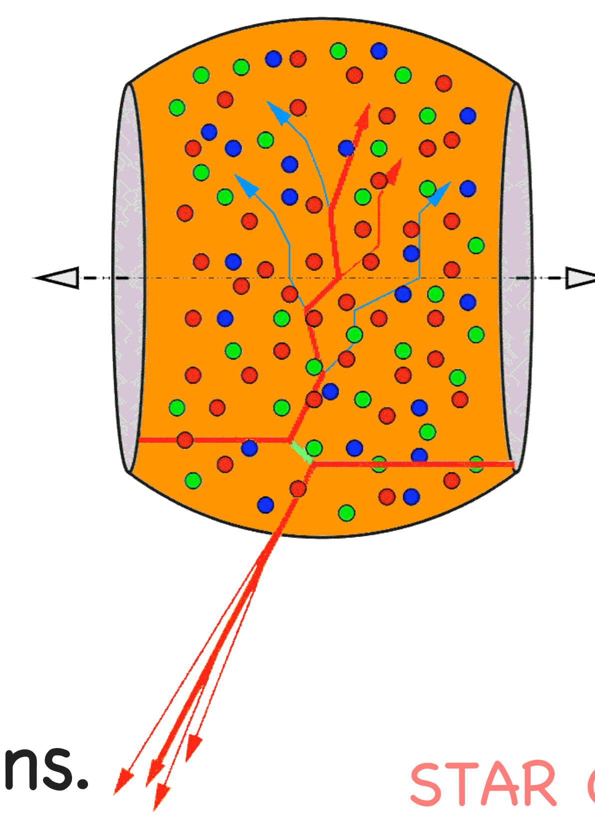
PHENIX Collaboration 2008

"Jet quenching": experimental findings









Jet-like correlations disappear in Au-Au collisions.

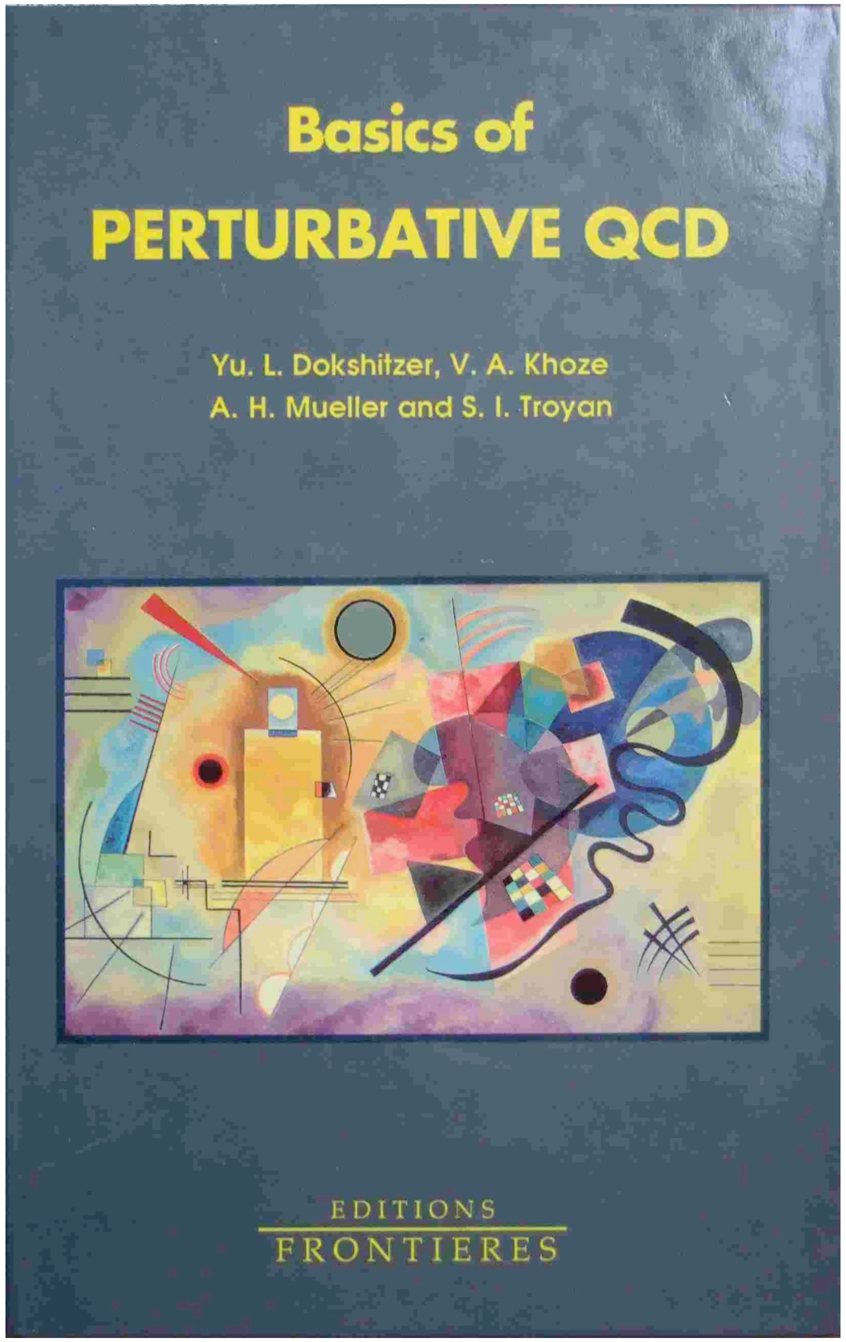
STAR Coll. 2003

Jets in heavy-ion collisions

After a while, our experimental friends know their detectors better, they have accumulated more statistics... so they want to turn to studying full jets.

Jets "in vacuum": Ye big Booke of pQCD

(especially for jet calculus)



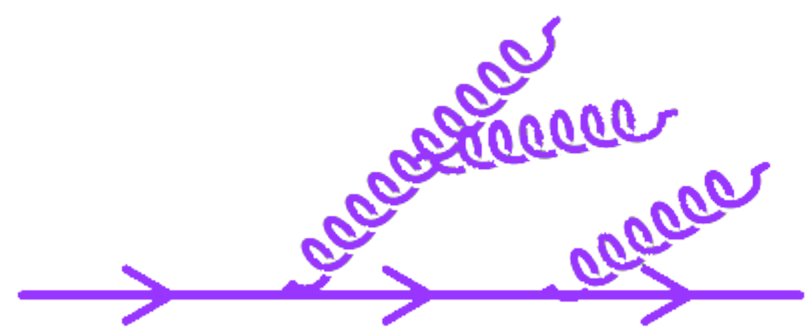
available @ http://www.lpthe.jussieu.fr/~yuri/BPQCD/cover.html

MLLA in one slide

Main ingredients:

- Resummation of double- and single-logarithms in $\ln\frac{1}{x}$ and $\ln\frac{E_{\rm jet}}{Q_0}$;
- Takes into account the running of α_s along the parton shower evolution;
- Probabilistic interpretation (results from intra-jet colour coherence):
  - independent successive branchings $g\to gg$, $g\to q\bar{q}$, $q\to qg$;
  - with angular ordering of the sequential parton decays:

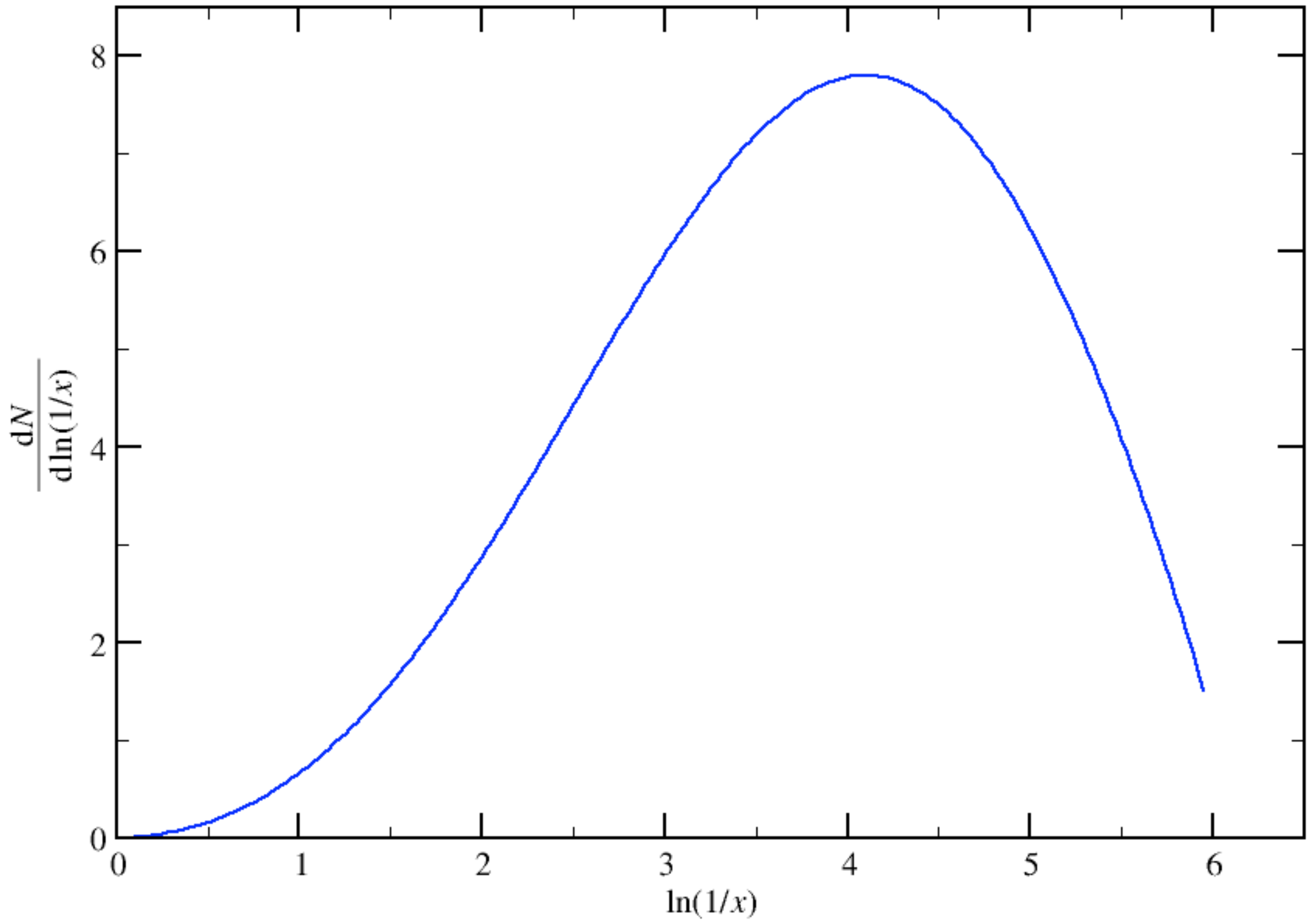
    at each step in the evolution, the angle between father and offspring partons decreases.



- Includes in a systematic way next-to-leading-order corrections. $\mathcal{O}(\sqrt{\alpha_s})$!

MLLA: limiting spectrum

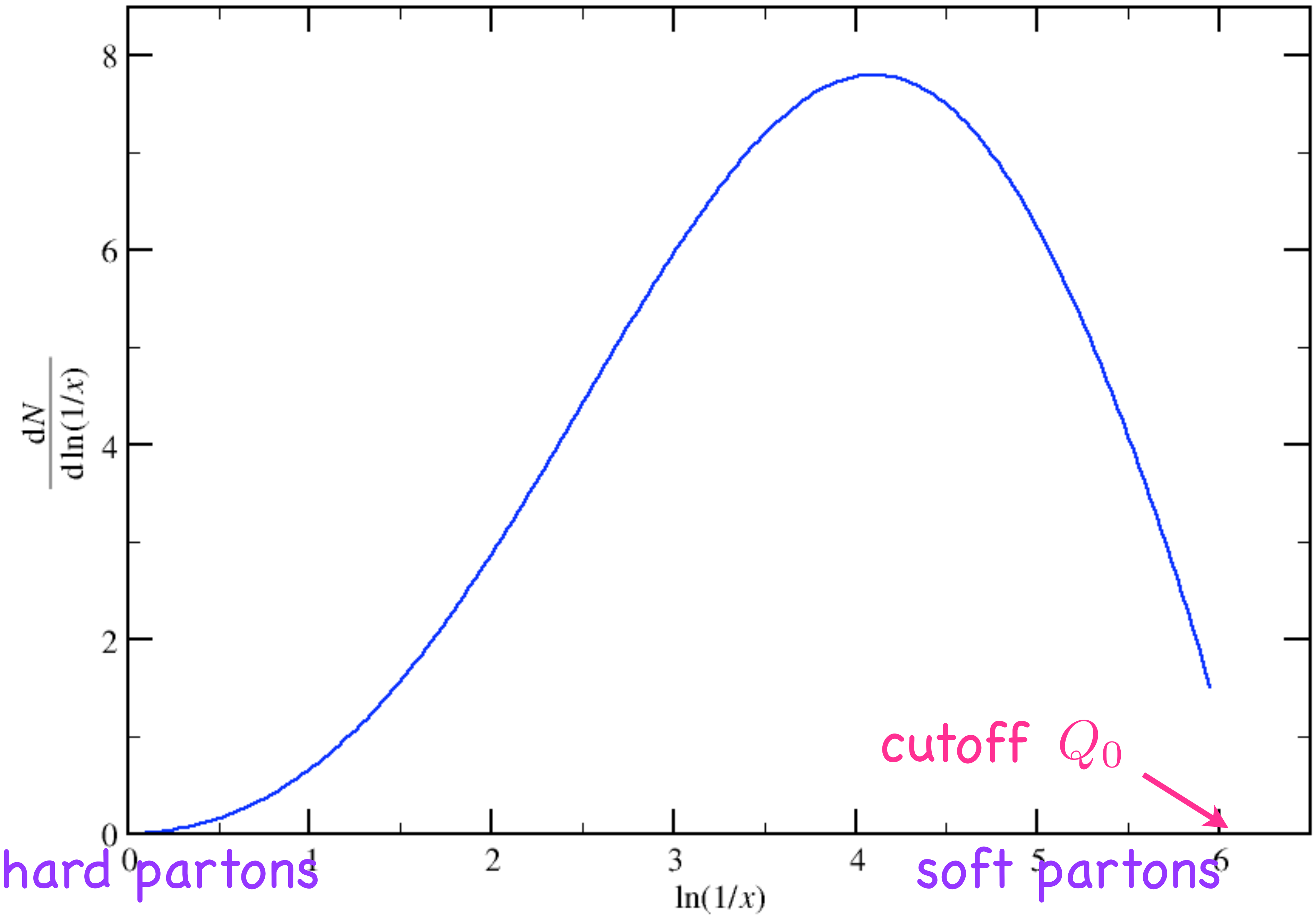
For a 100 GeV parton:



☞ "hump-backed plateau"

MLLA: limiting spectrum

For a 100 GeV parton:



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MLLA: limiting spectrum

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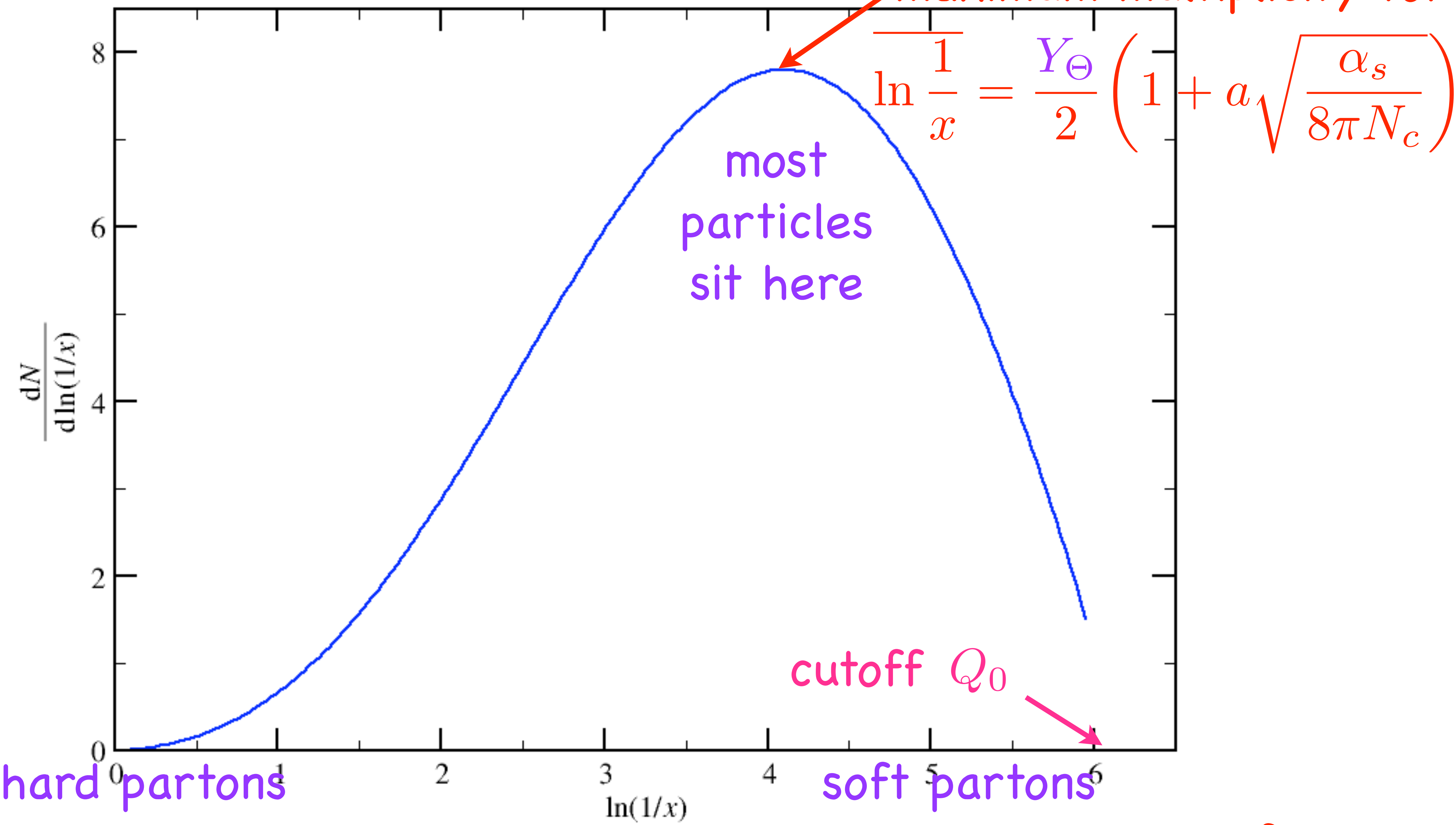
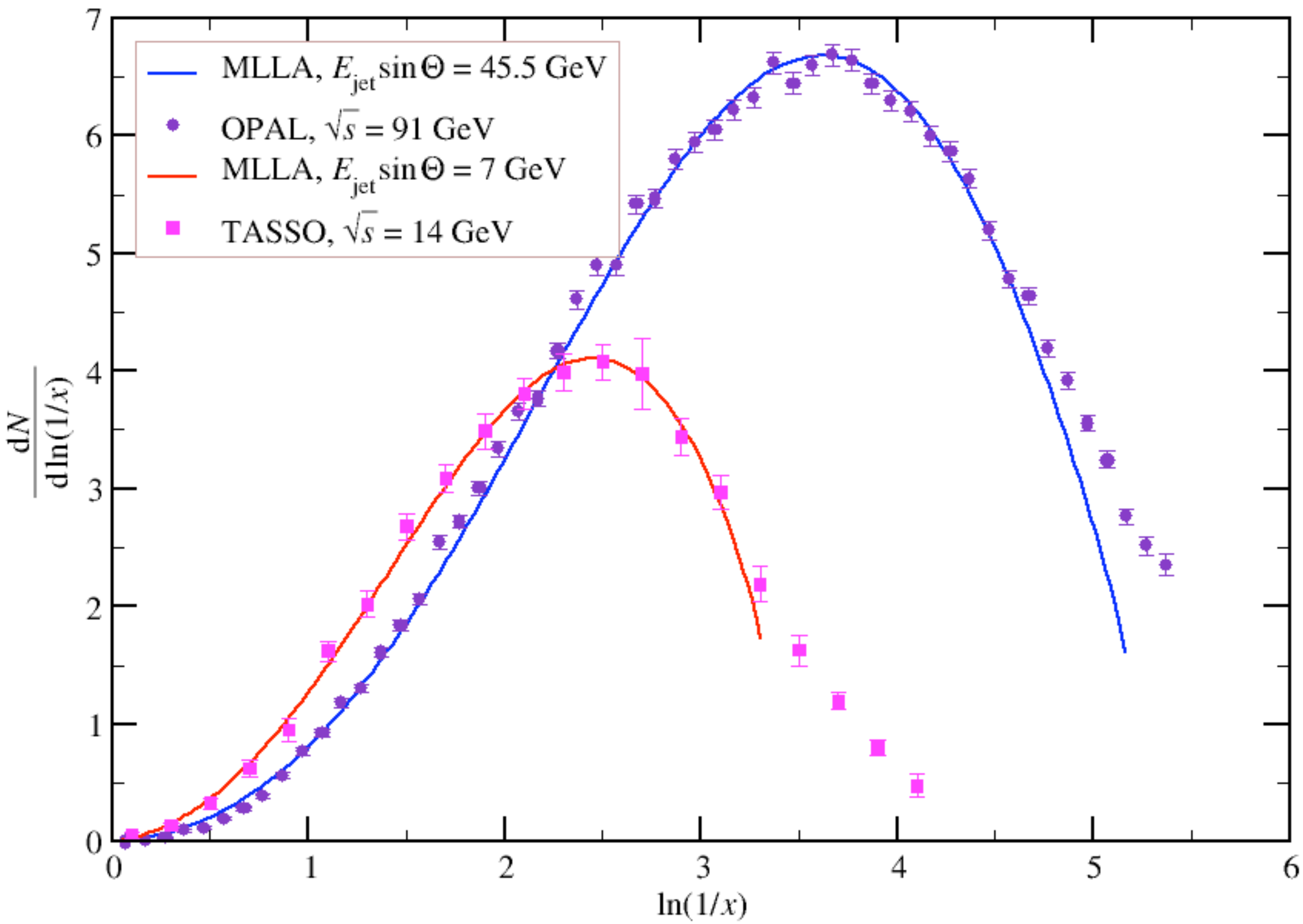


☞ "hump-backed plateau"

LO splitting function

Note: the hump is dominated by the singular parts of the $P_{ji}(z)$.

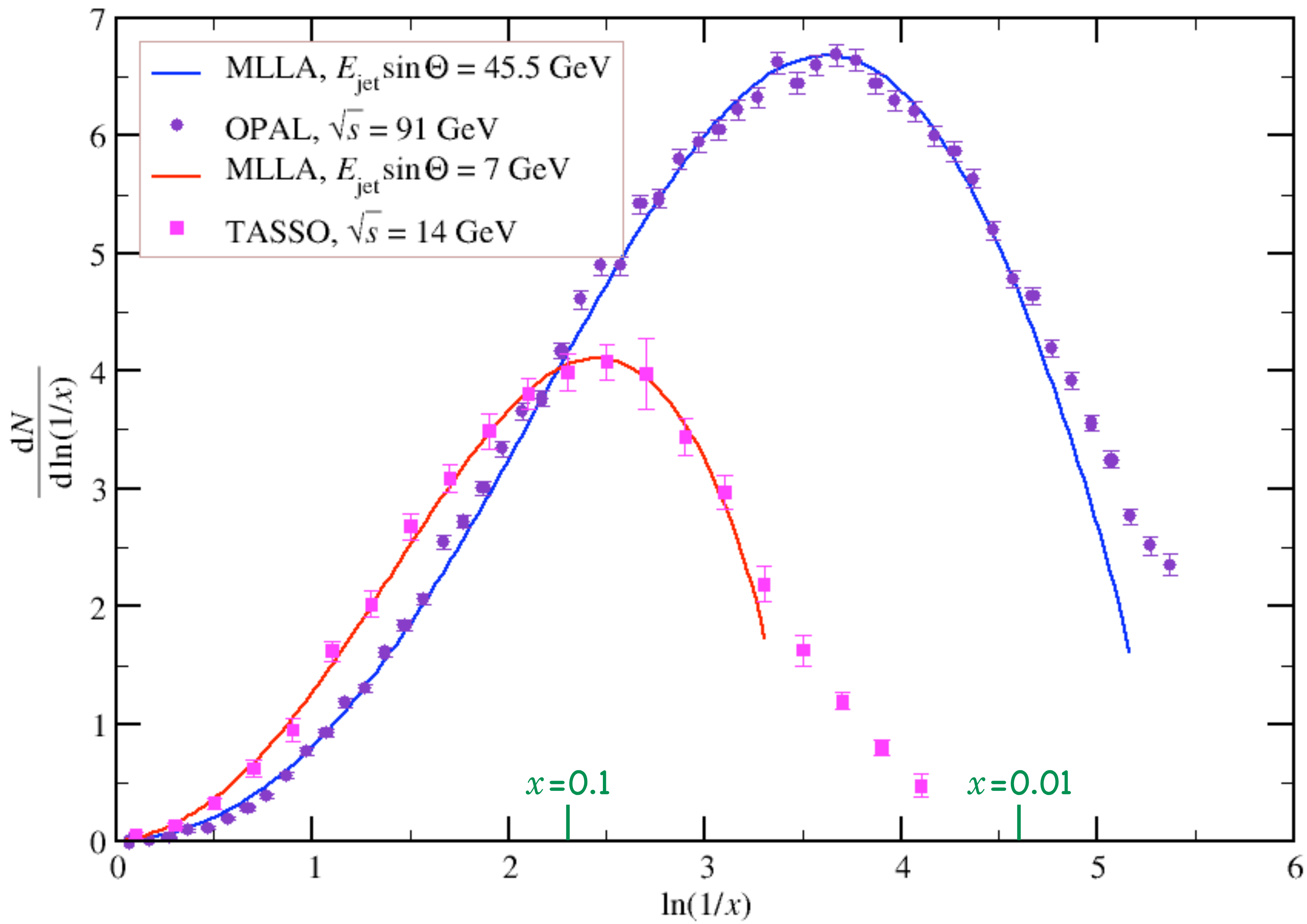
MLLA: a success!



TASSO Collaboration, Z. Phys. C **47** (1990) 187

OPAL Collaboration, Phys. Lett. B **247** (1990) 617 (includes comparison with MLLA)

MLLA: a success!



TASSO Collaboration, Z. Phys. C **47** (1990) 187

OPAL Collaboration, Phys. Lett. B **247** (1990) 617 (includes comparison with MLLA)

"Jets" in heavy-ion collisions

Modeling the medium influence: a suggestion

- The hump of the limiting spectrum is mostly due to the singular parts of the splitting functions.
- In medium, the emission of a soft gluons by a fast parton increases.

☞ One can model medium-induced effects by modifying the parton splitting functions $P_{ji}(z)$ and especially their singular $\frac{1}{z}$ parts:

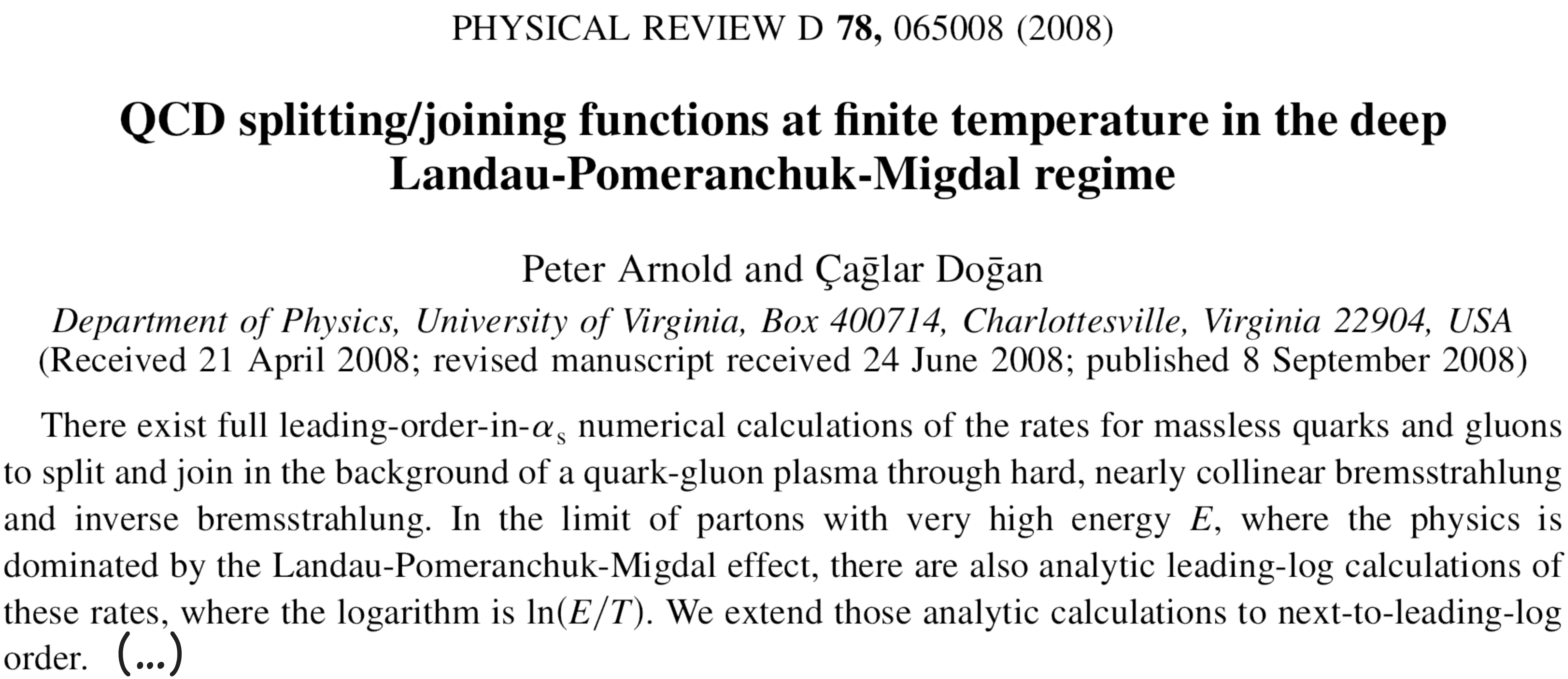
$$P_{Gq}(z) = \frac{4}{3}\left[\frac{2(1+f_{\rm med})}{z} - 2 + z\right]$$ and so on.

$f_{\rm med} > 0 \quad \Rightarrow$ Bremsstrahlung increases

Idea: put the emphasis on energy conservation at each step of the shower.

NB & U.Wiedemann, 2005

Medium-modified splitting functions vs. the "usual" approach to jet quenching


PHYSICAL REVIEW D **78,** 065008 (2008)

QCD splitting/joining functions at finite temperature in the deep Landau-Pomeranchuk-Migdal regime

Peter Arnold and Çağlar Doğan

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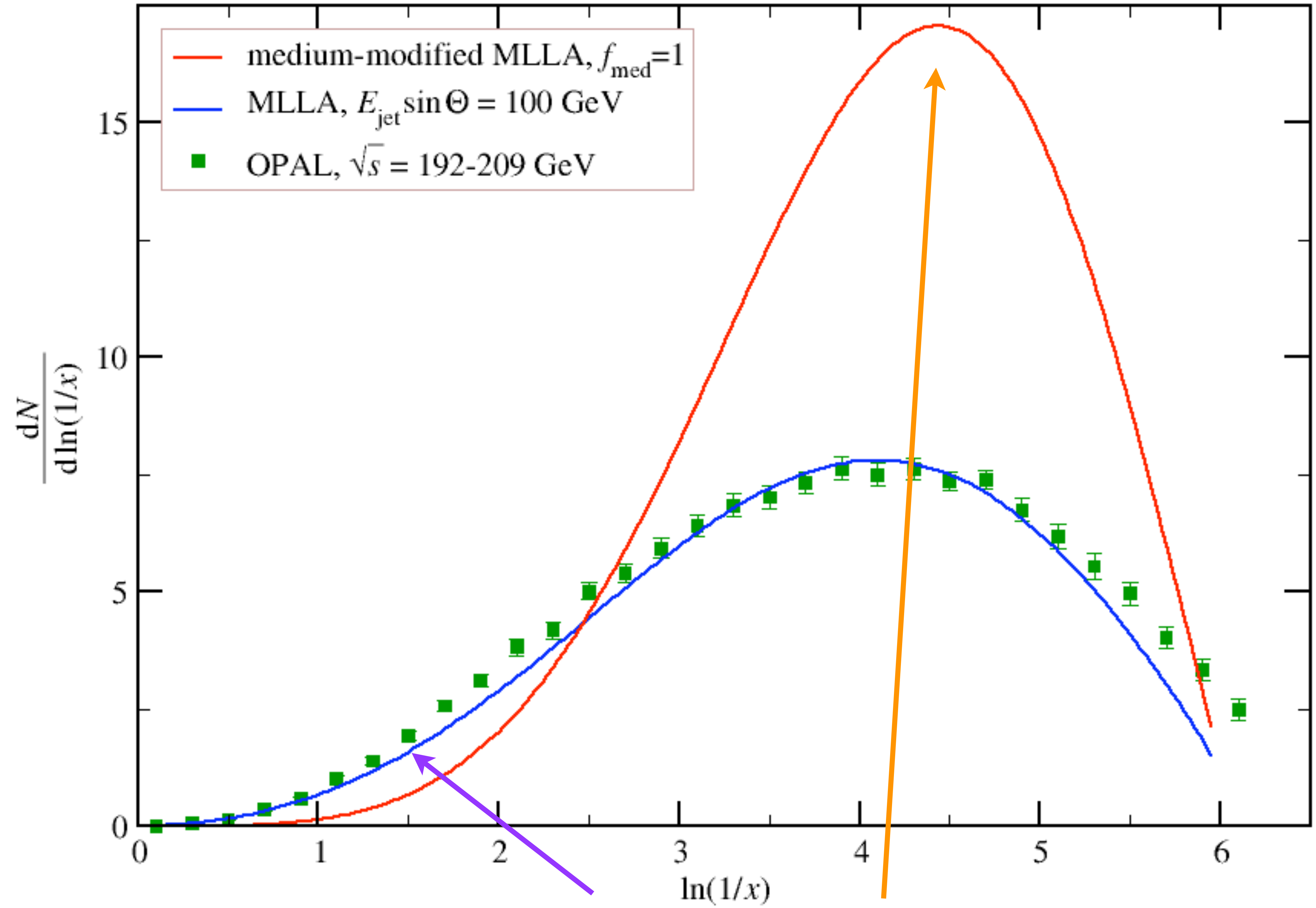
(Received 21 April 2008; revised manuscript received 24 June 2008; published 8 September 2008)

There exist full leading-order-in-α_s numerical calculations of the rates for massless quarks and gluons to split and join in the background of a quark-gluon plasma through hard, nearly collinear bremsstrahlung and inverse bremsstrahlung. In the limit of partons with very high energy E, where the physics is dominated by the Landau-Pomeranchuk-Migdal effect, there are also analytic leading-log calculations of these rates, where the logarithm is $\ln(E/T)$. We extend those analytic calculations to next-to-leading-log order. (...)

"My" constant $f_{\rm med}$: irrealistic, but allows analytical computations, to check (future) Monte-Carlo cascades.

Medium-modified hump-backed plateau

inclusive longitudinal distribution

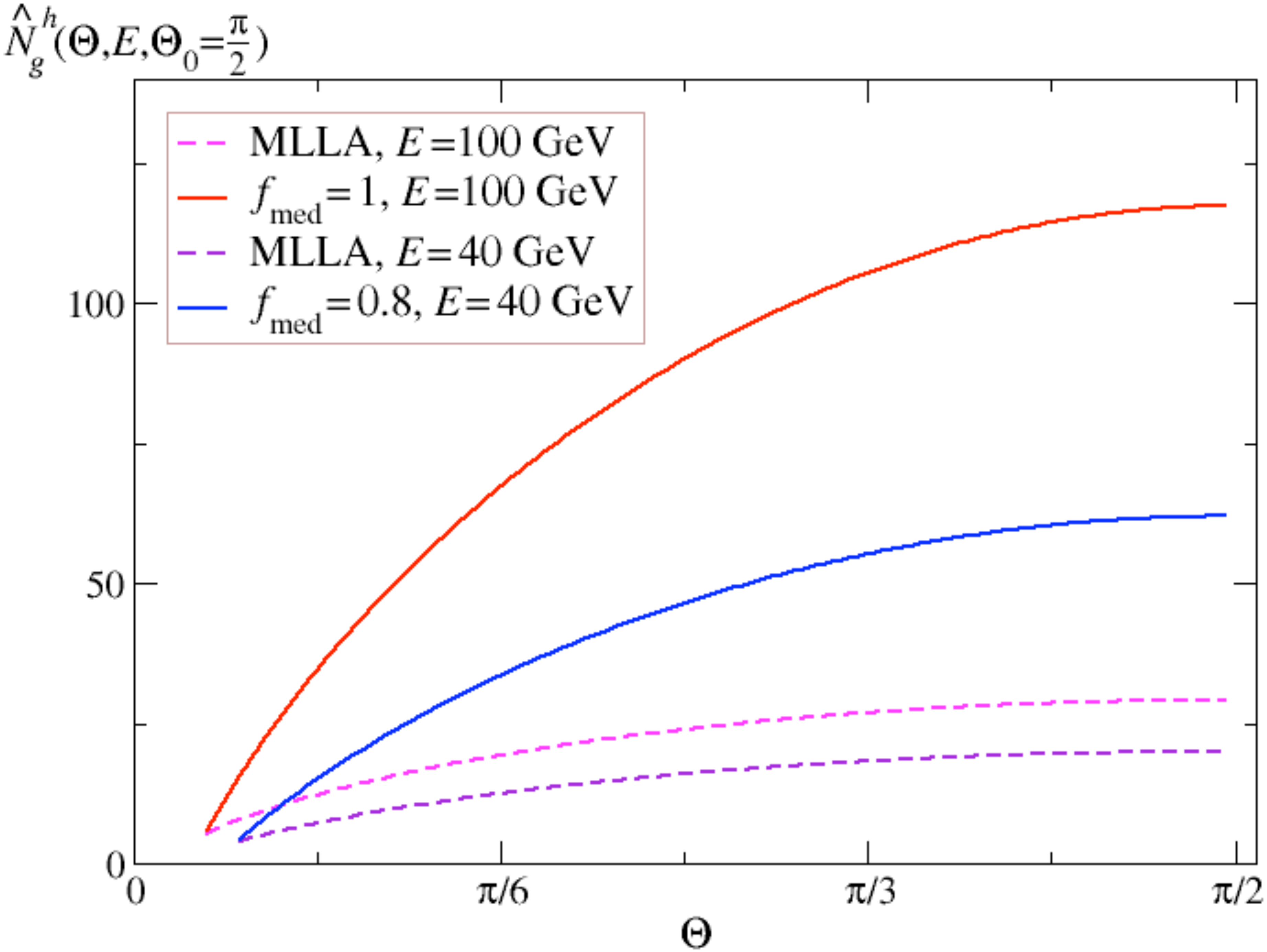


Partons are redistributed from large x to small x.

NB & Wiedemann, 2005

“Medium-modified MLLA”

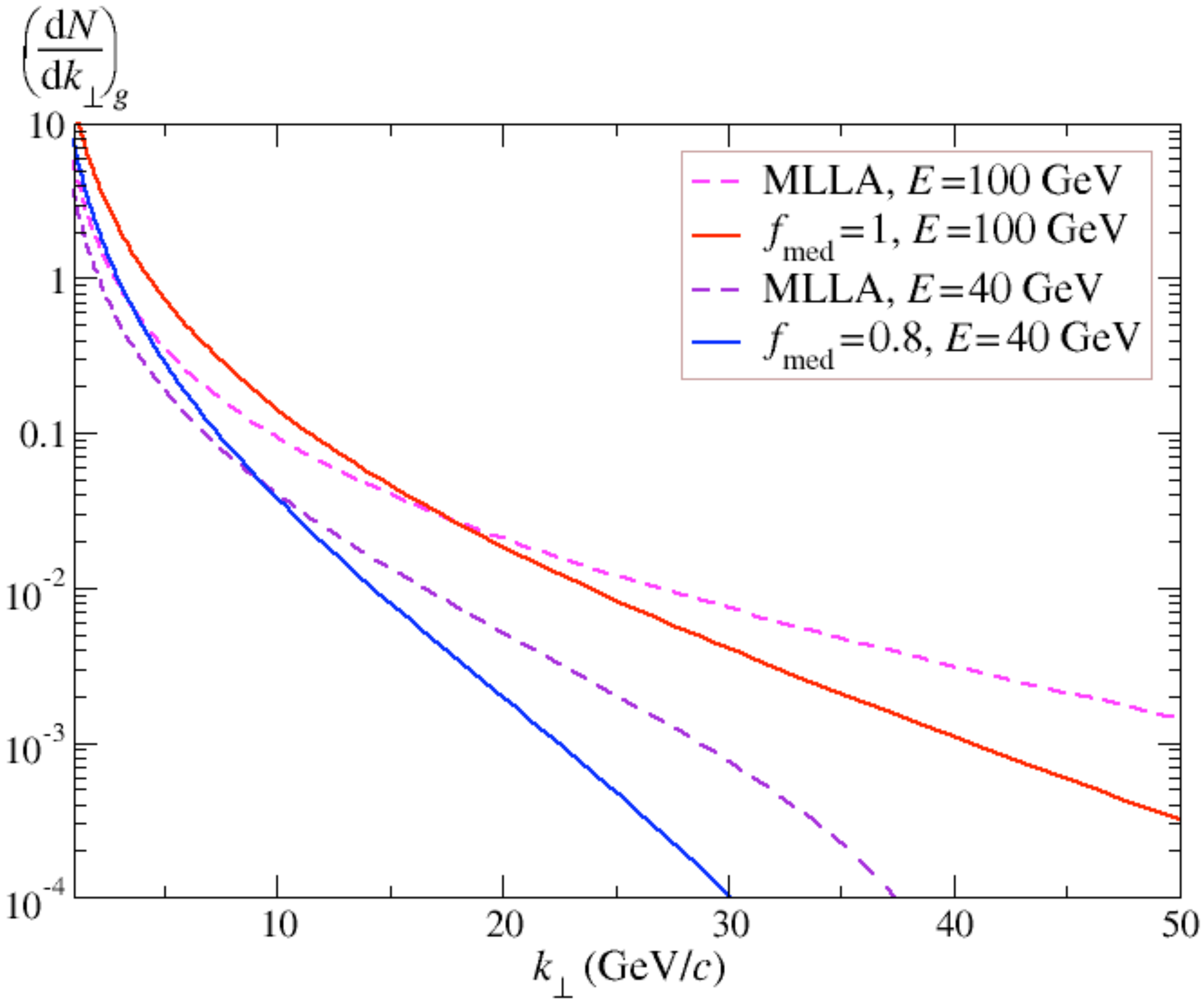
angular distribution: “jet broadening”



NB 2009

"Medium-modified MLLA"

transverse momentum distribution: "jet softening"



NB 2009

“Medium-modified MLLA”

What have I been doing???

- I am messing up with the splitting functions...
  - ☞ usual sum rules no longer hold.

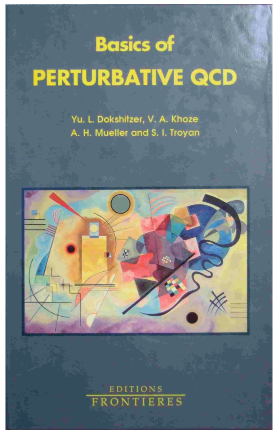
Yes, but with more realistic modifications....

- I have silently imported into my QCD-inspired(?) model the nice features of MLLA that are rigorously proven in QCD...
  - ☞ color coherence is an essential ingredient, which ensures angular ordering and the independence of successive branchings; is it preserved in a colored medium?

Well,...

- I am distorting a parton shower / jet, which I implicitly treat as an isolated object...
  - ☞ is this licit?

Does it all make sense?



9.2 QCD Portrait of an "Individual Jet"

Let us consider the general inclusive characteristics which may be called, in some sense, the characteristics of an isolated jet (neglecting the mutual influence of jets in their ensemble).

not obvious already in $e^+e^-/p\bar{p}$ collisions!

The notion of the isolated jet makes sense, of course, if one does not deal with the azimuthal effects but considers only multiplicities, energy spectra and correlations, *etc.* In this case all the influence of the jet ensemble on a given jet may be encoded in a single parameter Θ_0, the *jet opening angle*. This angle, in essence, is the angle between the considered jet and the nearest other one.

Multiplicity, energy spectra of particles and other characteristics of the QCD partonic cascade prove to depend not on the jet's energy E but on the *hardness* of the process producing this jet, *i.e.* on the largest possible transverse momentum of particles inside the jet, $Q = E\Theta_0$ at $\Theta_0 \ll 1$, which corresponds, of course, to the transverse momentum of the jet itself.

ELSEVIER

Nuclear Physics A638 (1998) 291c–303c

NUCLEAR PHYSICS A

Hard QCD

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Status of hard/perturbative QCD phenomena is briefly reviewed. Landau-Pomeranchuk-Migdal effect is discussed as a means for establishing links between particle and nuclear high-energy physics.

3.1. SOME MODERATELY NASTY REMARKS

As an ignorant outsider, I am allowed a couple of heretic comments concerning the ways some of the above-mentioned puzzles are being discussed.

To start with, the LPM physics sends a warning message: a classical Monte-Carlo modelling of intra-nuclear particle multiplication at very high energies is like robbing banks — tempting but dangerous.

The independence of successive branchings is not granted!

Note: Zapp, Stachel & Wiedemann (2008) are being careful.

“Jets” in heavy-ion collisions

“The devil is in the details!” (Barbara Jacak)

(see e.g. STAR’s jet-like correlations of slide 9: pp data are “pedestal-subtracted”; Au-Au are “pedestal and v_2-subtracted”)

+ first (and certainly not last) attempts are extracting “full jets” in nucleus-nucleus collisions (using cone / kt-algorithms; γ+jet).

This is also true on the theory side!

What a given theorist calls a “jet” in the medium might not be the same object as what his/her neighbor considers:

☞ emphasis put on different, maybe incompatible physics (color flow, energy conservation...);

Is the subfield already mature enough to think of some common jet definition?

(Remember that it took till 1990 to come to the Snowmass Standard.)

Larry & Jean-Paul,
please keep on forcing us
to question what we are doing!

Snowmass Accord

Several important properties that should be met by a jet definition are

- Simple to implement in an experimental analysis.
- Simple to implement in the theoretical computation.
- Defined at any order of perturbation theory.
- Yields finite cross section at any order of perturbation theory.
- Yields a cross section that is relatively insensitive to hadronization.