JETS IN STRONGLY INTERACTING MATTER

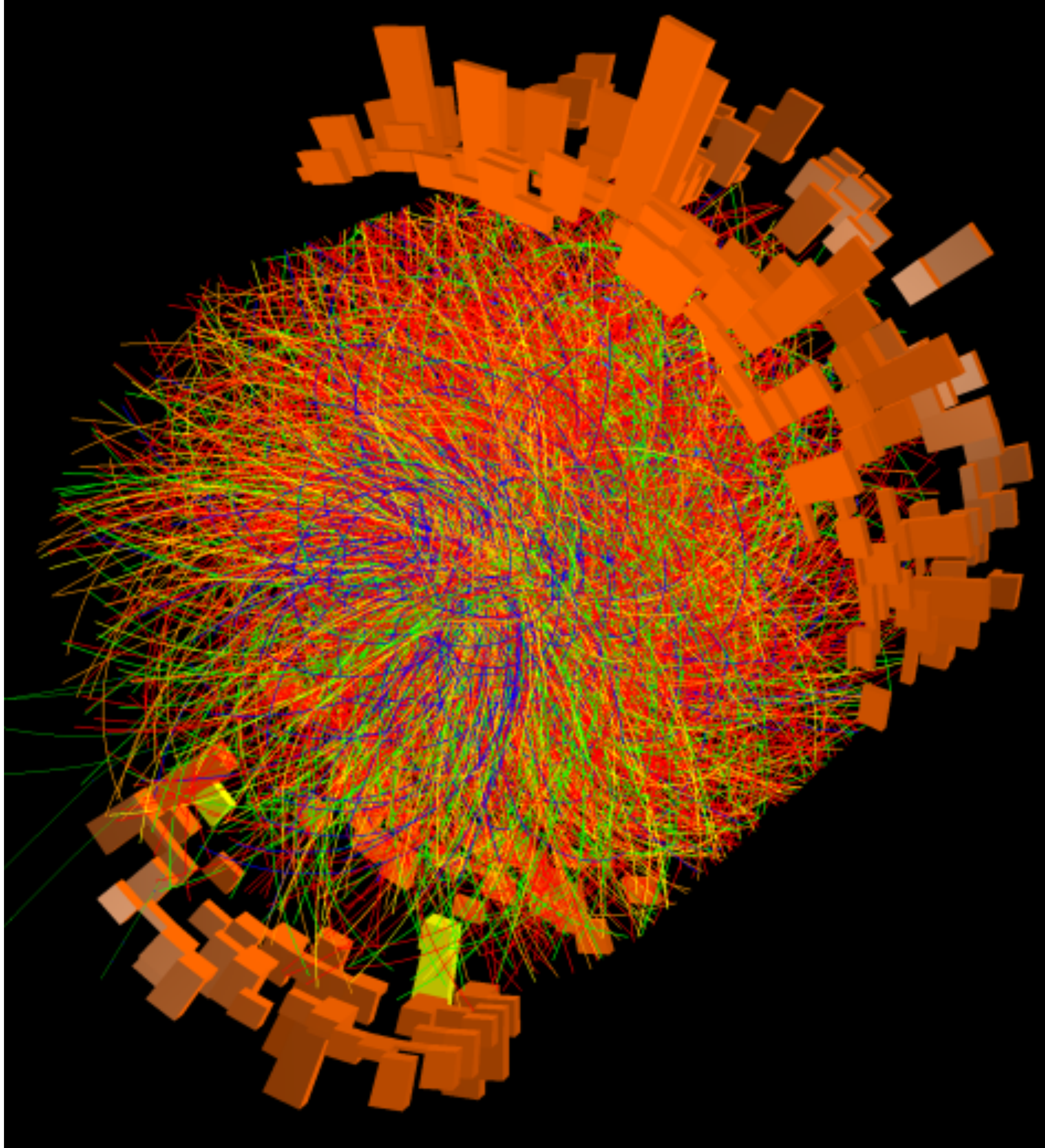
Konrad Tywoniuk (University of Bergen)

2nd Workshop of the Network NA7-HF-QGP of the European program "STRONG-2020" & 'HFHF Theory Retreat 2023'
28 September – 4 October 2023, Giardini Naxos, Italy

Outline

Main questions to be answered

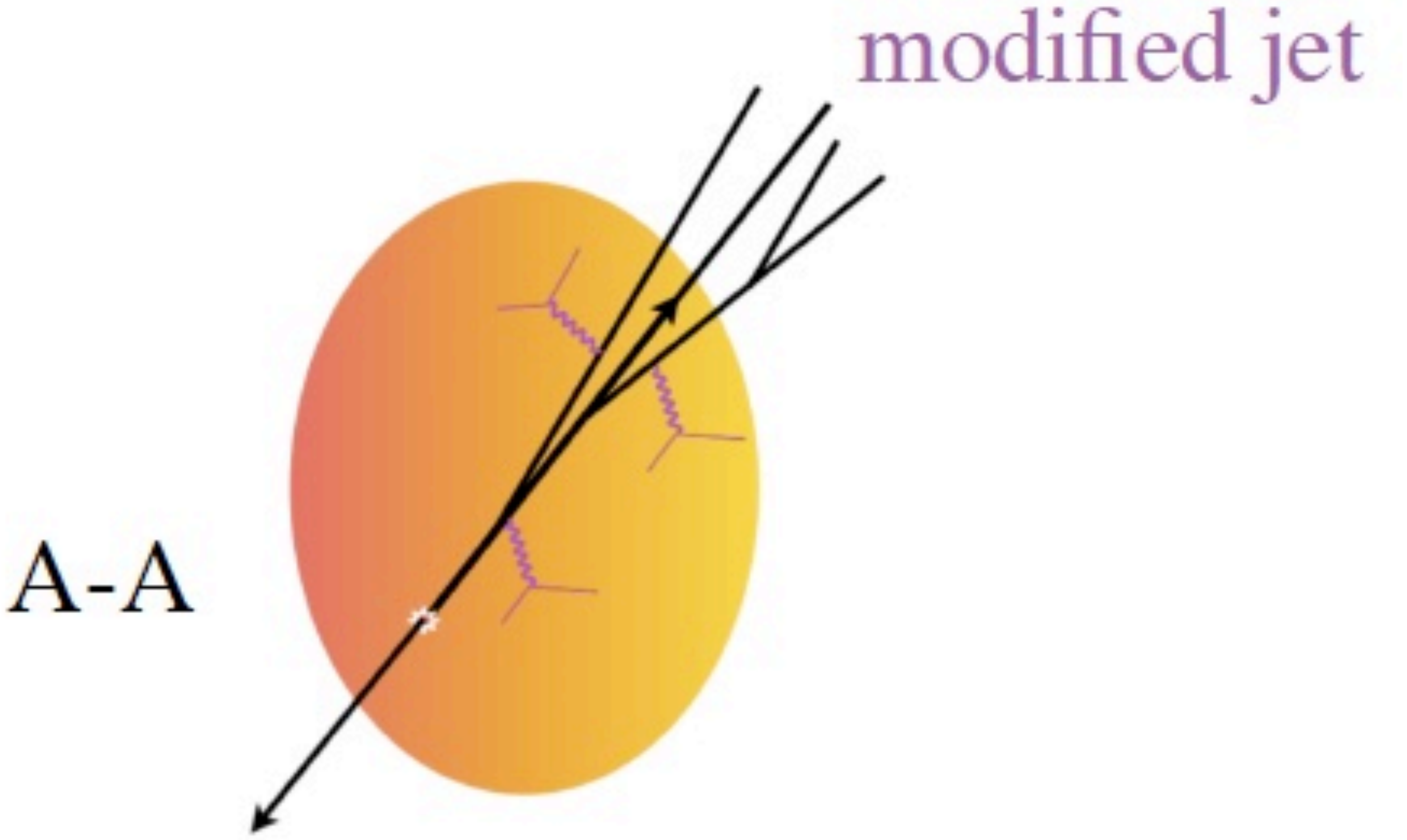
- what is "jet quenching"?
  - or a theorist's view of experimental data
- what are "jets"?
  - or how does a parton shed its virtuality?
- what is parton energy loss?
  - or how does the medium interact with fast particles?
- what is jet quenching?
  - or how does the medium modify jets?



Outline

Structure of the lectures

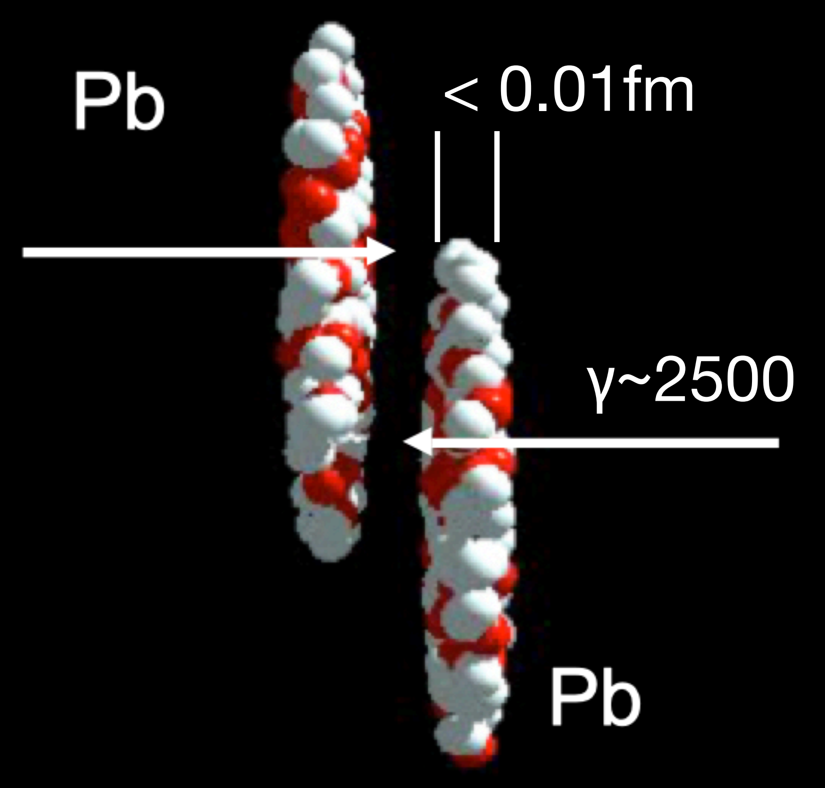
- Lecture 1
  - learning to interpret “jet quenching” in experimental data
  - QCD jets in vacuum
- Lecture 2
  - theory of radiative parton energy loss
- Lecture 3
  - theory of full jet quenching



Lecture 1

Part I: “jet quenching” phenomena in heavy-ion collisions

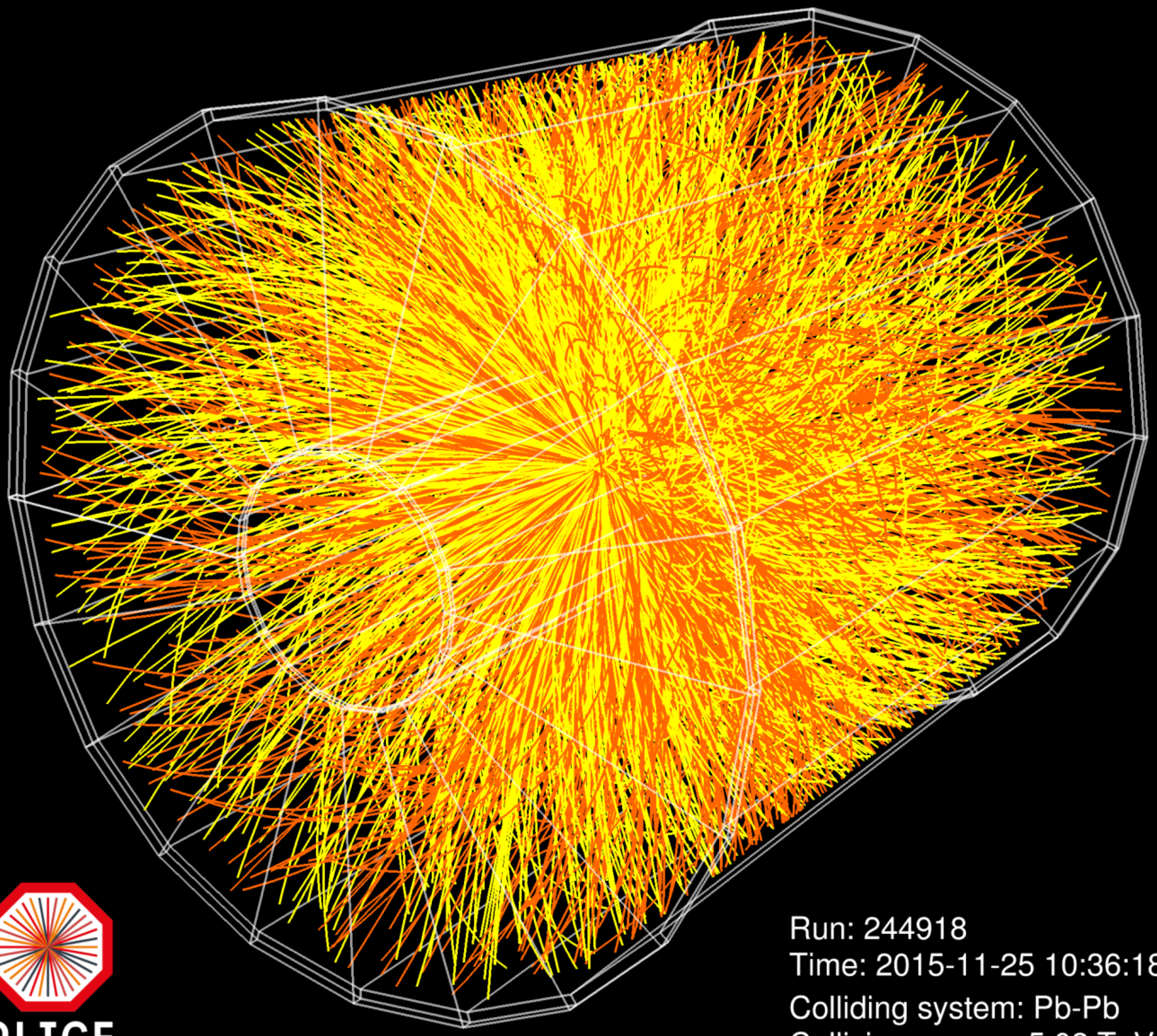
HEAVY-ION COLLISIONS



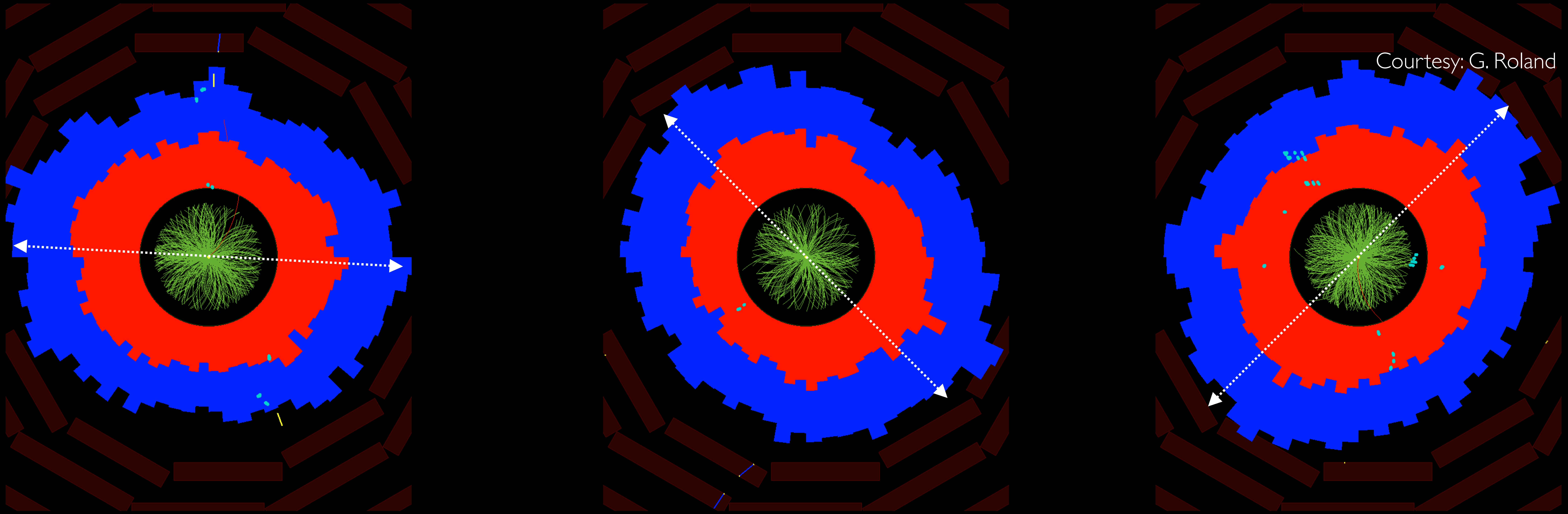
PbPb @ Large Hadron Collider at CERN.

30.000 particles are produced within lifetime 10^{-23}s.

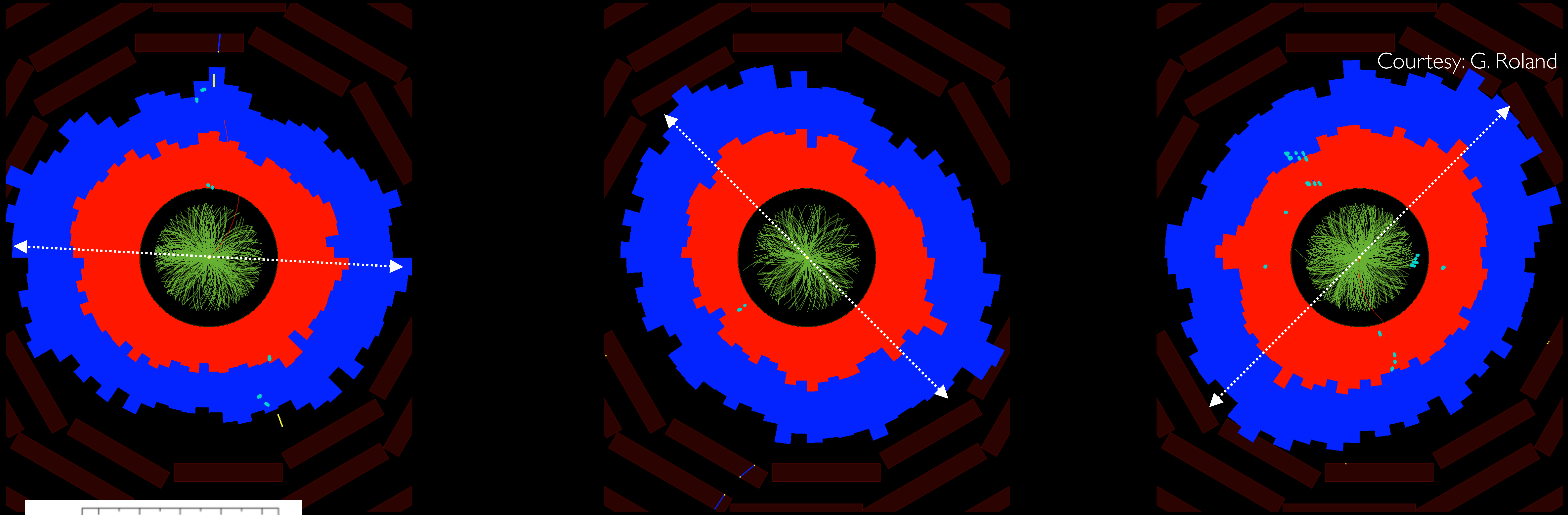
Wide and diverse physics program (bulk/heavy/hard probes, system size…).

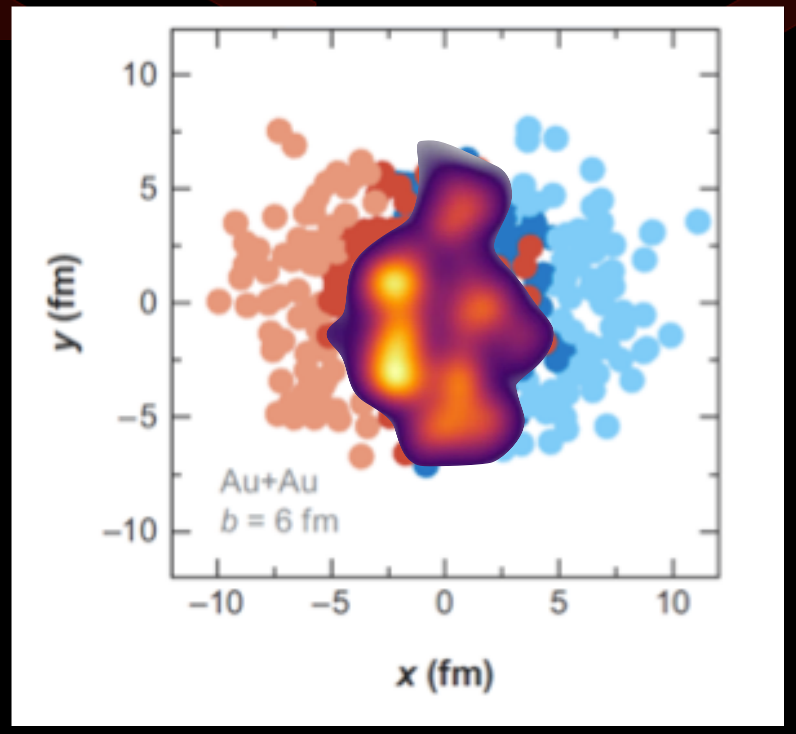


Azimuthal asymmetry of particle production



Azimuthal asymmetry of particle production

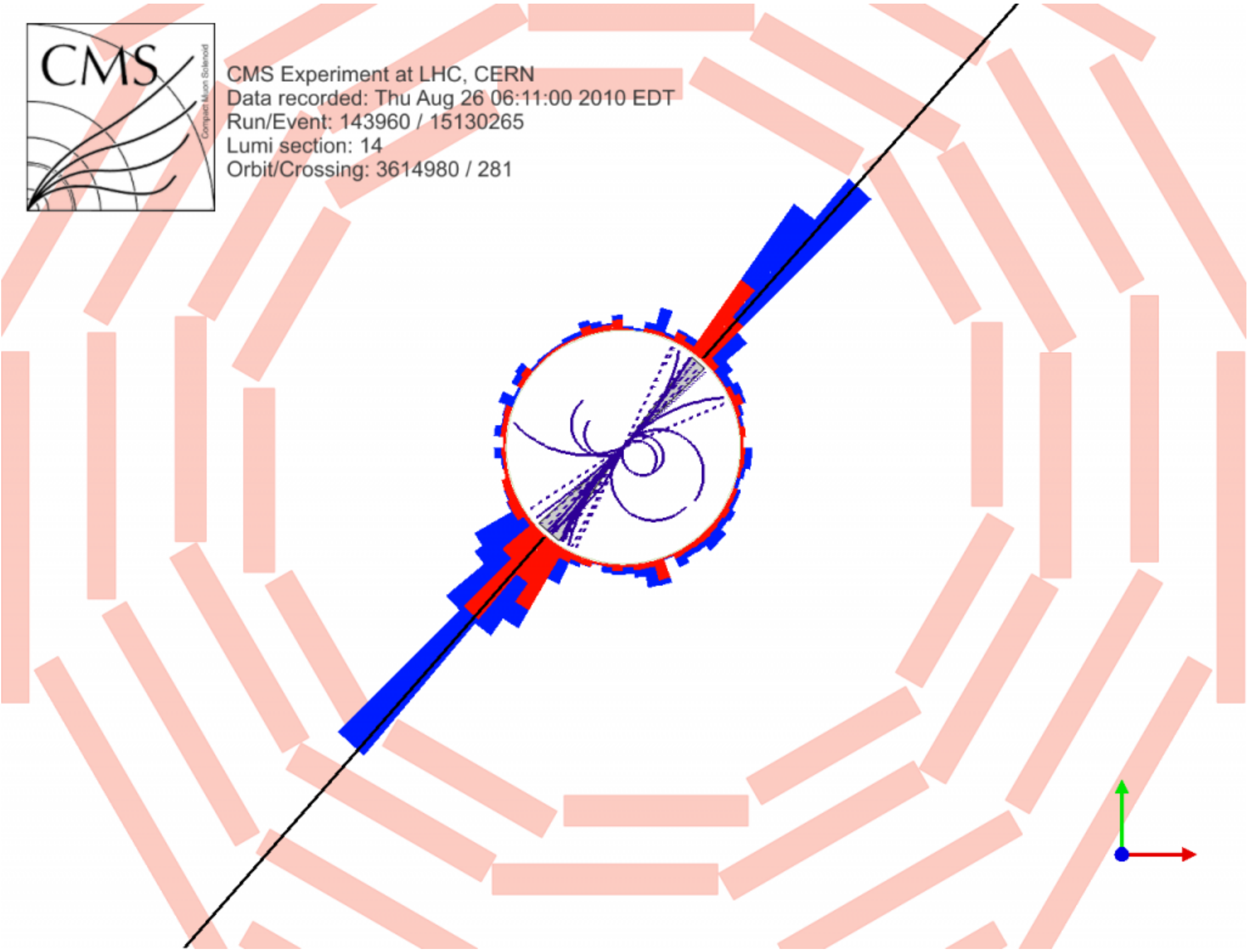


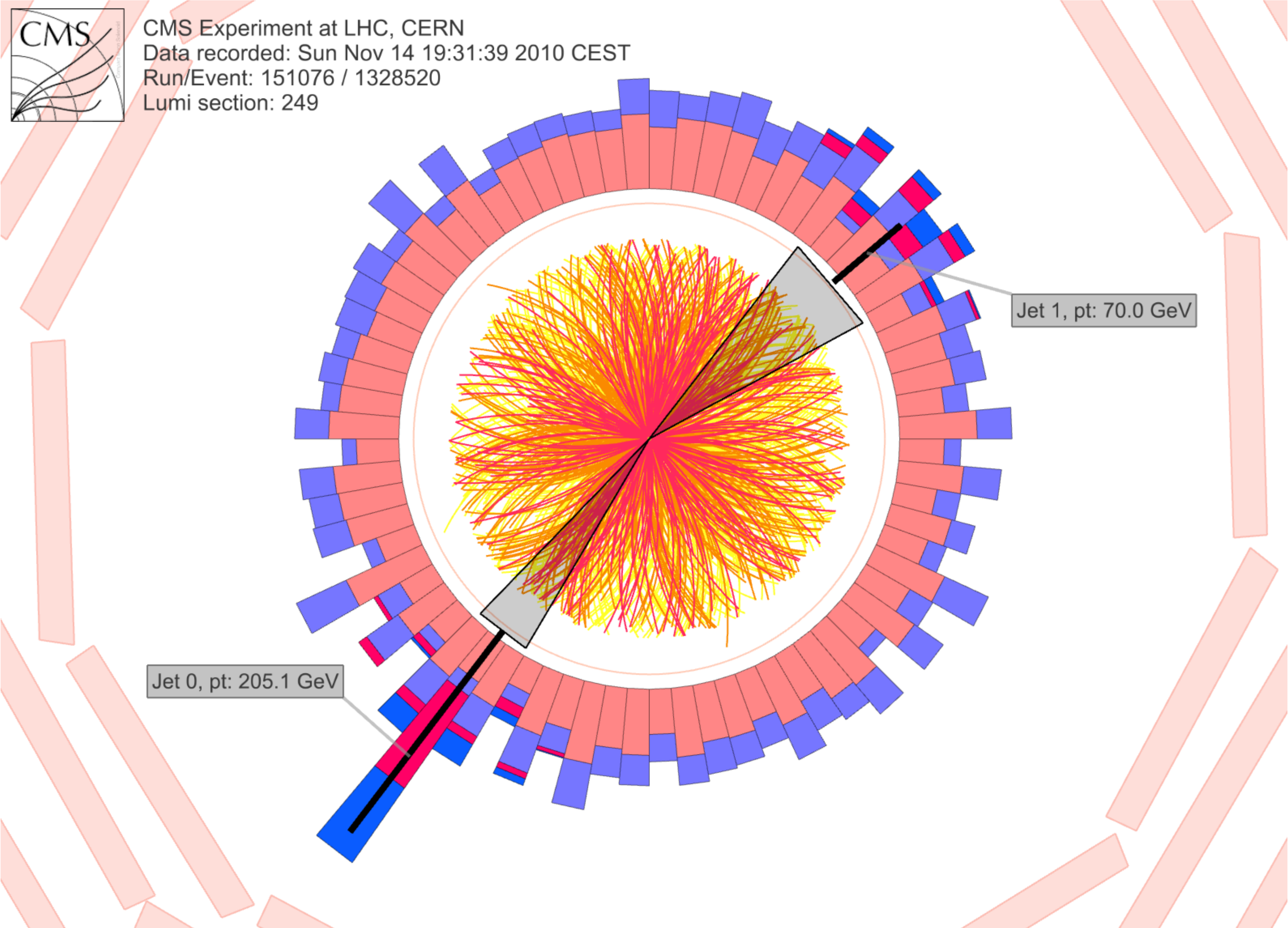


- 15% modulation seen "by eye"
- manifestation of collective effects
- described by relativistic hydrodynamics (strongly coupled fluid)

Manifestation of the quark-gluon plasma.

SUPPRESSION OF HIGH-ENERGY PROBES



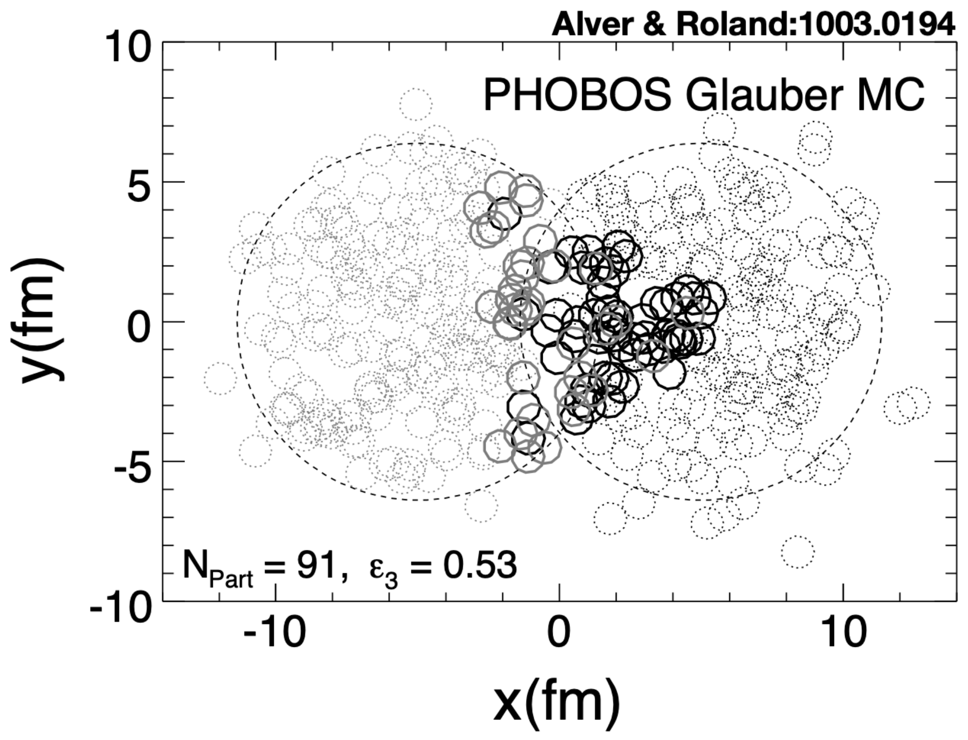


Two-jet event in proton-proton

Jet quenching in heavy-ion

Imbalanced jets because of interaction with the quark-gluon plasma!

How do we quantify "jet quenching"?



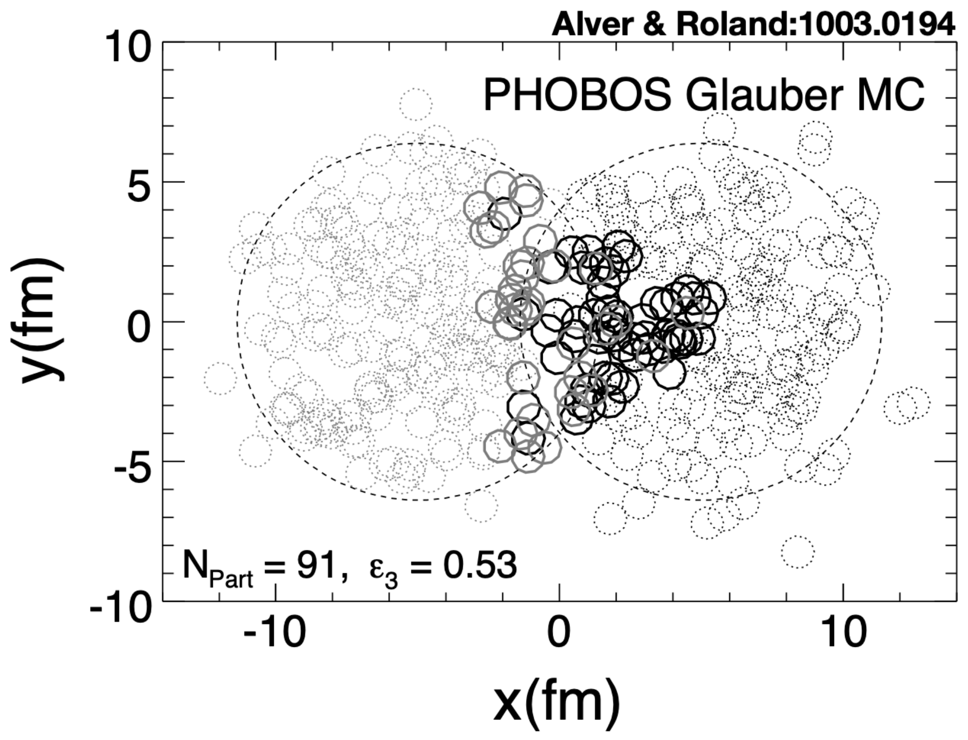
number of events observed in heavy-ion collision

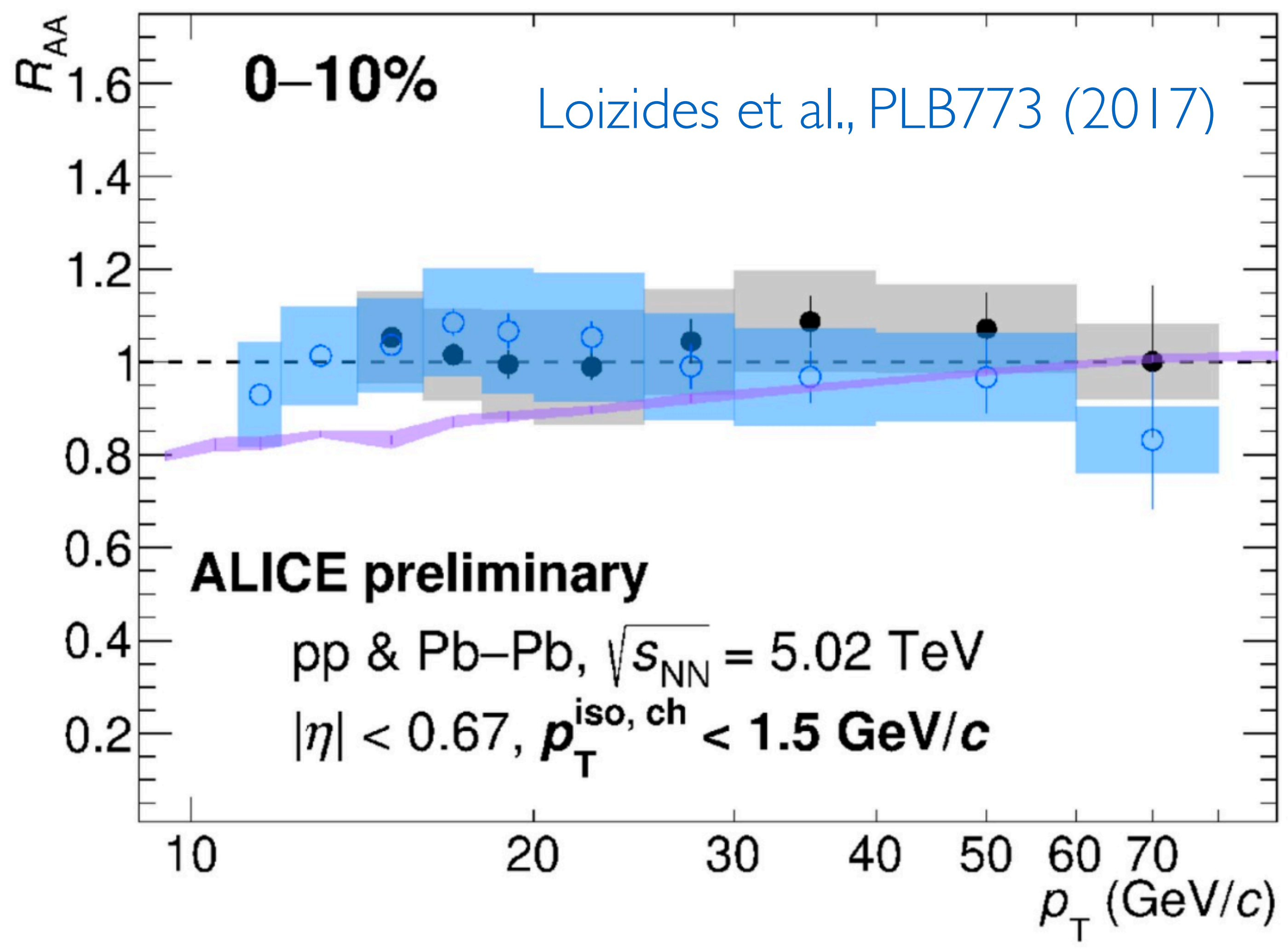
$$R_{AA} = \frac{\mathrm{d}N_{AA}/\mathrm{d}p_T}{\langle N_{\rm coll}\rangle \, \mathrm{d}\sigma_{pp}/\mathrm{d}p_T}$$

cross-section for process in proton-proton

- $\langle N_{\rm coll}\rangle$ (nuclear thickness function) extracted from Glauber model
- here for p_T but also constructed for other measures

How do we quantify "jet quenching"?





R_{AA} for photons shows no modification!

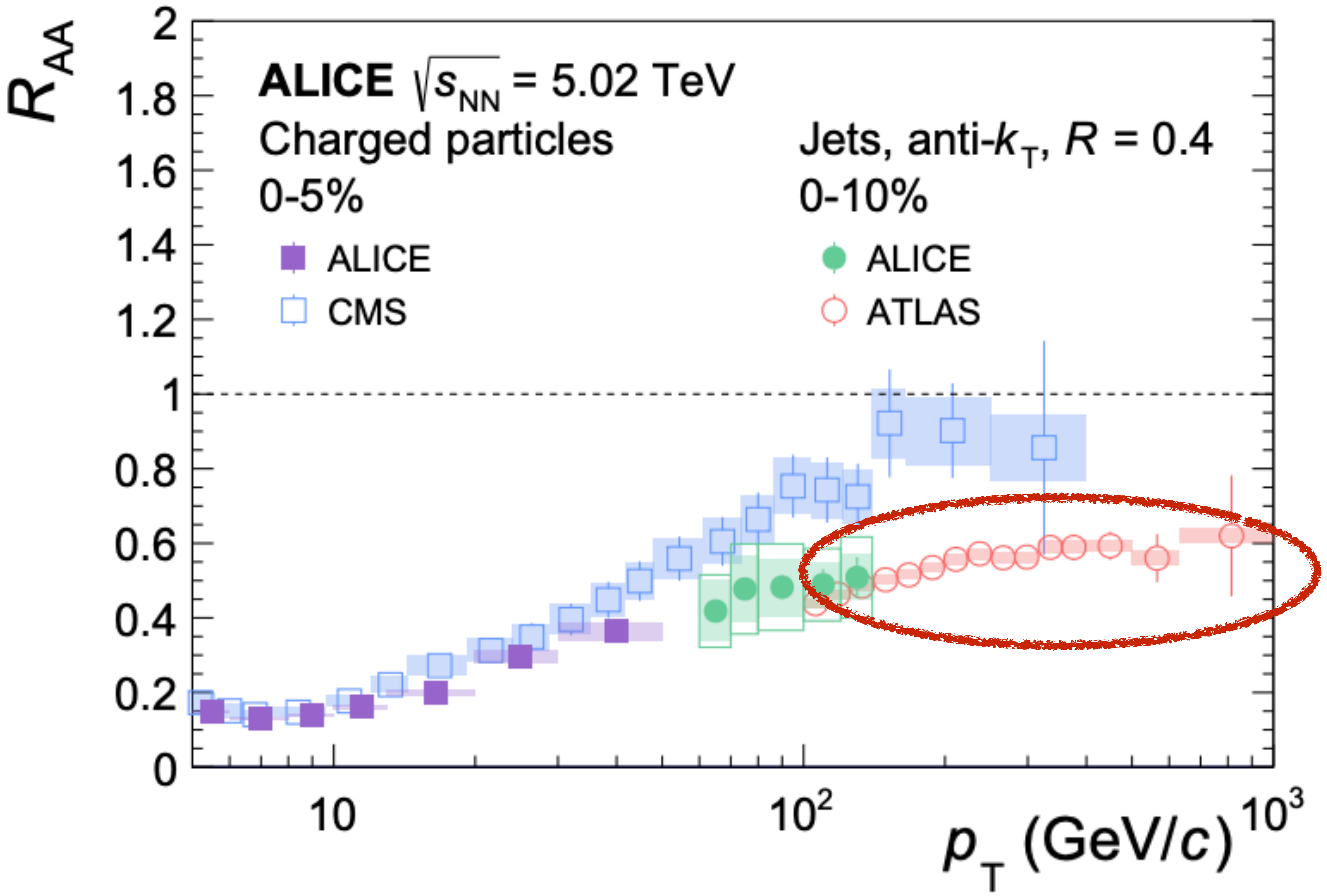
number of events observed in heavy-ion collision

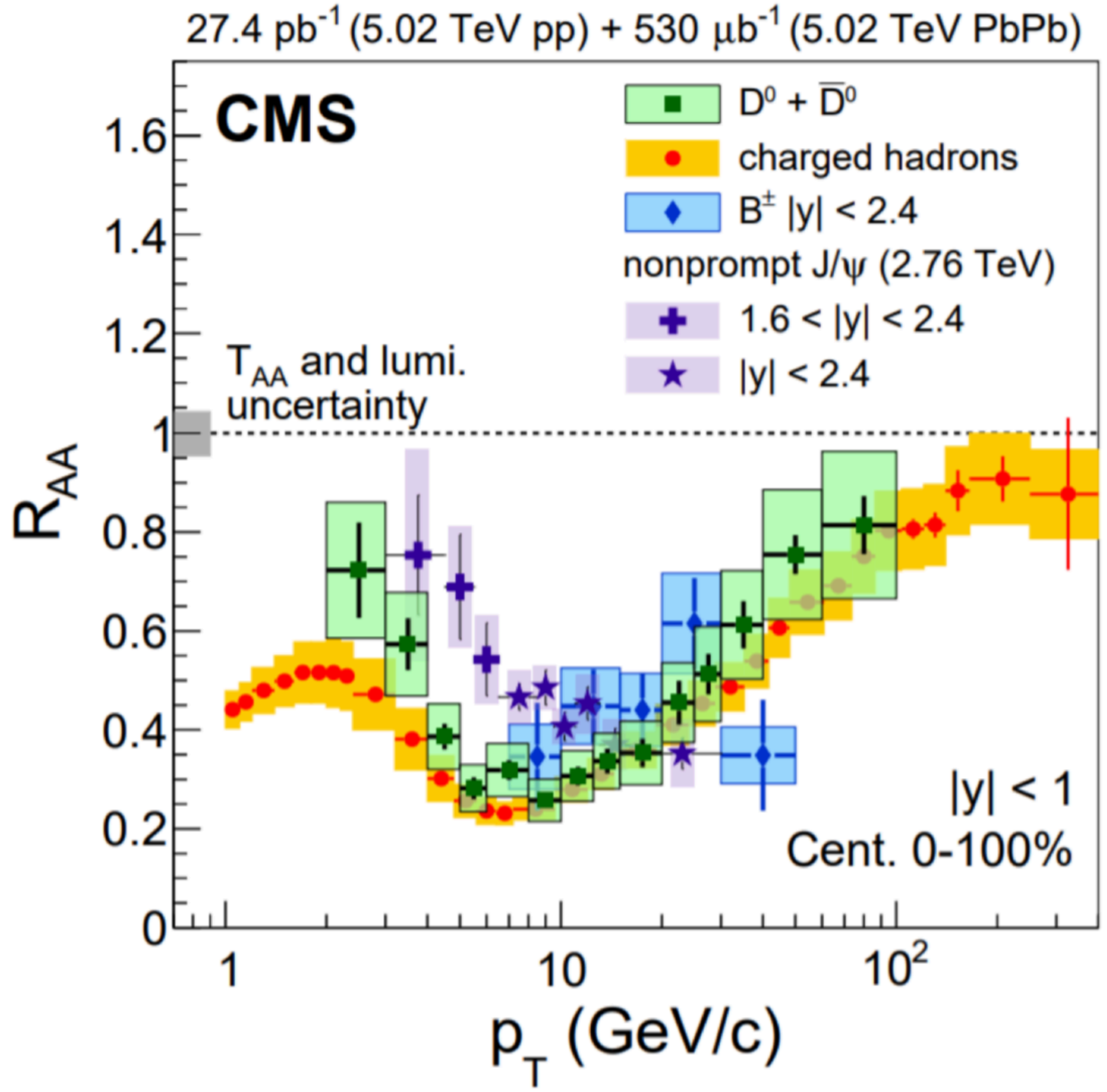
$$R_{AA} = \frac{\mathrm{d}N_{AA}/\mathrm{d}p_T}{\langle N_{\mathrm{coll}}\rangle\, \mathrm{d}\sigma_{pp}/\mathrm{d}p_T}$$

cross-section for process in proton-proton

- $\langle N_{\mathrm{coll}}\rangle$ (nuclear thickness function) extracted from Glauber model
- here for p_T but also constructed for other measures

JET SUPPRESSION IN DATA

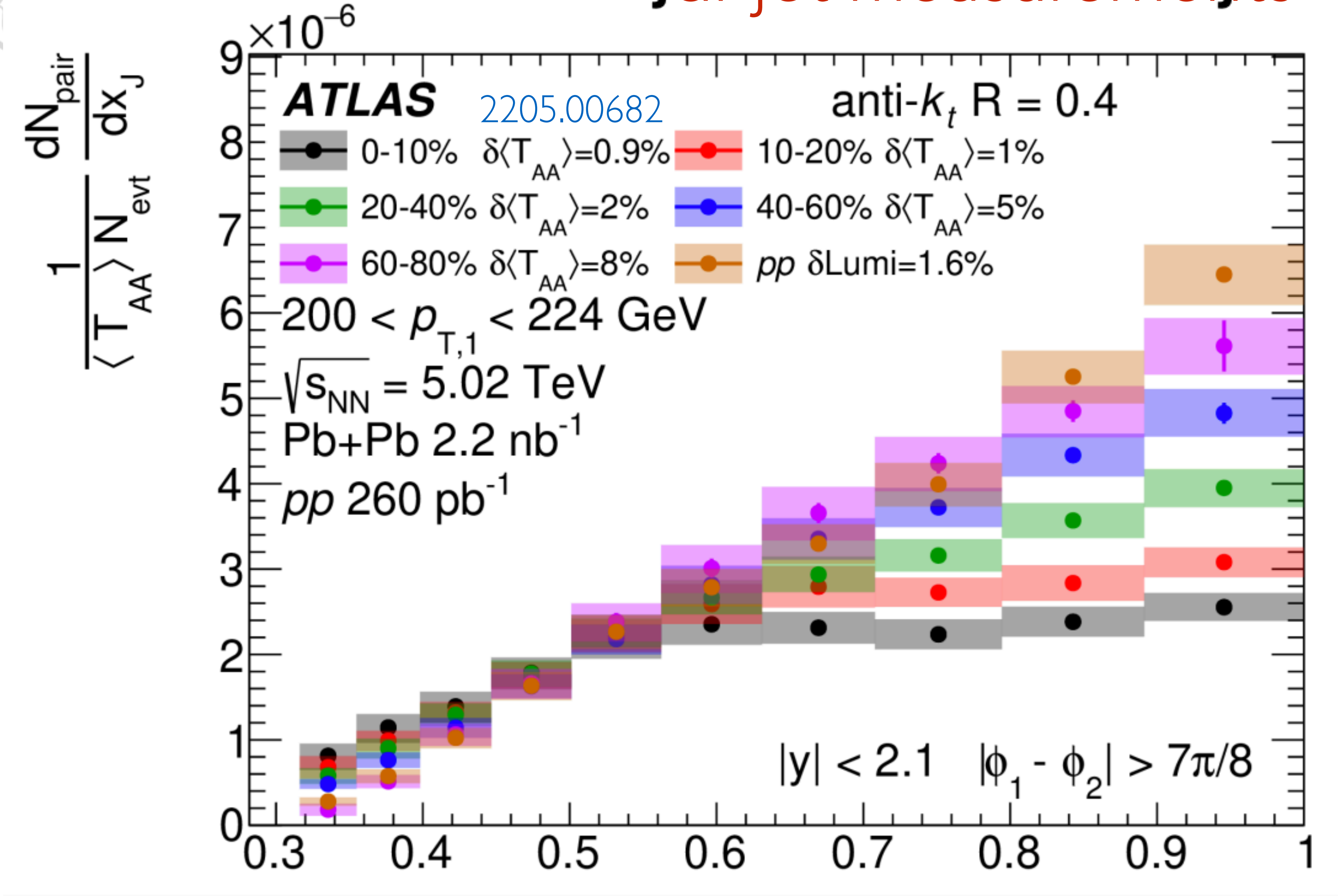




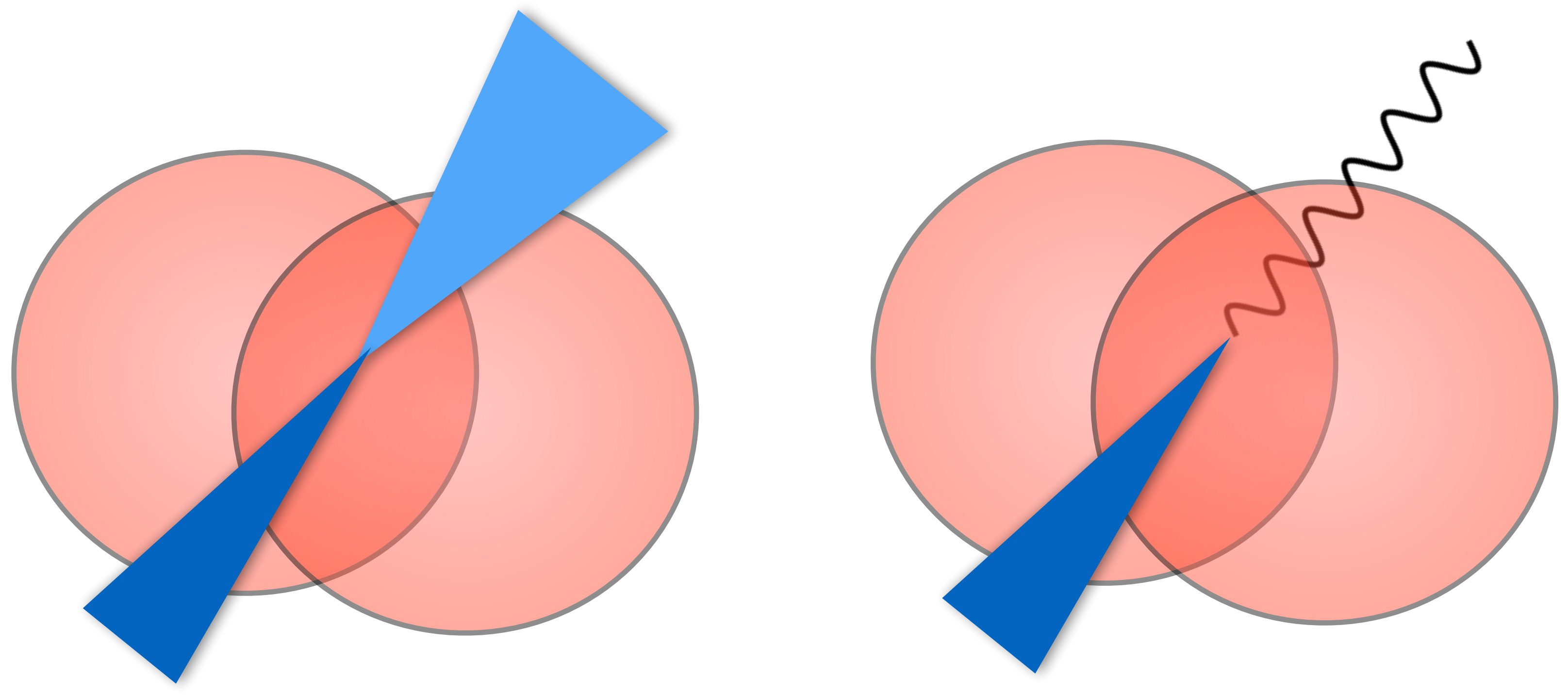
- kinematic range at LHC allows to probe jet quenching at varying scales & for different species (inclusive hadrons, heavy flavor, jets)
- (lack of) universal behavior at high-p_T

Coincidence measurements

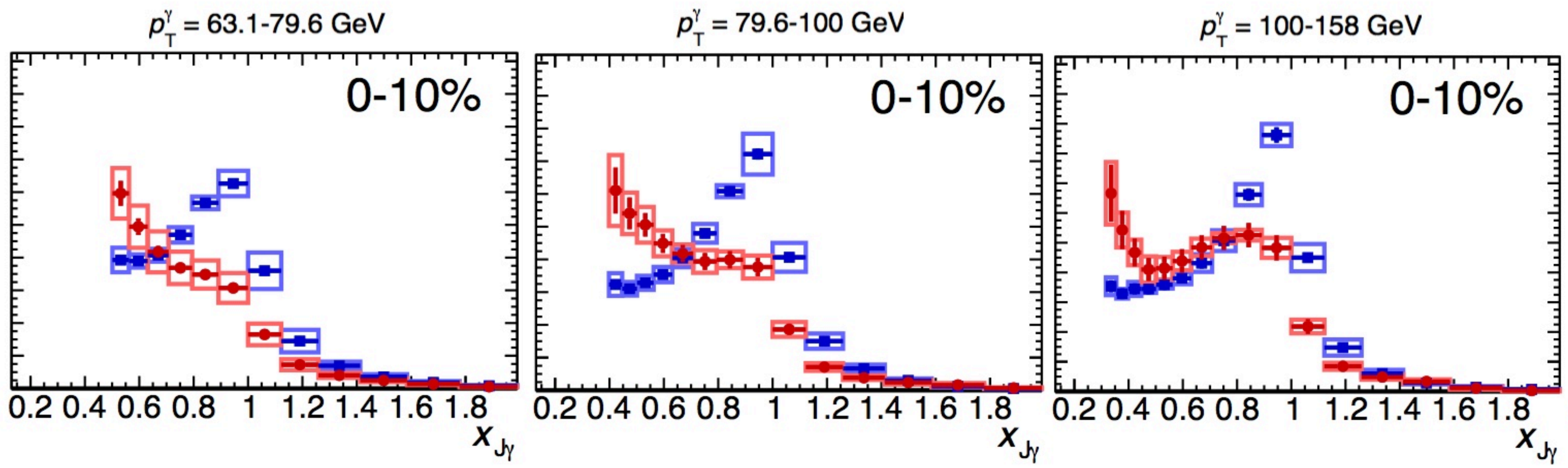
di-jet measurements



$$x_J = \frac{p_T^{\text{sub-lead}}}{p_T^{\text{lead}}}$$

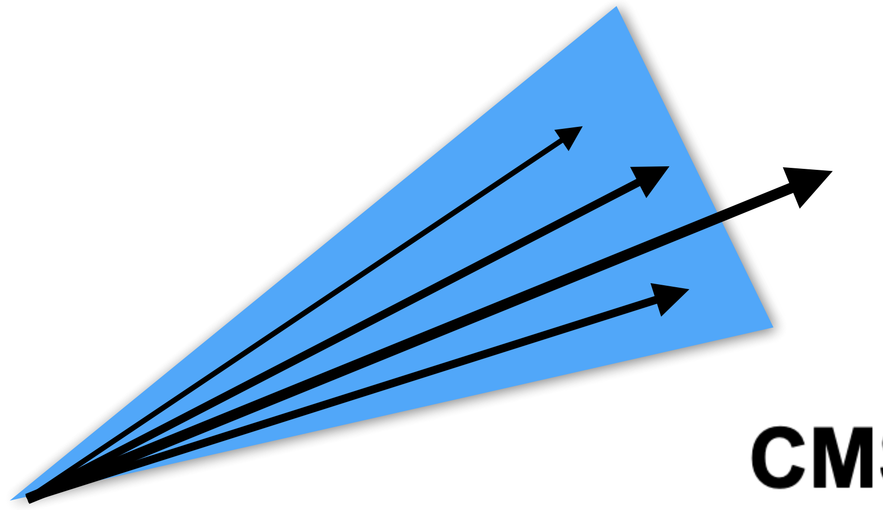


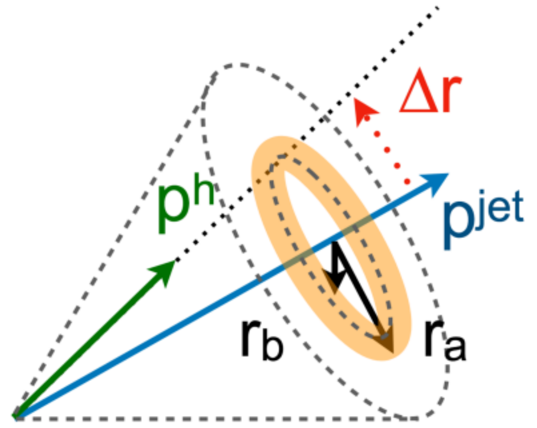
γ-triggered



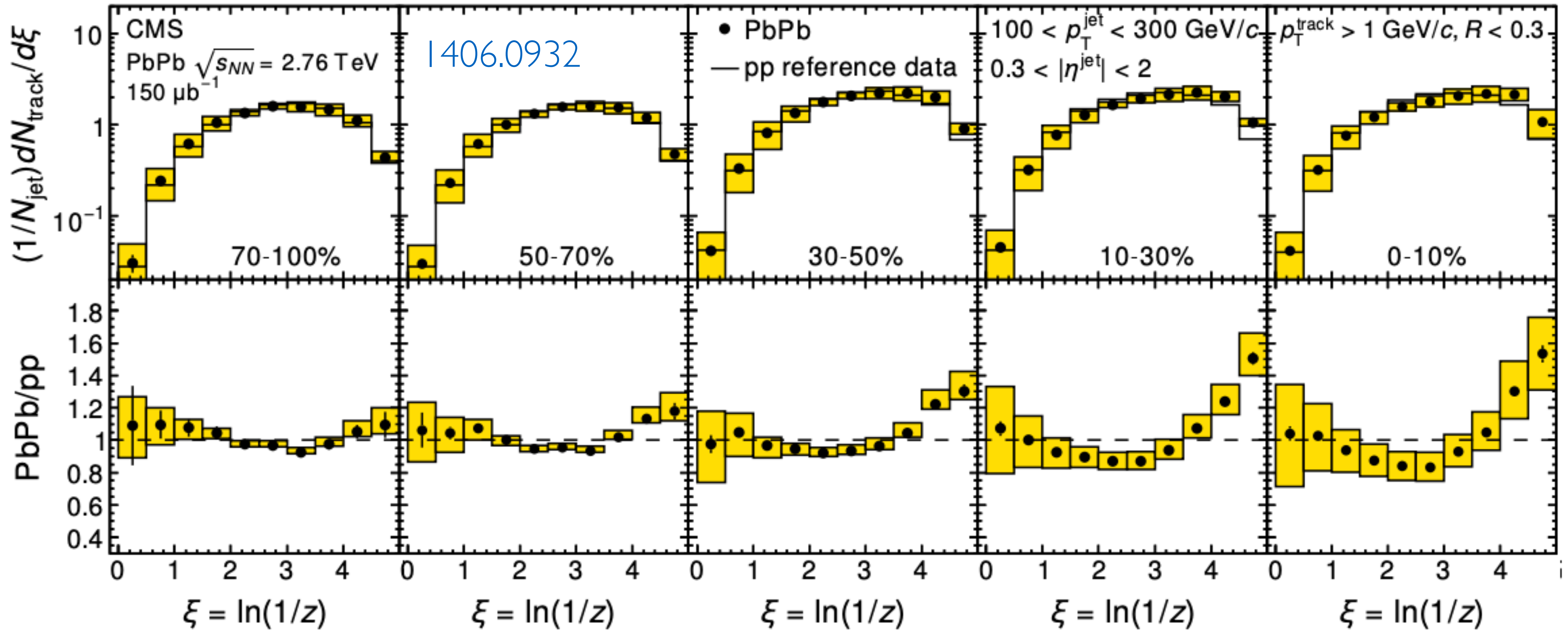
- offer a strong handle on jet quenching fluctuations:
  - path-length differences, energy-loss fluctuations, medium response…

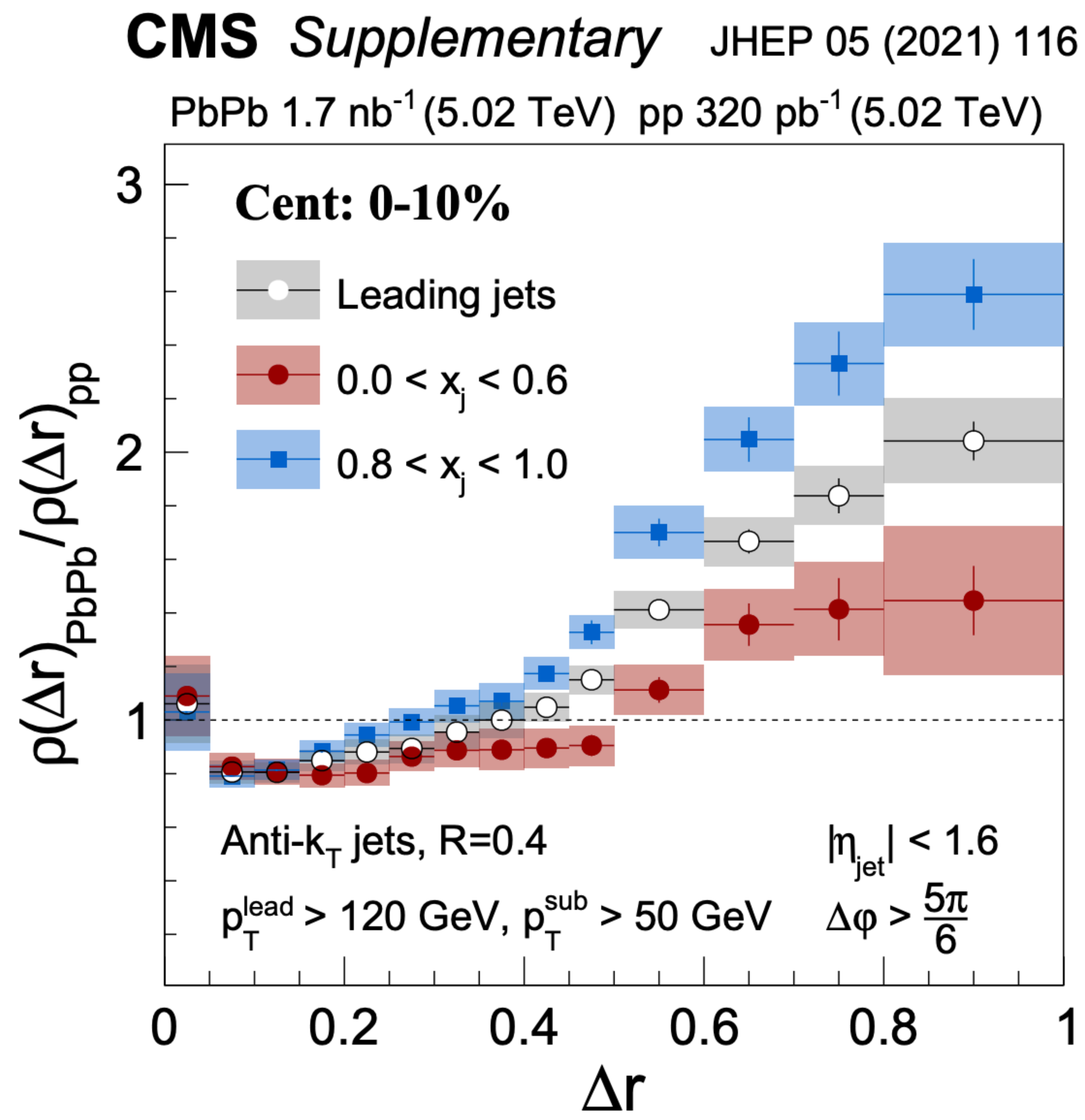
JET FRAGMENTATION

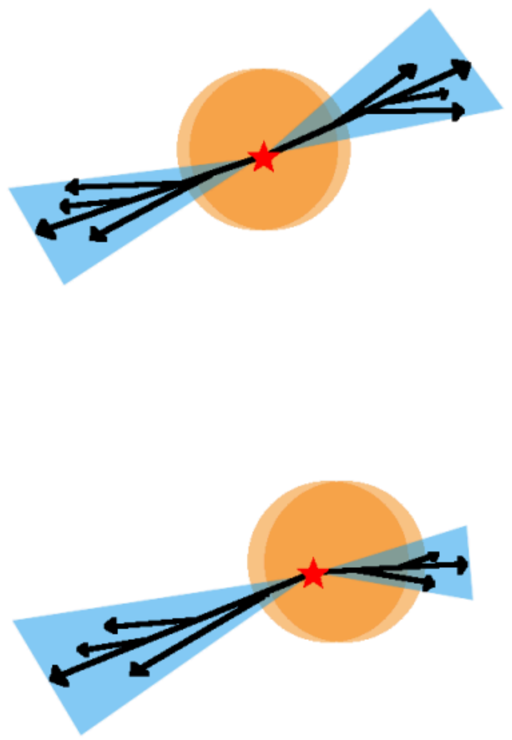




$$z = p_{T,i}/p_T^{jet}$$

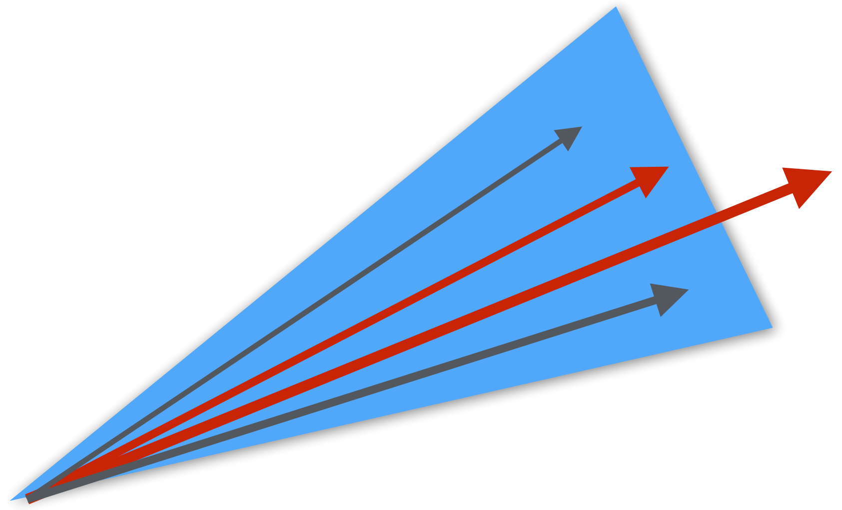


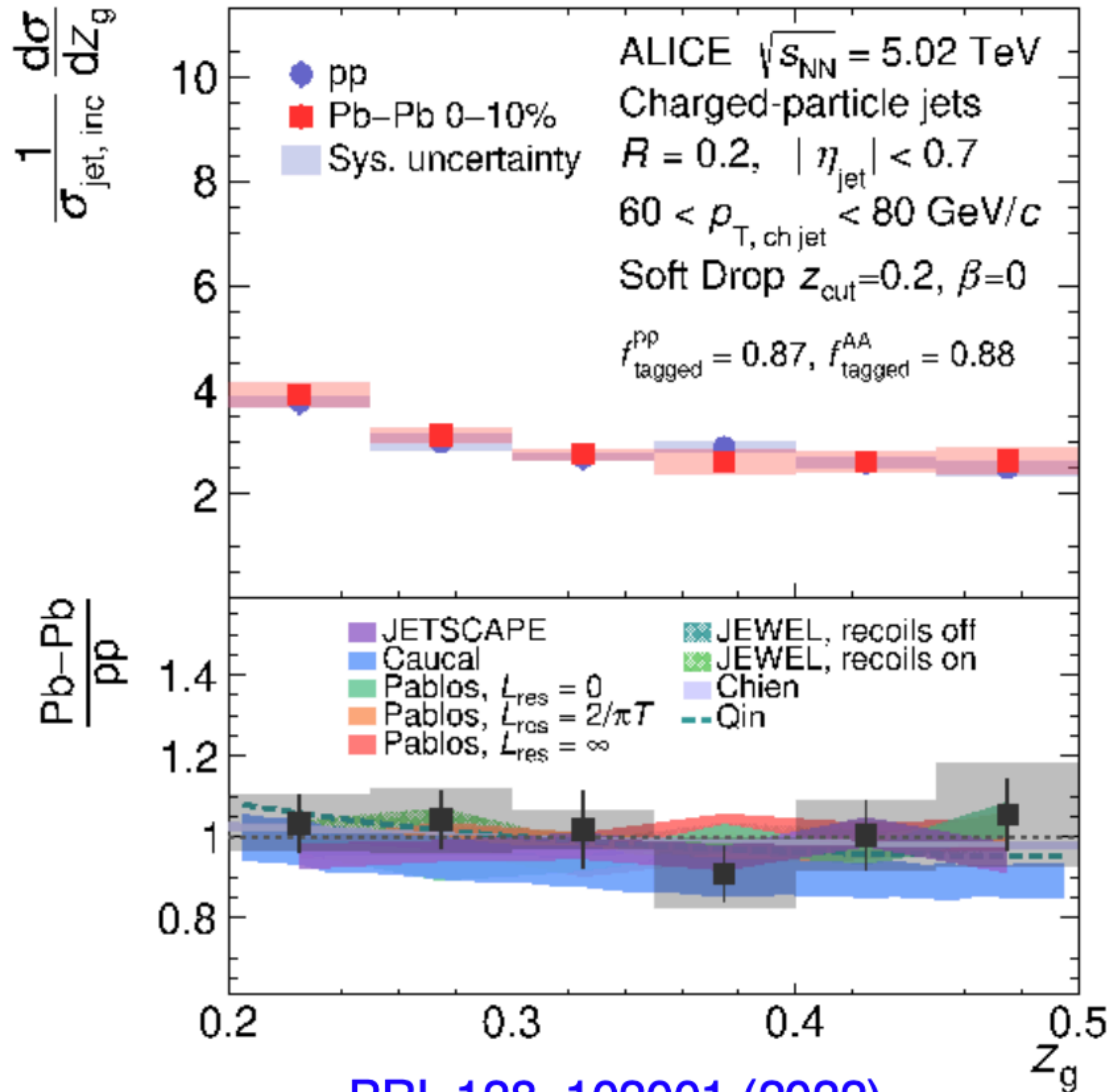




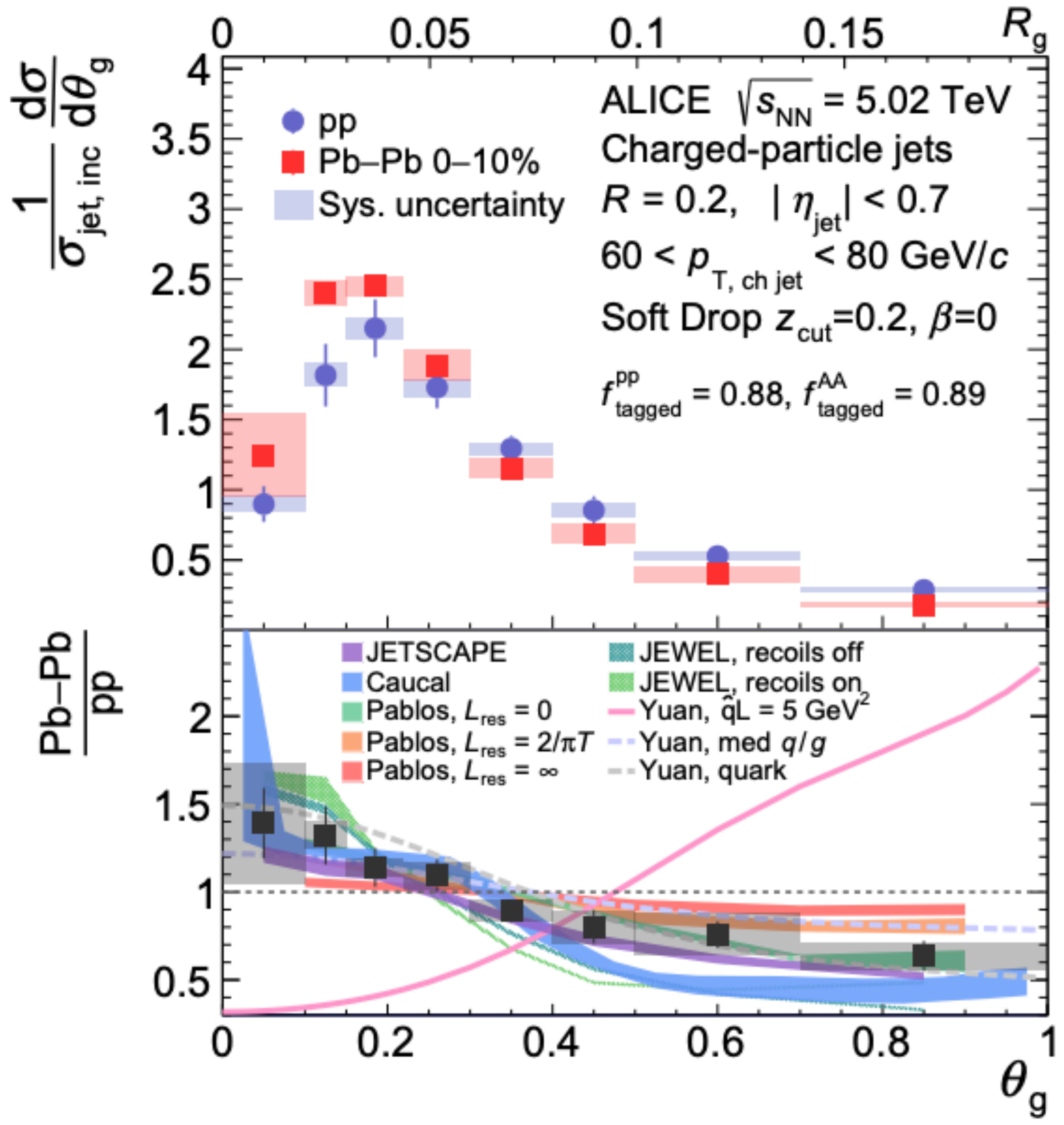
- intra-jet structure via longitudinal and transverse energy distributions
- jets are narrower with a large excess of soft particles at large angles!

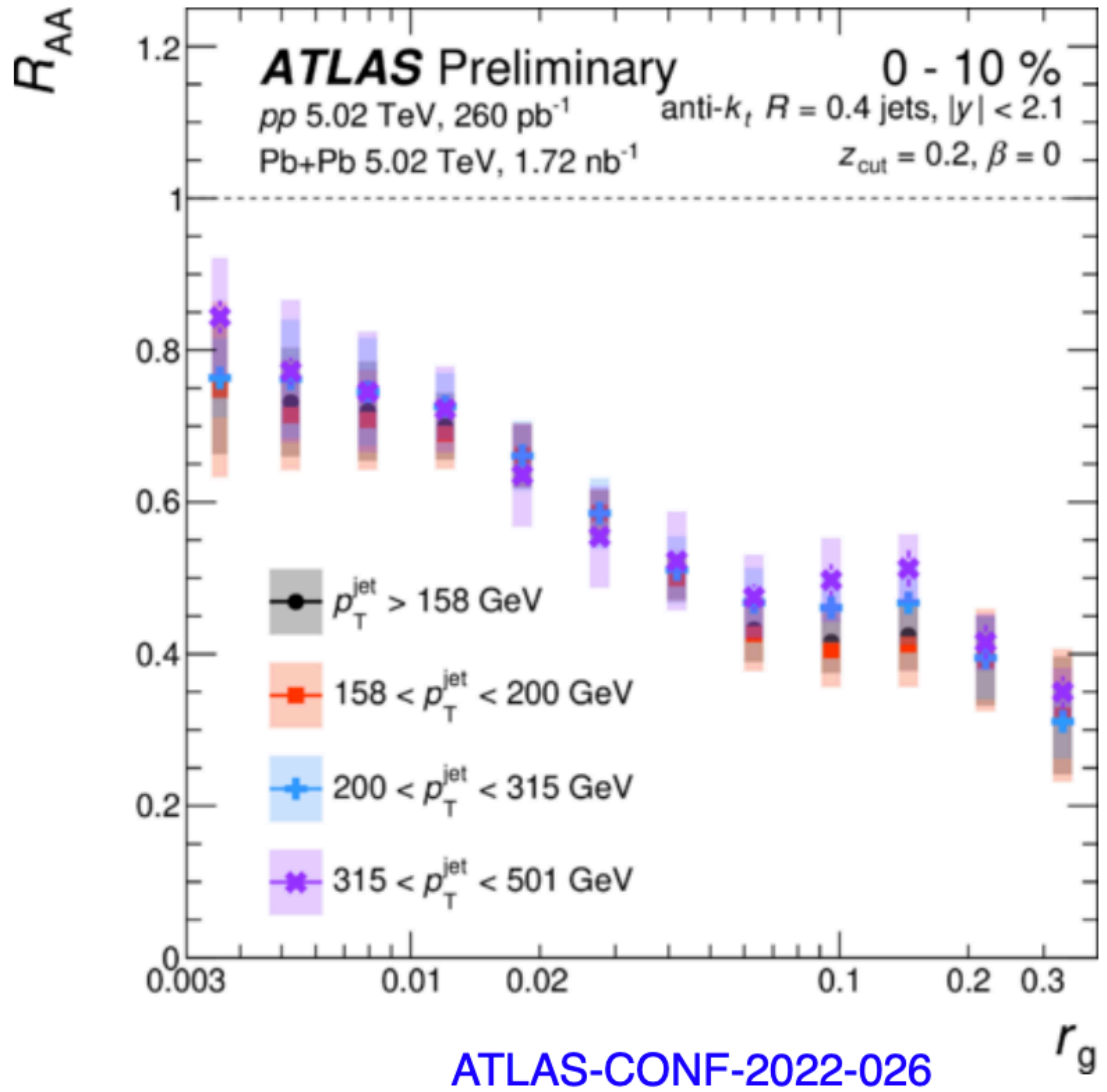
JET SUBSTRUCTURE OBSERVABLES



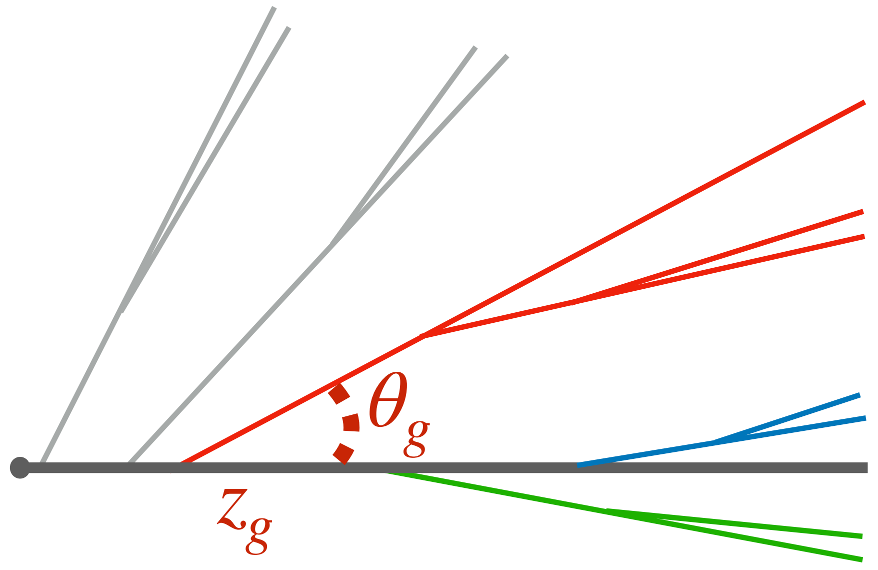


PRL 128, 102001 (2022)





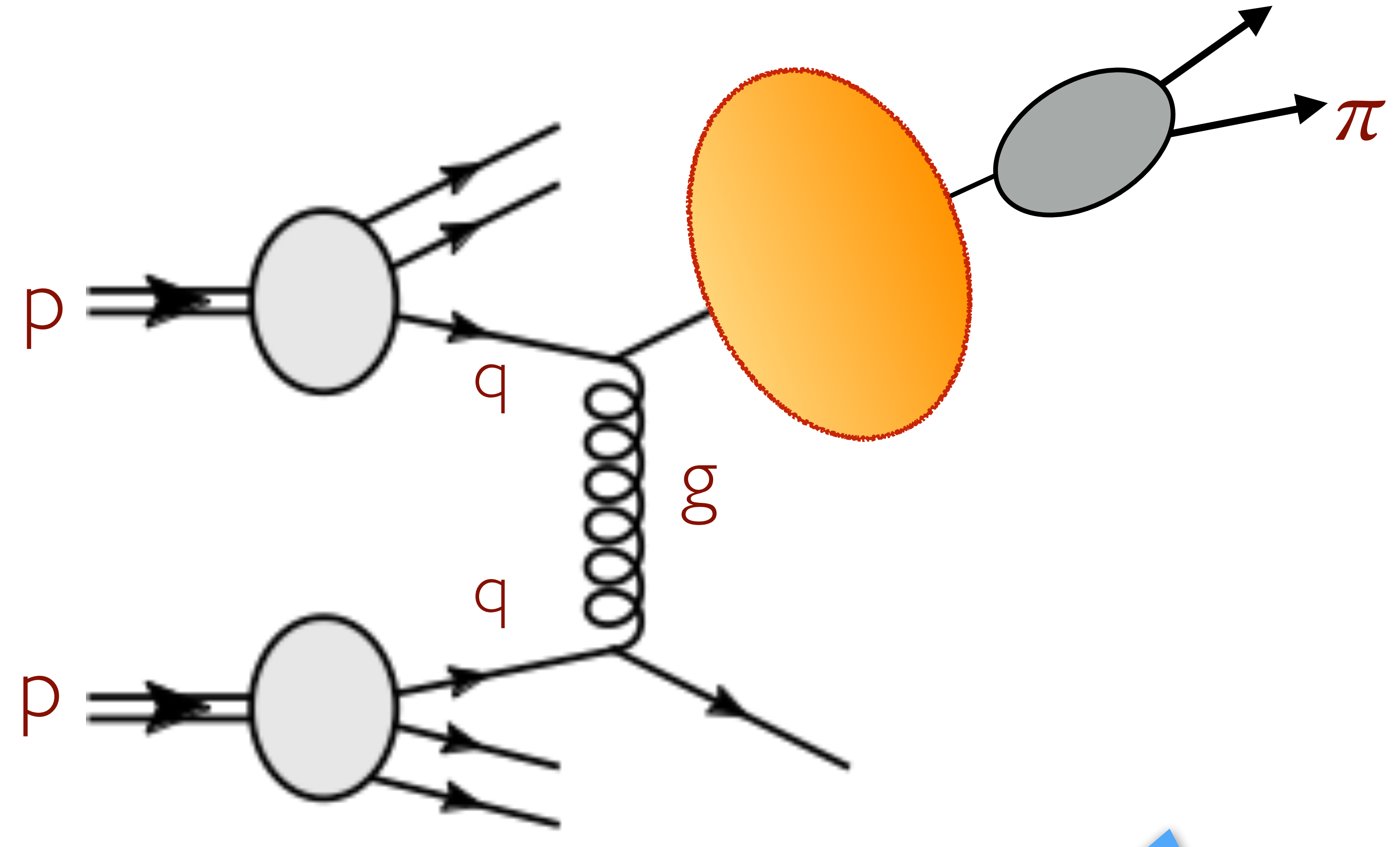
ATLAS-CONF-2022-026

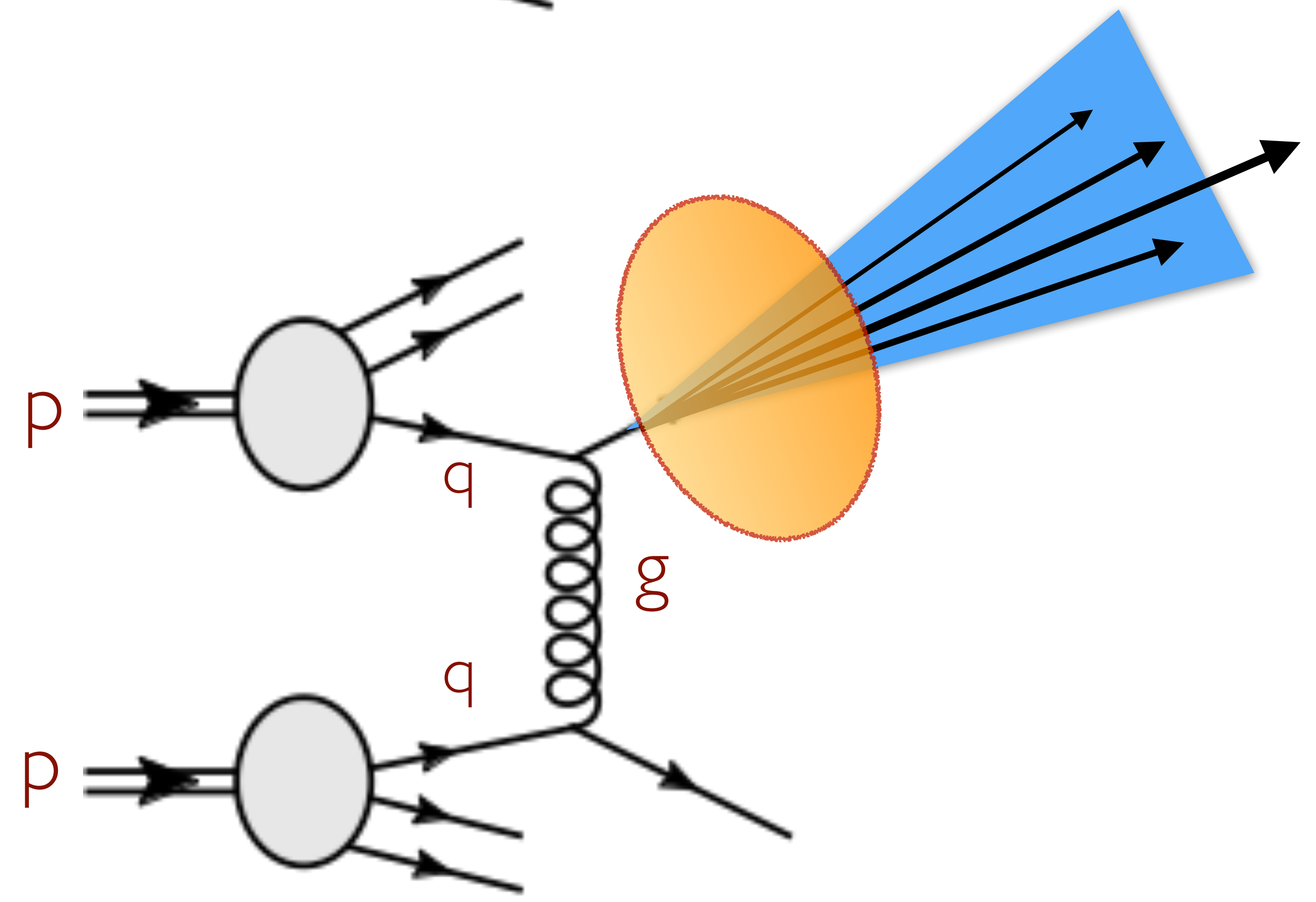


- IR safe jet substructure observables
- groomed observables: use information about the hardest splitting in the jet
- can also be used to select specific jet populatio (e.g. wide vs. narrow)

FACTORIZATION OF PQCD CROSS SECTION

- assume single parton propagates through the medium → hadronizes far outside the medium!
- good approximation since high-p_T hadrons are leading fragments $z \sim 0.5$ in jets
- jets are more complicated!
  - hadrons ≈ narrow jets (R~0)





$$\frac{\mathrm{d}\sigma^h_{\mathrm{med}}}{\mathrm{d}p_{\mathrm{T}}^2\mathrm{d}y} = \int \mathrm{d}q_{\mathrm{T}}^2\mathrm{d}z\,\frac{\mathrm{d}\sigma^k_{\mathrm{vac}}}{\mathrm{d}q_{\mathrm{T}}^2\mathrm{d}y} D^{k\to h}(z,\mu_F^2)\,\mathcal{P}_k(\epsilon)\delta(p_{\mathrm{T}} - z(q_{\mathrm{T}} - \epsilon))$$

$$q_{\mathrm{T}} = p_{\mathrm{T}}/z + \epsilon$$

IR SAFETY

- Important difference:
  - hadronic observables are **infrared unsafe** = sensitive to a IR scale ($\sim \Lambda_{\text{QED}}$)
  - jet observables can be defined as **infrared safe** w/ very little sensitivity to hadronization, NP,…
- clear indication when an observable is very different on "partonic" and "hadronic" level

Quenching hard spectrum

Baier, Dokshitzer, Mueller, Schiff (2001)
Salgado, Wiedemann (2003)

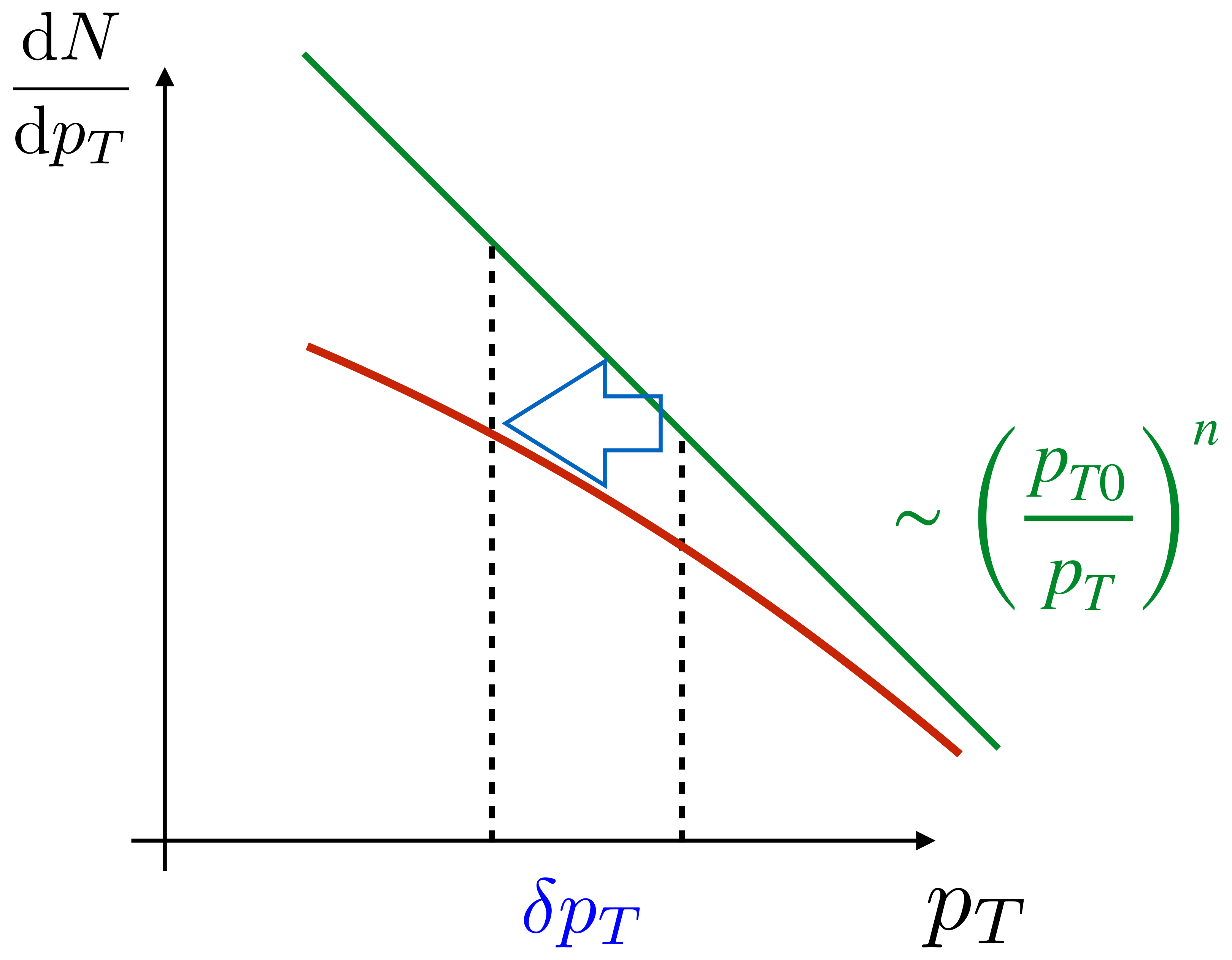
quenching weight (prob. distribution)

$$\frac{d\sigma_{\rm med}}{dp_T} = \int_0^\infty d\epsilon\, \mathcal{P}(\epsilon)\, \frac{d\sigma_{\rm vac}}{dp'_T}\Big|_{p'_T = p_T + \epsilon}$$

$$\approx \frac{d\sigma_{\rm vac}}{dp_T} \underbrace{\int_0^\infty d\epsilon\, \mathcal{P}(\epsilon) e^{-\epsilon \frac{n}{p_T}}}_{Q(p_T)}$$

quenching factor

For $\epsilon/p_T \ll 1$ and large n, $\frac{1}{(p_{\rm T}+\epsilon)^n} \approx \frac{1}{p_{\rm T}^n} e^{-\epsilon n/p_{\rm T}}$



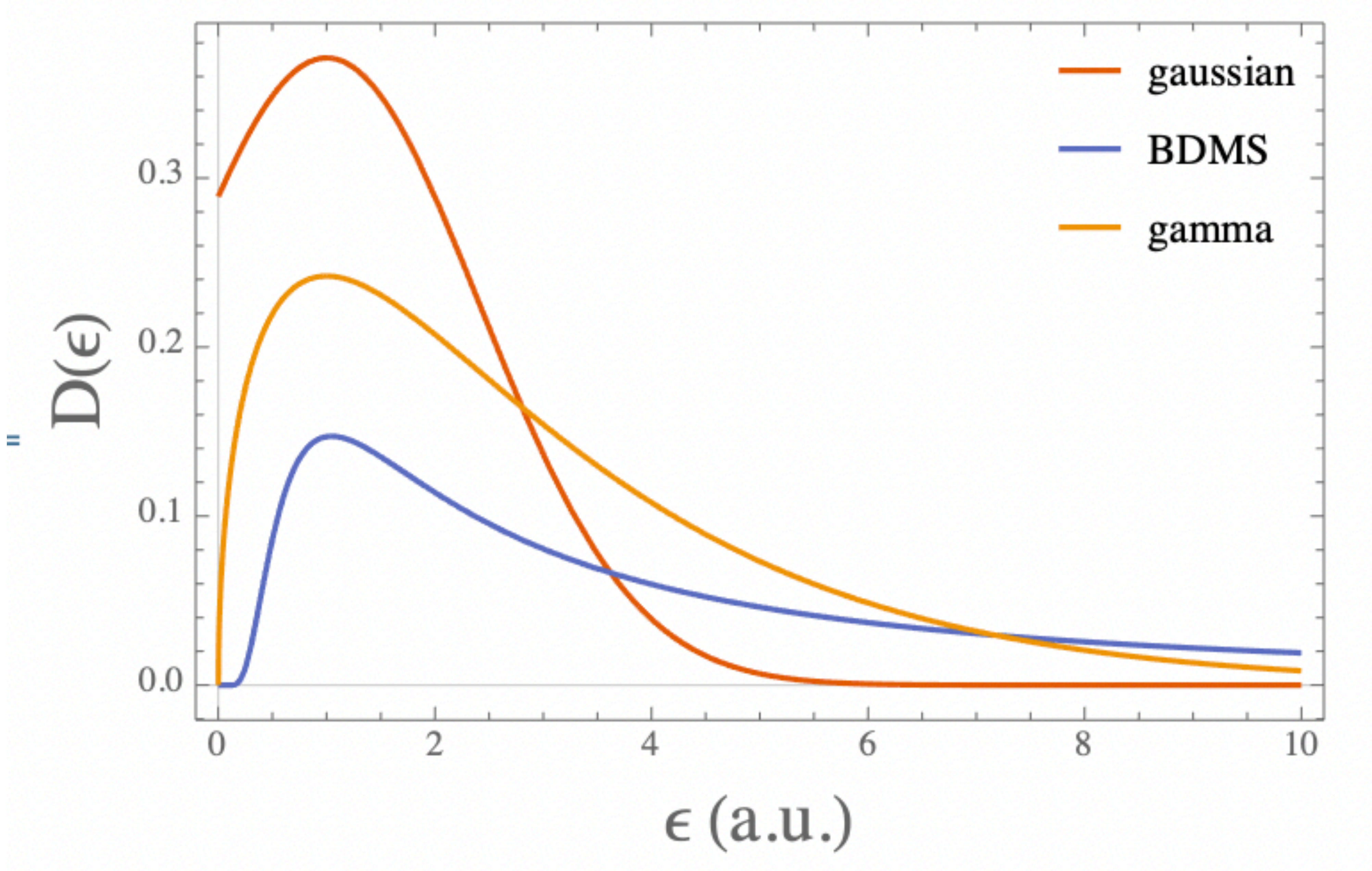
- applies for small energy losses & steeply falling spectra
- the exponential "weight" factor induces a strong survival bias
  - only **jets which lost little energy** (i.e. whose ϵ is small) contribute!

UNDERSTANDING "JET QUENCHING" AS SURVIVAL BIAS

- The flatter the spectrum, the less significant is the energy loss
- Naively, one would expect the first moment of $P(\epsilon)$ to dominate
  - where mean energy loss $\langle \epsilon \rangle = \int \mathrm{d}\epsilon \, \epsilon P(\epsilon)$ and $\frac{\mathrm{d}\sigma_{\mathrm{med}}}{\mathrm{d}p_T} \approx \frac{\mathrm{d}\sigma_0(p_T + \Delta E)}{\mathrm{d}p_T}$
- Steeply falling spectrum $n \gg 1$: sensitive to the **typical** energy loss ϵ^* (peak of distribution), not the **mean** $\langle \epsilon \rangle$!
  - applies to fat-tailed distributions

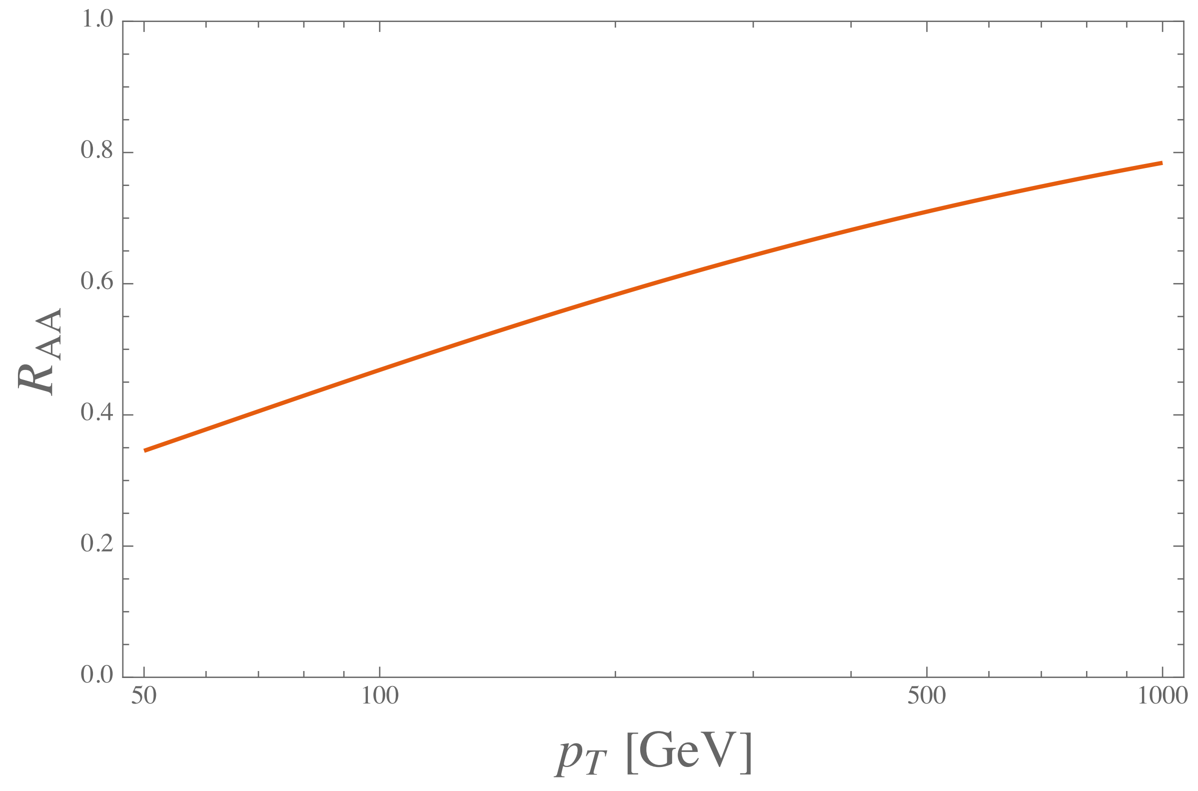
if $n = 0$, no quenching

$$\int d\epsilon \, P(\epsilon) = 1$$

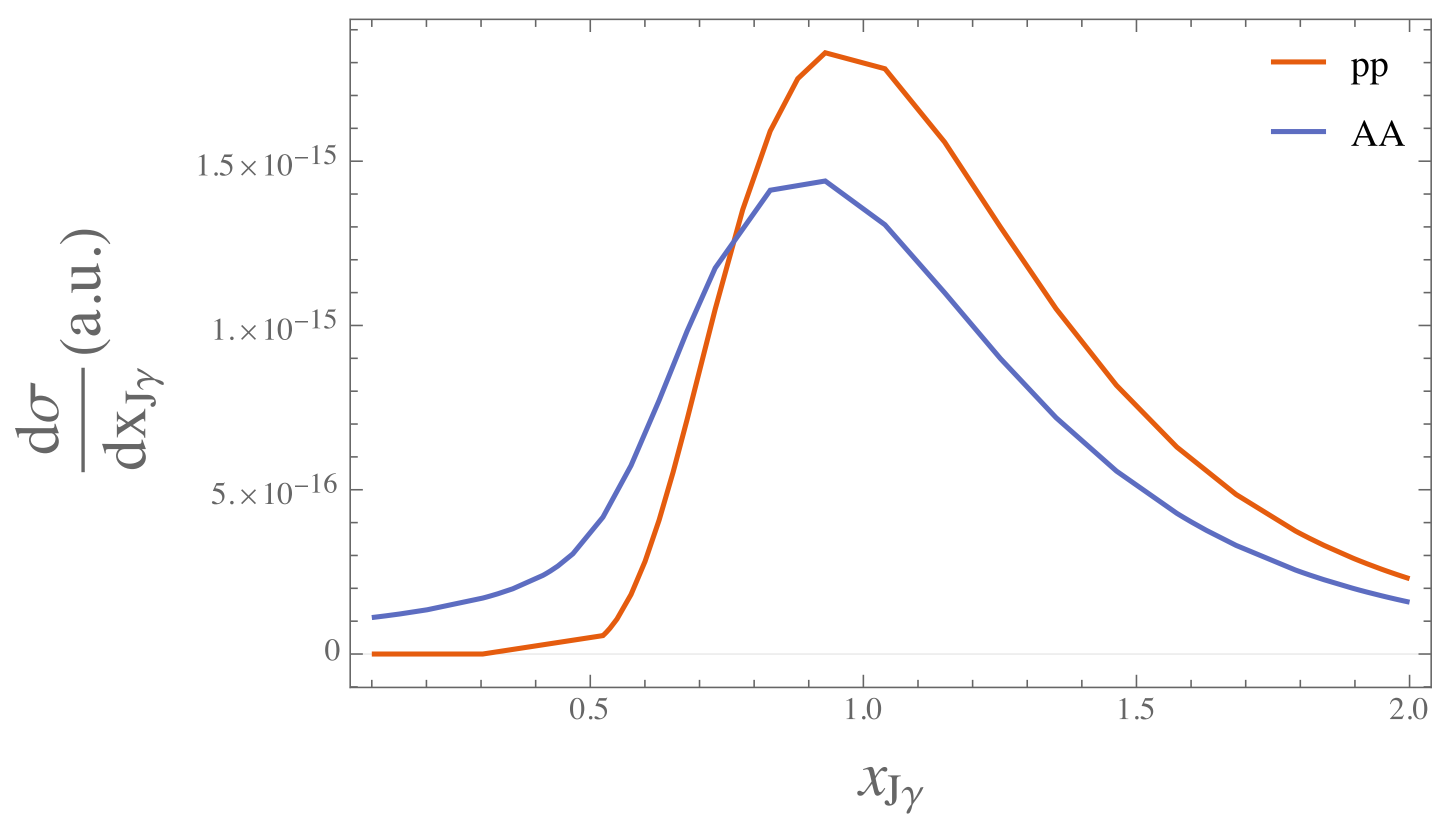


SIMPLE MODEL OF ENERGY-LOSS

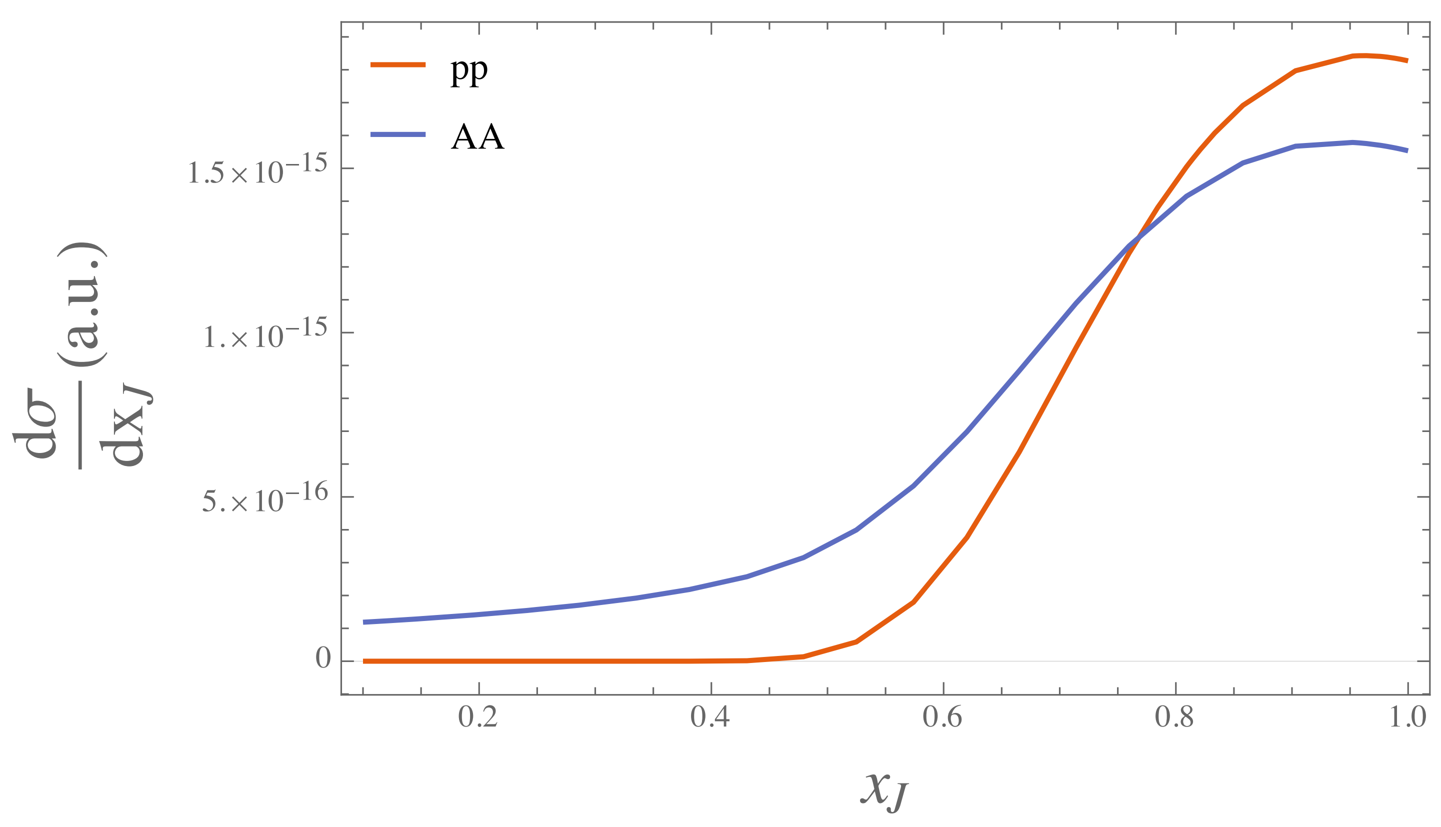
inclusive jets



γ-tagged



di-jets



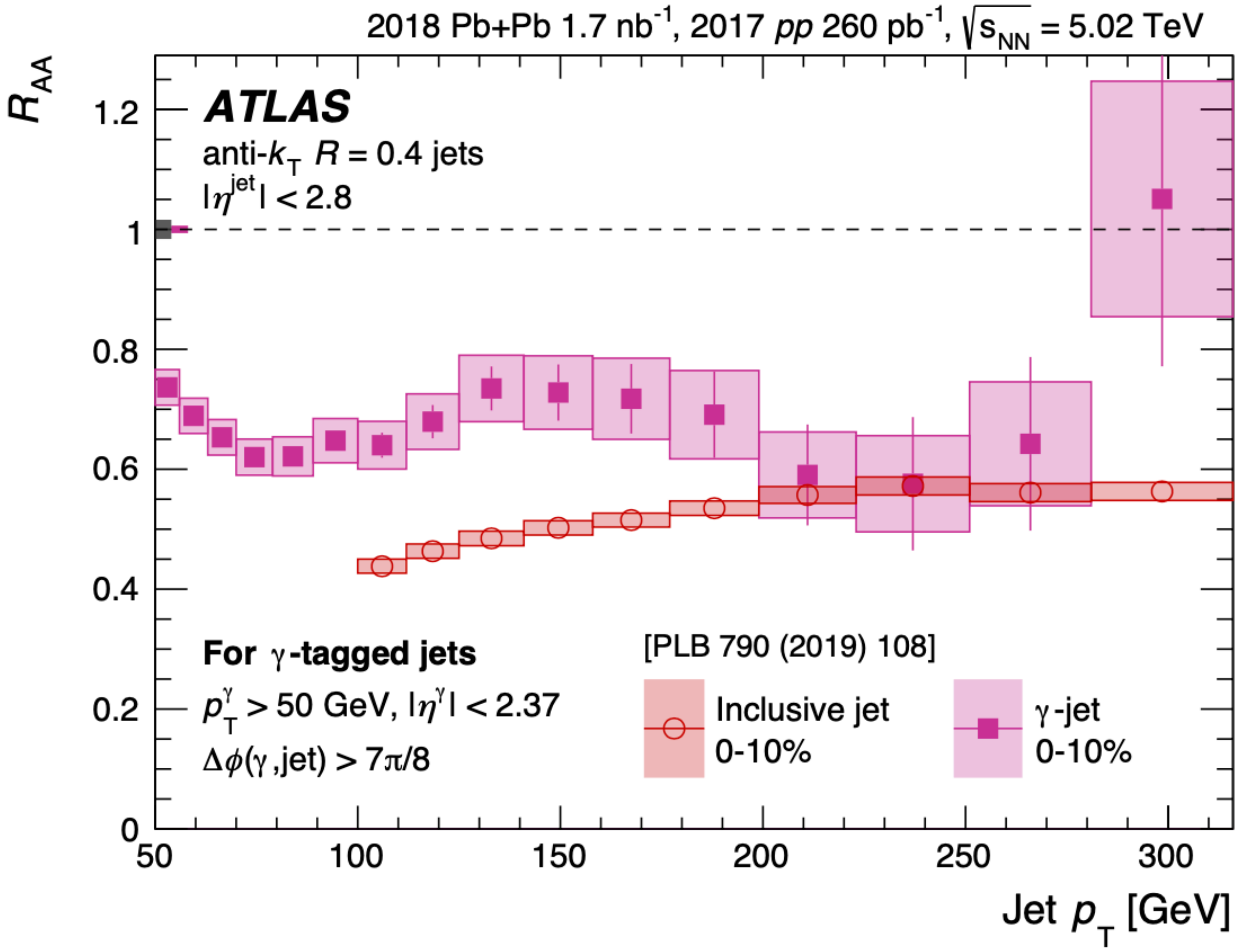
- qualitative features are described by a simple model of energy loss
- no path length dependence, but energy-loss fluctuations!

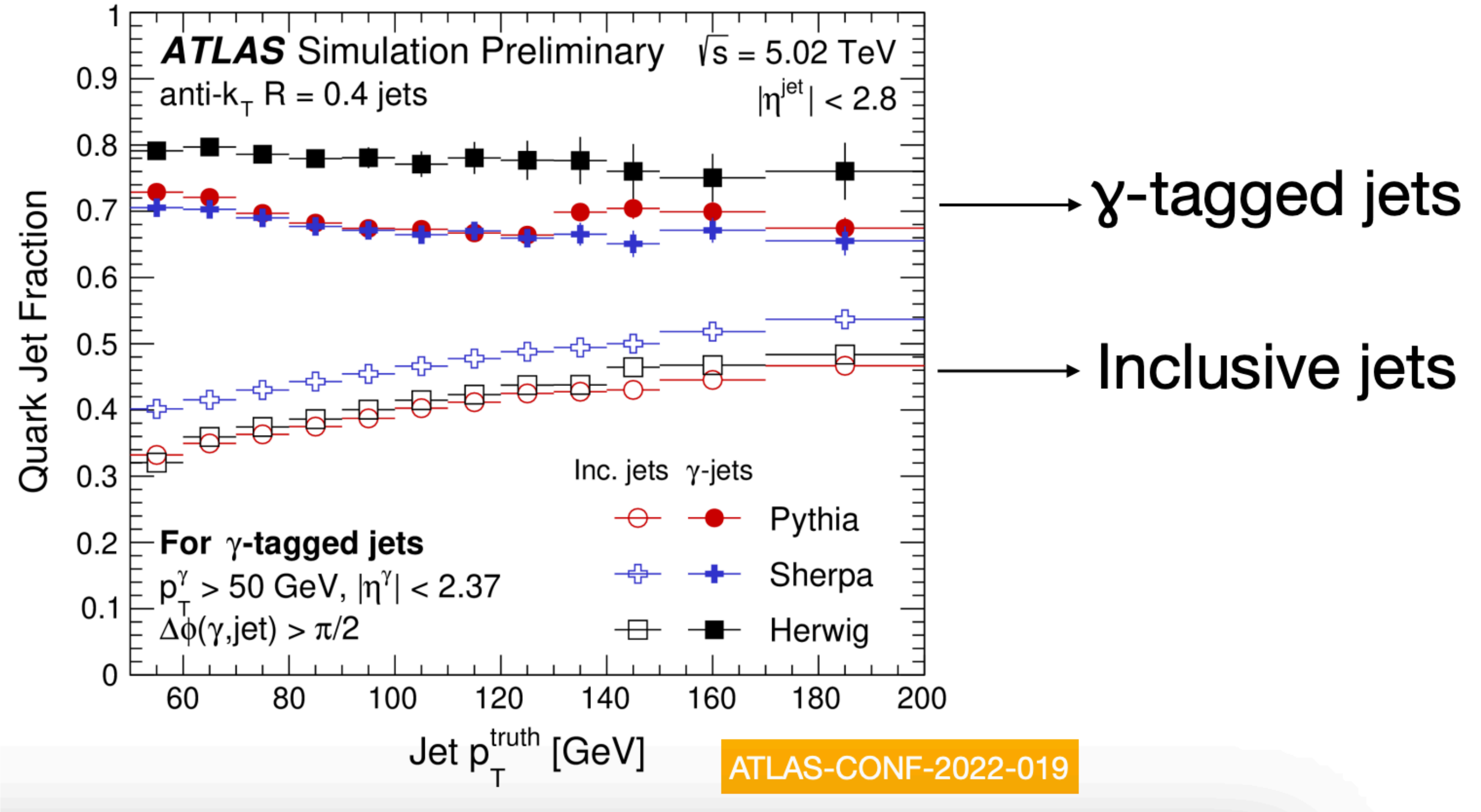
$$D(\epsilon) = \sqrt{\frac{\omega_s}{\epsilon^3}}\,\mathrm{e}^{-\frac{\pi\omega_s}{\epsilon}}$$

$$\frac{\mathrm{d}\sigma^{AA}}{\mathrm{d}x_{J\gamma}} = \int \mathrm{d}\epsilon \int \mathrm{d}^2p_T\mathrm{d}^2p_T^\gamma\, \mathcal{P}(\epsilon)\delta\left(x_{J\gamma} - \frac{p_T}{p_T^\gamma}\right) \frac{\mathrm{d}\sigma}{\mathrm{d}^2p_T\mathrm{d}^2p_T^\gamma}\bigg|_{\mathrm{cuts},p_T+\epsilon}$$

$$\frac{\mathrm{d}\sigma^{AA}}{\mathrm{d}x_J} = \int \mathrm{d}\epsilon_1\mathrm{d}\epsilon_2 \int \mathrm{d}^2p_T^1\mathrm{d}^2p_T^2\, \mathcal{P}(\epsilon_1)P(\epsilon_2) \times \delta\left(x_J - \frac{\min(p_T^1,p_T^2)}{\max(p_T^1,p_T^2)}\right) \frac{\mathrm{d}\sigma}{\mathrm{d}^2p_T^1\mathrm{d}^2p_T^2}\bigg|_{\mathrm{cuts},p_T^1+\epsilon_1,p_T^2+\epsilon_2}$$

STATE-OF-THE-ART

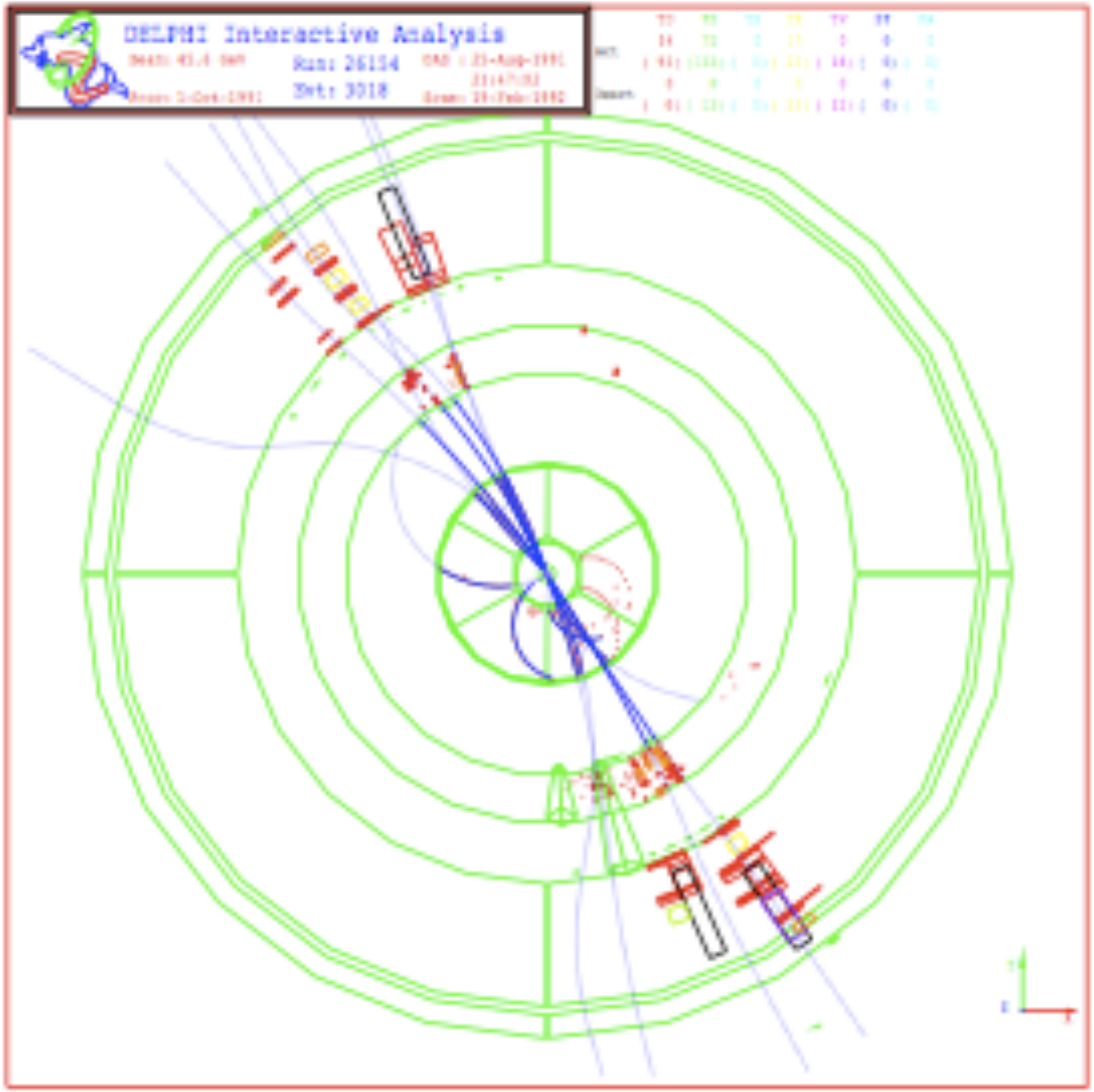




- state-of-the-art calculations have to use **realistic quark/gluon spectra**, account for **medium evolution**, include detailed description of **radiative & elastic** energy loss
- rise of MC tools (JETSCAPE, JEWEL, hybrid model, Saclay model, LIDO etc..)
- key feature: combining vacuum jet fragmentation & medium effects

Lecture 1

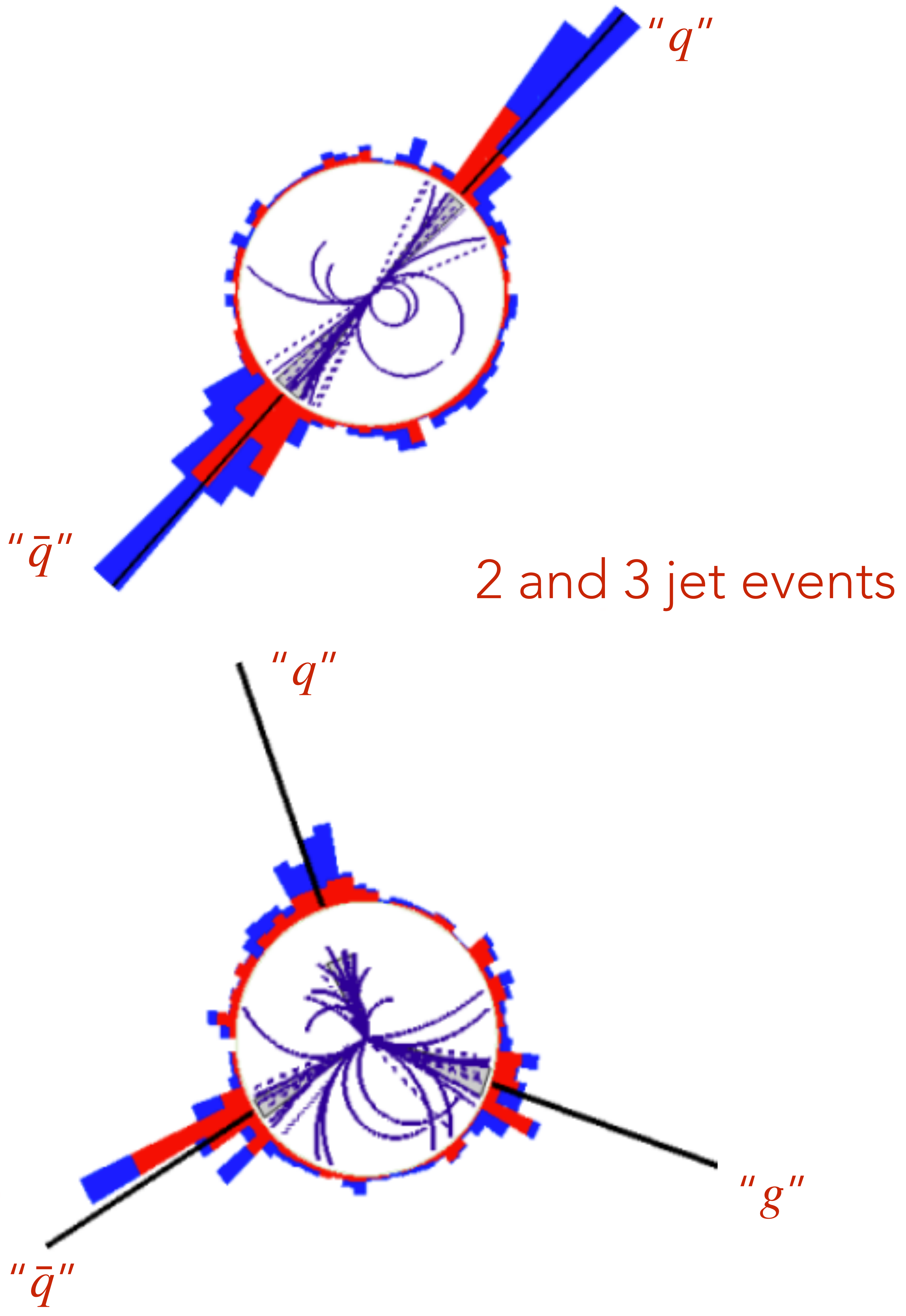
Part II: QCD jet fragmentation in vacuum



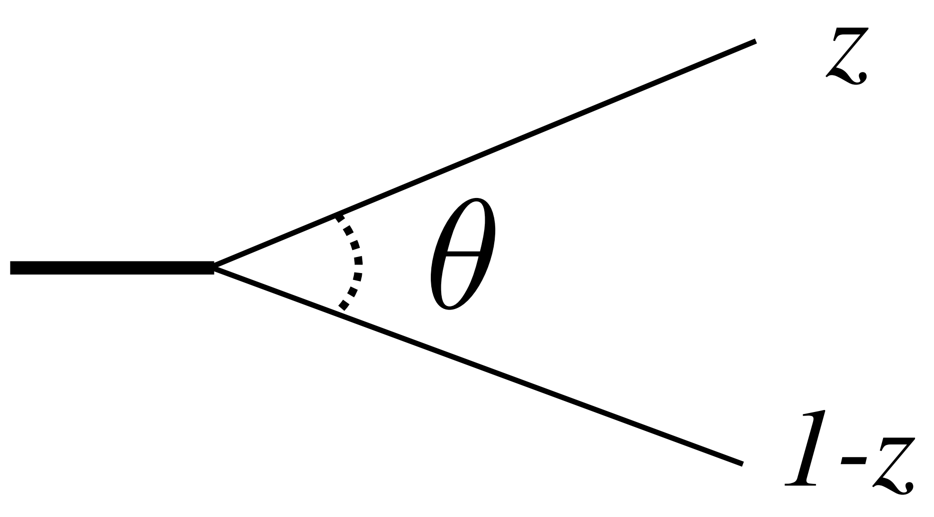
x-y plane

JETS IN QCD

- asymptotic freedom: high energy quarks and gluons manifested as collimated sprays of particles and energy.
- jets: well-defined objects in experiment & theory.
- multi-scale & long-distance dynamics.
- **powerful probe** of the quark-gluon plasma in heavy-ion collisions.



PARTON SPLITTING

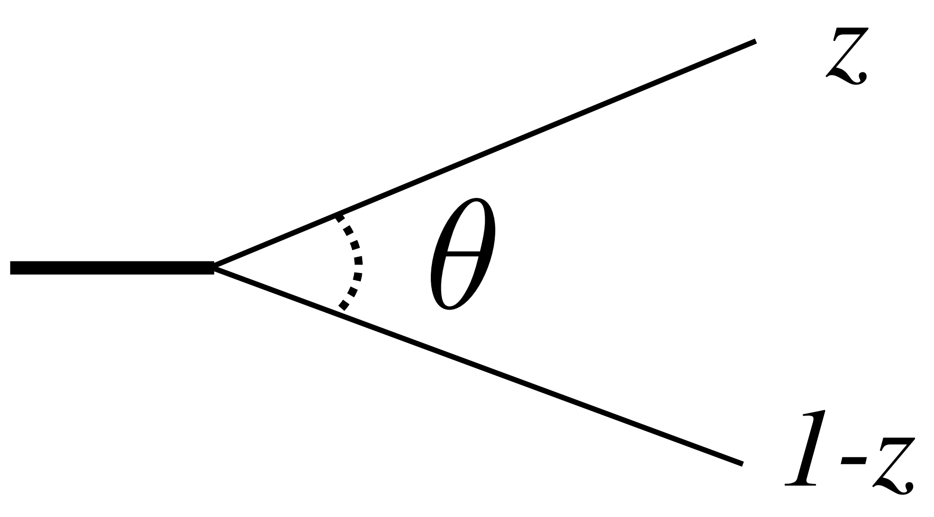


Generic 1→2 (on-shell) splitting in QCD:

$$\mathcal{P}_{a\to bc} = \frac{\alpha_s}{\pi}\frac{\mathrm{d}\theta}{\theta}P_{ba}^{(c)}(z)\mathrm{d}z \approx \frac{2\alpha_s C_R}{\pi}\frac{\mathrm{d}\theta}{\theta}\frac{\mathrm{d}z}{z}$$

Diverges for soft & collinear radiation!

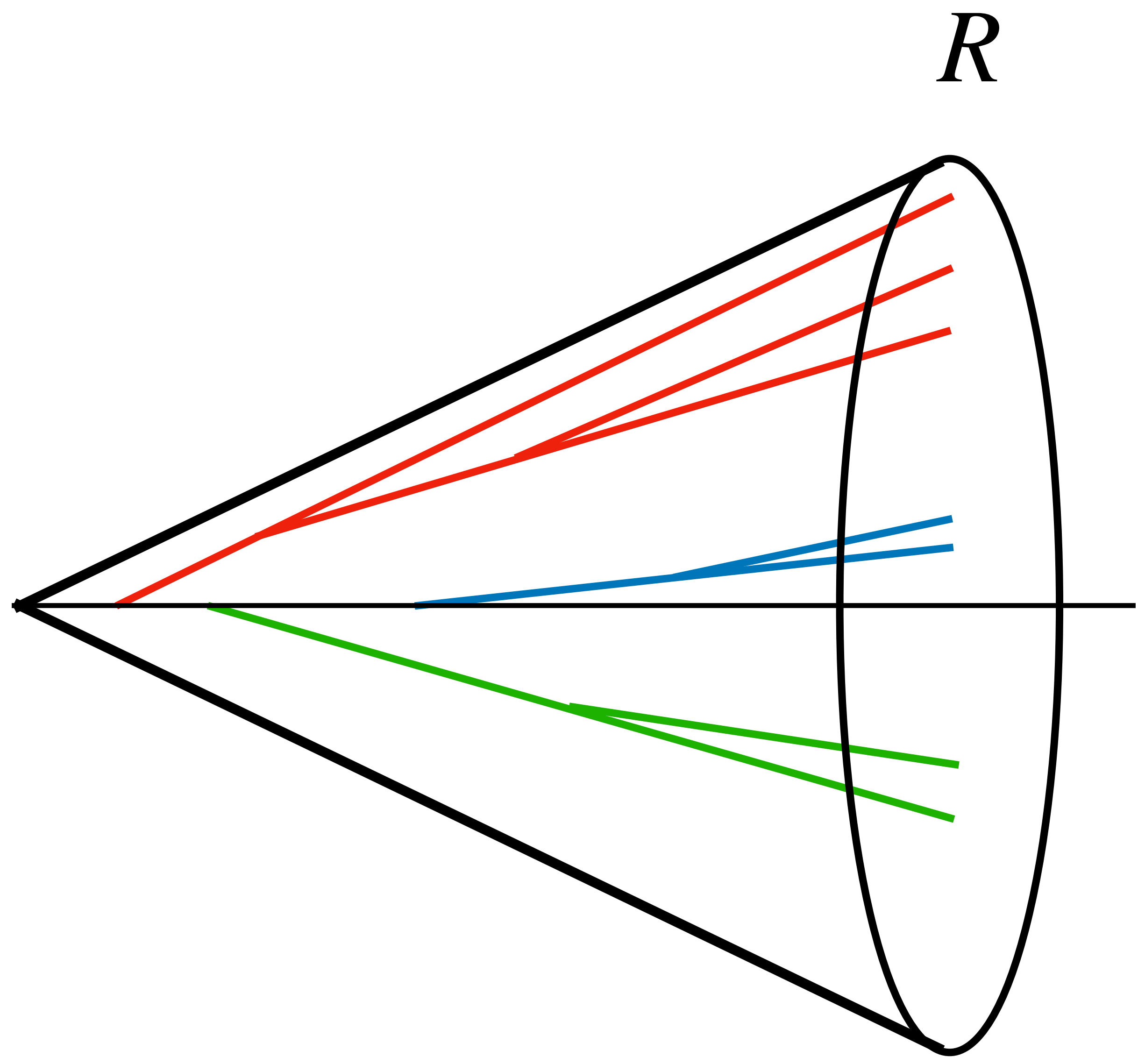
PARTON SPLITTING



Generic 1→2 (on-shell) splitting in QCD:

$$\mathcal{P}_{a\to bc} = \frac{\alpha_s}{\pi}\frac{\mathrm{d}\theta}{\theta}P_{ba}^{(c)}(z)\mathrm{d}z \approx \frac{2\alpha_s C_R}{\pi}\frac{\mathrm{d}\theta}{\theta}\frac{\mathrm{d}z}{z}$$

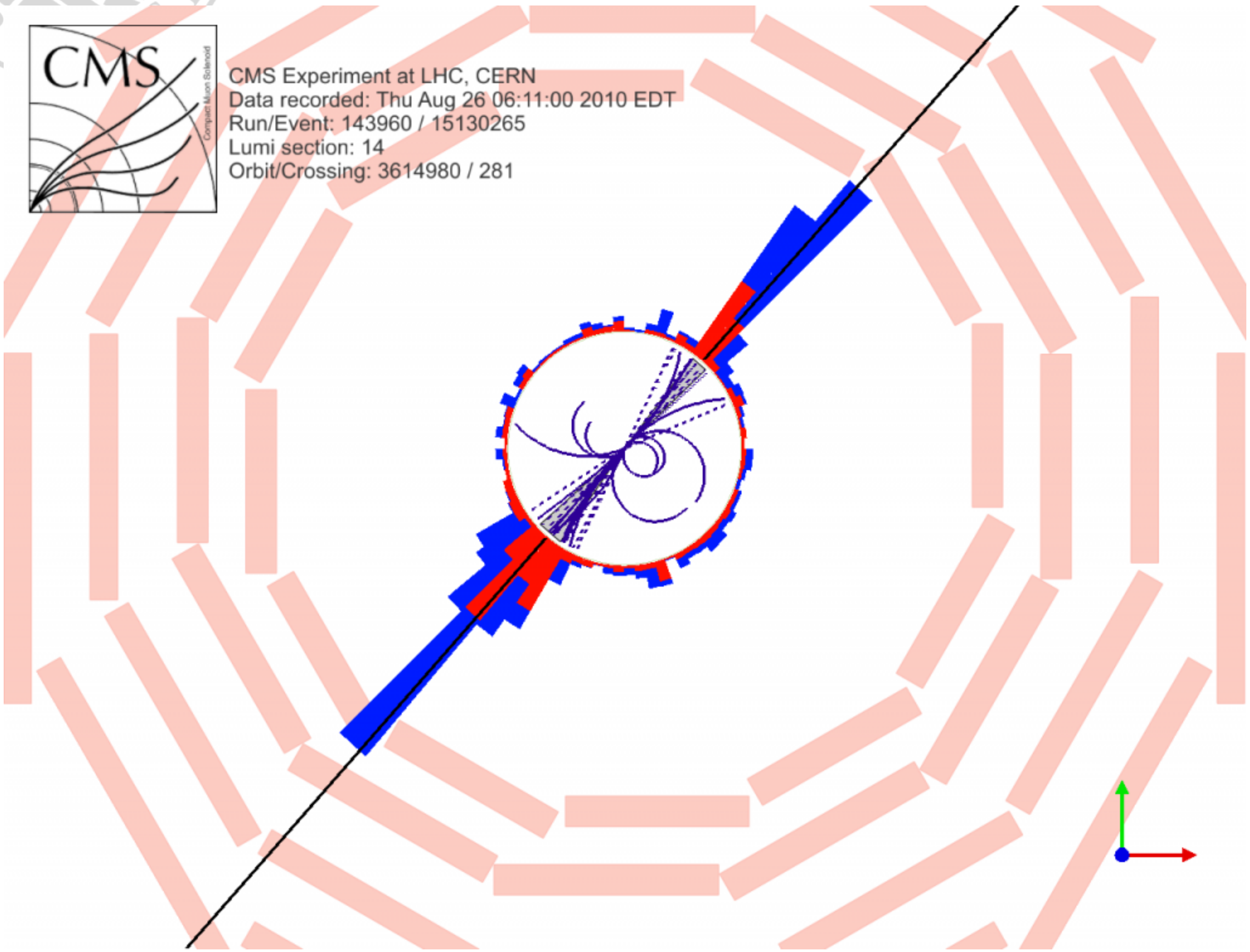
Diverges for soft & collinear radiation!



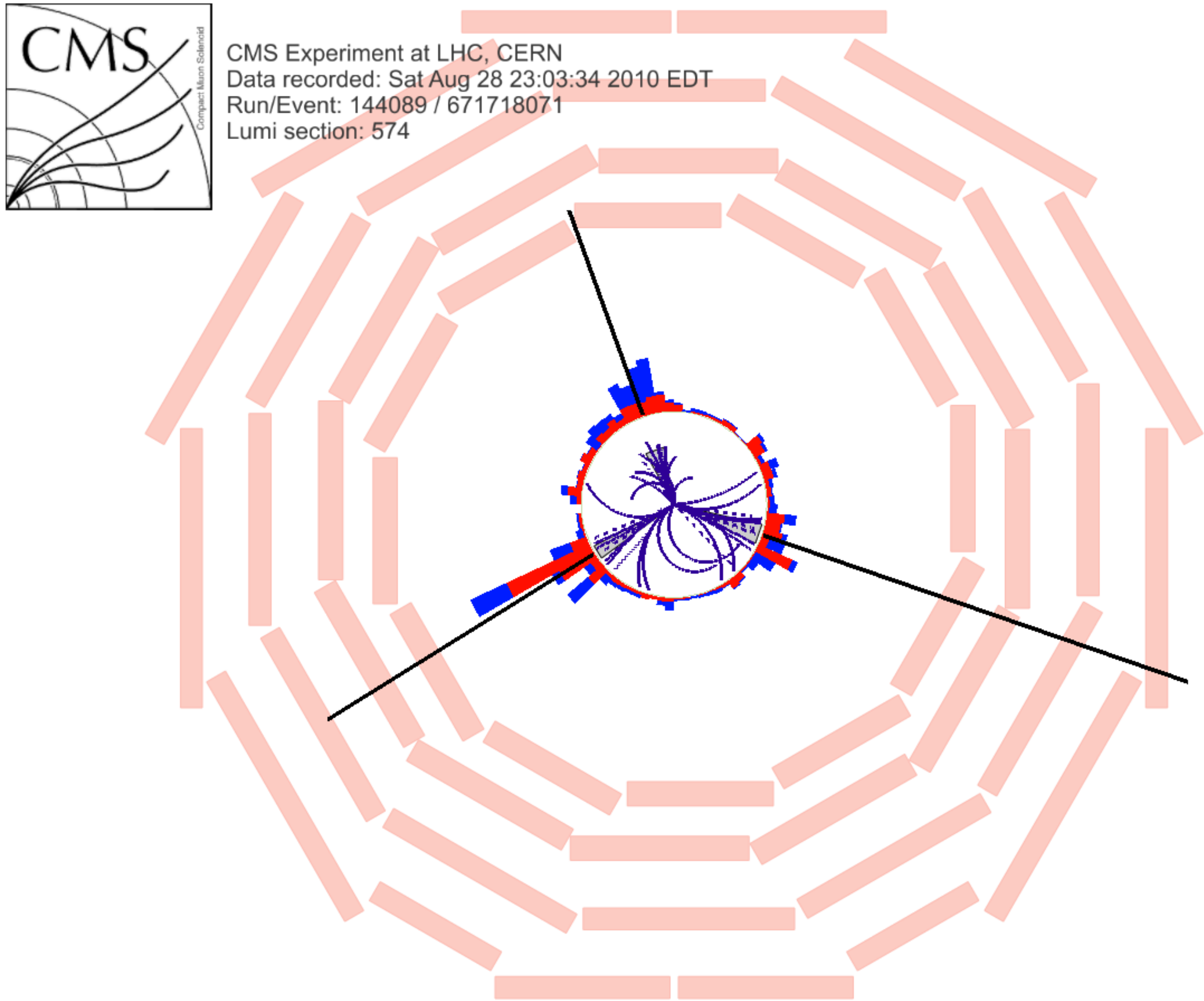
Large phase space for radiation compensates α_s!

$$\mathrm{Prob} = \frac{\alpha_s C_R}{\pi}\log^2\frac{p_T R}{\Lambda_{\mathrm{QCD}}} \gg 1$$

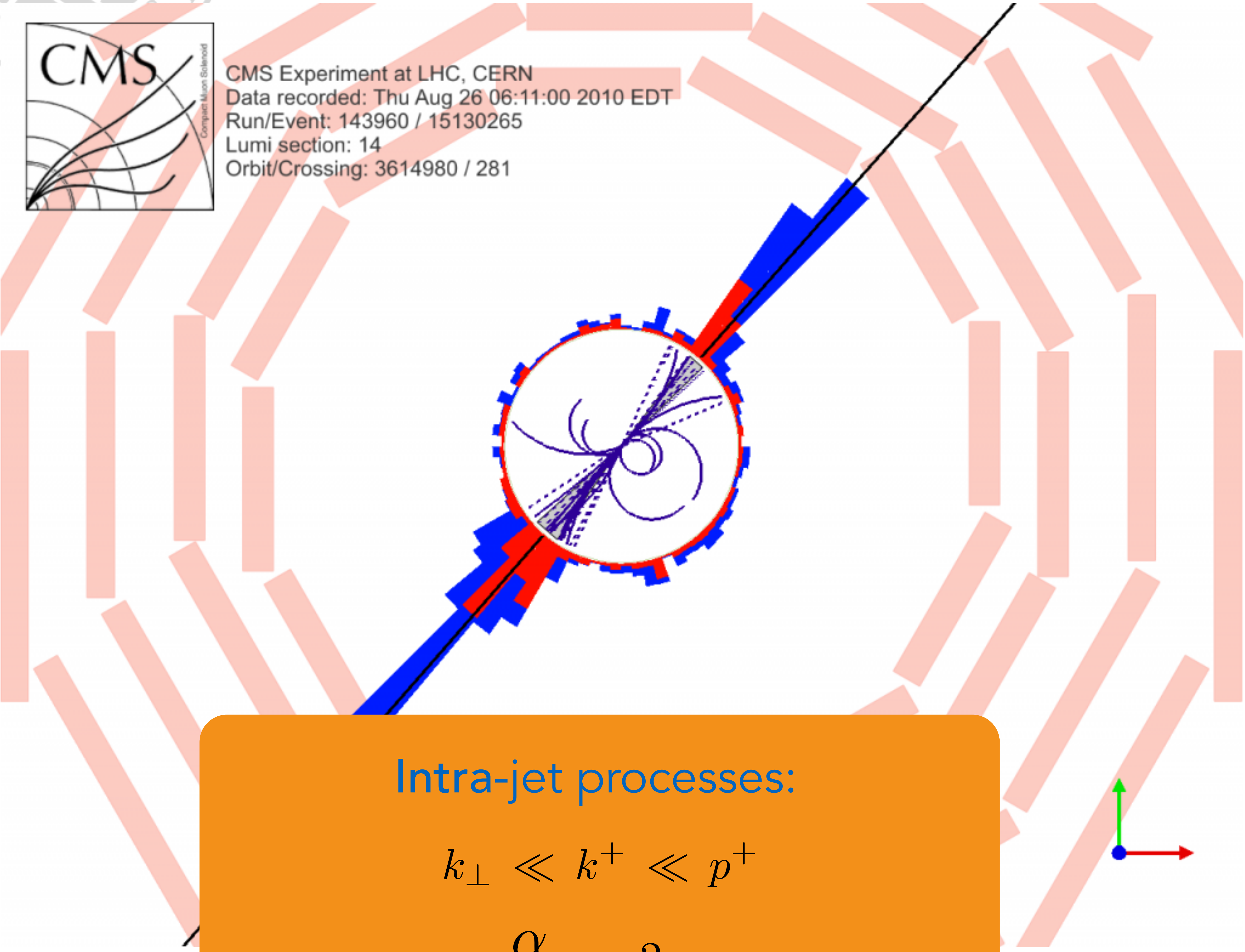
Need for resummation of collinear logarithms for final-state radiation.



proton-proton
two-jet event (?)



proton-proton
three-jet event (?)

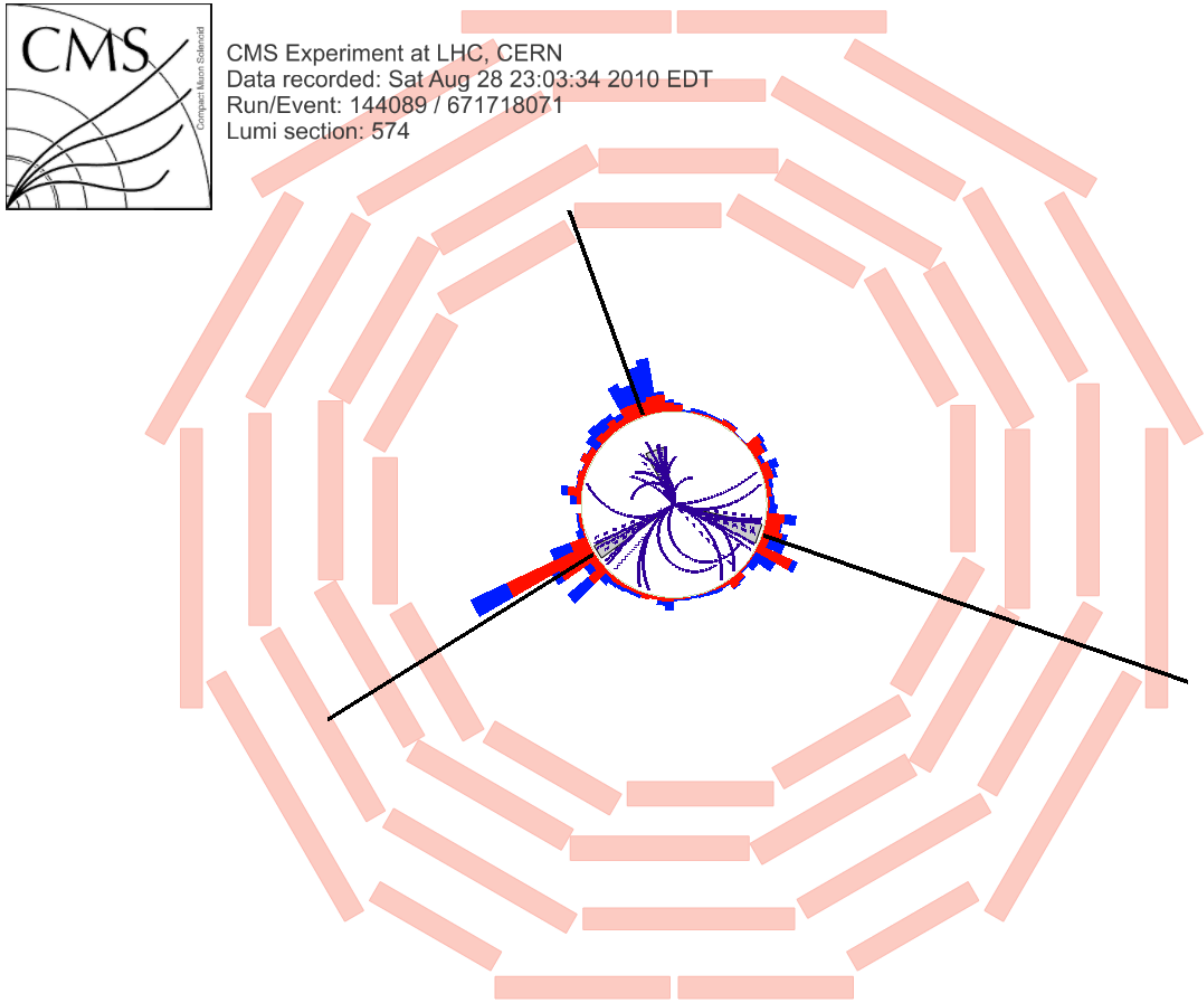


Intra-jet processes:

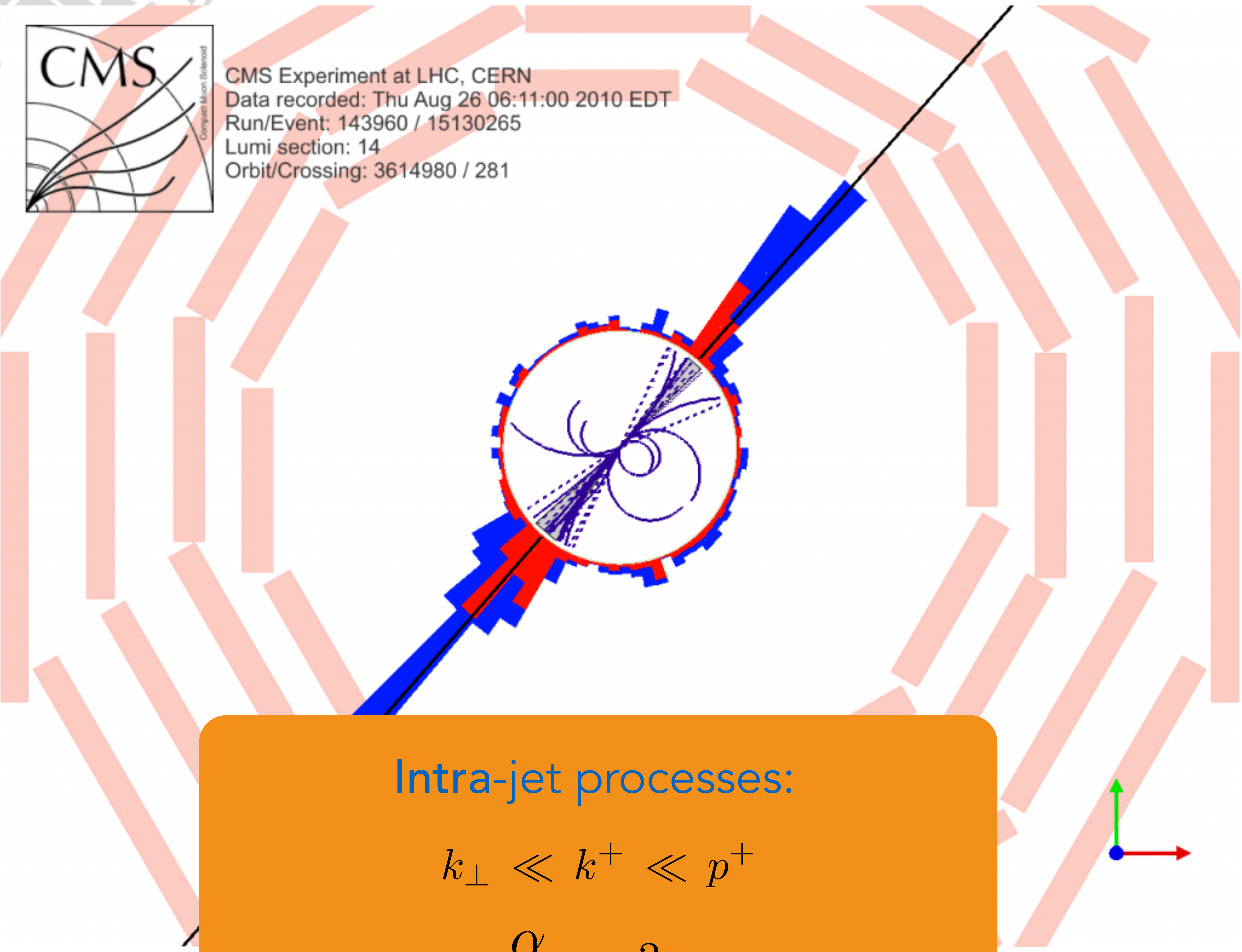
$$k_\perp \ll k^+ \ll p^+$$

$$N \sim \frac{\alpha}{\pi} \log^2 E \gtrsim 1$$

logarithmic resummations (LL)



proton-proton
three-jet event (?)

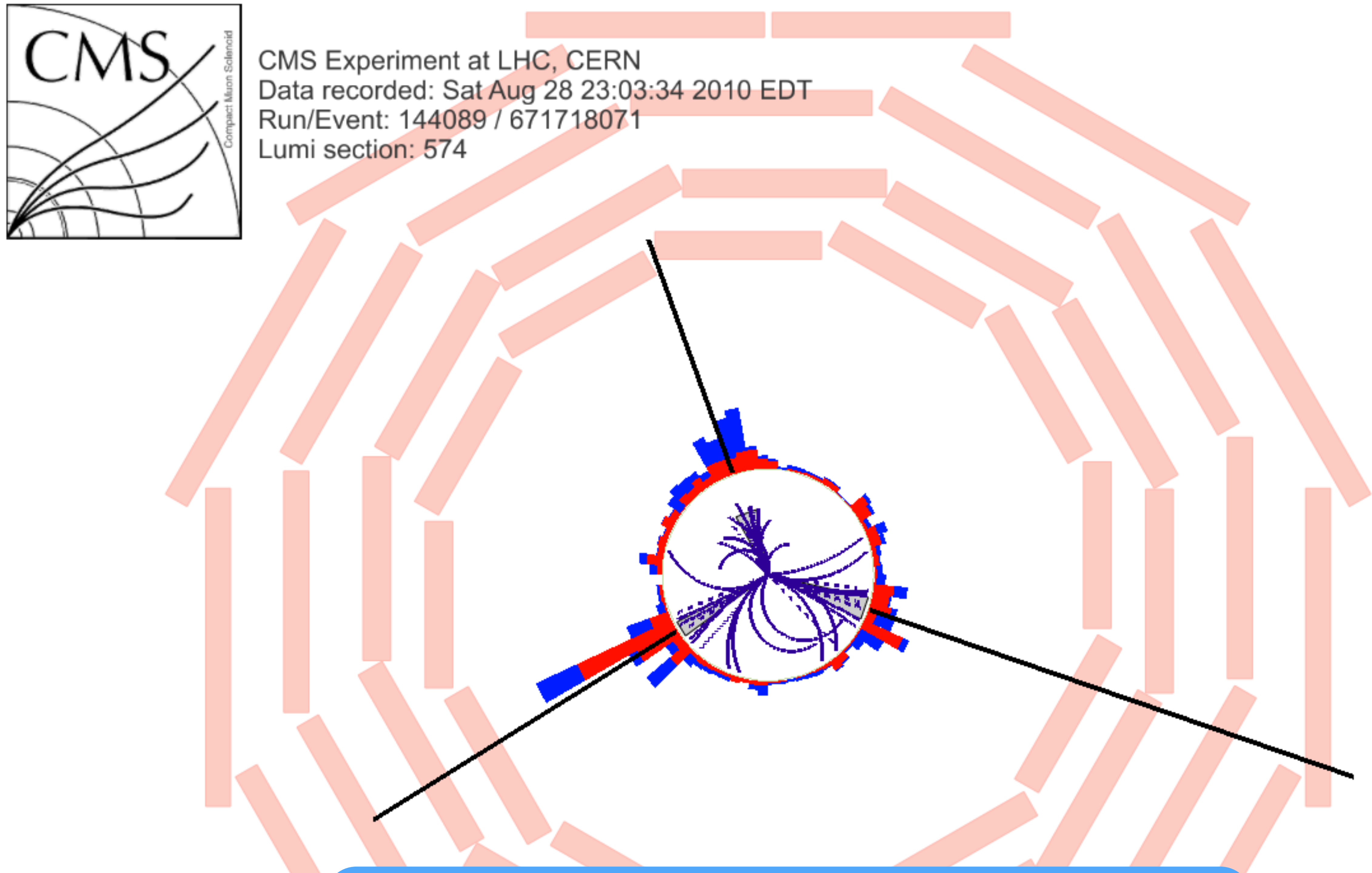


Intra-jet processes:

$$k_\perp \ll k^+ \ll p^+$$

$$N \sim \frac{\alpha}{\pi} \log^2 E \gtrsim 1$$

logarithmic resummations (LL)



Inter-jet processes:

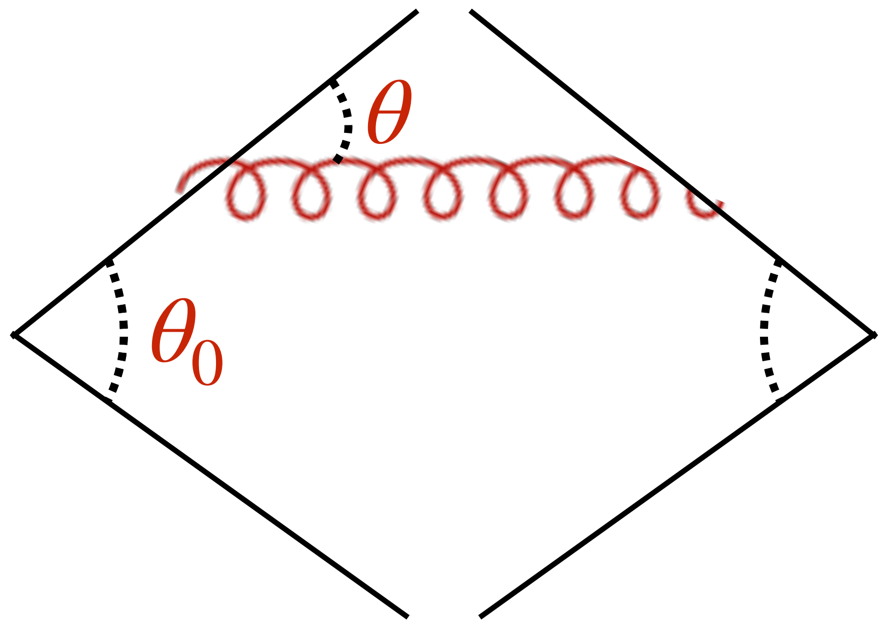
$$k_\perp \sim k^+ \sim p^+$$

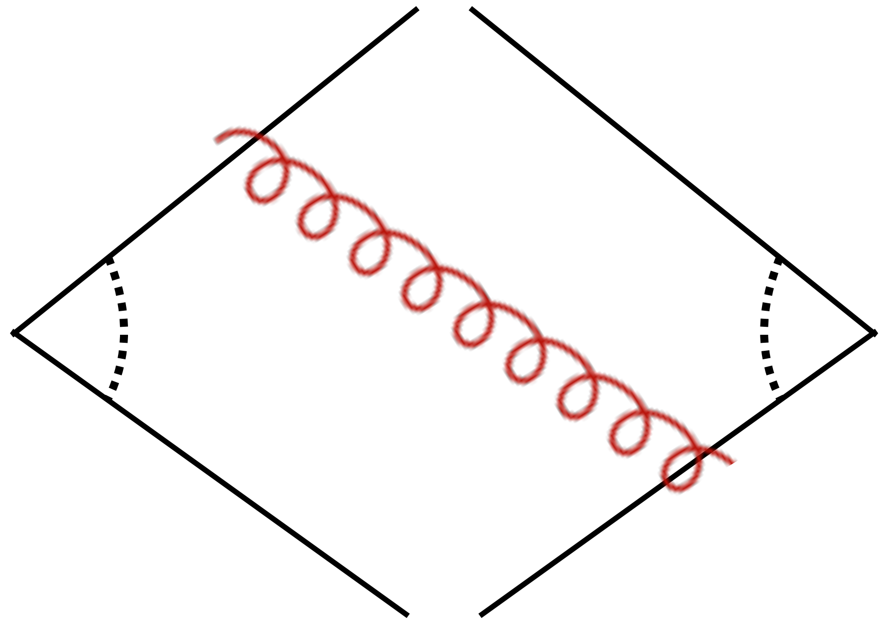
$$N \sim \frac{\alpha}{\pi} \ll 1$$

fixed-order (N…LO)

INTERFERENCES & ORDERING

At 2nd order:

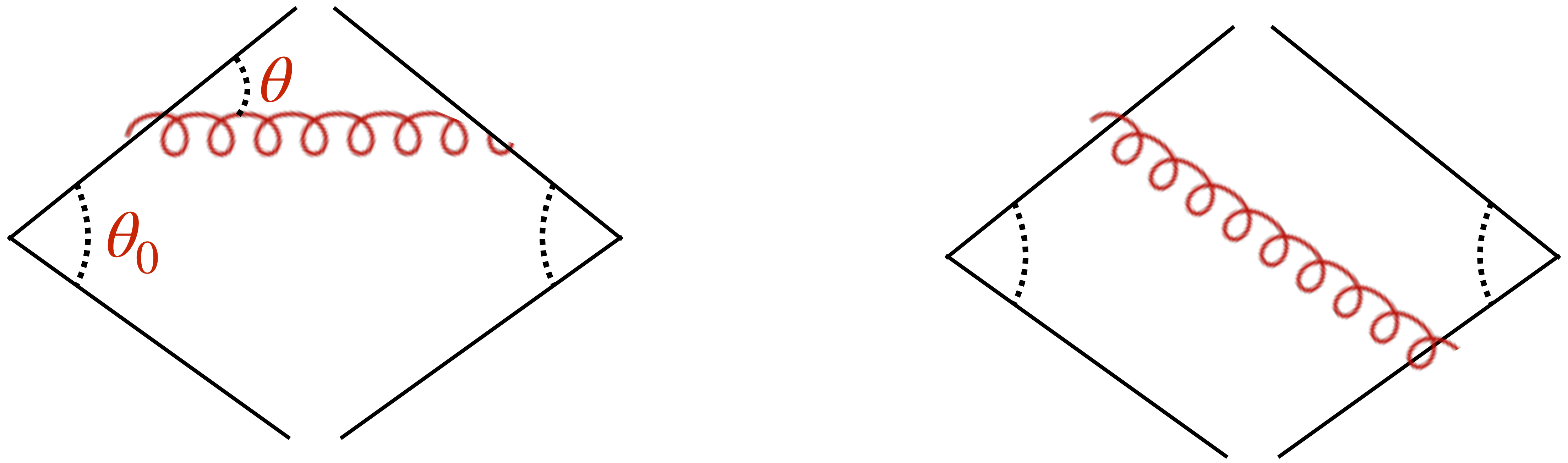




In the soft limit ($z_2 \ll 1$), it is easy to show that the emission has to lie within the dipole: $\theta < \theta_0$

INTERFERENCES & ORDERING

At 2nd order:



In the soft limit ($z_2 \ll 1$), it is easy to show that the emission has to lie within the dipole: $\theta < \theta_0$

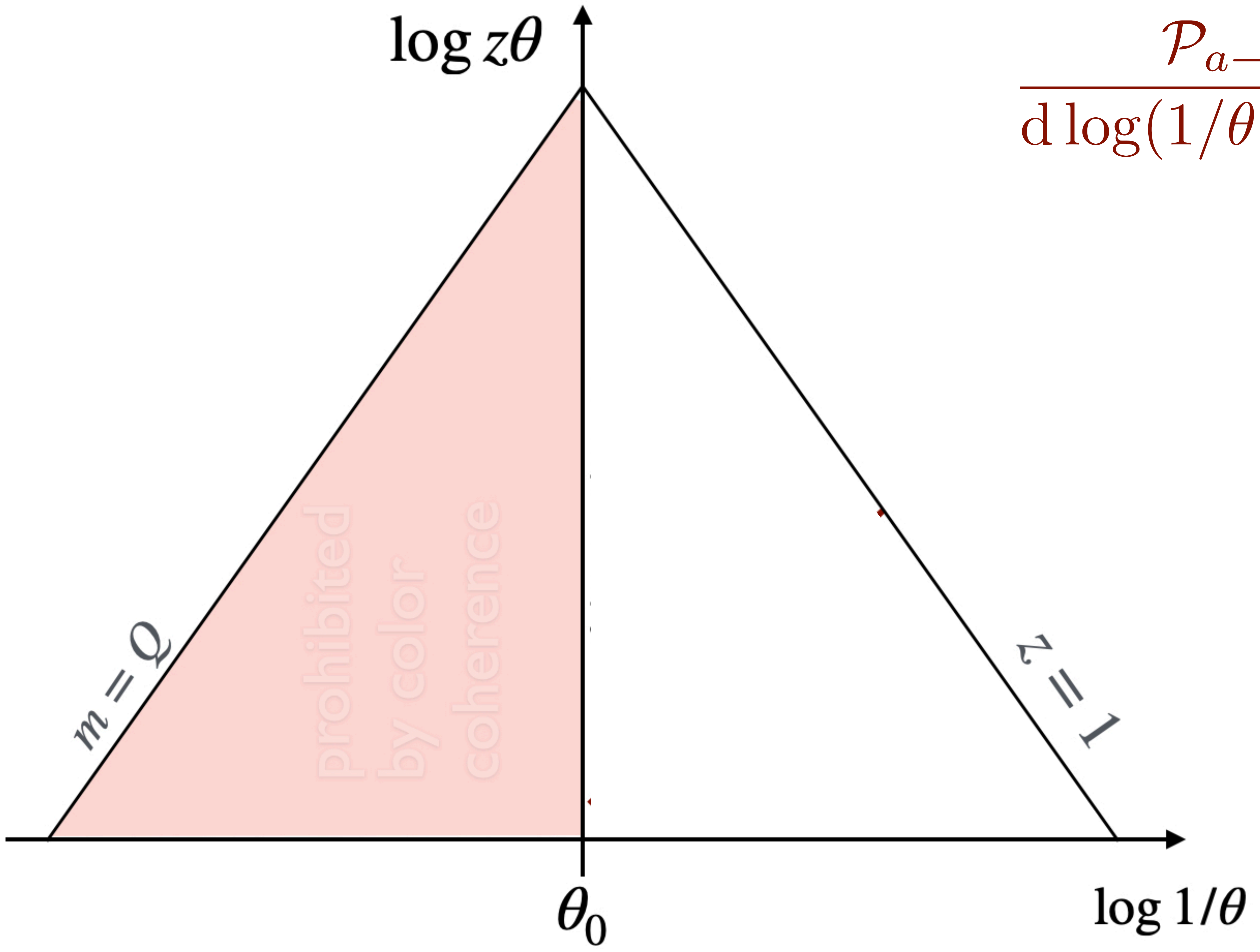
Heuristic argument: the emission of the gluon has to be able to resolve the individual charges of the dipole.

Compare the transverse size of antenna $r_\perp(t) \sim \theta_0 t$ at the formation time of the gluon, $t_f \sim 1/(\omega\theta^2)$, to the size of the gluon fluctuation $\lambda_\perp \sim 1/k_\perp \sim 1/(\omega\theta)$.

$$\lambda_\perp \ll r_\perp \quad \Rightarrow \quad \theta \ll \theta_0$$

RADIATION PHASE SPACE

Andersson, Gustafson, Lönnblad, Pettersson Z.Phys.C (1989)
Andersson, Gustafson, Samuelsson NPB (1996)



$$\frac{\mathcal{P}_{a\to bc}}{\mathrm{d}\log(1/\theta)\mathrm{d}\log k_t} = 2\frac{\alpha_s C_R}{\pi}$$

~uniformly filled!
up to running of α_s

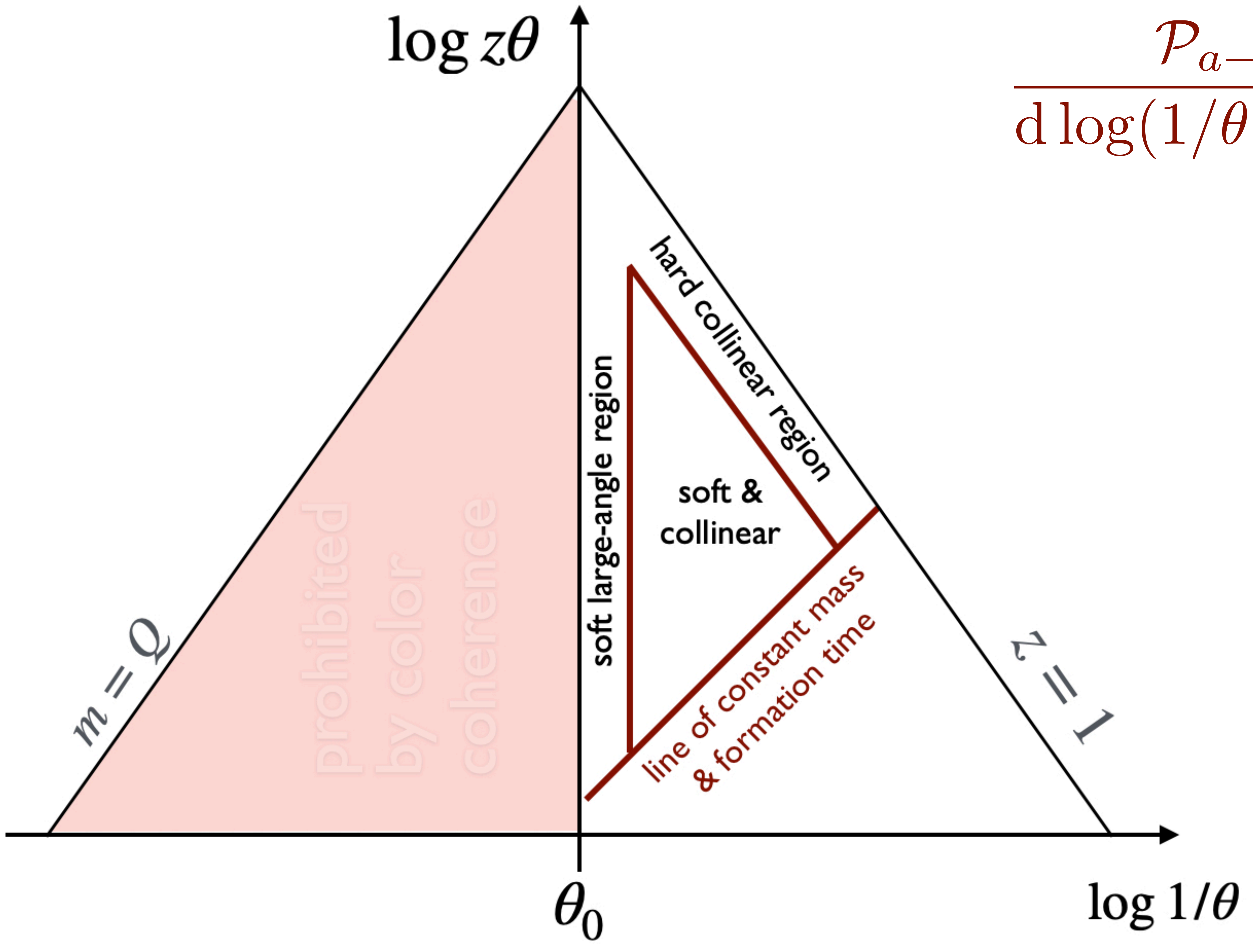
$$k_t \approx z p_T \theta$$

MC parton shower fills available phase with the proper weights as given by the Sudakov factor:

$$\Delta(\theta,\theta_0) = \exp\left[-\int_{\theta_0}^{\theta}\frac{\mathrm{d}\theta}{\theta}\int_{\epsilon}^{1}\frac{\mathrm{d}k_t}{k_t}\frac{2\alpha_s C_R}{\pi}\right]$$

RADIATION PHASE SPACE

Andersson, Gustafson, Lönnblad, Pettersson Z.Phys.C (1989)
Andersson, Gustafson, Samuelsson NPB (1996)



$$\frac{\mathcal{P}_{a\to bc}}{\mathrm{d}\log(1/\theta)\mathrm{d}\log k_t} = 2\frac{\alpha_s C_R}{\pi}$$

~uniformly filled!
up to running of α_s

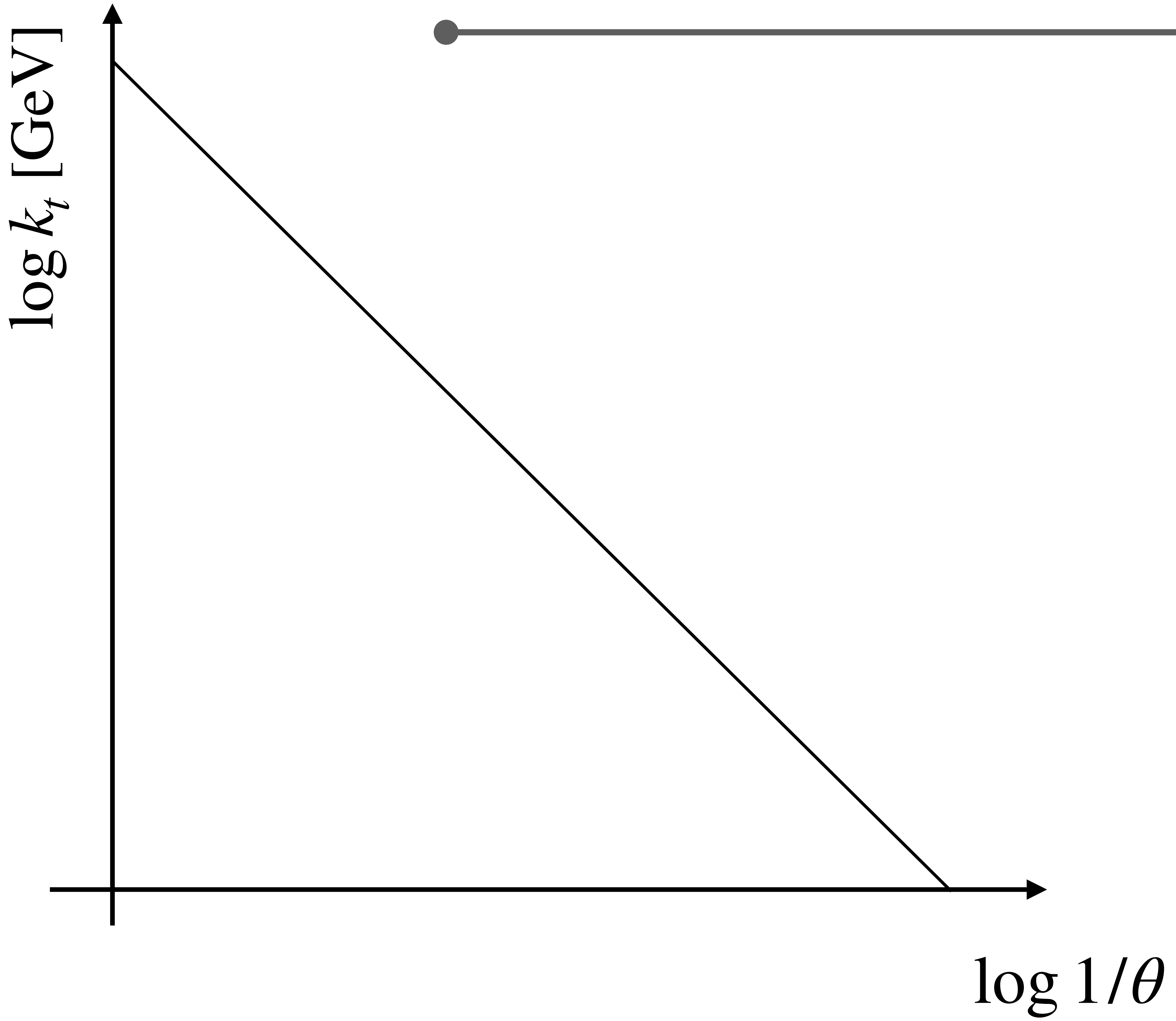
$$k_t \approx z p_T \theta$$

MC parton shower fills available phase with the proper weights as given by the Sudakov factor:

$$\Delta(\theta,\theta_0) = \exp\left[-\int_{\theta_0}^{\theta}\frac{\mathrm{d}\theta}{\theta}\int_{\epsilon}^{1}\frac{\mathrm{d}k_t}{k_t}\frac{2\alpha_s C_R}{\pi}\right]$$

SPACE-TIME PICTURE OF A JET

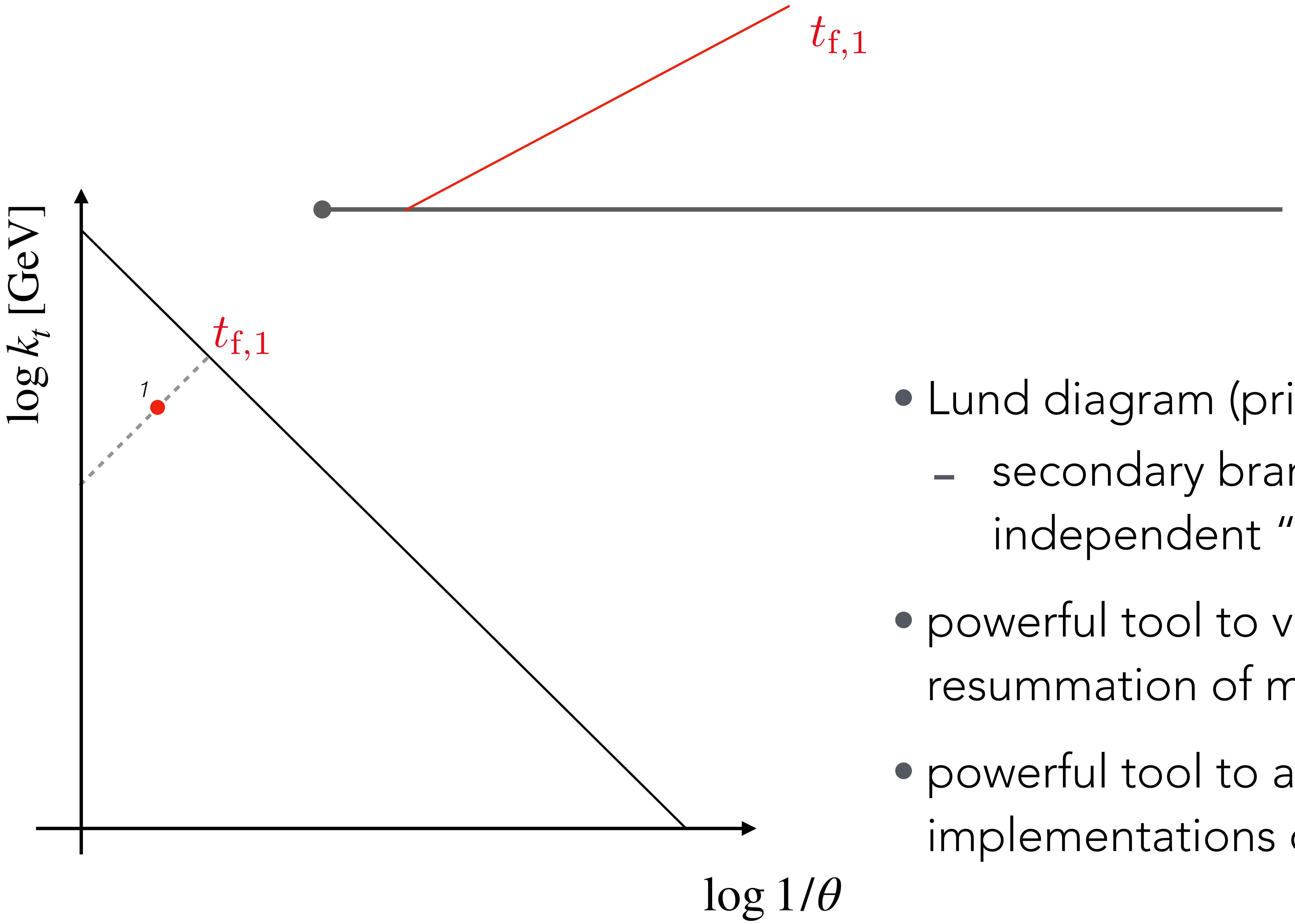
Andersson, Gustafson, Lönnblad, Pettersson Z.Phys.C (1989)
Andersson, Gustafson, Samuelsson NPB (1996)



- Lund diagram (primary emission plane)
  - secondary branchings located on independent "leaves"
- powerful tool to visualize impact of resummation of multiple emissions
- powerful tool to analyze MC implementations of parton shower

SPACE-TIME PICTURE OF A JET

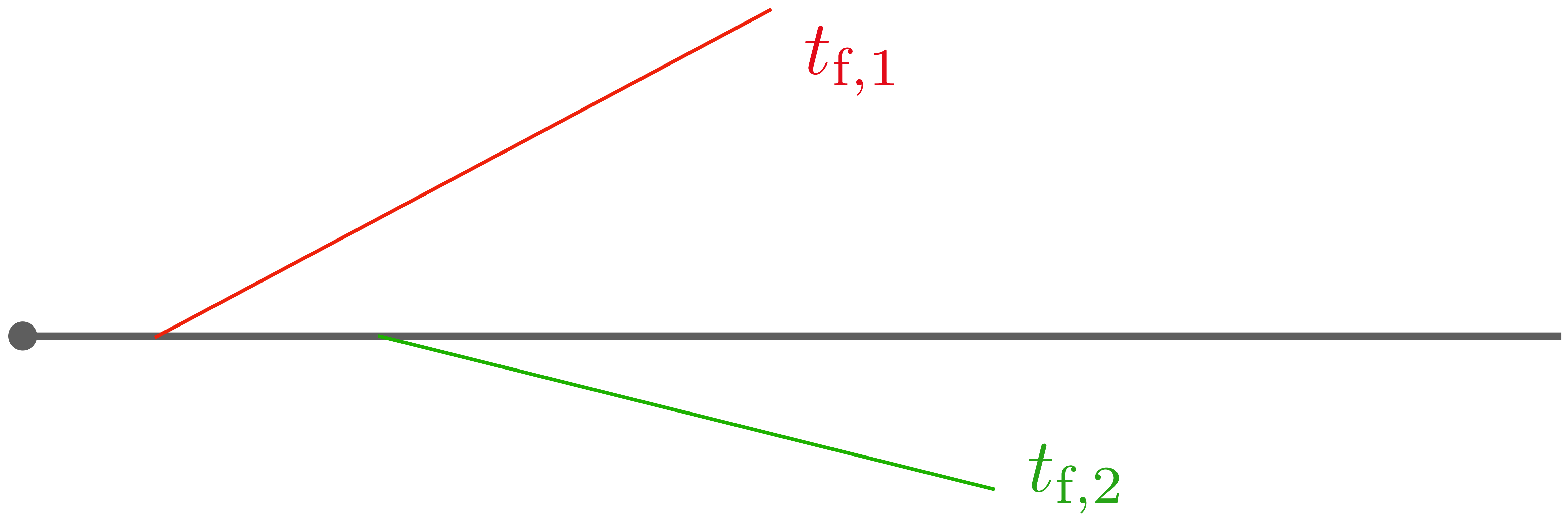
Andersson, Gustafson, Lönnblad, Pettersson Z.Phys.C (1989)
Andersson, Gustafson, Samuelsson NPB (1996)

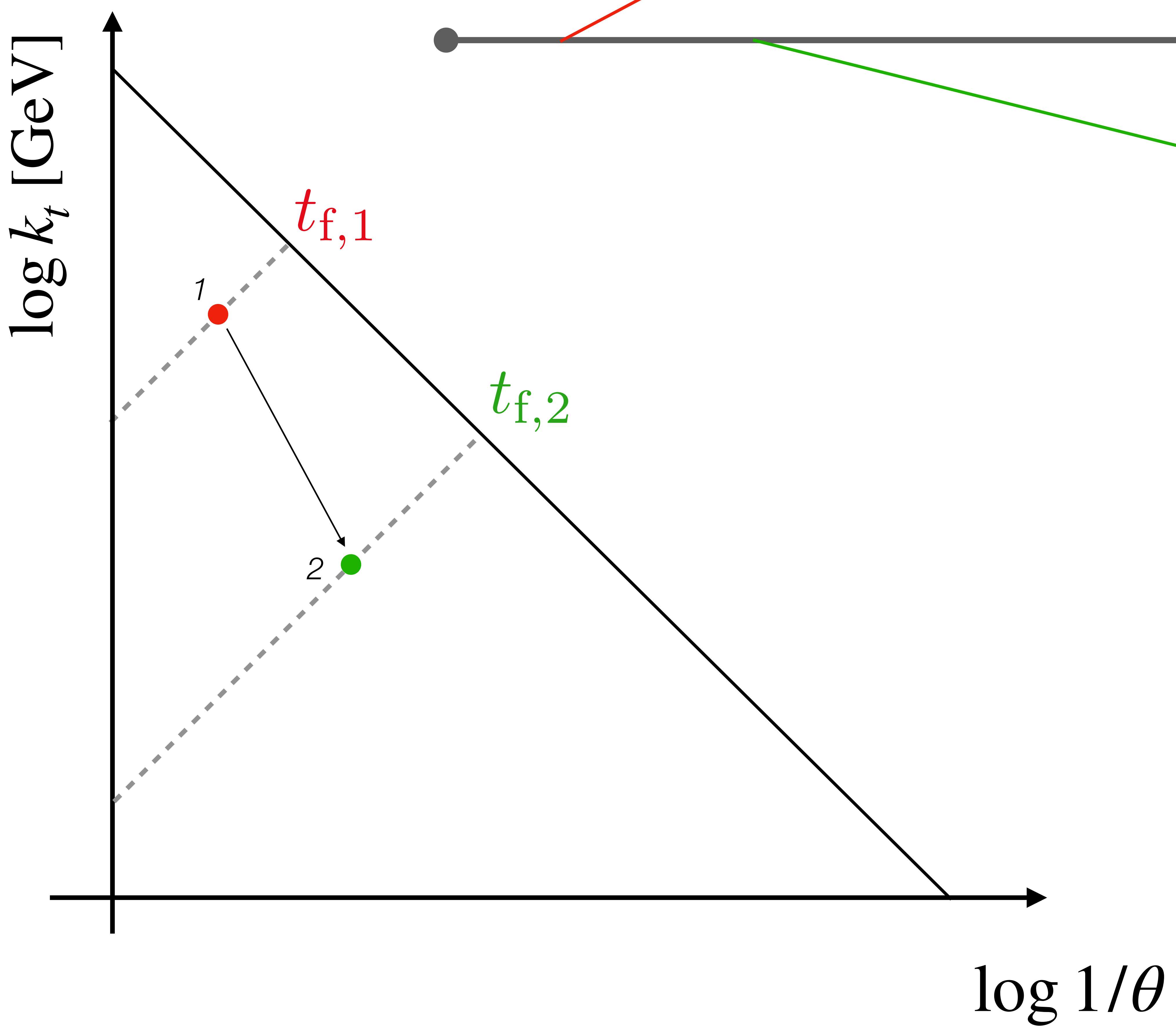


- Lund diagram (primary emission plane)
  - secondary branchings located on independent "leaves"
- powerful tool to visualize impact of resummation of multiple emissions
- powerful tool to analyze MC implementations of parton shower

Space-time picture of a jet

Andersson, Gustafson, Lönnblad, Pettersson Z.Phys.C (1989)
Andersson, Gustafson, Samuelsson NPB (1996)

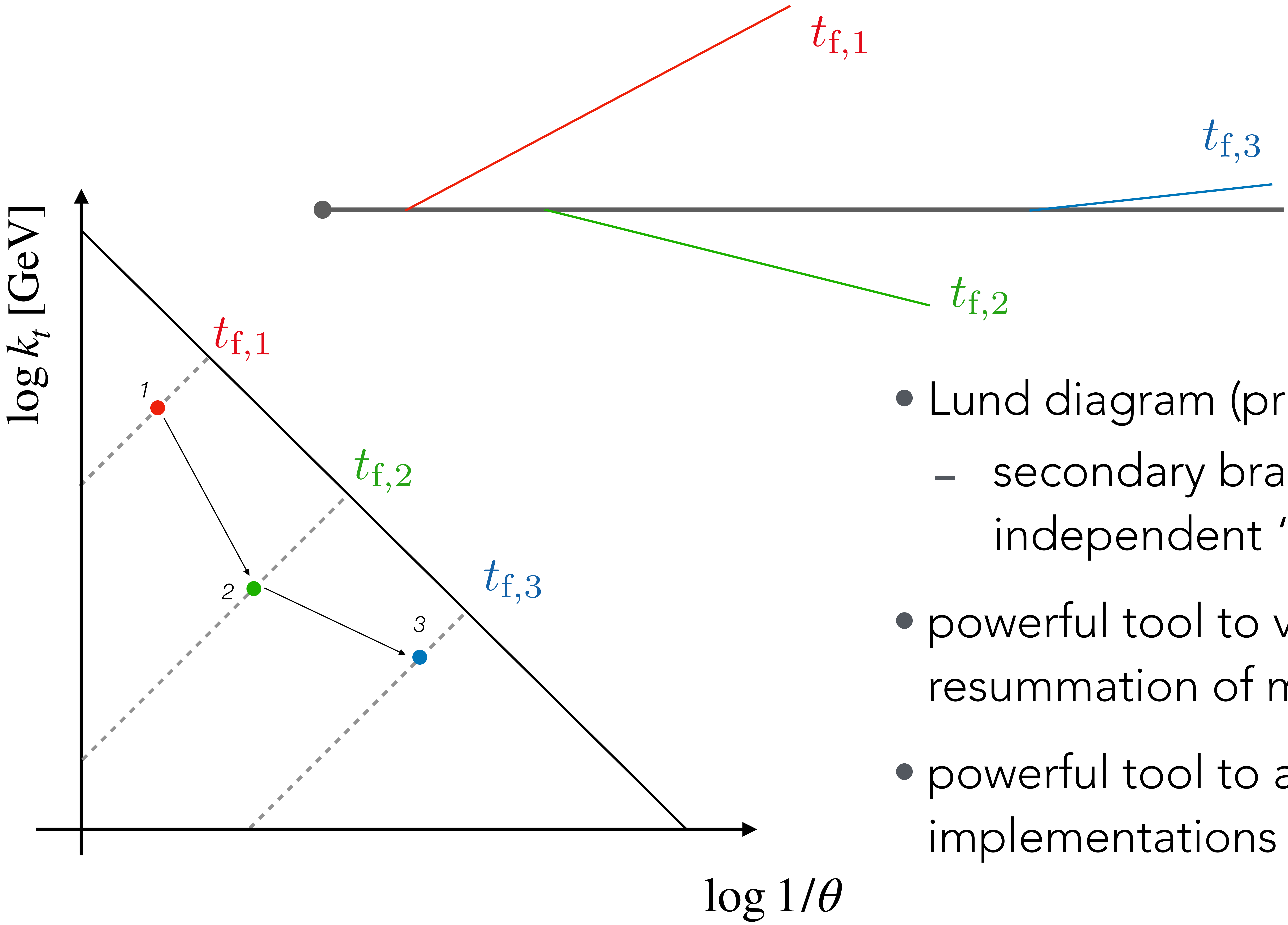




- Lund diagram (primary emission plane)
  - secondary branchings located on independent "leaves"
- powerful tool to visualize impact of resummation of multiple emissions
- powerful tool to analyze MC implementations of parton shower

SPACE-TIME PICTURE OF A JET

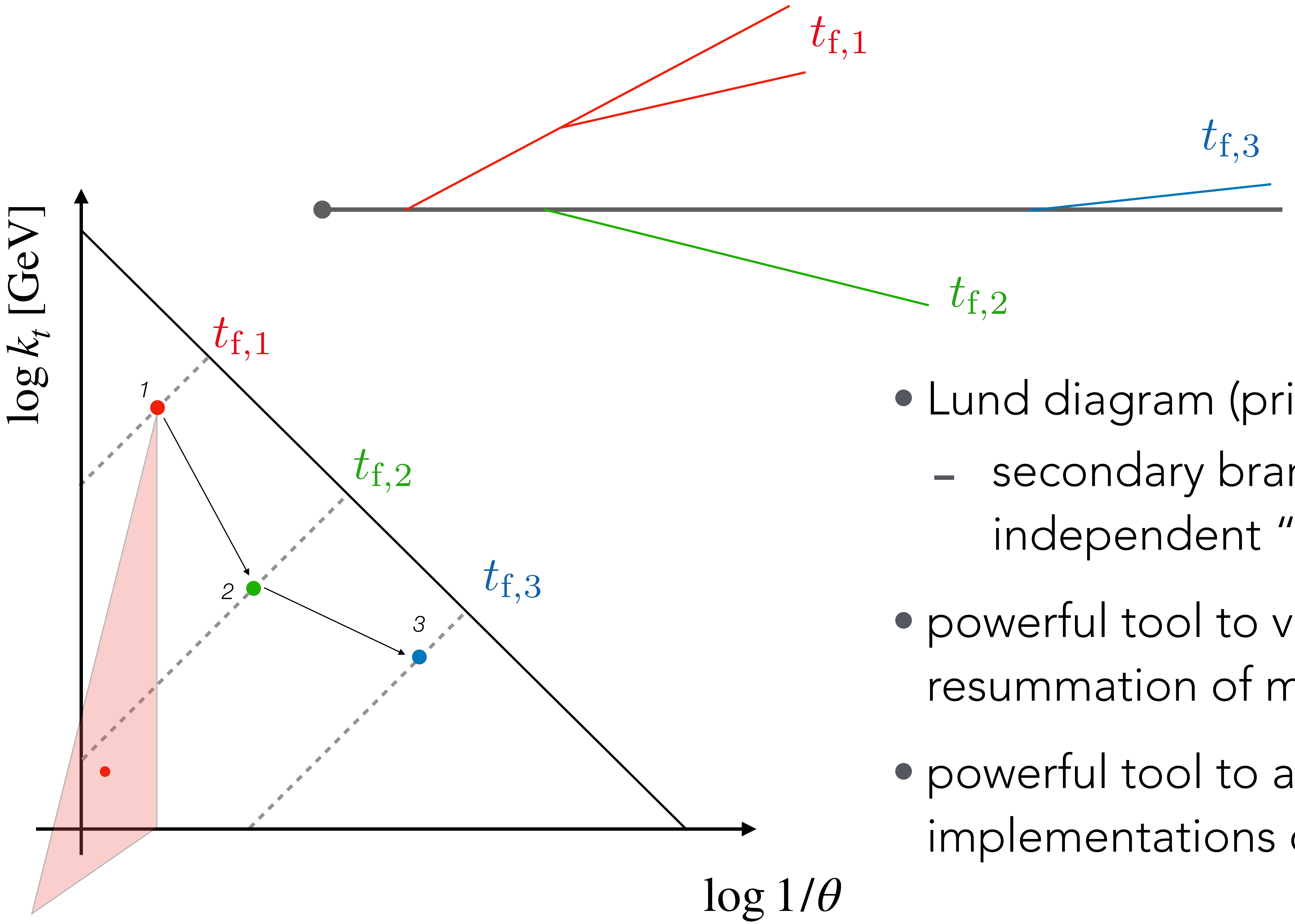
Andersson, Gustafson, Lönnblad, Pettersson Z.Phys.C (1989)
Andersson, Gustafson, Samuelsson NPB (1996)



- Lund diagram (primary emission plane)
  - secondary branchings located on independent "leaves"
- powerful tool to visualize impact of resummation of multiple emissions
- powerful tool to analyze MC implementations of parton shower

SPACE-TIME PICTURE OF A JET

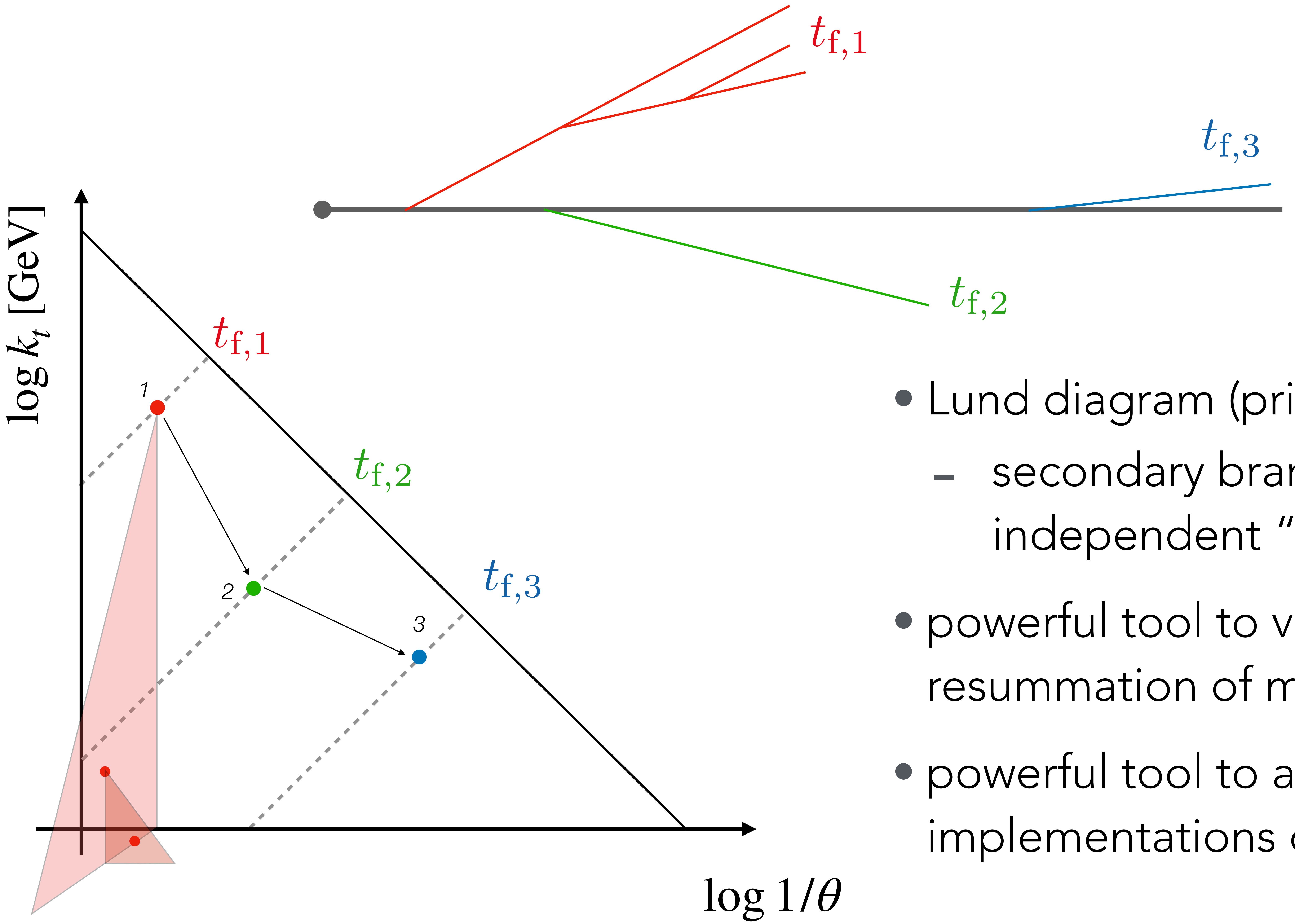
Andersson, Gustafson, Lönnblad, Pettersson Z.Phys.C (1989)
Andersson, Gustafson, Samuelsson NPB (1996)



- Lund diagram (primary emission plane)
  - secondary branchings located on independent "leaves"
- powerful tool to visualize impact of resummation of multiple emissions
- powerful tool to analyze MC implementations of parton shower

SPACE-TIME PICTURE OF A JET

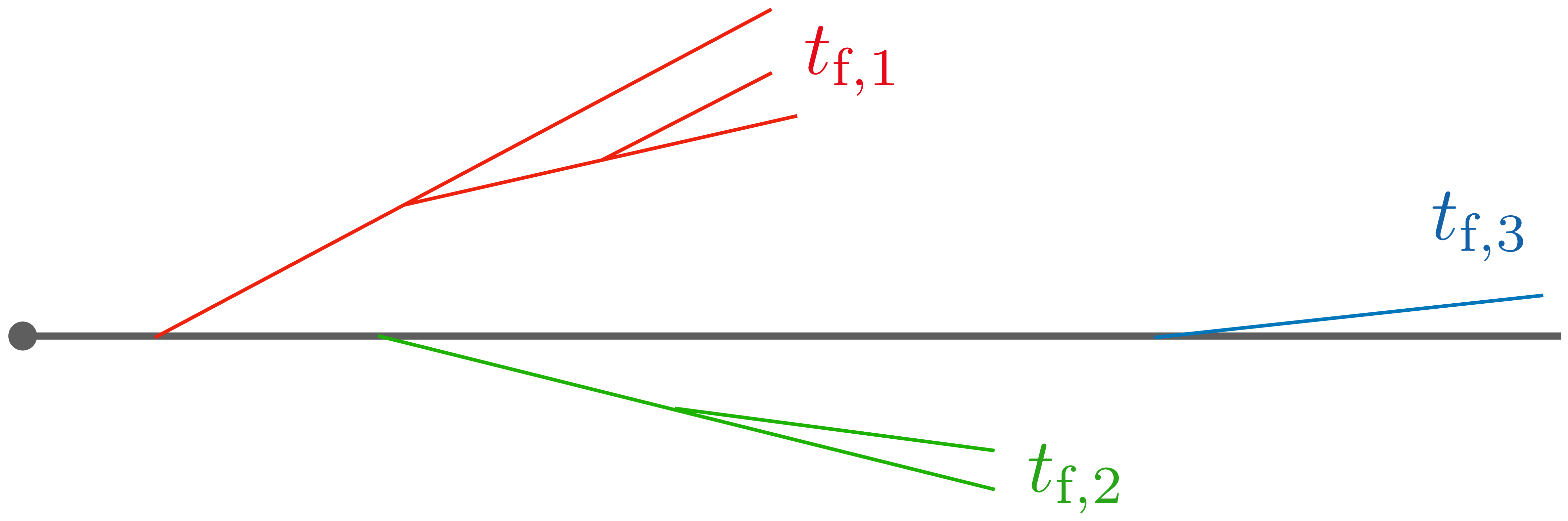
Andersson, Gustafson, Lönnblad, Pettersson Z.Phys.C (1989)
Andersson, Gustafson, Samuelsson NPB (1996)

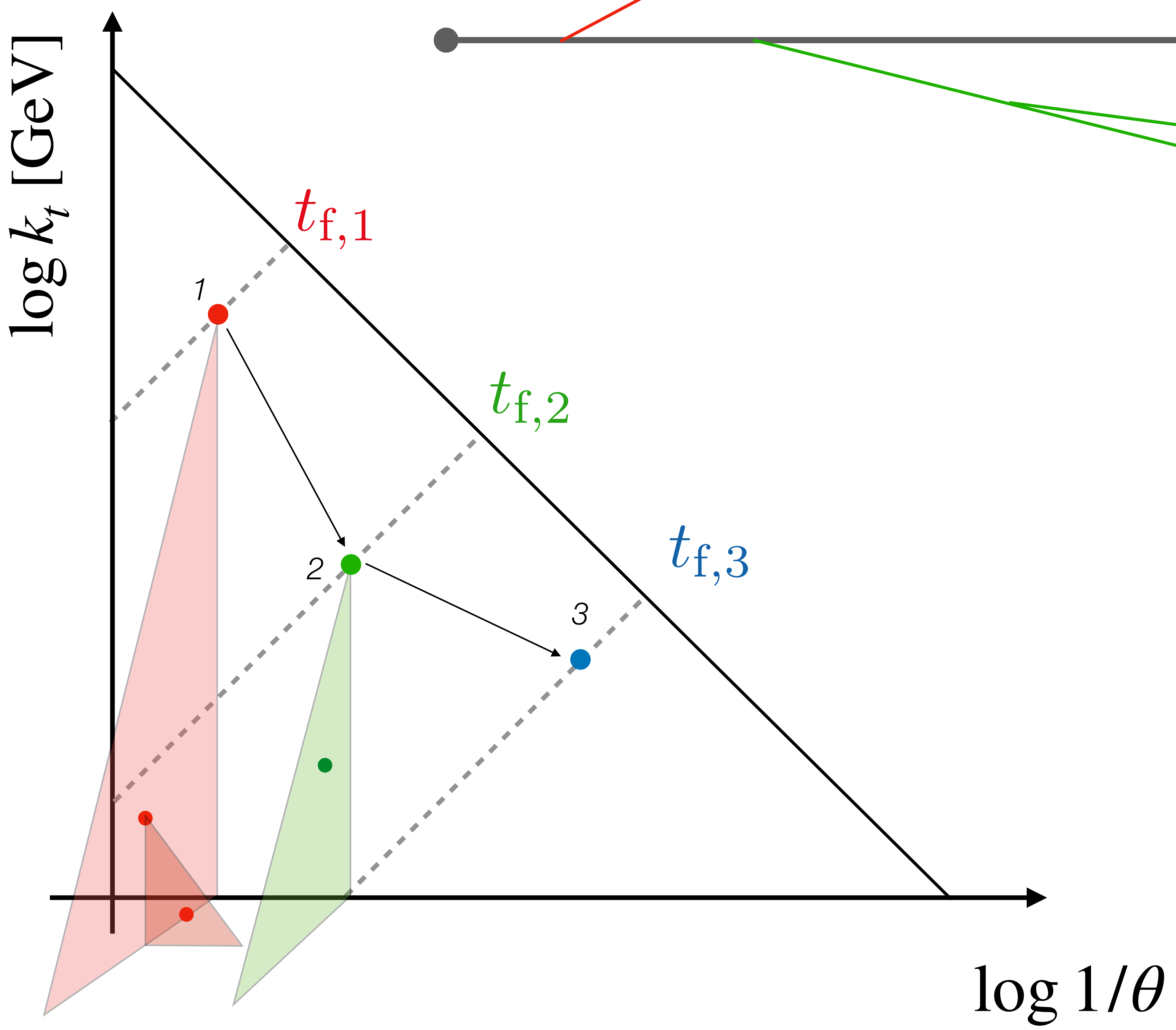


- Lund diagram (primary emission plane)
  - secondary branchings located on independent "leaves"
- powerful tool to visualize impact of resummation of multiple emissions
- powerful tool to analyze MC implementations of parton shower

SPACE-TIME PICTURE OF A JET

Andersson, Gustafson, Lönnblad, Pettersson Z.Phys.C (1989)
Andersson, Gustafson, Samuelsson NPB (1996)

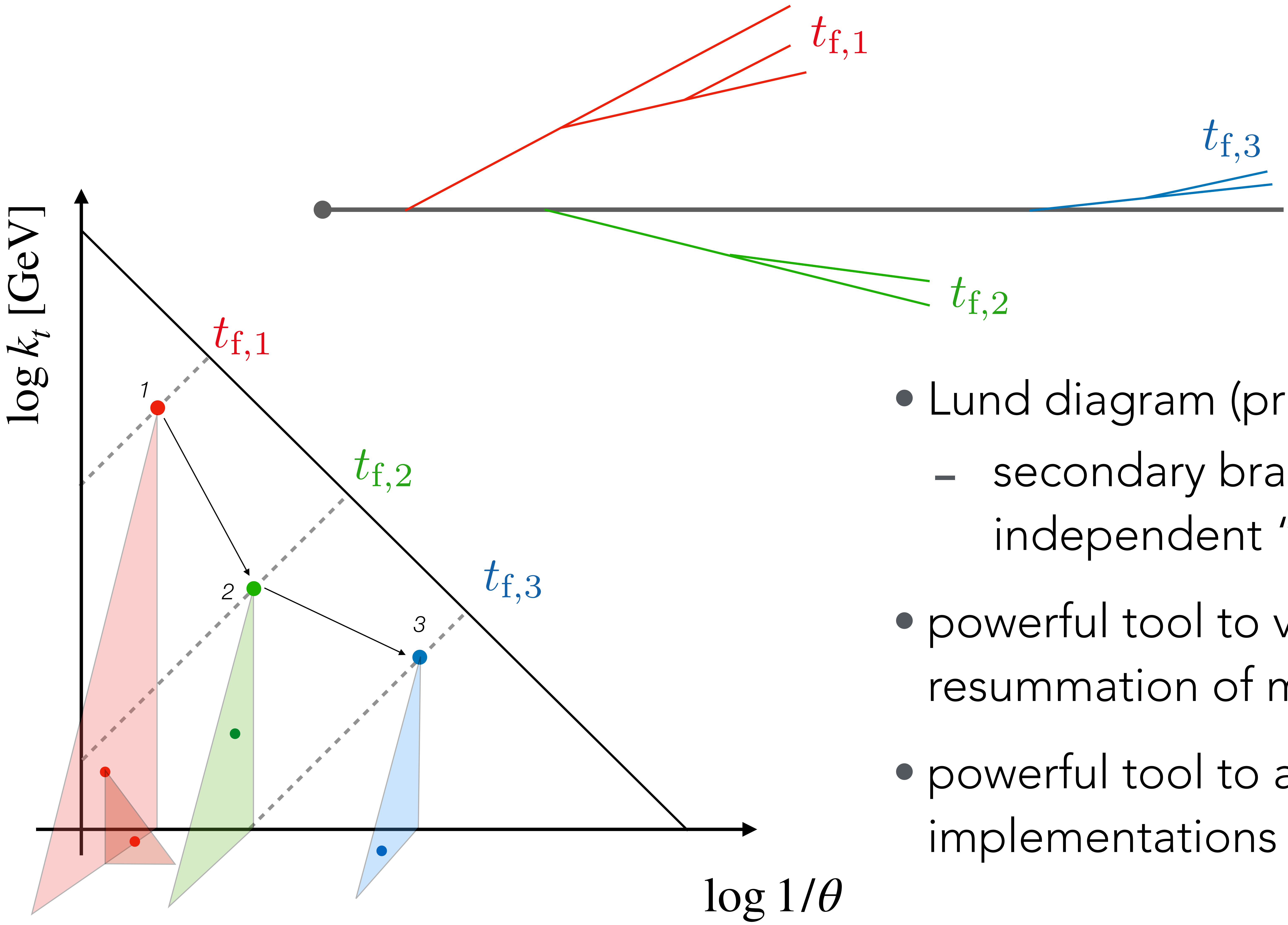




- Lund diagram (primary emission plane)
  - secondary branchings located on independent "leaves"
- powerful tool to visualize impact of resummation of multiple emissions
- powerful tool to analyze MC implementations of parton shower

Space-time picture of a jet

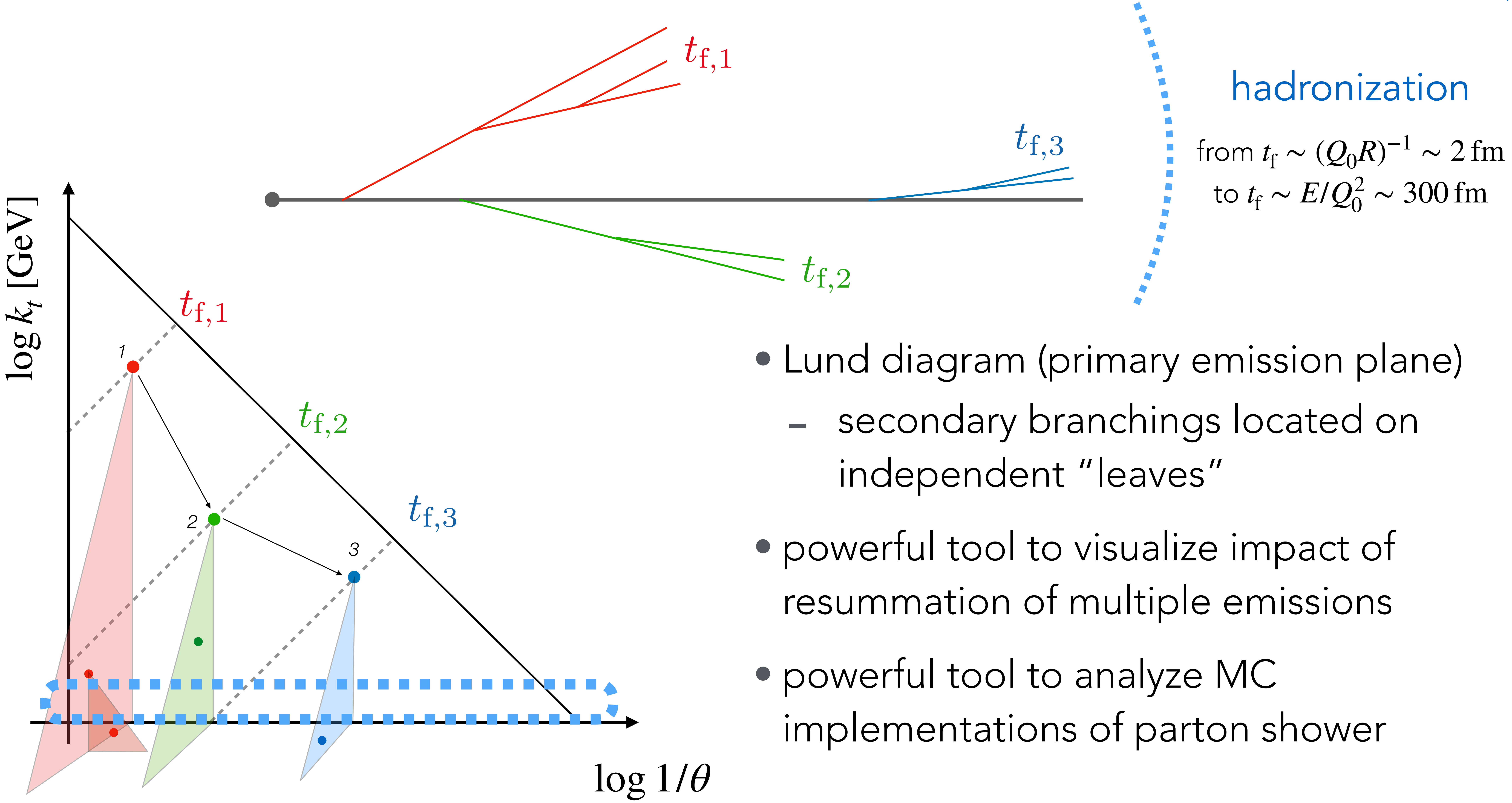
Andersson, Gustafson, Lönnblad, Pettersson Z.Phys.C (1989)
Andersson, Gustafson, Samuelsson NPB (1996)



- Lund diagram (primary emission plane)
  - secondary branchings located on independent "leaves"
- powerful tool to visualize impact of resummation of multiple emissions
- powerful tool to analyze MC implementations of parton shower

SPACE-TIME PICTURE OF A JET

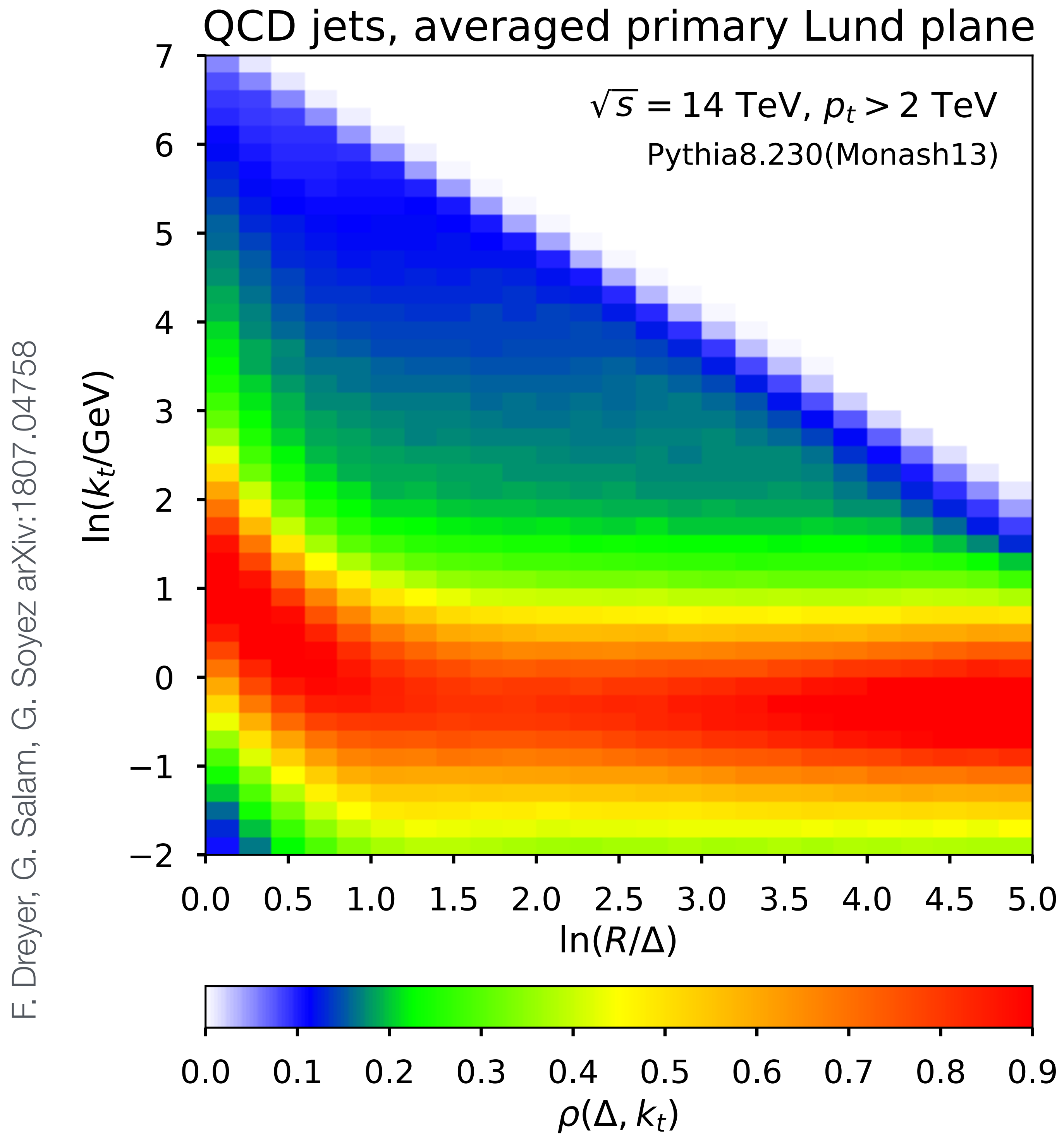
Andersson, Gustafson, Lönnblad, Pettersson Z.Phys.C (1989)
Andersson, Gustafson, Samuelsson NPB (1996)



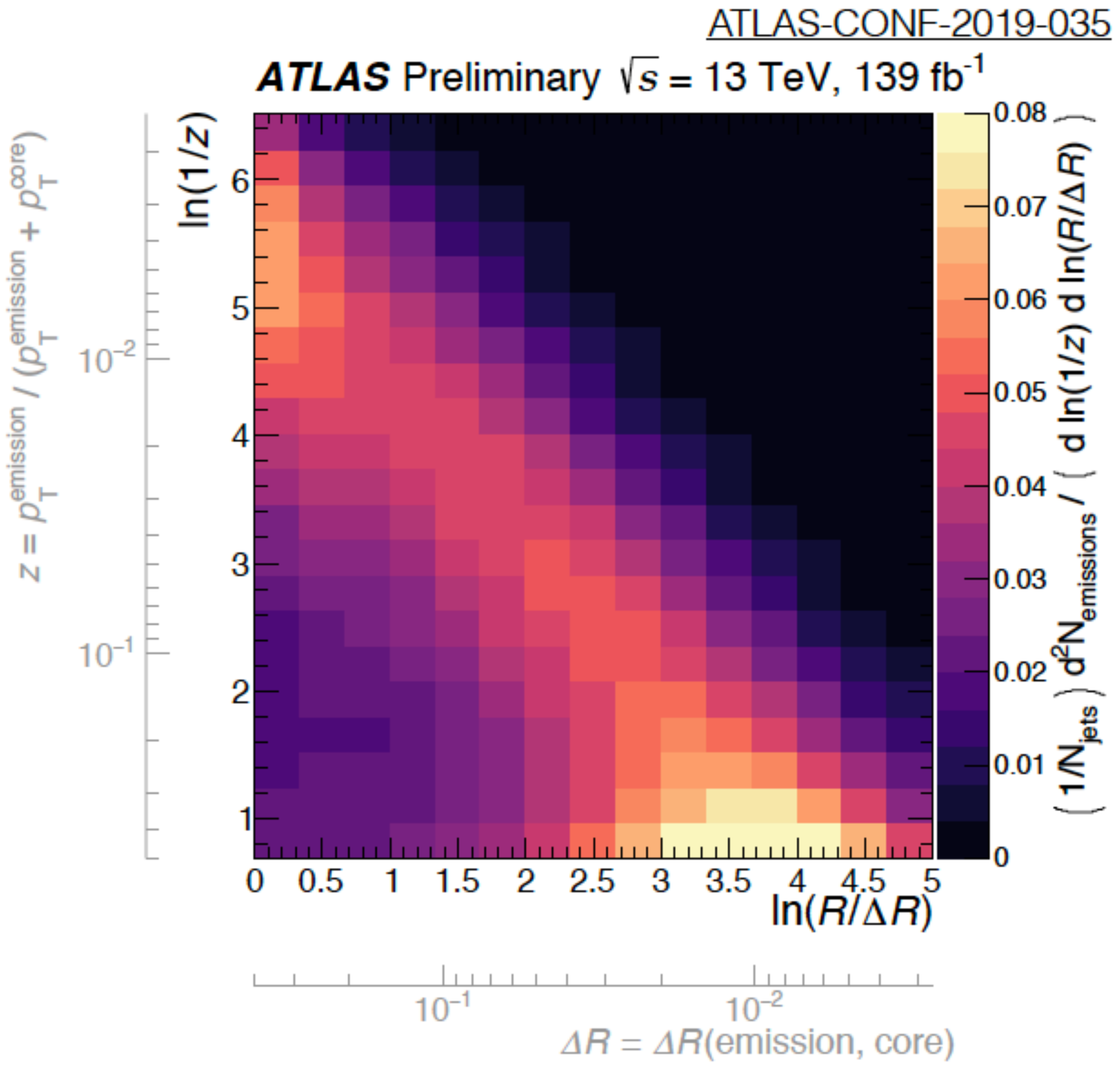
- Lund diagram (primary emission plane)
  - secondary branchings located on independent "leaves"
- powerful tool to visualize impact of resummation of multiple emissions
- powerful tool to analyze MC implementations of parton shower

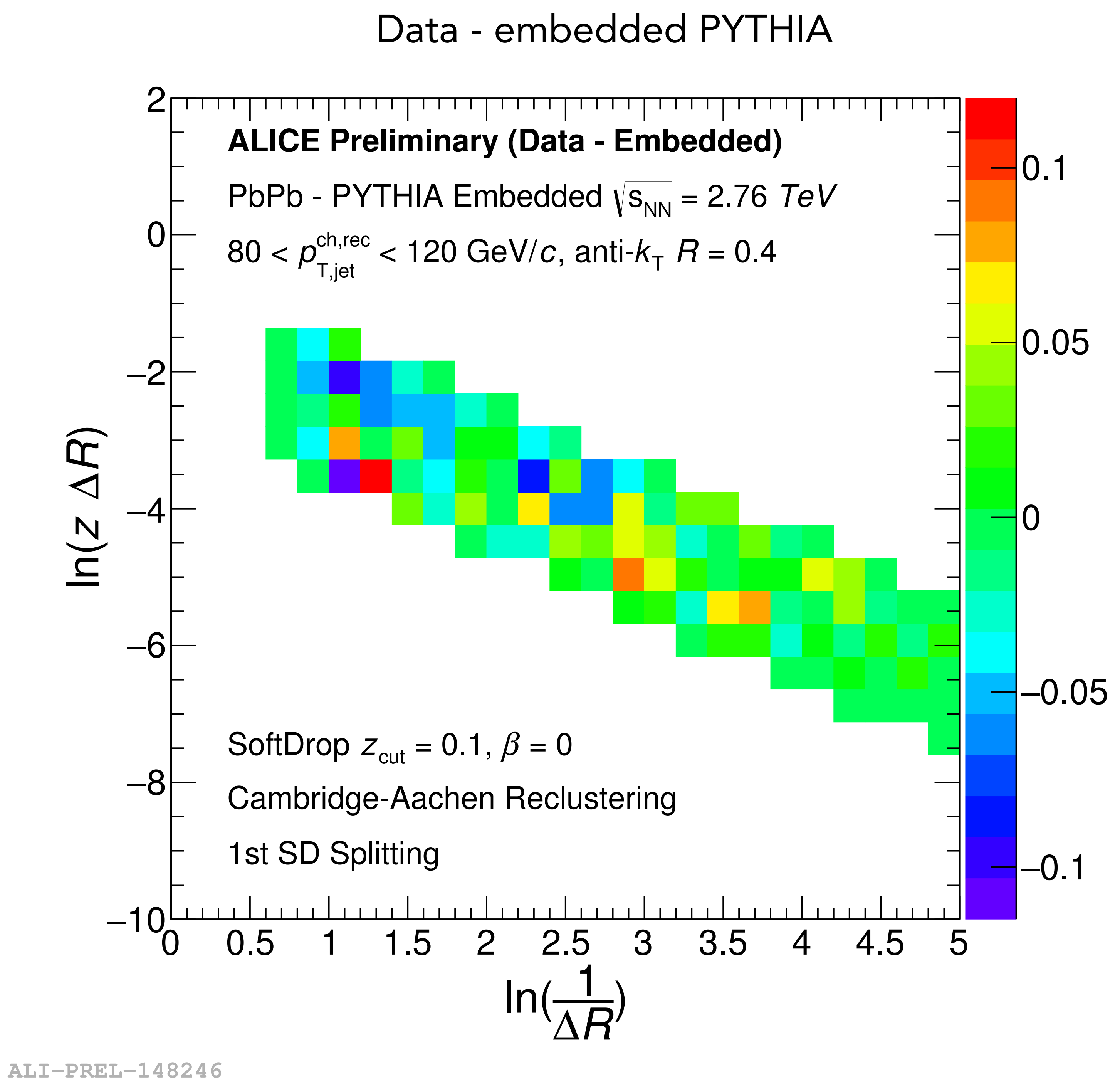
MEASURING THE LUND PLANE

Dreyer, Salam, Soyez 1807.04758



ATLAS-CONF-2019-035



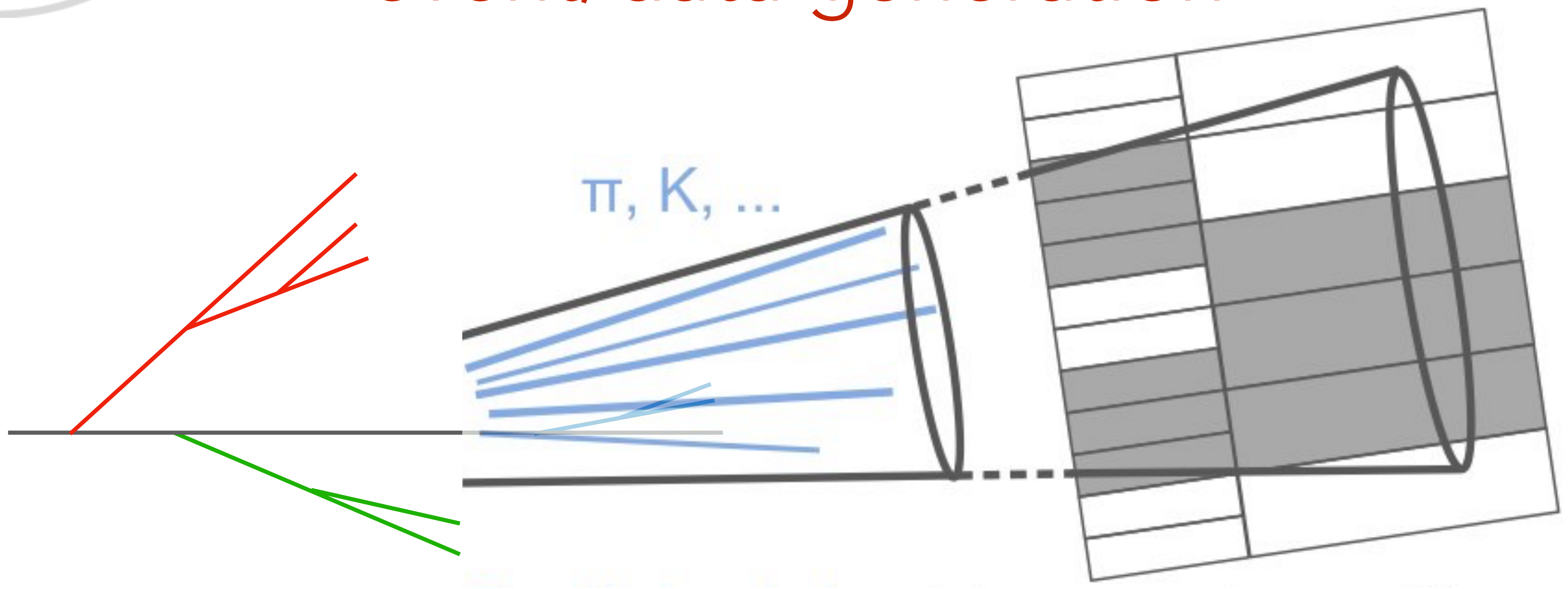


Lund Plane for PYTHIA jets

Lund Plane for jets @ LHC

JET RECONSTRUCTION PIPELINE ...simplified

event/data generation



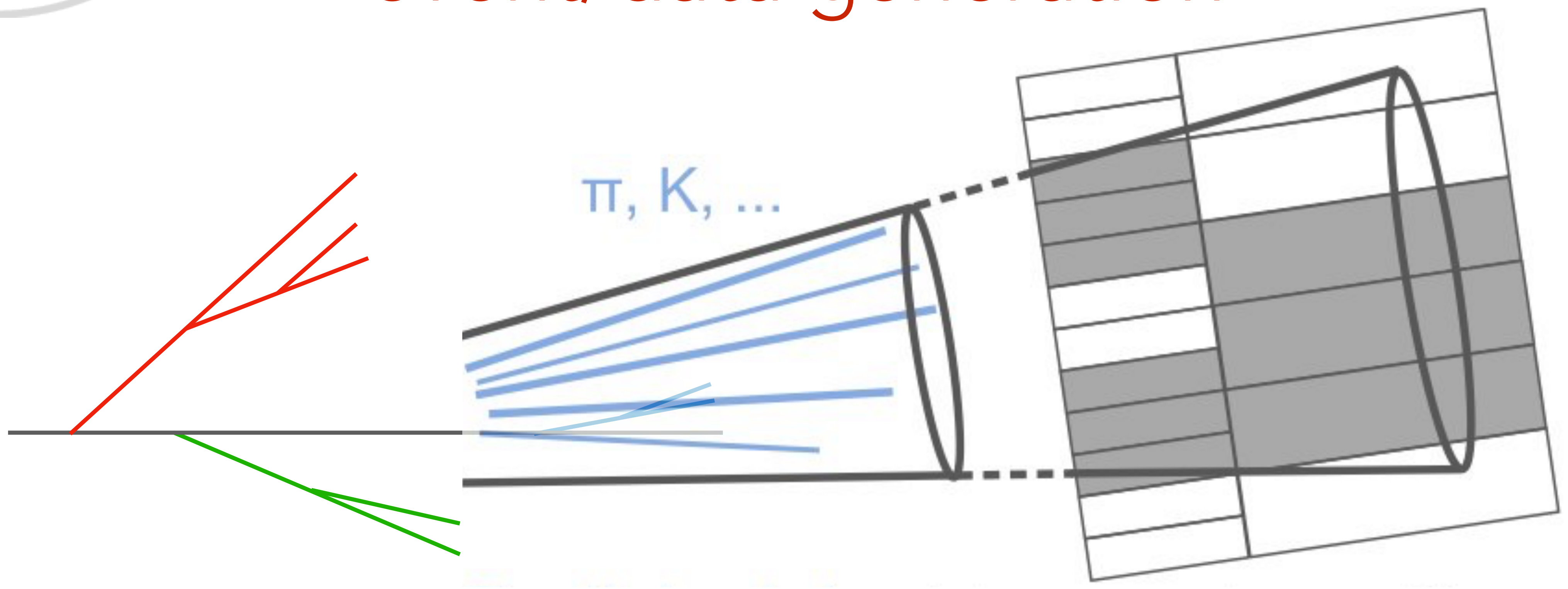
parton
level

particle
jet

energy
deposition

JET RECONSTRUCTION PIPELINE ...simplified

event/data generation



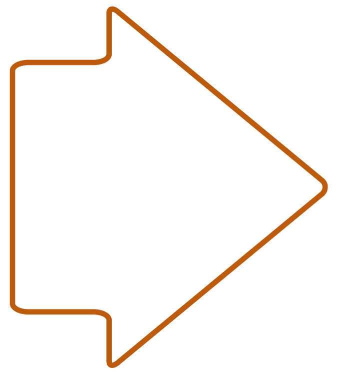
parton level

particle jet

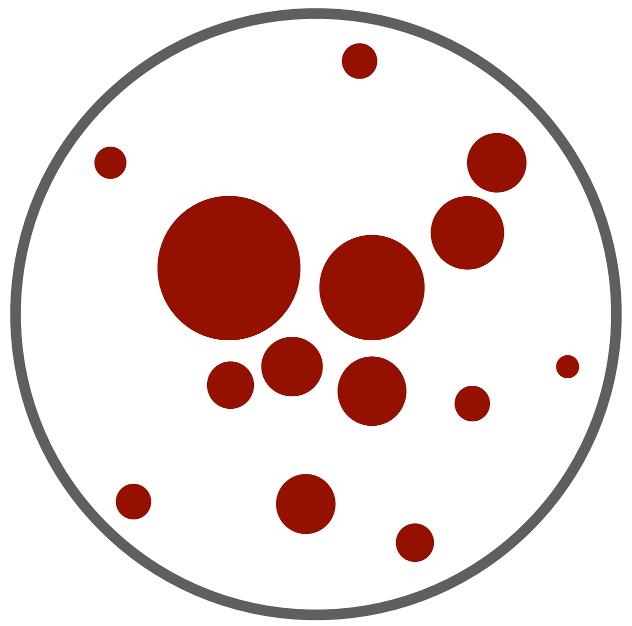
energy deposition

jet finding*

(typically anti-k_t w/ R~0.4)



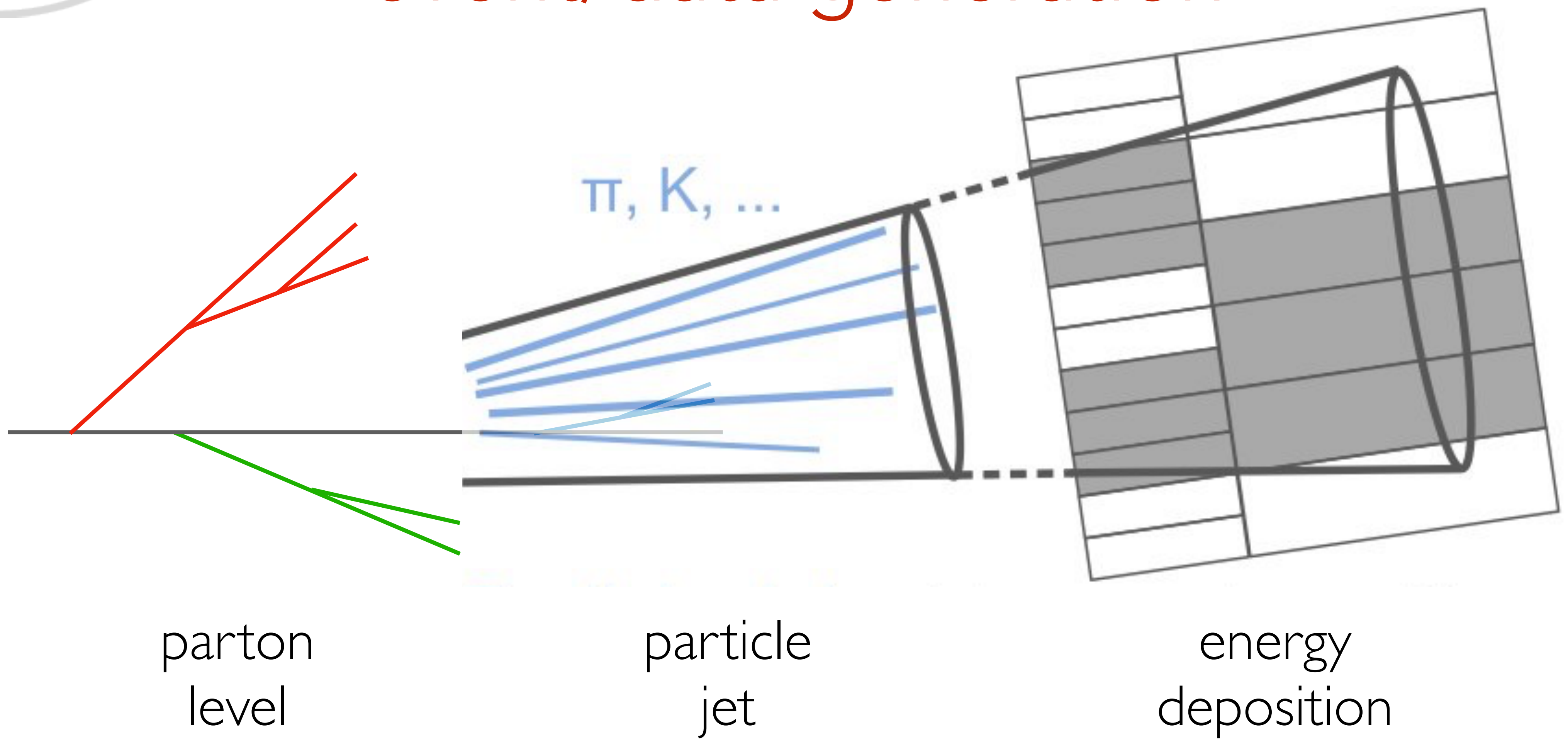
[*after background subtraction]



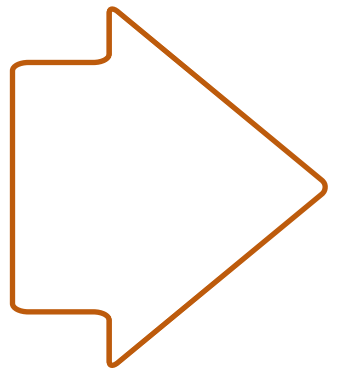
reconstructed jet

JET RECONSTRUCTION PIPELINE ...simplified

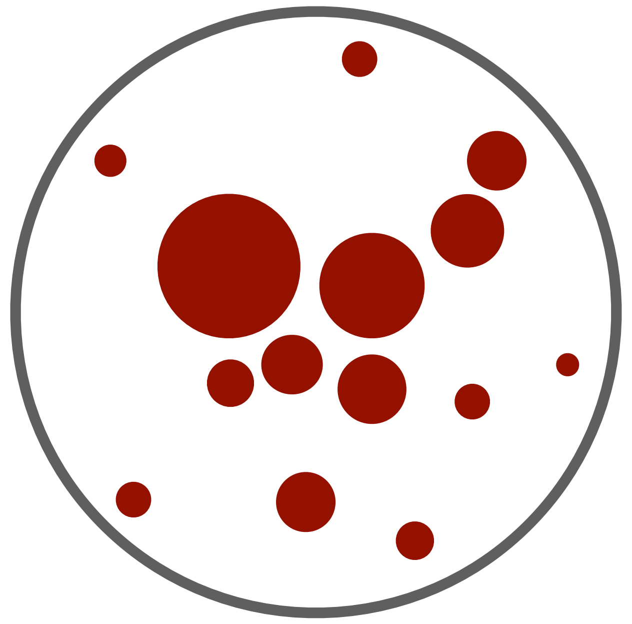
event/data generation



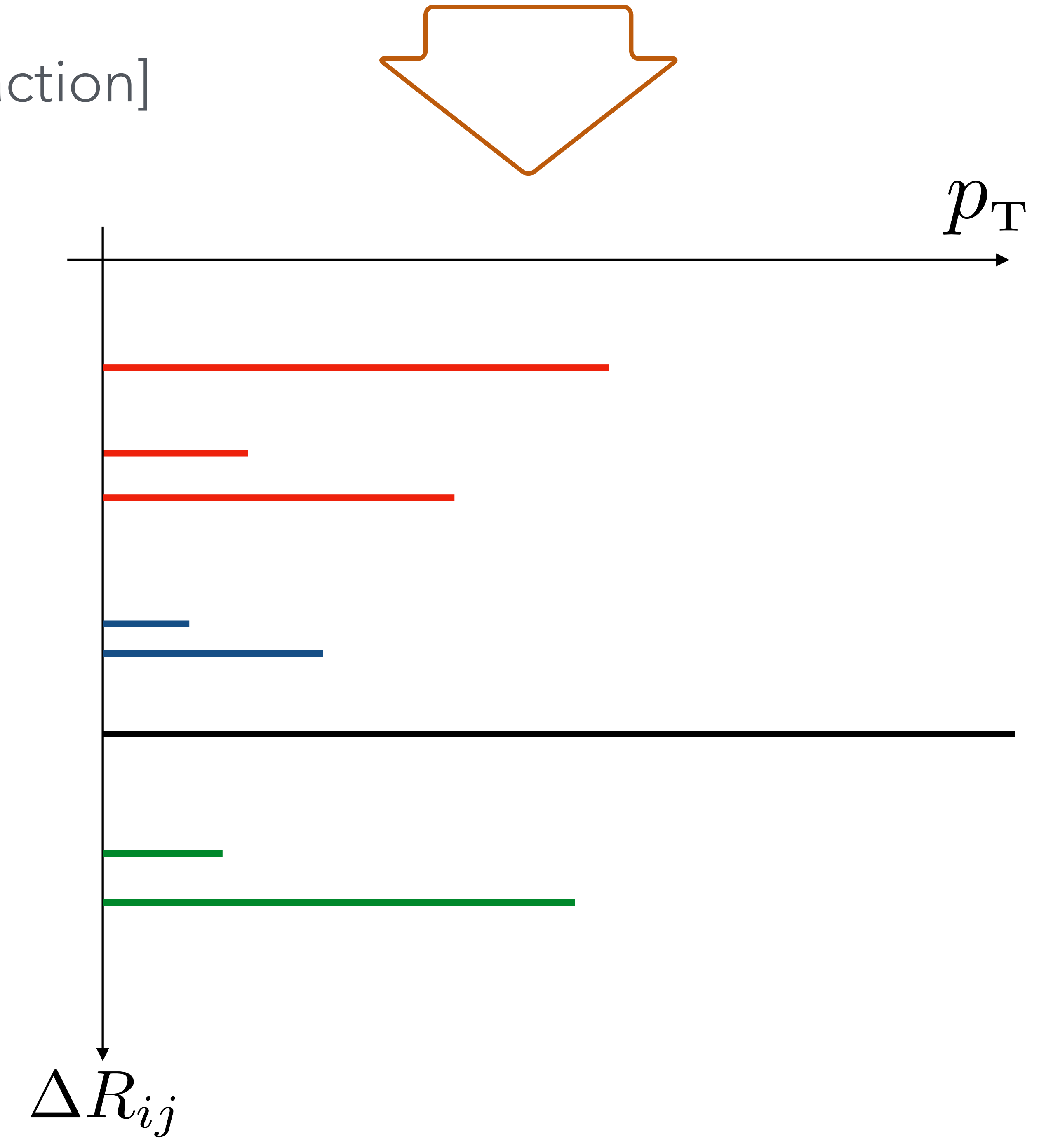
jet finding*
(typically anti-k_t w/ R~0.4)



[*after background subtraction]

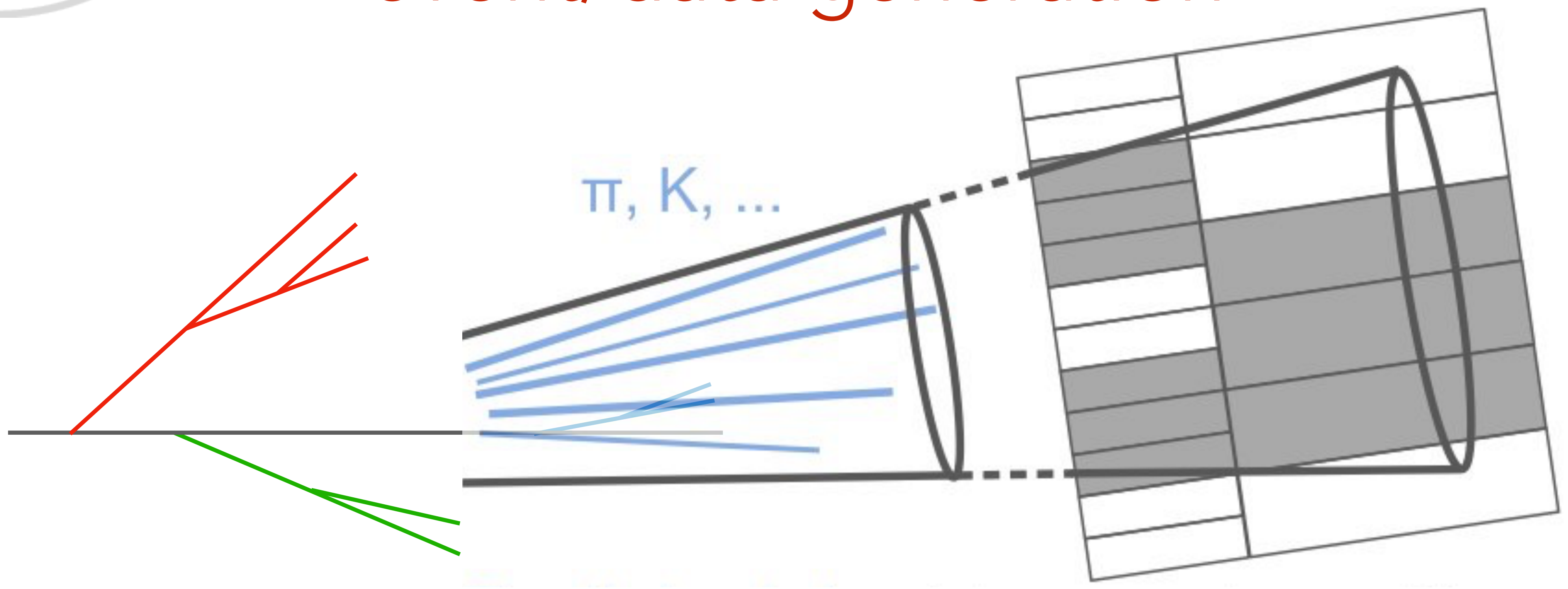


reconstructed
jet



JET RECONSTRUCTION PIPELINE ...simplified

event/data generation



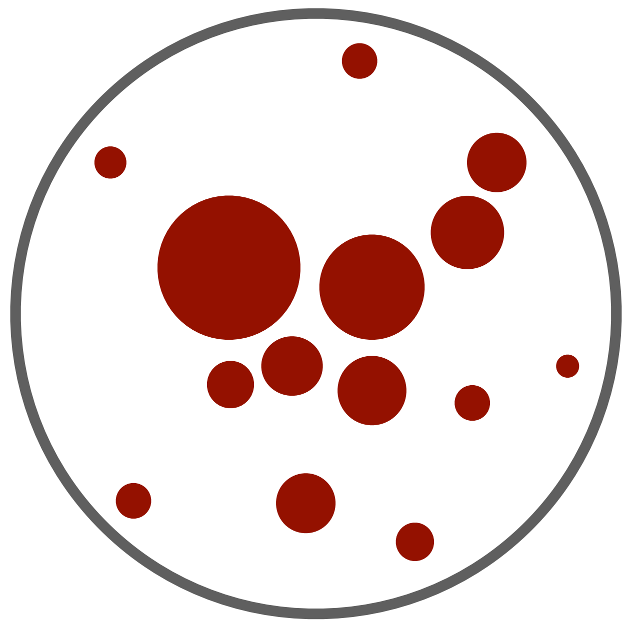
parton level

particle jet

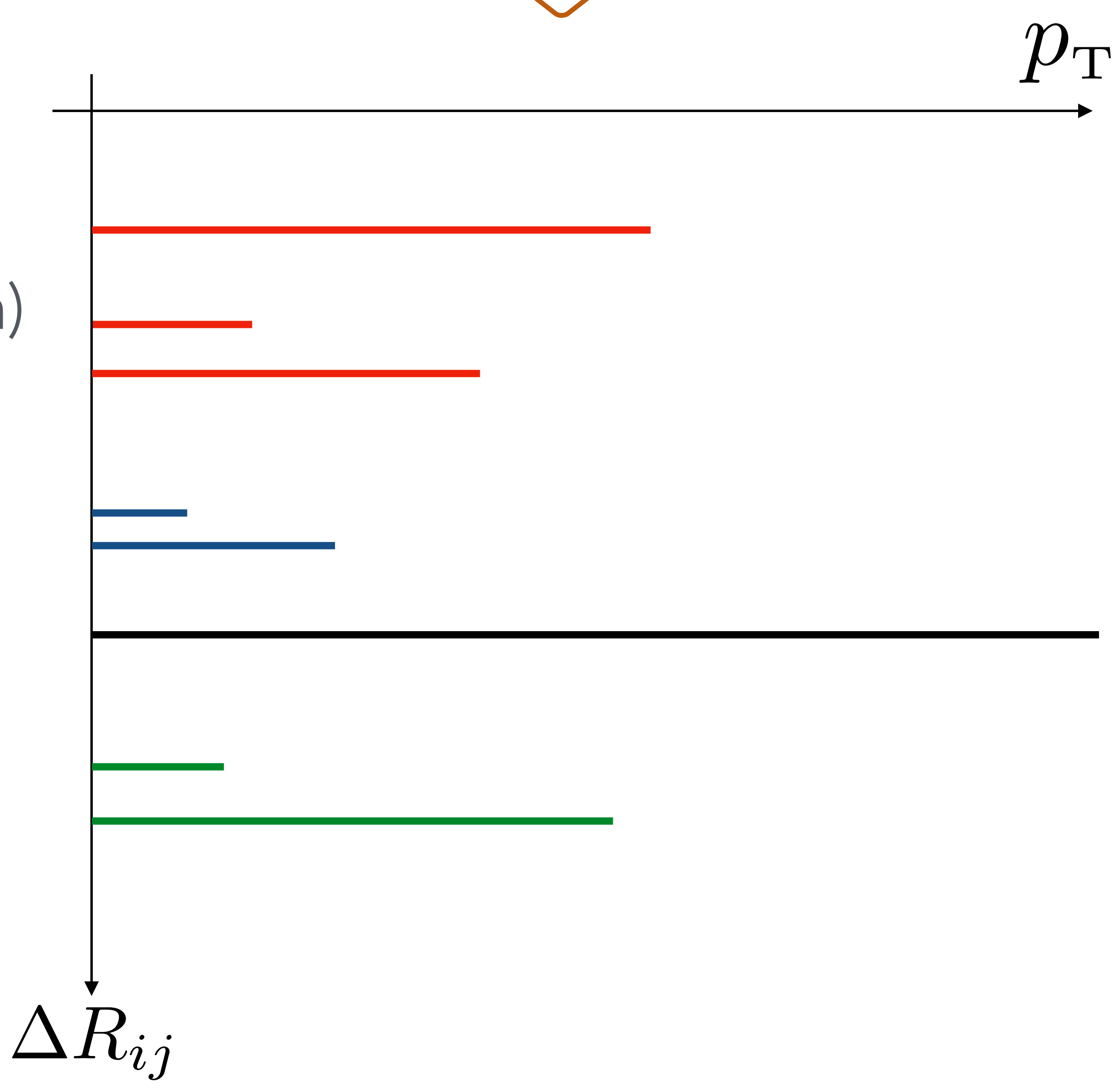
energy deposition

jet finding*
(typically anti-k_t w/ R~0.4)

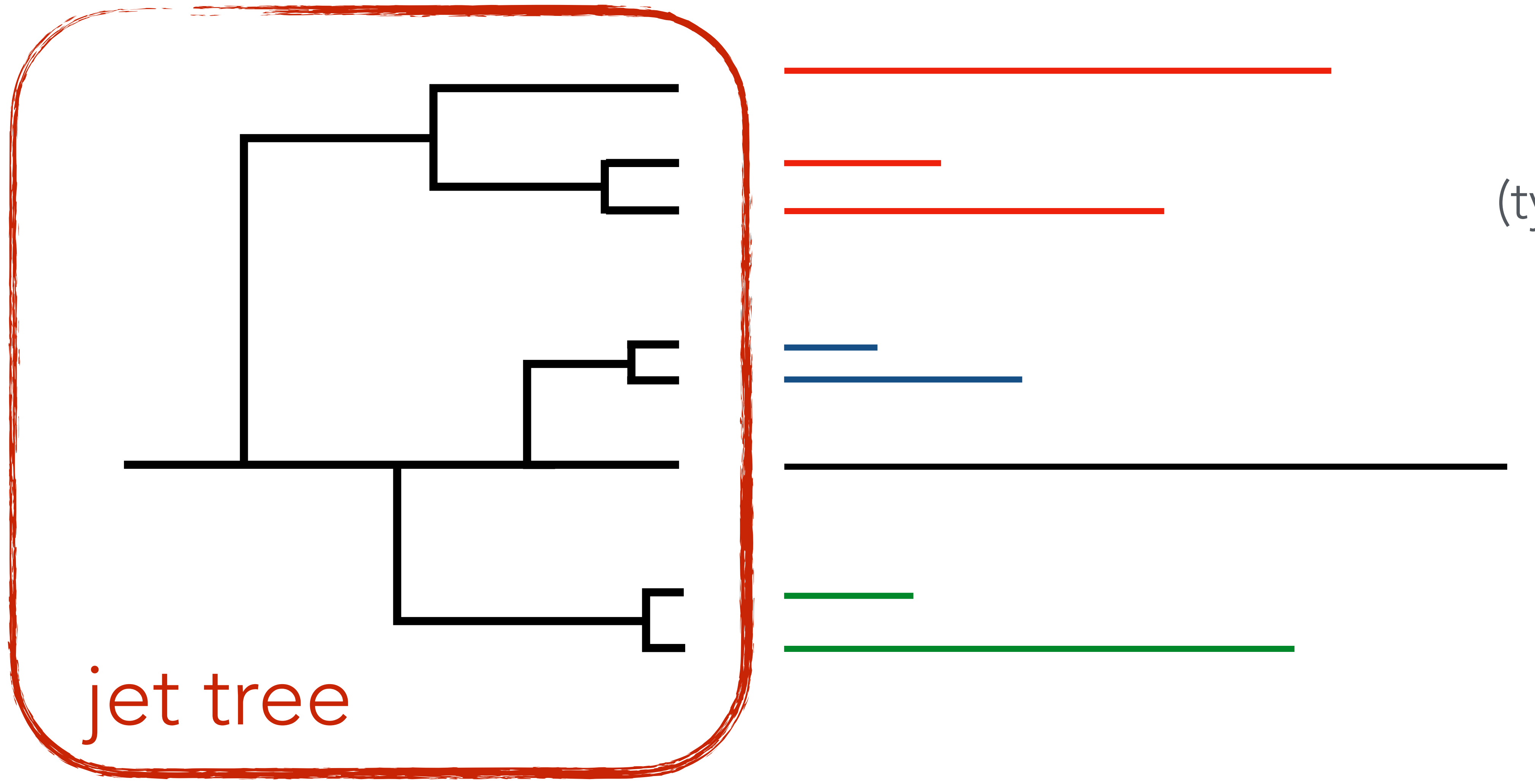
[*after background subtraction]



reconstructed jet

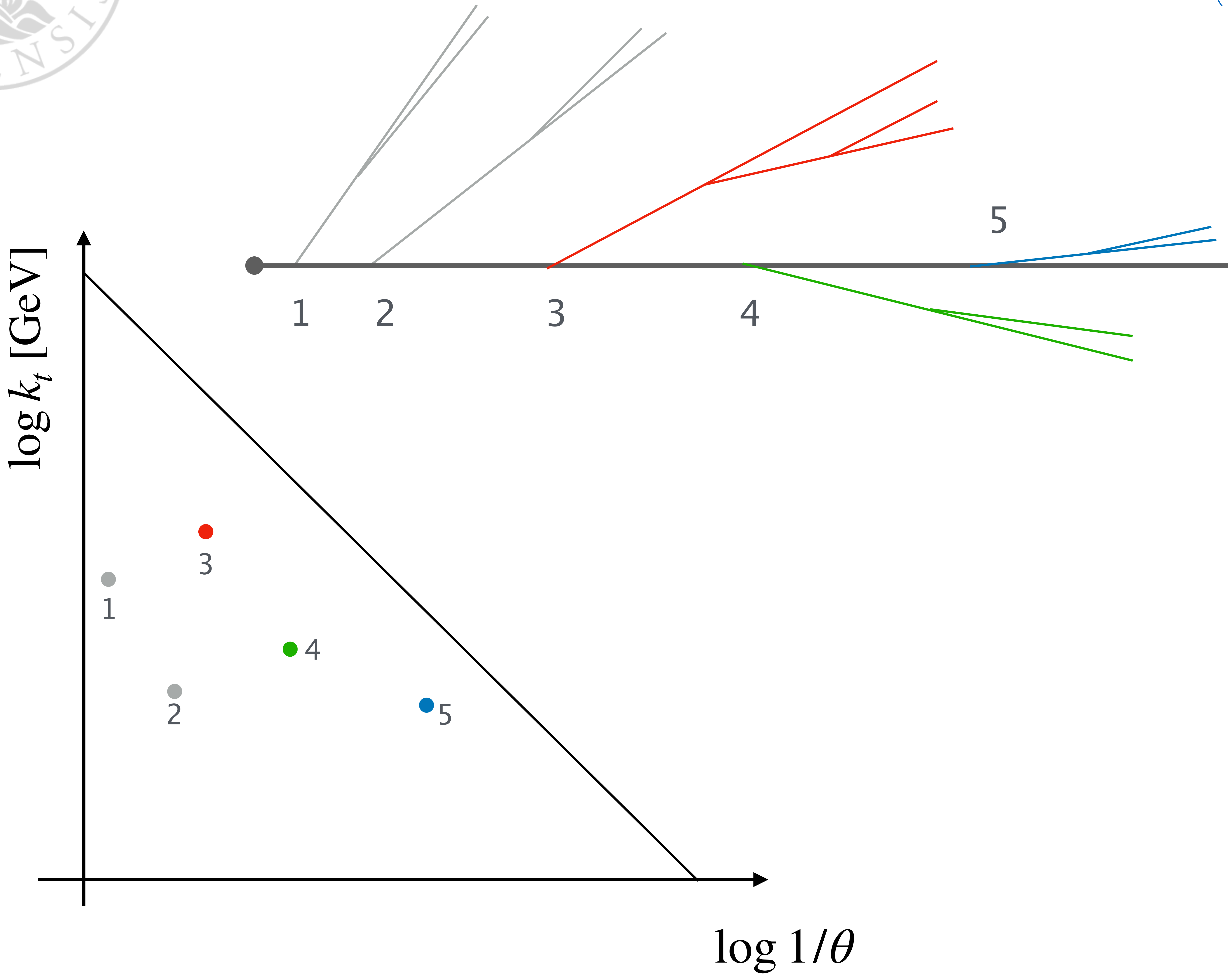


jet reclustering
(typically Cambridge/Aachen)



SoftDrop/mMDT grooming

(modified mass drop tagger) Dasgupta, Fregoso, Marzani, Salam 1307.0007
Larkoski, Marzani, Soyez, Thaler 1402.2657

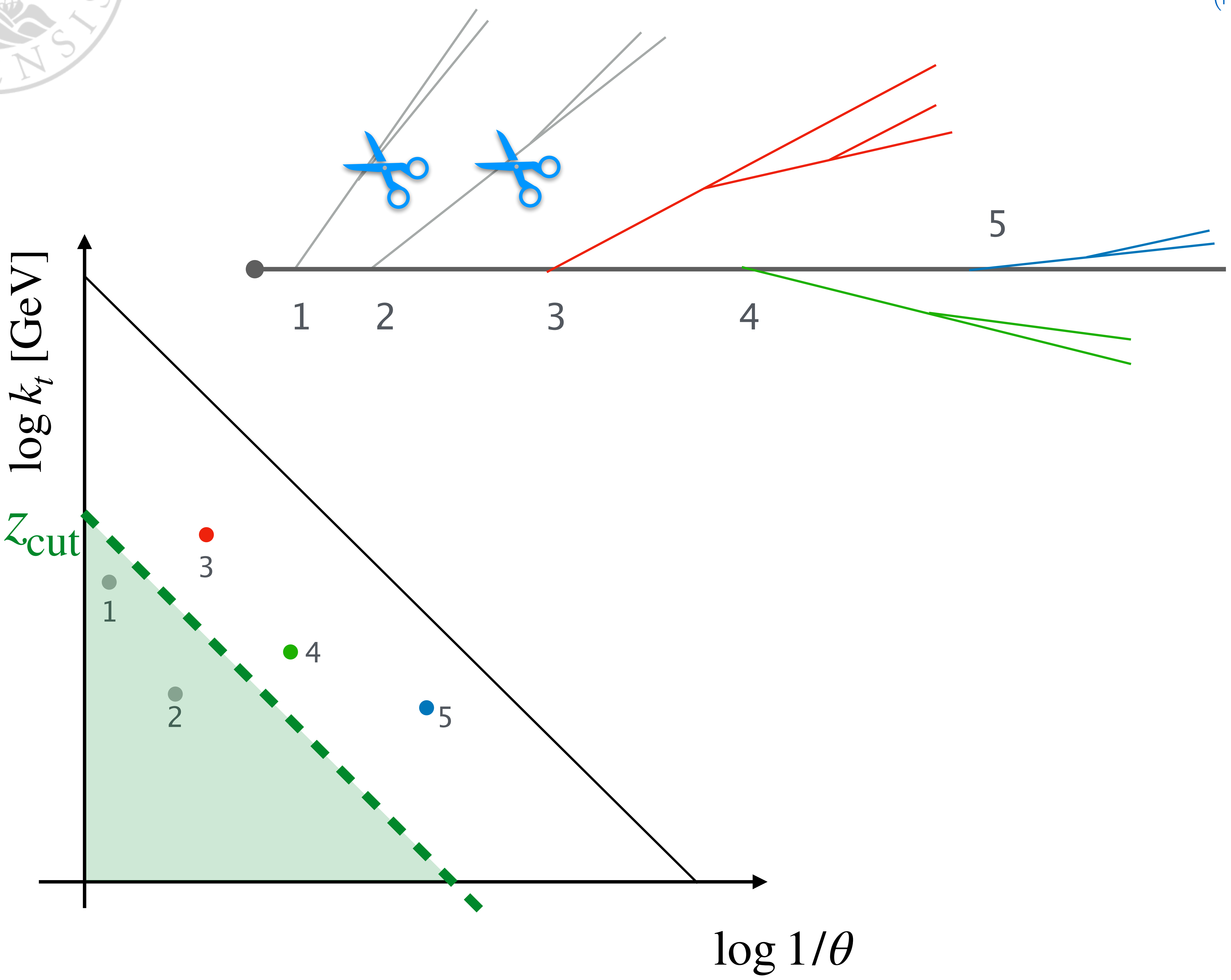


Follow jet tree until finding first branch that satisfies:

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

SoftDrop/mMDT grooming

(modified mass drop tagger) Dasgupta, Fregoso, Marzani, Salam 1307.0007
Larkoski, Marzani, Soyez, Thaler 1402.2657

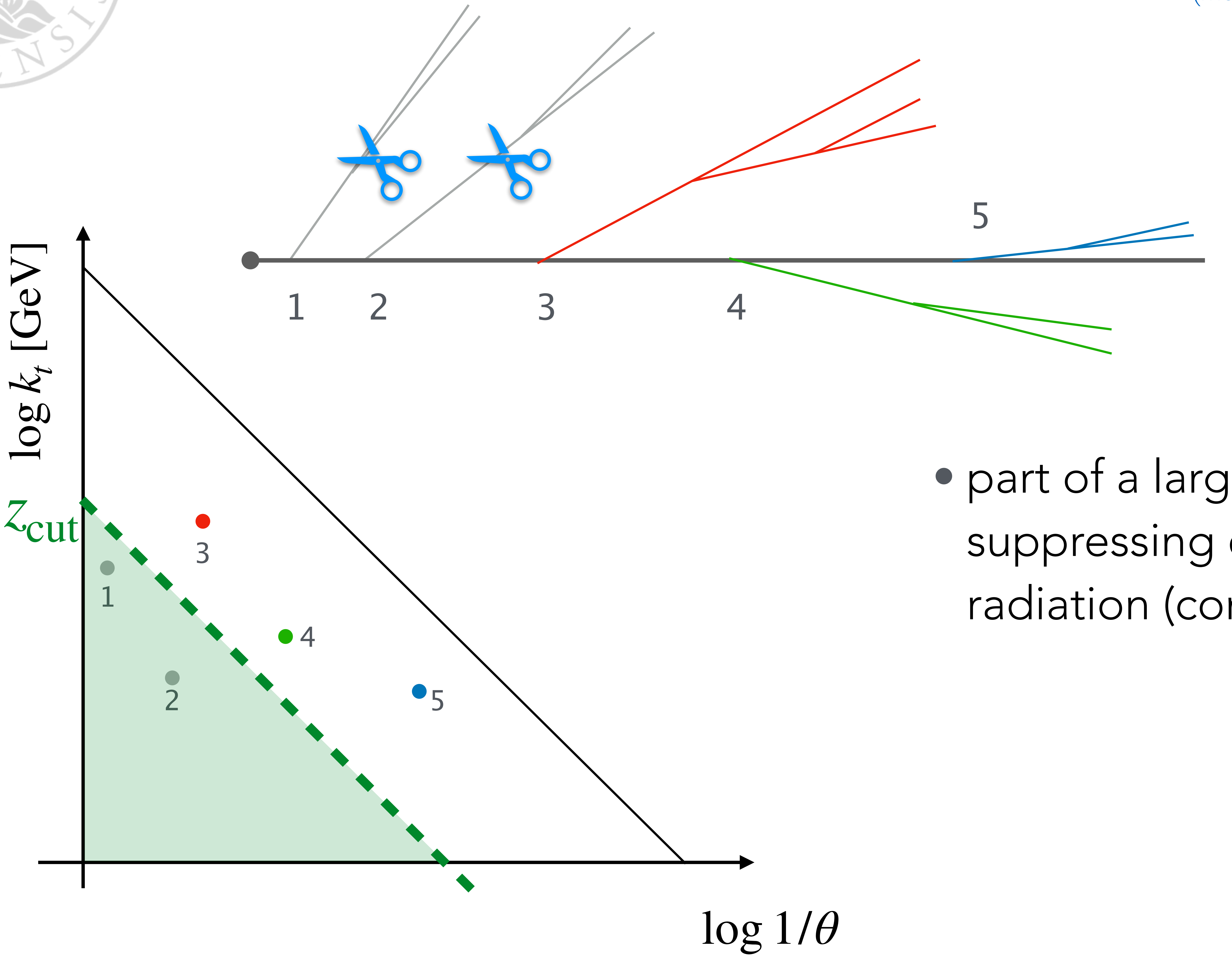


Follow jet tree until finding first branch that satisfies:

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

SoftDrop/mMDT grooming

(modified mass drop tagger) Dasgupta, Fregoso, Marzani, Salam 1307.0007
Larkoski, Marzani, Soyez, Thaler 1402.2657



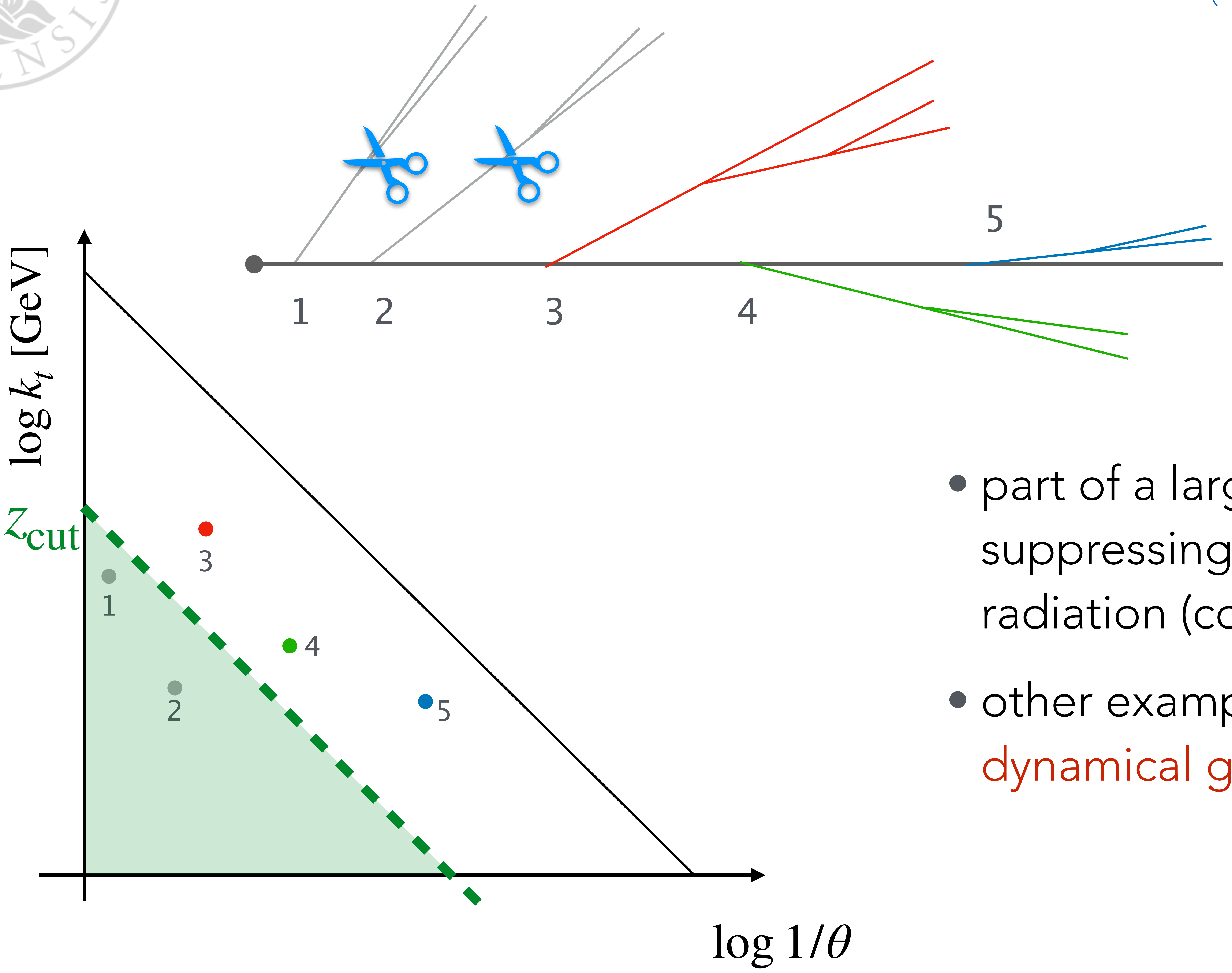
Follow jet tree until finding first branch that satisfies:

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

- part of a large class of algorithms aimed at suppressing effects of soft & large-angle radiation (contamination)

SoftDrop/mMDT grooming

(modified mass drop tagger) Dasgupta, Fregoso, Marzani, Salam 1307.0007
Larkoski, Marzani, Soyez, Thaler 1402.2657



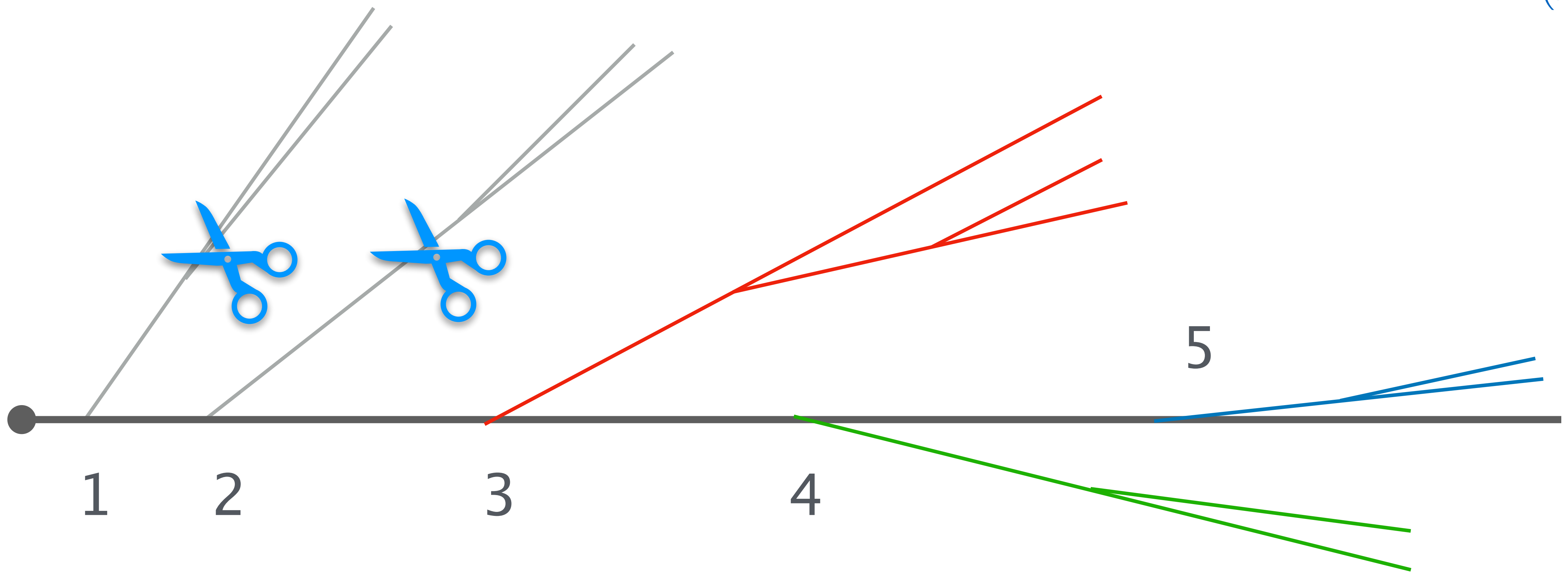
Follow jet tree until finding first branch that satisfies:

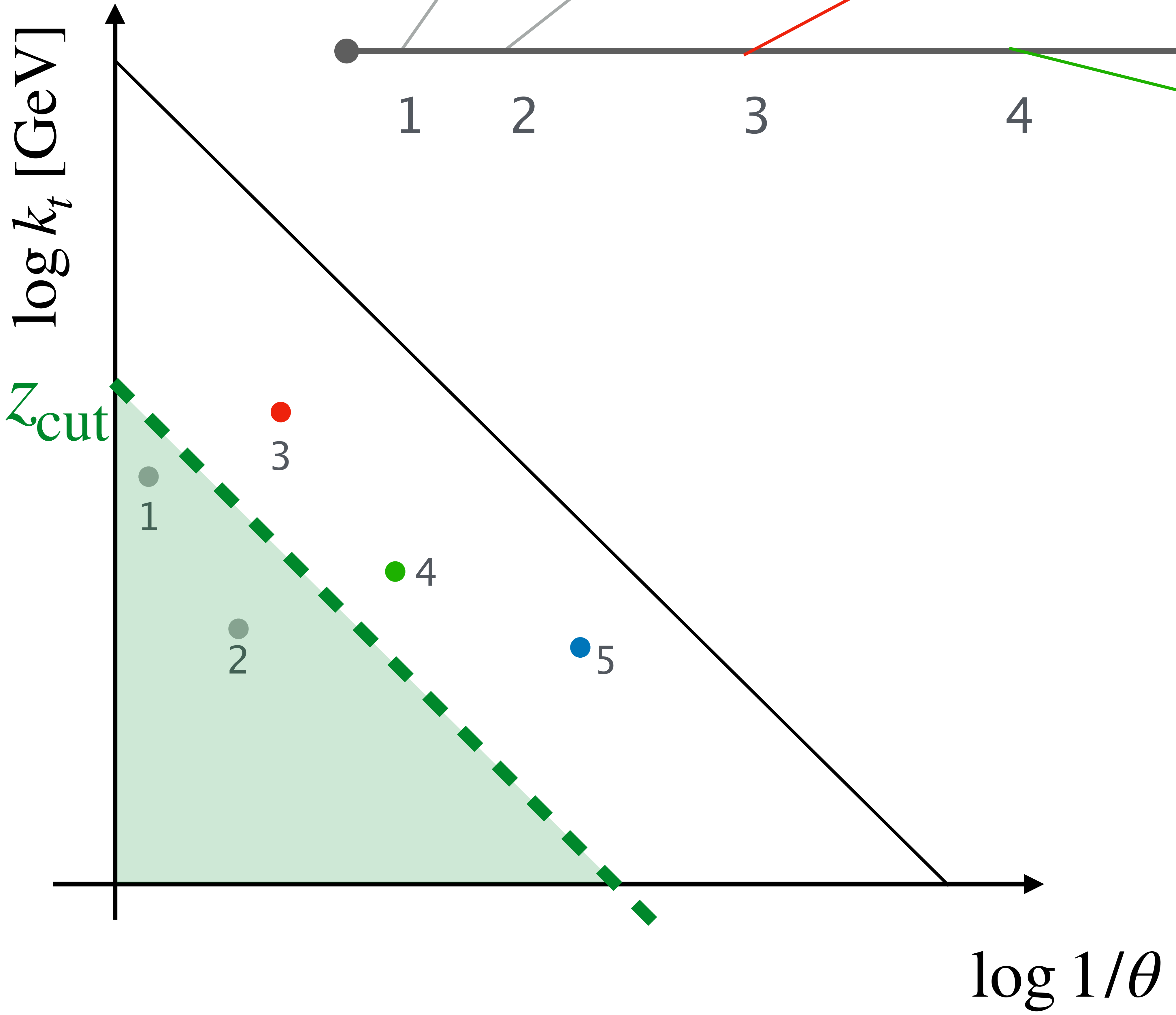
$$z > z_{\rm cut}\theta^{\beta}$$

- part of a large class of algorithms aimed at suppressing effects of soft & large-angle radiation (contamination)
- other examples: trimming, pruning,…, dynamical grooming

SoftDrop/mMDT grooming

(modified mass drop tagger) Dasgupta, Fregoso, Marzani, Salam 1307.0007
Larkoski, Marzani, Soyez, Thaler 1402.2657





Follow jet tree until finding first branch that satisfies:

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

- part of a large class of algorithms aimed at suppressing effects of soft & large-angle radiation (contamination)
- other examples: trimming, pruning,…, dynamical grooming

measure of "hardness" $\kappa^{(a)} = \max_{i \in C/A} z_i(1-z_i)(\theta/R)^a$

Mehtar-Tani, Soto-Ontoso, KT 1911.00375, 2005.07584

Summary

Lecture 1

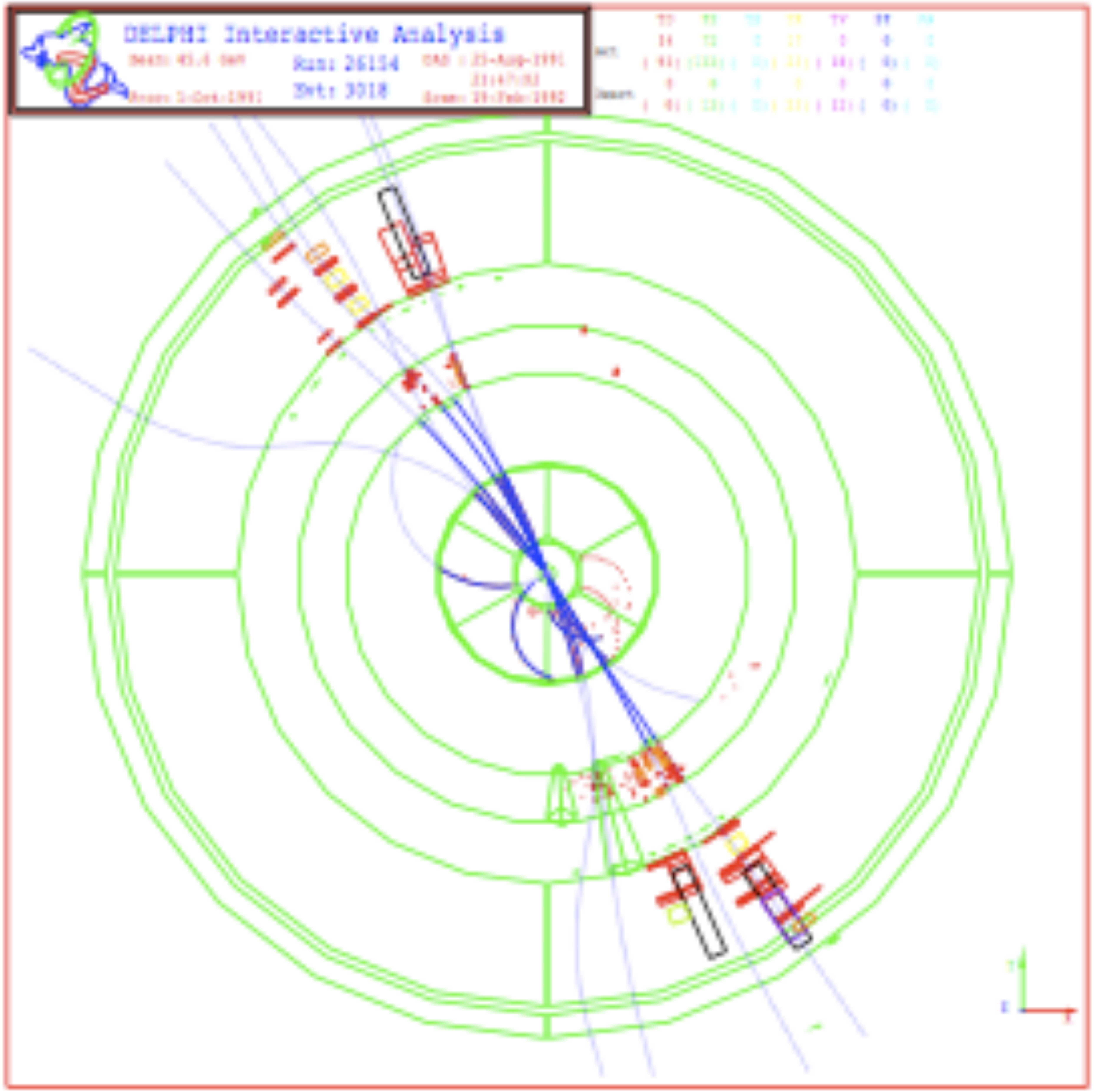
- “jet quenching” is a set of striking phenomena affecting high-energy observables in heavy-ion collisions
- closely related to energy-loss
  - our job in the next lectures is to relate this to induced radiative processes in the quark-gluon plasma

Summary
Lecture 1

- QCD jets are formed when an initially virtual parton fragments
- have an interesting structure related to logarithmic resummation (e.g. angular ordering)
  - can be used as calibrated probes of the medium

Lecture 2

theory of radiative parton energy loss in matter



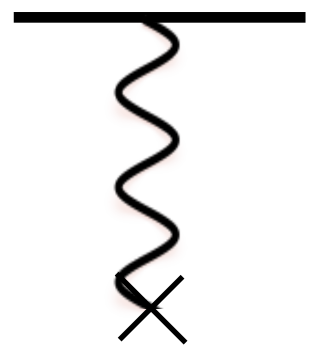
x-y plane

PARTON PROPAGATION IN MEDIUM

Baier, Dokshitzer, Mueller, Peigné, Schiff (1996); Zakharov (1996); Arnold, Moore, Yaffe (2003)
Barata, Milhano, Mehtar-Tani, Salgado, KT (in preparation)

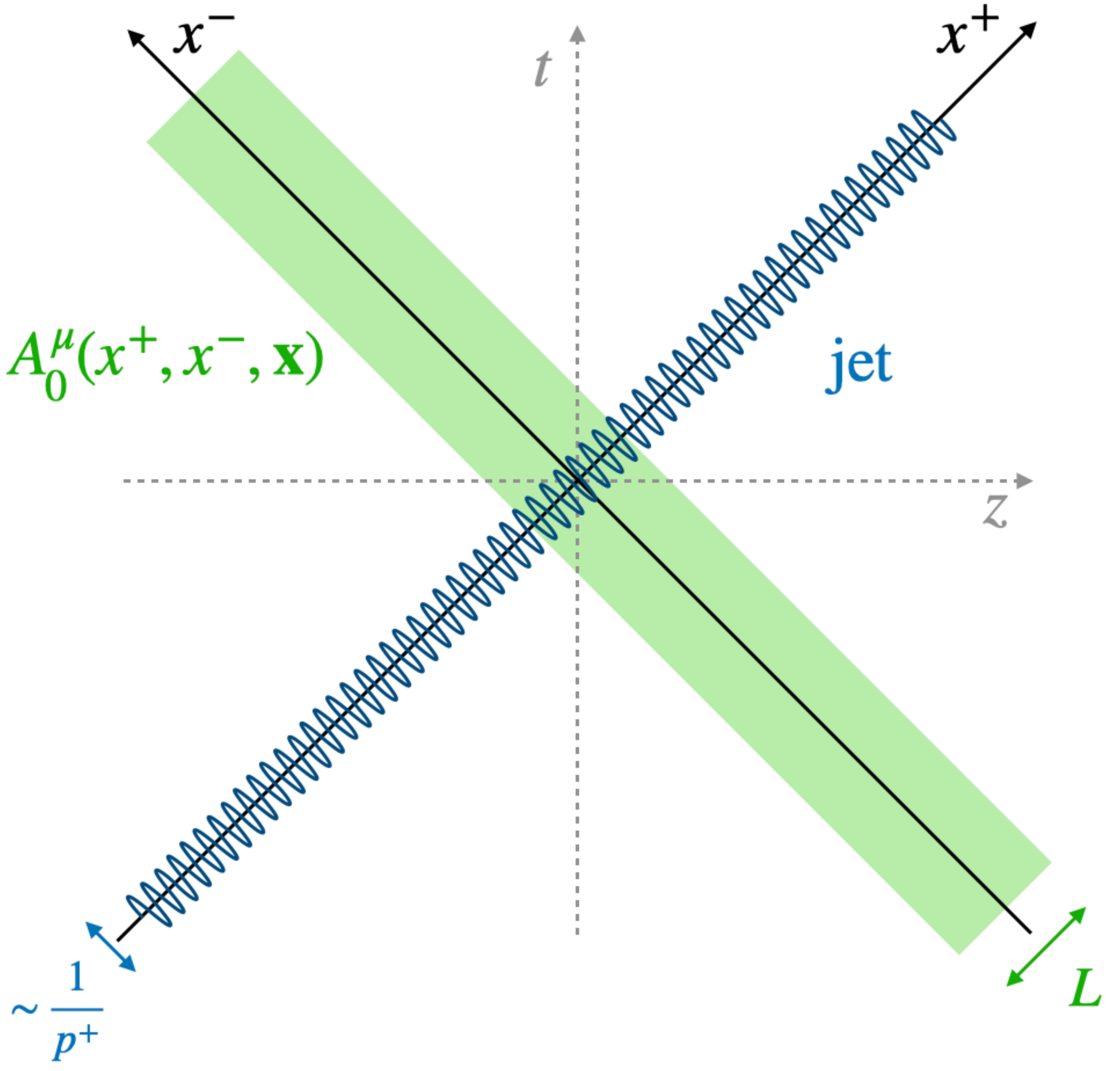
Setup: light-front perturbation theory in A^- background field ($A^+ = 0$ gauge).

Interaction vertex: treated in the eikonal approximation



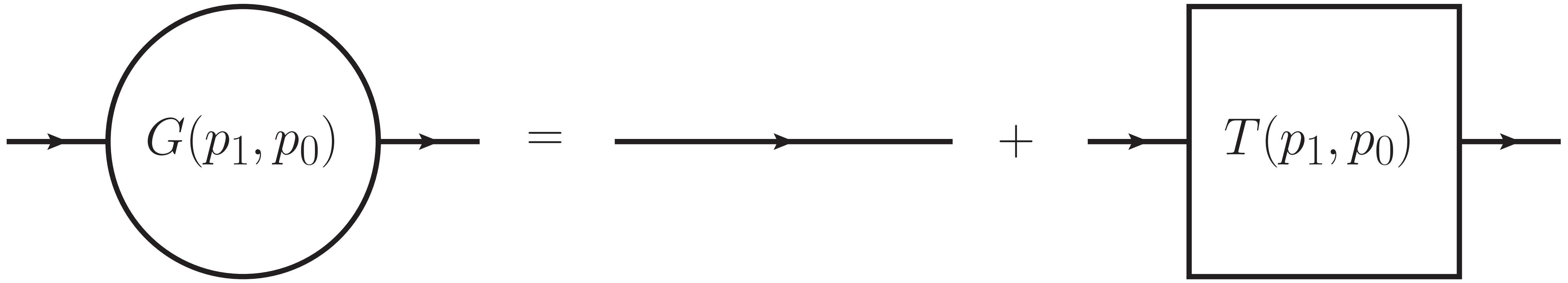
$$\simeq = ig\boldsymbol{T}^a \, 2p^+ \, A^{-,a}(x)$$

We assume the medium potential does not have a extent in the x^- direction, i.e. $A(x^+, x^-, \boldsymbol{x}) \simeq A(x^+, 0, \boldsymbol{x})$. In Fourier space, this leads to $\delta(q^+)$ - no longitudinal momentum transfer & no elastic energy loss.



Parton propagation in the medium

Baier, Dokshitzer, Mueller, Peigné, Schiff (1996); Zakharov (1996); Arnold, Moore, Yaffe (2003)
Barata, Milhano, Mehtar-Tani, Salgado, KT (in preparation)

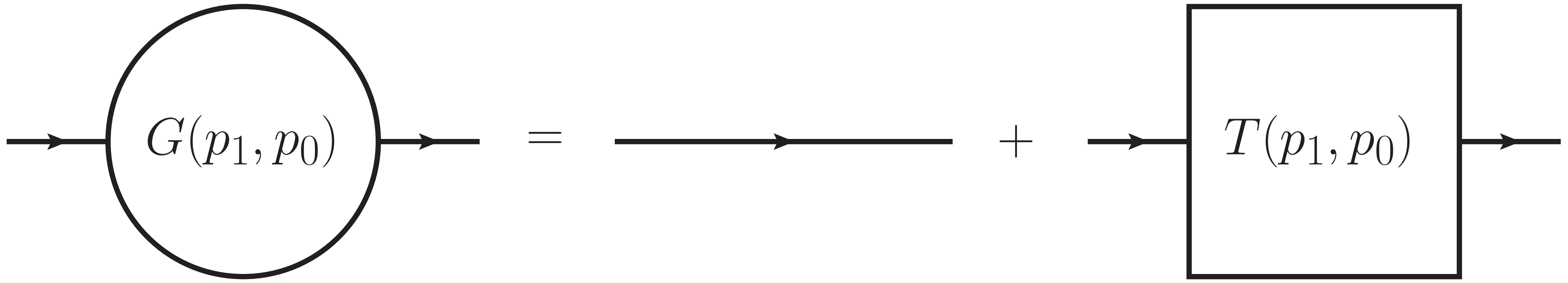


Dressed (scalar) propagator:

$$(x|G_{\rm scal}|x_0) = (x|G_0|x_0) + 2p^+ \int_z (x|G_0|z)\, ig\mathcal{A}_0(z)\, (z|G_{\rm scal}|x_0)$$

Parton propagation in the medium

Baier, Dokshitzer, Mueller, Peigné, Schiff (1996); Zakharov (1996); Arnold, Moore, Yaffe (2003)
Barata, Milhano, Mehtar-Tani, Salgado, KT (in preparation)



Dressed (scalar) propagator:

$$(x|G_{\text{scal}}|x_0) = (x|G_0|x_0) + 2p^+ \int_z (x|G_0|z)\, ig\mathcal{A}_0(z)\, (z|G_{\text{scal}}|x_0)$$

Translational invariance in x^- components:

Conservation of large momentum component p^+.

$$(\boldsymbol{x}|\mathcal{G}(t,t_0)|\boldsymbol{x}_0) \equiv 2p^+ \int \mathrm{d}x^-\, \mathrm{e}^{ip^+(x-x_0)^-} (x|G_{\text{scal}}|x_0)$$

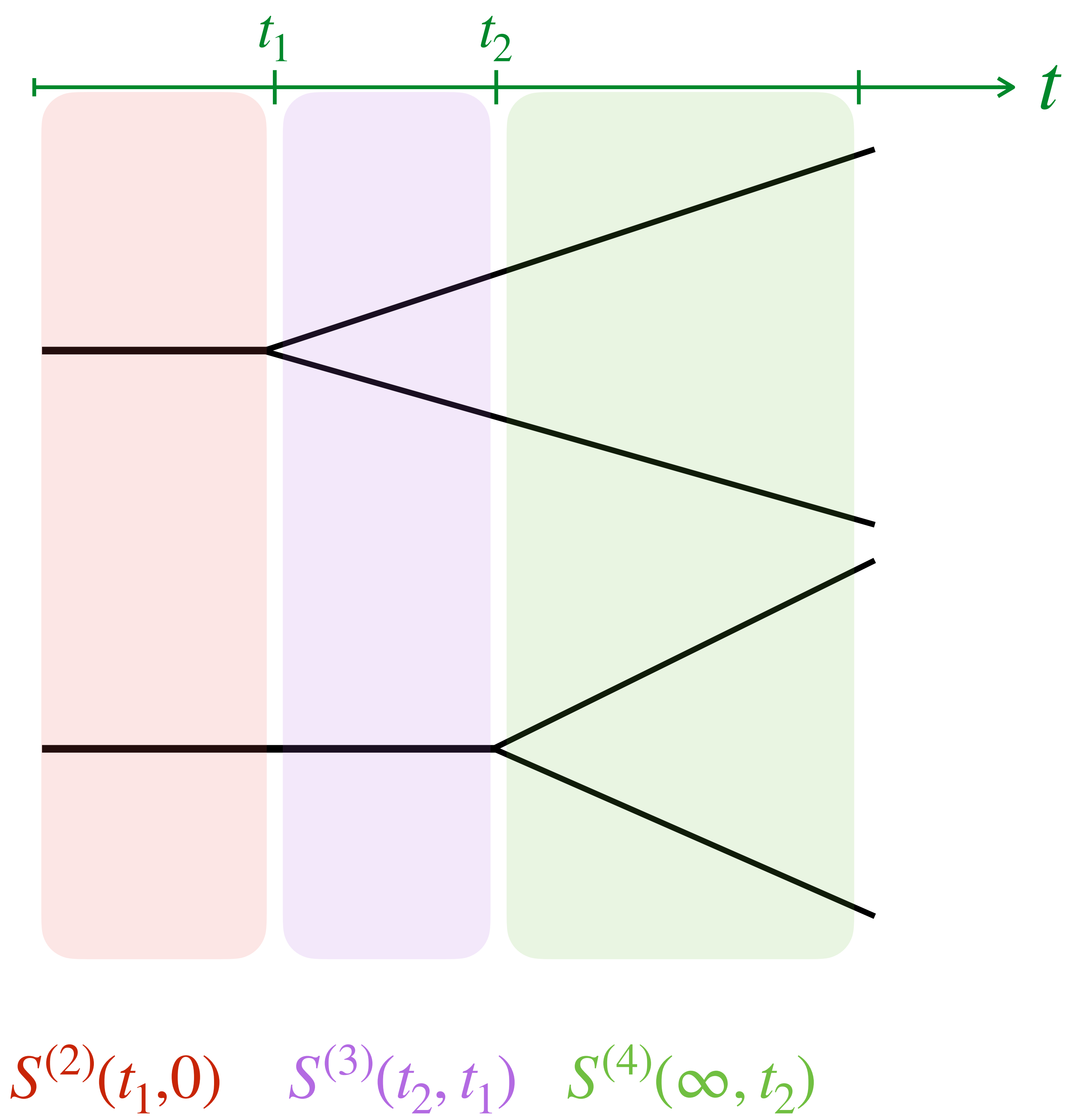
$$\left[i\frac{\partial}{\partial t} + \frac{\partial_\perp^2}{2E} + g\mathcal{A}_0(t,\boldsymbol{x})\right] (\boldsymbol{x}|\mathcal{G}(t,t_0)|\boldsymbol{x}_0) = i\delta(t-t_0)\delta(\boldsymbol{x}-\boldsymbol{x}_0)$$

2+1D Schrödinger equation with $m = E$.

FEYNMAN RULES

PARTON SPLITTING IN MEDIUM

Blaizot, Dominguez, Iancu, Mehtar-Tani (2013)
Apolinario, Armesto, Milhano, Salgado (2015)

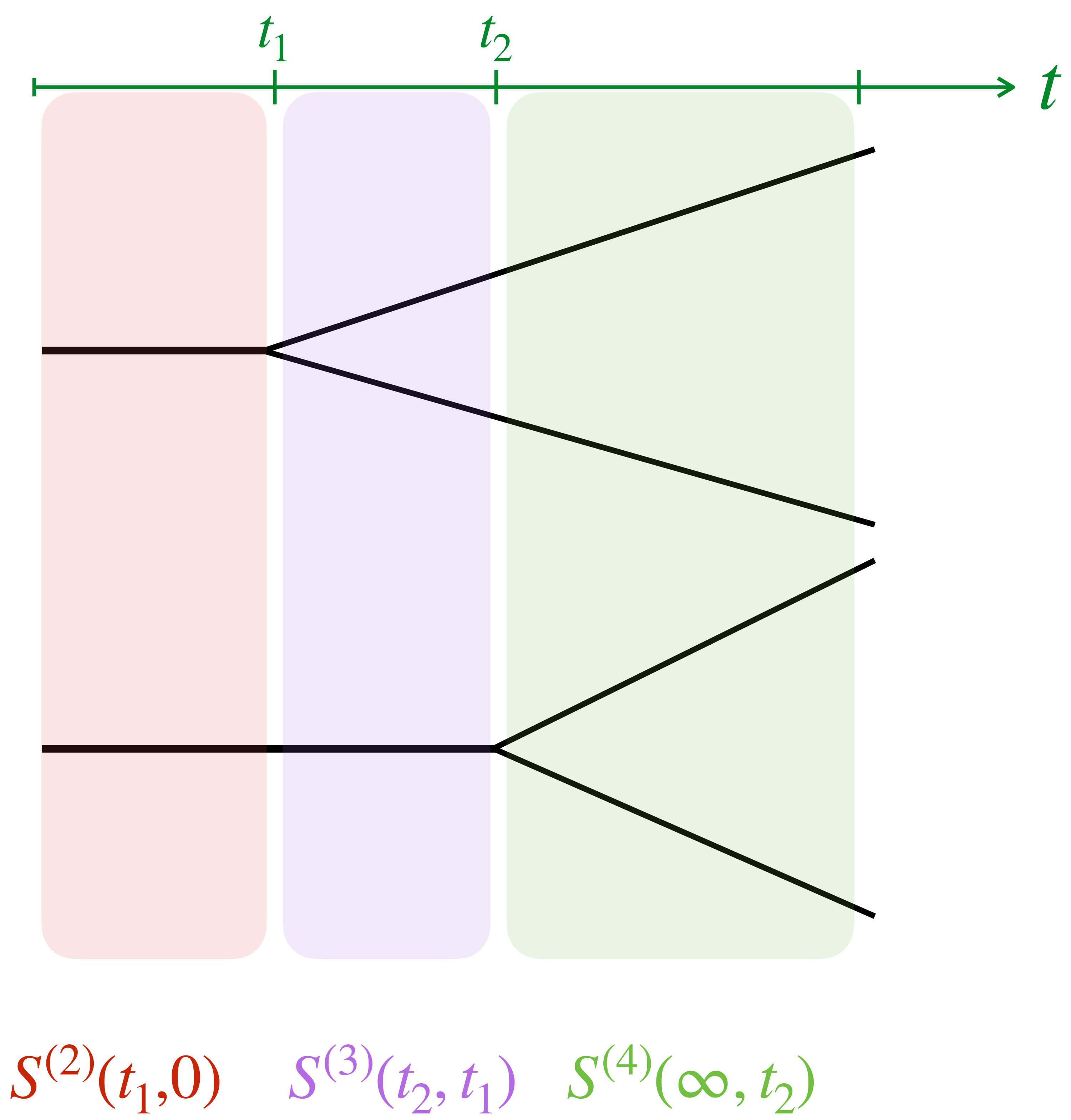


- Spectrum of $1 \to 2$ splitting involves n-body correlators of dressed propagators.
- Correlators evaluated in the background of fluctuating medium.
- Time-evolution governed by corresponding Schrödinger equation(s).

also, see talk by Arnold (this workshop, Mon, Jul 26)

PARTON SPLITTING IN MEDIUM

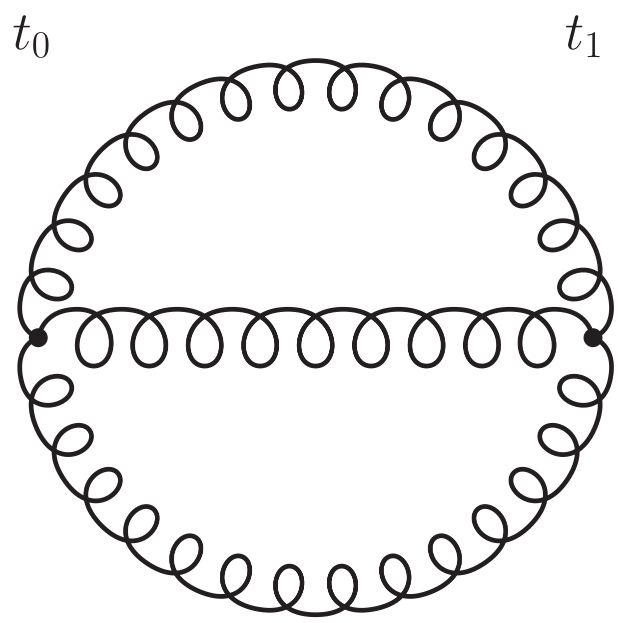
Blaizot, Dominguez, Iancu, Mehtar-Tani (2013)
Apolinario, Armesto, Milhano, Salgado (2015)



- Spectrum of $1 \to 2$ splitting involves n-body correlators of dressed propagators.
- Correlators evaluated in the background of fluctuating medium.
- Time-evolution governed by corresponding Schrödinger equation(s).

also, see talk by Arnold (this workshop, Mon, Jul 26)

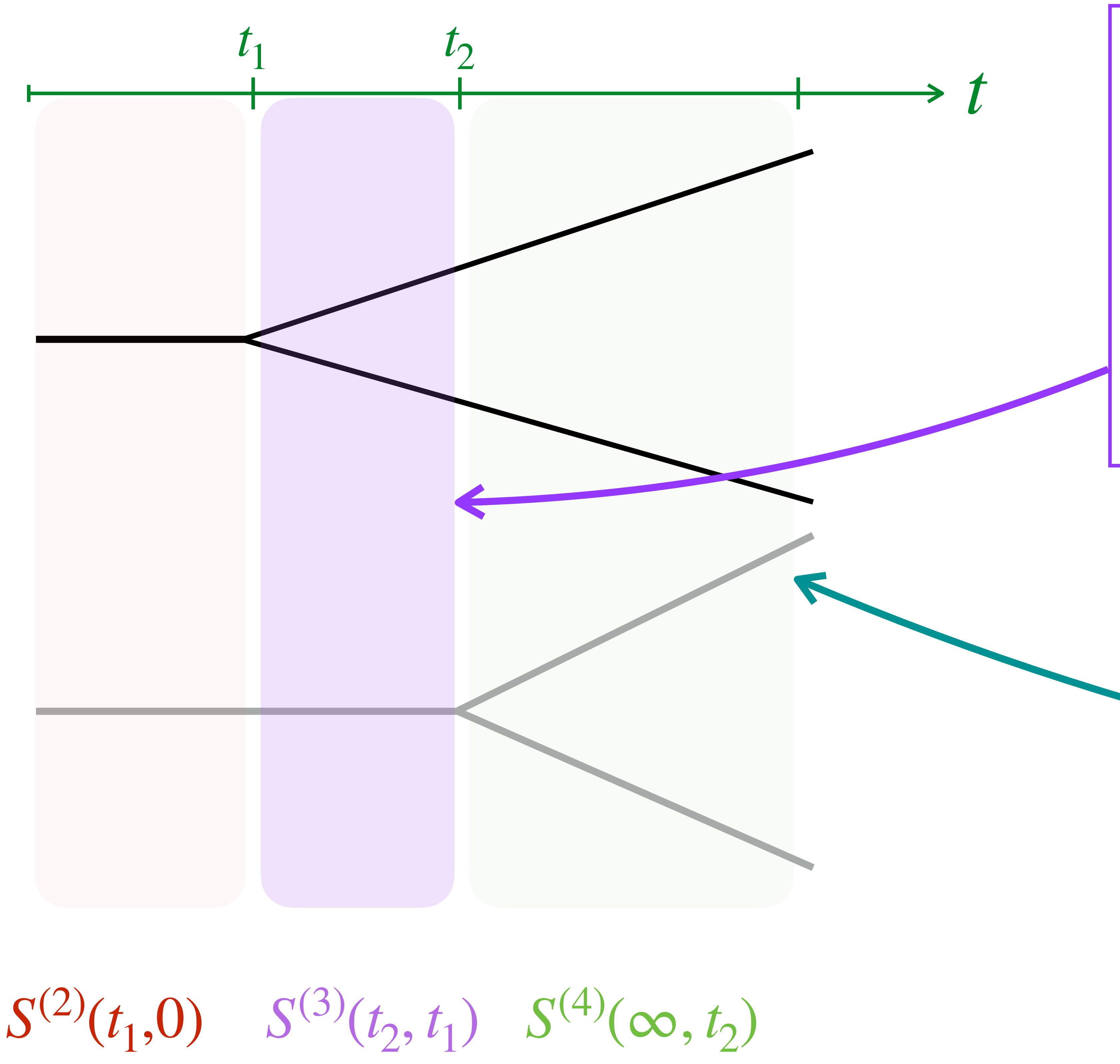
For example:
3-body correlator in gluon-gluon splitting

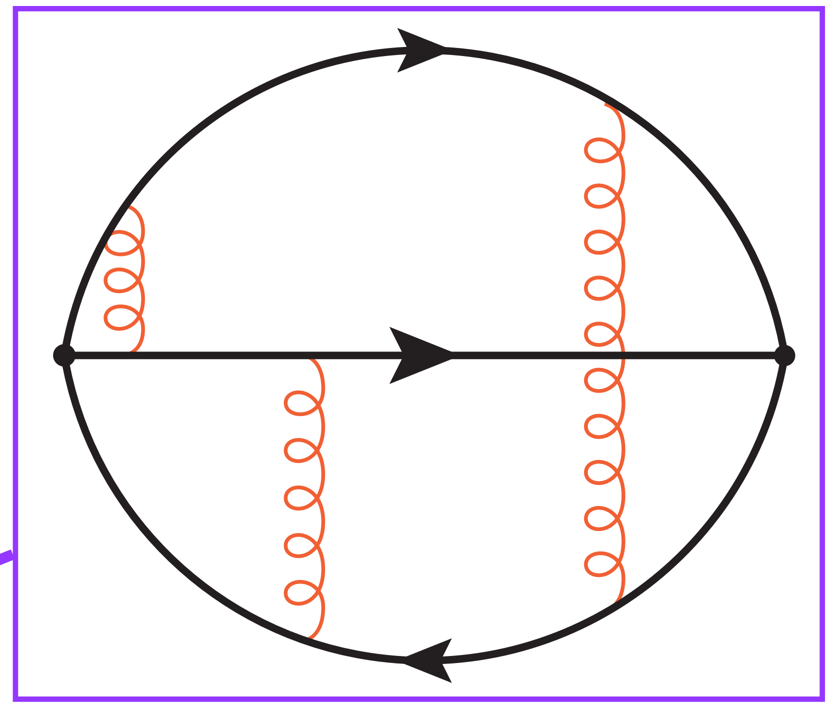


$$\left[i\frac{\partial}{\partial t} + \frac{\partial_{\boldsymbol{x}}^2}{2E} + iv(t,\boldsymbol{x})\right]\mathcal{K}(\boldsymbol{x},t;\boldsymbol{y},t_0) = i\delta^{(2)}(\boldsymbol{x}-\boldsymbol{y})\delta(t-t_0)$$

e.g. Casalderrey, Salgado 0712.3443

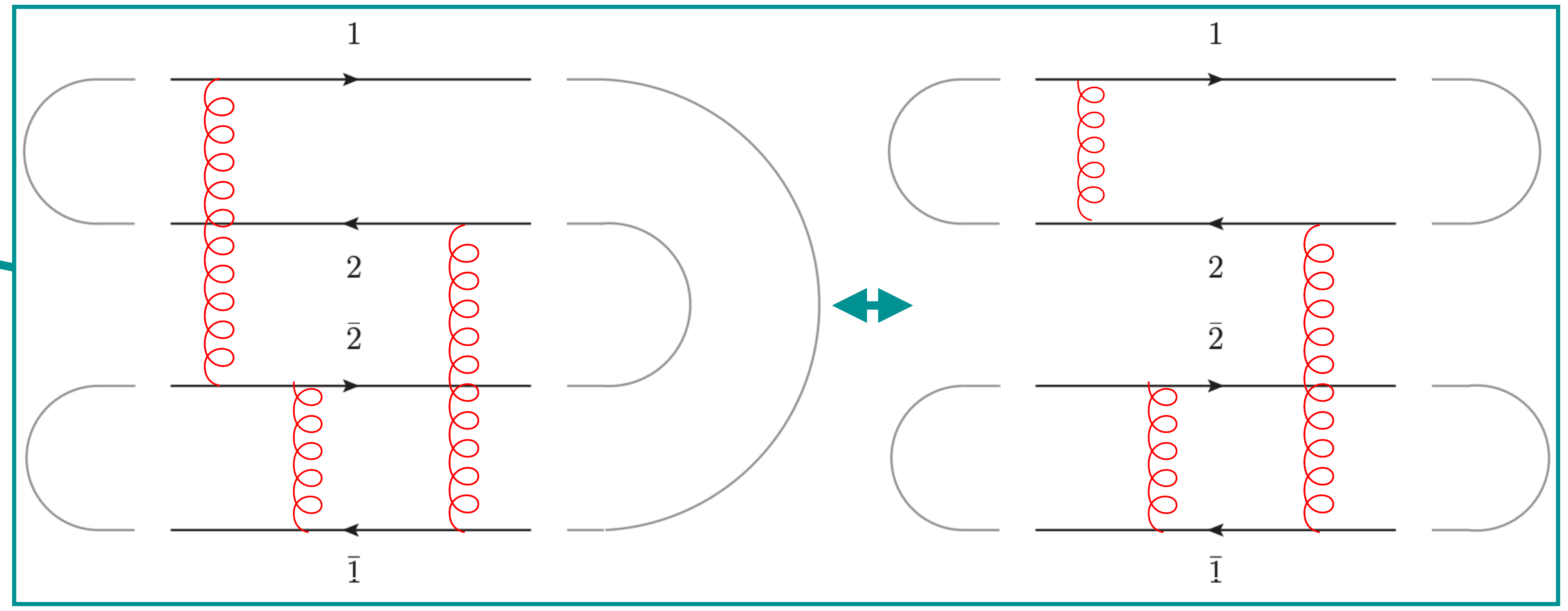
2+1D QUANTUM MECHANICS ON THE LIGHT-CONE





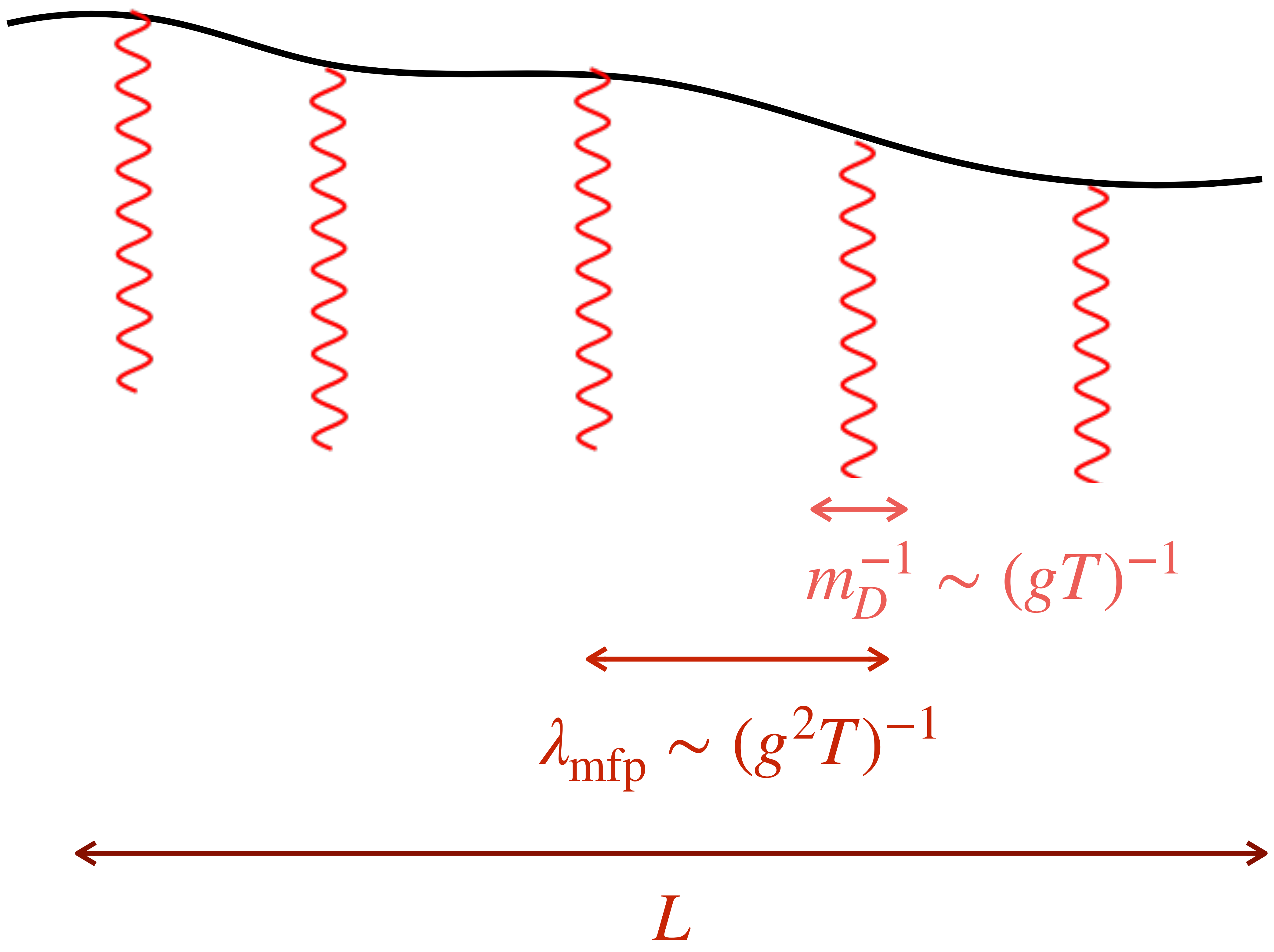
Baier, Dokshitzer, Mueller, Peigné, Schiff (1996); Zakharov (1996) (Arnold, Moore, Yaffe (2003))

Blaizot, Dominguez, Iancu, Mehtar-Tani (2013)
Apolinario, Armesto, Milhano, Salgado (2015)
Isaksen, KT 2107.02542



- decomposed into gauge-invariant objects (Wilson line correlators).
- **medium potential**: non-perturbative input about medium transport properties!

SCALES OF THE MEDIUM

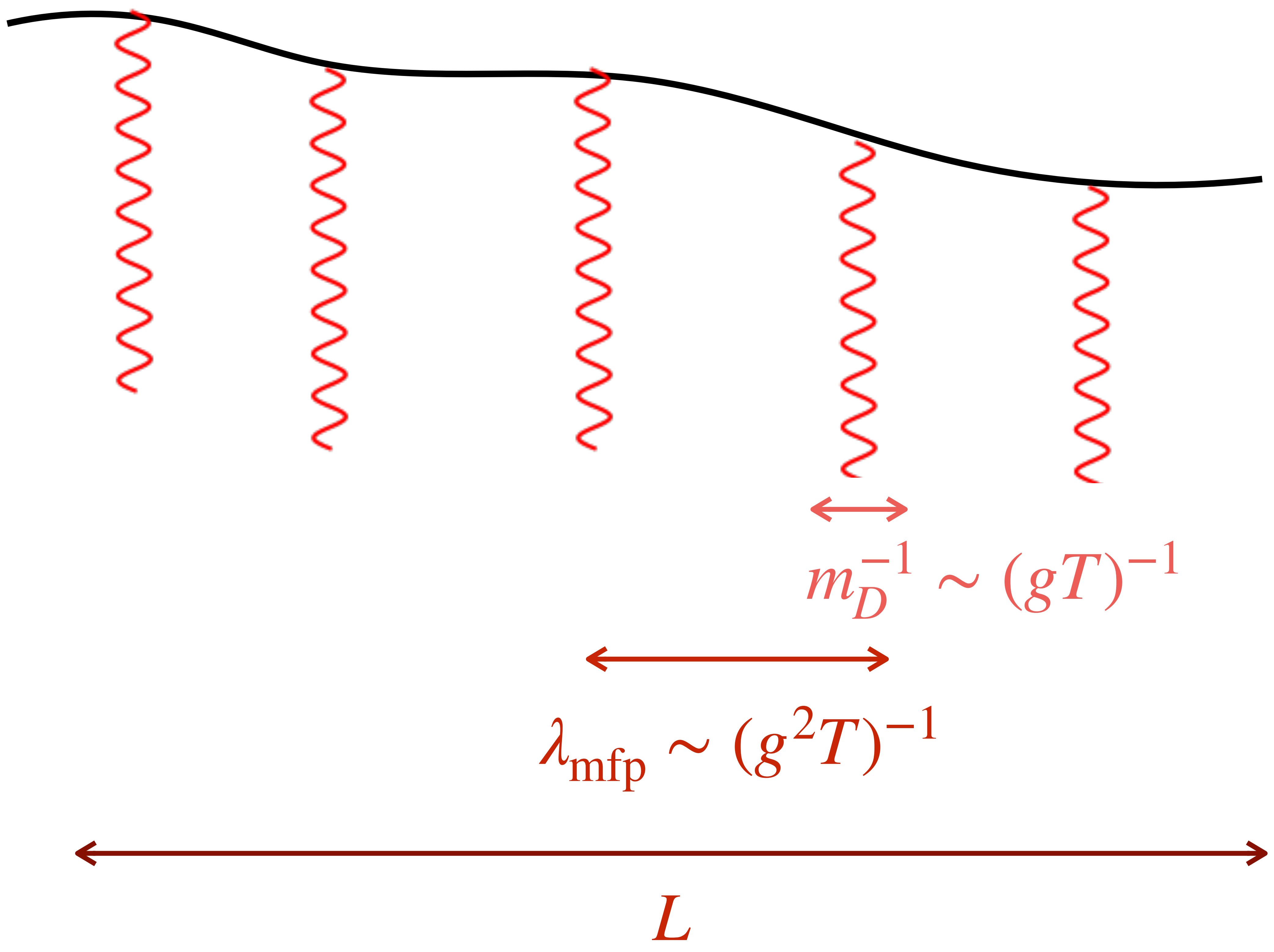


- typically weak-coupling $g \ll 1$
- thermal distribution of medium scattering centers $n \sim T^3$
- separation of scales!

$$\sigma_{\rm el} \sim \frac{g^4}{m_D^2}$$

$$\lambda_{\rm mfp} \sim \frac{1}{n\sigma_{\rm el}}$$

SCALES OF THE MEDIUM



- typically weak-coupling $g \ll 1$
- thermal distribution of medium scattering centers $n \sim T^3$
- separation of scales!

$$\sigma_{\rm el} \sim \frac{g^4}{m_D^2}$$

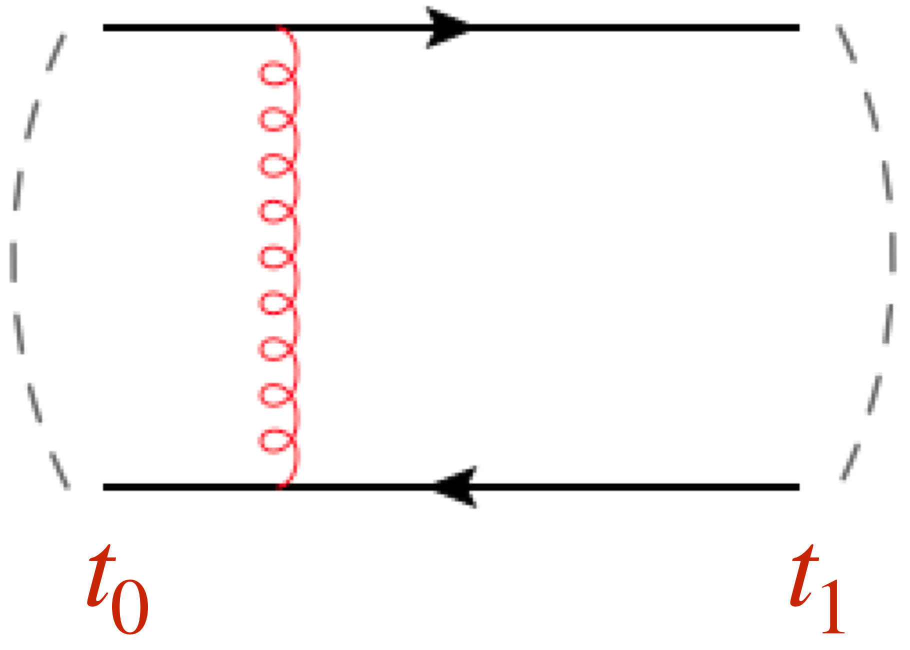
$$\lambda_{\rm mfp} \sim \frac{1}{n\sigma_{\rm el}}$$

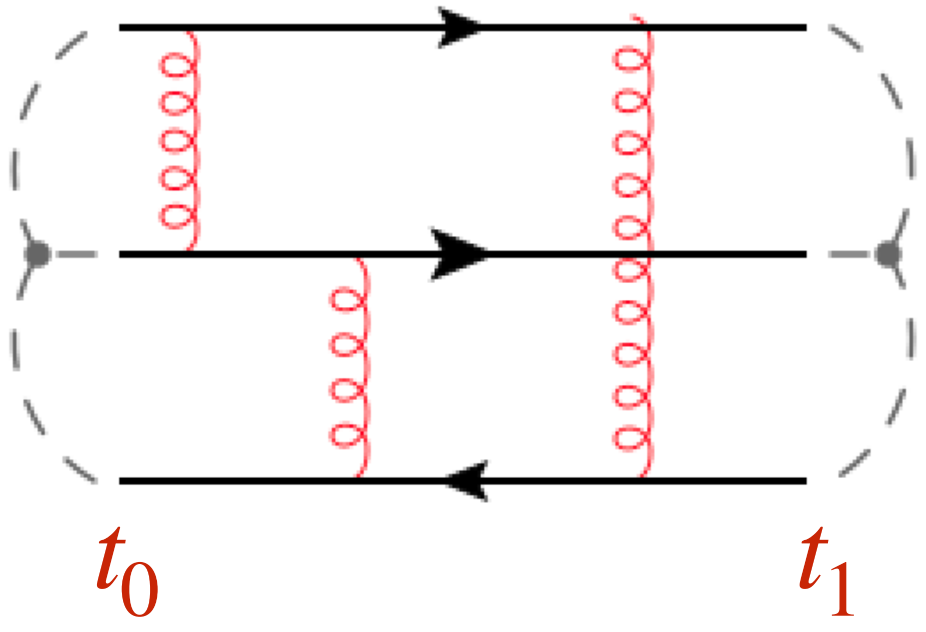
Markov approximation: $$\langle A^{-,a}(t,\boldsymbol{x})A^{-,b}(t',\boldsymbol{x}')\rangle = \delta^{ab}\delta(t-t')\delta(\boldsymbol{x}-\boldsymbol{x}')\gamma(t,\boldsymbol{x})$$

MEDIUM-AVERAGED CORRELATORS

Broadening

(2-body correlator)





Radiation

(3-body correlator)

Resumming interactions via potential:

(Including real and virtual exchanges.)

$$v(t,\boldsymbol{x}) = \gamma(t,0) - \gamma(t,\boldsymbol{x}) = \int_{\boldsymbol{q}} \frac{\mathrm{d}^2\sigma_{\rm el}}{\mathrm{d}\boldsymbol{q}^2}\left(1 - \mathrm{e}^{i\boldsymbol{q}\cdot\boldsymbol{x}}\right)$$

$$\simeq \frac{1}{4}\hat{q}_0 \boldsymbol{x}^2 \ln\frac{1}{\boldsymbol{x}^2\mu_*^2} + \mathcal{O}(\boldsymbol{x}^4\mu_*^2)$$

First term is universal, e.g. for HTL potential $\hat{q}_0 = \alpha_s C_A m_D^2 T$ and $\mu_*^2 = m_D^2 e^{-2+2\gamma_E}/4$.

$$S(t_2,t_1) = S_{\rm HO}(t_2,t_1) \qquad \text{with } v(t) = \frac{1}{4}\hat{q}x^2$$

harmonic oscillator approximation

BDMPS-Z; Wiedemann, Salgado (2001), Armesto Wiedemann, Salgado (2003)

$$S(t_2,t_1) = S_0(t_2-t_1) + \int_{t_1}^{t_2}\mathrm{d}t\, S_0(t_2-t)v(t)S_0(t-t_1) + \ldots$$

opacity expansion

Wiedemann (2000); Gyulassy, Levai, Vitev (2001)

Sievert, Vitev, Yoon 1903.06170; Wang, Gu (2001), Majumder 0912.2987

Medium-averaged correlators

Resumming interactions via potential:

(Including real and virtual exchanges.)

$$v(t,\boldsymbol{x}) = \gamma(t,0) - \gamma(t,\boldsymbol{x}) = \int_{\boldsymbol{q}} \frac{\mathrm{d}^2\sigma_{\rm el}}{\mathrm{d}\boldsymbol{q}^2}\left(1 - \mathrm{e}^{i\boldsymbol{q}\cdot\boldsymbol{x}}\right)$$

$$\simeq \frac{1}{4}\hat{q}_0 \boldsymbol{x}^2 \ln \frac{1}{\boldsymbol{x}^2\mu_*^2} + \mathcal{O}(\boldsymbol{x}^4\mu_*^2)$$

First term is universal:

$$\mu_*^2 = \begin{cases} \frac{1}{4}m_D^2 \mathrm{e}^{-2+2\gamma_E} & \text{for HTL potential} \\ \frac{1}{4}m_D^2 \mathrm{e}^{-1+2\gamma_E} & \text{for GW potential} \end{cases}$$

MEDIUM-AVERAGED CORRELATORS

Resumming interactions via potential:

(Including real and virtual exchanges.)

$$v(t,\boldsymbol{x}) = \gamma(t,0) - \gamma(t,\boldsymbol{x}) = \int_{\boldsymbol{q}} \frac{\mathrm{d}^2\sigma_{\mathrm{el}}}{\mathrm{d}\boldsymbol{q}^2}\left(1-\mathrm{e}^{i\boldsymbol{q}\cdot\boldsymbol{x}}\right)$$
$$\simeq \frac{1}{4}\hat{q}_0\boldsymbol{x}^2 \ln\frac{1}{\boldsymbol{x}^2\mu_*^2} + \mathcal{O}(\boldsymbol{x}^4\mu_*^2)$$

First term is universal:

$$\mu_*^2 = \begin{cases} \frac{1}{4}m_D^2\mathrm{e}^{-2+2\gamma_E} & \text{for HTL potential} \\ \frac{1}{4}m_D^2\mathrm{e}^{-1+2\gamma_E} & \text{for GW potential} \end{cases}$$

Numerical solutions to Schrödinger equation with full $v(t,x)$ can be found!

MEDIUM-AVERAGED CORRELATORS

Resumming interactions via potential:

(Including real and virtual exchanges.)

$$v(t,\boldsymbol{x}) = \gamma(t,0) - \gamma(t,\boldsymbol{x}) = \int_{\boldsymbol{q}} \frac{\mathrm{d}^2\sigma_{\mathrm{el}}}{\mathrm{d}\boldsymbol{q}^2}\left(1 - \mathrm{e}^{i\boldsymbol{q}\cdot\boldsymbol{x}}\right)$$

$$\simeq \frac{1}{4}\hat{q}_0 \boldsymbol{x}^2 \ln\frac{1}{\boldsymbol{x}^2\mu_*^2} + \mathcal{O}(\boldsymbol{x}^4\mu_*^2)$$

First term is universal:

$$\mu_*^2 = \begin{cases} \frac{1}{4}m_D^2\mathrm{e}^{-2+2\gamma_E} & \text{for HTL potential} \\ \frac{1}{4}m_D^2\mathrm{e}^{-1+2\gamma_E} & \text{for GW potential} \end{cases}$$

Numerical solutions to Schrödinger equation with full $v(t,x)$ can be found!

Two main approximations/schemes:

$$S(t_2,t_1) = S_{\mathrm{HO}}(t_2,t_1) \qquad \text{with } v(t) = \frac{1}{4}\hat{q}x^2$$

harmonic oscillator approximation

BDMPS-Z; Wiedemann, Salgado (2001), Armesto Wiedemann, Salgado (2003)

$$S(t_2,t_1) = S_0(t_2-t_1) + \int_{t_1}^{t_2}\mathrm{d}t\, S_0(t_2-t)v(t)S_0(t-t_1) + \ldots$$

opacity expansion

Wiedemann (2000); Gyulassy, Levai, Vitev (2001)

Sievert, Vitev, Yoon 1903.06170; Wang, Gu (2001), Majumder 0912.2987

Broadening

G. Molière, Zeitschrift Naturforschung Teil A 3, 78 (1948)
Barata, Mehtar-Tani, Soto-Ontoso, KT 2009.13667

Transverse momentum broadening of a single particle $\langle \boldsymbol{k}^2 \rangle \sim \hat{q}t$

$$\frac{\partial}{\partial L}\mathcal{P}(\boldsymbol{k},L) = C_R \int_{\boldsymbol{q}} \gamma(\boldsymbol{q}) \, [\mathcal{P}(\boldsymbol{k}-\boldsymbol{q},L) - \mathcal{P}(\boldsymbol{k},L)]$$

BROADENING

G. Molière, Zeitschrift Naturforschung Teil A 3, 78 (1948)
Barata, Mehtar-Tani, Soto-Ontoso, KT 2009.13667

Transverse momentum broadening of a single particle $\langle \boldsymbol{k}^2 \rangle \sim \hat{q}t$

$$\frac{\partial}{\partial L}\mathcal{P}(\boldsymbol{k},L) = C_R \int_{\boldsymbol{q}} \gamma(\boldsymbol{q}) \, [\mathcal{P}(\boldsymbol{k}-\boldsymbol{q},L) - \mathcal{P}(\boldsymbol{k},L)]$$

Molière distribution (1948)

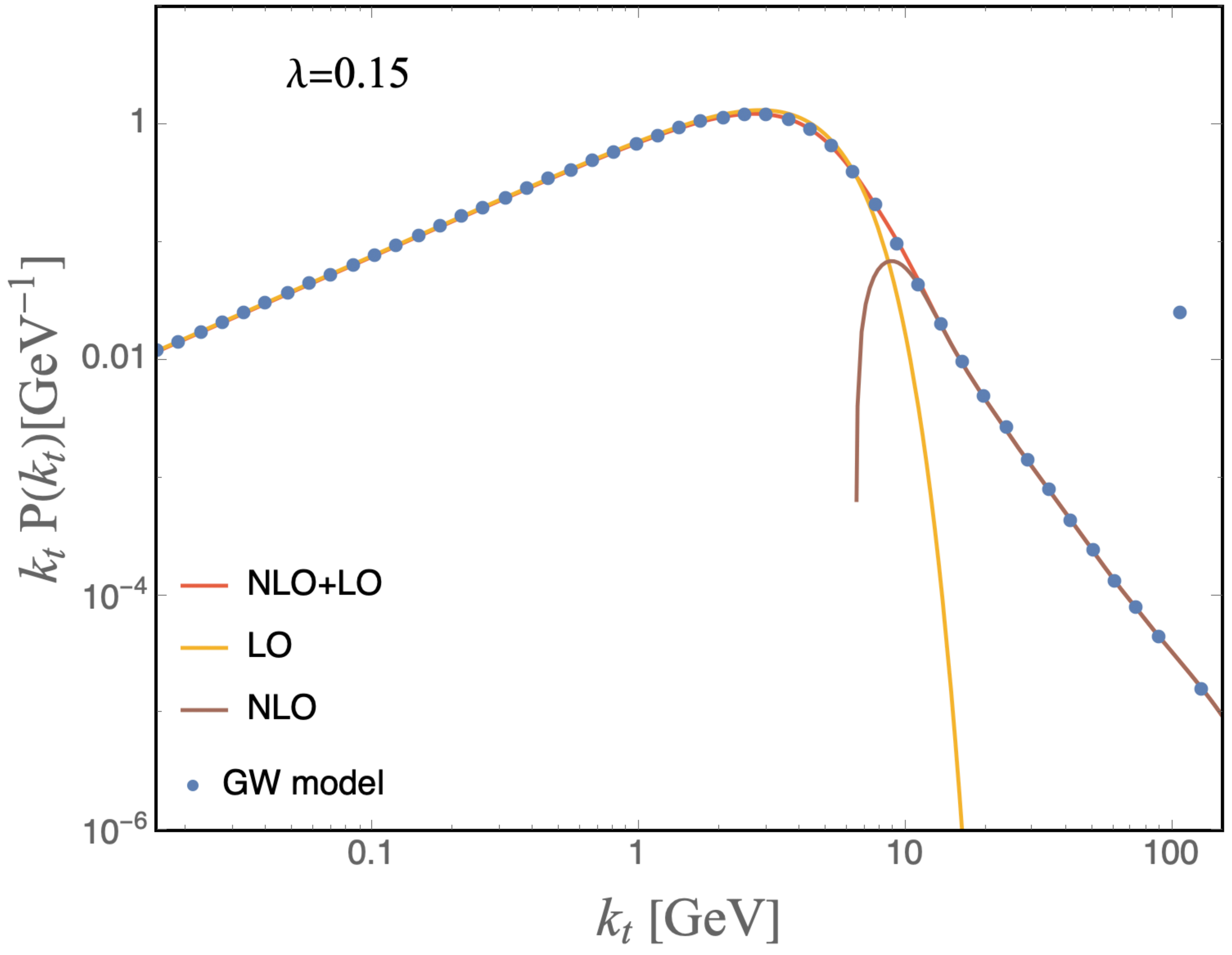
$x = \boldsymbol{k}^2/Q_s^2$, where $Q_s^2 = \hat{q}_0 L \log \frac{Q_s^2}{\mu_\star^2}$

$$\mathcal{P}^{\rm LO+NLO}(\boldsymbol{k},L) = \frac{4\pi}{Q_s^2} {\rm e}^{-x} \Big\{ 1 - \lambda \left({\rm e}^{x} - 2 + (1-x) \, \left({\rm Ei}\,(x) - \log(4x\,a) \right) \right) \Big\}$$

Expansion parameter

$$\lambda \equiv \frac{\hat{q}_0}{\hat{q}} = \frac{1}{\log(Q_s^2/\mu_\star^2)} \ll 1$$

Describes the distribution from diffusion dominated regime to higher-twist (HT) dominated regime.

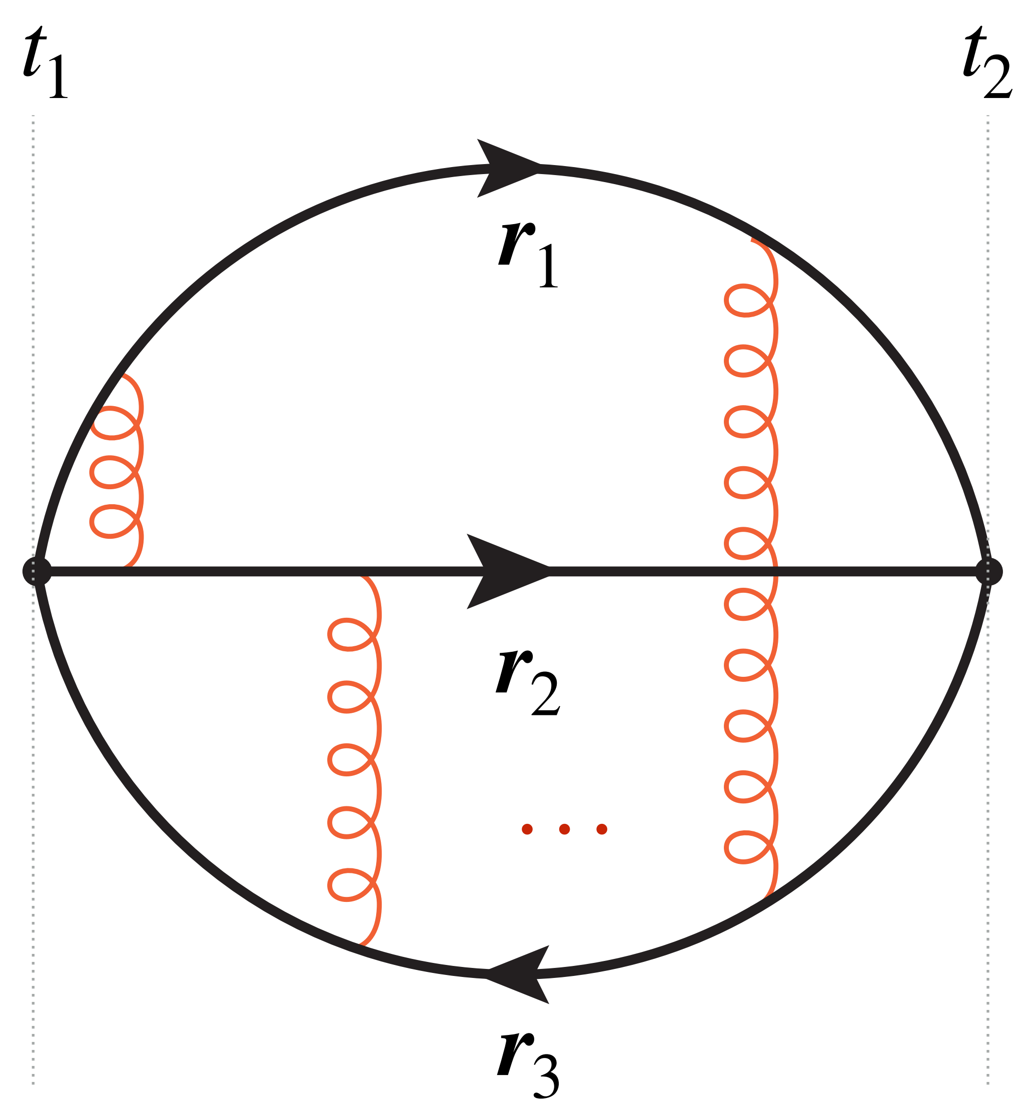


MEDIUM-INDUCED RADIATION

Baier, Dokshitzer, Mueller, Peigné, Schiff (1996); Zakharov (1996) (Arnold, Moore, Yaffe (2003))

$$z\frac{\mathrm{d}I_{ba}}{\mathrm{d}z} = \frac{\alpha_s\, zP_{ba}(z)}{(z(1-z)E)^2}\, 2\mathrm{Re}\int_0^\infty \mathrm{d}t_2 \int_0^{t_2} \mathrm{d}t_1$$

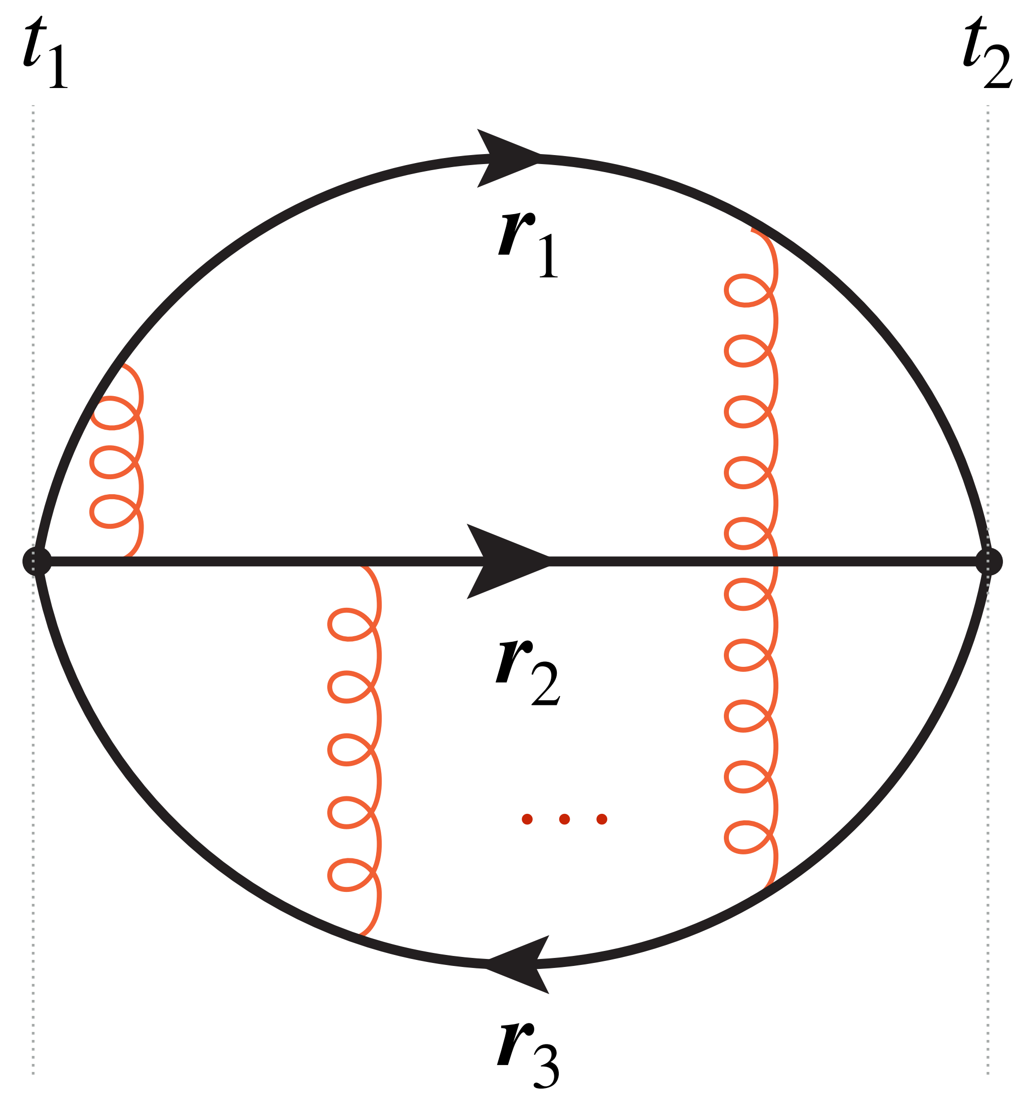
$$\boldsymbol{\partial}_{\boldsymbol{x}} \cdot \boldsymbol{\partial}_{\boldsymbol{y}} \Big[\mathcal{K}_{ba}(\boldsymbol{x}, t_2; \boldsymbol{y}, t_1) - \mathcal{K}_0(\boldsymbol{x}, t_2; \boldsymbol{y}, t_1)\Big]_{\boldsymbol{x}=\boldsymbol{y}=0}$$



Medium-induced radiation

Baier, Dokshitzer, Mueller, Peigné, Schiff (1996); Zakharov (1996) (Arnold, Moore, Yaffe (2003))

$$z\frac{\mathrm{d}I_{ba}}{\mathrm{d}z} = \frac{\alpha_s\, zP_{ba}(z)}{(z(1-z)E)^2}\, 2\mathrm{Re}\int_0^\infty \mathrm{d}t_2 \int_0^{t_2} \mathrm{d}t_1$$
$$\boldsymbol{\partial}_{\boldsymbol{x}}\cdot\boldsymbol{\partial}_{\boldsymbol{y}}\Big[\mathcal{K}_{ba}(\boldsymbol{x},t_2;\boldsymbol{y},t_1) - \mathcal{K}_0(\boldsymbol{x},t_2;\boldsymbol{y},t_1)\Big]_{\boldsymbol{x}=\boldsymbol{y}=0}$$



3-body interactions of the medium via Schrödinger equation with potential:

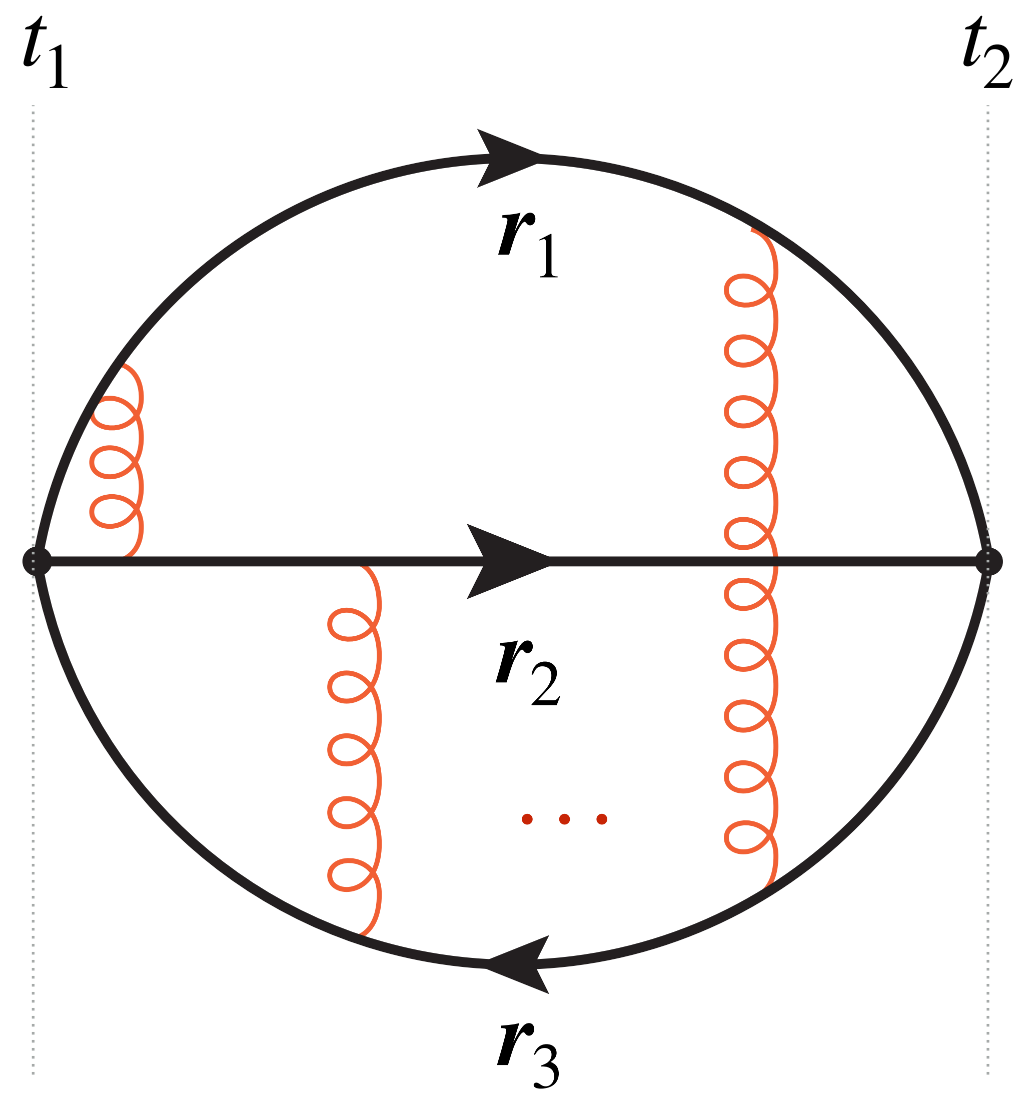
$$v(\boldsymbol{x},t) = \int_{\boldsymbol{q}} \frac{\mathrm{d}\sigma_{\mathrm{el}}}{\mathrm{d}^2\boldsymbol{q}}\left(1-\mathrm{e}^{i\boldsymbol{q}\cdot\boldsymbol{x}}\right) \approx \underbrace{\frac{1}{4}\hat{q}\boldsymbol{x}^2}_{\mathrm{HO}} \log\frac{4}{\mu^2\boldsymbol{x}^2}$$

Solved numerically in Caron-Huot, Gale 1006.2379, Feal, Vazquez 1811.01591, Ke, Xu and Bass 1810.08177, Feal, Salgado, Vazquez 1911.01309

MEDIUM-INDUCED RADIATION

Baier, Dokshitzer, Mueller, Peigné, Schiff (1996); Zakharov (1996) (Arnold, Moore, Yaffe (2003))

$$z\frac{\mathrm{d}I_{ba}}{\mathrm{d}z} = \frac{\alpha_s\, zP_{ba}(z)}{(z(1-z)E)^2}\, 2\mathrm{Re}\int_0^\infty \mathrm{d}t_2 \int_0^{t_2} \mathrm{d}t_1$$
$$\boldsymbol{\partial_x}\cdot\boldsymbol{\partial_y}\Big[\mathcal{K}_{ba}(\boldsymbol{x},t_2;\boldsymbol{y},t_1)-\mathcal{K}_0(\boldsymbol{x},t_2;\boldsymbol{y},t_1)\Big]_{\boldsymbol{x}=\boldsymbol{y}=0}$$



3-body interactions of the medium via Schrödinger equation with potential:

$$v(\boldsymbol{x},t) = \int_{\boldsymbol{q}} \frac{\mathrm{d}\sigma_{\rm el}}{\mathrm{d}^2\boldsymbol{q}}\left(1-\mathrm{e}^{i\boldsymbol{q}\cdot\boldsymbol{x}}\right) \approx \underbrace{\frac{1}{4}\hat{q}\boldsymbol{x}^2}_{\rm HO}\log\frac{4}{\mu^2\boldsymbol{x}^2}$$

Solved numerically in Caron-Huot, Gale 1006.2379, Feal, Vazquez 1811.01591, Ke, Xu and Bass 1810.08177, Feal, Salgado, Vazquez 1911.01309

$$\mathcal{K}(t_2,t_1) = \mathcal{K}_0(t_2-t_1) + \int \mathrm{d}t\, \mathcal{K}_0(t_2-t)\, v(t)\, \mathcal{K}(t,t_1)$$

opacity expansion

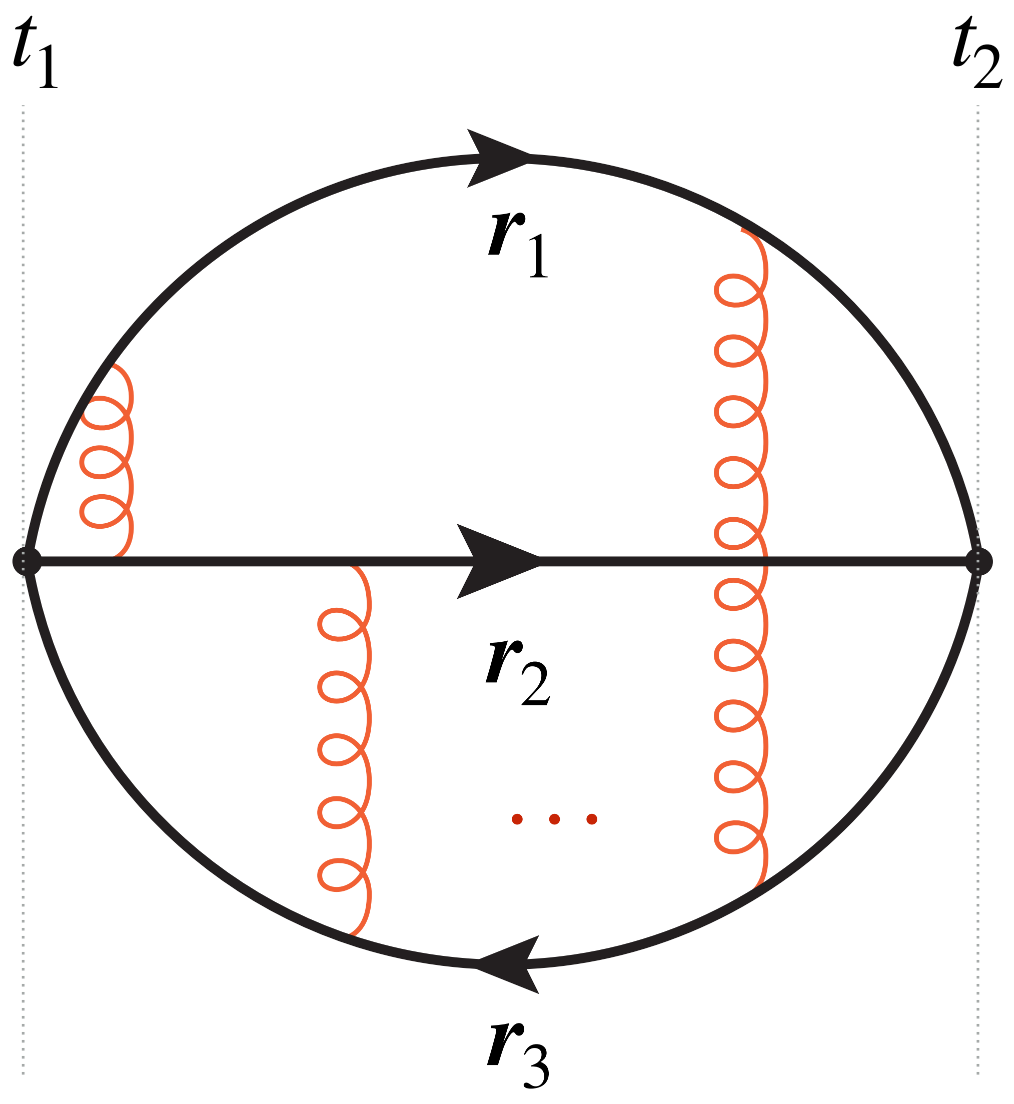
Wiedemann (2000); Gyulassy, Levai, Vitev (2001); Sievert, Vitev, Yoon 1903.06170
Wang, Gu (2001), Majumder 0912.2987
Mehtar-Tani 1903.00506, Mehtar-Tani KT 1910.02032

MEDIUM-INDUCED RADIATION

Baier, Dokshitzer, Mueller, Peigné, Schiff (1996); Zakharov (1996) (Arnold, Moore, Yaffe (2003))

$$z\frac{\mathrm{d}I_{ba}}{\mathrm{d}z} = \frac{\alpha_s\, zP_{ba}(z)}{(z(1-z)E)^2}\, 2\mathrm{Re}\int_0^\infty \mathrm{d}t_2 \int_0^{t_2} \mathrm{d}t_1$$

$$\boldsymbol{\partial_x}\cdot\boldsymbol{\partial_y}\Big[\mathcal{K}_{ba}(\boldsymbol{x},t_2;\boldsymbol{y},t_1) - \mathcal{K}_0(\boldsymbol{x},t_2;\boldsymbol{y},t_1)\Big]_{\boldsymbol{x}=\boldsymbol{y}=0}$$



3-body interactions of the medium via Schrödinger equation with potential:

$$v(\boldsymbol{x},t) = \int_{\boldsymbol{q}} \frac{\mathrm{d}\sigma_{\mathrm{el}}}{\mathrm{d}^2\boldsymbol{q}}\left(1-\mathrm{e}^{i\boldsymbol{q}\cdot\boldsymbol{x}}\right) \approx \underbrace{\frac{1}{4}\hat{q}\boldsymbol{x}^2}_{\mathrm{HO}} \log\frac{4}{\mu^2\boldsymbol{x}^2}$$

Solved numerically in Caron-Huot, Gale 1006.2379, Feal, Vazquez 1811.01591, Ke, Xu and Bass 1810.08177, Feal, Salgado, Vazquez 1911.01309

$$\mathcal{K}(t_2,t_1) = \mathcal{K}_0(t_2-t_1) + \int \mathrm{d}t\, \mathcal{K}_0(t_2-t)\, v(t)\, \mathcal{K}(t,t_1)$$

opacity expansion

Wiedemann (2000); Gyulassy, Levai, Vitev (2001); Sievert, Vitev, Yoon 1903.06170
Wang, Gu (2001), Majumder 0912.2987
Mehtar-Tani 1903.00506, Mehtar-Tani KT 1910.02032

Iqbal (Wed 15:40)
Djordjevic (Wed 10:20)
Hauksson (Tue 15:20)

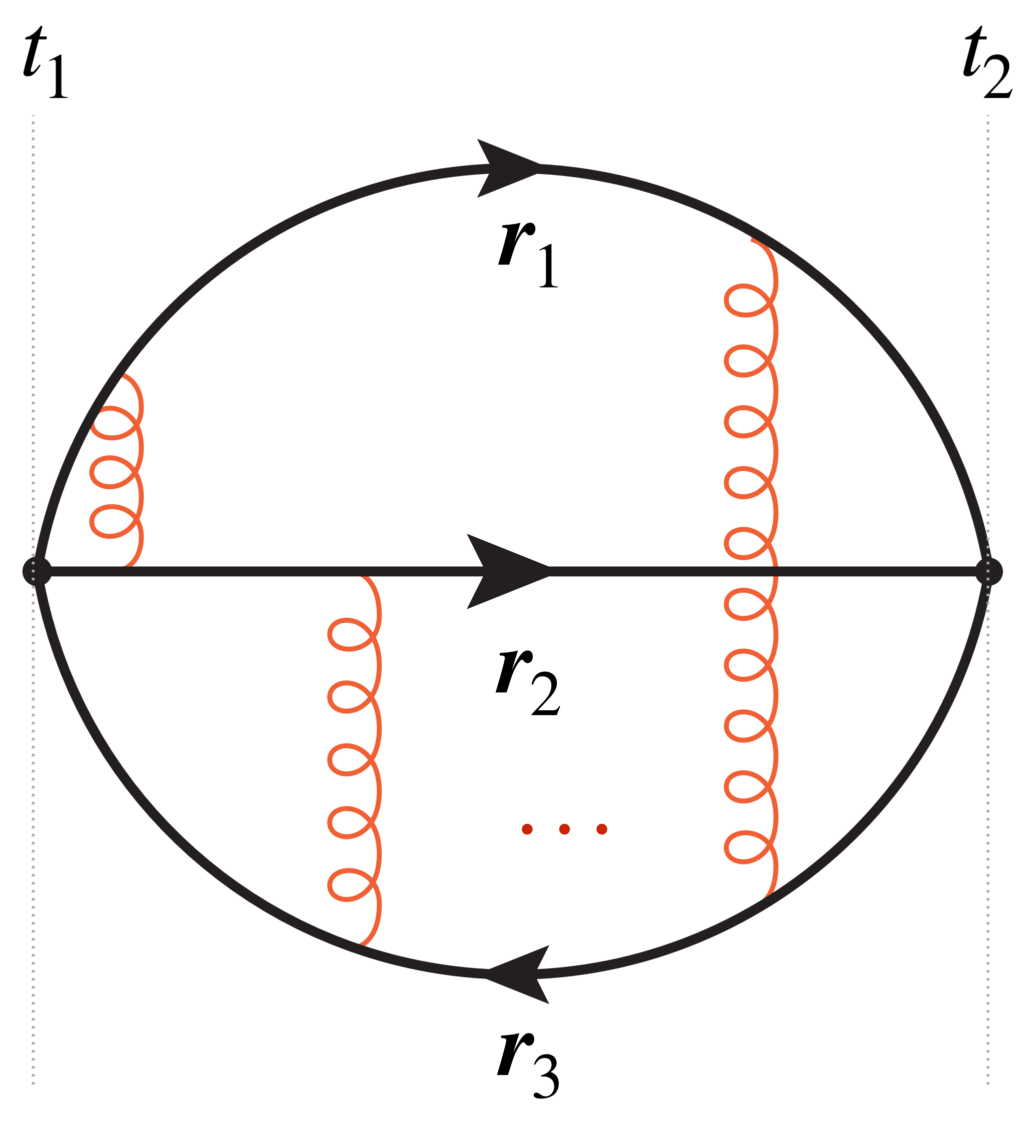
Unified understanding of in-medium radiative proce

Medium-induced radiation

Baier, Dokshitzer, Mueller, Peigné, Schiff (1996); Zakharov (1996); …

$$z\frac{\mathrm{d}I_{ba}}{\mathrm{d}z} = \frac{\alpha_s\, zP_{ba}(z)}{(z(1-z)E)^2}\, 2\mathrm{Re}\int_0^\infty \mathrm{d}t_2 \int_0^{t_2} \mathrm{d}t_1$$

$$\boldsymbol{\partial_x}\cdot\boldsymbol{\partial_y}\Big[\mathcal{K}_{ba}(\boldsymbol{x},t_2;\boldsymbol{y},t_1) - \mathcal{K}_0(\boldsymbol{x},t_2;\boldsymbol{y},t_1)\Big]_{\boldsymbol{x}=\boldsymbol{y}=0}$$

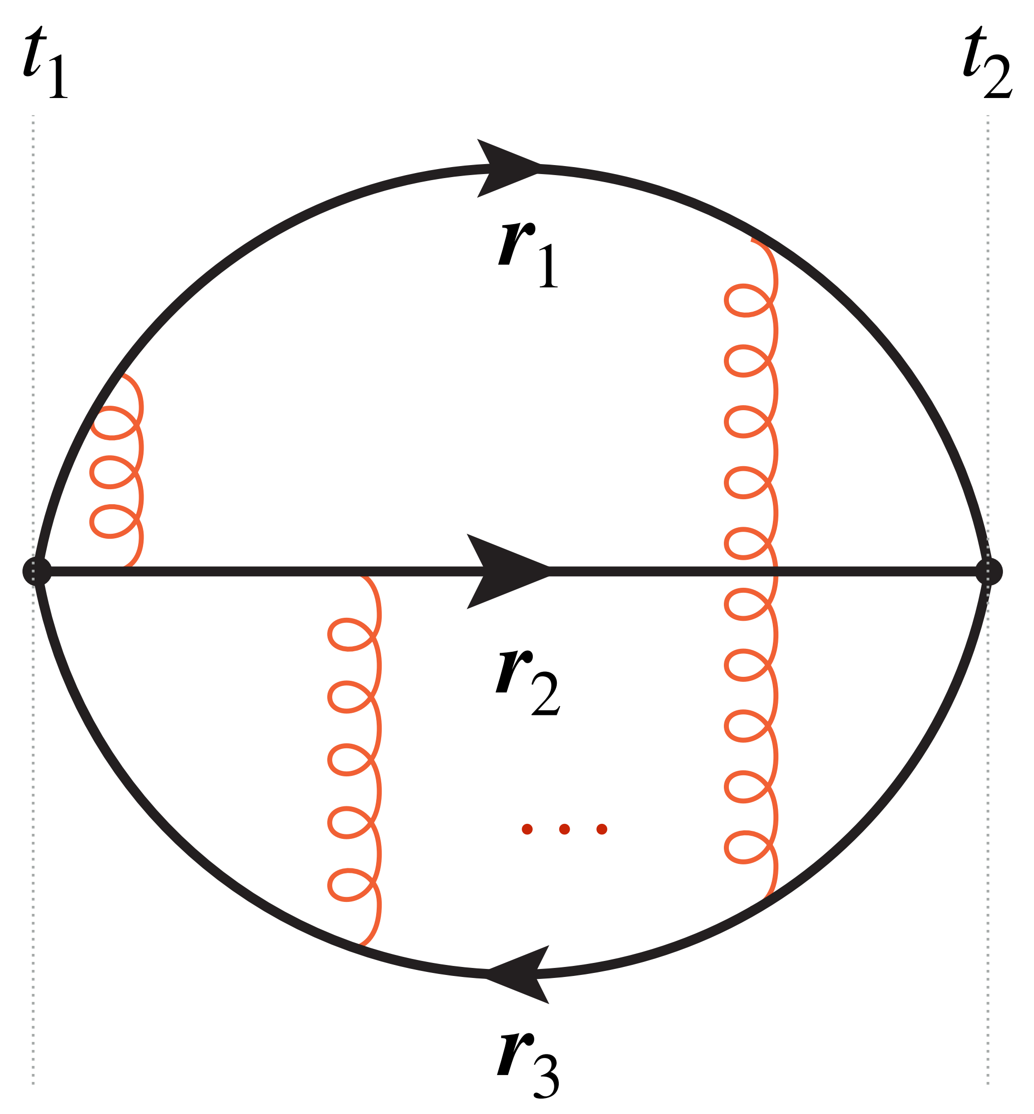


MEDIUM-INDUCED RADIATION

Baier, Dokshitzer, Mueller, Peigné, Schiff (1996); Zakharov (1996); …

$$z\frac{\mathrm{d}I_{ba}}{\mathrm{d}z} = \frac{\alpha_s\, zP_{ba}(z)}{(z(1-z)E)^2}\, 2\mathrm{Re}\int_0^\infty \mathrm{d}t_2 \int_0^{t_2} \mathrm{d}t_1$$

$$\boldsymbol{\partial}_{\boldsymbol{x}} \cdot \boldsymbol{\partial}_{\boldsymbol{y}} \Big[\mathcal{K}_{ba}(\boldsymbol{x},t_2;\boldsymbol{y},t_1) - \mathcal{K}_0(\boldsymbol{x},t_2;\boldsymbol{y},t_1)\Big]_{\boldsymbol{x}=\boldsymbol{y}=0}$$



3-body interactions of the medium via Schrödinger equation with potential:

$$v(\boldsymbol{x},t) = \int_{\boldsymbol{q}} \frac{\mathrm{d}\sigma_{\mathrm{el}}}{\mathrm{d}^2\boldsymbol{q}}\left(1 - \mathrm{e}^{i\boldsymbol{q}\cdot\boldsymbol{x}}\right) \approx \underbrace{\frac{1}{4}\hat{q}\boldsymbol{x}^2}_{\mathrm{HO}} \log\frac{4}{\mu^2\boldsymbol{x}^2}$$

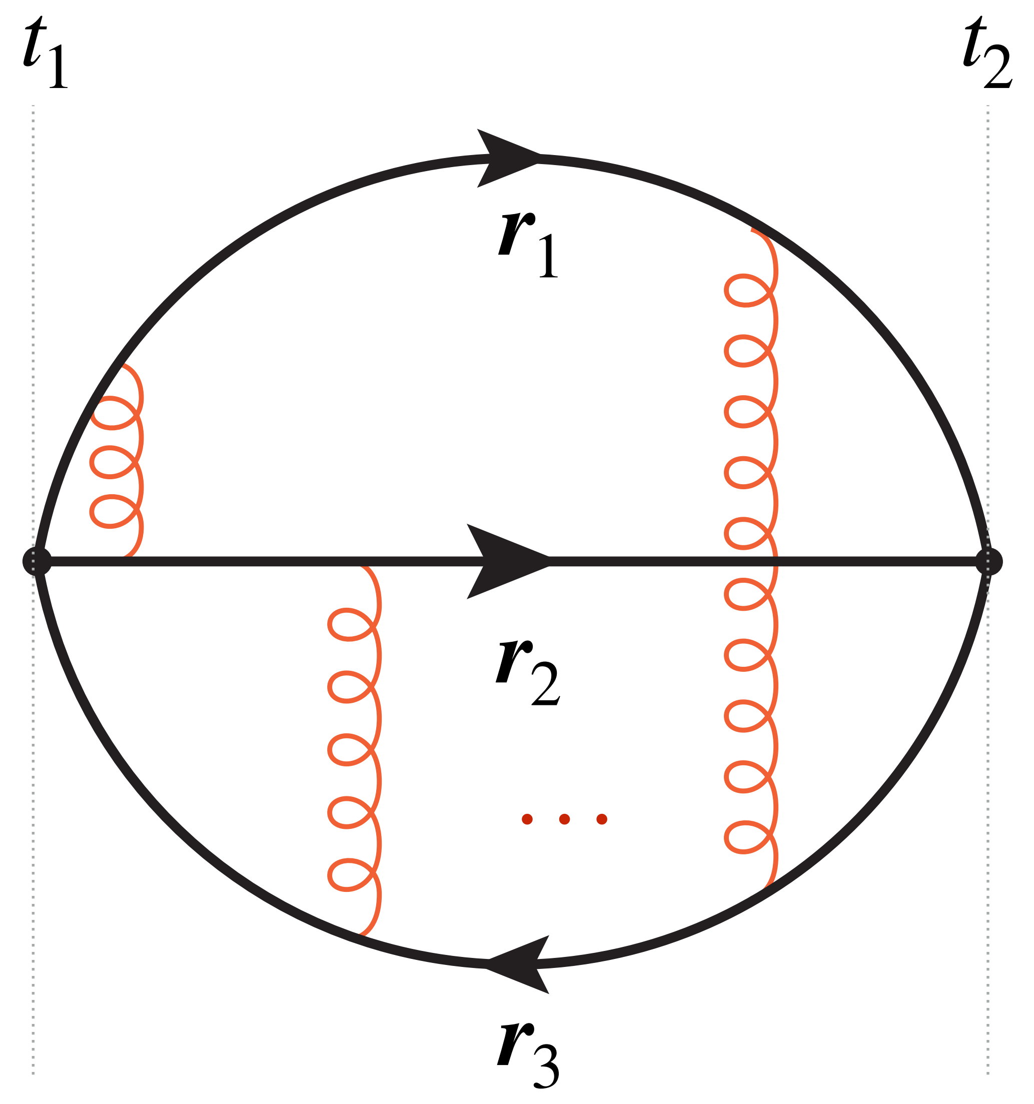
Solved numerically in Caron-Huot, Gale 1006.2379, Feal, Vazquez 1811.01591

Medium-induced radiation

Baier, Dokshitzer, Mueller, Peigné, Schiff (1996); Zakharov (1996); …

$$z\frac{\mathrm{d}I_{ba}}{\mathrm{d}z} = \frac{\alpha_s\, zP_{ba}(z)}{(z(1-z)E)^2}\, 2\mathrm{Re}\int_0^\infty \mathrm{d}t_2 \int_0^{t_2} \mathrm{d}t_1$$

$$\boldsymbol{\partial}_{\boldsymbol{x}}\cdot\boldsymbol{\partial}_{\boldsymbol{y}}\Big[\mathcal{K}_{ba}(\boldsymbol{x},t_2;\boldsymbol{y},t_1) - \mathcal{K}_0(\boldsymbol{x},t_2;\boldsymbol{y},t_1)\Big]_{\boldsymbol{x}=\boldsymbol{y}=0}$$



3-body interactions of the medium via Schrödinger equation with potential:

$$v(\boldsymbol{x},t) = \int_{\boldsymbol{q}} \frac{\mathrm{d}\sigma_{\mathrm{el}}}{\mathrm{d}^2\boldsymbol{q}}\left(1-\mathrm{e}^{i\boldsymbol{q}\cdot\boldsymbol{x}}\right) \approx \underbrace{\frac{1}{4}\hat{q}\boldsymbol{x}^2}_{\mathrm{HO}}\log\frac{4}{\mu^2\boldsymbol{x}^2}$$

Solved numerically in Caron-Huot, Gale 1006.2379, Feal, Vazquez 1811.01591

$$\mathcal{K}(t_2,t_1) = \mathcal{K}_0(t_2-t_1) + \int \mathrm{d}t\,\mathcal{K}_0(t_2-t)\,v(t)\,\mathcal{K}(t,t_1)$$

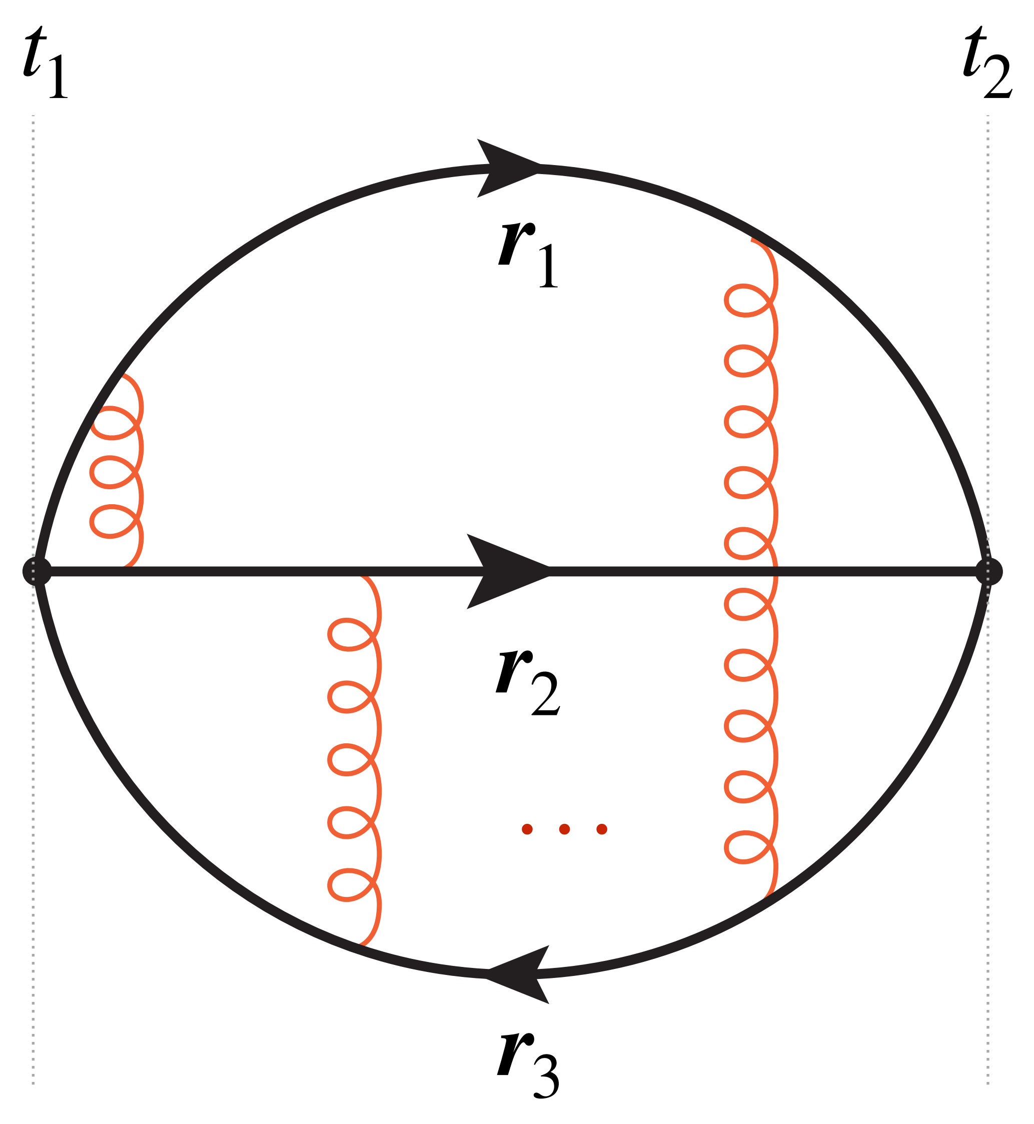
opacity expansion

Wiedemann (2000); Gyulassy, Levai, Vitev (2001); Sievert, Vitev, Yoon 1903.06170

MEDIUM-INDUCED RADIATION

Baier, Dokshitzer, Mueller, Peigné, Schiff (1996); Zakharov (1996); …

$$z\frac{\mathrm{d}I_{ba}}{\mathrm{d}z} = \frac{\alpha_s\, zP_{ba}(z)}{(z(1-z)E)^2}\, 2\mathrm{Re}\int_0^\infty \mathrm{d}t_2 \int_0^{t_2} \mathrm{d}t_1$$
$$\boldsymbol{\partial_x}\cdot\boldsymbol{\partial_y}\Big[\mathcal{K}_{ba}(\boldsymbol{x},t_2;\boldsymbol{y},t_1) - \mathcal{K}_0(\boldsymbol{x},t_2;\boldsymbol{y},t_1)\Big]_{\boldsymbol{x}=\boldsymbol{y}=0}$$



3-body interactions of the medium via Schrödinger equation with potential:

$$v(\boldsymbol{x},t) = \int_{\boldsymbol{q}} \frac{\mathrm{d}\sigma_{\mathrm{el}}}{\mathrm{d}^2\boldsymbol{q}}\left(1 - \mathrm{e}^{i\boldsymbol{q}\cdot\boldsymbol{x}}\right) \approx \underbrace{\frac{1}{4}\hat{q}\boldsymbol{x}^2}_{\mathrm{HO}}\log\frac{4}{\mu^2\boldsymbol{x}^2}$$

Solved numerically in Caron-Huot, Gale 1006.2379, Feal, Vazquez 1811.01591

$$\mathcal{K}(t_2,t_1) = \mathcal{K}_0(t_2-t_1) + \int \mathrm{d}t\, \mathcal{K}_0(t_2-t)\, v(t)\, \mathcal{K}(t,t_1)$$

opacity expansion

Wiedemann (2000); Gyulassy, Levai, Vitev (2001); Sievert, Vitev, Yoon 1903.06170

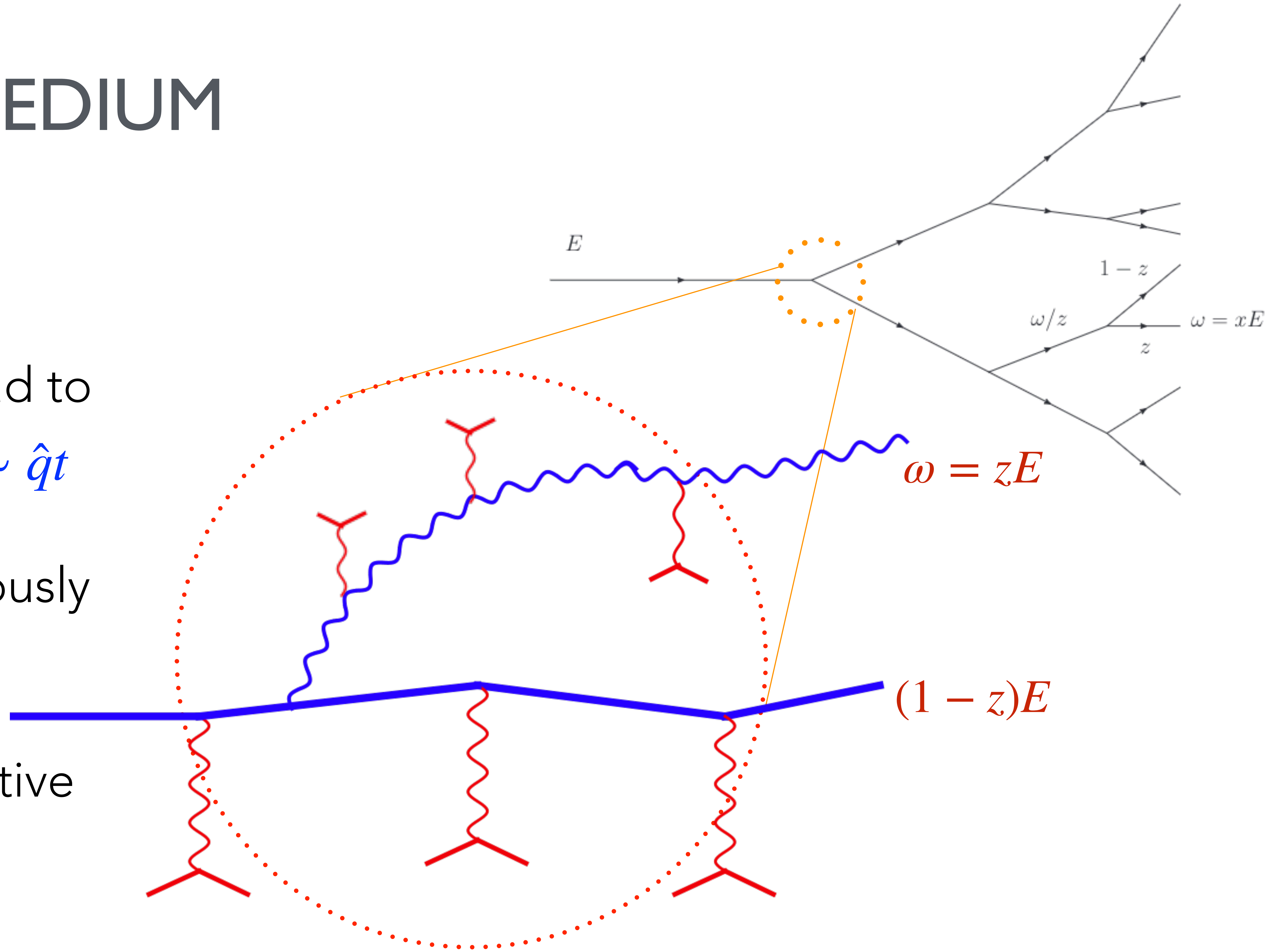
$$\mathcal{K}(t_2,t_1) = \mathcal{K}_{\mathrm{HO}}(t_2,t_1) + \int \mathrm{d}t\, \mathcal{K}_{\mathrm{HO}}(t_2,t)\delta v_{\mathrm{hard}}(t)\mathcal{K}(t,t_1)$$

"improved"
unifying HO & N=1

Mehtar-Tani, Tywoniuk 1910.02032

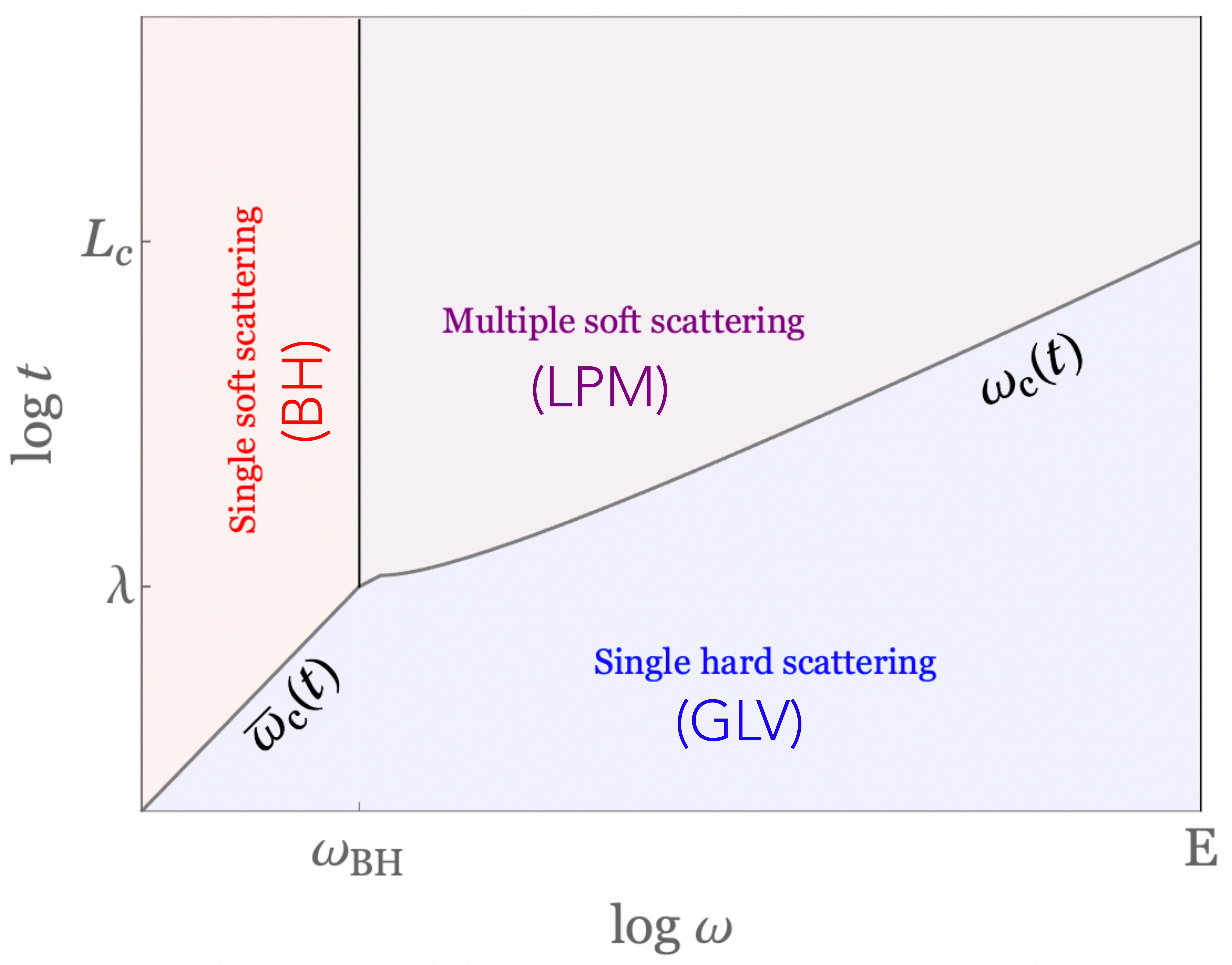
SPLITTING IN MEDIUM

- interactions with the medium lead to Gaussian broadening with $\langle k_t^2 \rangle \sim \hat{q} t$
- soft gluons are rapidly and copiously produced
- medium potential: non-perturbative input about medium transport properties.



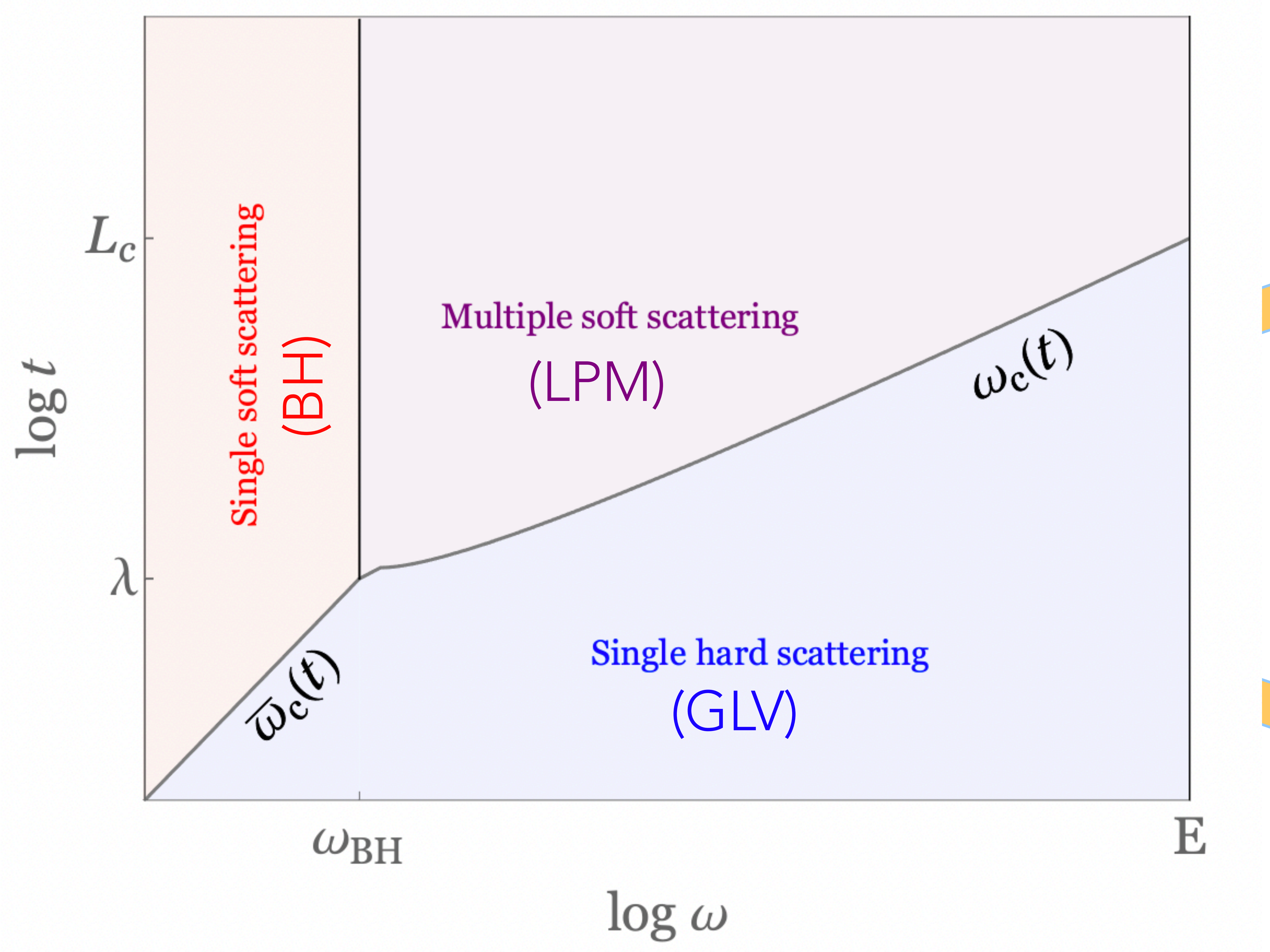
$$t_{\rm f} = \frac{\omega}{\langle k_t^2 \rangle} \sim \sqrt{\frac{\omega}{\hat{q}}}$$

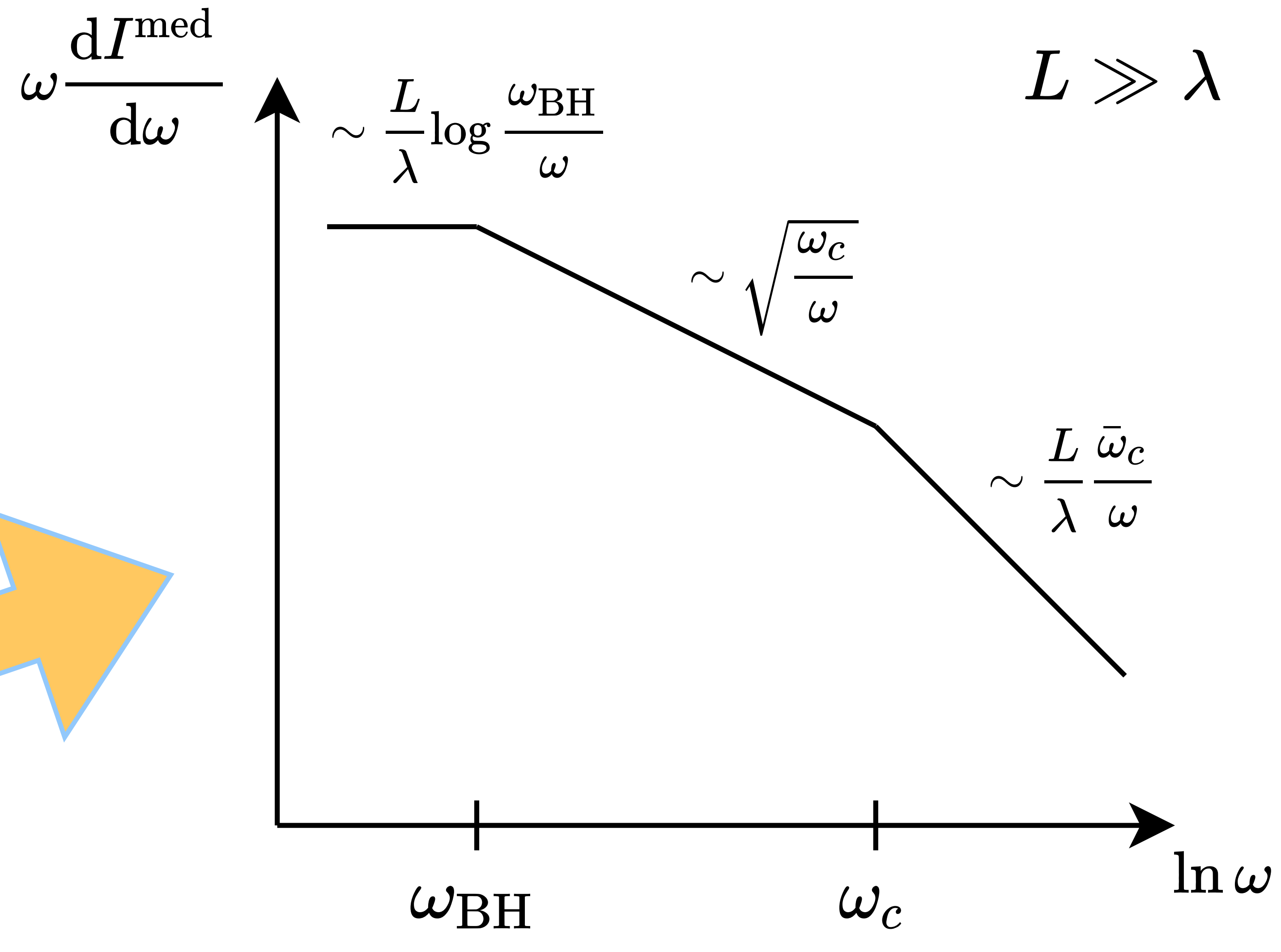
Full description of medium-induced radiation

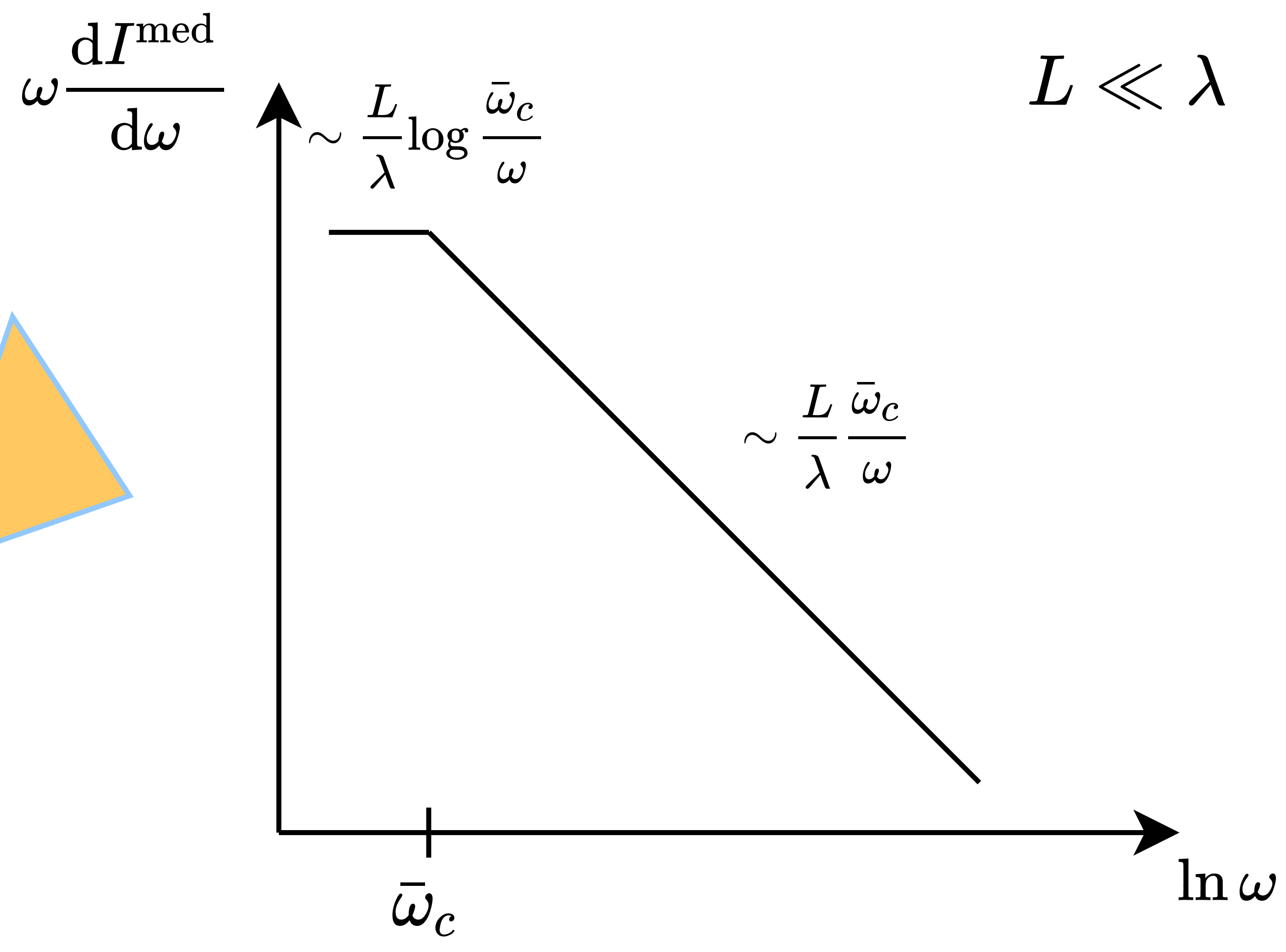


- picture breaks down in two limits:
  - when formation time becomes larger than the medium $t_{\rm f} \sim L$ (at $\omega > \hat{q}t^2/2$)
  - when formation time is of the order of mean free path $t_f \sim \lambda$ (at $\omega < \mu^2\lambda/2$)
- three expansion schemes cover the whole phase space
  - opacity expansion (in real+virtual momentum exchanges)
  - improved opacity expansion (around harmonic oscillator)
  - resummed opacity expansion (in real momentum exchanges)

Full description of medium-induced radiation







When is jet quenching effective?

$$L \gg \lambda$$

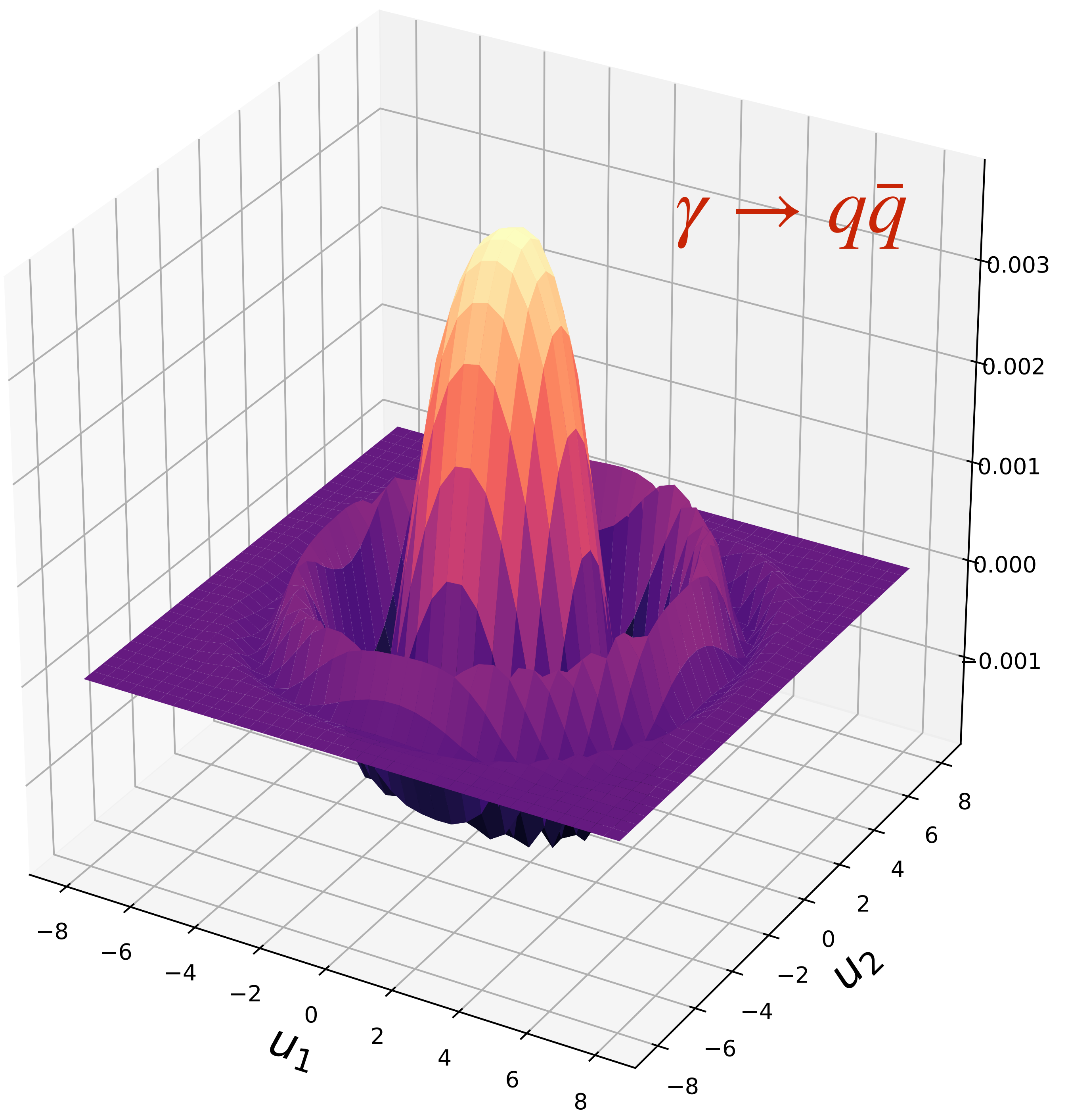
- anticipating: the appearance of the LPM regime is extremely important for phenomenology
- leads to large multiplicity of emitted gluons &
- $1/\sqrt{x}$ spectrum gives rise to efficient transport of energy from leading particle to many soft particles
- all other regions lead to few ~$\mathcal{O}(\alpha_s)$ emissions
- currently: exploring the consequences of rapid medium expansion

Splitting in full kinematics

Isaksen, KT 2107.02542
Dominguez; Isaksen, Takacs, KT (in preparation)

$$\frac{\mathrm{d}\sigma}{\mathrm{d}z\,\mathrm{d}^2\boldsymbol{k}} = \frac{g^2\,P(z)}{2(2\pi)^3[z(1-z)E]^2}\,\mathrm{Re}\int_0^\infty \mathrm{d}t_1 \int_{t_1}^\infty \mathrm{d}t_2 \int_{\boldsymbol{x},\boldsymbol{u},\bar{\boldsymbol{u}}} \mathrm{e}^{-i(\boldsymbol{u}-\bar{\boldsymbol{u}})\cdot\boldsymbol{k}}$$
$$\times\, \partial_{\boldsymbol{y}} \cdot \partial_{\boldsymbol{z}} (\boldsymbol{u};\bar{\boldsymbol{u}}|\tilde{S}^{(4)}(L,t_2)|\boldsymbol{x};\boldsymbol{z})(\boldsymbol{x}|\tilde{S}^{(3)}(t_2,t_1)|\boldsymbol{y})\Big|_{\boldsymbol{y}=\boldsymbol{z}=0}$$

- depends on **3-point** and **4-point** correlators of Wilson lines.
- numerical solutions of 1 or 2 body **Schrödinger equations in 2+1D** for n-level system in color space.
- toward full-kinematics precision calculation of splitting dynamics for all fundamental processes.



Two-body in-medium wave function.

TWO REGIMES

$$t_\mathrm{f} \sim \sqrt{\omega/\hat{q}} \quad \Rightarrow \quad k_\mathrm{br}^2 \sim \sqrt{\omega\hat{q}} \quad \Rightarrow \quad \theta_\mathrm{br} \sim (\hat{q}/\omega^3)^{1/4}$$

Multiplicity of emitted gluons

$$N(\omega) = \int_\omega^\infty \mathrm{d}\omega' \frac{\mathrm{d}I}{\mathrm{d}\omega'} = 2\sqrt{\frac{\bar{\alpha}^2\hat{q}L^2}{\omega}}$$

Energy loss

$$\Delta E = \int_0^\infty \mathrm{d}\omega'\, \omega' \frac{\mathrm{d}I}{\mathrm{d}\omega'} = 2\bar{\alpha}\hat{q}L^2$$

BUT: average energy loss ≠ typical energy loss!

TWO REGIMES

$$t_{\mathrm{f}} \sim \sqrt{\omega/\hat{q}} \quad \Rightarrow \quad k_{\mathrm{br}}^2 \sim \sqrt{\omega \hat{q}} \quad \Rightarrow \quad \theta_{\mathrm{br}} \sim (\hat{q}/\omega^3)^{1/4}$$

Multiplicity of emitted gluons

$$N(\omega) = \int_\omega^\infty \mathrm{d}\omega' \, \frac{\mathrm{d}I}{\mathrm{d}\omega'} = 2\sqrt{\frac{\bar{\alpha}^2 \hat{q} L^2}{\omega}}$$

Energy loss

BUT: average energy loss ≠ typical energy loss!

$$\Delta E = \int_0^\infty \mathrm{d}\omega' \, \omega' \frac{\mathrm{d}I}{\mathrm{d}\omega'} = 2\bar{\alpha}\hat{q}L^2$$

rare, small-angle emission

$$\omega_c = \hat{q}L^2$$

$$\theta_{\mathrm{br}}(\omega_c) \sim \sqrt{\frac{1}{\hat{q}L^3}} \equiv \theta_c$$

Two regimes

$$t_{\rm f} \sim \sqrt{\omega/\hat{q}} \quad \Rightarrow \quad k_{\rm br}^2 \sim \sqrt{\omega\hat{q}} \quad \Rightarrow \quad \theta_{\rm br} \sim (\hat{q}/\omega^3)^{1/4}$$

Multiplicity of emitted gluons

$$N(\omega) = \int_\omega^\infty \mathrm{d}\omega' \frac{\mathrm{d}I}{\mathrm{d}\omega'} = 2\sqrt{\frac{\bar{\alpha}^2\hat{q}L^2}{\omega}}$$

Energy loss

$$\Delta E = \int_0^\infty \mathrm{d}\omega'\, \omega' \frac{\mathrm{d}I}{\mathrm{d}\omega'} = 2\bar{\alpha}\hat{q}L^2$$

BUT: average energy loss ≠ typical energy loss!

rare, small-angle emission

$$\omega_c = \hat{q}L^2$$

$$\theta_{\rm br}(\omega_c) \sim \sqrt{\frac{1}{\hat{q}L^3}} \equiv \theta_c$$

copious, large-angle emissions

$$\omega_s = \bar{\alpha}^2\hat{q}L^2$$

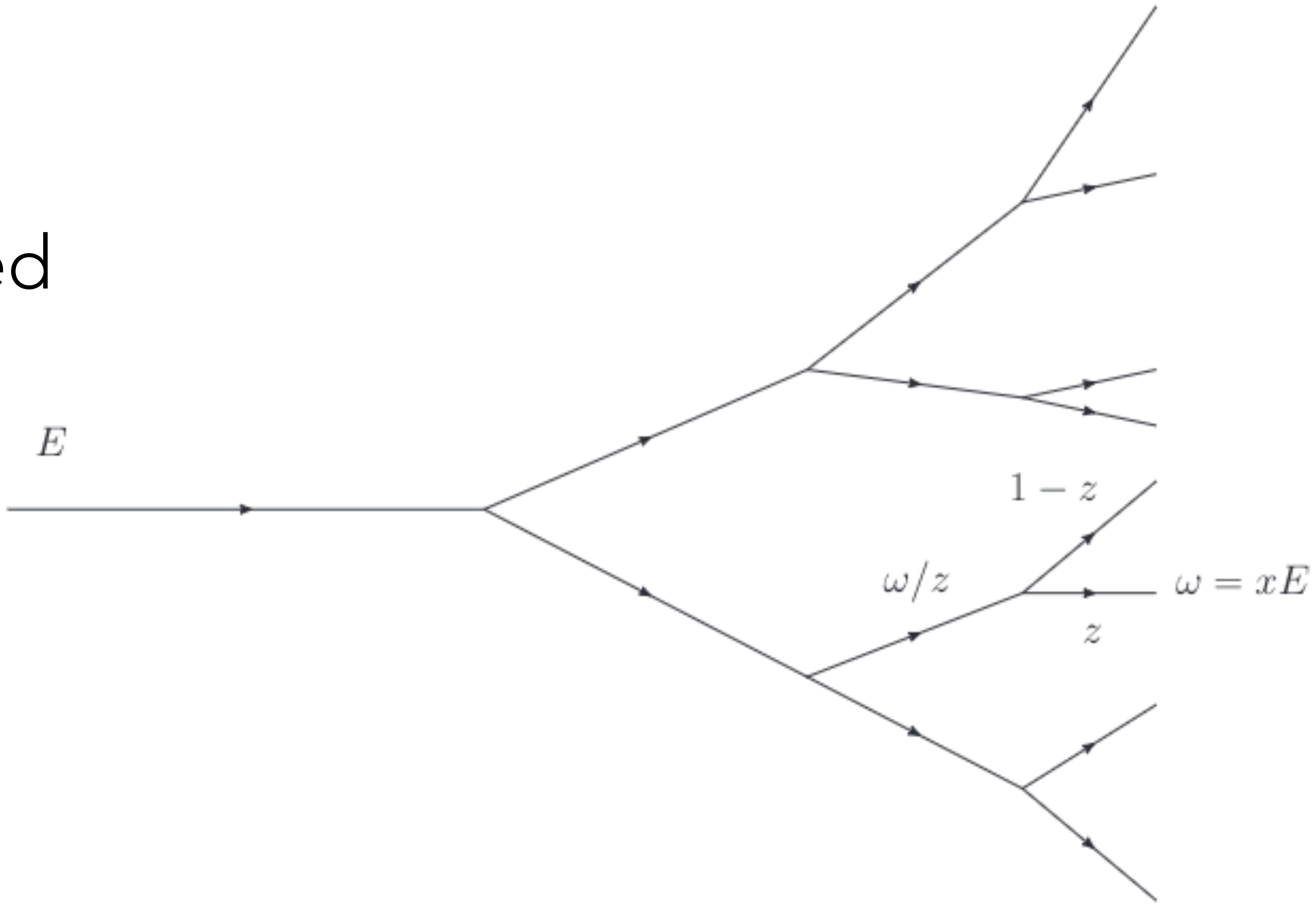
$$\theta_{\rm br}(\omega_s) \sim \frac{1}{\bar{\alpha}^{3/2}}\theta_c$$

MEDIUM-INDUCED CASCADE

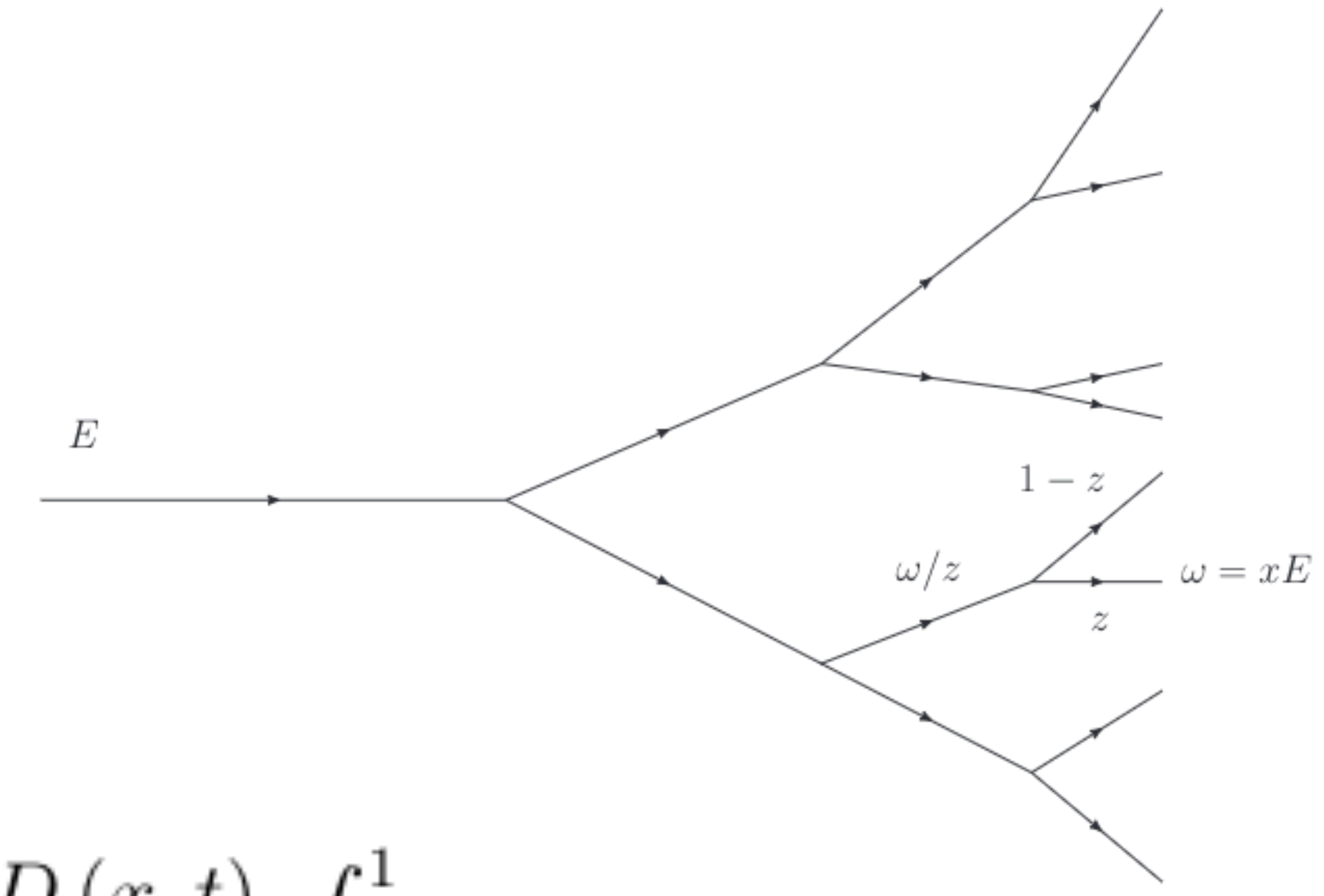
When multiplicity becomes large $N(\omega) \gg 1$, we need to take into account multiple splittings.

Can treat splittings as independent as long as the time between splittings is long compared to the individual formation times!

$$t_{\mathrm{f}} \sim \sqrt{\omega/\hat{q}}$$



EVOLUTION EQUATIONS



Evolution equation for energy distribution

$$\frac{\partial}{\partial t} D(x,t) = \int_x^1 \mathrm{d}z\, \mathcal{K}(z) \frac{D(x/z,t)}{t_*(x/z)} - \frac{D(x,t)}{t_*(x)} \int_0^1 \mathrm{d}z\, z\mathcal{K}(z)$$

evolution variable

splitting kernel

characteristic time-scale
"stopping" time

In vacuum (DGLAP):

$$t = \ln \theta_0/\theta$$
$$t_*(x) = 1/\alpha_s$$

In medium:

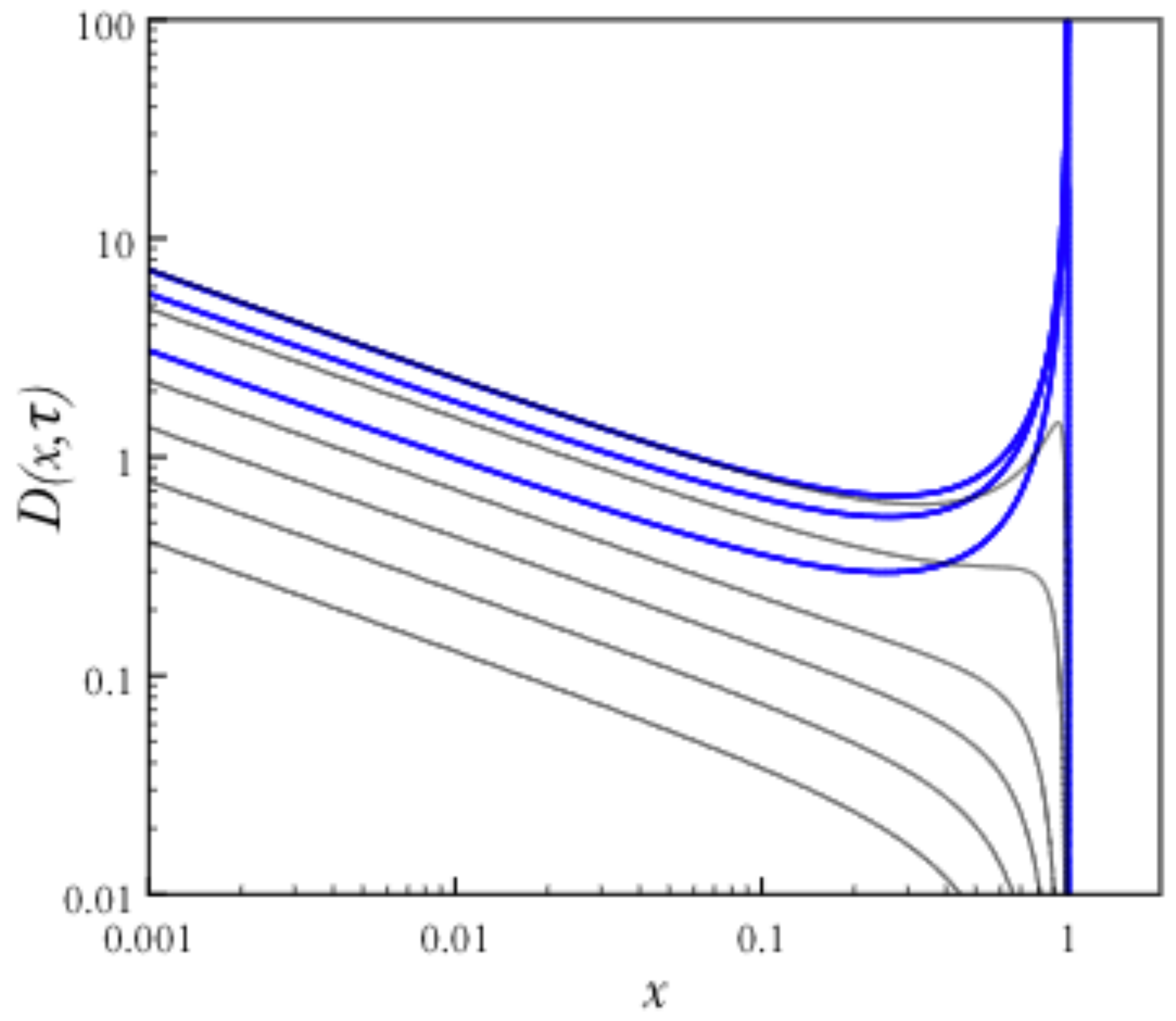
$$t = L$$
$$t_*(x) = \frac{1}{\alpha_s}\sqrt{\frac{xE}{\hat{q}}}$$

TURBULENCE IN JET QUENCHING

Blaizot, Mehtar-Tani 1501.03443

Medium evolution equation permits analytical solution:

$$D(x,\tau) = \frac{\tau}{\sqrt{x}(1-x)^{3/2}} \mathrm{e}^{-\pi \frac{\tau^2}{1-x}} \qquad \tau = t/t_*$$



TURBULENCE IN JET QUENCHING

Blaizot, Mehtar-Tani 1501.03443

Medium evolution equation permits analytical solution:

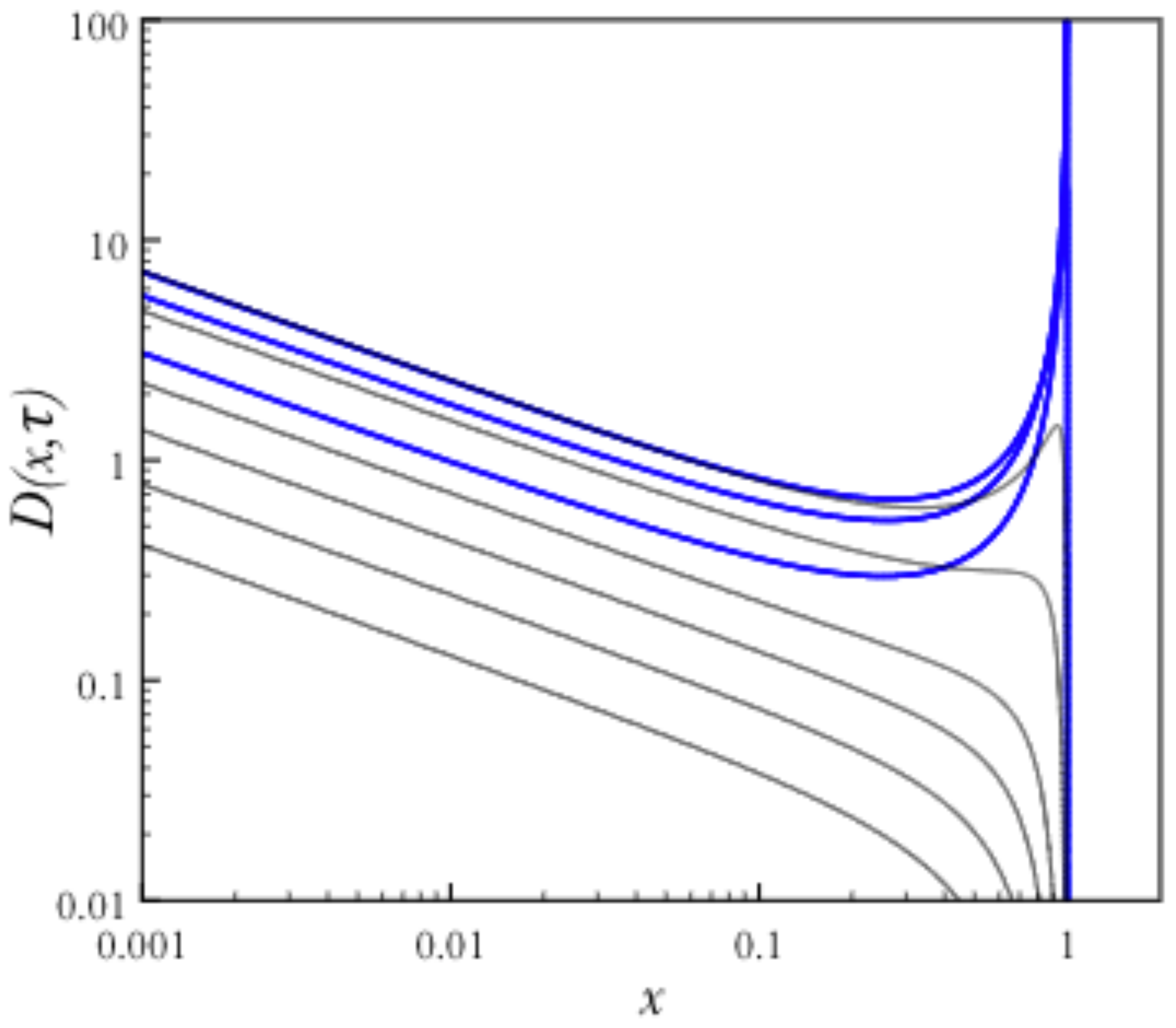
$$D(x,\tau) = \frac{\tau}{\sqrt{x}(1-x)^{3/2}} \mathrm{e}^{-\pi \frac{\tau^2}{1-x}} \qquad \tau = t/t_*$$

$$\mathcal{E}(x_0,\tau) = \int_{x_0}^{1} \mathrm{d}x\, D(x,\tau)$$

energy stored in particles with $x > x_0$

$$\mathcal{F}(x,\tau) = -\frac{\partial \mathcal{E}(x_0,\tau)}{\partial \tau}$$

flux of energy to modes at $x < x_0$

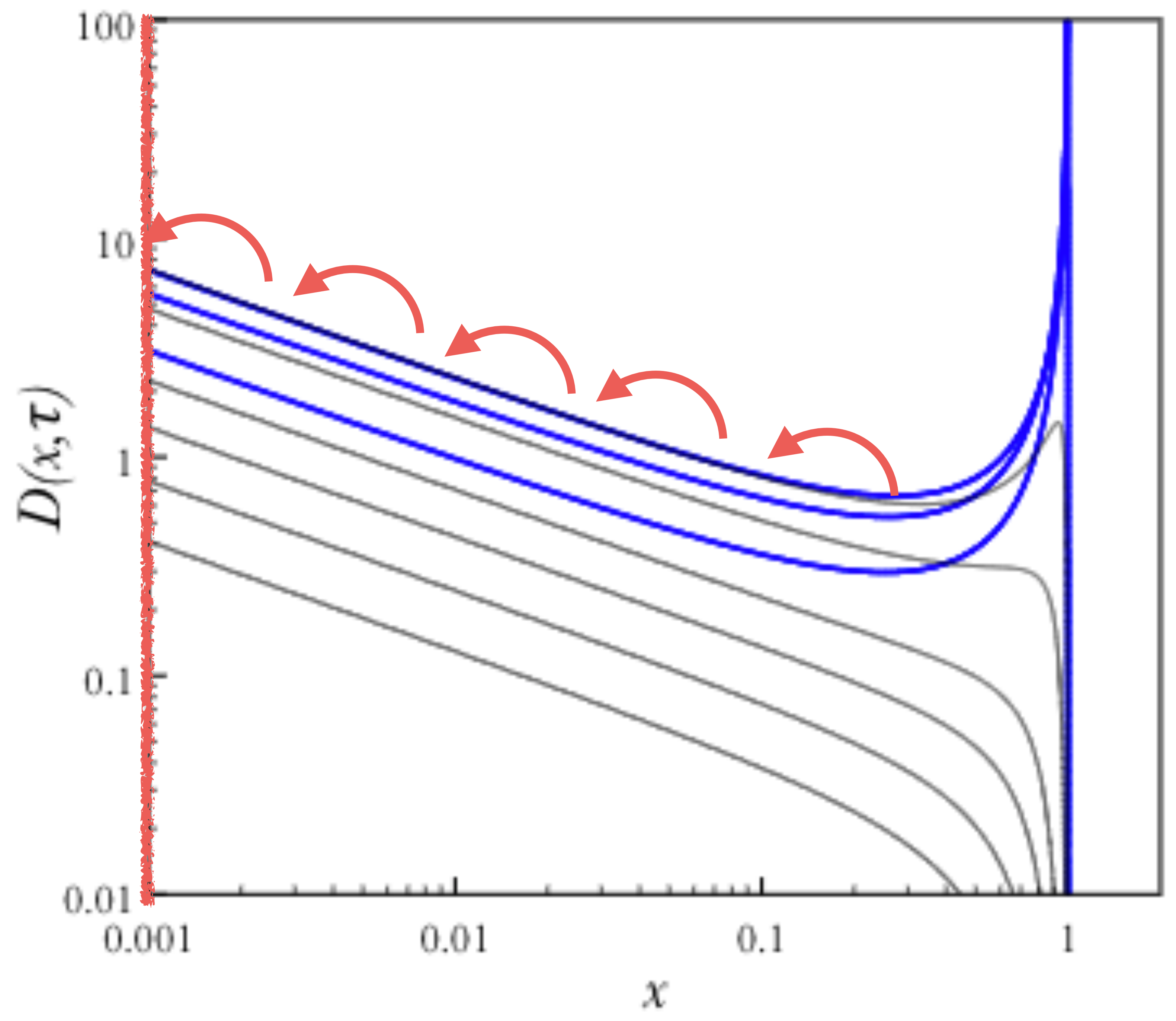


Turbulence in jet quenching

Blaizot, Mehtar-Tani 1501.03443

Medium evolution equation permits analytical solution:

$$D(x,\tau) = \frac{\tau}{\sqrt{x}(1-x)^{3/2}} \mathrm{e}^{-\pi \frac{\tau^2}{1-x}} \qquad \tau = t/t_*$$



$$\mathcal{E}(x_0,\tau) = \int_{x_0}^{1} \mathrm{d}x\, D(x,\tau)$$ energy stored in particles with $x > x_0$

$$\mathcal{F}(x,\tau) = -\frac{\partial \mathcal{E}(x_0,\tau)}{\partial \tau}$$ flux of energy to modes at $x < x_0$

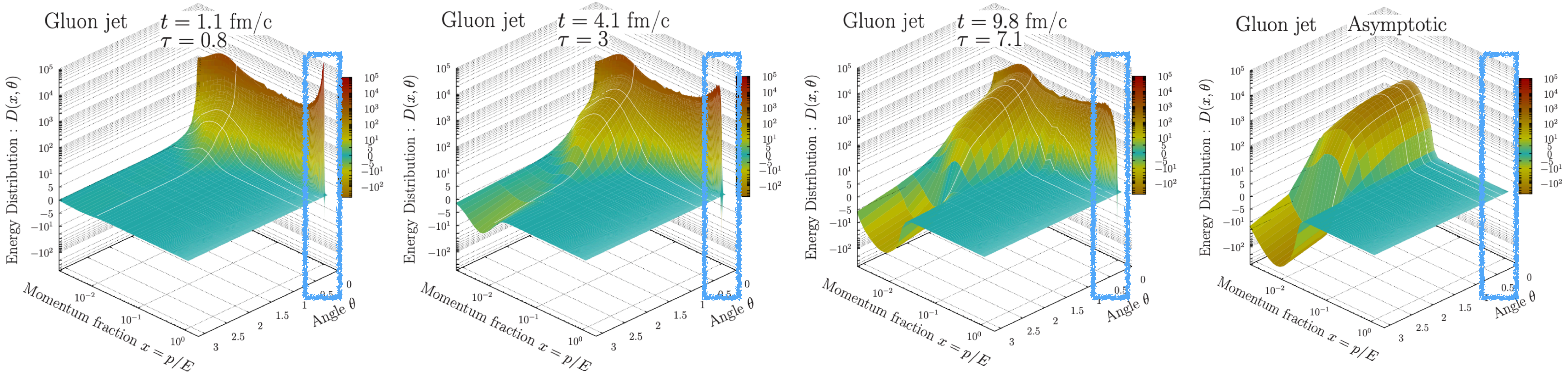
Energy flow all the way to zero energy:

- "source" at $x = 1$ & "sink" at $x = 0$
- similar to "weak" wave turbulence

$$\mathcal{F}(0,\tau) = 2\pi\tau\, \mathrm{e}^{-\pi\tau^2}$$

$$\lim_{x_0 \to 0} \mathcal{E}(x_0,\tau) = \mathrm{e}^{-\pi\tau^2}$$

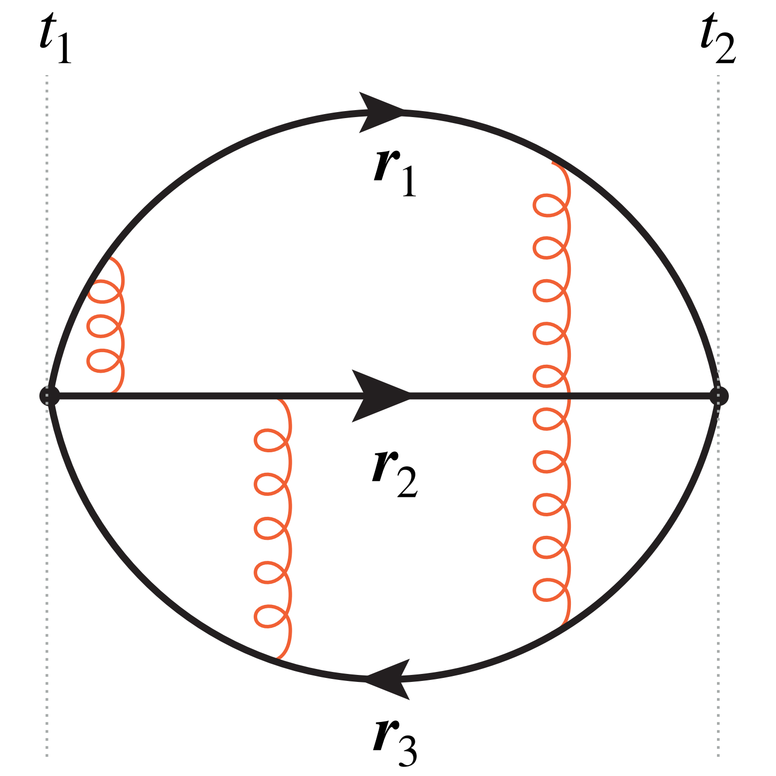
ENERGY DISTRIBUTION



- evolution of leading particle: **energy loss**
- energy is located in soft peak & broadens to large angles

THREE-POINT CORRELATOR

$$\mathcal{K}(\boldsymbol{x}, t_2; \boldsymbol{y}, t_1) = \int_{\boldsymbol{r}(t_1)=\boldsymbol{y}}^{\boldsymbol{r}(t_2)=\boldsymbol{x}} \mathcal{D}\boldsymbol{r}\, \exp\left\{ i \int_{t_1}^{t_2} \mathrm{d}s \left[\frac{\omega}{2}\dot{\boldsymbol{r}}^2 + iv(\boldsymbol{r}, s)\right]\right\}$$



Resumming 3-body interactions via potential:

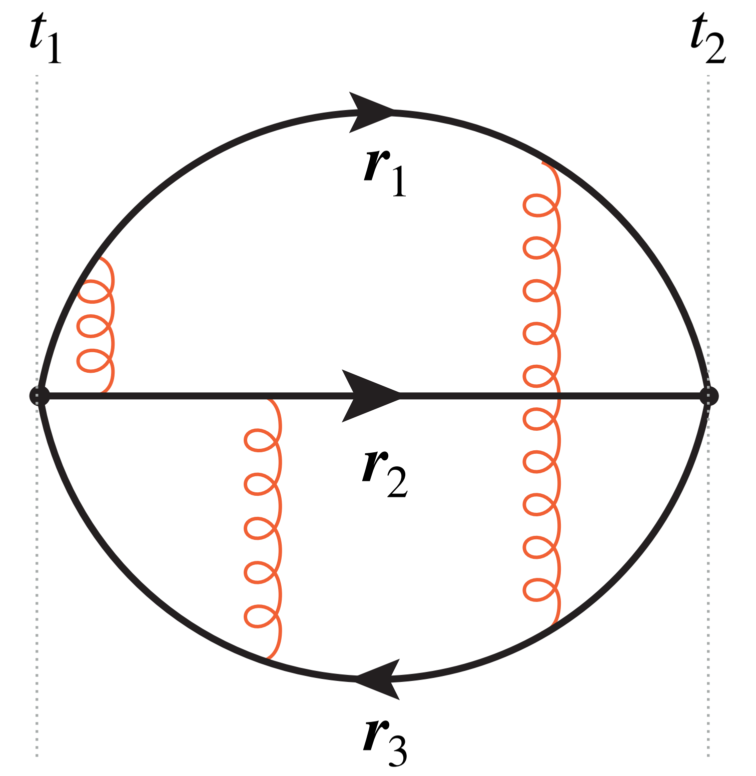
(Including real and virtual exchanges.)

$$v(t, \boldsymbol{x}) = \gamma(t, 0) - \gamma(t, \boldsymbol{x}) = \int_{\boldsymbol{q}} \frac{\mathrm{d}^2\sigma_{\text{el}}}{\mathrm{d}\boldsymbol{q}^2}\left(1 - \mathrm{e}^{i\boldsymbol{q}\cdot\boldsymbol{x}}\right)$$

$$\simeq \frac{1}{4}\hat{q}_0 \boldsymbol{x}^2 \ln \frac{1}{\boldsymbol{x}^2\mu_*^2} + \mathcal{O}(\boldsymbol{x}^4\mu_*^2)$$

THREE-POINT CORRELATOR

$$\mathcal{K}(\boldsymbol{x}, t_2; \boldsymbol{y}, t_1) = \int_{\boldsymbol{r}(t_1)=\boldsymbol{y}}^{\boldsymbol{r}(t_2)=\boldsymbol{x}} \mathcal{D}\boldsymbol{r} \, \exp\left\{ i \int_{t_1}^{t_2} \mathrm{d}s \left[\frac{\omega}{2} \dot{\boldsymbol{r}}^2 + i v(\boldsymbol{r}, s) \right] \right\}$$



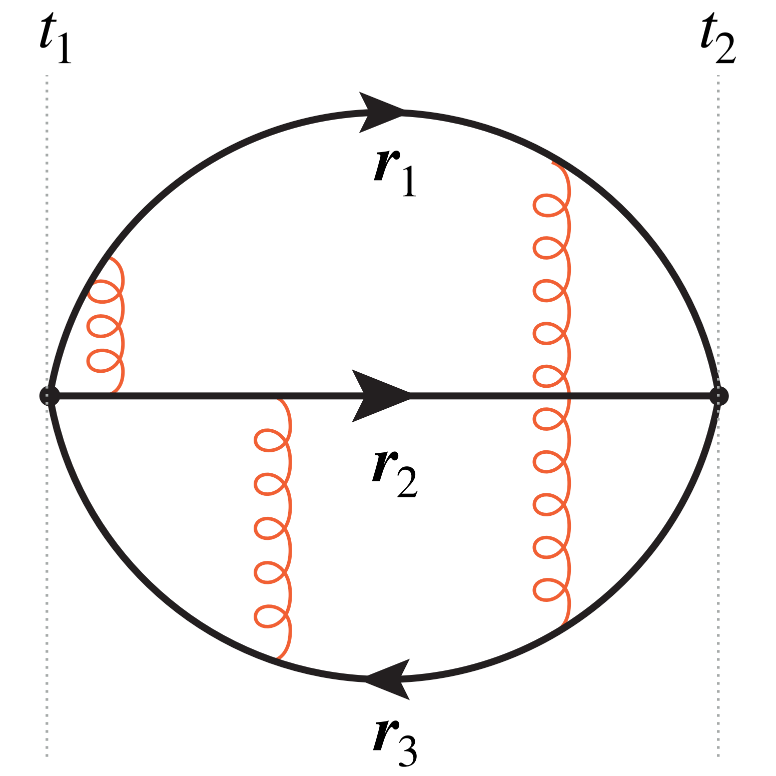
Resumming 3-body interactions via potential: $v(t, \boldsymbol{x}) = \gamma(t, 0) - \gamma(t, \boldsymbol{x}) = \int_{\boldsymbol{q}} \frac{\mathrm{d}^2 \sigma_{\mathrm{el}}}{\mathrm{d}\boldsymbol{q}^2} \left(1 - \mathrm{e}^{i \boldsymbol{q} \cdot \boldsymbol{x}}\right)$

(Including real and virtual exchanges.)

$$\simeq \frac{1}{4} \hat{q}_0 \boldsymbol{x}^2 \ln \frac{1}{\boldsymbol{x}^2 \mu_*^2} + \mathcal{O}(\boldsymbol{x}^4 \mu_*^2)$$

First term is universal/perturbative.
Harmonic oscillator (up to a log).

Three-point correlator



$$\mathcal{K}(\boldsymbol{x}, t_2; \boldsymbol{y}, t_1) = \int_{\boldsymbol{r}(t_1)=\boldsymbol{y}}^{\boldsymbol{r}(t_2)=\boldsymbol{x}} \mathcal{D}\boldsymbol{r}\, \exp\left\{ i \int_{t_1}^{t_2} \mathrm{d}s \left[\frac{\omega}{2}\dot{\boldsymbol{r}}^2 + iv(\boldsymbol{r}, s) \right] \right\}$$

Resumming 3-body interactions via potential:

(Including real and virtual exchanges.)

$$v(t, \boldsymbol{x}) = \gamma(t, 0) - \gamma(t, \boldsymbol{x}) = \int_{\boldsymbol{q}} \frac{\mathrm{d}^2\sigma_{\rm el}}{\mathrm{d}\boldsymbol{q}^2} \left(1 - \mathrm{e}^{i\boldsymbol{q}\cdot\boldsymbol{x}}\right)$$

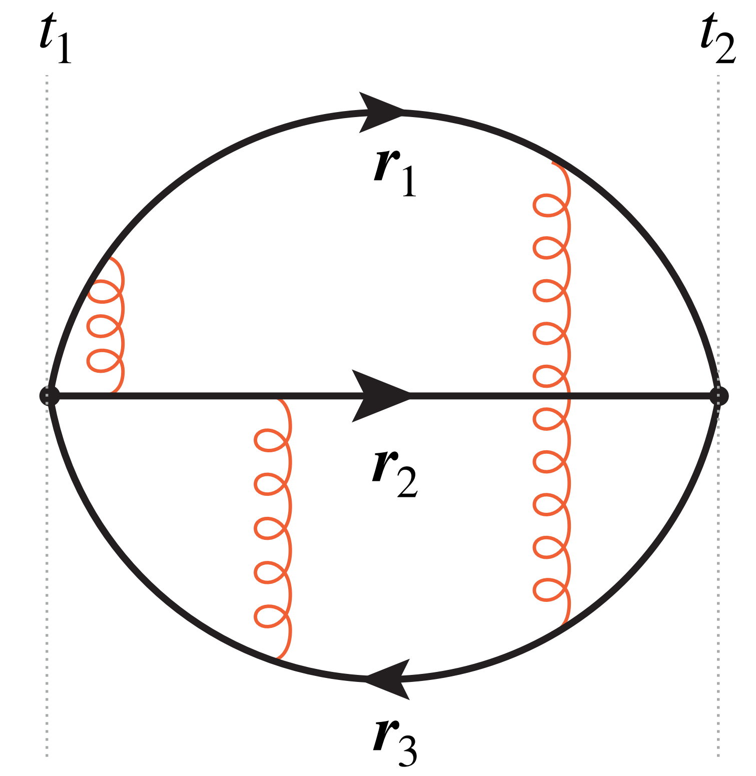
$$\simeq \frac{1}{4}\hat{q}_0 \boldsymbol{x}^2 \ln \frac{1}{\boldsymbol{x}^2\mu_*^2} + \mathcal{O}(\boldsymbol{x}^4\mu_*^2)$$

First term is universal/perturbative.
Harmonic oscillator (up to a log).

Jet transport coefficient

$$\hat{q}_0 = 4\pi\alpha_s^2 N_c n_0 = \frac{\mu^2}{\lambda}$$

THREE-POINT CORRELATOR



$$\mathcal{K}(\boldsymbol{x}, t_2; \boldsymbol{y}, t_1) = \int_{\boldsymbol{r}(t_1)=\boldsymbol{y}}^{\boldsymbol{r}(t_2)=\boldsymbol{x}} \mathcal{D}\boldsymbol{r} \, \exp\left\{ i \int_{t_1}^{t_2} \mathrm{d}s \left[\frac{\omega}{2} \dot{\boldsymbol{r}}^2 + i v(\boldsymbol{r}, s) \right] \right\}$$

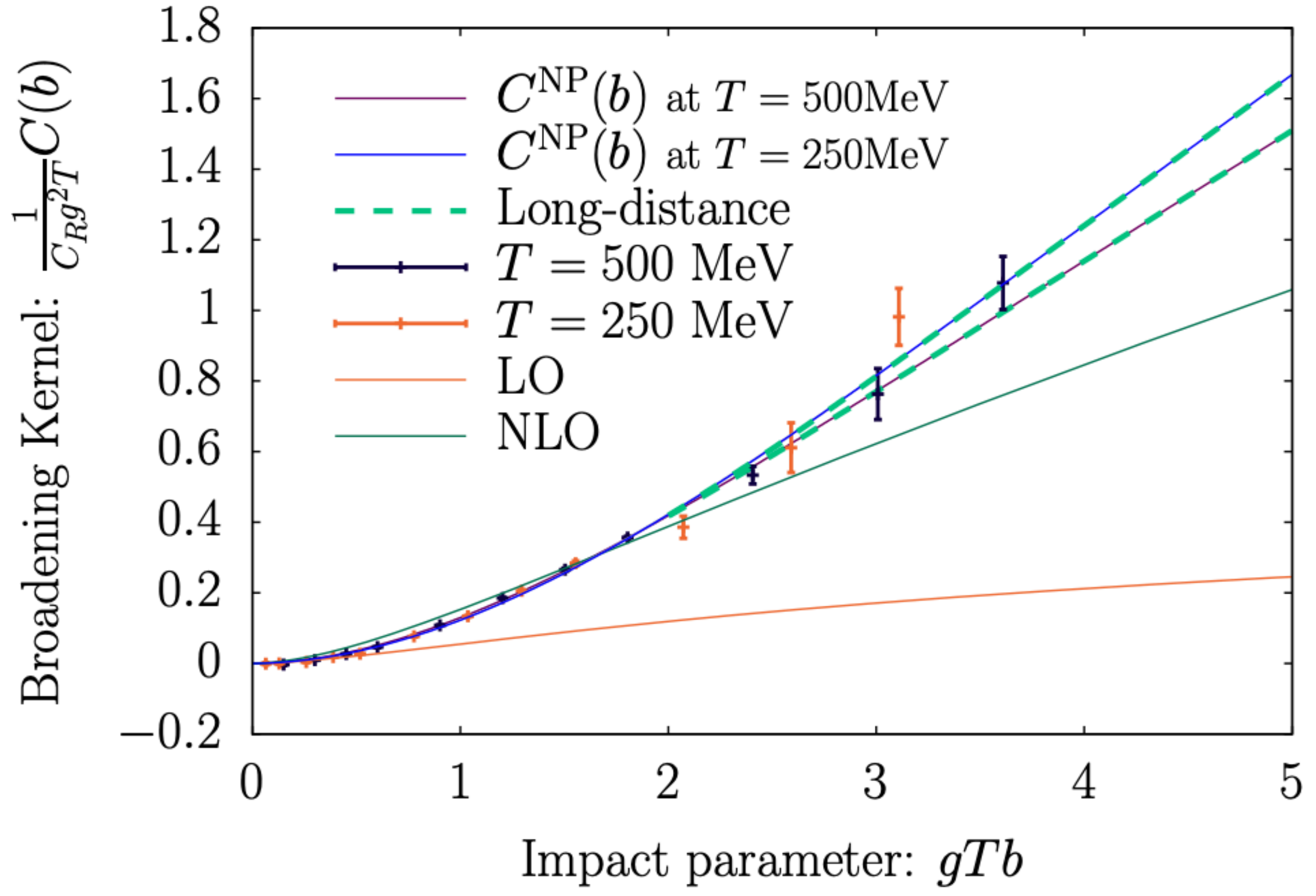
Resumming 3-body interactions via potential: $v(t, \boldsymbol{x}) = \gamma(t, 0) - \gamma(t, \boldsymbol{x}) = \int_{\boldsymbol{q}} \frac{\mathrm{d}^2 \sigma_{\mathrm{el}}}{\mathrm{d}\boldsymbol{q}^2} \left(1 - \mathrm{e}^{i \boldsymbol{q} \cdot \boldsymbol{x}}\right)$

(Including real and virtual exchanges.)

$$\simeq \frac{1}{4} \hat{q}_0 \boldsymbol{x}^2 \ln \frac{1}{\boldsymbol{x}^2 \mu_*^2} + \mathcal{O}(\boldsymbol{x}^4 \mu_*^2)$$

First term is universal/perturbative.
Harmonic oscillator (up to a log).

Non-perturbative contributions from EQCD



Schlichting, Soudi 2111.13731

Jet transport coefficient

$$\hat{q}_0 = 4\pi \alpha_s^2 N_c n_0 = \frac{\mu^2}{\lambda}$$

QUENCHING WEIGHTS

Baier, Dokshitzer, Mueller, Schiff (2001); Arleo (2002); Salgado, Wiedemann (2003)

For many applications, it is sufficient to consider small energy loss off a (set of) hard particles!

Probability of loosing energy off a single parton:

$$\mathcal{P}(\epsilon) = \delta(\epsilon)\left[1 - \int \mathrm{d}\omega \, \frac{\mathrm{d}I}{\mathrm{d}\omega}\right] + \frac{\mathrm{d}I}{\mathrm{d}\epsilon}$$

one emission

QUENCHING WEIGHTS

Baier, Dokshitzer, Mueller, Schiff (2001); Arleo (2002); Salgado, Wiedemann (2003)

For many applications, it is sufficient to consider small energy loss off a (set of) hard particles!

Probability of loosing energy off a single parton:

$$\mathcal{P}(\epsilon) = \delta(\epsilon)\left[1 - \int \mathrm{d}\omega\, \frac{\mathrm{d}I}{\mathrm{d}\omega}\right] + \frac{\mathrm{d}I}{\mathrm{d}\epsilon}$$

one emission

$$\mathcal{P}(\epsilon) = \mathrm{e}^{-\int \mathrm{d}\omega\, \frac{\mathrm{d}I}{\mathrm{d}\omega}} \sum_{n=0}^{\infty} \frac{1}{n!}\left[\prod_{i=1}^{n} \int \mathrm{d}\omega_i\, \frac{\mathrm{d}I}{\mathrm{d}\omega_i}\right] \delta\left(\epsilon - \sum_{i=1}^{n} \omega_i\right)$$

multiple (independent) emissions

Ubiquitous tool to study jet modifications at RHIC and LHC!

QUENCHING WEIGHTS

Baier, Dokshitzer, Mueller, Schiff (2001); Arleo (2002); Salgado, Wiedemann (2003)

For many applications, it is sufficient to consider small energy loss off a (set of) hard particles!

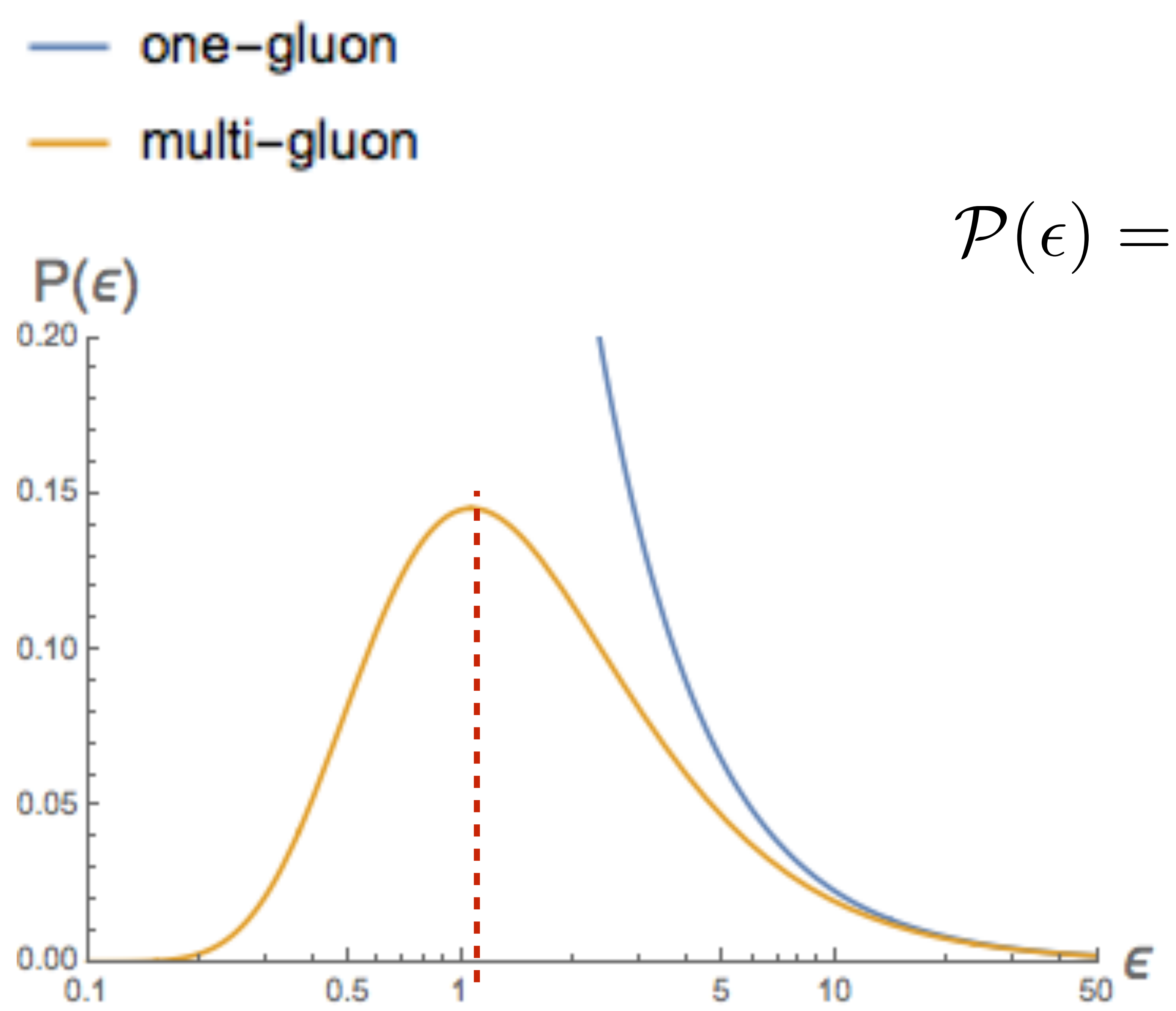
Probability of loosing energy off a single parton:

$$\mathcal{P}(\epsilon) = \delta(\epsilon)\left[1 - \int \mathrm{d}\omega \, \frac{\mathrm{d}I}{\mathrm{d}\omega}\right] + \frac{\mathrm{d}I}{\mathrm{d}\epsilon}$$

one emission

$$\mathcal{P}(\epsilon) = \mathrm{e}^{-\int \mathrm{d}\omega \, \frac{\mathrm{d}I}{\mathrm{d}\omega}} \sum_{n=0}^{\infty} \frac{1}{n!}\left[\prod_{i=1}^{n} \int \mathrm{d}\omega_i \, \frac{\mathrm{d}I}{\mathrm{d}\omega_i}\right] \delta\left(\epsilon - \sum_{i=1}^{n} \omega_i\right)$$

multiple (independent) emissions



$\omega_s = \bar{\alpha}^2 \hat{q} L^2$

Ubiquitous tool to study jet modifications at RHIC and LHC!

$$\frac{\mathrm{d}I}{\mathrm{d}\omega} = \bar{\alpha}\sqrt{\frac{\hat{q}L^2}{\omega^3}} \quad \Rightarrow \quad \mathcal{P}(\epsilon) = \sqrt{\frac{\omega_s}{\epsilon^3}}\,\mathrm{e}^{-\pi\omega_s/\epsilon}$$

QUENCHING OF SINGLE PARTON

$$\mathcal{Q}(p_\mathrm{T}) = \mathrm{e}^{-2\bar\alpha L\sqrt{n\pi\hat q/p_\mathrm{T}}}$$

$$\mathcal{Q}_g(p_\mathrm{T}) = \left(\mathcal{Q}_q(p_\mathrm{T})\right)^{N_c/C_F}$$

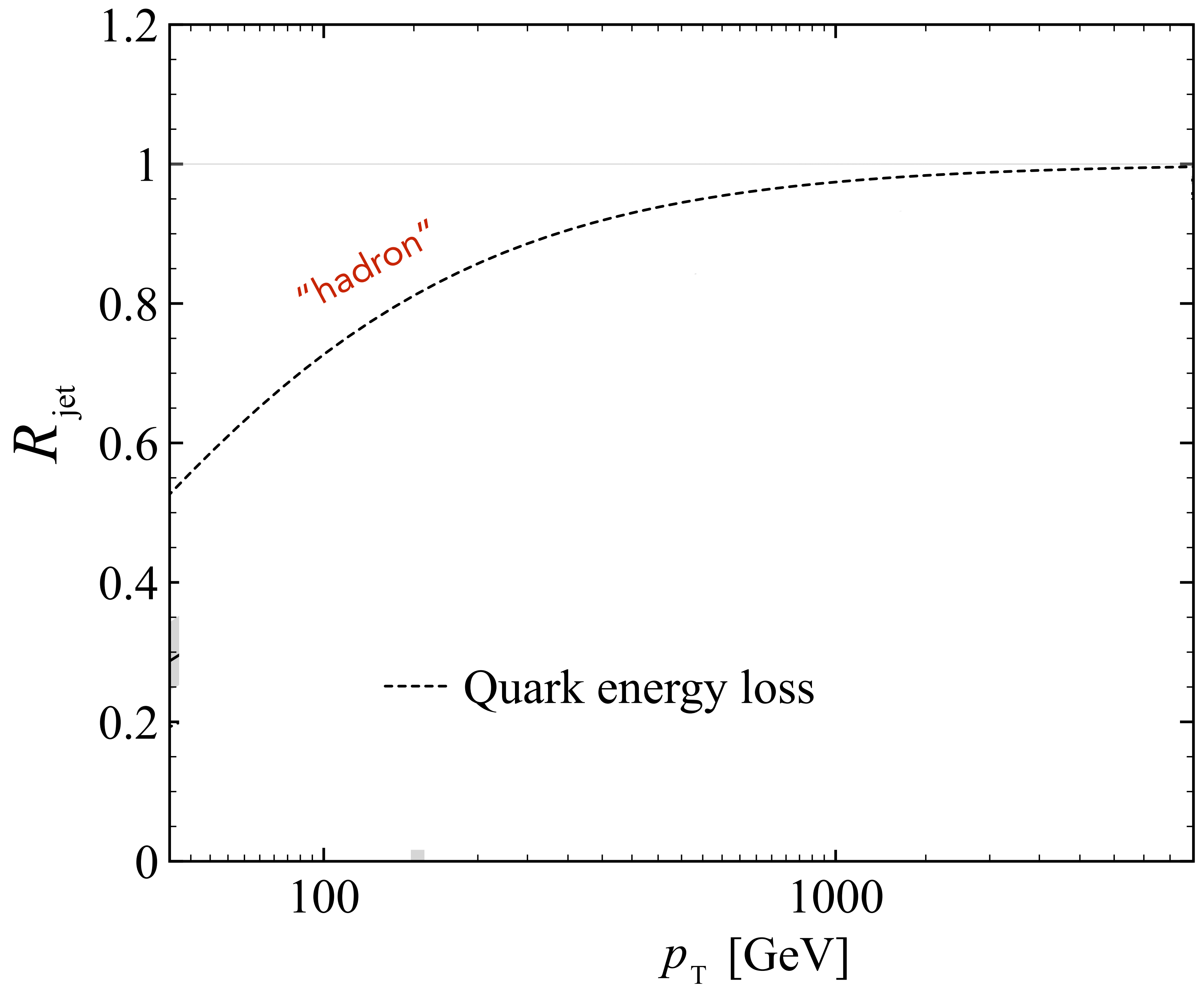
- quenching factor is form factor related related to multiplicity of emitted gluons

$$Q(p_T) \sim e^{-N(\omega > p_T/n)}$$

- strong quenching for

$$p_T < n\bar\alpha^2\hat q L^2$$

- possibility for large gluon multiplicity drives the quenching (not so much the max energy, only at $p_T > n\hat q L^2 \ldots$.)



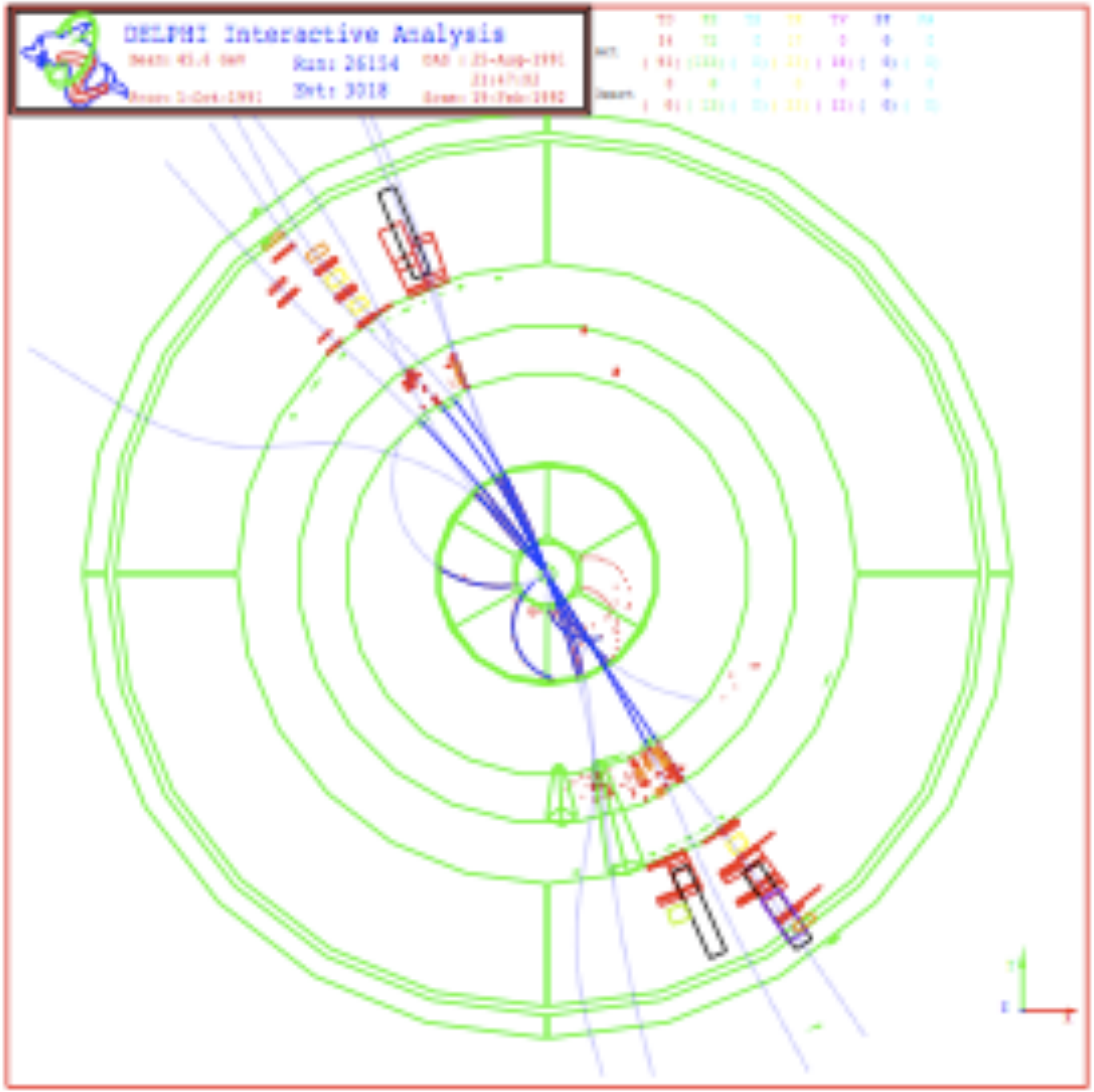
Our analysis have resulted in a "model" w/

$$\delta p_T = \sqrt{\frac{8\pi\bar\alpha^2\hat q L^2\, p_T}{n}}$$

at high-p_T, $\delta p_T = \bar\alpha\hat q L^2$, but quenching is small $Q(p_T) \sim \mathcal{O}(1-\bar\alpha)$

Lecture 3

theory of jet modification in medium



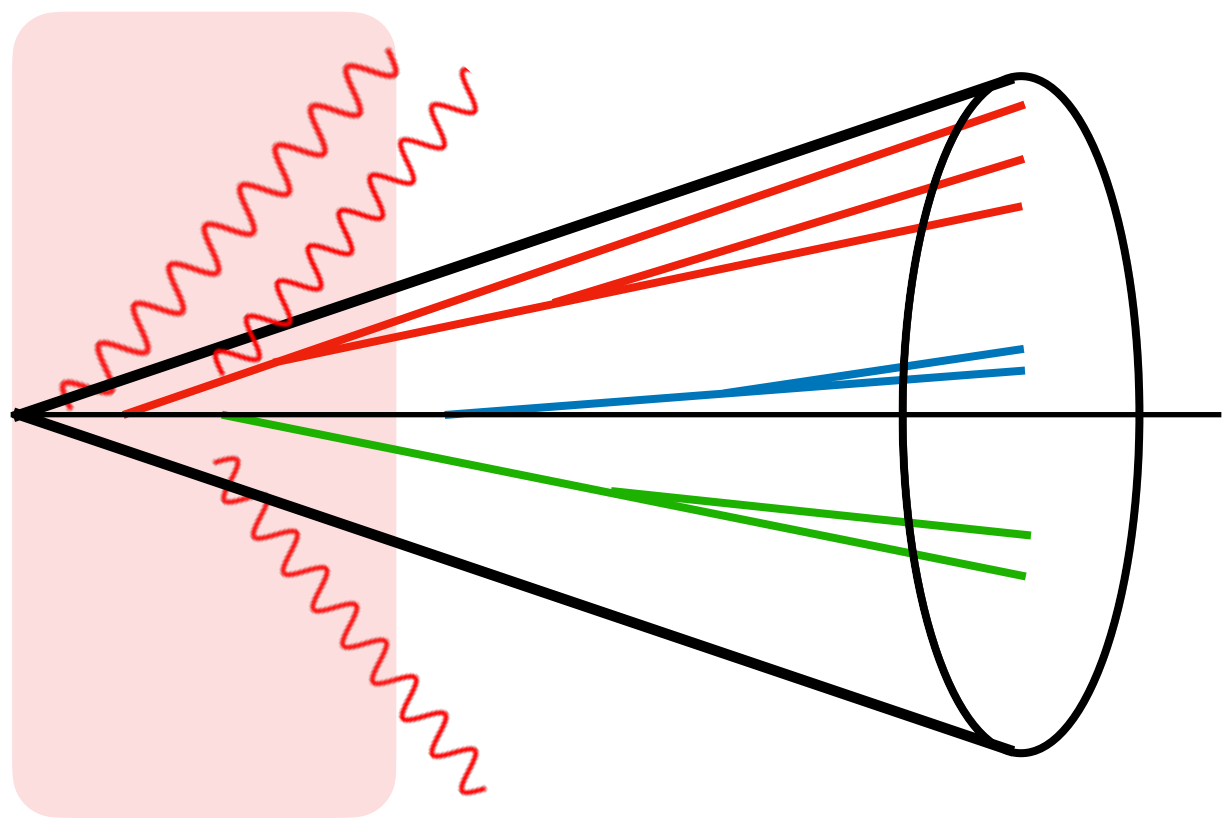
x-y plane

Jet fragmentation in the medium

Mehtar-Tani, Salgado, KT (2011); Casalderrey-Solana, Iancu (2011); Y. Mehtar-Tani, KT 1706.06047, 1707.07361
Caucal, Iancu, Mueller, Soyez 1801.09703

⟹ color dynamics in the medium (color coherence…)

⟹ every color source inside jet resolved by the QGP contribute to energy loss.

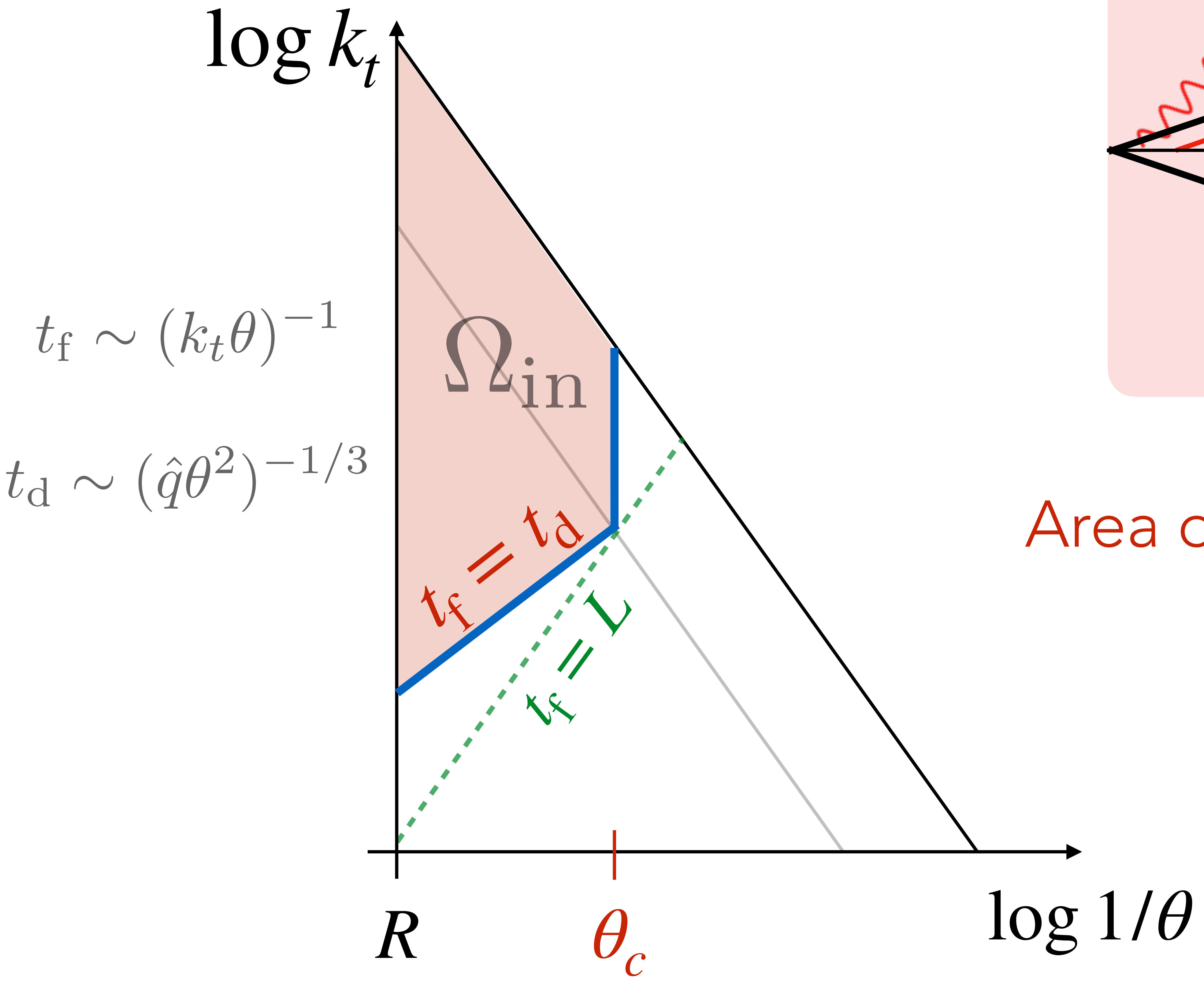


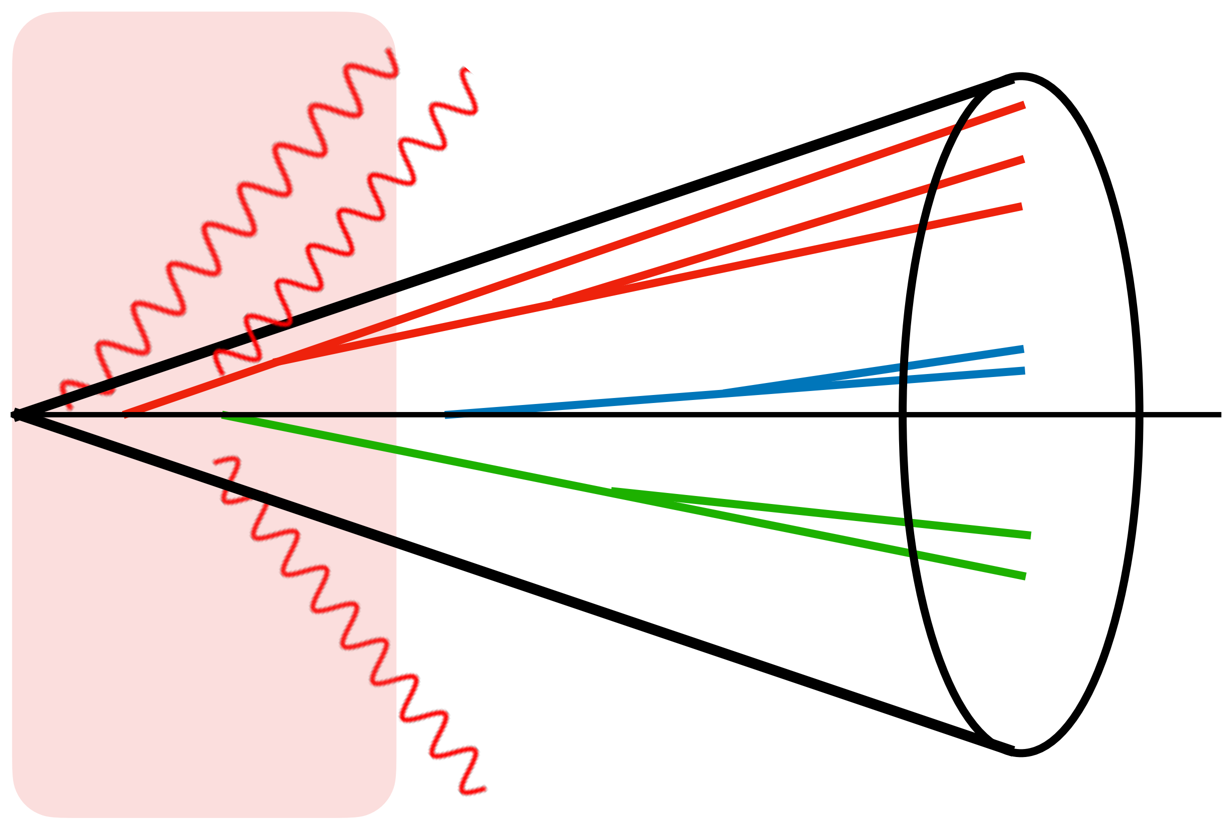
Jet fragmentation in the medium

Mehtar-Tani, Salgado, KT (2011); Casalderrey-Solana, Iancu (2011); Y. Mehtar-Tani, KT 1706.06047, 1707.07361
Caucal, Iancu, Mueller, Soyez 1801.09703

$\Longrightarrow$ color dynamics in the medium (color coherence…)

$\Longrightarrow$ every color source inside jet resolved by the QGP contribute to energy loss.





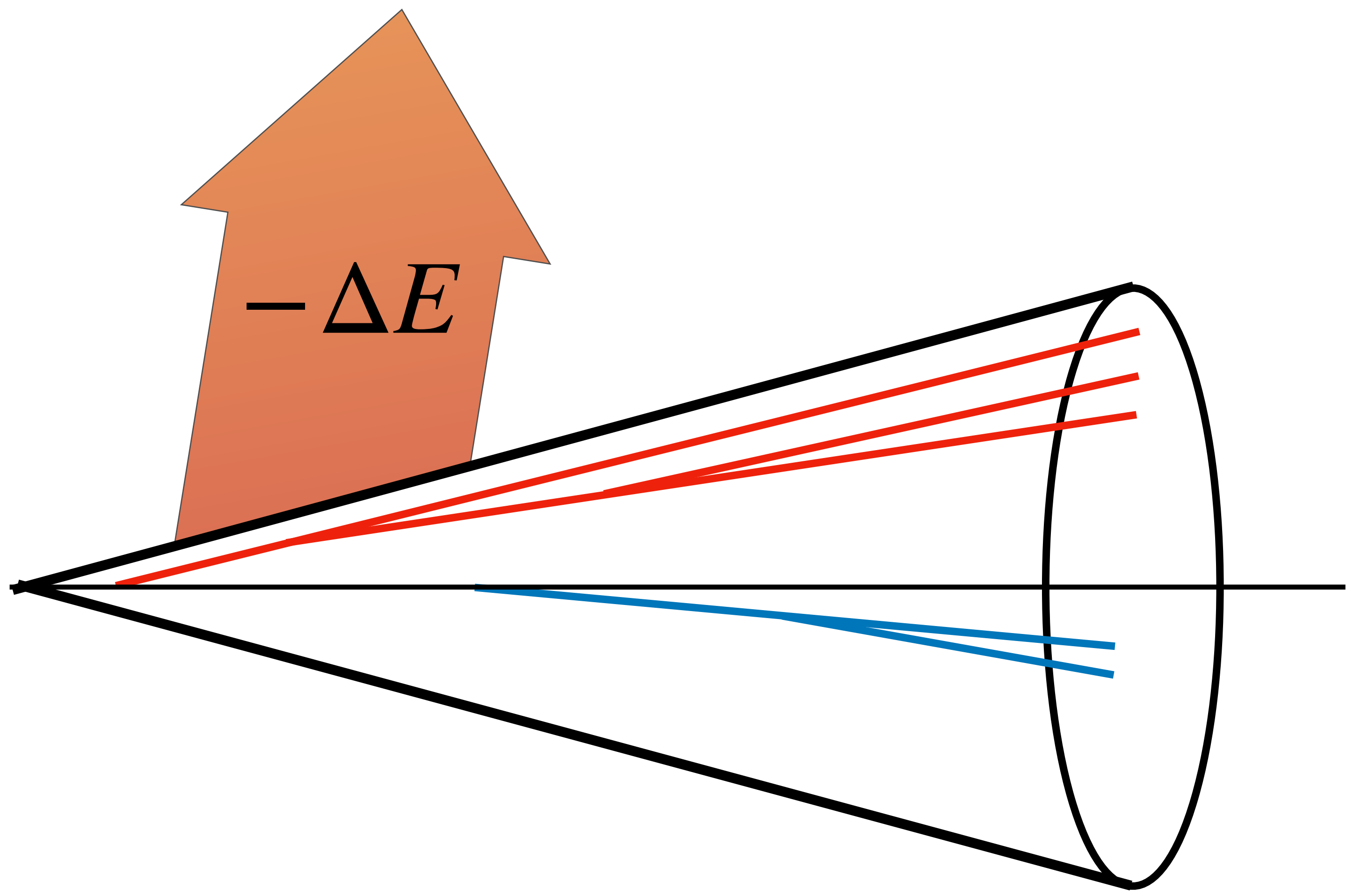
Area of red region is multiplicity of **in-medium** & **resolved** splittings

$$\Omega_\mathrm{in}^\mathrm{DLA} \approx 2\frac{\alpha_s C_R}{\pi} \log\frac{R}{\theta_c}\left(\log\frac{p_T}{\omega_c} + \frac{2}{3}\log\frac{R}{\theta_c}\right)$$

Potentially large and calls for **resummation**.

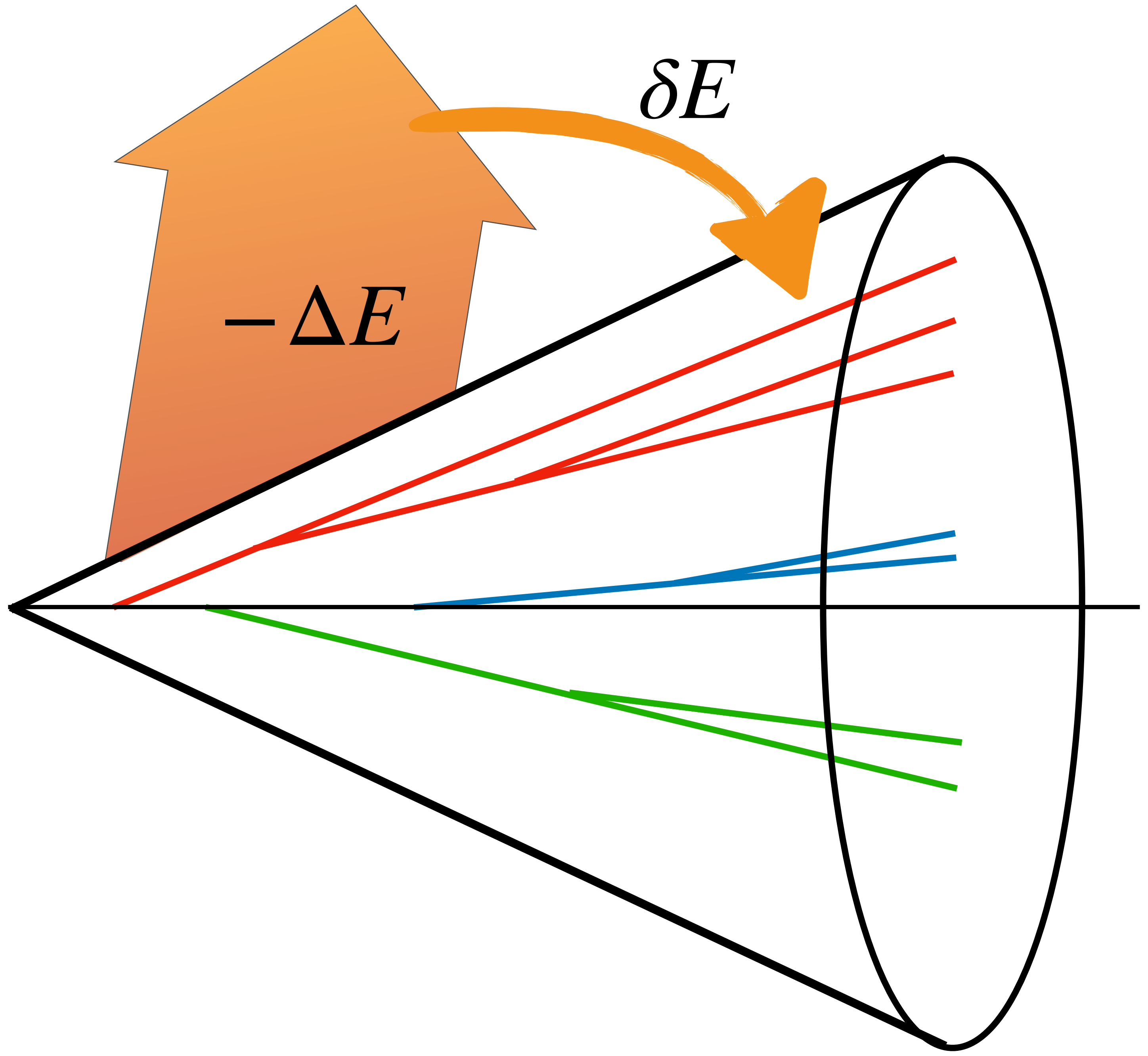
CONE-SIZE DEPENDENCE

Narrow jets



less energy loss BUT
easier to escape the cone

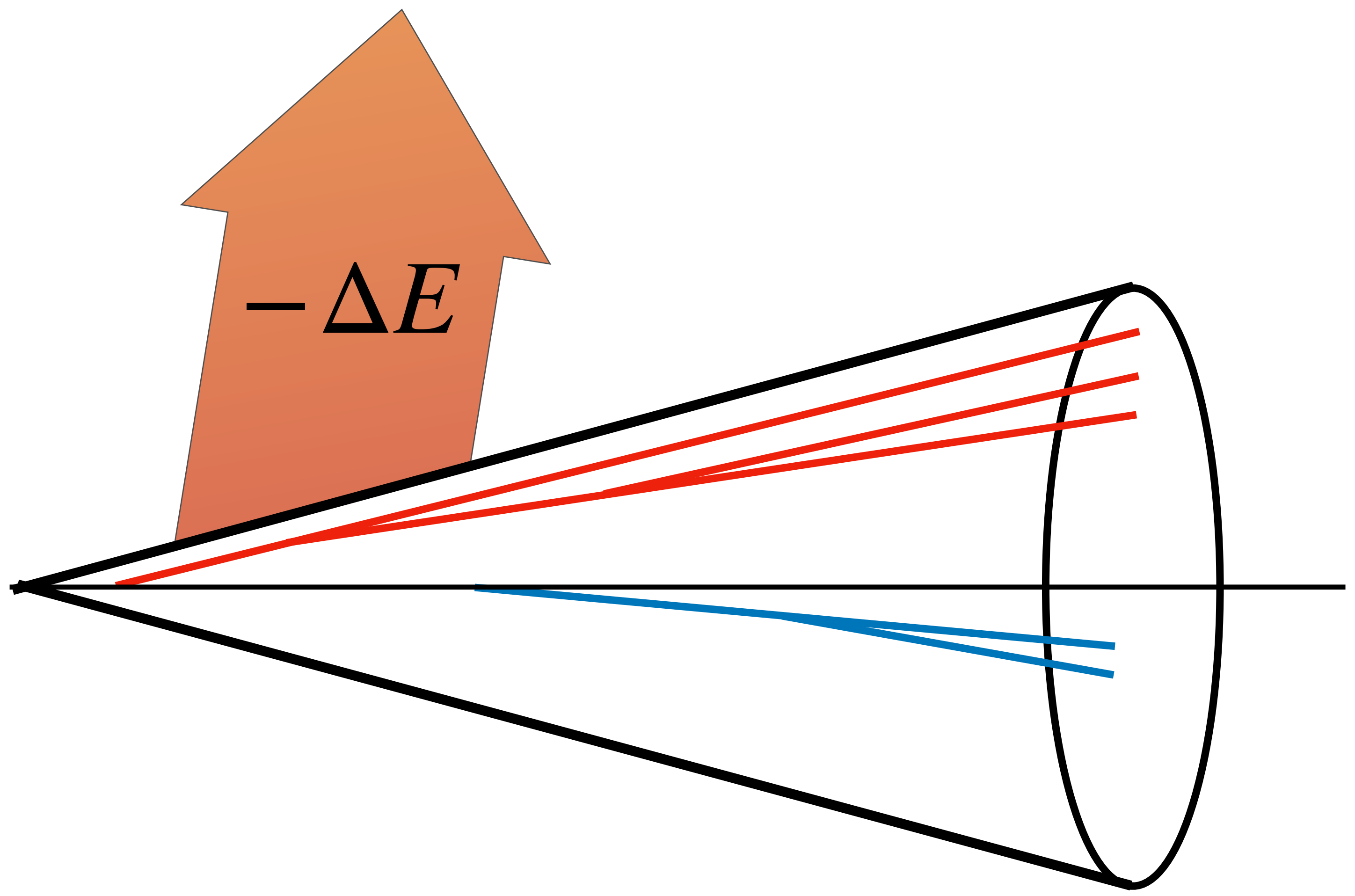
Wide jets



more energy loss BUT
emitted energy **leaks back** into cone

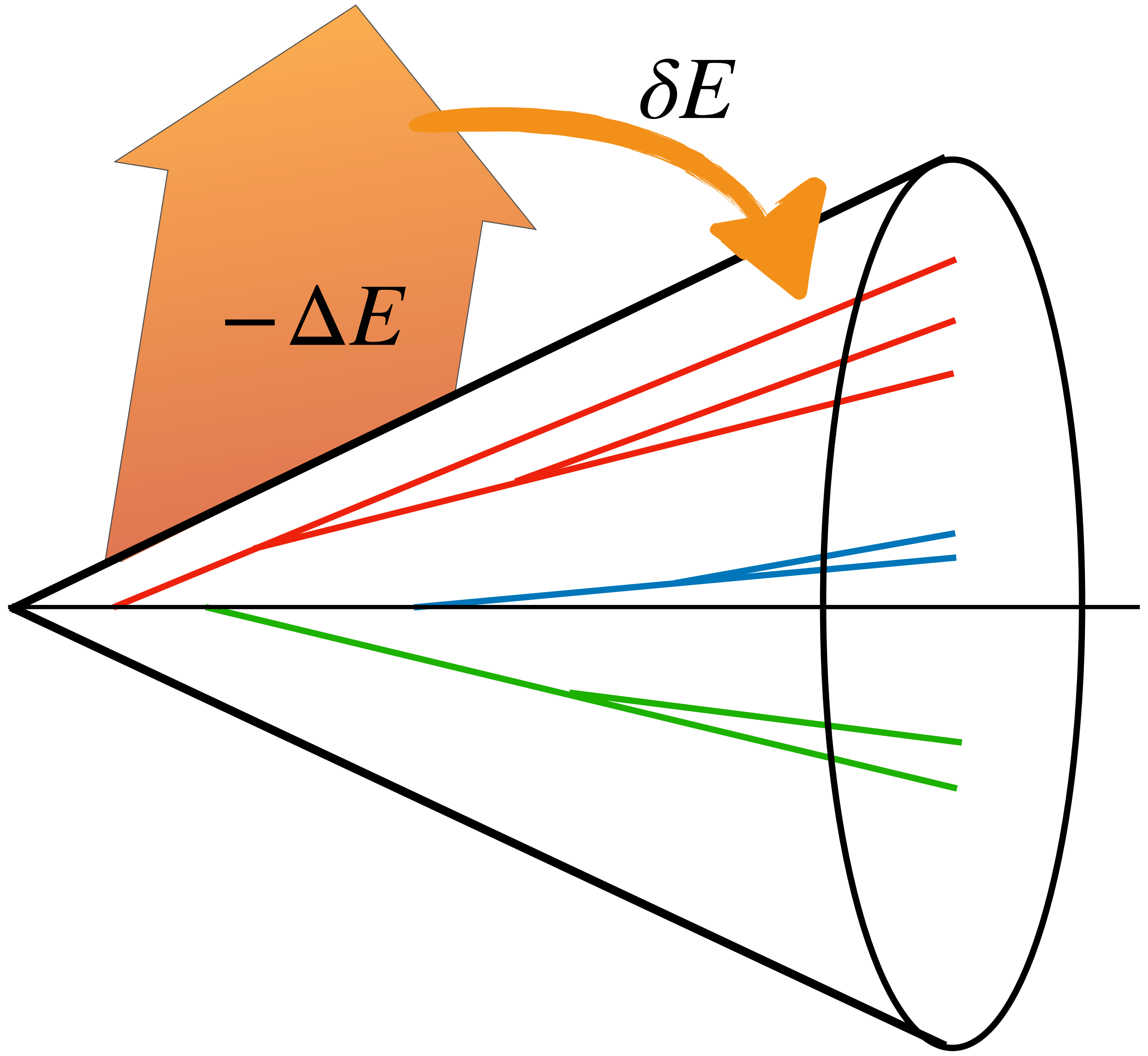
CONE-SIZE DEPENDENCE

Narrow jets



less energy loss BUT
easier to escape the cone

Wide jets

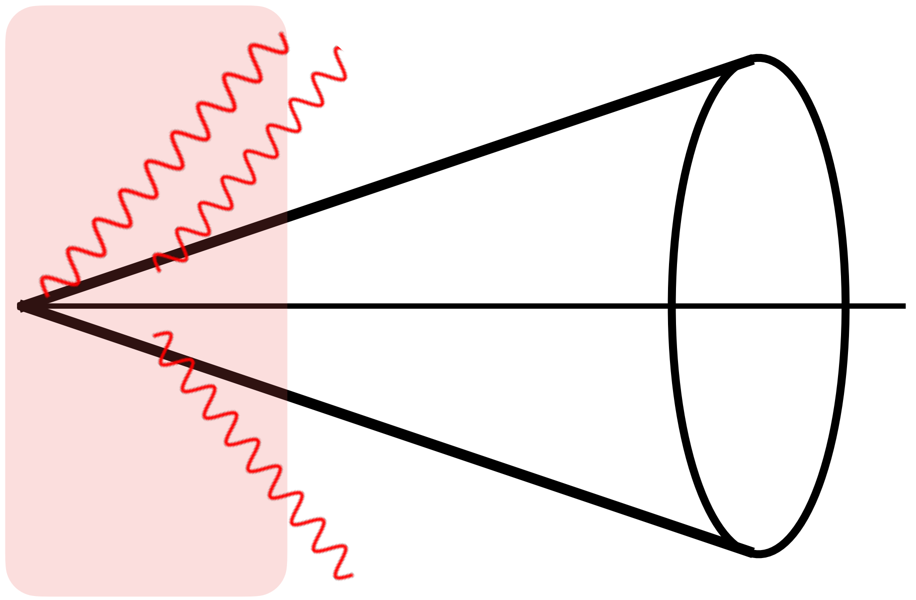


more energy loss BUT
emitted energy **leaks back** into cone

$\Longrightarrow$ new handle on medium effects: $\hat{q}$ affects **resolution** & **energy loss**

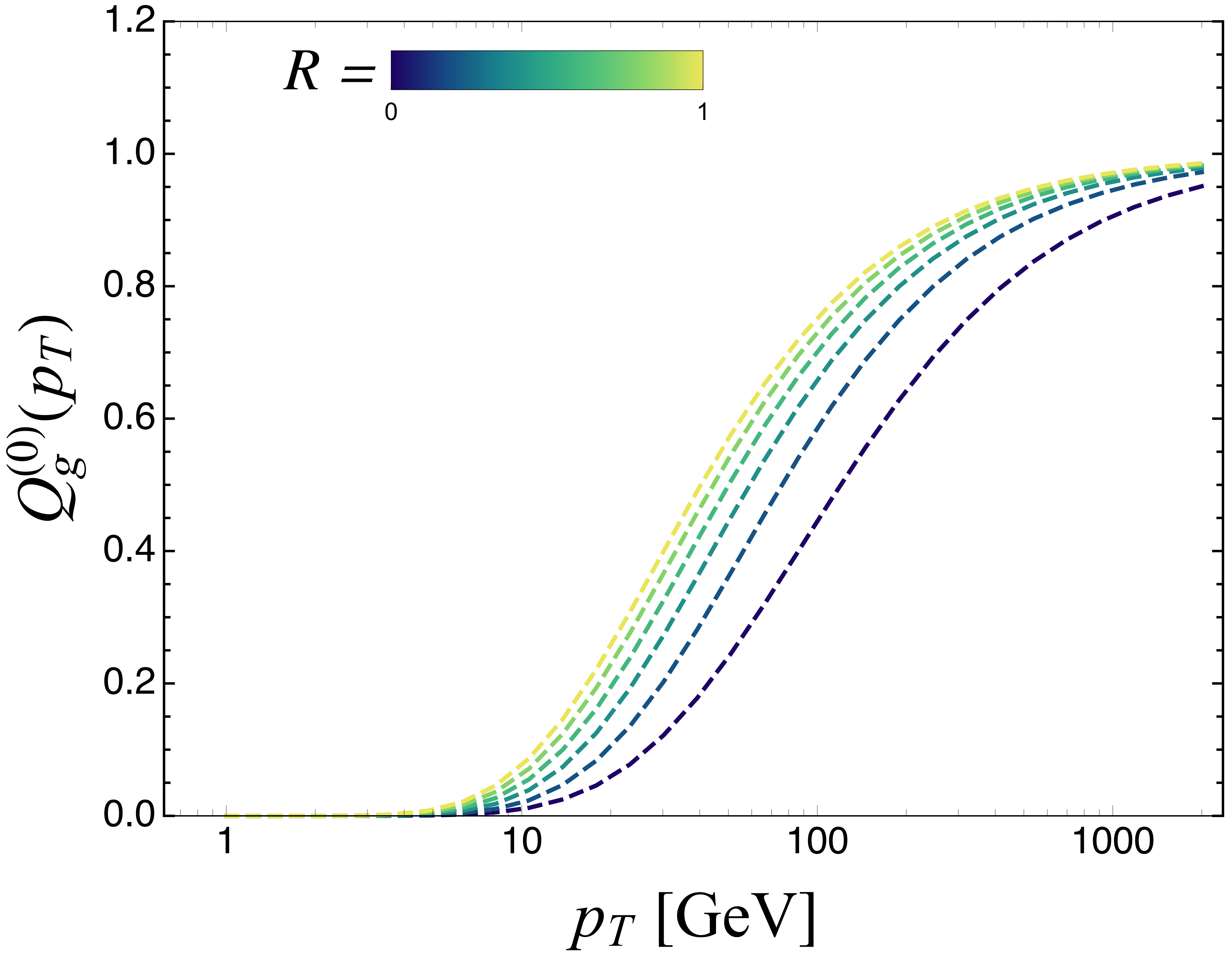
ENERGY LOSS OF SINGLE PARTON

Baier, Dokshitzer, Mueller, Schiff (2001); Salgado, Wiedemann (2003)



$$\frac{d\sigma}{dp_T} = Q_>^{(0)}(p_T, R)\hat{\sigma}_{AA\to i}$$

$$Q_>^{(0)}(p_T, R) = \exp\left[-\int_{T_0}^{\infty} d\omega \, \frac{dI_>}{d\omega}\left(1 - e^{-\nu\omega(1-\Theta(\omega_s-\omega)R^2/R^2_{\rm rec})}\right)\right]$$

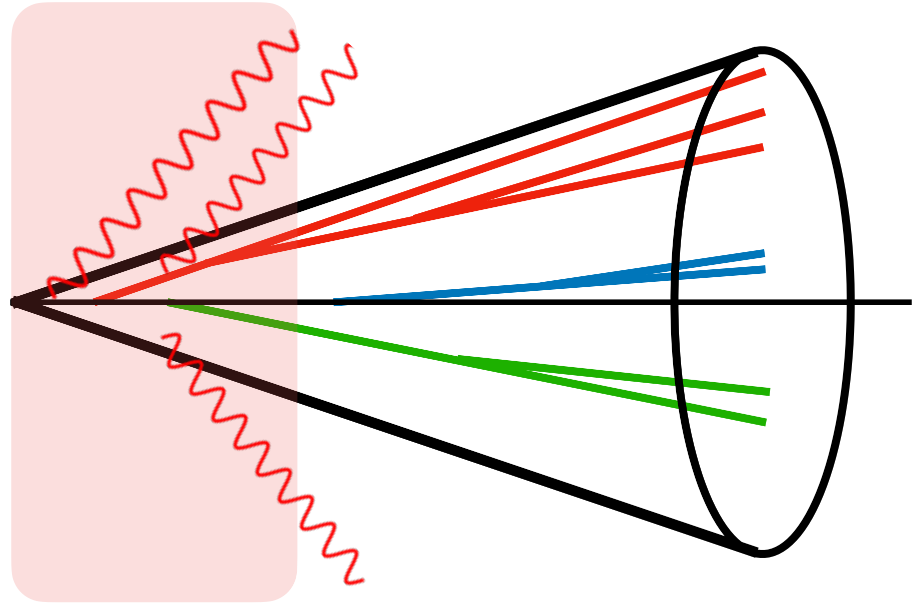


- Laplace variable $\nu = n/p_T$.
- out-of-cone emissions using differential IOE spectrum. Barata, Mehtar-Tani, Soto-Ontoso, KT 2106.07402
- dominated by emissions with $\omega_s \sim \alpha_s^2 \hat{q} L^2$.
- lost energy smeared over the solid angle $R_{\rm rec}$ - free parameter.

see talks by Takacs, Thu 09:00 & Isaksen, Wed 14:40

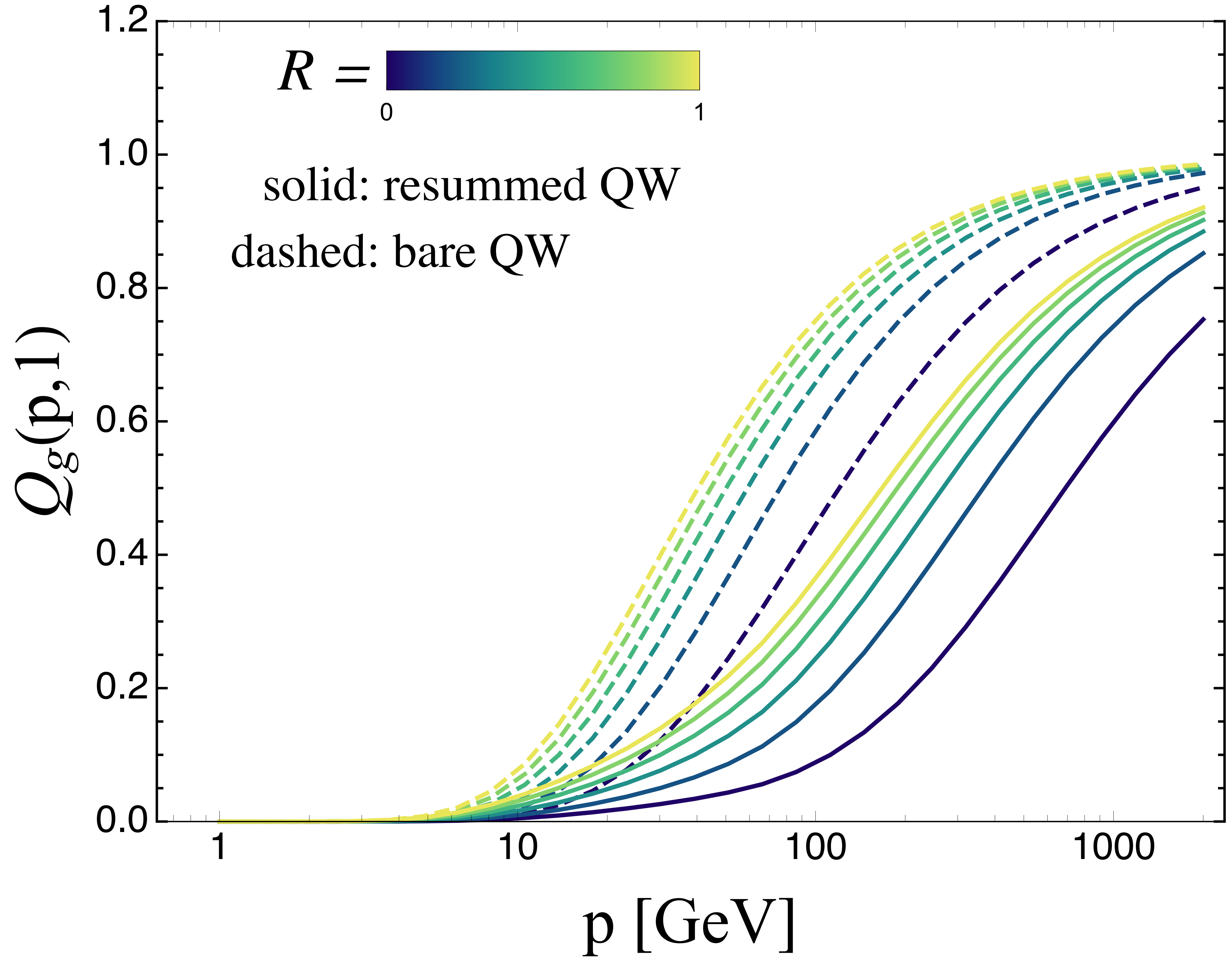
Energy loss of full jet

Mehtar-Tani, KT 1707.07361; Mehtar-Tani, Pablos, KT PRL 127 (2021)



$$\frac{\mathrm{d}\sigma^{\mathrm{jet}}}{\mathrm{d}p_T} = Q_>(p_T, R)\hat{\sigma}_{AA\to jet}$$

$$\frac{\partial Q_i(p,\theta)}{\partial \log\theta} = \int_0^1 \mathrm{d}z\, \frac{\alpha_s}{2\pi} p_{ij}(z)\Theta_{\mathrm{in}}\Big[Q_j(zp,\theta)Q_k((1-z)p,\theta)) - Q_i(p,\theta)\Big]$$

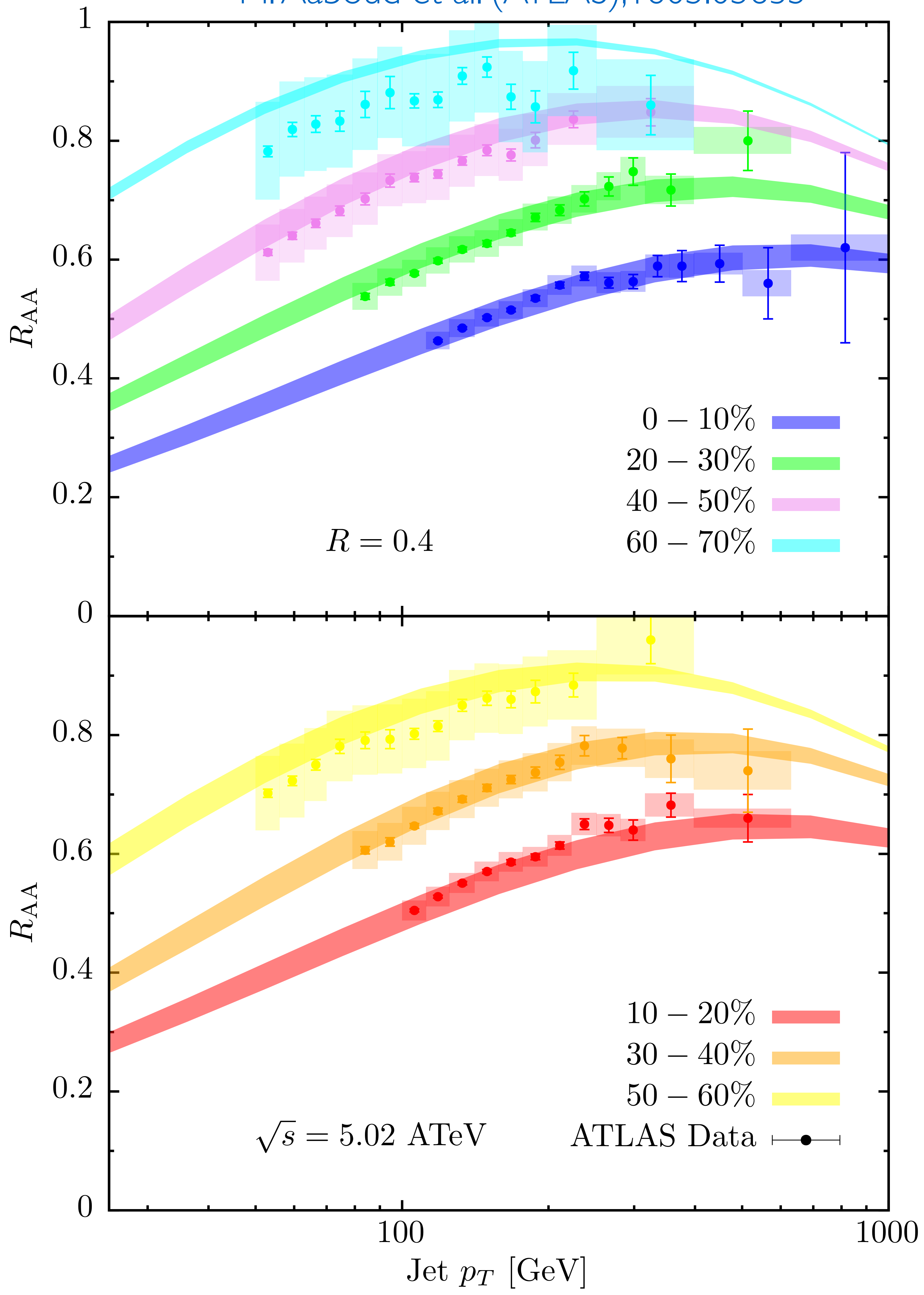


- non-linear evolution equation counting all **in-medium** & **resolved** splittings to compute full jet quenching.
- initial condition $Q_i(p,0) = Q^{(0)}_{>,\mathrm{rad}}(p_T) \times Q^{(0)}_{\mathrm{el}}(p_T) \times \ldots$

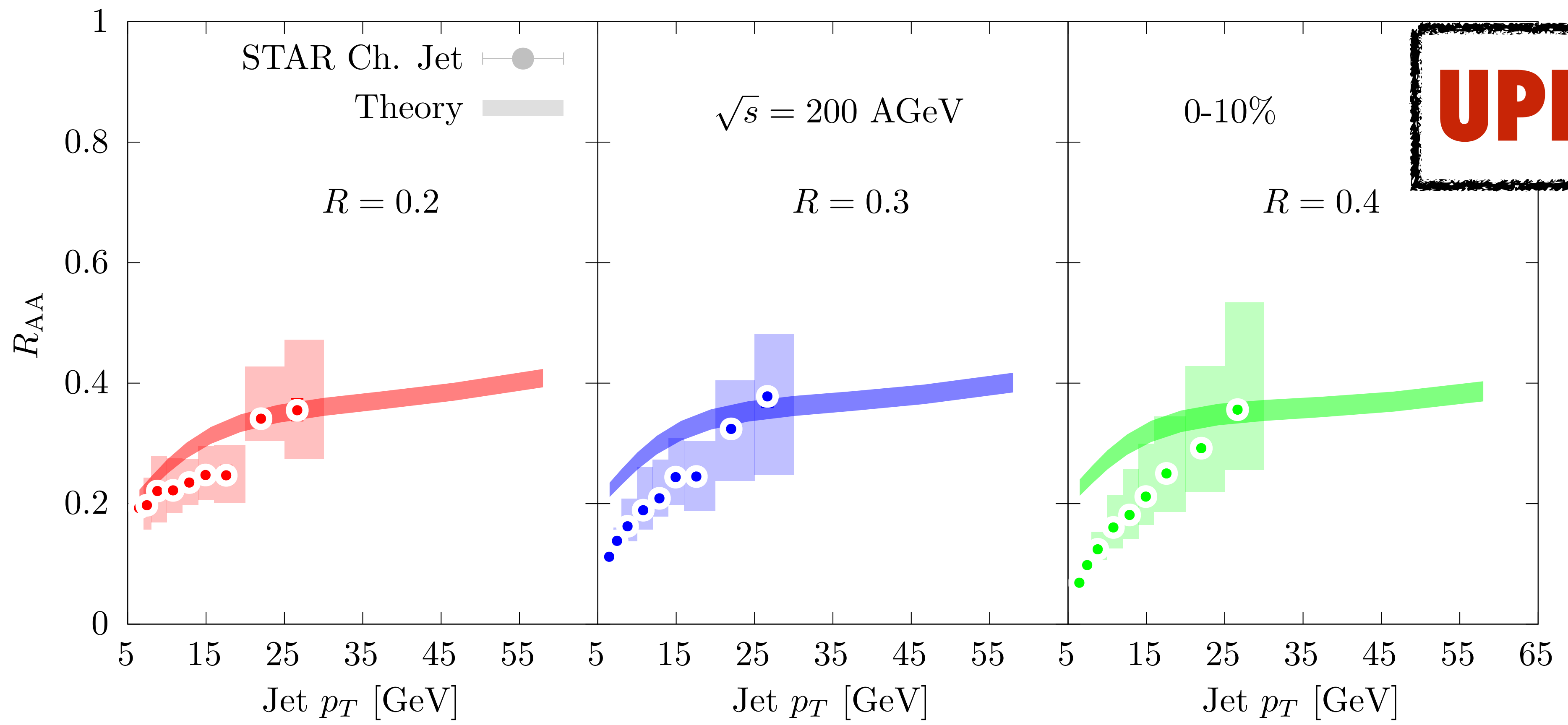
Linearized solution: $Q_i(p_T,R) = Q^{(0)}_{>,i}(p_T,R)\mathrm{e}^{(Q_g^{(0)}-1)\Omega_{\mathrm{in}}}$

JET SUPPRESSION FACTOR

M. Aaboud et al. (ATLAS), 1805.05635



Mehtar-Tani, Pablos, KT Phys. Rev. Lett. 127 (2021); Takacs, KT 2103.14676

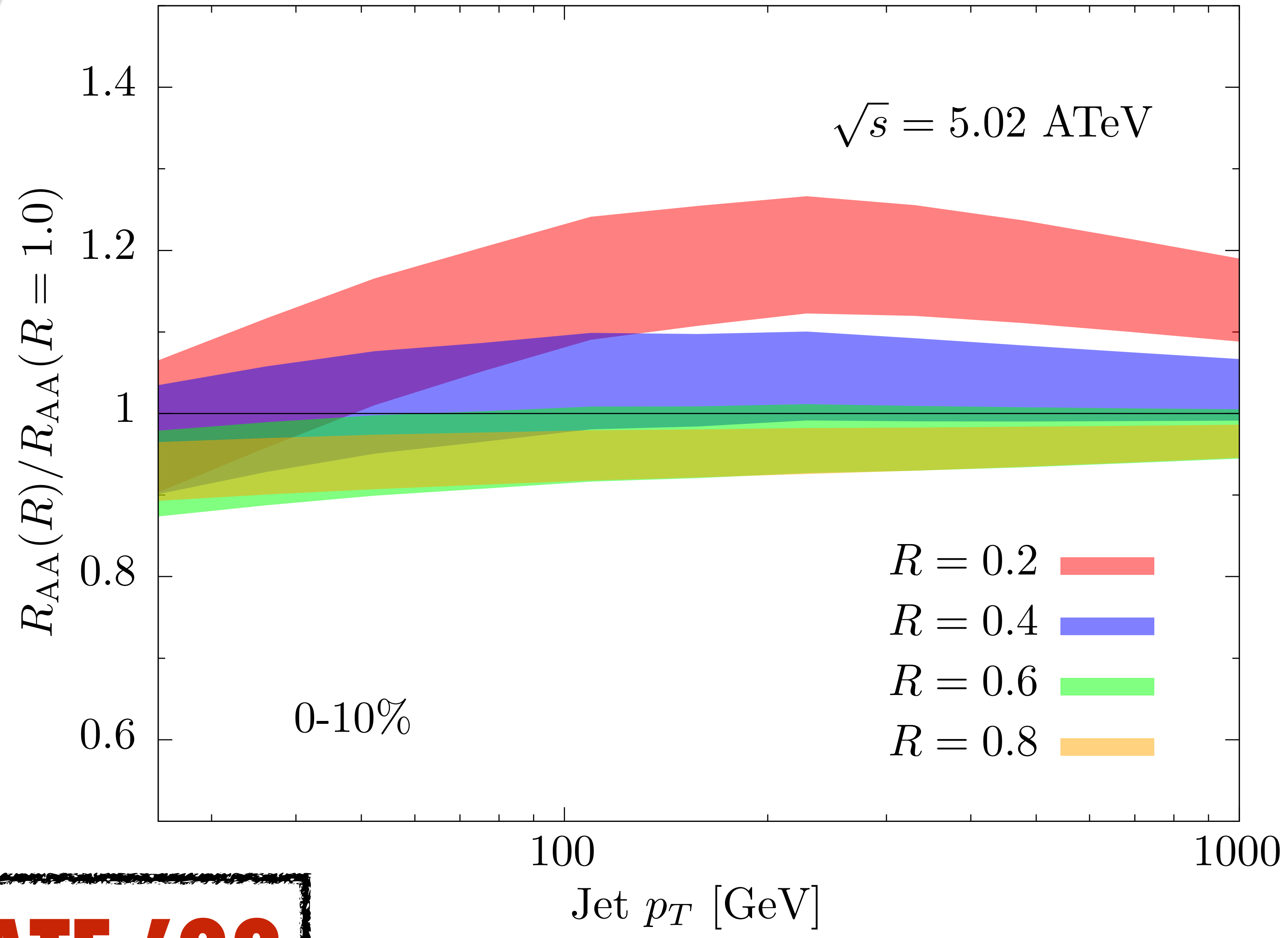


UPDATE '23

- collinear factorization w/nPDF (EPS09)
- $\log \frac{1}{R}$ resummation (AO DGLAP)
- full resummation of **radiative** and **elastic** processes in the medium
- **sampling of geometry** and medium evolution (VISHNU) Shen, Qiu, Song, Bernhard, Bass, Heinz 1409.8164
- only **two free parameters:** $g_{\rm med}$ and $R_{\rm rec}$

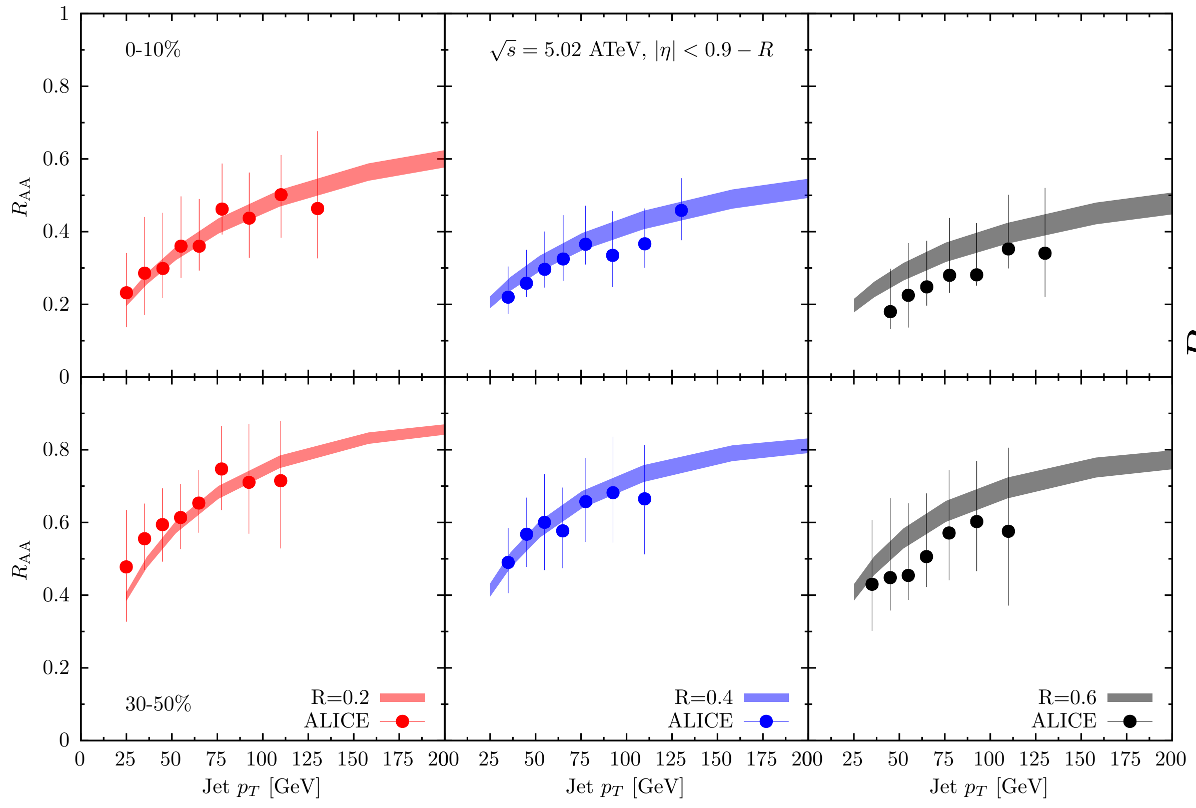
CONE-SIZE DEPENDENCE

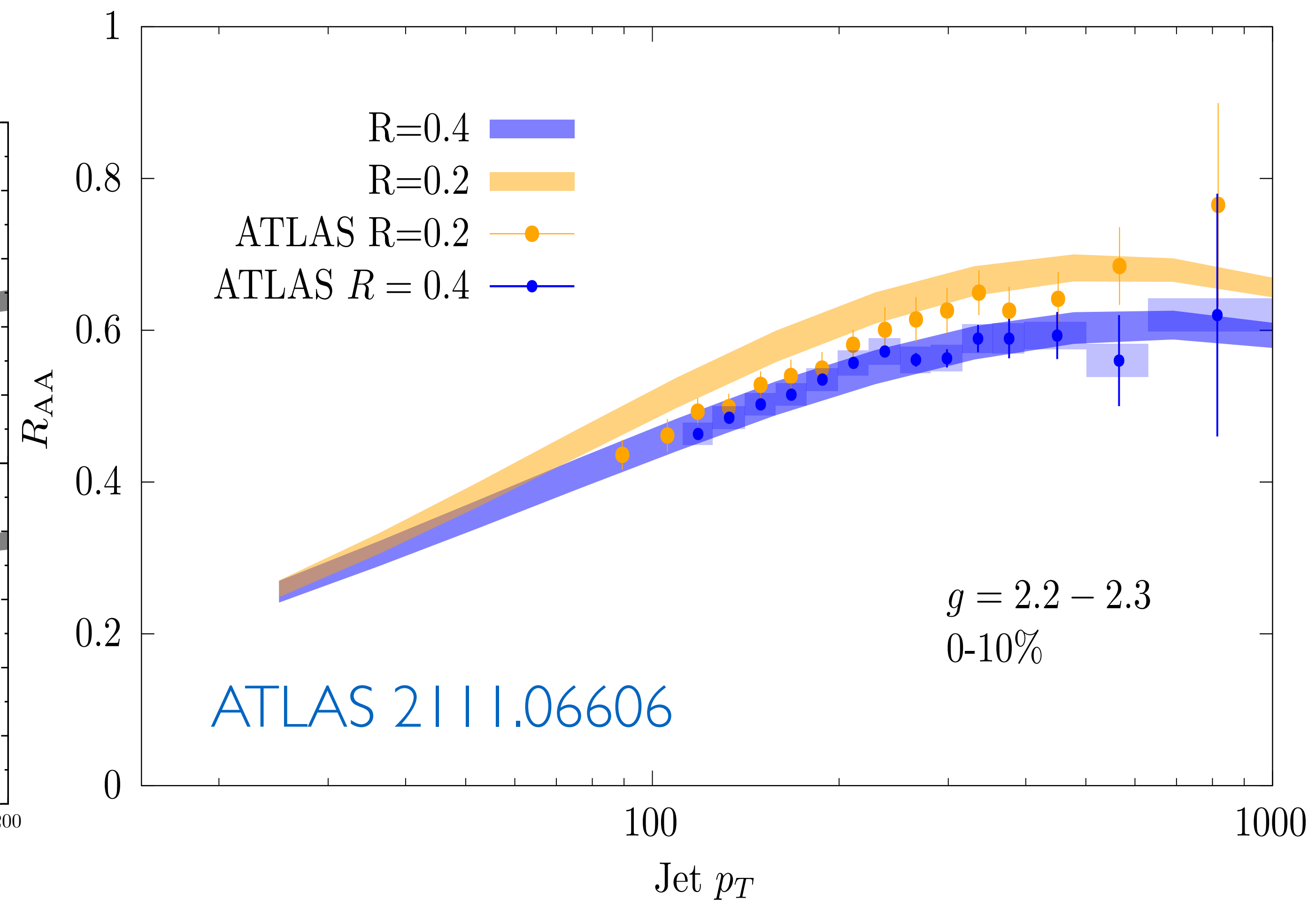
Mehtar-Tani, Pablos, KT PRL 127 (2021)
M. Aaboud et al. (ATLAS) 1805.05635
S. Acharya et al. (ALICE) 1909.09718
CMS-PAS-HIN-18-014



UPDATE '23

ALICE 2303.00592





- main uncertainties for $R \leq 0.6$:
  - perturbative sector (vacuum-like emissions + medium-induced $\omega > \omega_s$) dominates!
  - higher-twist contributions at IOE-NLO **negligible.**
  - details of thermalization/recovery ($R_{\rm rec}$) important at $R \gtrsim 0.6$.

- excellent agreement with existing experimental data!

Flowing to v_2

resolving path length dependence

Azimuthal angle dependence

Mehtar-Tani, Pablos, KT (to appear)

$$v_2 \approx \frac{1}{2} \frac{R_{AA}(L) - R_{AA}(L + \Delta L)}{R_{AA}(L) + R_{AA}(L + \Delta L)}$$

$$\mathrm{e} \sim \frac{\Delta L}{2L}$$

- flow @ high-p_T: **sensitivity to path length.**
- studied since a long time (puzzles…).

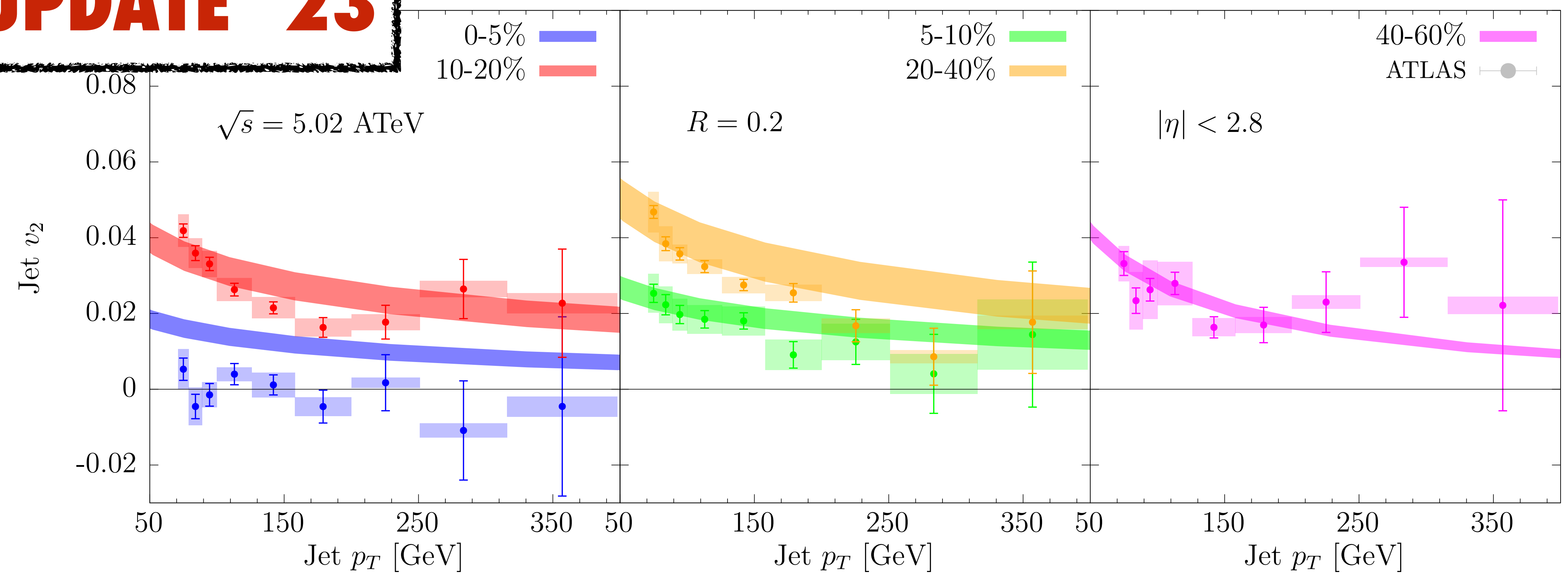
  Wang PRC (2001); Noronha-Hostler et al. (2016); Andres et al. 1902.03231; Barreto et al. 2208.02061;…
- for one single color charge: $v_2/\mathrm{e} \sim \partial \log R_{AA} / \partial \log p_T$.
  - works for hadron, too small for jets…

    Arleo, Falmagne 2212.01324
- additional effect for jets: $v_2 \sim [\Omega_{\rm in}(L) - \Omega_{\rm in}(L + \Delta L)](Q_g - 1)$.
  - sensitive to resolution effects!

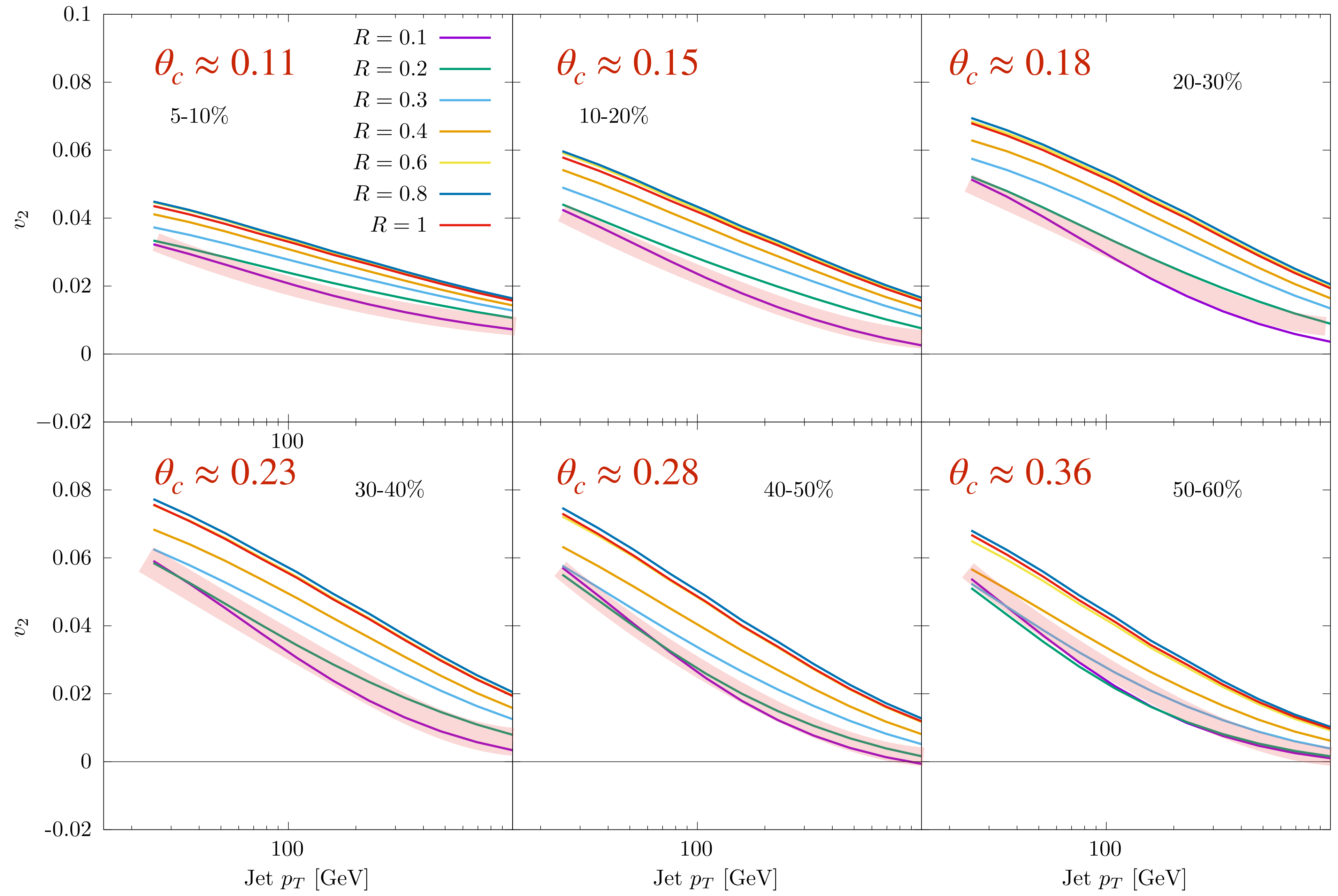
AZIMUTHAL ASYMMETRY

Mehtar-Tani, Pablos, KT (to appear)

UPDATE ’23

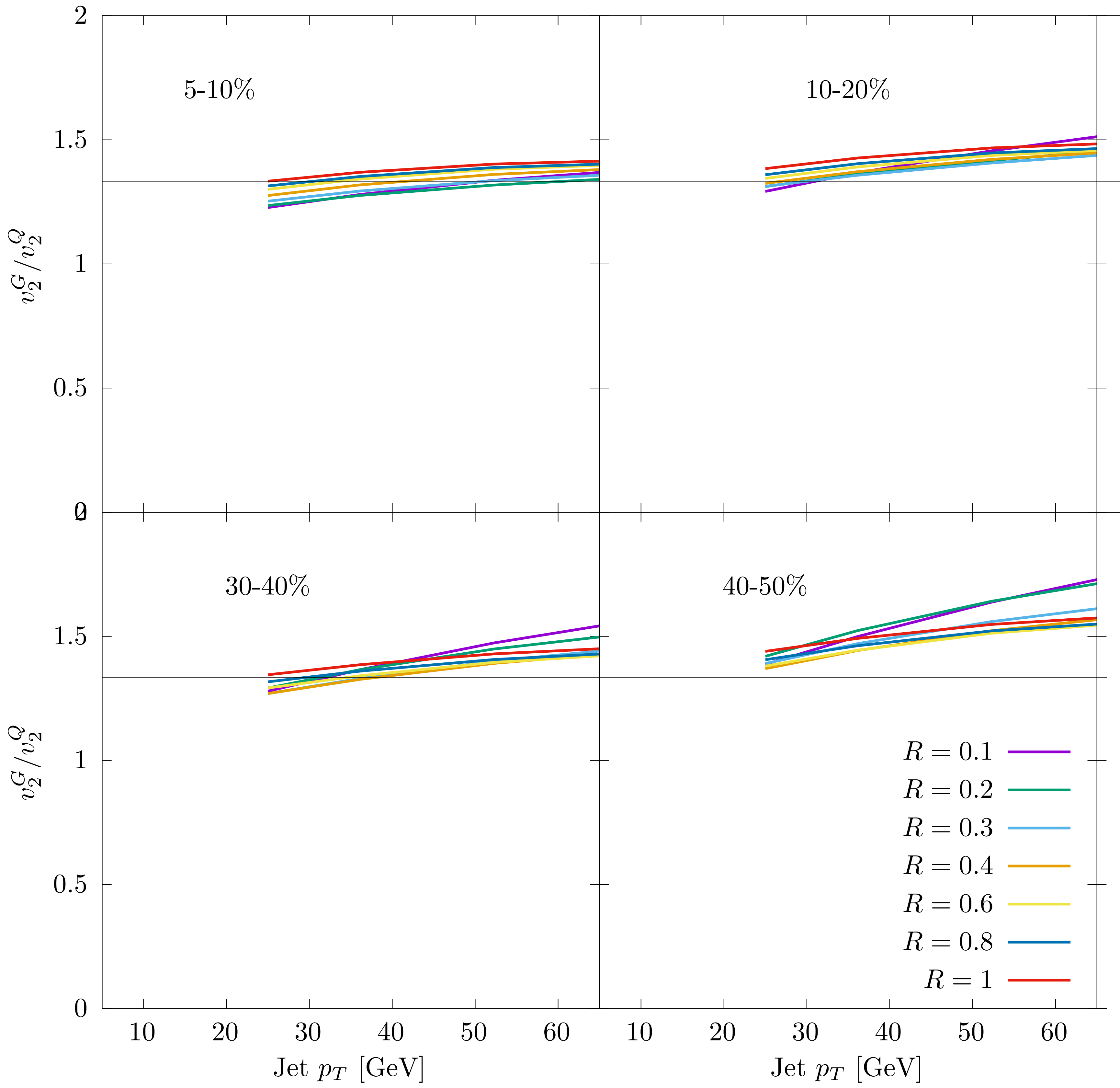


$$\frac{v_2^{\rm jet}}{\rm e} \approx \begin{cases} \frac{v_2^{\rm parton}}{\rm e} & \text{for } R < \theta_c \\ \frac{v_2^{\rm parton}}{\rm e} + \frac{3}{2}\bar{\alpha} \log \frac{p_T}{\omega_c}(1 - Q_g) & \text{for } R > \theta_c \end{cases}$$



- jet v_2 receives additional contribution from resolution effects.
- full simulation yields **excellent agreement with experimental data.**
- **prediction**: cone-size dependence vs centrality reveal sensitivity to coherence angle (grouping).

APPROXIMATE CASIMIR SCALING OF v_2



see talk by Pablos, Wed 11:10

$$\frac{v_2^g}{v_2^q} \approx \frac{N_c}{C_F} \Leftrightarrow Q_g \approx (Q_q)^{N_c/C_F}$$

- flow scales with color factors.
- **correlation** between R_{AA} and v_2
- tuning the quark fraction by comparing flow in
  - inclusive and γ-triggered events
  - as a function of jet rapidity

Summary

jet quenching & flow

- **medium controls simultaneously:** energy loss, me.dium recoil and jet resolution connected through $\hat{q}$
- **resummation framework describe the data across the board:** p_T, centrality, and R dependence provides a basis for more precision computations.
- **azimuthal dependence:** additional handle on length dependence & sensitivity to coherence angle.

Summary

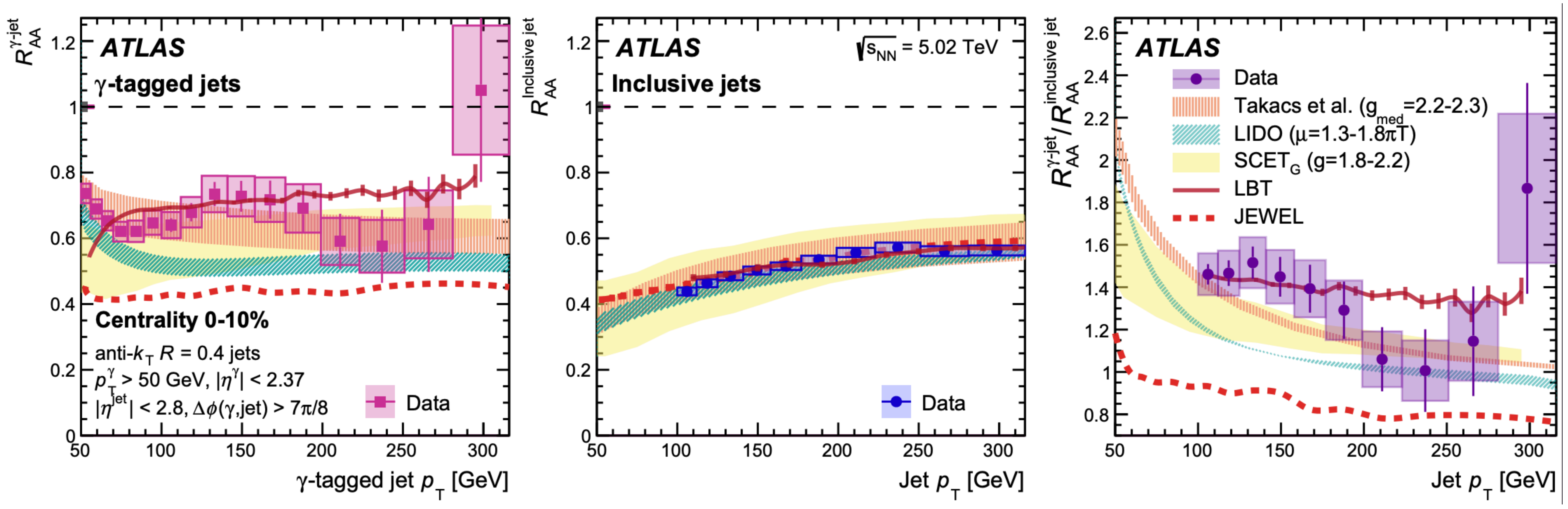
jet quenching & flow

- **medium controls simultaneously:** energy loss, me.dium recoil and jet resolution connected through $\hat{q}$
- **resummation framework describe the data across the board:** p_T, centrality, and R dependence provides a basis for more precision computations.
- **azimuthal dependence:** additional handle on length dependence & sensitivity to coherence angle.

A **huge thanks** to Dani Pablos & Yacine Mehtar-Tani for collaboration on the project!

Any questions?

γ-TAGGED JET R_{AA}



see talk by McGinn, Wed 09:00

- work by Adam Takacs and Dani Pablos
- γ-tagging give quark-enriched sample of jets
- but slope is much **smaller** - complicated interplay!