PARTON PROPAGATION AND ENERGY LOSS: NEW THEORETICAL PROGRESS

Konrad Tywoniuk

28th International Conference on Ultrarelativistic Nucleus-Nucleus Collisions (Quark Matter 2019)
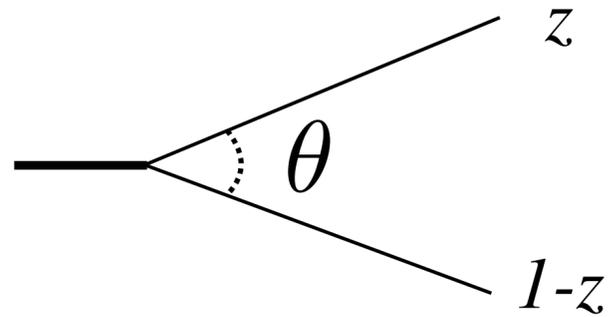*3-9 November, 2019, Wuhan, China*

OUTLINE

- the structure of QCD jets

- the evolving story of an observable

- inevitability of jet substructure

- R-dependent jet spectrum in PbPb collisions
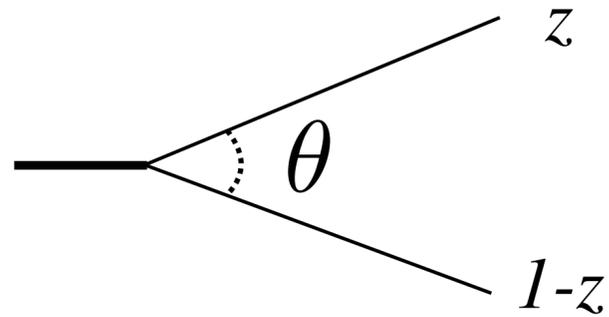
Jet physics in vacuum

VACUUM SPLITTING

z

θ

1-z

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

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

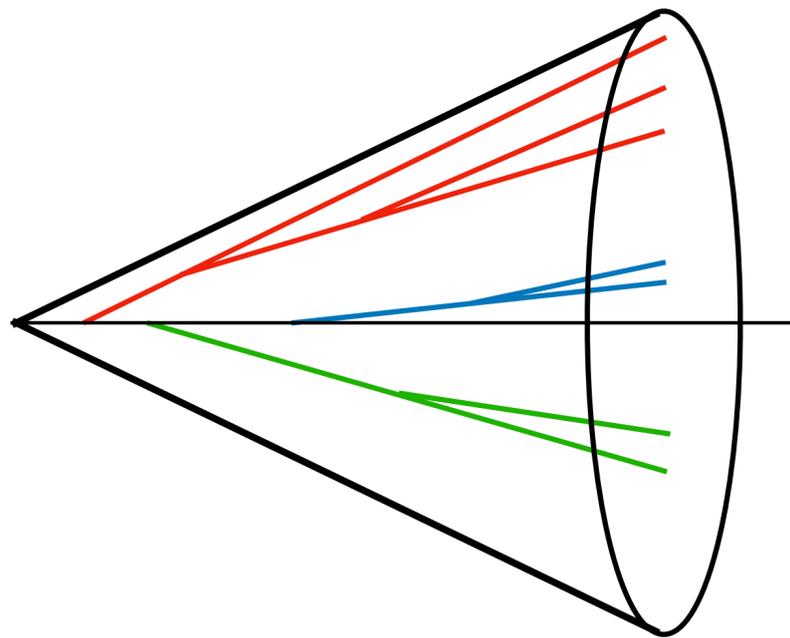Diverges for soft & collinear radiation!

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Diverges for soft & collinear radiation!

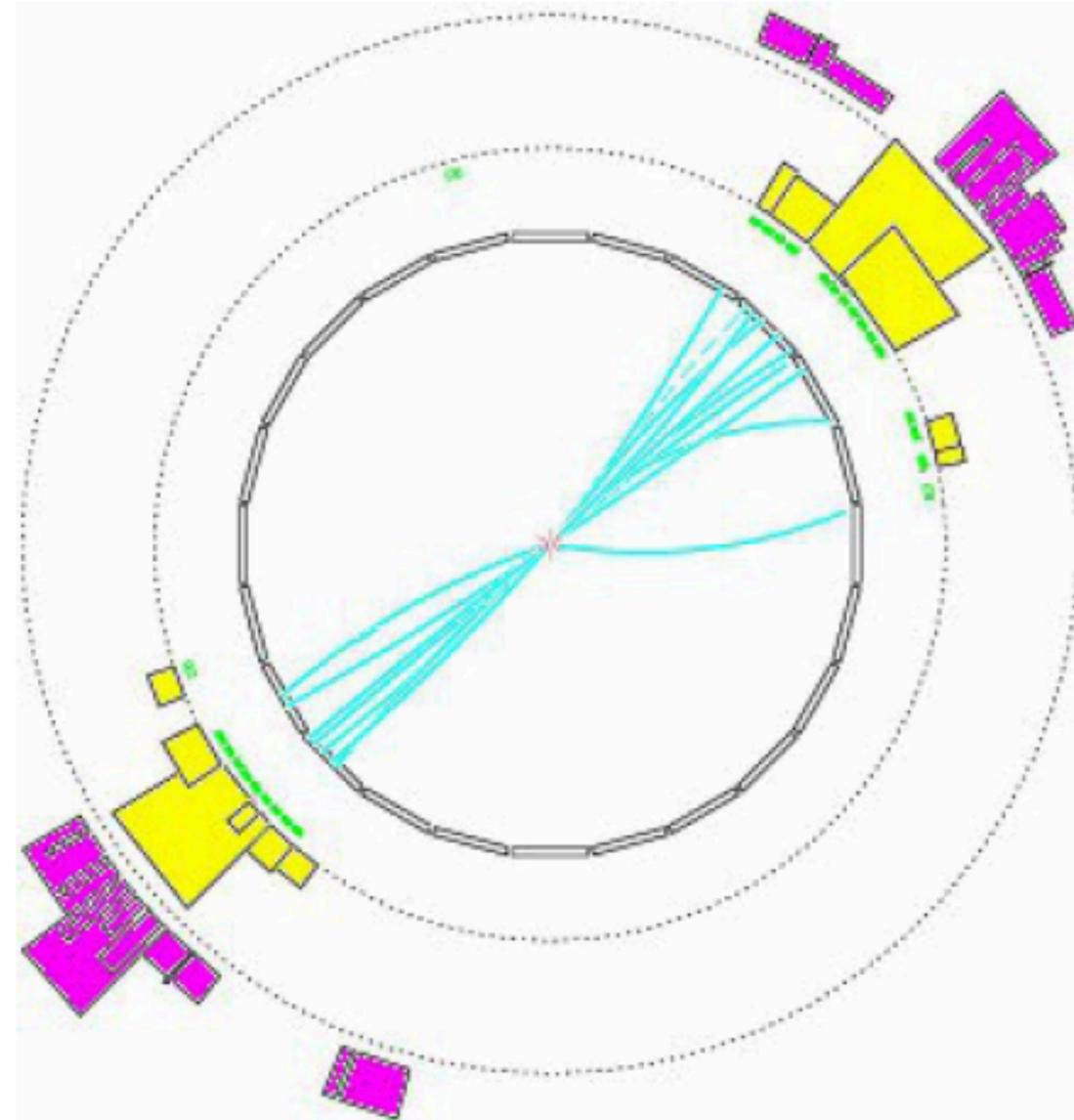Large phase space for radiation compensates α_s!

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

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

Vacuum splitting

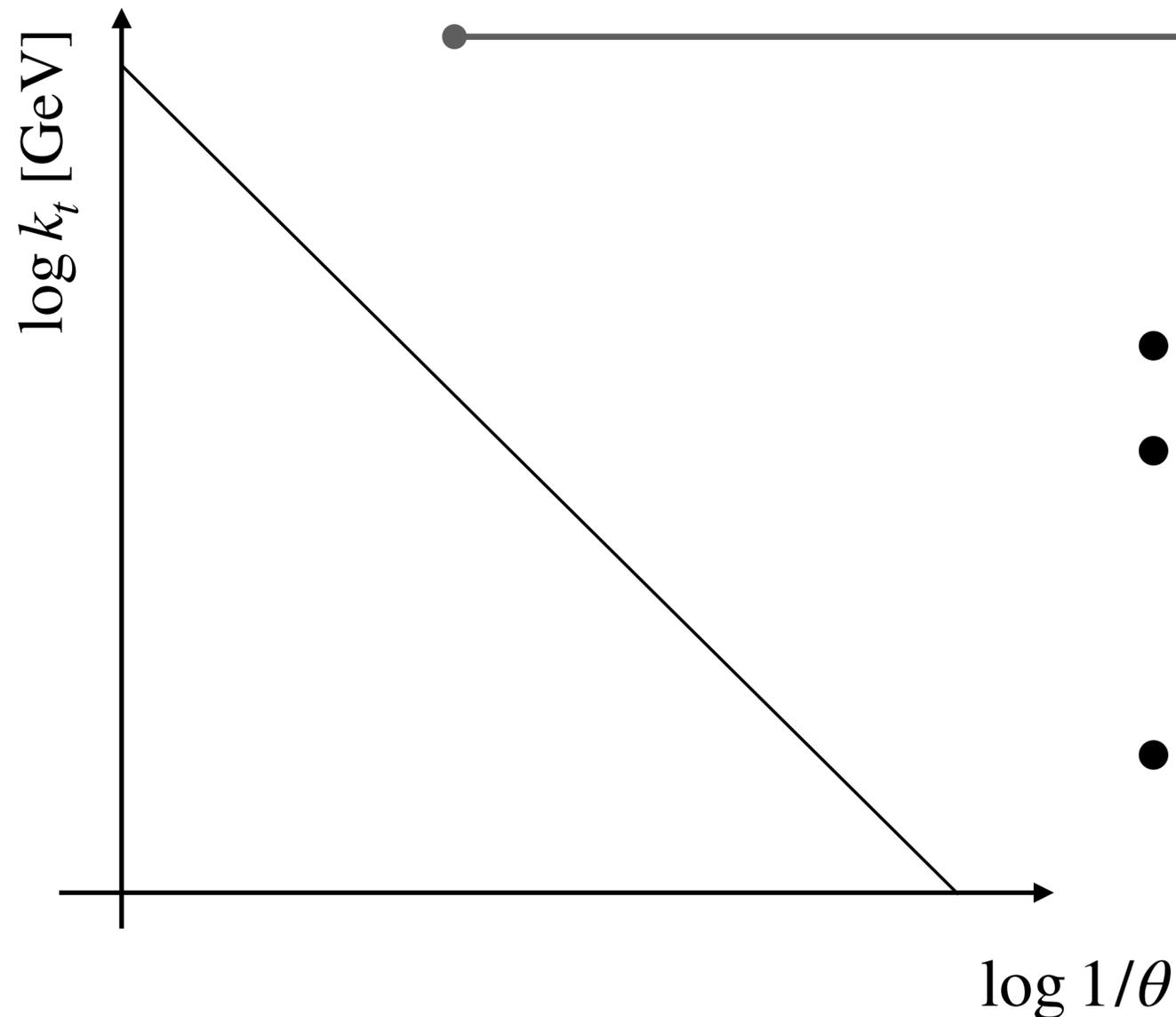Observed as "jets": collimated sprays of particles/energy.

Sterman, Weinberg (1977)

SPACE-TIME PICTURE OF A JET

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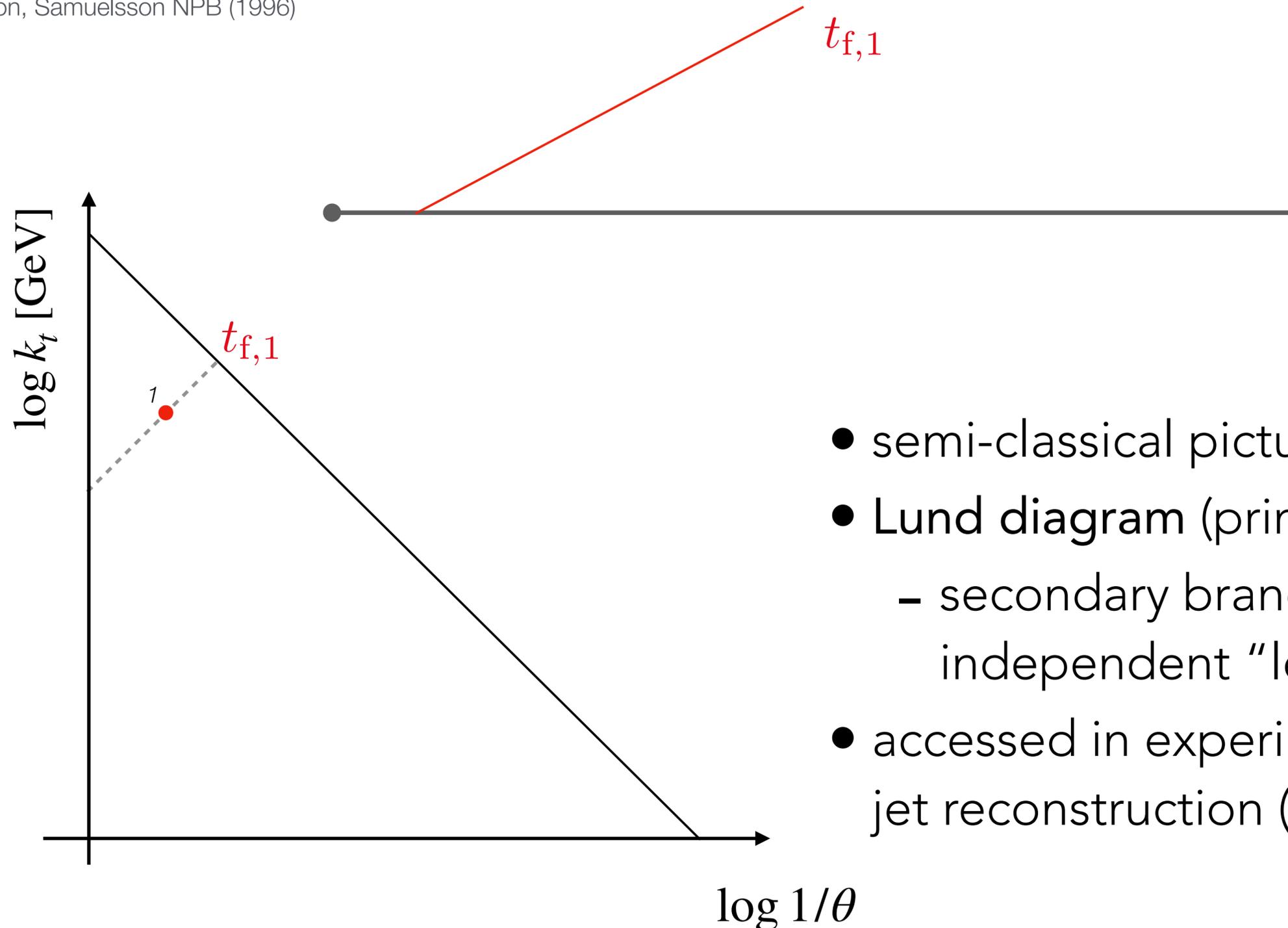Andersson, Gustafson, Samuelsson NPB (1996)

- semi-classical picture, angular ordering
- **Lund diagram** (primary emission plane)
  - secondary branchings located on independent "leaves"
- accessed in experimental data using jet reconstruction (C/A algorithm)

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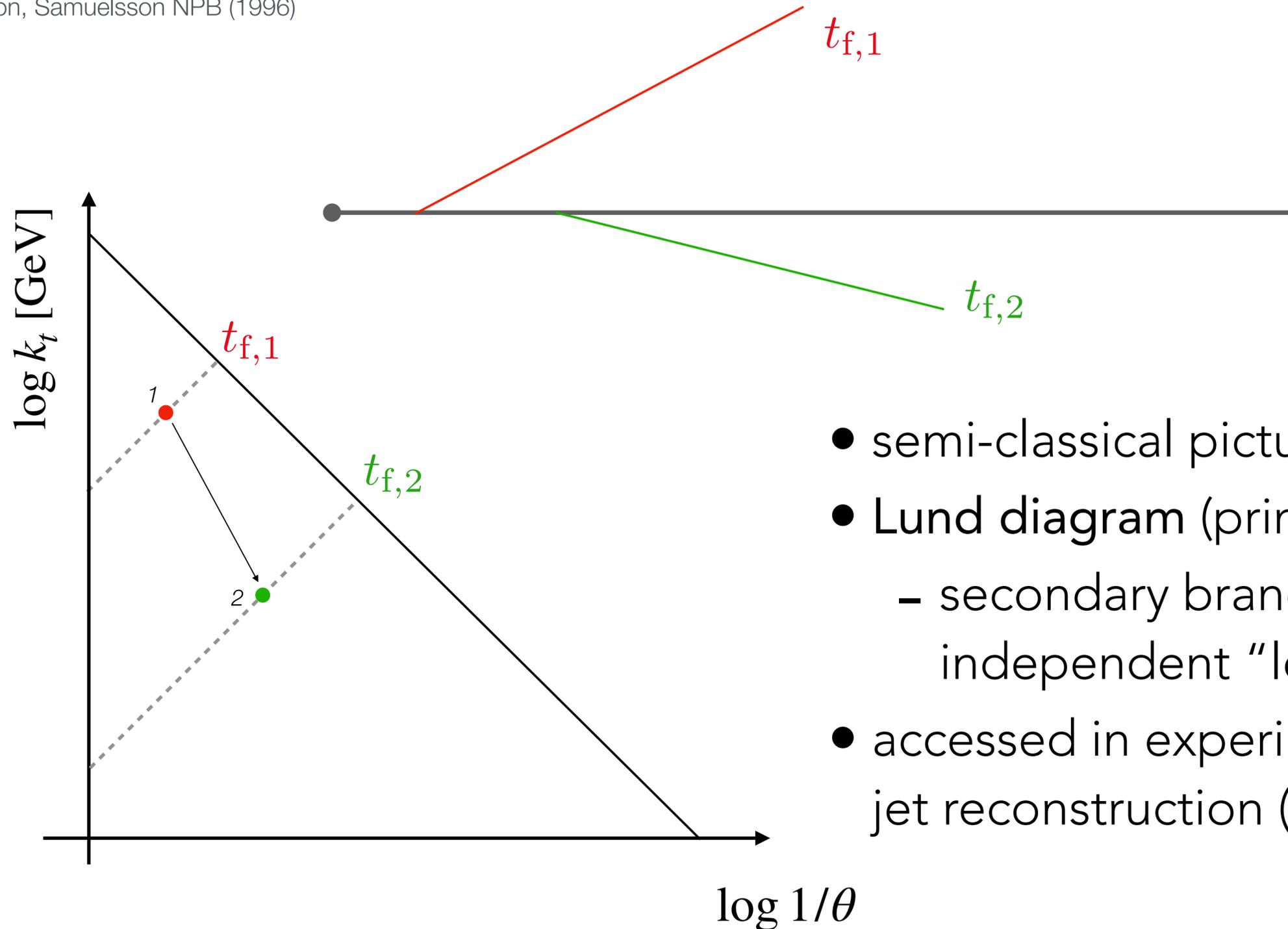Andersson, Gustafson, Samuelsson NPB (1996)

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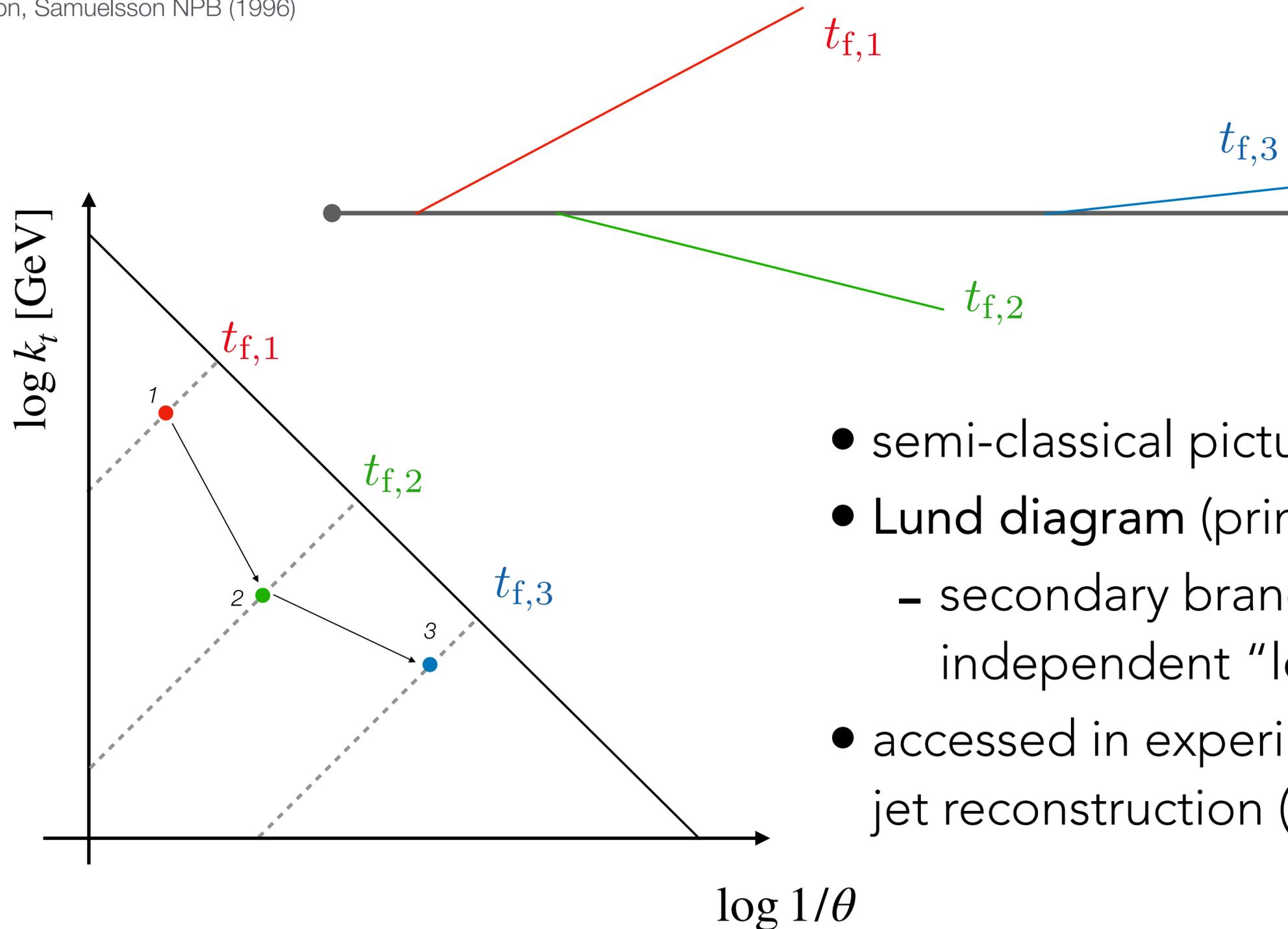Andersson, Gustafson, Samuelsson NPB (1996)

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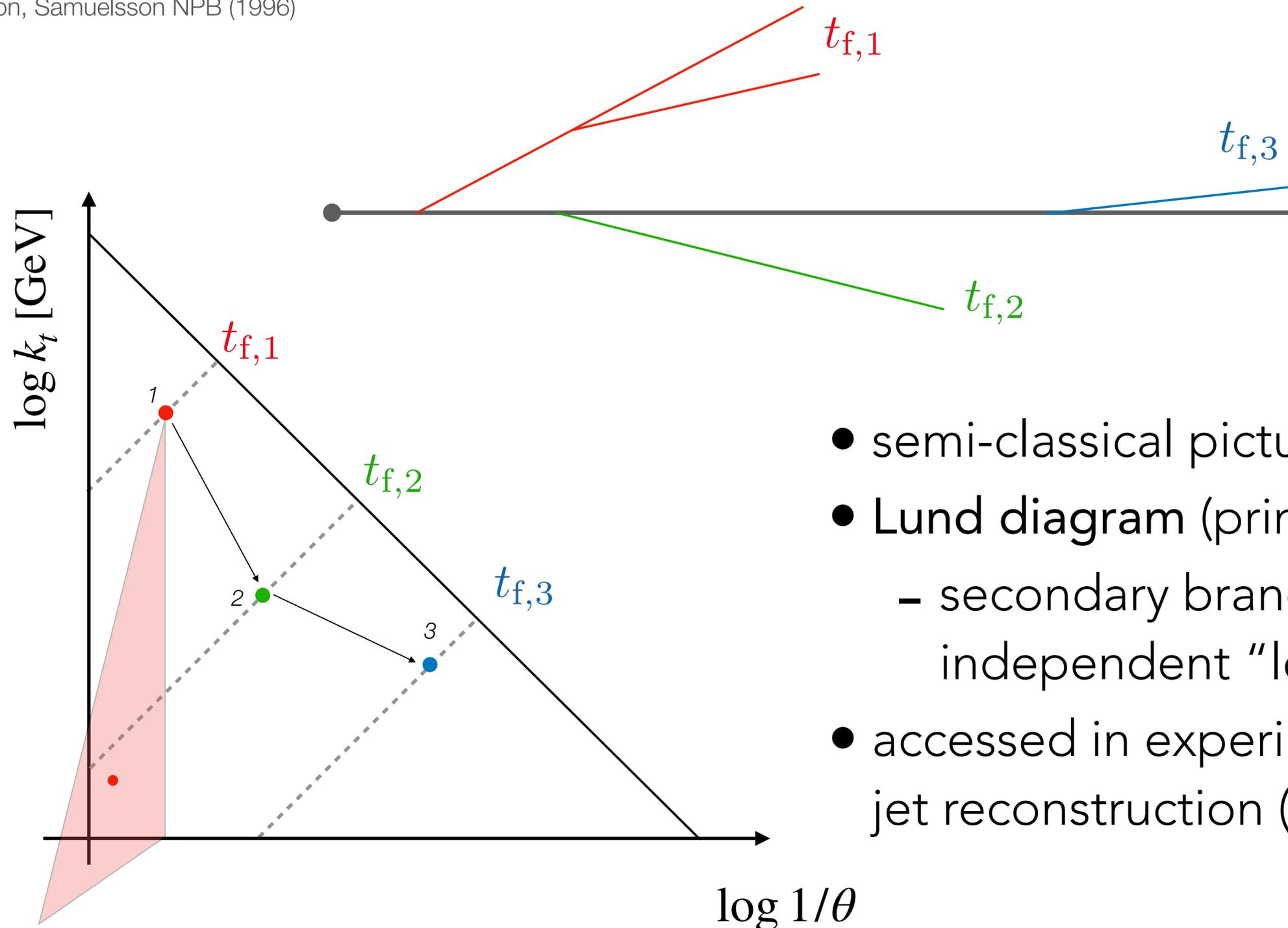Andersson, Gustafson, Samuelsson NPB (1996)

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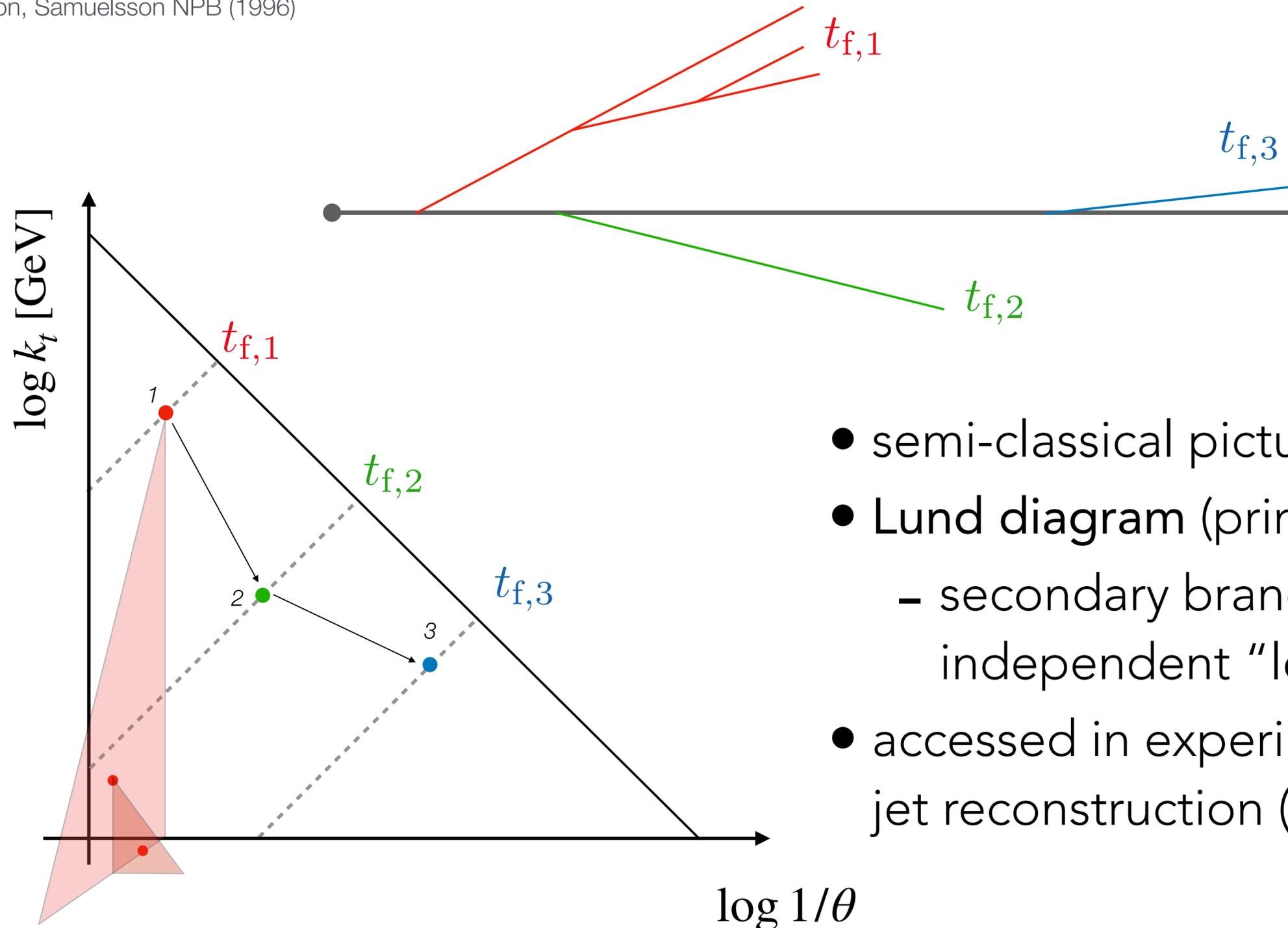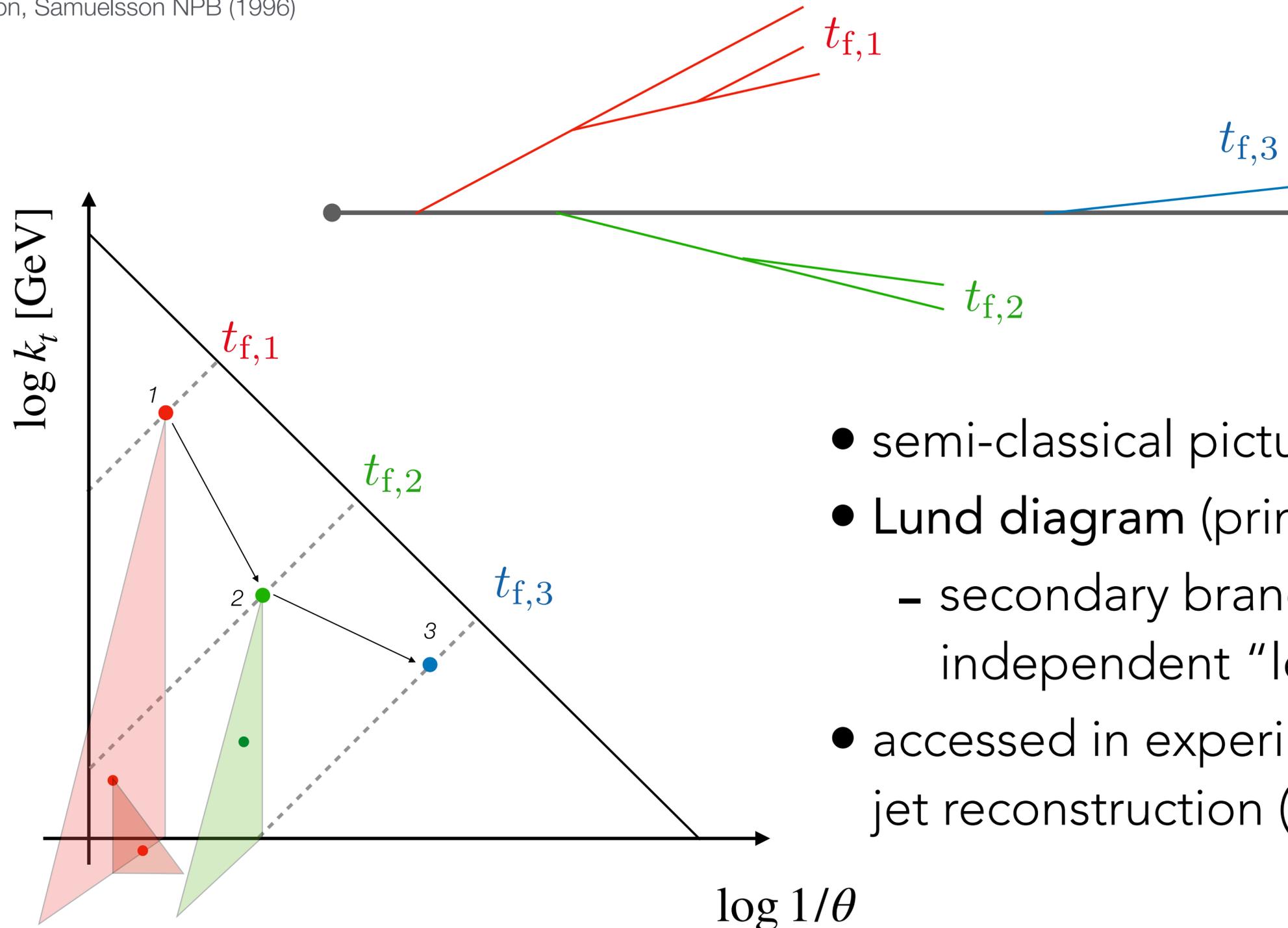Andersson, Gustafson, Samuelsson NPB (1996)

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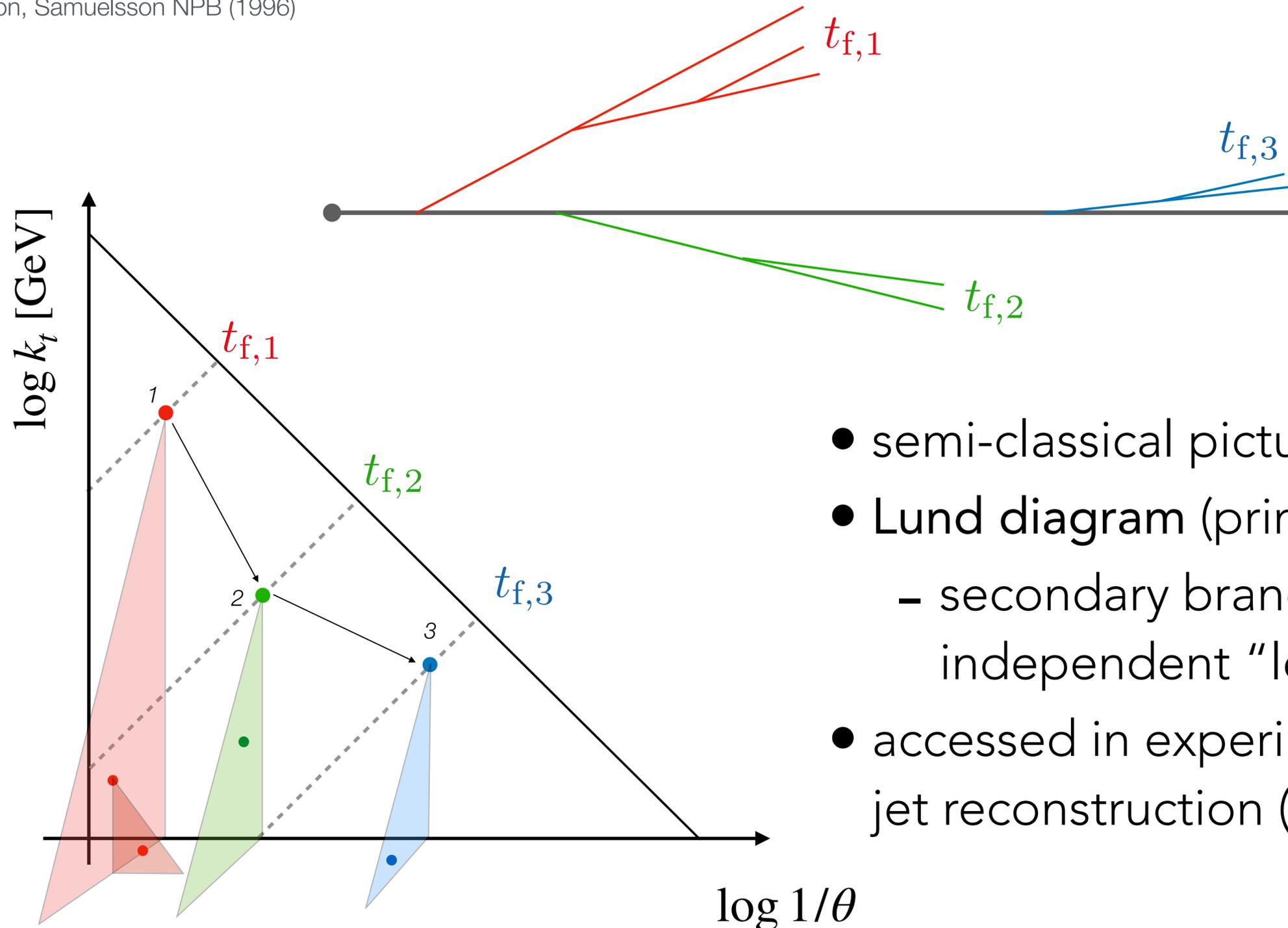Andersson, Gustafson, Samuelsson NPB (1996)

hadronization

from $t_{\rm f} \sim (Q_0 R)^{-1} \sim 2\,{\rm fm}$
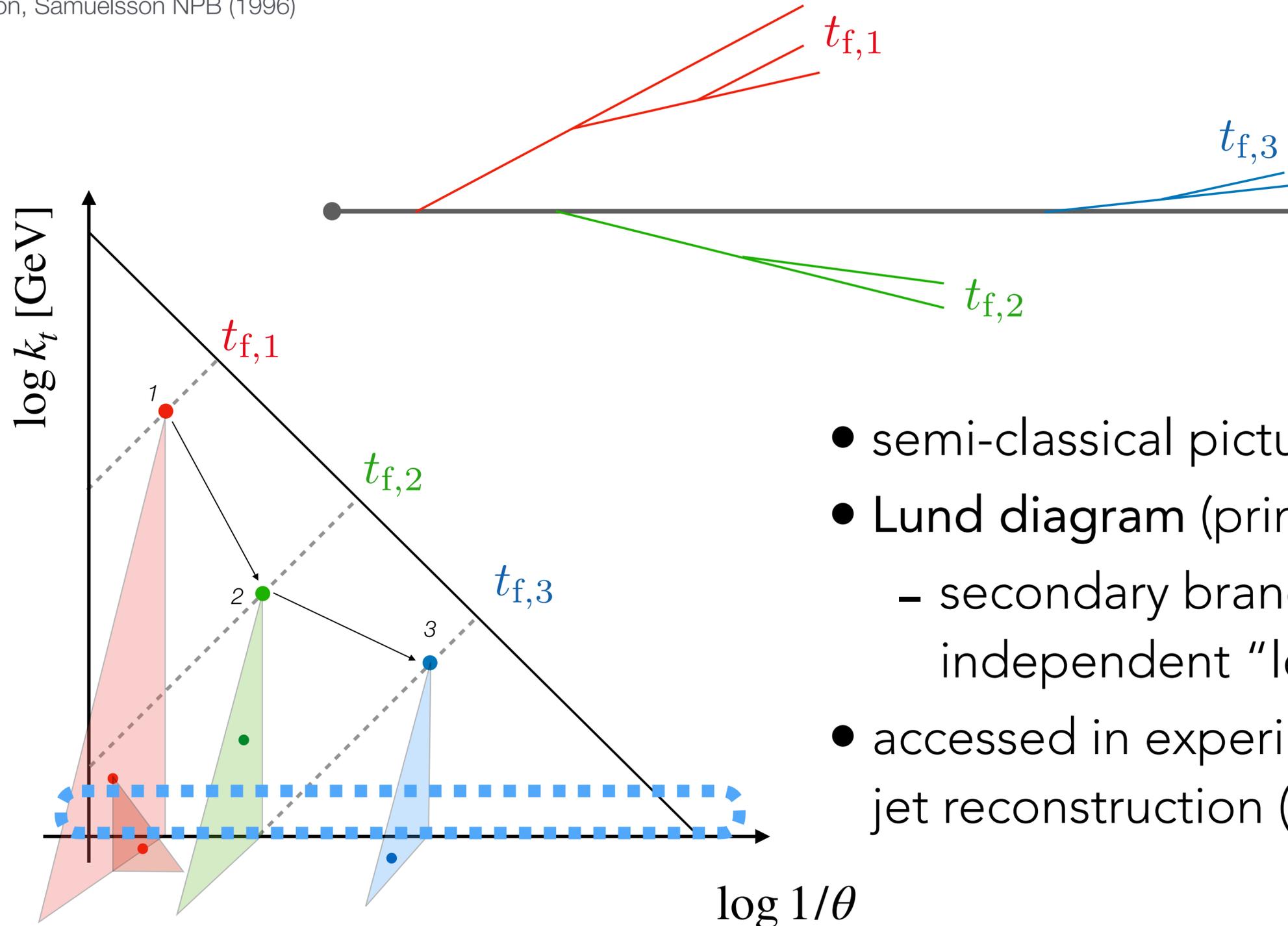to $t_{\rm f} \sim E/Q_0^2 \sim 300\,{\rm fm}$

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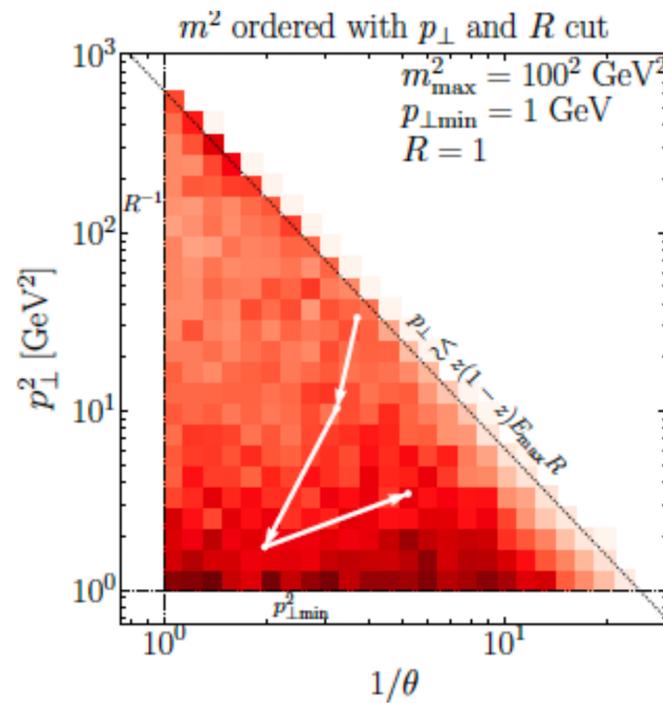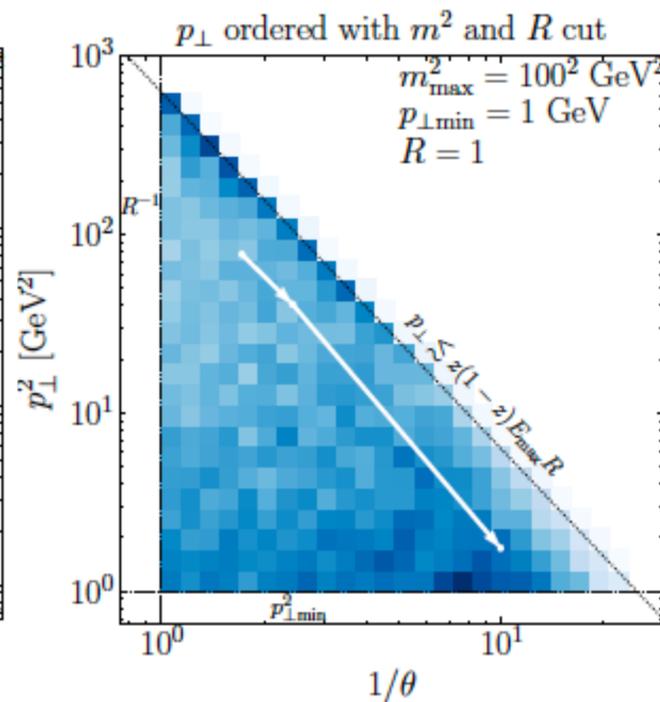
mass/virtuality   **transverse momentum**   **angle**   **formation time**
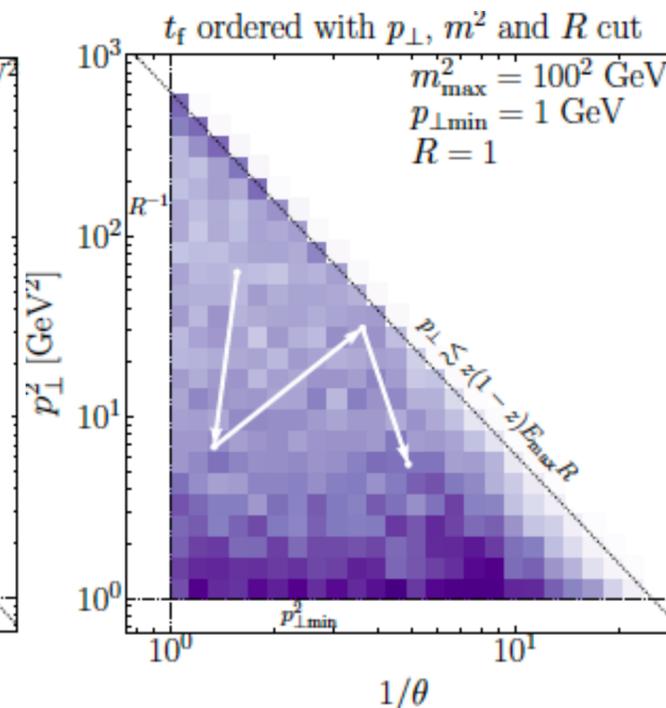
Freedom to choose ordering variable at leading logarithmic approximation.

Color coherence dictates angular ordering.

LOGARITHMIC RESUMMATION

Konishi, Ukawa, Veneziano Nucl. Phys. B1567 (1979);
Bassetto, Ciafaloni, Marchesini Phys. Rept. 100 (1983);
Dokshitzer, Khoze, Mueller, Troyan "Basics of Perturbative QCD" (1991)

Multi-gluon emissions: resummation of leading logarithmic contributions and Monte Carlo development.

R-dependent corrections to the inclusive-jet spectrum

solid: $R_0 = 1.0$
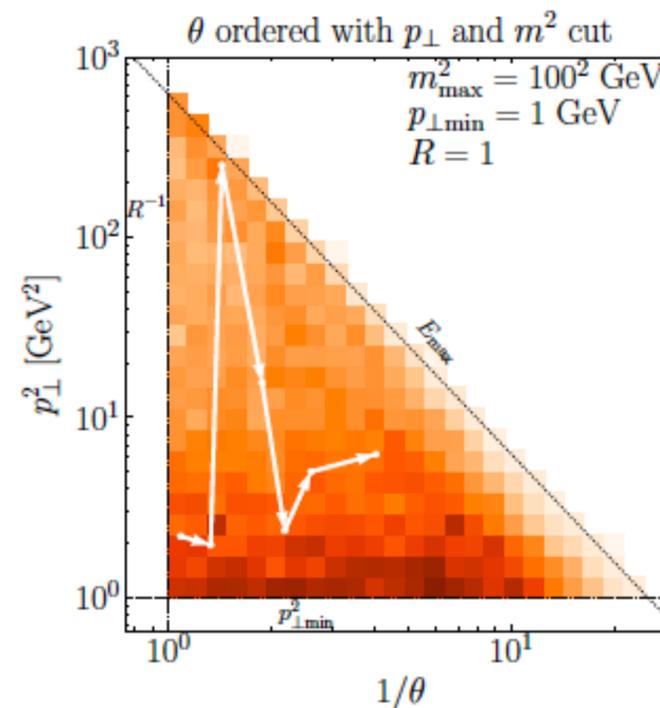dashed: $R_0 = 1.5$

pp, 7 TeV, |y|<0.5, CT10

R = 1.0
R = 0.6
R = 0.4
R = 0.2
R = 0.1
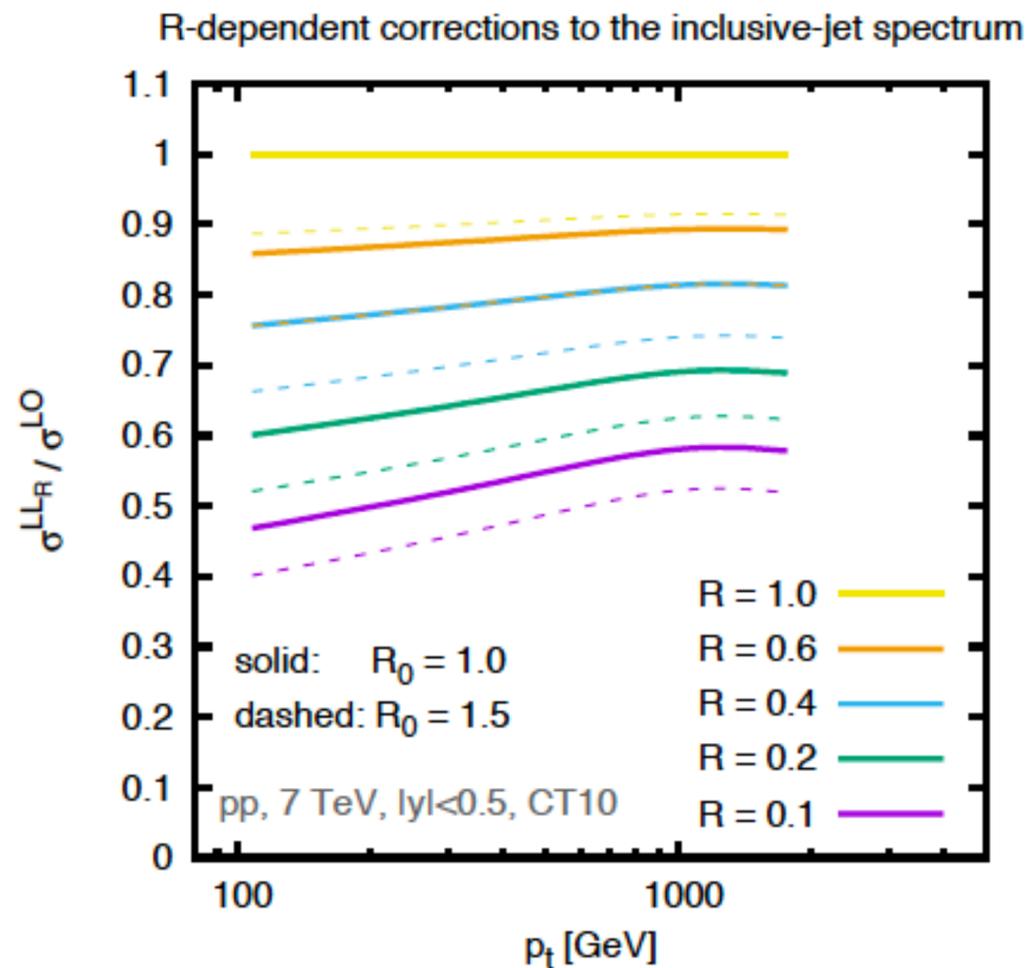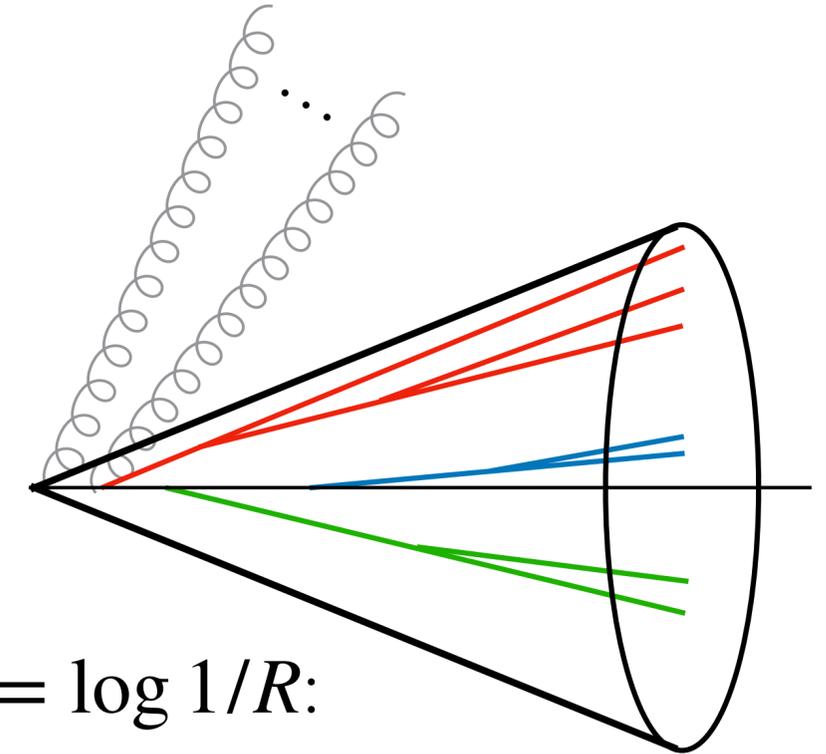
Example: small-R resummation in $t = \log 1/R$:

$$\frac{\partial}{\partial t} f_{\text{jet}/i}(z,t) = \int_0^1 \frac{\mathrm{d}z'}{z'} \frac{\alpha_s}{\pi} P_{ji}(z) f_{jet/j}\left(\frac{z}{z'}, t\right)$$

Evolution from hard scale to jet scale via DGLAP.

Dasgupta, Dreyer, Salam, Soyez 1411.5182, 1602.01110
Kang, Ringer, Vitev 1606.06732

Jet physics in medium

ENERGY-LOSS BASICS
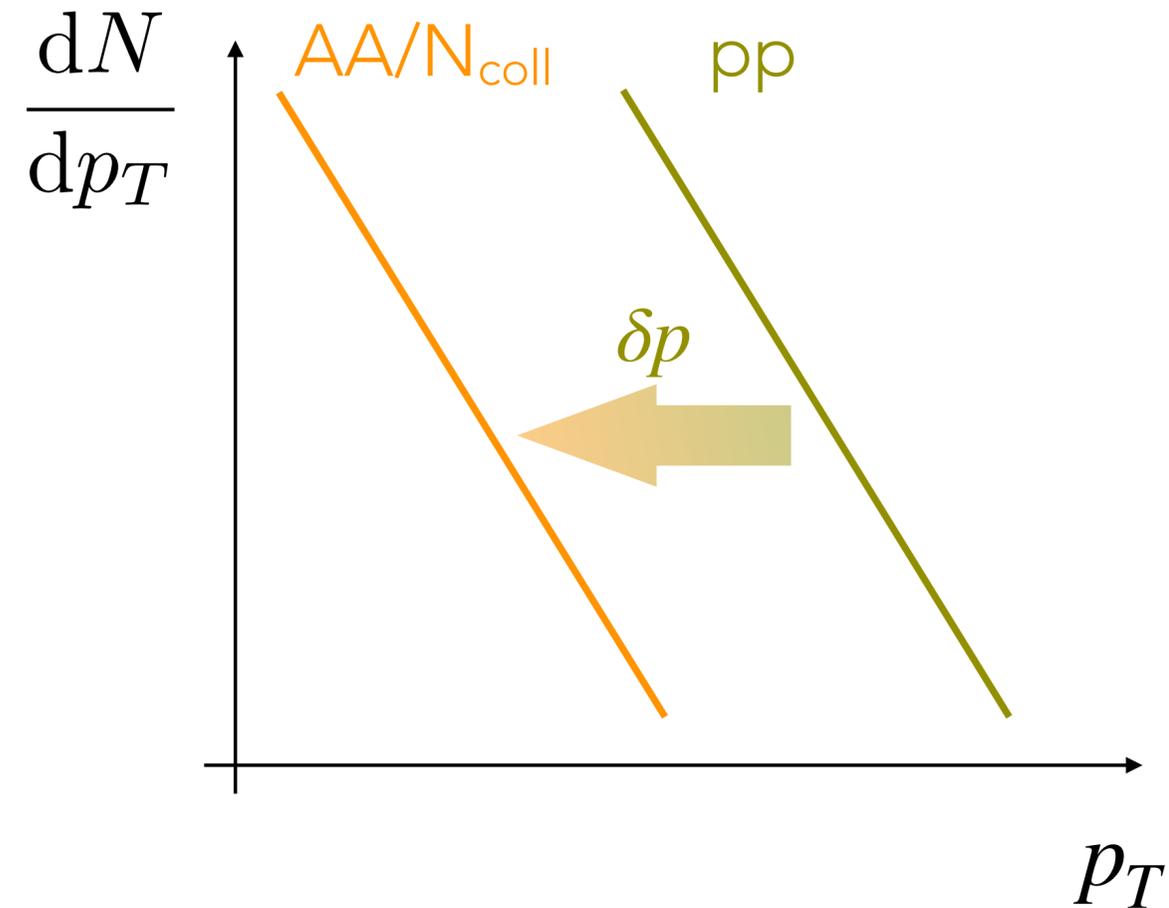
Workhorse of the field: measuring & parameterizing the shift of spectrum to access information about medium interactions.

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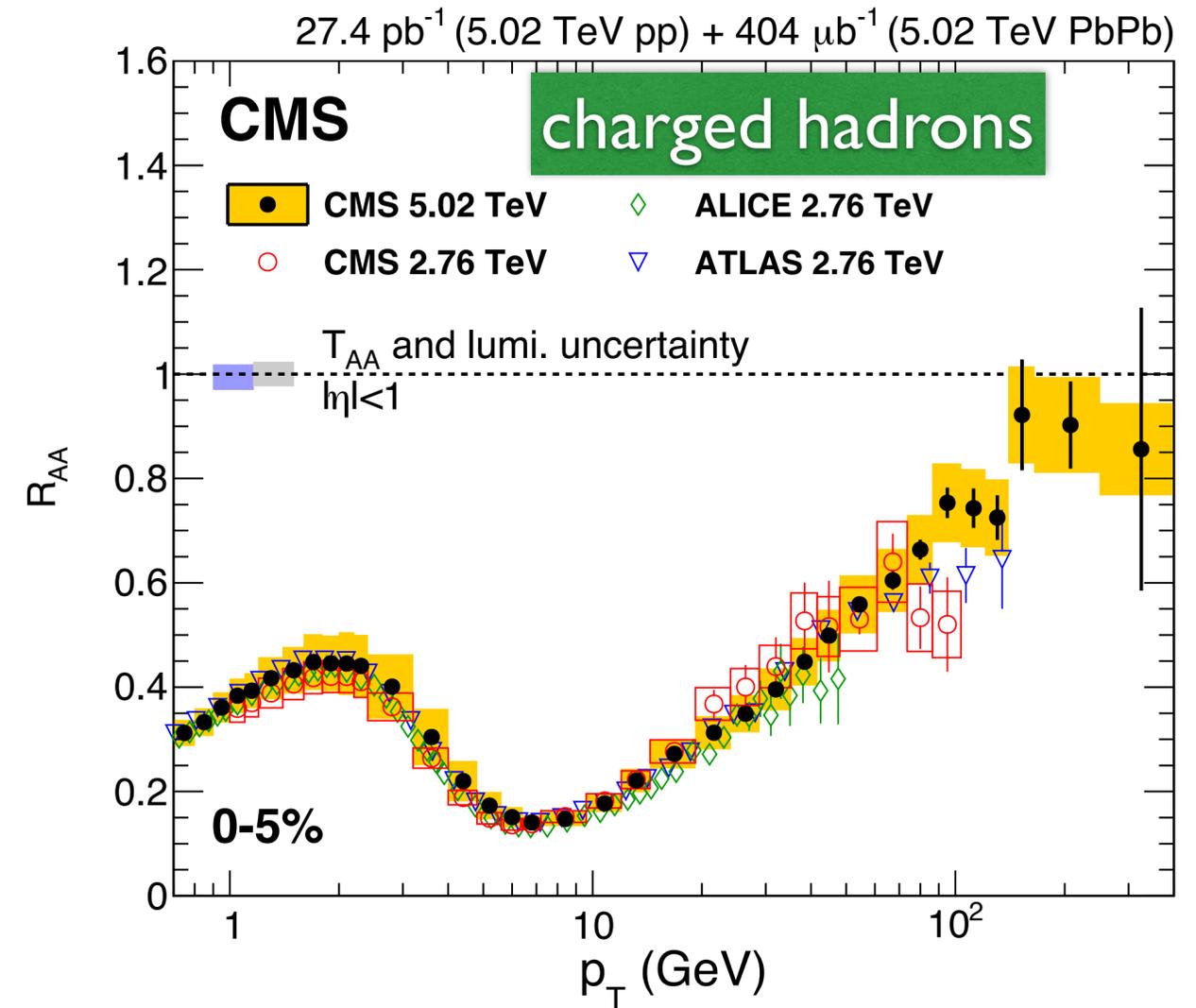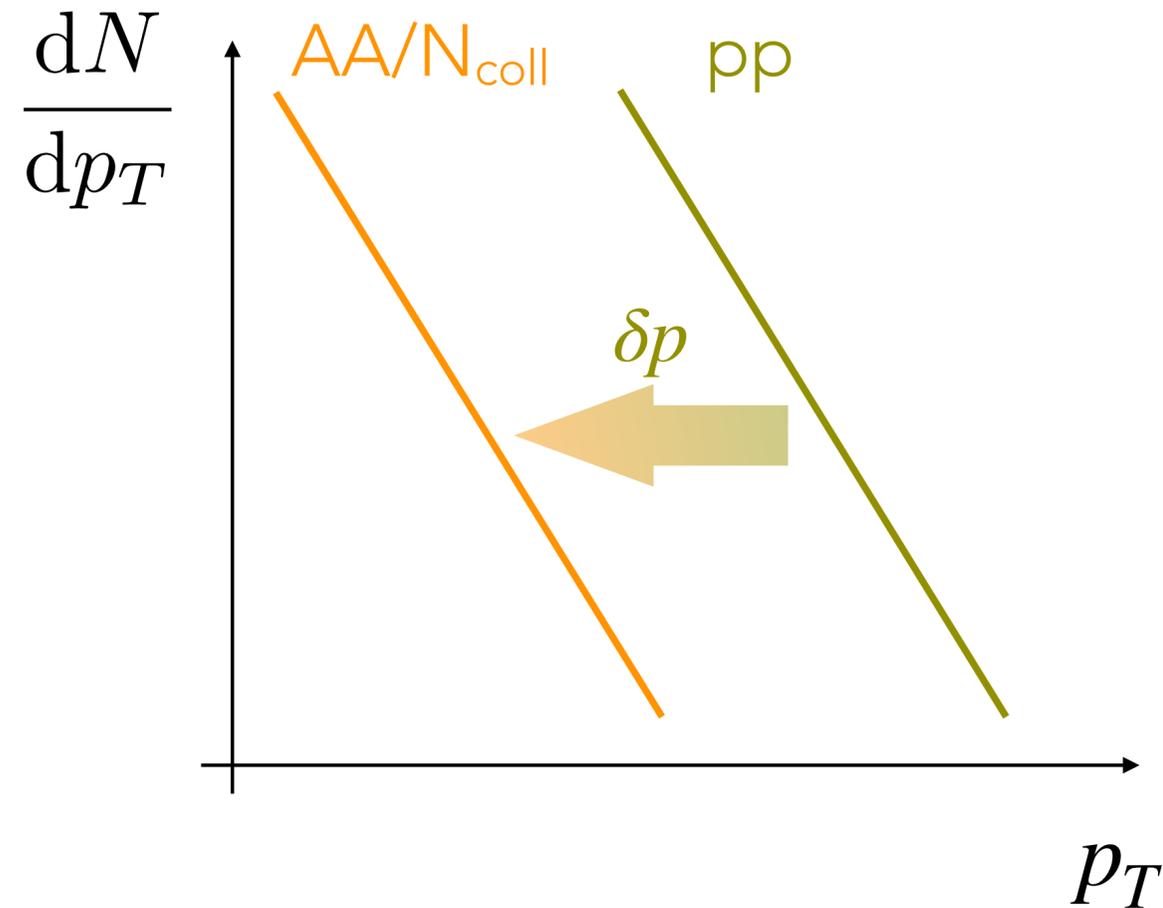
Energy-loss basics

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ENERGY-LOSS BASICS

Workhorse of the field: measuring & parameterizing the shift of spectrum to access information about medium interactions.

Significant difference of hadron and jet suppression at high-p_T!

ENERGY-LOSS BASICS
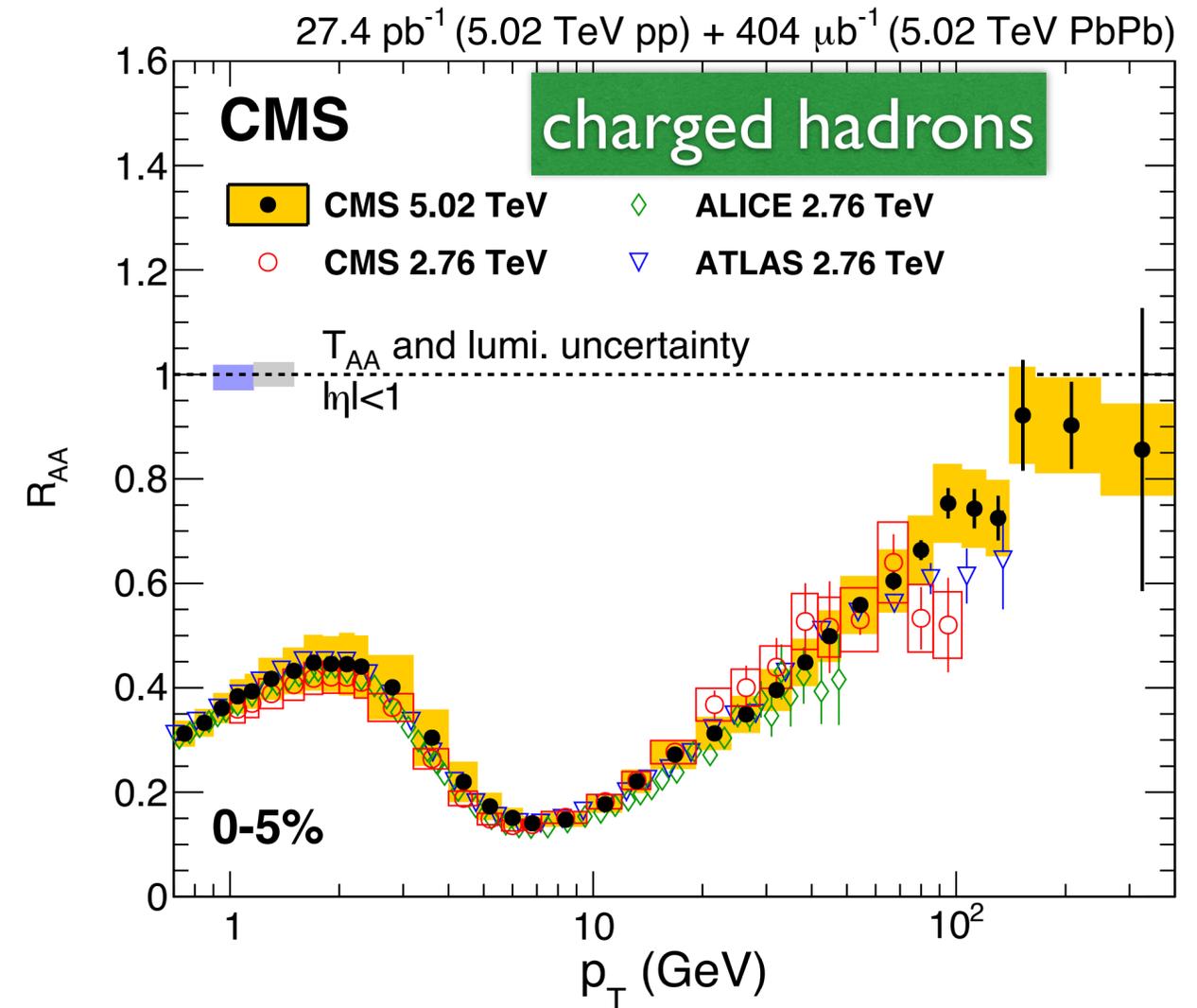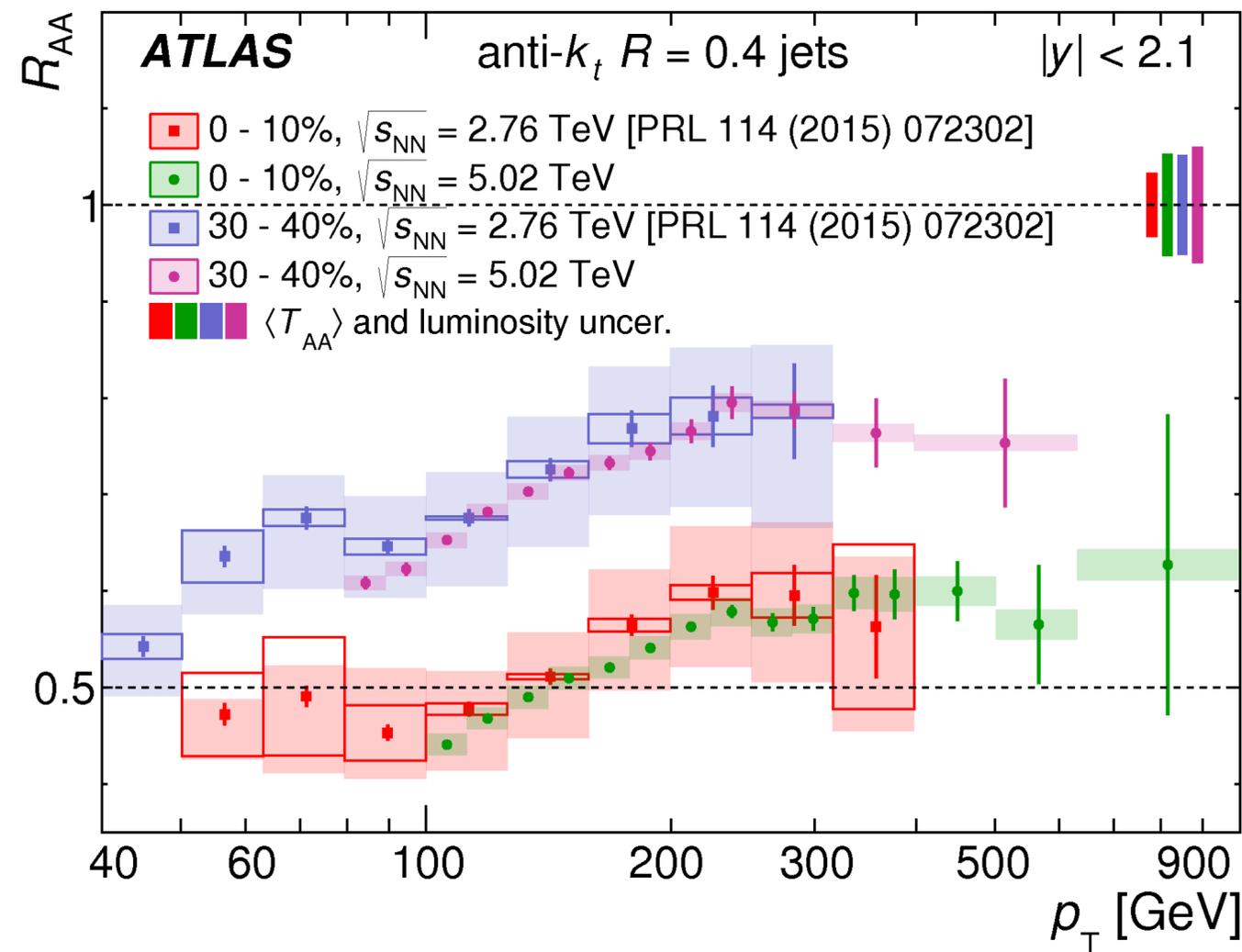
- disclaimer: in my talk, I will focus on effects above the thermal scale - however, close connection to bottom-up thermalization & hydrodynamization should be further investigated.

Tachibana (Tue 10:00), Chen (Tue 10:20); Kumar (Wed 09:40), He (Wed 10:00); Pablos (Wed 12:20)

Medium-induced radiation

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

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

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

K. Tywoniuk (UiB)

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t_1 t_2

$\boldsymbol{r}_1$

$\boldsymbol{r}_2$

$\dots$

$\boldsymbol{r}_3$

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
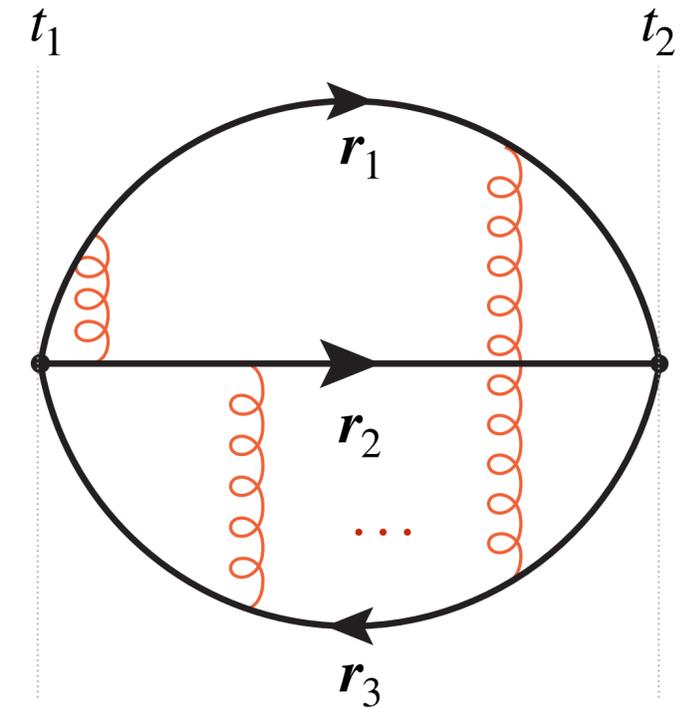
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Feal, Salgado, Vazquez 1911.01309

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

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))

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

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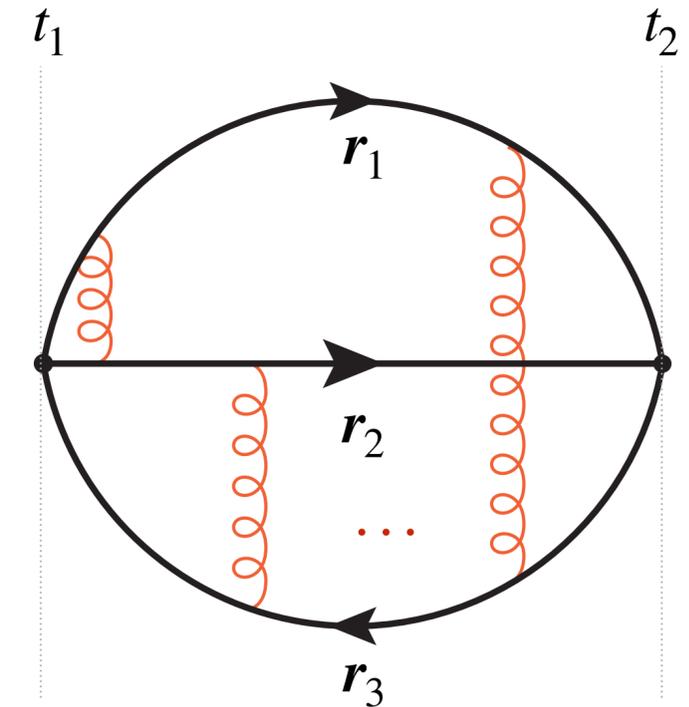
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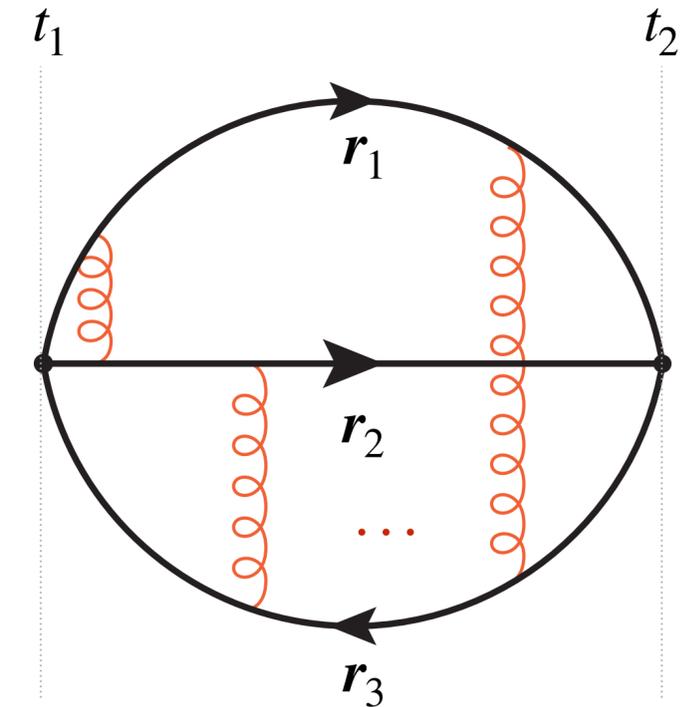
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Mehtar-Tani 1903.00506, Mehtar-Tani KT 1910.02032

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

Unified understanding of in-medium radiative processes!

REGIMES
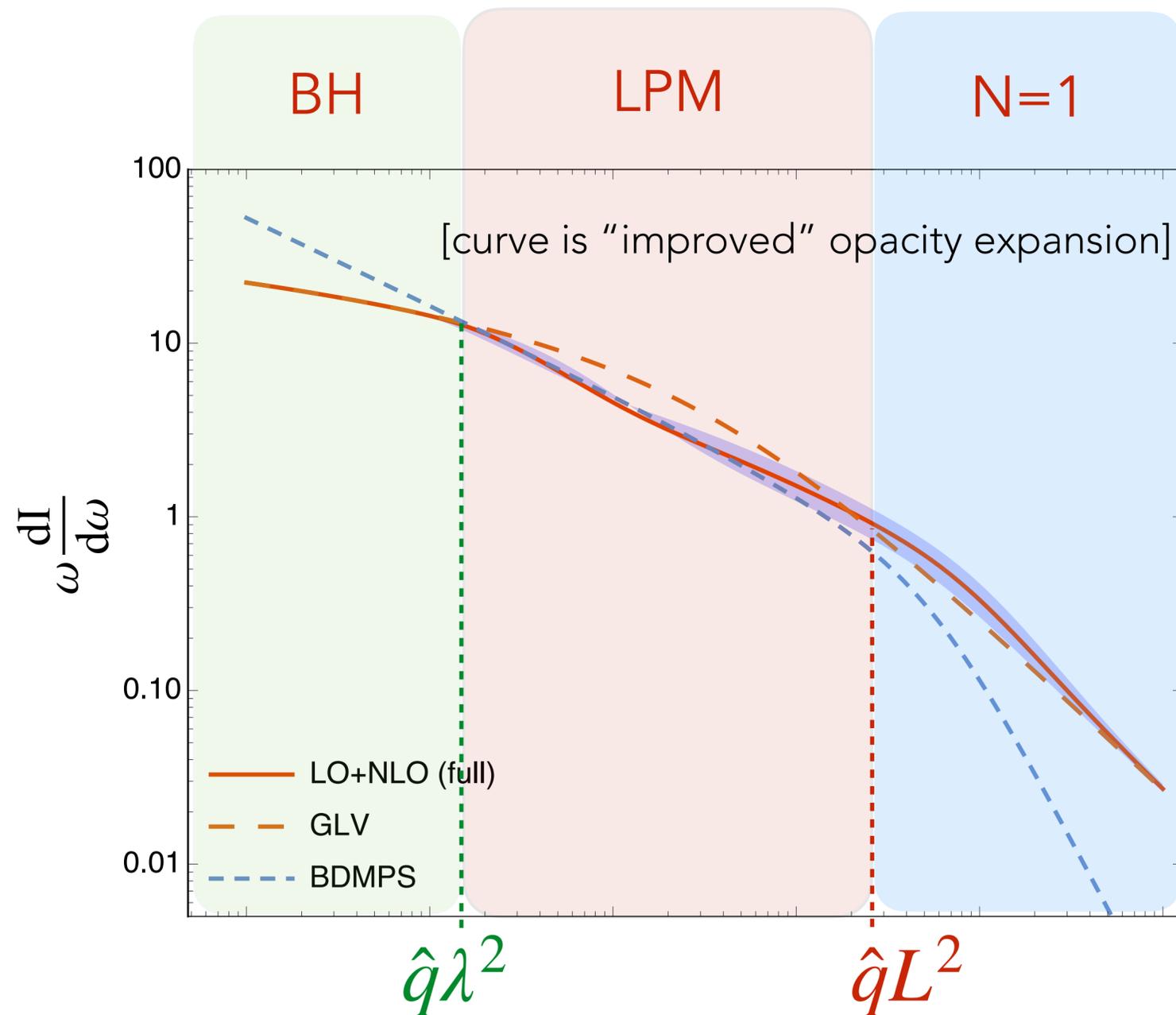
Mehtar-Tani (Wed 10:20)

Momentum broadening $\langle \boldsymbol{k}^2 \rangle \sim \hat{q}t$ leads to modified bremsstrahlung spectrum → no collinear divergence!

$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega} = \frac{\alpha_s C_R}{\pi} \frac{L}{t_{\mathrm{f}}} = \frac{\alpha_s C_R}{\pi} \sqrt{\frac{\hat{q}L^2}{\omega}}$$

Bethe-Heitler regime ($t_{\mathrm{f}} \lesssim \lambda$)

LPM regime ($\lambda < t_{\mathrm{f}} < L$)

N=1 regime ($L < t_{\mathrm{f}} \sim E/\mu^2$)

REGIMES
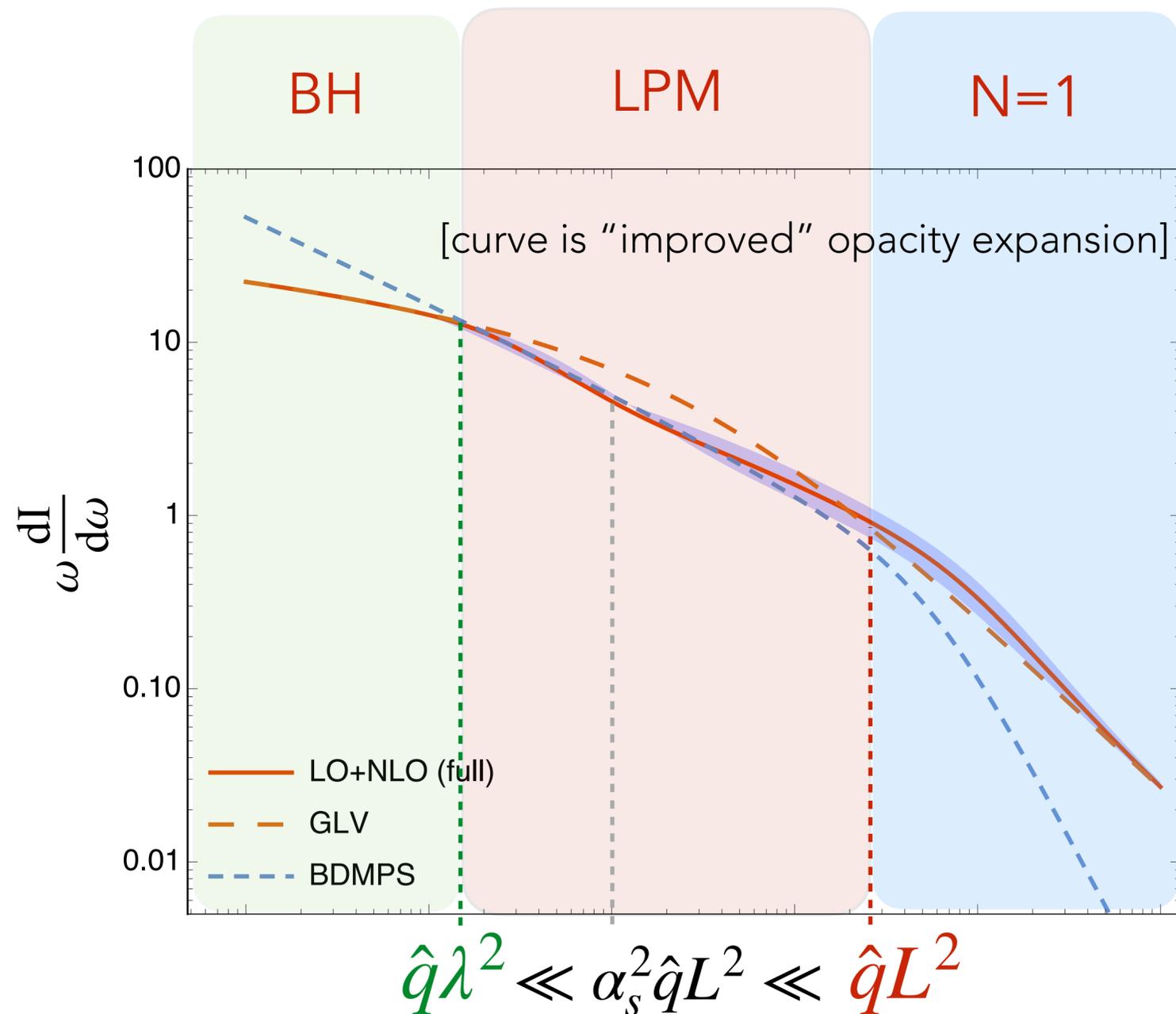
Mehtar-Tani (Wed 10:20)

BH   LPM   N=1

[curve is "improved" opacity expansion]

LO+NLO (full)

GLV

BDMPS

$\hat{q}\lambda^2 \ll \alpha_s^2 \hat{q}L^2 \ll \hat{q}L^2$

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Bethe-Heitler regime ($t_\mathrm{f} \lesssim \lambda$)

LPM regime ($\lambda < t_\mathrm{f} < L$)

N=1 regime ($L < t_\mathrm{f} \sim E/\mu^2$)

Soft scale: copious, large angle gluons leading to energy loss & thermalization.

QUENCHING OF PARTONIC HARD SPECTRUM

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

Probability of radiating energy ϵ out of the cone
(1 gluon emission)

$$\mathcal{P}(\epsilon) \simeq \delta(\epsilon) \left[1 - \int_0^\infty d\omega \, \frac{dI_>}{d\omega} \right] + \frac{dI_>}{d\epsilon}$$

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$$\frac{\mathrm{d}\sigma_{\mathrm{med}}}{\mathrm{d}p_T} = \int_0^\infty \mathrm{d}\epsilon \, \mathcal{P}(\epsilon) \, \left. \frac{\mathrm{d}\sigma_{\mathrm{vac}}}{\mathrm{d}p_T'} \right|_{p_T' = p_T + \epsilon} \approx \frac{\mathrm{d}\sigma_{\mathrm{vac}}}{\mathrm{d}p_T} \underbrace{\int_0^\infty \mathrm{d}\epsilon \, \mathcal{P}(\epsilon) \mathrm{e}^{-\epsilon \frac{n}{p_T}}}_{Q(p_T)}$$

quenching factor
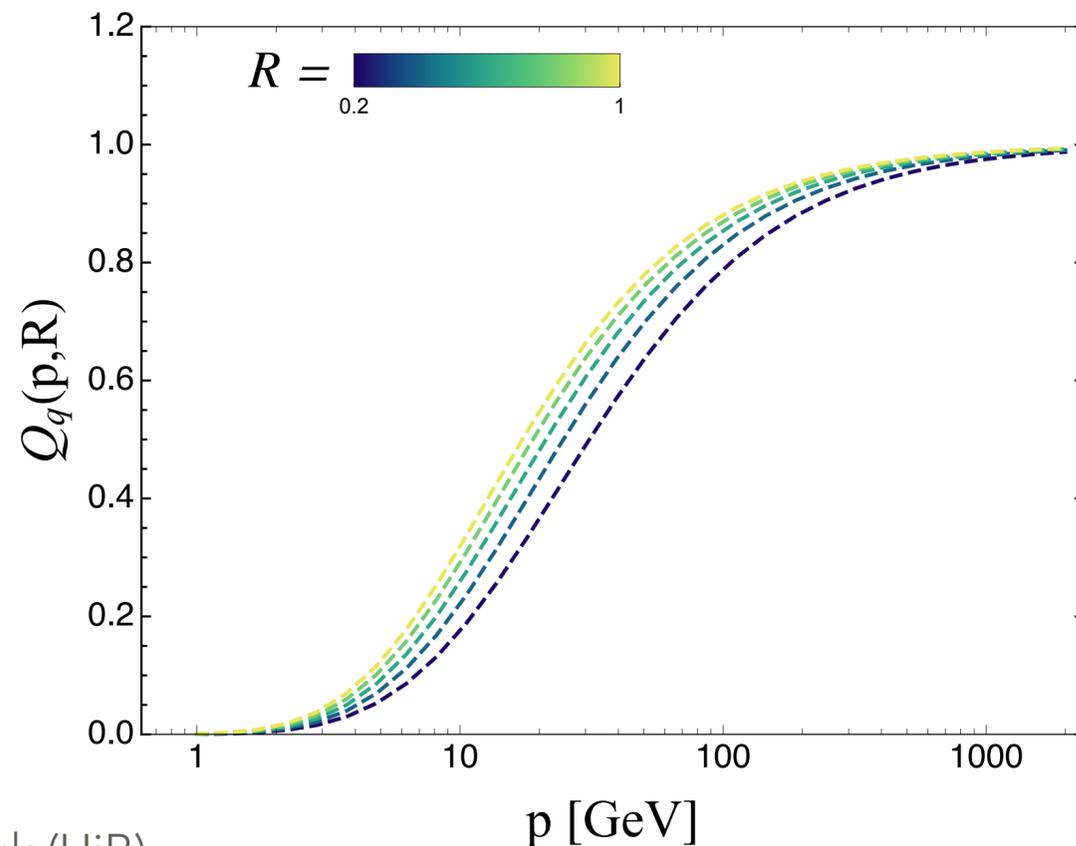
QUENCHING OF PARTONIC HARD SPECTRUM

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quenching factor

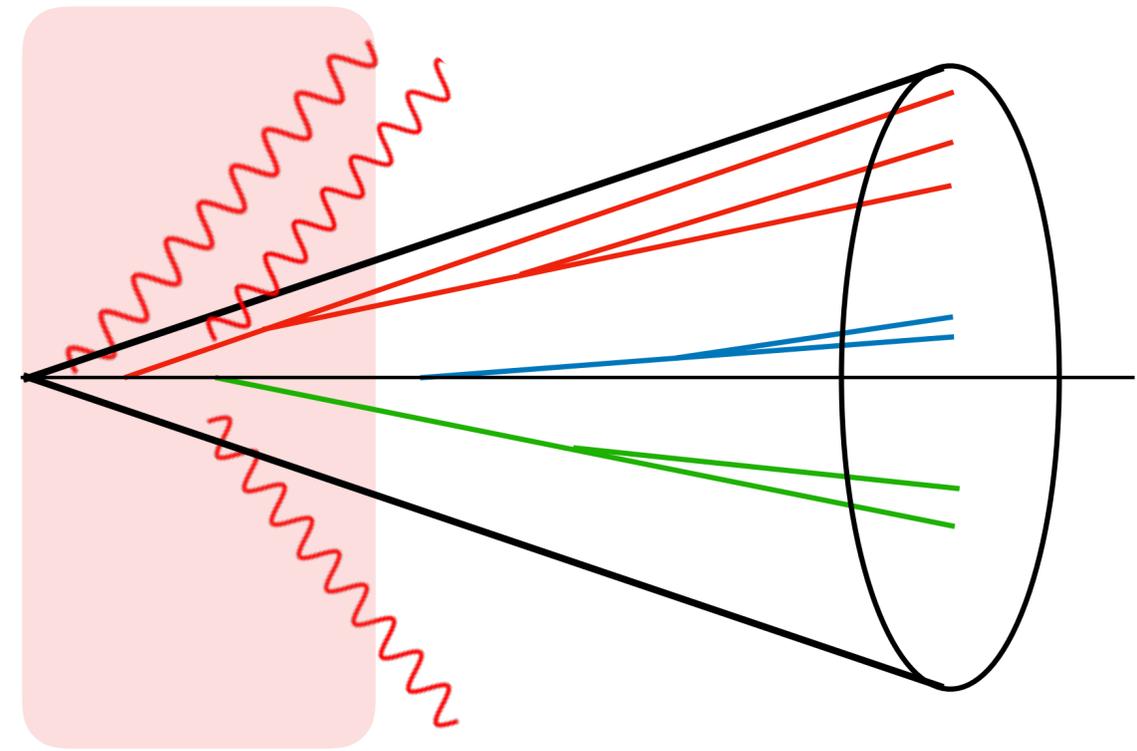

- full $P(\epsilon)$ resums multiple soft gluon emission via rate equation
- generalizes for N partons $Q \to Q^N$ (incoherent case)

K. Tywoniuk (UiB)

12
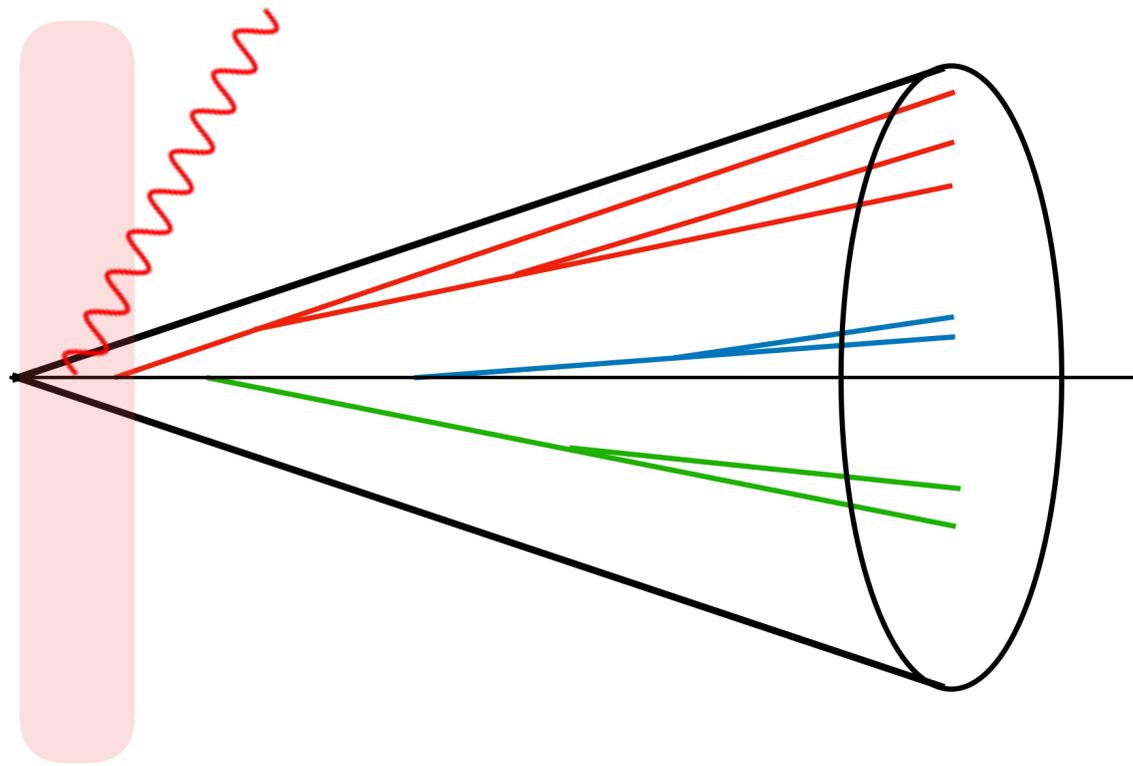
1 emitter (coherent)
factorisation

n emitters (partially incoherent)
factorisation breaking

new element: importance of jet substructure fluctuations!

also seen in MC studies: Milhano, Zapp 1512.08107; Casalderrey-Solana, Milhano, Pablos, Rajagopal 1808.07386

Ringer (Wed 09:40)

VACUUM RADIATION IN MEDIUM

Vacuum radiation at short timescales was considered first in the context of antenna radiation.

Mehtar-Tani, Salgado, KT PRL (2010), PLB (2012), JHEP (20132; Casalderrey, Iancu JHEP (2011)

Dominguez, Milhano, Salgado, KT, Vila 1907.03653
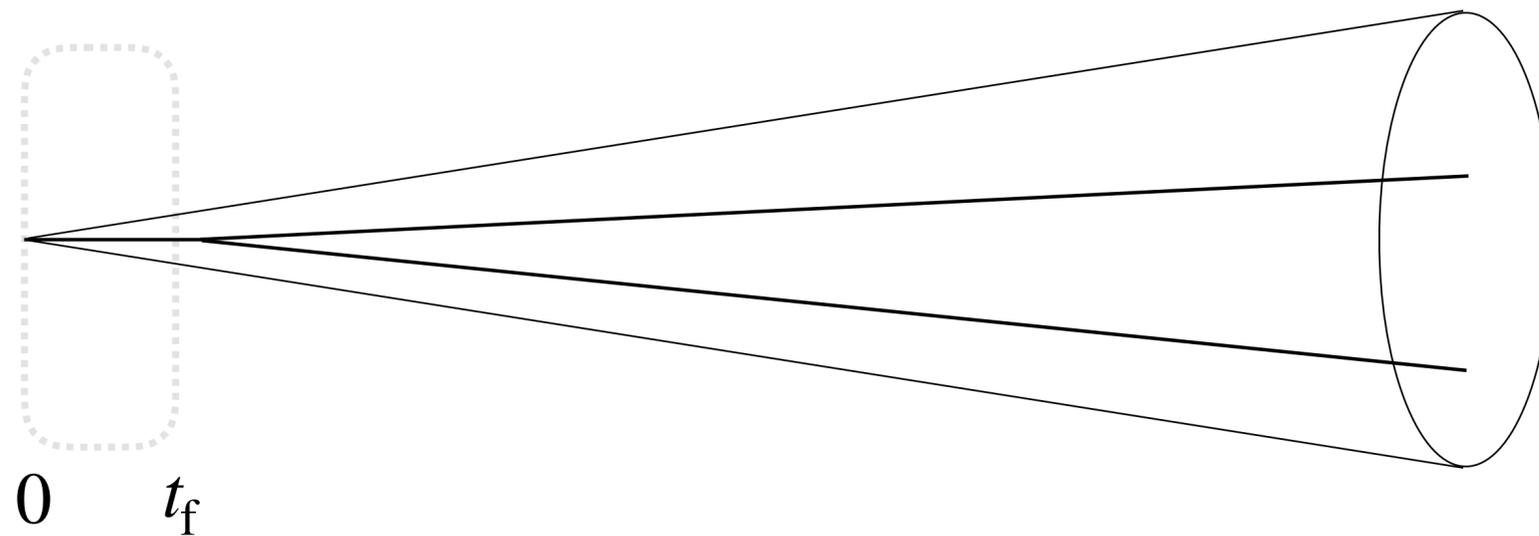
VACUUM RADIATION IN MEDIUM

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First step: calculation of decoherence and energy loss of an initially color correlated pair

Mehtar-Tani, KT 1706.06047

$0 \qquad t_{\mathrm{f}}$
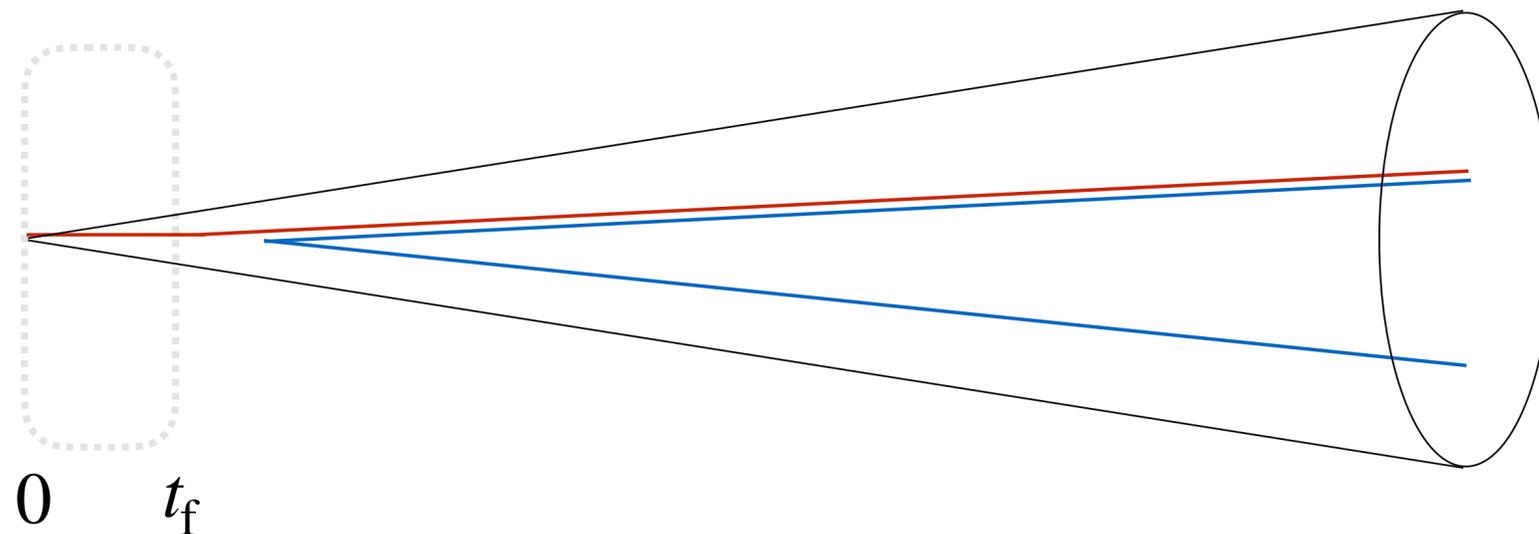
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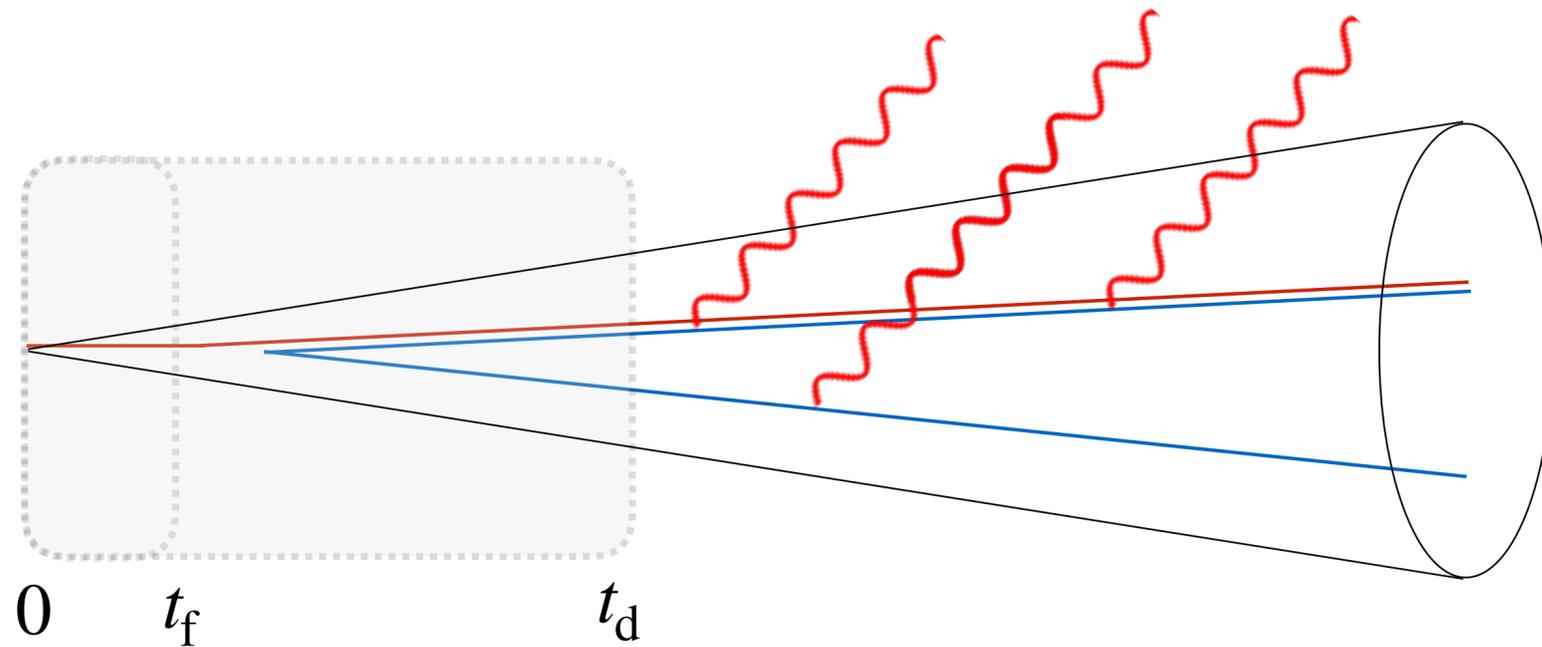
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Mehtar-Tani, KT 1706.06047

$$t_{\rm d} \sim (\hat{q}\theta_{12}^2)^{-1/3}$$

$$\theta_c \sim \sqrt{\frac{1}{\hat{q}L^3}}$$

$0 \quad t_{\rm f} \quad\quad\quad t_{\rm d}$

$$Q_2(p_T) = Q(p_T) \times Q_{\rm sing}(p_T)$$

energy loss of total
color charge

delayed energy loss from
resolved partons

Red area: vacuum emissions (w/ $k_t^2 > \sqrt{\hat{q}\omega}$ and $\theta > \theta_c$) that are not resolved by the medium.

At border: all inside emissions get quenched
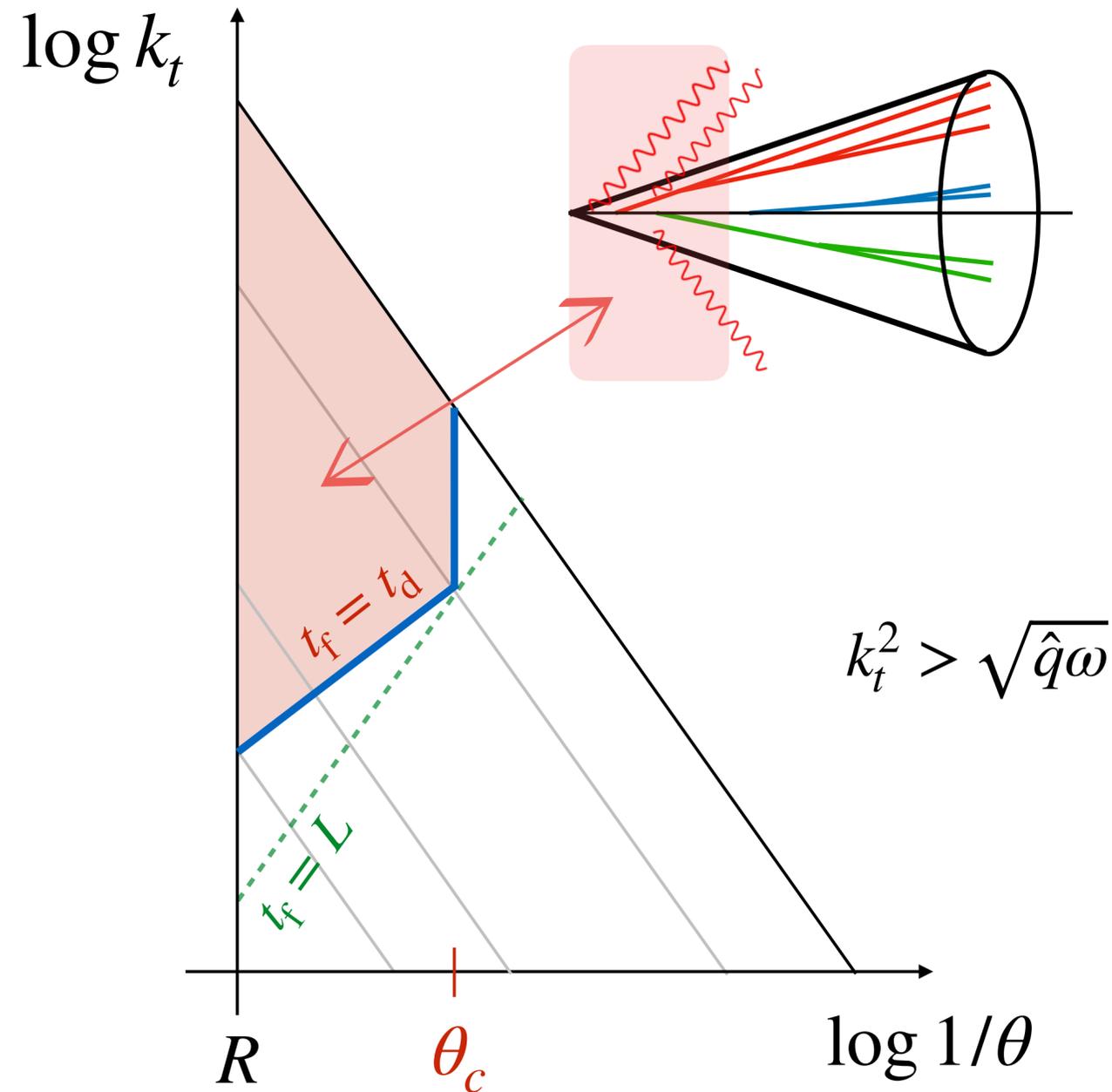
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How many modes are emitted inside?

$$k_t^2 > \sqrt{\hat{q}\omega}$$

PHASE SPACE ANALYSIS

$$k_t^2 > \sqrt{\hat{q}\omega}$$

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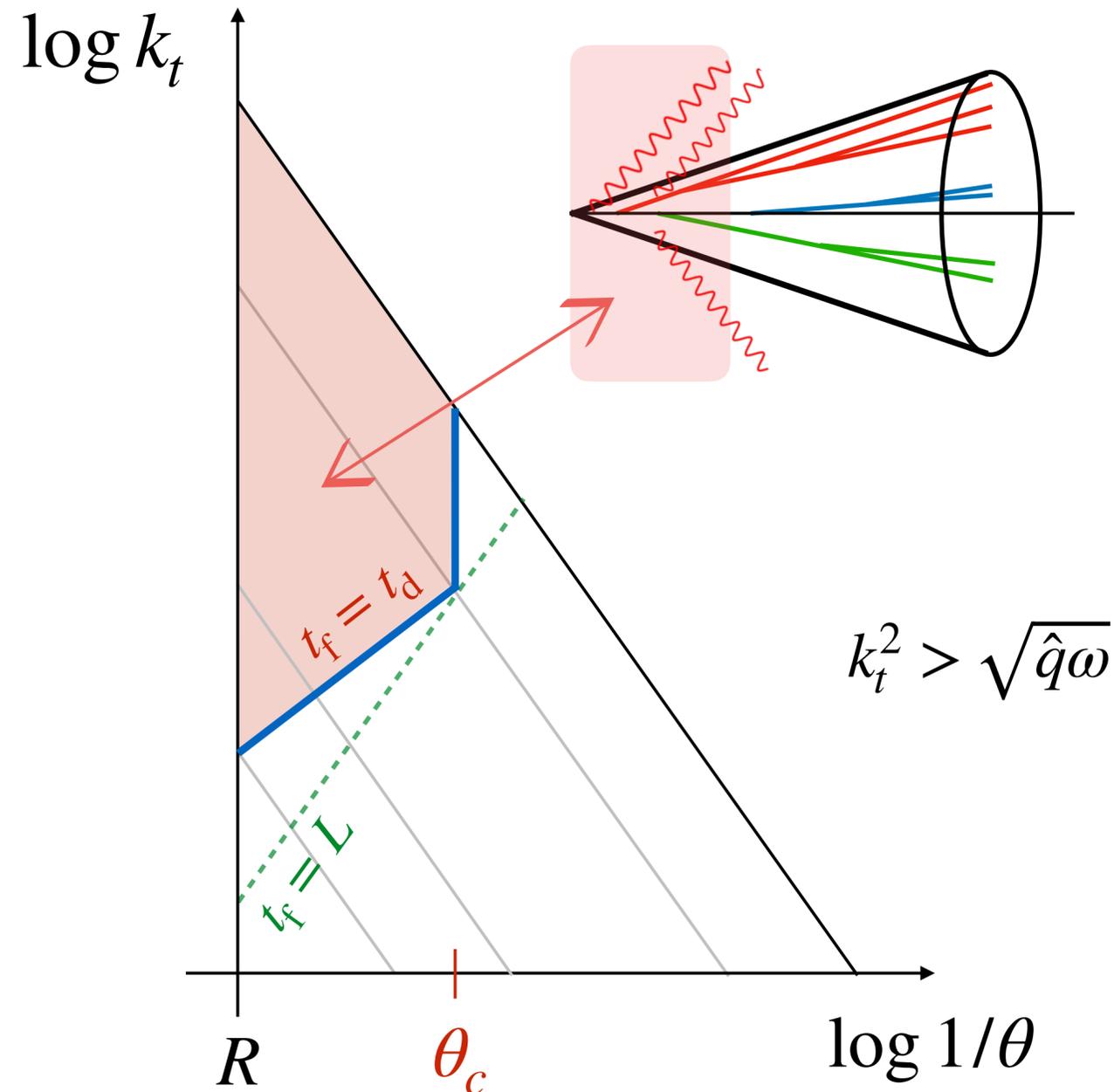**At border:** all inside emissions get quenched

How many modes are emitted inside?

$$(\text{PS})_{\text{in}} = \int_0^R \frac{\mathrm{d}\theta}{\theta} \int_0^1 \mathrm{d}z \, \frac{\alpha_s}{\pi} P(z) \Theta_{\text{in}}$$

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

Potentially large and needs to be resummed.

No coherence leads to stronger $\sim \log^2 p_T$ dependence!

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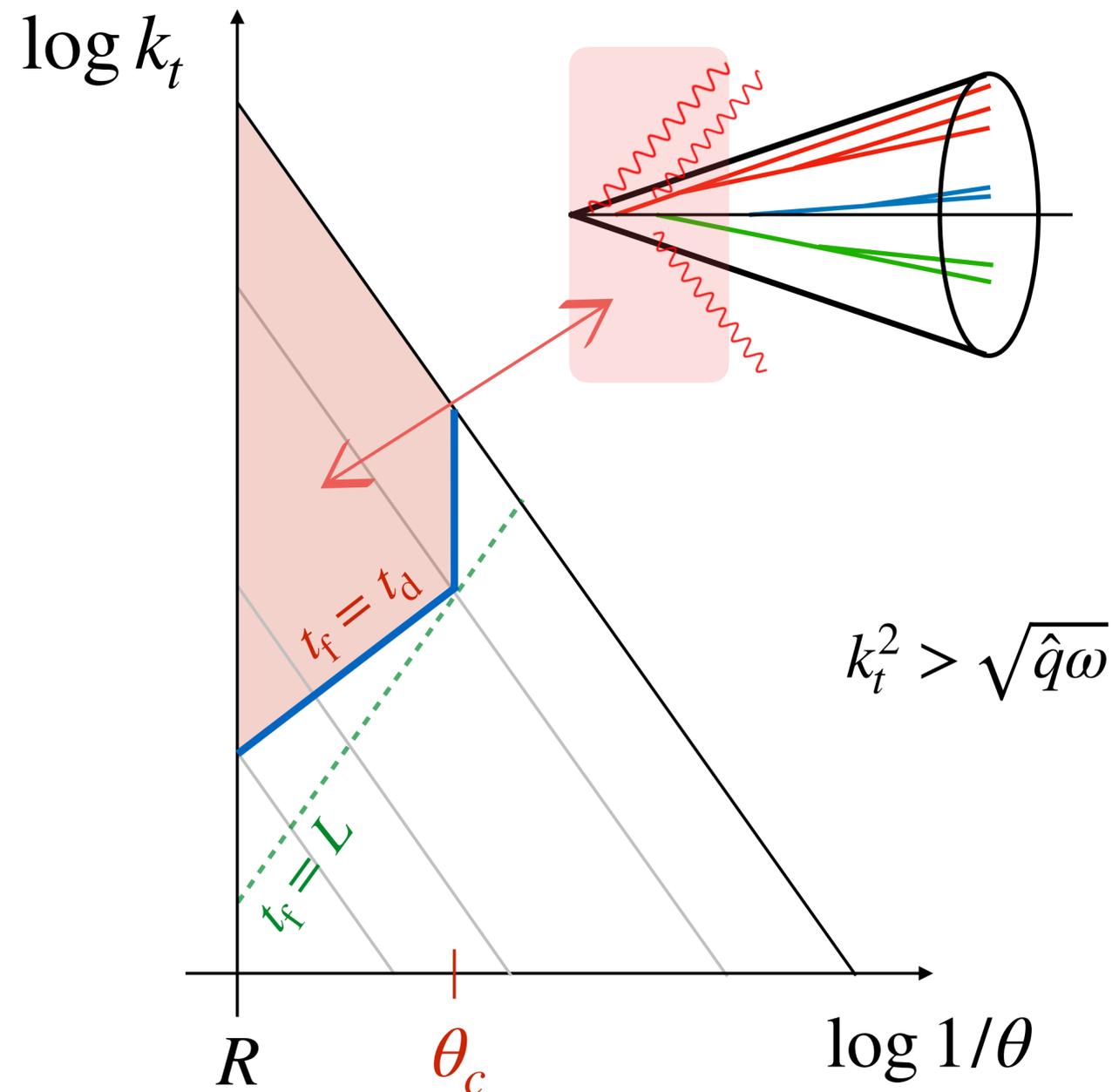
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Caucal (Wed 15:20)
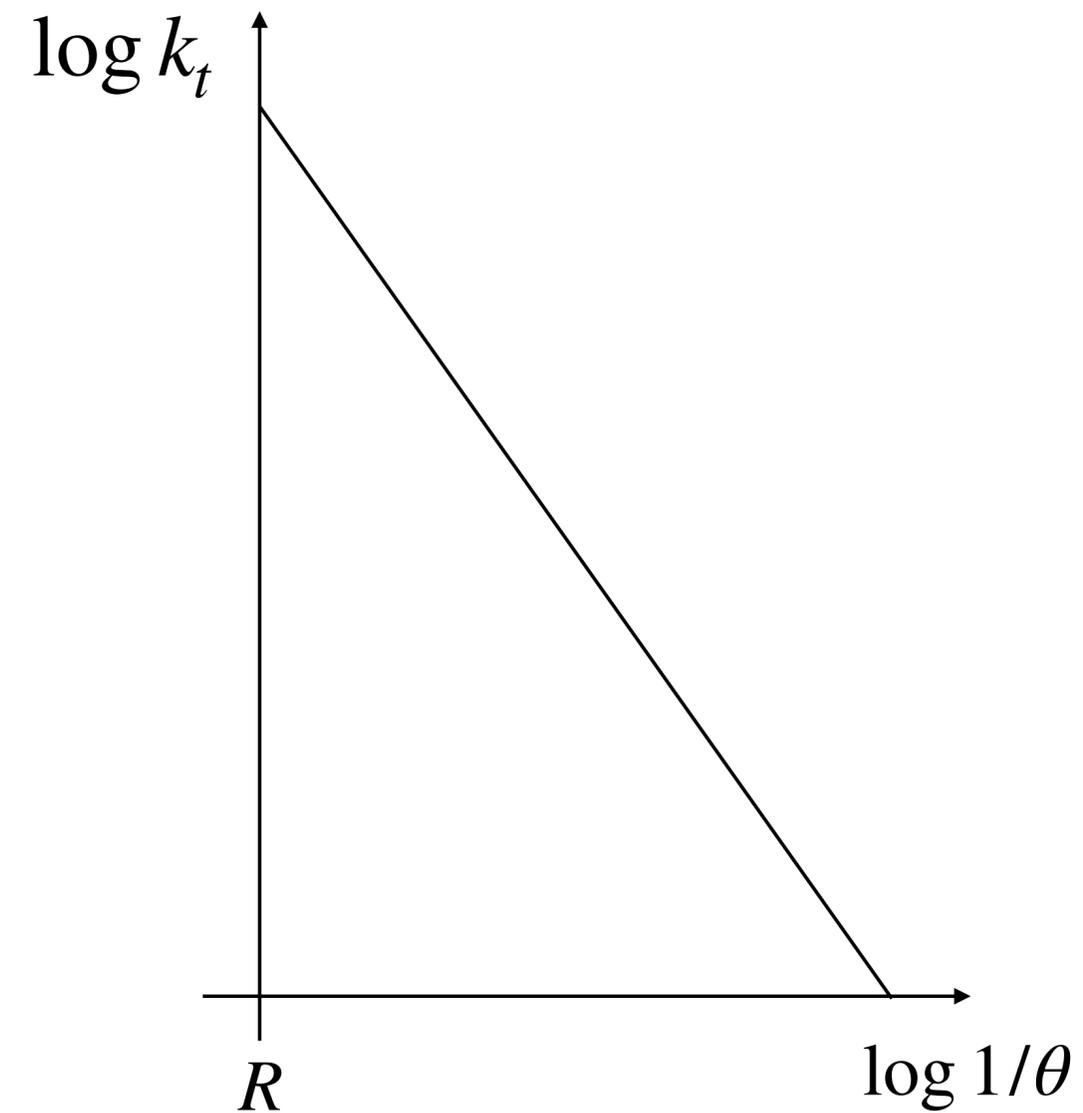
Non-trivial correlation between jet energy loss and substructure!

EFFECTIVE THEORY OF JET QUENCHING

A probabilistic picture can be established due to the separation of jet and medium scales.

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Outside of the medium, we have AO vacuum (vetoed shower):

$$Z_{\text{out}}(p, R) = u(p) + \int^{R} d\Pi \left(1 - \Theta_{\text{in}}\right) \left[Z_{\text{out}}(zp, \theta) Z_{\text{out}}((1-z)p, \theta) - Z_{\text{out}}(p, \theta)\right]$$

$\log k_t$

$\log 1/\theta$

R

Mehtar-Tani, KT in preparation

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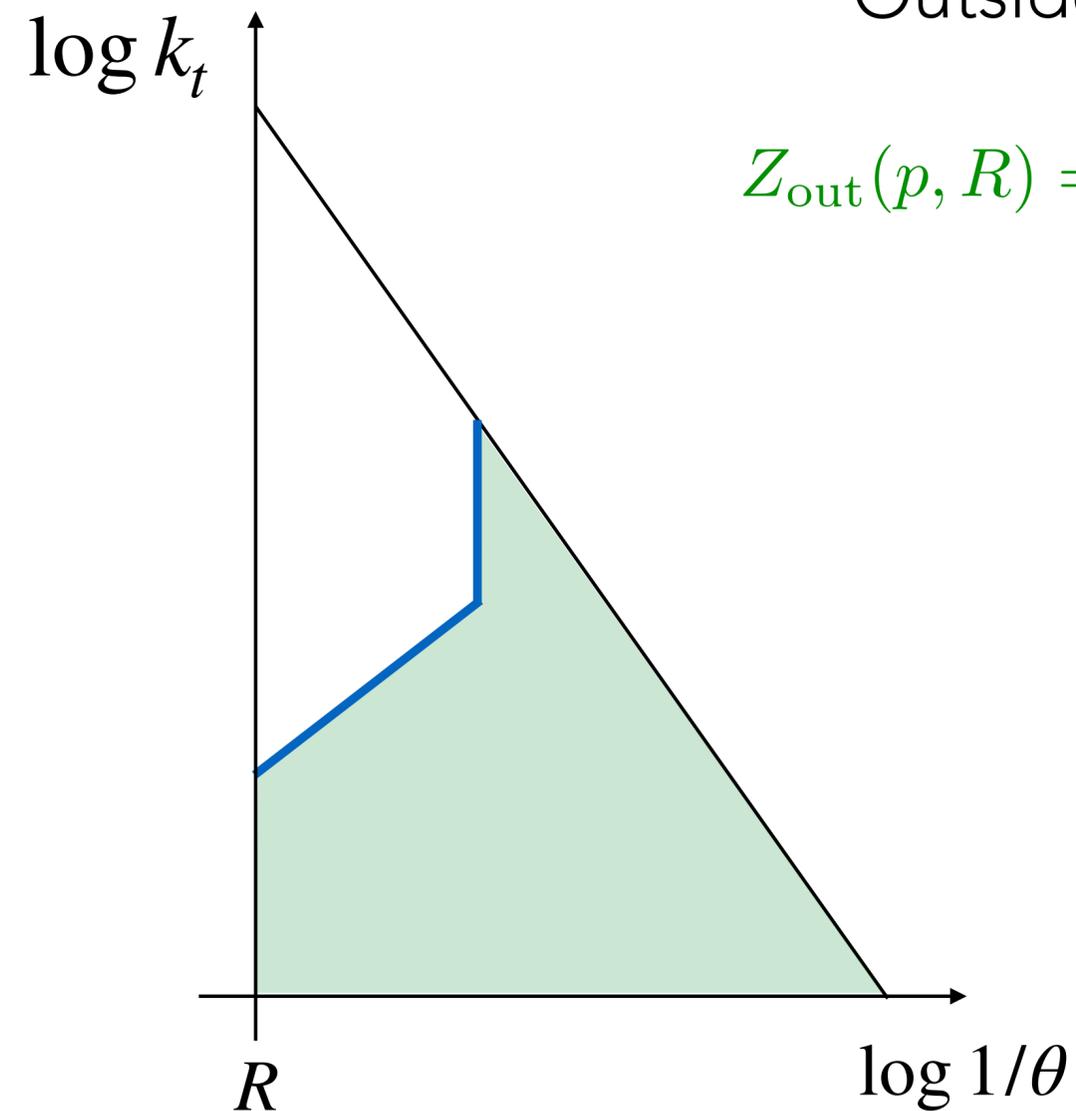Outside of the medium, we have AO vacuum (vetoed shower):

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Vacuum-like (vetoed) AO shower inside the medium

$$Z(p, R) = Q(p_{\mathrm{T}}) Z_{\mathrm{out}}(p, 1) + \int^{R} \mathrm{d}\Pi \, \Theta_{\mathrm{in}} \left[Z(zp, \theta) Z((1-z)p, \theta) - Z(p, \theta) \right]$$

$\log k_t$

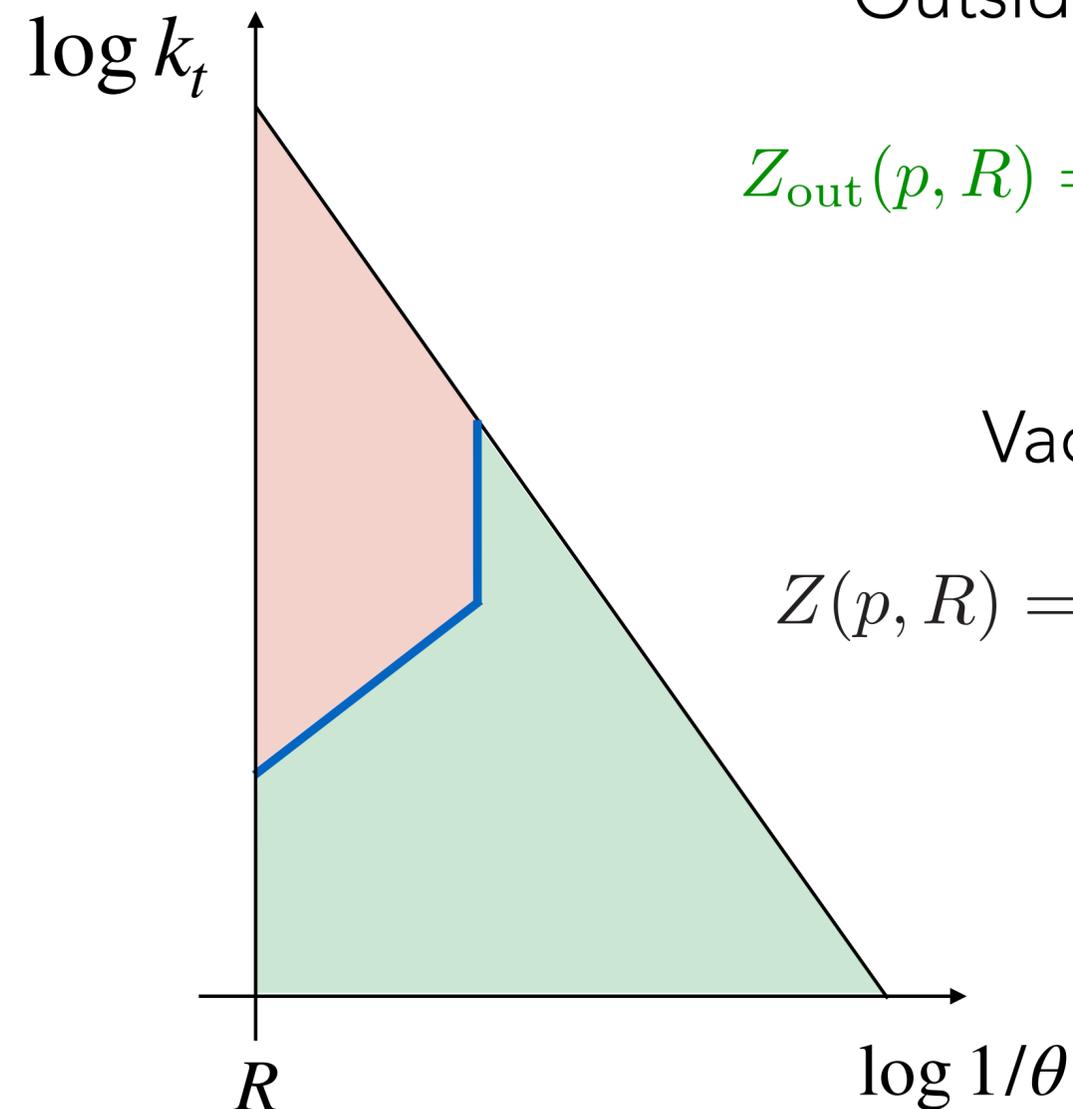$\log 1/\theta$

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EFFECTIVE THEORY OF JET QUENCHING

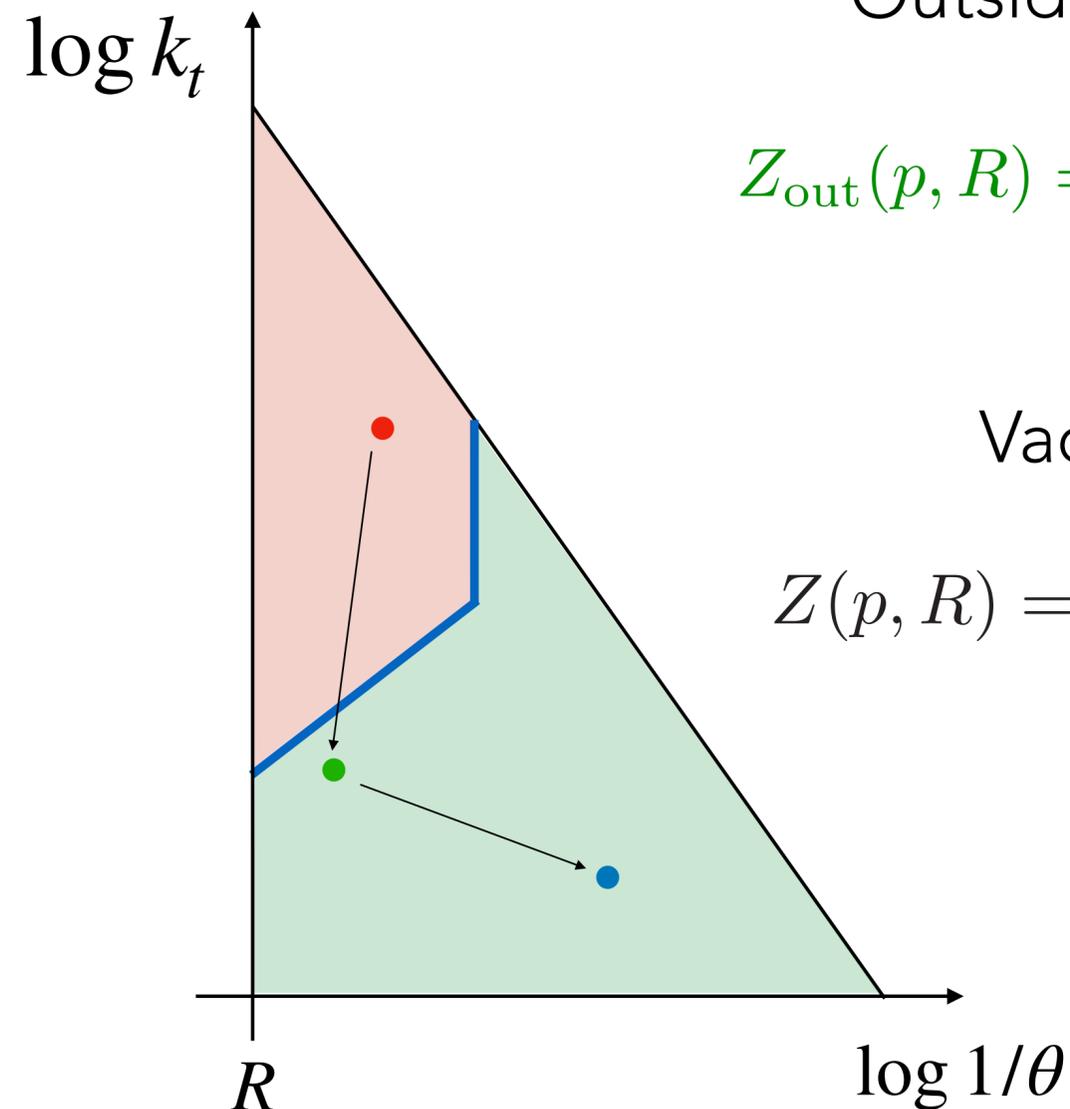A probabilistic picture can be established due to the separation of jet and medium scales.

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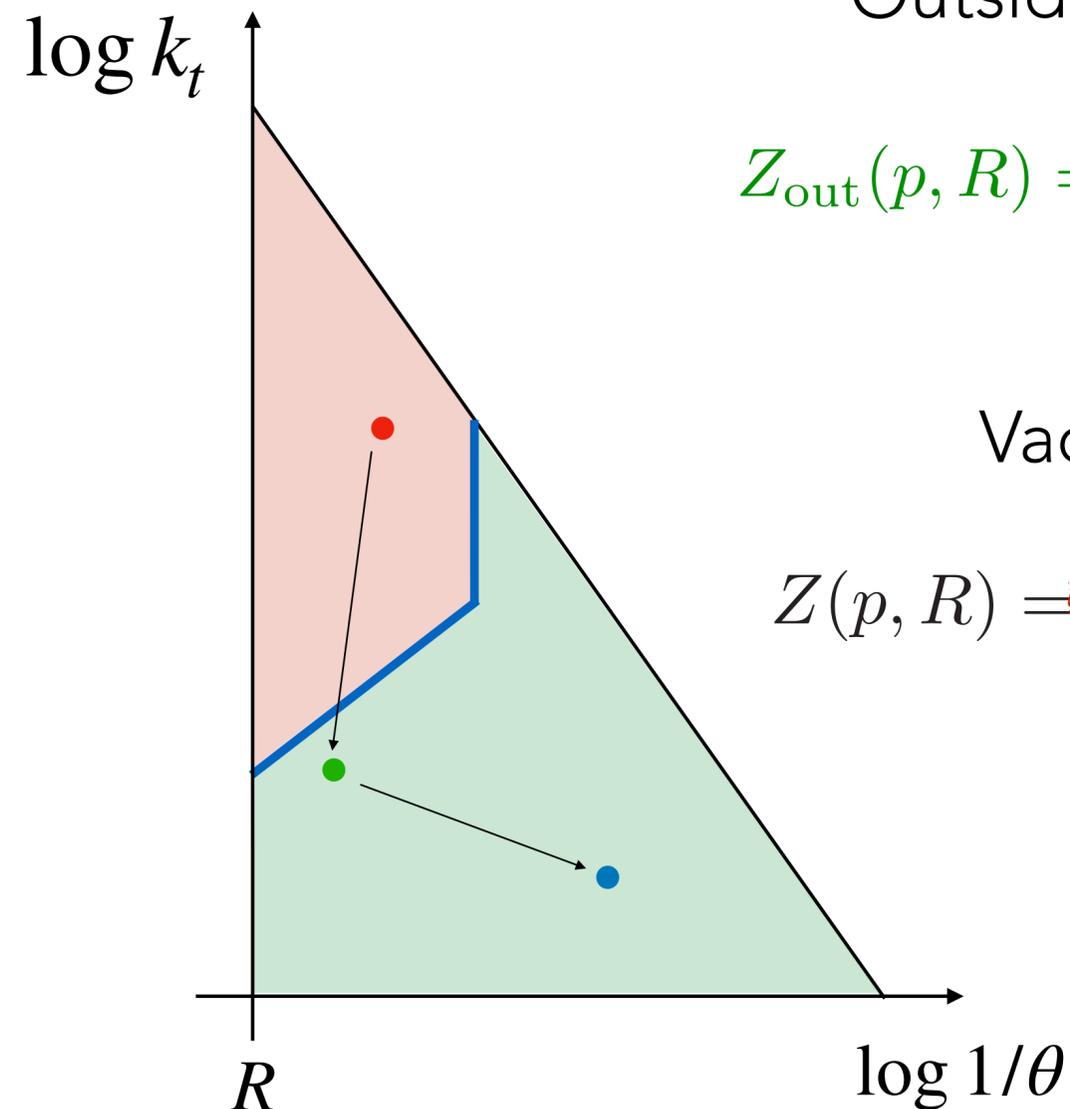
out-shower restarted from max angle (AAO)

$\log k_t$

$\log 1/\theta$

R

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out-shower restarted from max angle (AAO)

accounts for quenching through iterative use of GF

$\log k_t$

R $\qquad$ $\log 1/\theta$

RESUMMED QUENCHING WEIGHT

Non-trivial normalization of the GF: $Z(p, R; \{u = 1\}) = Q(p, R)$!

Mismatch between real and virtual diagrams!

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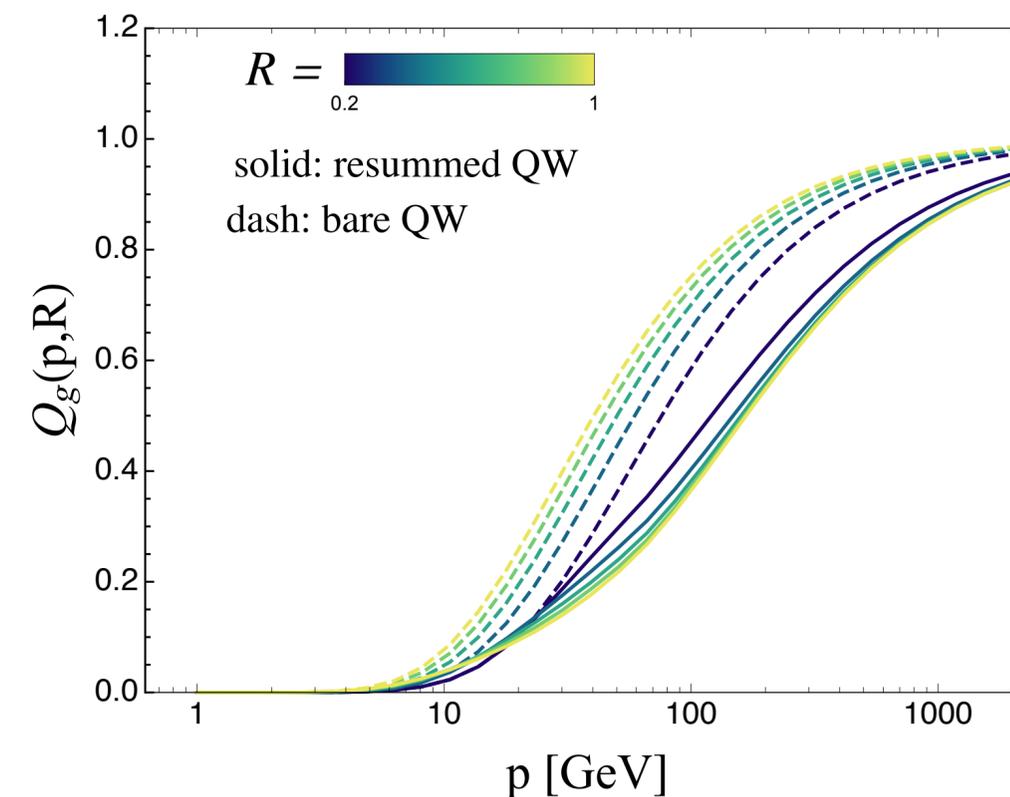non-linear evolution of quenching

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non-linear evolution of quenching

K. Tywoniuk (UiB)

17

- quenching is not restricted to the cone!

- in-cone fragmentation: not measured but affects energy loss.

- out-of-cone evolution: governed by DGLAP-like equation

R-dependence of the jet spectrum in terms of a jet fragmentation function

$$\frac{\mathrm{d}\sigma^{\mathrm{jet}}(R)}{\mathrm{d}p_T} = \sum_{i=q,g} \frac{\mathrm{d}\sigma_i}{\mathrm{d}p_{\mathrm{T}}} \int_0^1 \mathrm{d}z \, z^{n_i(p_T)-1} f_{\mathrm{jet}/i}(z,t)$$

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$$Q_q(p,1)f_{\mathrm{jet}/q}(z,p,t) = Q_q(p,R)\delta(1-z)$$

$$+ \int \mathrm{d}\Pi \, \Theta_{\mathrm{in}} \frac{1}{z'} P_{qq}(z') f_{\mathrm{jet}/q}\left(\frac{z}{z'}, z'p, t'\right) Q_q(z'p, \theta') Q_g\big((1-z')p, \theta'\big)$$

$$- \int \mathrm{d}\Pi \, \Theta_{\mathrm{in}} P_{qq}(z') f_{\mathrm{jet}/q}(z,p,t') Q_q(p,\theta')$$

Medium modified DGLAP

THE MICROJET SPECTRUM IN MEDIUM

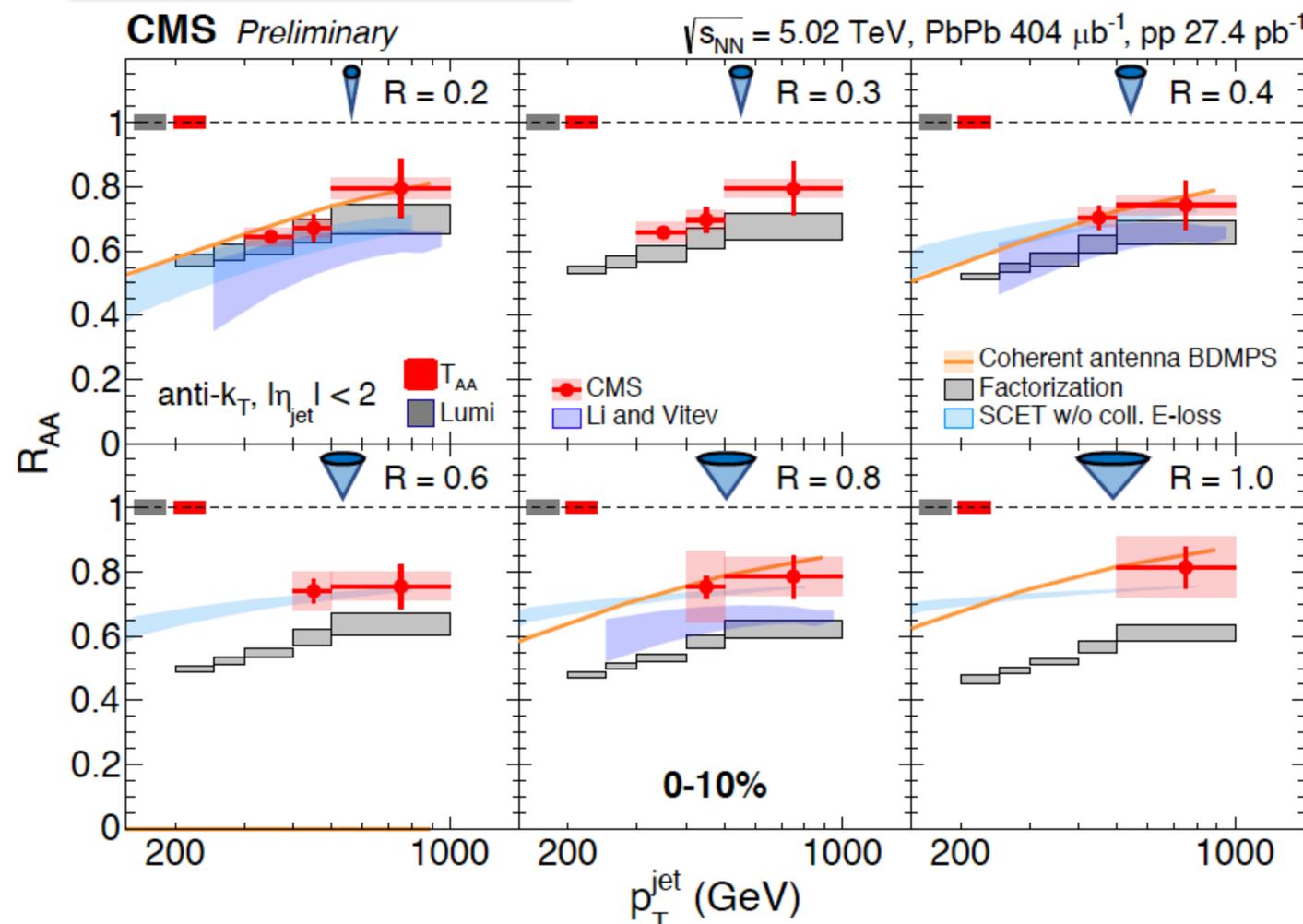R-dependence of the jet spectrum in terms of a jet fragmentation function

$$\frac{d\sigma^{\text{jet}}(R)}{dp_T} = \sum_{i=q,g} \frac{d\sigma_i}{dp_T} \int_0^1 dz\, z^{n_i(p_T)-1} f_{\text{jet}/i}(z,t)$$

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Medium modified DGLAP

Taylor (Wed 11:20)

- non-trivial evolution with jet cone size reproduced in pp and AA!

- sensitive to the of recapturing of energy at large angles and multi-parton quenching

Outlook

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- hierarchy of jet vs medium scales established

  - scaling of energy loss with relevant phase space

  - probabilistic interpretation

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- jet R_{AA} spectra well described: promising for future substructure studies

Backup
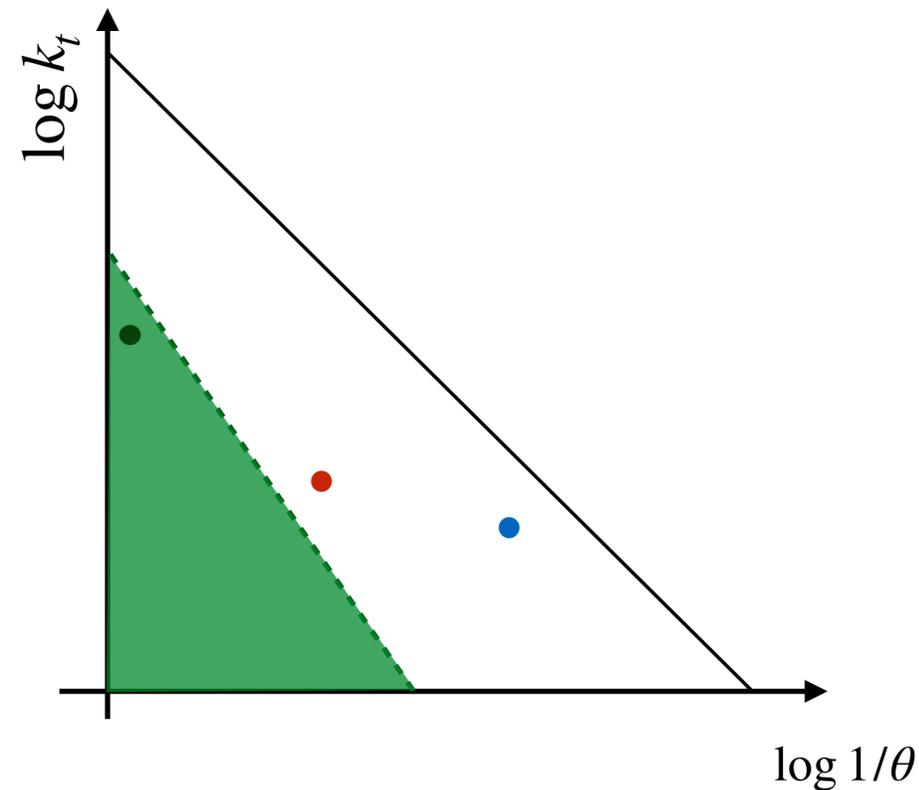
OBSERVABLES FROM PRIMARY EMISSIONS
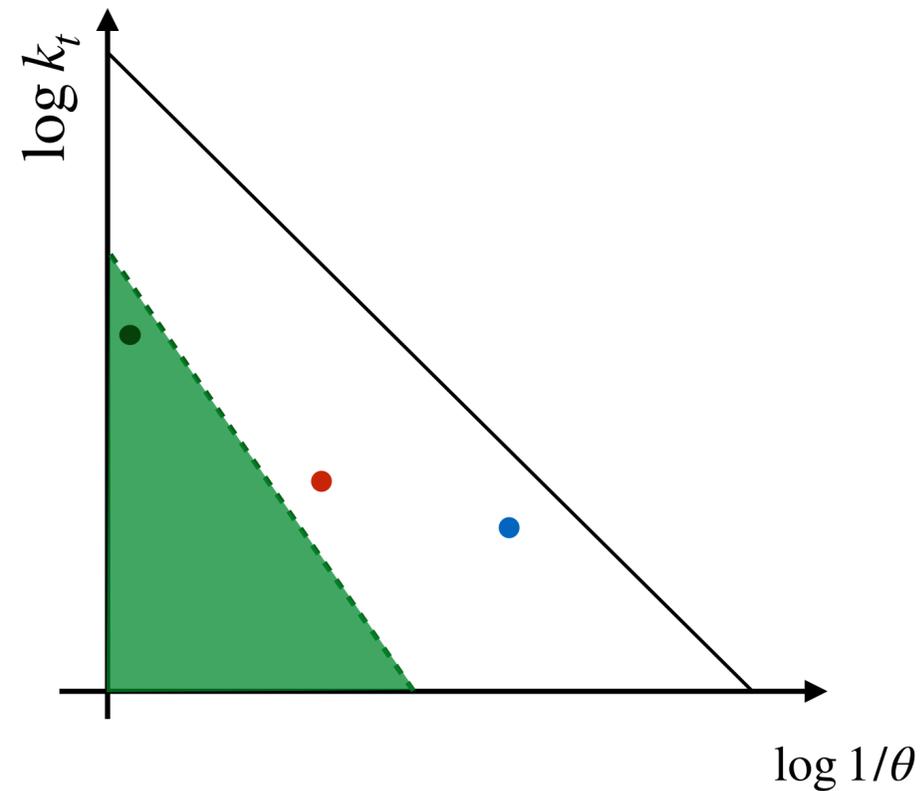
Soft Drop/mMDT

[Dasgupta, Fregoso, Marzani, Salam1307.0007;
Larkoski, Marzani, Soyez, Thaler 1402.2657]

- find first primary branch in the
  tree that satisfies $z > z_{\text{cut}}(\theta/R)^{\beta}$

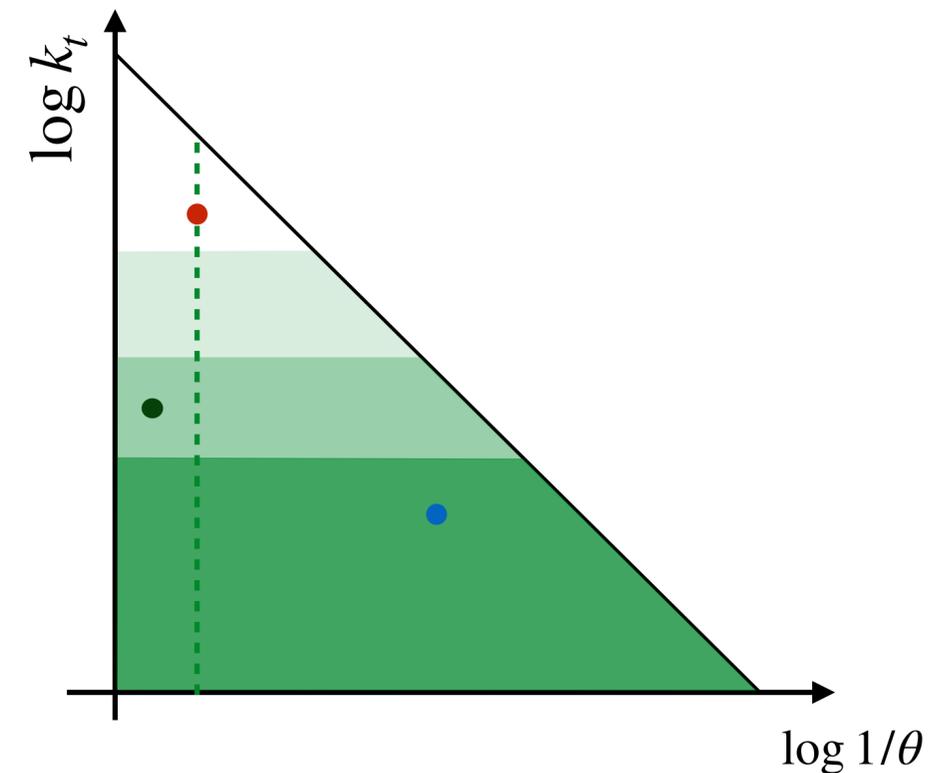- many observables: z_g, m_g and n_{SD}

OBSERVABLES FROM PRIMARY EMISSIONS

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NEW! Dynamical grooming
[Mehtar-Tani, Soto-Ontoso, KT 1911.00375]
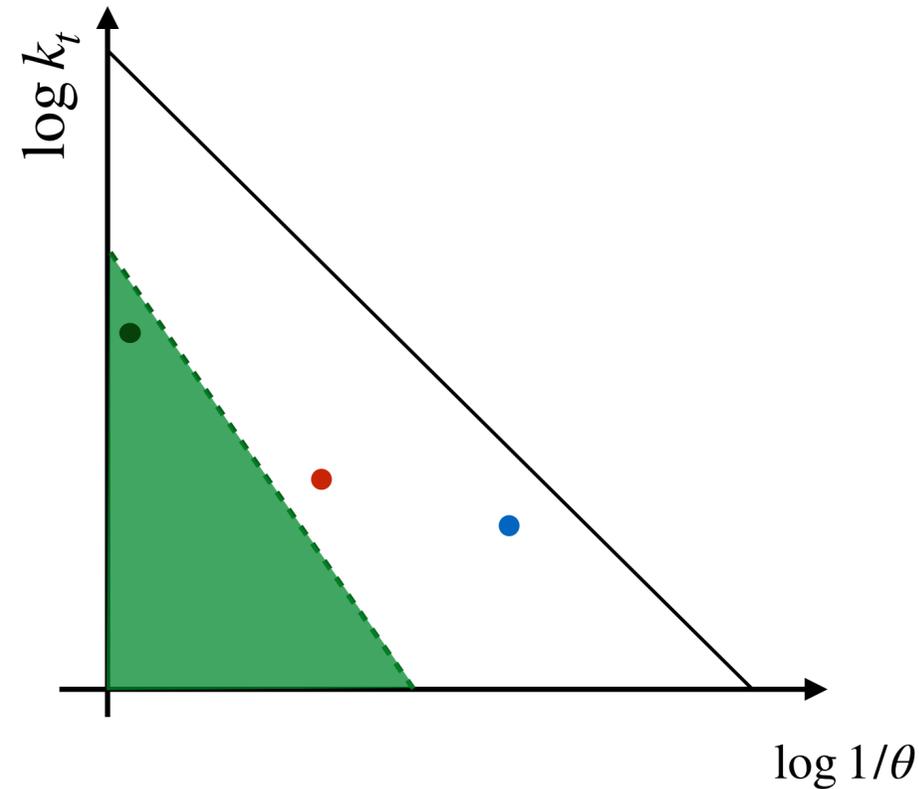
- find hardest branch in the tree,
$$\kappa^{(a)} = \max_{i \in \text{C/A}} z_i(1-z_i)(\theta/R)^a$$

- earlier emissions interpreted as radiation off total color charge.

OBSERVABLES FROM PRIMARY EMISSIONS
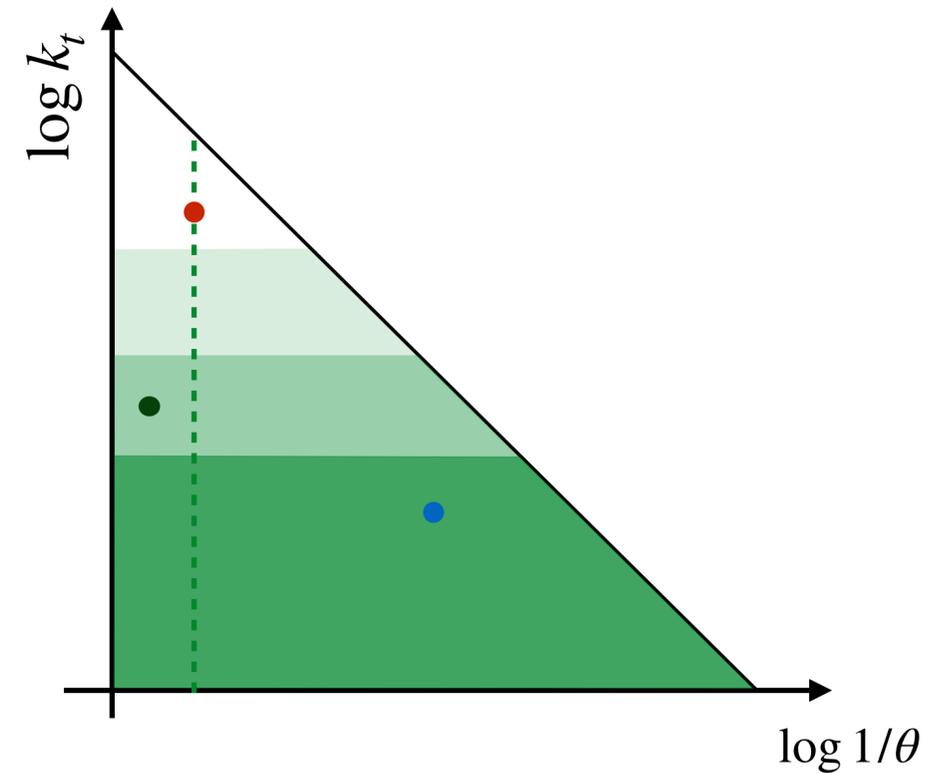

Zardoshti (Tue 09:20)

Havener (Wed 09:00)

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[Dasgupta, Fregoso, Marzani, Salam1307.0007;
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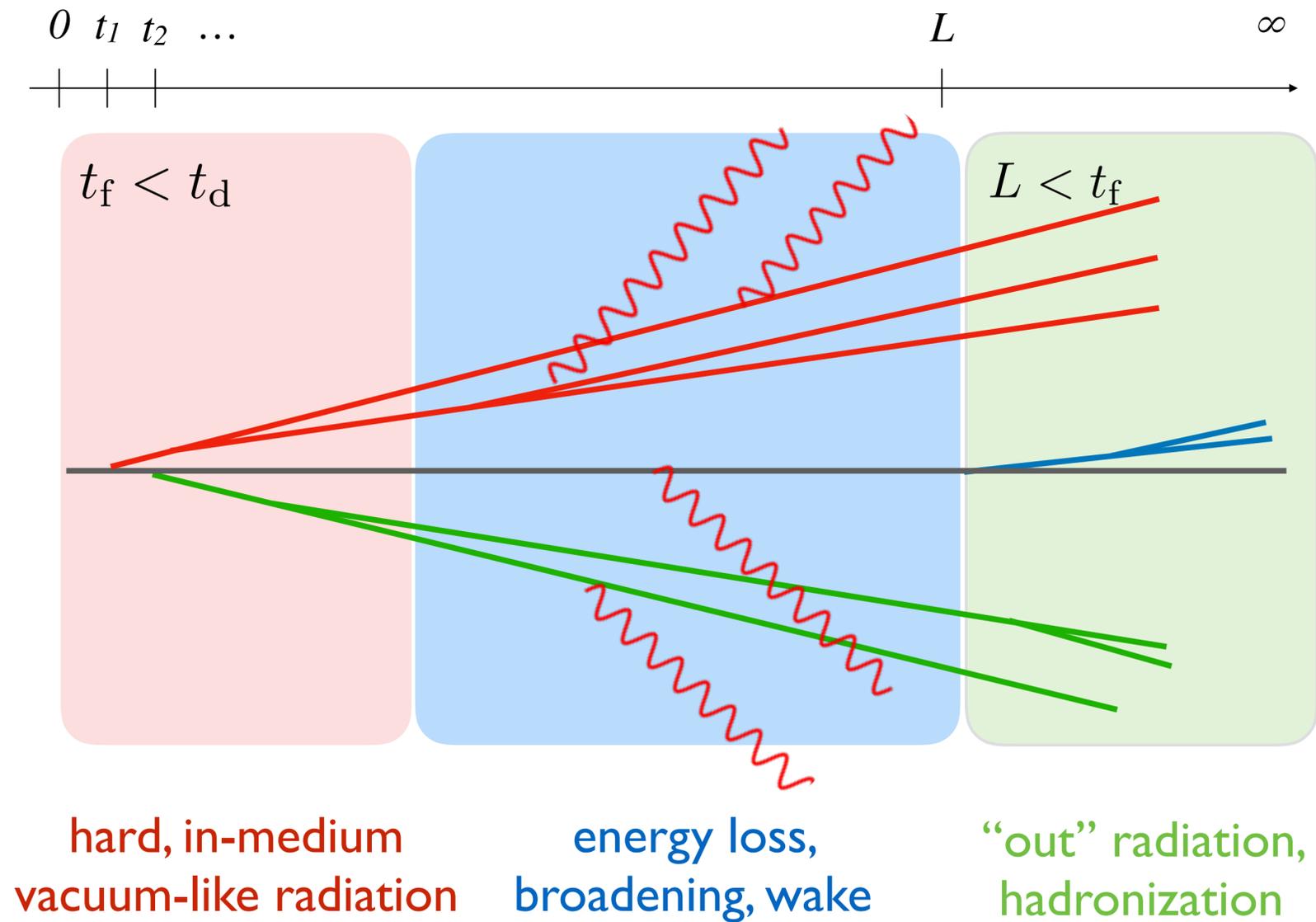- many observables: z_g, m_g and $n_{\rm SD}$

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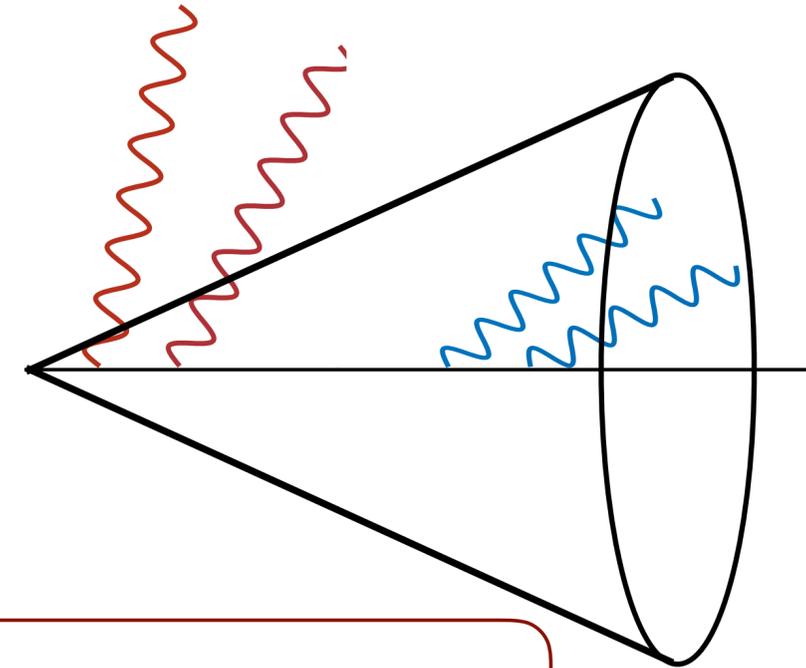
EMERGING PROBABILISTIC PICTURE

[See also Caucal, Iancu, Soyez, Mueller 1801.09703]

TWO SEPARATED REGIMES

see also Kurkela, Wiedemann 1407.0293

Energy loss for jets is driven by out-of-cone emissions.

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

$$N \sim \mathcal{O}(\alpha_s)$$

$$\theta_{\text{br}} \sim \theta_c = (\hat{q}L^3)^{-1/2}$$

perturbative: rare, small-angle radiation

intra-jet structure modifications

$$\omega \sim \omega_s = \alpha_s^2 \hat{q}L^2$$

$$N \sim 1$$

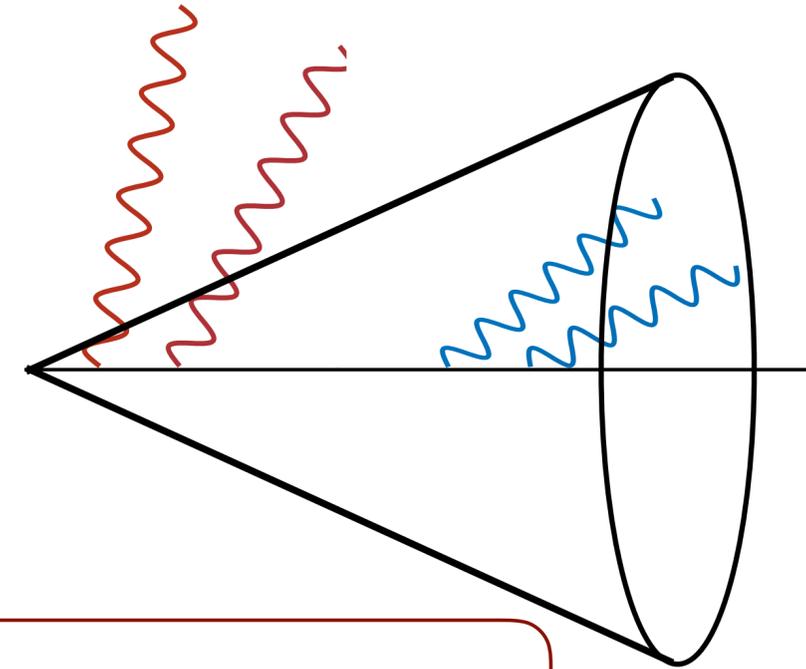$$\theta_{\text{br}} \sim \frac{1}{\alpha_s^2} \theta_c$$

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out-of-cone energy-loss, thermalization

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non-perturbative: copious, large-angle emissions

out-of-cone energy-loss, thermalization

Gluons with $\omega_s \sim 5\,\mathrm{GeV}$ melt into the plasma!

Blaizot, Dominguez, Iancu, Mehtar-Tani 1301.6102

SUPPRESSION OF HARD SPECTRUM

Simplified example: consider a $1 \to N$ process followed by energy loss.

$$\frac{\mathrm{d}\sigma_{\mathrm{excl}}}{\mathrm{d}k_1 \dots \mathrm{d}k_N} = \int \mathrm{d}p \left\{ \prod_i \int \mathrm{d}\epsilon_i \, \mathscr{P}(\epsilon_i) \right\} f_{1 \to N}\left(k_1 + \epsilon_1, \dots, k_N + \epsilon_N \,|\, p\right) \delta\left(p - \sum_i k_i - \sum_i \epsilon_i\right) \frac{\mathrm{d}\sigma_0}{\mathrm{d}p}$$

Leading-order effect: $\qquad \dfrac{\mathrm{d}\sigma_{\mathrm{excl}}}{\mathrm{d}k_1 \dots \mathrm{d}k_N} \simeq \left(\int \mathrm{d}\epsilon \, \mathscr{P}(\epsilon) \mathrm{e}^{-n\epsilon/p} \right)^N \dfrac{\mathrm{d}\sigma_{0,\mathrm{excl}}}{\mathrm{d}k_1 \dots \mathrm{d}k_N} + \dots$
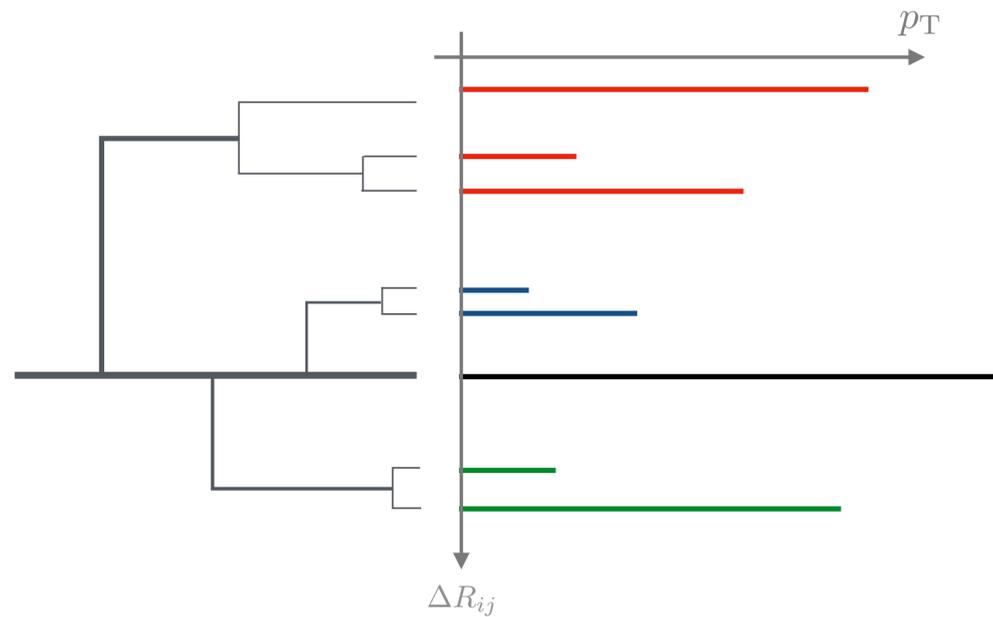
systematically improvable…

Provides a framework for studying multi-parton energy-loss effects for inclusive observables !
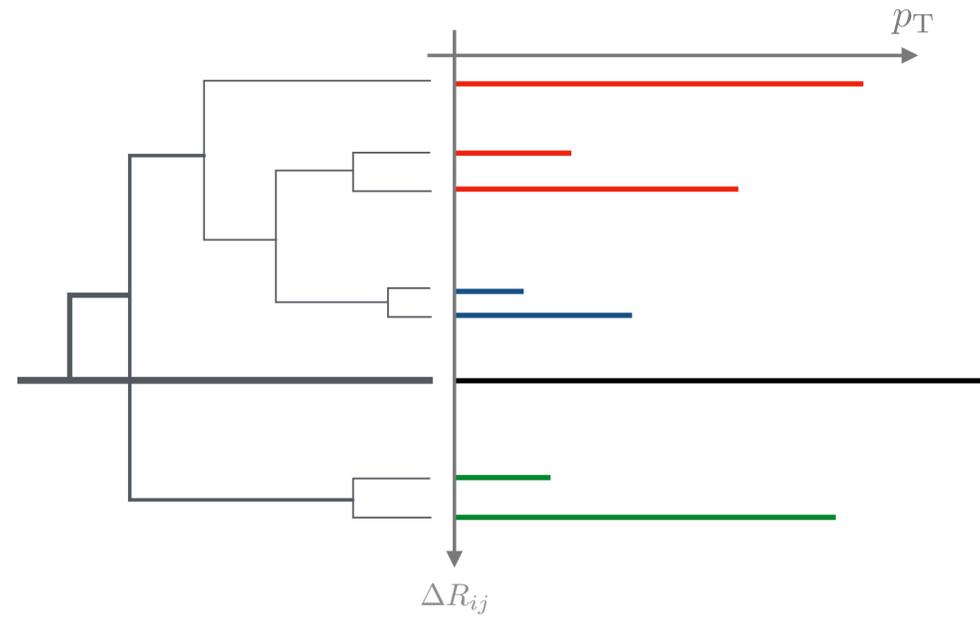
RECOMBINATION ALGORITHMS

Pairwise clustering of particles that minimize $d_{ij} = \min(p_{\mathrm{T},i}^{2\alpha}, p_{\mathrm{T},j}^{2\alpha})\Delta R_{ij}^2/R^2$

1) Cambridge/Aachen (CA)
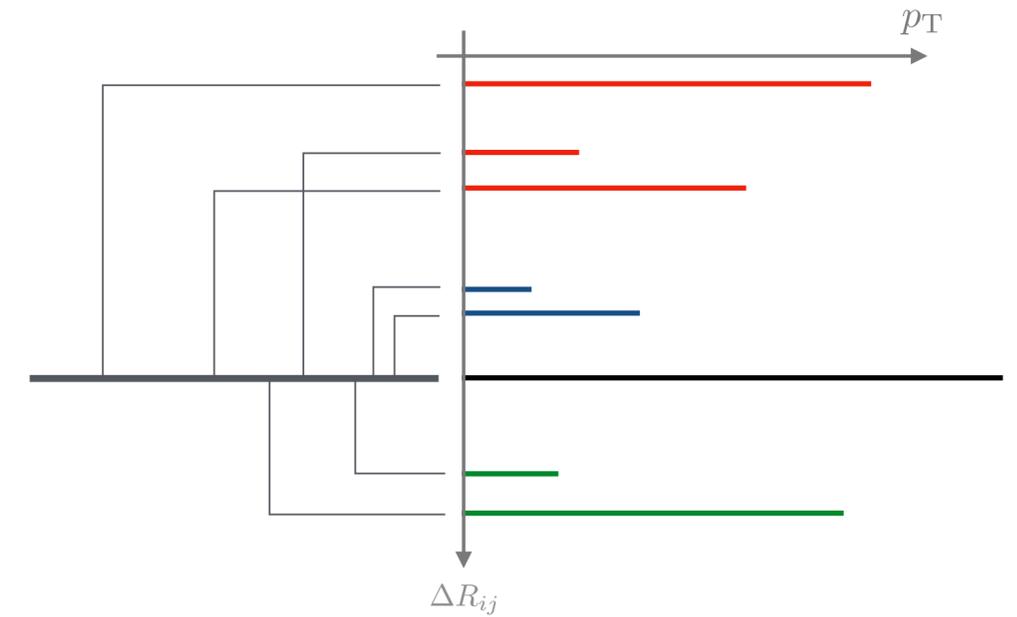[Dokshitzer, Leder, Moretti, Webber (1997)]

- only angular measure (α=0)
- ideal for substructure measurements

2) k_t algorithm
[Catani, Dokshitzer, Seymour, Webber (1993); Ellis, Soper (1993)]

- k_t weighted metric ($\alpha = 1$)
- sensitive to soft activity

3) anti-k_t algorithm
[Cacciari, Salam, Soyez (2008)]

- anti-k_t weighted metric ($\alpha = -1$)
- resilient to soft activity, ideal for identifying candidate jets

Jets are separated whenever beam distance is shortest $d_{iB} = p_{\mathrm{T},i}^{2\alpha}$