UNIVERSITY OF BERGEN

PROBING SPACE-TIME STRUCTURE AND THERMALIZATION OF QCD JETS

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UHnett-Vest - Western Norway Network for Nuclear Matter Research
Quo vadis QCD theory? Heavy-ion perspectives and beyond
30 Sep - 2 Oct 2019, UiS, Stavanger

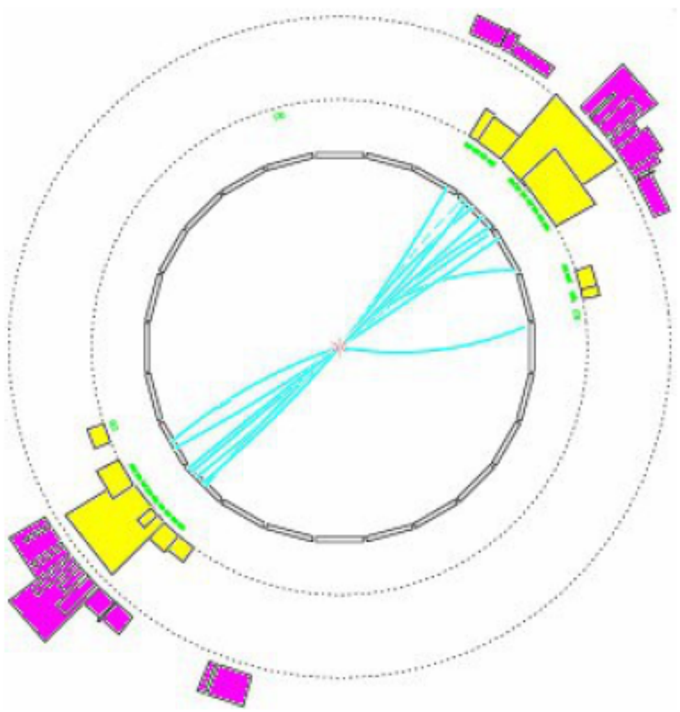
OUTLINE

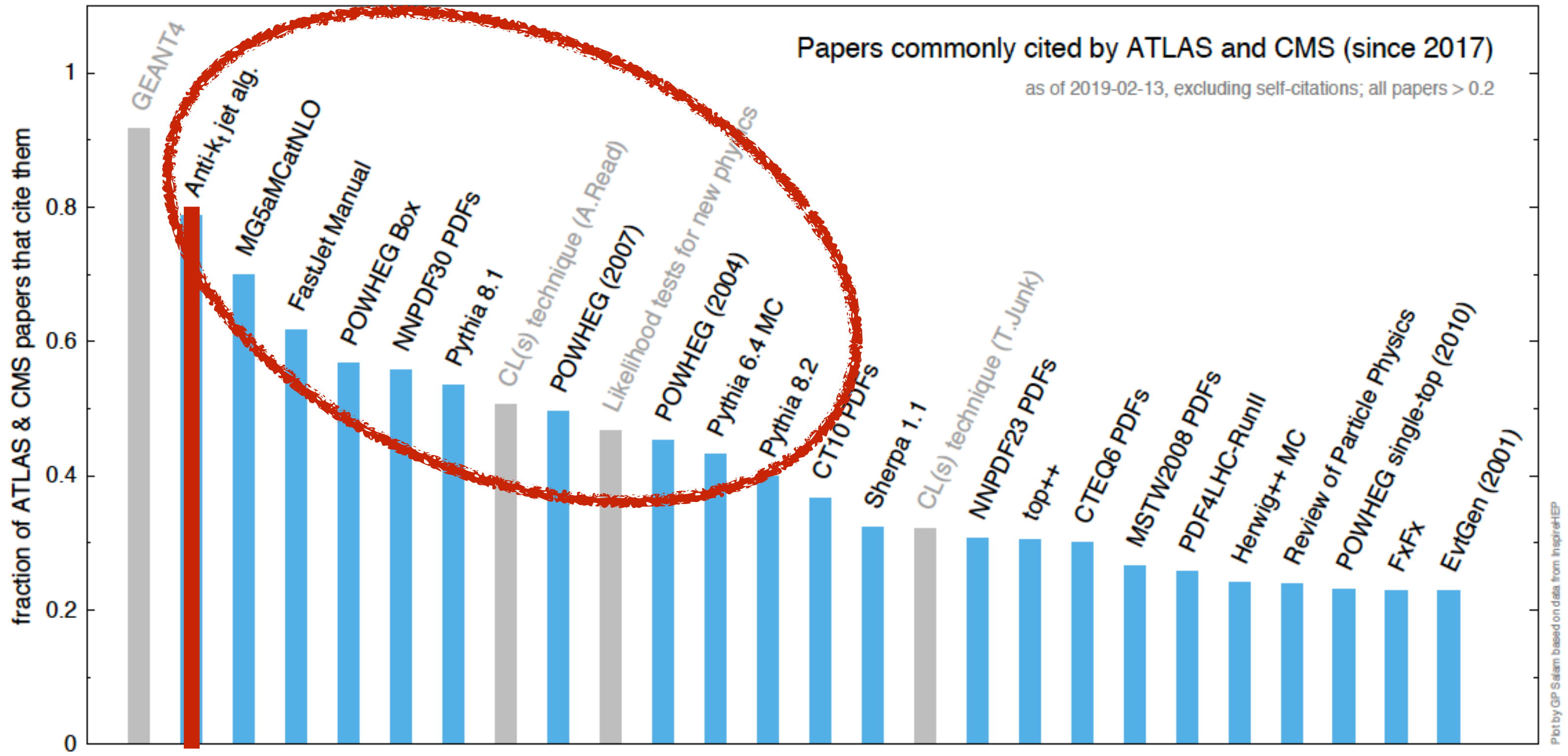
- Concepts & tools
- Observables
- Heavy-ions
- Merging vacuum and medium-induced showers

CONCEPTS & TOOLS

JETS

G. Salam (2019)

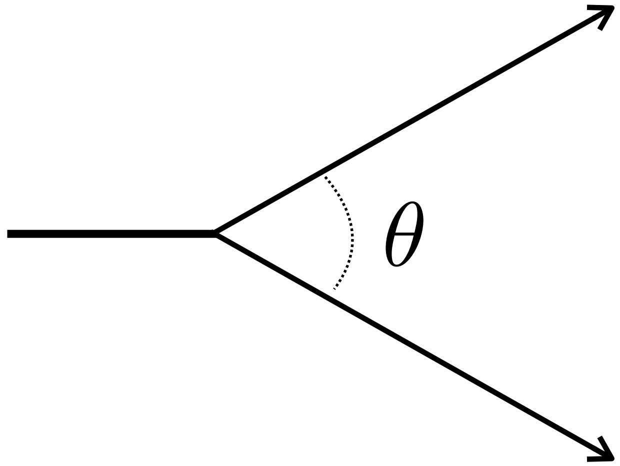




- jet acts as proxy for quark/gluon
- smallness of coupling compensated by phase space for radiation
- resummation of soft & collinear divergences
- workhorse for collider physics

QCD VACUUM SPLITTING

Consider a generic 1→2 splitting in QCD.



$$p_\perp = z(1-z)E\theta$$

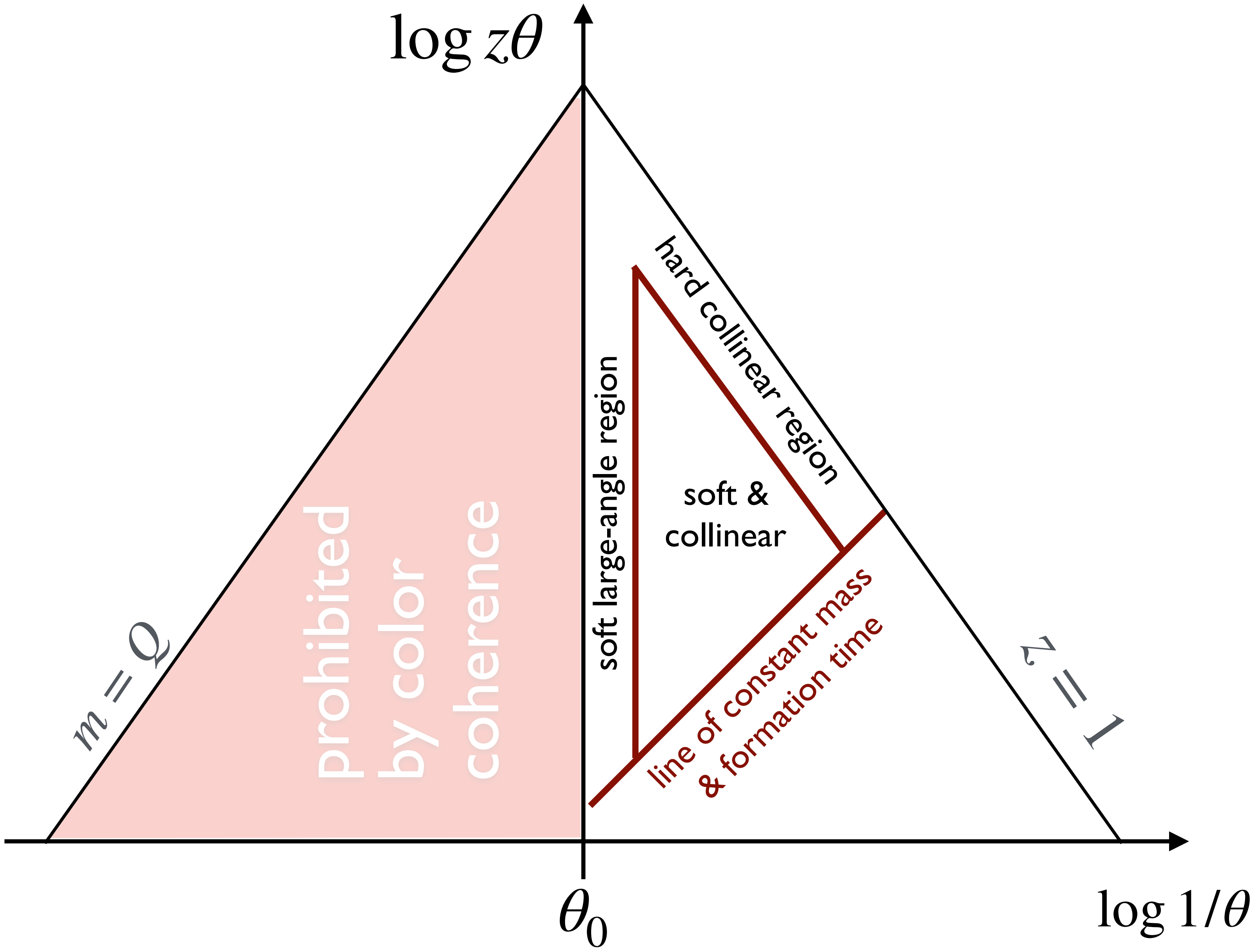
$$\mathrm{d}\mathcal{P}_{\mathrm{vac}} = 2\frac{\alpha_s C_R}{\pi}\,\mathrm{d}\log z\theta\,\mathrm{d}\log\frac{1}{\theta}$$

The pair invariant mass $m^2 = z(1-z)E^2\theta^2$

Formation time of splitting: $t_{\mathrm{f}} \sim \Delta E^{-1} = \frac{2z(1-z)E}{p_\perp^2}$

RADIATION PHASE SPACE

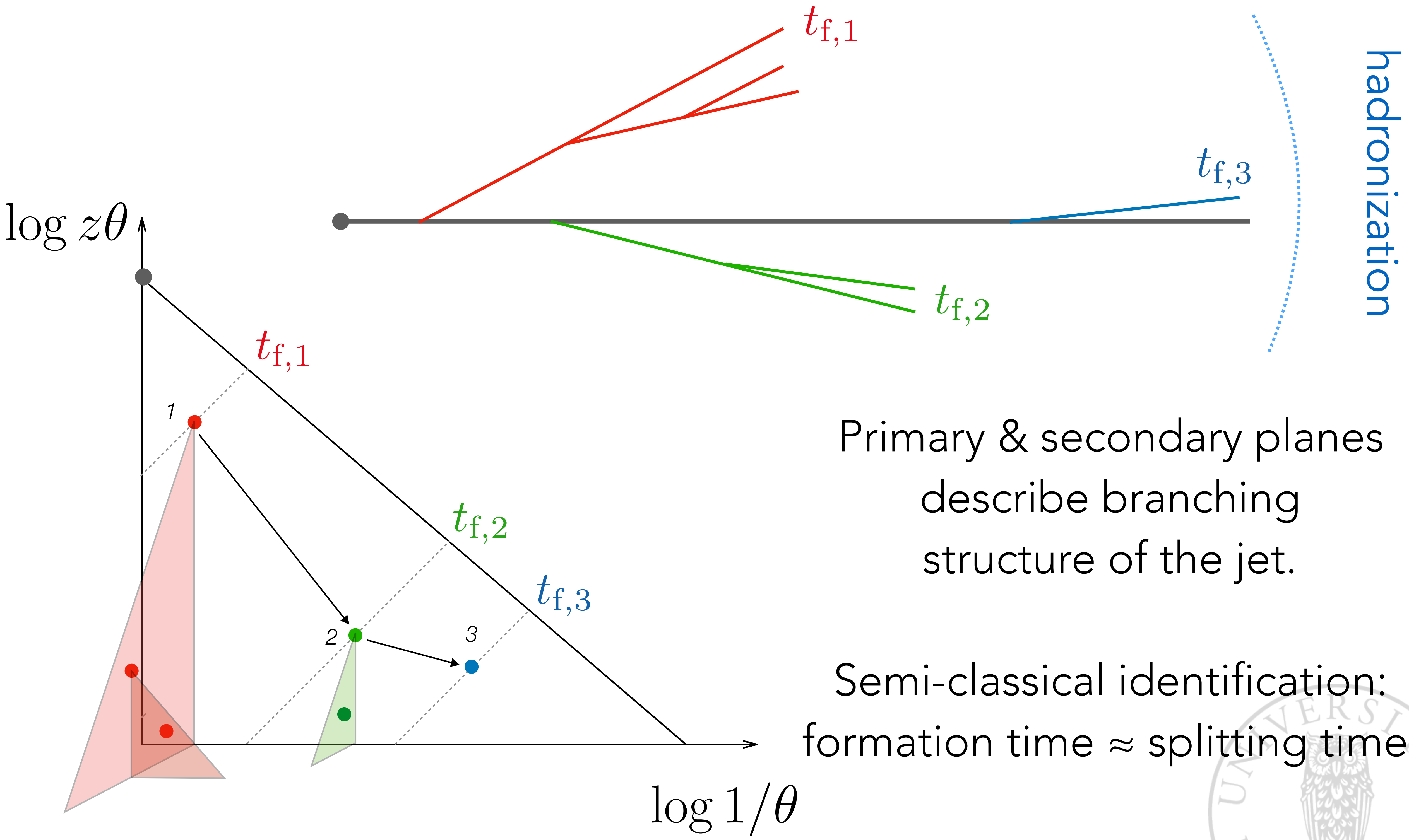
Andersson, Gustafson, Lönnblad, Pettersson Z.Phys.C (1989)



Sudakov form factor
(no-emission probability)

$$\Delta(t_1, t_0) = \exp\left[-\int_{t_0}^{t_1} \frac{\mathrm{d}t}{t} \int_0^1 \mathrm{d}z \, \frac{\alpha_s(p_\perp)}{2\pi} P(z) \Theta_{\mathrm{PT}}\right]$$

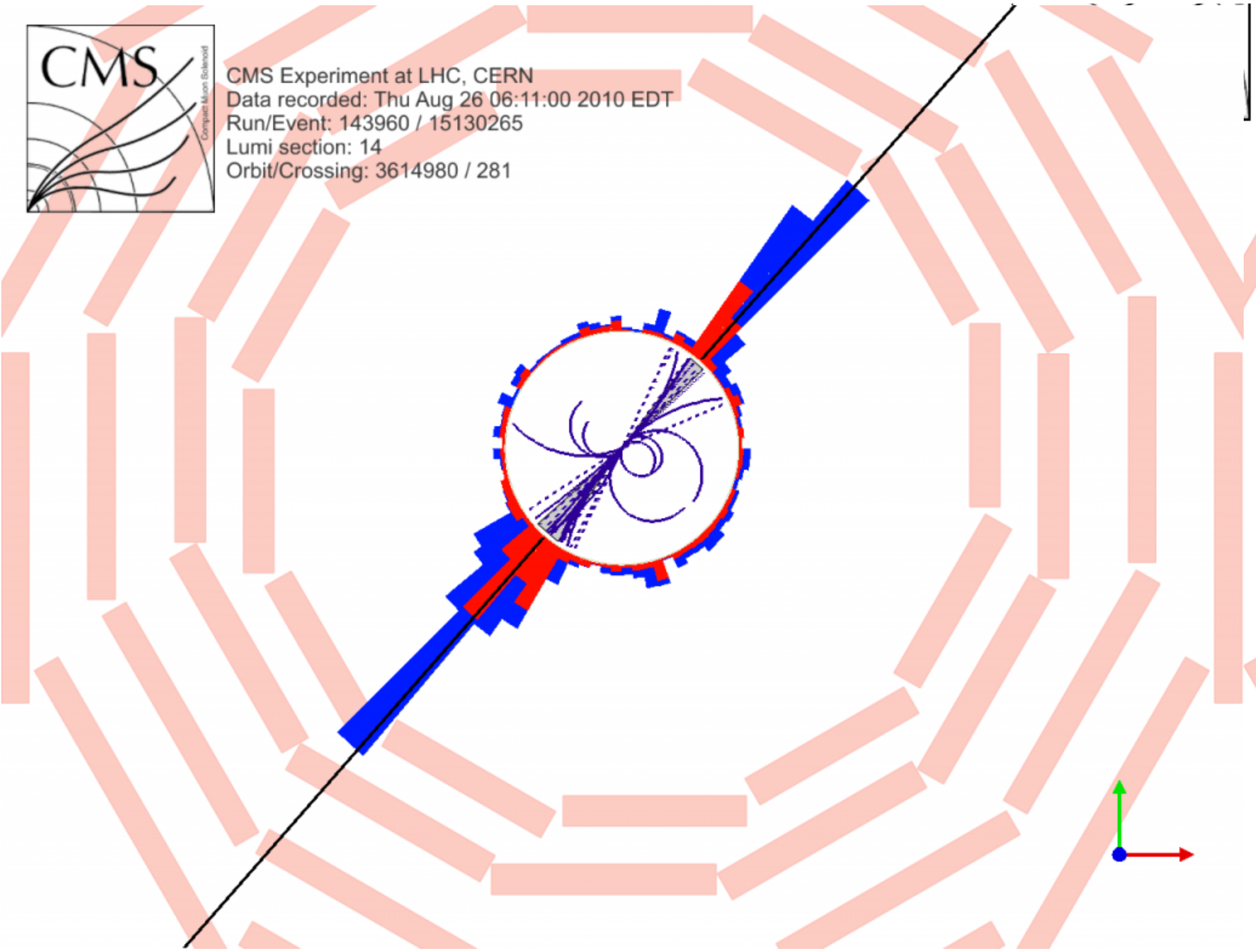
SPACE-TIME PICTURE OF THE JET



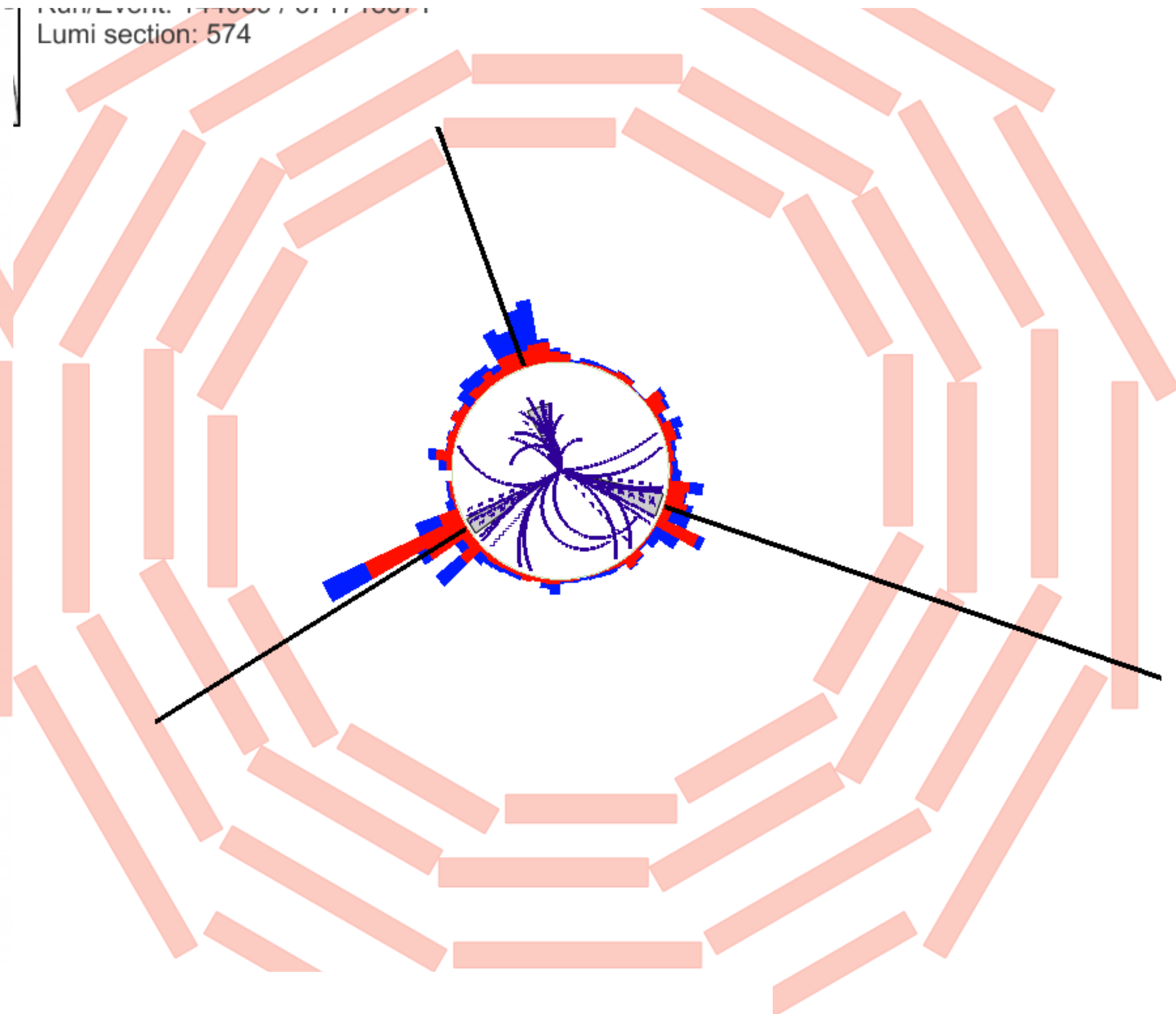
Primary & secondary planes describe branching structure of the jet.

Semi-classical identification: formation time ≈ splitting time.

JET DEFINITIONS

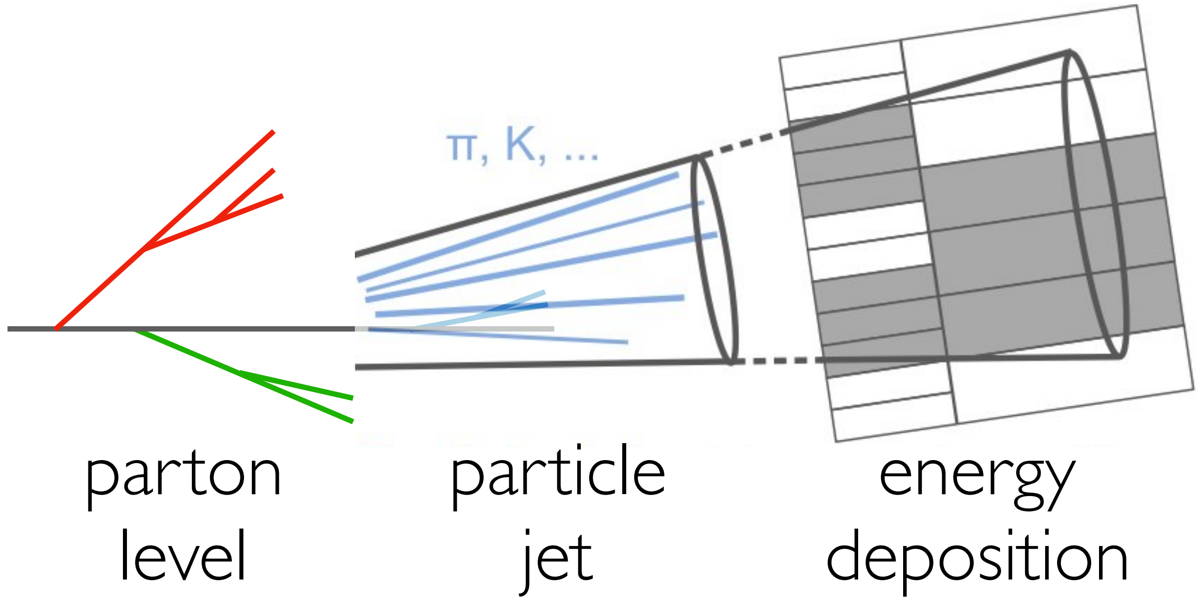


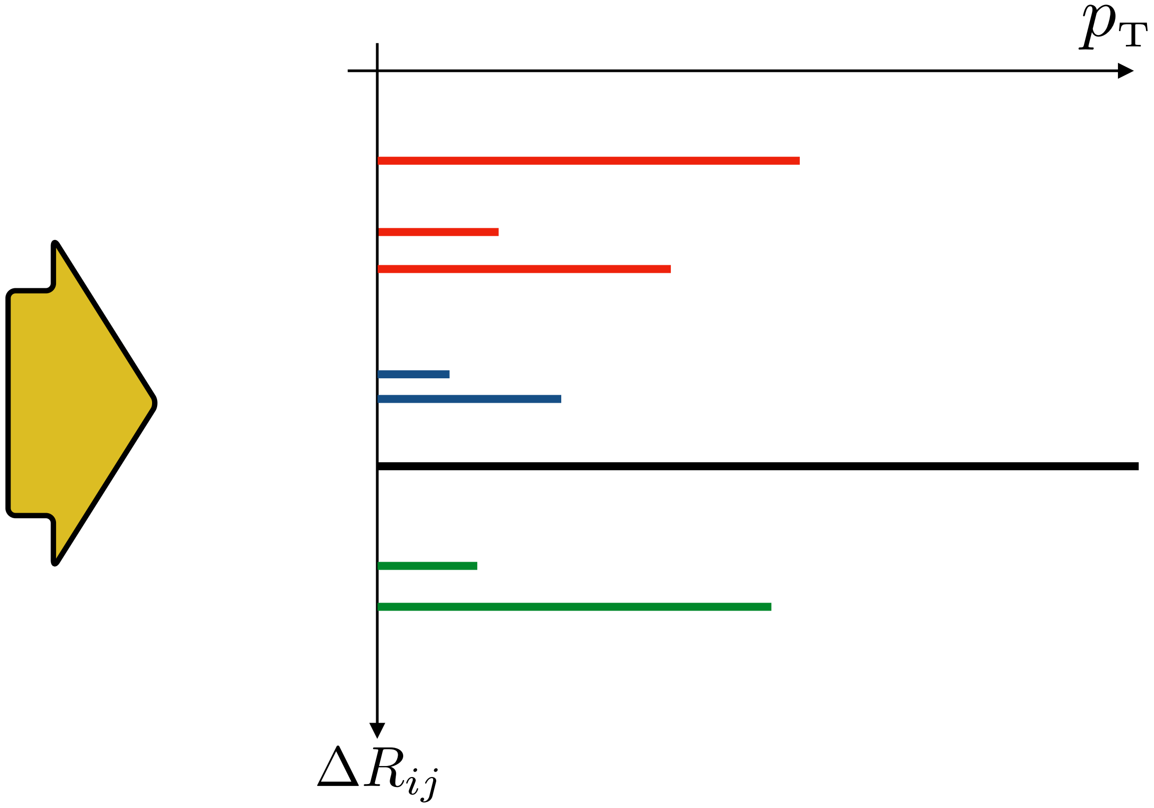
proton-proton
two-jet event (?)



proton-proton
three-jet event (?)

RECOMBINATION ALGORITHMS





$$d_{ij} = \min\left(p_{\mathrm{T},i}^{2\alpha}, p_{\mathrm{T},j}^{2\alpha}\right)\frac{\Delta R_{ij}^2}{R^2}$$

$$d_{i\mathrm{B}} = p_{\mathrm{T},i}^{2\alpha}$$

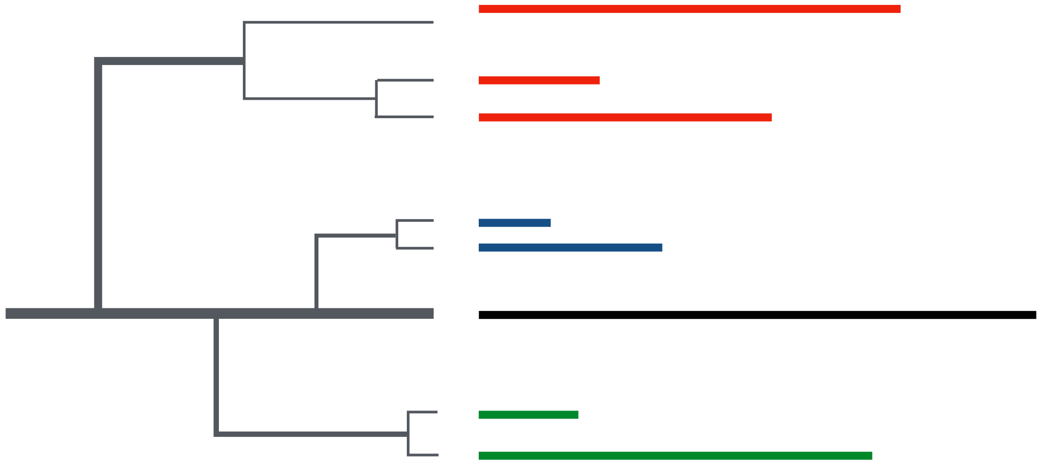
\+ recombination scheme

The algorithm is instrumental to identify the jet (clustering)

&

to associate a branching history to it (re-clustering).

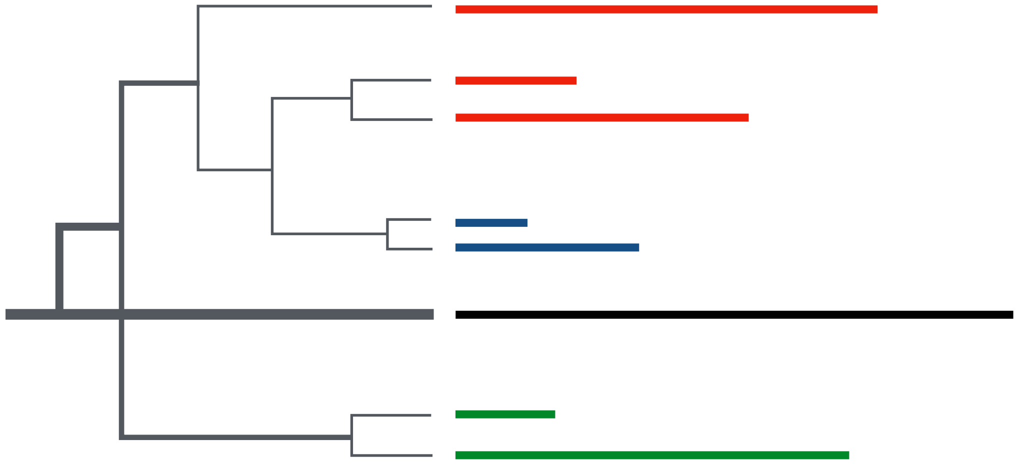
RECOMBINATION ALGORITHMS



1) Cambridge/Aachen (CA)

[Dokshitzer, Leder, Moretti, Webber (1997)]

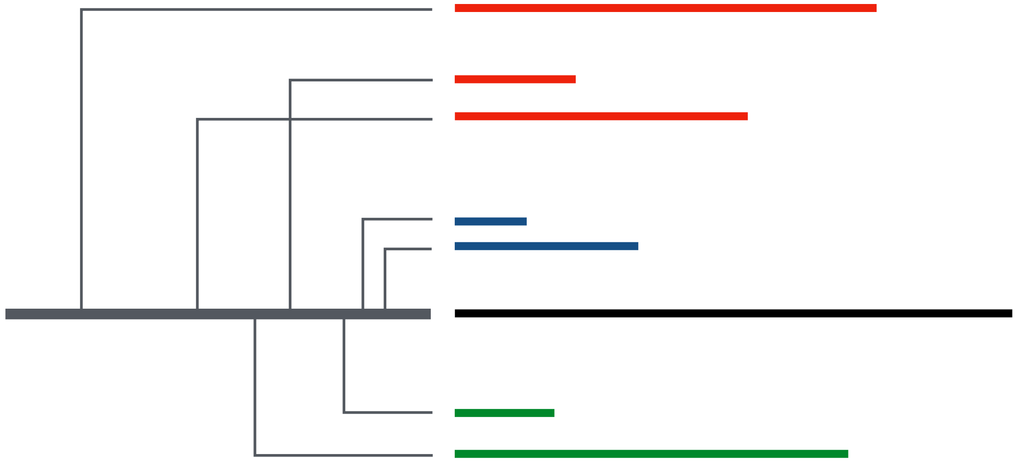
- only angular measure (α=0)
- ideal for substructure measurements



2) k_t algorithm

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

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

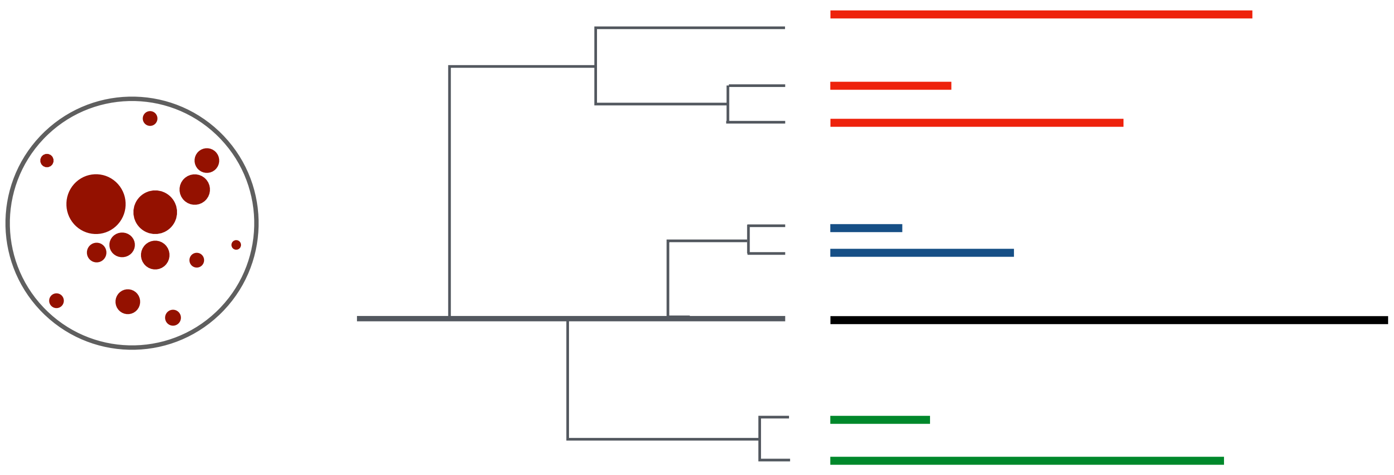


3) anti-k_t algorithm

[Cacciari, Salam, Soyez (2008)]

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

BUILDING THE LUND JET PLANE

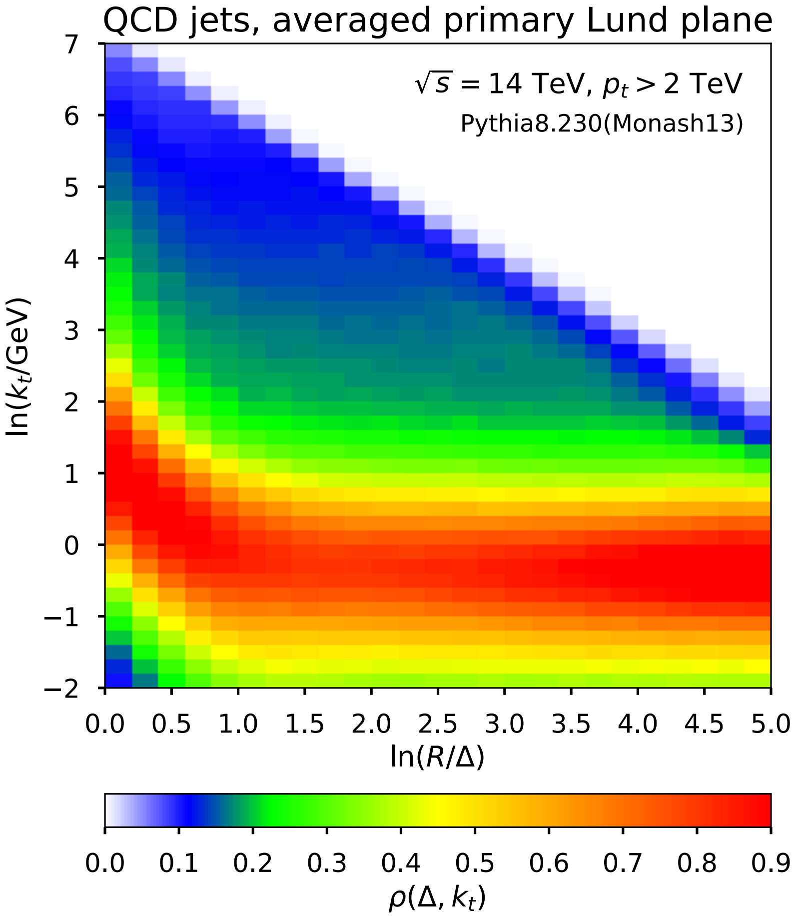


Cambridge/Aachen (CA)

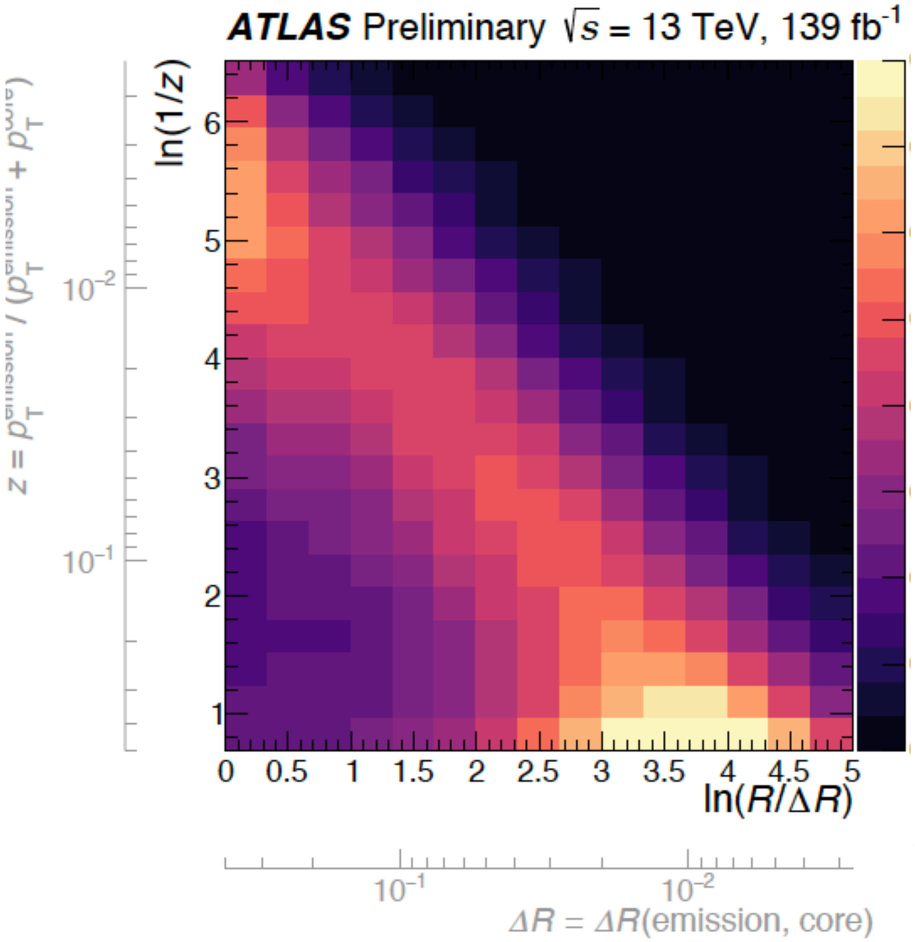
Dokshitzer, Leder, Moretti, Webber (1997)

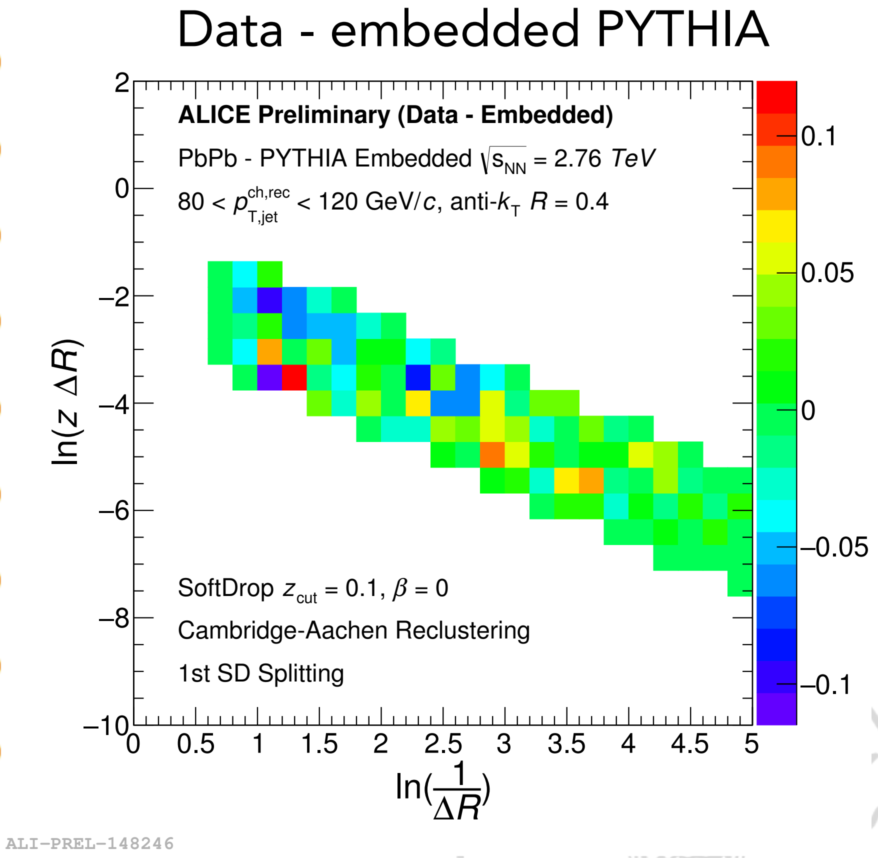
- at each "node" of the tree, extract the kinematics of the splitting

F. Dreyer, G. Salam, G. Soyez arXiv:1807.04758



ATLAS-CONF-2019-035

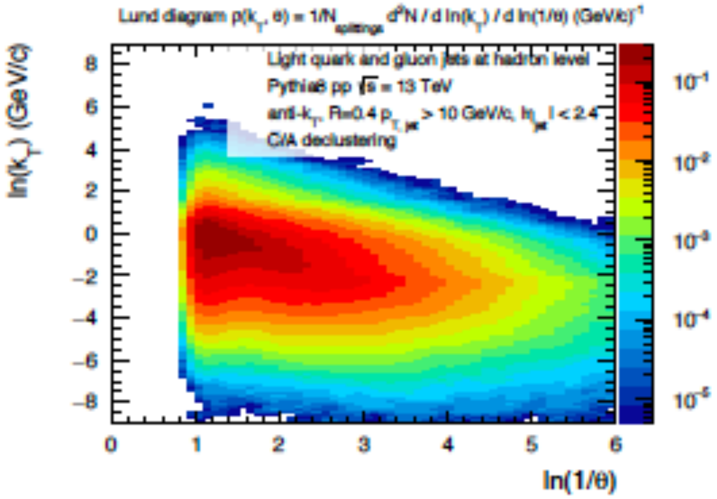




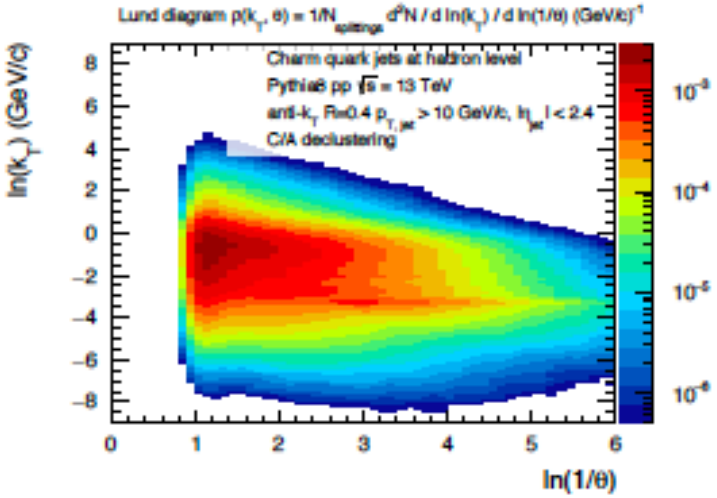
PEERING INTO THE JET

Cunqueiro, Ploskon 1812.00102

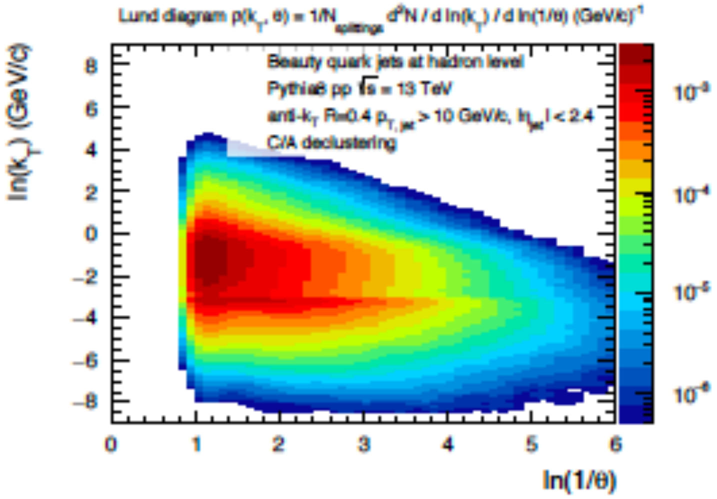
Inclusive



Charm



Bottom



GROOMING

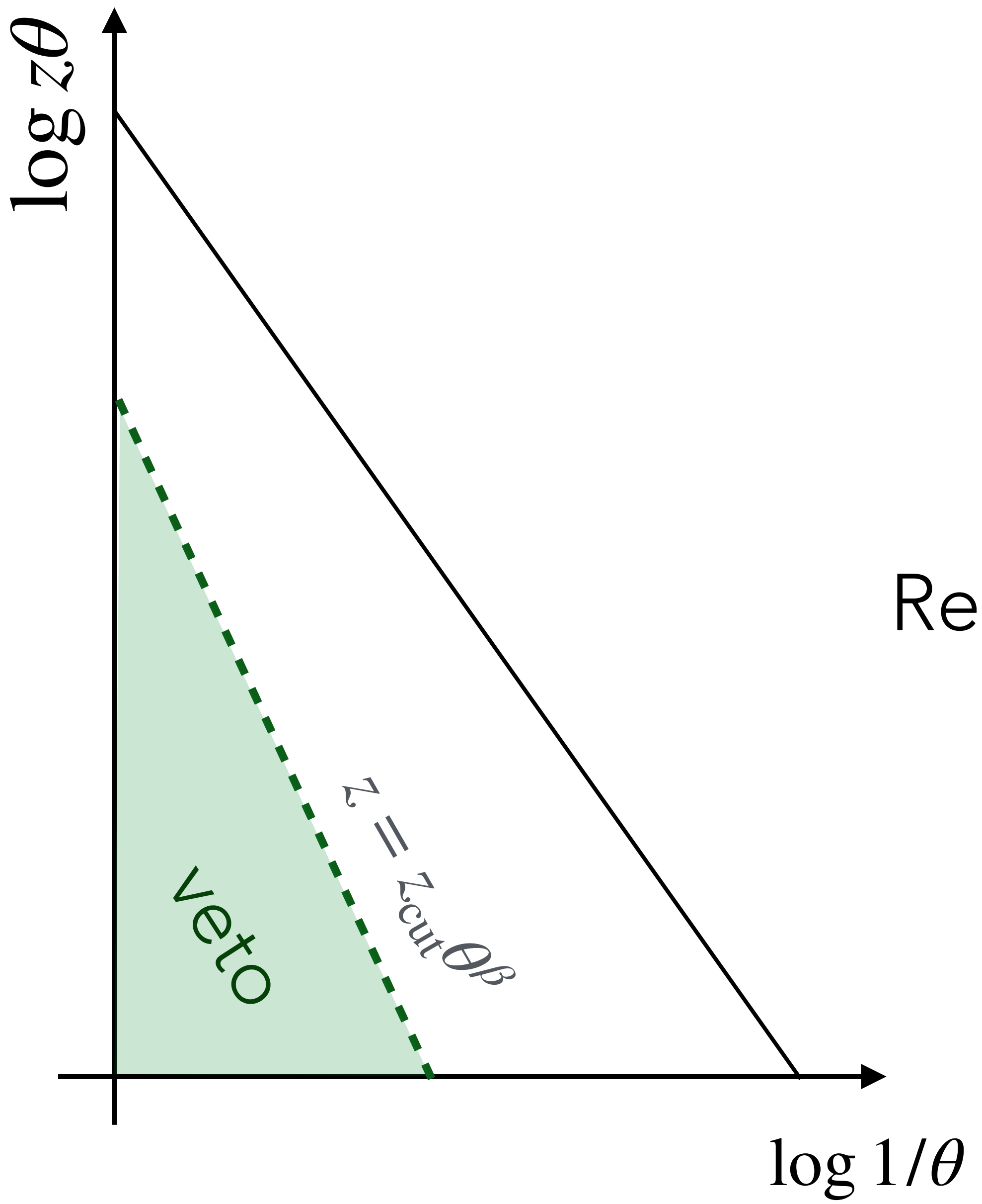
- *trimming*
- *filtering*
- *pruning*
- modified Mass-Drop Tagger/SoftDrop
- recursive SD
- **dynamical grooming**

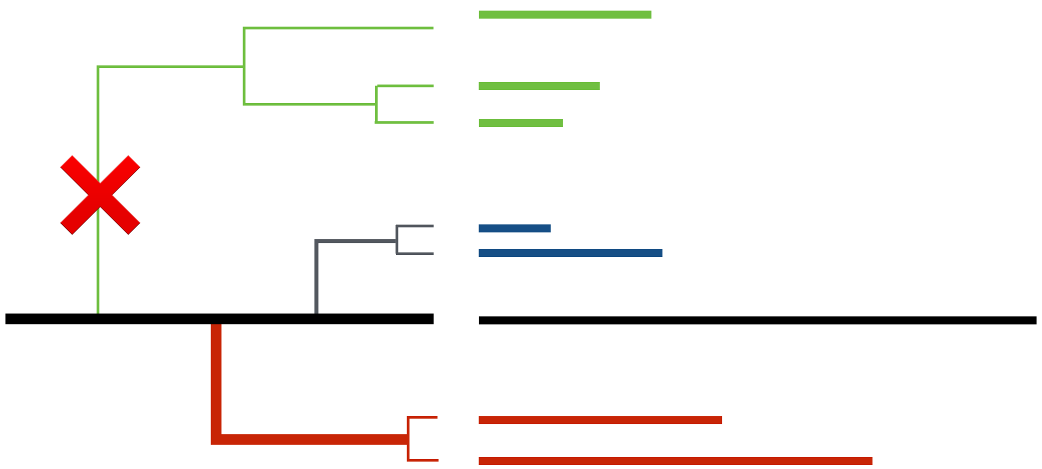
Aimed at reducing the sensitivity to underlying event
& non-global logarithms.

Background subtraction & pile-up mitigation is also performed.

SOFT DROP

Dasgupta, Fregoso, Marzani, Salam 1307.0007
Larkoski, Marzani, Soyez, Thaler 1402.2657
Larkoski, Marzani, Thaler 1502.01719





Re-cluster jet with C/A until finding first branch that satisfies:

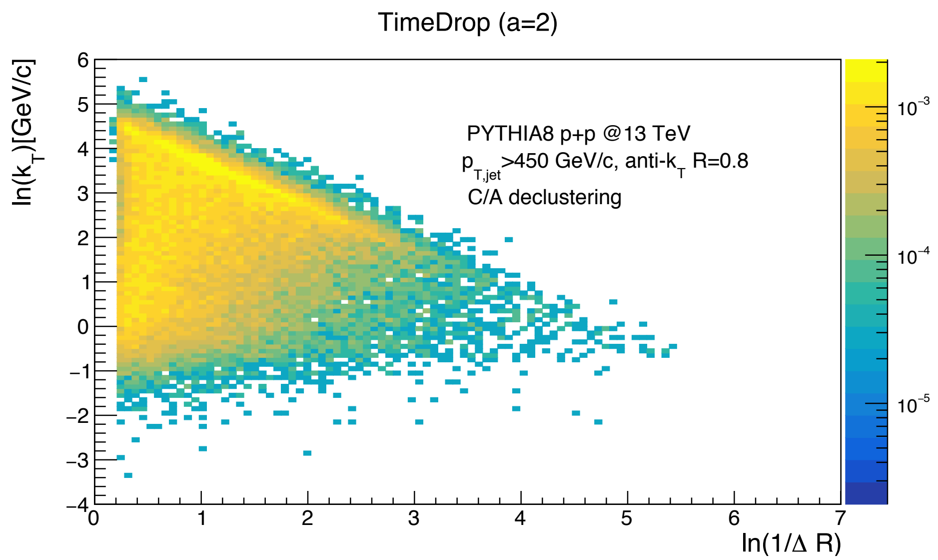
$$z > z_{\rm cut}\theta^\beta$$

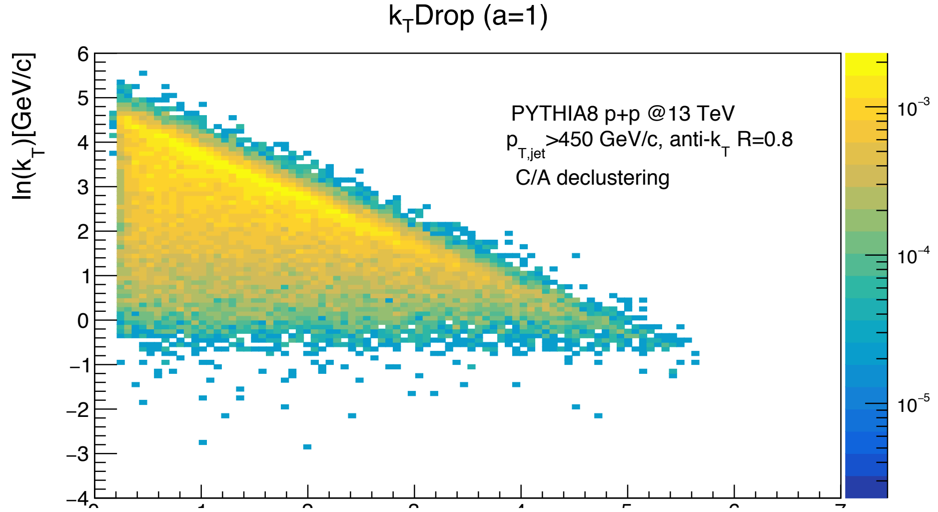
- removes soft & large-angle radiation

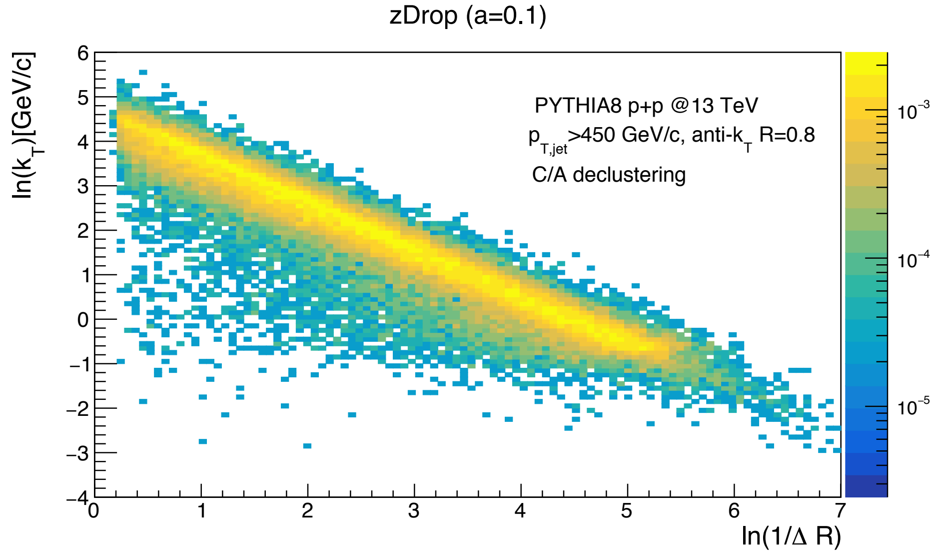
Recursive SD: continues to identify *all* branches that satisfy this condition (pruning)

Dreyer, Necib, Soyez, Thaler 1804.03657
Frye, Larkoski, Thaler, Zhou 1704.06266

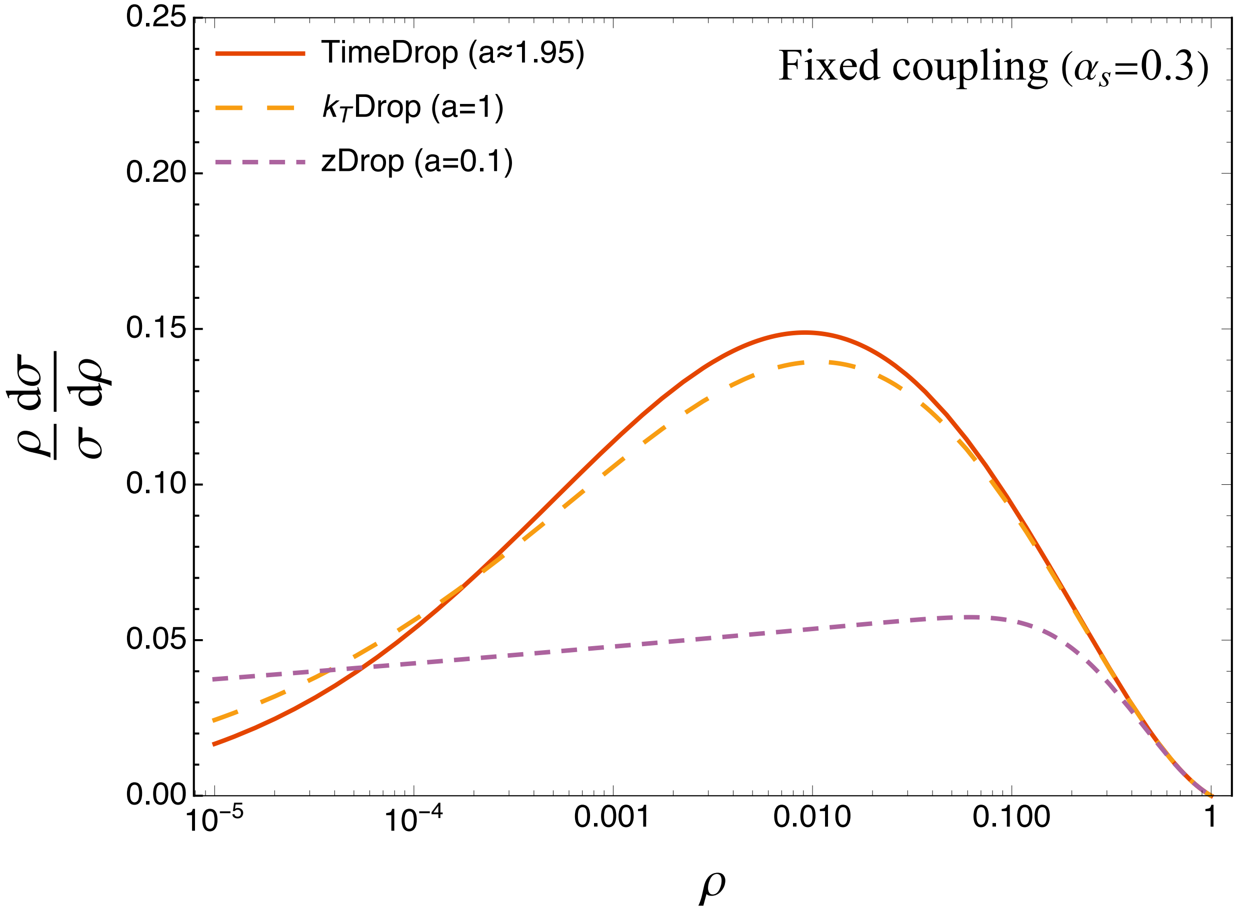
DYNAMICAL GROOMING







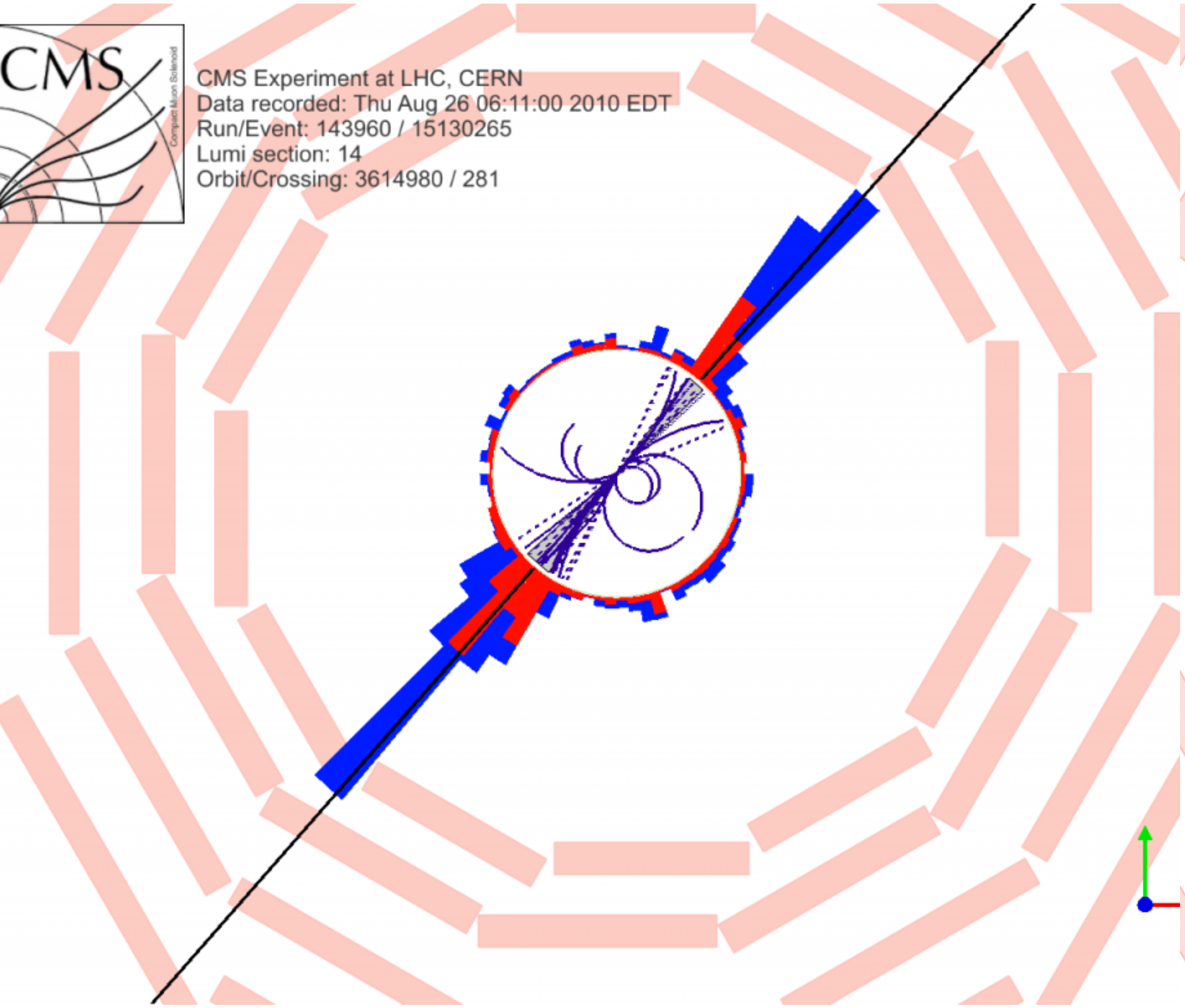
Mehtar-Tani, Soto-Ontoso, KT (in preparation)



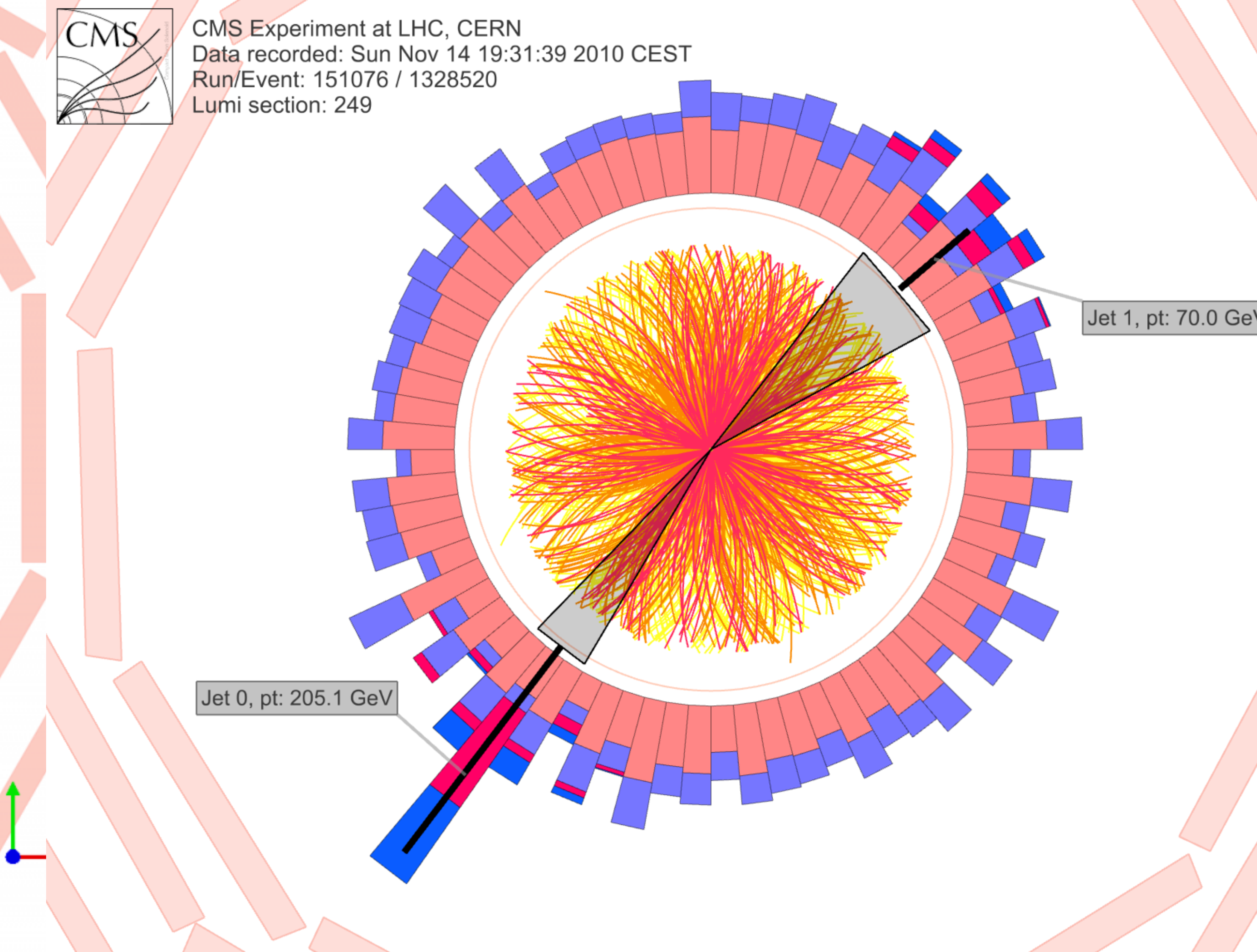
- identify “hardest” emission in jet
- dynamical jet scale event-by event
- softer emissions at larger angles groomed away (violation of ordering)

HEAVY-IONS

JET QUENCHING IN HEAVY-ION COLLISIONS

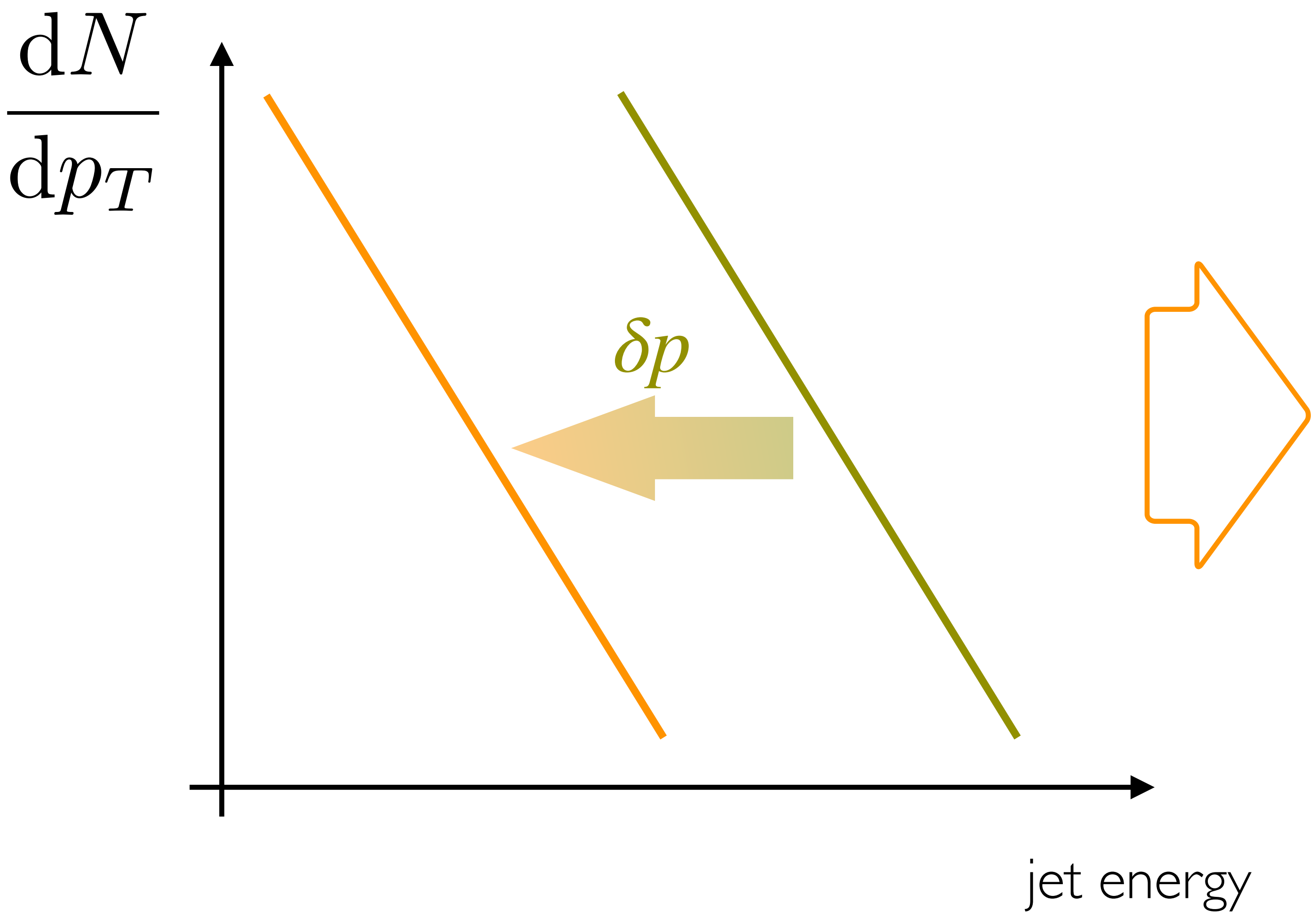


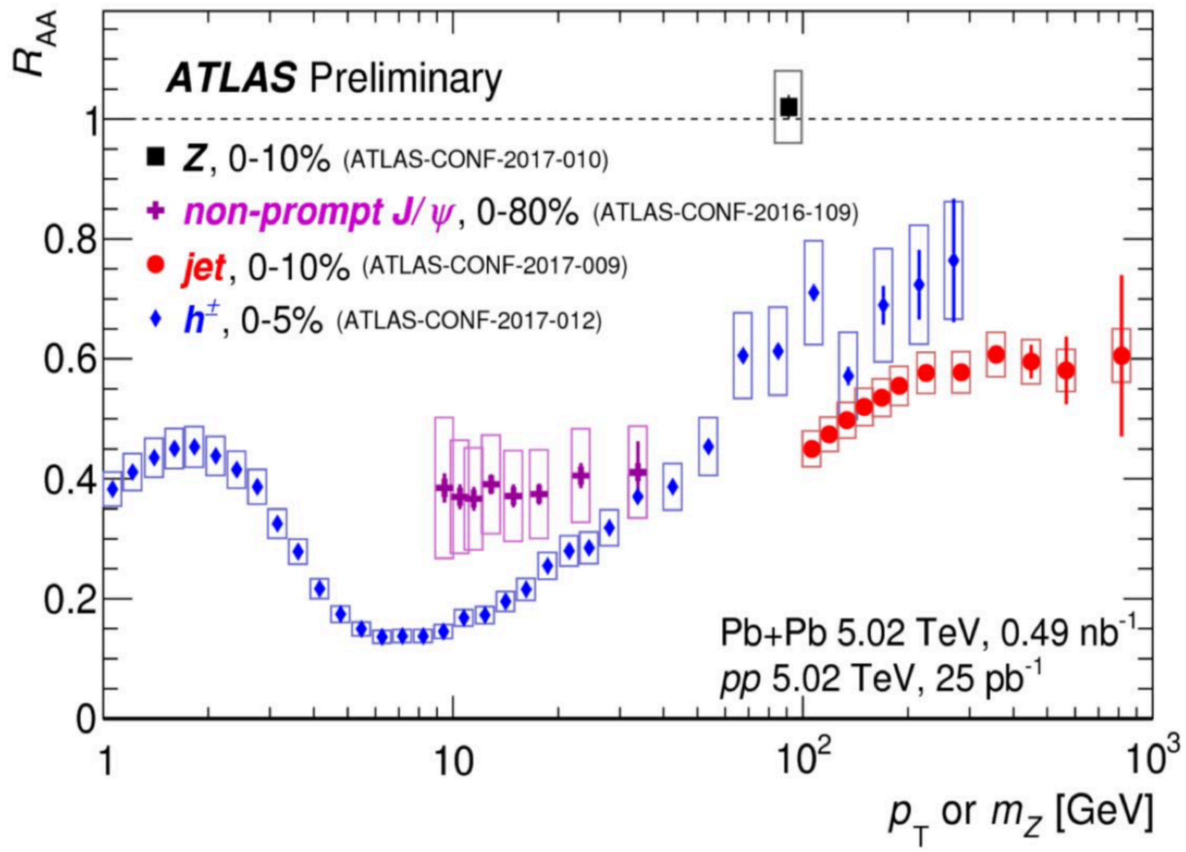
proton-proton
two-jet event



heavy-ion
two-jet event

ENERGY-LOSS BASICS



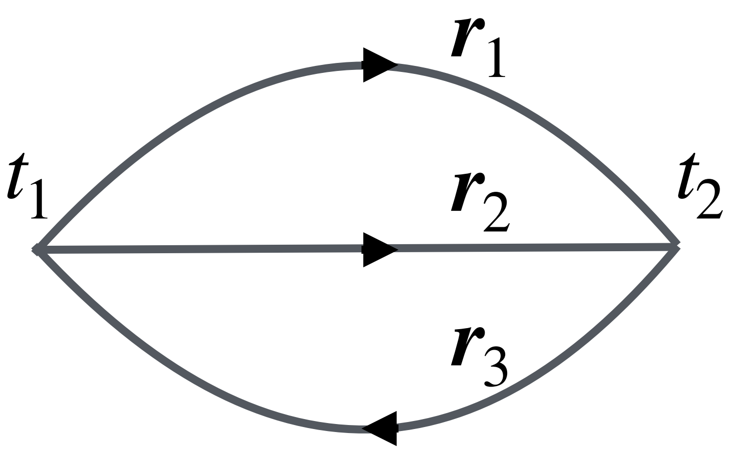


Workhorse of the field: measuring & parameterizing the shift of spectrum to access information about medium interactions.

However: many confounding factors (jet/medium components)!

COMPUTING THE SPECTRUM

Dynamics on the LC: 3-body problem!



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

$$\left[i\frac{\partial}{\partial t} + \frac{\boldsymbol{\partial}^2}{2z(1-z)E} + iv_{ba}(\boldsymbol{x},t)\right]\mathcal{K}_{ba}(\boldsymbol{x},t;\boldsymbol{y},t_0) = i\delta(t-t_0)\delta(\boldsymbol{x}-\boldsymbol{y})$$

New idea: expand around the harmonic oscillator!

$$\mathcal{K}(\boldsymbol{x},t_1;\boldsymbol{y},t_0) = \mathcal{K}_{\mathrm{HO}}(\boldsymbol{x},t_1;\boldsymbol{y},t_0) - \int \mathrm{d}^2\boldsymbol{z}\int_{t_0}^{t_1}\mathrm{d}t\,\mathcal{K}_{\mathrm{HO}}(\boldsymbol{x},t_1;\boldsymbol{z},t)\delta v_{\mathrm{hard}}(\boldsymbol{z},t)\mathcal{K}(\boldsymbol{z},t;\boldsymbol{y},t_0)\,.$$

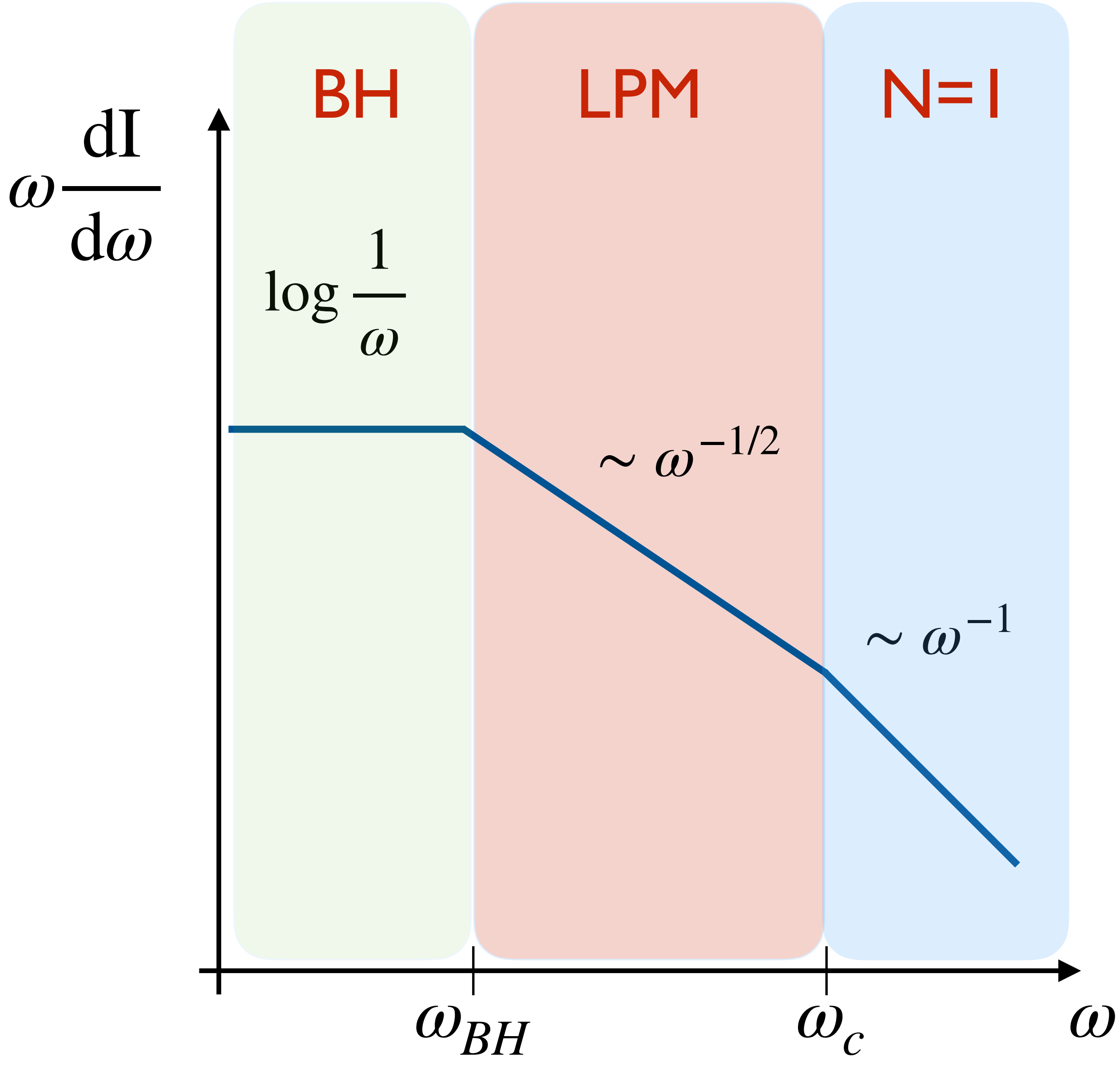
- accounts for (perturbative) hard kicks in the plasma…

QCD BREMSSTRAHLUNG

Baier, Dokshitzer, Mueller, Peigné, Schiff (1997-2000); Zakharov (1996); Gyulassy, Levai, Vitev (2001); Arnold, Moore, Yaffe (2002)

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

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



$$\omega \frac{dI}{d\omega} = \frac{\alpha_s C_R}{\pi} \frac{L}{t_\mathrm{br}}$$

- $t_\mathrm{br} \sim \lambda$ → $\omega \sim \omega_\mathrm{BH} = \hat{q}\lambda^2 \sim T$
- $t_\mathrm{br} \sim L$ → $\omega \sim \omega_c = \hat{q}L^2$
- $t_\mathrm{br} \sim \frac{\omega}{\mu^2} \gtrsim L$ → N=1 dominates

TWO SEPARATED REGIMES

Multi-gluon emissions are dominated by the LPM regime.

$$N_{\mathrm{LPM}}(\omega) = \int_0^\infty \mathrm{d}\omega' \frac{\mathrm{d}I}{\mathrm{d}\omega'} = \frac{2\alpha_s C_R}{\pi}\sqrt{\hat{q}L^2/\omega}$$

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

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

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

perturbative: rare, small-angle radiation can modify intra-jet structure, N=1 also contributes

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

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

$$N \sim 1$$

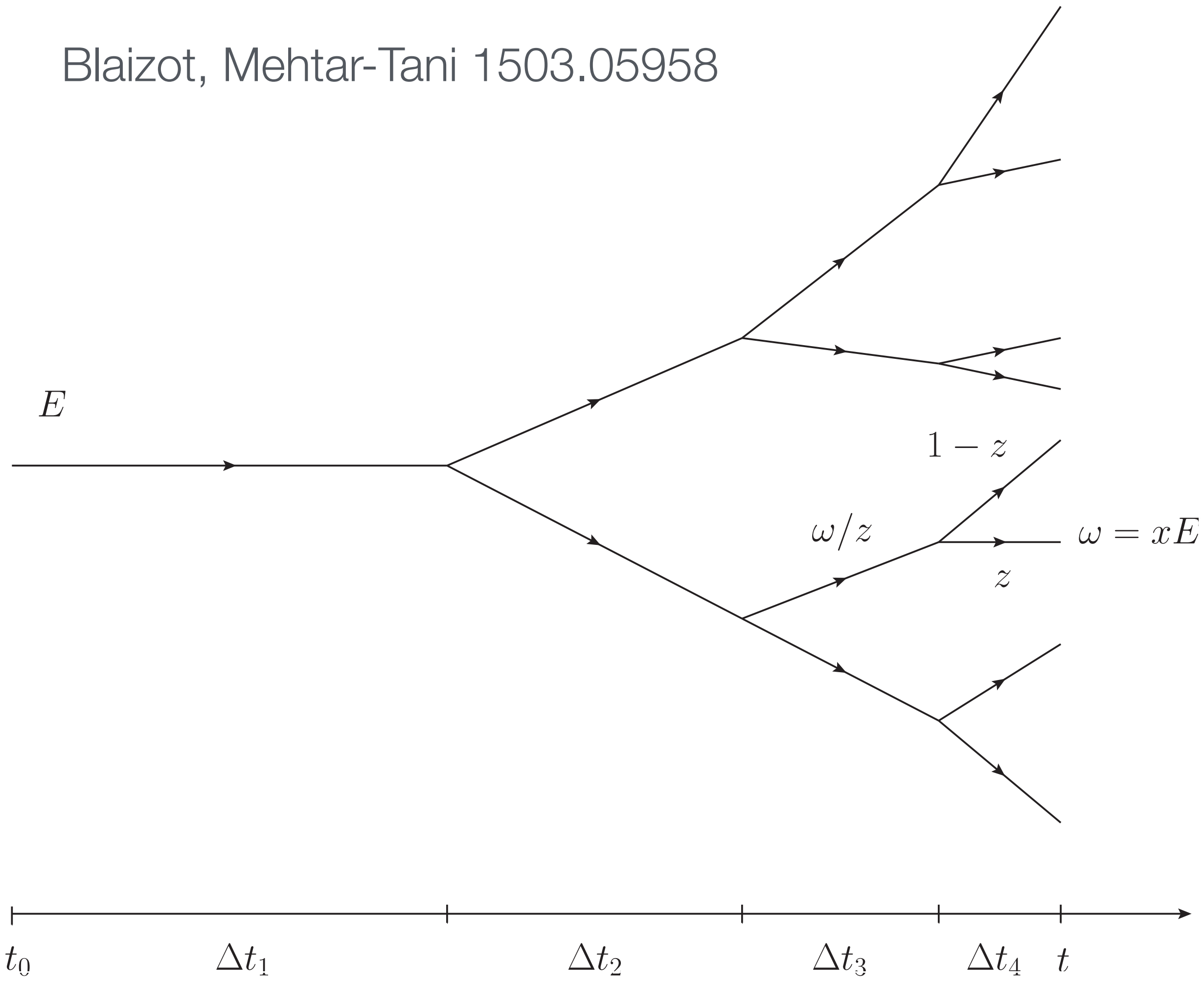
non-perturbative: copious, large-angle emissions

out-of-cone energy-loss, thermalization

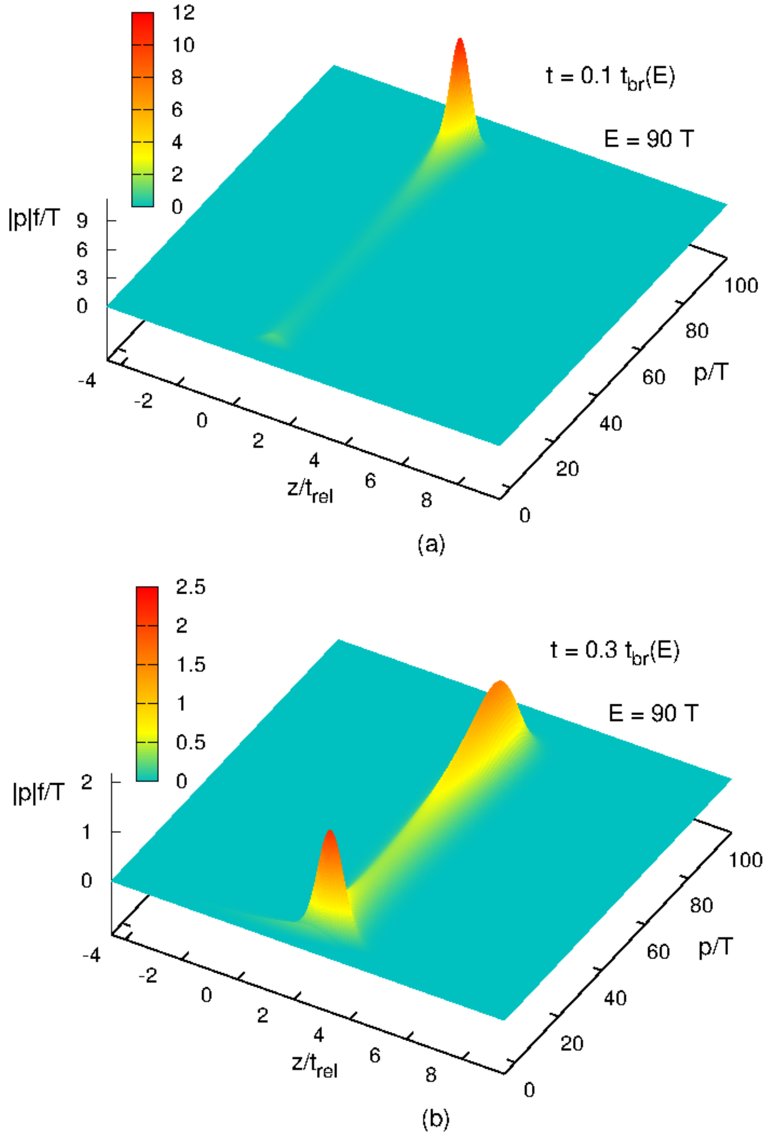
SOFT BRANCHINGS

$$\omega_{\rm BH} \ll \omega \ll \bar\alpha^2 \omega_c \qquad\qquad t_{\rm split} = \frac{t_{\rm br}}{\bar\alpha}$$

short splitting time → many splittings inside the medium!



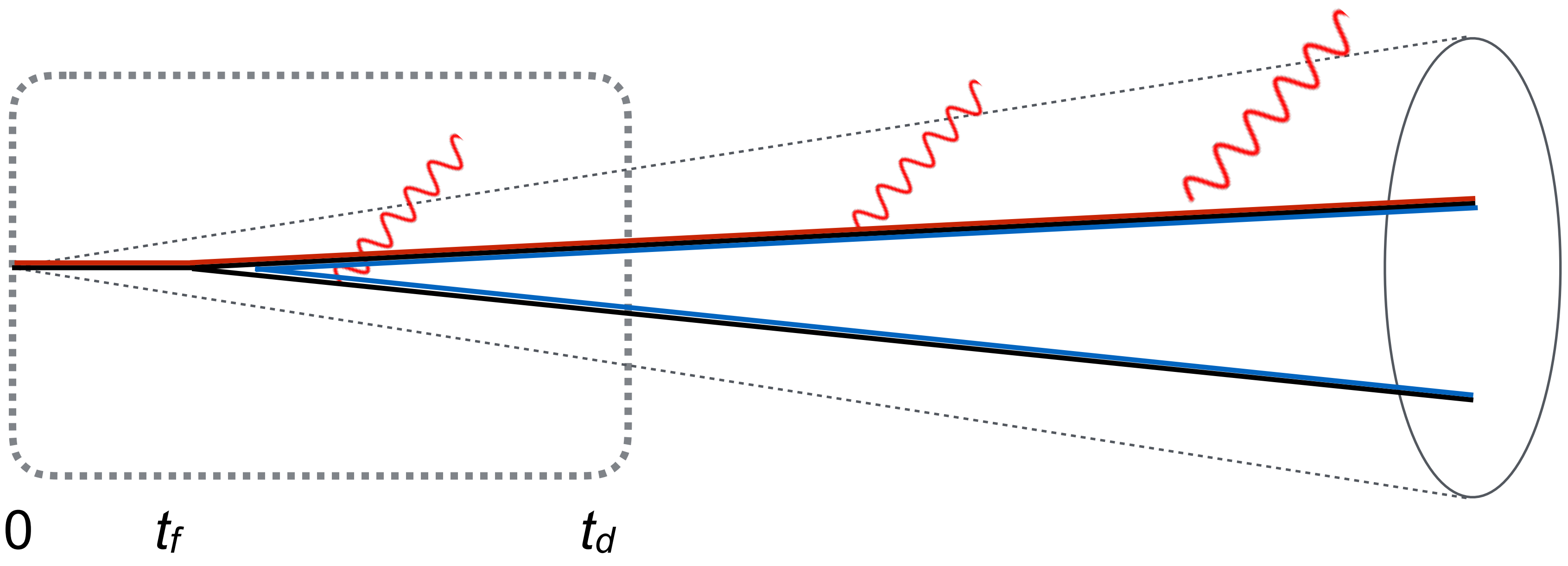
Blaizot, Mehtar-Tani 1503.05958



Iancu, Wu 1506.07871

NEIGHBORING JET ENERGY LOSS

Y. Mehtar-Tani, KT 1706.06047



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

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

$$\mathcal{Q}_2(p_{\rm T}) = \mathcal{Q}(p_{\rm T}) \times \mathcal{Q}_{\rm sing}(p_{\rm T})$$

energy loss of total color charge

delayed energy loss from resolved partons

$$\mathcal{S}_2(t) = \exp\left[-\frac{1}{4}\int_0^t {\rm d}s\, \hat{q}(\boldsymbol{x}_{12}, t)\boldsymbol{x}_{12}^2(s)\right]$$

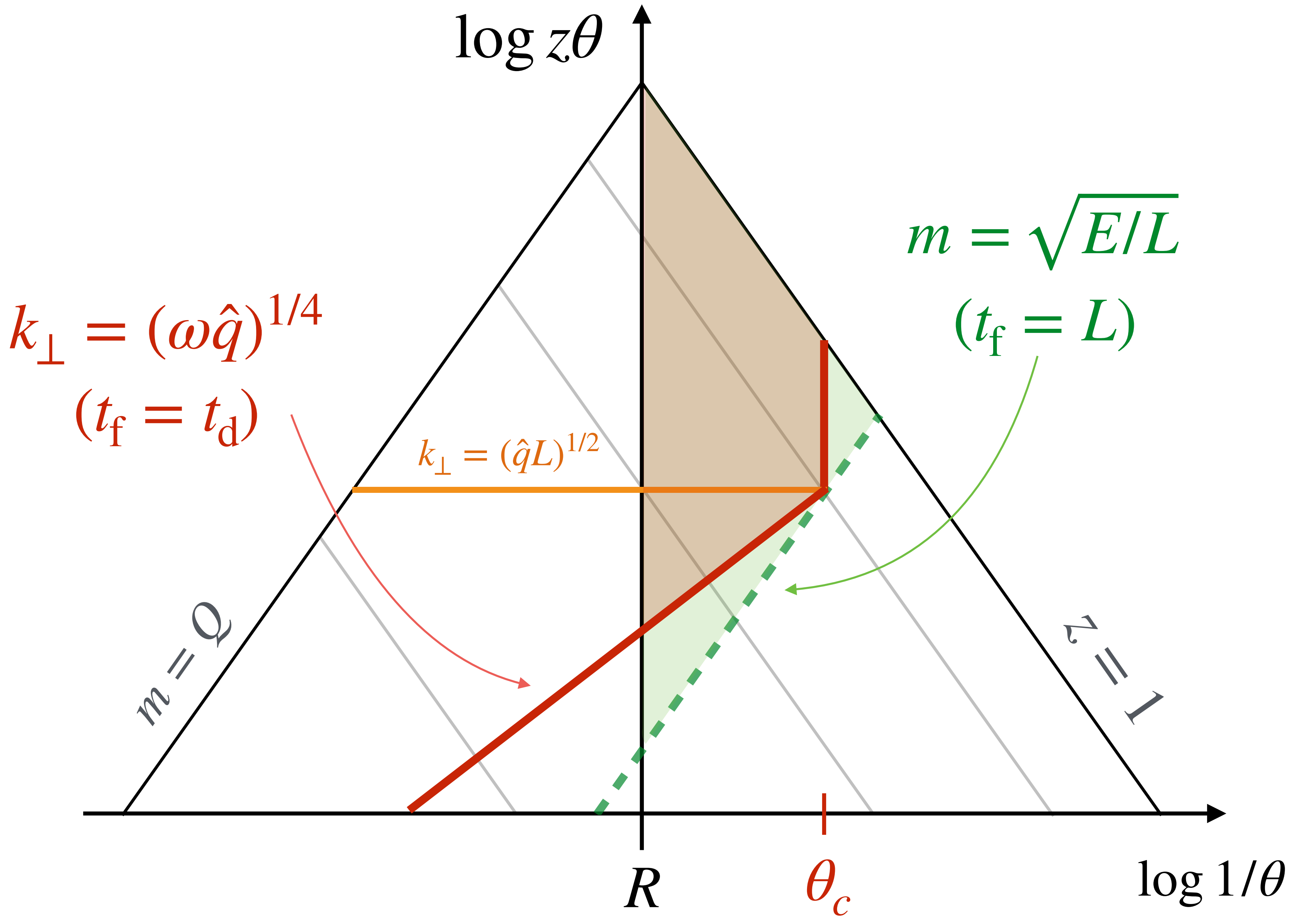
decoherence parameter

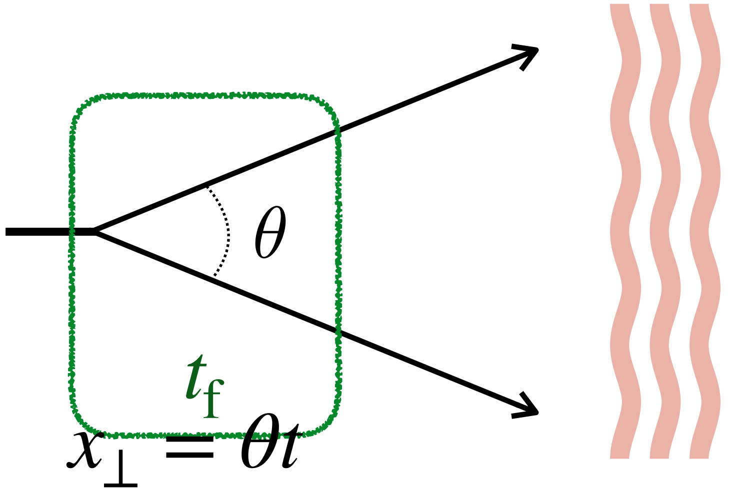
color randomization of a $q\bar{q}$ pair

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

PHASE SPACE ANALYSIS

Y. Mehtar-Tani, KT 1706.06047, 1707.07361
Caucal, Iancu, Mueller, Soyez 1801.09703
Dominguez, Milhano, Salgado, KT, Vila 1907.03653





$$(PS)_{in} = \frac{\bar\alpha}{4}\log^2 ER^2L$$

$$\lambda_\perp^2 = \frac{1}{\sqrt{\hat q t}}$$

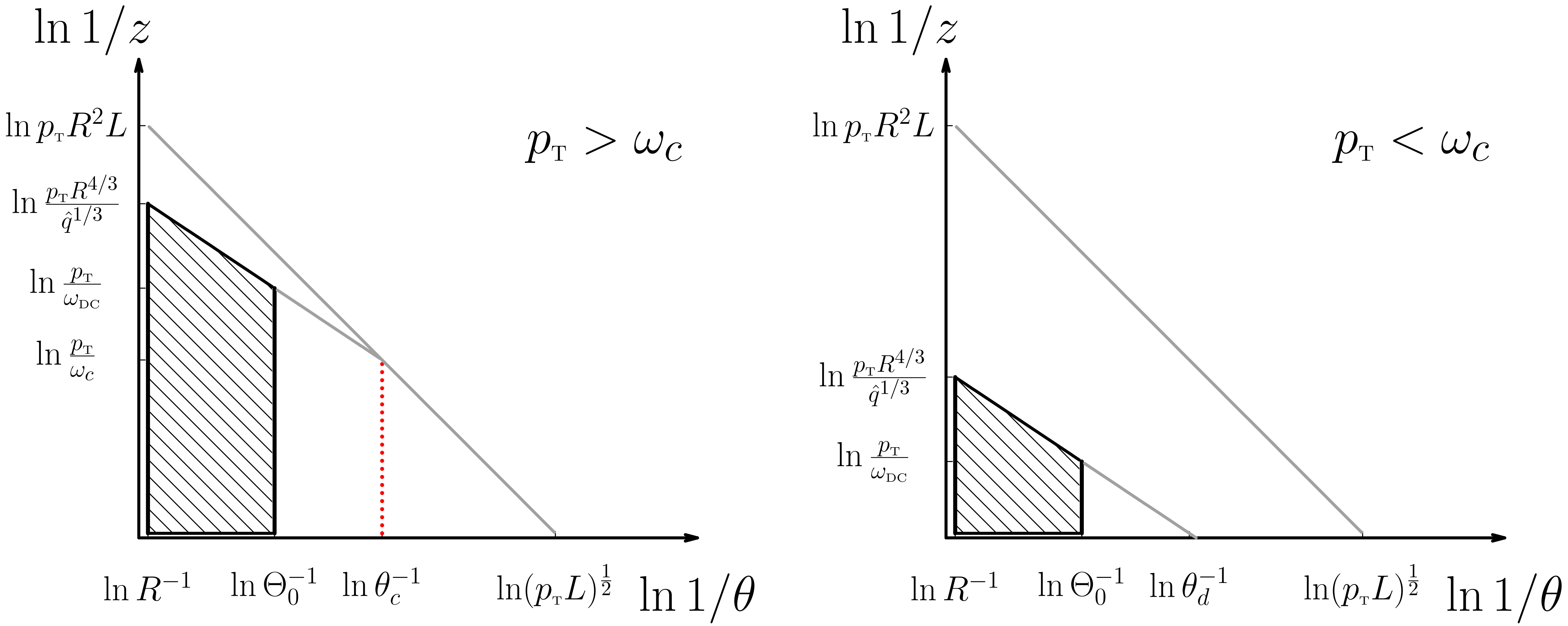
Large probability for splitting inside!

Red area: *vacuum emissions taking place inside the medium*
- could be modified by the medium (long-distance effects).

HEAVY-QUARK JET QUENCHING

Blok, KT arXiv:1901.07864

Considering a heavy-quark initiated jet:

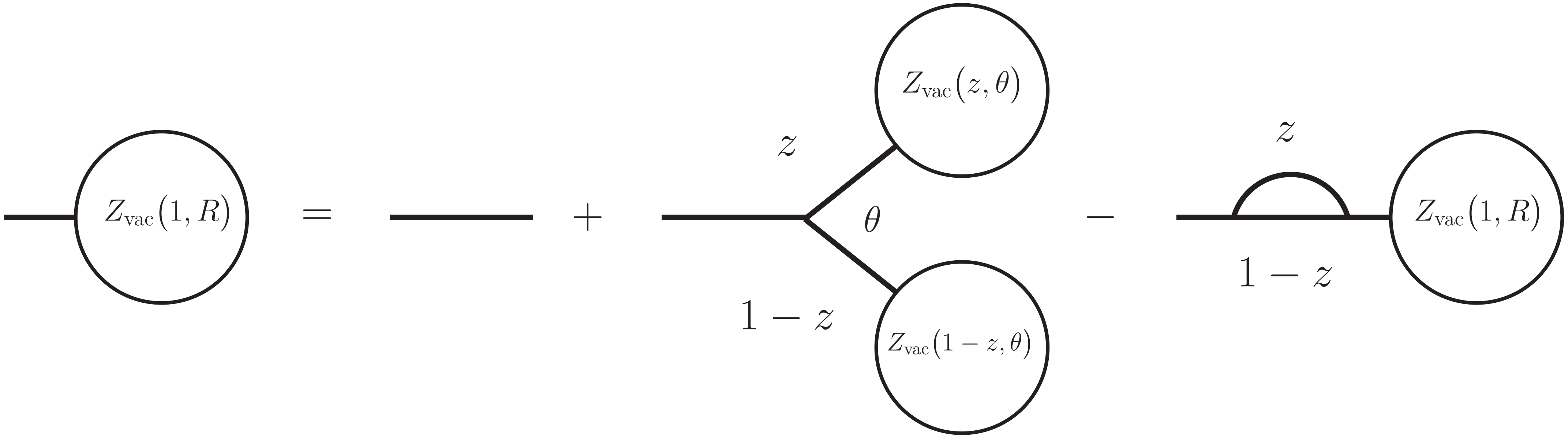


Interplay of dead-cone and coherence!

Characteristic mass scale: $m_* = (\hat{q}L)^{1/2}$

GENERATING FUNCTIONAL

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



$$
Z_{\rm vac}(p,R;u) = u(p) + \int_0^R \frac{{\rm d}\theta}{\theta} \int_0^1 {\rm d}z\, \frac{\alpha_s}{\pi} P(z)
$$

$$
\times \left[Z_{\rm vac}(zp,\theta) Z_{\rm vac}\big((1-z)p,\theta\big) - Z_{\rm vac}(p,\theta)\right]
$$

E.g. gives the angular ordered (MLLA) evolution equation!

GF FOR QUENCHED JETS

Y. Mehtar-Tani, KT (in preparation)

$$Z(p,R\,|\,u) = u(p) + \int^{R} \mathrm{d}\Omega\,\Theta_{\rm in}\left[Z_{\rm io}(zp,\theta)Z_{\rm io}((1-z)p,\theta)\mathcal{Q}(p)^2 - Z(p,\theta)\right]$$

$$+ \int^{R} \mathrm{d}\Omega\,\Theta_{\rm out}\left[Z_{\rm vac}(zp,\theta)Z_{\rm vac}((1-z)p,\theta) - Z_{\rm vac}(p,\theta)\right]$$

- in addition, the total charge of jet comes with $\mathcal{Q}(p)$
- couples in-medium and out-of-medium showers via $Z_{\rm io}(p,\theta) = Z(p,\theta) + Z_{\rm out}(p,\theta)$
  - including possible violations of AO
- implements quenching effects for the in-medium radiation
- $\Theta_{\rm in}$ and $\Theta_{\rm out}$ encode the jet/medium scale analysis

GF NORMALIZATION

Y. Mehtar-Tani, KT arXiv:1707.07361 [hep-ph]

Probability is no longer conserved: $Z(p, R \,|\, u = 1) = \mathscr{C}(p, R)$!

Mismatch between real and virtual diagrams!

$$C(p,R) = 1 + \bar{\alpha} \int_0^R \frac{\mathrm{d}\theta}{\theta} \int_0^1 \mathrm{d}z\, P(z)\, \boxed{\Theta(t_\mathrm{f} < t_\mathrm{d} < L)} \\ \times \left[C(zp,\theta)\, C((1-z)p,\theta)\, \mathcal{Q}^2(p_T) - C(p,\theta) \right]$$

assumptions about medium effects (quenching)

affected phase space for vacuum radiation

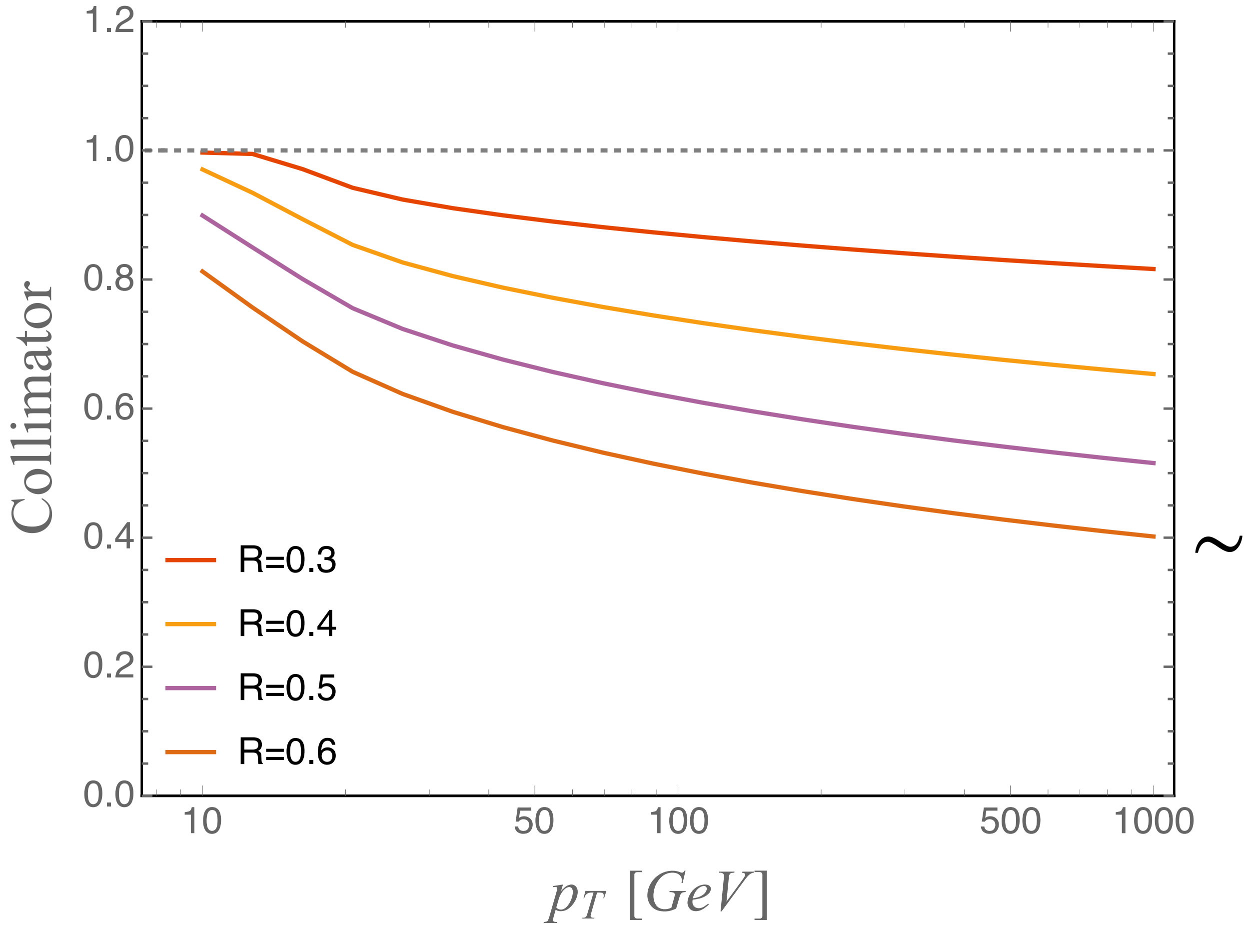
collimator function (normalization)

*) mismatch can also arise due to other processes than energy loss!

SUDAKOV SUPPRESSION

For $\mathcal{Q} = 1$ fixed point of the equation is simply $\mathcal{C} = 1$.

It is natural to expect this to be the limit at high-p_T.



Strong quenching limit

$\mathcal{Q}(p_T) \ll 1$ (Sudakov factor):

$$\sim \exp\left[-2\bar{\alpha}\log\frac{R}{\theta_c}\left(\log\frac{p_T}{\omega_c} + \frac{2}{3}\log\frac{R}{\theta_c}\right)\right]$$

$$R_{\rm jet} = \mathcal{Q}_q(p_{\rm T}) \times \mathcal{C}(p_{\rm T}, R)$$

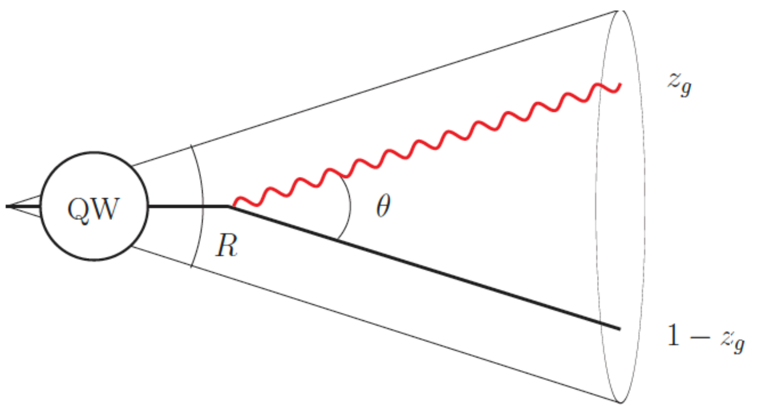
jet loses energy via total charge & resolved substructure fluctuations

Phenomenological studies

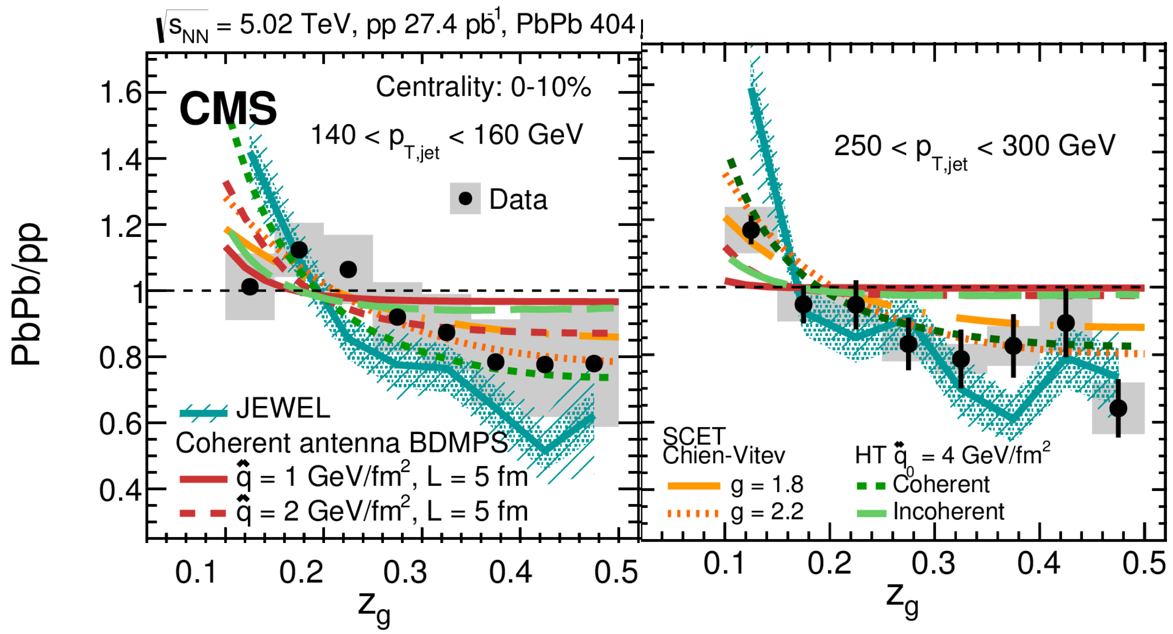
COMMUNITY EFFORT

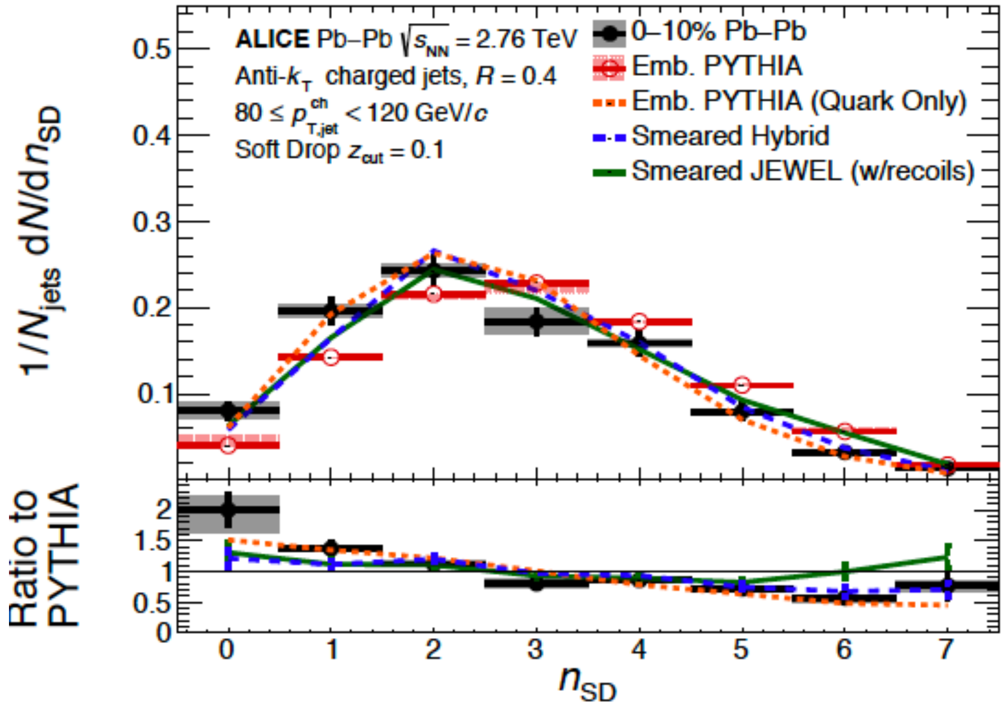
- complex interplay of many effects & demanding understanding of background fluctuations
- need community drive theory-experiment effort to establish common practices, observables…
- started out as CERN TH institute 2017, now JetTools Workshop (Bergen 2019,…), EMMI RRTF 2019

SUBSTRUCTURE STUDIES IN HIC



- sheds new light on the physics of jet quenching
- potential to isolate/enhance regimes
  - sensitivity to "new" physics (QCD bremsstrahlung, medium response)
  - purified samples to study microscopic properties (color, mass)

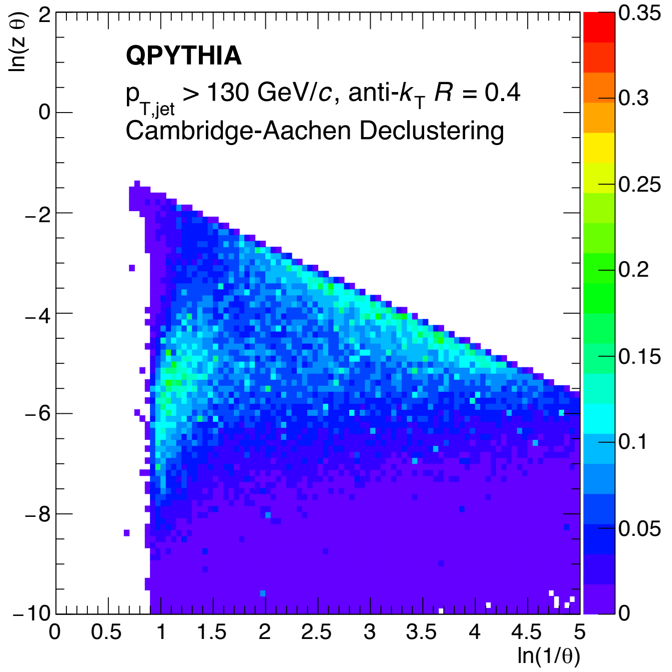


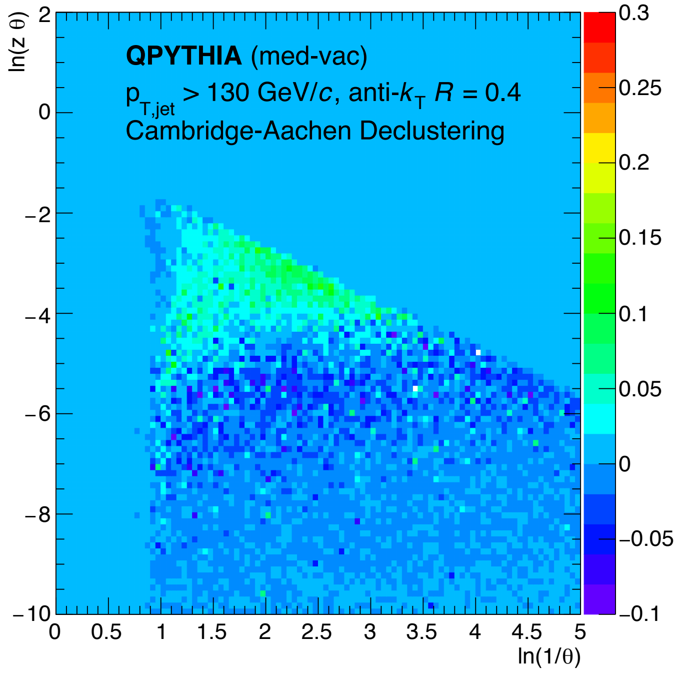


CERN WORKSHOP: COMPARING LUND PLANES

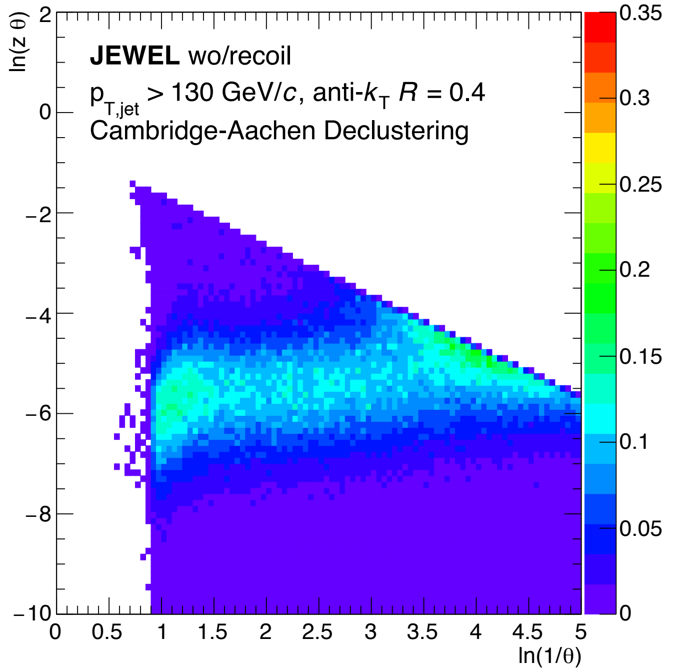
Andrews et al. 1808.03689

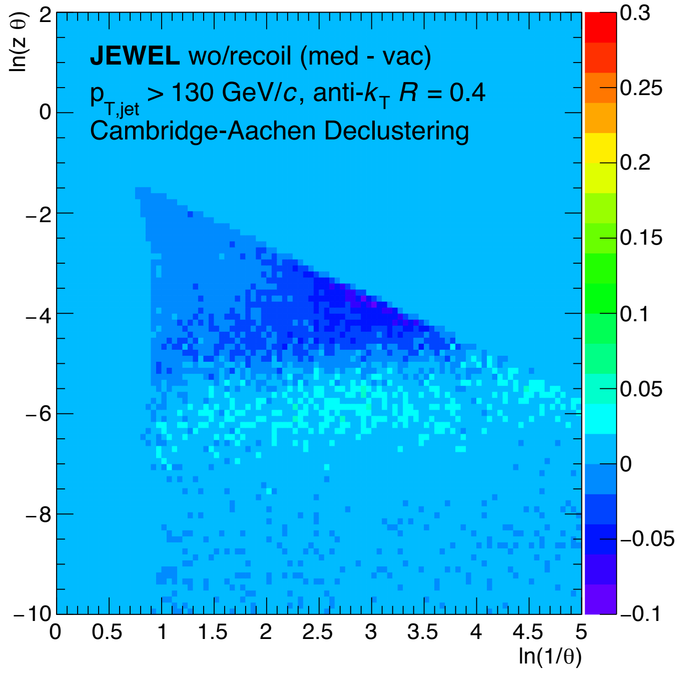
QPYTHIA



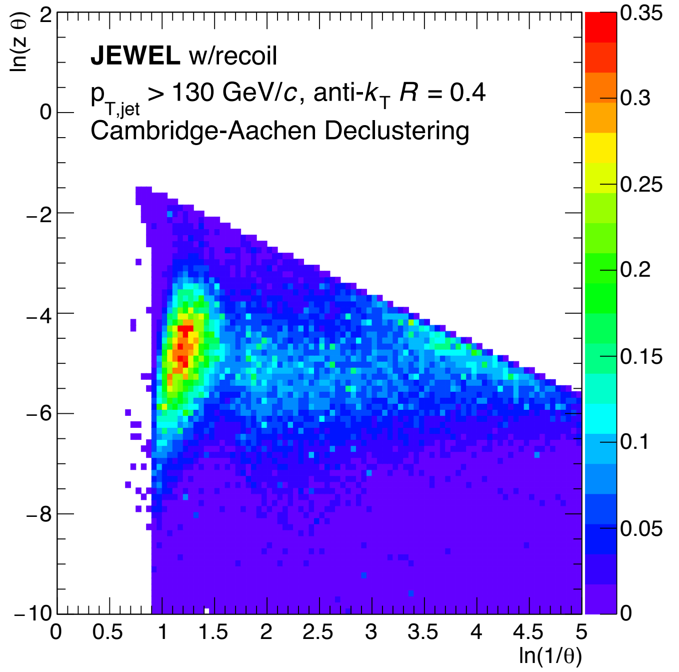


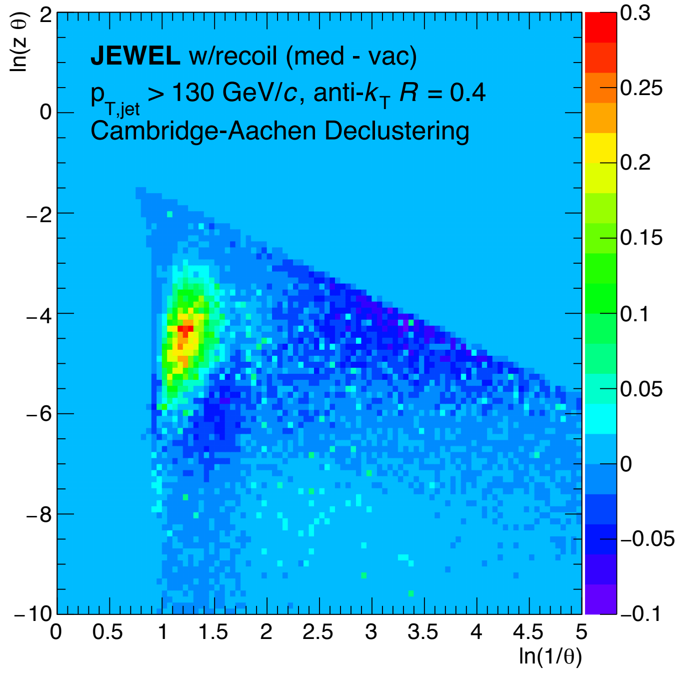
JEWEL (wo/ recoil)





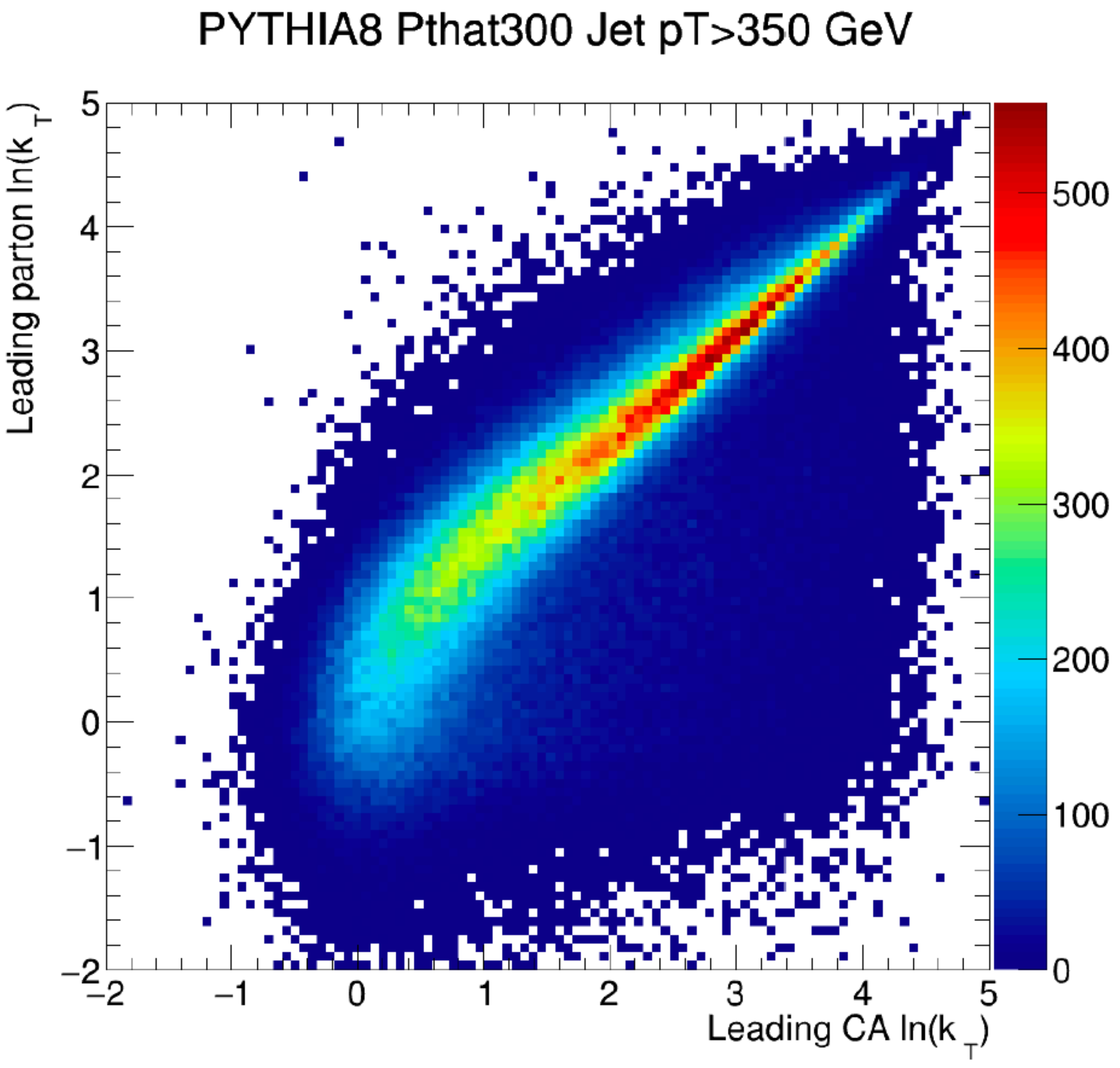
JEWEL (w/ recoil)

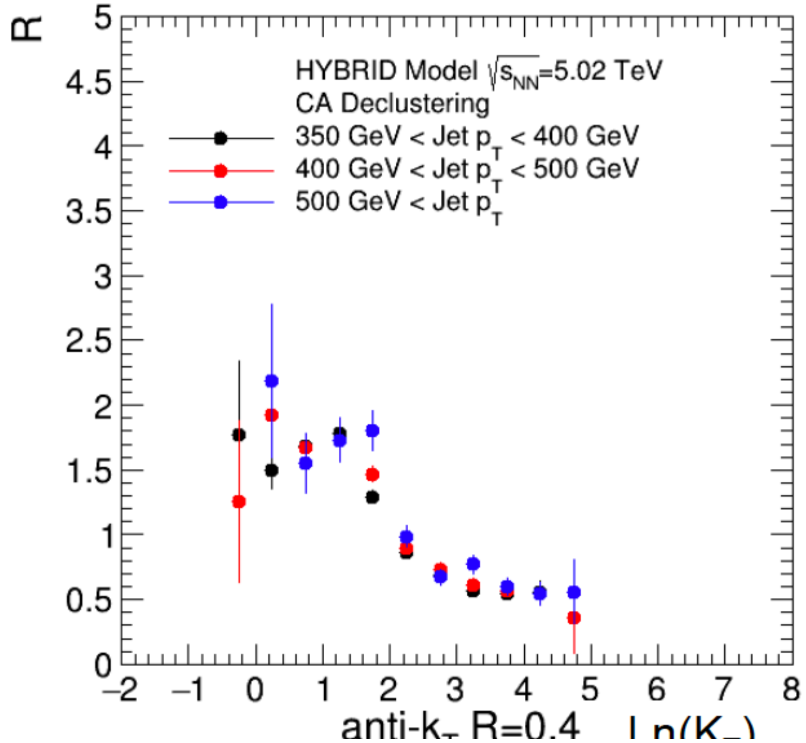


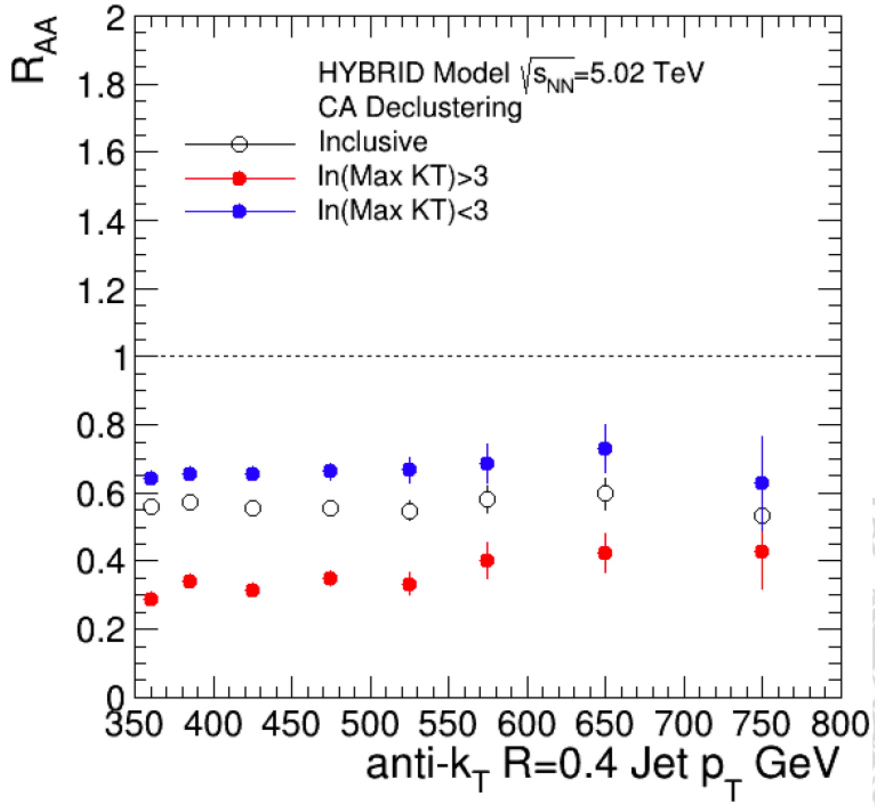


EMMI RRTF: TAG JET CONFIGURATIONS VIA PARTONS

Ed. Heinz, Jacobs, KT, Wiedemann







CONCLUSIONS

- QCD jet physics is experiencing a resurgence
  - new tools, deeper understanding
- brings profound insight to in-medium physics & powerful techniques to shed light on medium properties
- not there yet…
  - still a long way to go to fully make use of the potential
  - demands hard work and intensive theory/experiment cross-talk
  - many ongoing initiatives!

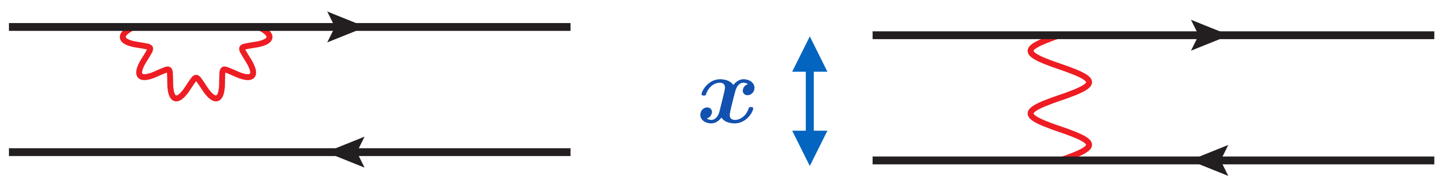
Thank you for your attention!

BACK-UP

MEDIUM TRANSPORT COEFFICIENT

$$\gamma(\boldsymbol{x}) = g^2 \int \frac{\mathrm{d}^2\boldsymbol{q}}{(2\pi)^2} \frac{\mathrm{e}^{i\boldsymbol{q}\cdot\boldsymbol{x}}}{\boldsymbol{q}^2(\boldsymbol{q}^2+m_D^2)}$$

Sensitive to the transverse extension of the "dipole".



$\gamma(0)$ $\gamma(\boldsymbol{x})$

"Harmonic oscillator" approximation

$$\sigma(\boldsymbol{x}) = 2g^2[\gamma(0)-\gamma(\boldsymbol{x})] \simeq \frac{1}{2N_c}\hat{q}\boldsymbol{x}^2$$