UNIVERSITY OF BERGEN

MAPPING OUT JETS IN HEAVY-ION COLLISIONS

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EMMI Rapid Reaction Task Force
Open Symposium: "The space-time structure of jet quenching: theory and experiment"
12 August 2019, GSI, Darmstadt

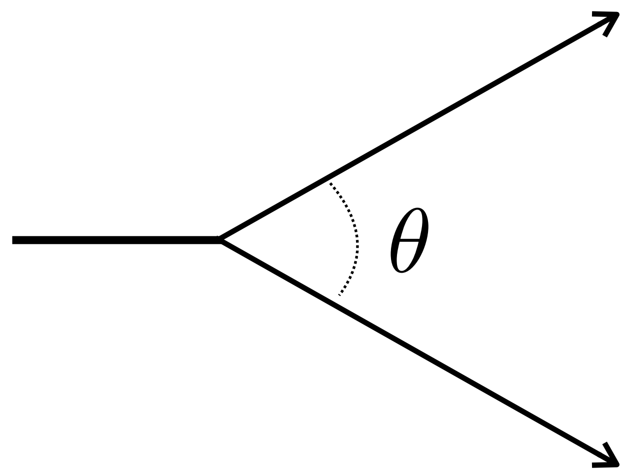
Outline

- Concepts
- Tools
- Observables
- Heavy-ions

Concepts

QCD VACUUM SPLITTING

Consider a generic 1→2 splitting in QCD.



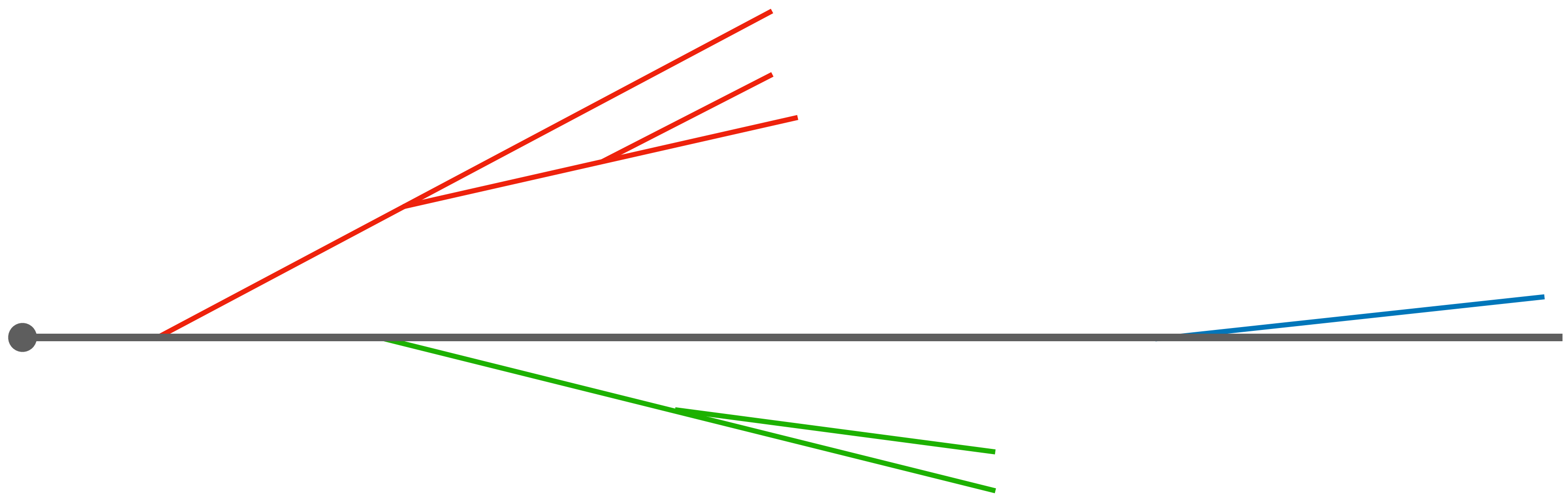
$$p_\perp = z(1-z)E\theta$$

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

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

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

JETS

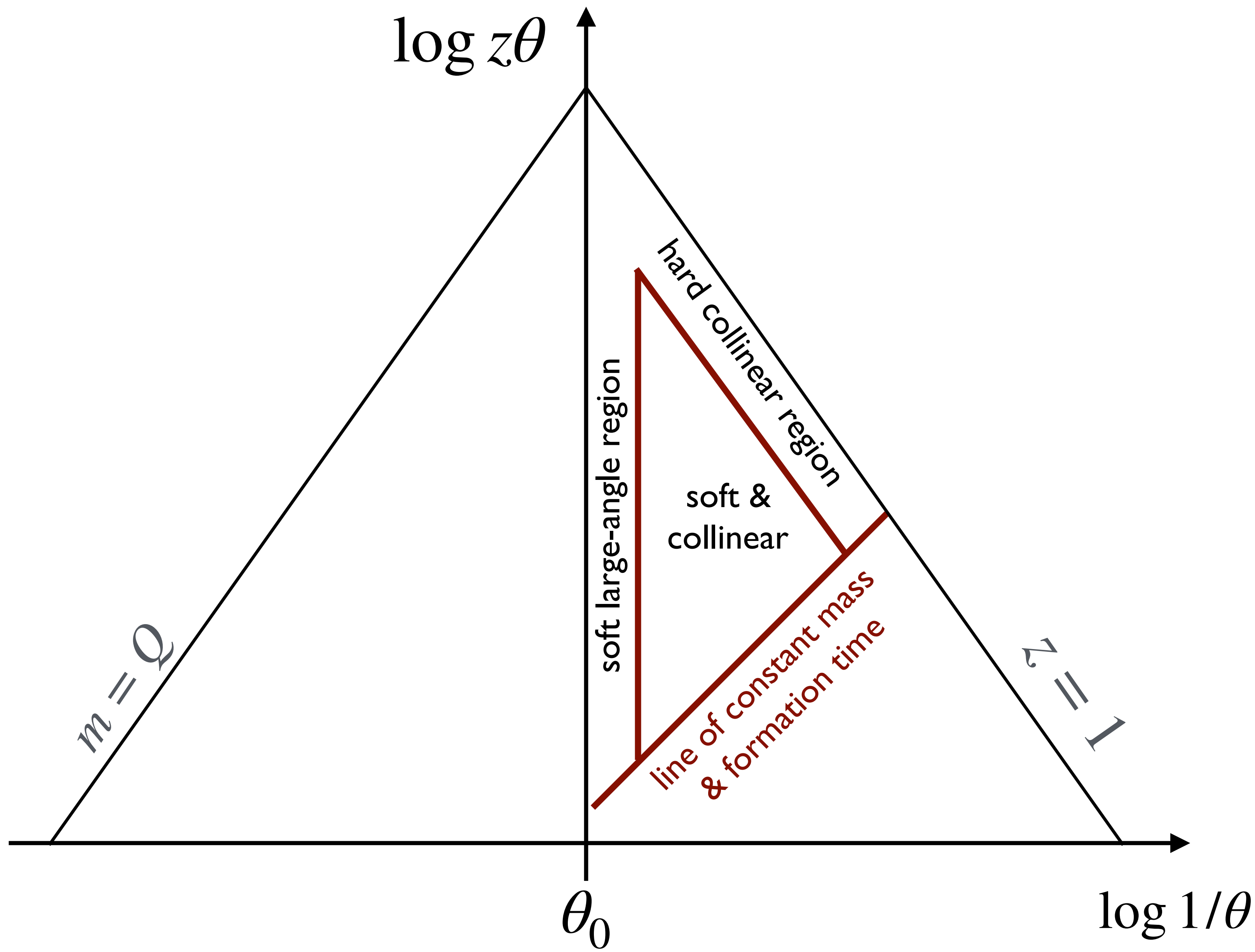


$$N = \frac{\alpha_s C_R}{\pi} \int_{Q_0/E}^{R} \frac{\mathrm{d}\theta}{\theta} \int_{Q_0/\theta}^{E} \frac{\mathrm{d}\omega}{\omega} = \frac{\alpha_s C_R}{2\pi} \log^2 \frac{ER}{Q_0}$$

- smallness of coupling compensated by phase space for radiation
- resummation of soft & collinear divergences
- strong separation of scales (semi-classical)
- color coherence

RADIATION PHASE SPACE

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



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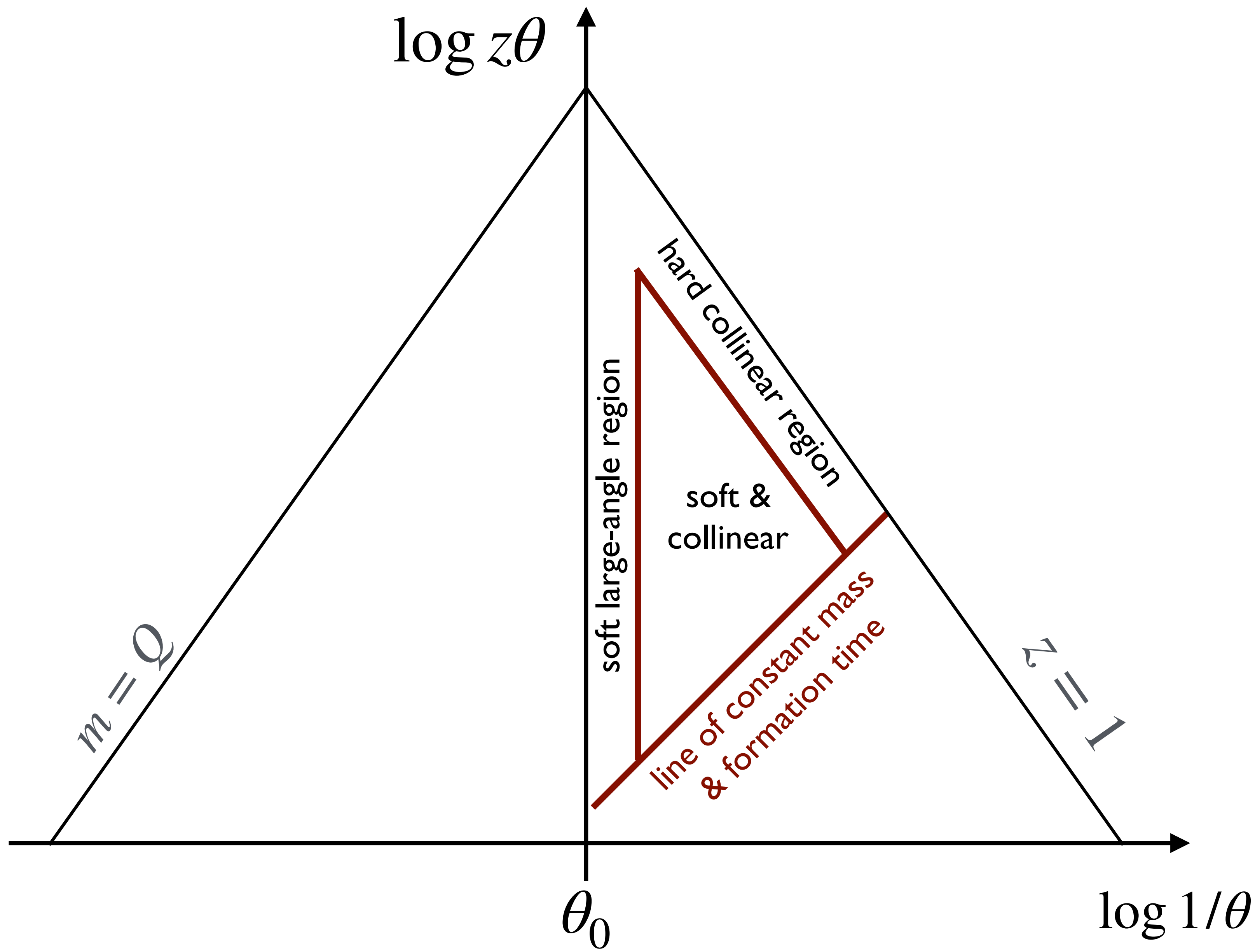

Sudakov form factor
(no-emission probability)

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

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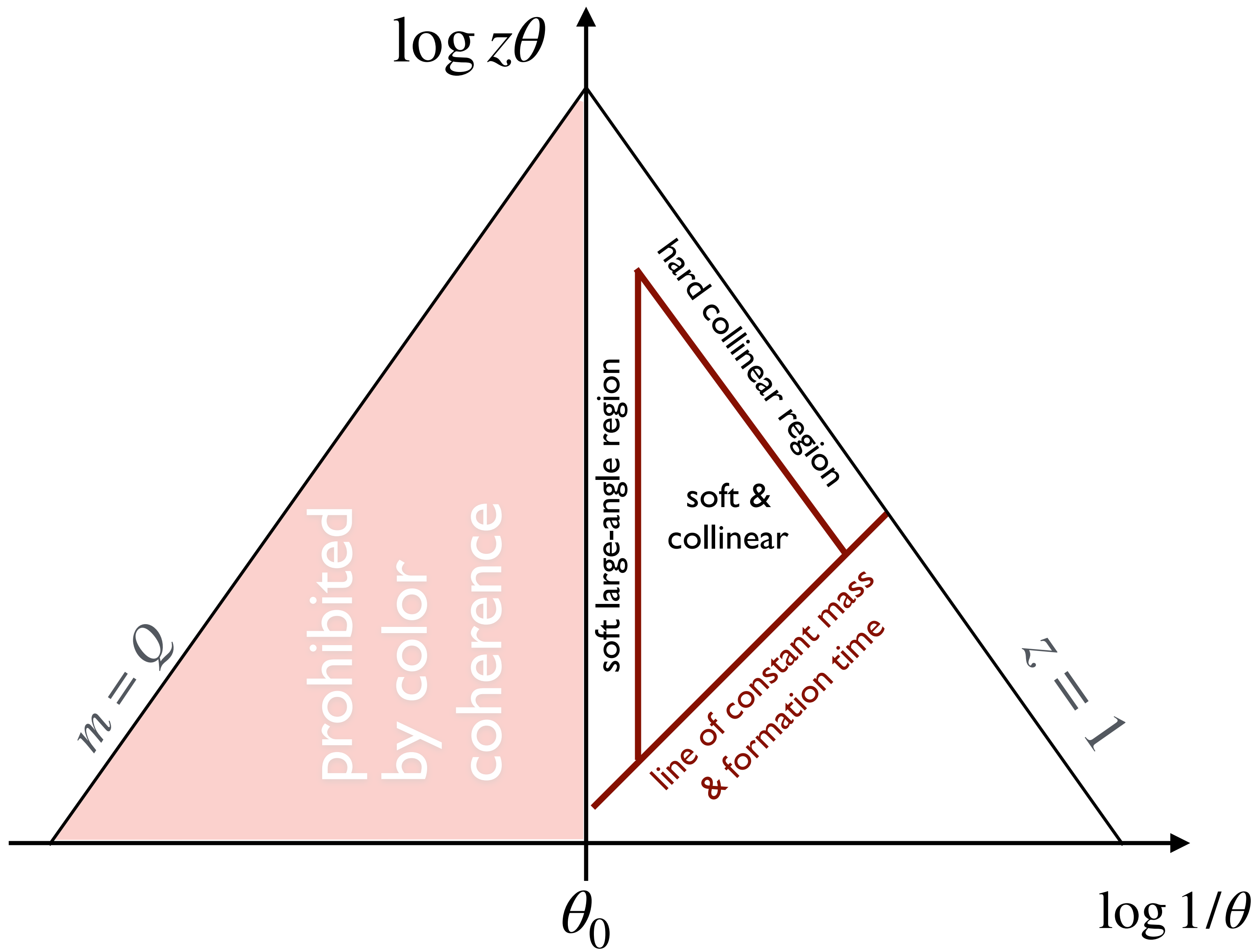

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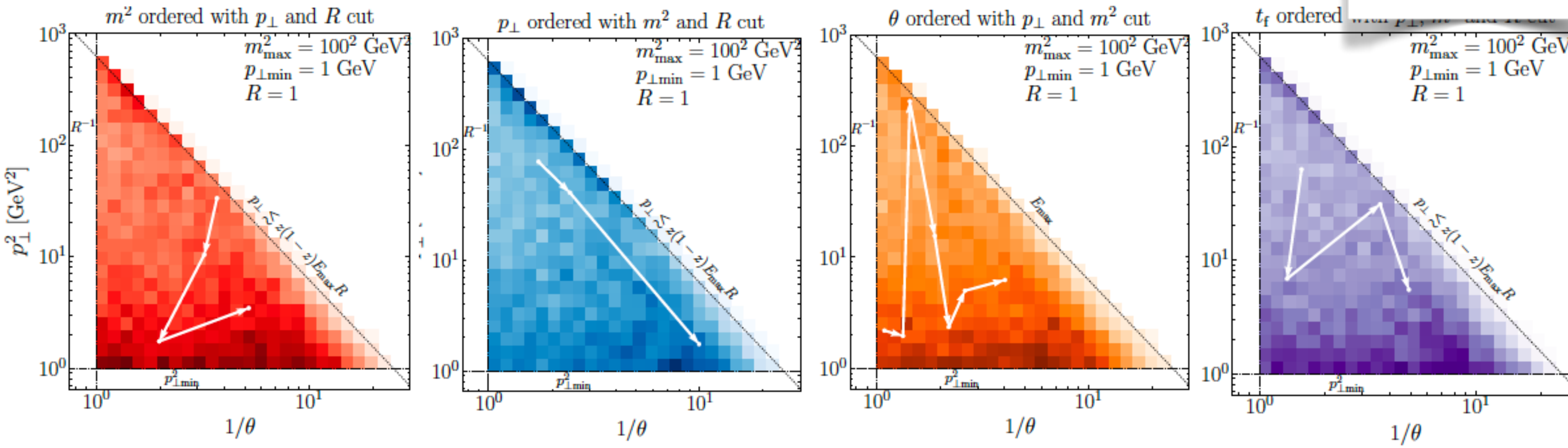
Shower realizations

Adam Takacs (UiB)



mass/virtuality

transverse momentum

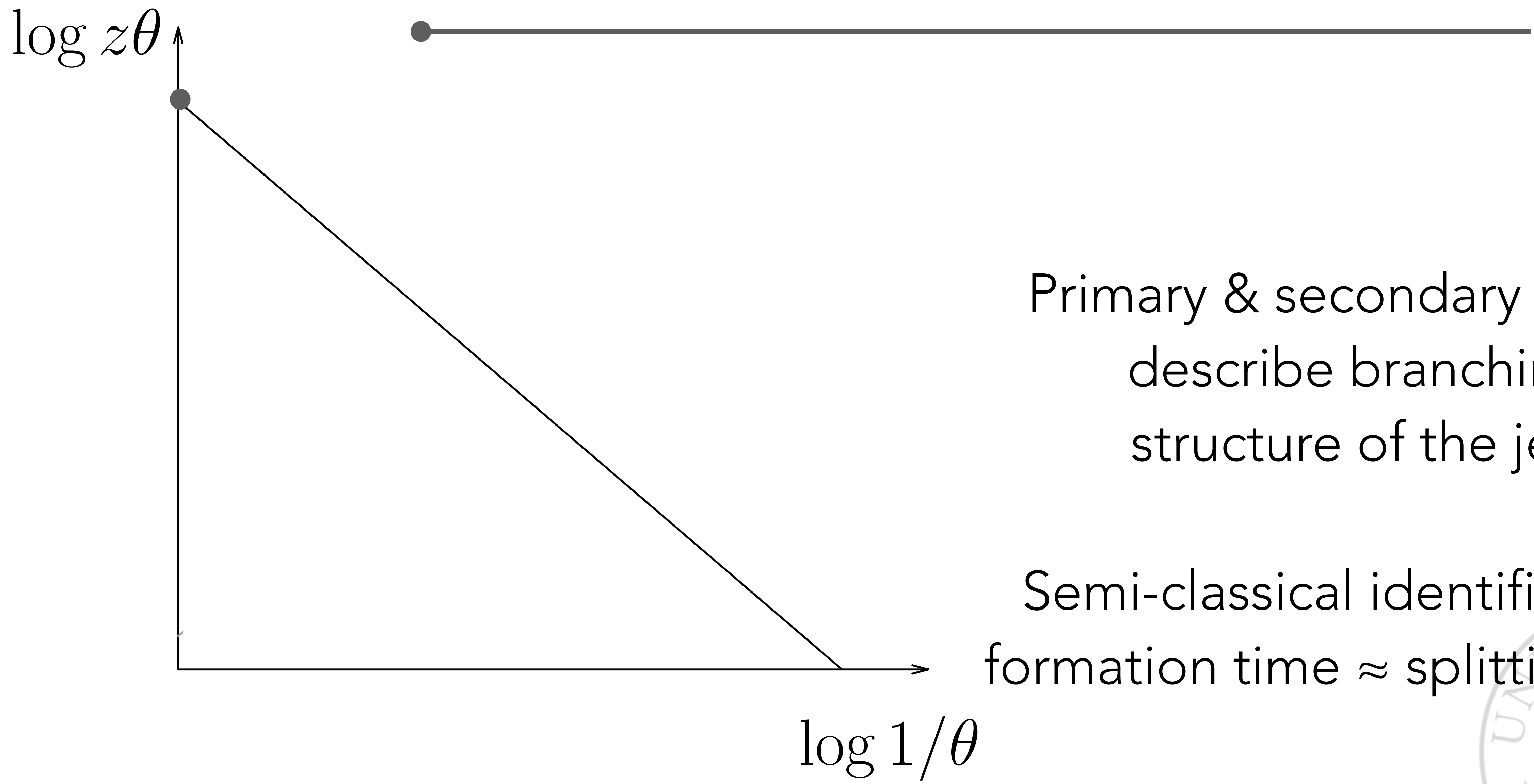
angle

formation time

Amenable to Monte Carlo sampling!

Plane is filled uniformly (running of α_s) - histories vary!

SPACE-TIME PICTURE OF THE JET



Primary & secondary planes describe branching structure of the jet.

Semi-classical identification: formation time ≈ splitting time.

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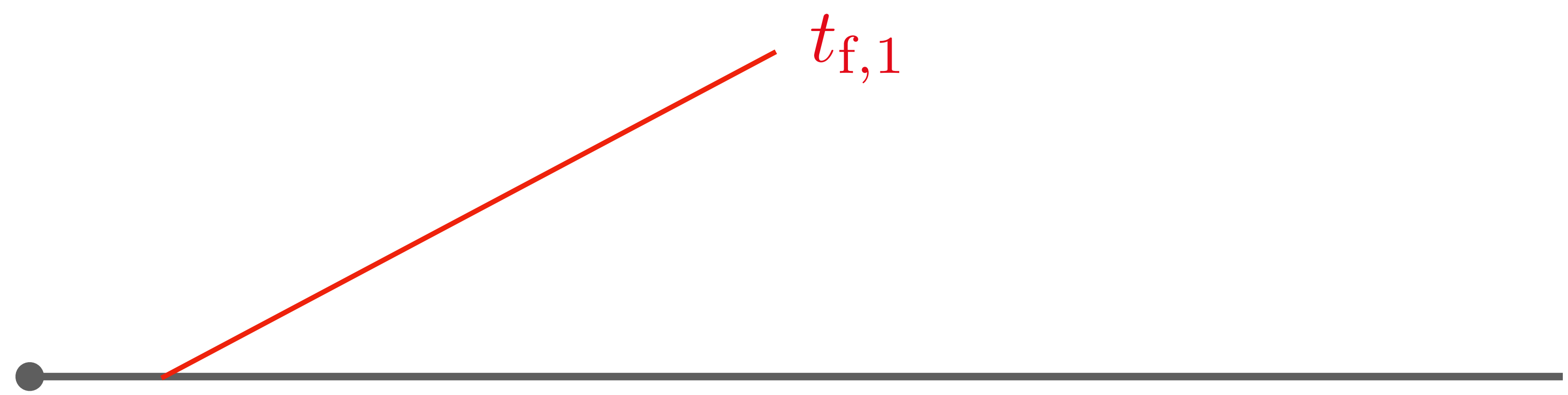

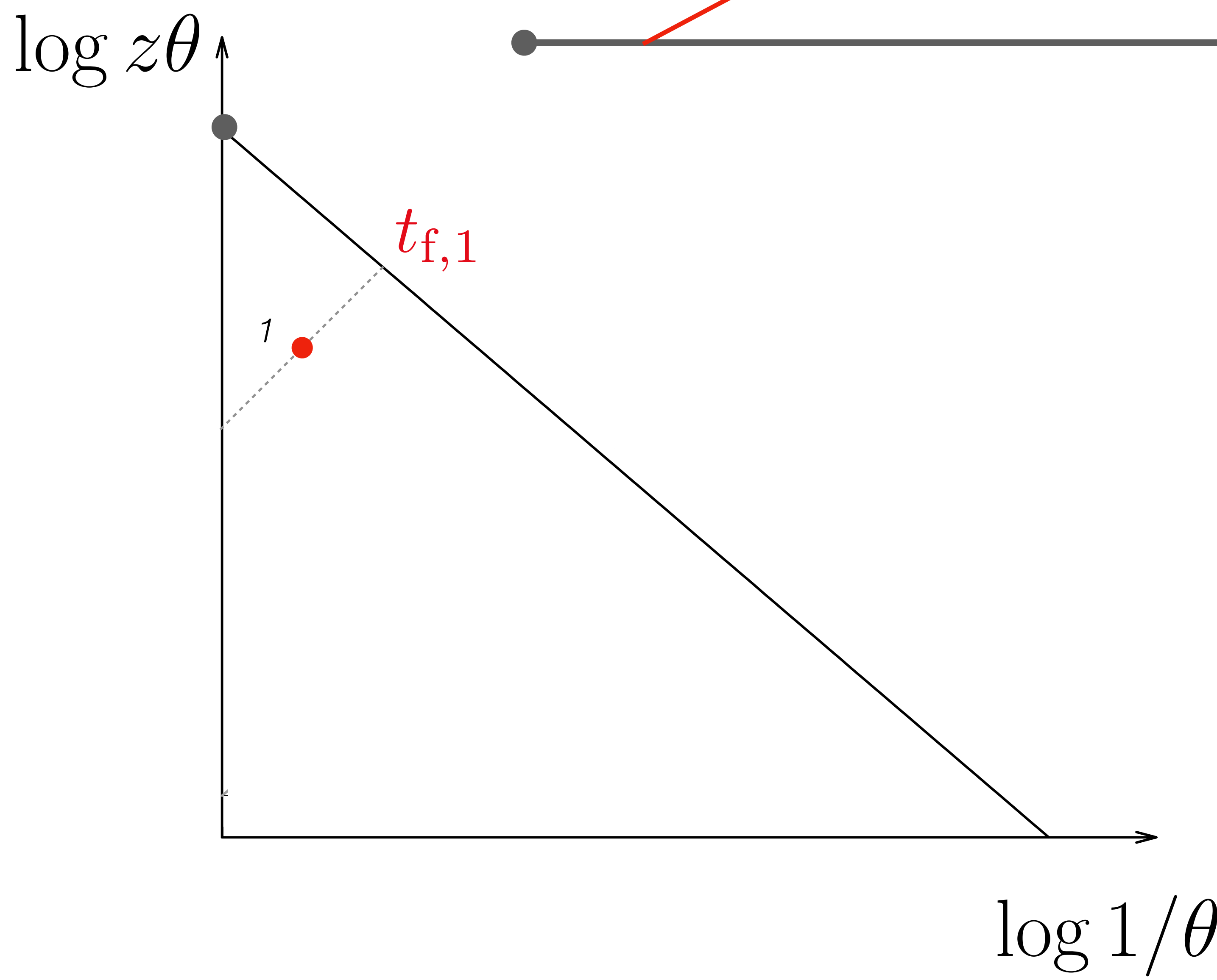

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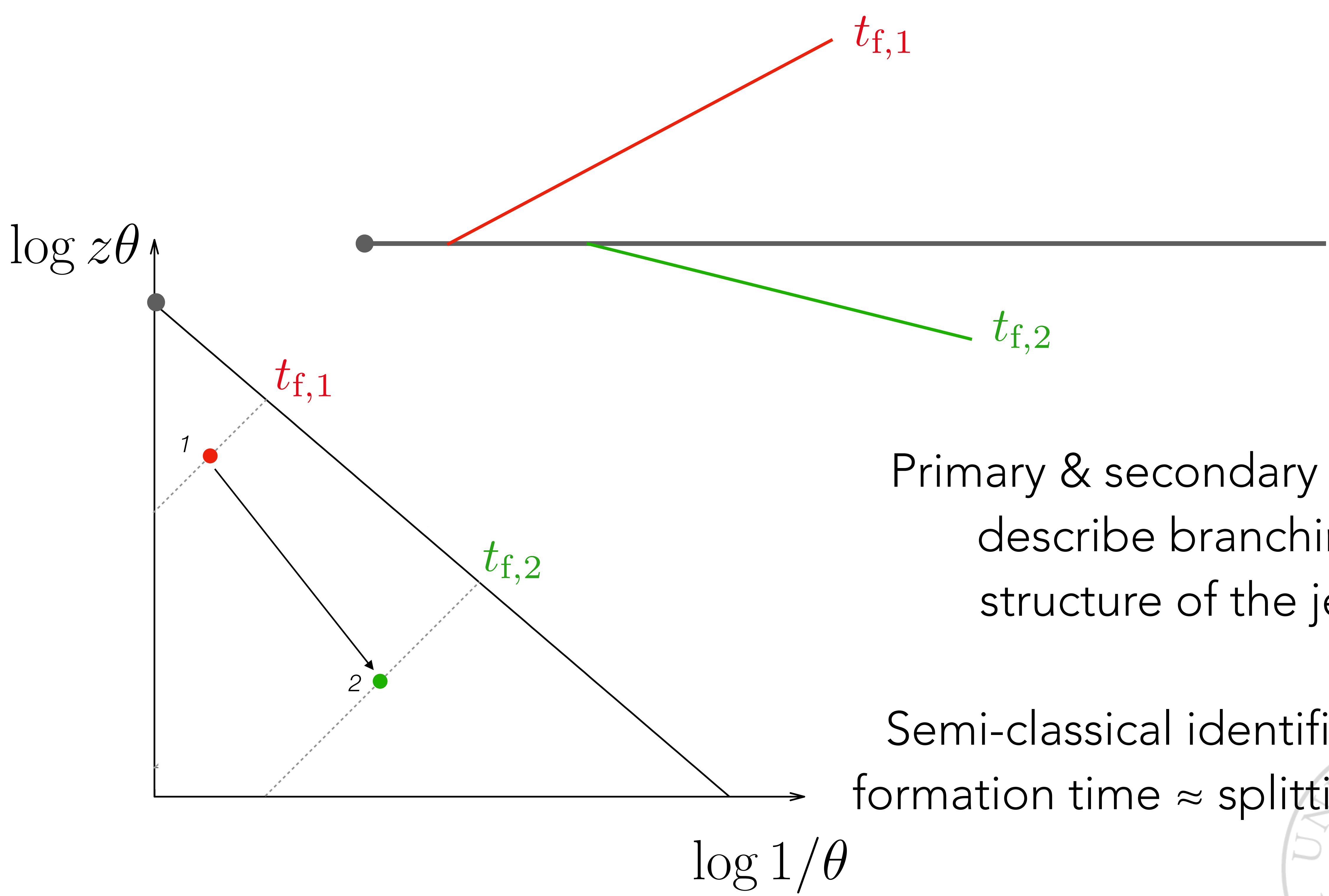

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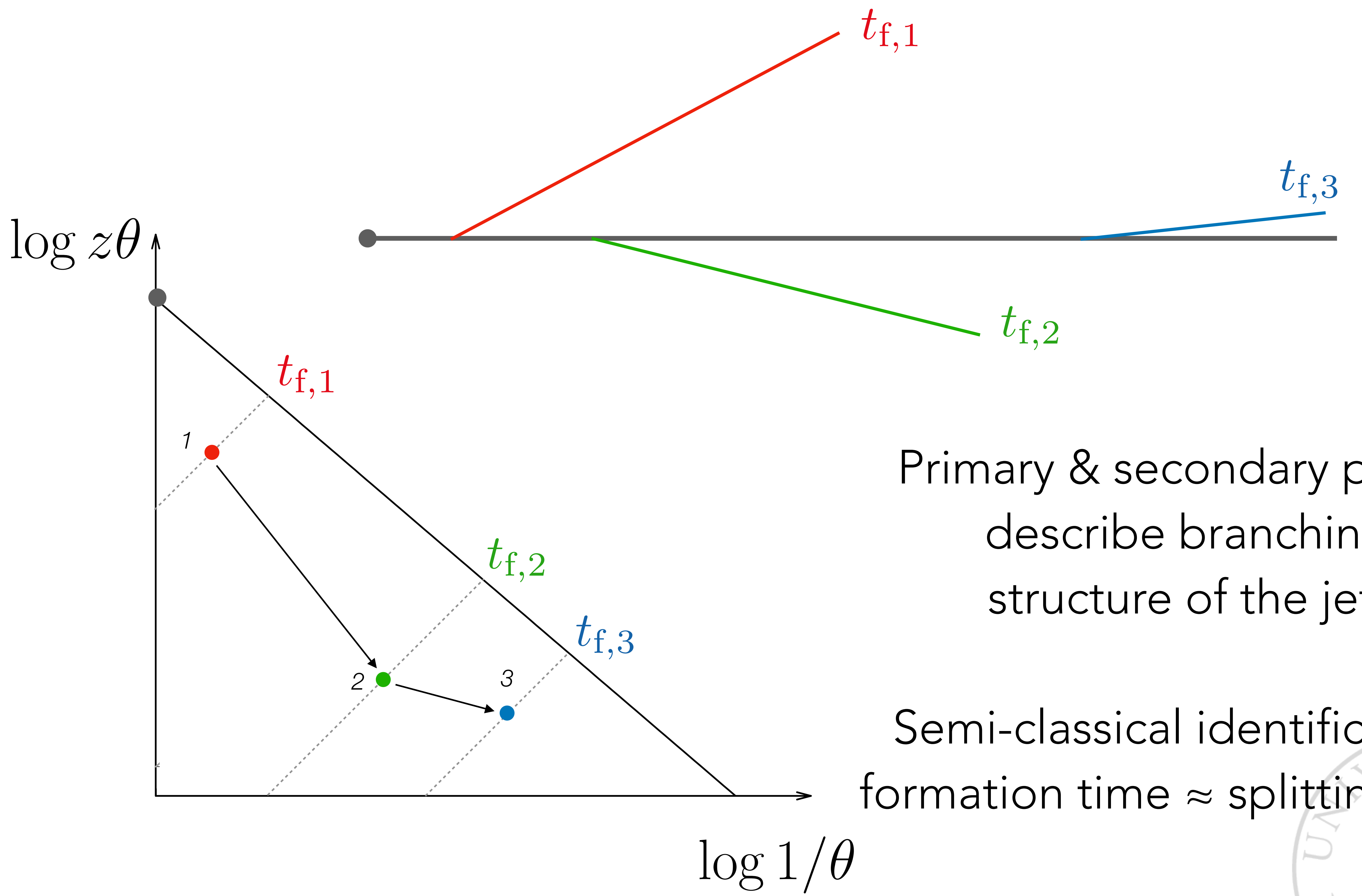

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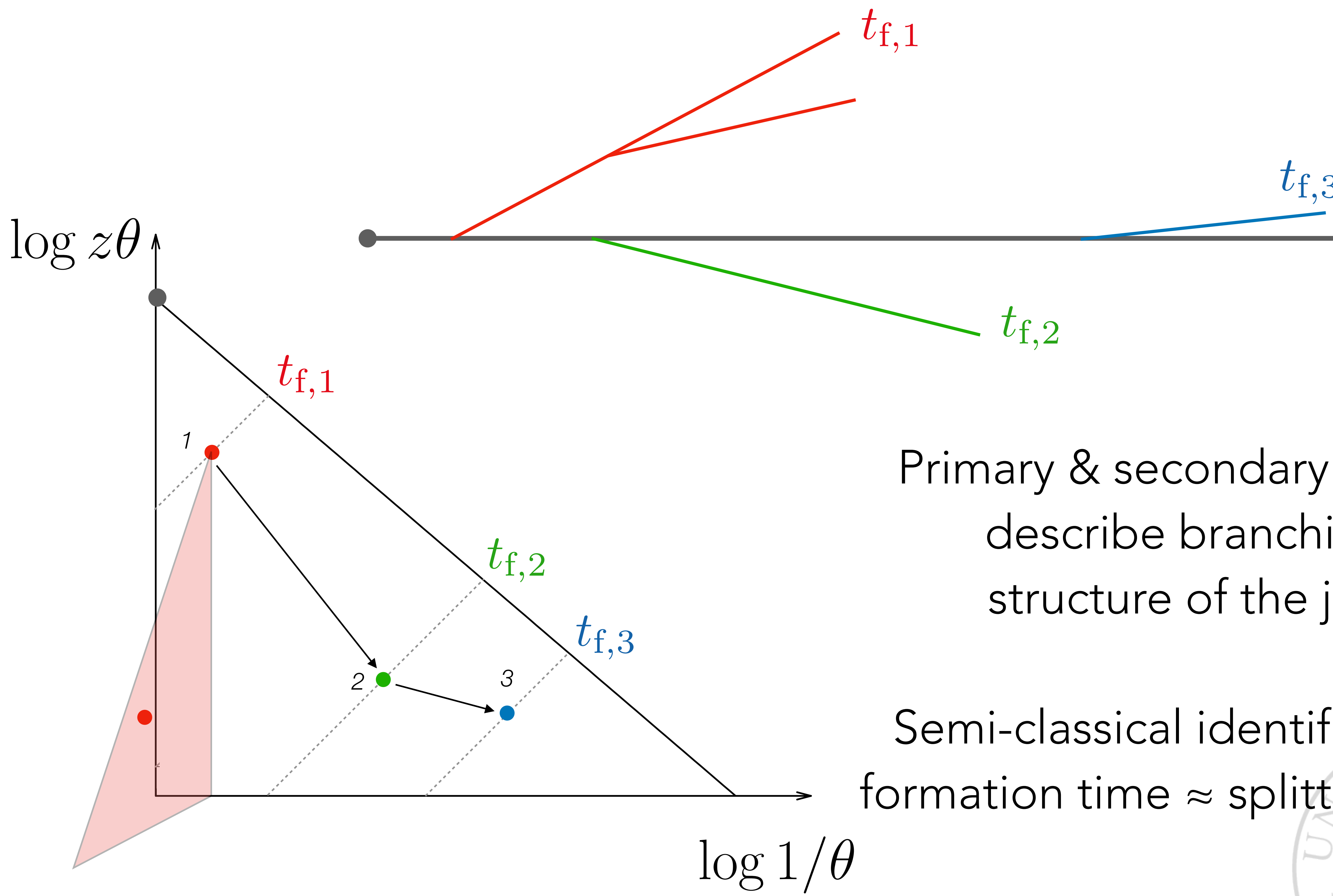
SPACE-TIME PICTURE OF THE JET



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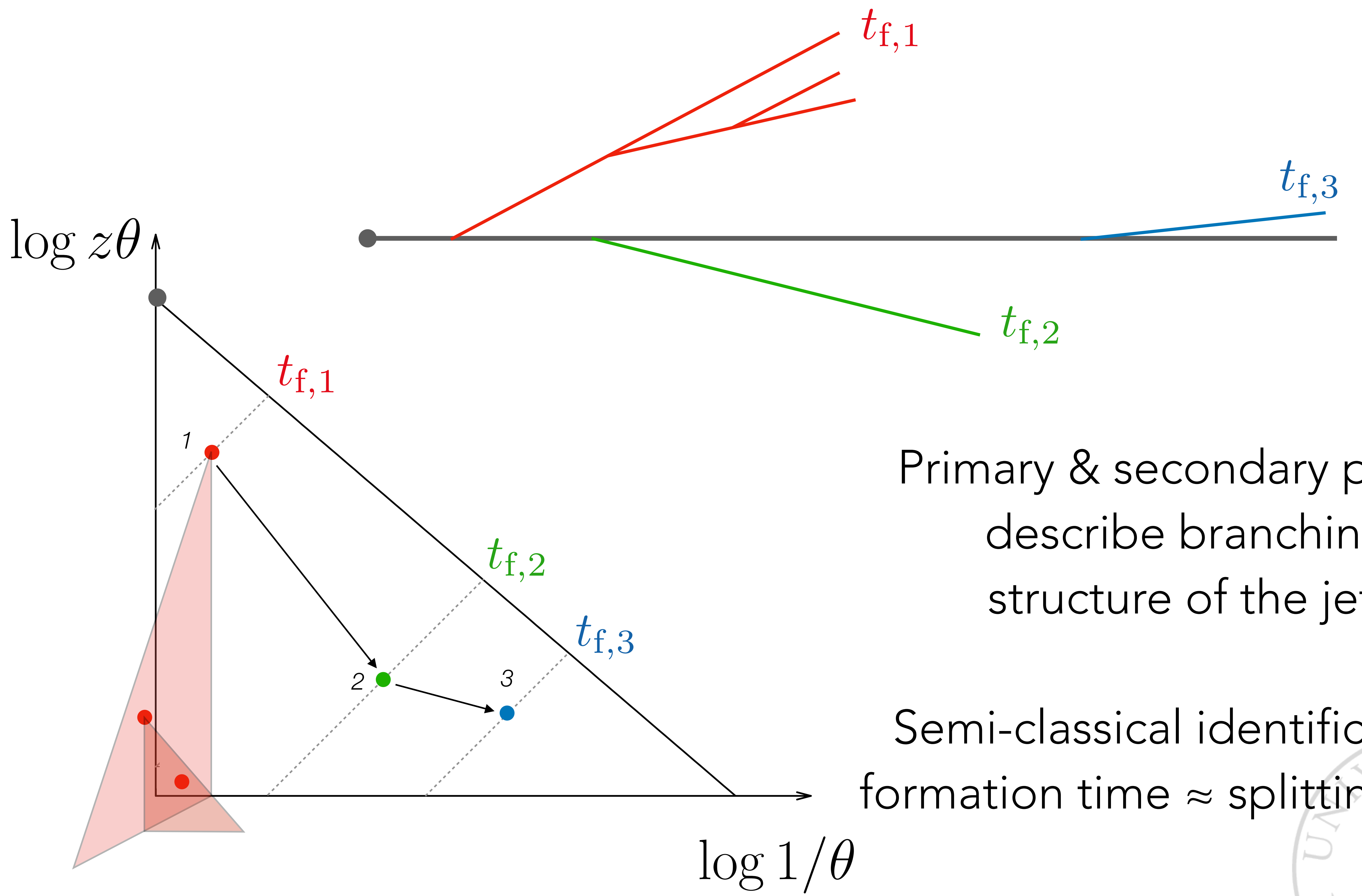

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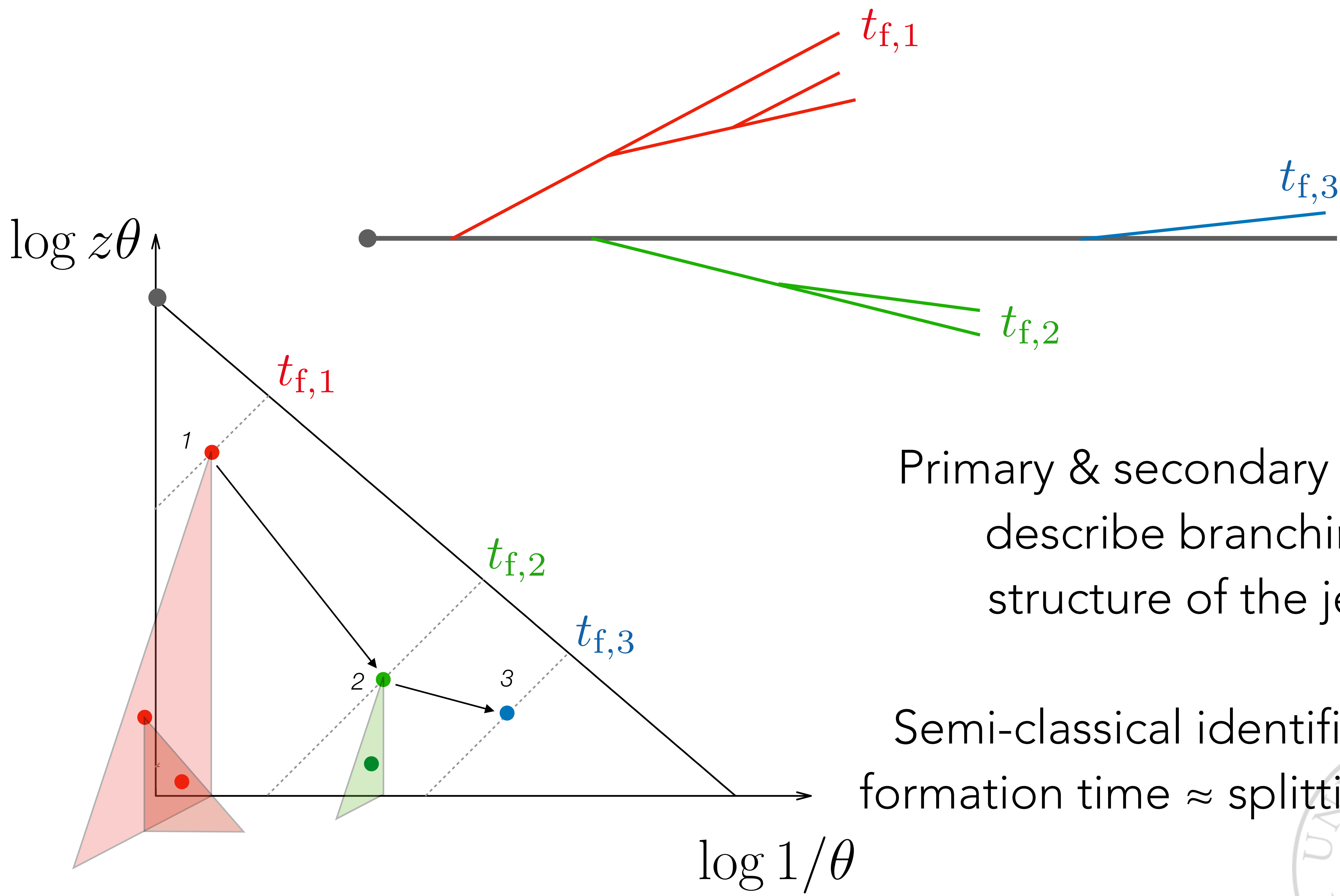

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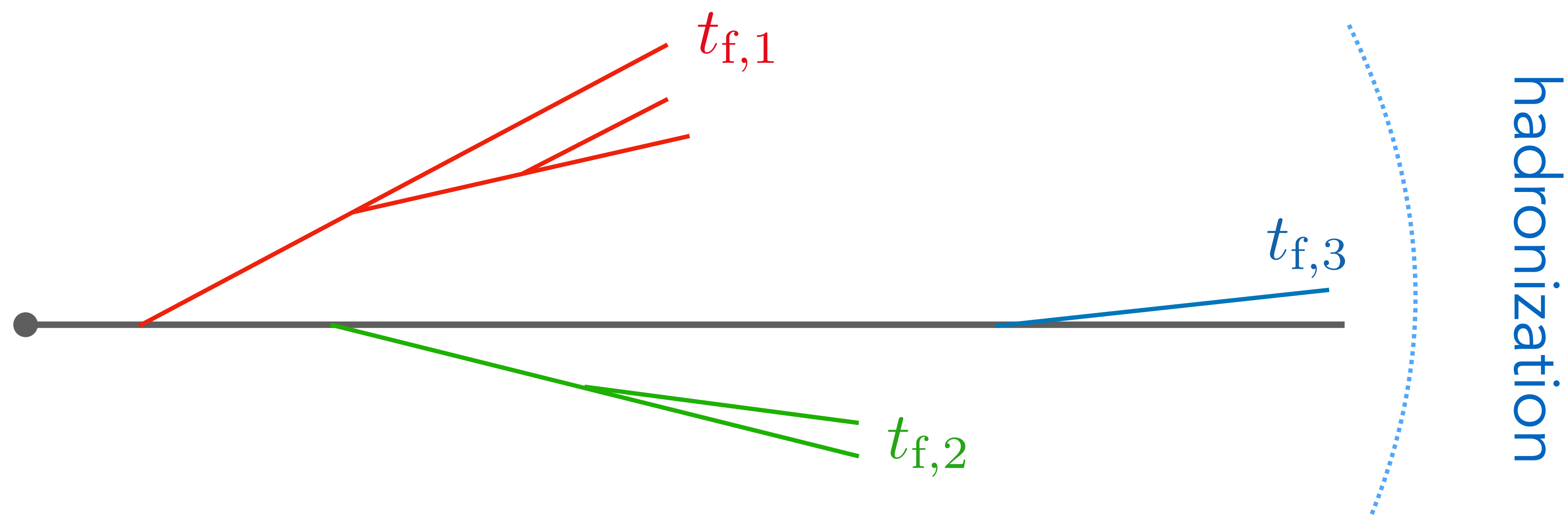

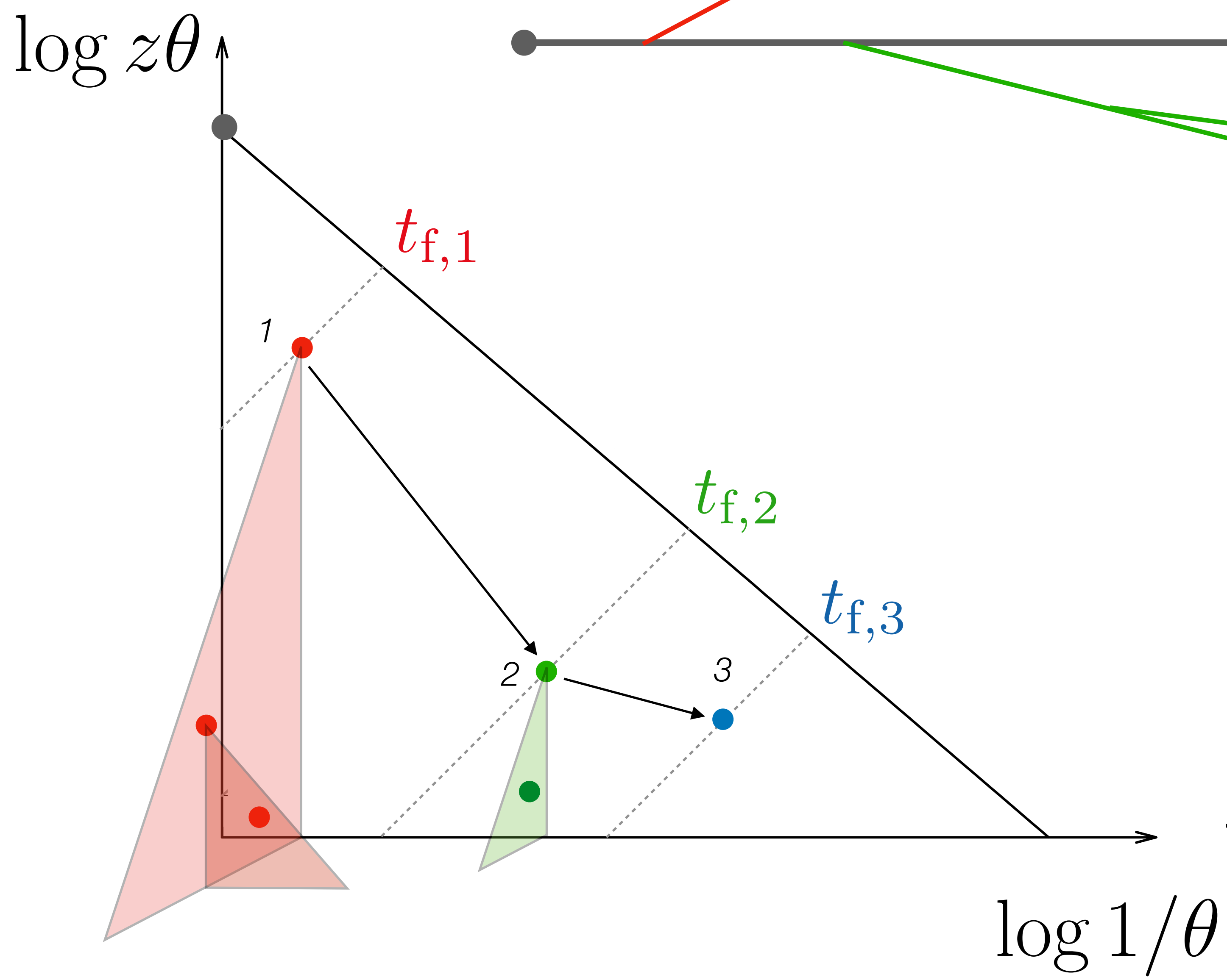

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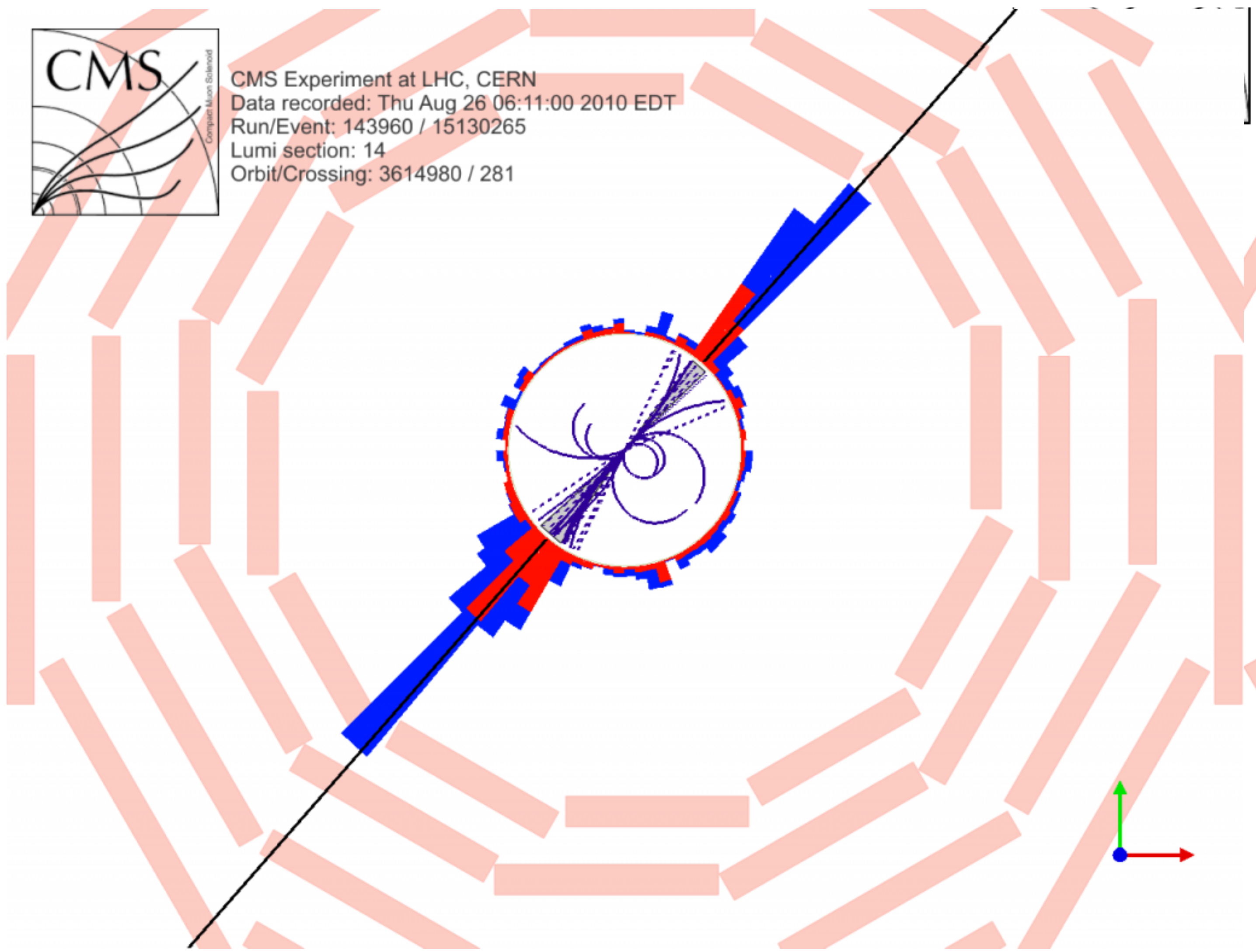
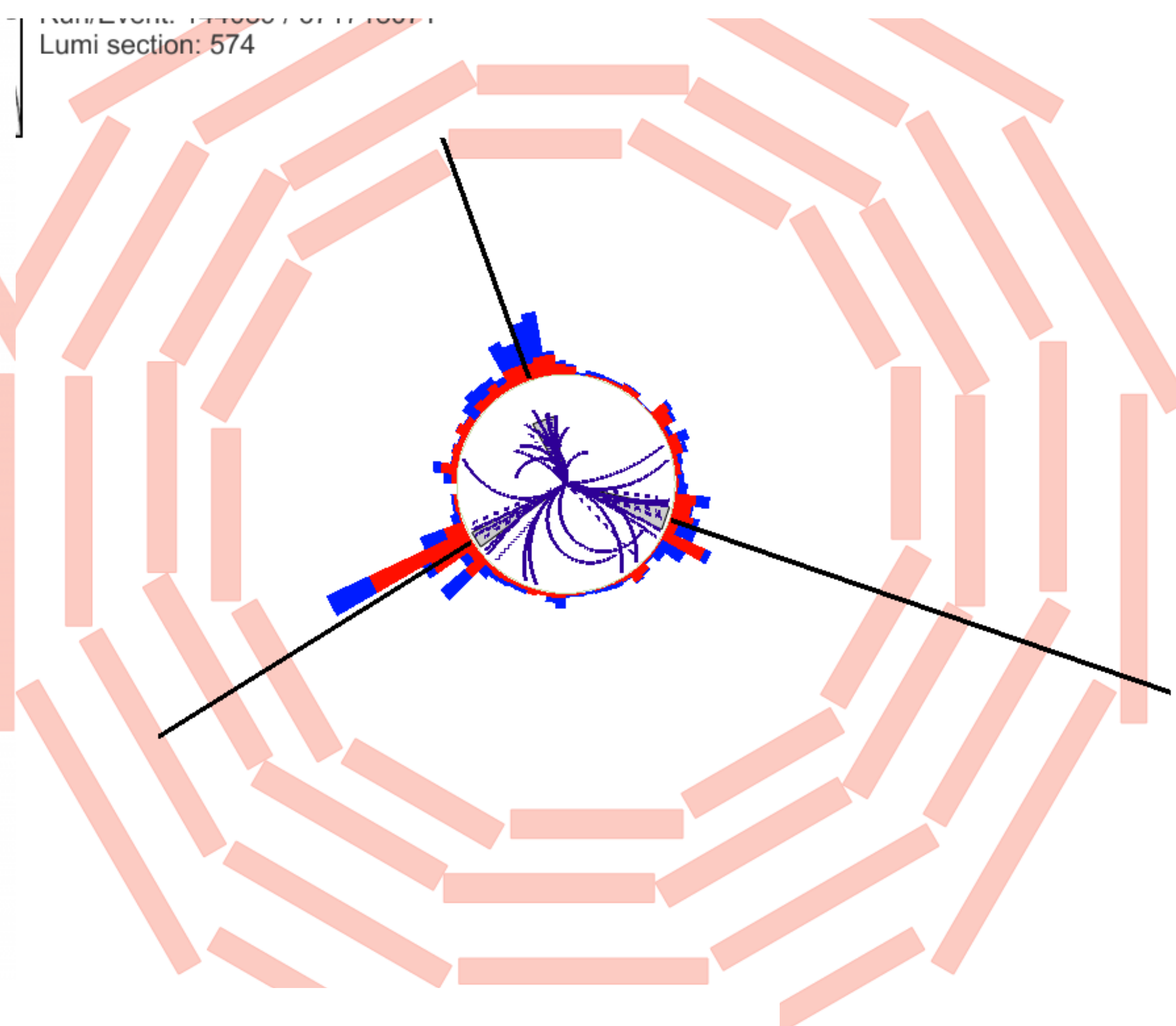
Tools

JET DEFINITIONS

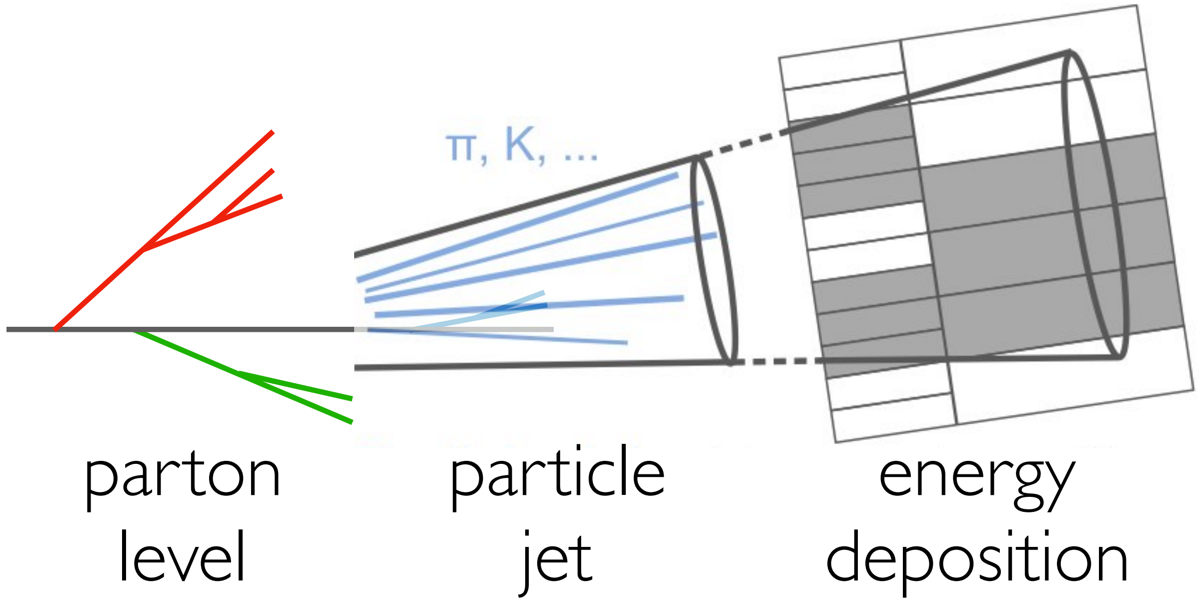


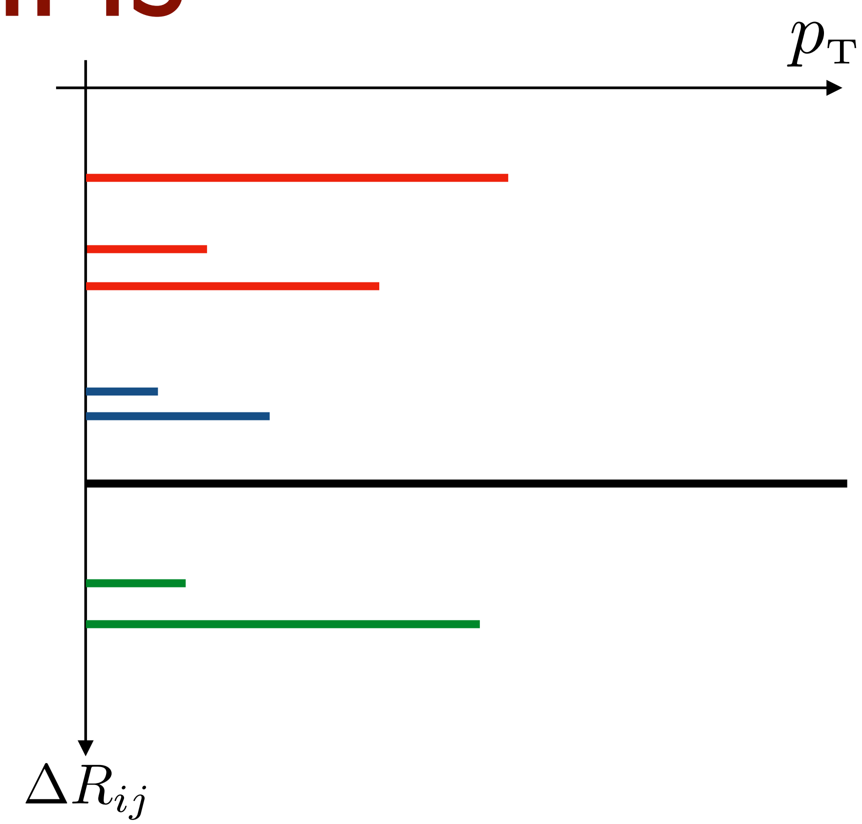
proton-proton
two-jet event (?)



proton-proton
three-jet event (?)

Recombination algorithms





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

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

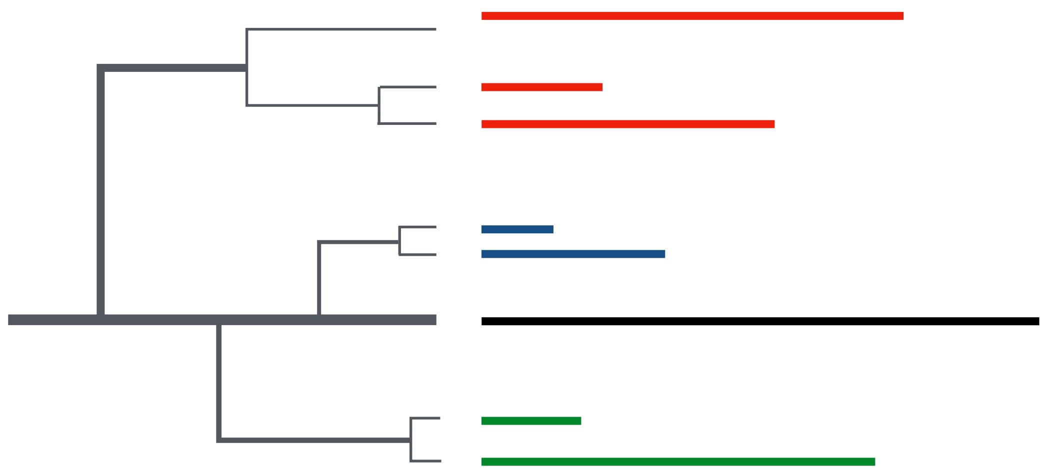
\+ recombination scheme

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

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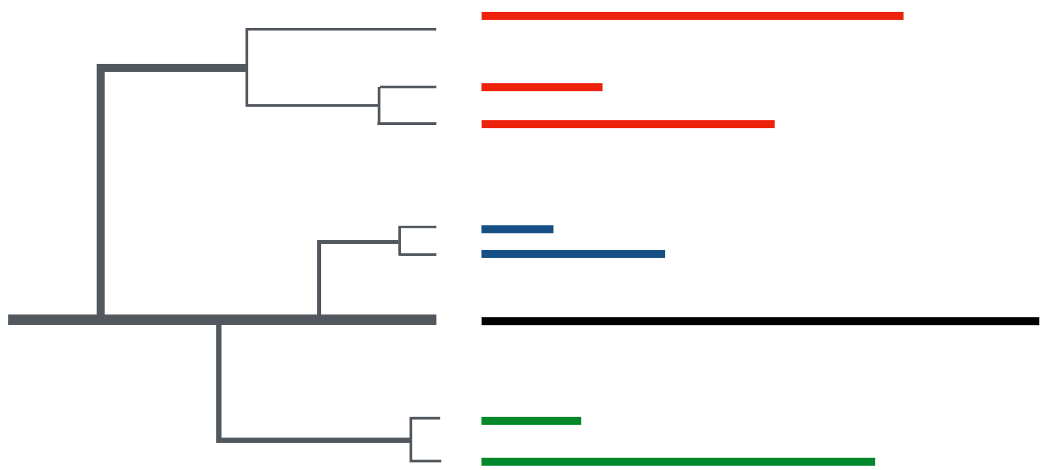

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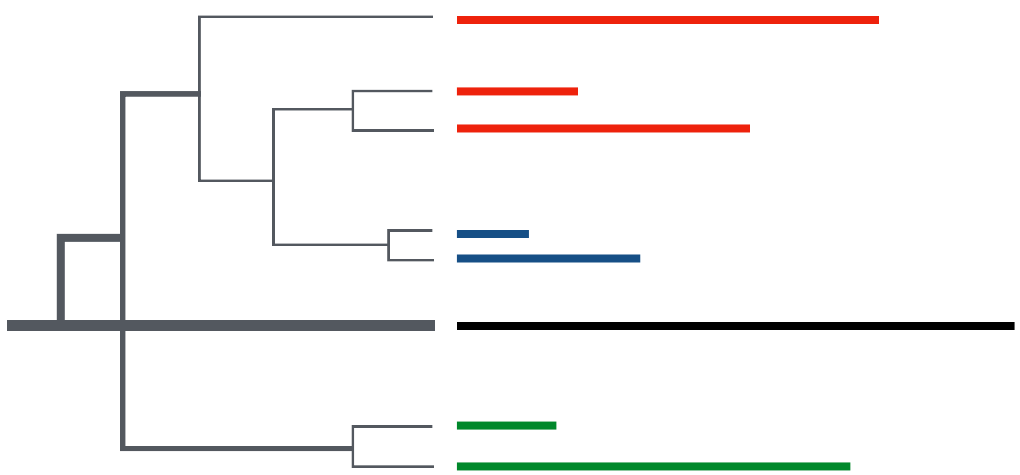
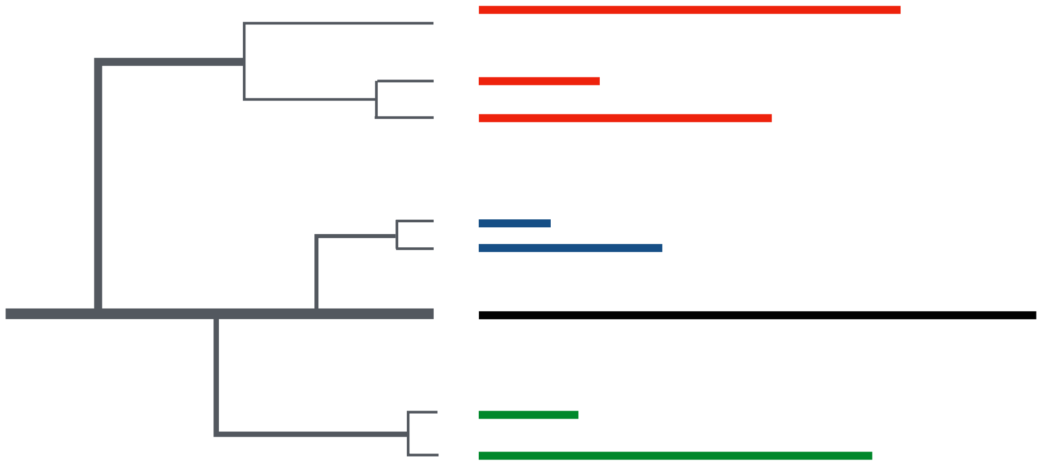


2) k_t algorithm

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

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

Recombination algorithms



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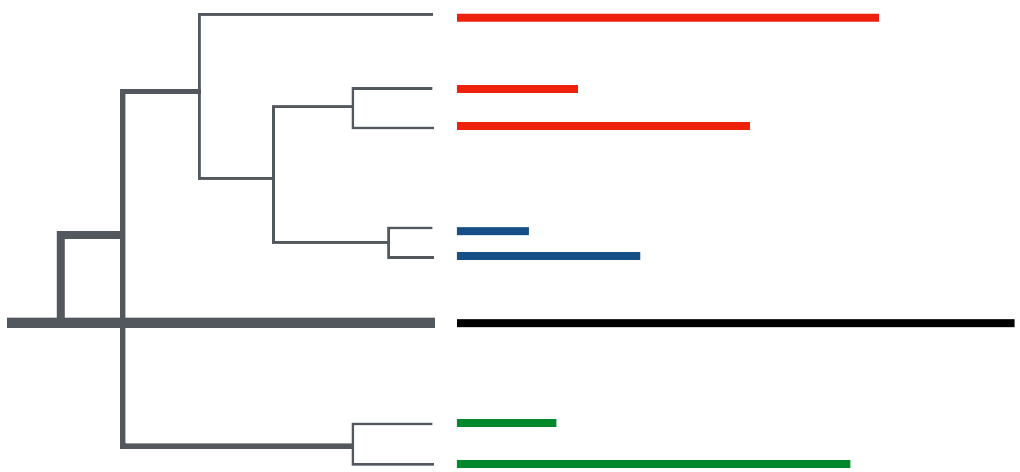

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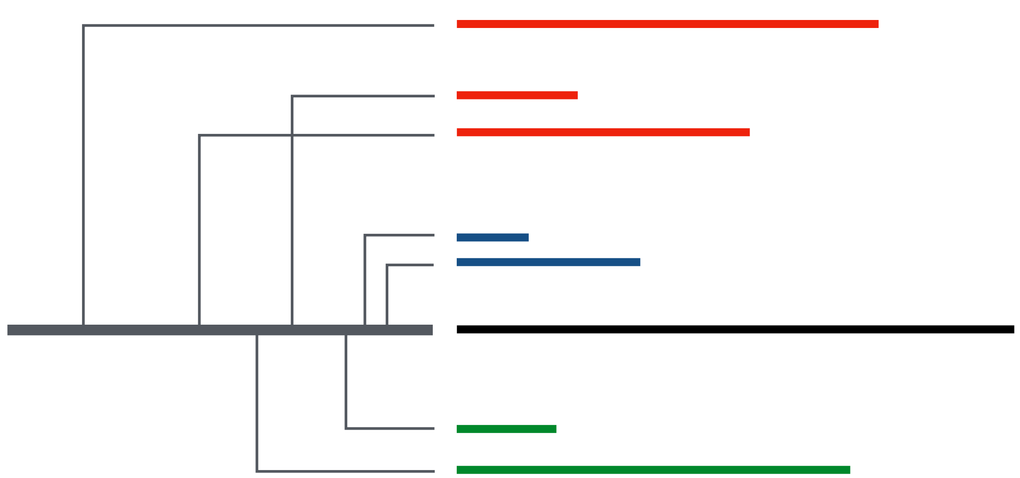


3) anti-k_t algorithm

[Cacciari, Salam, Soyez (2008)]

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

Grooming

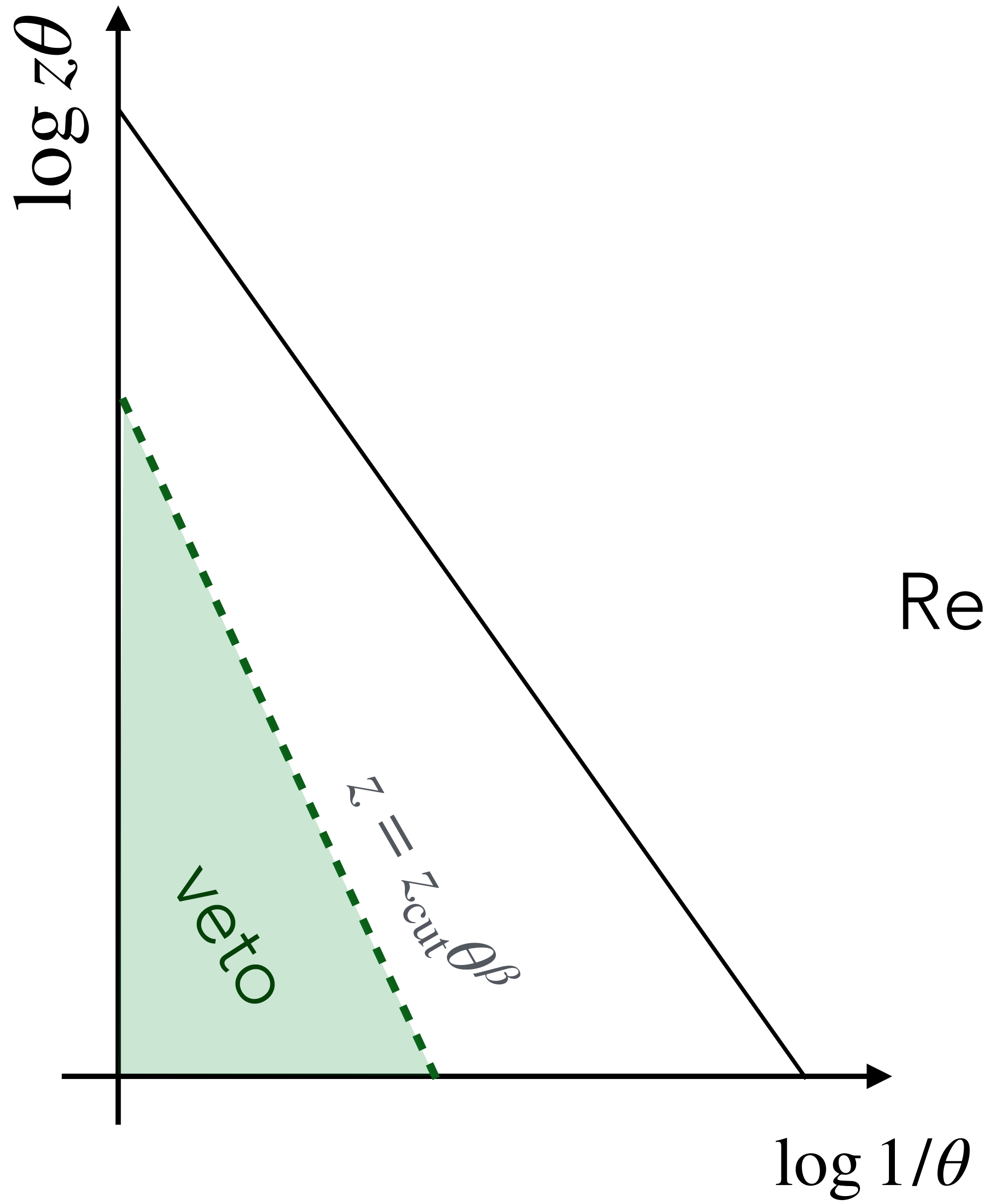
- *trimming*
- *filtering*
- *pruning*
- modified Mass-Drop Tagger/SoftDrop
- recursive SD

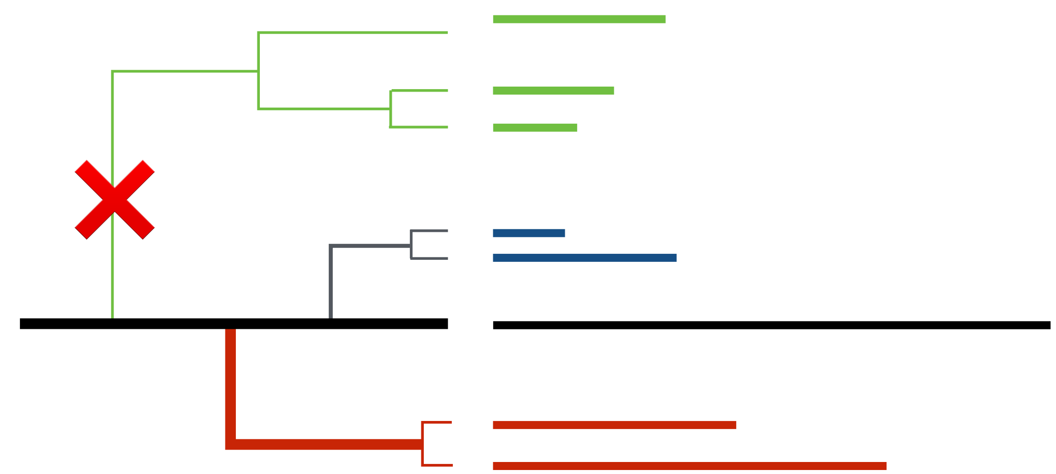
Aimed at reducing the sensitivity to underlying event & non-global logarithms.

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

Observables

Lund plane

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

Promote of idea phase space map to a genuine observable.

1) re-cluster jet with C/A algorithm
2) at each branching collect ($p_{\mathrm{T}i} > p_{\mathrm{T}j}$)

$$k_t = p_{\mathrm{T}j} \Delta R_{ij}$$

$$z = p_{\mathrm{T}j}/(p_{\mathrm{T}i} + p_{\mathrm{T}j})$$

$$m^2 = (p_i + p_j)^2$$

$$\psi = \tan^{-1} \frac{y_j - y_i}{\phi_j - \phi_i}$$

3) produces an ordered list

$$\mathscr{L}_{\mathrm{primary}} = \{\mathscr{T}^{(1)}, \ldots, \mathscr{T}^{(N)}\}$$

$$\mathscr{T}^{(i)} = \{\Delta R^{(i)}, k_t^{(i)}, \ldots\}$$

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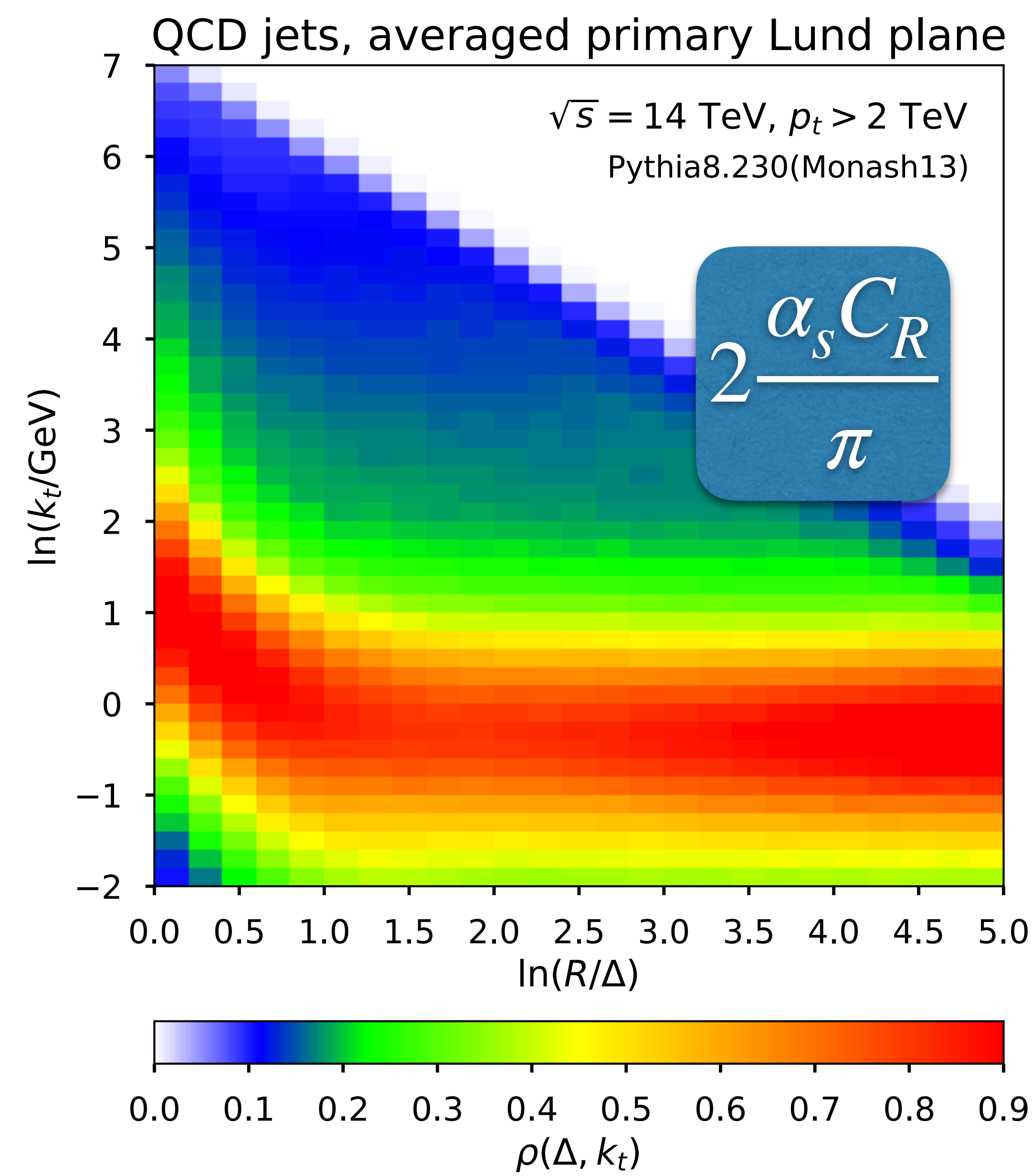
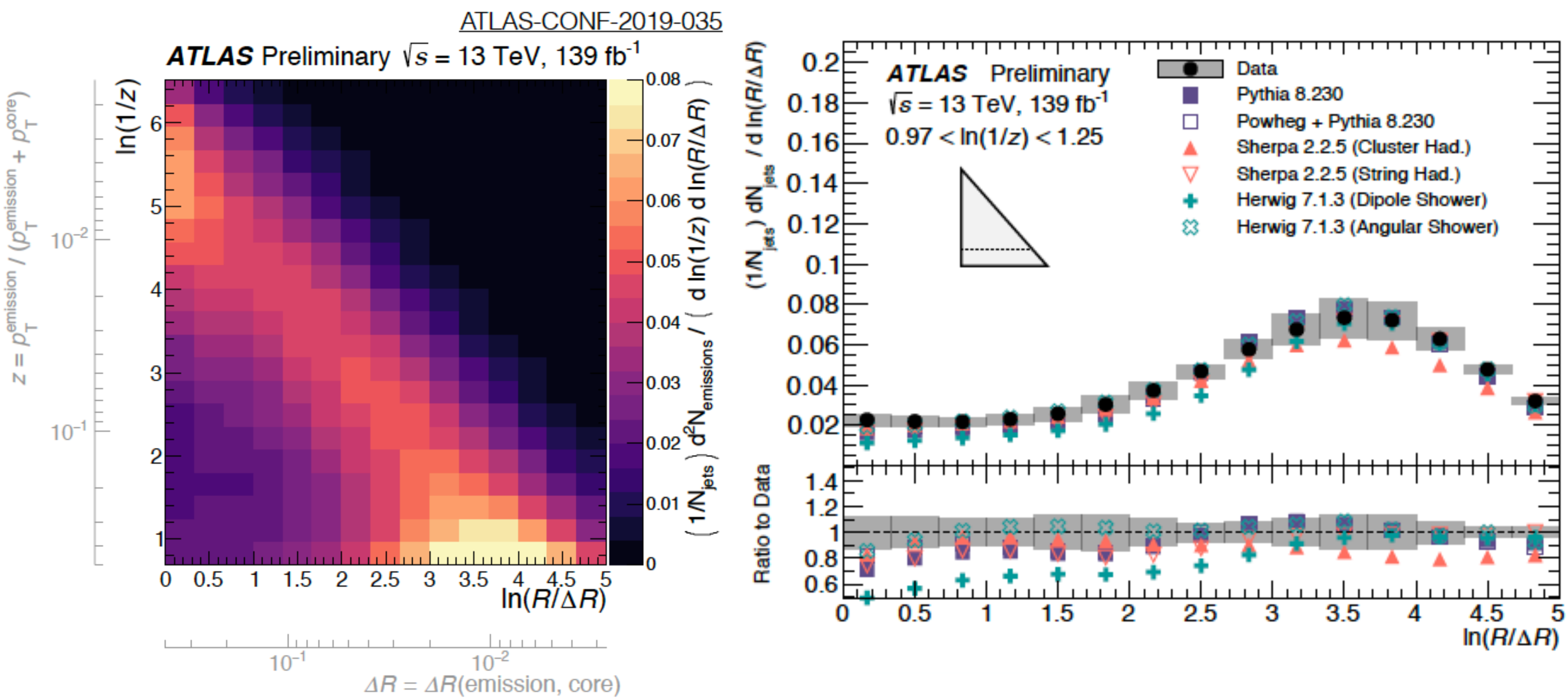


Plane is uniformly filled!

Measuring the Lund plane

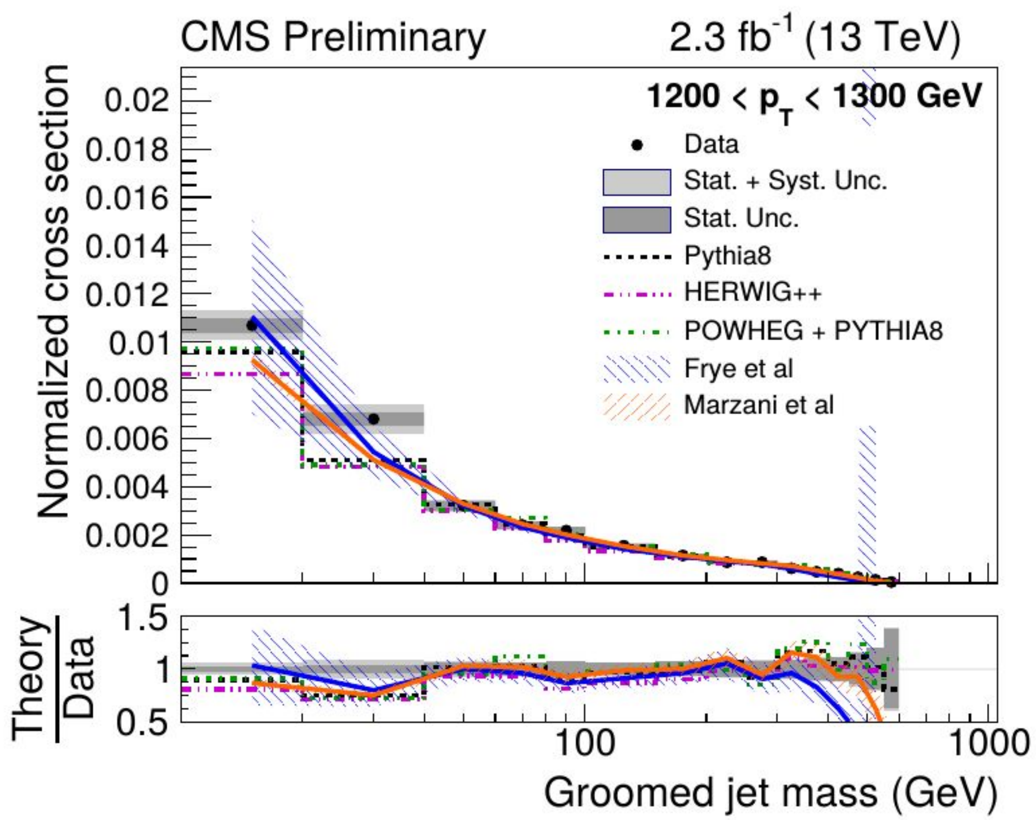


Measured in real data (pp @ 13 TeV).

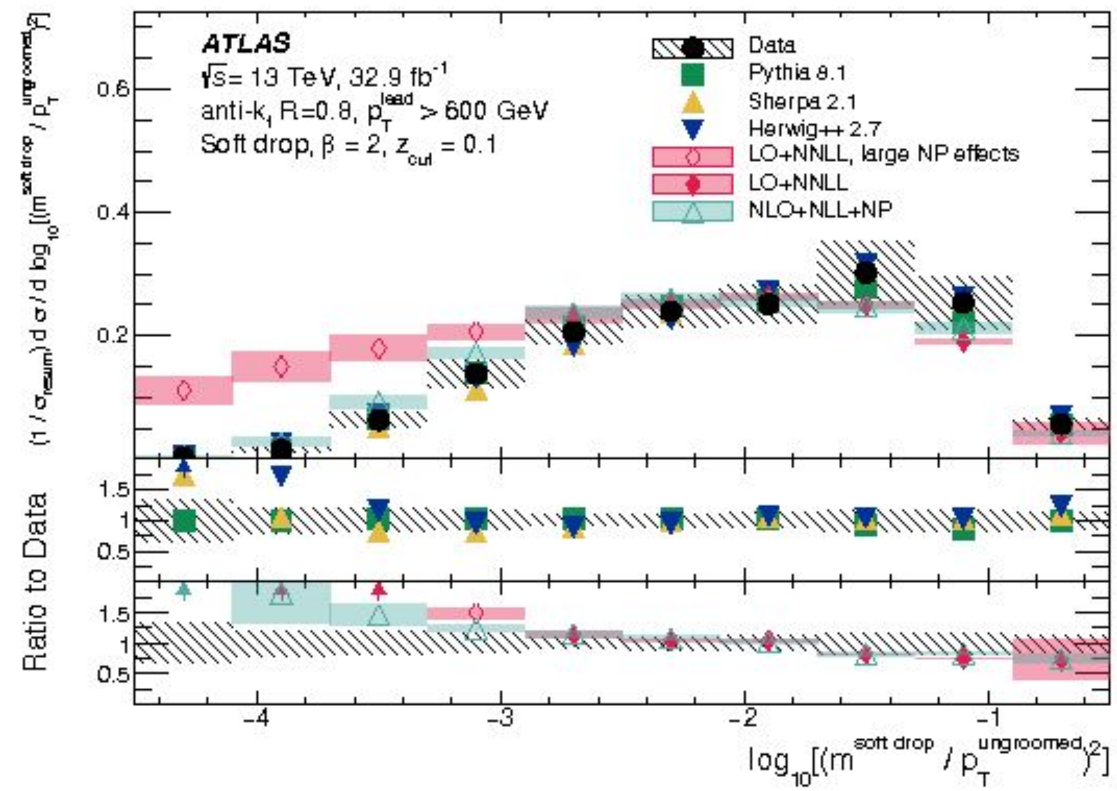
Exciting new tool: constraining branching structure of MC.

GROOMED OBSERVABLES

CMS-PAS-SMP-16-010



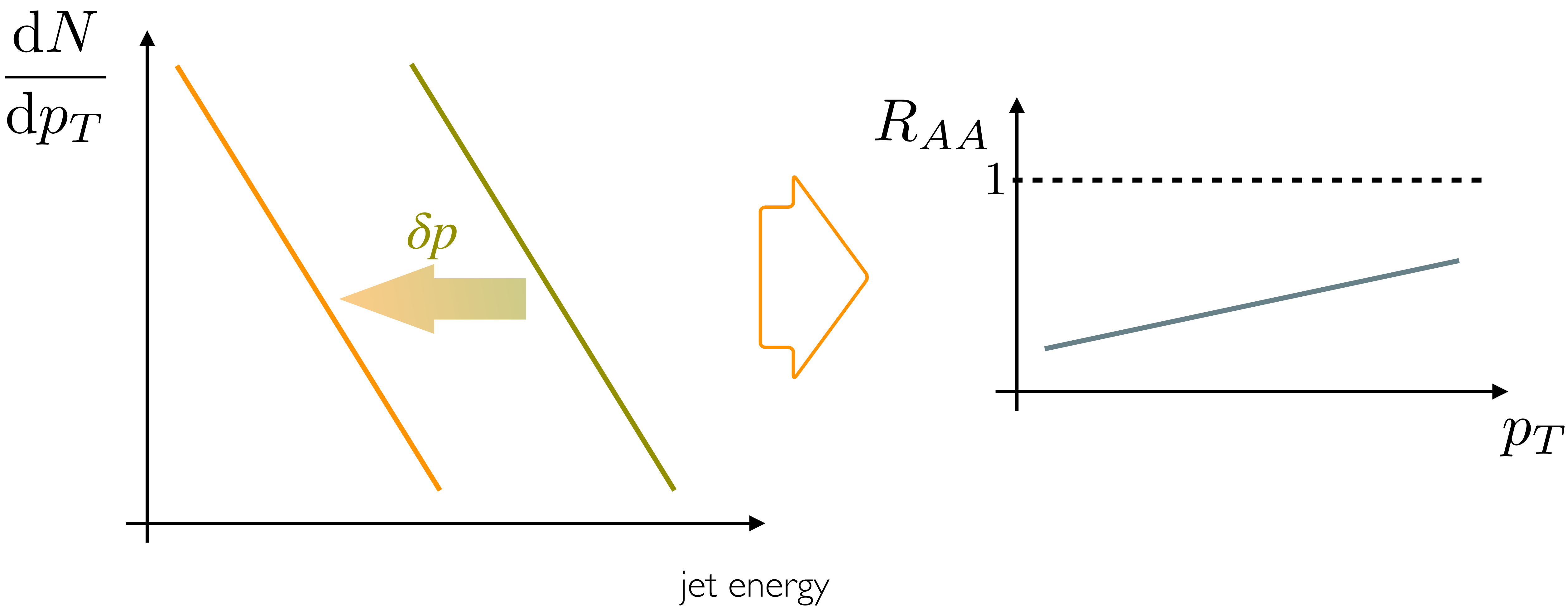
CERN-EP-2017-231



- set of new observables after SD procedure
  - directly linked to density on primary Lund plane
  - theory-MC-data comparison at LHC!
- beyond infrared-collinear safe (Sudakov safety)
- counting observables n_{SD}

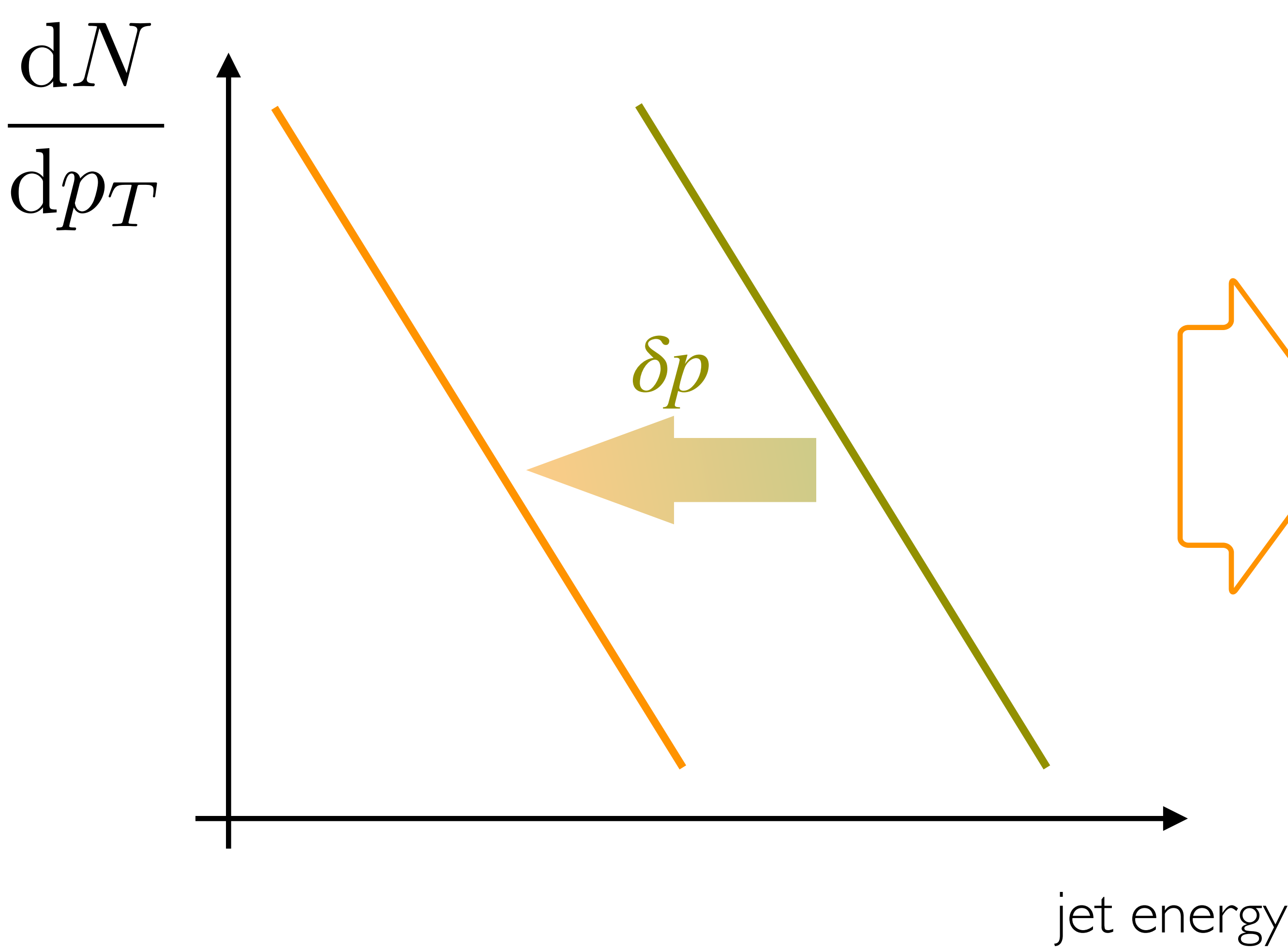
Heavy-ions

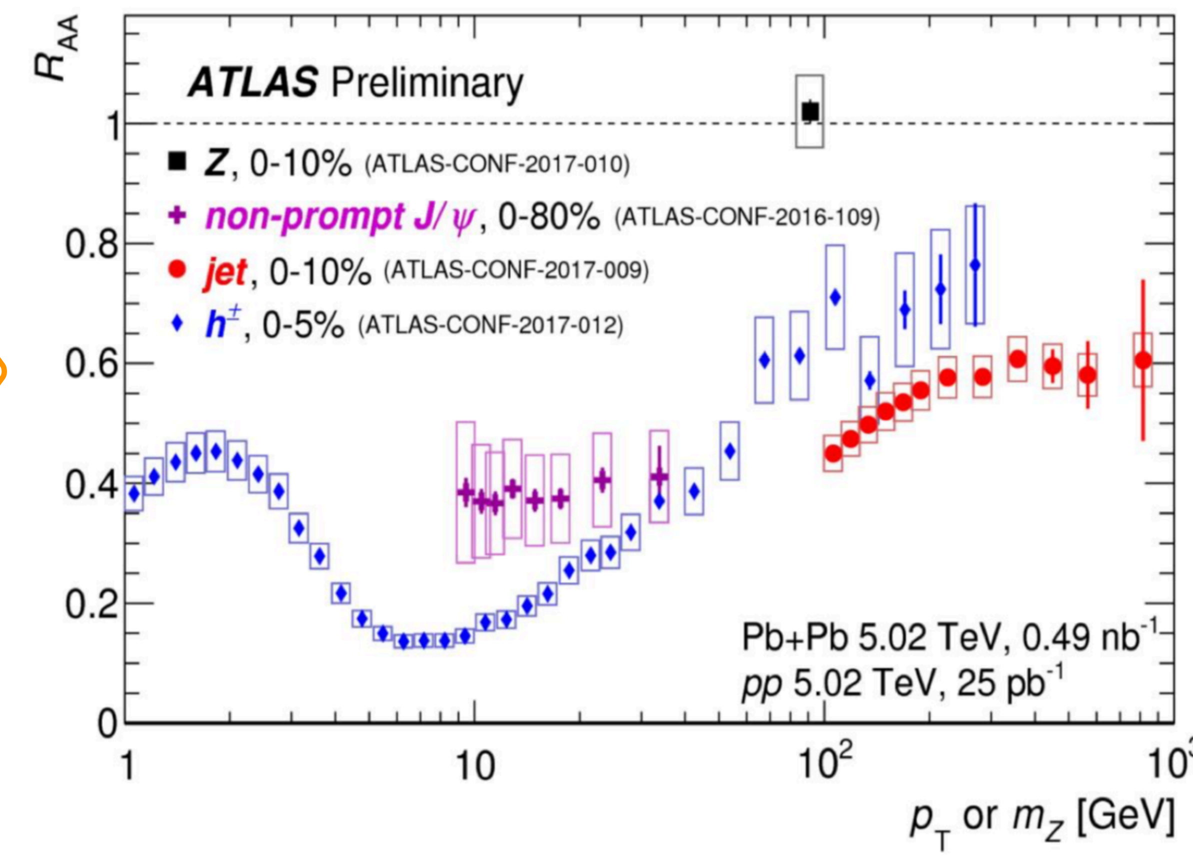
Energy-loss basics



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

ENERGY-LOSS BASICS





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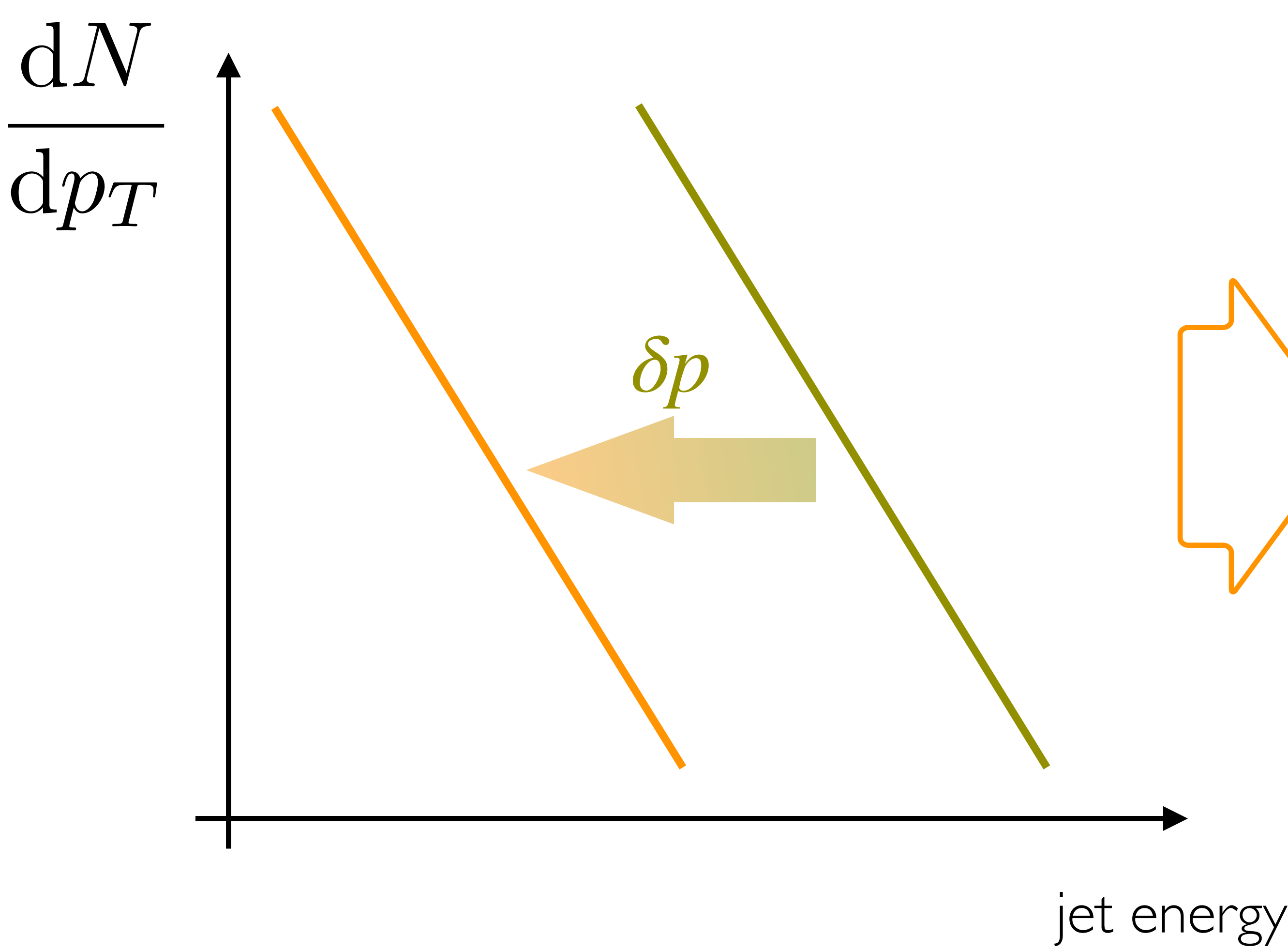
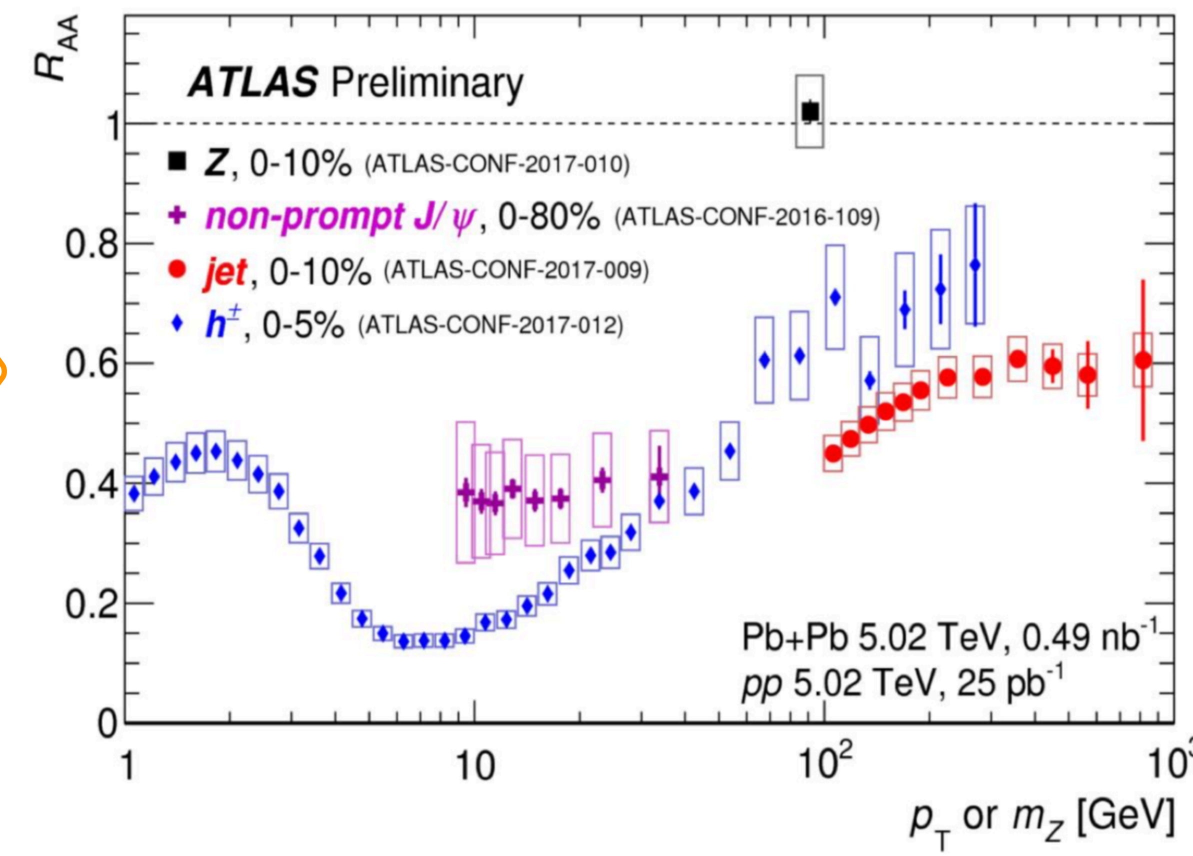


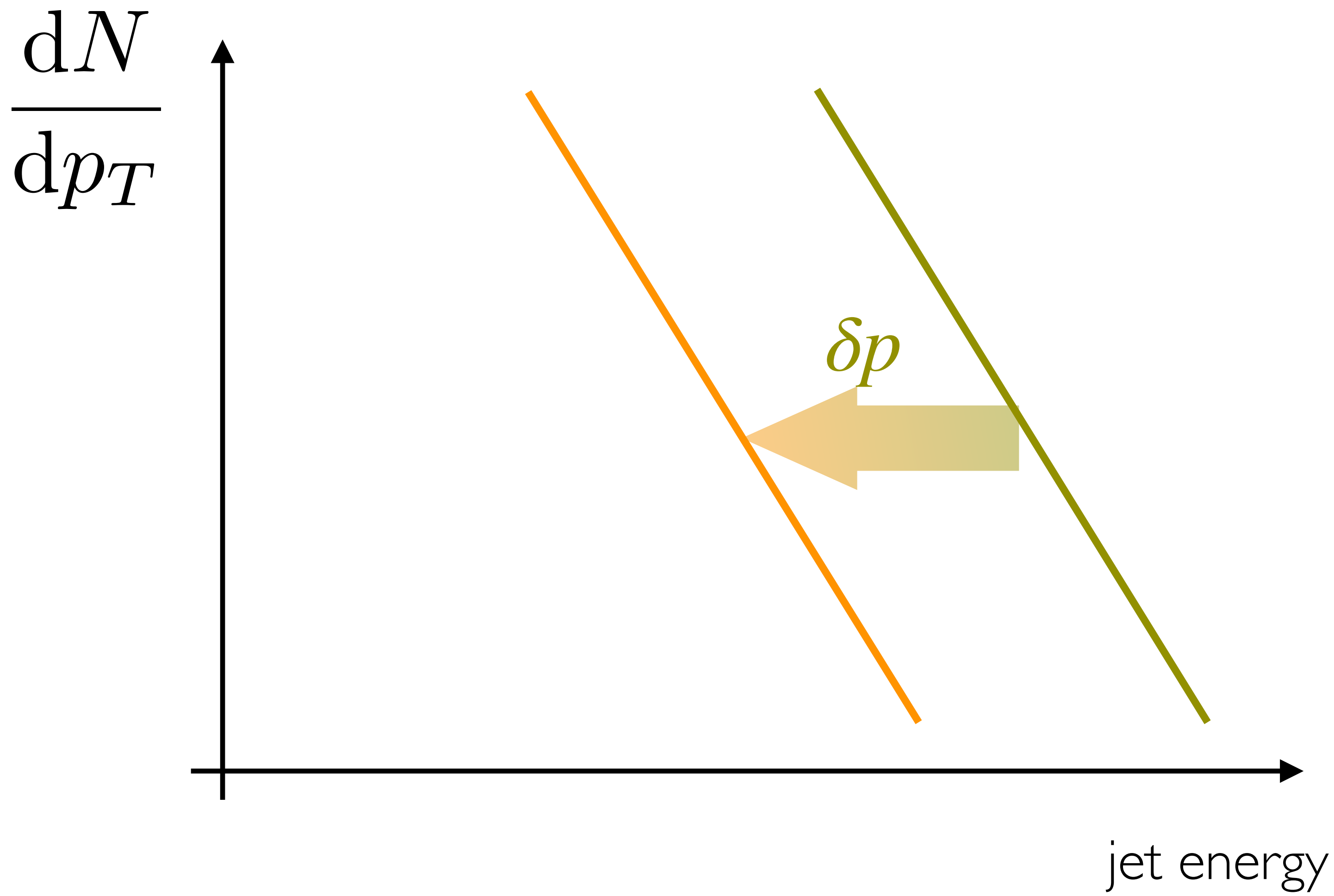


Workhorse of the field: measuring & parameterizing the shift of spectrum to access information about medium interactions.

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

Multi-variate migration effects

Consider a two-parameter dependence of δp.



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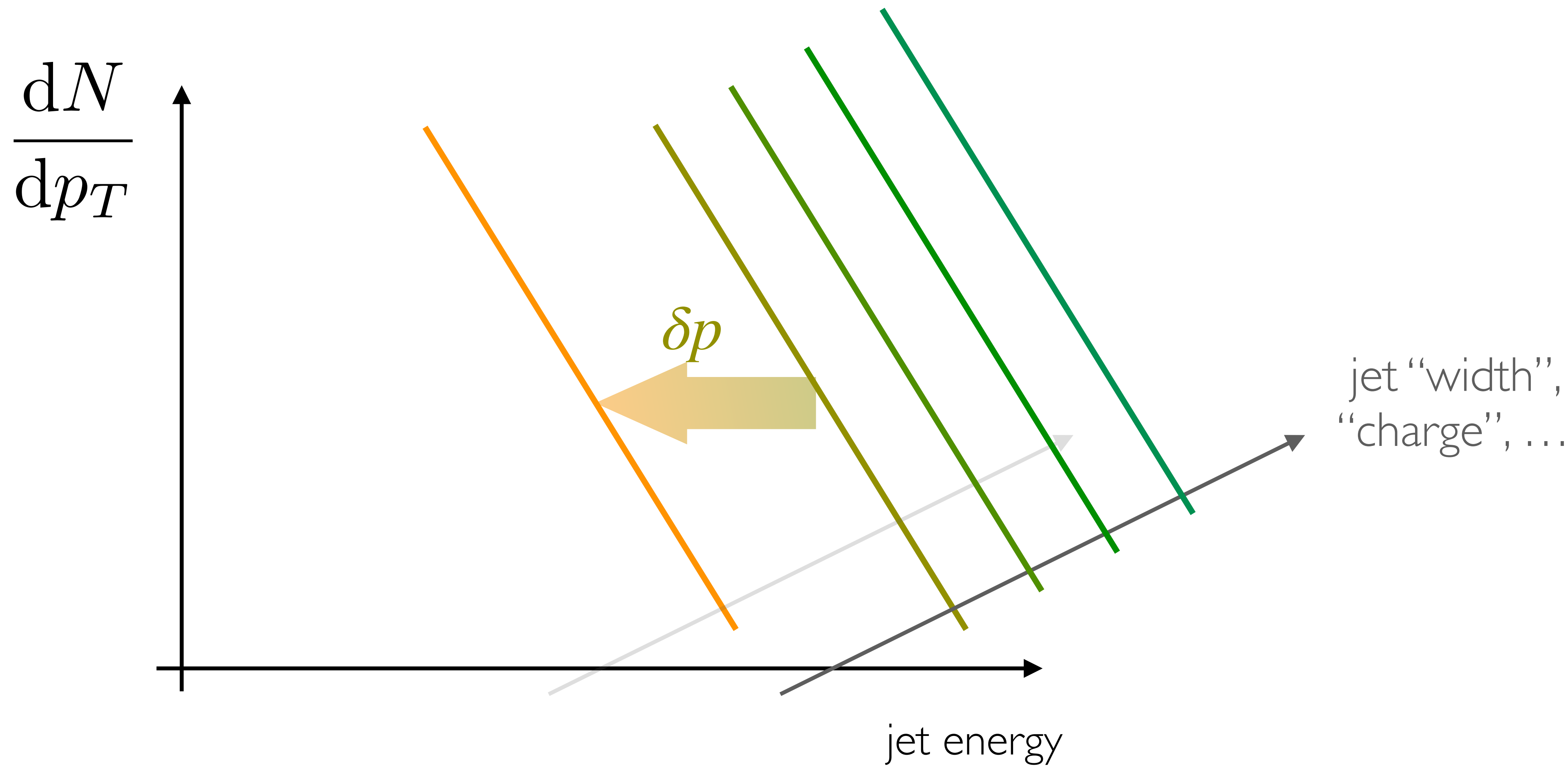

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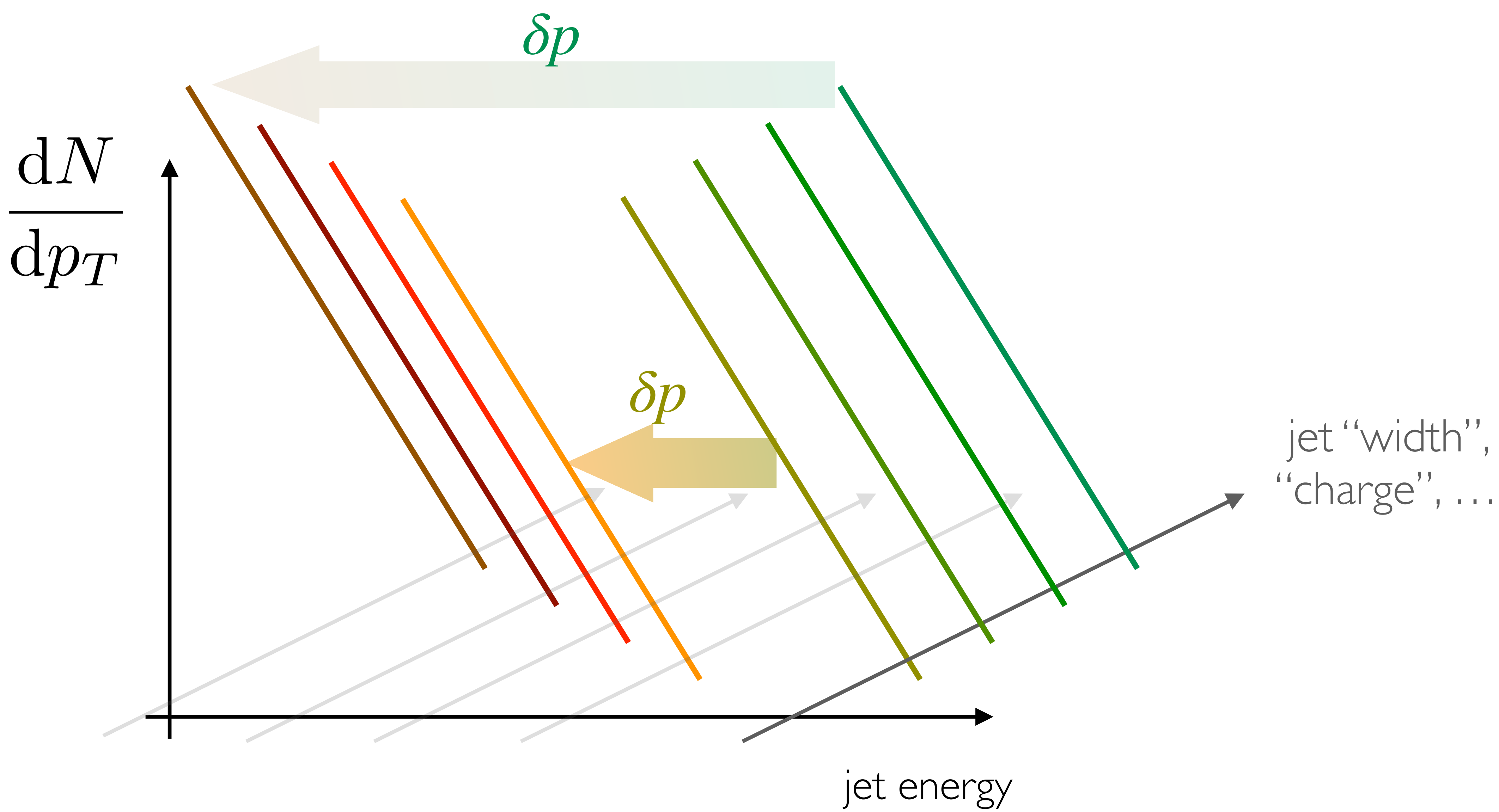

MULTI-VARIATE MIGRATION EFFECTS

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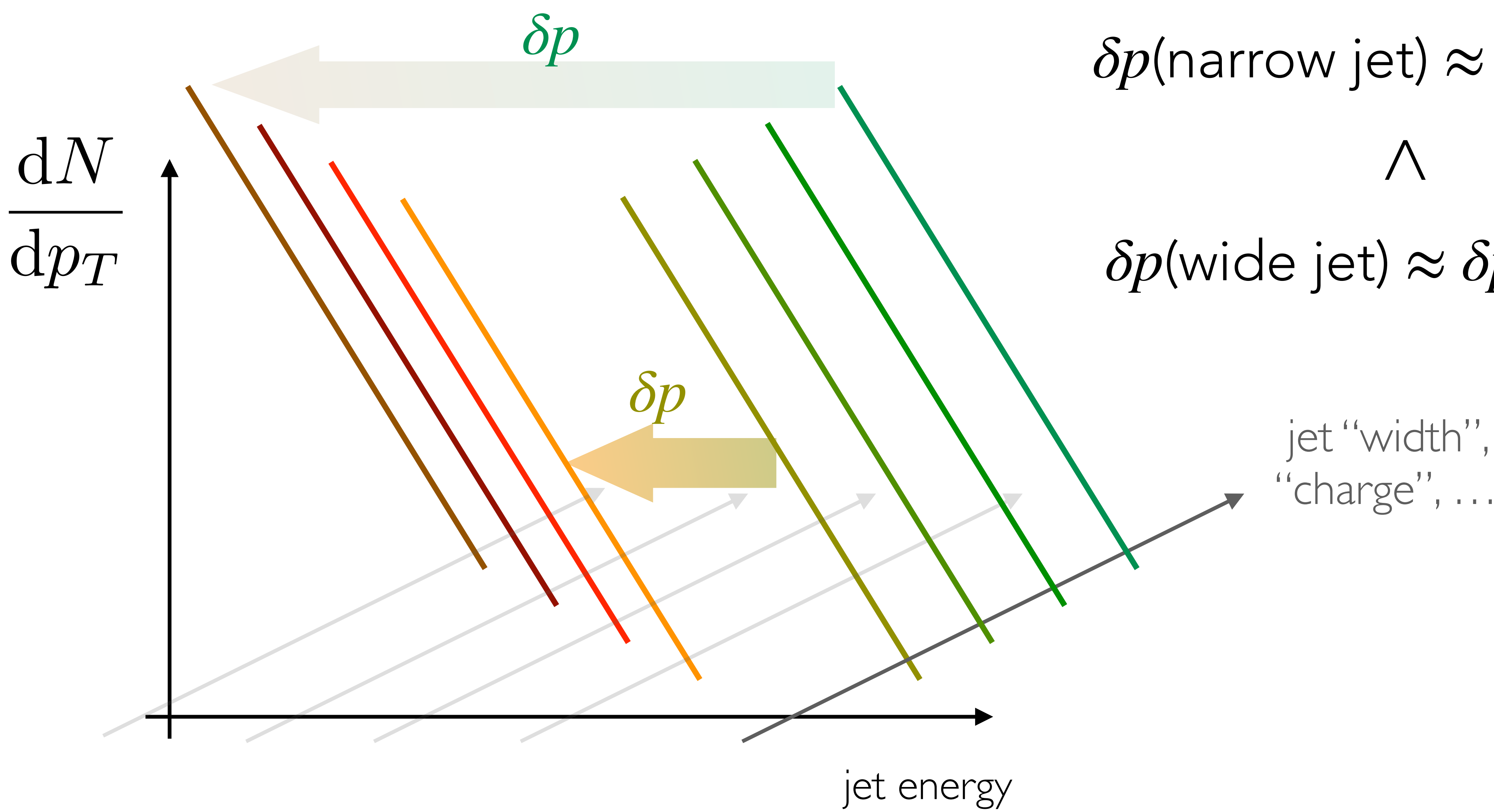


δp(narrow jet) $\approx$ δp(1 parton)

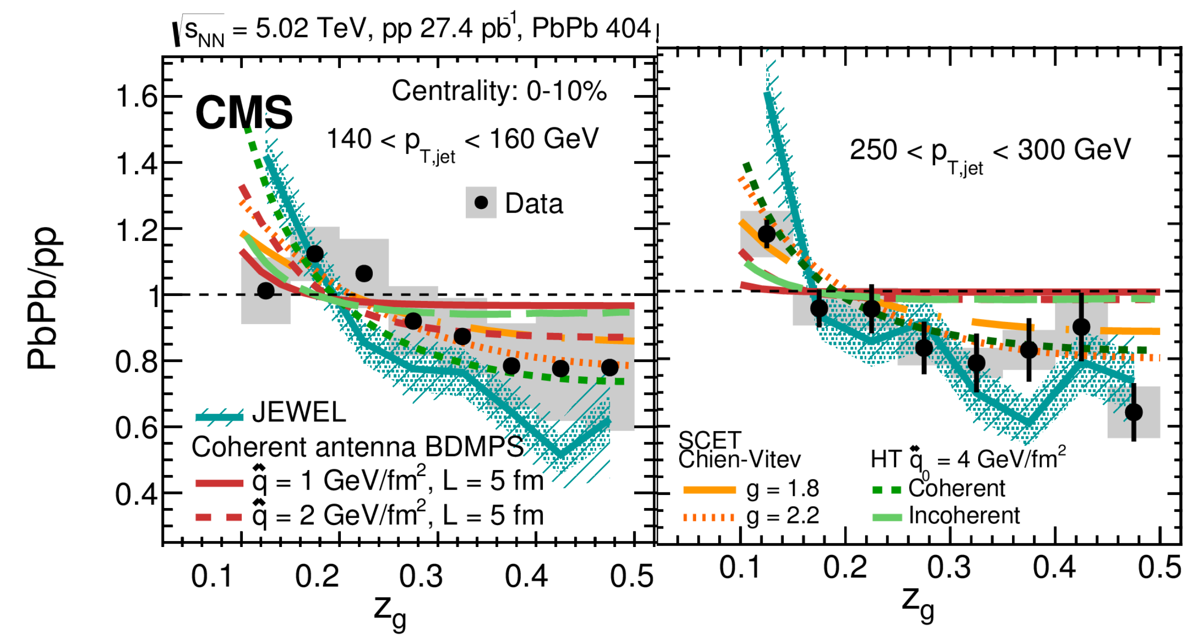
$\wedge$

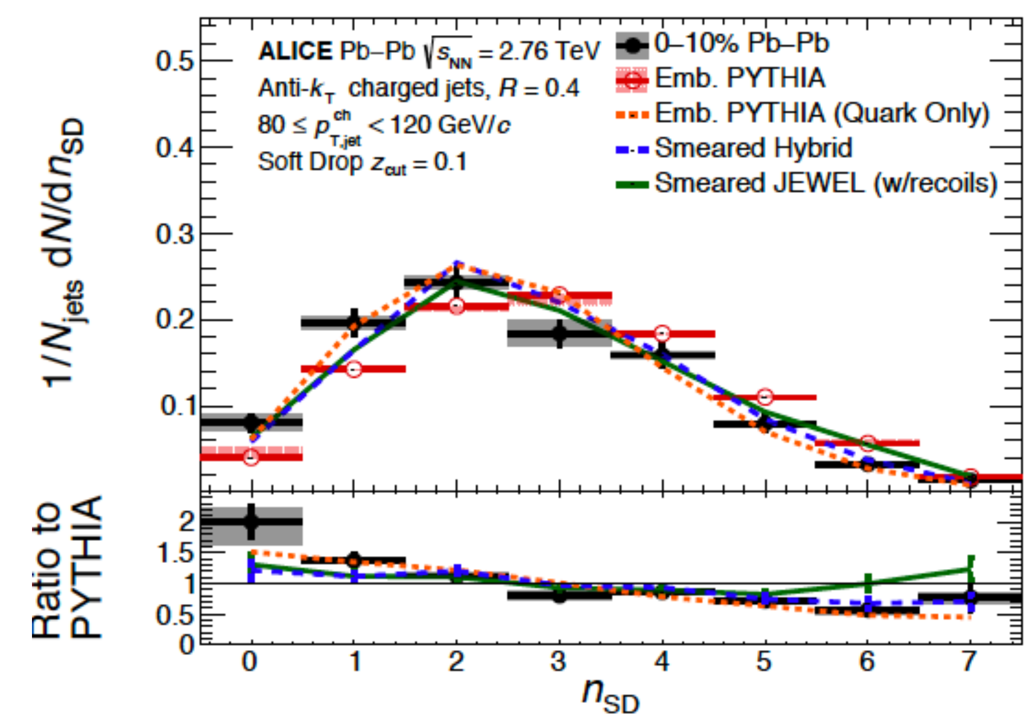
δp(wide jet) $\approx$ δp(n partons)

Open data/theory question: what drives quenching and substructure modifications?

SUBSTRUCTURE STUDIES IN HIC

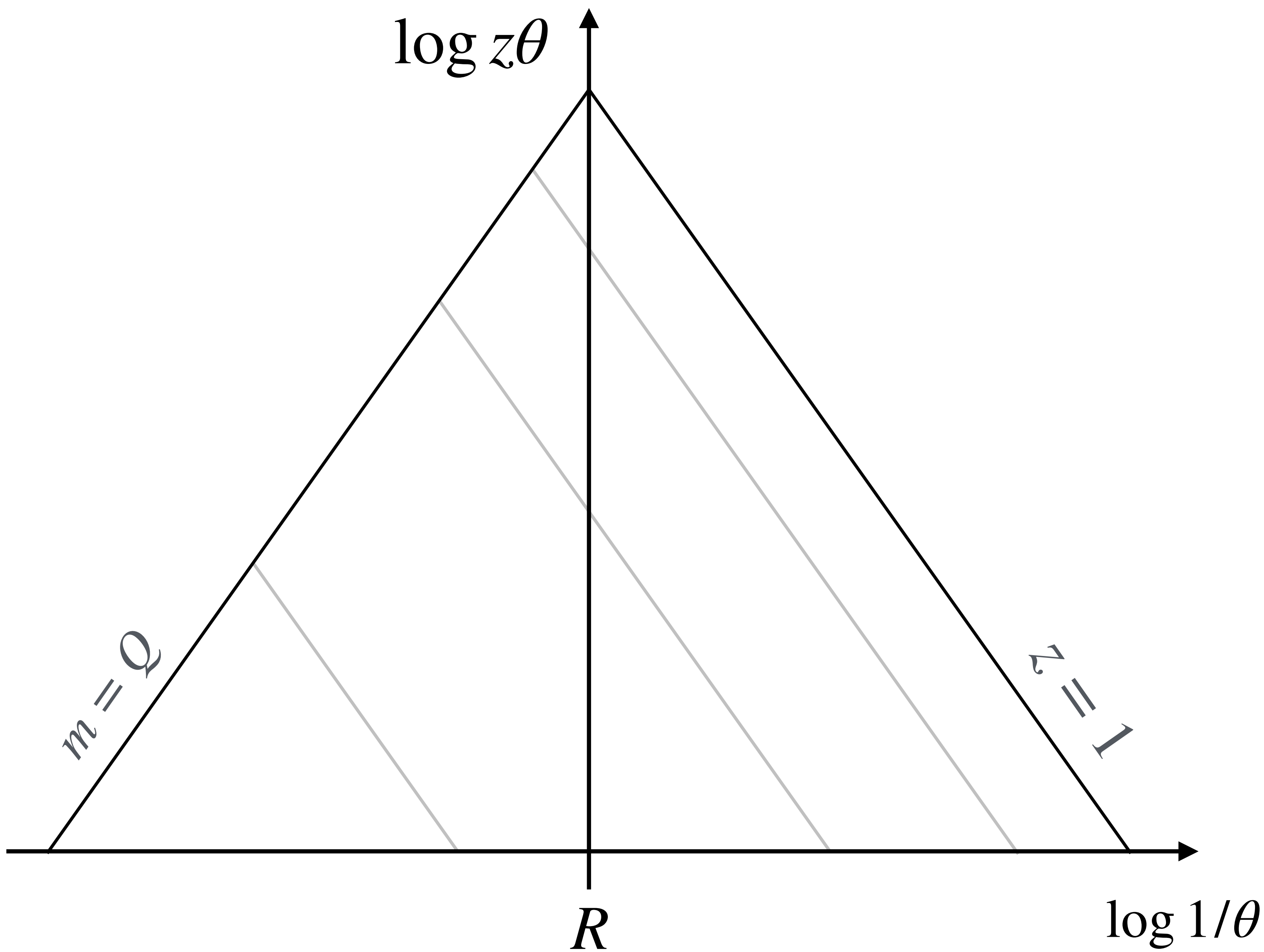
- sheds new light on the physics of jet quenching
- potential to isolate/enhance regimes
  - sensitivity to "new" physics (QCD bremsstrahlung, medium response)
  - purified samples to study microscopic properties (color, mass)
- at the forefront of developments in pp/PbPb





Phase space analysis

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



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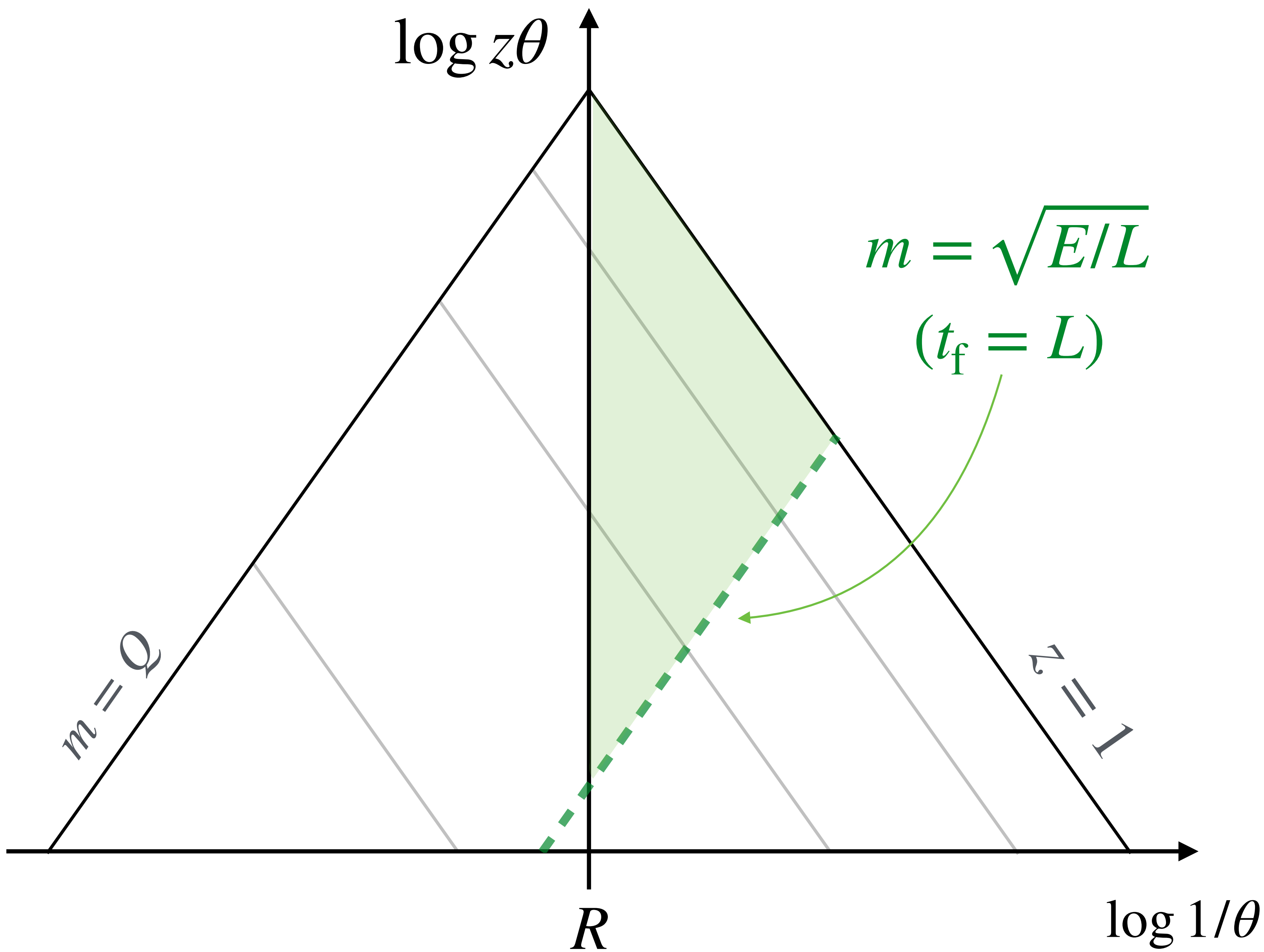

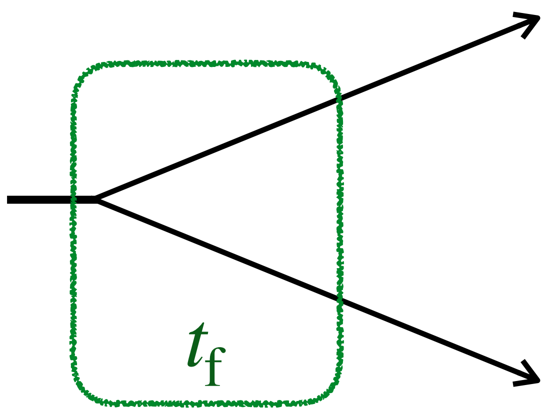

$$(PS)_{\rm in} = \frac{\bar{\alpha}}{4} \log^2 ER^2 L$$

Large probability for splitting inside!

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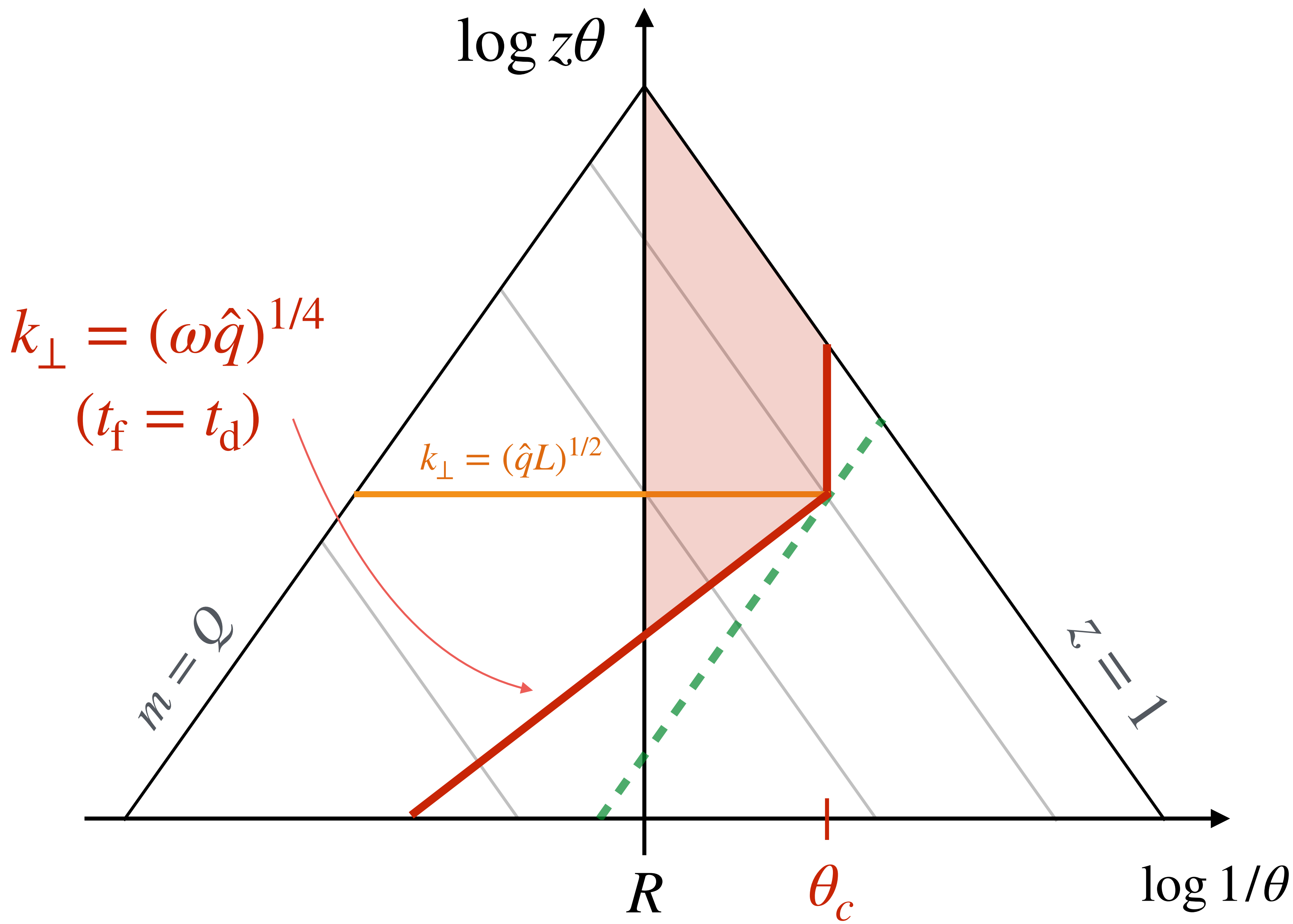
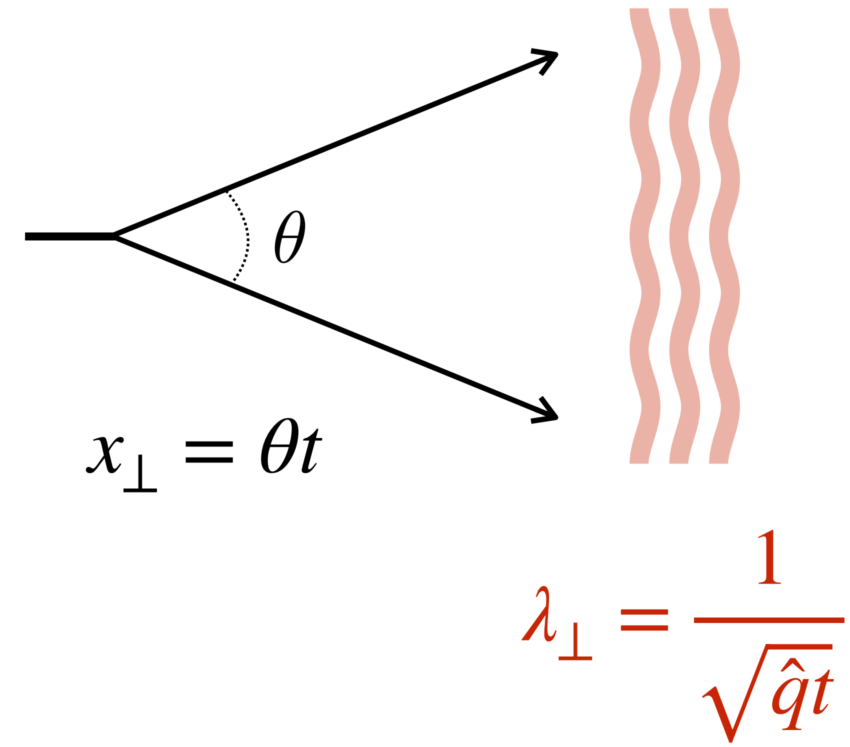
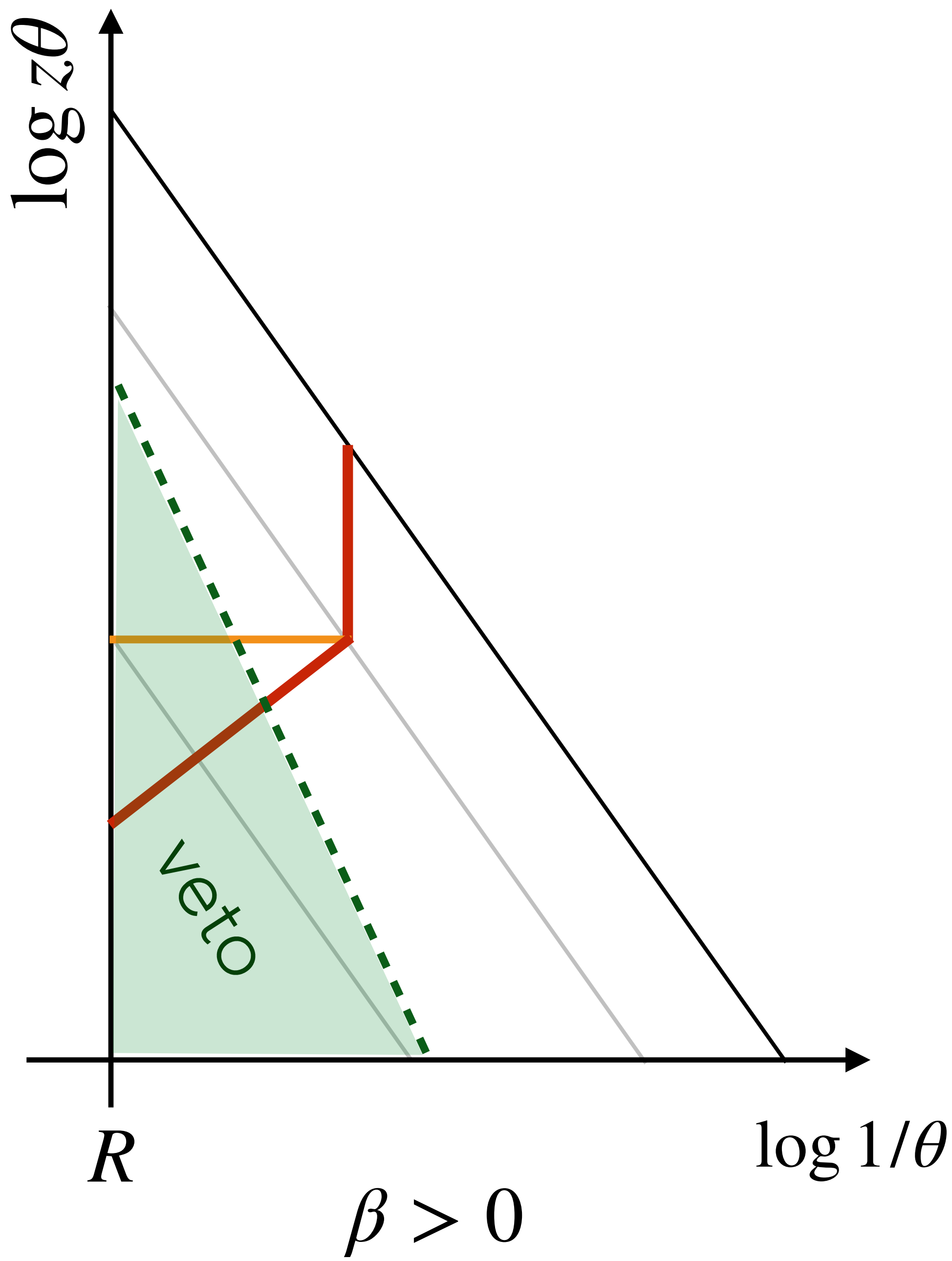


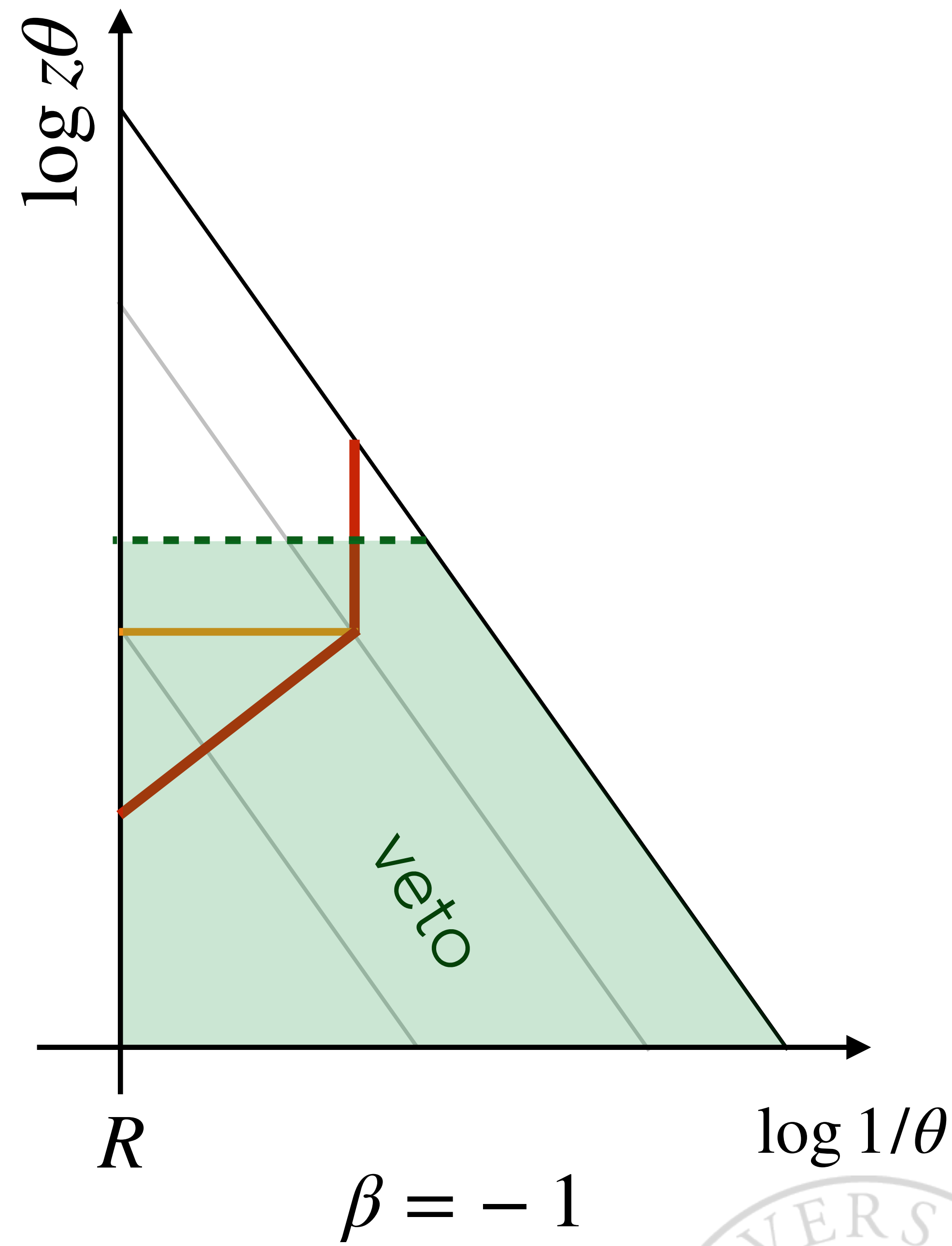


Red area: *vacuum emissions taking place inside the medium*

- could be modified by the medium (long-distance effects).

INTERPLAY OF CUTS





Can severely constrain phase space for medium effects!

COMMUNITY EFFORT

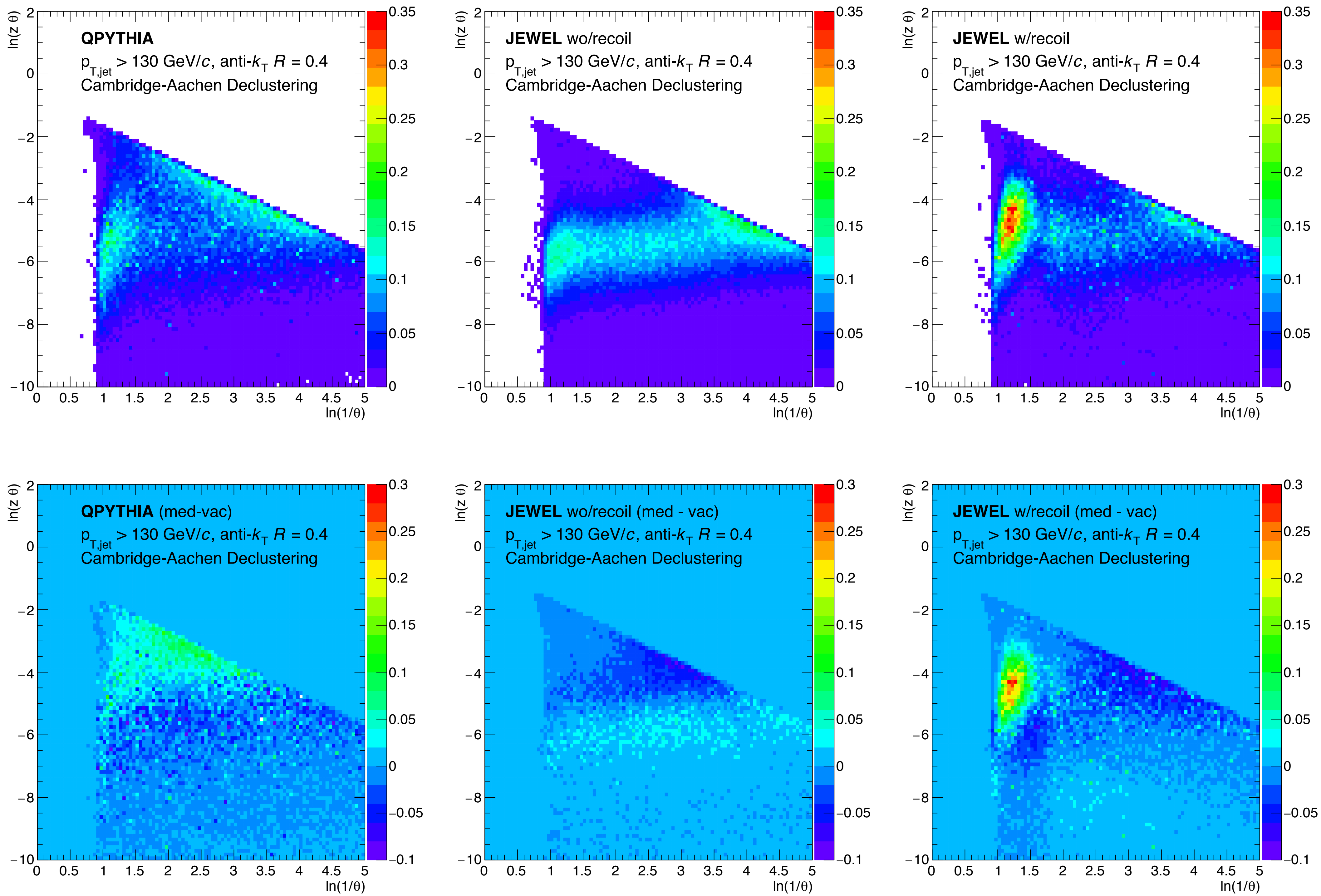
- complex interplay of many effects & demanding understanding of background fluctuations
- need community drive theory-experiment effort to establish common practices, observables…
- started out as CERN TH institute 2017, now JetTools Workshop (Bergen 2019,…)
- …and currently also EMMI RRTF! ☺

Some examples follow…

COMPARING LUND PLANES

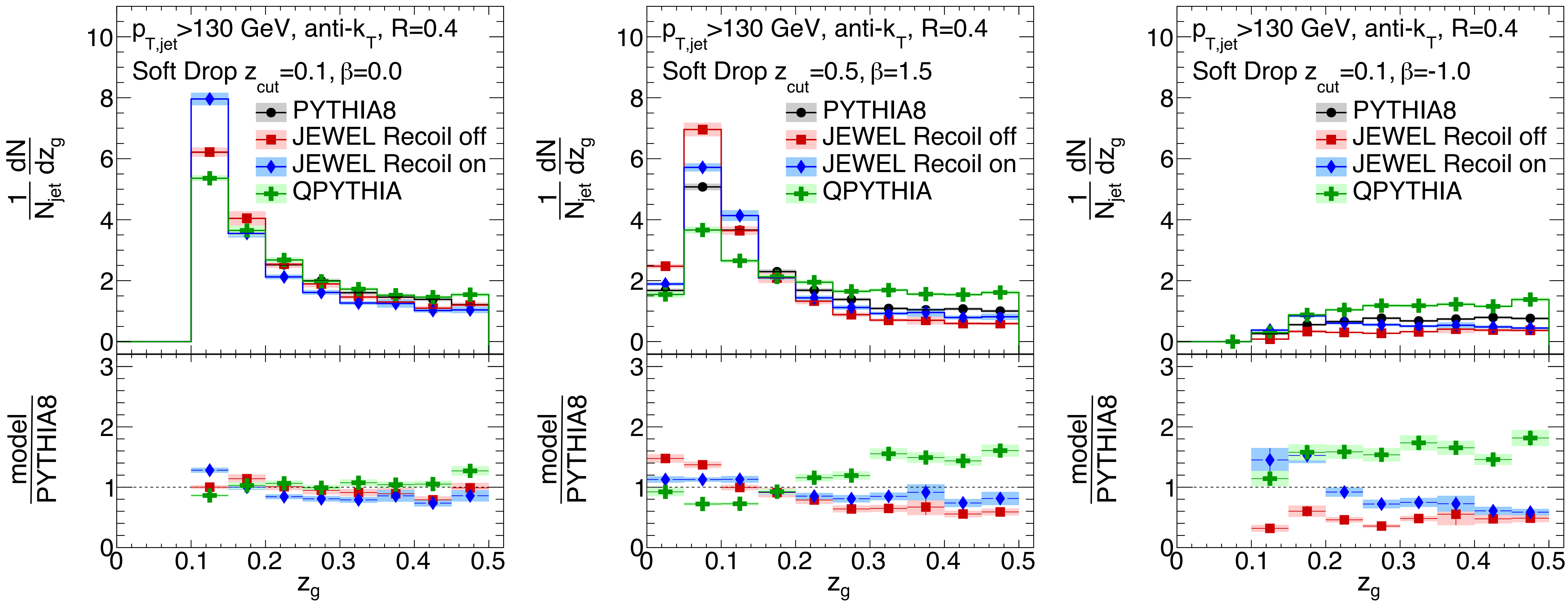
Andrews et al. 1808.03689

QPYTHIA | JEWEL (wo/ recoil) | JEWEL (w/ recoil)



GROOMED MOMENTUM FRACTION

Andrews et al. 1808.03689



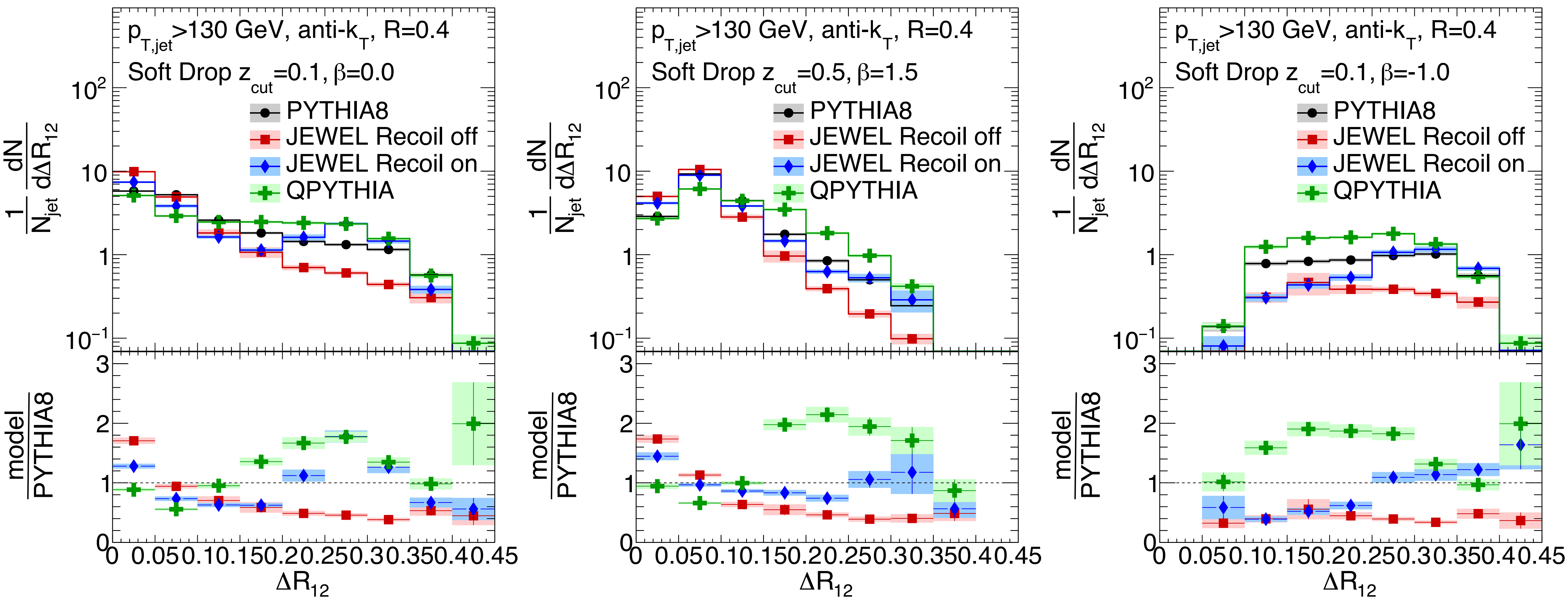
Analyzed three different SD settings.

Observable (z_g) is quite resilient to medium effects for different settings.

Potentially a probe of modified splitting function.

GROOMED JET RADIUS

Andrews et al. 1808.03689

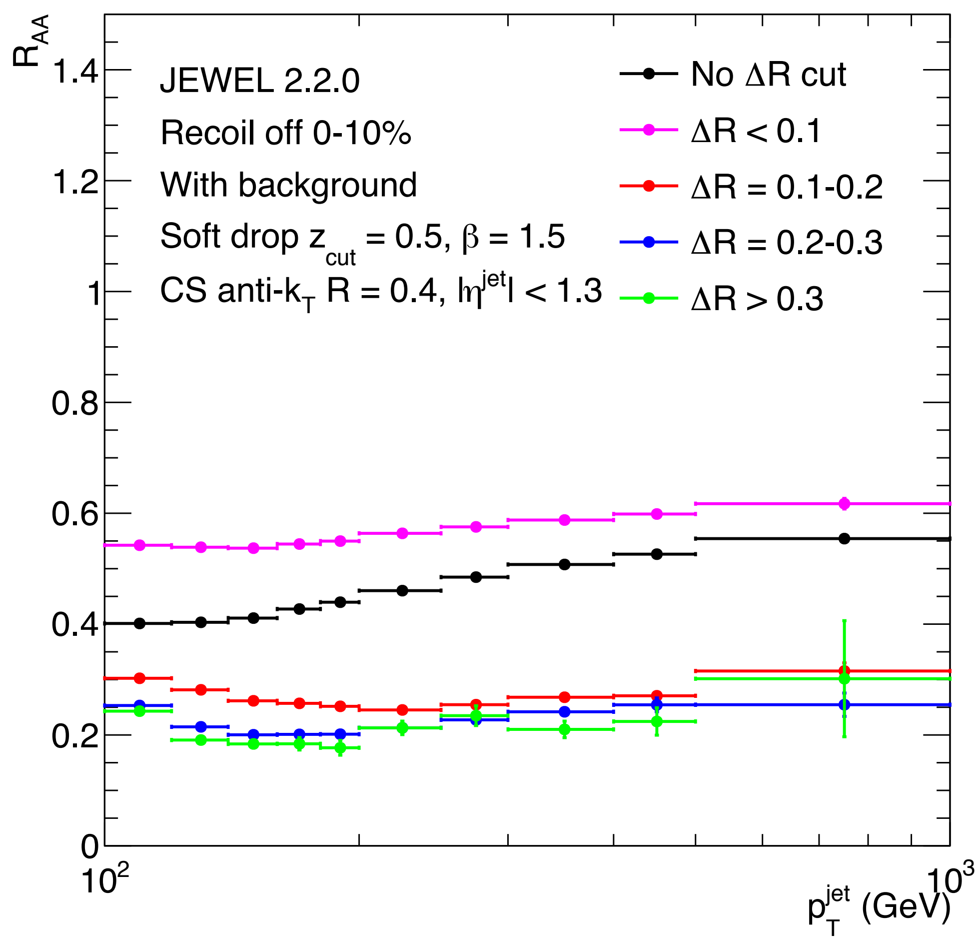


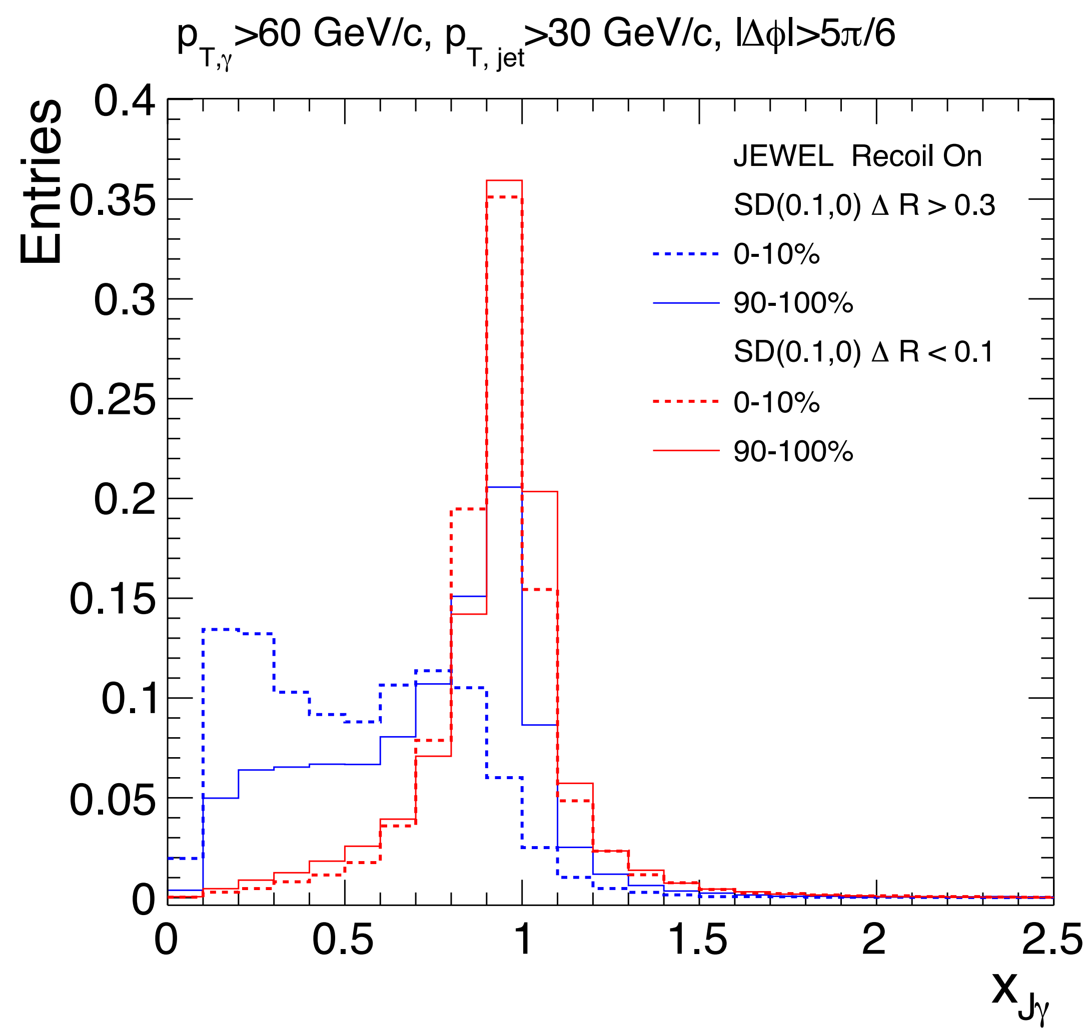
QPYTHIA broadens jets with respect to vacuum - consequence of increased splitting probability early in the shower.

JEWEL jets more collimated.

FURTHER USE OF GROOMING

Andrews et al. 1808.03689





SoftDrop "tags" populations of small- and large-angle jet configurations.

Sheds light on how these configurations are modified in the medium.

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!

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Thank you for your attention!