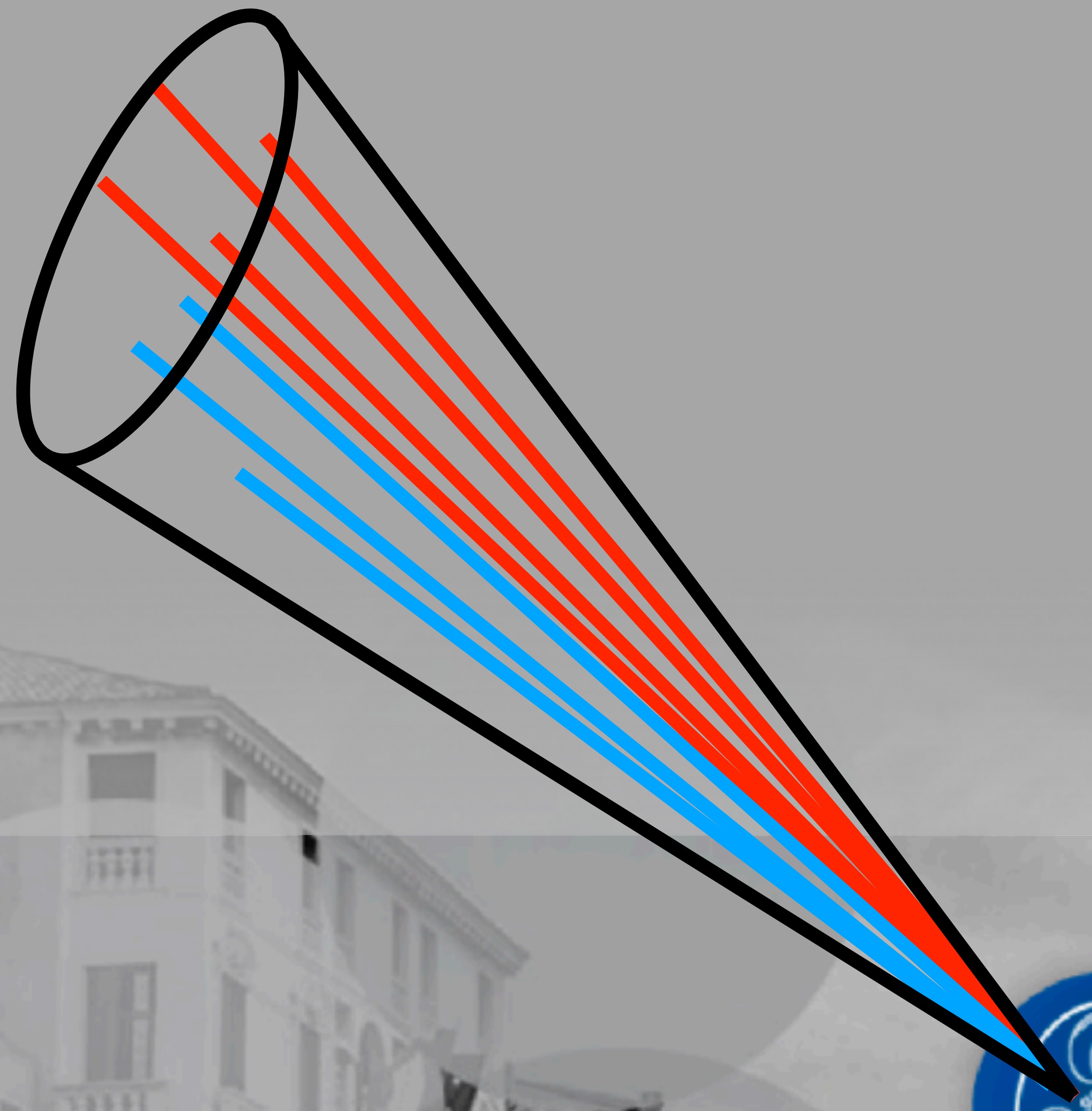
Modification of jet structure in nuclear collisions: theory overview (& pp perspective)

*Gavin P. Salam, CERN**

**on leave from CNRS and University of Oxford*



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

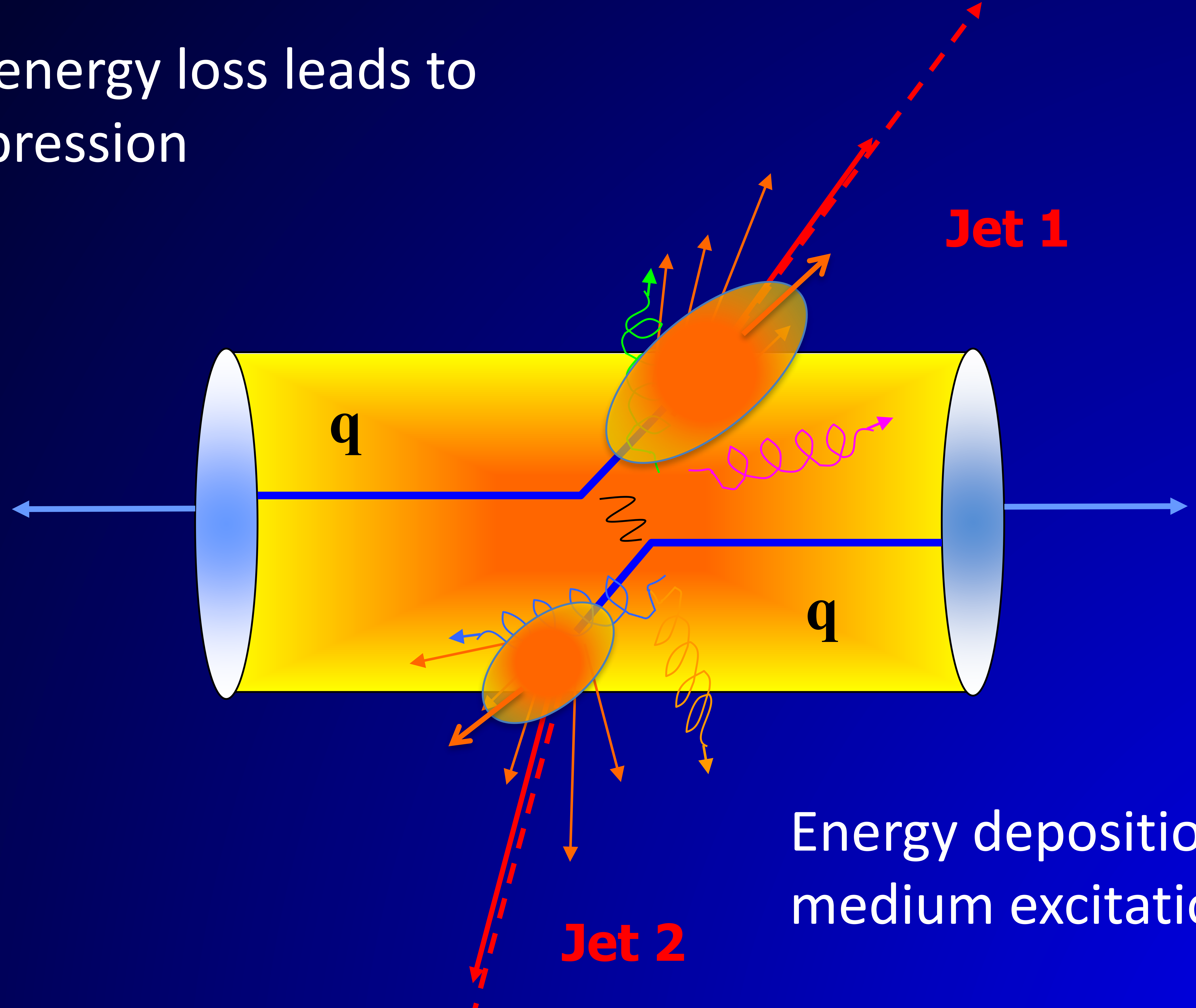
Energy Loss of Energetic Partons in Quark-Gluon Plasma: Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

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

Abstract

High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma. [...]

Parton energy loss leads to jet suppression



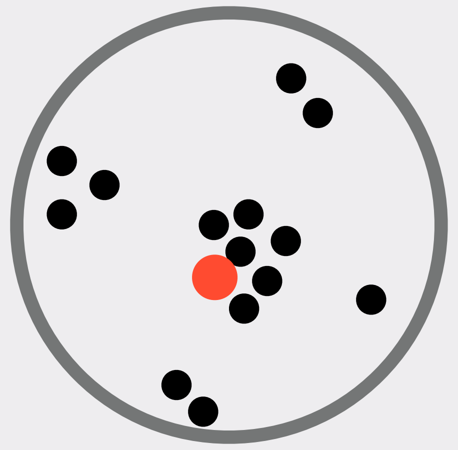
Energy deposition leads to medium excitation

from X-N. Wang

Jet structure observables

fragmentation function

$$D(z) = \left\langle \sum_{i \in \text{jet}} \delta(z - p_{ti}/p_{t,\text{jet}}) \right\rangle_{\text{jets}}$$



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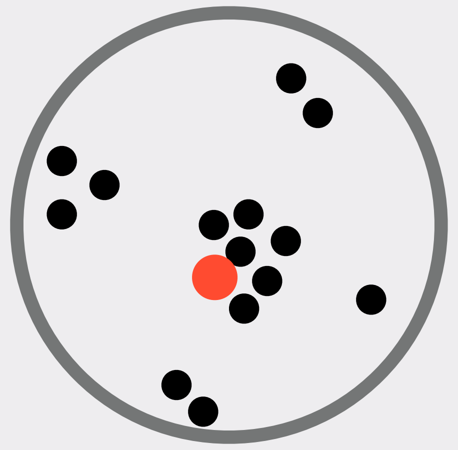
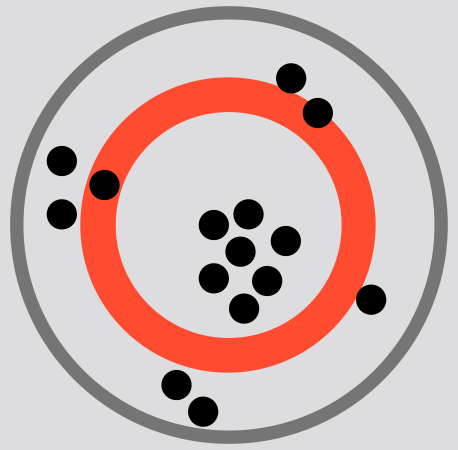


differential jet shape

$$\rho(r) = \frac{1}{p_\perp^{\text{jet}}} \sum_{\substack{k \text{ with} \\ \Delta R_{kJ} \in [r, r+\delta r]}} p_\perp^{(k)} \,,$$



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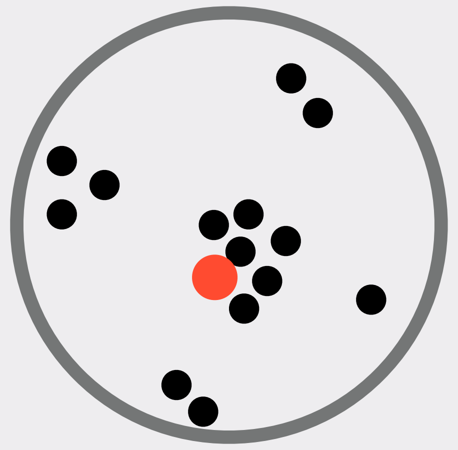

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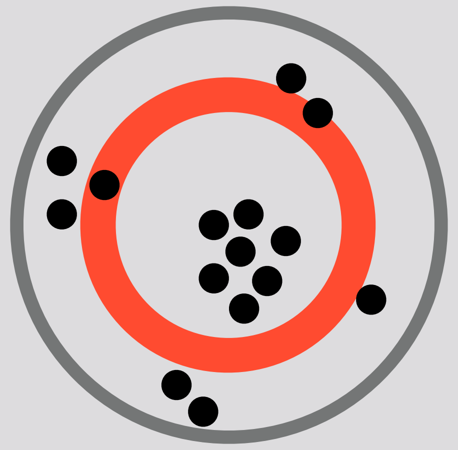
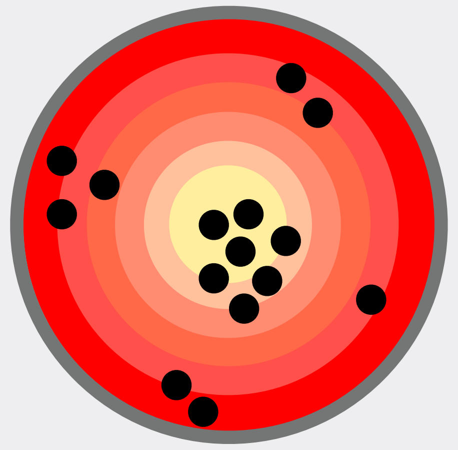


girth ≡ broadening

$$g = \frac{1}{p_\perp^{\text{jet}}} \sum_{k\in J} p_\perp^{(k)} \Delta R_{kJ} \, ,$$



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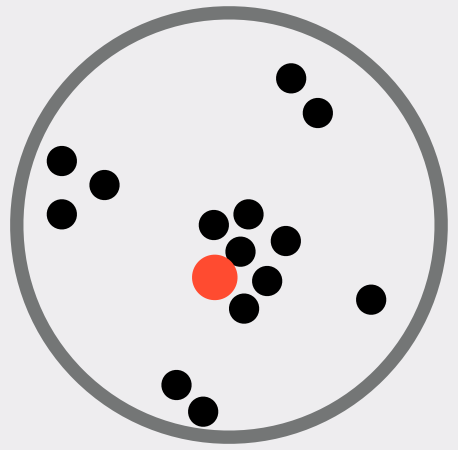
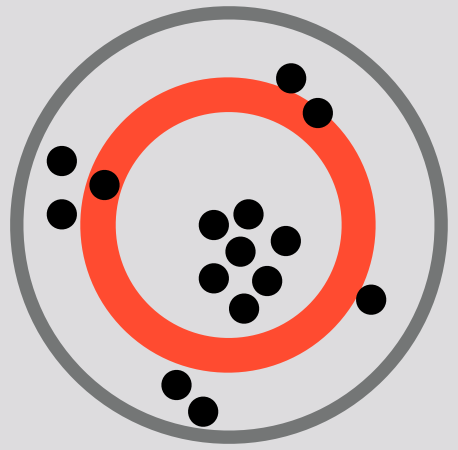
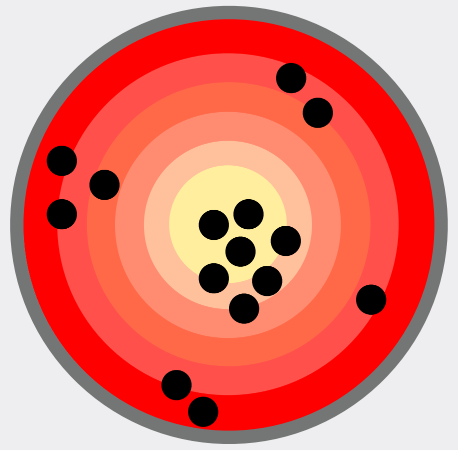
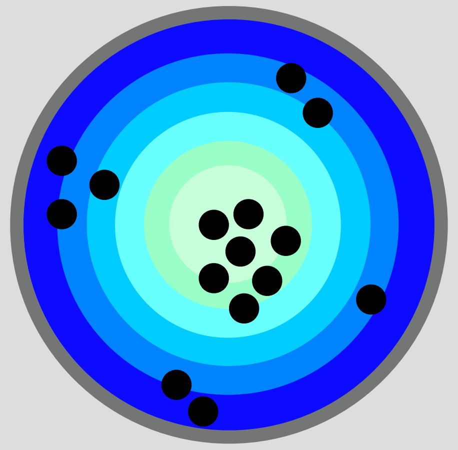
fragmentation function	$D(z) = \left\langle \sum_{i \in \text{jet}} \delta(z - p_{ti}/p_{t,\text{jet}}) \right\rangle_{\text{jets}}$	
differential jet shape	$\rho(r) = \frac{1}{p_\perp^{\text{jet}}} \sum_{\substack{k \text{ with} \\ \Delta R_{kJ} \in [r, r+\delta r]}} p_\perp^{(k)} \, ,$	
girth ≡ broadening	$g = \frac{1}{p_\perp^{\text{jet}}} \sum_{k \in J} p_\perp^{(k)} \Delta R_{kJ} \, ,$	
jet mass, groomed & ungroomed	$m^2 = \left(\sum_{i \in (\text{sub})\text{jet}} p_i^\mu \right)^2$	

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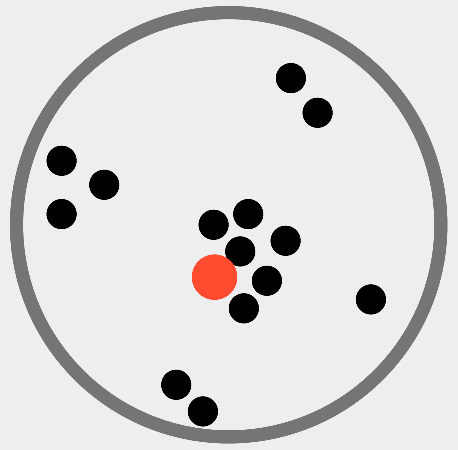

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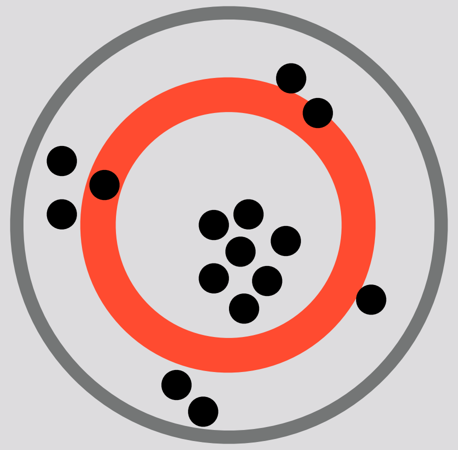

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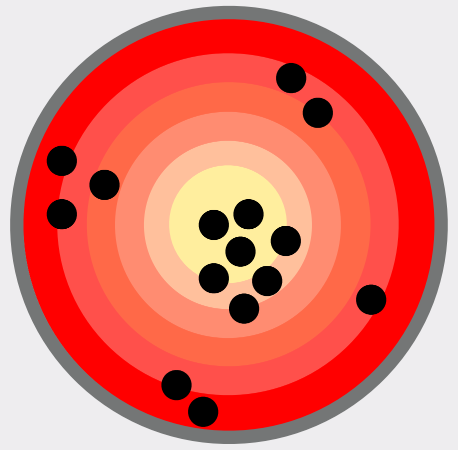

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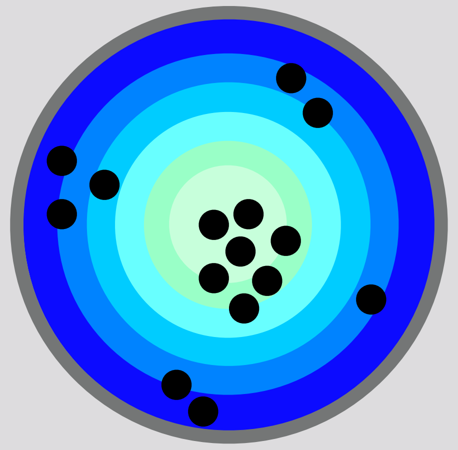
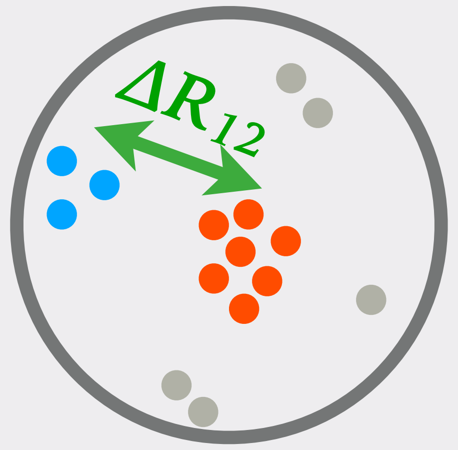


z_g, ΔR_{12}

$$z_g = \frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}} > z_{\text{cut}} \left(\frac{\Delta R_{1,2}}{R_J} \right)^\beta$$



two theoretical approaches

(semi)-ANALYTIC

- Gives insight into what physics is relevant where (energy loss, decoherence, etc.)
- Can inspire what to measure
- Cannot capture all dimensions of full experimental analysis

Monte Carlo Event Generator

- Gives ultimate realism (accuracy depends on what's inside)
- Can in principle include full medium embedding & subtraction (but that's often work in progress)
- Risks looking like a black box

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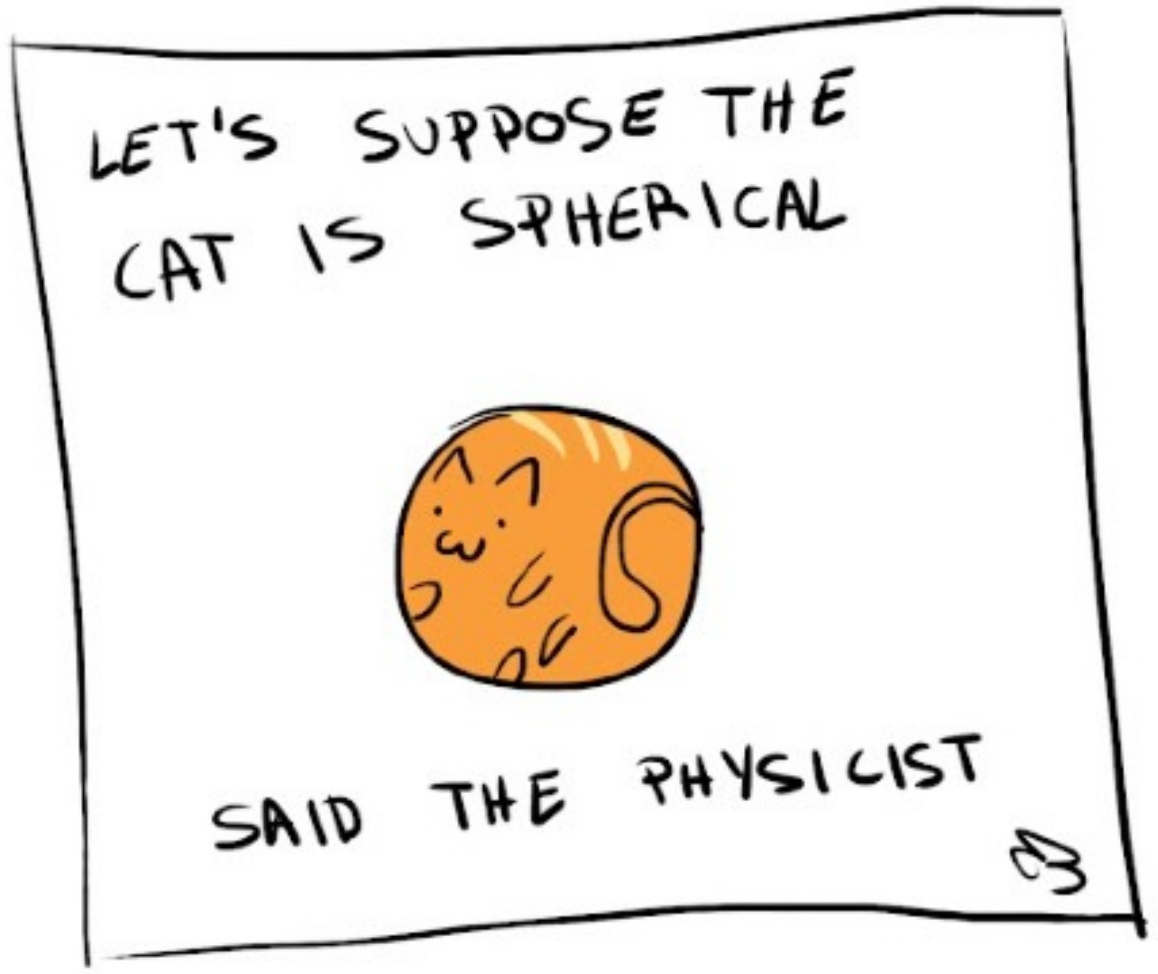
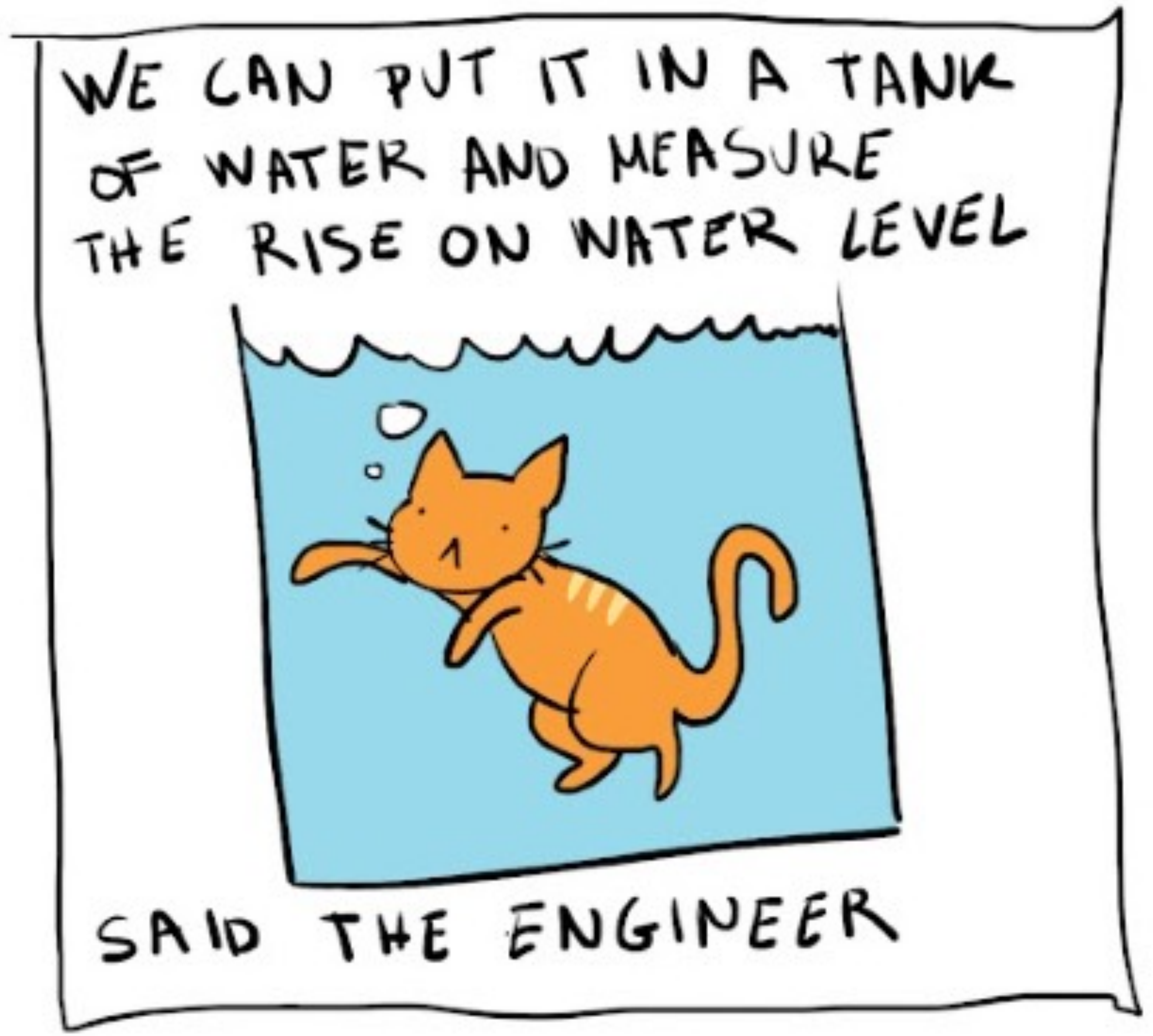


HOW TO CALCULATE THE VOLUME OF A CAT ?

[this morning's newsletter]



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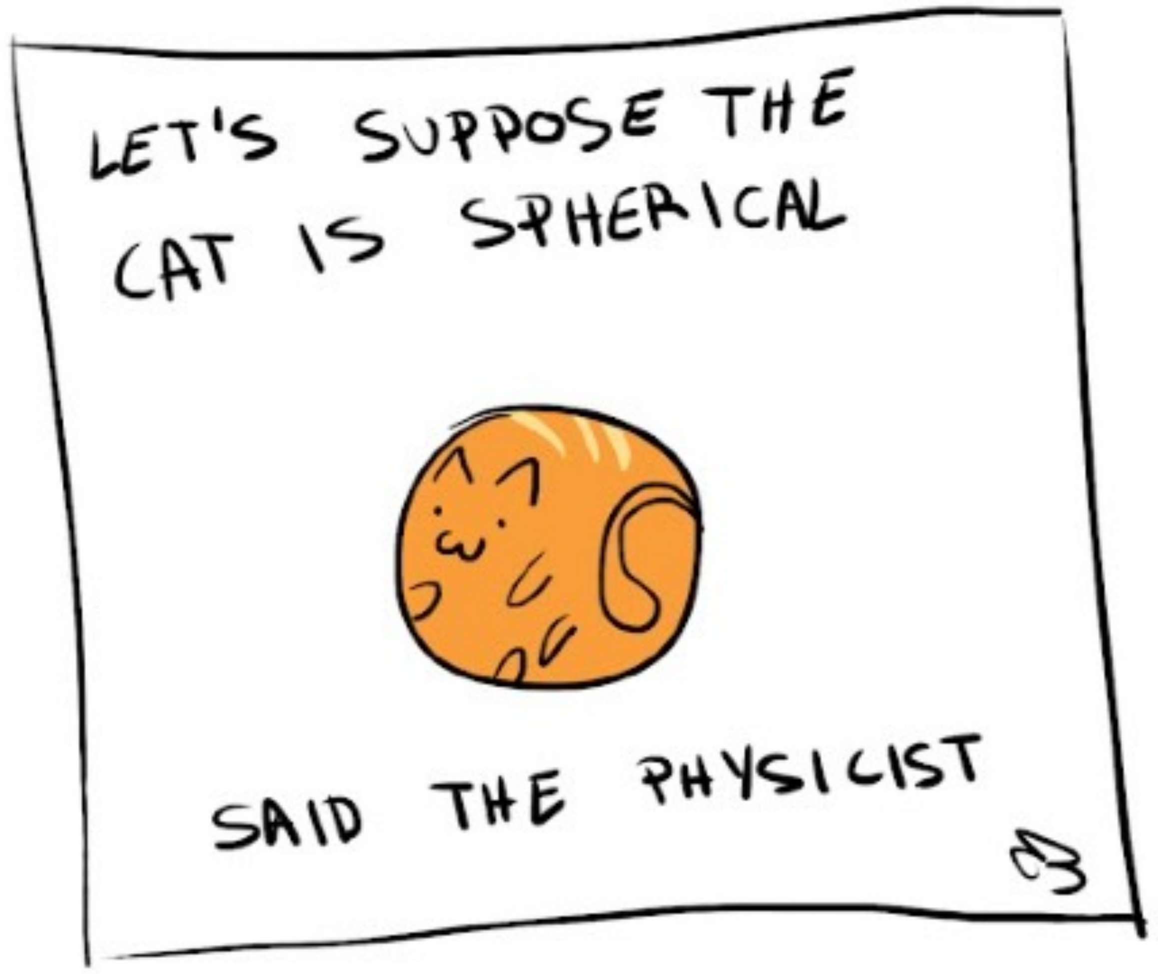

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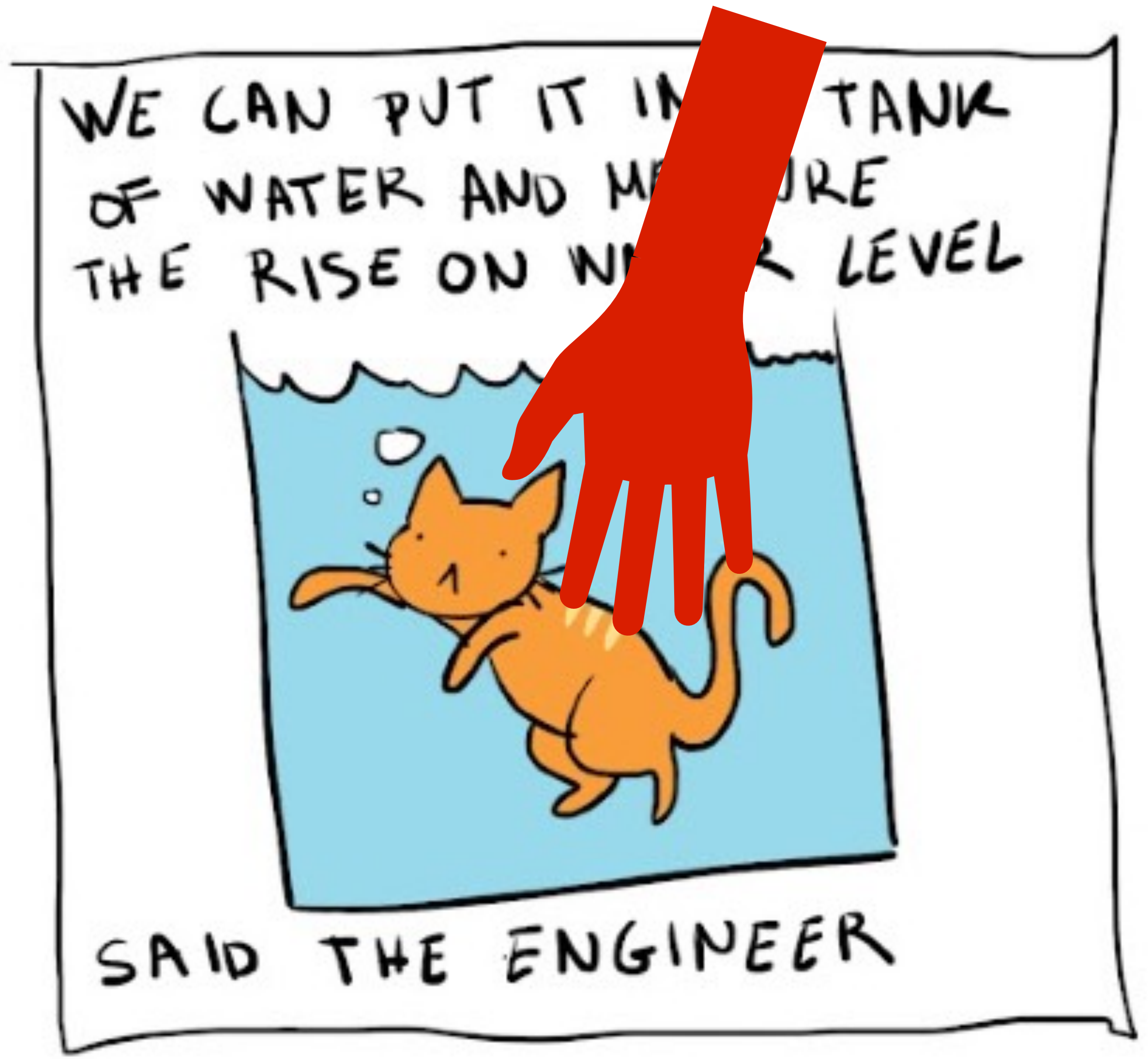


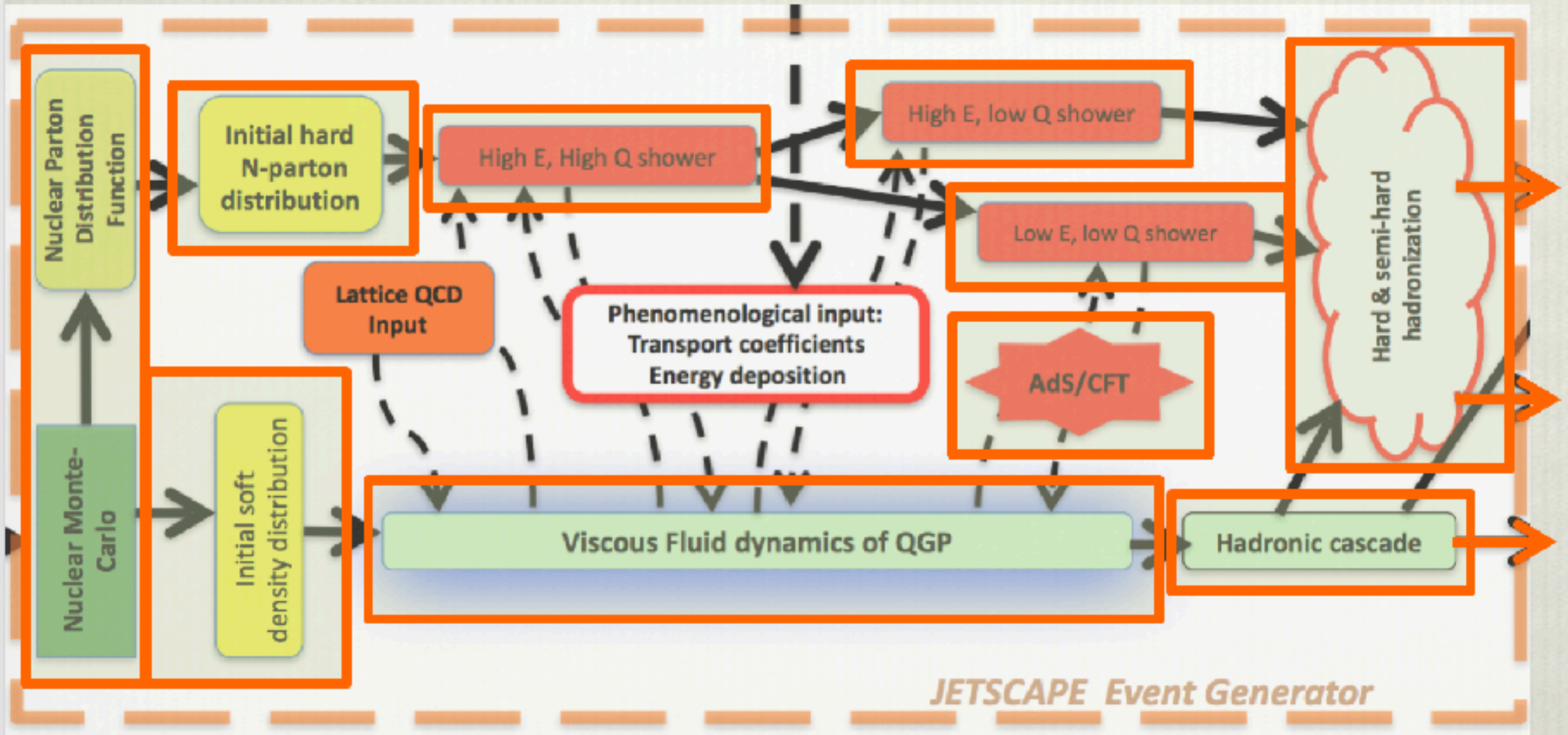
MONTE CARLOS EVENT GENERATORS

an MC selection of MC results

Jetscape: current status: pp baseline (// Kauder)

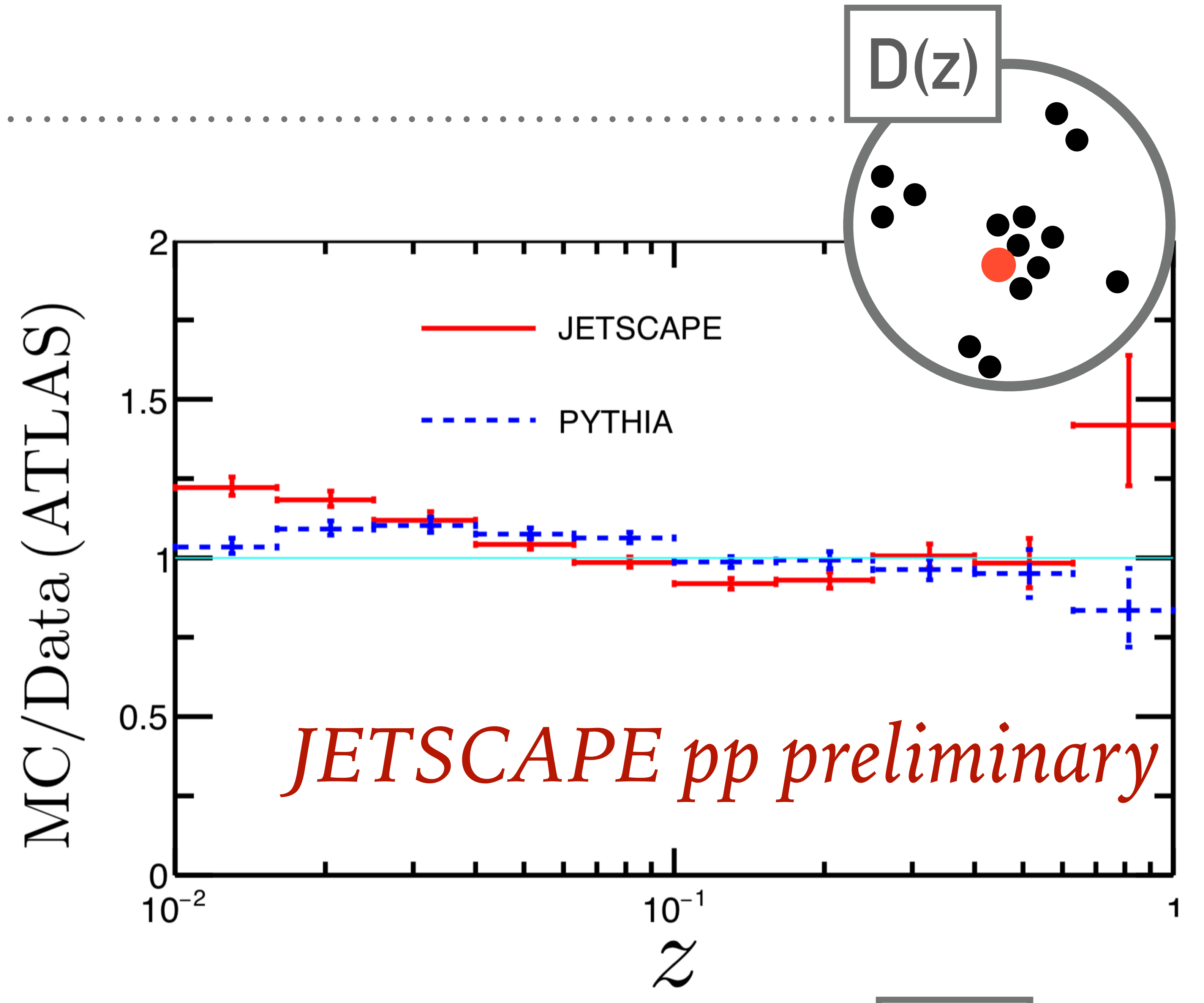
Program

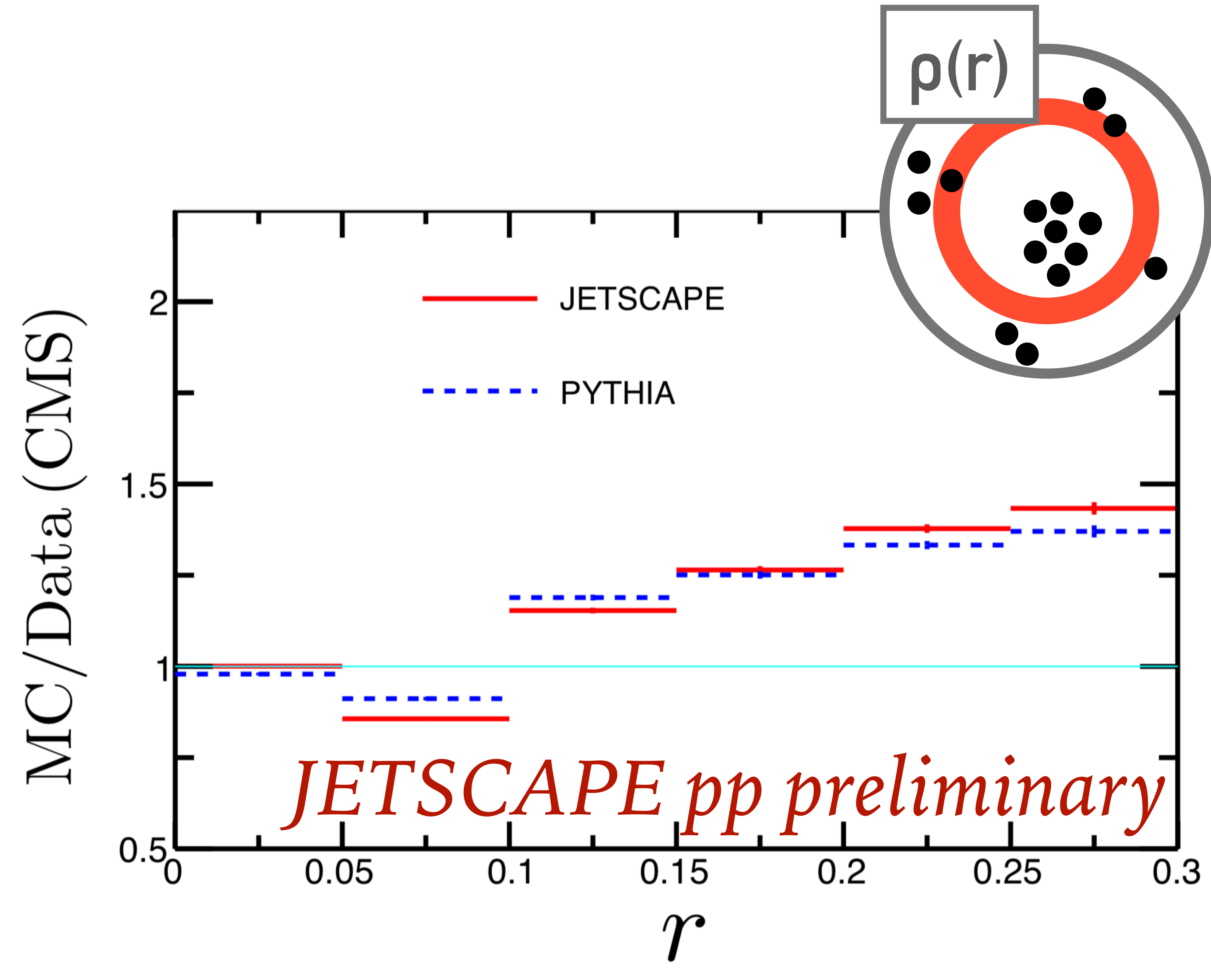
- What's included in the event generator (as optional download)



- ✓ Trento (2+1)
- ✓ Free Streaming
- ✓ MUSIC (2+1, 3+1), external reader, brick, Gubser,
- ✓ Pythia8, parton gun
- ✓ MATTER, Martini, AdS/CFT, LBT
- ✓ Cooper Frye
- ✓ Pythia8 string fragmentation
- ✓ Custom and HepMC output

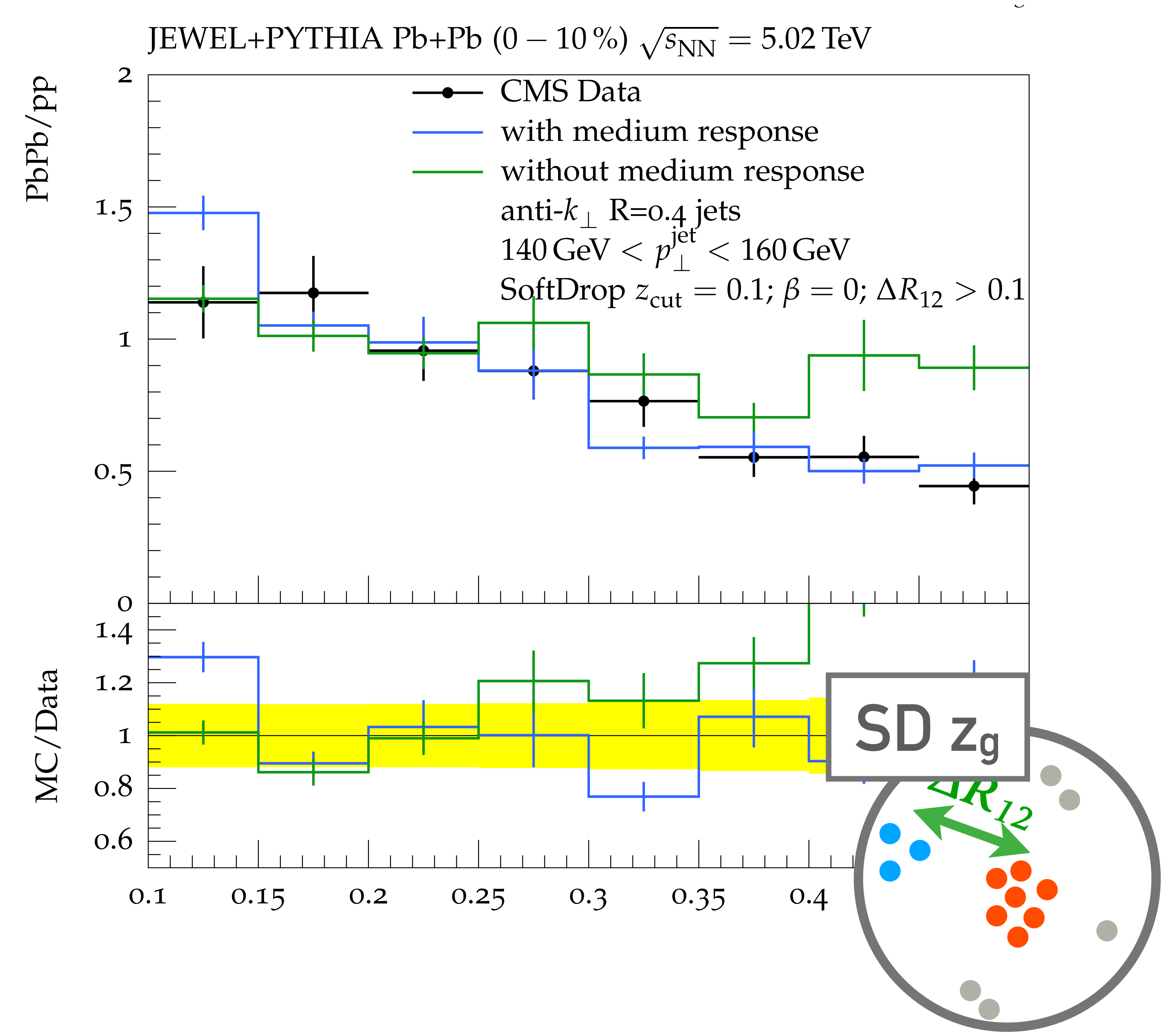
5/16/18 Kauder - JETSCAPE 1.0 - QM2018 6

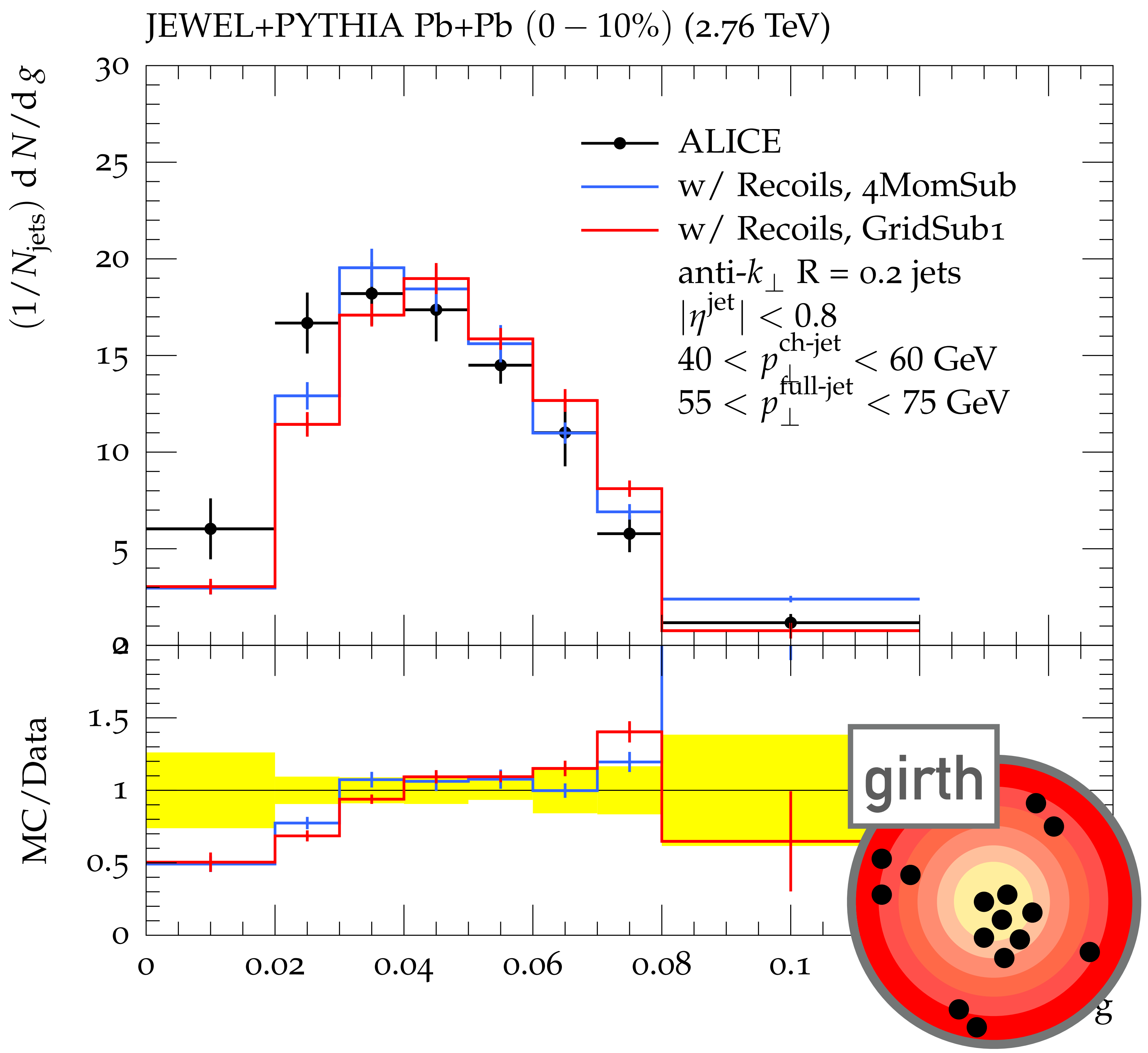


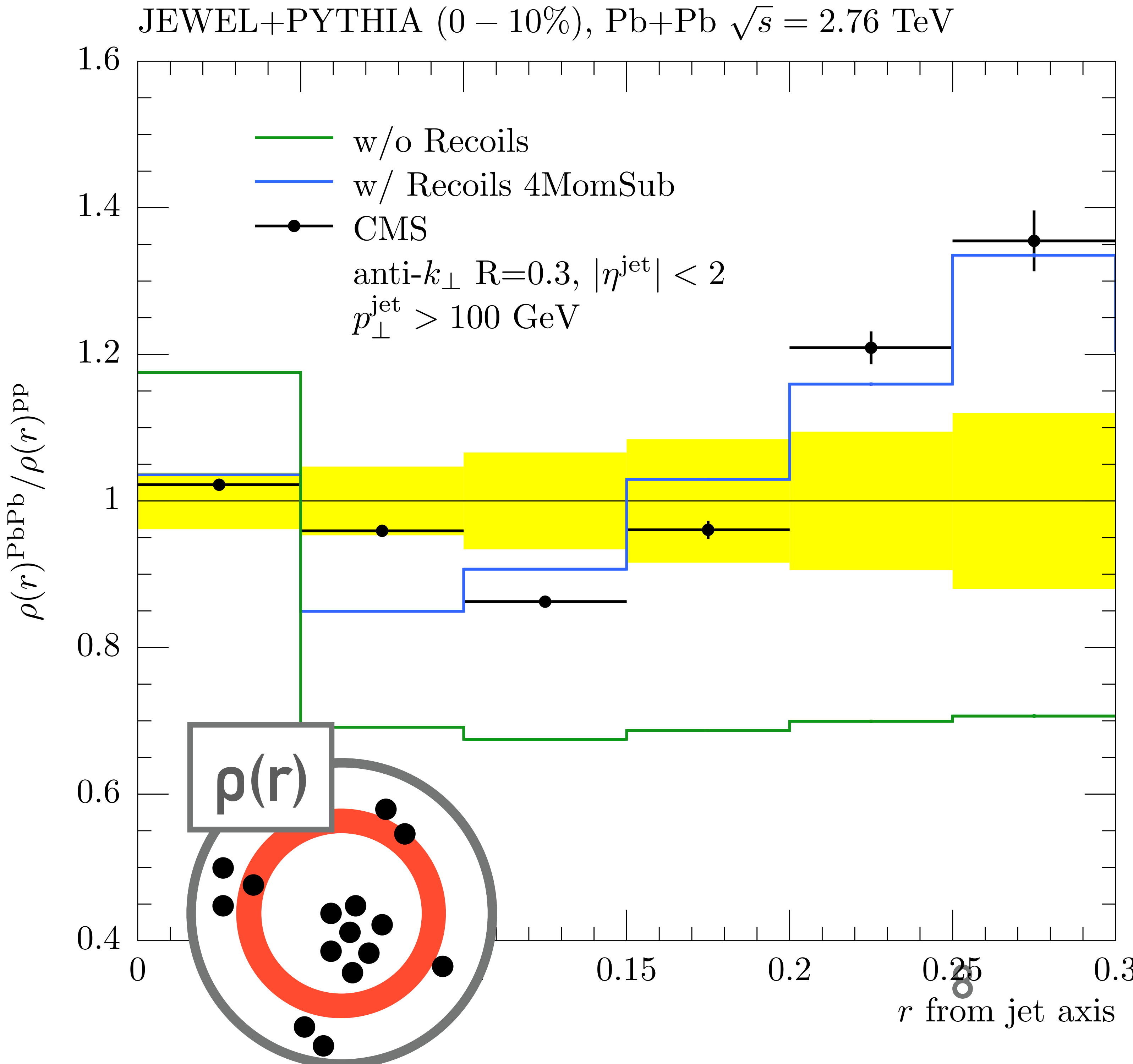


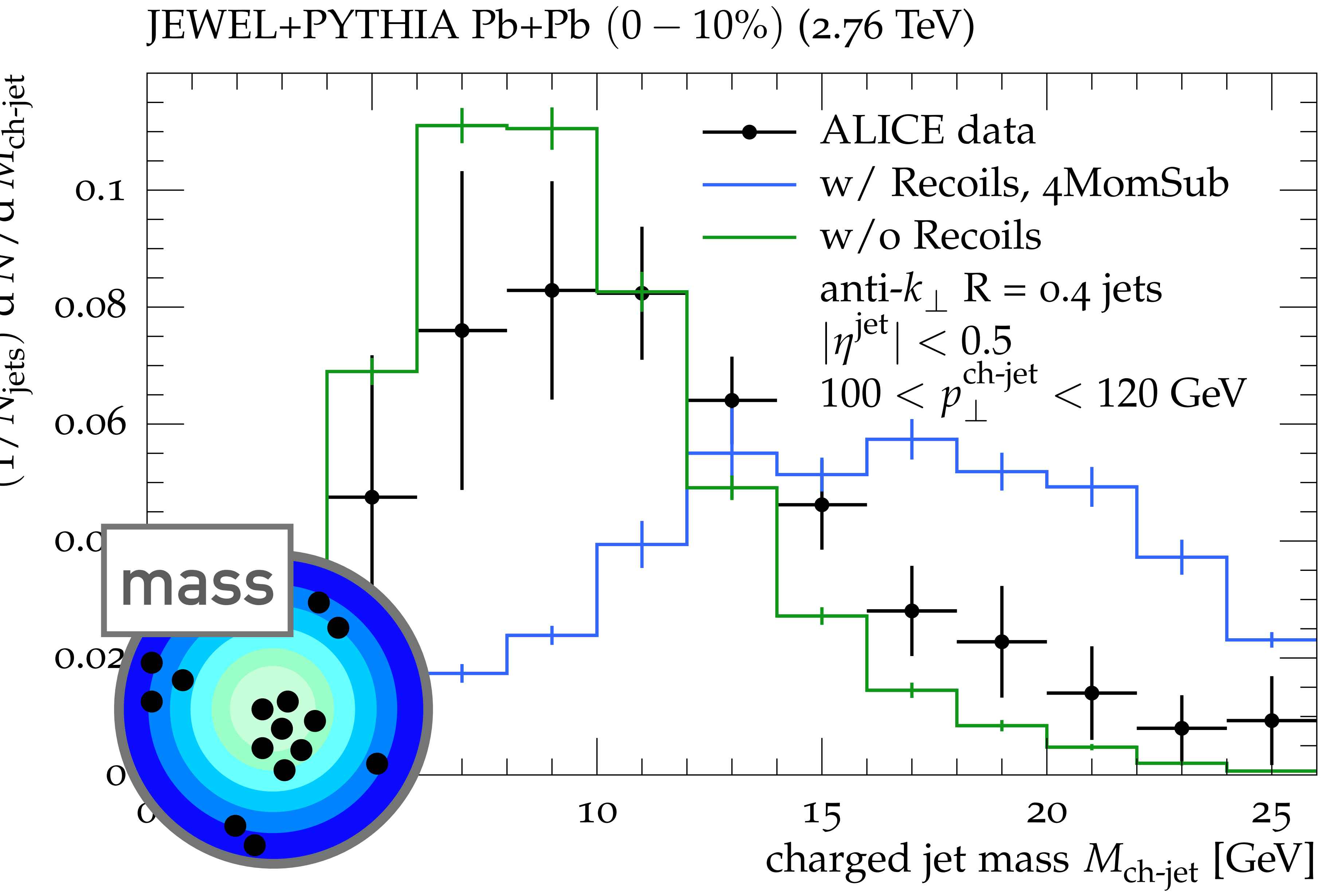
JEWEL v. data

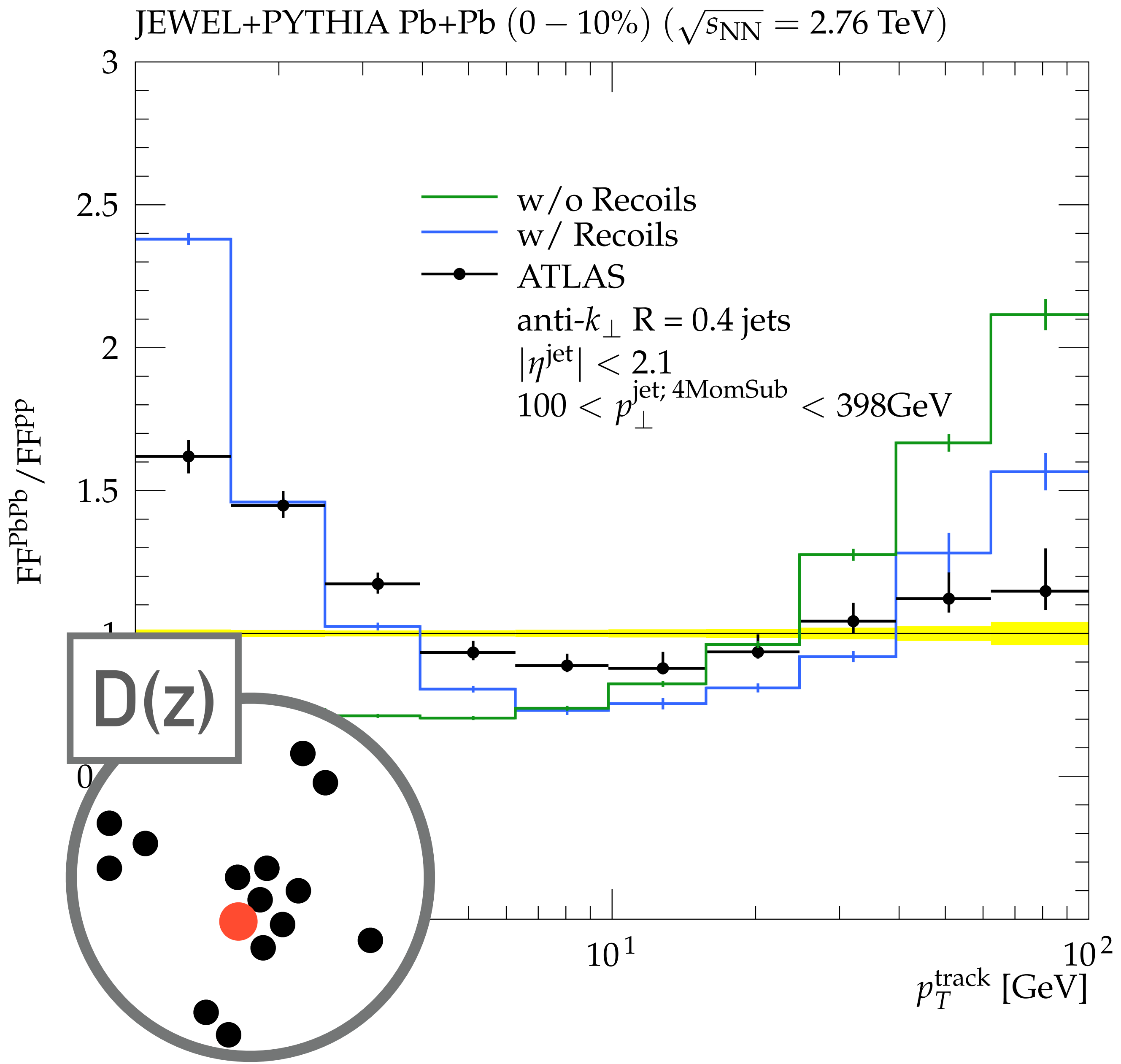
- arXiv:1707.01539, by Milhano, Wiedemann and Zapp with medium response









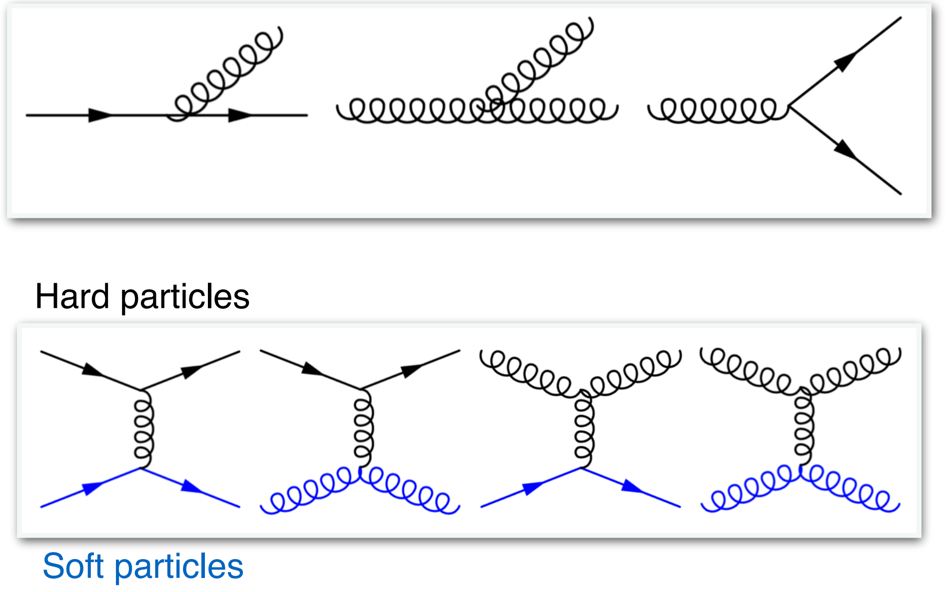


Jet evolution in MARTINI

MARTINI[1]

- Event generator for jet simulation in heavy ion collisions
- Compatible with event-by-event 3D hydrodynamic medium

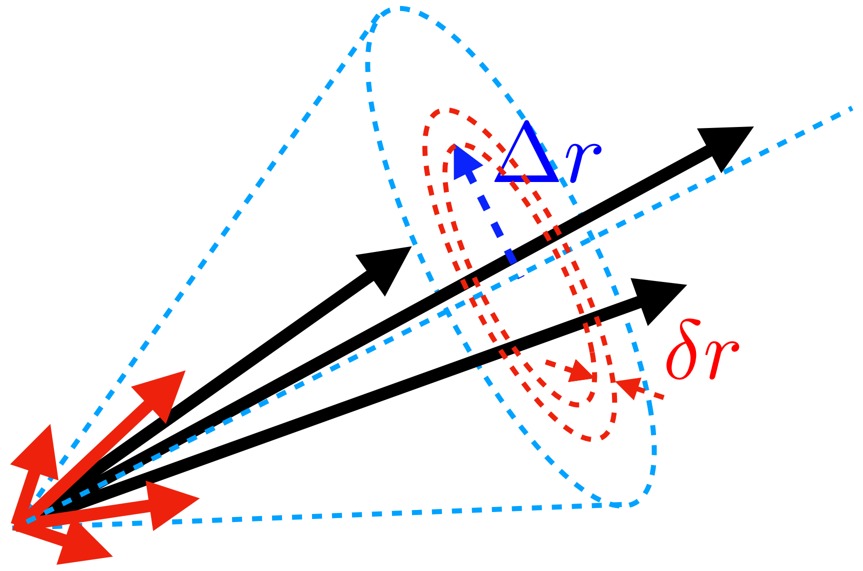
- **Radiation** : AMY formalism[2] (collinear)
  - Formation time of radiation[3], $t_f \sim k/k_\perp^2$
  - Running coupling in splitting vertex[4], $\alpha_s(Q)$
- **Elastic Scattering**[5]
  - 2-2 scattering causing space-like momentum transfer, q
  - Momentum broadening
- **Conversion**[1]
  - quark-gluon, jet-photon, photon conversion



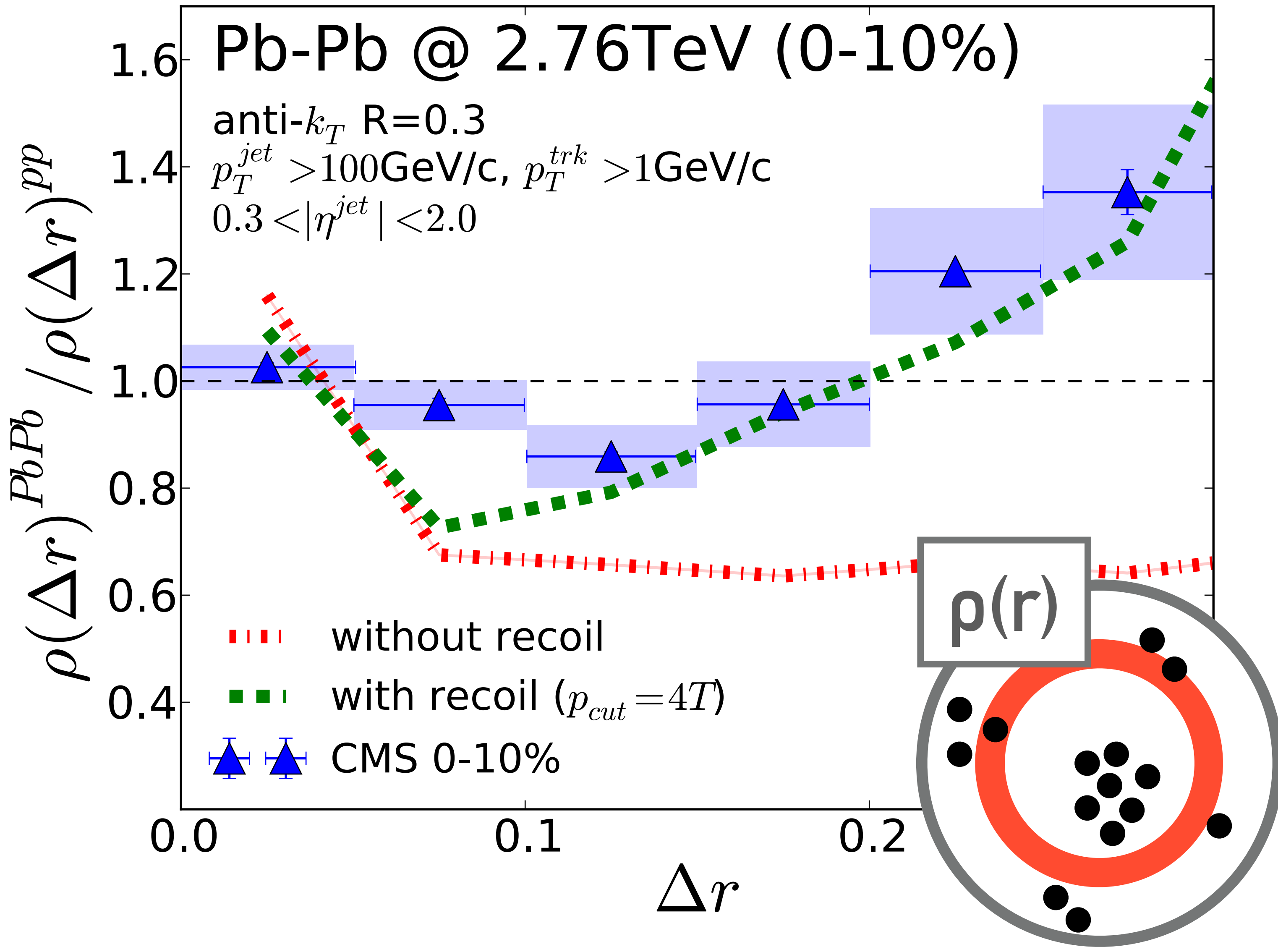
[1] B. Schenke, C. Gale, and S. Jeon, Phys. Rev. **C 80**, 054913 (2009)
[2] P. Arnold, G. D. Moore, and L. G. Yaffe, JHEP 0206 (2002) 030
[3] S. Caron-Huot and C. Gale, Phys. Rev. **C 82**, 064902 (2010)
[4] C. Young, B. Schenke, S. Jeon, and C. Gale, Nucl. Phys. **A 910-911**, 494 (2013)
[5] B. Schenke, C. Gale, and G-Y. Qin, Phys. Rev. **C 79**, 054908 (2009)

Jet shape with recoil

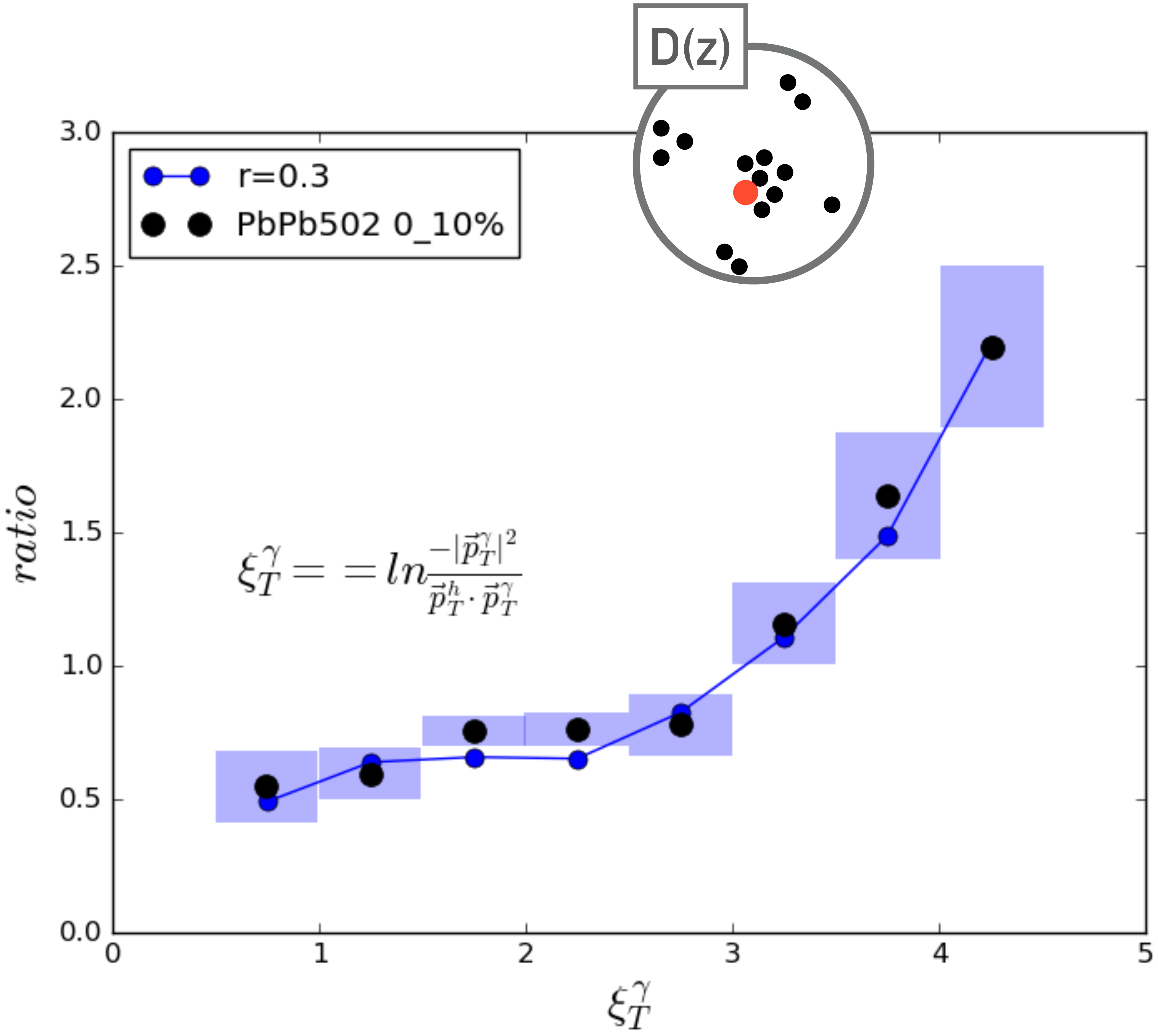
$$\rho(\Delta r) = \frac{1}{\delta r}\frac{1}{N^{jet}}\sum_{jet}\frac{\sum_{track\in[\Delta r-\delta r/2,\Delta r+\delta r/2)} p_T^{track}}{p_T^{jet}}$$

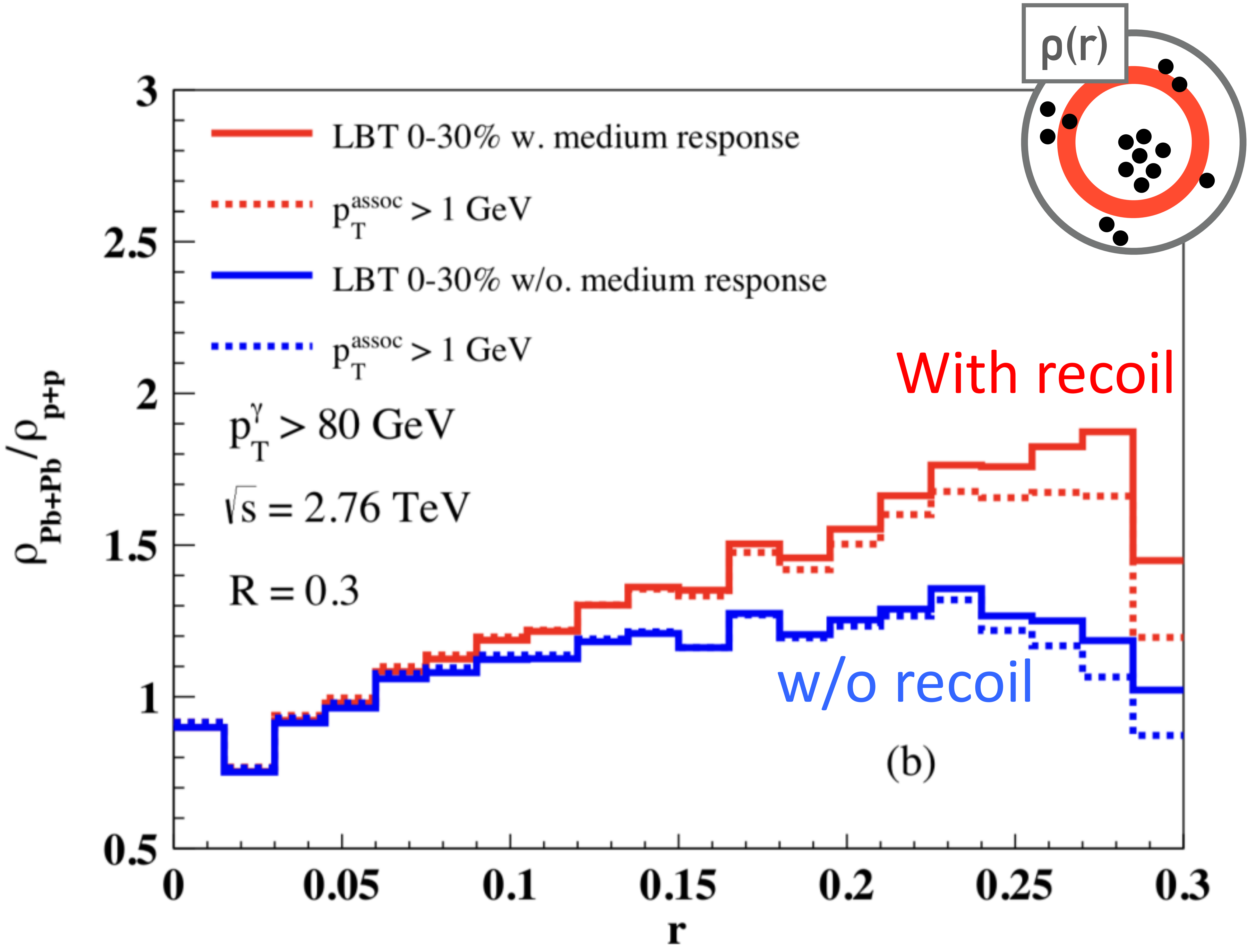


- The ratio shows flat without recoil.
- Recoil yields a significant contribution to the jet shape at large angles.



LINEAR BOLTZMANN TRANSPORT





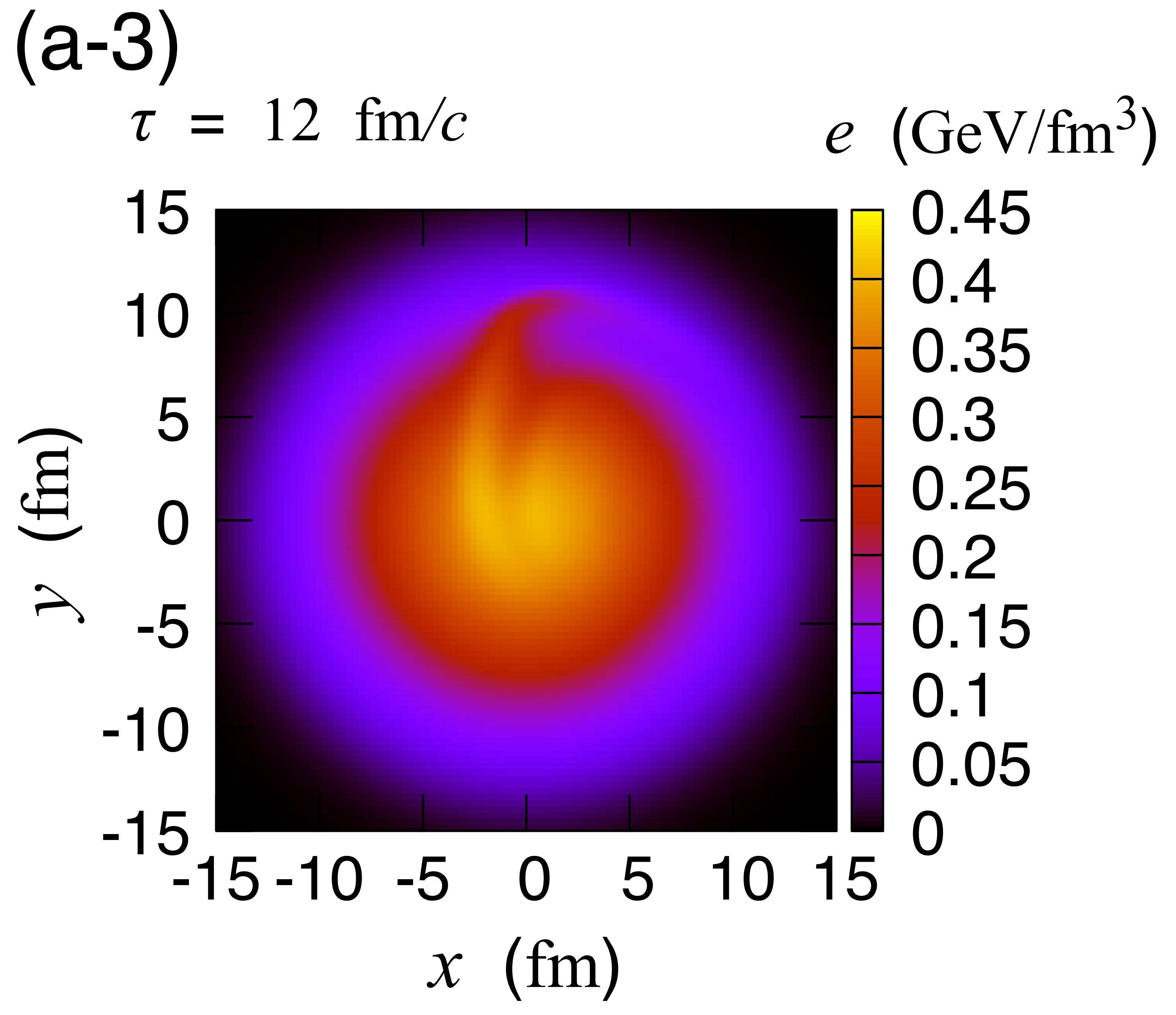
Xin-Nian Wang's // talk

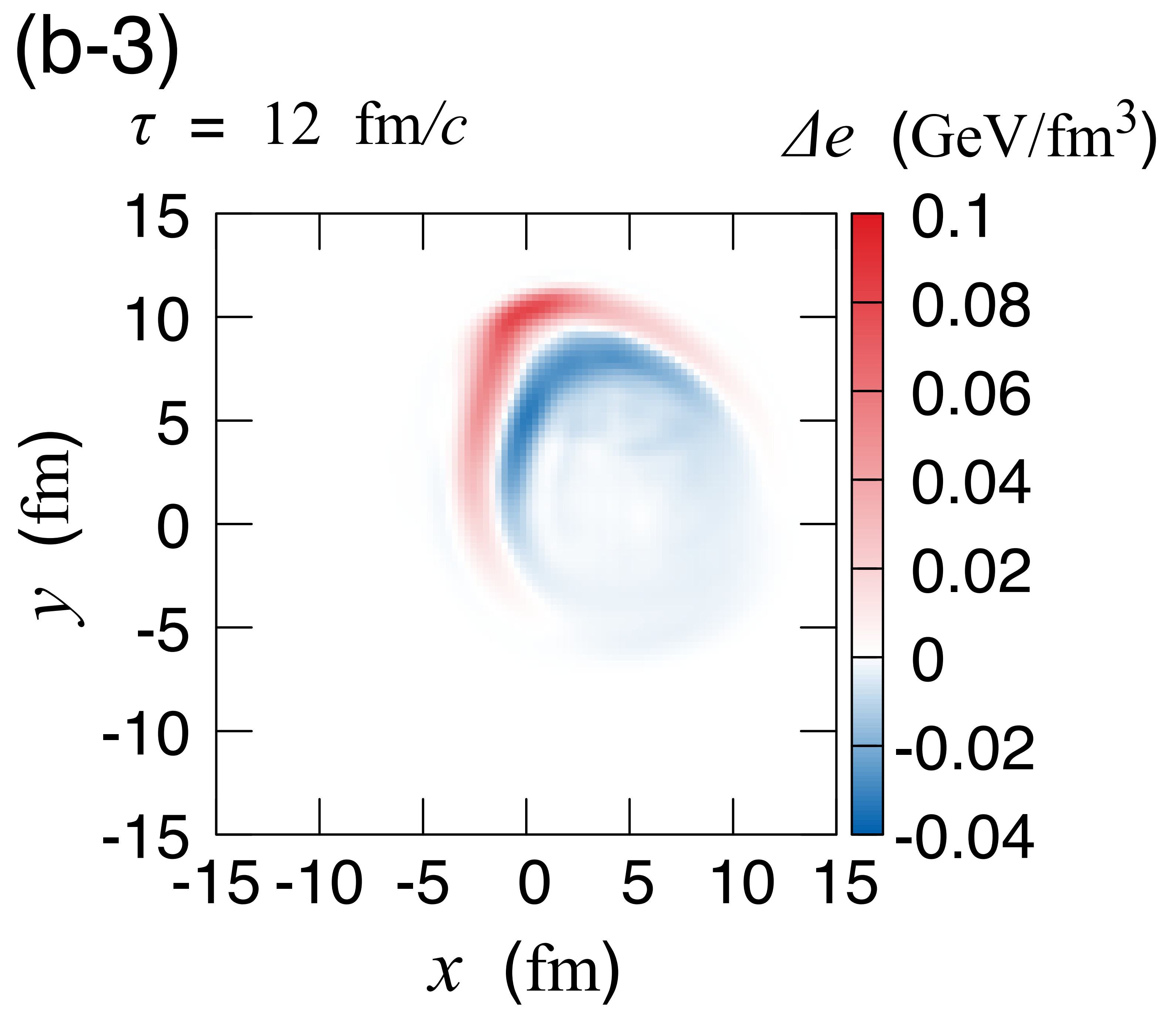
Luo, Cao, He & XNW, arXiv:1803.06785

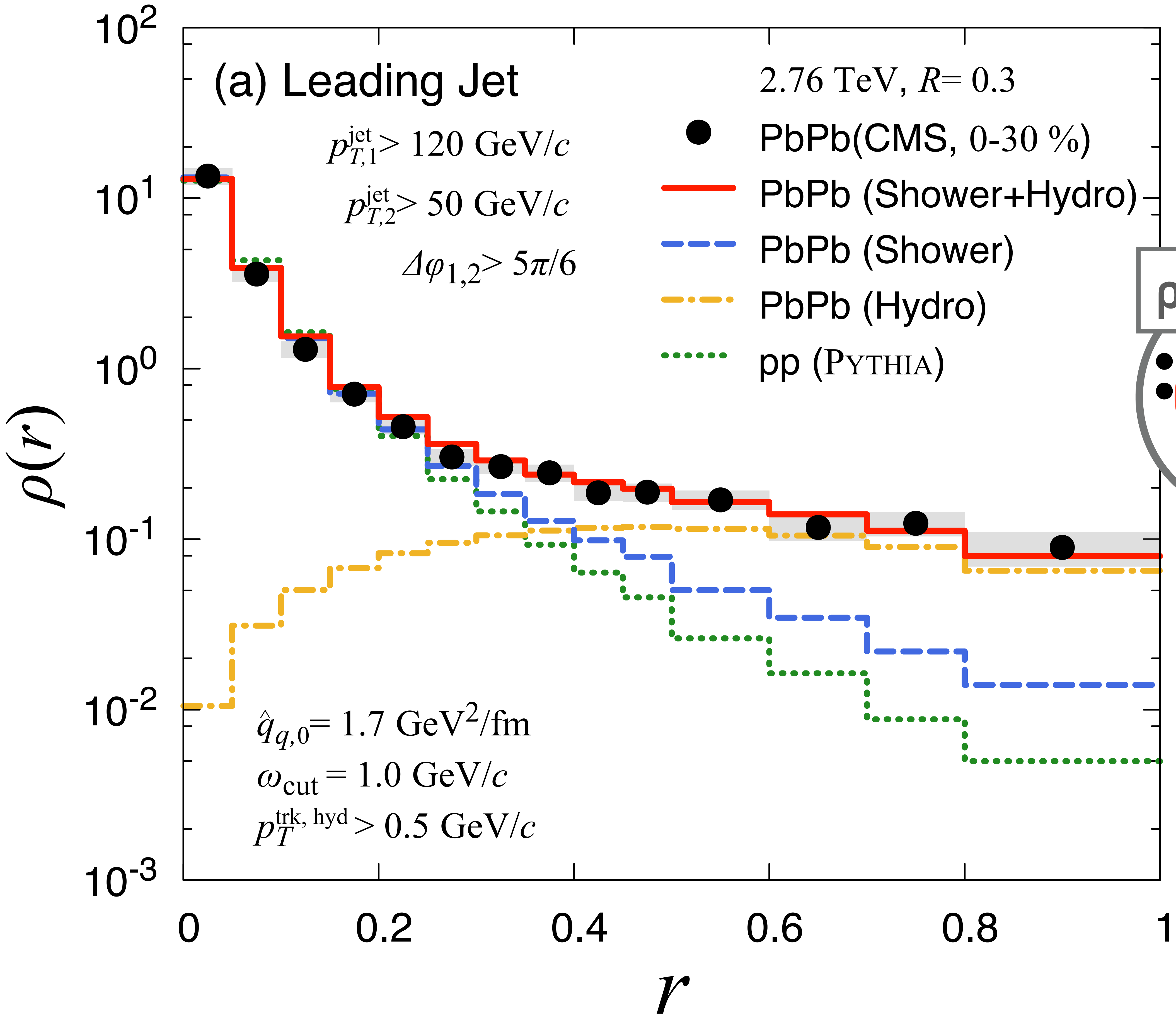
Poster: JET 18 T Luo

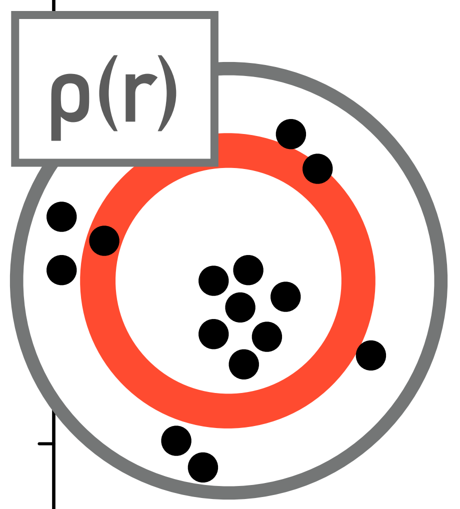
medium mach-cones

- ➤ Tachibana, Chang & Qin, 1701.07951, 12fm/c









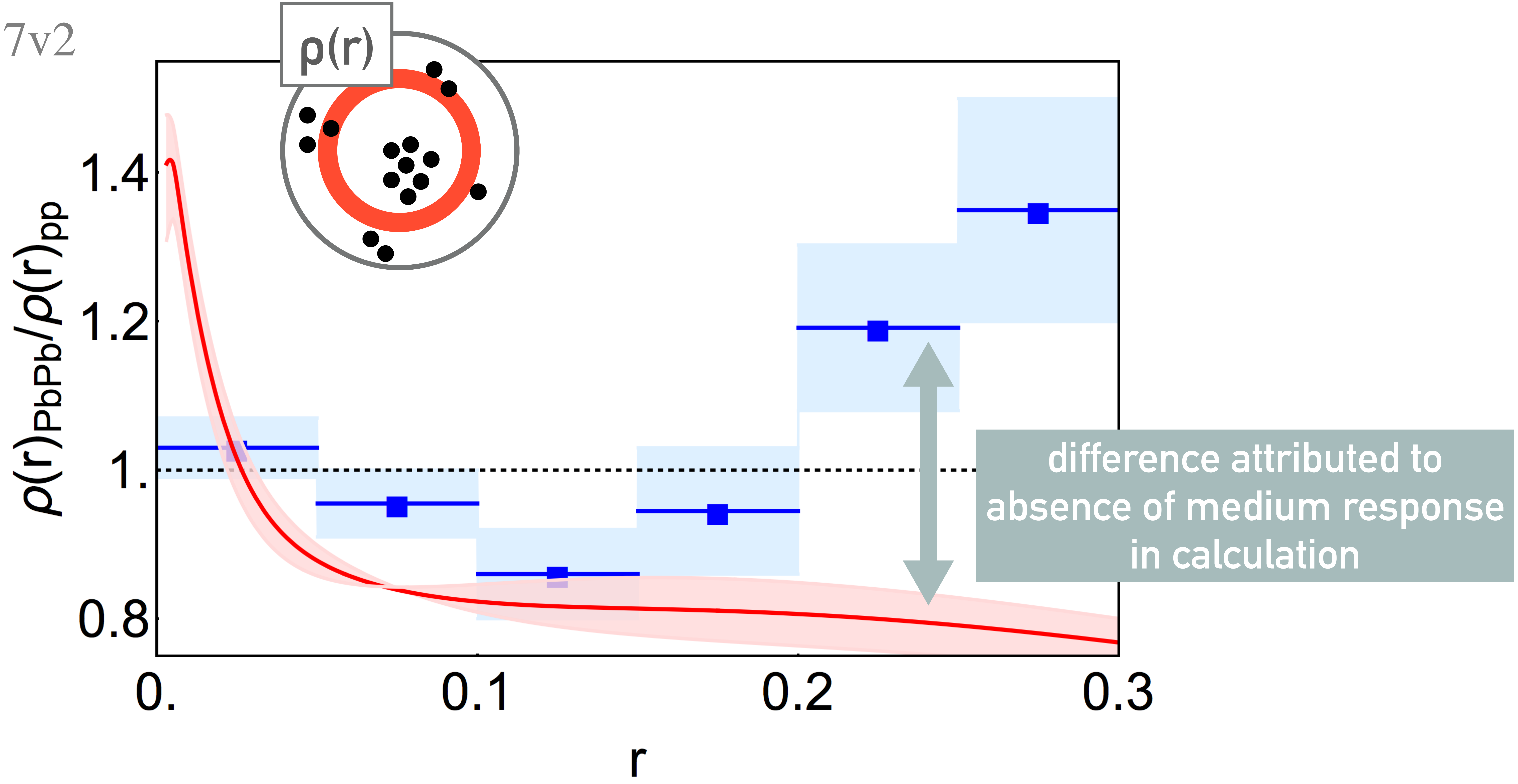
(semi)-ANALYTICAL

still an MC selection

holographic jets in strongly coupled plasma

Jasmine Brewer,[a] **Krishna Rajagopal,**[a] **Andrey Sadofyev,**[a,b] **Wilke van der Schee**[a,c]

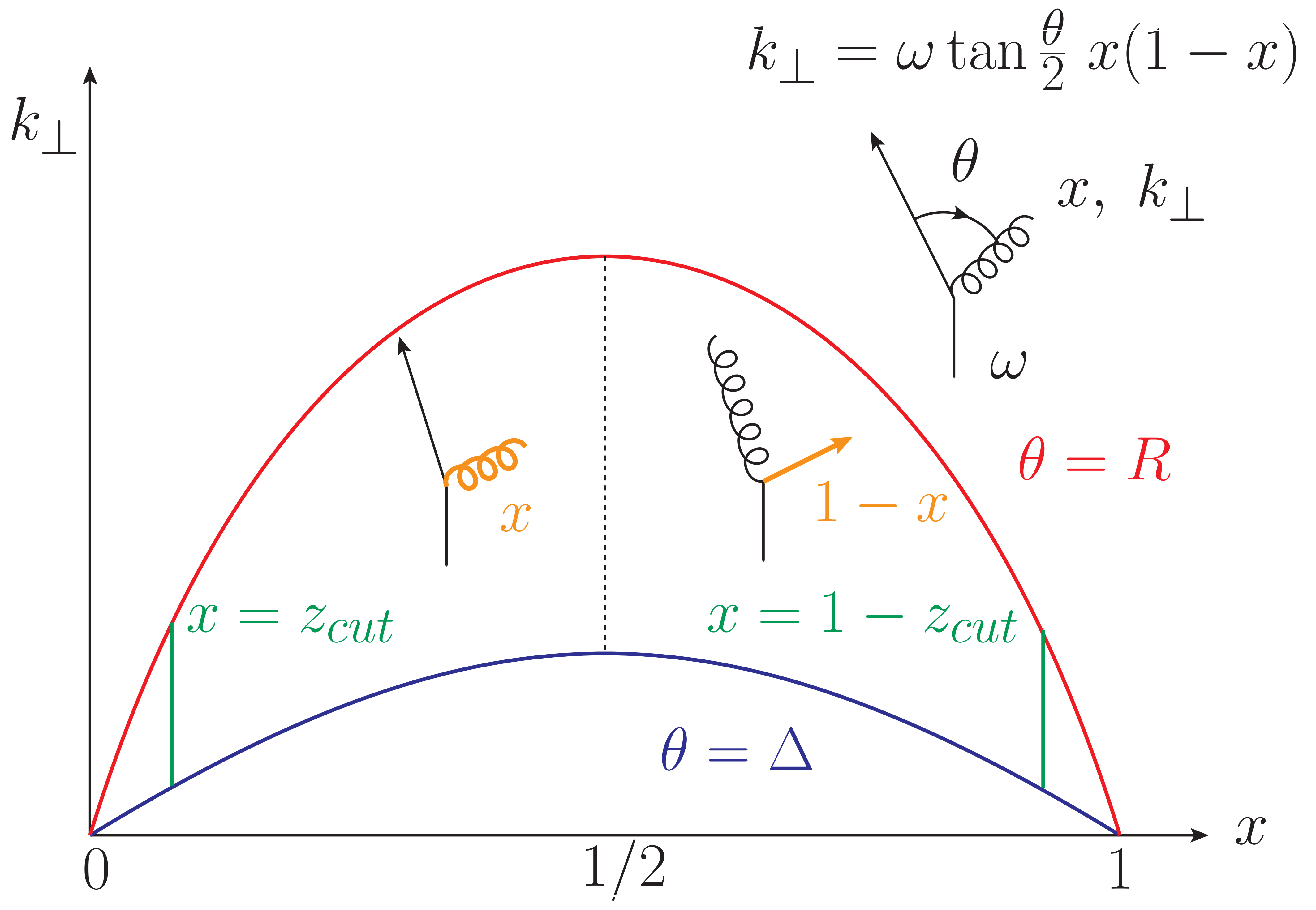
arXiv:1710.03237v2

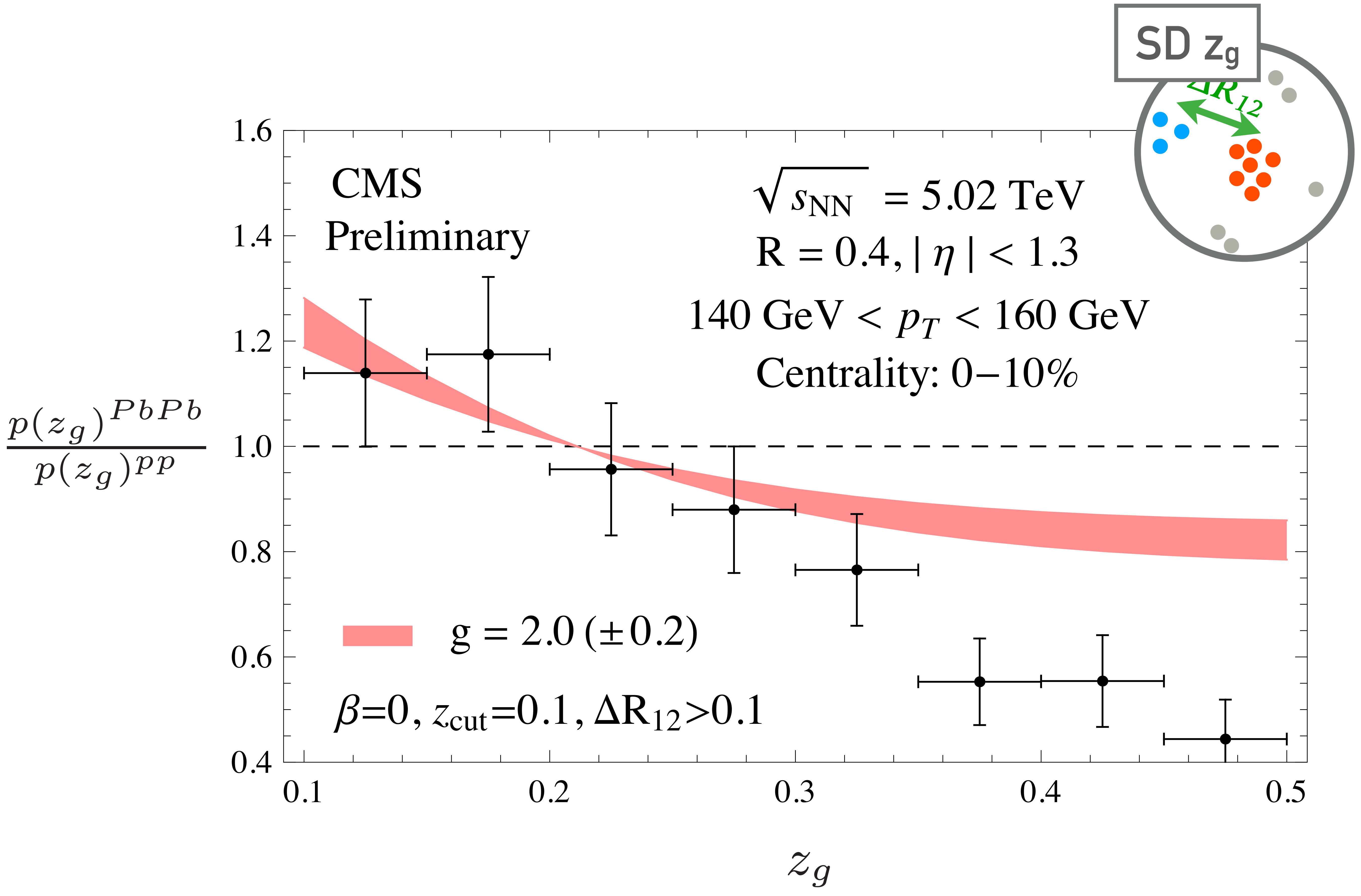


SCET with Glauber gluons

Yang-Ting Chien[a,b] and Ivan Vitev[a]

arXiv:1608.07283v1





P. Caucal, E. Iancu, A.H. Mueller, G. Soyez

arXiv:1801.09703

vacuum-like fragmentation in a dense medium

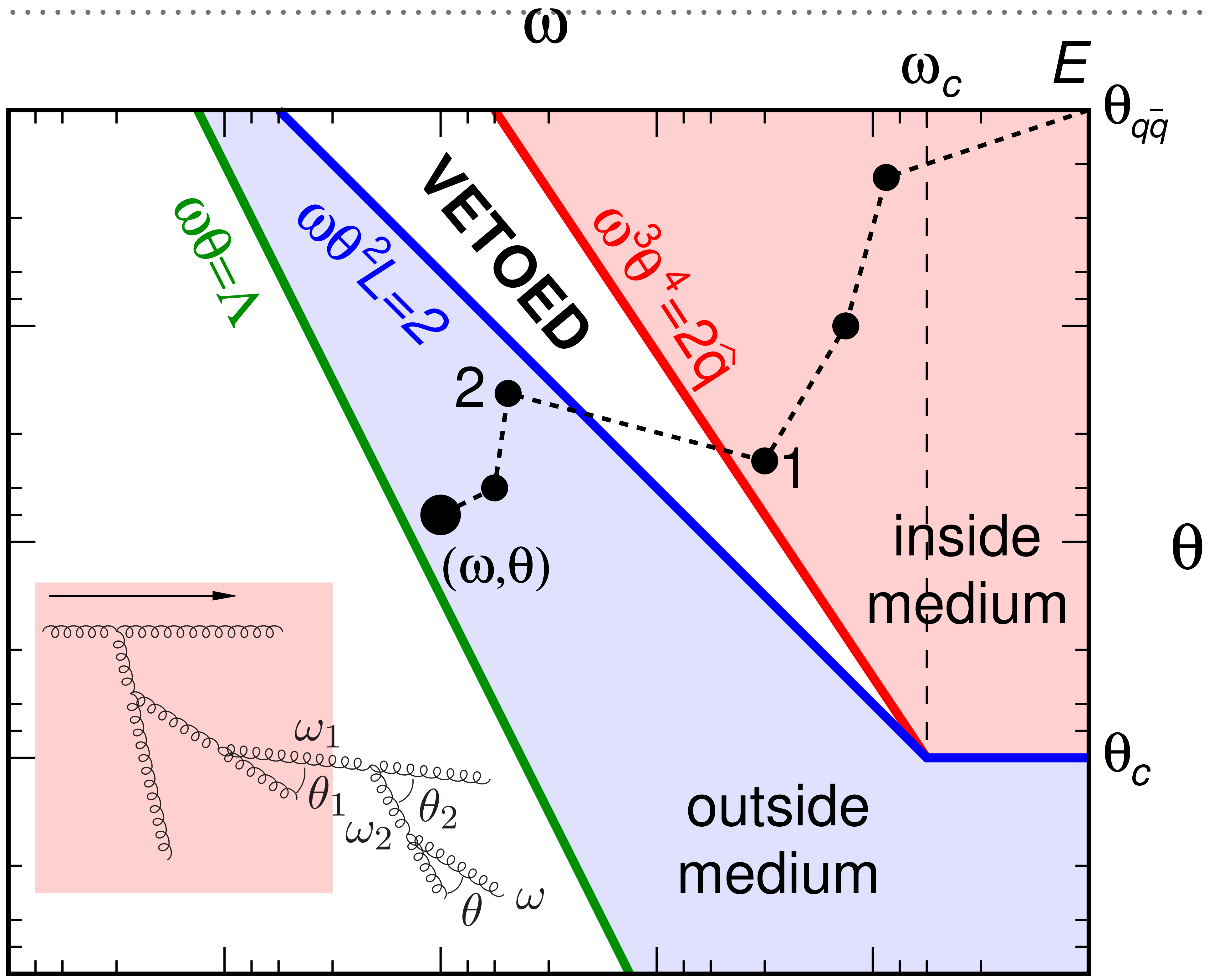


FIG. 1. Schematic representation of the phase-space available for VLEs, including an example of a cascade with "1" the last emission inside the medium and "2" the first emission outside.

P. Caucal, E. Iancu, A.H. Mueller, G. Soyez

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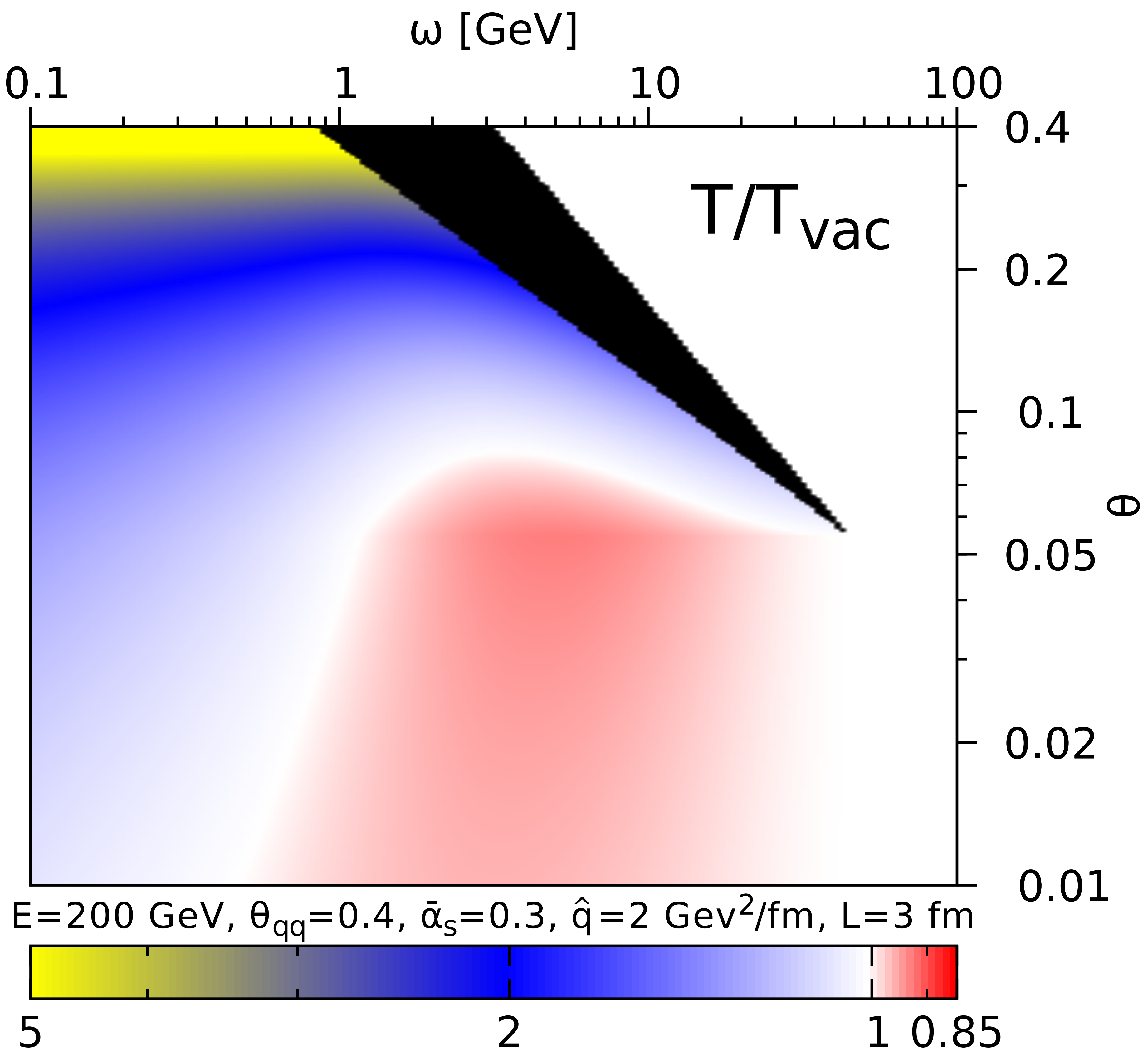


FIG. 2. The ratio $T(\omega, \theta^2)/T_{\text{vac}}(\omega, \theta^2)$ between the two-dimensional gluon distributions in the medium and respectively the vacuum, both computed to DLA and for the values of the free parameters E, $\theta_{q\bar{q}}$, $\bar{\alpha}_s$, $\hat{q}$ and L shown in the figure.

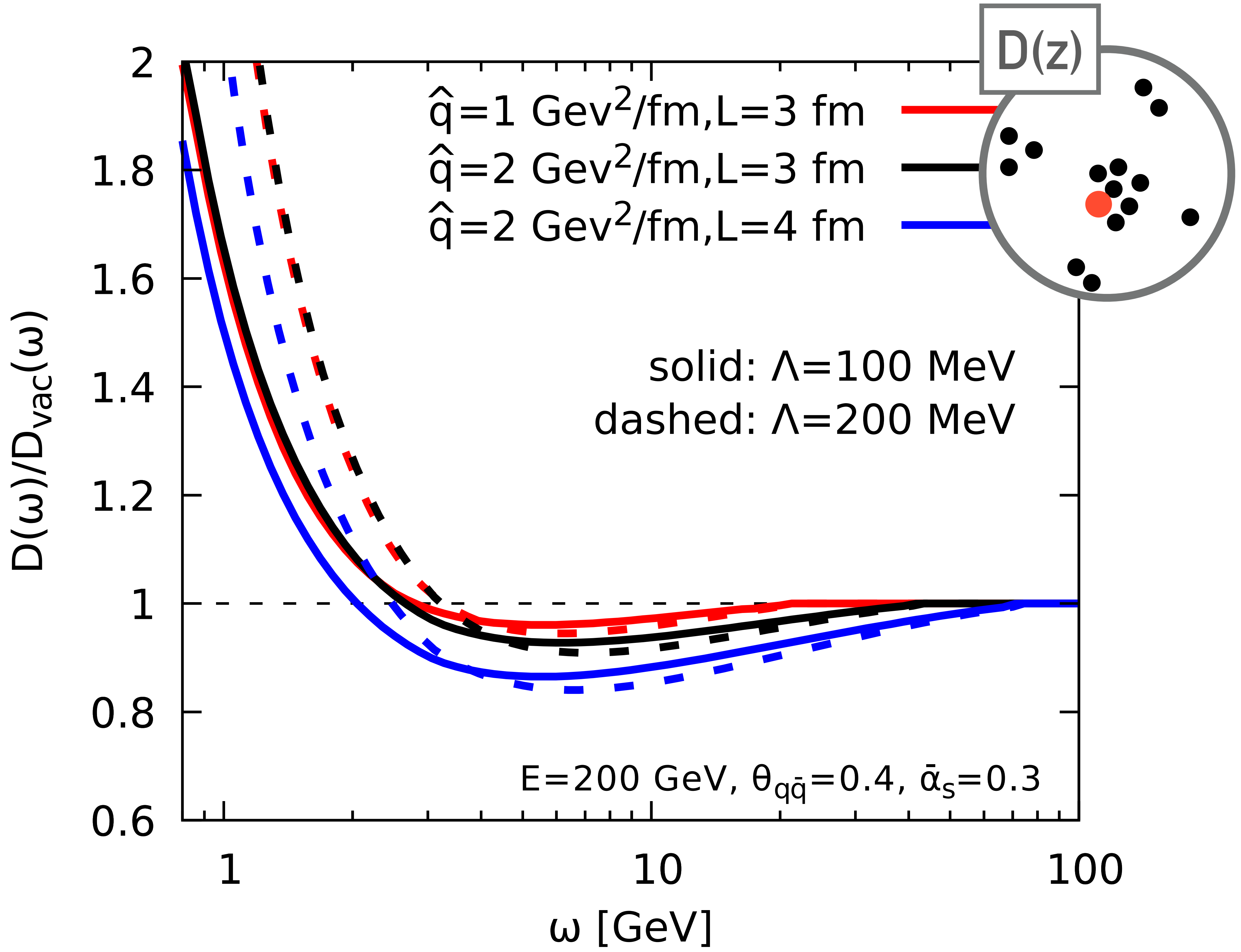
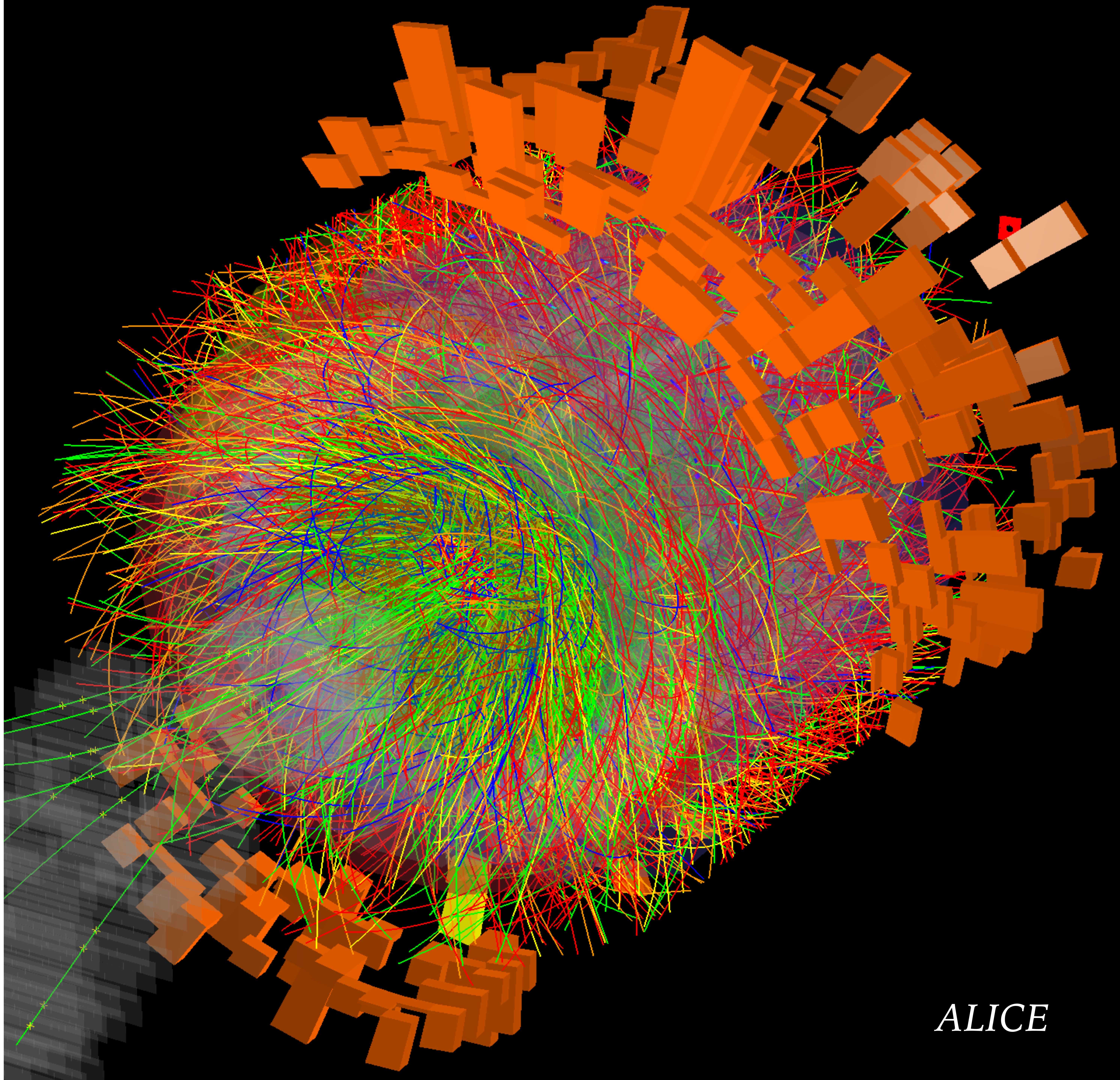


FIG. 3. The ratio $D(\omega)/D_{\text{vac}}(\omega)$ between the fragmentation functions in the medium and respectively the vacuum, for different choices for the medium parameters $\hat{q}$ and L and the hadronisation scale Λ (and fixed values for E, $\theta_{q\bar{q}}$, and $\bar{\alpha}_s$).

OBSERVABLES

What is observable?

- Jets are always in the medium (100-200 GeV/unit area)
- Measurements done after background subtraction
- Subtraction procedure is **essential part of observable definition**
- **Conclusions only solid if they're independent of subtraction procedure**
- Subtraction procedure should be taken into account in comparisons with MCs and other theory predictions



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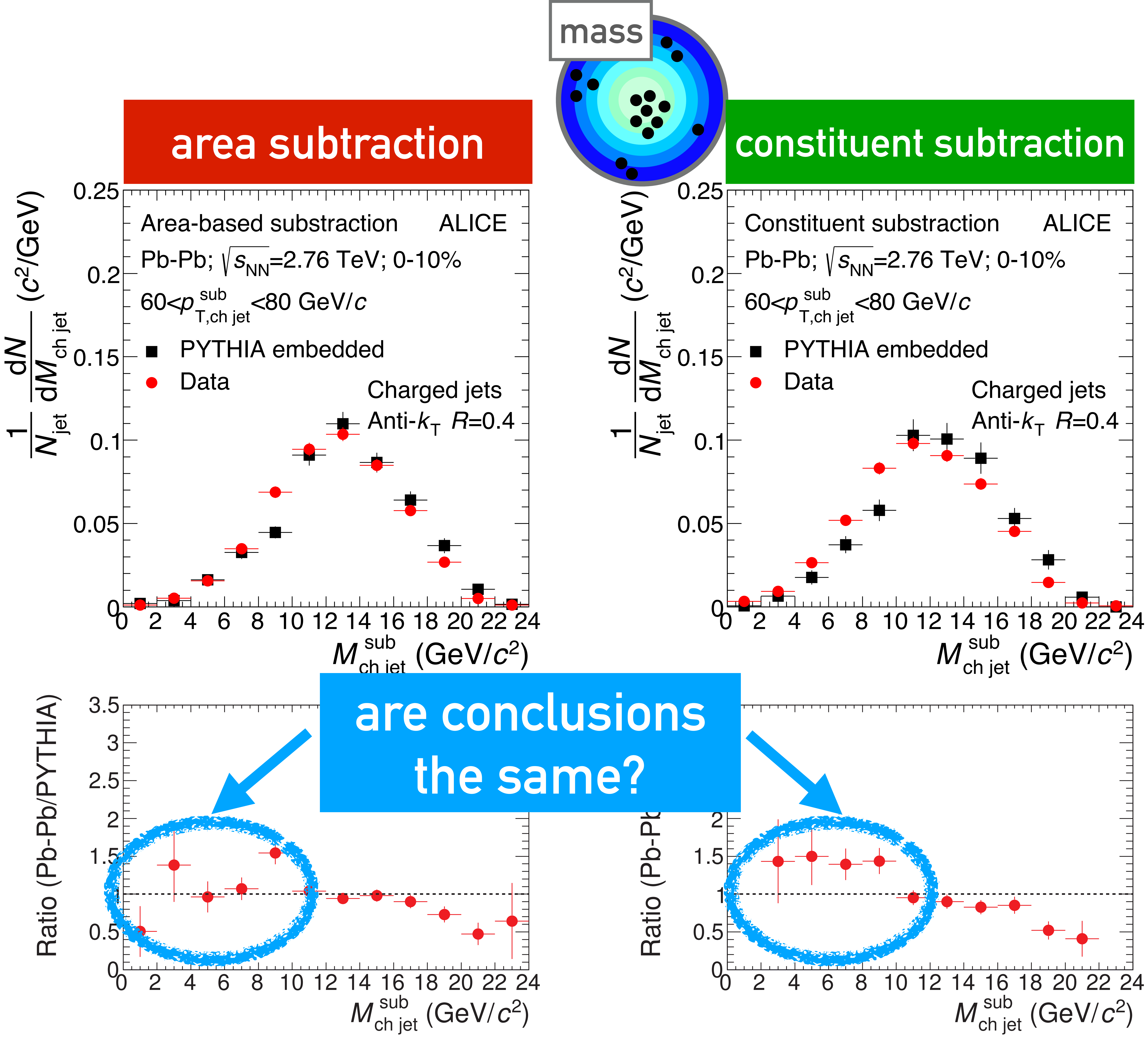

arXiv:1702.00804

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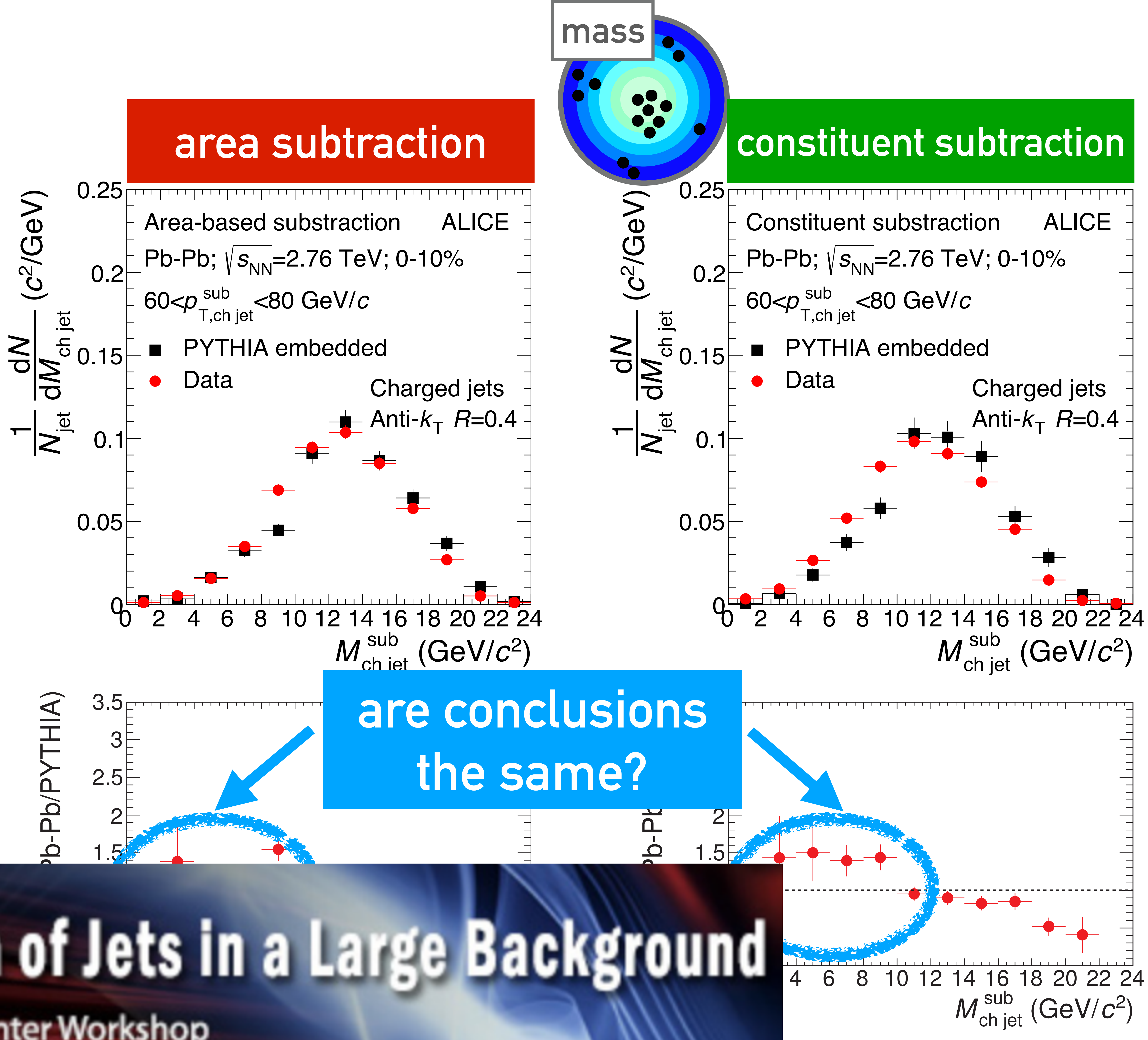
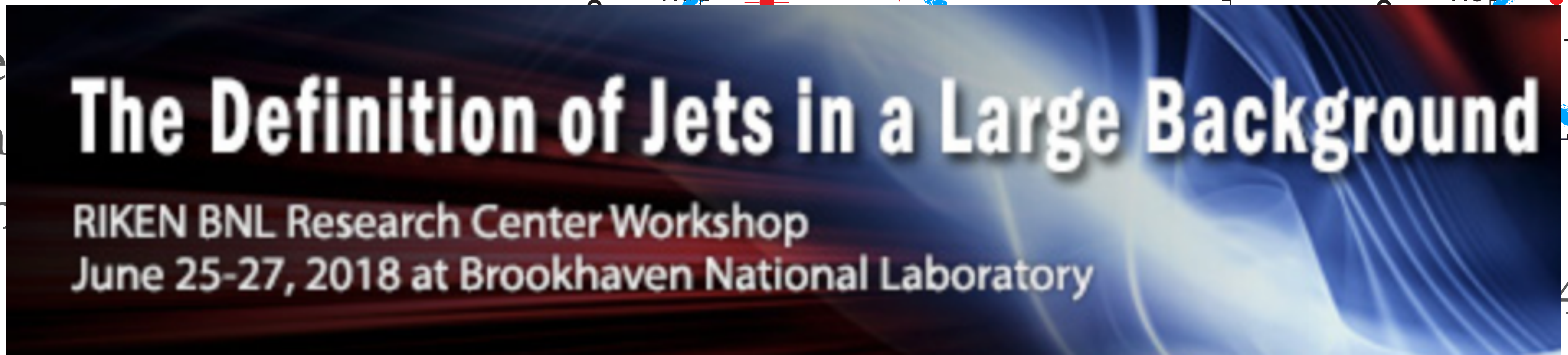
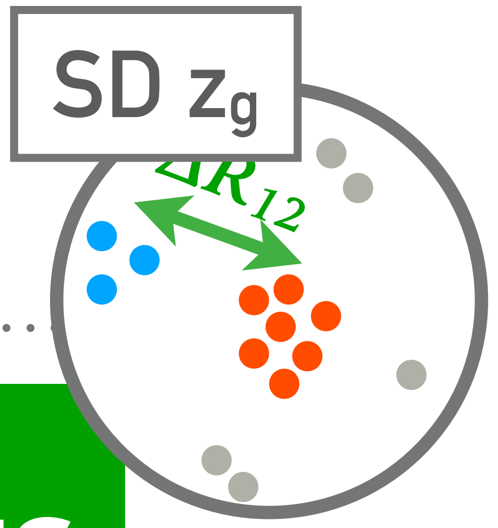
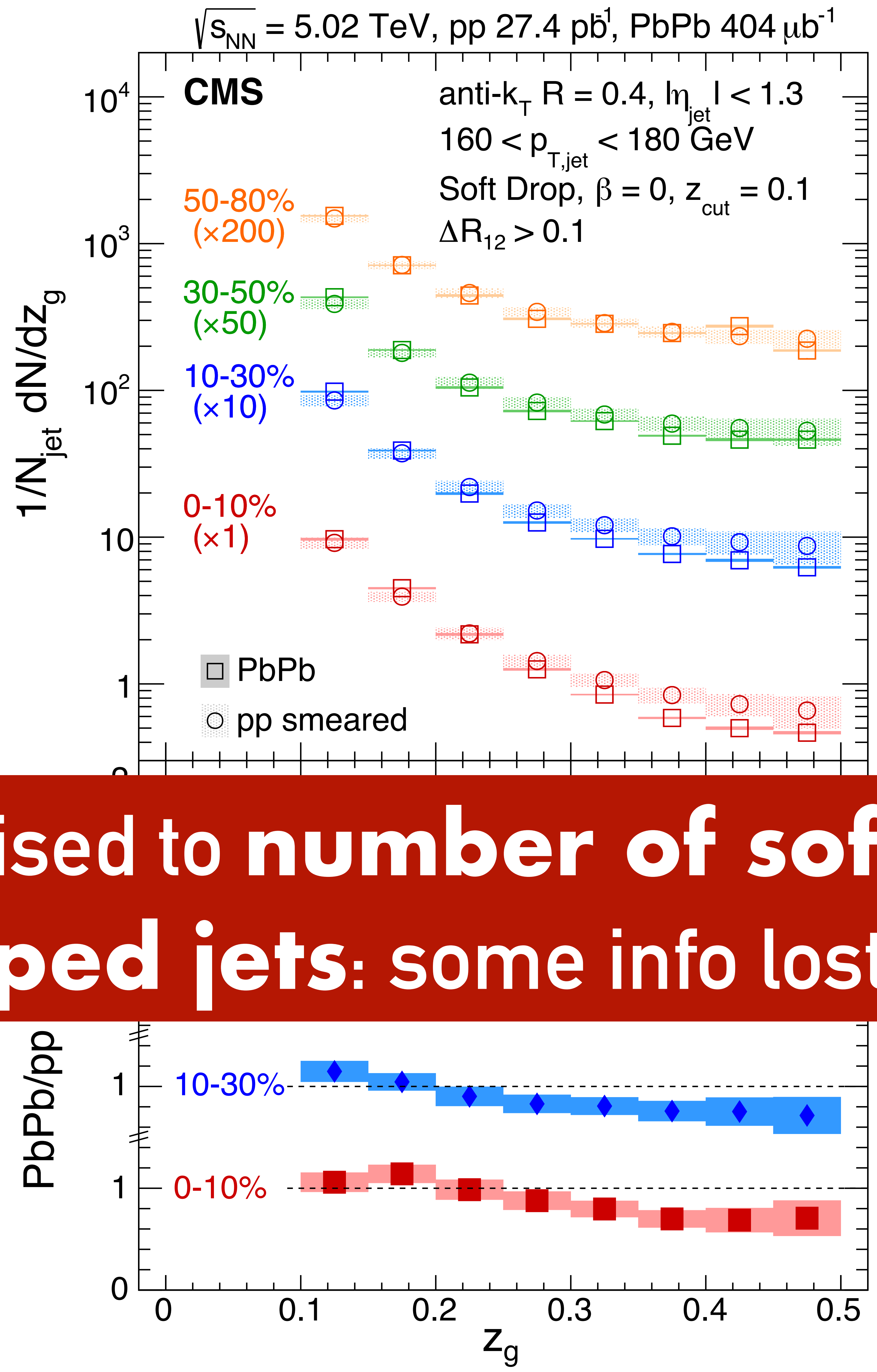




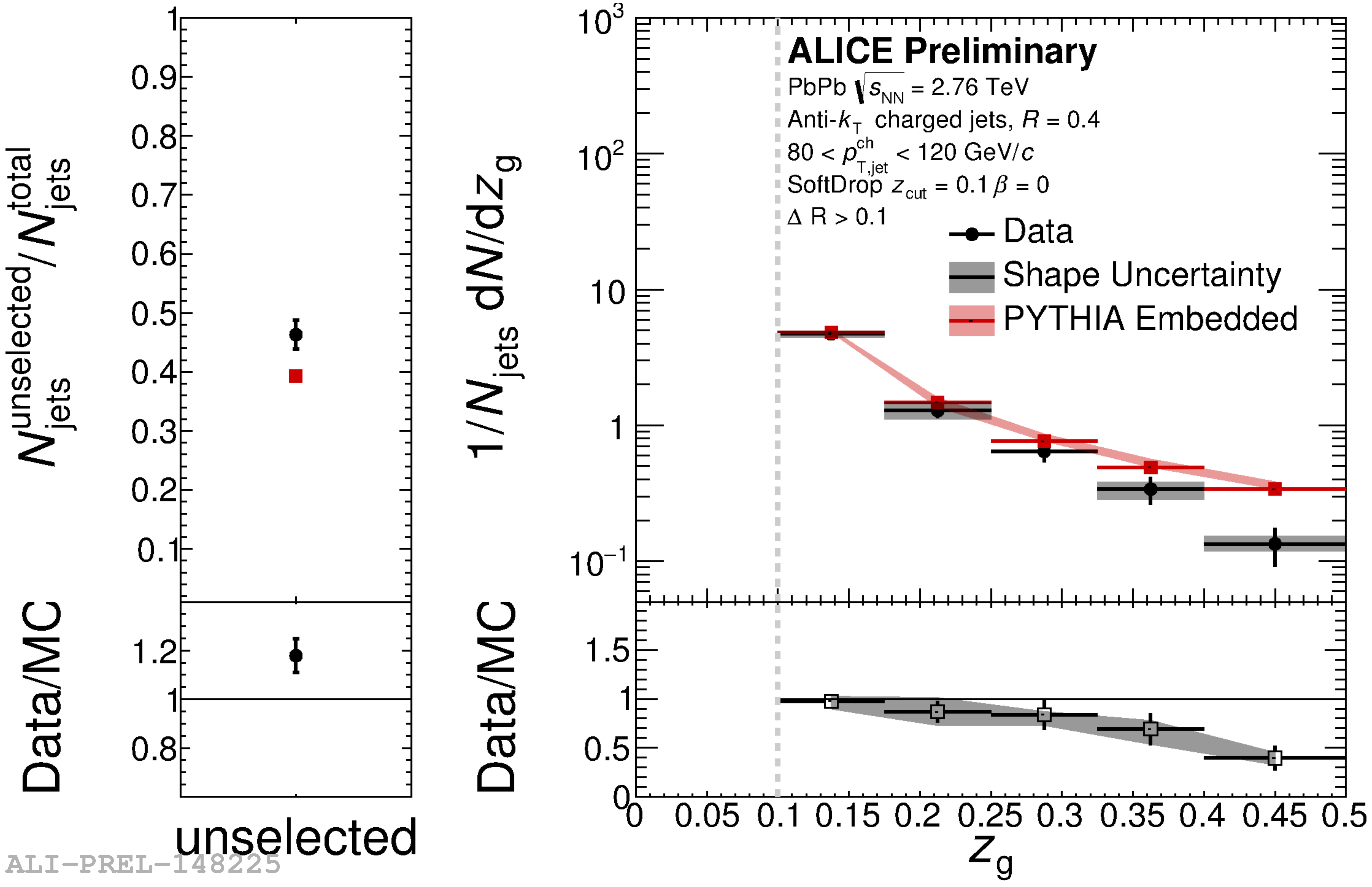
Soft-Drop normalisation





Normalised to number of soft-dropped jets: some info lost

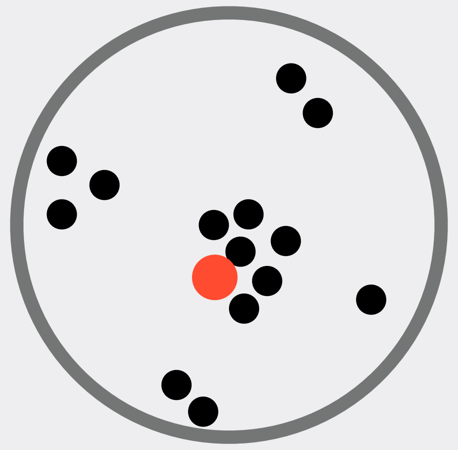
Normalised to number of jets in p_t bin: contains full info



Jet structure observables

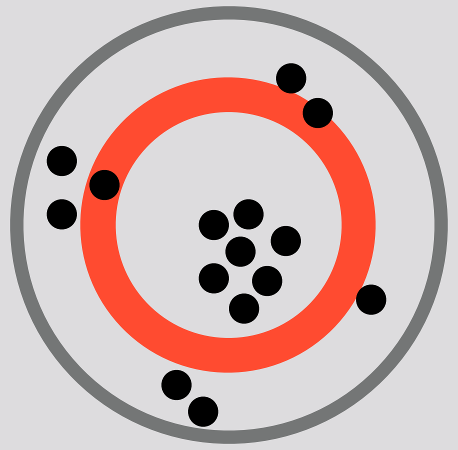
fragmentation function

$$D(z) = \left\langle \sum_{i \in \text{jet}} \delta(z - p_{ti}/p_{t,\text{jet}}) \right\rangle_{\text{jets}}$$



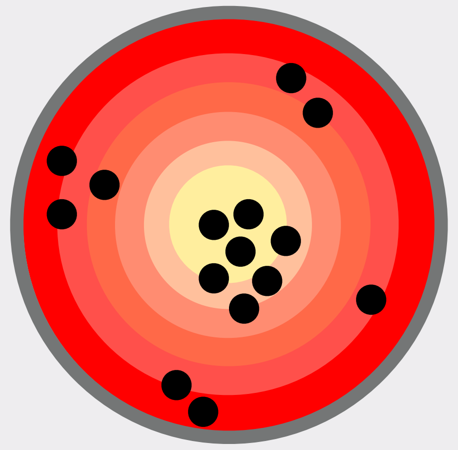
differential jet shape

$$\rho(r) = \frac{1}{p_\perp^{\text{jet}}} \sum_{\substack{k \text{ with} \\ \Delta R_{kJ} \in [r, r+\delta r]}} p_\perp^{(k)},$$



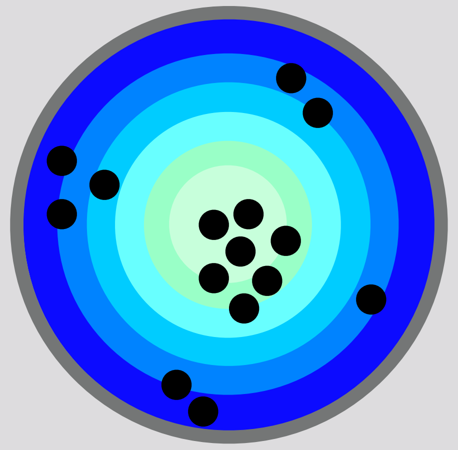
girth ≡ broadening

$g = \frac{1}{\ldots} \ldots {}_{kJ}\,,$



jet mas

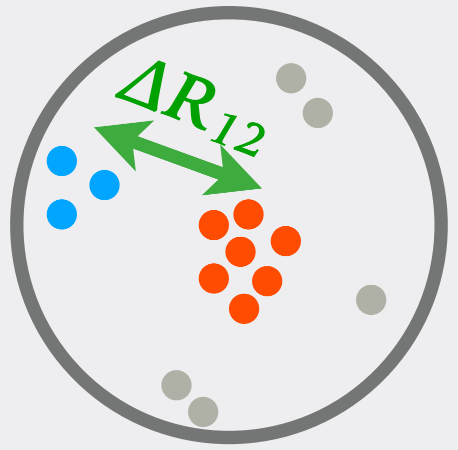
$$m^2 = \left(\sum_{i \in \text{(sub)jet}} p_i^\mu \right)^2$$



Is this a sufficiently informative set of observables?

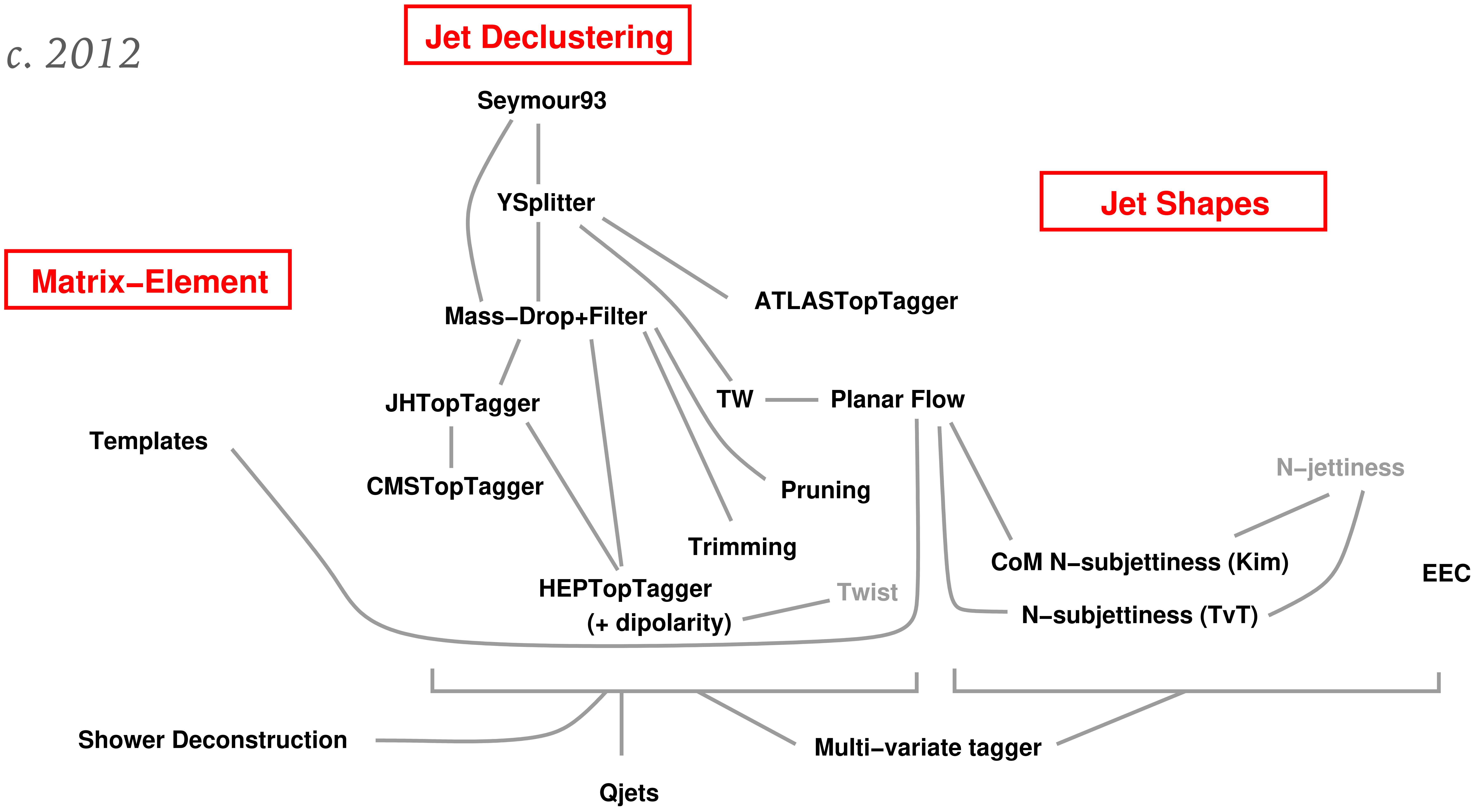
z_g, ΔR_{12}

$$z_g = \frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}} > z_{\text{cut}} \left(\frac{\Delta R_{1,2}}{R_J} \right)^\beta$$



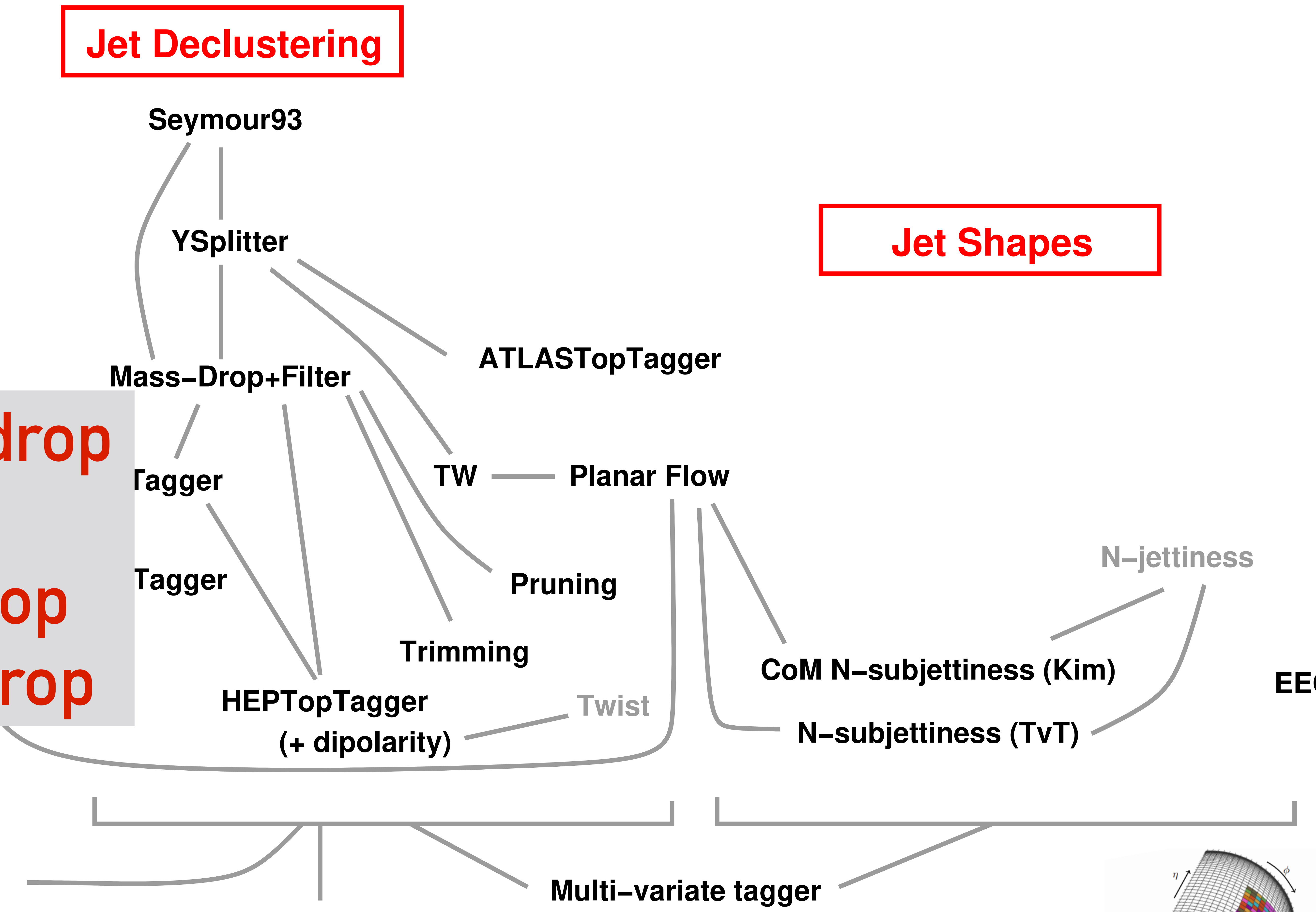
pp jet substructure field is full of activity

c. 2012

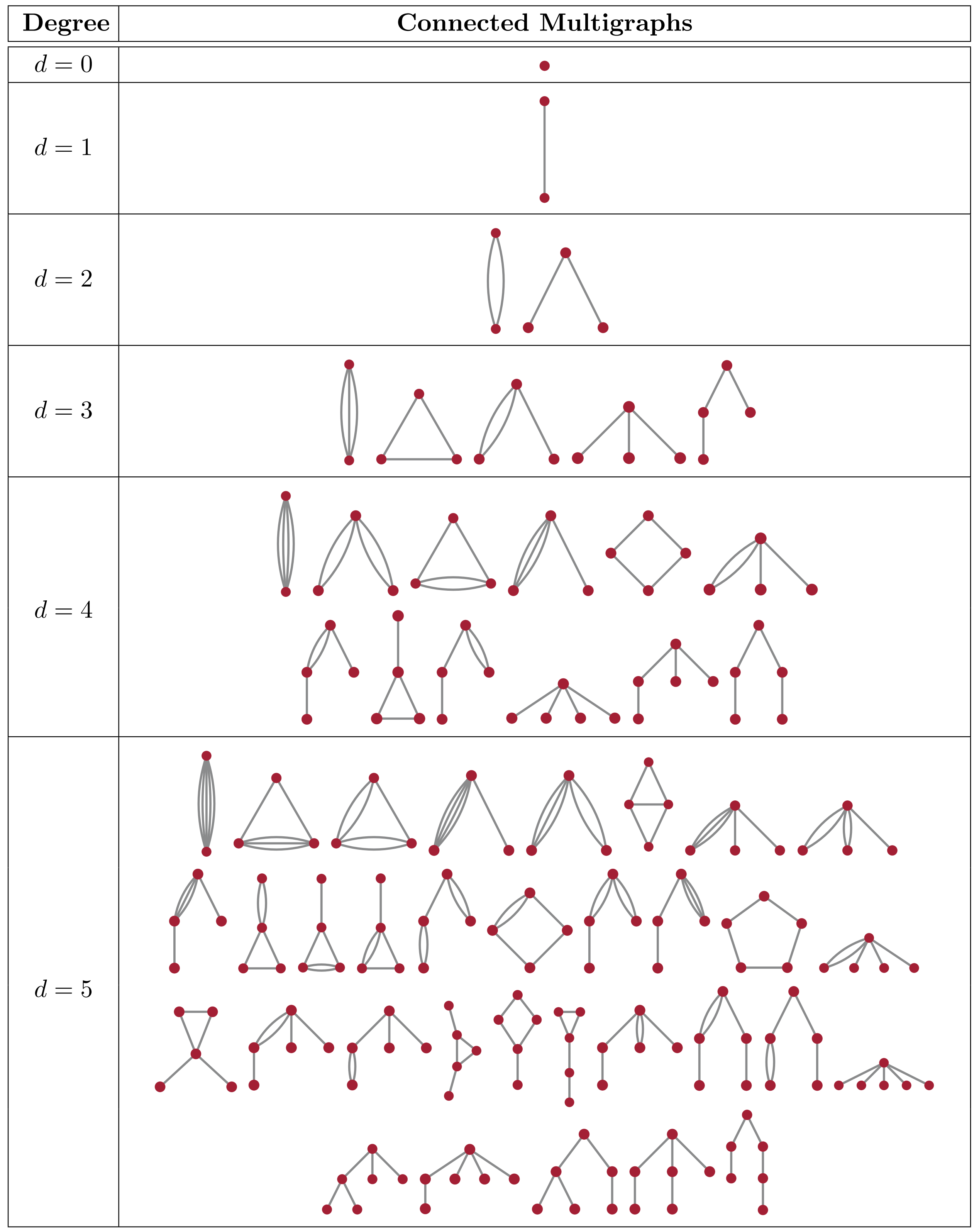


pp jet substructure field is full of activity

c. 2018



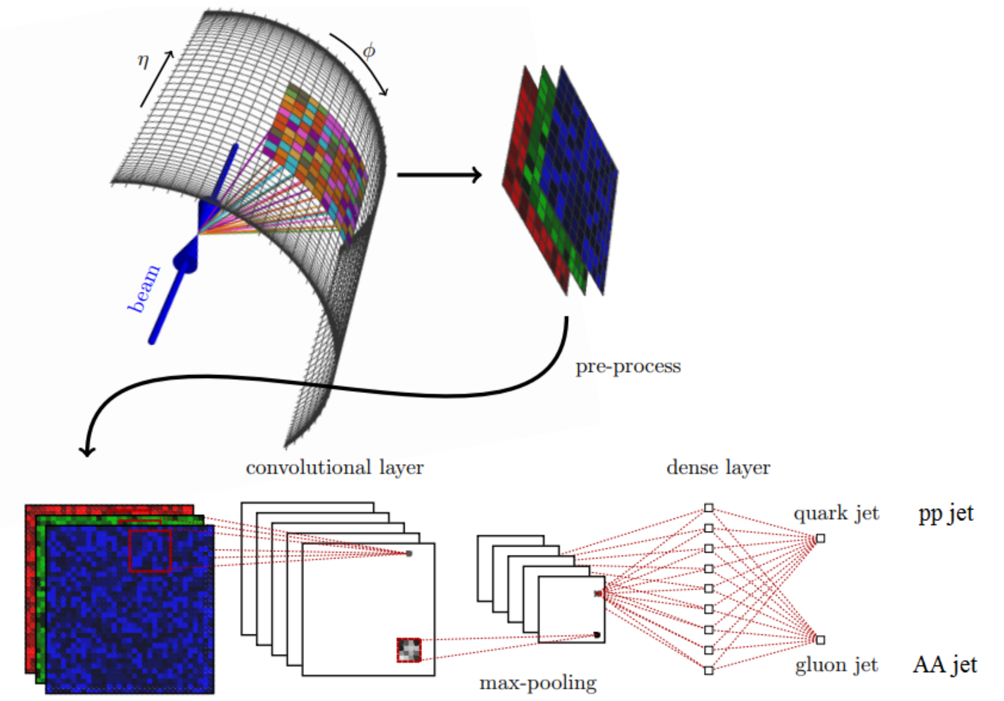
modified mass drop
soft drop
iterated soft drop
recursive soft drop



C_n, D_n, ${}_v e_n^{(\beta)}$, M_n, N_n, U_n, EFPs

classification without labels
weak supervision

machine learning
DNN, CNN,
RNN, LSTM, etc



etc.

recurrent theme in calculations: 2d phasespace plots

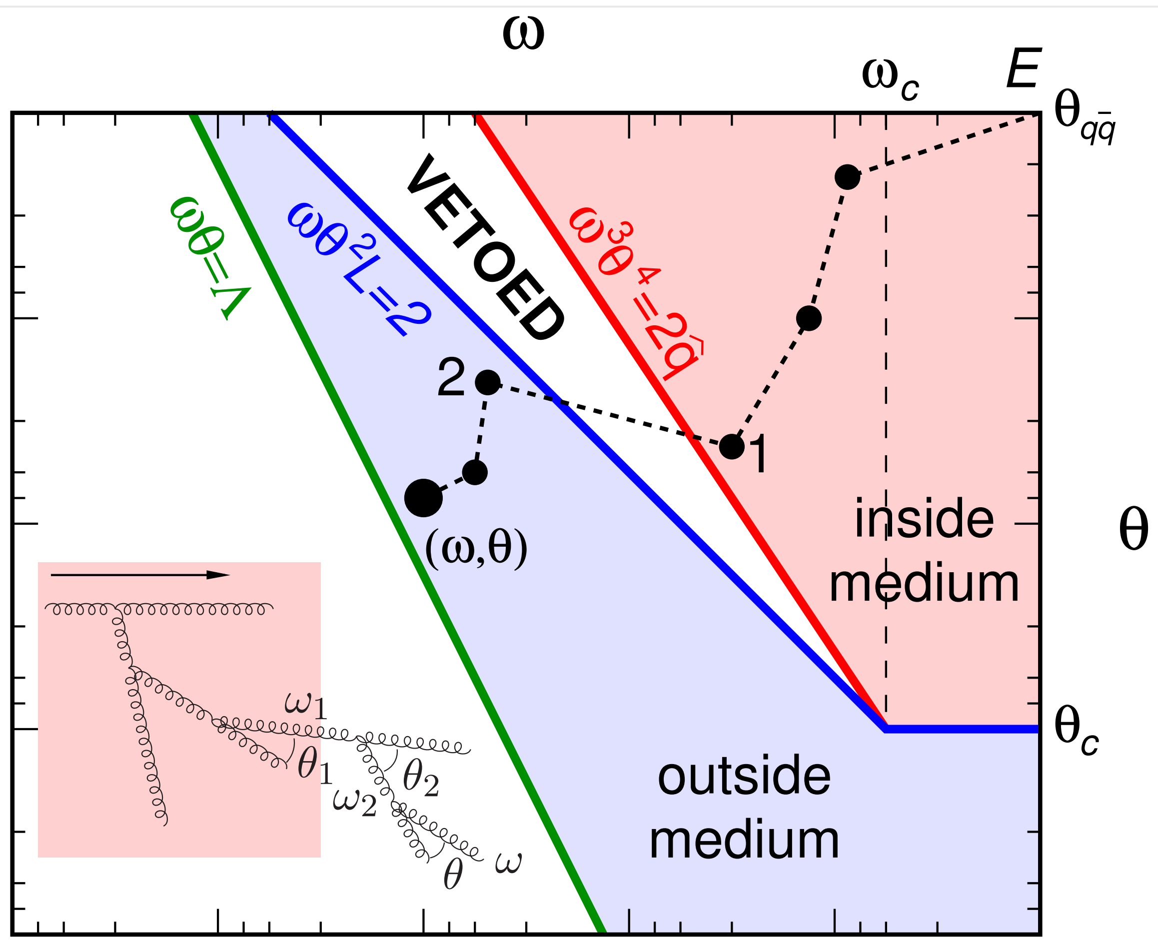
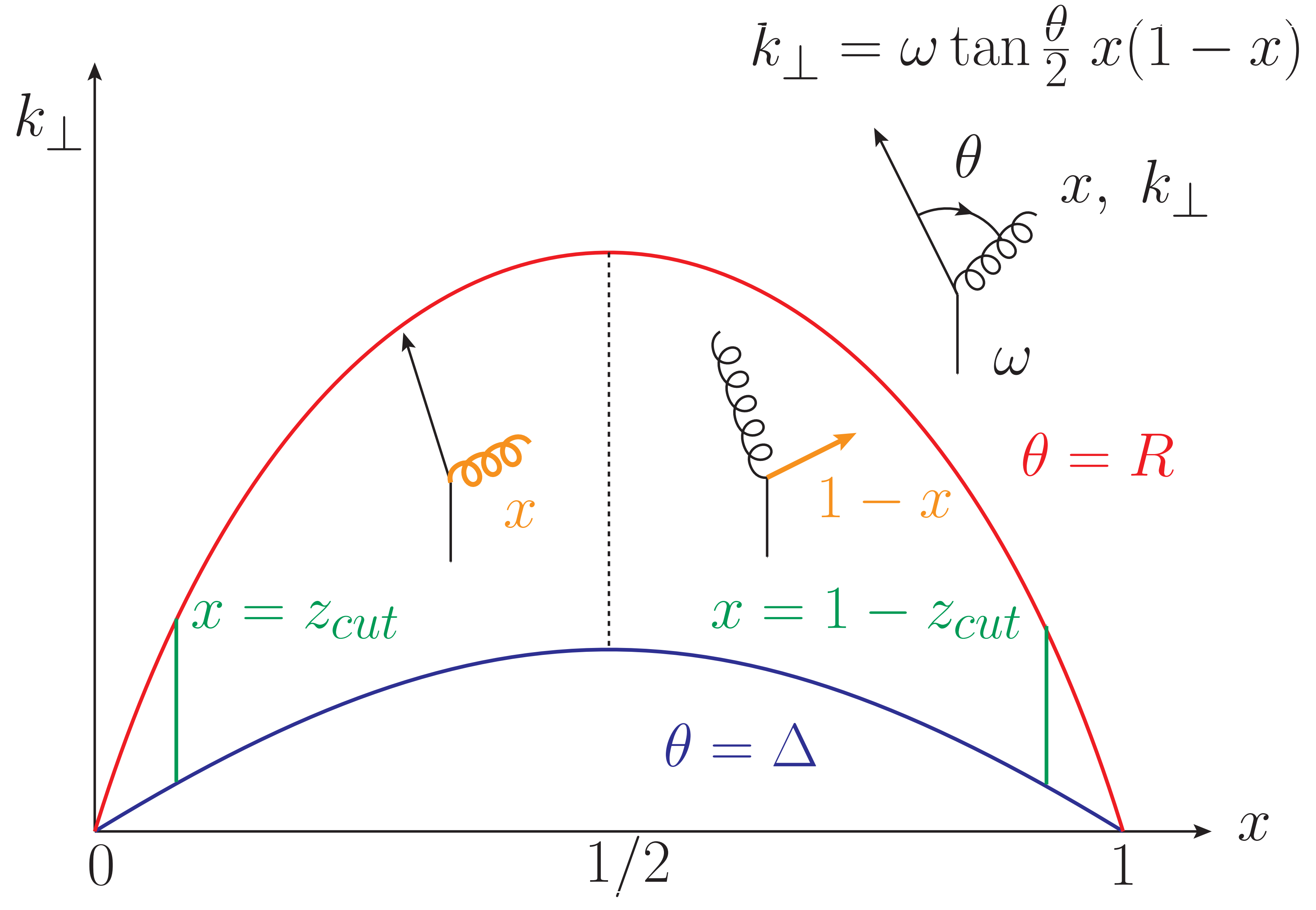
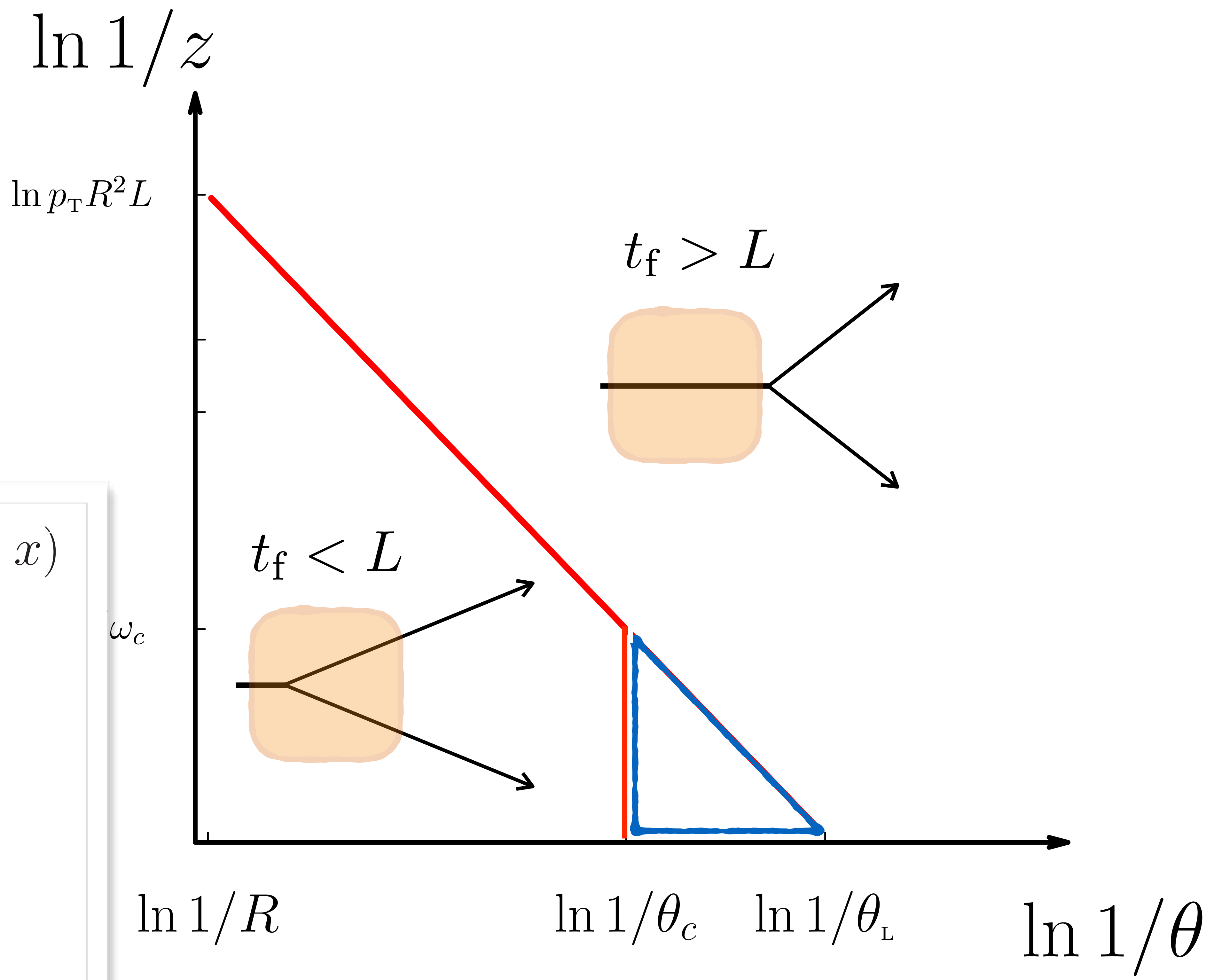


FIG. 1. Schematic representation of the phase-space available for VLEs, including an example of a cascade with "1" the last emission inside the medium and "2" the first emission outside

P. Caucal, E. Iancu, A.H. Mueller, G. Soyez

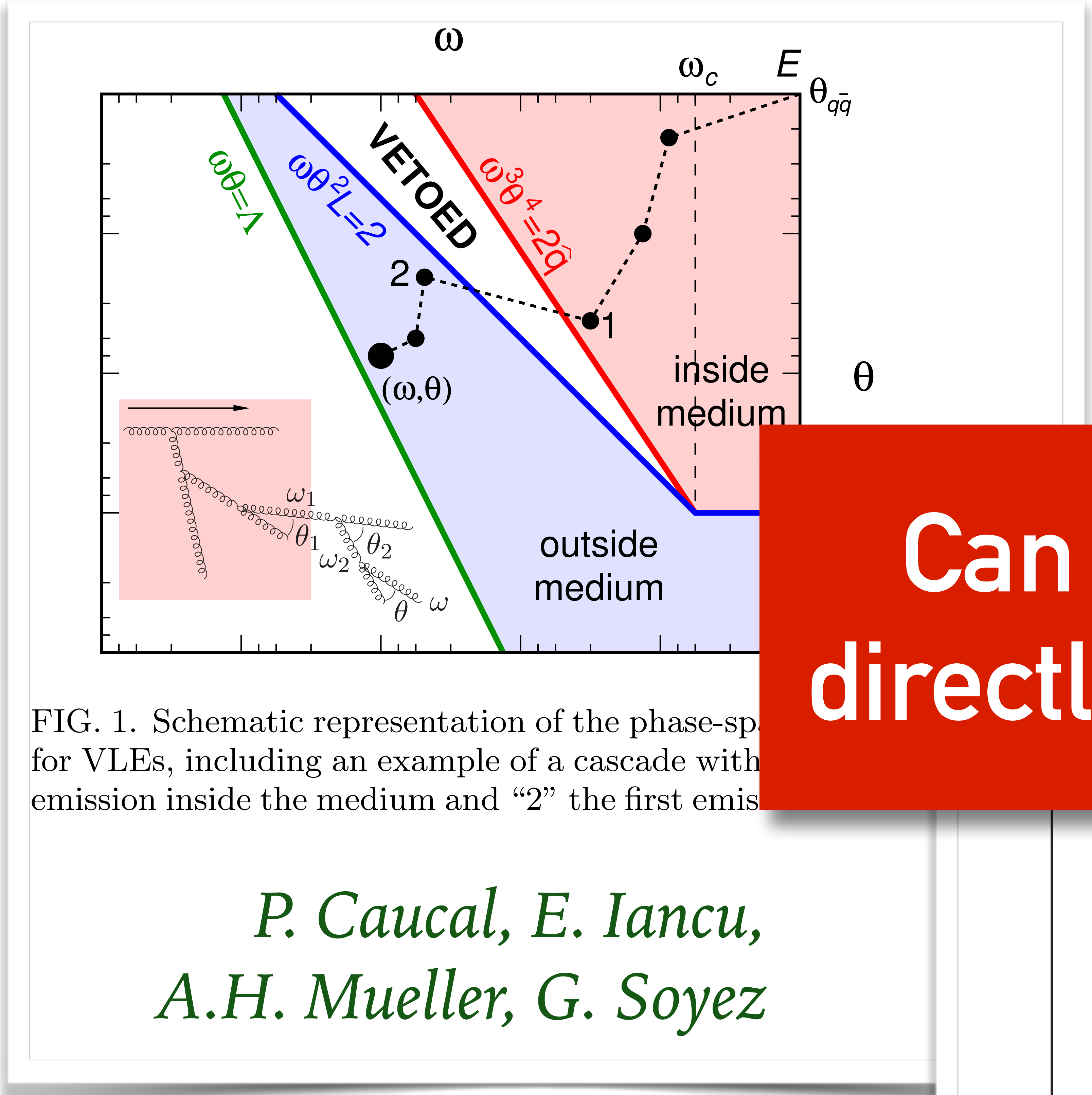


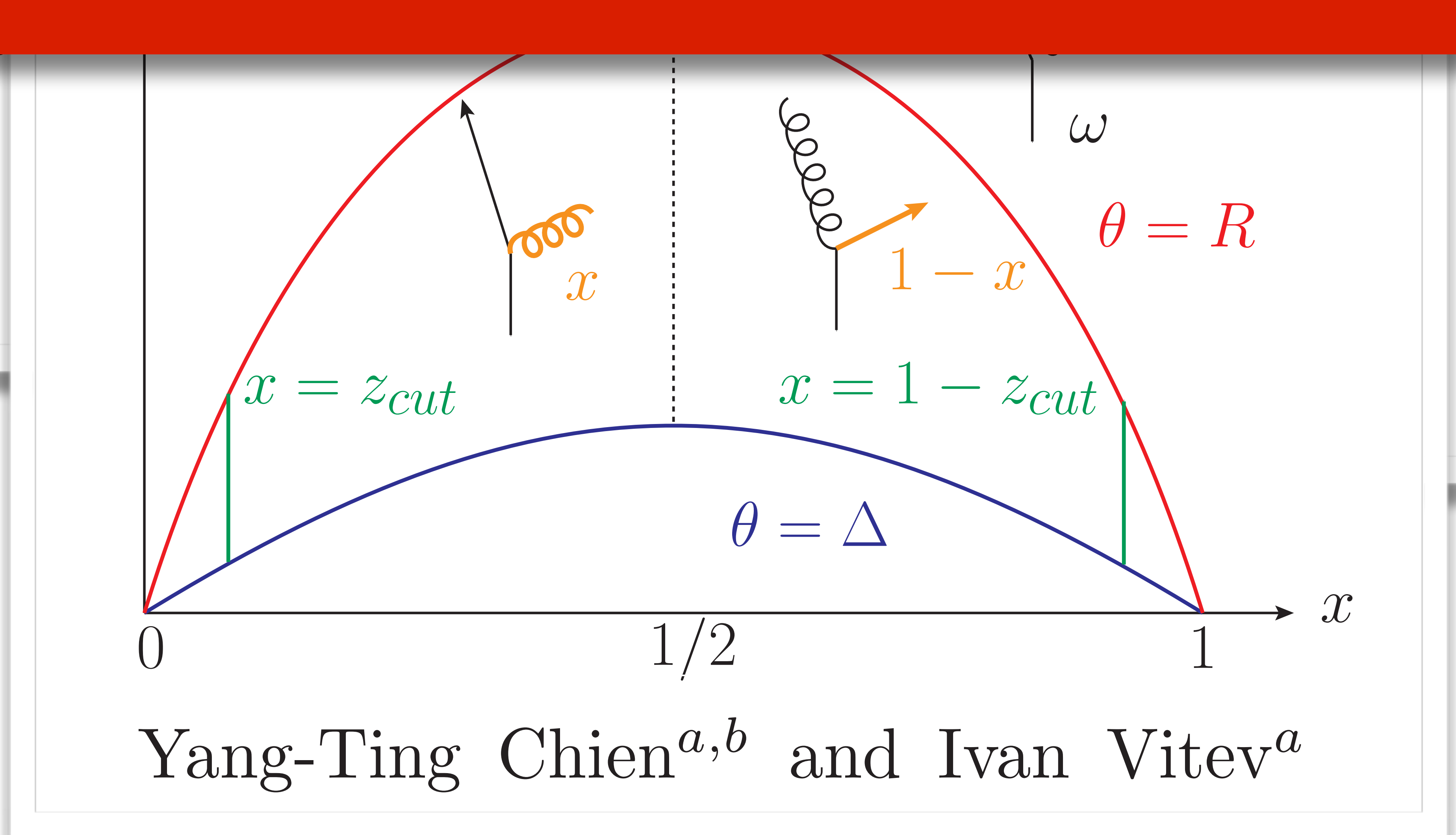
Yang-Ting Chien[a,b] and Ivan Vitev[a]

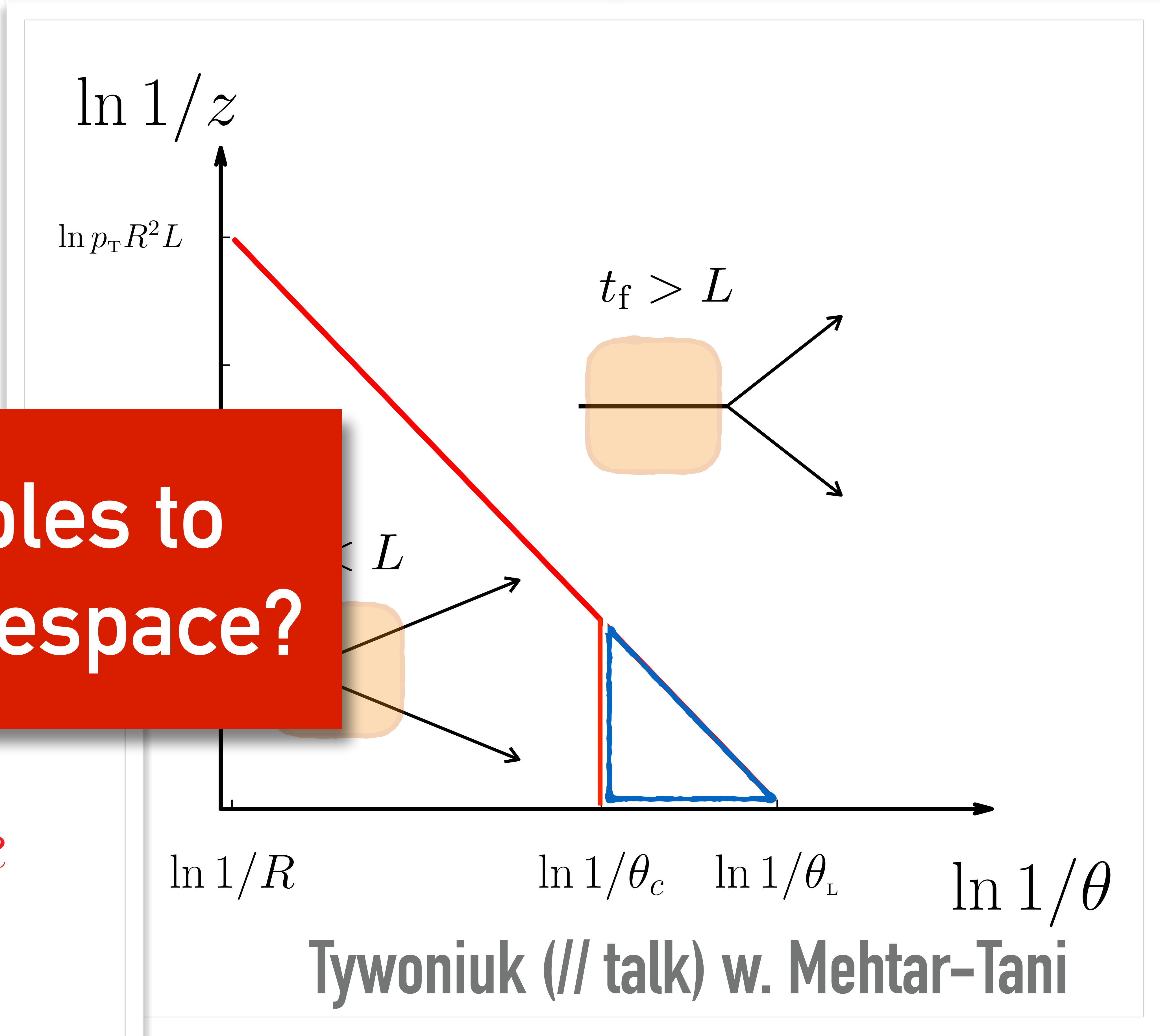


Tywoniuk (// talk) w. Mehtar-Tani

recurrent theme in calculations: 2d phasespace plots







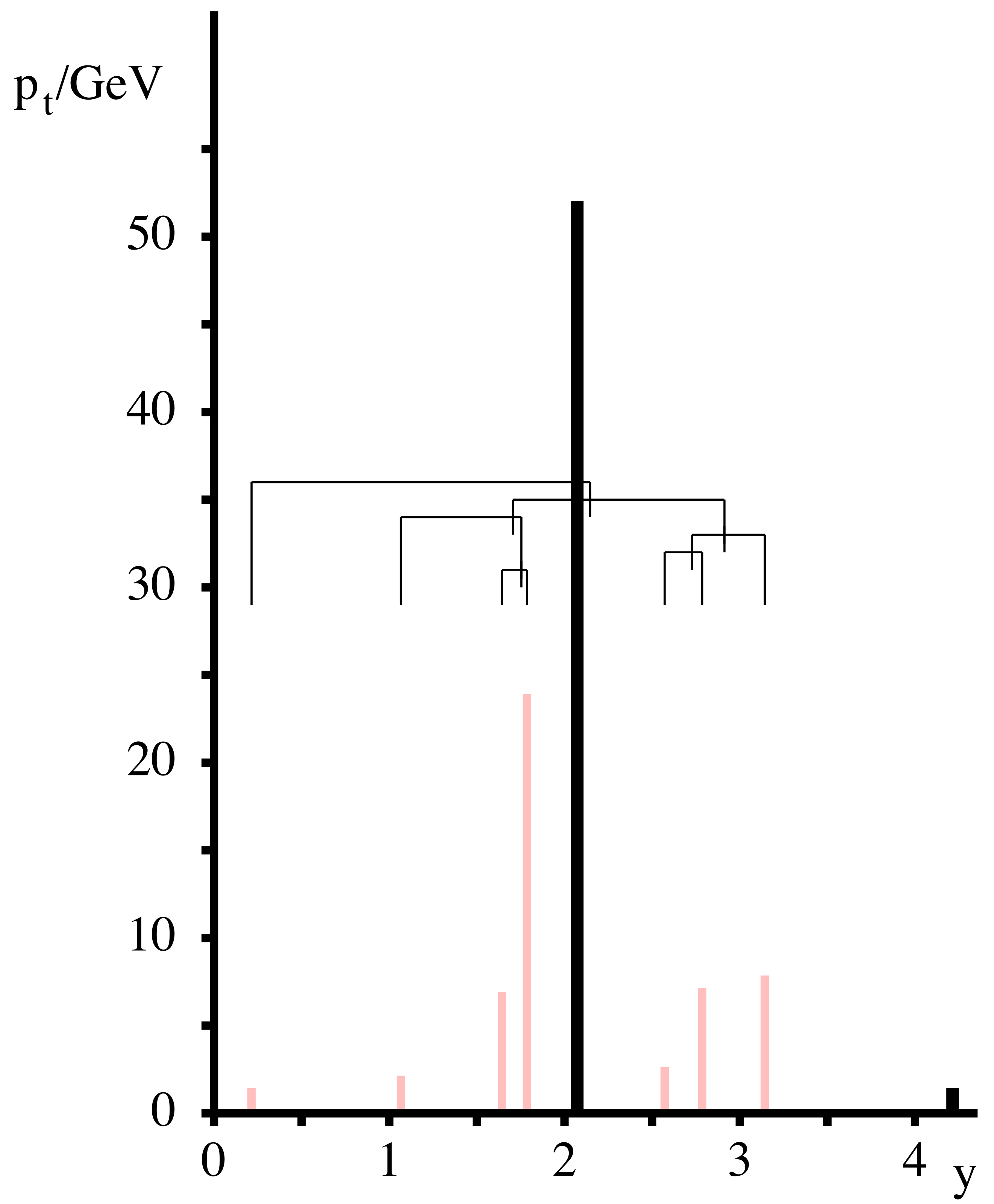
Can we design observables to directly probe the 2d phasespace?

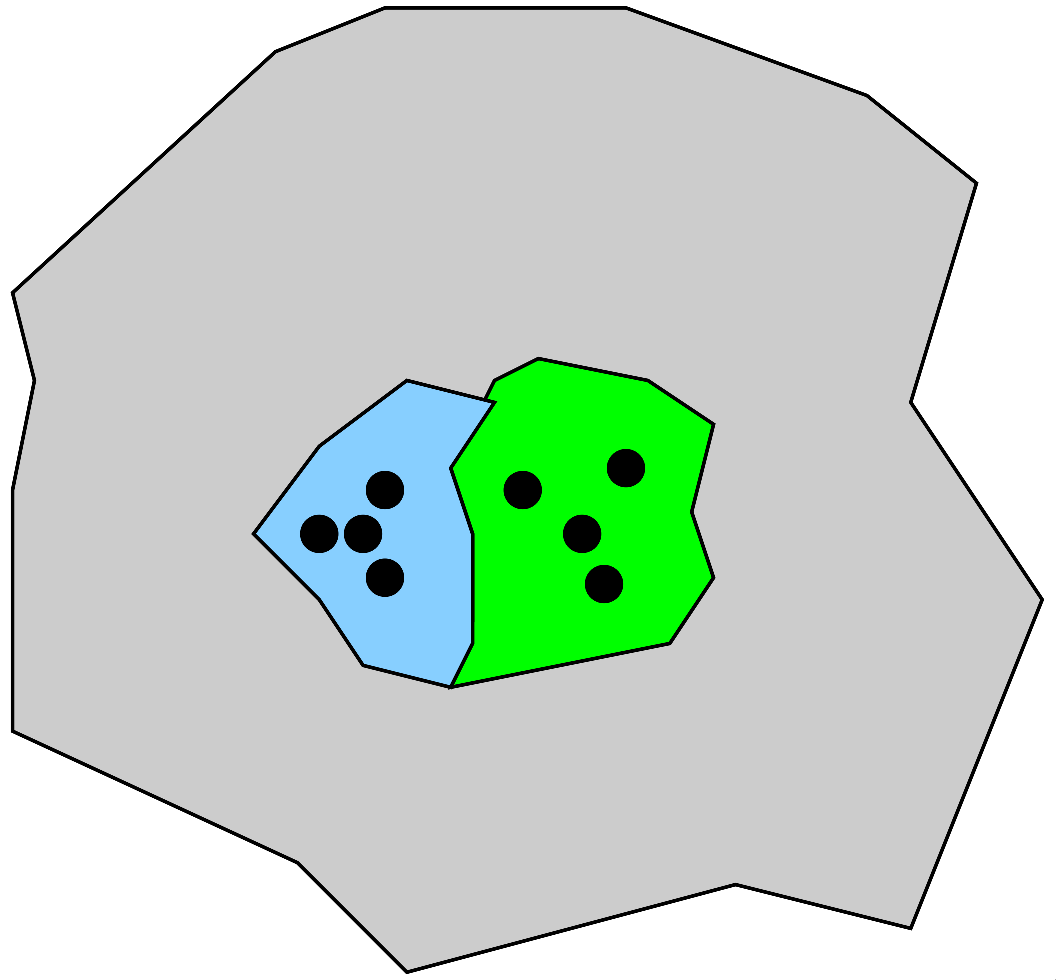
A sequence of jet substructure tools taggers

- 1993: k_t declustering for boosted W's: [Seymour]
- 2002: Y-Splitter (k_t declustering with a cut) [Butterworth. Cox, Forshaw]
- 2008: Mass-Drop Tagger (C/A declustering with a k_t/m cut) [Butterworth, Davison, Rubin, GPS]
- 2013: Soft Drop, β=0 [Dasgupta, Fregoso, Marzani, GPS]
- 2014: Soft Drop, β≠0 [Larkoski, Marzani, Soyez, Thaler]

1. Undo last clustering of C/A jet into subjets 1, 2
2. Stop if $z = \frac{\min(p_{t1}, p_{t2})}{p_{t1} + p_{t2}} \left(\frac{\Delta R_{12}}{R}\right)^{\beta} > z_{\text{cut}}$
3. Else discard softer branch, repeat step 1 with harder branch

Cambridge/Aachen





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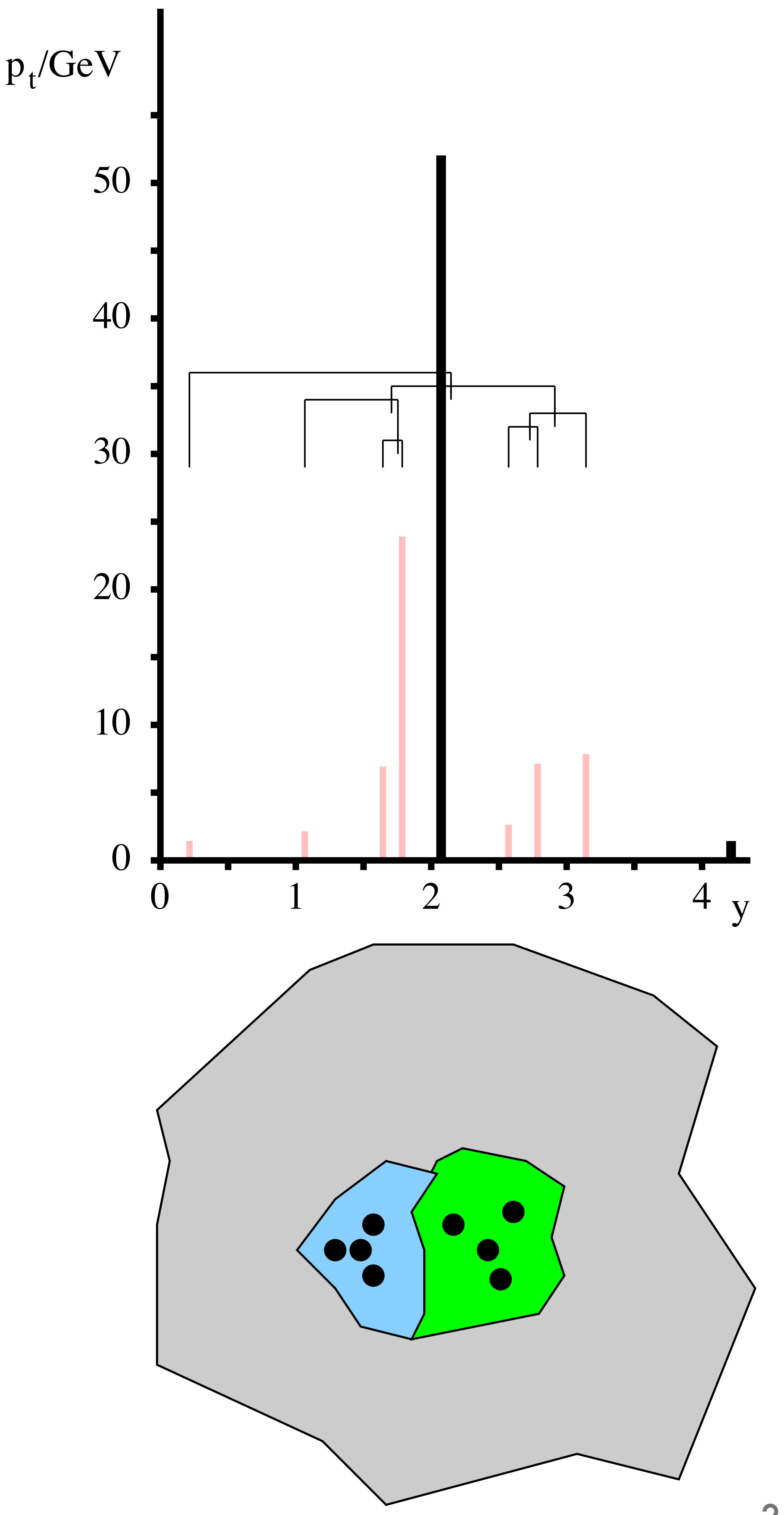
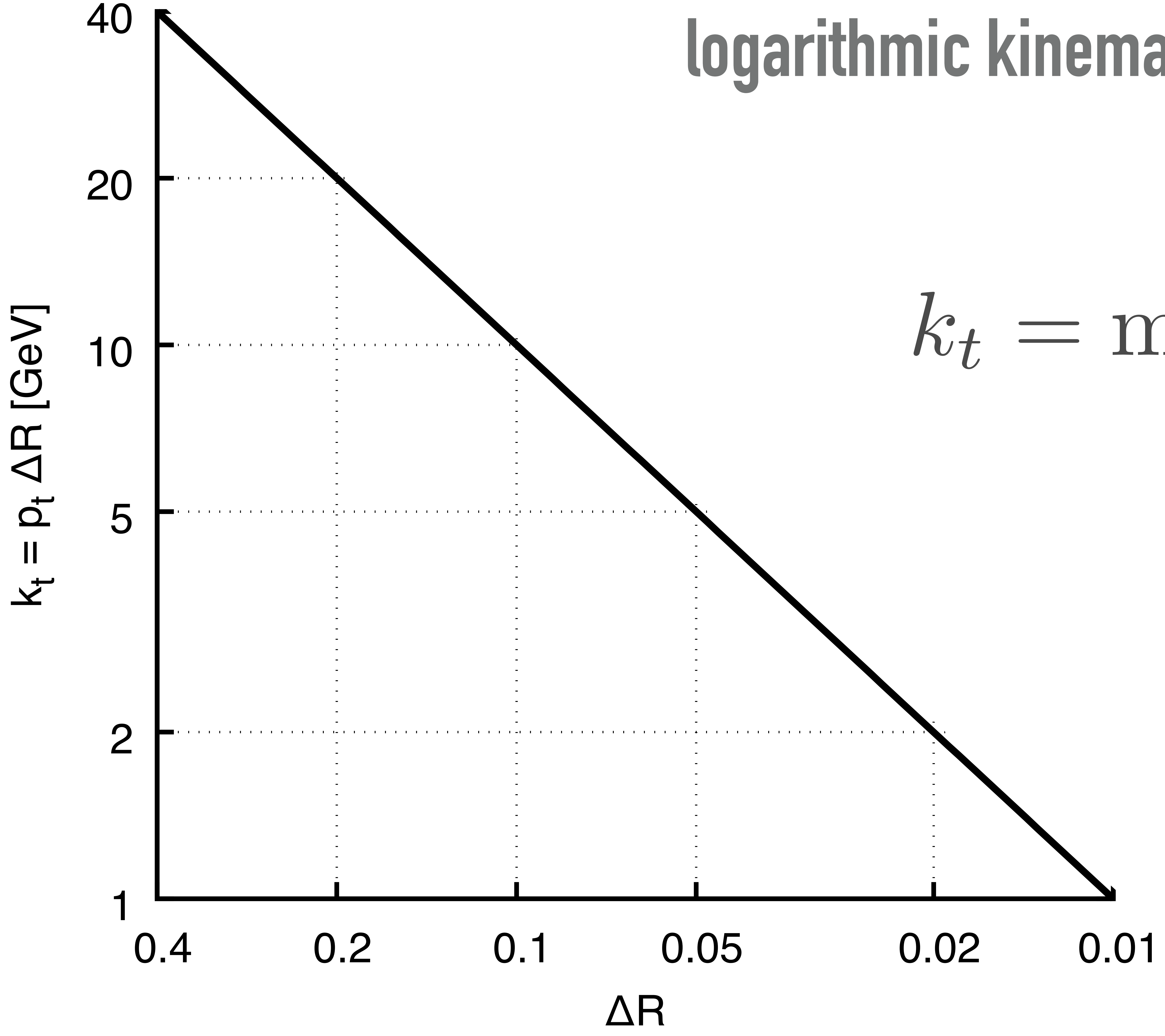
- 2014: Soft Drop, $\beta\neq0$ [Larkoski, Marzani, Soyez, Thaler]
- 2017: Iterated Soft Drop [Frye, Larkoski, Thaler, Zhou]
  count number of iterations until you reach 1 particle
- **2018: ?**

Cambridge/Aachen



jet with $R = 0.4$, $p_t = 200$ GeV



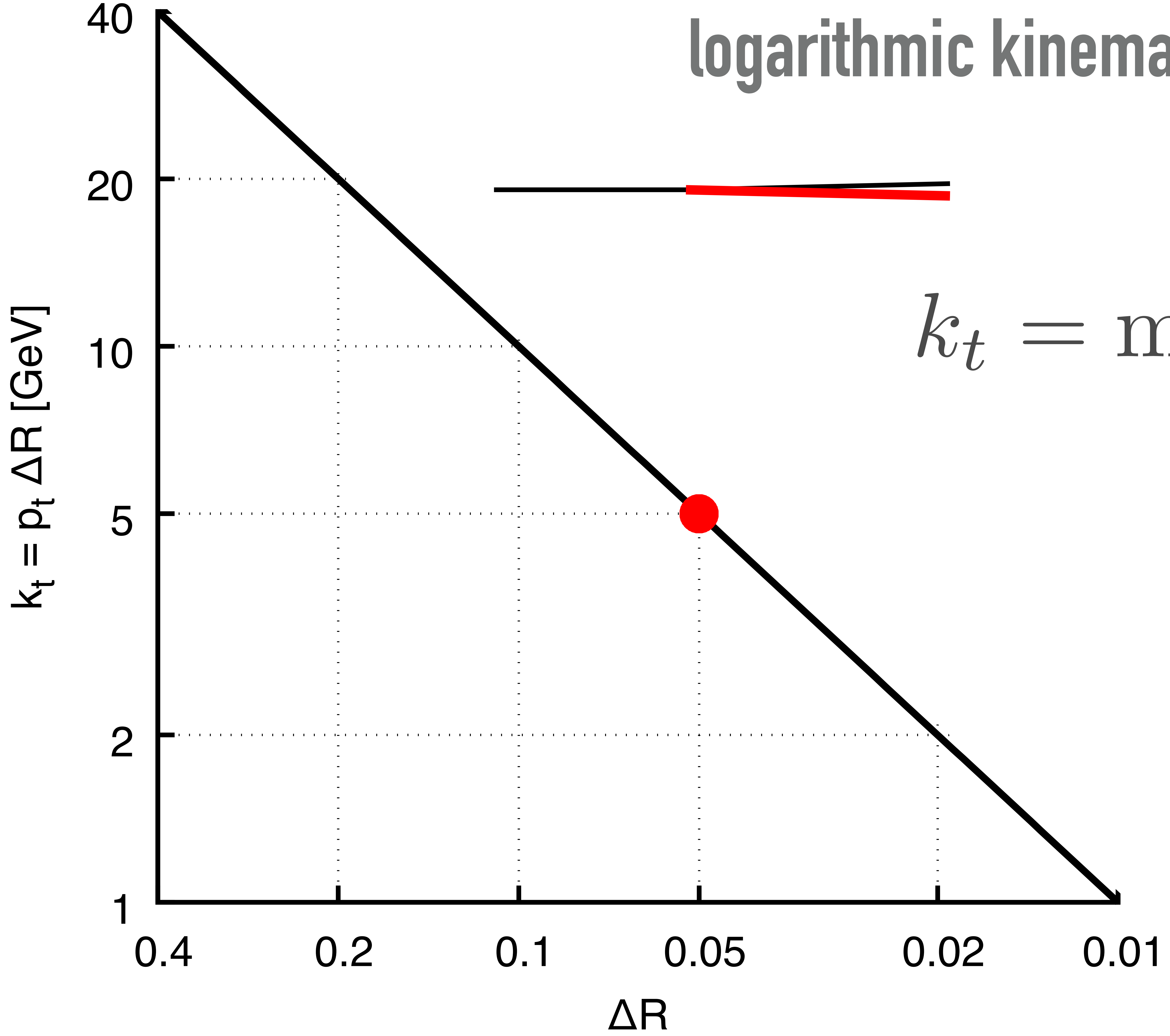
logarithmic kinematic plane whose two variables are

$$\Delta R_{ij}$$

$$k_t = \min(p_{ti}, p_{tj})\Delta R_{ij}$$

Introduced for understanding Parton Shower Monte Carlos by B. Andersson,G. Gustafson L. Lonnblad and Pettersson 1989

The Lund Plane



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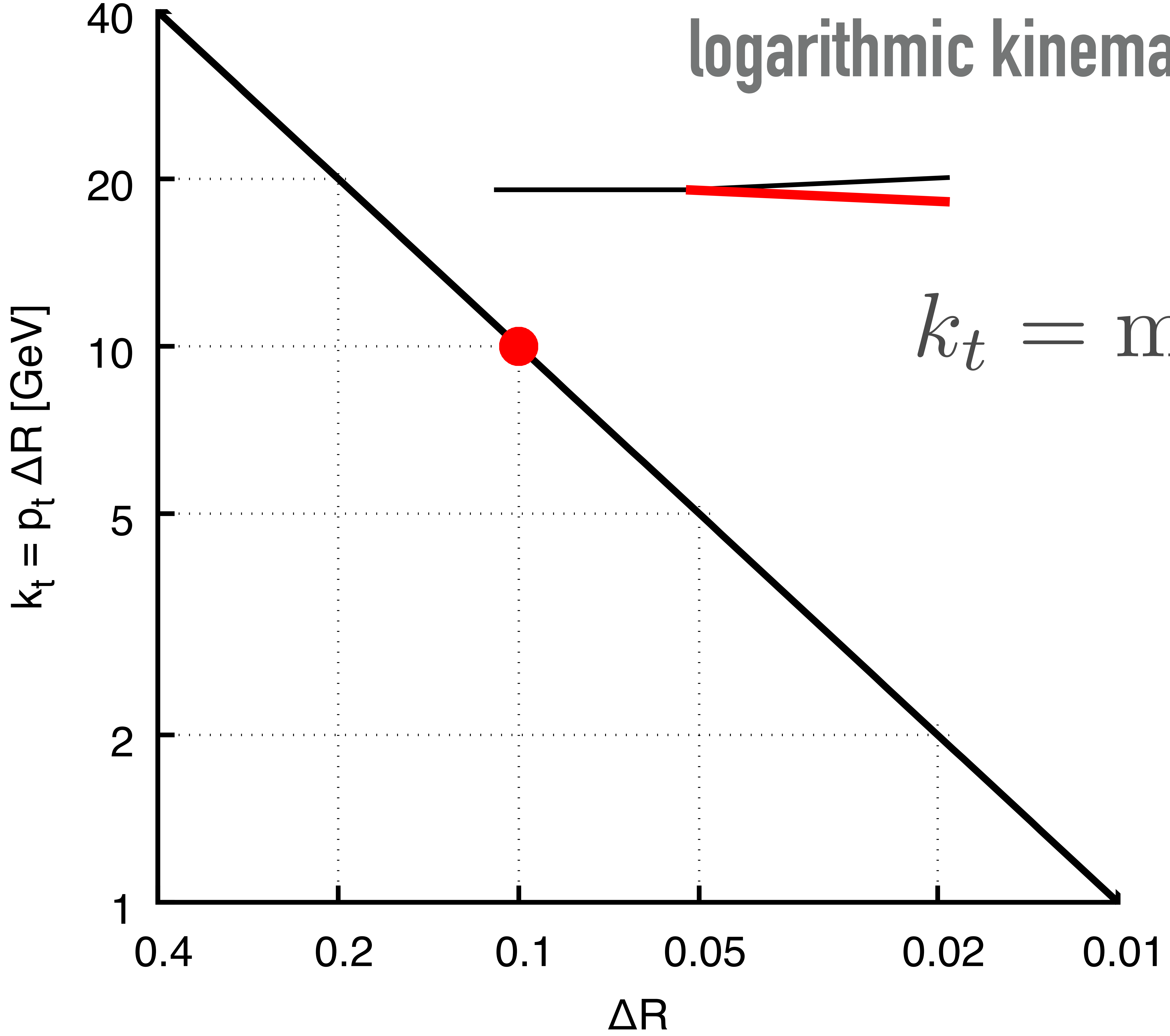

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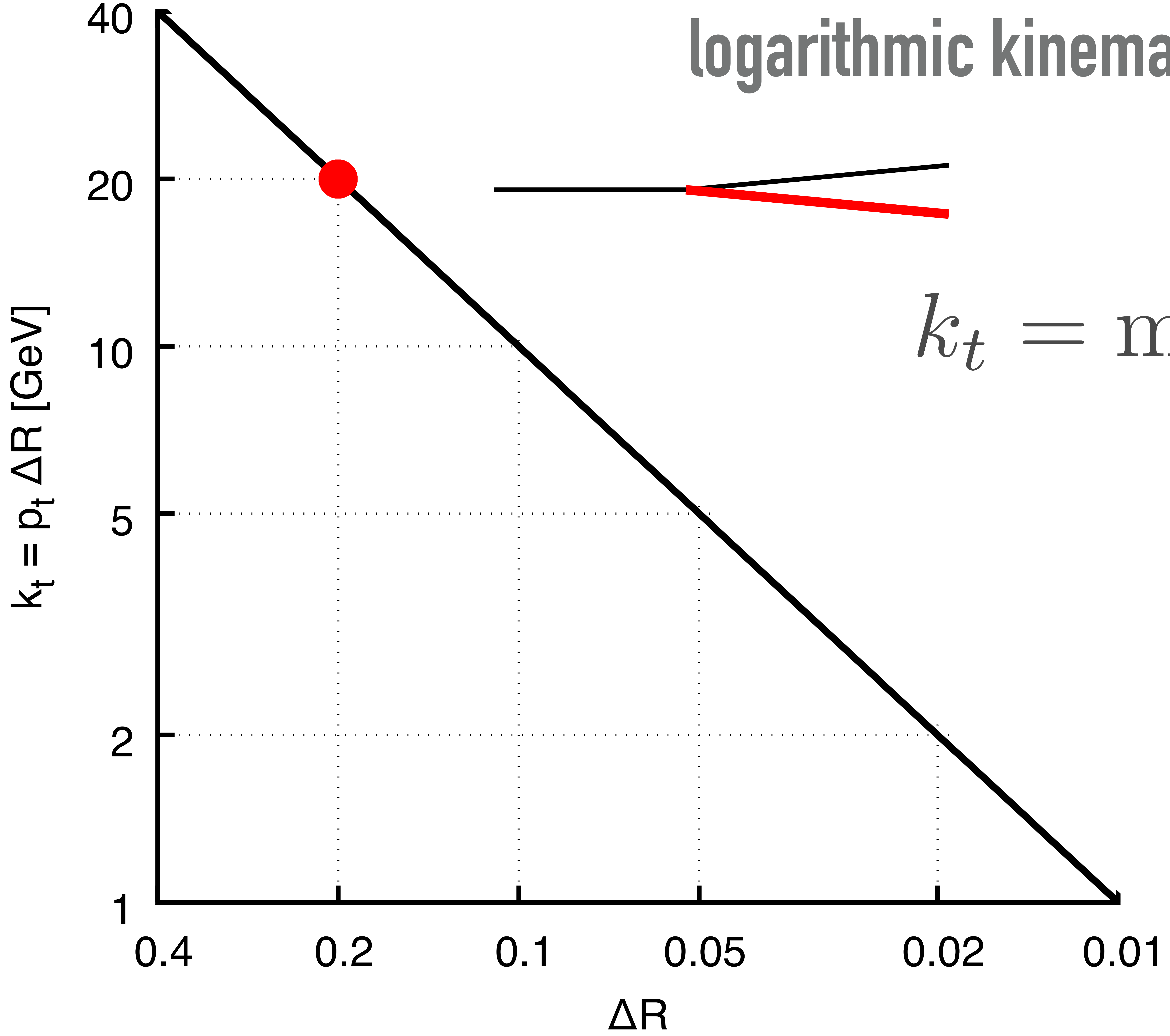

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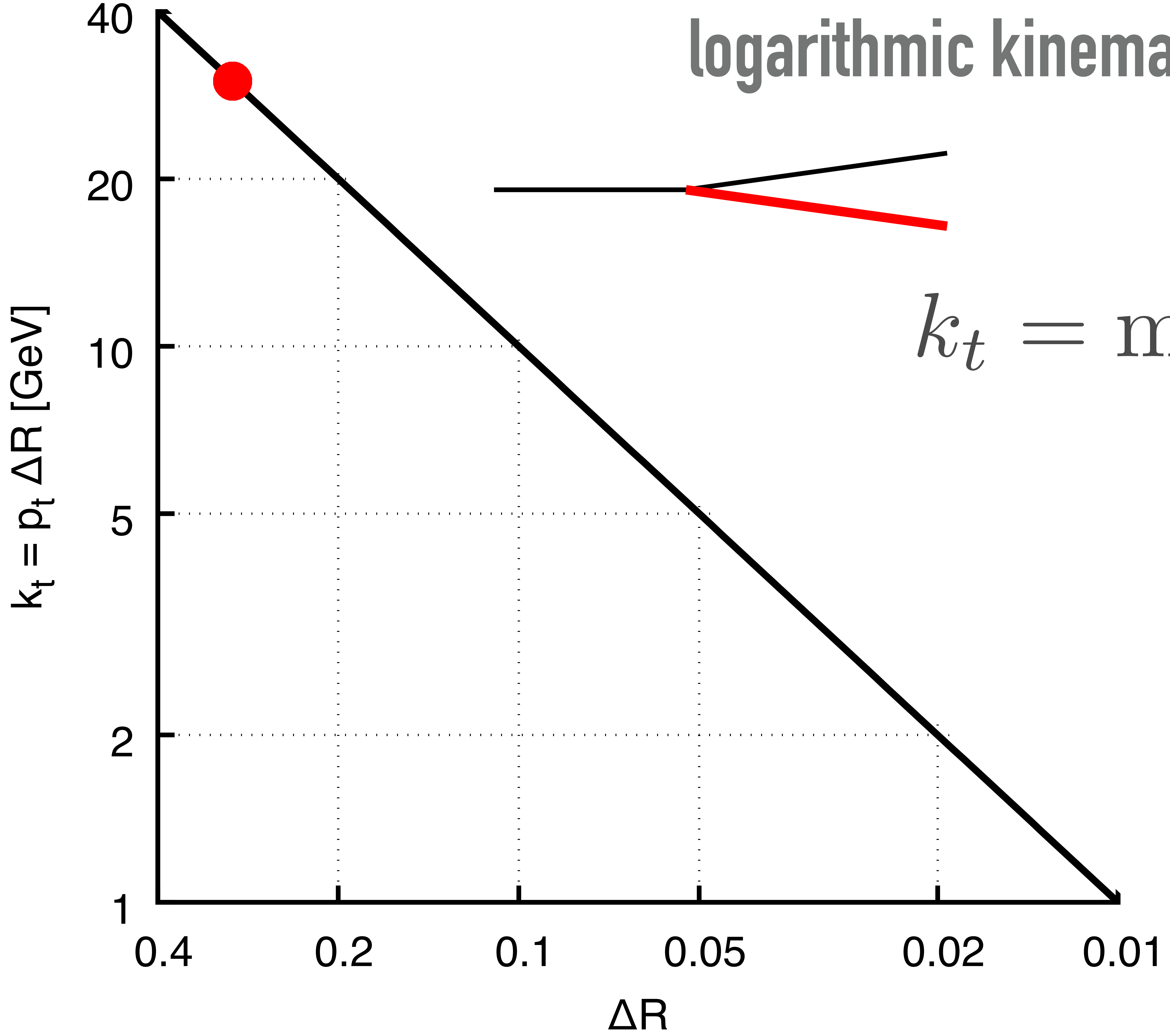

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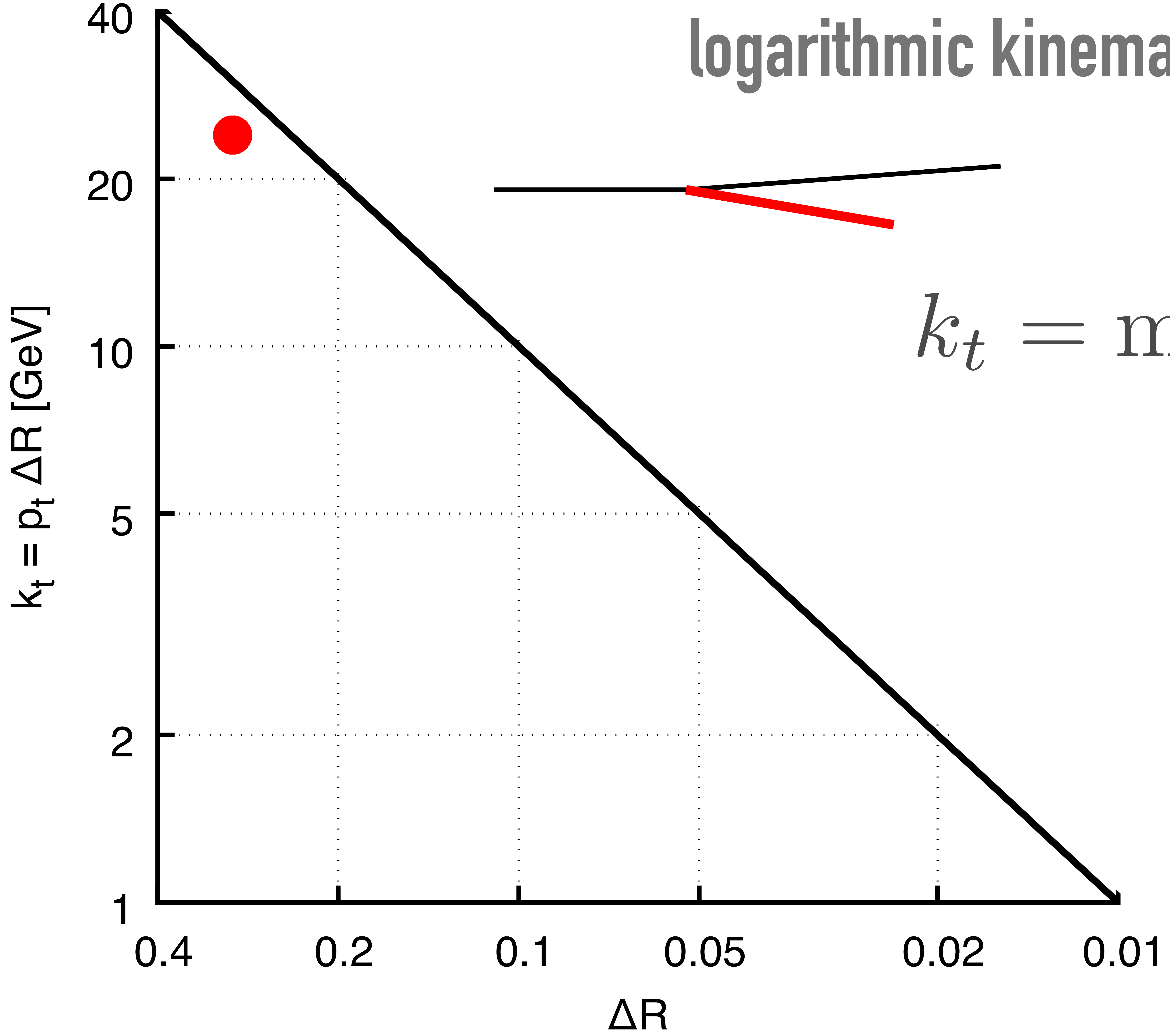

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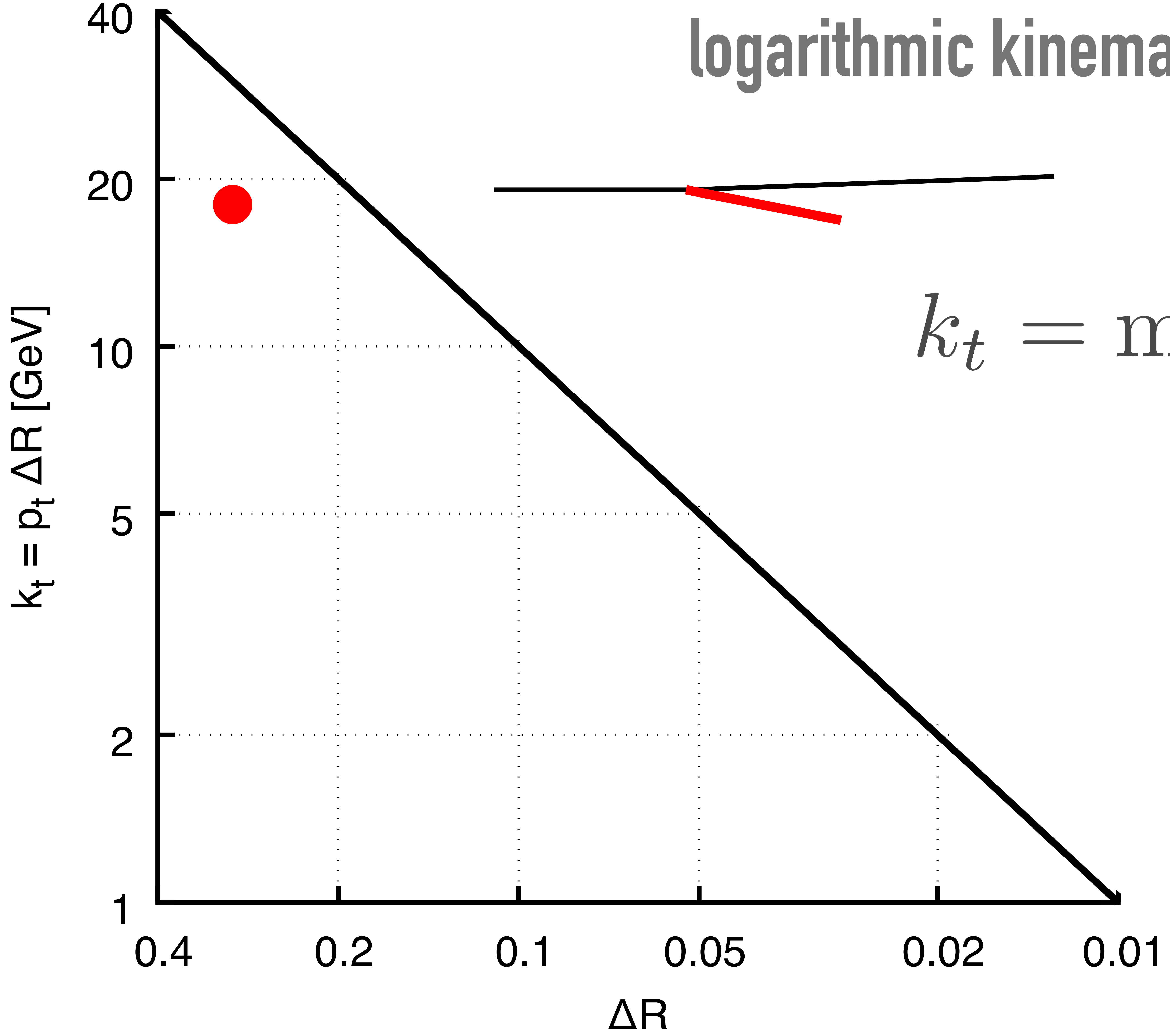

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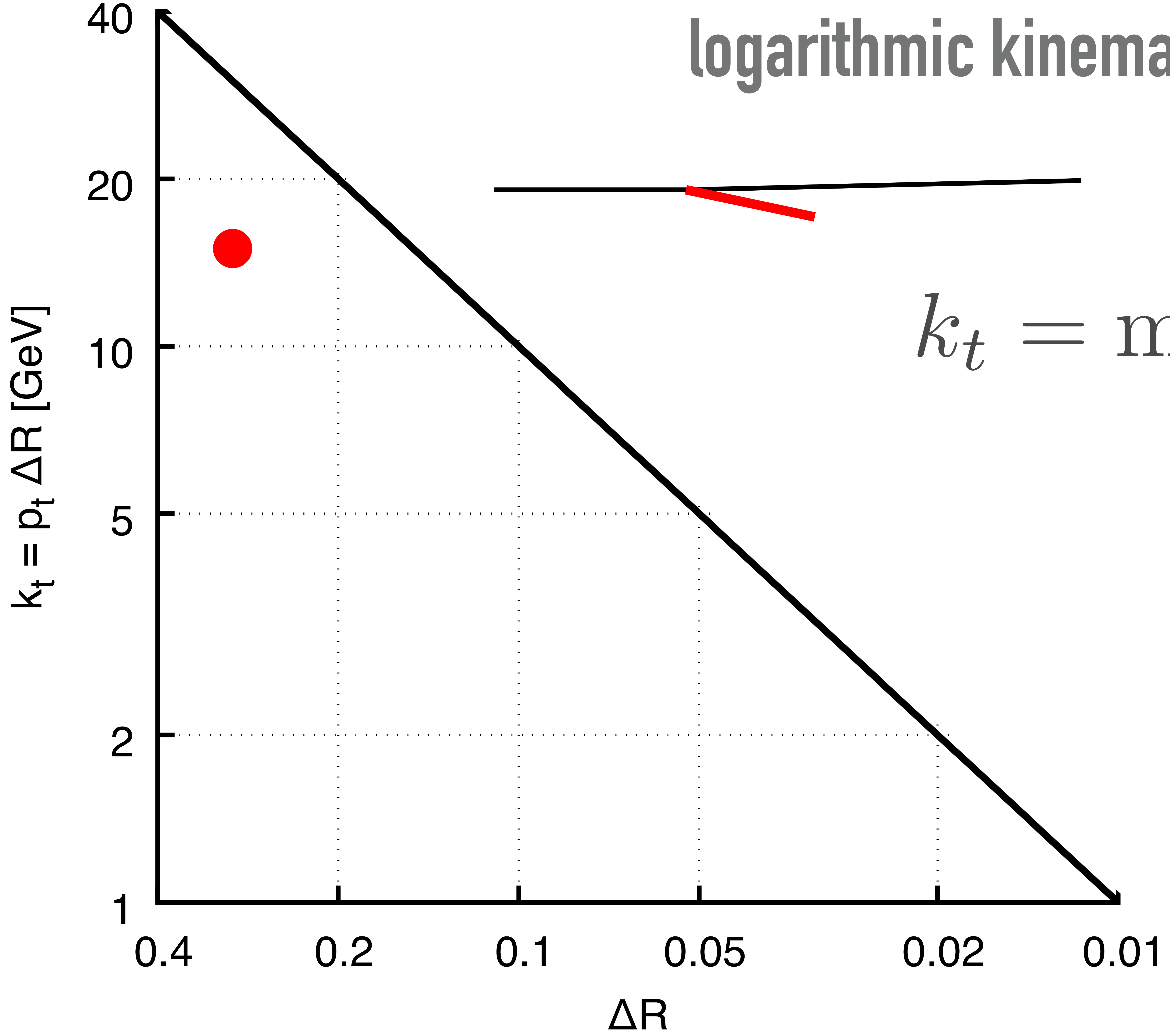

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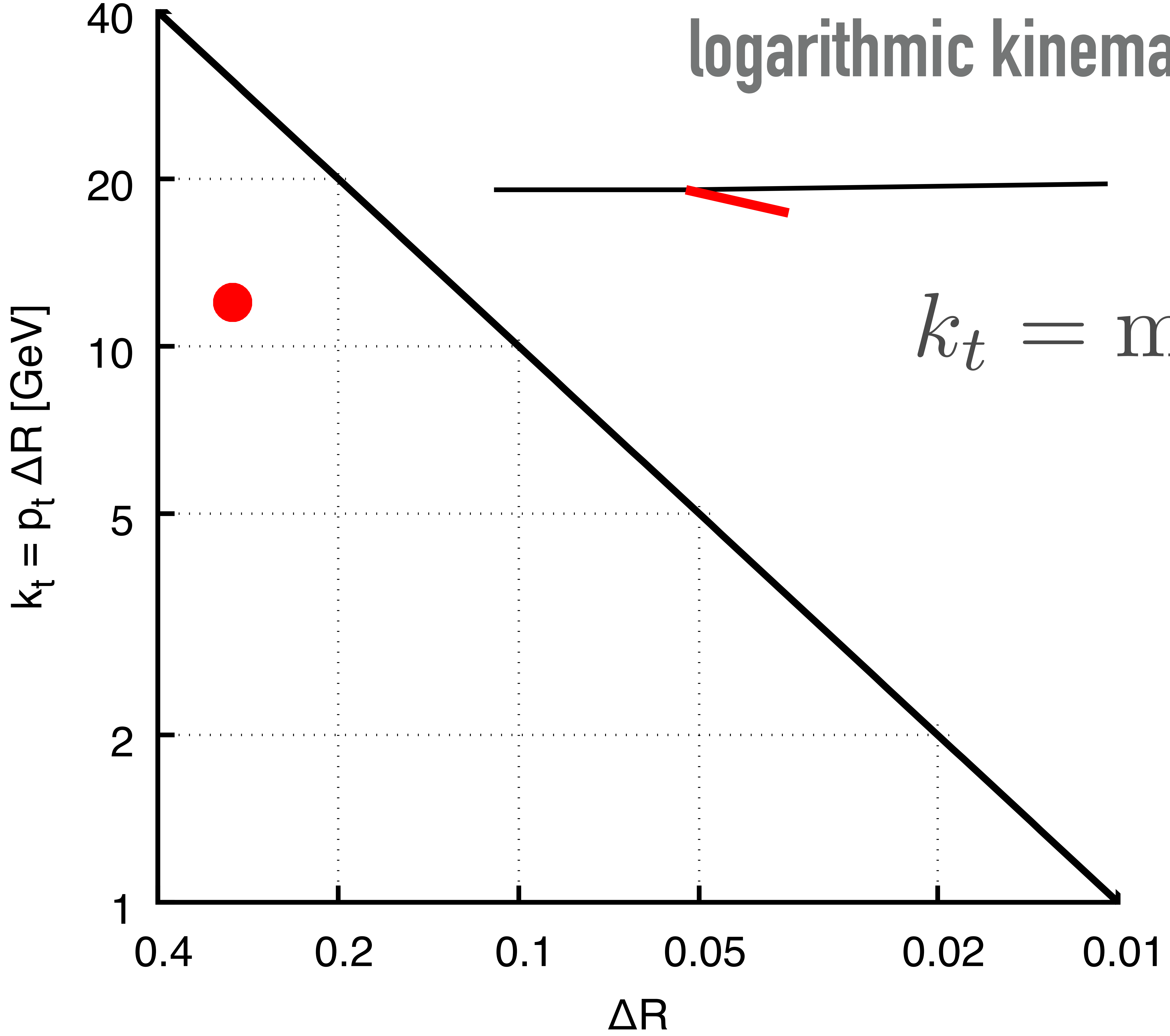

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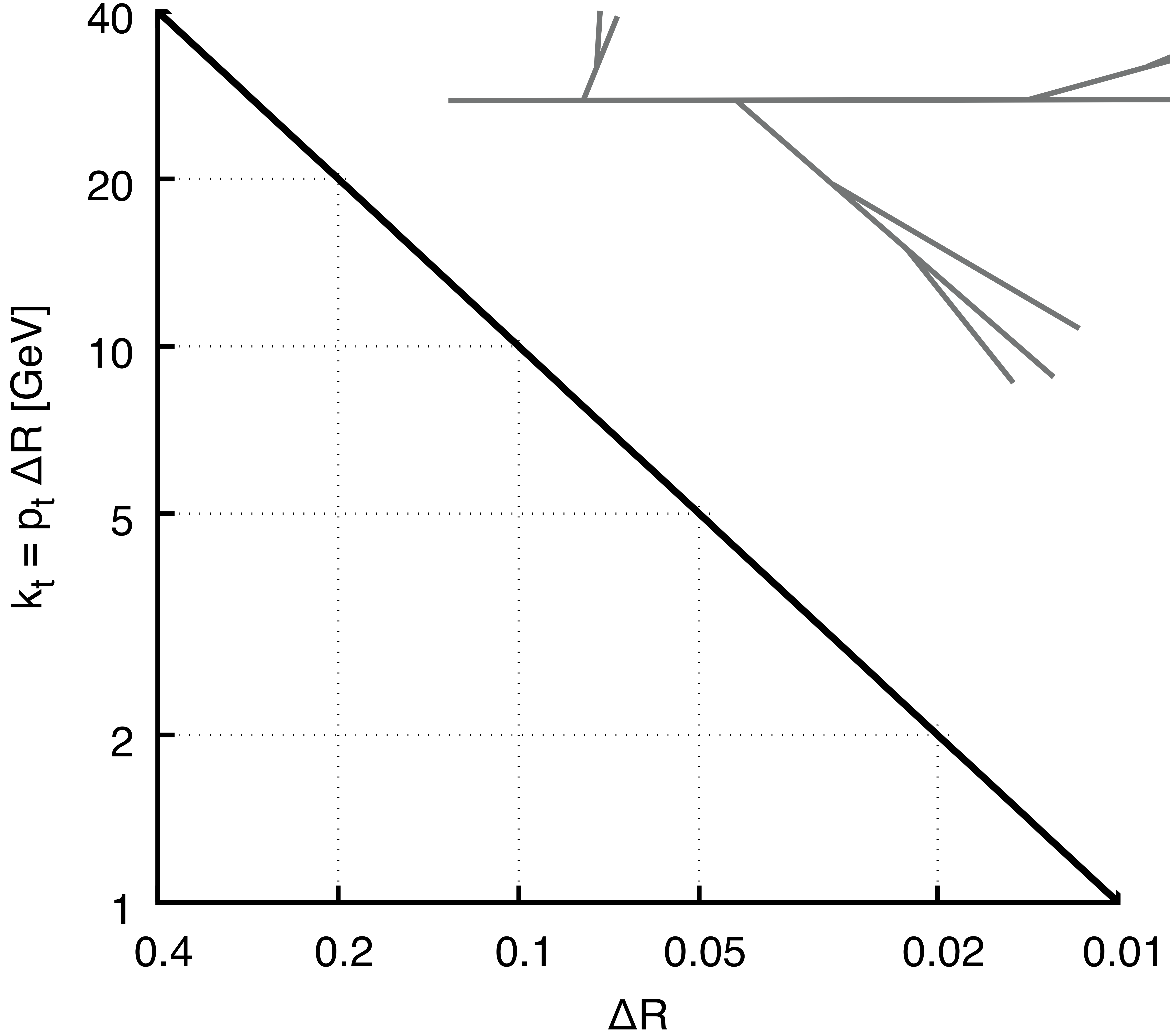
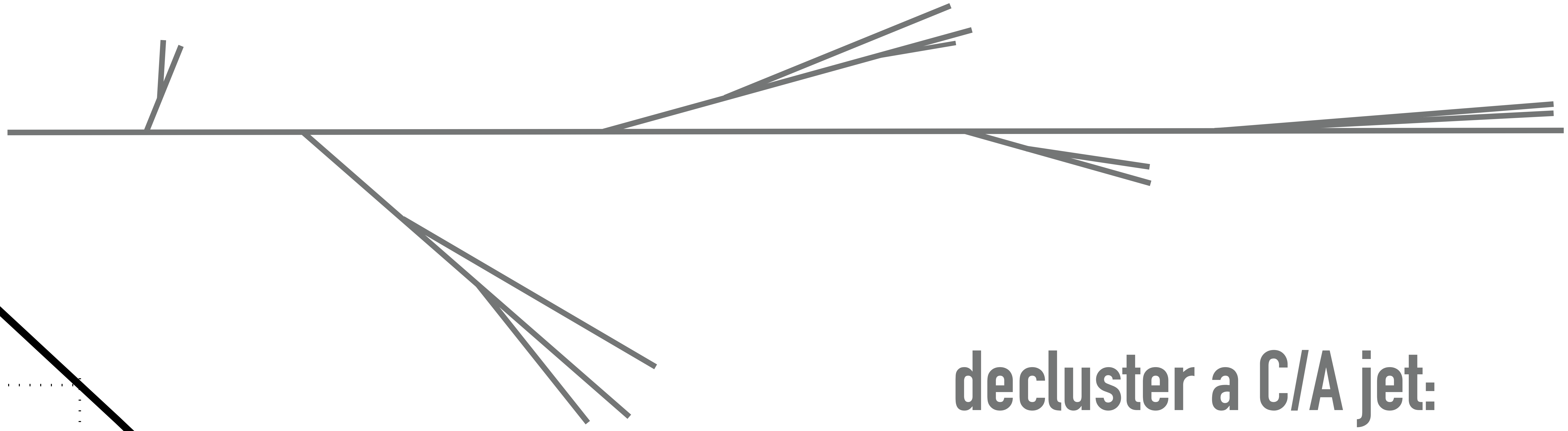


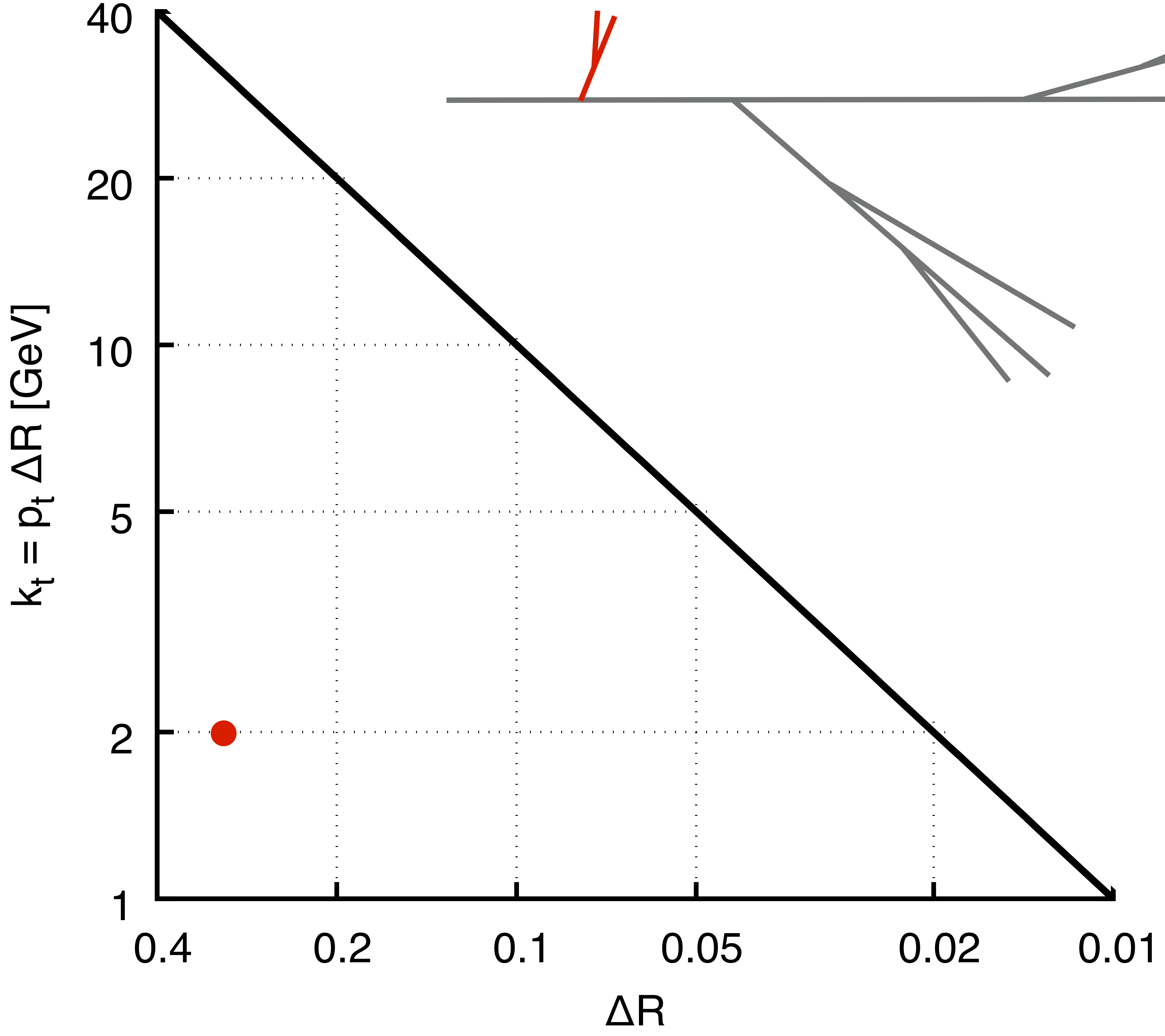


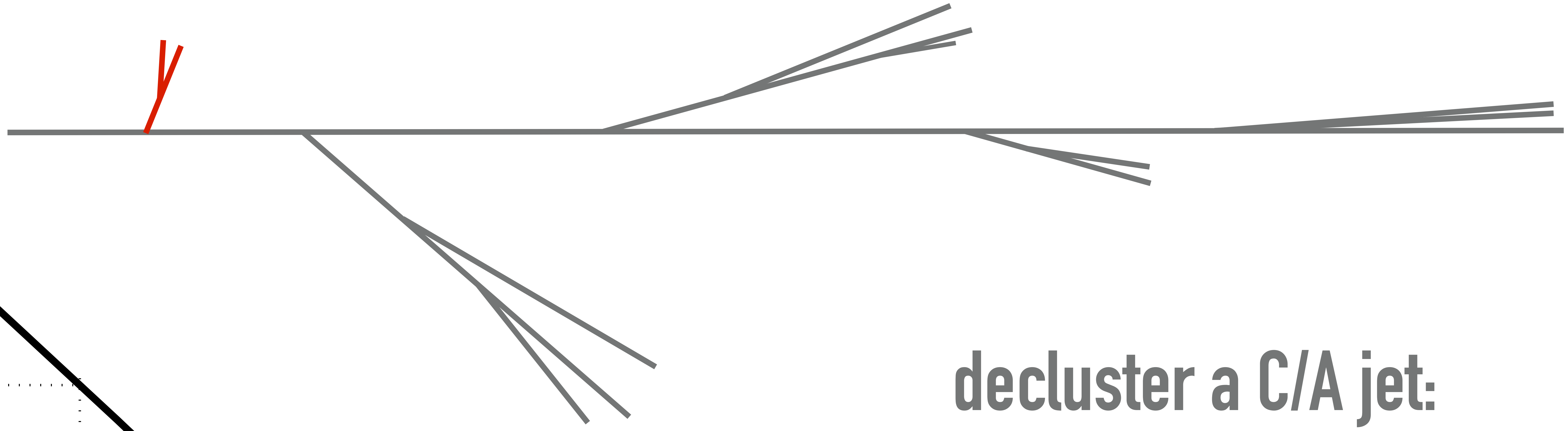
decluster a C/A jet:
at each step record ΔR,kt
as a point in the Lund plane

repeatedly follow harder branch

5th heavy-ion workshop @ CERN
+ Dreyer, Soyez & GPS, in progress (for pp applications)

constructing the Lund plane





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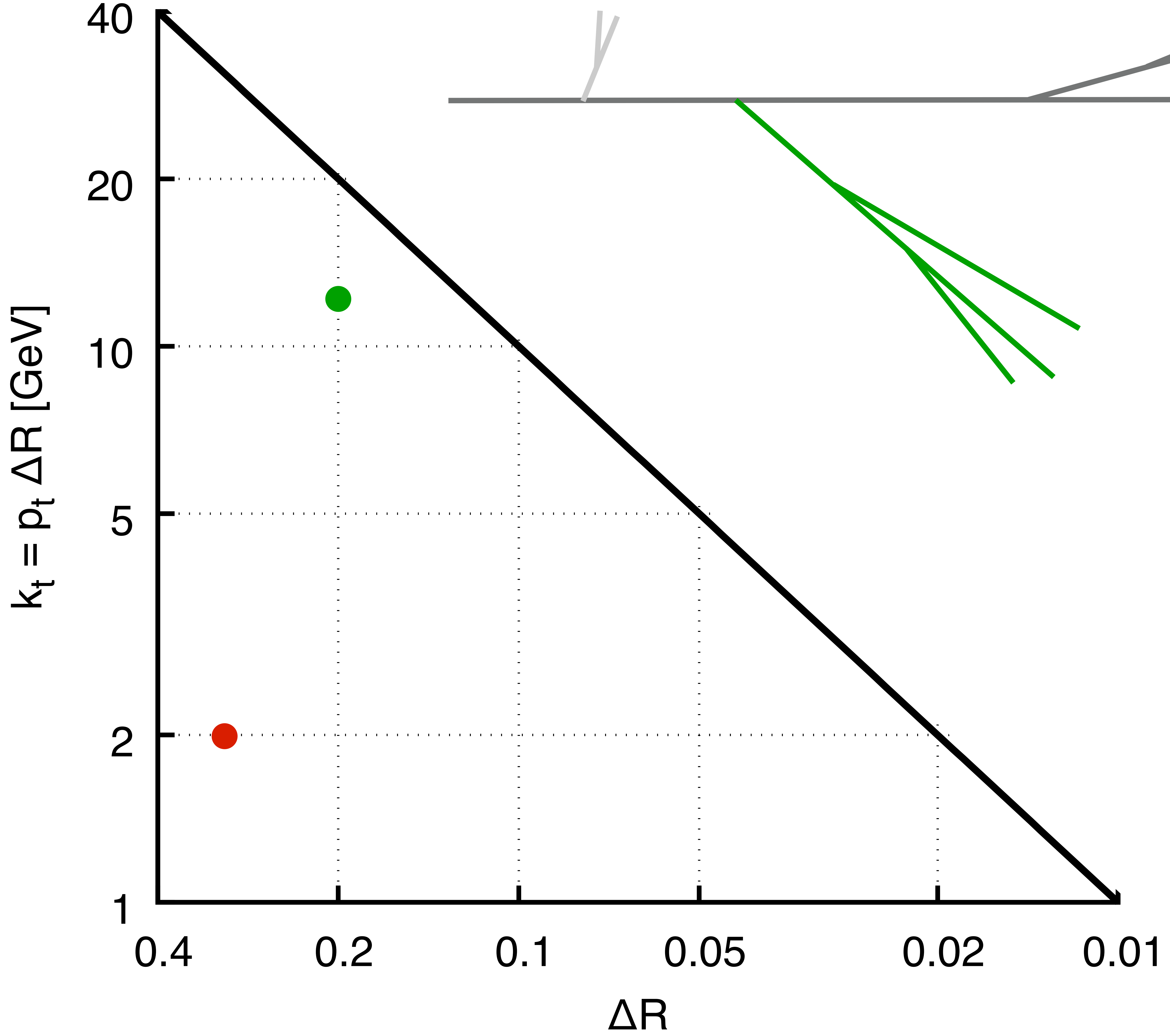

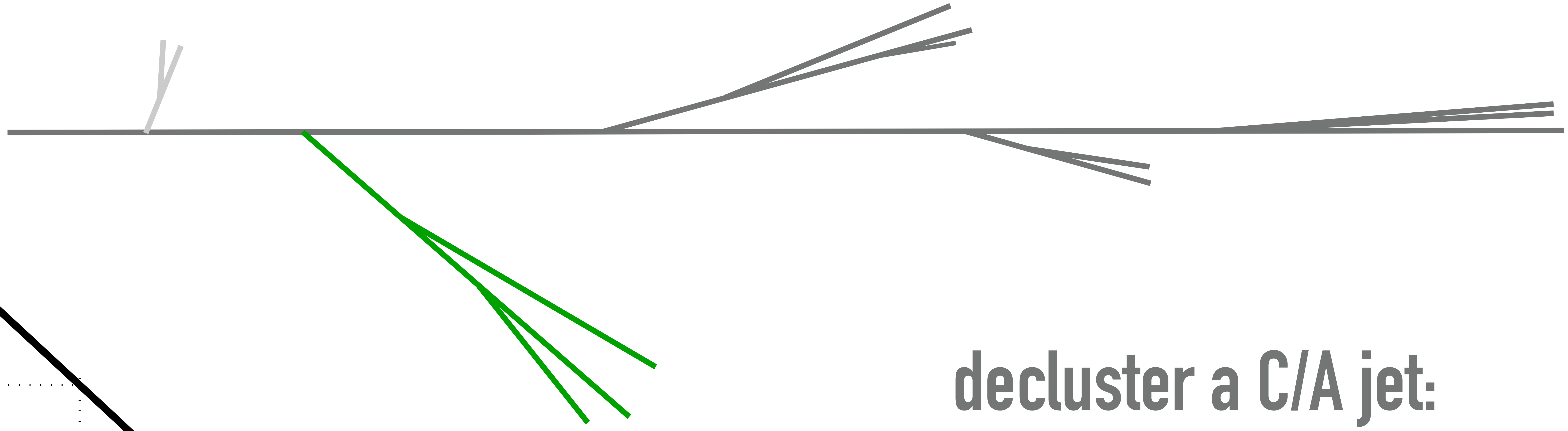

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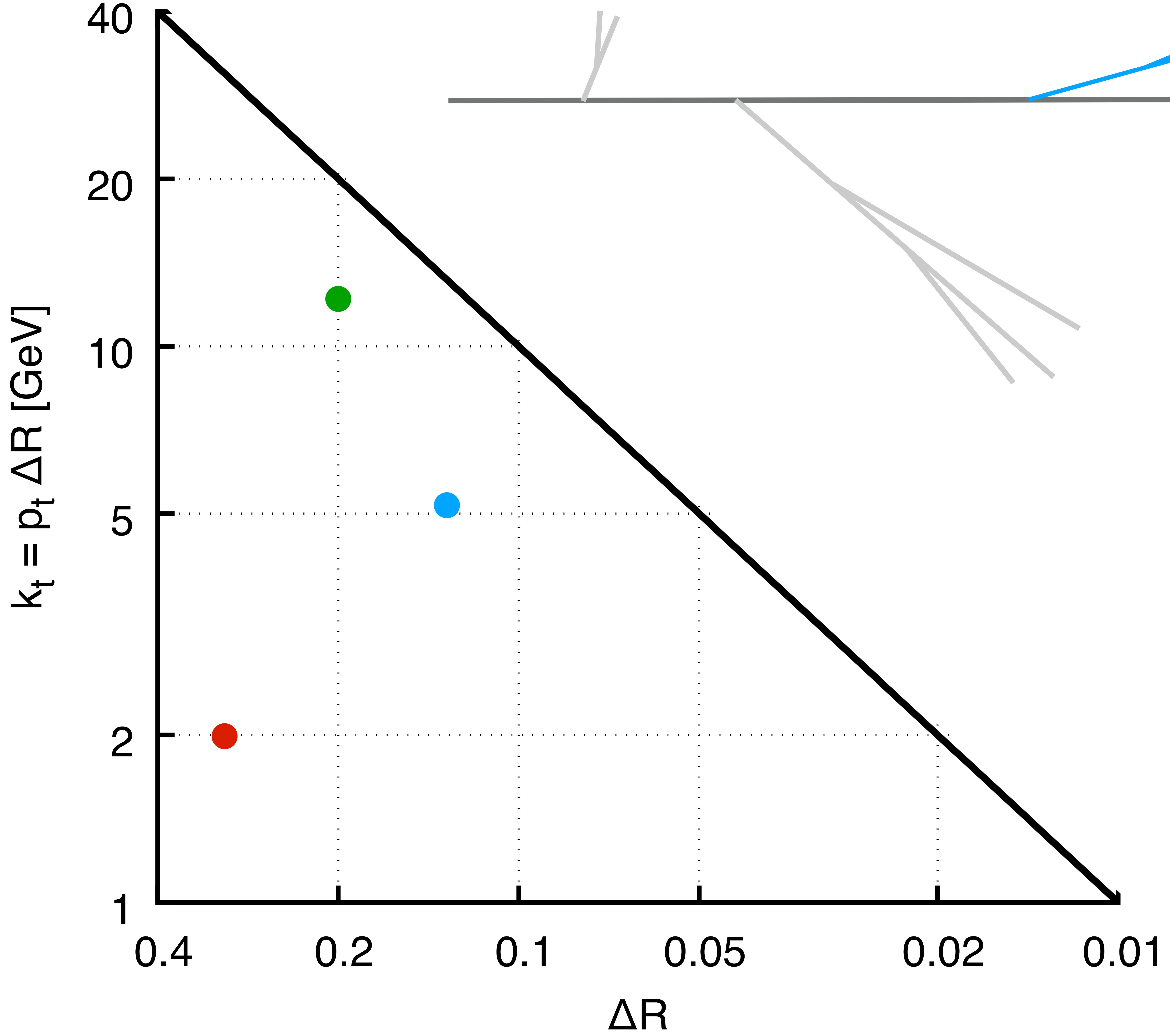

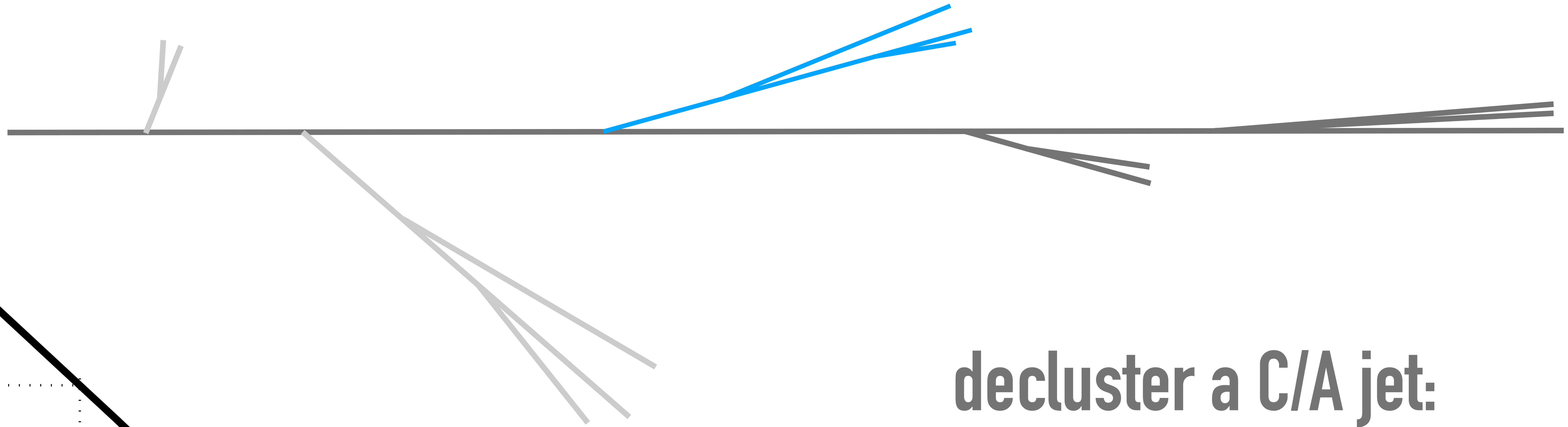

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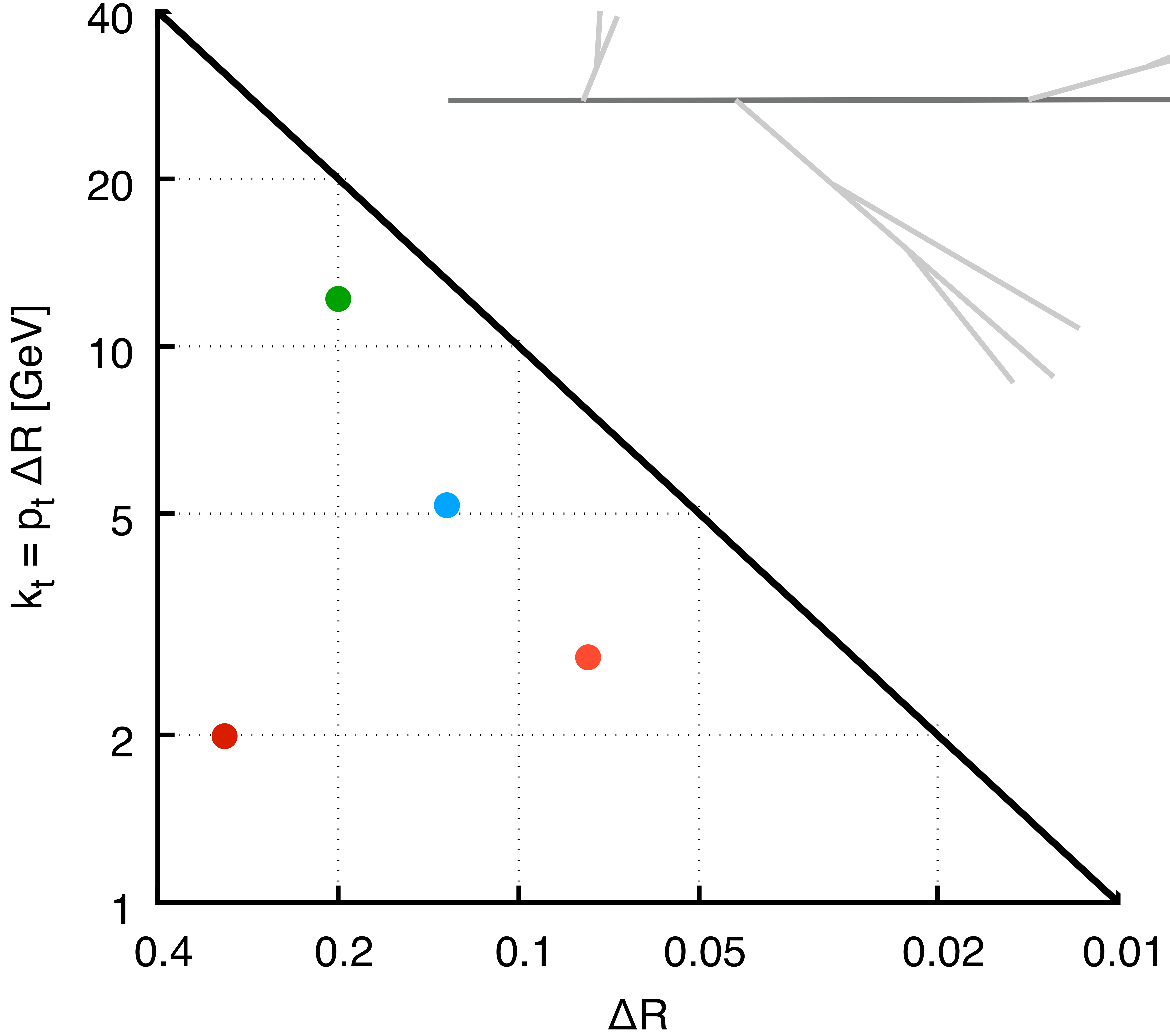

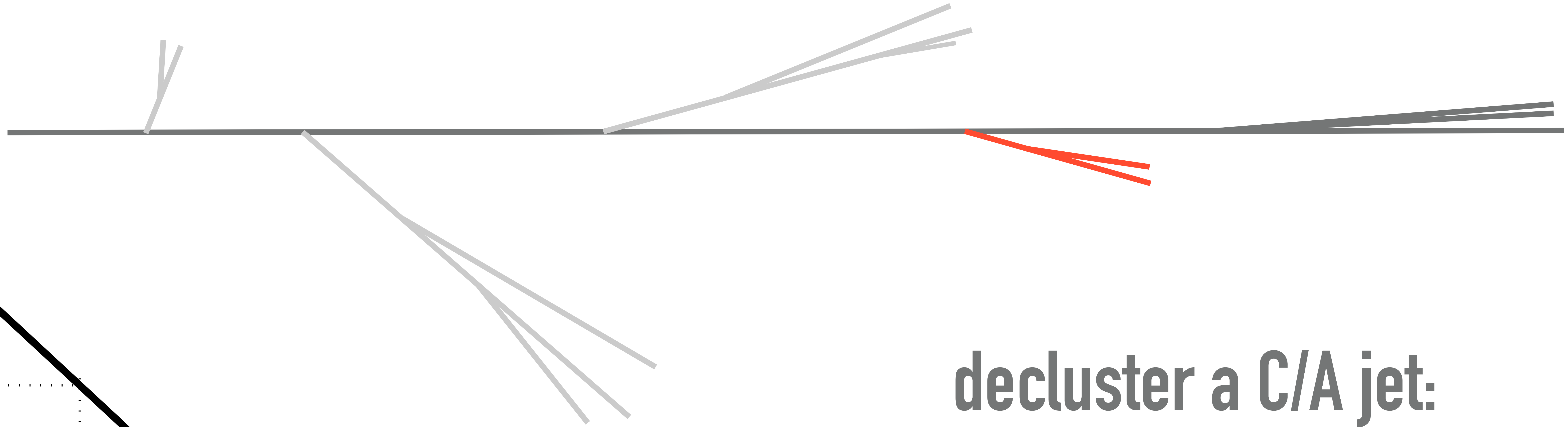

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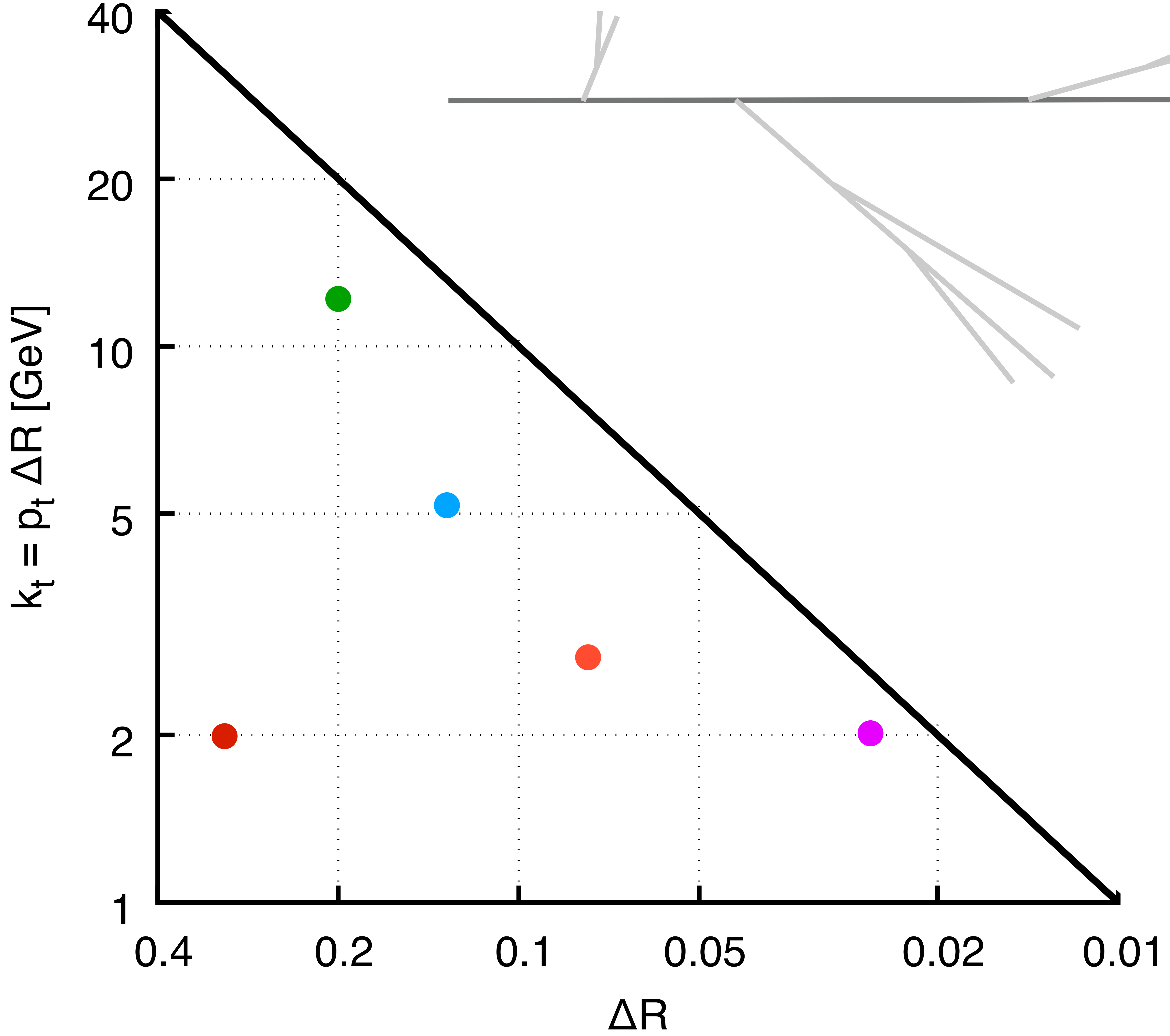

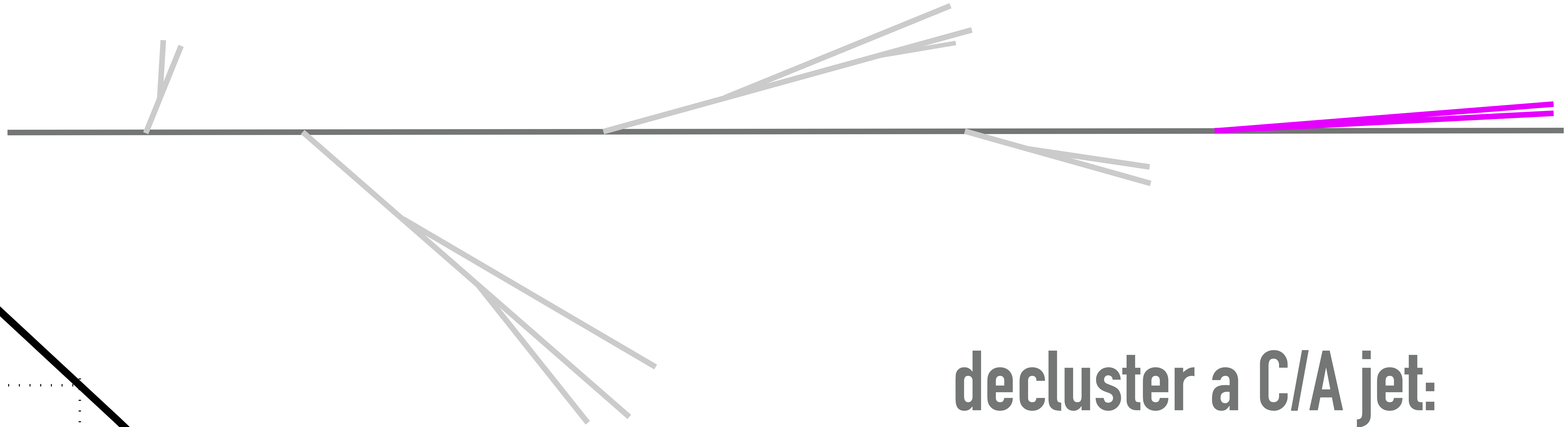

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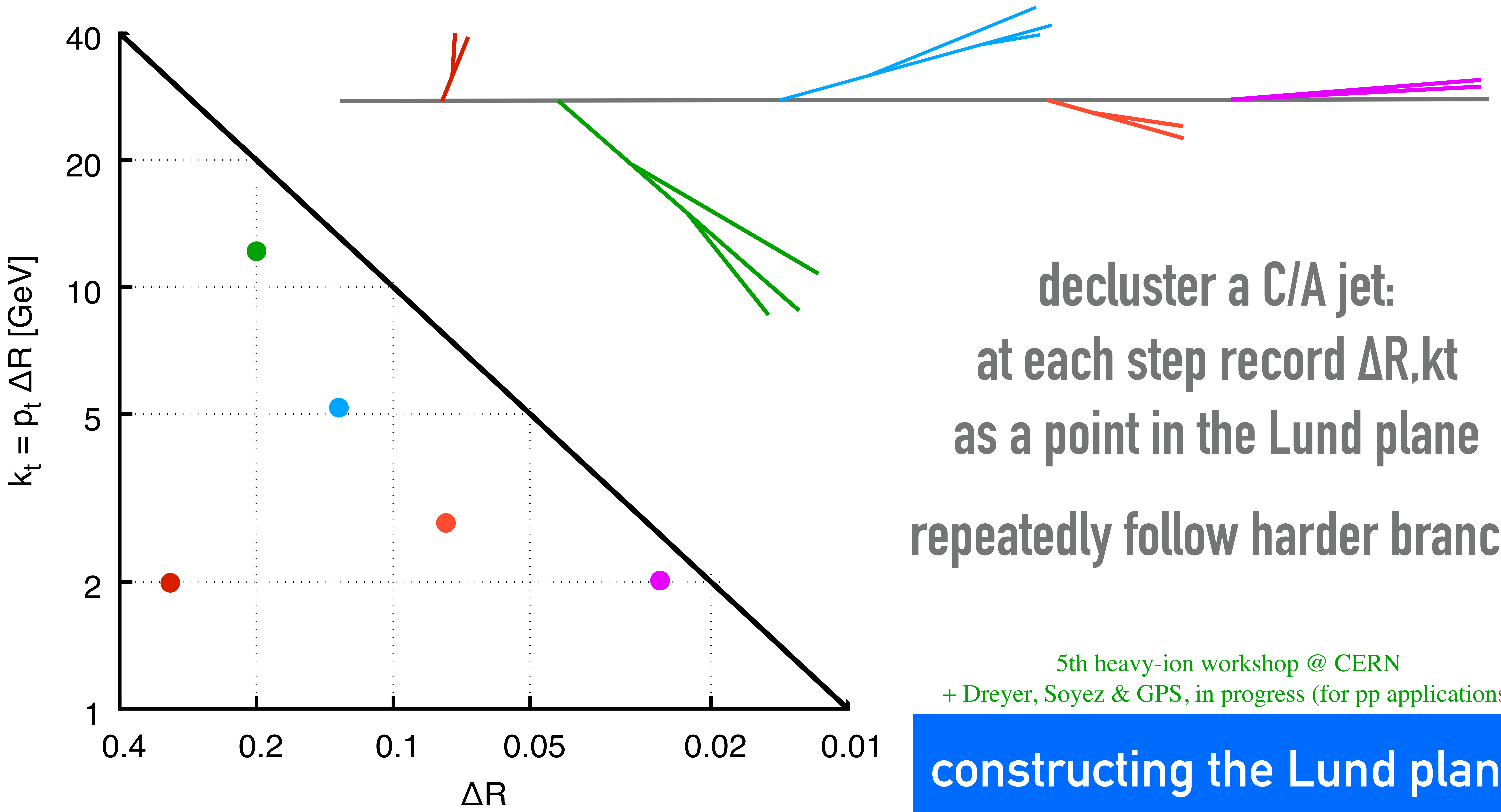

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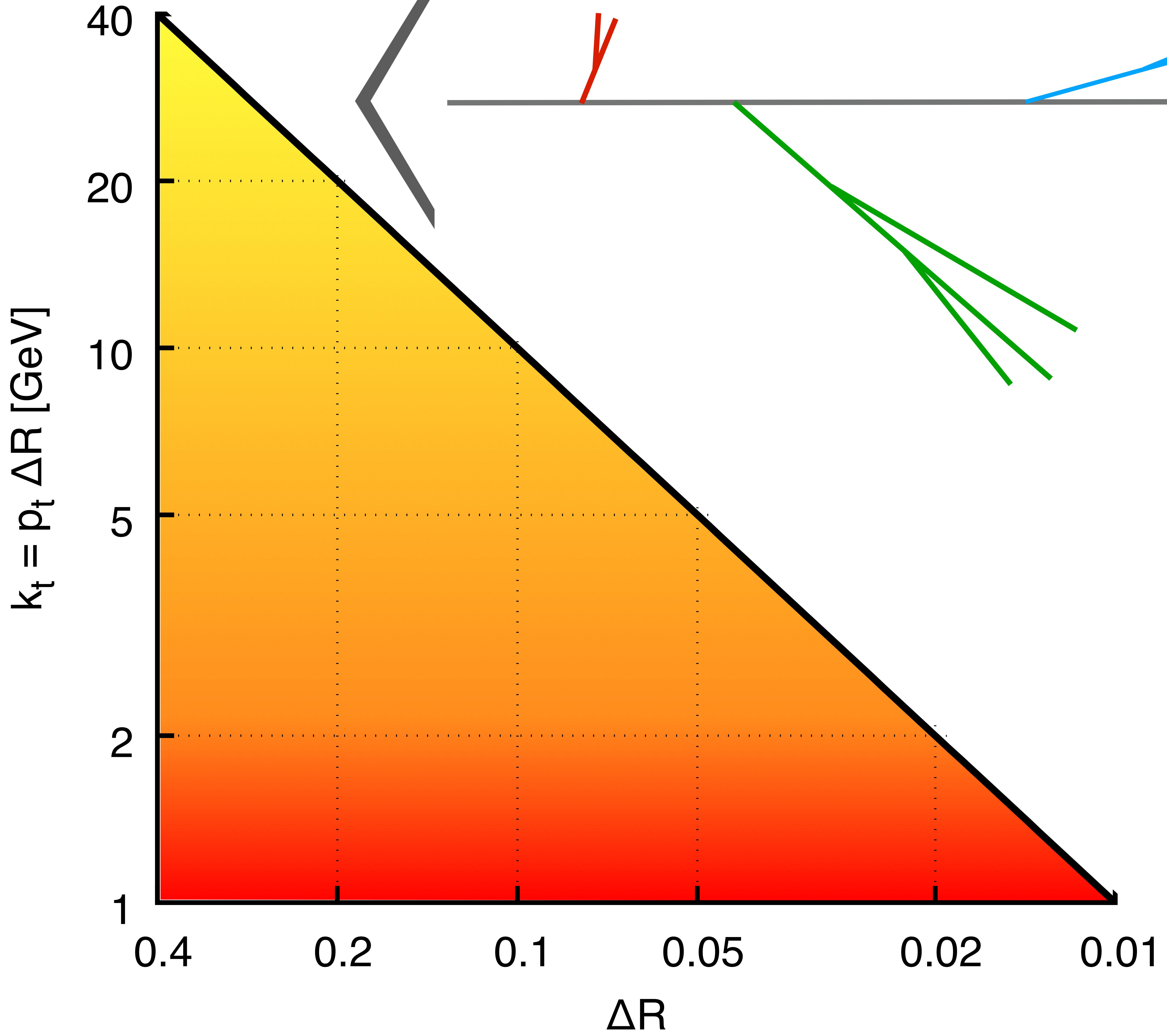
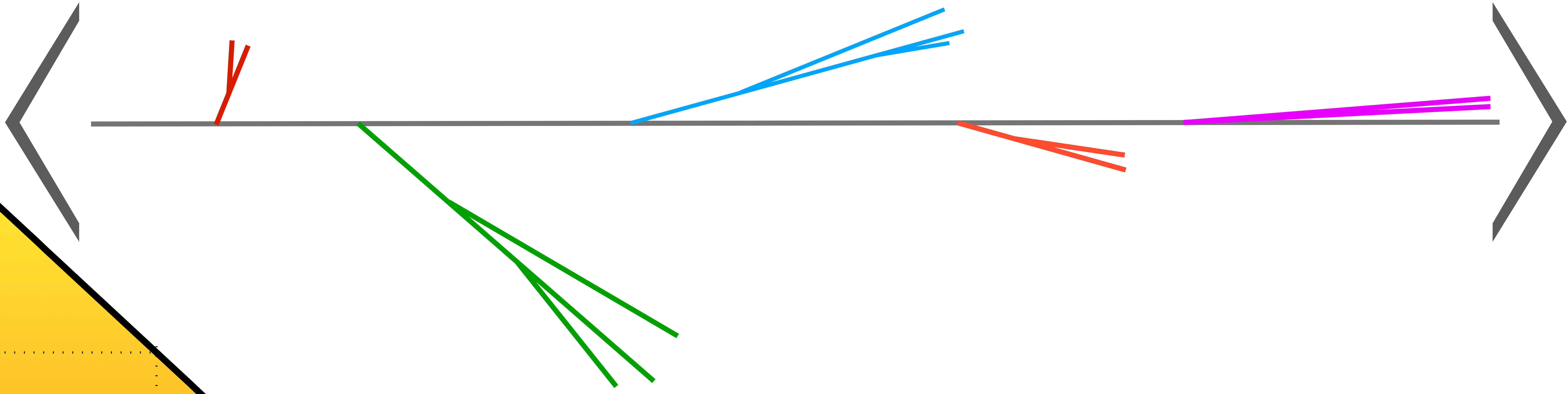
jet with $R = 0.4$, $p_t = 200$ GeV





average over many jets:

Lund plane density

5th heavy-ion workshop @ CERN
+ Dreyer, Soyez & GPS, in progress (for pp applications)

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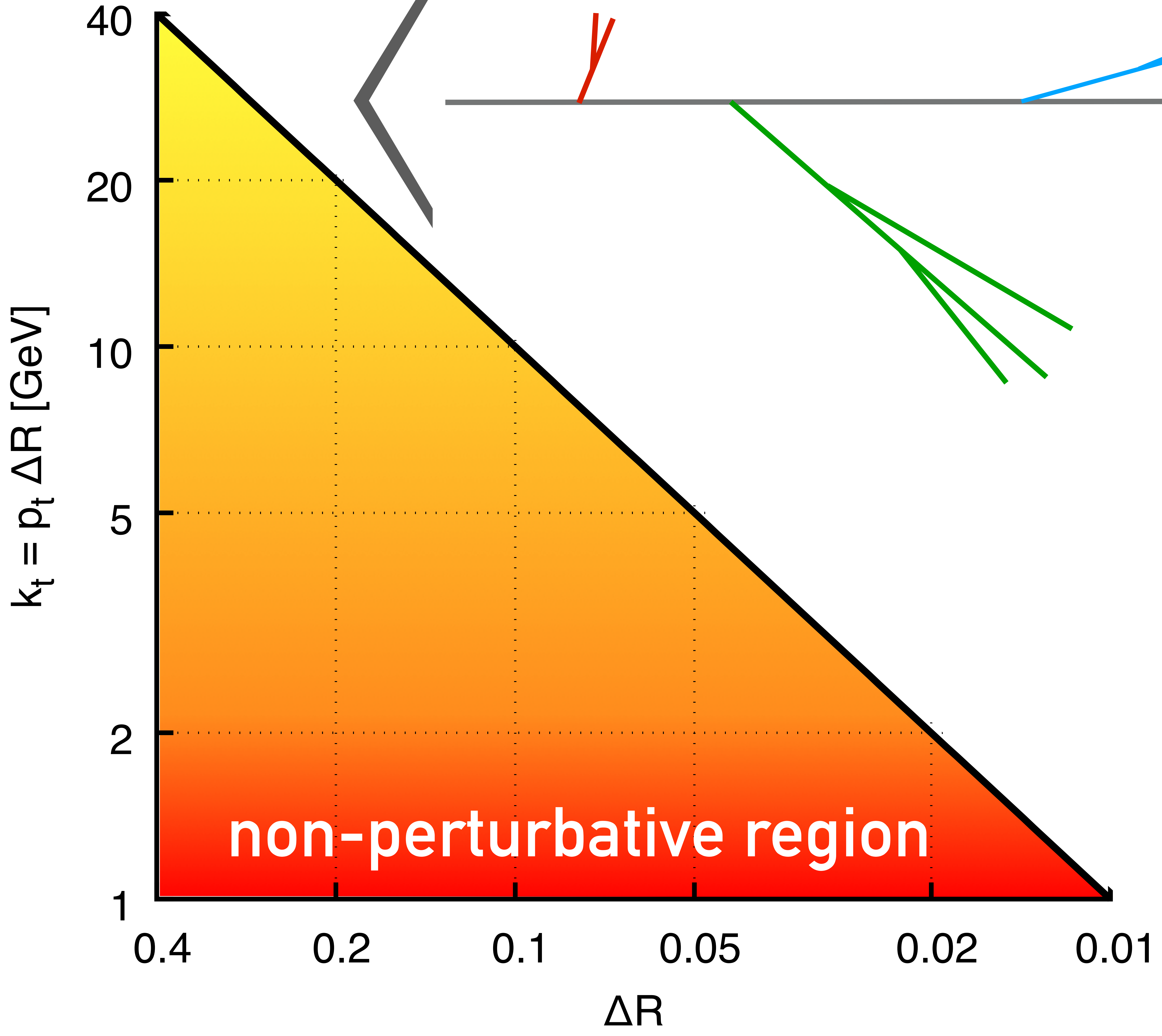

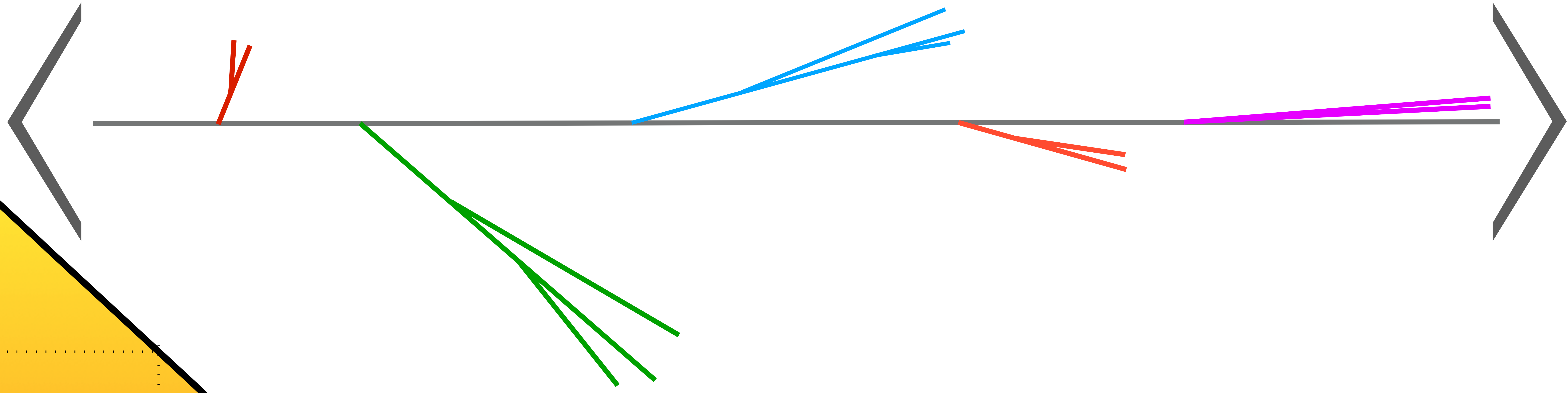

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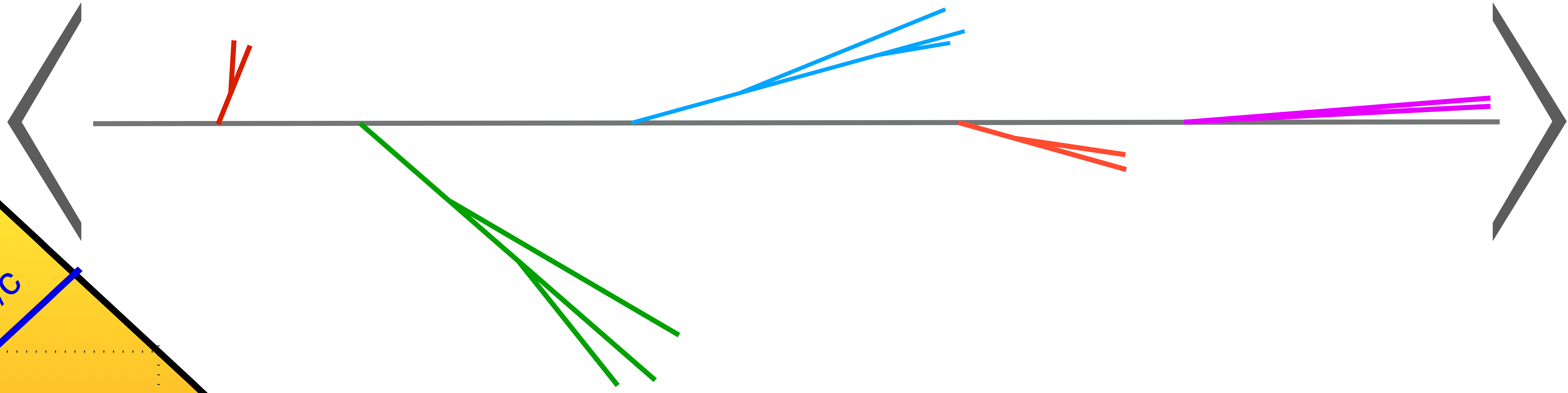

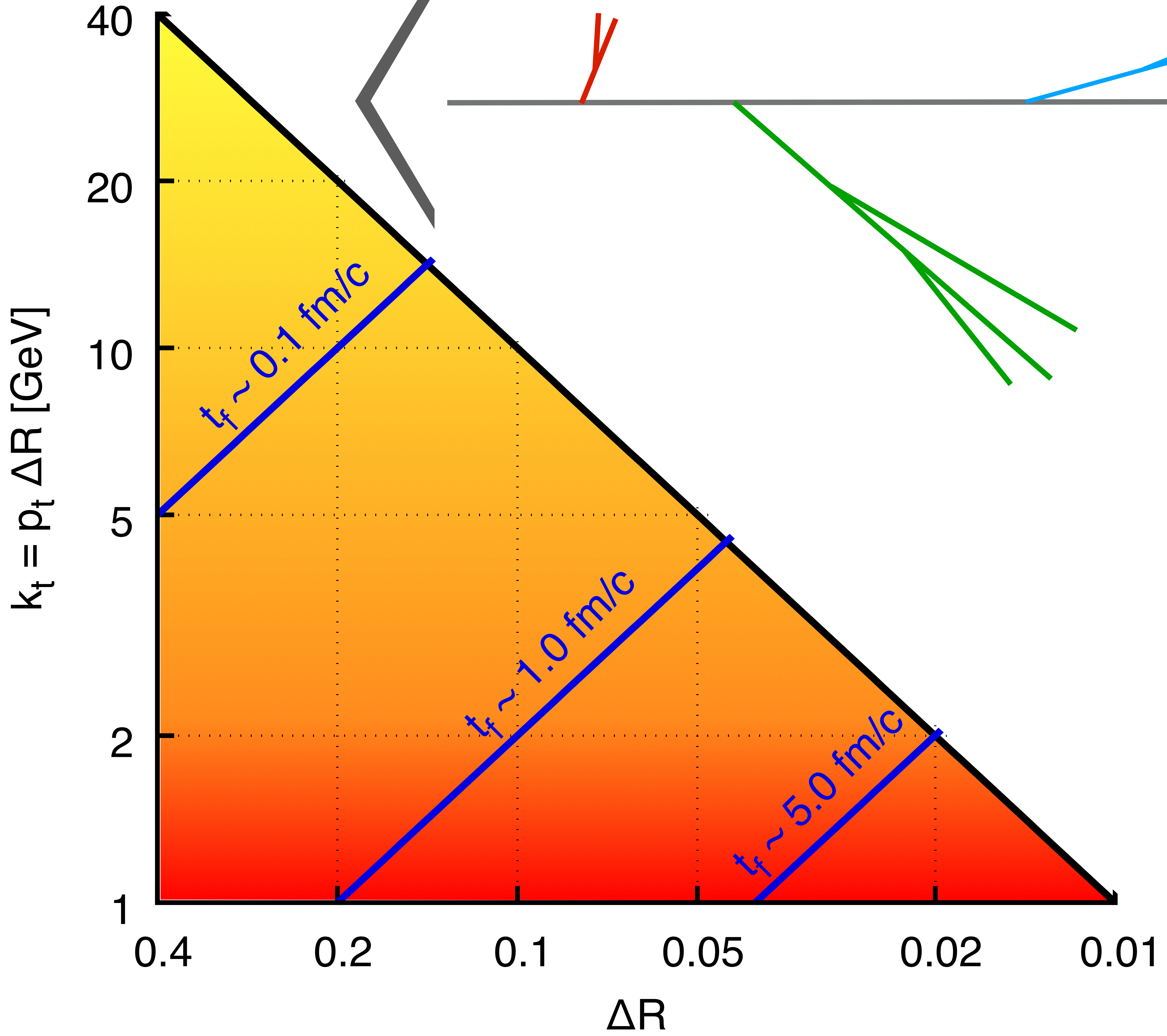

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constructing the Lund plane

constructing the Lund plane

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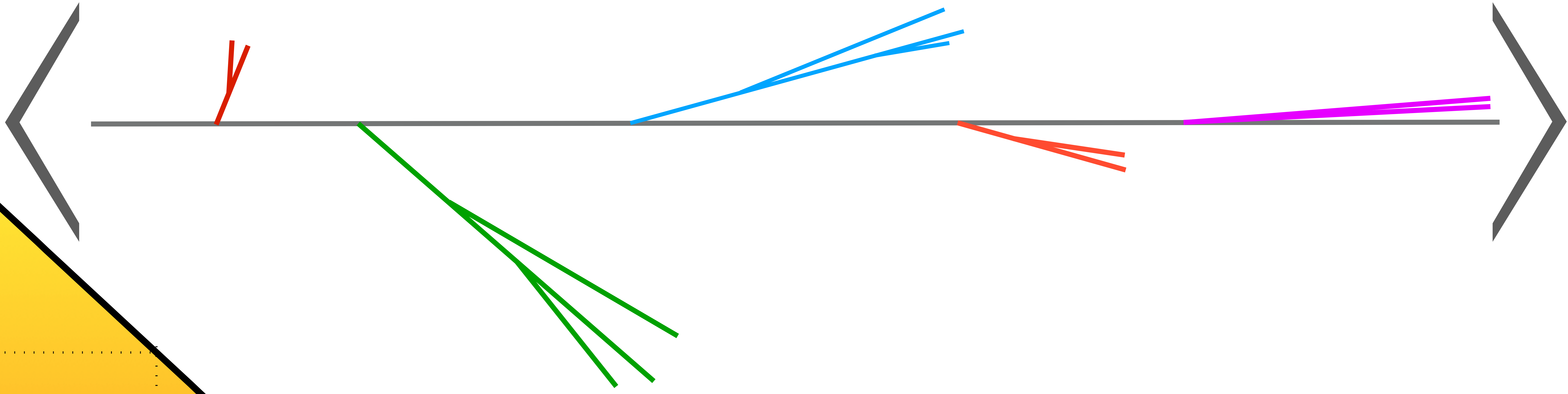

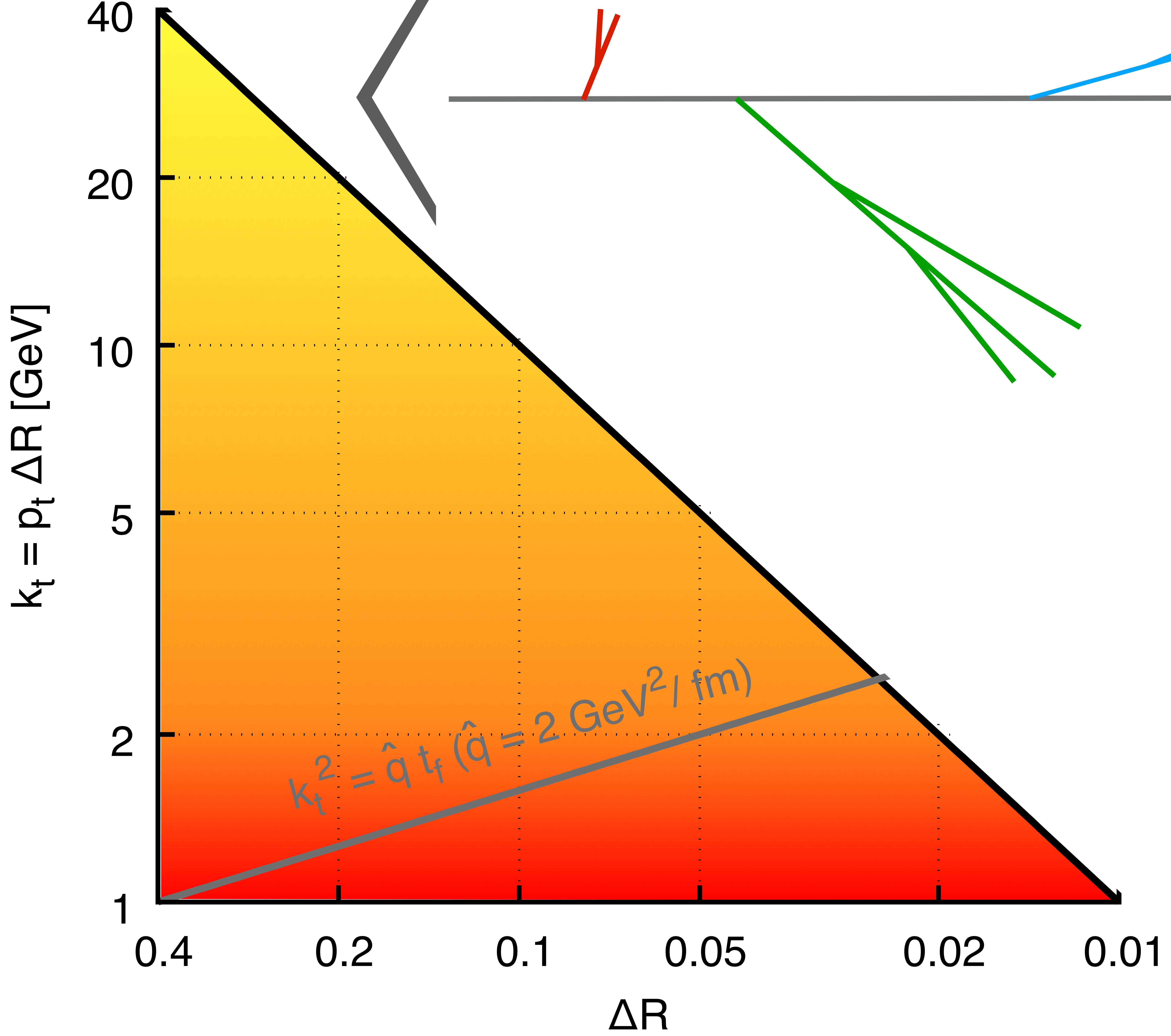

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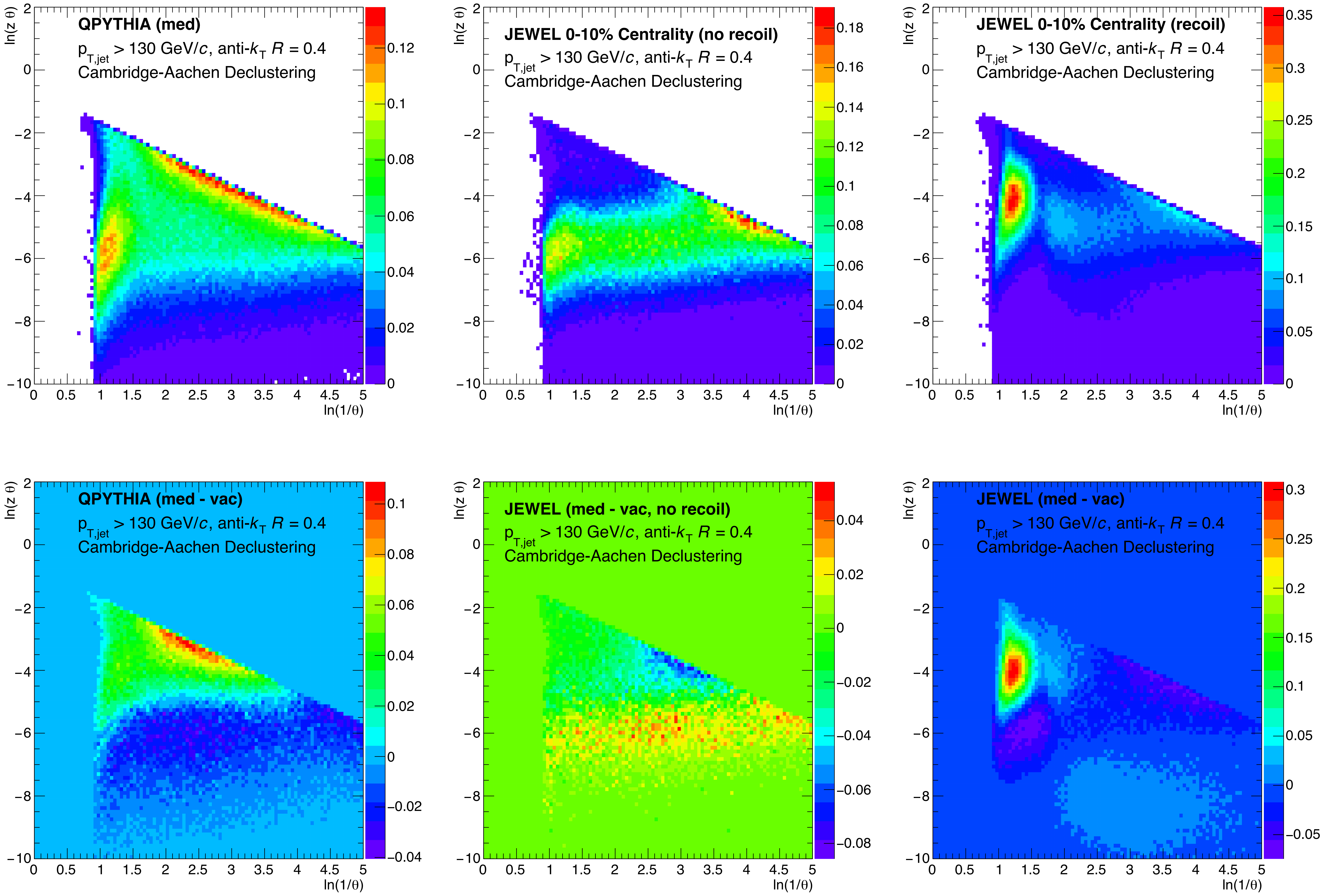
Lund planes from draft 5th heavy-ion workshop proceedings



see also


arXiv.org > hep-ph > arXiv:1803.03589

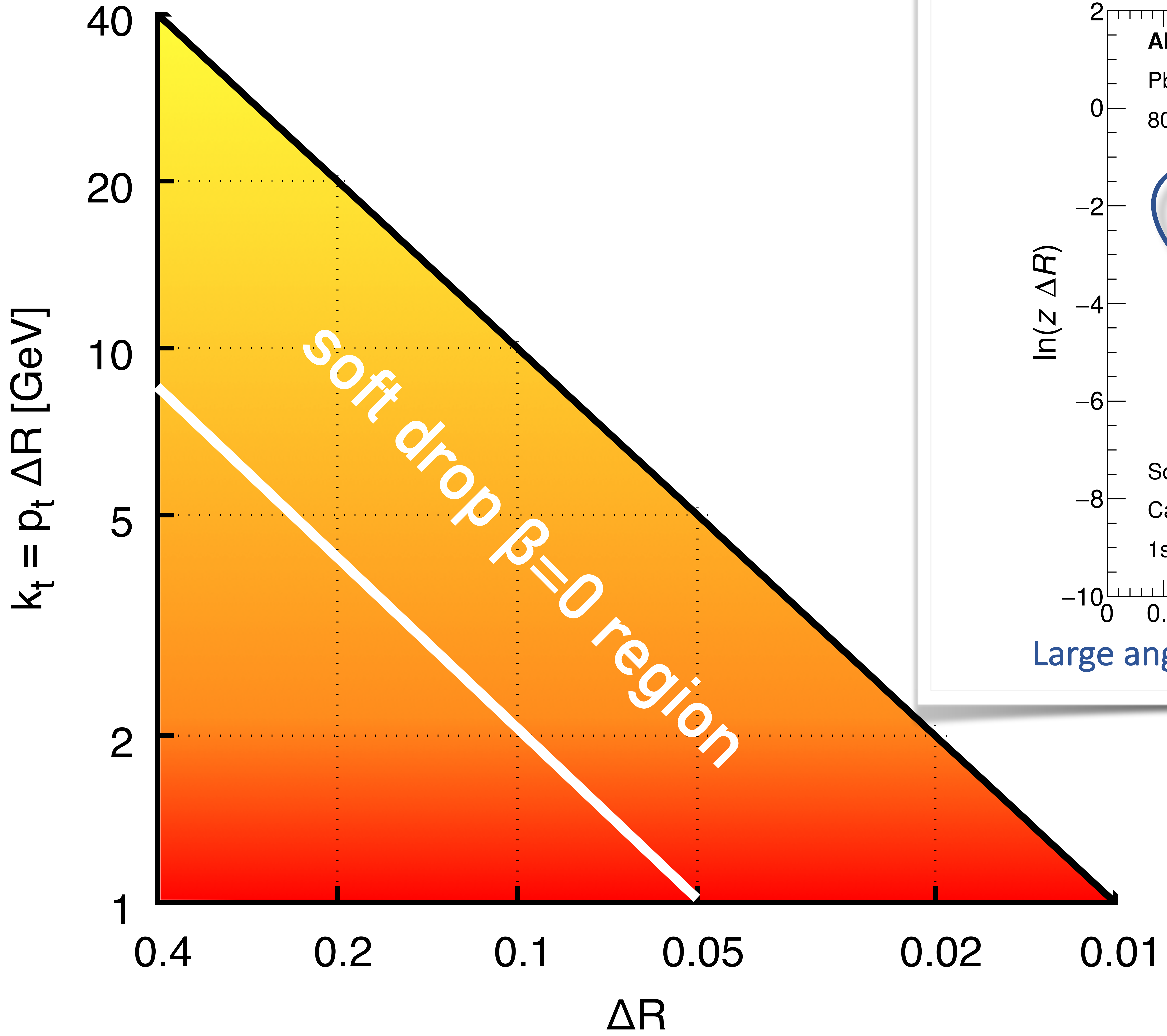
High Energy Physics – Phenomenology

Probing heavy ion collisions using quark and gluon jet substructure

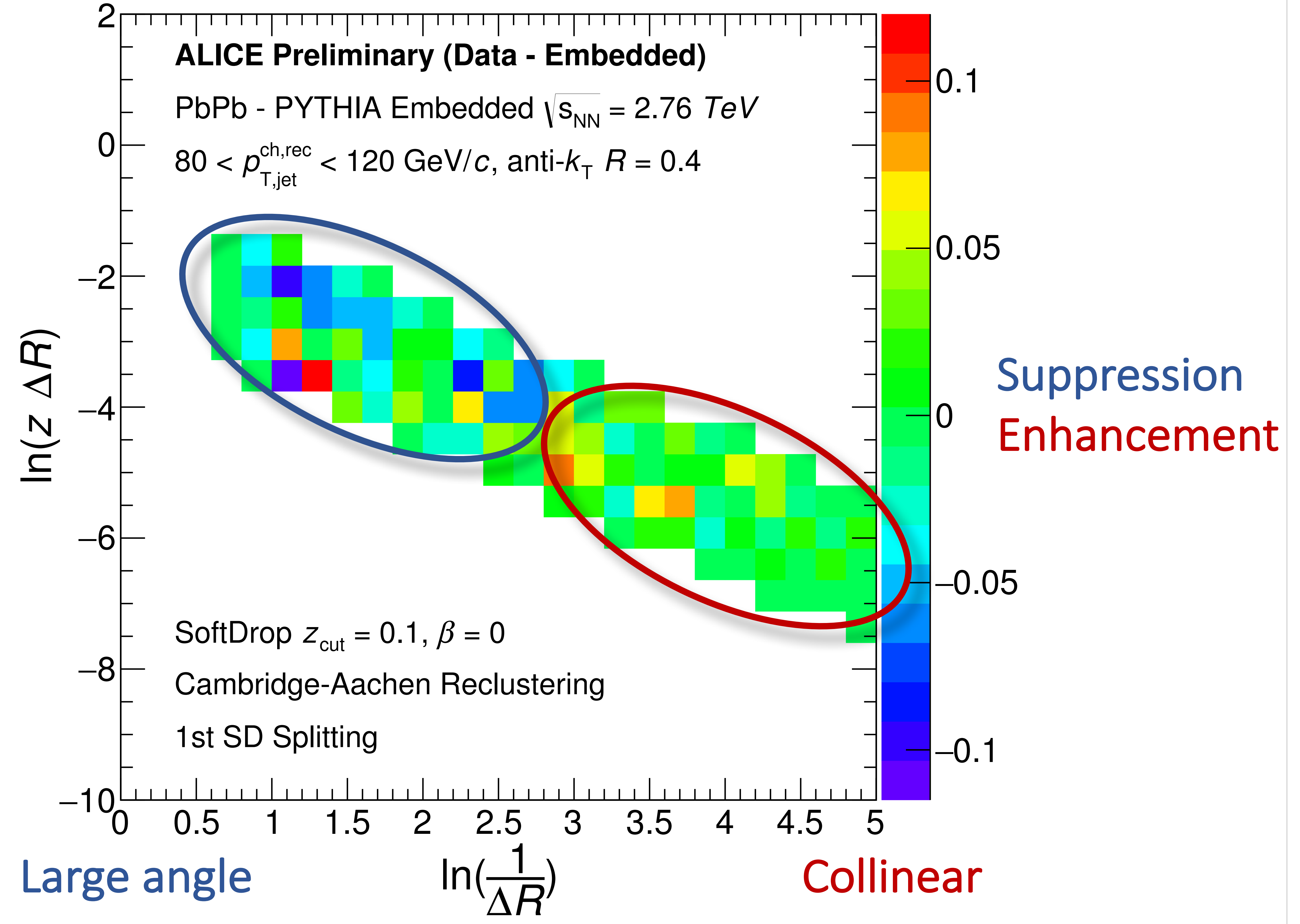
Yang-Ting Chien, Raghav Kunnawalkam Elayavalli

+ Harry Andrews ALICE // talk

jet with R= 0.4, p_t = 200 GeV



Splittings map for difference of data and embedded PYTHIA



OUTLOOK

OUTLOOK

- jet substructure → many handles for investigating physics of passage of fragmenting partons through a jet
- Many substructure observables naturally derive from a single "Lund plane" density, which gives direct access to the kinematic regions being discussed in theory calculations

What did I not have time for?

- Machine learning — in pp "searches" world this is becoming a workhorse for substructure; what can be done in heavy-ions?
- Beyond R=0.4 — cf. CMS high-p_t results
- Heavy-flavour within jets

BACKUP

Jet algorithms

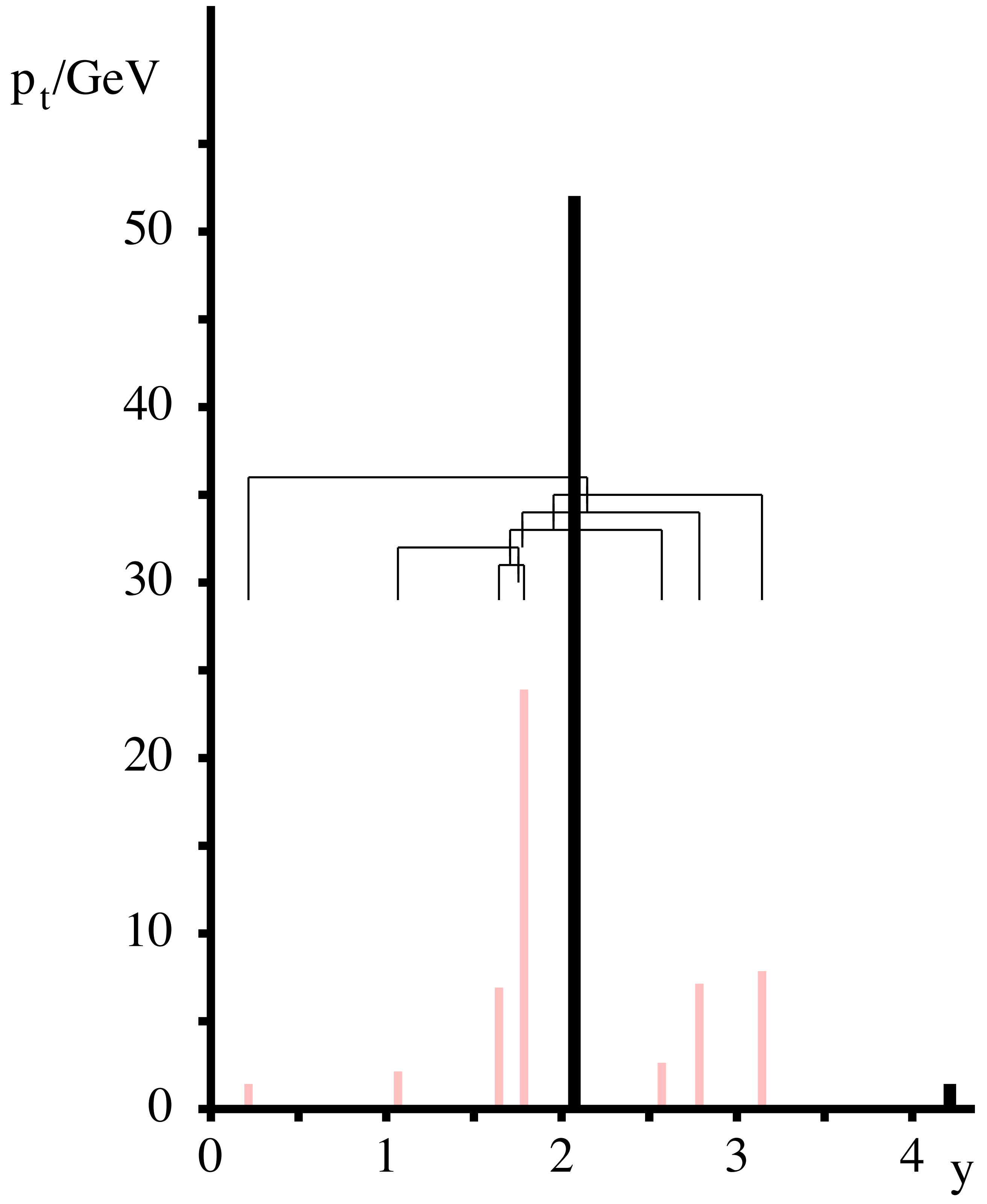
1. *Identify pair of particles i,j with smallest d_{ij}*
2. *If their d_{ij} < smallest d_{iB}, recombine them into a new (pseudo)particle*
3. *Else particle with smallest d_{iB} becomes a jet and is removed from the list of particles*
4. *Repeat until no particles left*

$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p})\,\Delta R_{ij}^2 / R^2$$
$$d_{iB} = p_{ti}^{2p}\,.$$

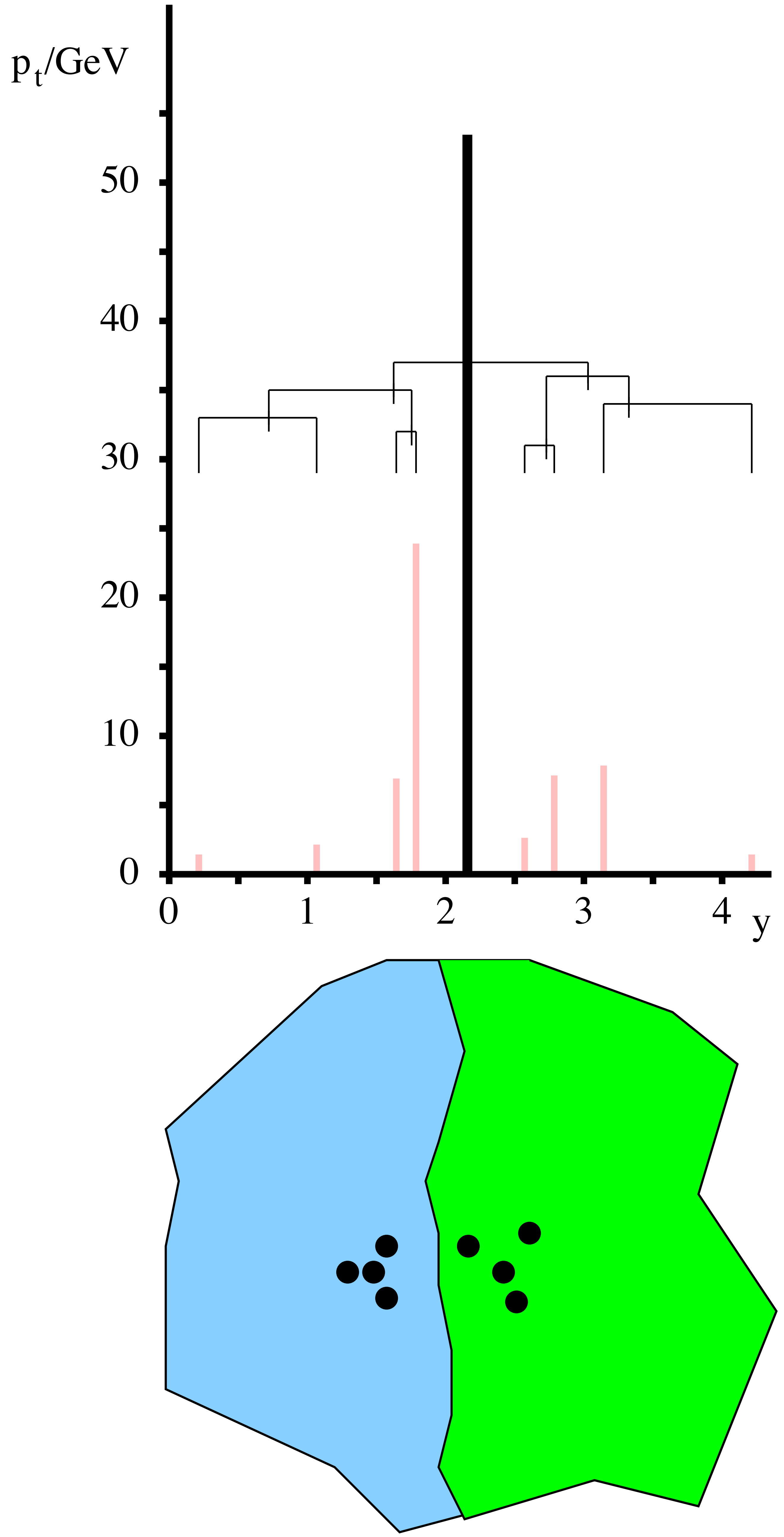
algorithm	p
k_t	1
Cambridge –Aachen	0
anti-k_t	-1

Jet algorithms

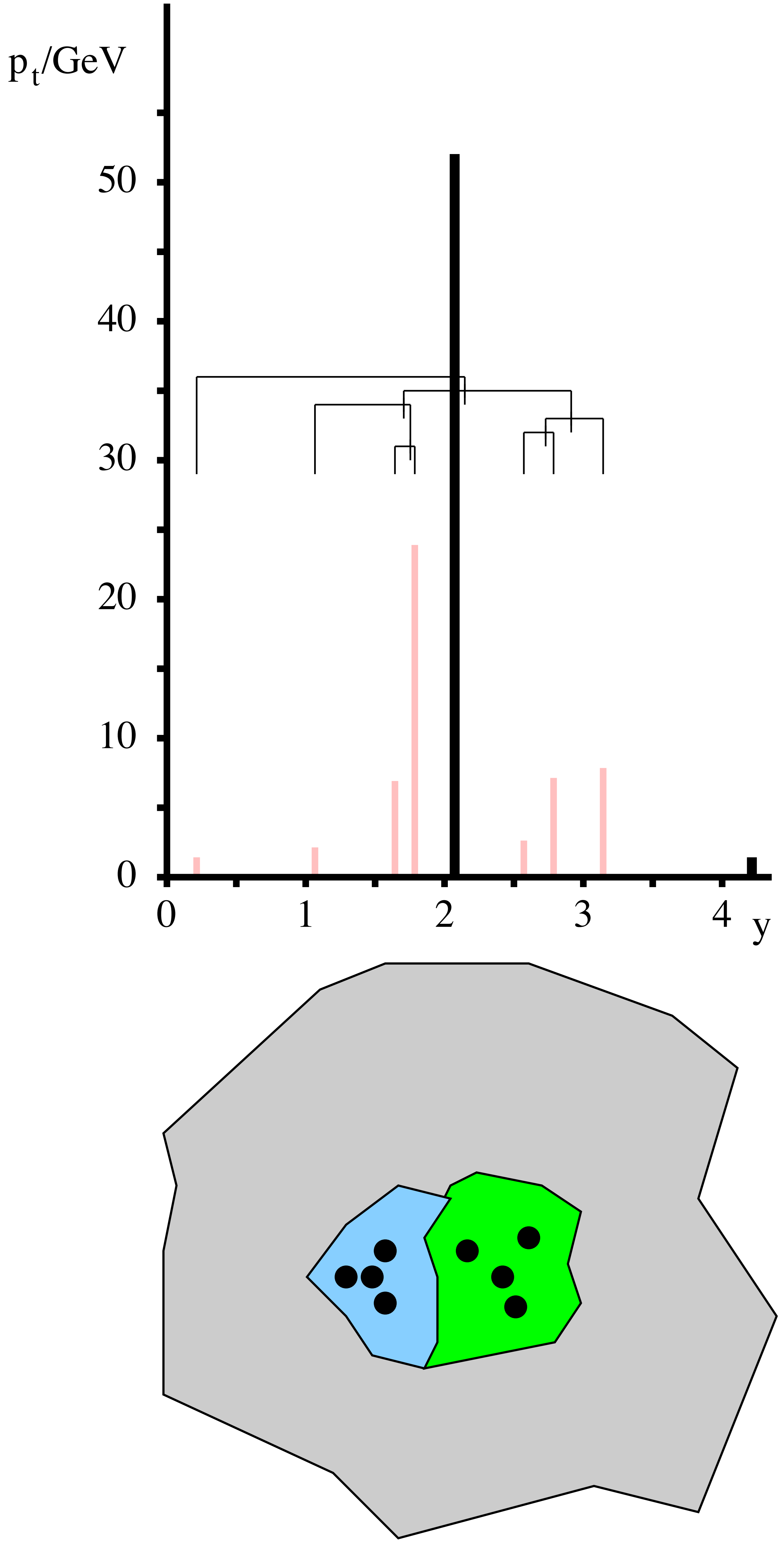
anti-k_t algorithm



k_t algorithm

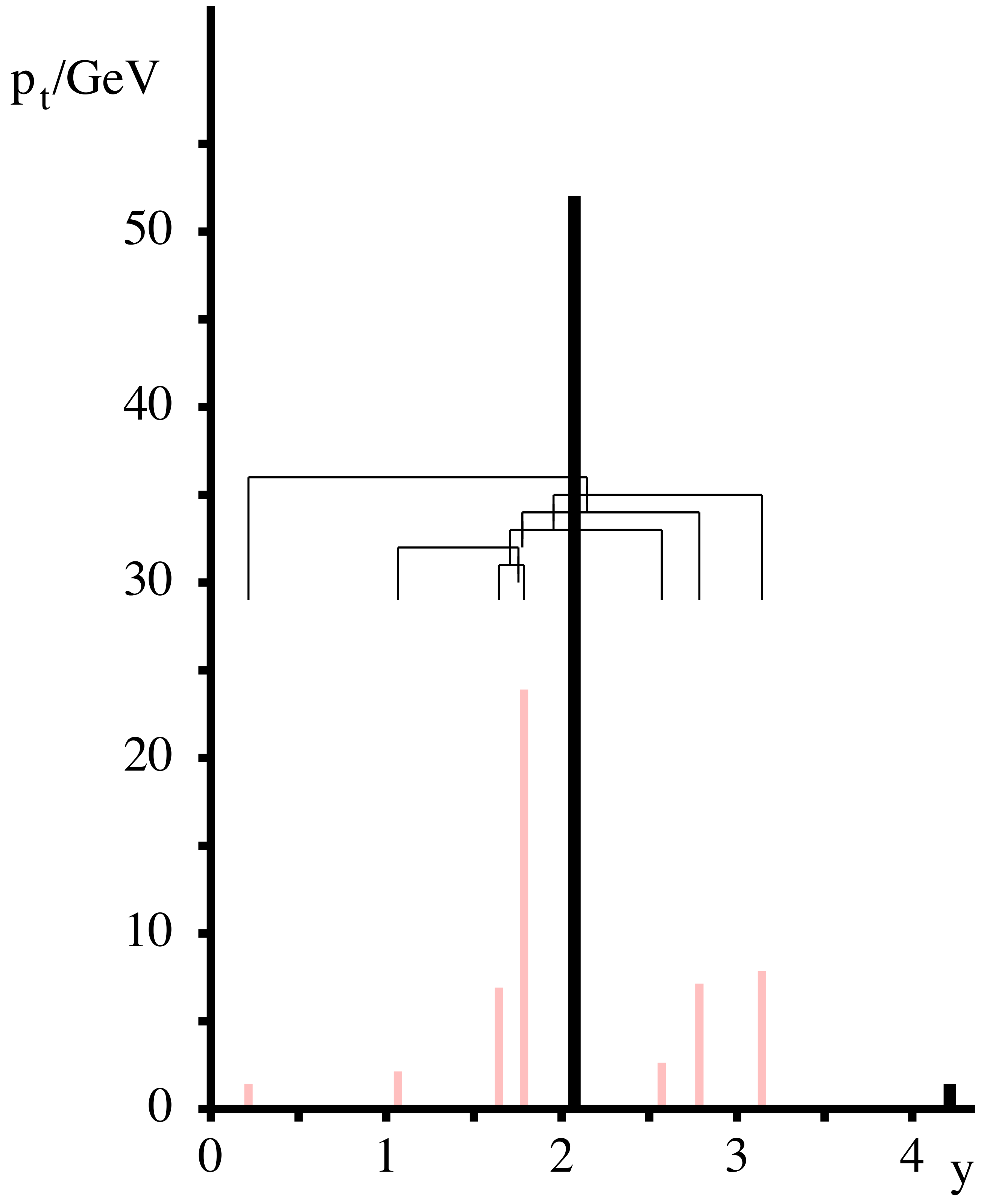


Cambridge/Aachen

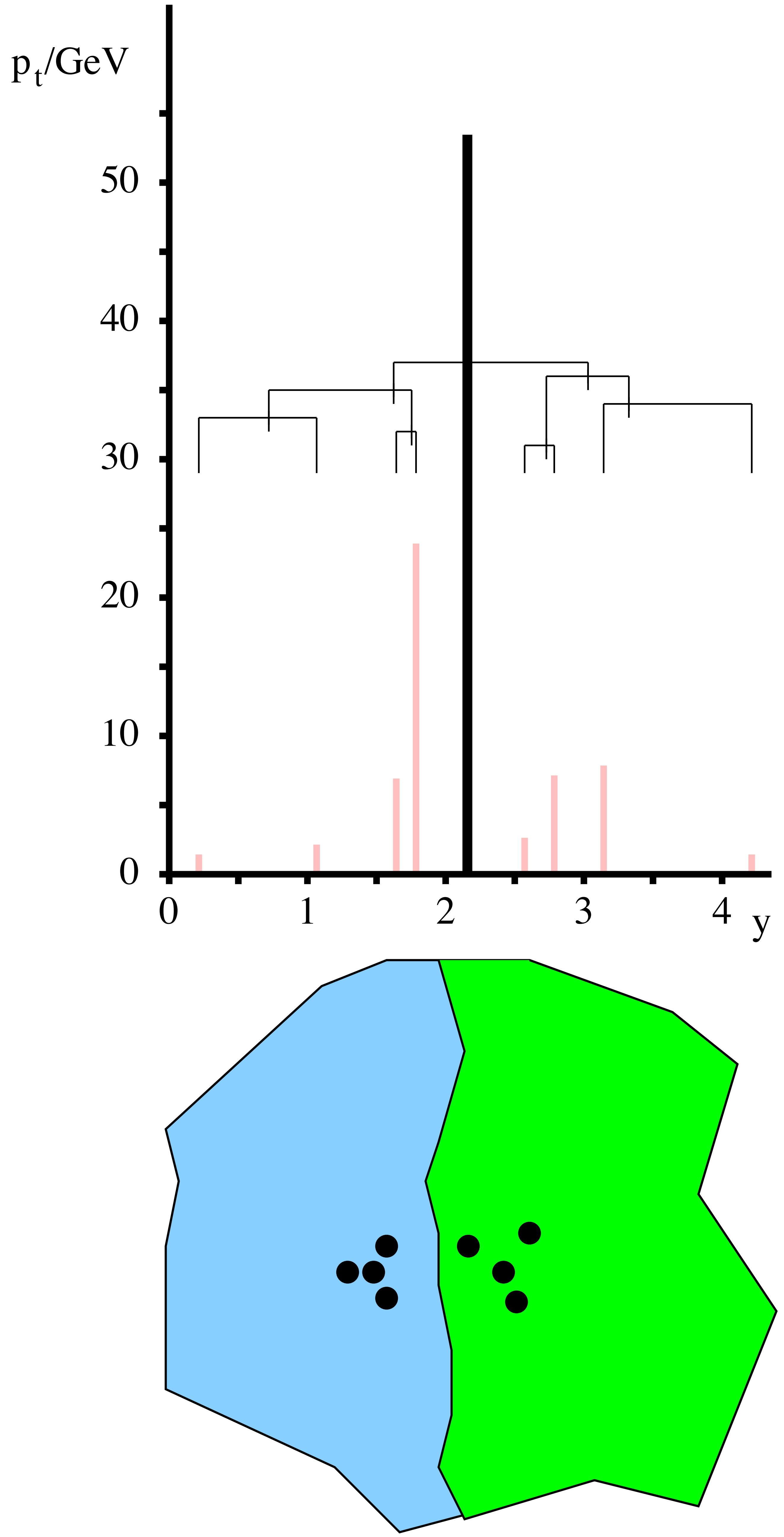


Jet algorithms

anti-k_t algorithm



k_t algorithm



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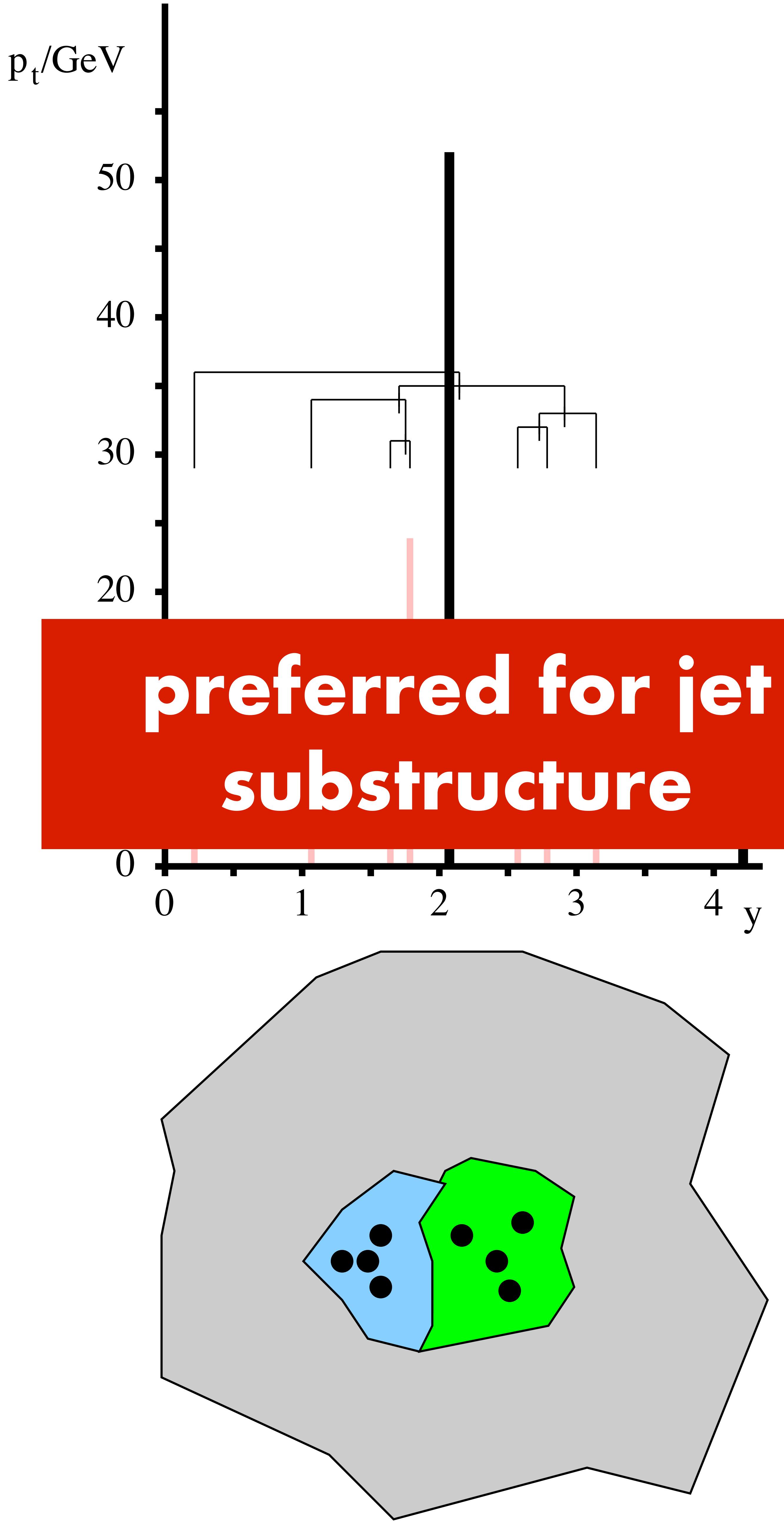
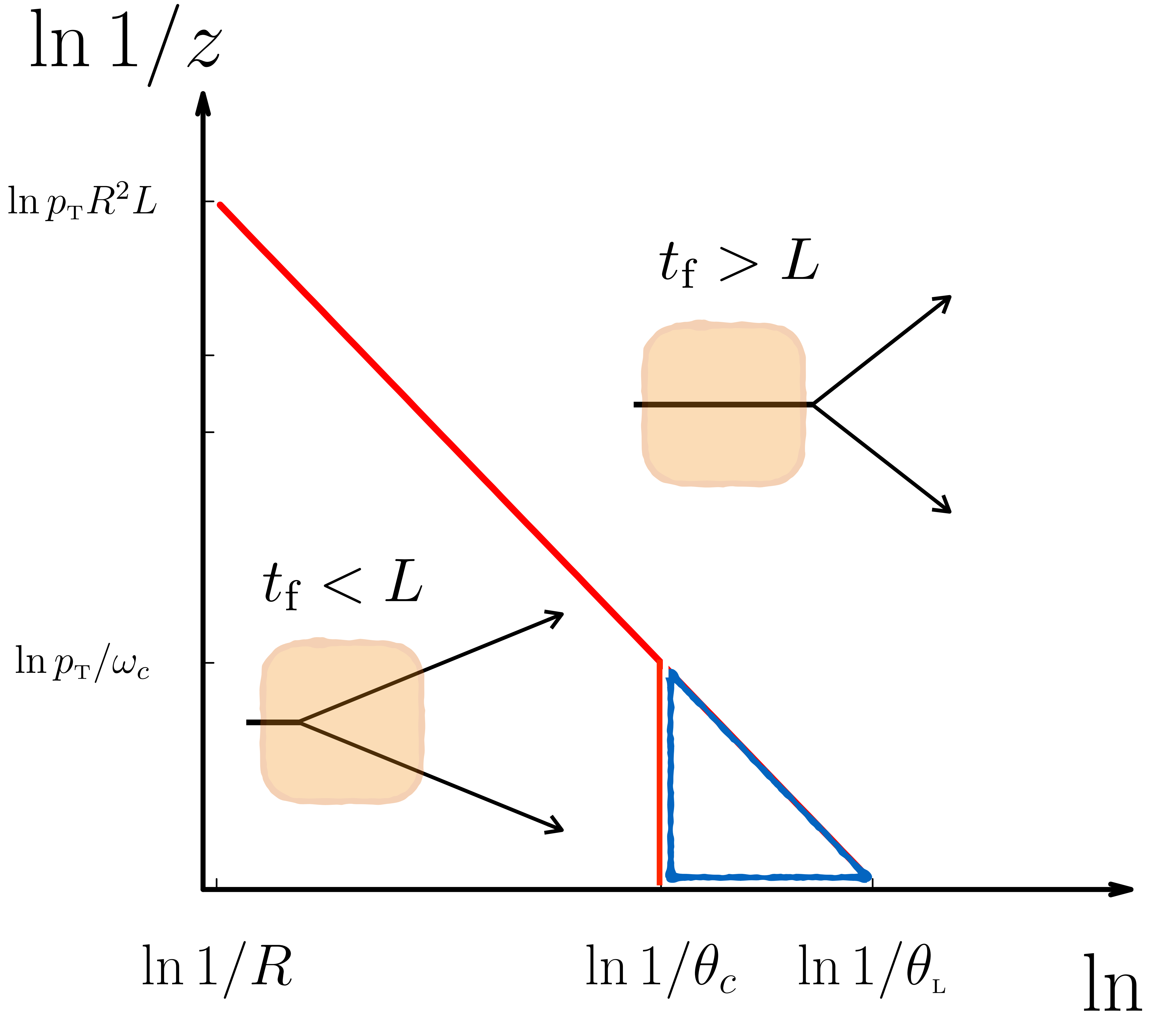
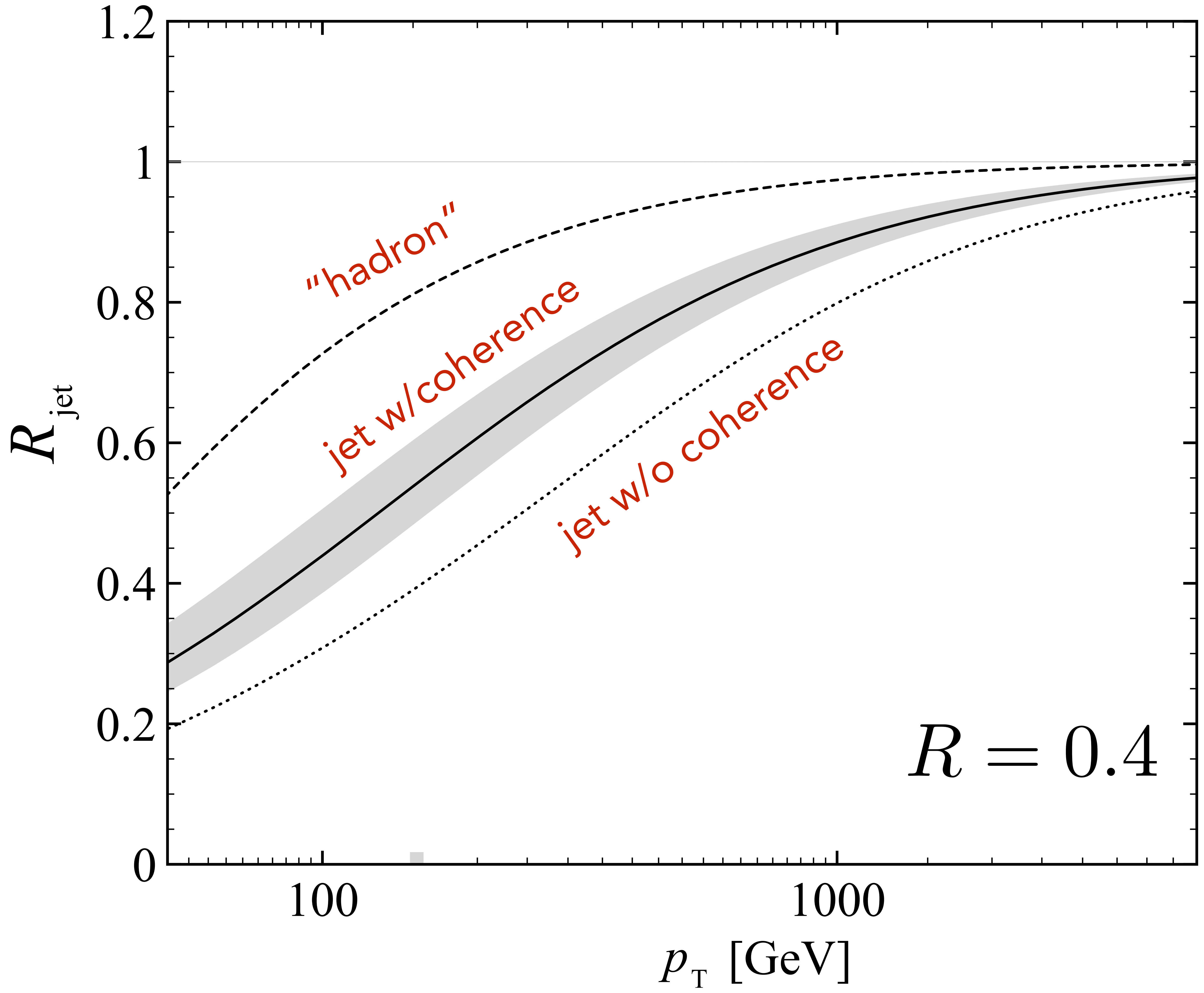


preferred for jet substructure

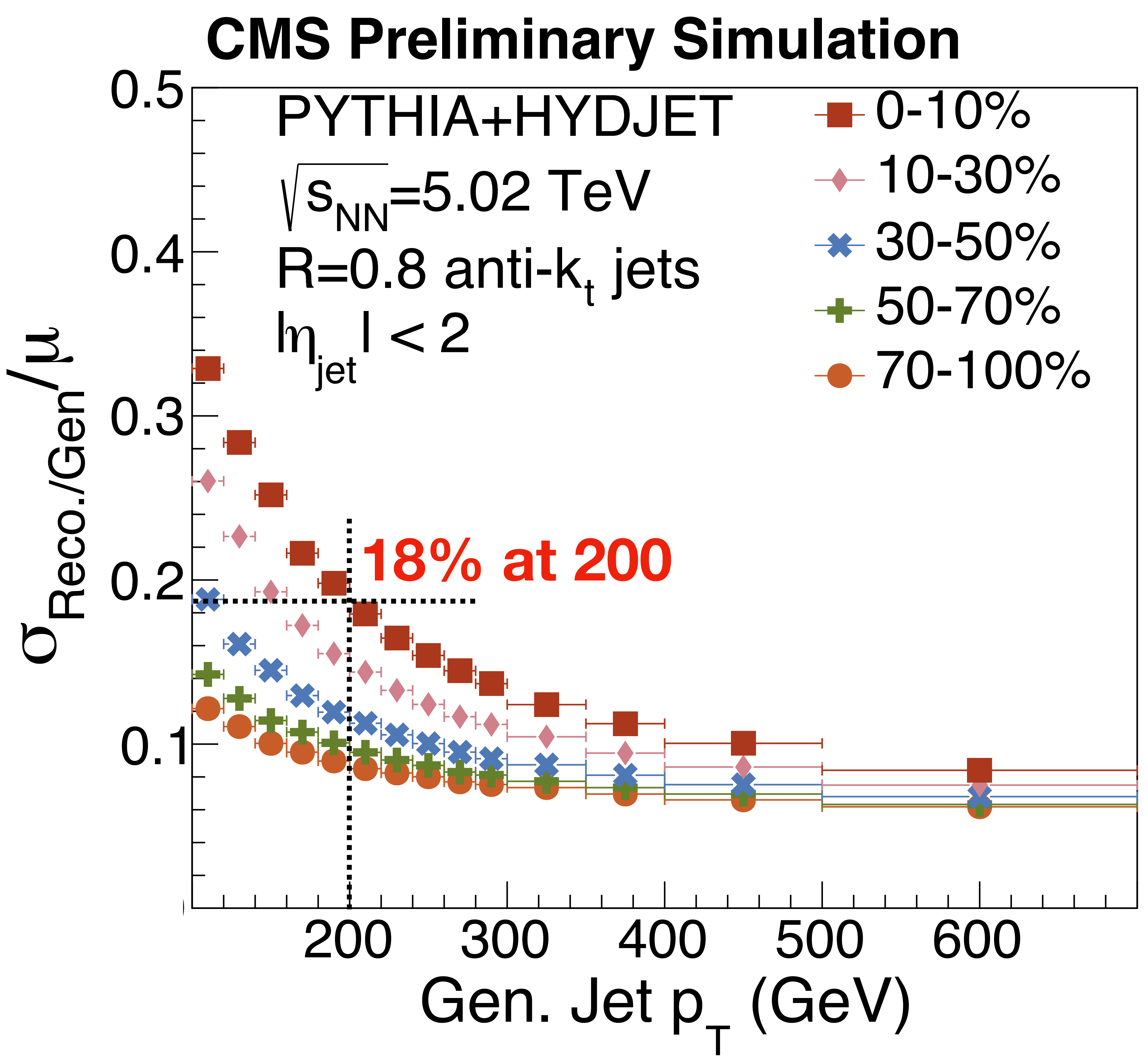
Tywoniuk (// talk) w. Mehtar-Tani





CMS large-R?

Conclusions

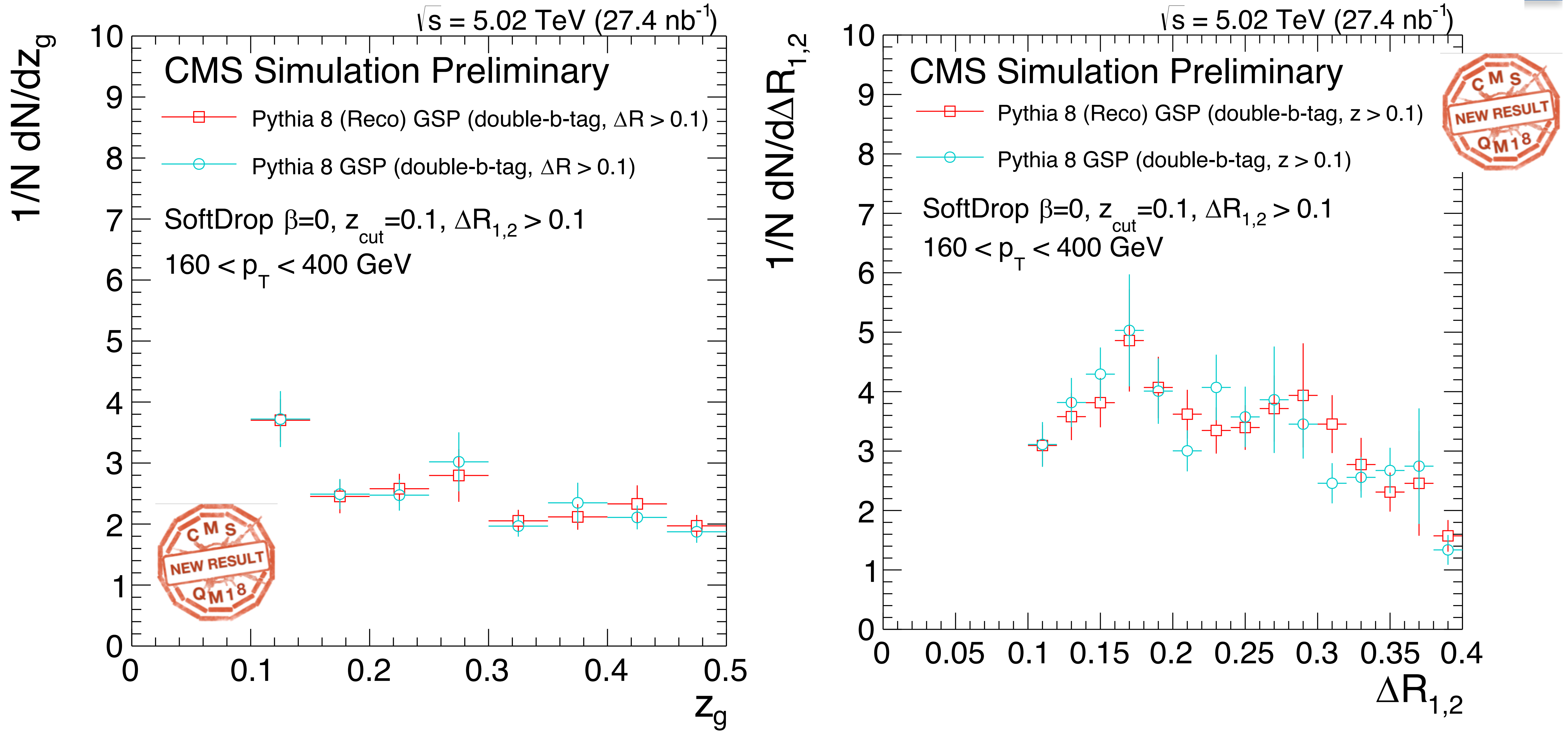


- An alternative view of how to handle UE subtraction in jets is presented
  - Instead of exploring tight cone R at low-p_T, consider large R at high-p_T
- Jet reconstruction is updated for forward-η and to account for flow modulations
  - **Perform Jet Nuclear Modification Factor Radius Scan up to R=1 for p_T > 200**
  - Extend CMS jet substructure measurements to large cone size

The MIT group's work was
supported by US DOE-NP

CMS subjet flavour tagging

Subjet Splitting Results



- Wide-angle gluon-splitting jets ($\Delta R_{1,2}$ ~ 0.2) have a balanced subjet splitting distribution
  - Important to note that ***this is a small subset*** of total GSP jet contribution
  - B-tagging + reconstruction methodology confirmed by Pythia8 simulation

CMS-DPN-2018

zg modifications

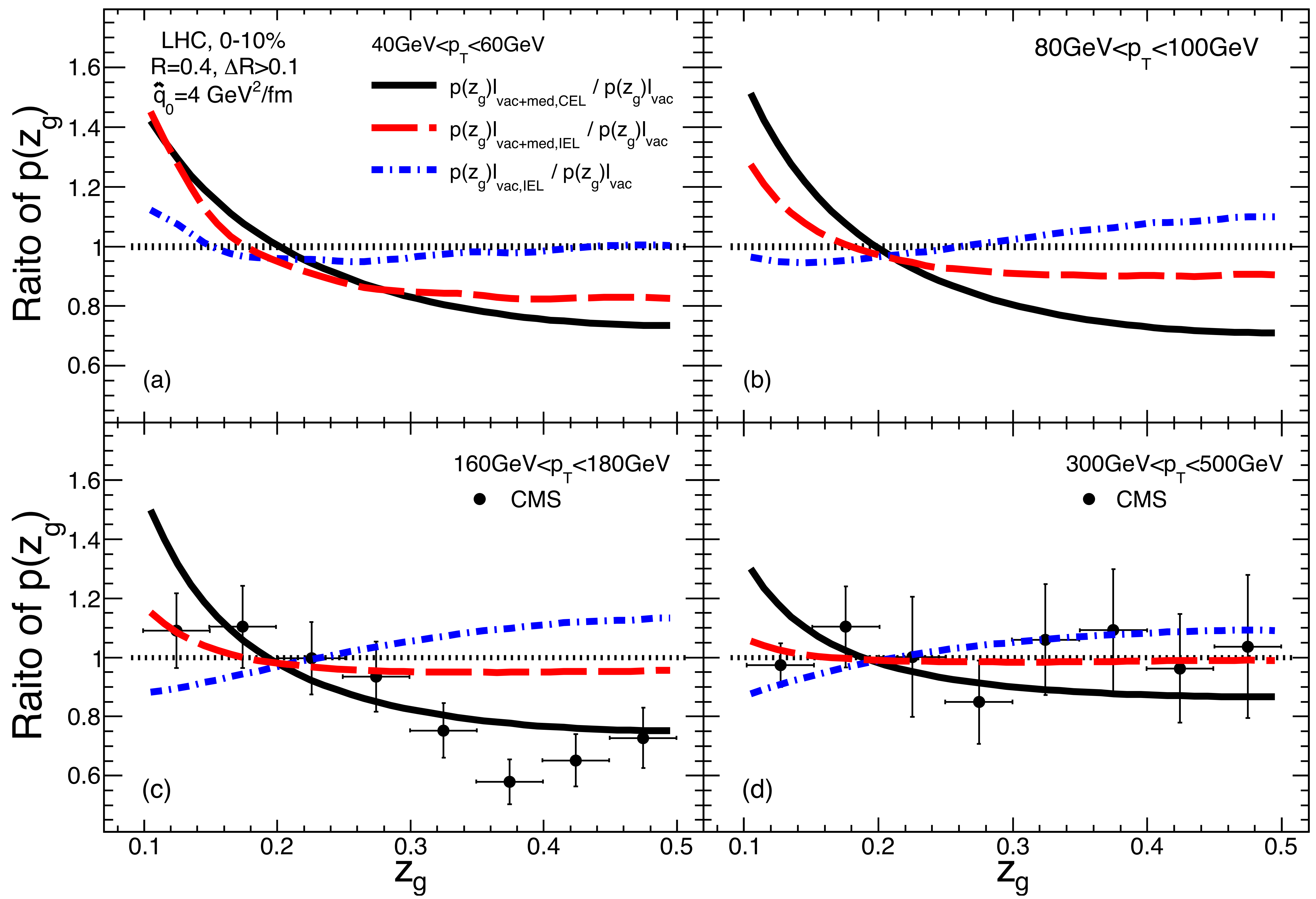
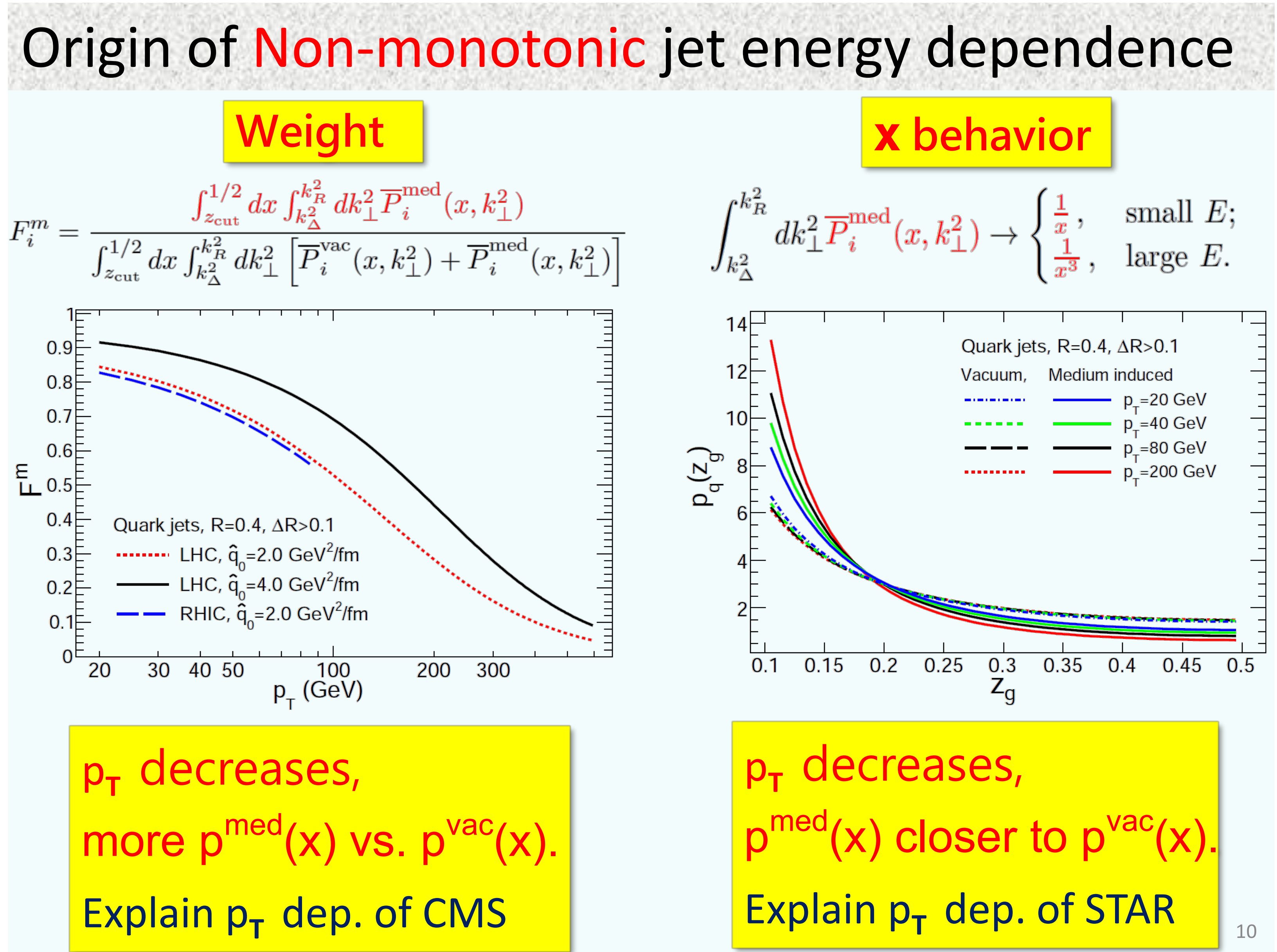


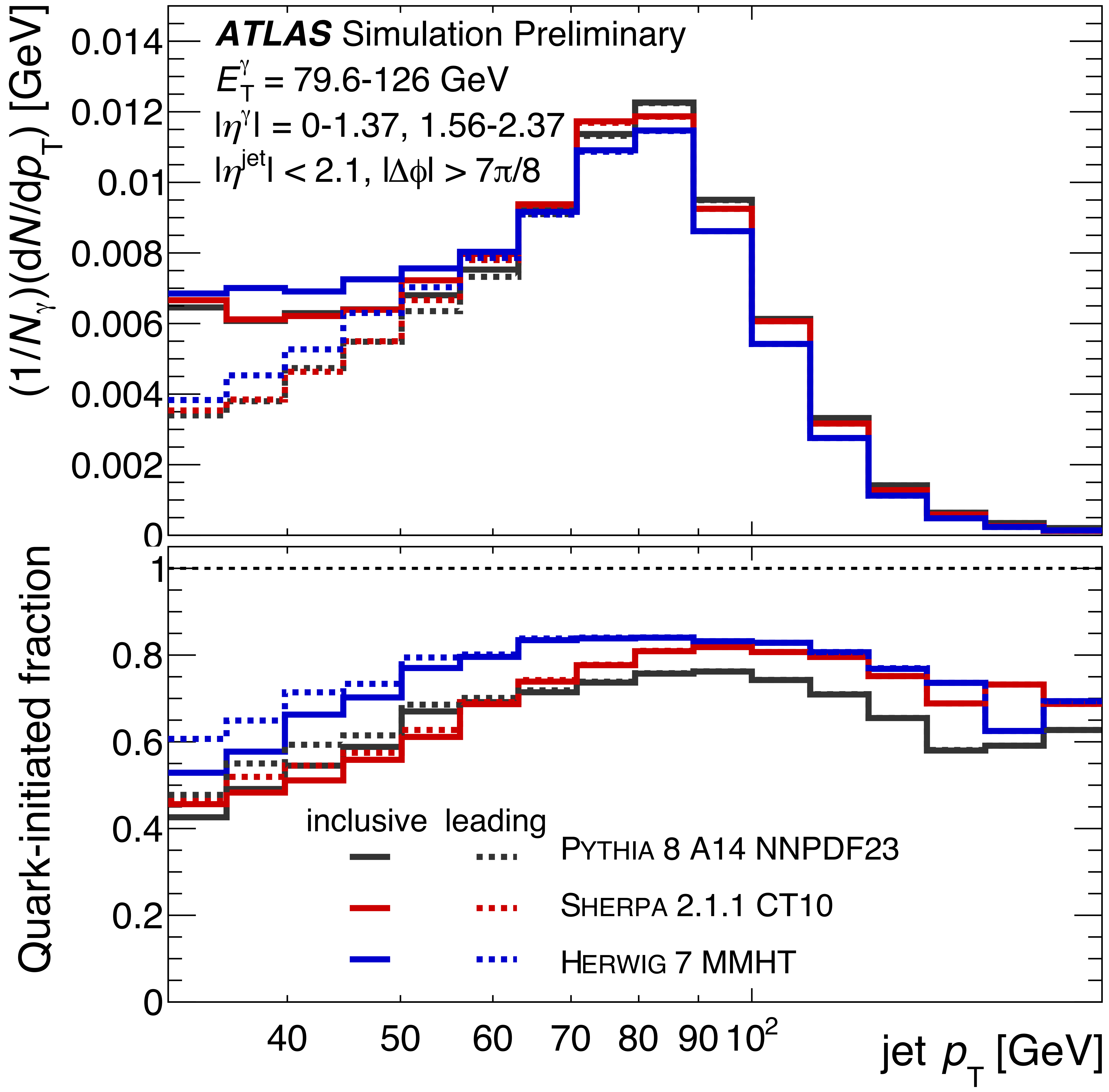
FIG. 12. (Color online) Modification of the groomed jet z_g distributions at the LHC for three different scenarios: solid for medium-modified splitting with coherent energy loss (CEL) of subjets, dashed for medium-modified splitting with independent energy loss (IEL) of subjets, and dash-dotted for vacuum splitting with IEL of subjets.

Probing medium-induced jet splitting and energy loss in heavy-ion collisions

Ning-Bo Chang,[1,2] Shanshan Cao,[3] and Guang-You Qin[2]

arXiv:1707.03767v2





pt dist & quark fraction

- ATLAS-CONF-2017-074