The Lund jet plane: organising QCD radiation at colliders

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based on arXiv:1807.04758 with
F. Dreyer, G. Soyez (with some of their slides)

** on leave from CERN and CNRS*

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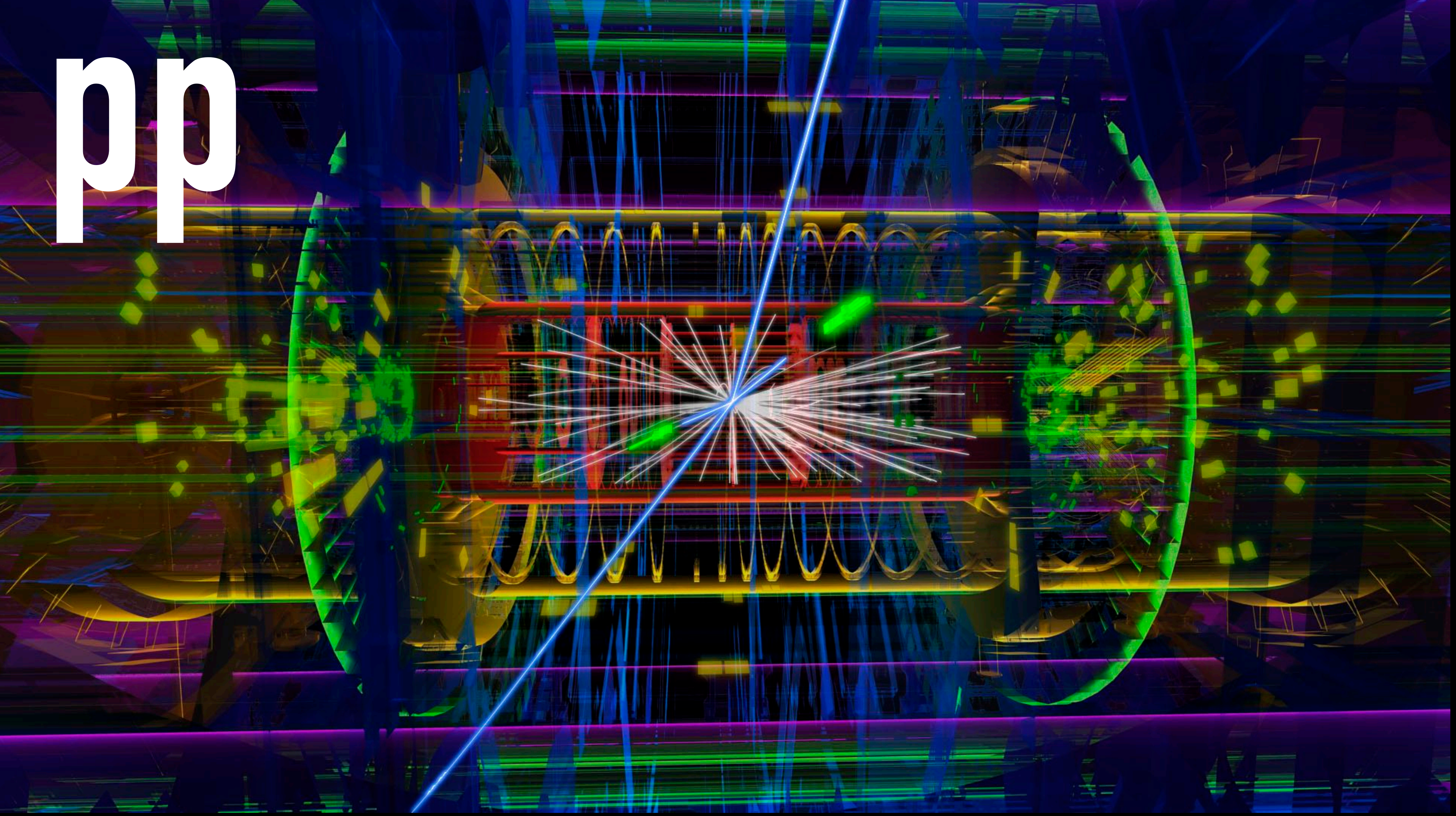
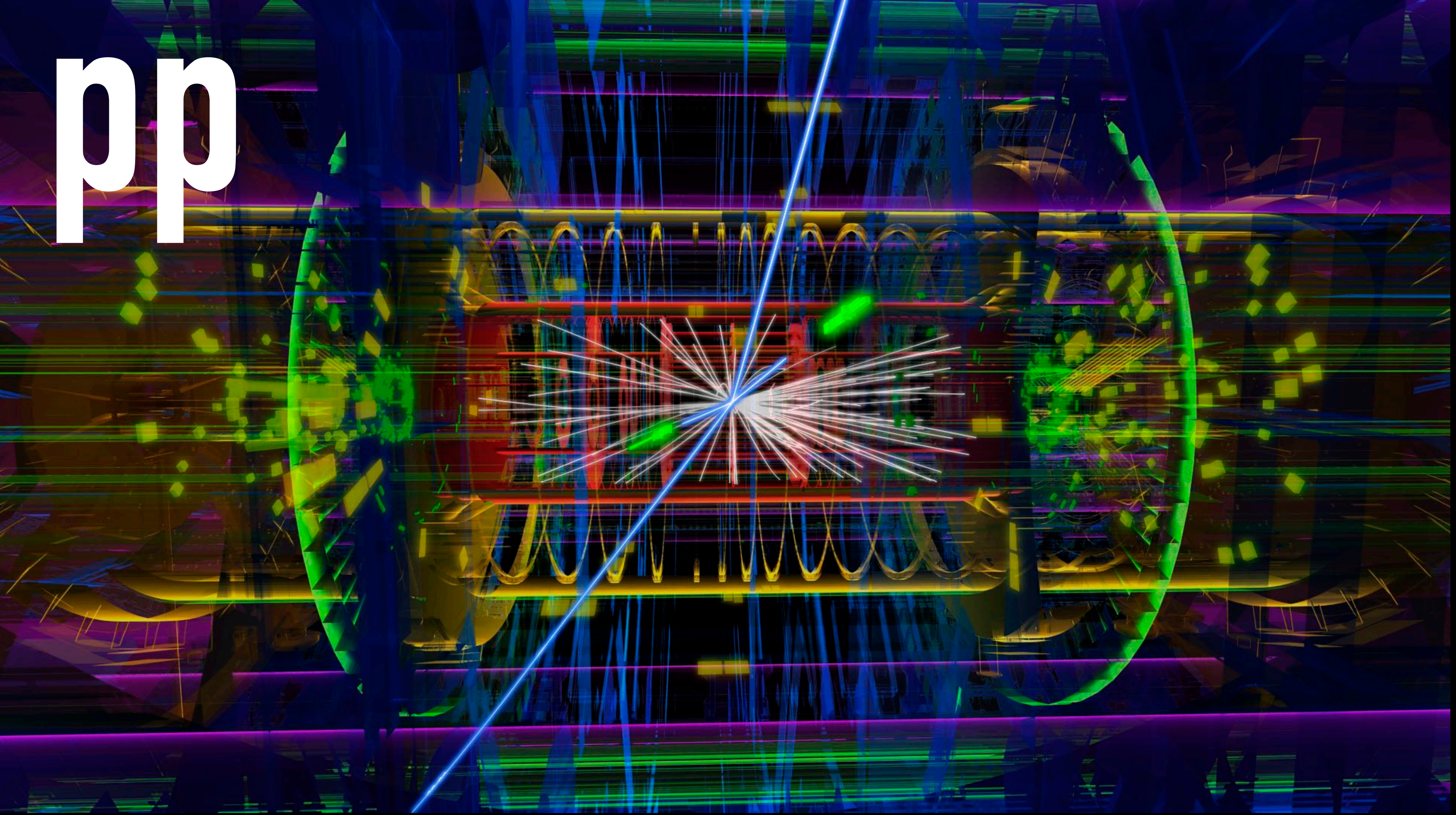
Birmingham
4/3/2019

pp

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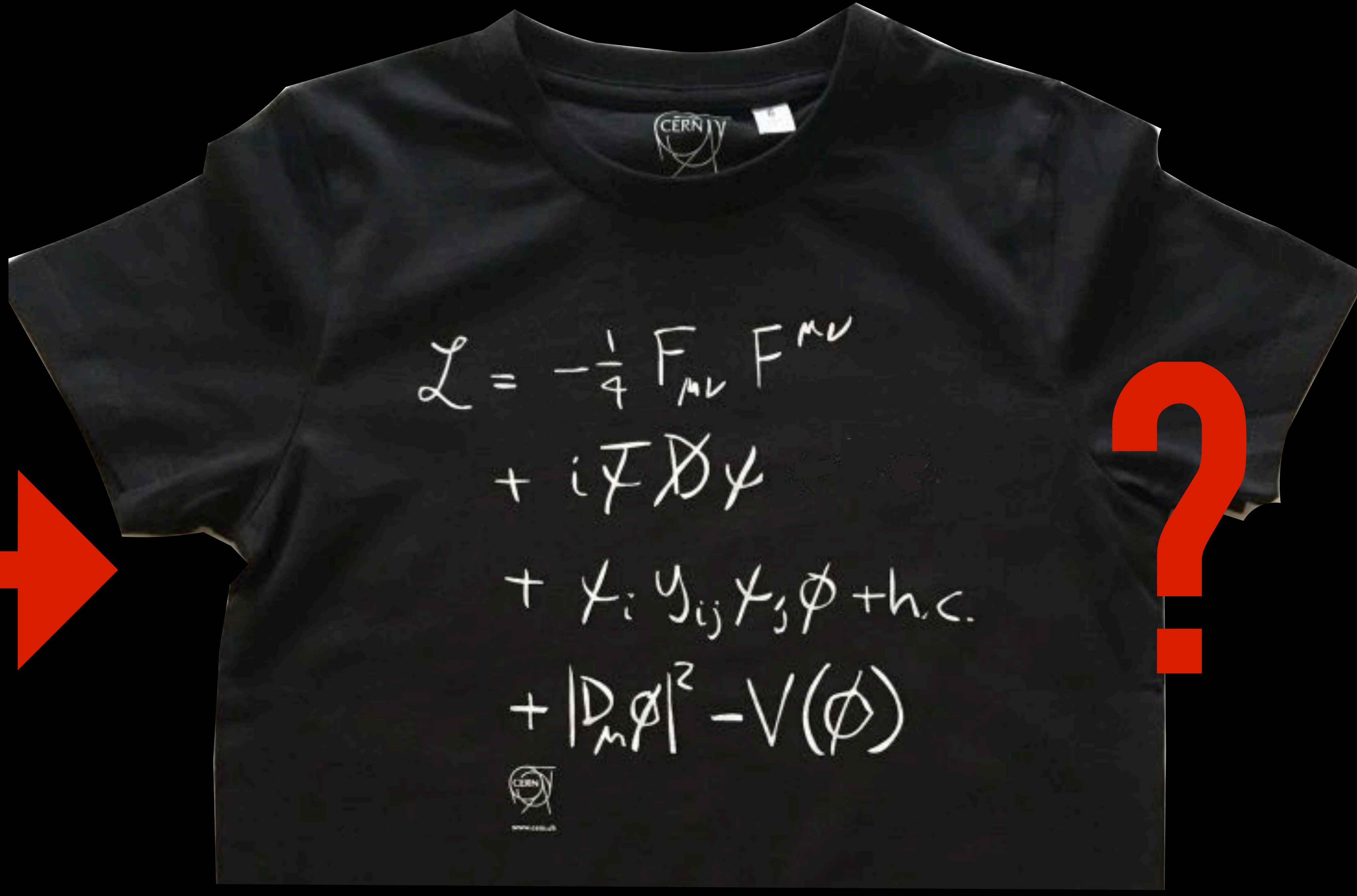
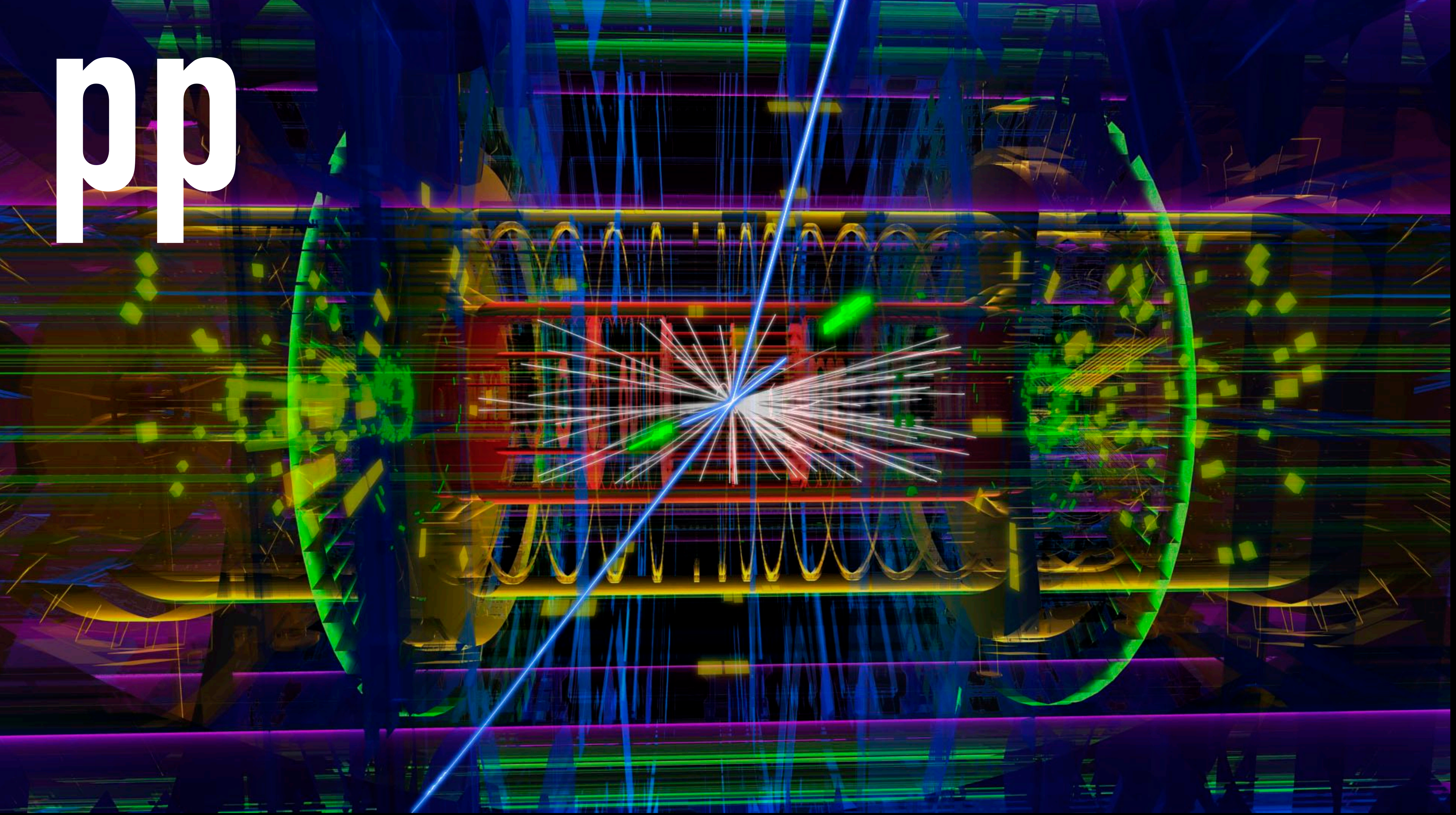

$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i \bar{\psi} \not{D} \psi$
$+ \psi_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$
CERN

?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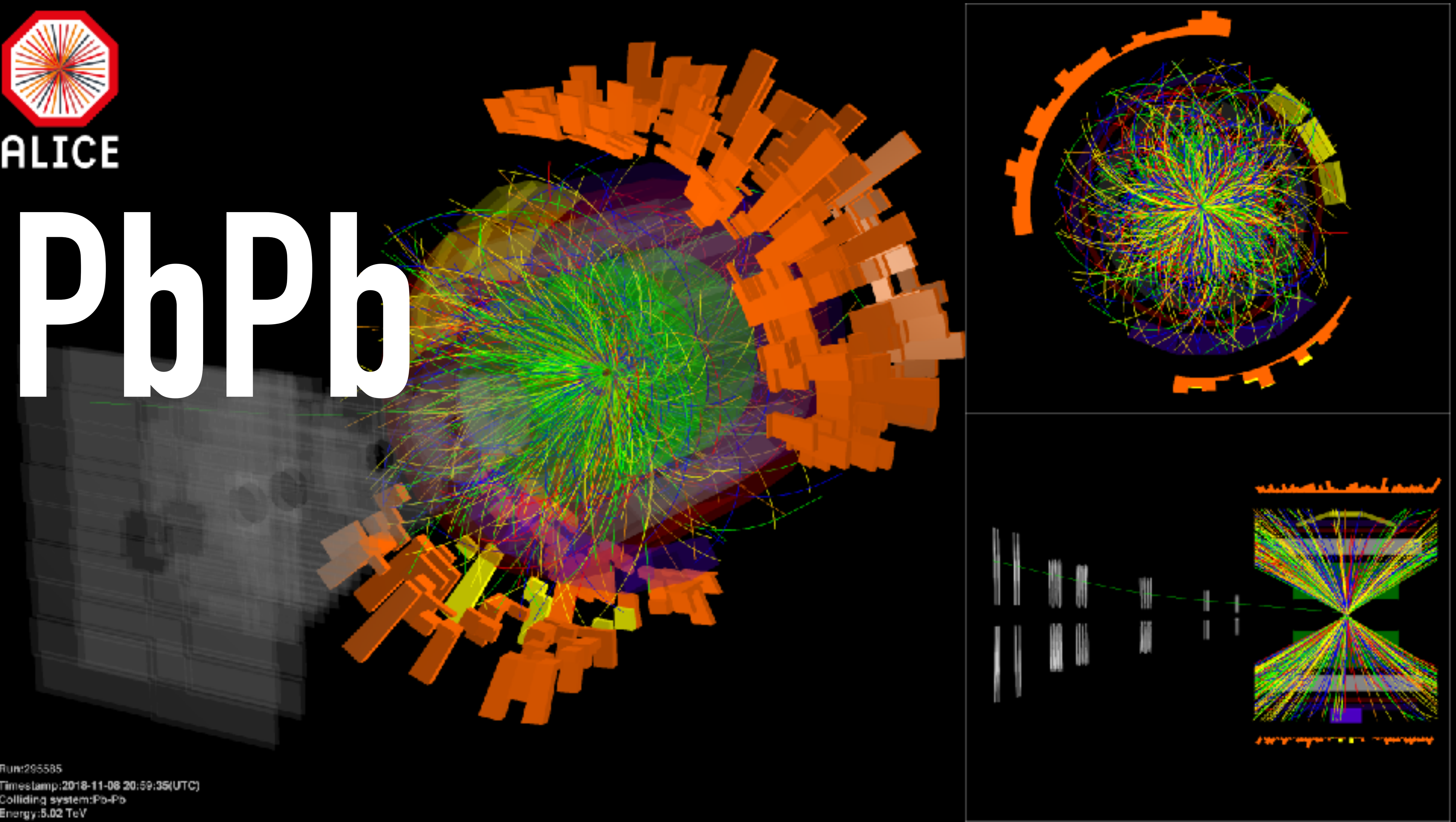
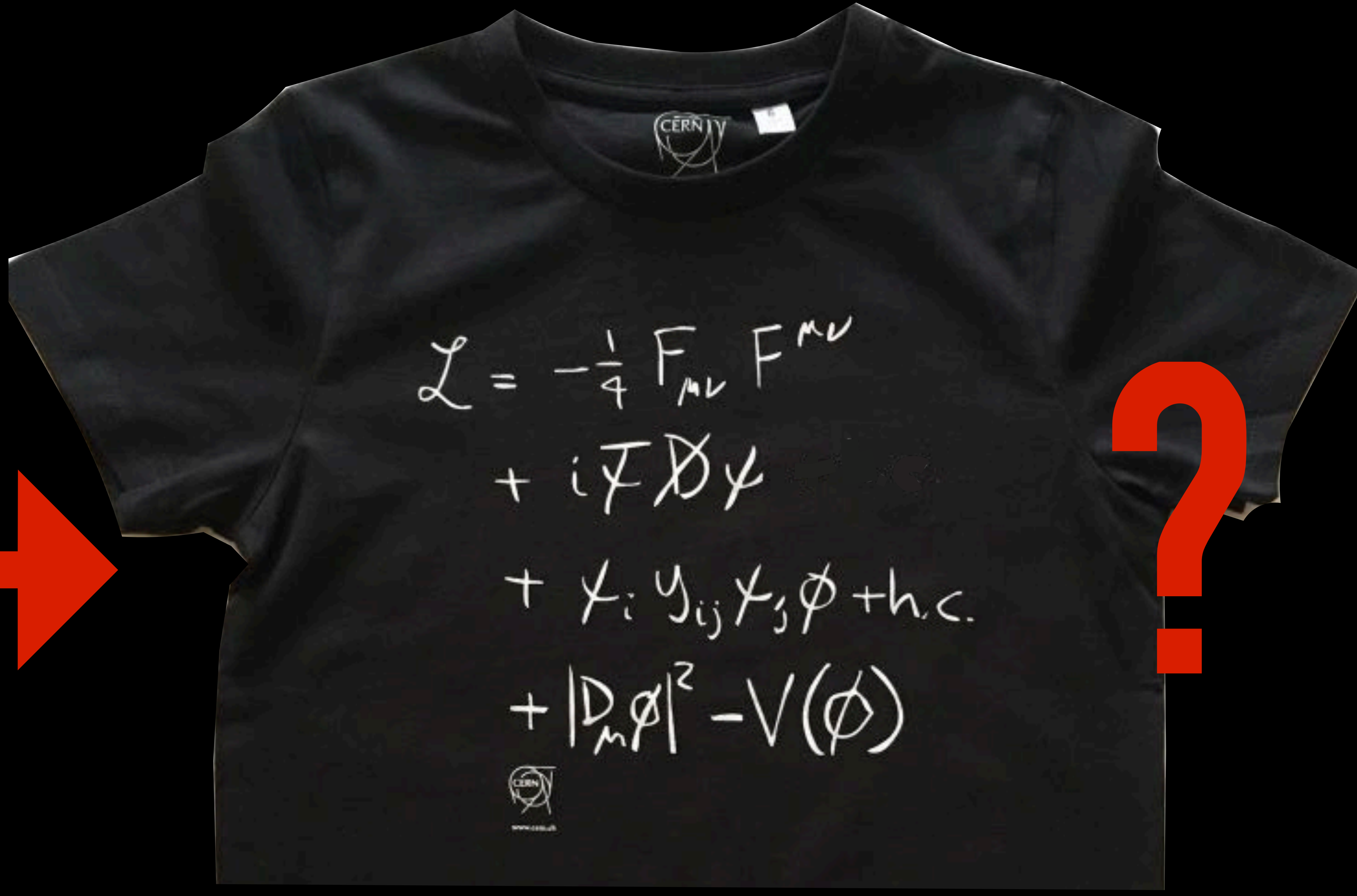

ALICE
PbPb
Run:295585
Timestamp:2018-11-08 20:59:35(UTC)
Colliding system:Pb-Pb
Energy:5.02 TeV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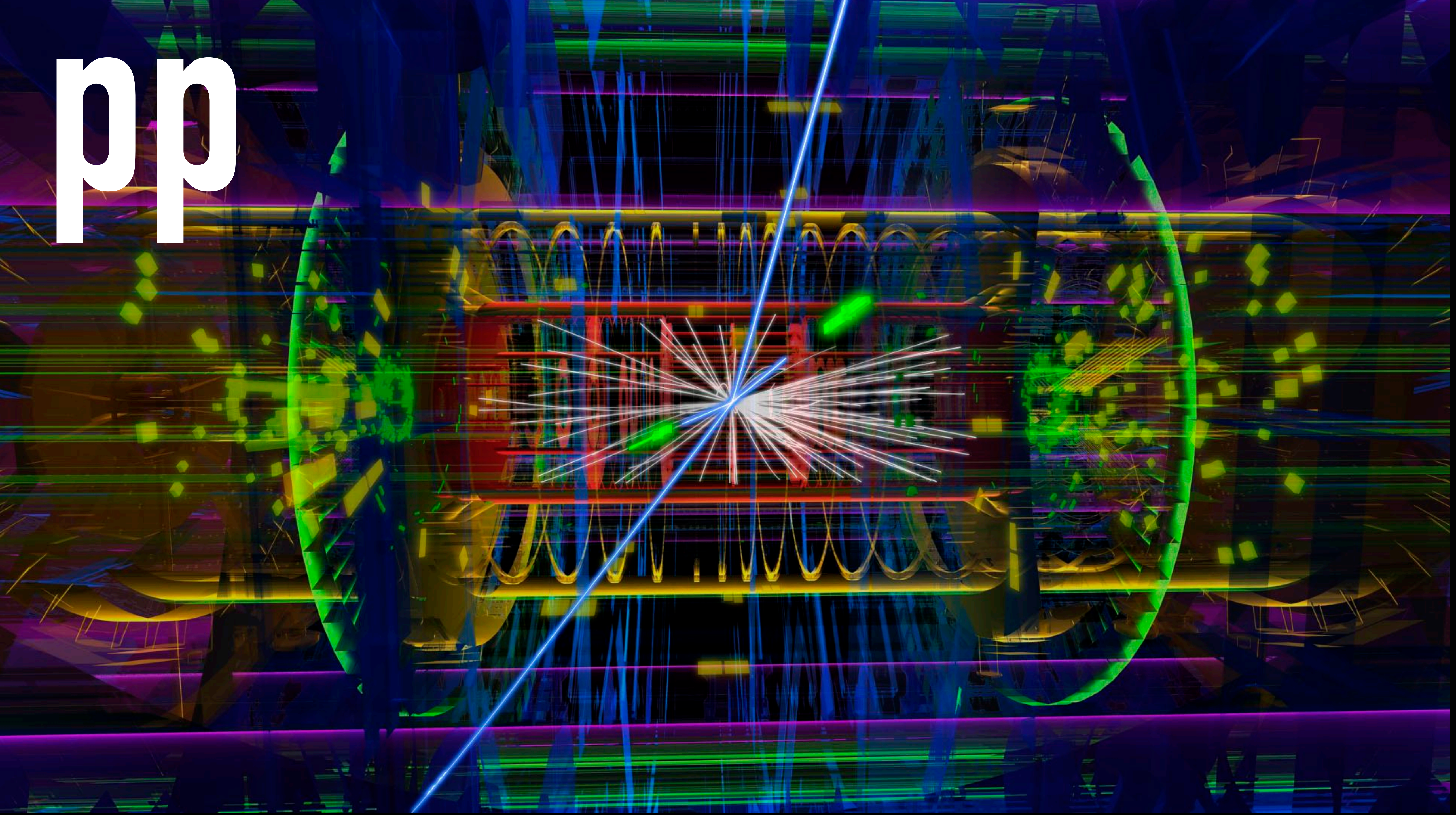
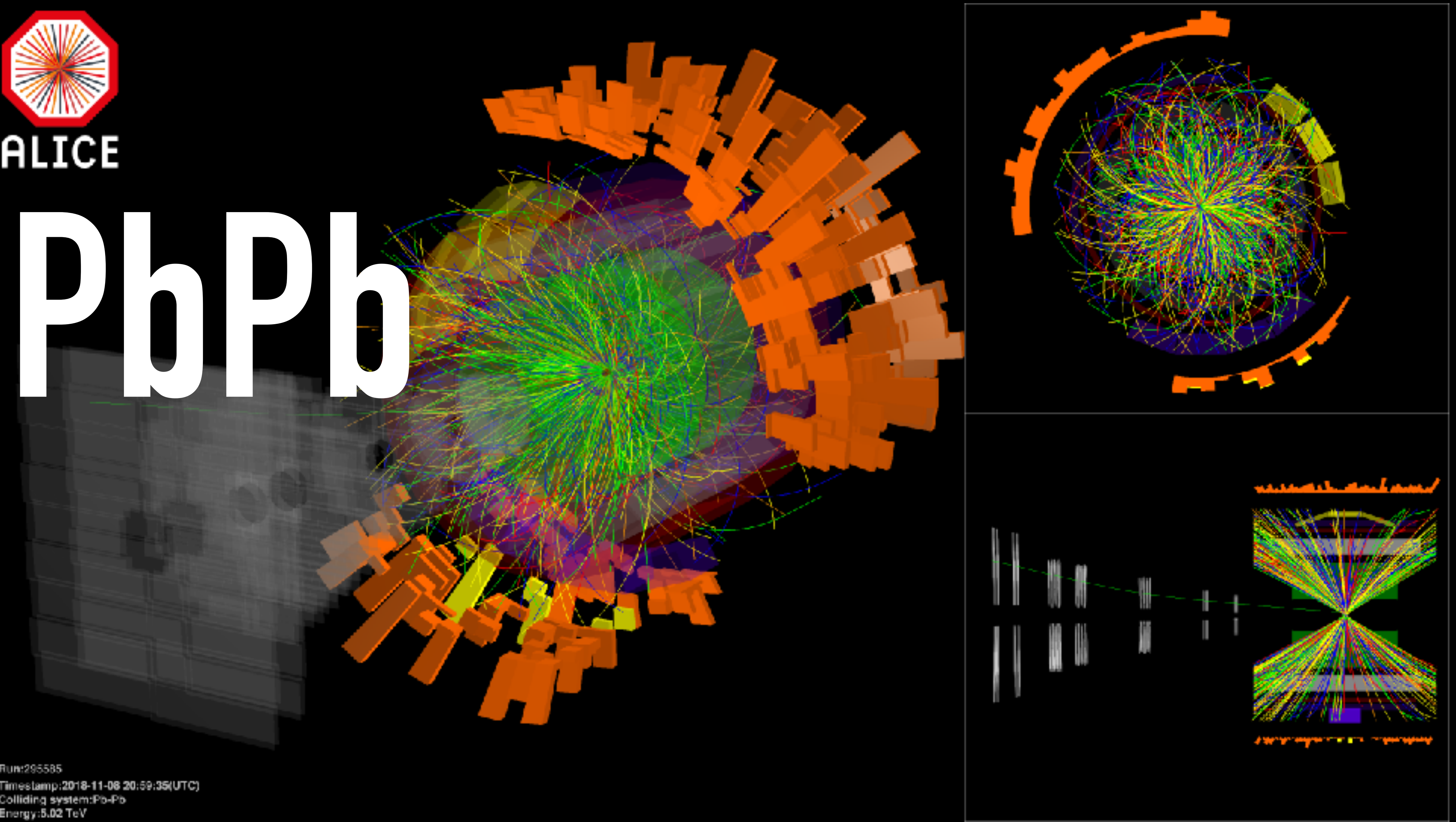

pp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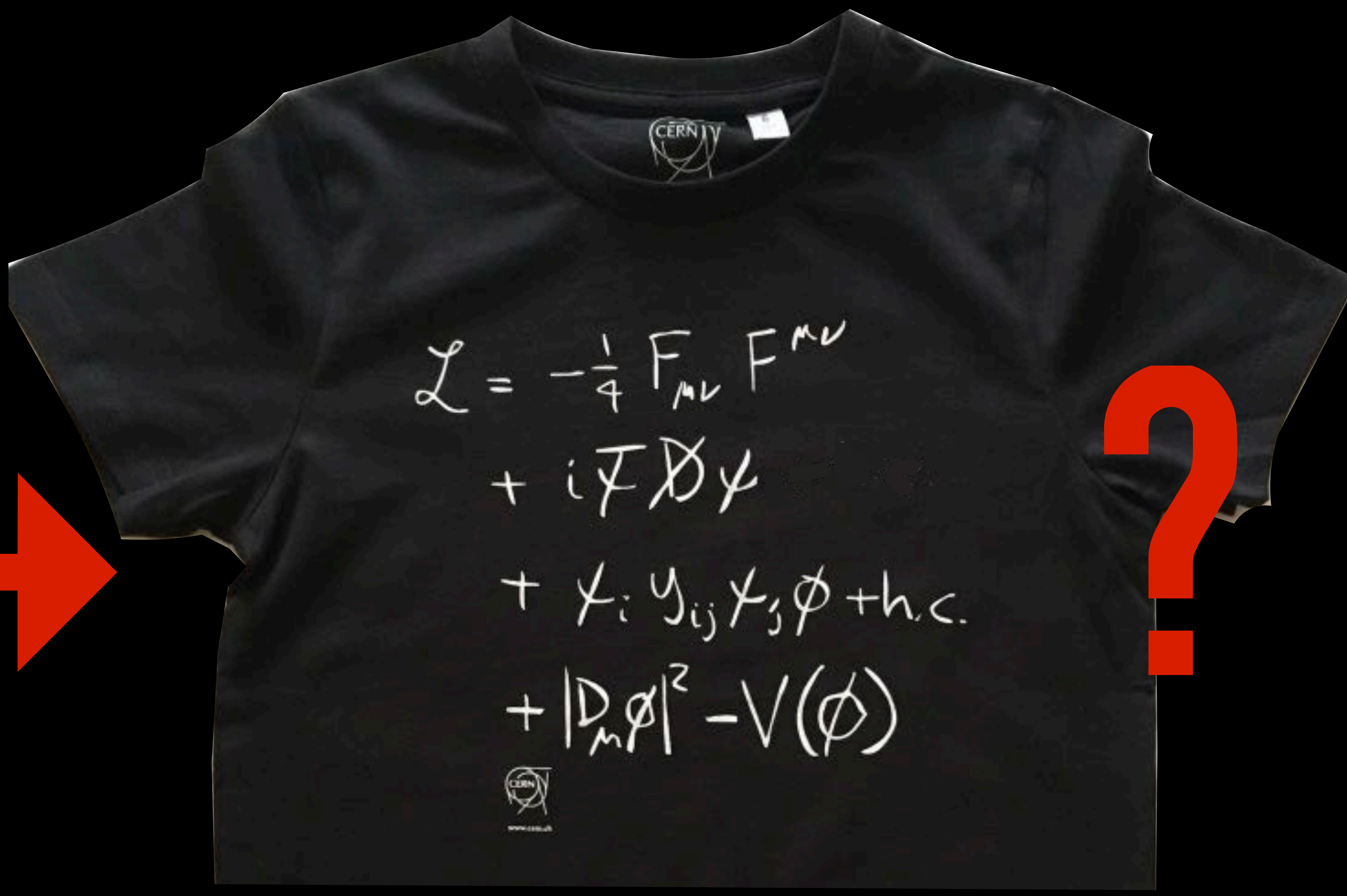
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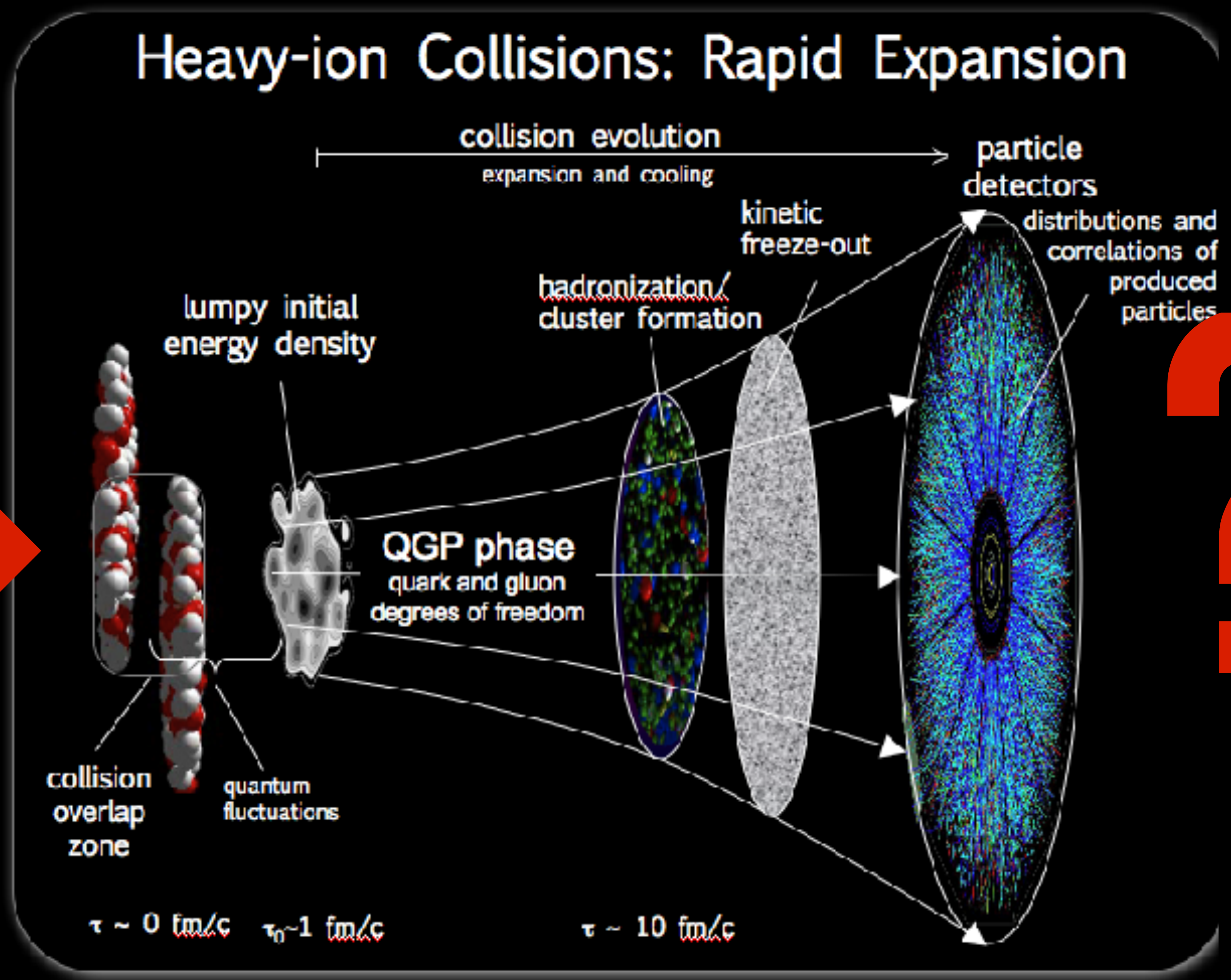

Heavy-ion Collisions: Rapid Expansion
collision evolution
expansion and cooling
particle detectors
distributions and correlations of produced particles
kinetic freeze-out
hadronization/ cluster formation
lumpy initial energy density
QGP phase
quark and gluon degrees of freedom
collision overlap zone
quantum fluctuations
$\tau \sim 0$ fm/c
$\tau_0 \sim 1$ fm/c
$\tau \sim 10$ fm/c

?

jets

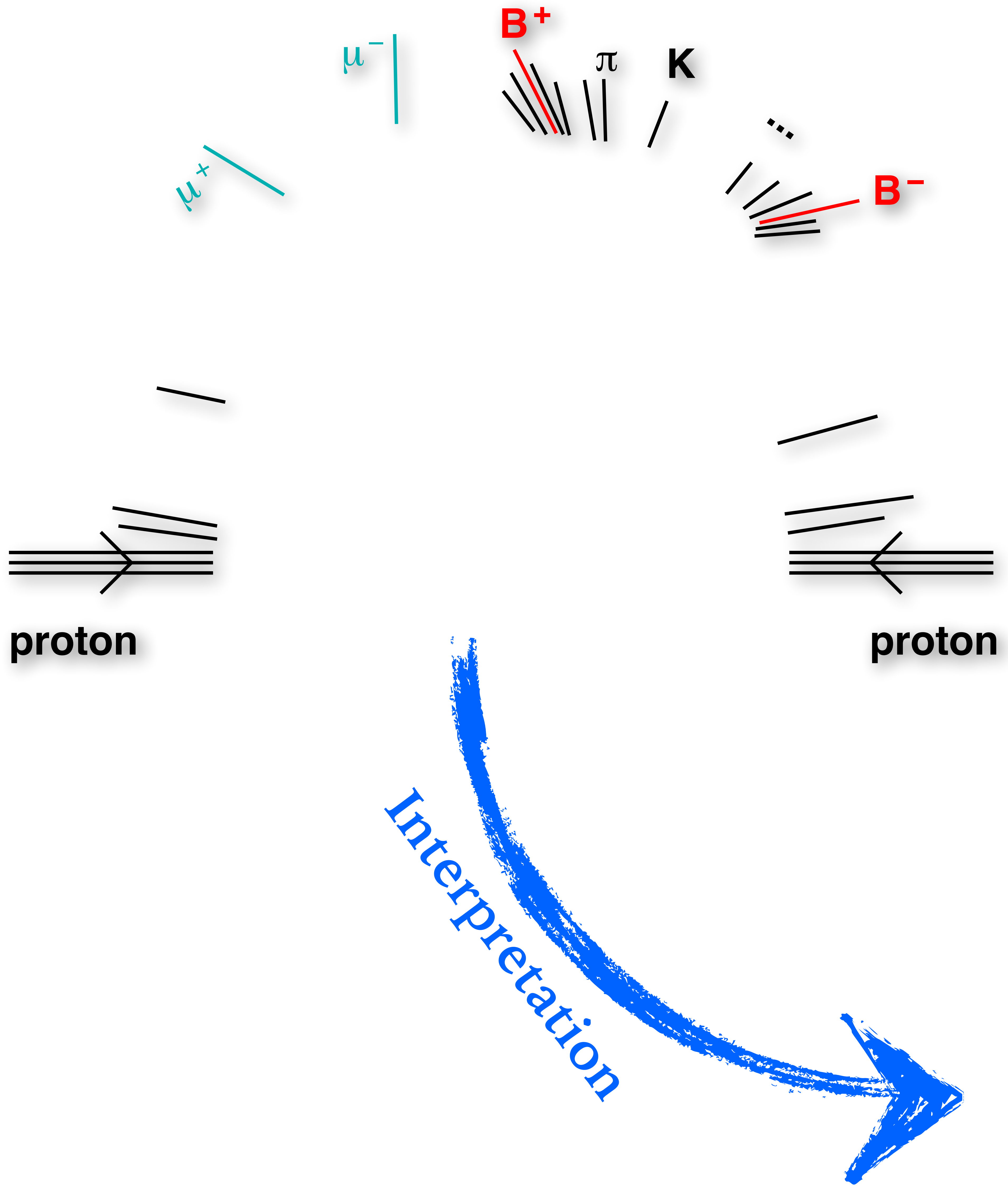

CMS
CMS Experiment at the LHC, CERN
Simulated event at 13 TeV centre-of-mass energy
Y

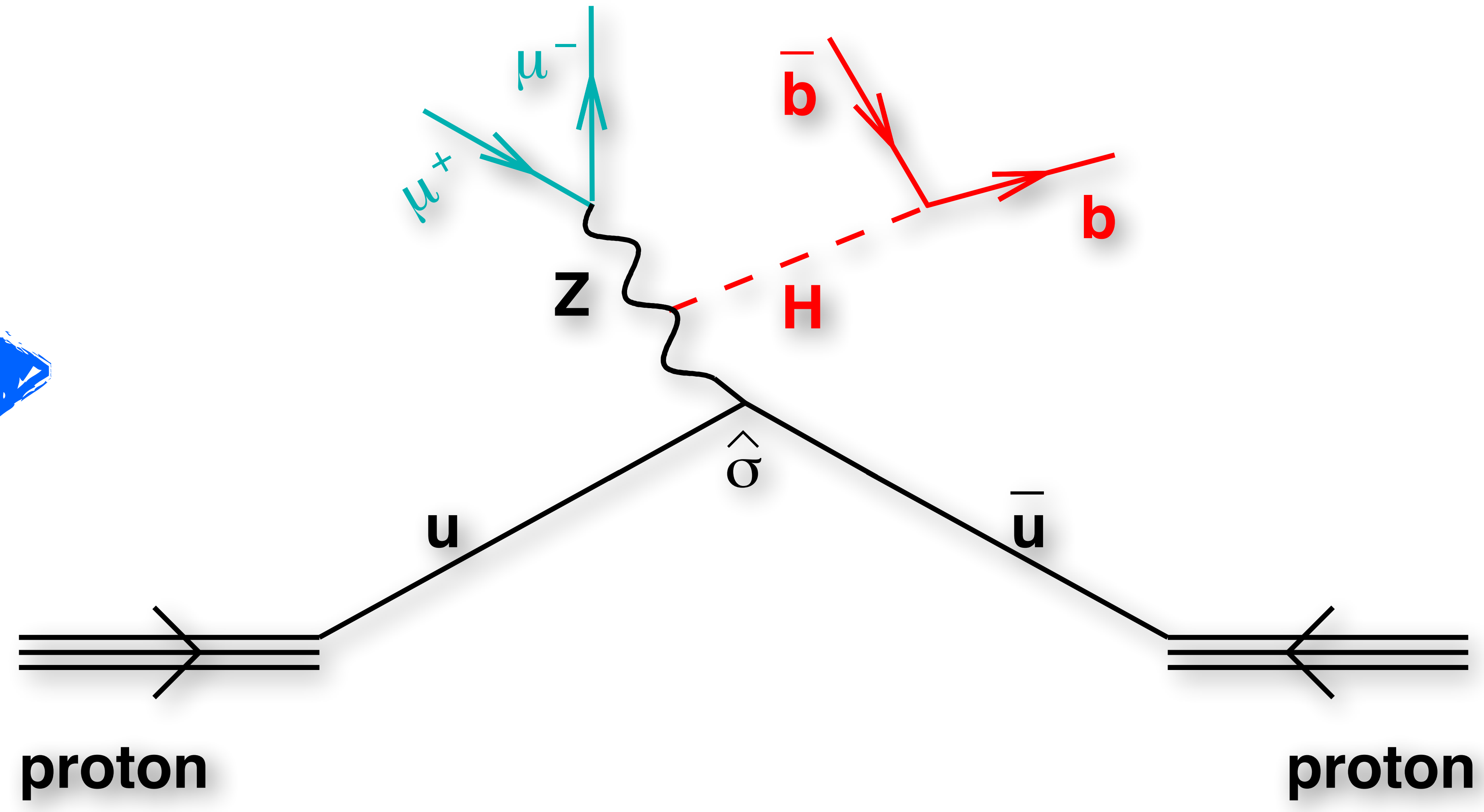

CMS Experiment at the LHC, CERN
Simulated event at 13 TeV centre-of-mass energy

jets are about organizing the information from hundreds (or thousands) of particles into a form that we as humans can understand and process

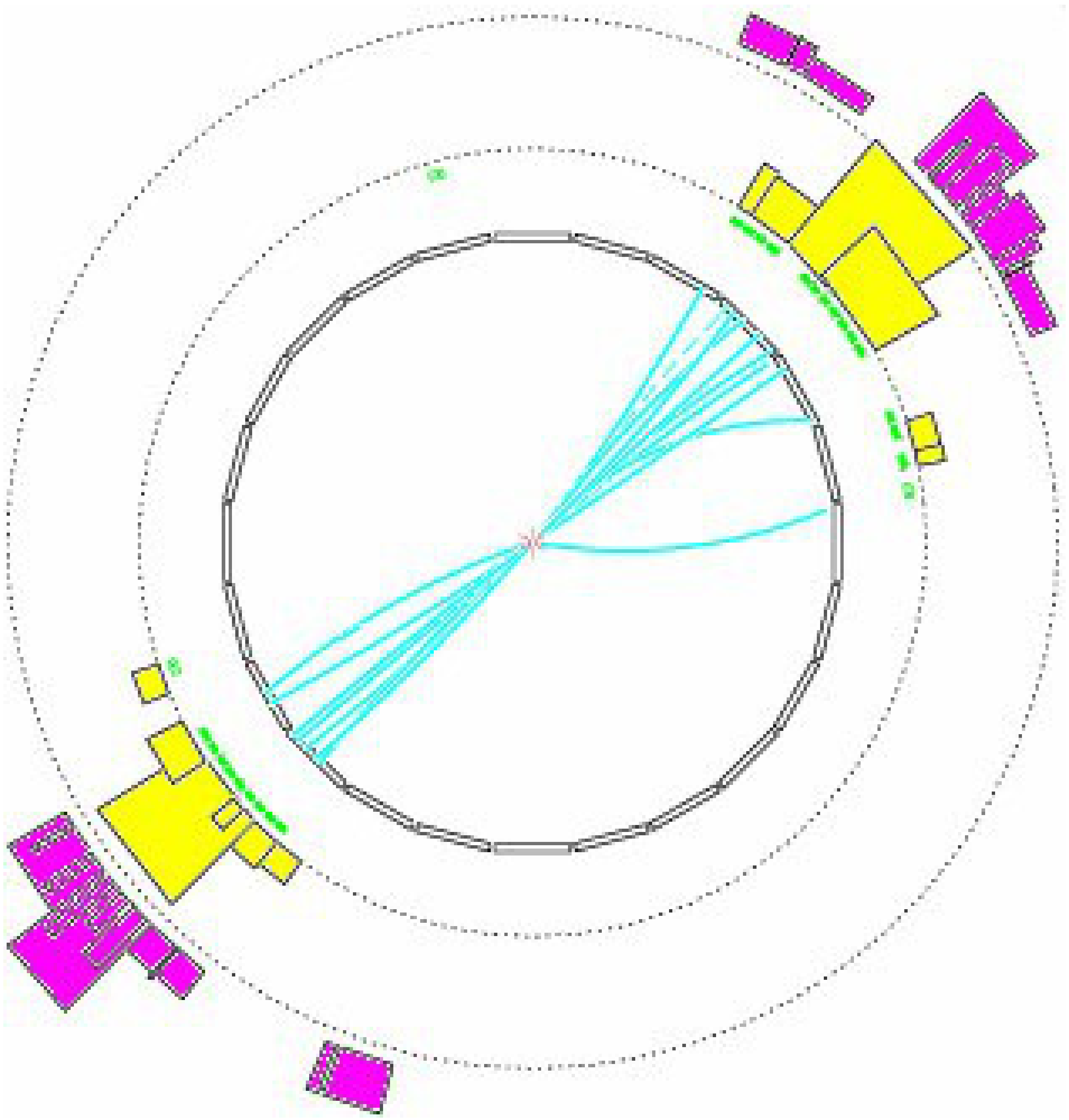
jets

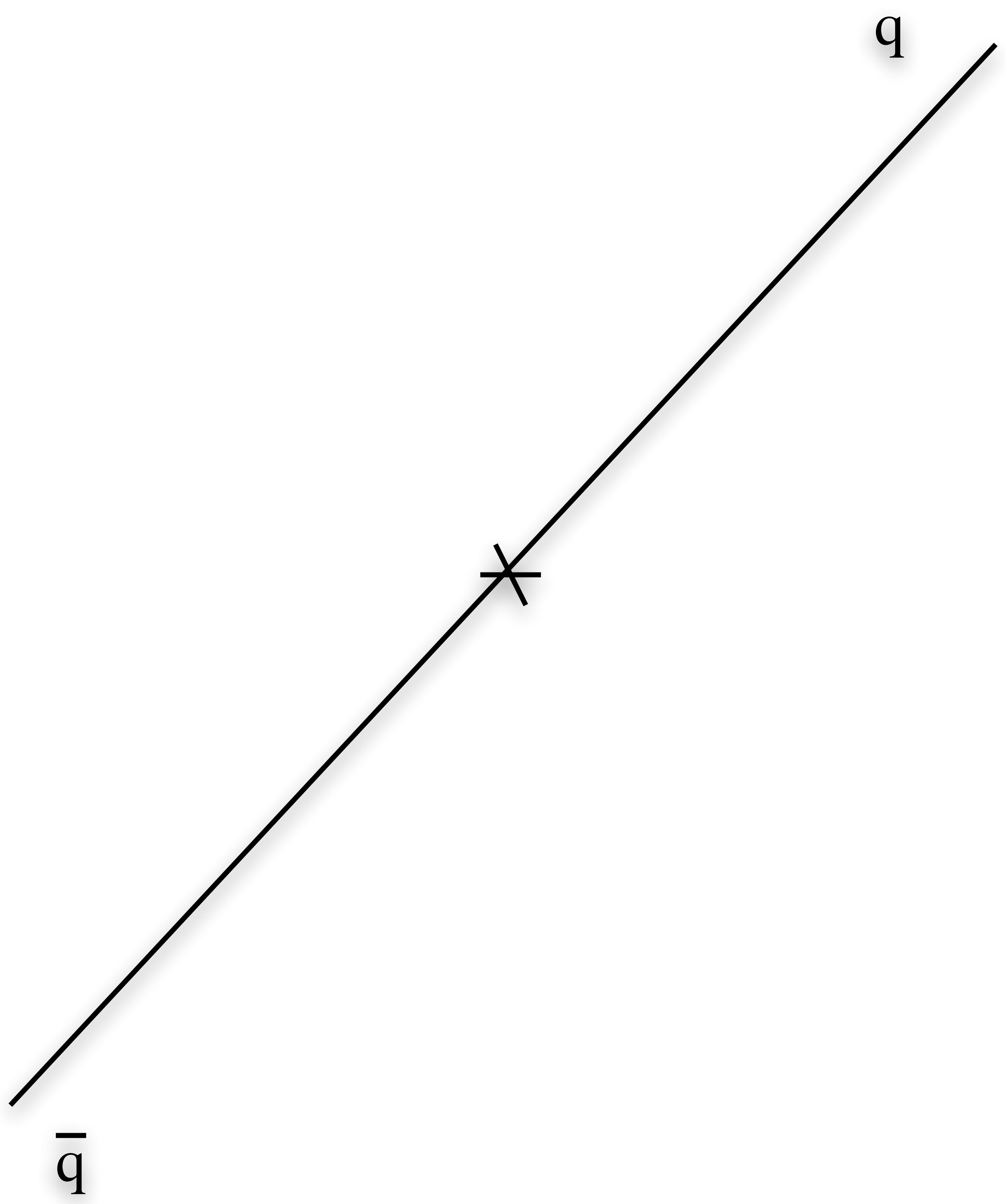
i.e. how we make sense of the hadronic part of events





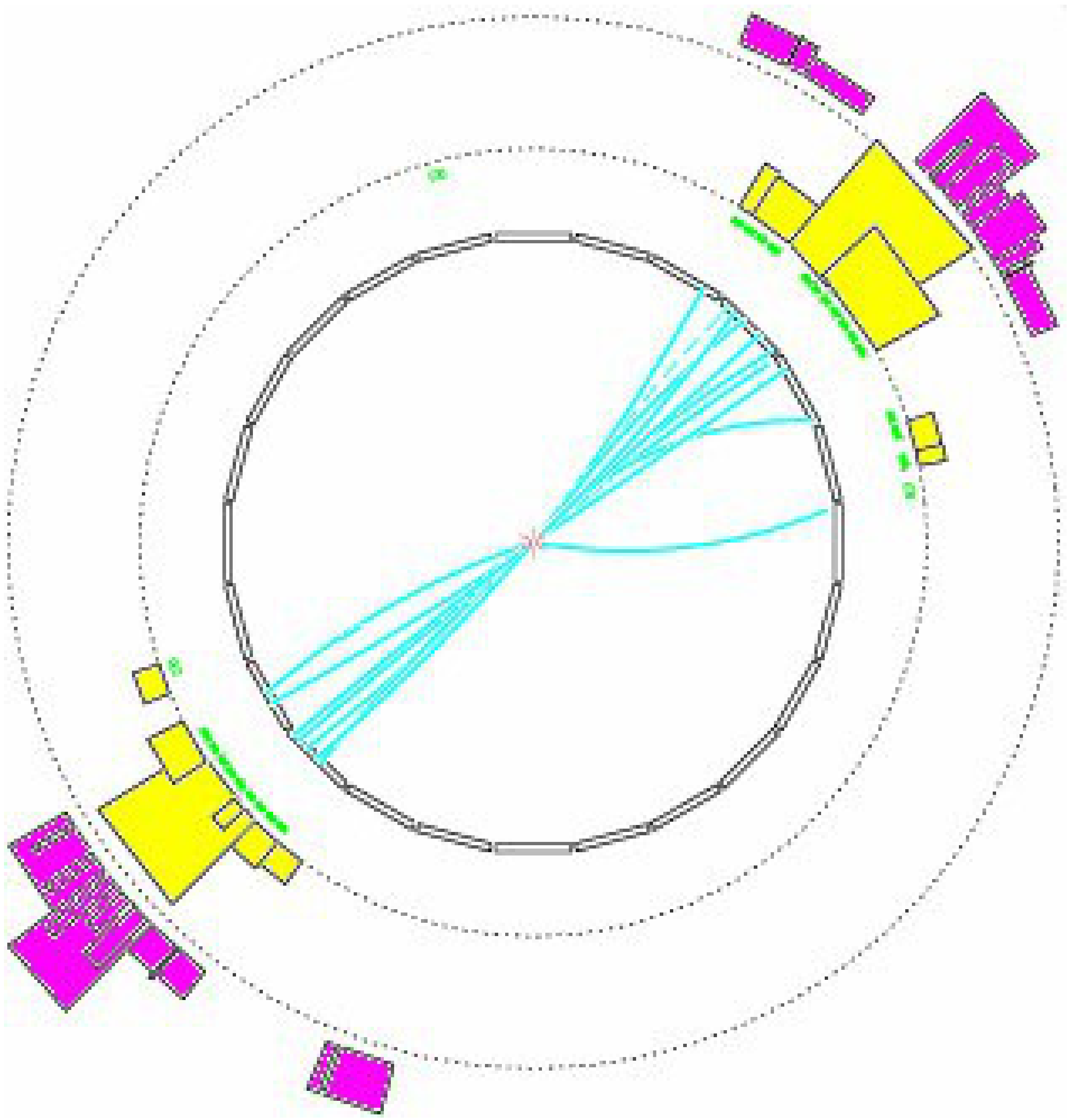
The Quantum-Chromodynamic (QCD) origin of jets

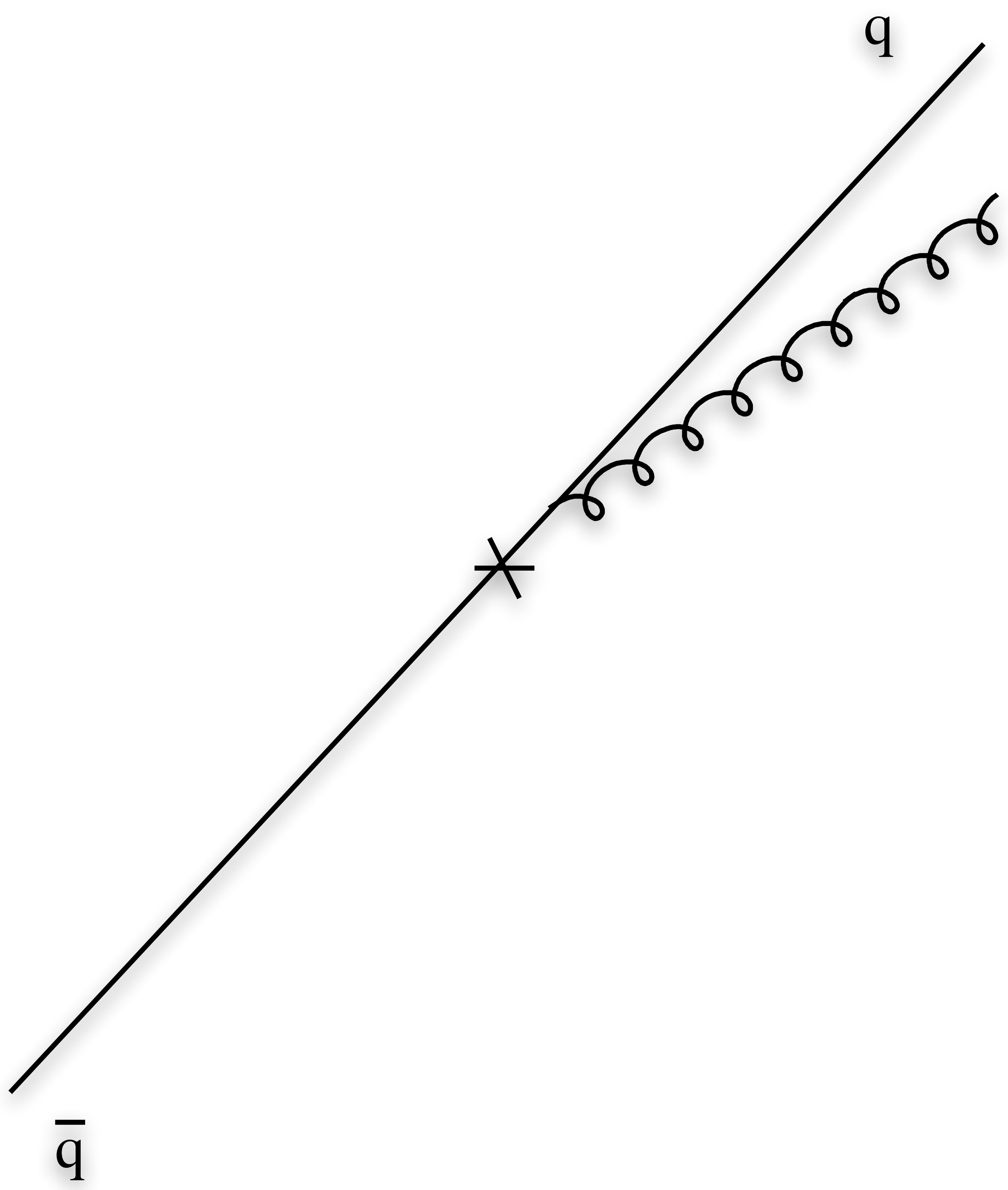




Start off with a qqbar system

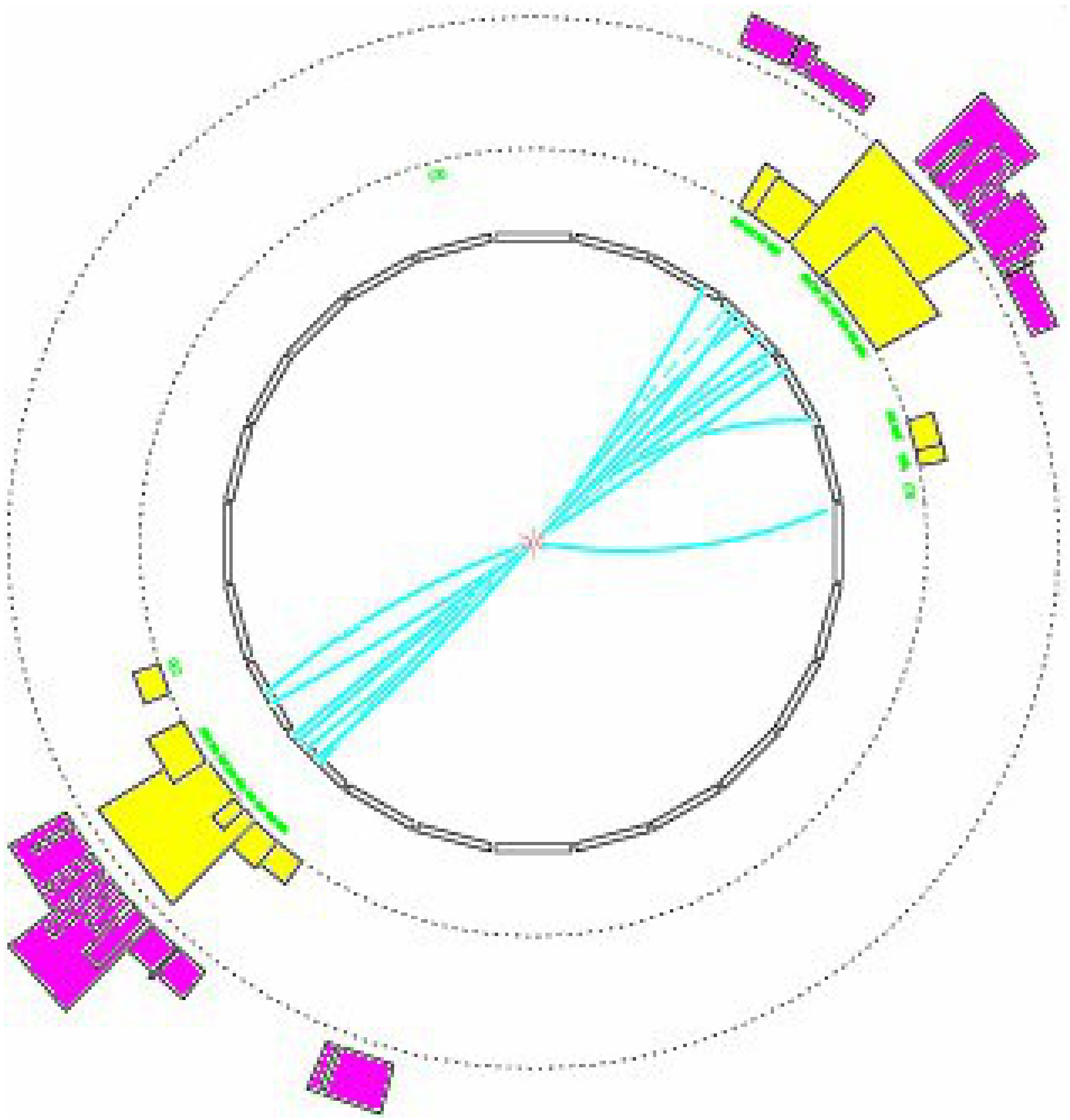
A key QCD tool: jets

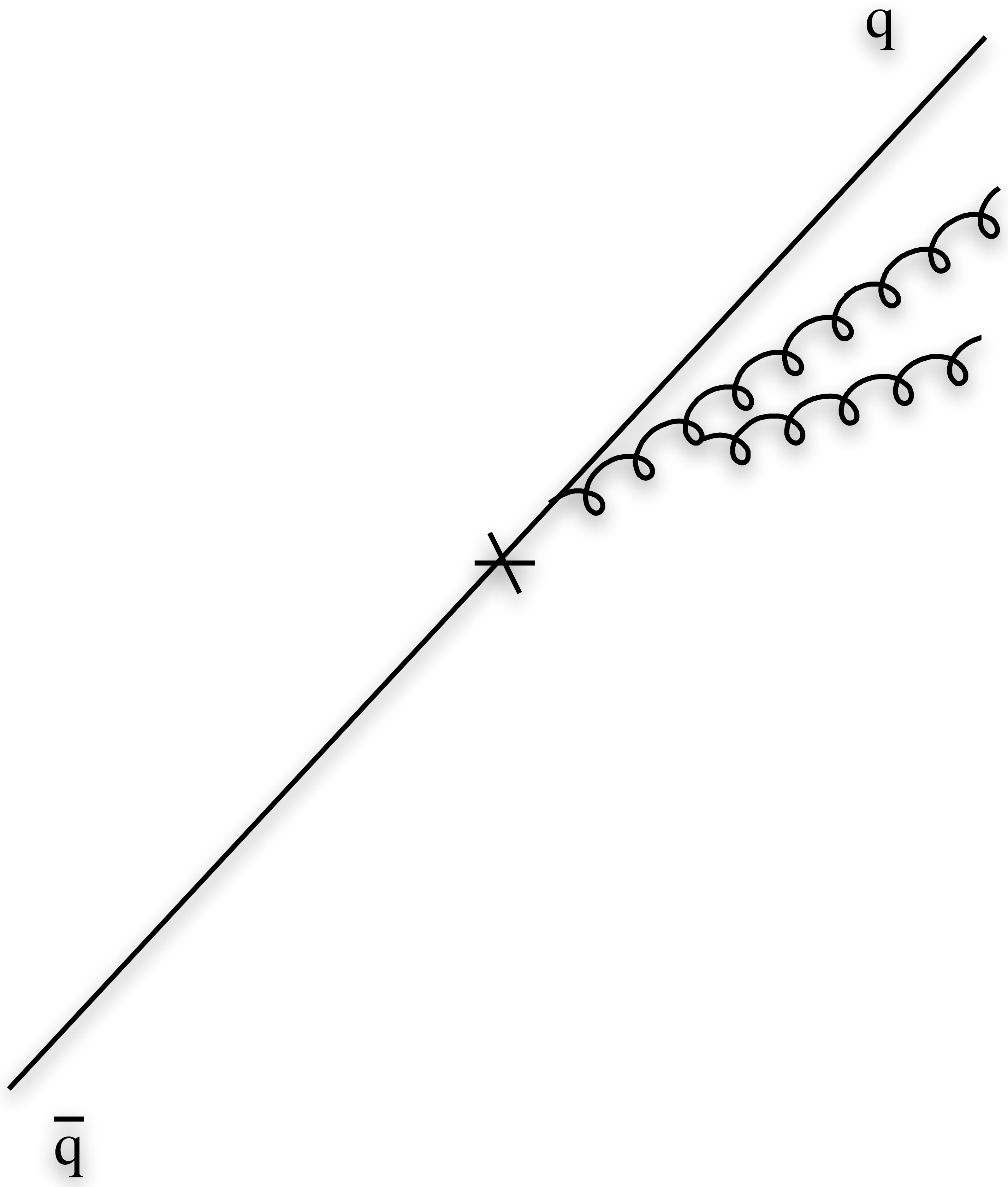




a gluon gets emitted at small angles

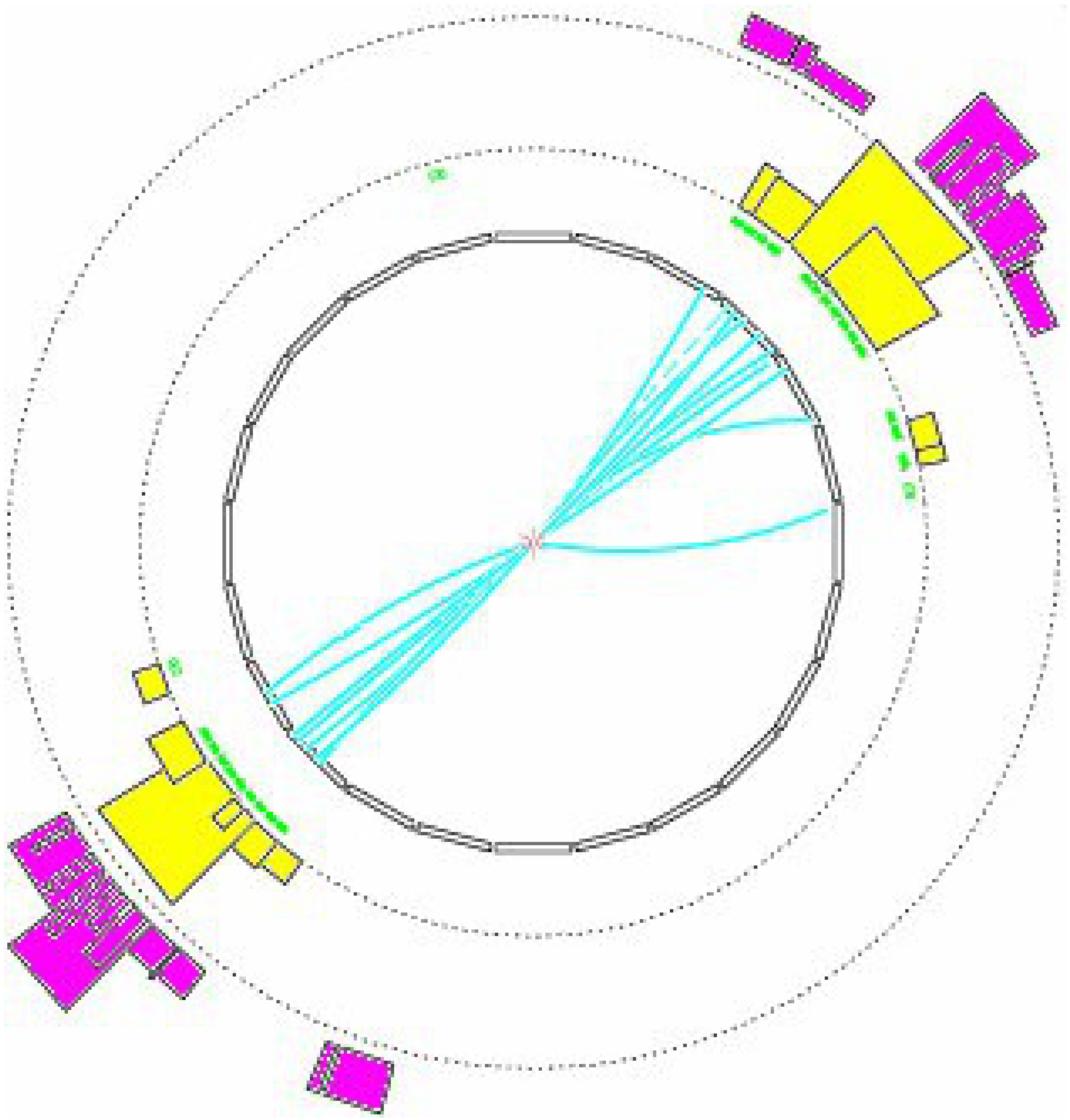
A key QCD tool: jets

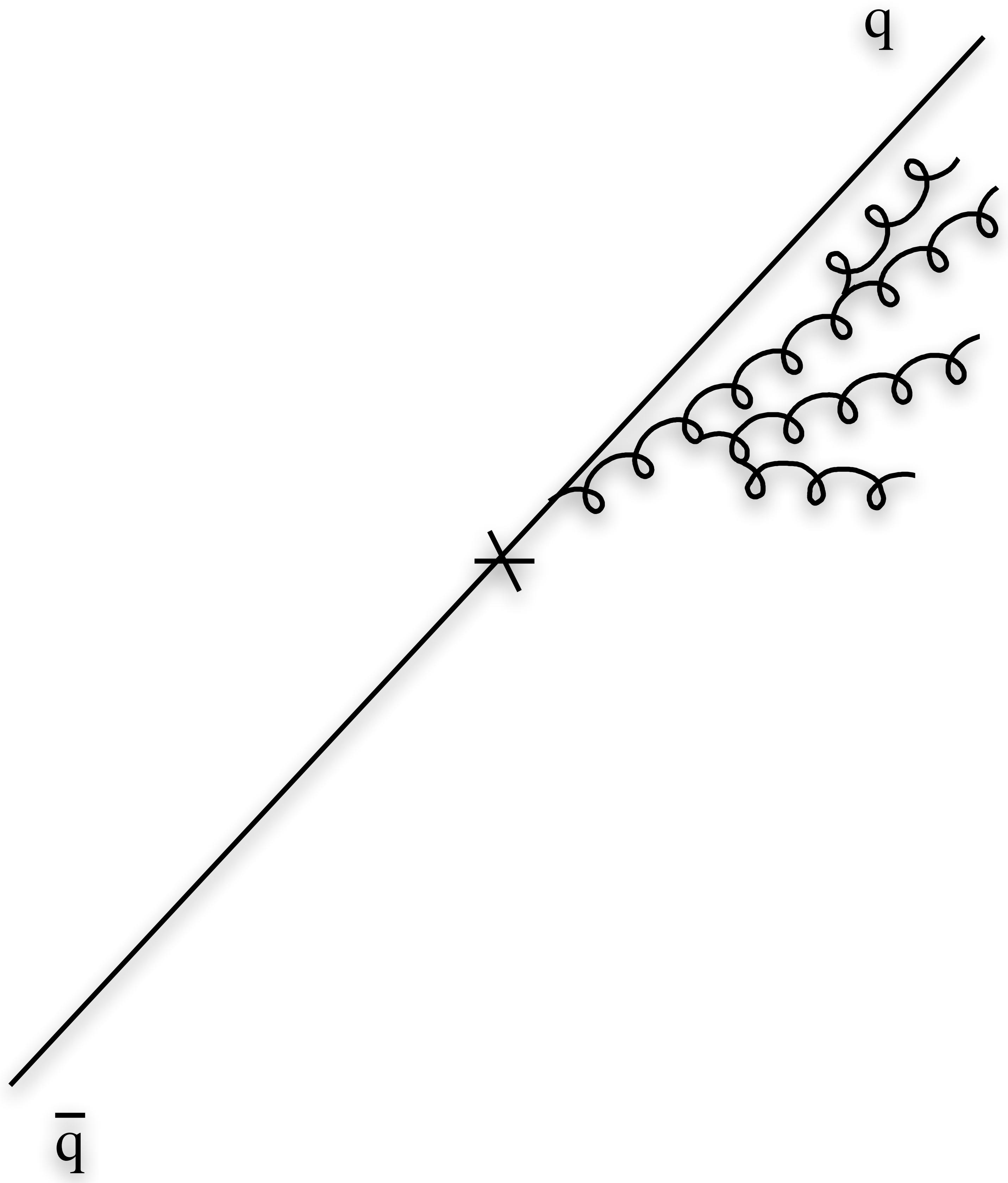




it radiates a further gluon

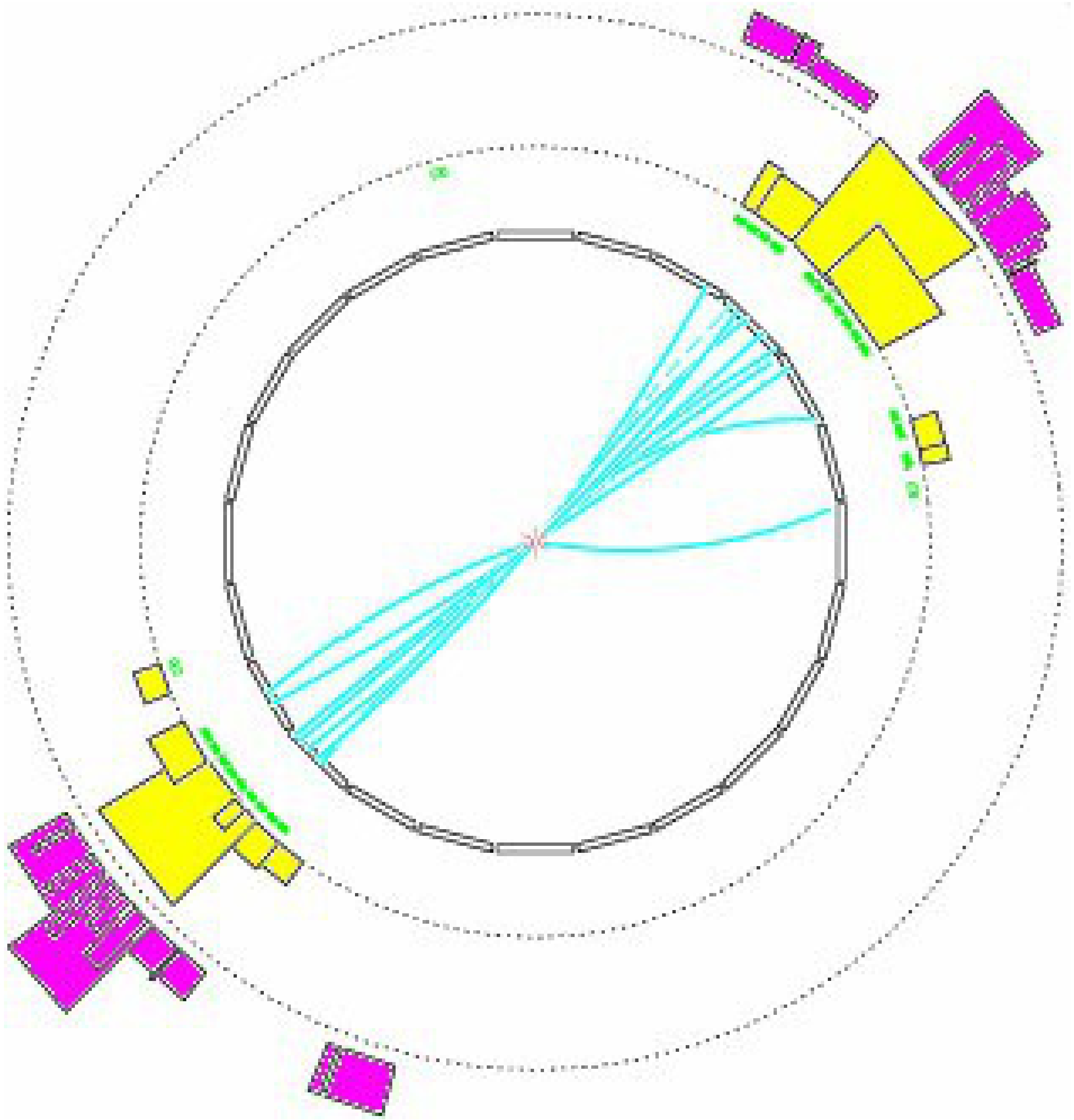
A key QCD tool: jets

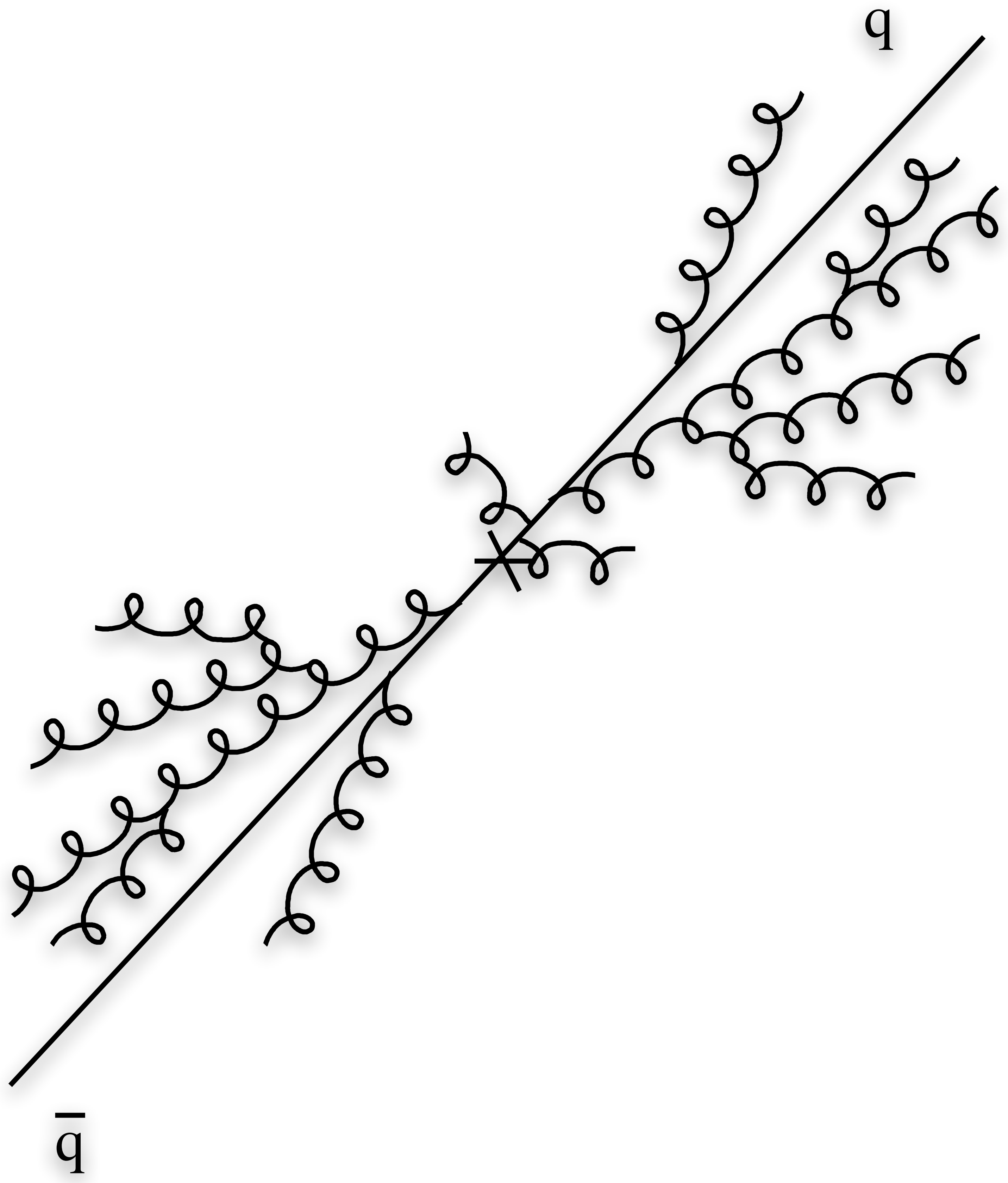




and so forth

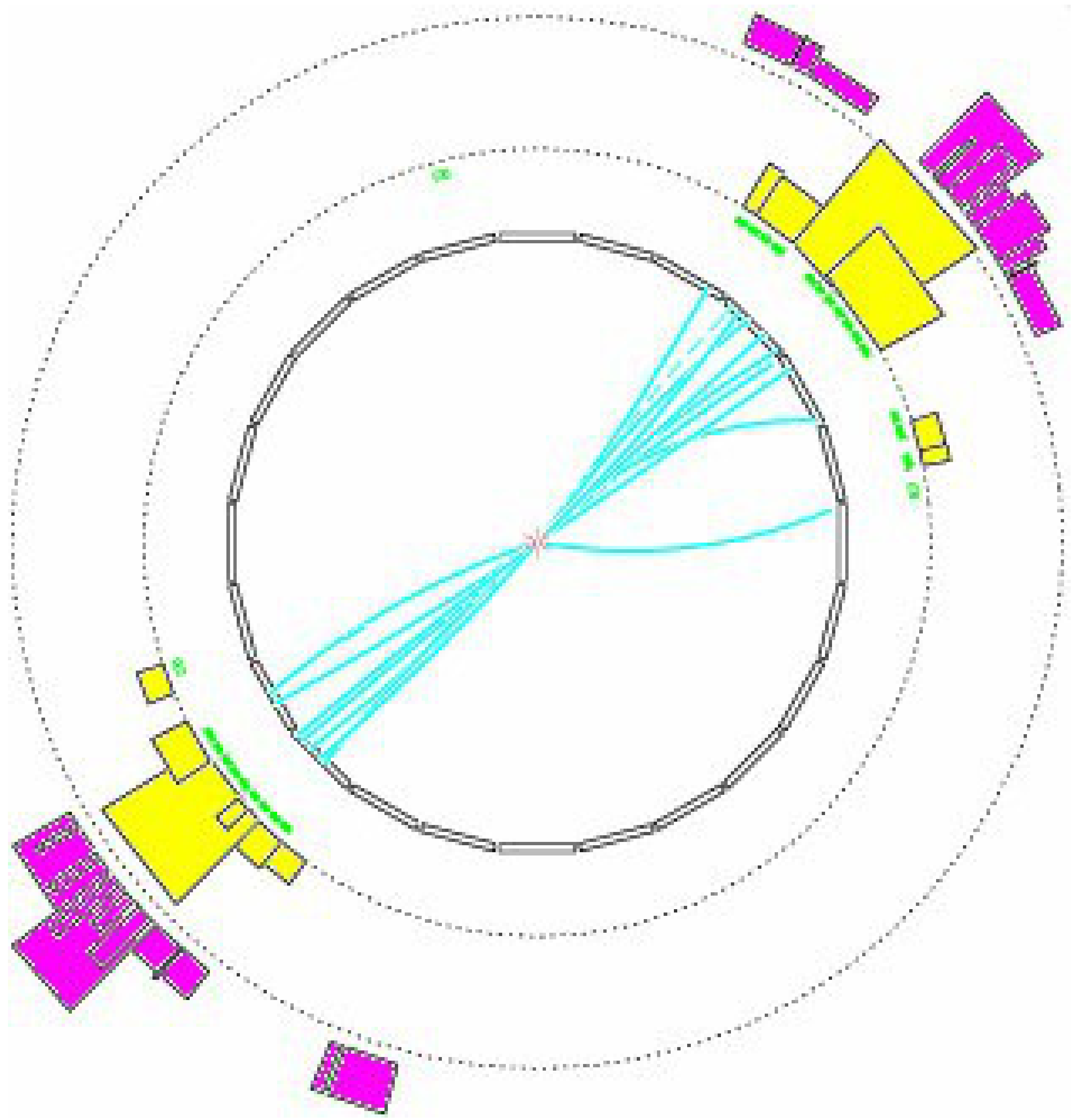
A key QCD tool: jets





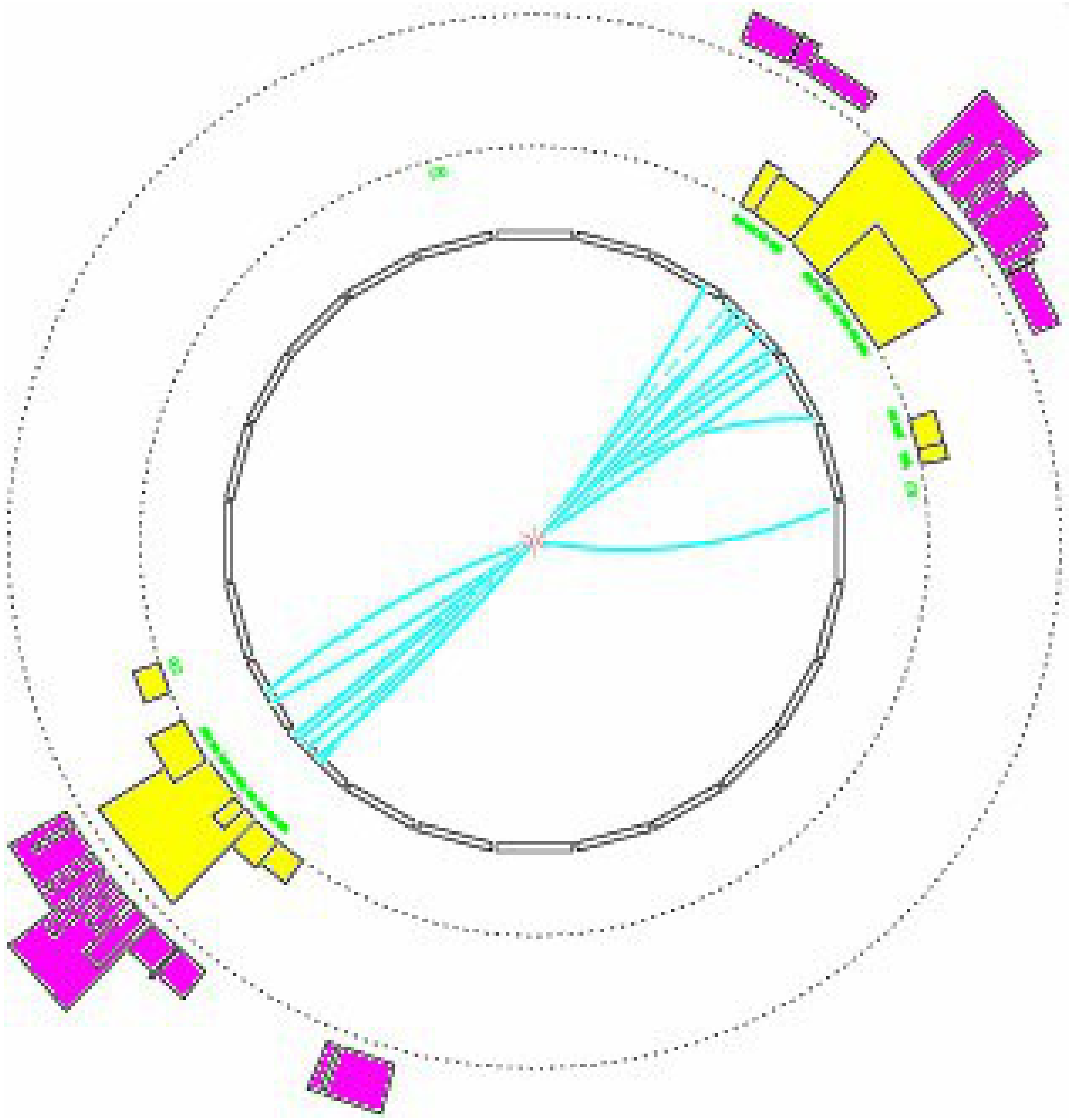
meanwhile the same happened on the other side

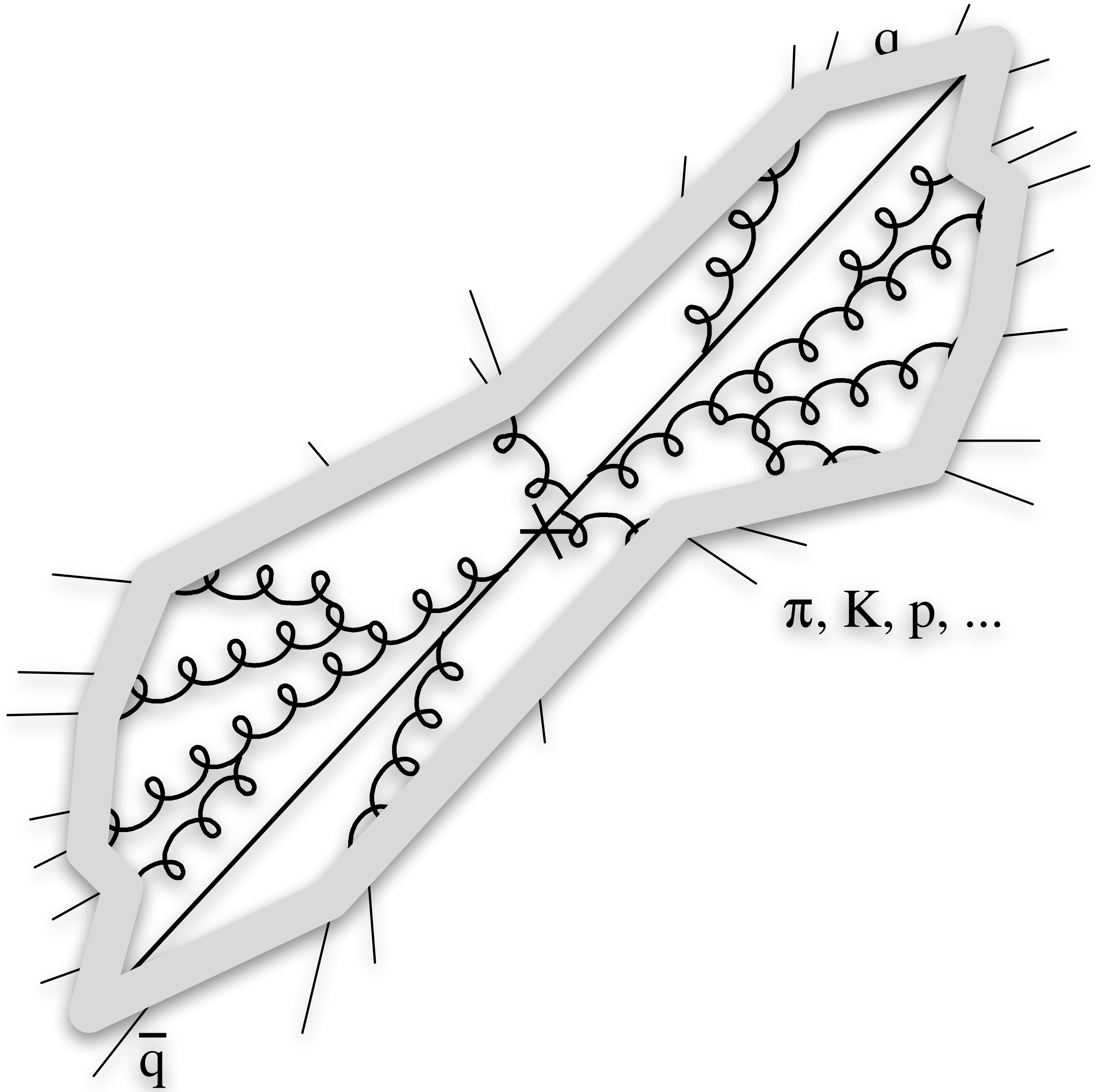
A key QCD tool: jets



then a non-perturbative transition occurs

A key QCD tool: jets

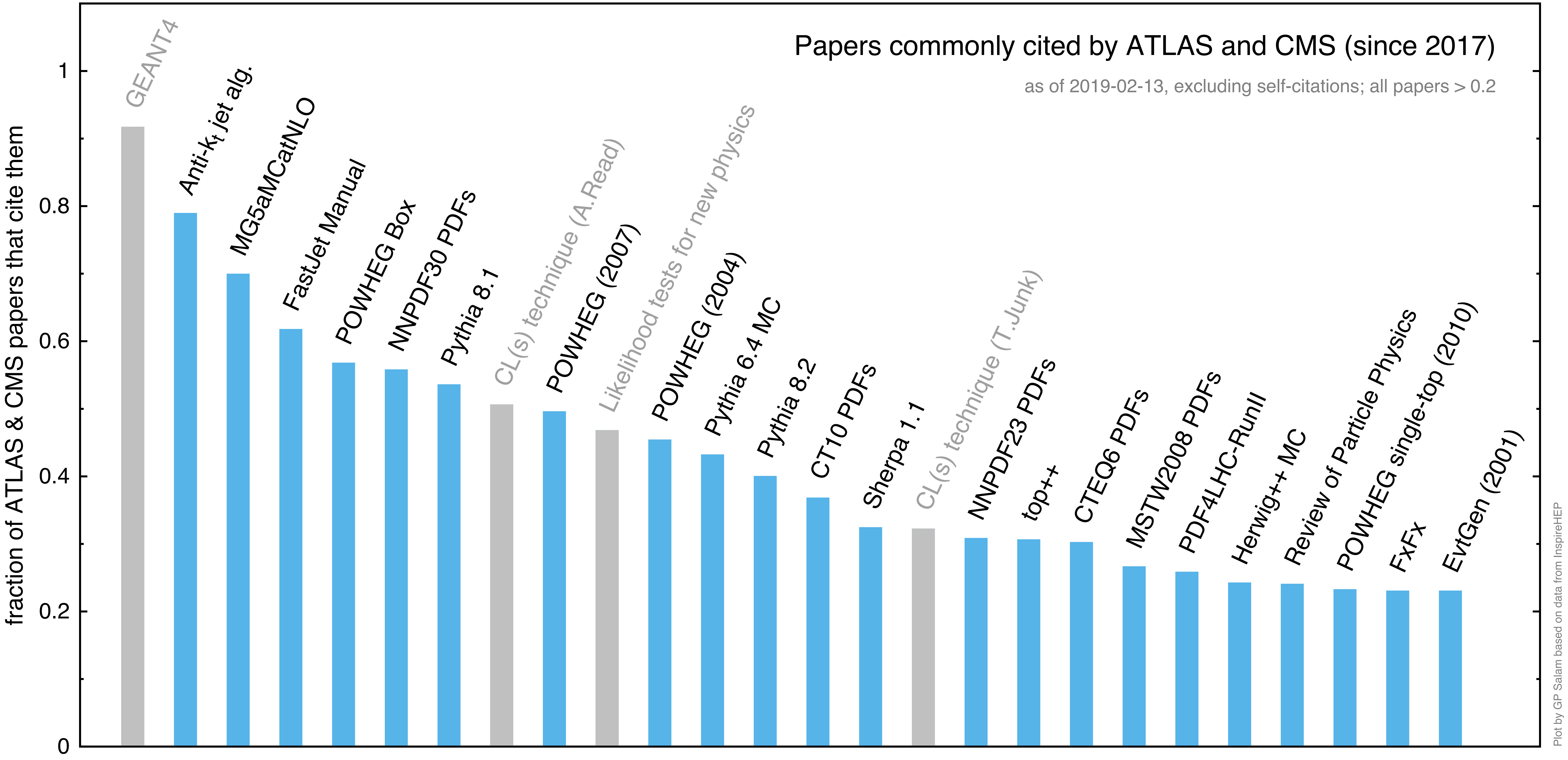




giving a pattern of hadrons that "remembers" the gluon branching

(hadrons mostly produced at small angles wrt qqbar directions — two **"jets"**)

The tools used by ATLAS & CMS



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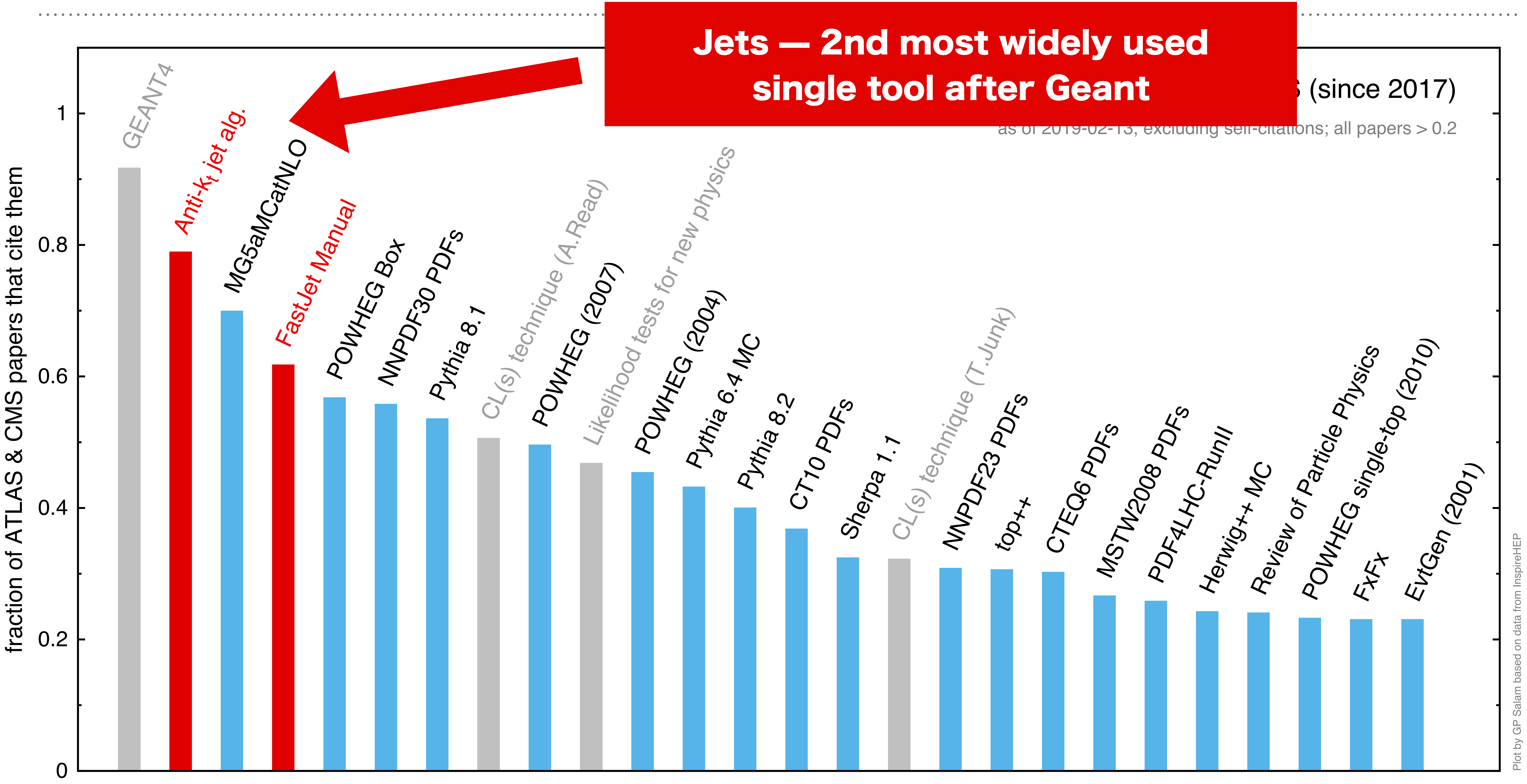
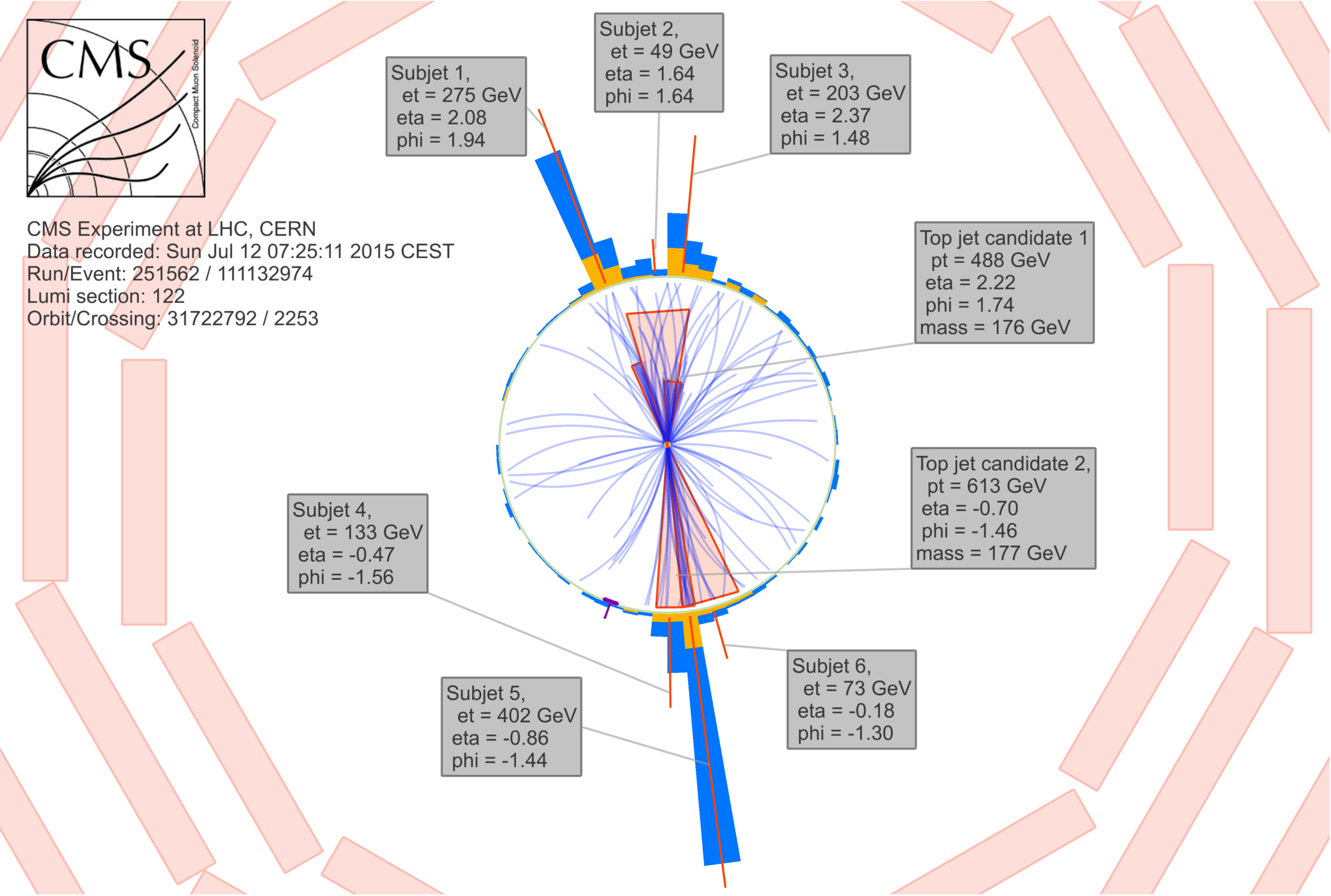


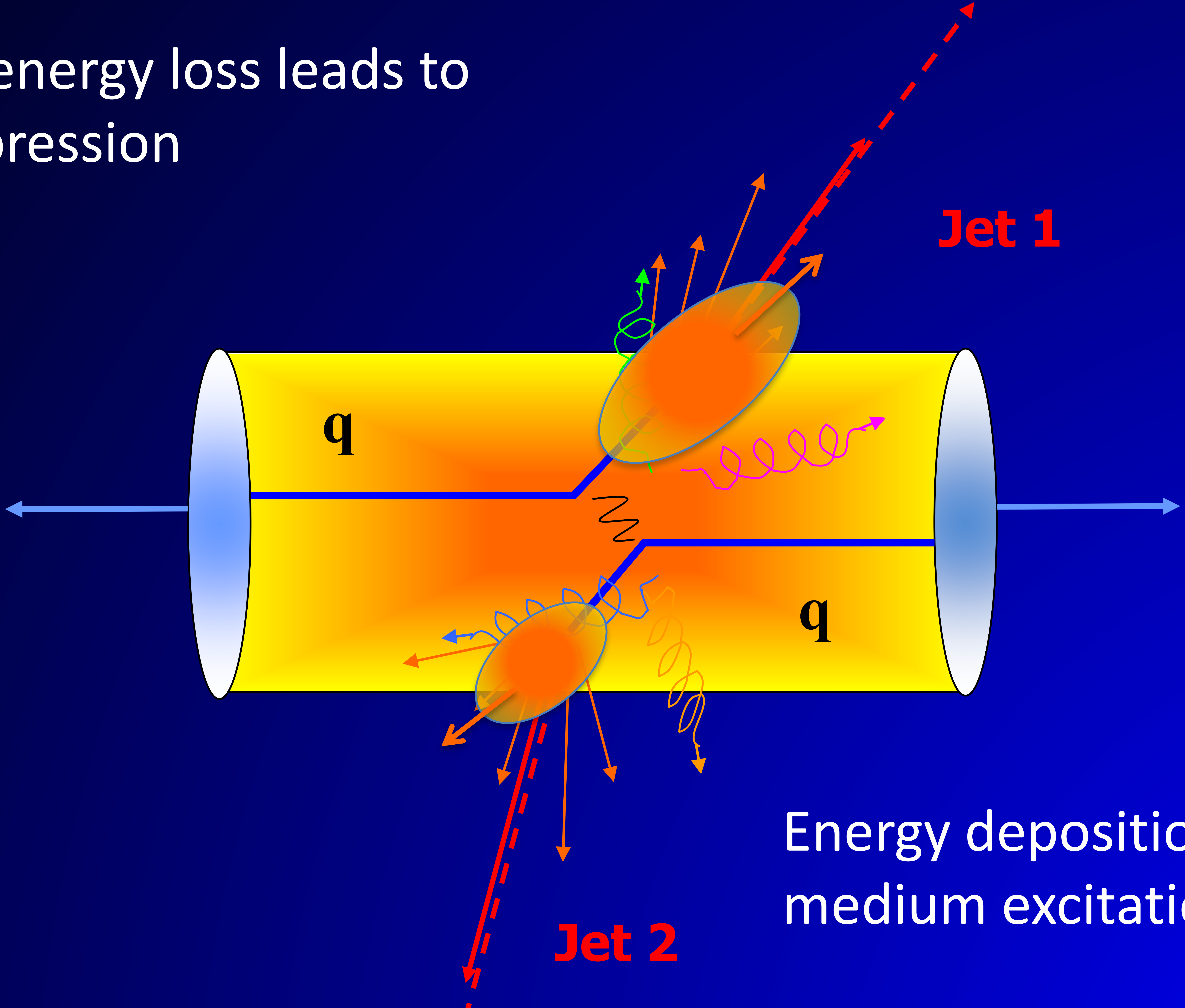


a pp collision that produces a high p_t top-antitop pair, resulting in two "top-jets", each with subjets

Such events probe point-like nature of top quarks to TeV scale & allow you to search for new ttbar resonances

Parton energy loss leads to jet suppression

PbPb

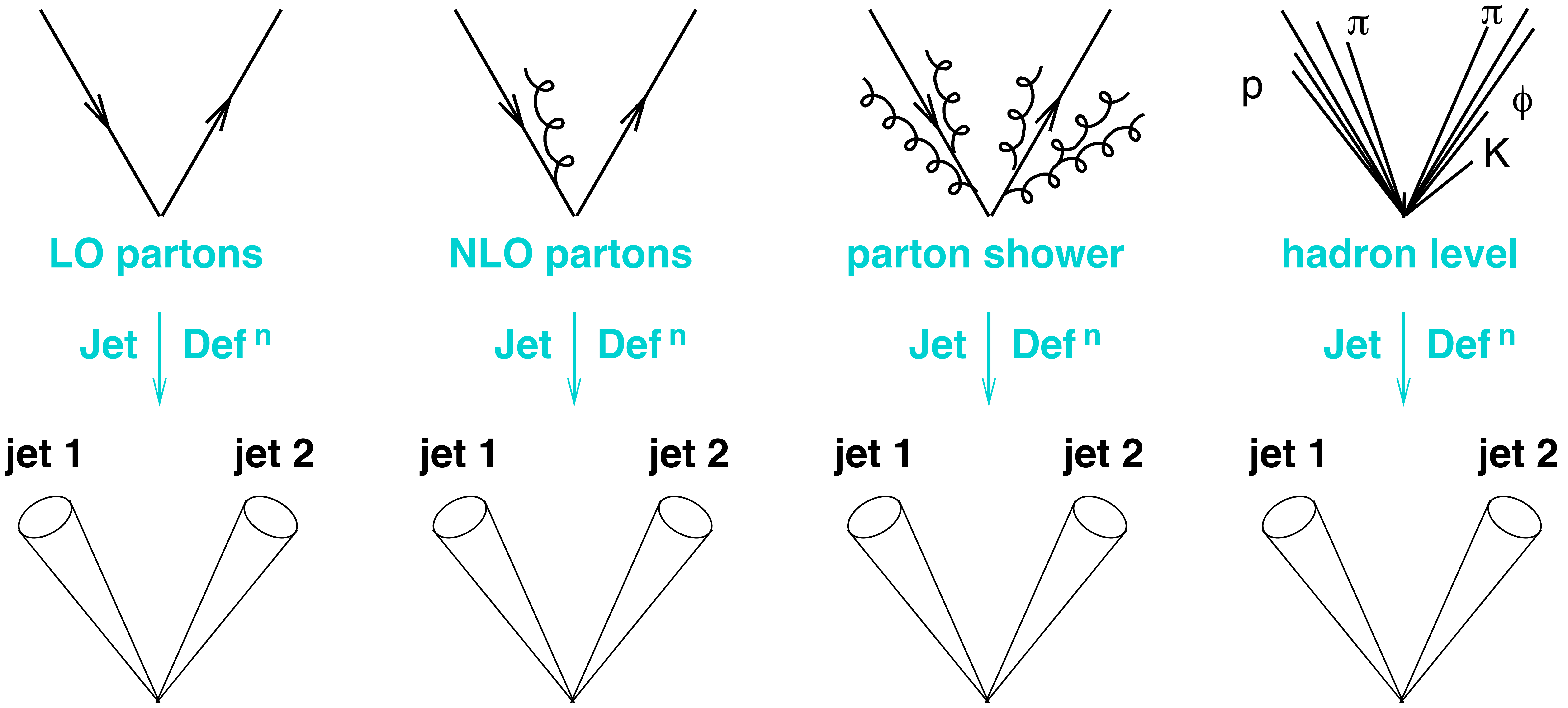


Energy deposition leads to medium excitation

from X-N. Wang

jet substructure for pp

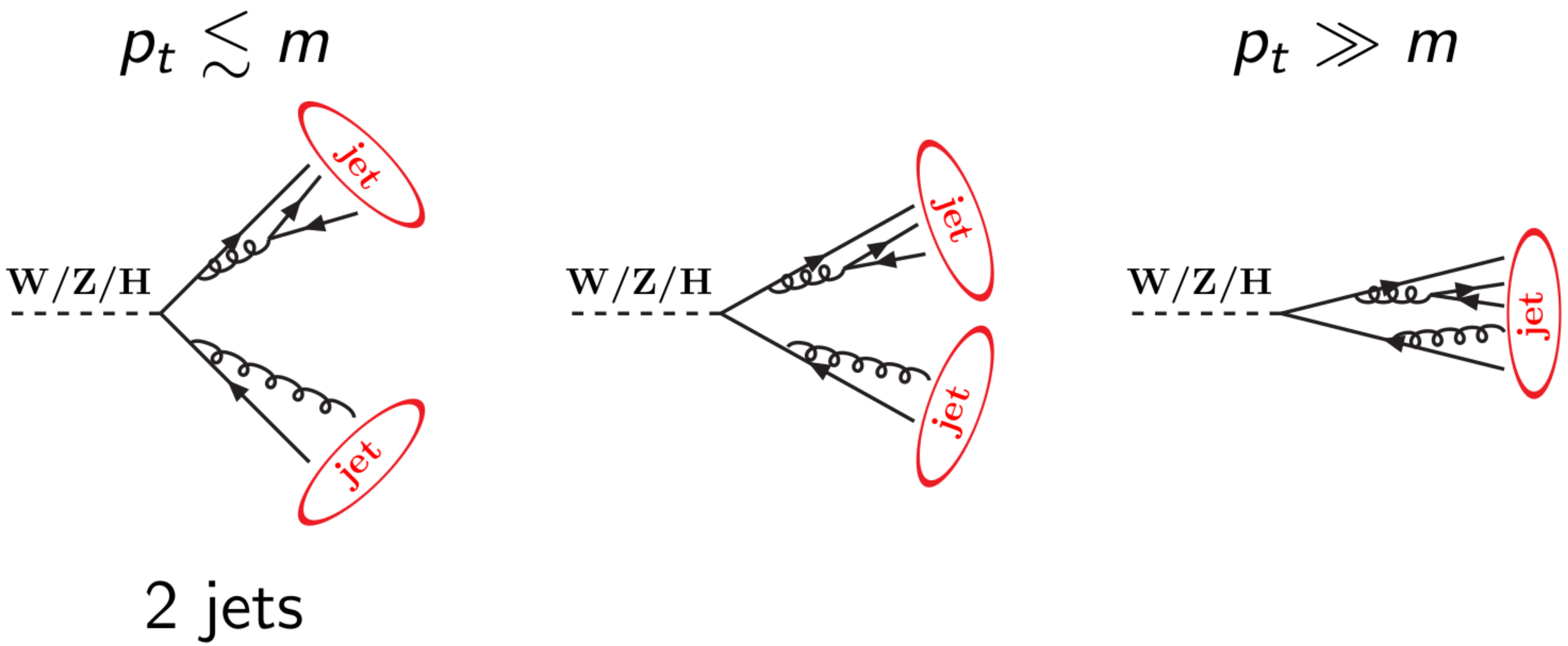
what should a jet definition achieve?



projection to jets should be resilient to QCD effects

Jet substructure for boosted hadronc W/Z/H/t etc. decays

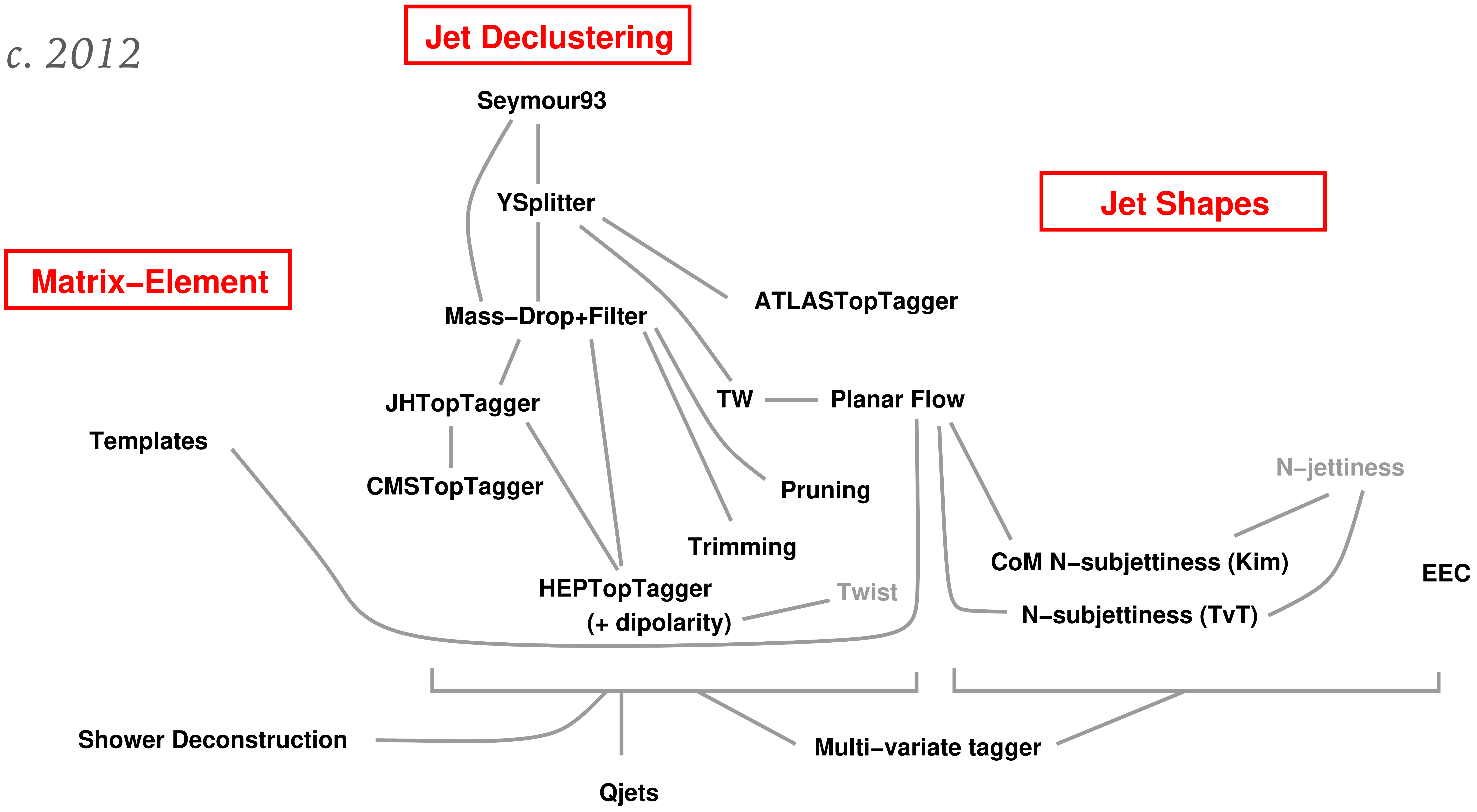
- At LHC energies, EW-scale particles (W/Z/t...) are often produced with $p_t \gg m$, leading to collimated decays.
- Hadronic decay products are thus often reconstructed into single jets.



[Figure by G. Soyez]

pp jet substructure field is full of activity

c. 2012



pp jet substructure field is full of activity

c. 2018

Jet Declustering

Seymour93

YSplitter

Mass–Drop+Filter

ATLASTopTagger

Tagger

Tagger

TW — Planar Flow

Pruning

Trimming

HEPTopTagger (+ dipolarity)

Twist

Jet Shapes

N–jettiness

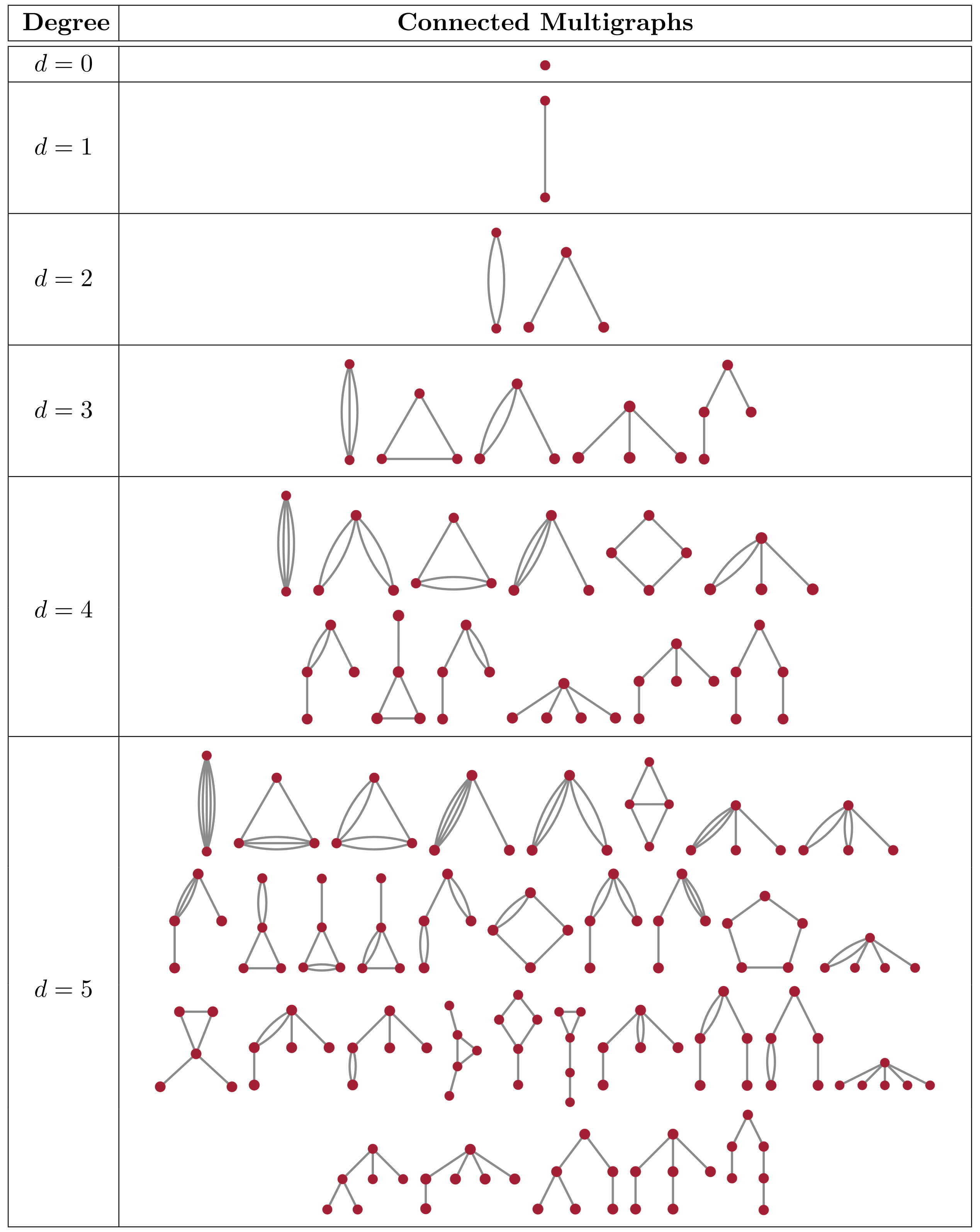
CoM N–subjettiness (Kim)

N–subjettiness (TvT)

EEC

Matrix–Element

modified mass drop
soft drop
iterated soft drop
recursive soft drop



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

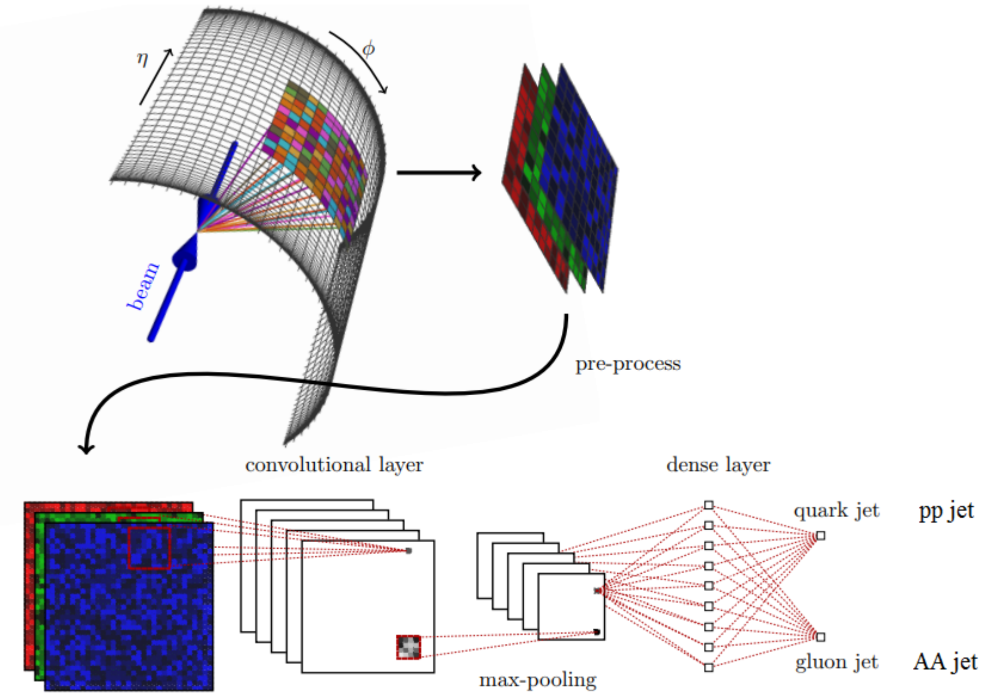
Shower Deconstruction

Qjets

Multi–variate tagger

machine learning
DNN, CNN,
RNN, LSTM, etc

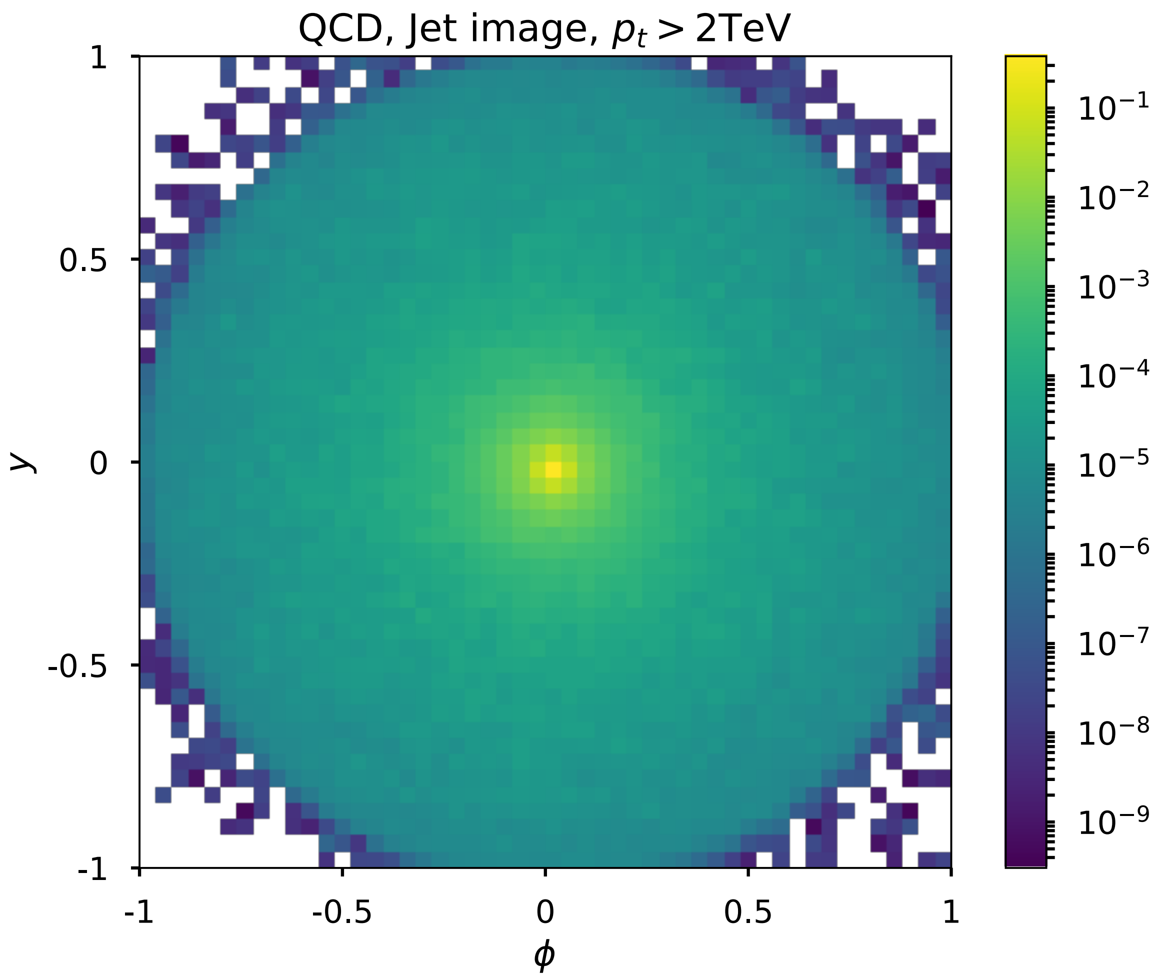
classification without labels
weak supervision

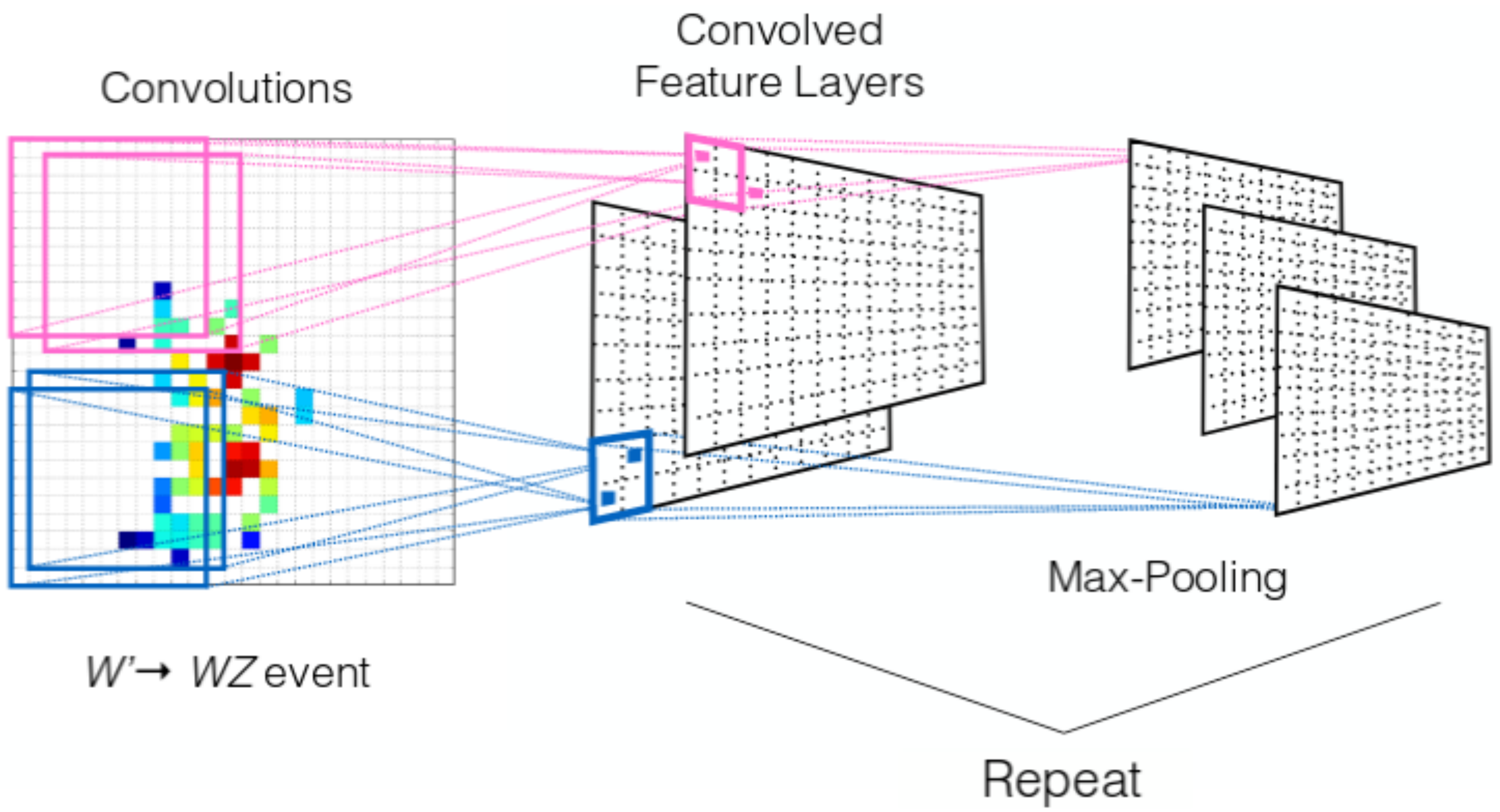


etc.

Convolutional neural networks and jet images

- Project a jet onto a fixed $n \times n$ pixel image in rapidity-azimuth, where each pixel intensity corresponds to the momentum of particles in that cell.
- Can be used as input for classification methods used in computer vision, such as deep convolutional neural networks.



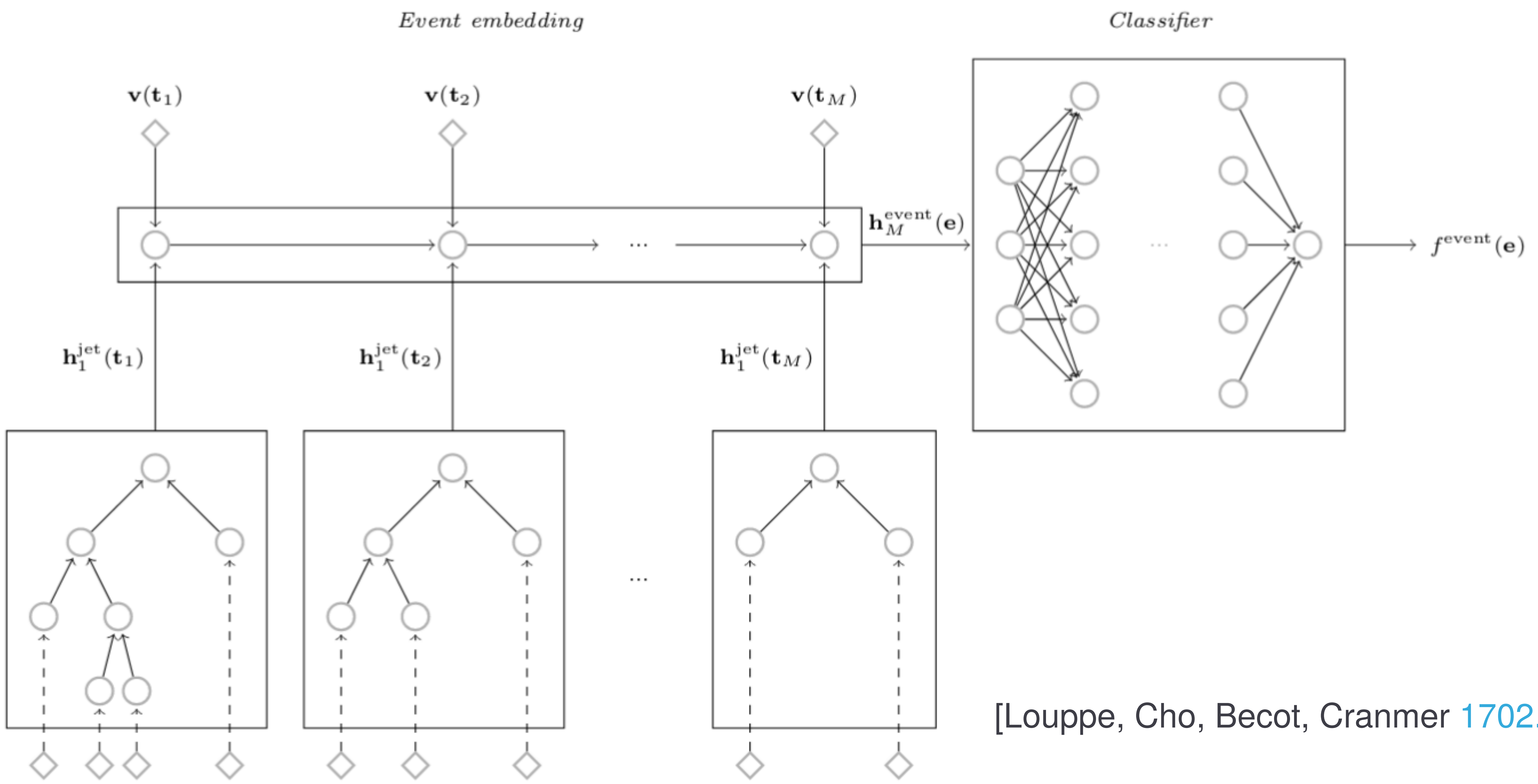


[Cogan, Kagan, Strauss, Schwartzman JHEP 1502 (2015) 118]

[de Oliveira, Kagan, Mackey, Nachman, Schwartzman JHEP 1607 (2016) 069]

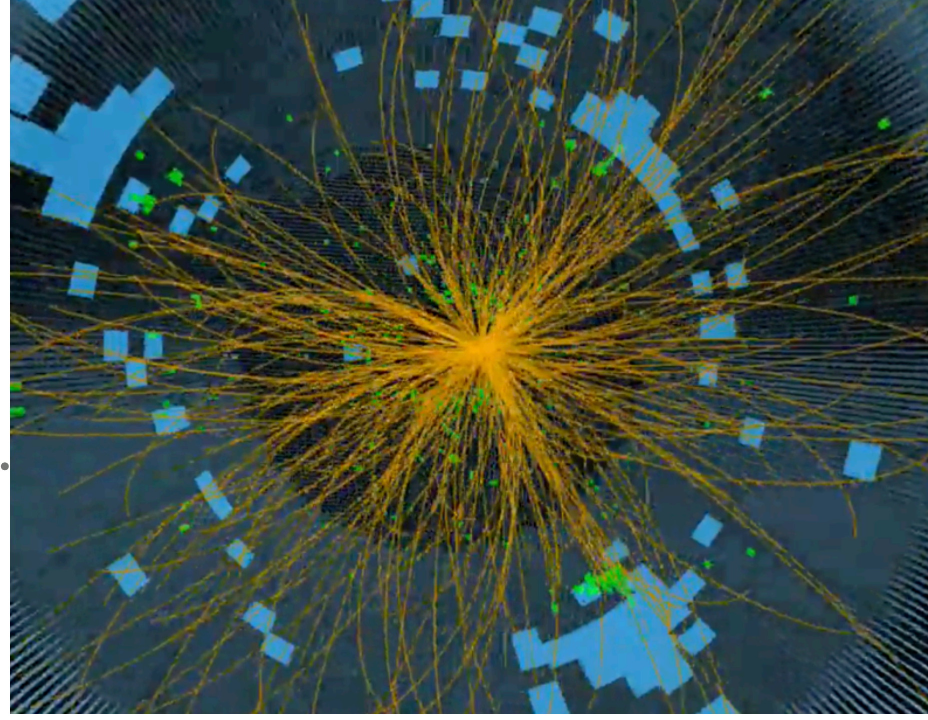
Recurrent neural network on clustering trees

- Train a recurrent neural network on successive declusterings of a jet.
- Techniques inspired from Natural Language Processing with powerful applications in handwriting and speech recognition.

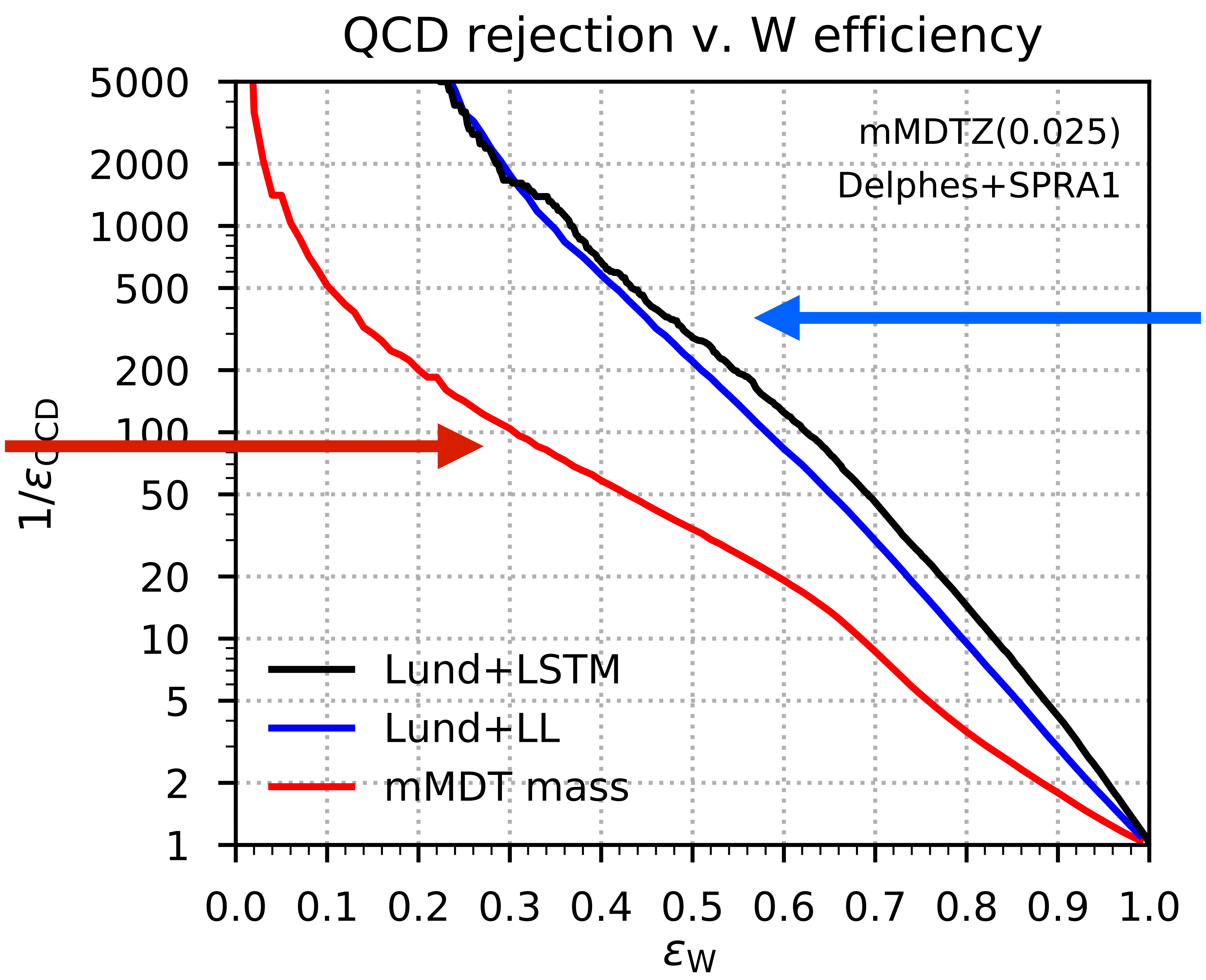


[Louppe, Cho, Becot, Cranmer 1702.00748]

using full event information: jet substructure for W tagging



QCD rejection with just jet mass (SD/mMDT)



QCD rejection with use of full jet substructure

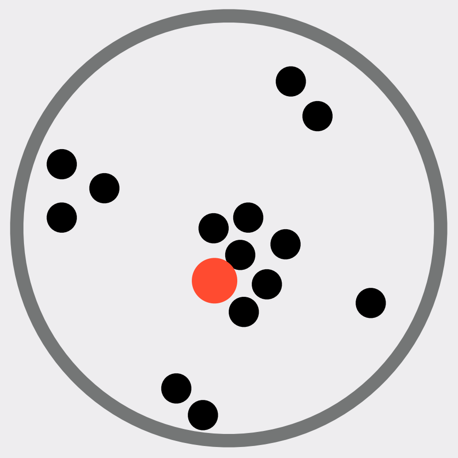
5–10x better

jet substructure for HI collisions

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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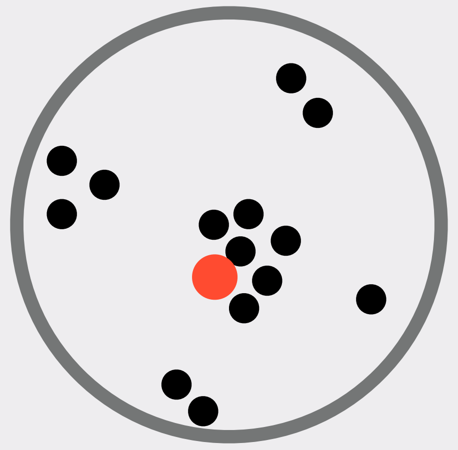
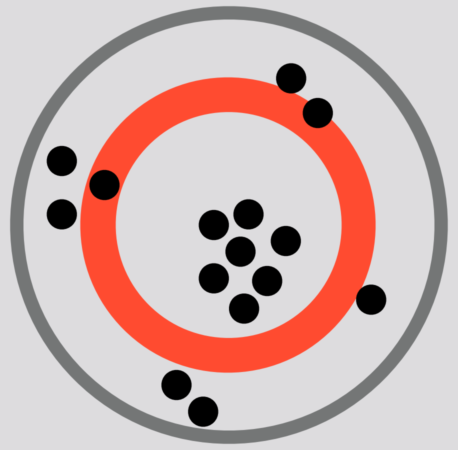


differential jet shape

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



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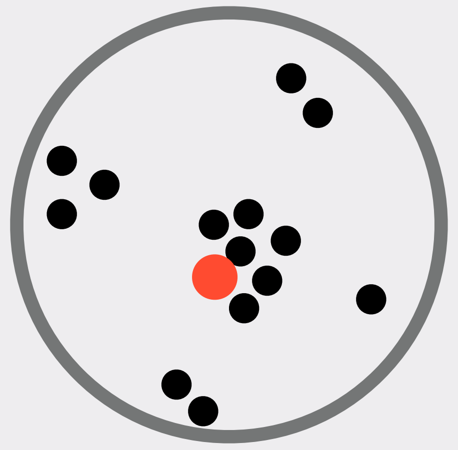

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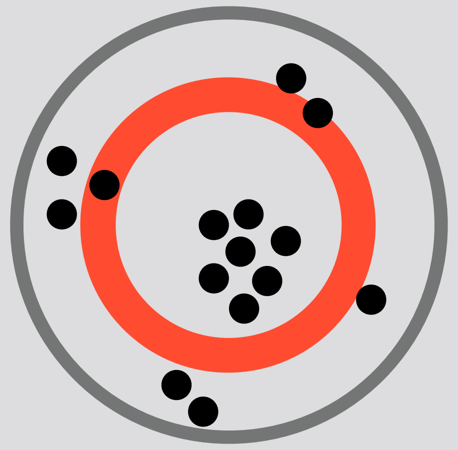
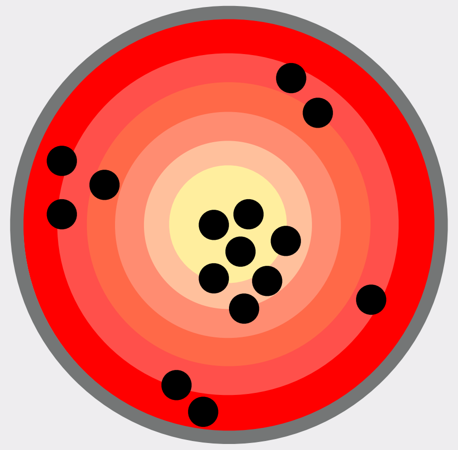


girth ≡ broadening

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



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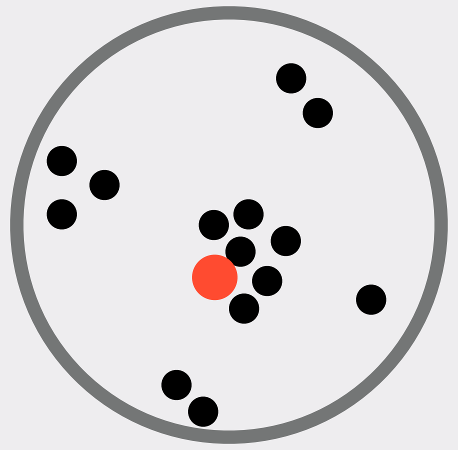

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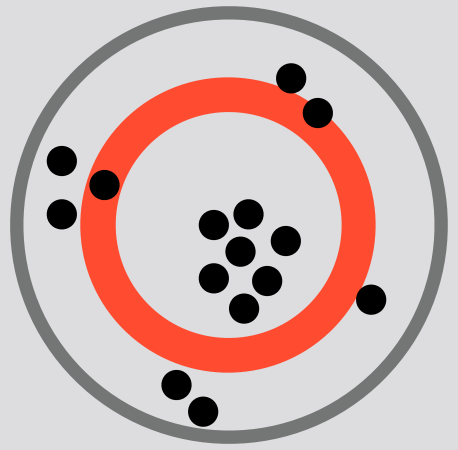

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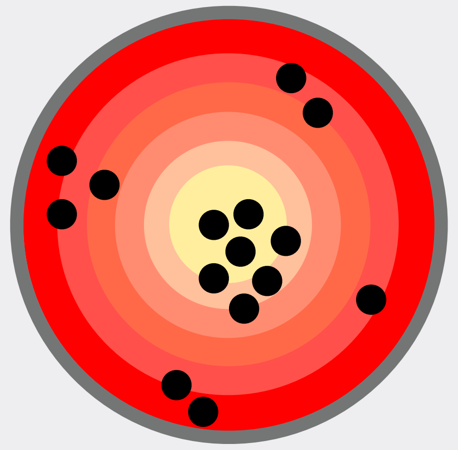
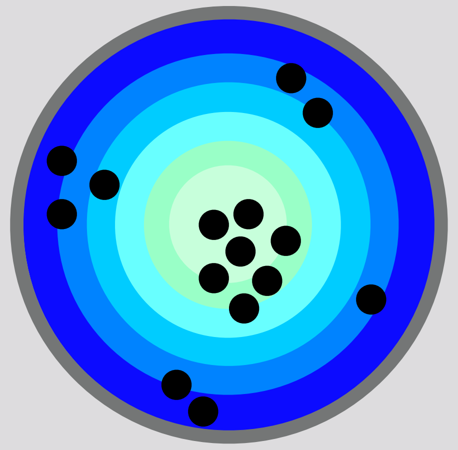


jet mass, groomed & ungroomed

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



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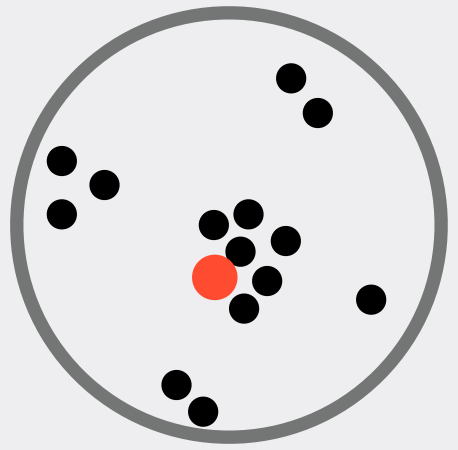

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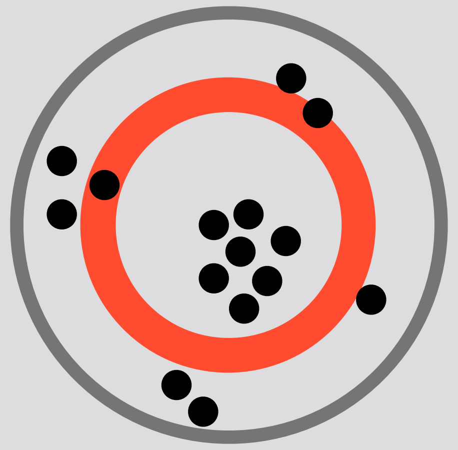

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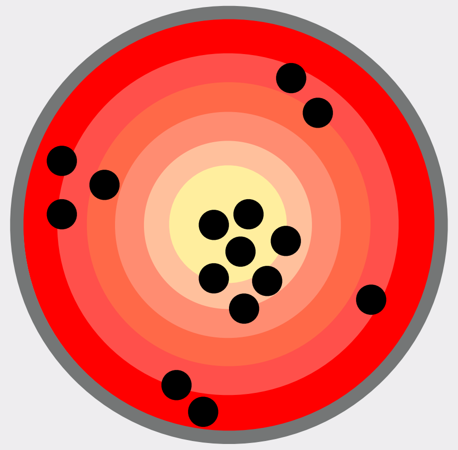

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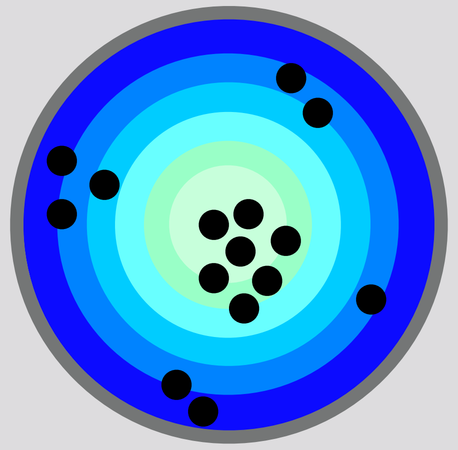
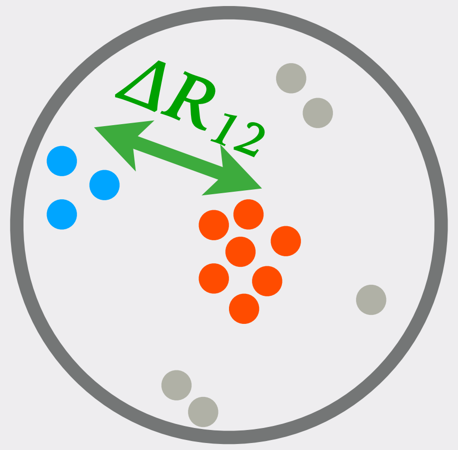


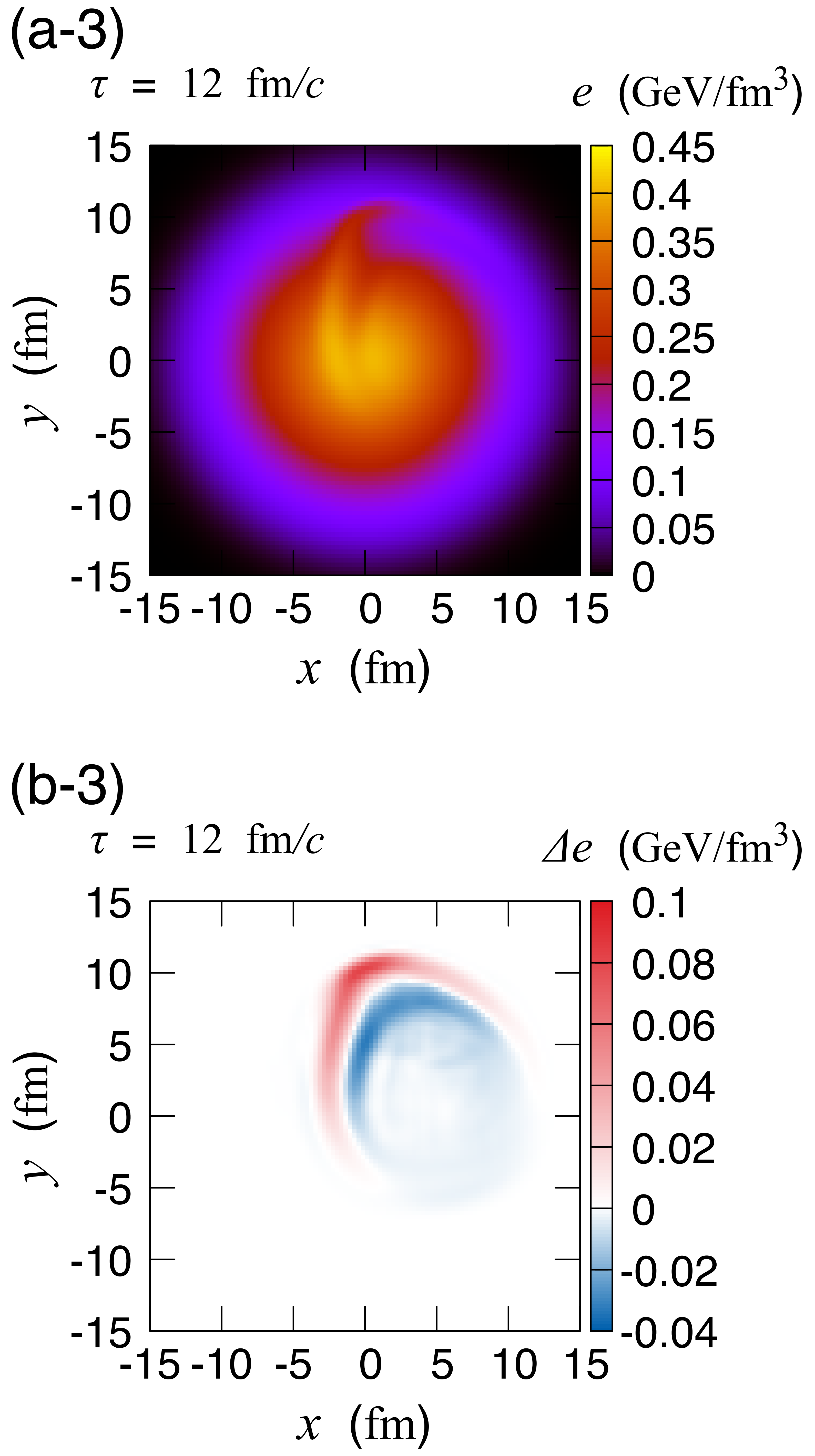
z_g, ΔR_{12}

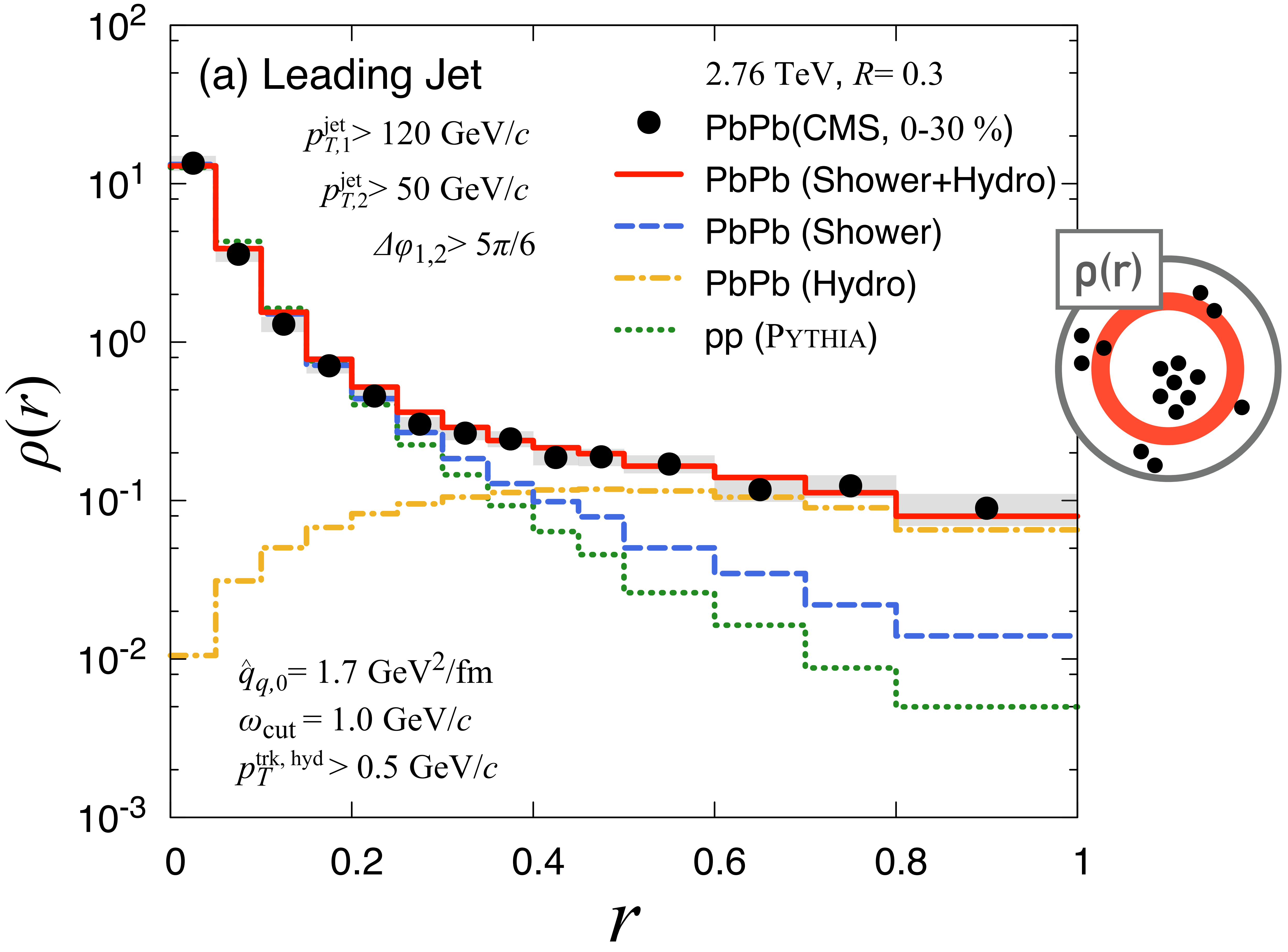
$$z_g = \frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}} > z_{\text{cut}} \left(\frac{\Delta R_{1,2}}{R_J} \right)^\beta$$



medium mach-cones

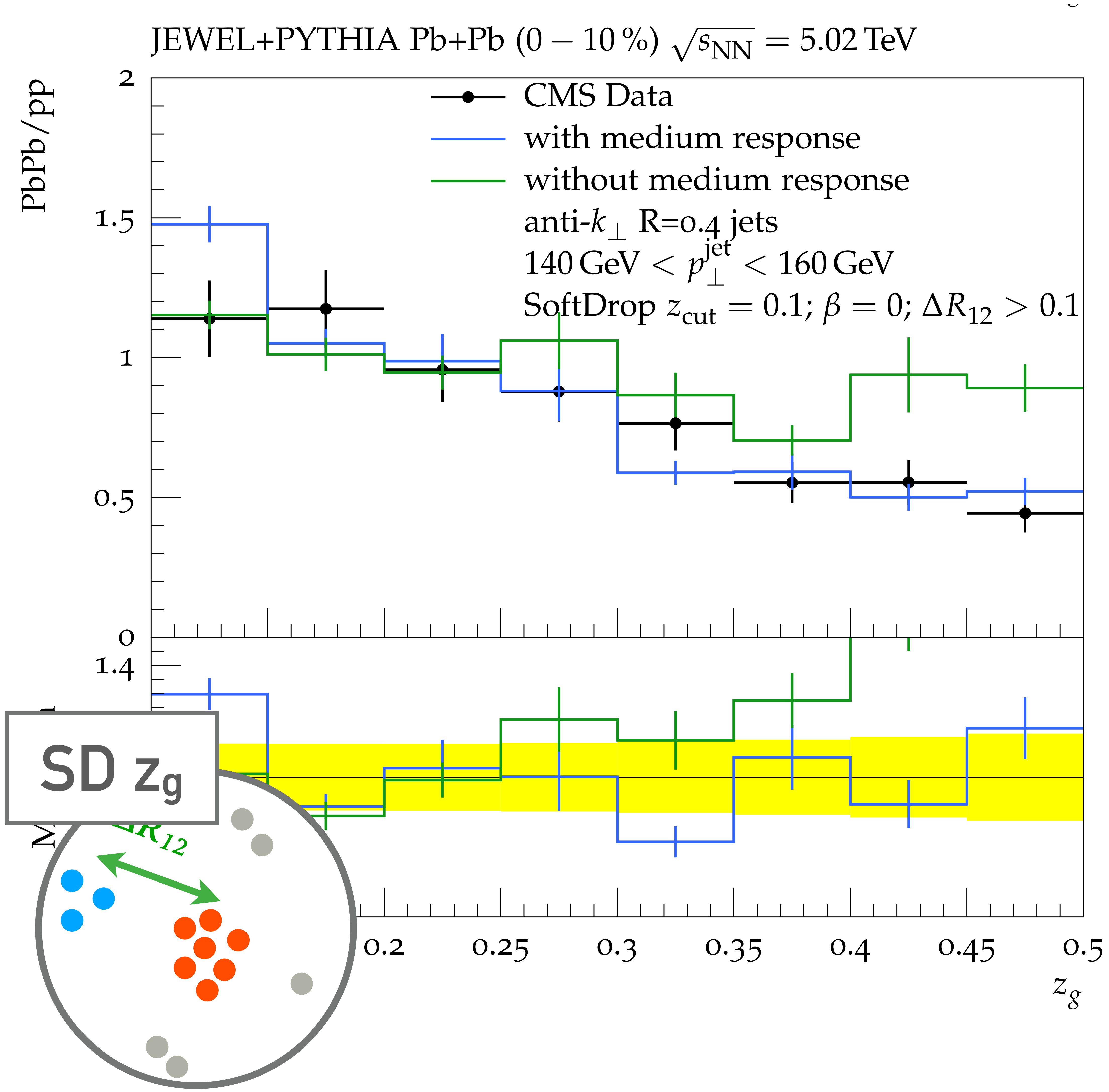
- Tachibana, Chang & Qin, 1701.07951, 12fm/c

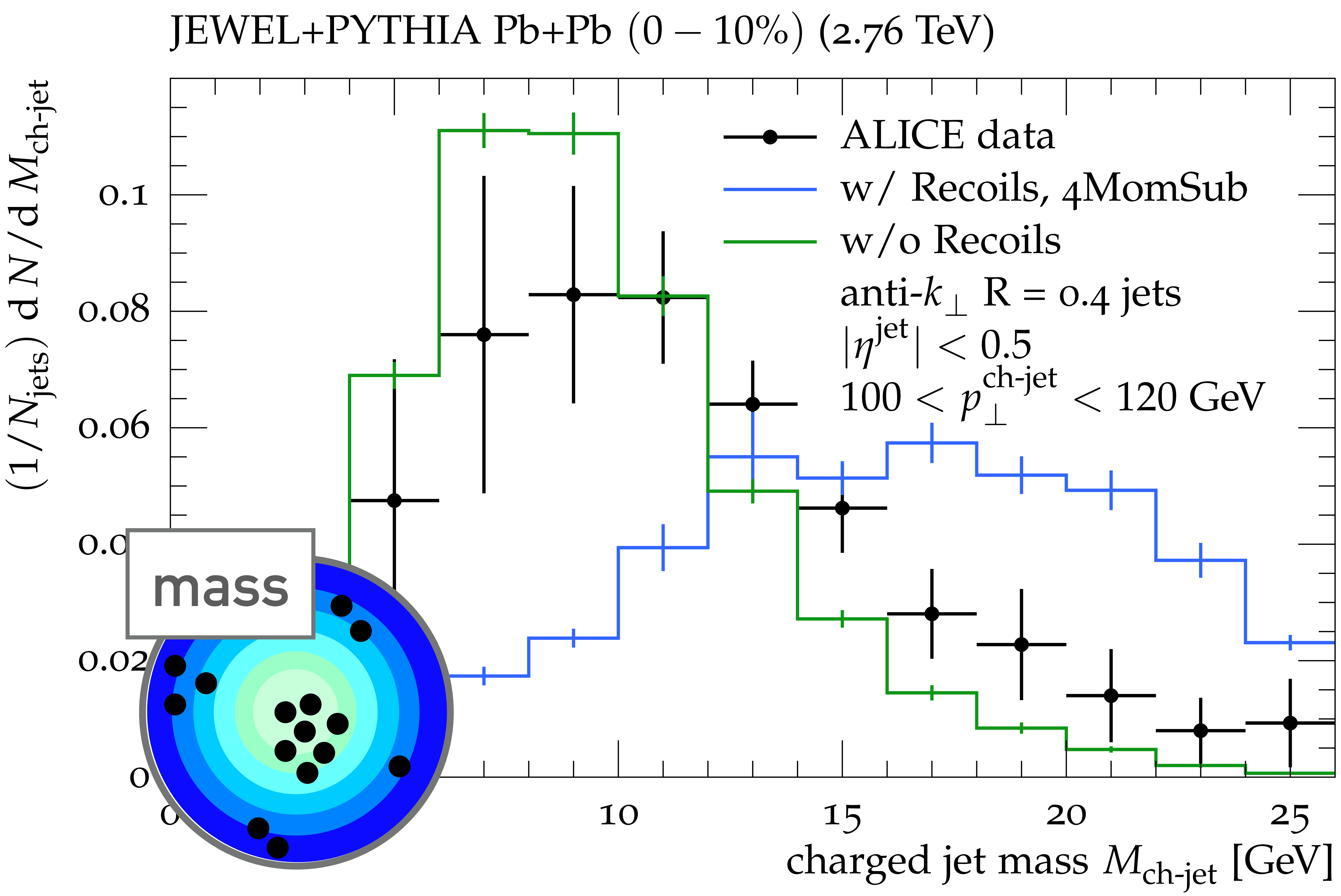




JEWEL v. data

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





recurrent theme in heavy-ion calculations: 2d phasespace plots

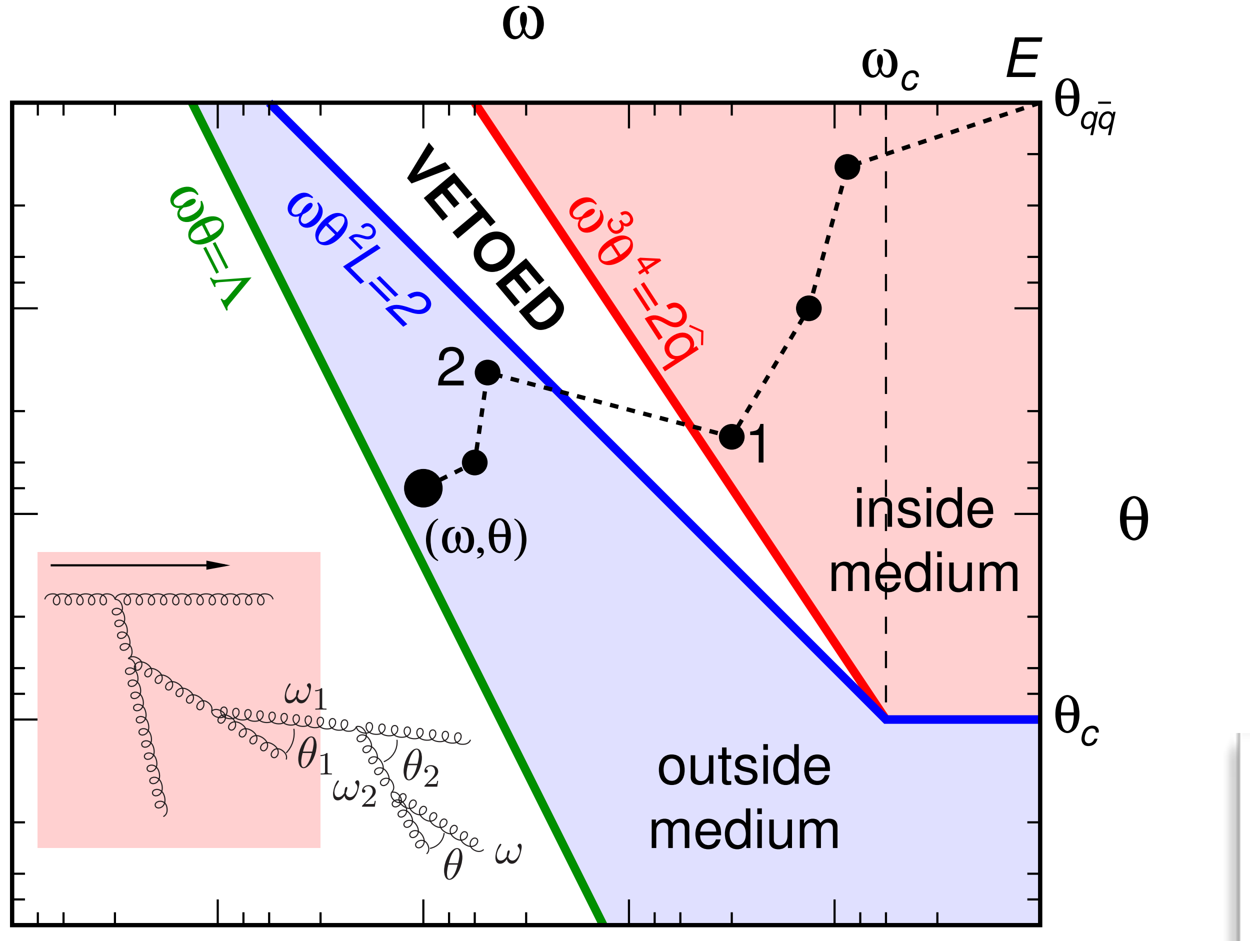
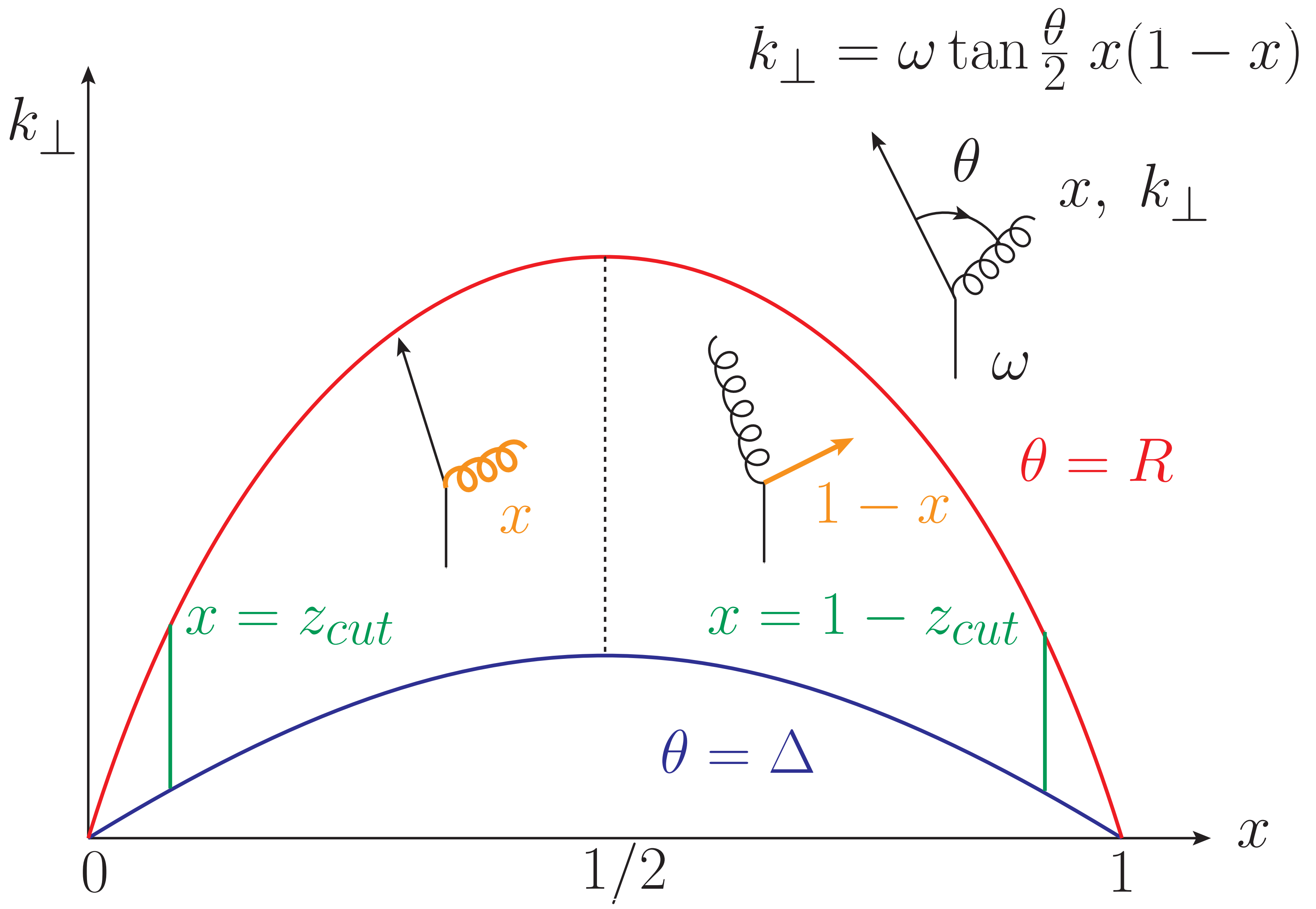
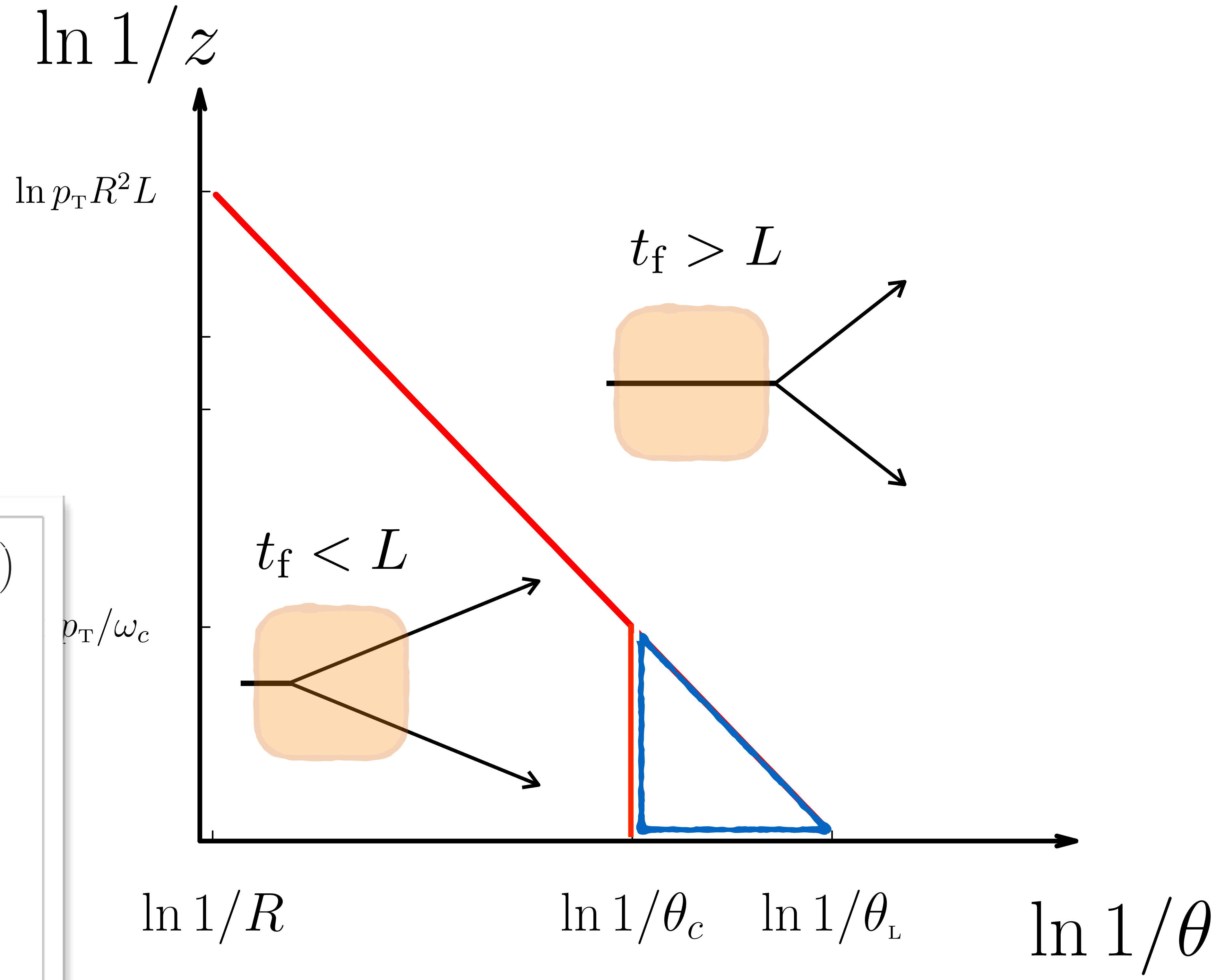


FIG. 1. Schematic representation of the phase-space available for VLEs, including an example of a cascade with "1" the last emission inside the medium and "2" the first emission outside

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

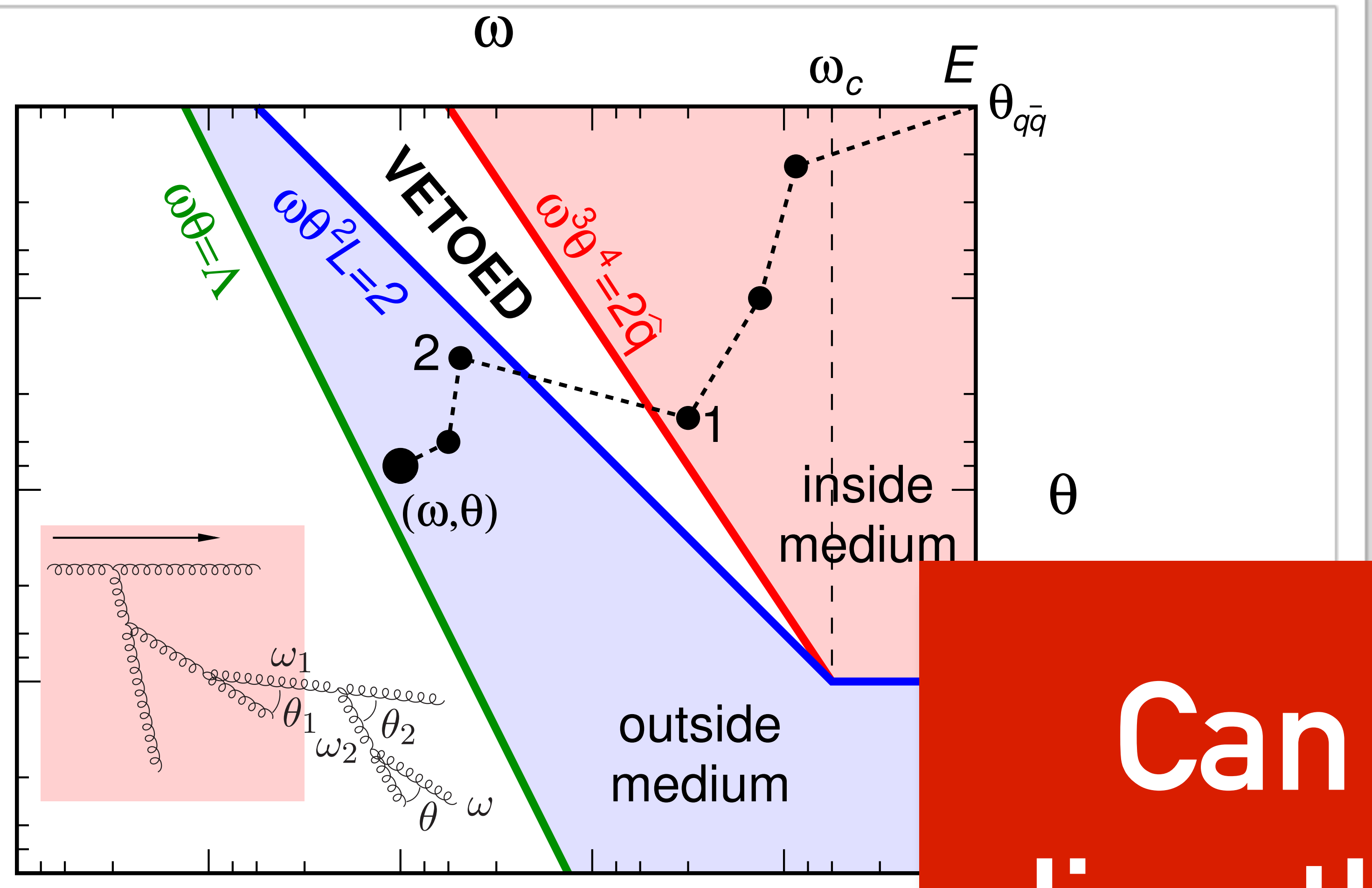


Yang-Ting Chien[a,b] and Ivan Vitev[a]



Mehtar-Tani & Tywoniuk@QM18

recurrent theme in heavy-ion calculations: 2d phasespace plots



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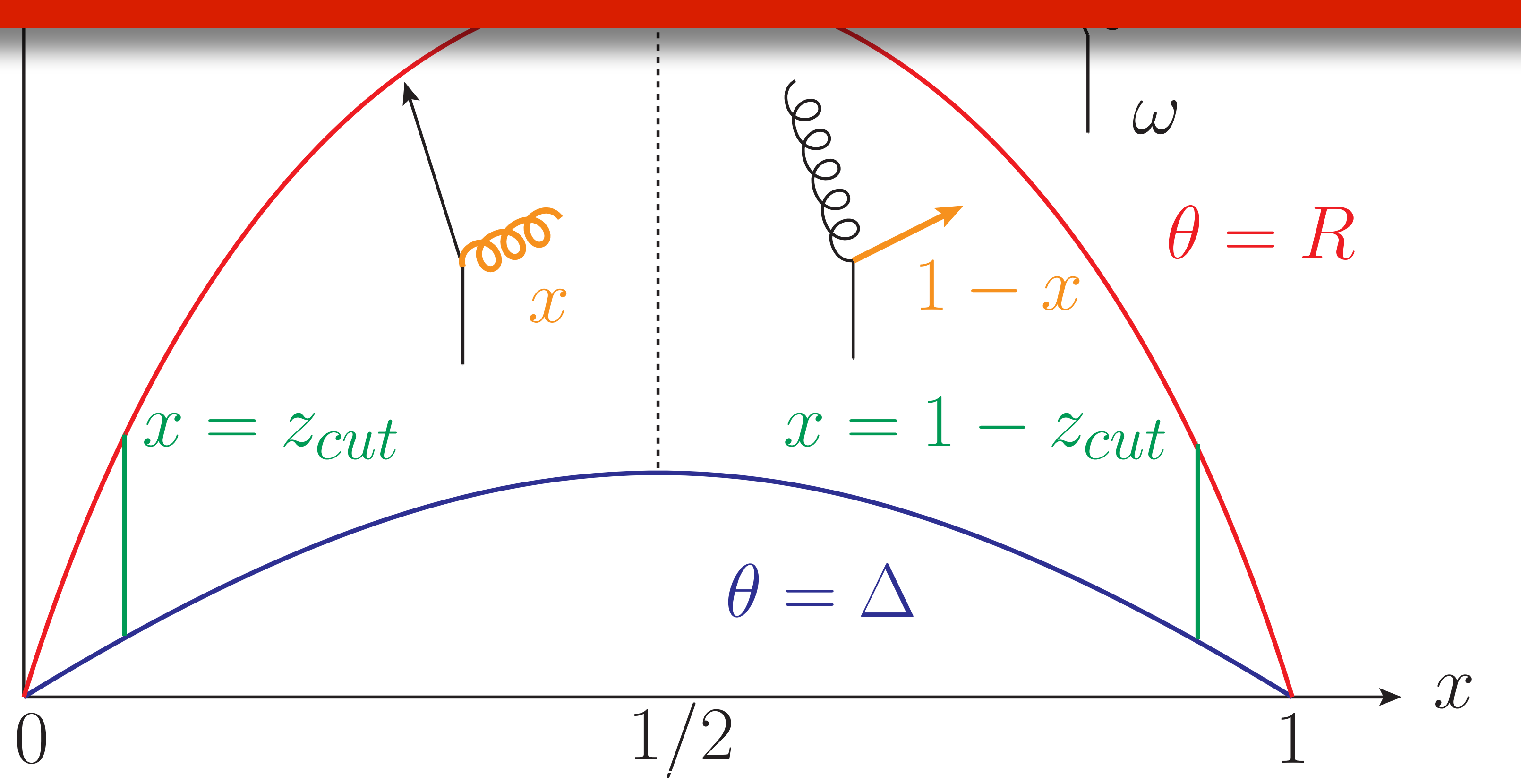

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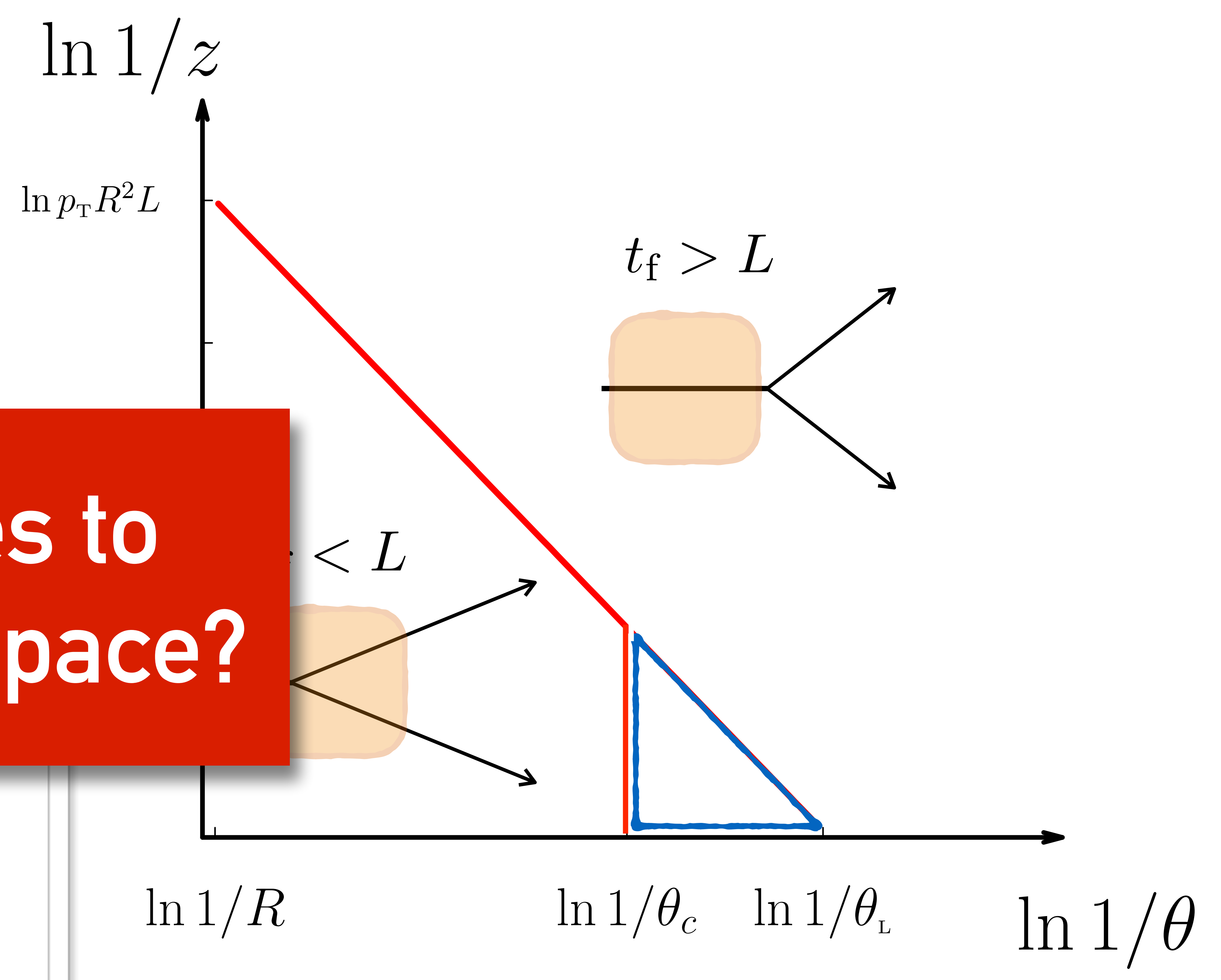


Mehtar-Tani & Tywoniuk@QM18

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

the “Lund plane”

can we construct observables that are

(a) ***more transparent*** *in terms of the physical info they extract?*

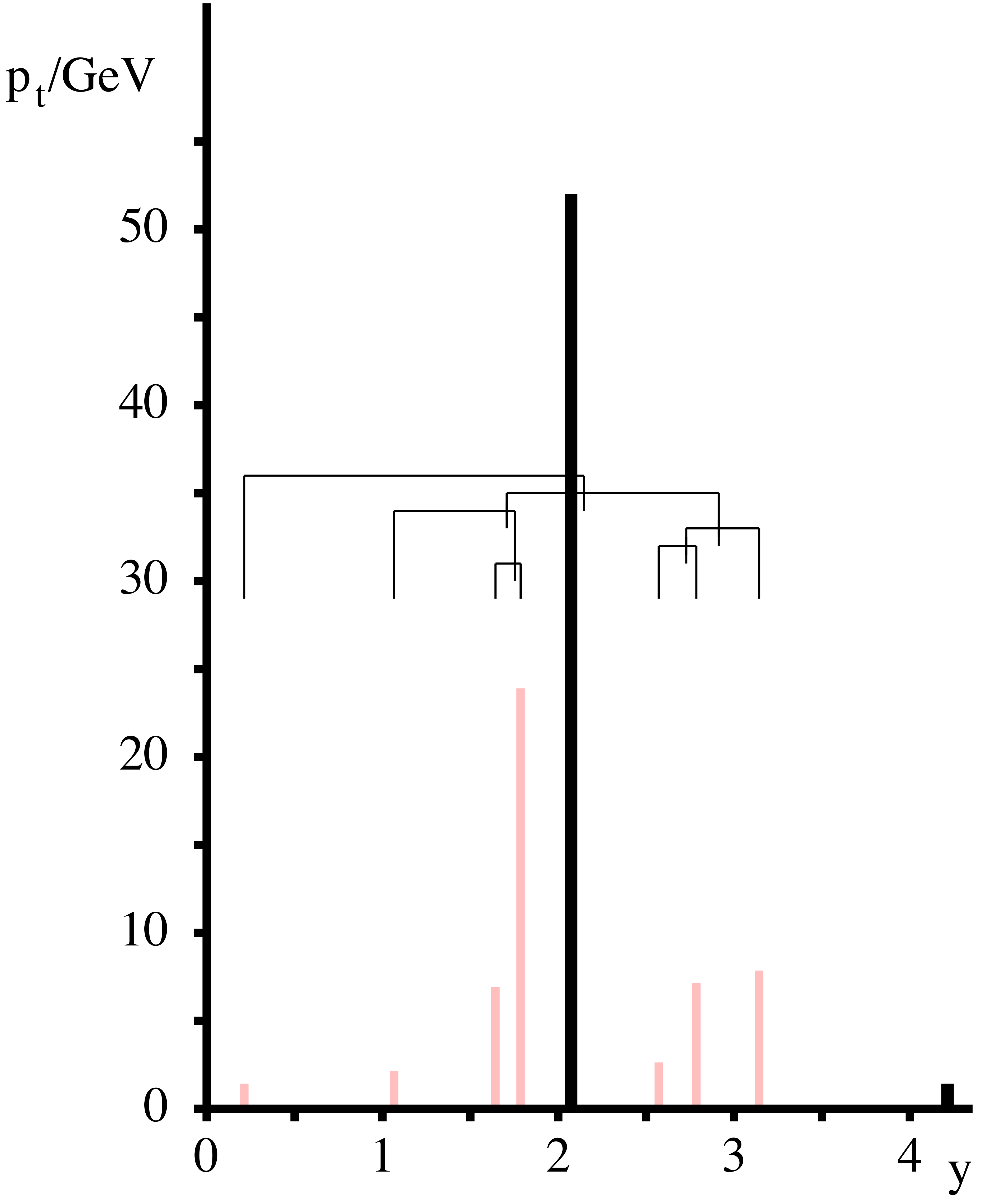
(b) close to ***optimal*** *for multivariate techniques & machine-learning?*

the Cambridge / Aachen (C/A) jet algorithm

1. Identify pair of particles, i & j, with smallest ΔR_{ij}
2. If $\Delta R_{ij} < R$ (jet radius parameter)
   A. recombine i & j into a single particle
   B. loop back to step 1
3. Otherwise, stop the clustering

Dokshitzer, Leder, Moretti & Webber '97
Wobisch & Wengler '98

Cambridge/Aachen

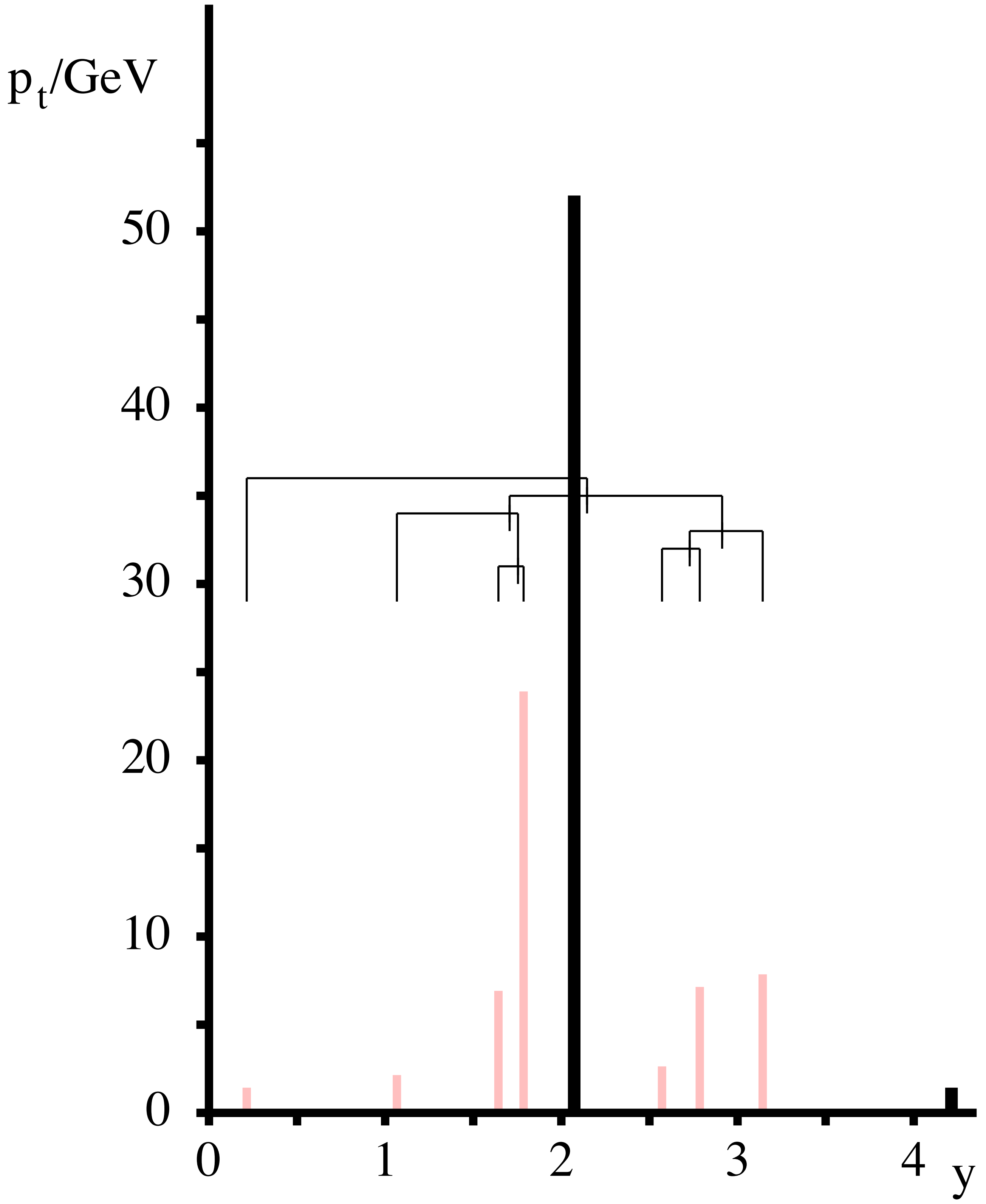


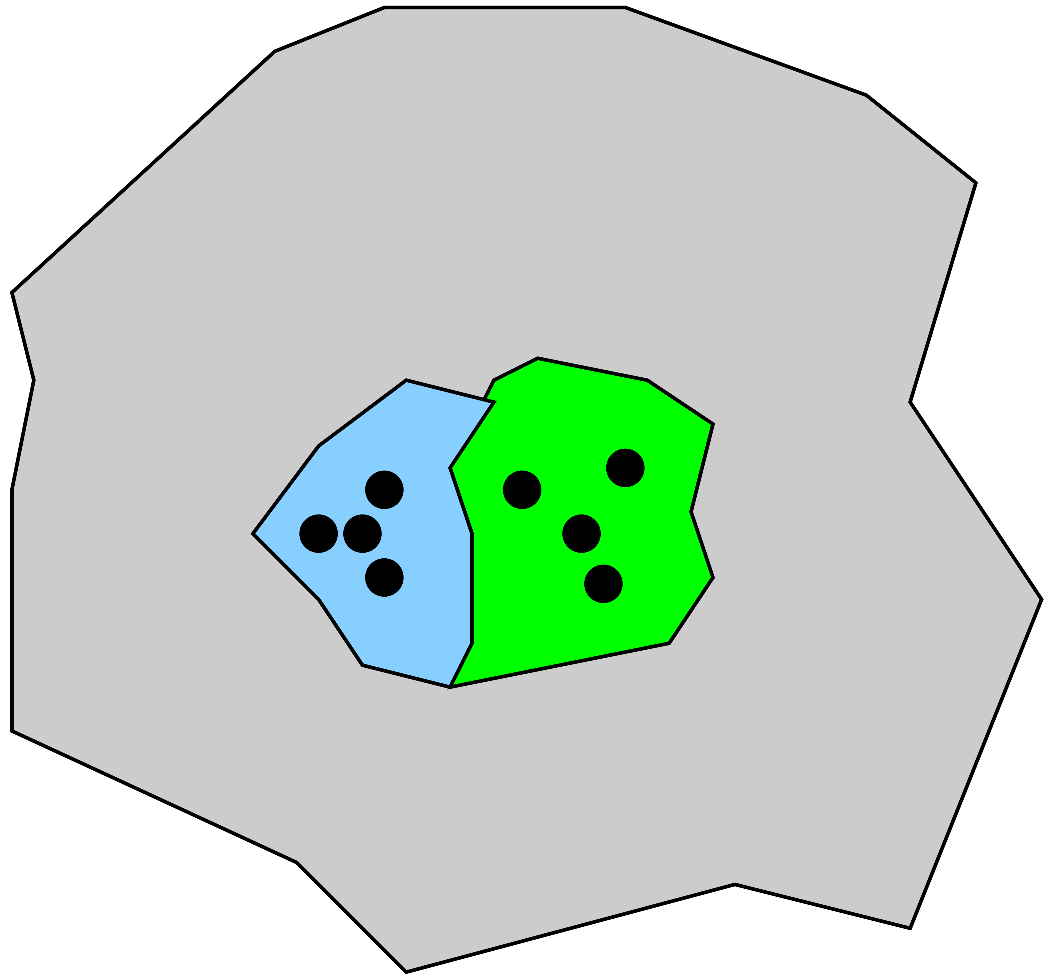
A sequence of jet substructure tools taggers

- 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, $\beta \neq 0$ [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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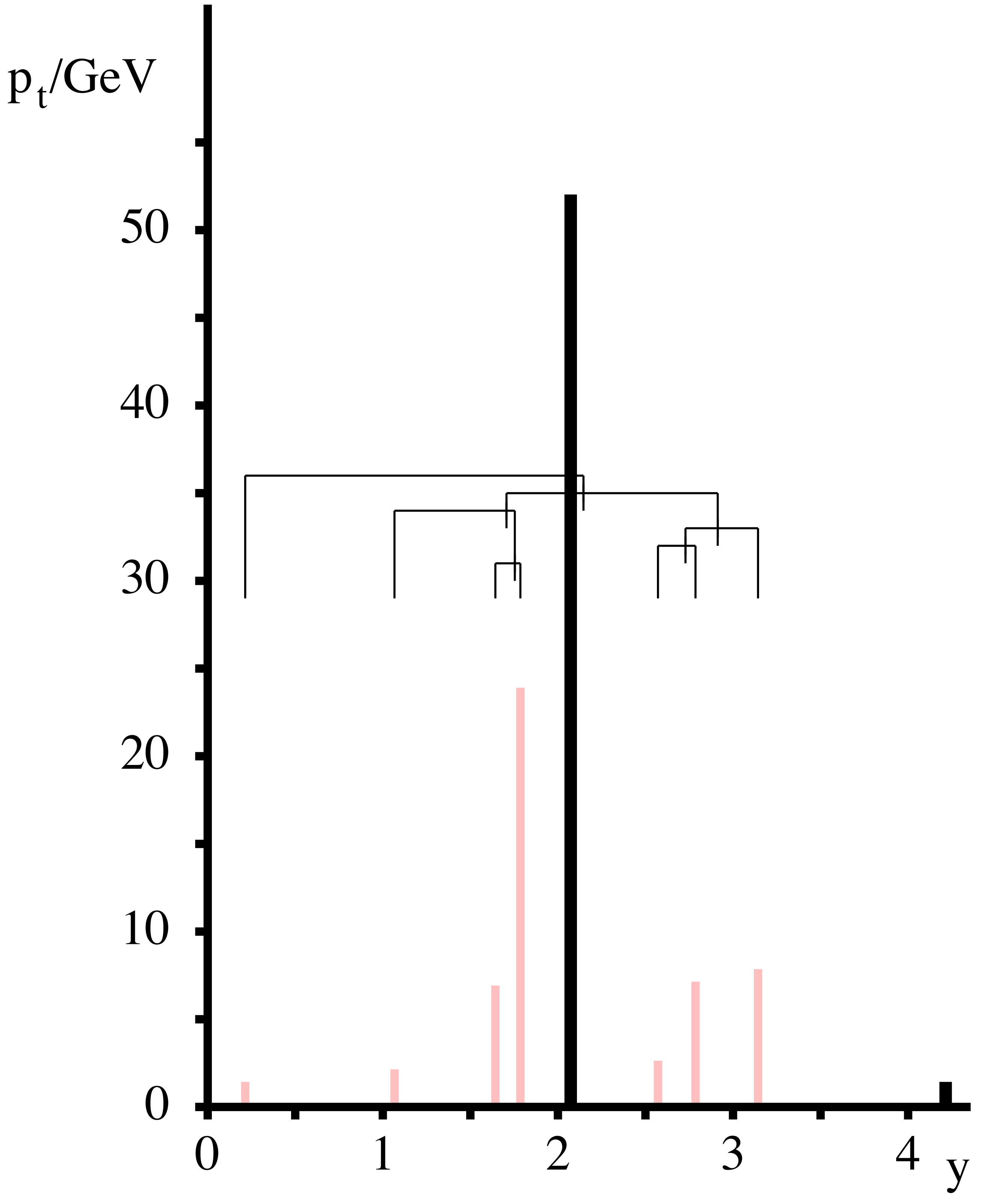
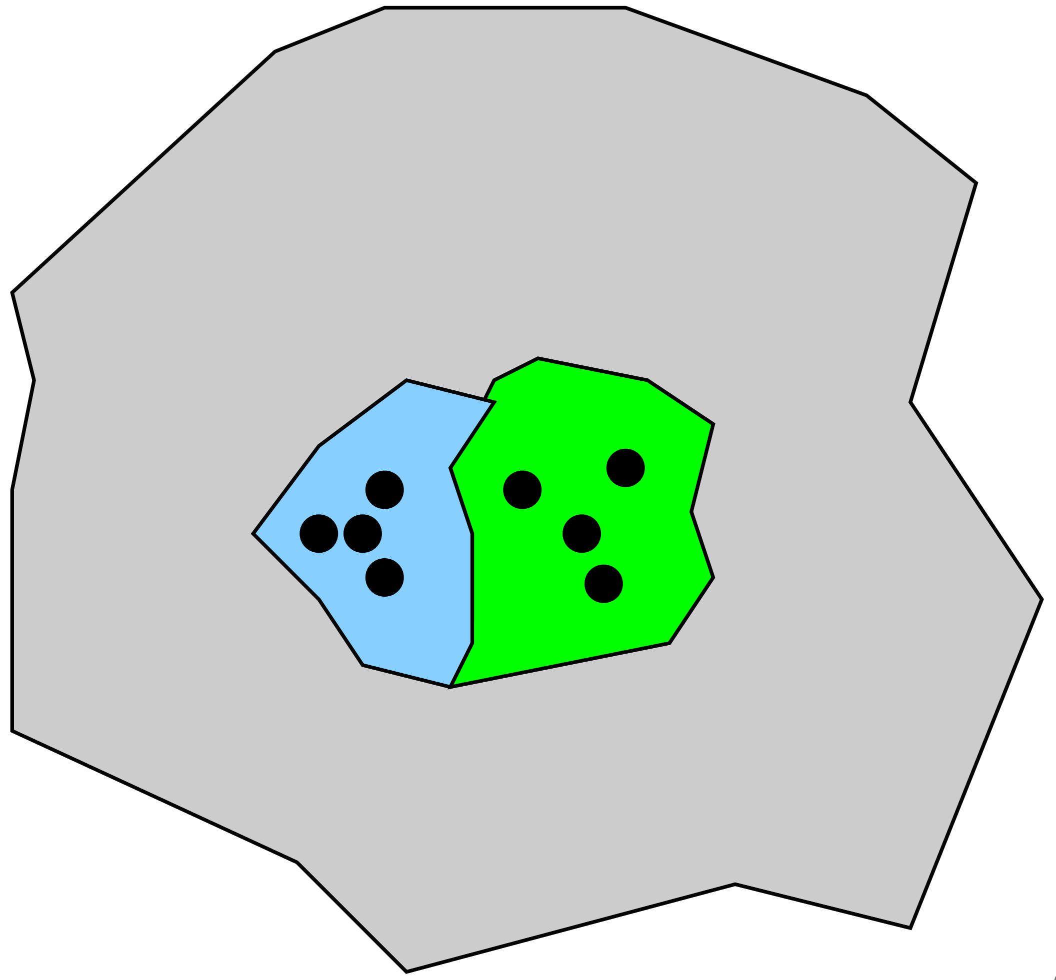
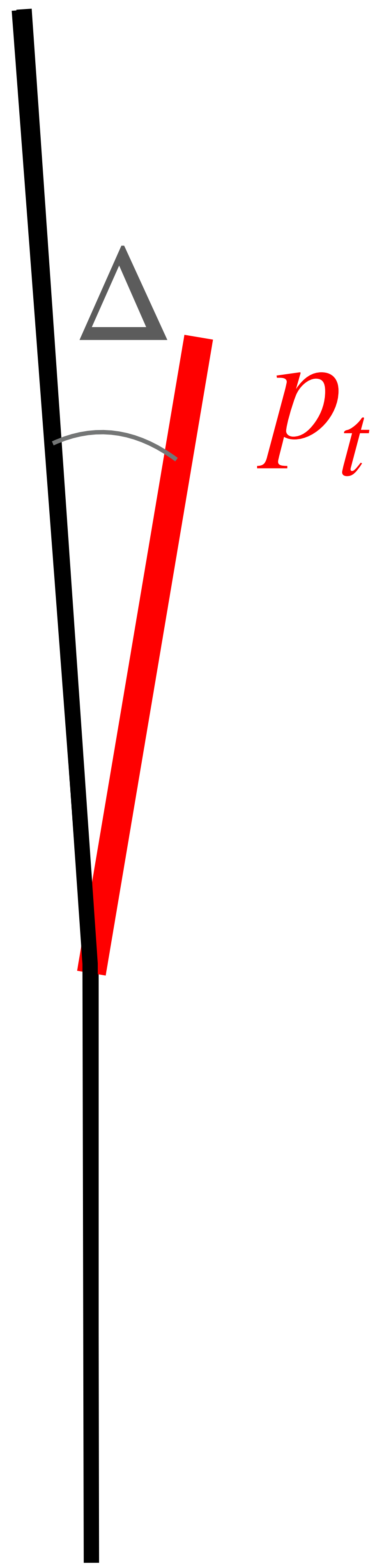
- 2017: Iterated Soft Drop [Frye, Larkoski, Thaler, Zhou]
  count number of iterations until you reach 1 particle
- **2018/19: ?**

Cambridge/Aachen





Phase space: two key variables (+ azimuth)

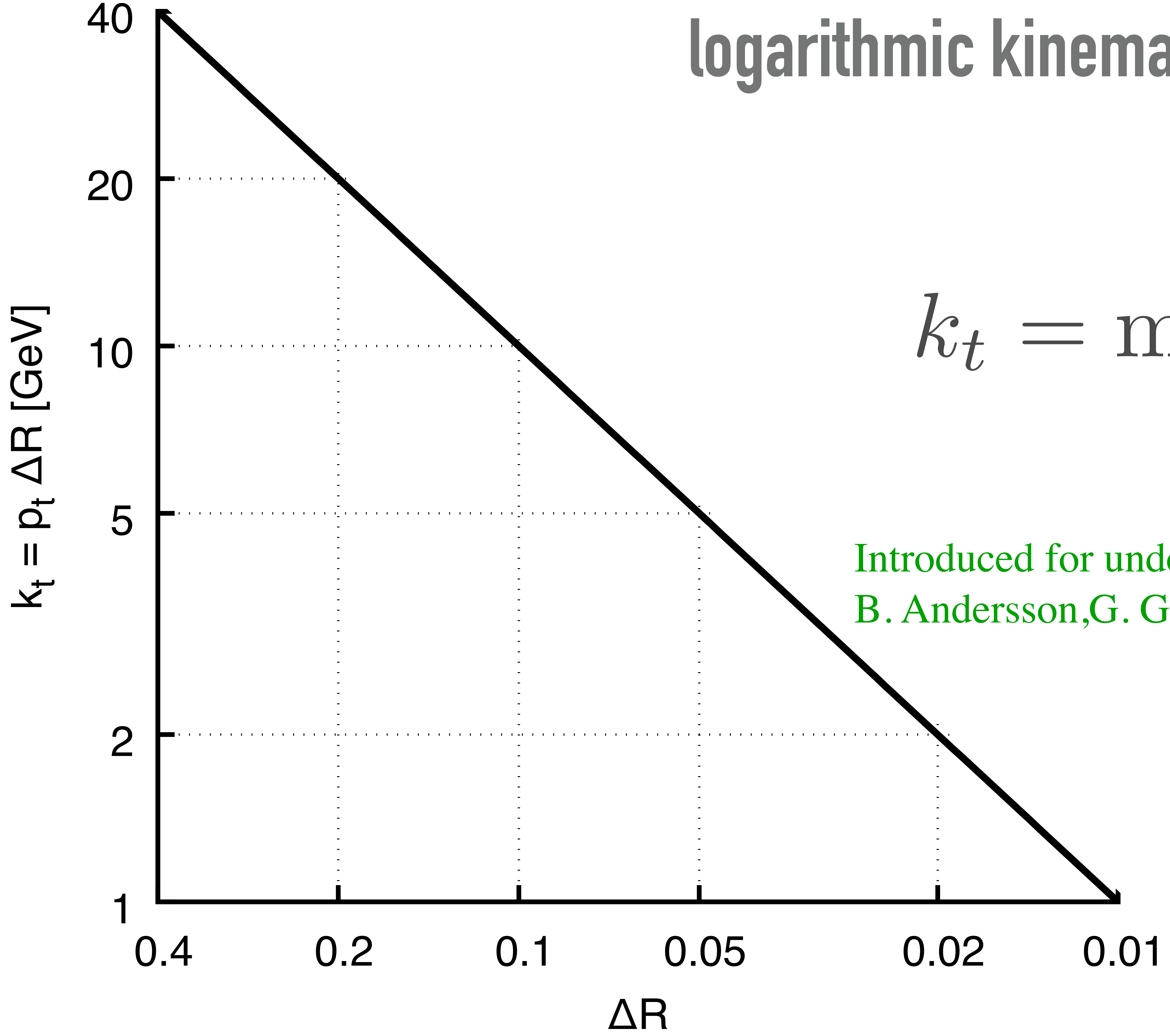


ΔR (or just Δ) — *opening angle of a splitting*

$k_t = p_t \Delta$ — p_t (or $p_\perp$) *is transverse momentum wrt beam*

k_t *is* $\sim$ *transverse momentum wrt jet axis*

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



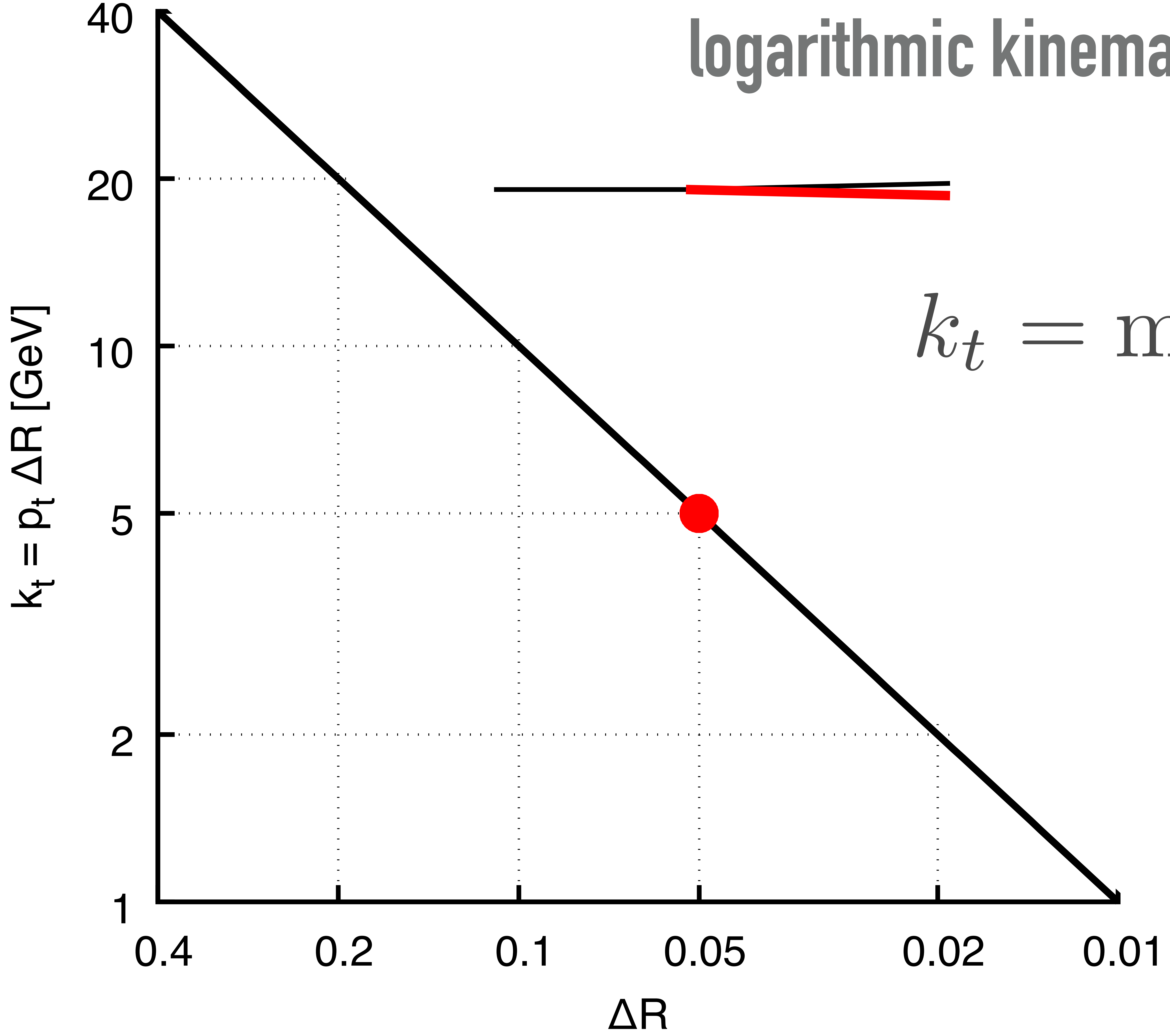
logarithmic kinematic plane whose two variables are

$$\Delta R_{ij}$$

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

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

The Lund Plane



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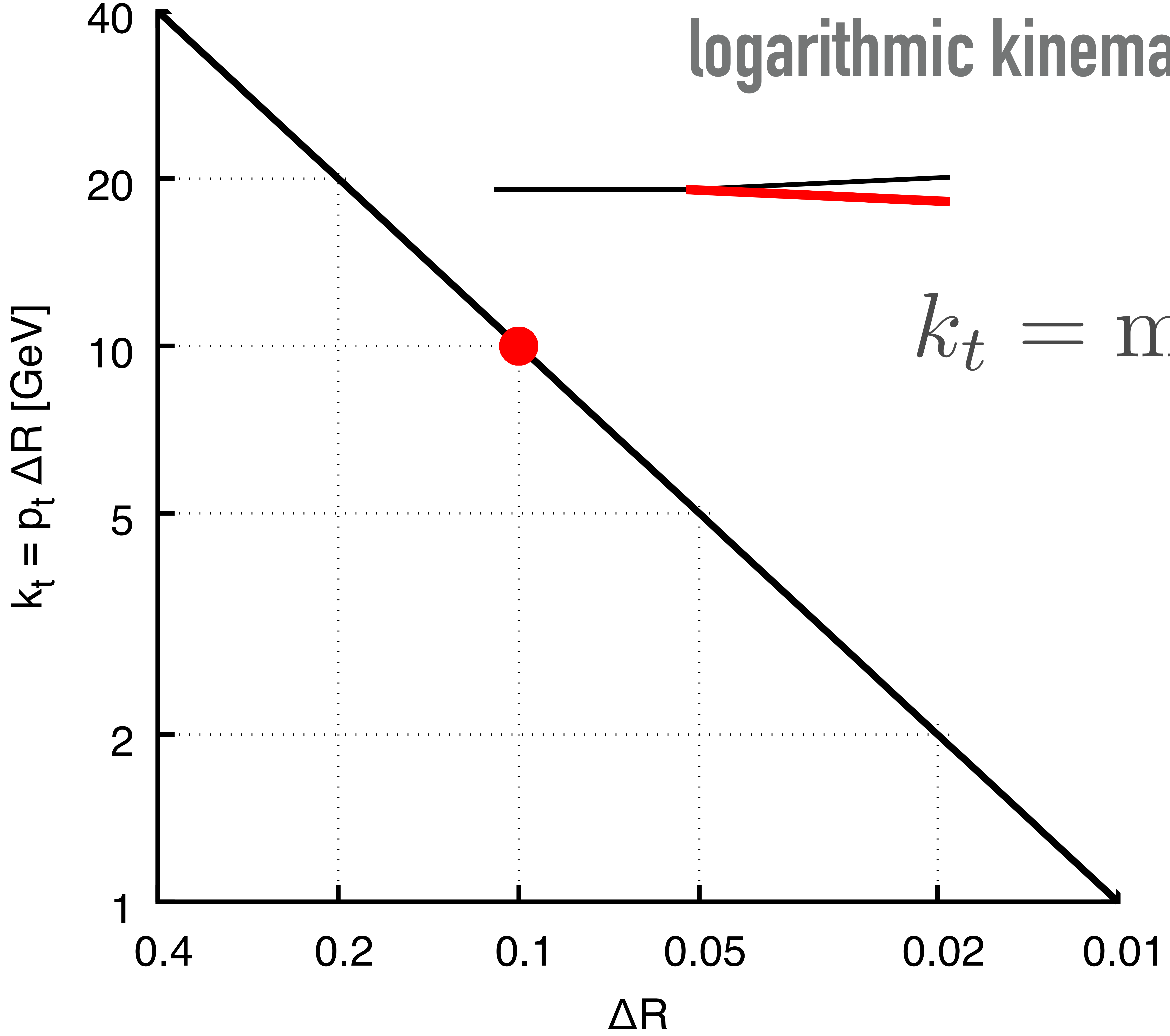

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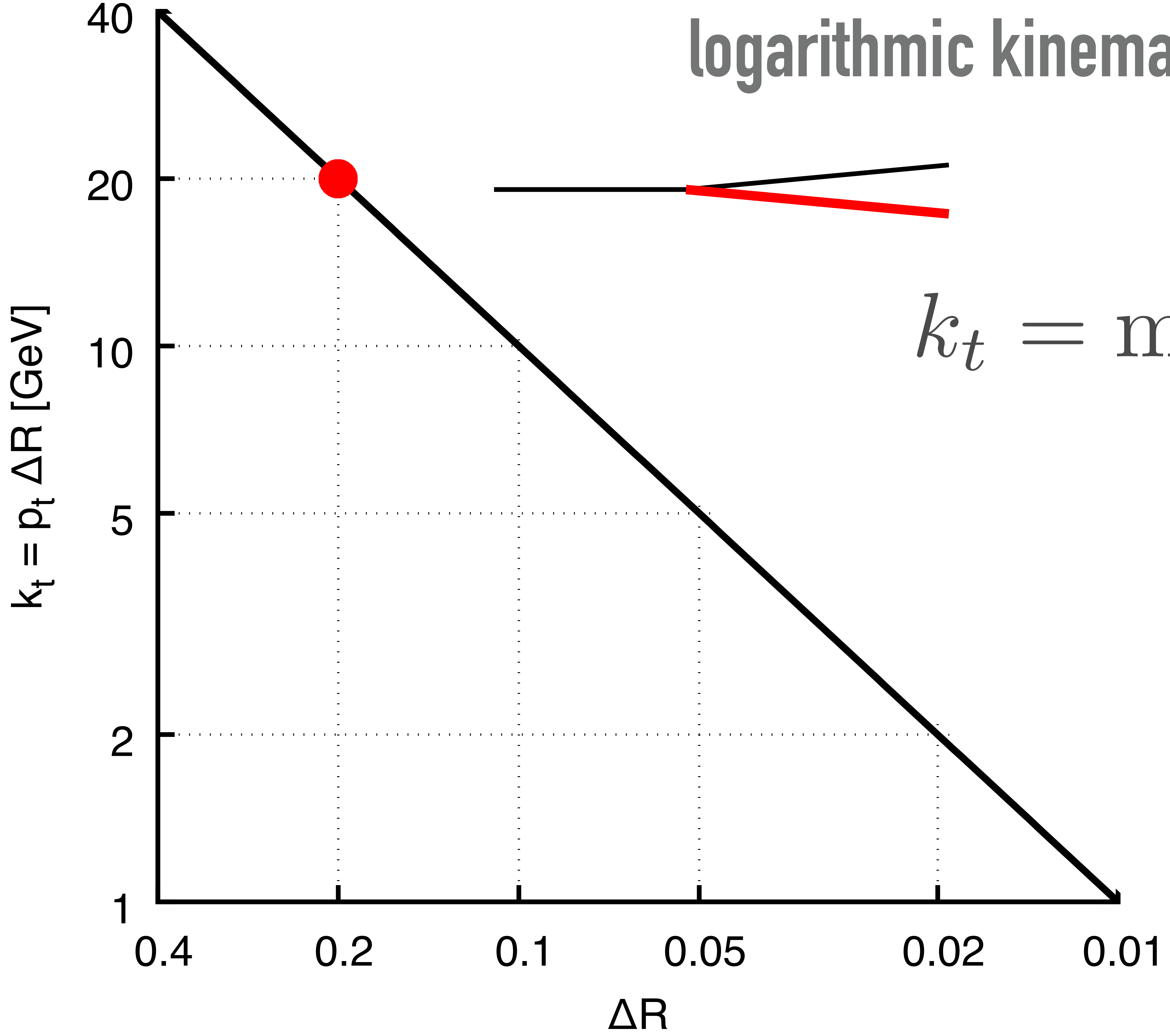
The Lund Plane

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



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The Lund Plane

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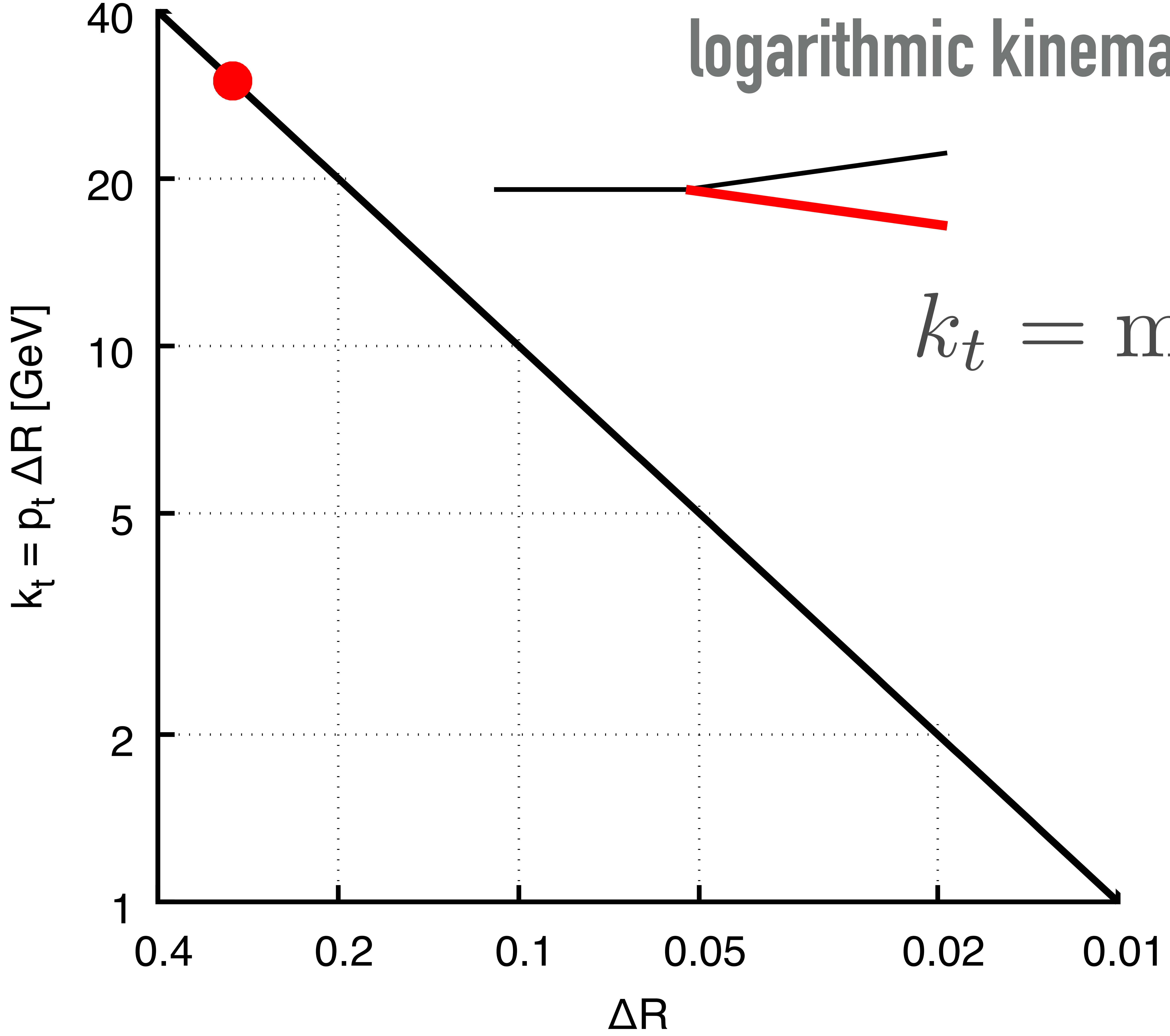

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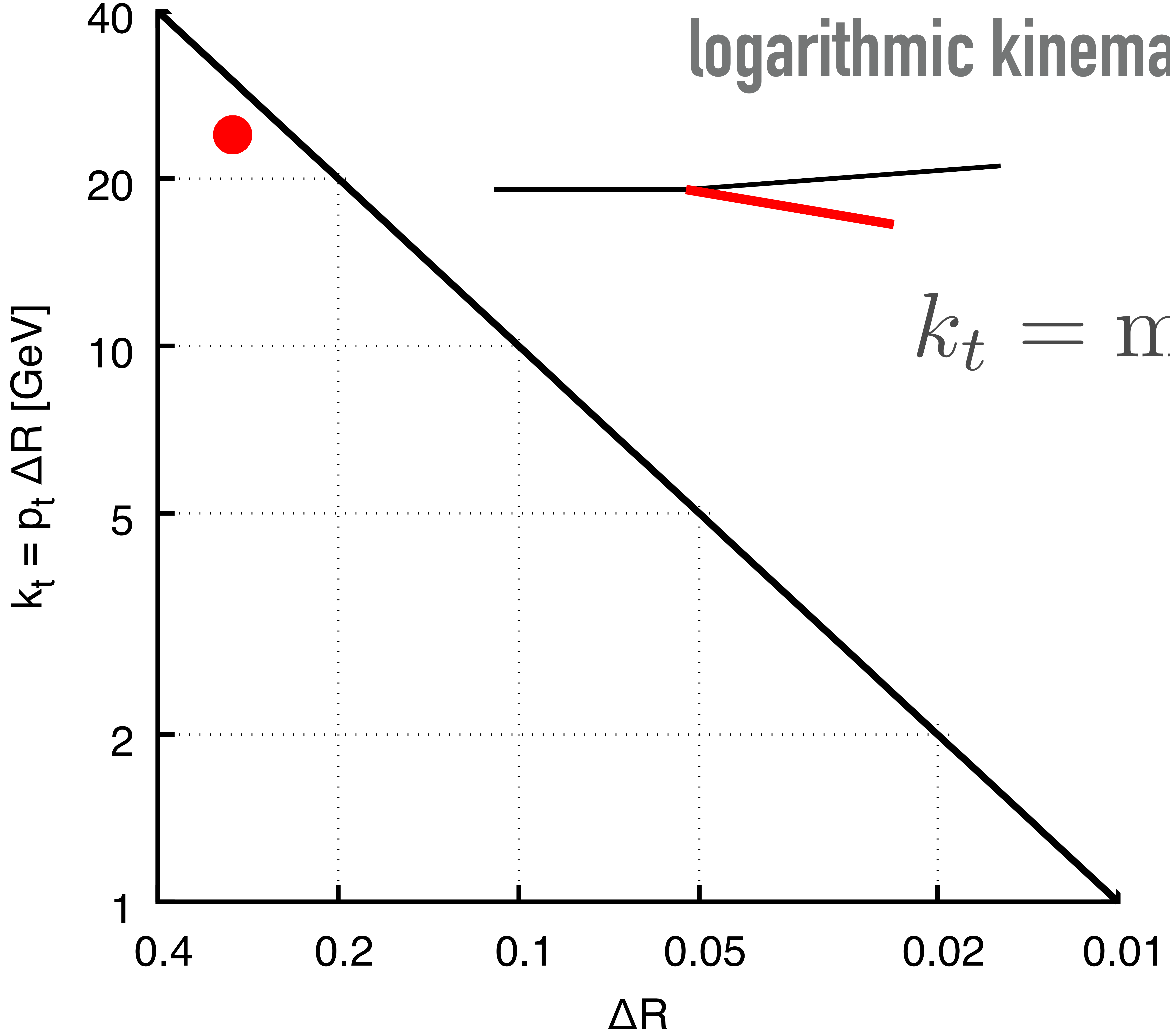

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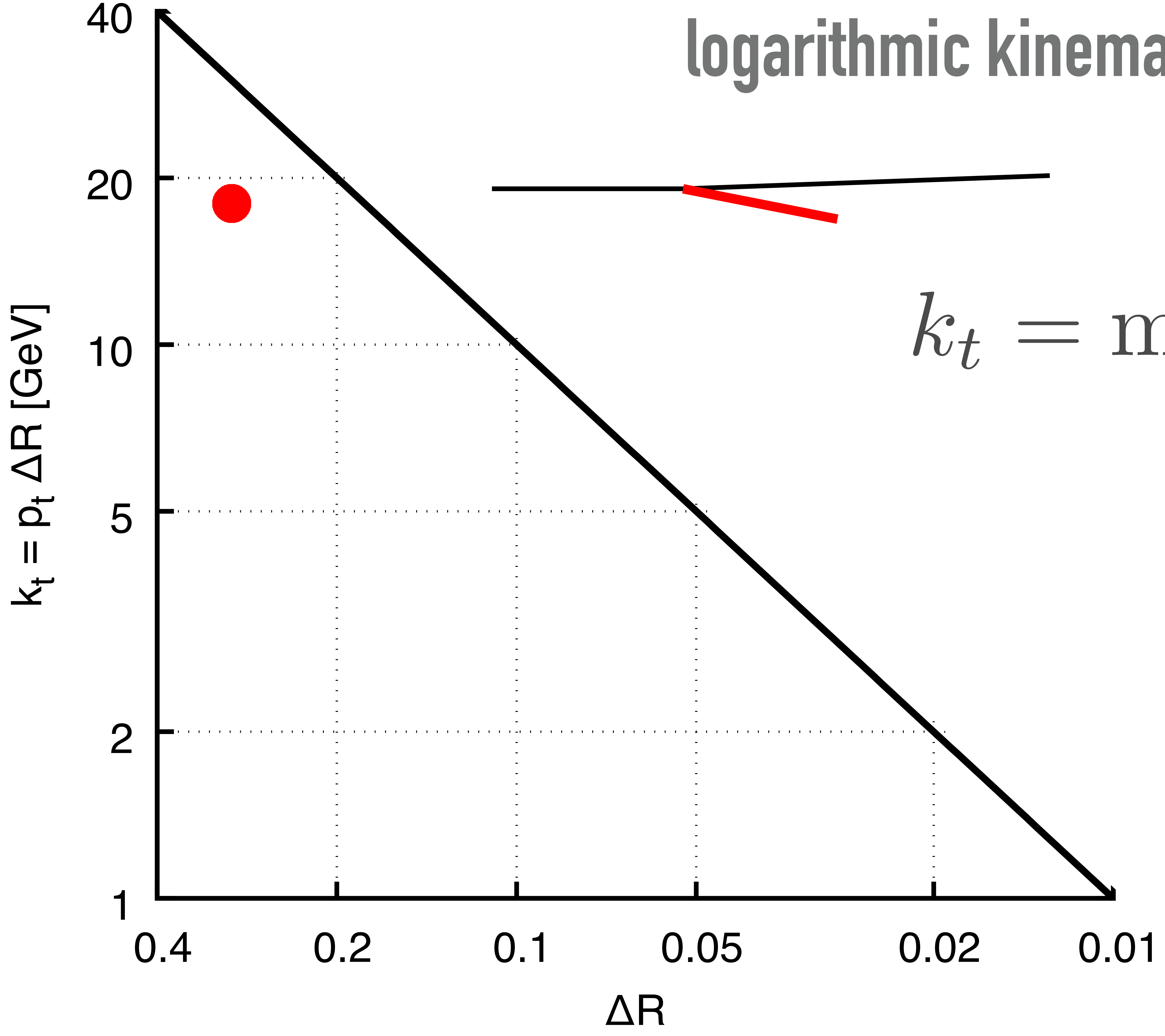

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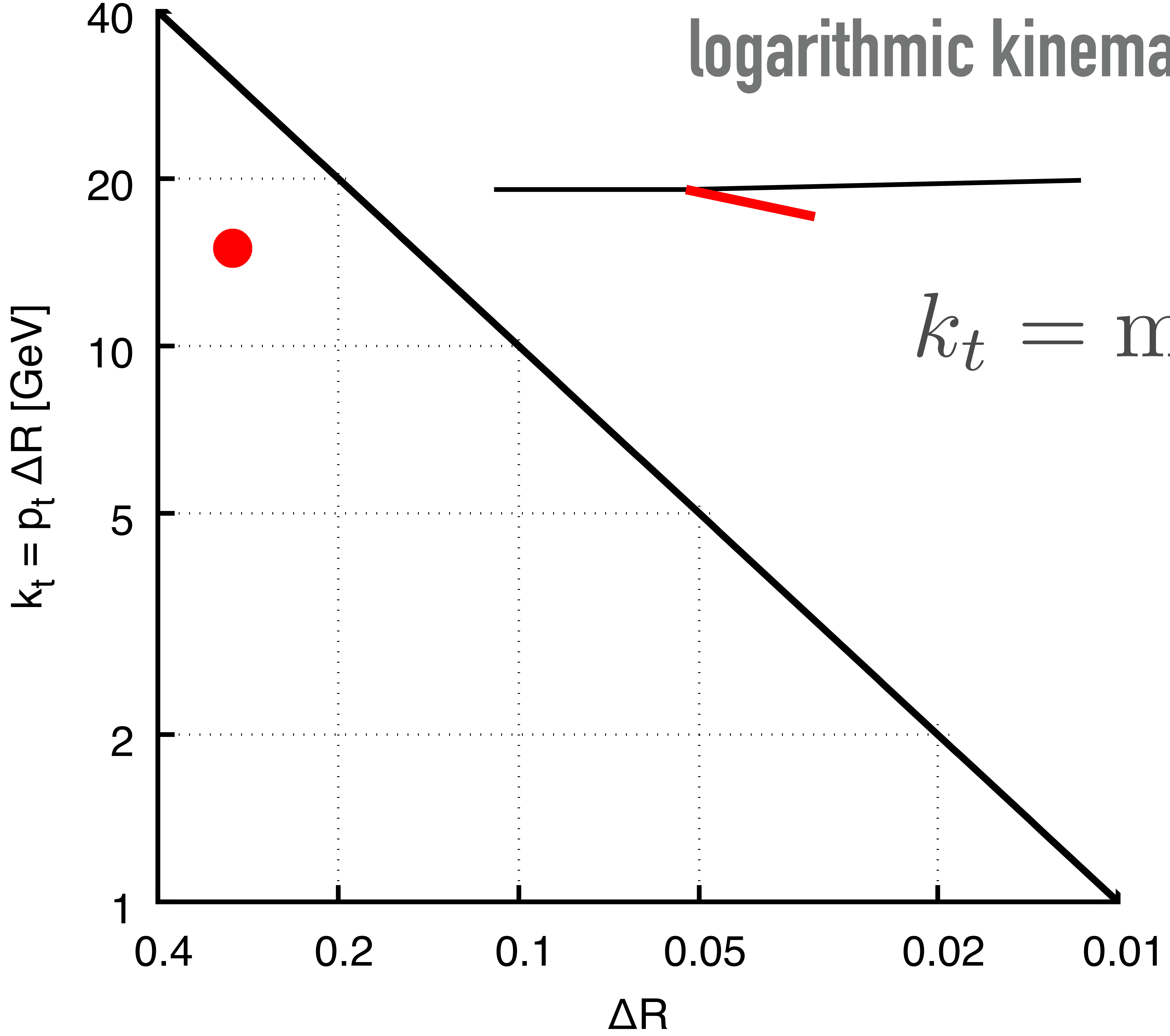

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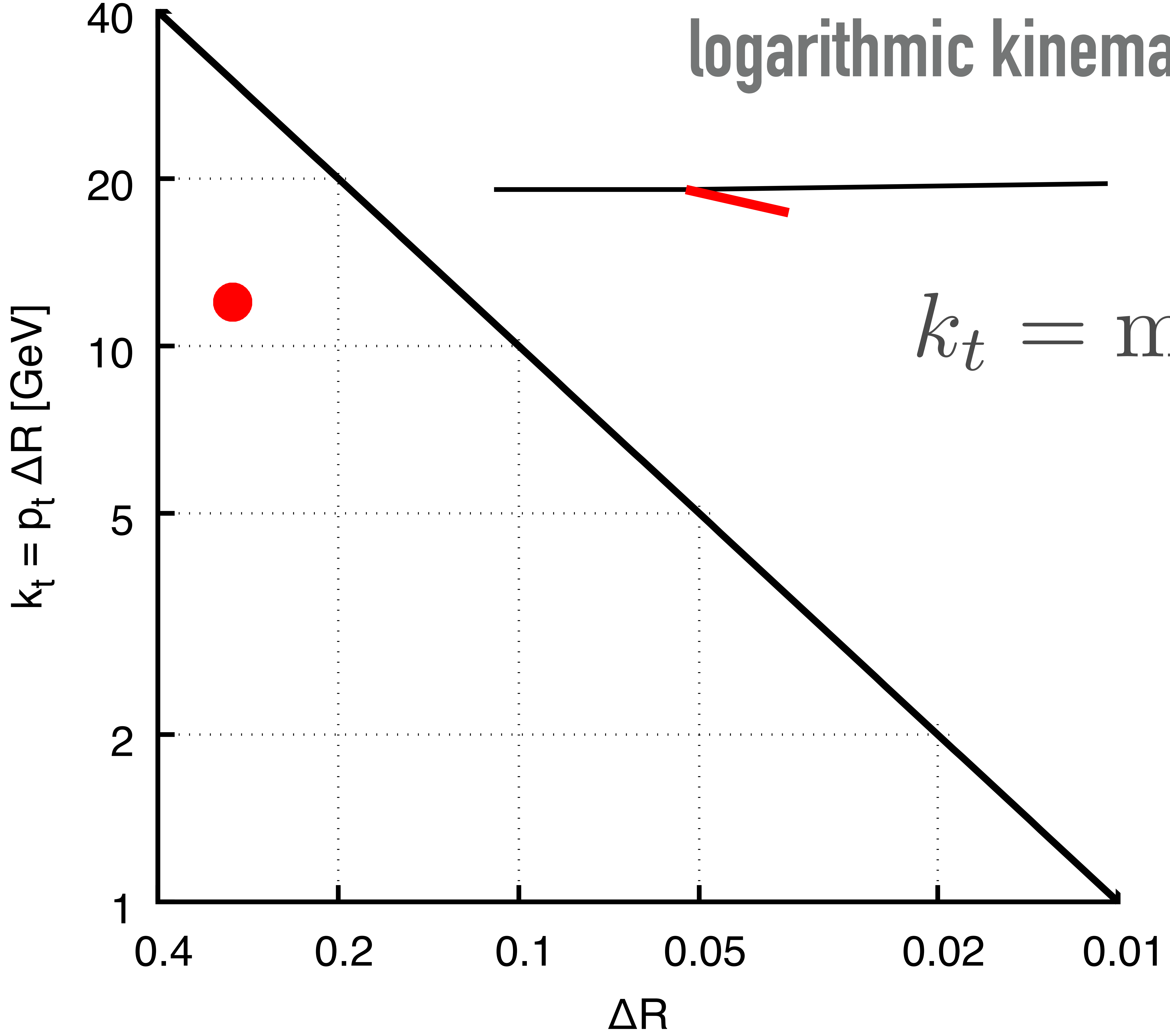

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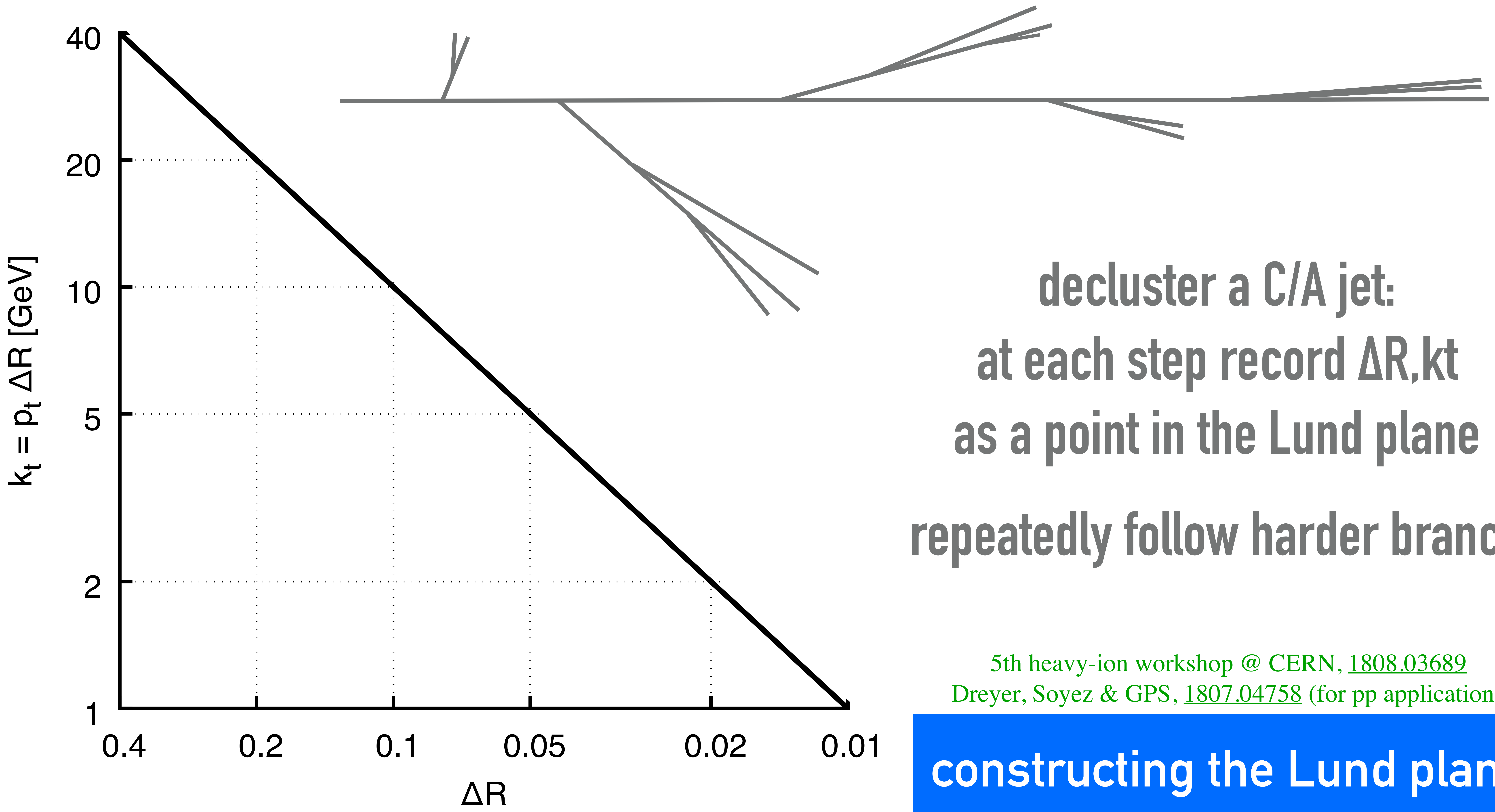
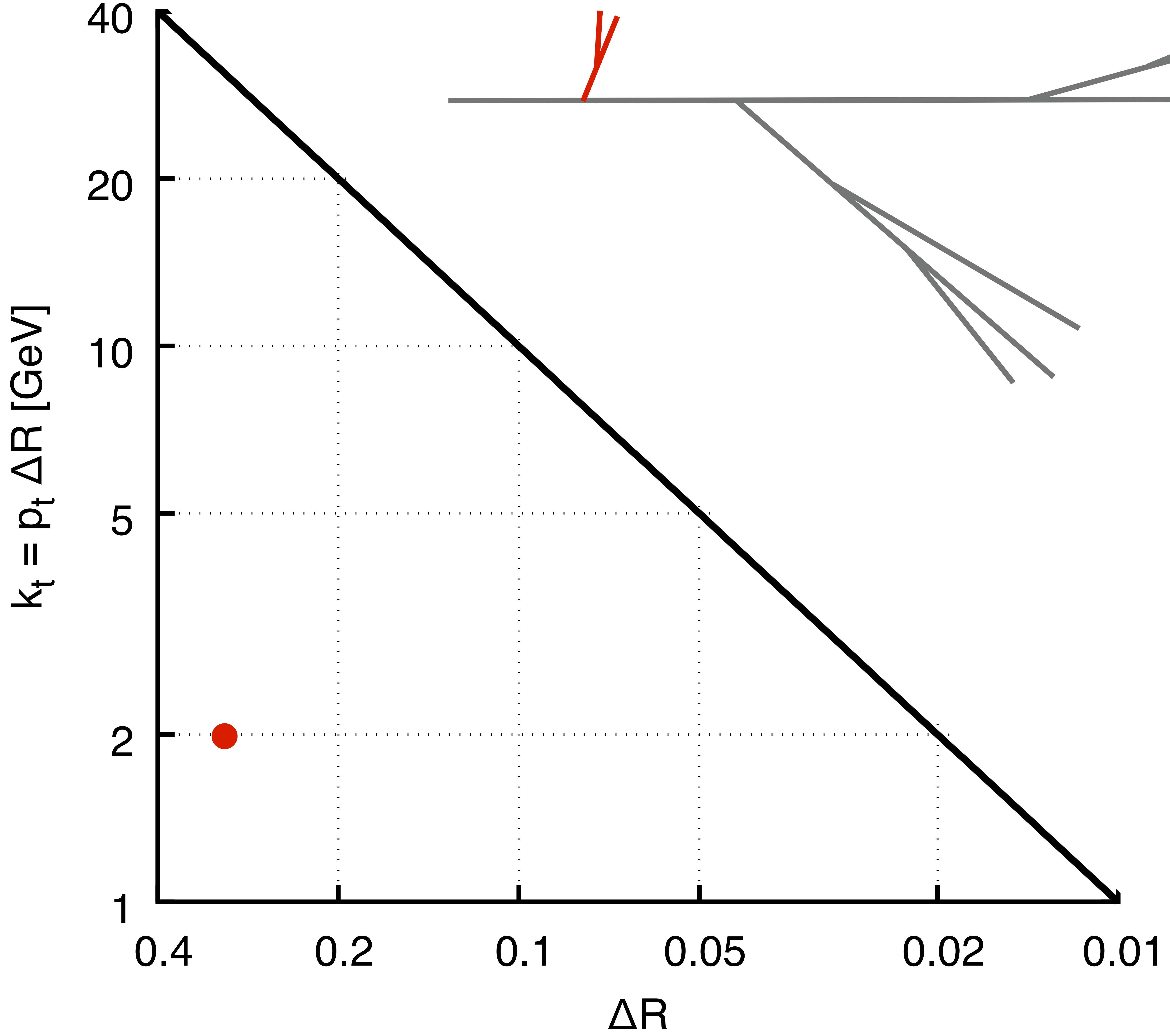


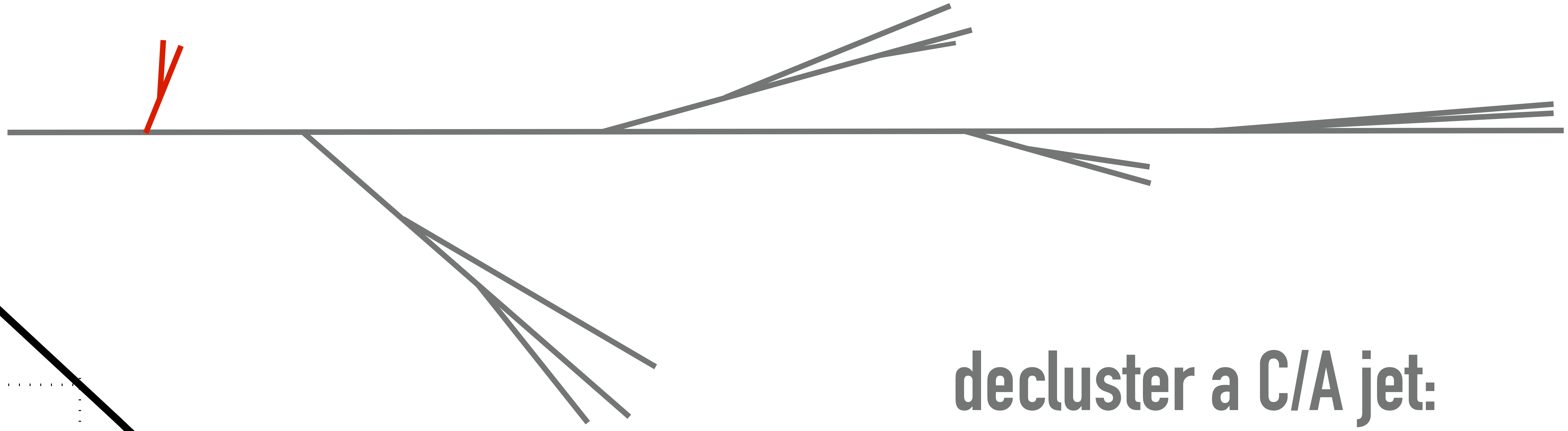
decluster a C/A jet:
at each step record ΔR,kt
as a point in the Lund plane

repeatedly follow harder branch

5th heavy-ion workshop @ CERN, 1808.03689
Dreyer, Soyez & GPS, 1807.04758 (for pp applications)

constructing the Lund plane





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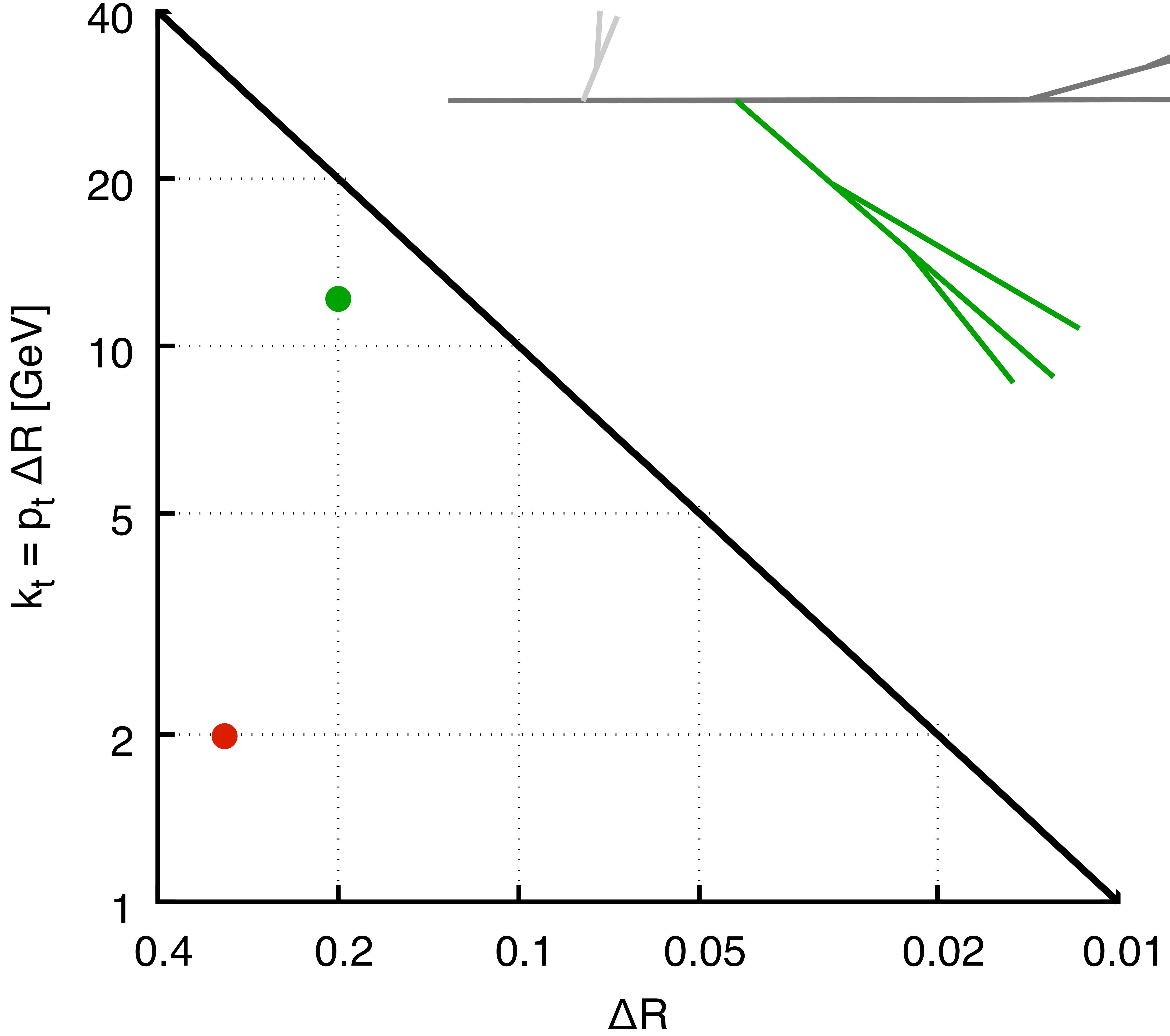

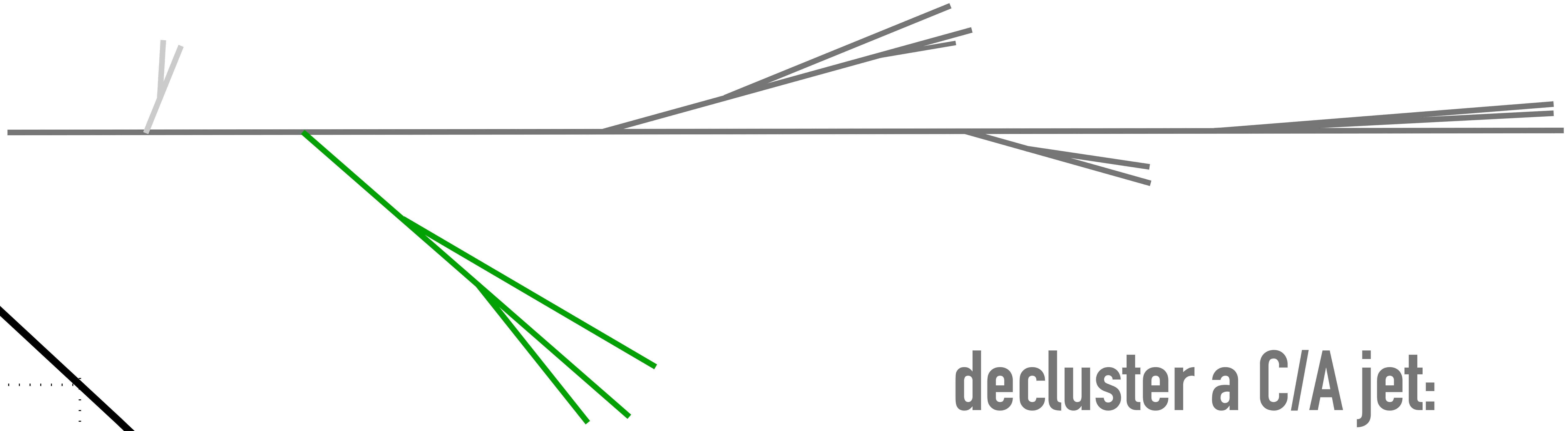

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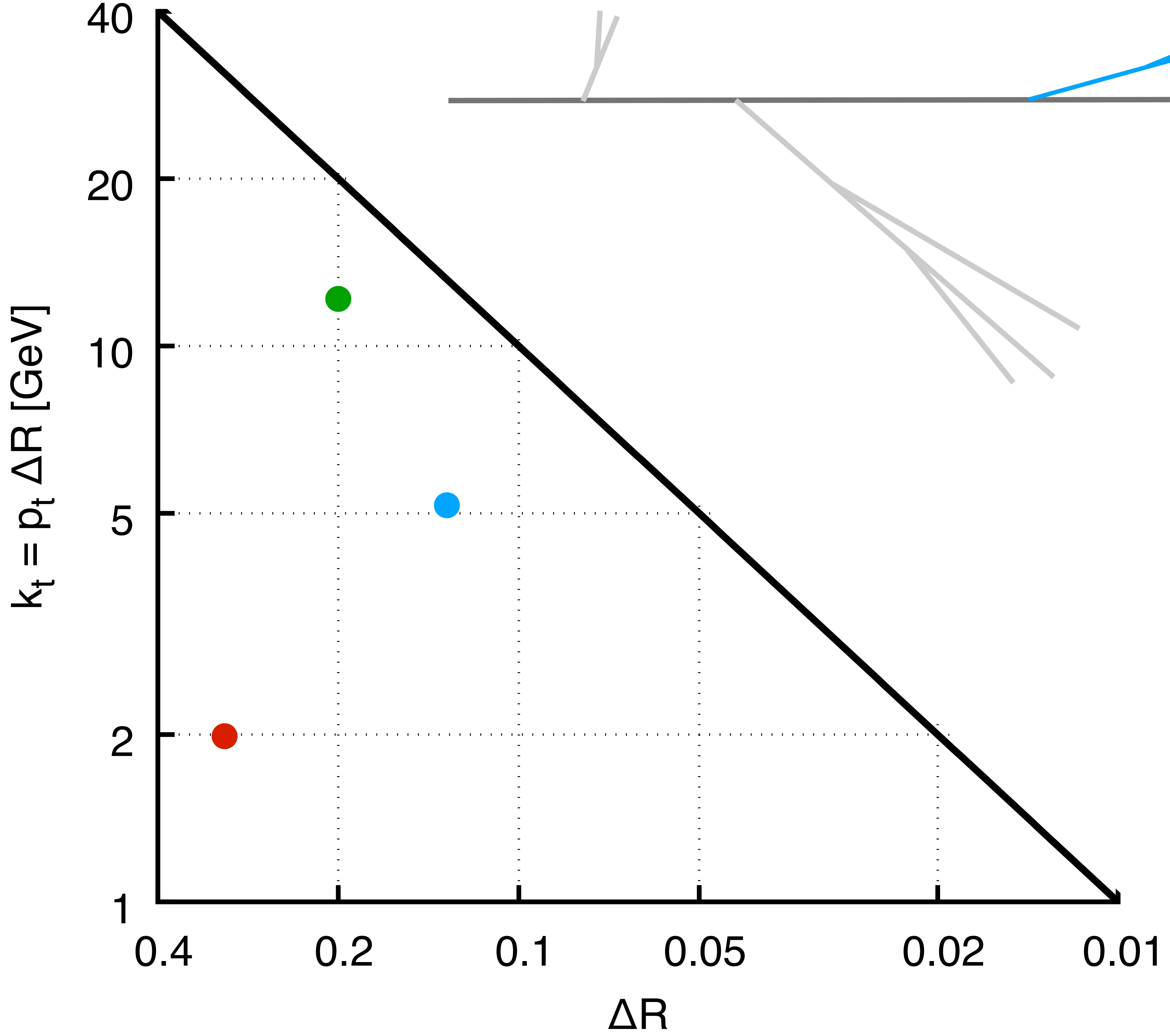

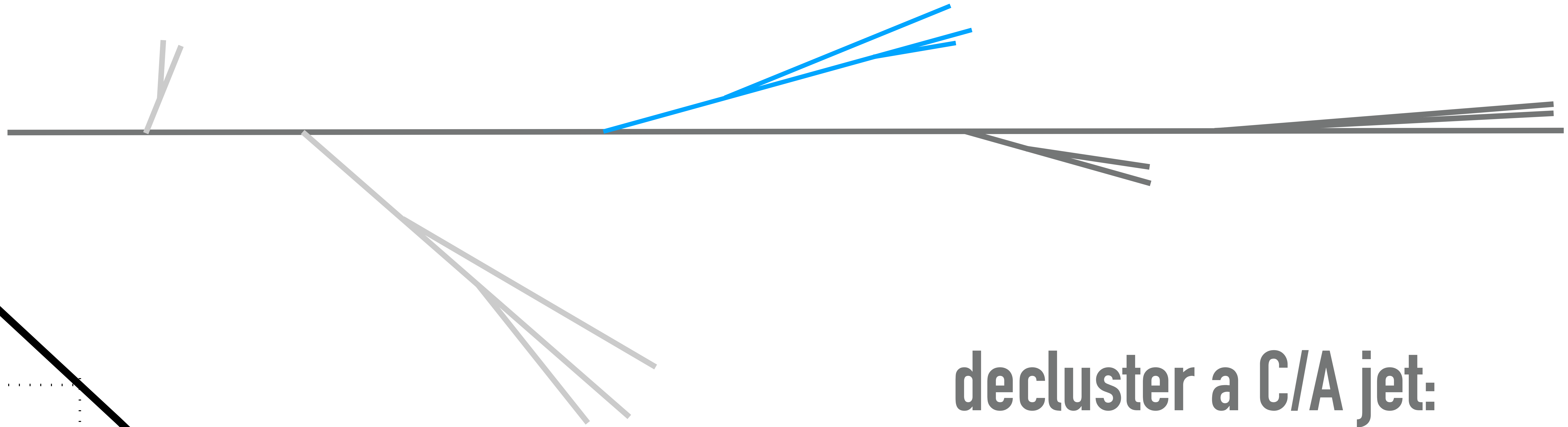

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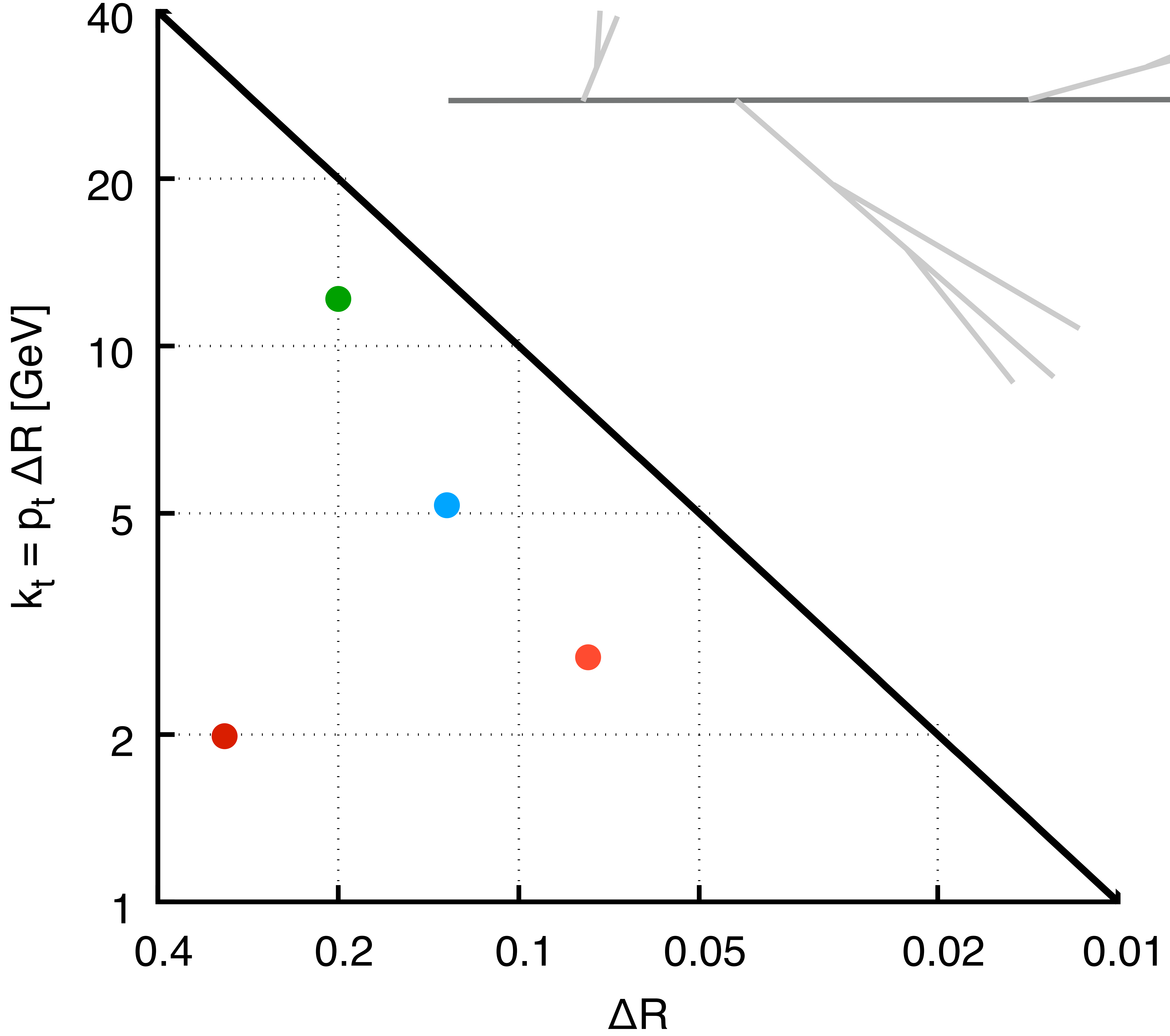

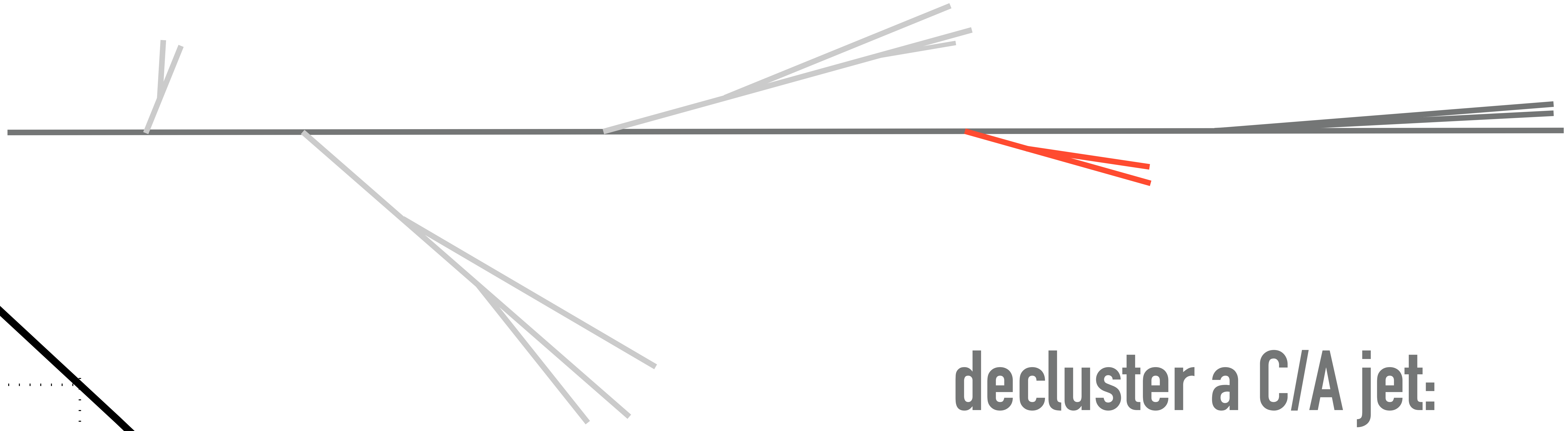

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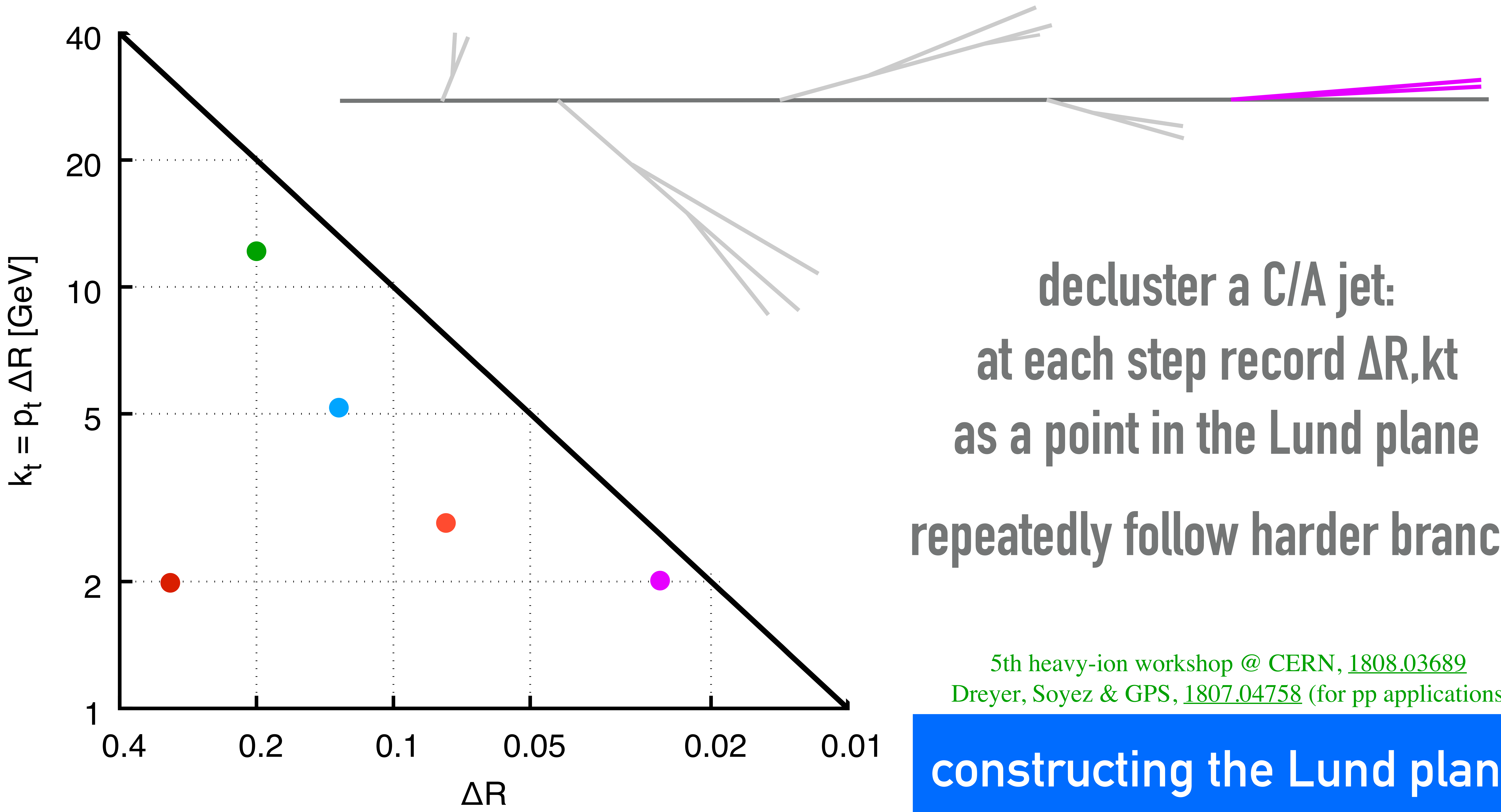

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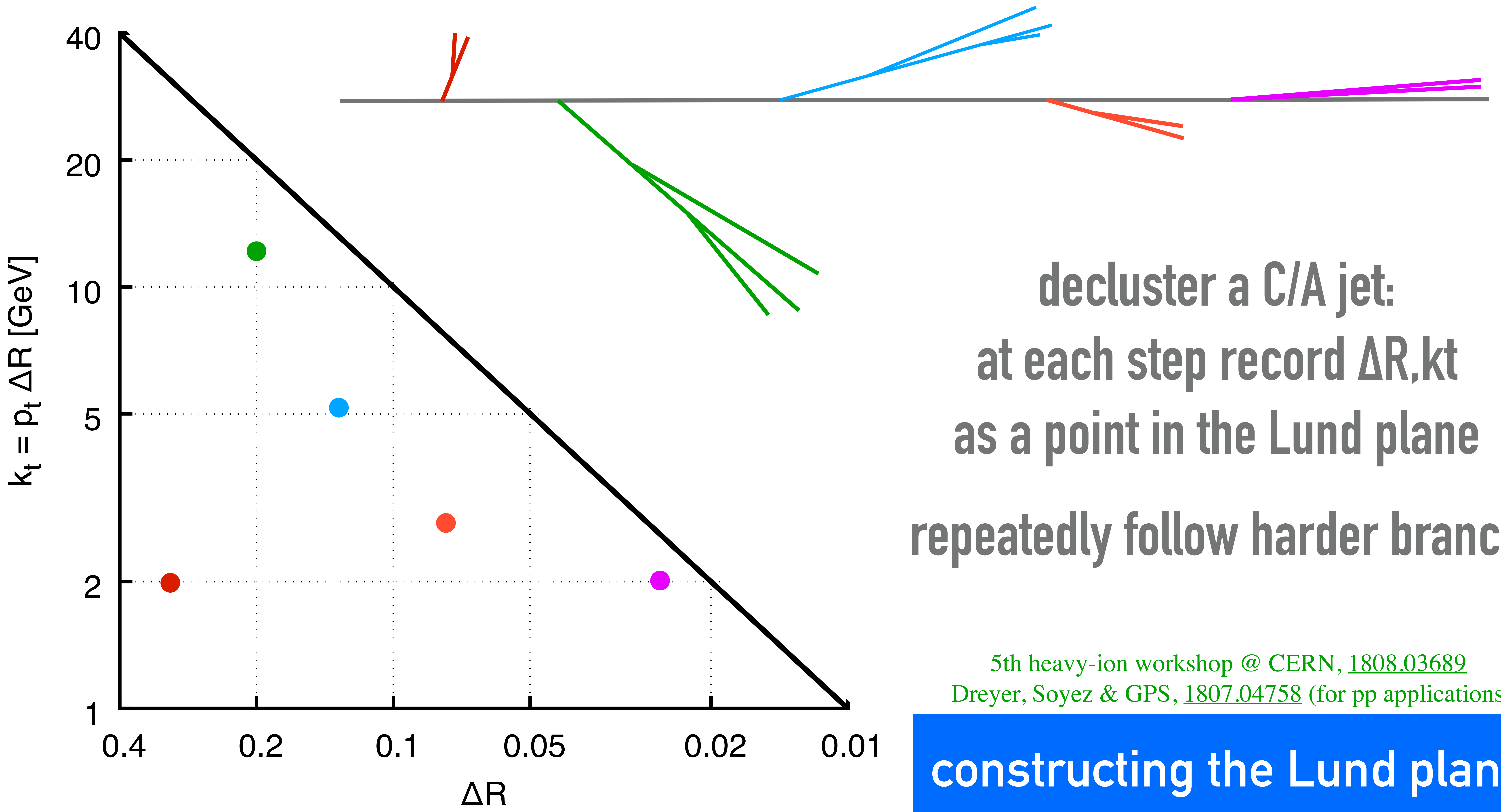

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5th heavy-ion workshop @ CERN, [1808.03689](1808.03689)
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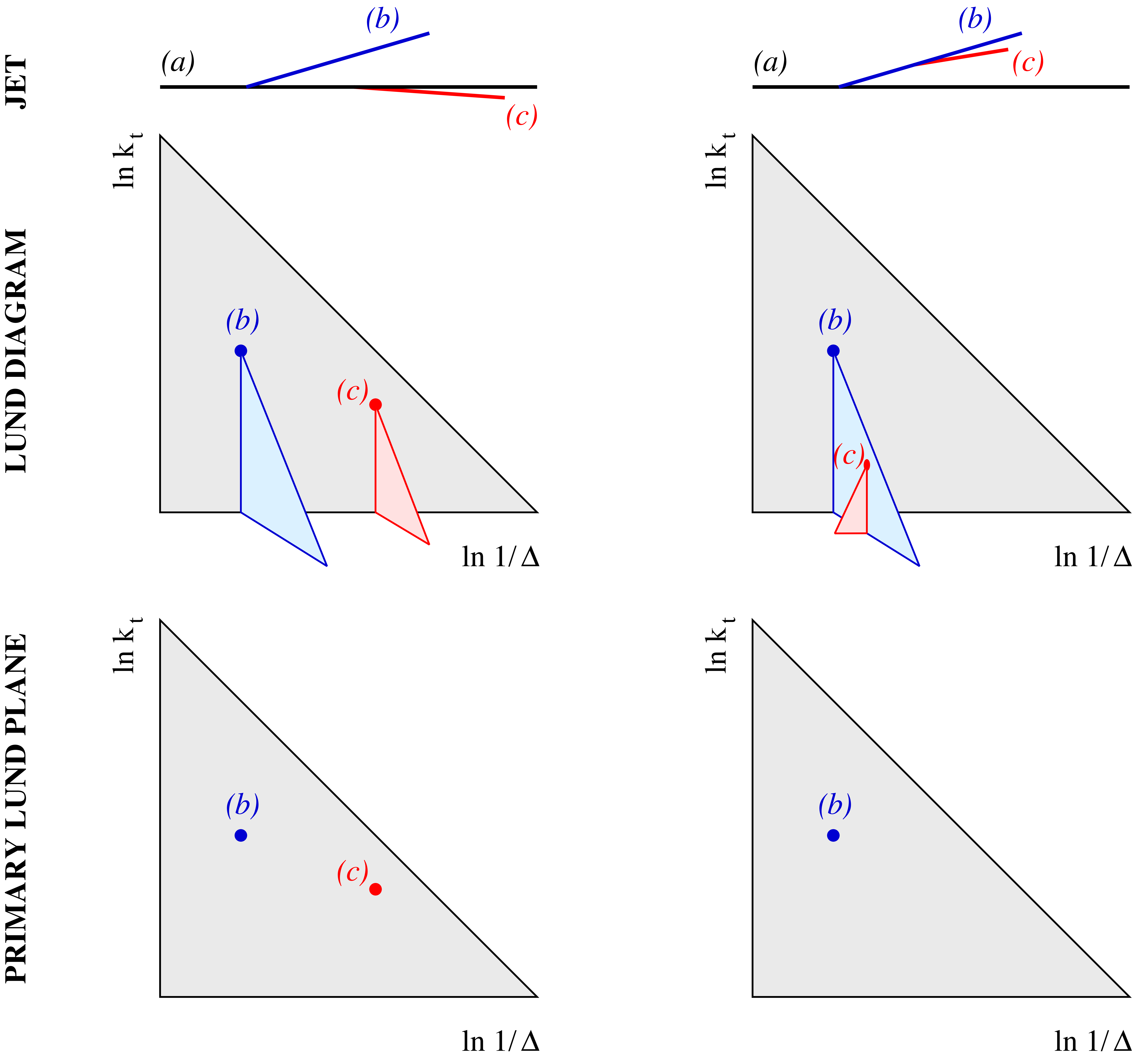
JET
LUND DIAGRAM
PRIMARY LUND PLANE
(a)
(b)
(c)
ln k_t
ln 1/Δ

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

average over many jets:

Lund plane density

5th heavy-ion workshop @ CERN, 1808.03689
Dreyer, Soyez & GPS, 1807.04758 (for pp applications)

constructing the Lund plane

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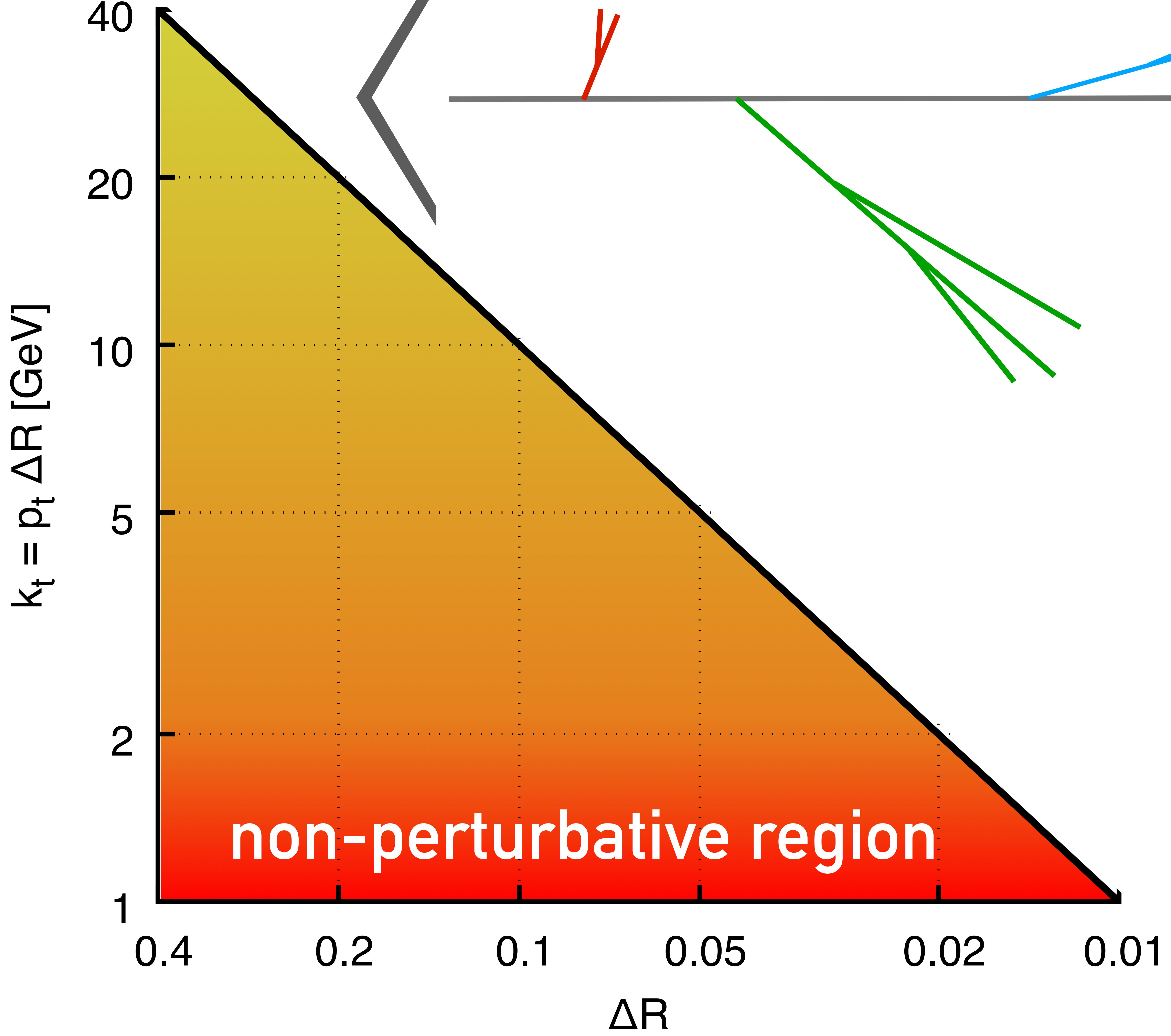

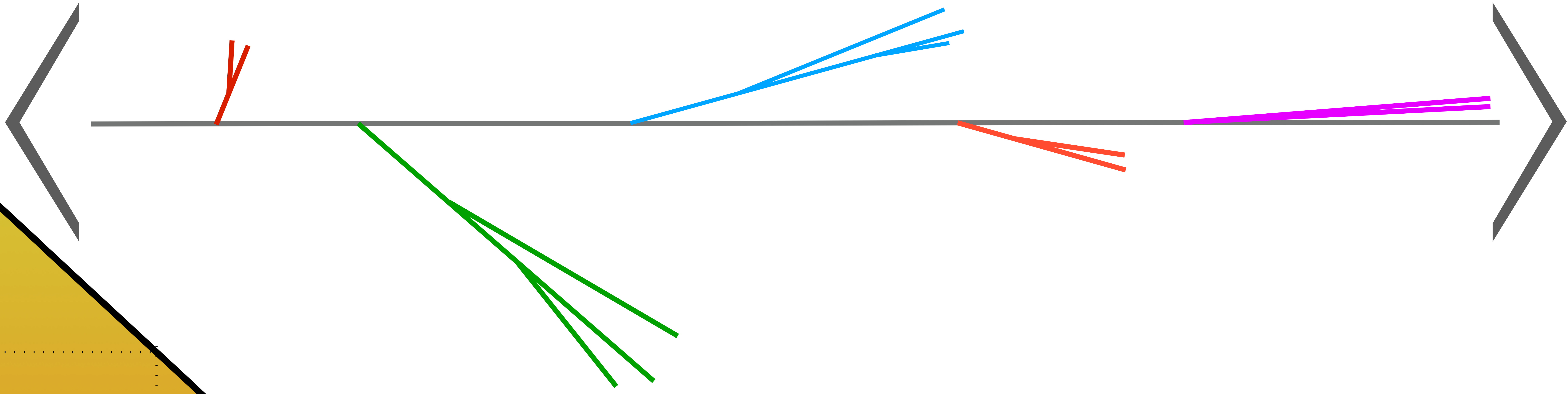

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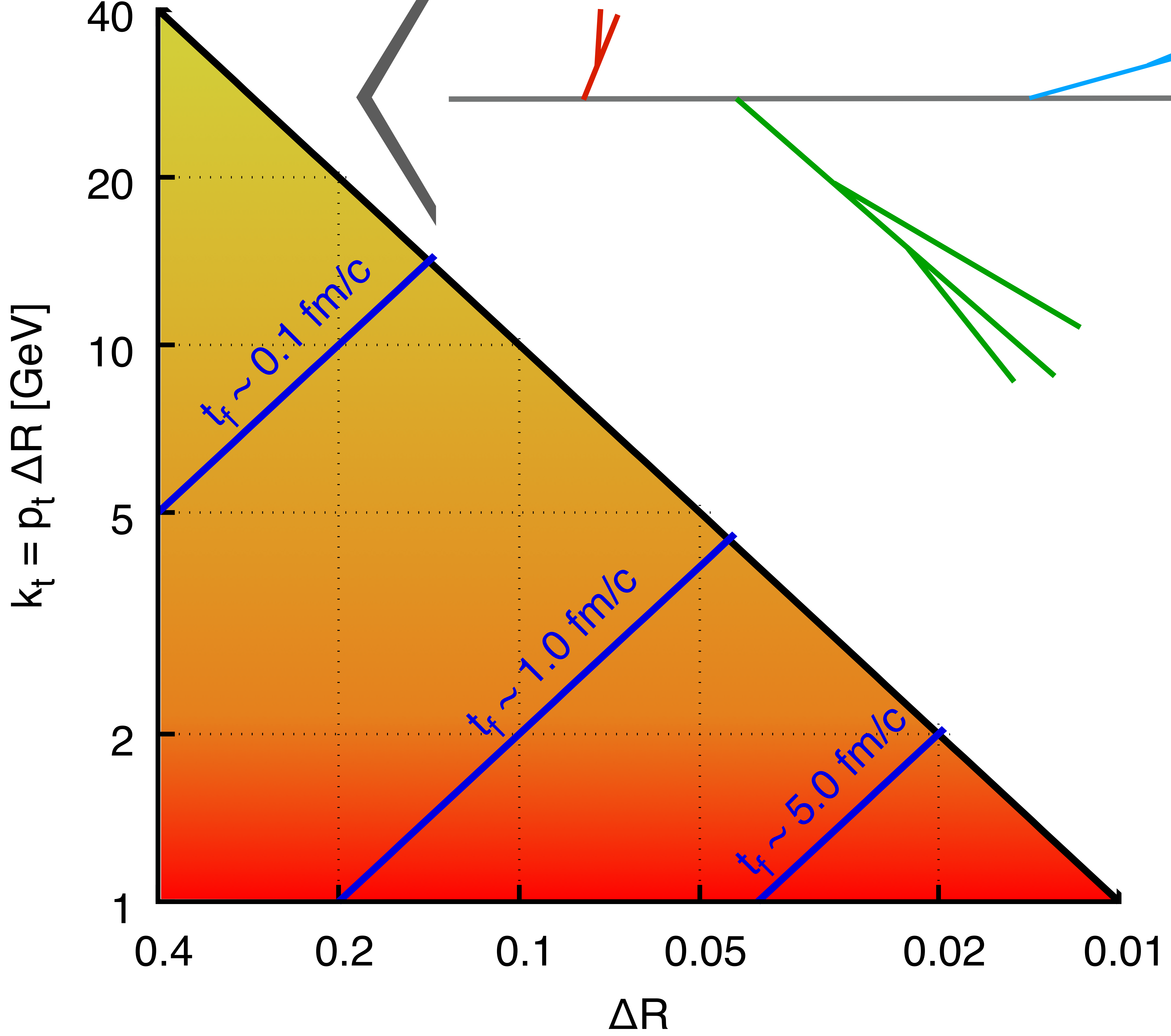

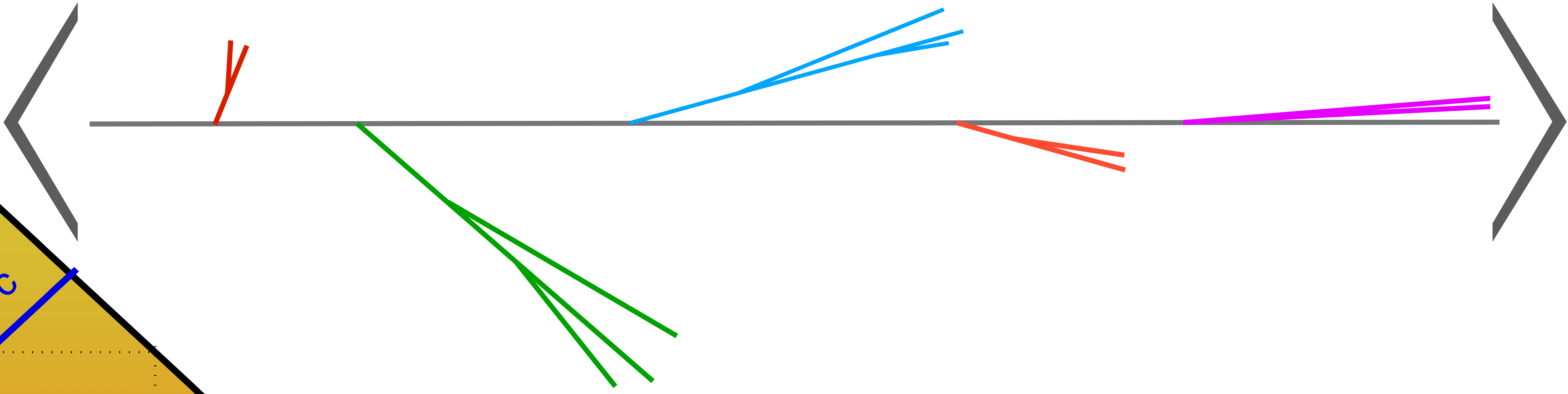

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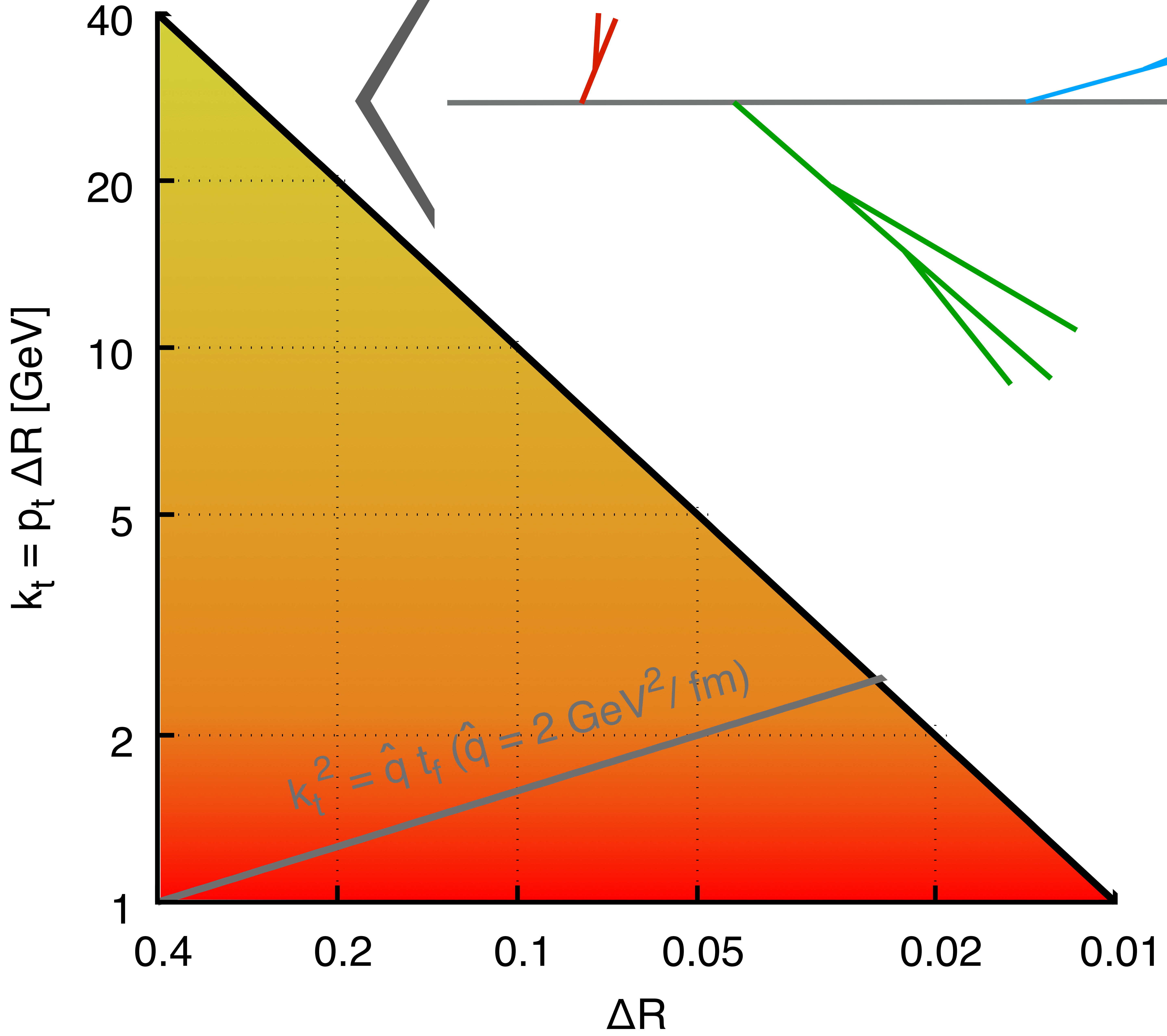

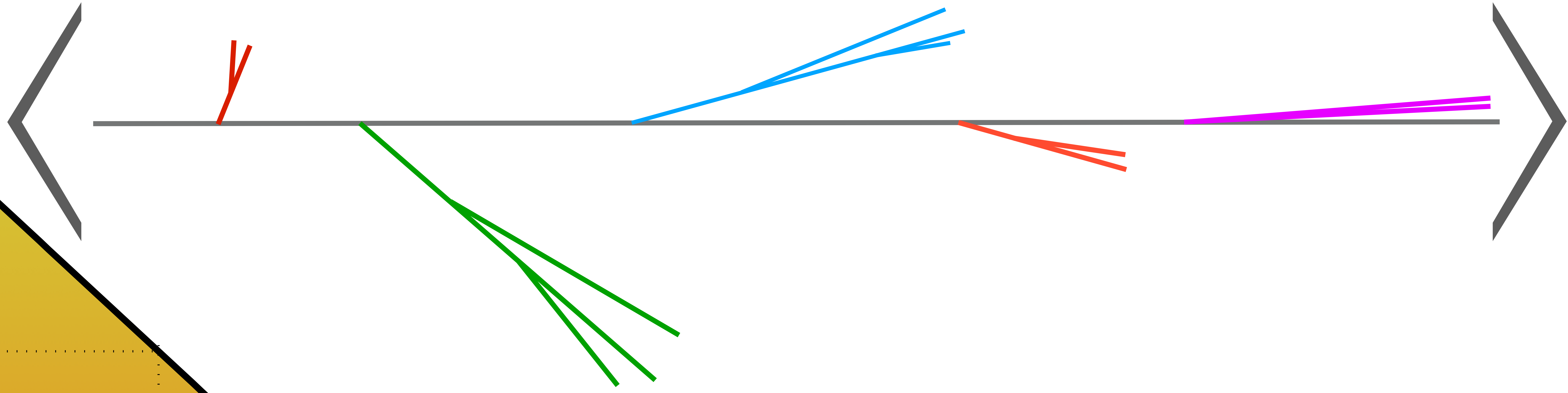

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Lund plane density

5th heavy-ion workshop @ CERN, 1808.03689
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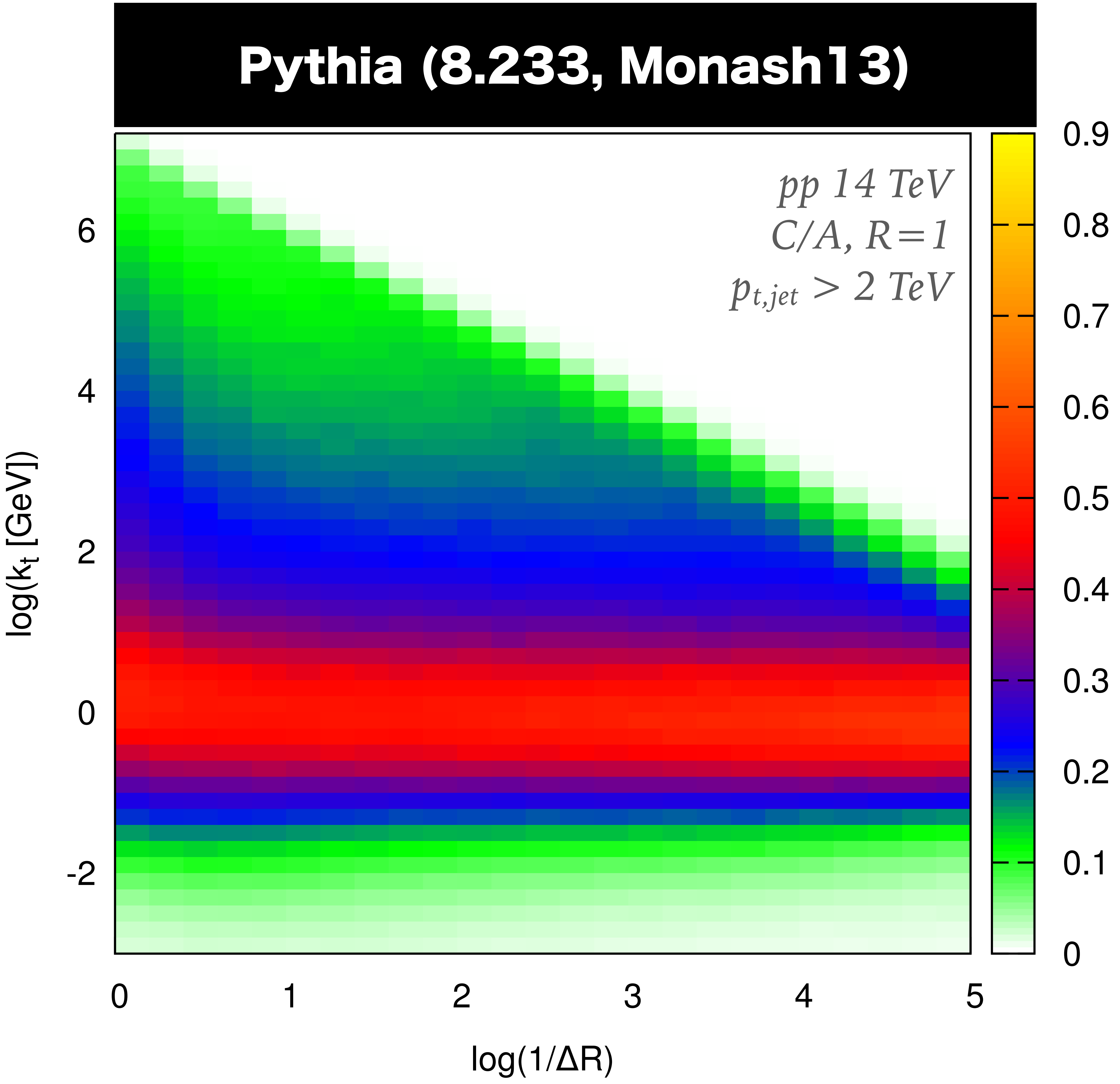
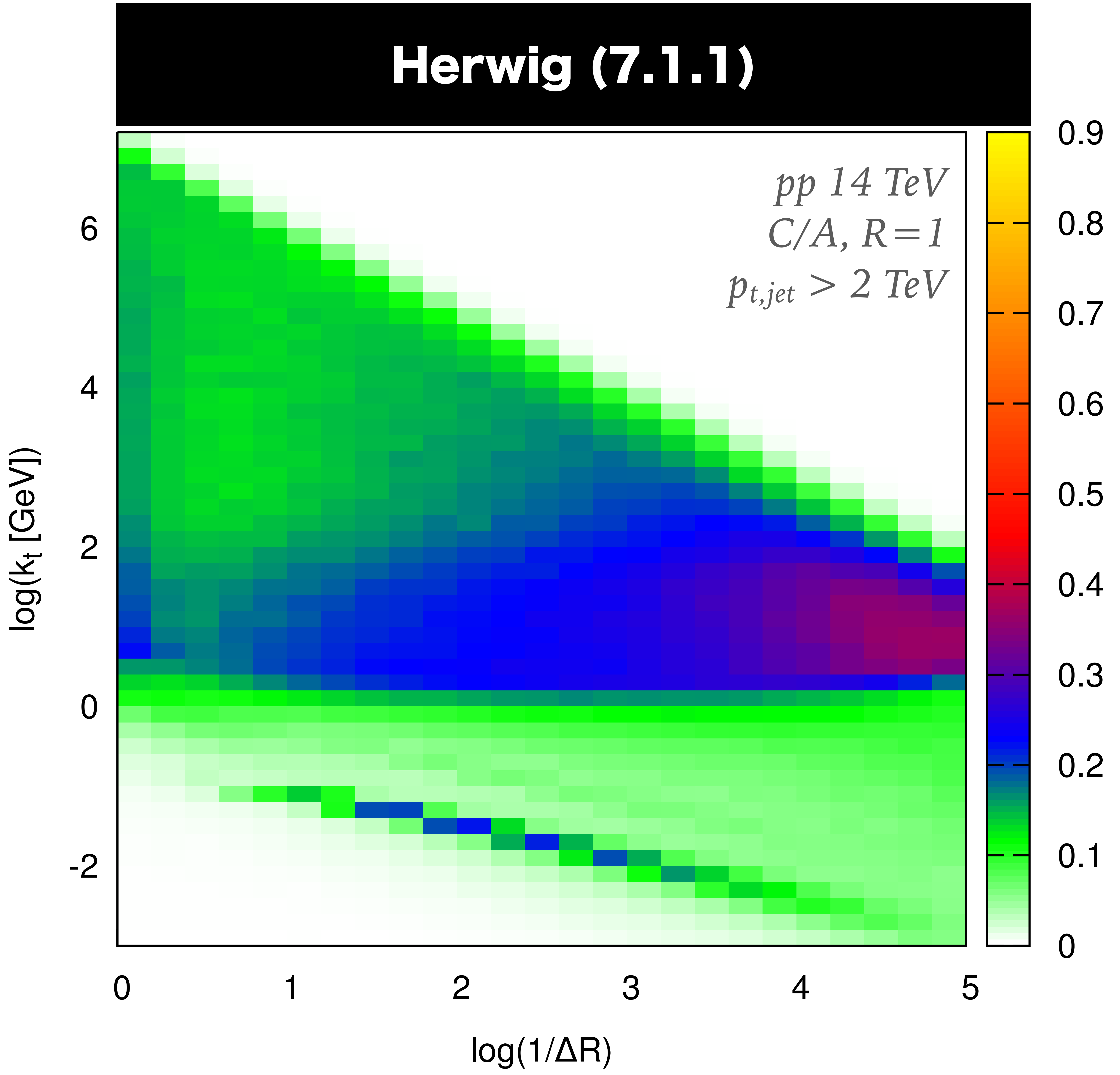
constructing the Lund plane

application to pp QCD studies

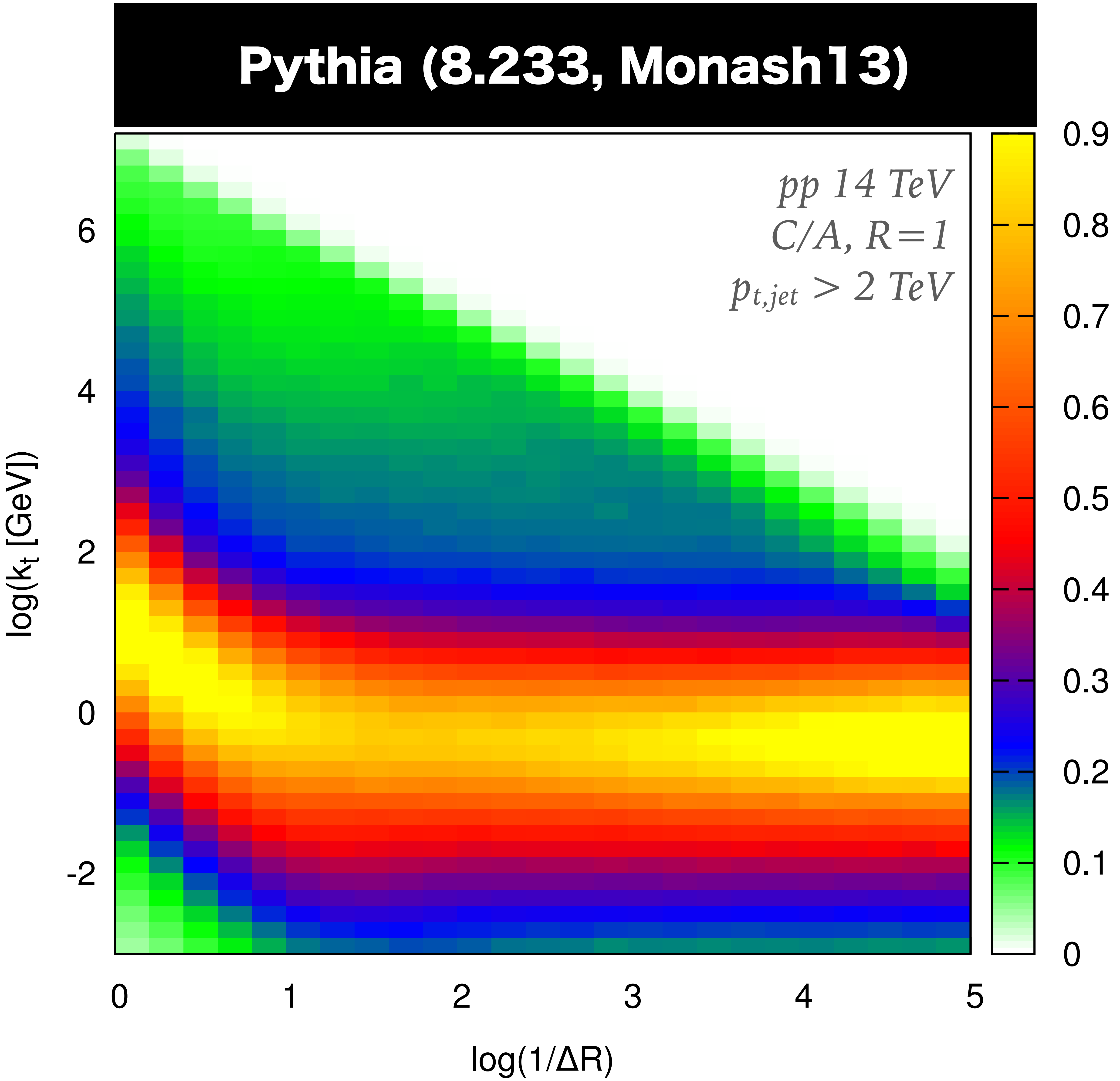
average pp Lund density: parton level

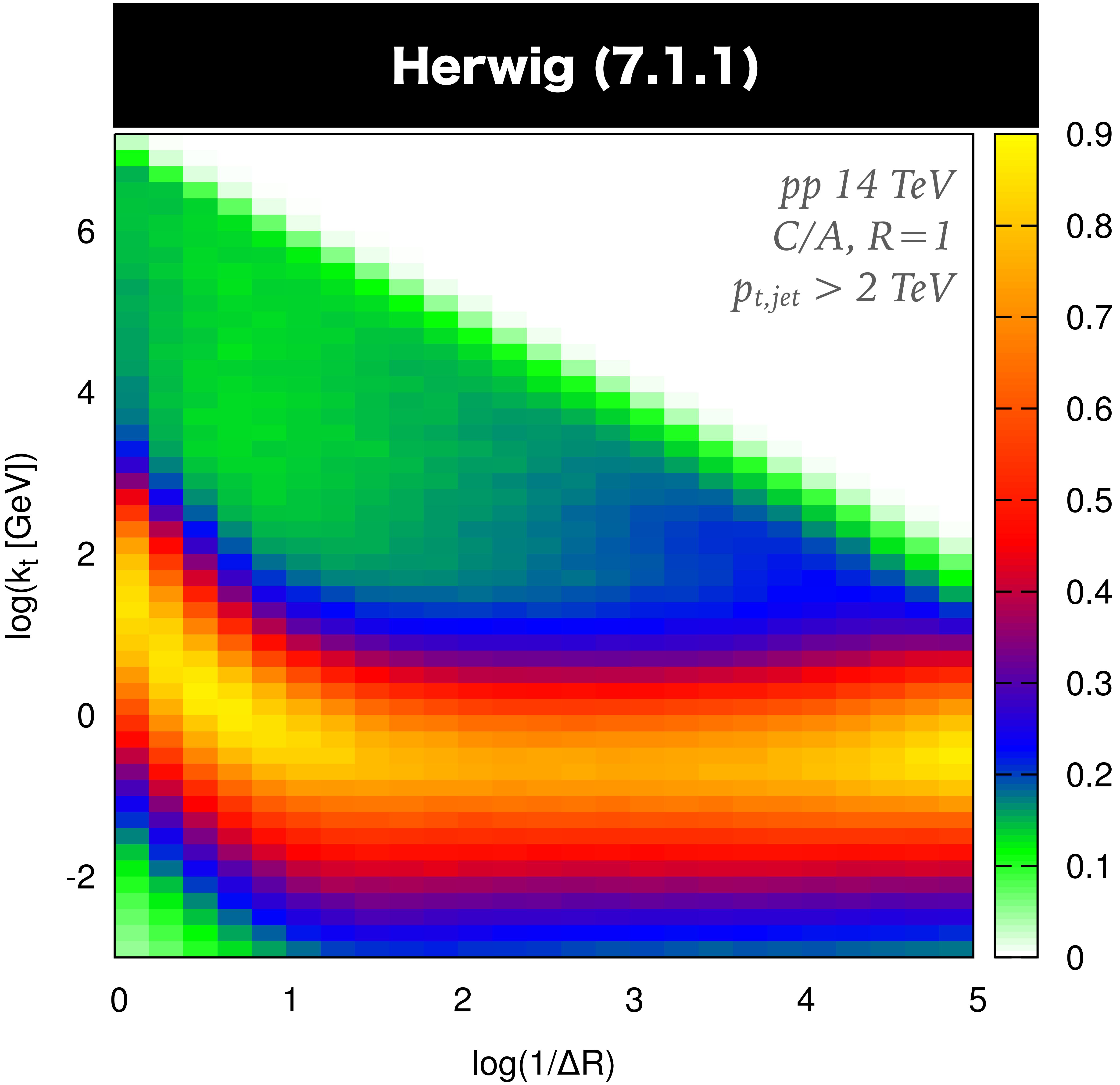




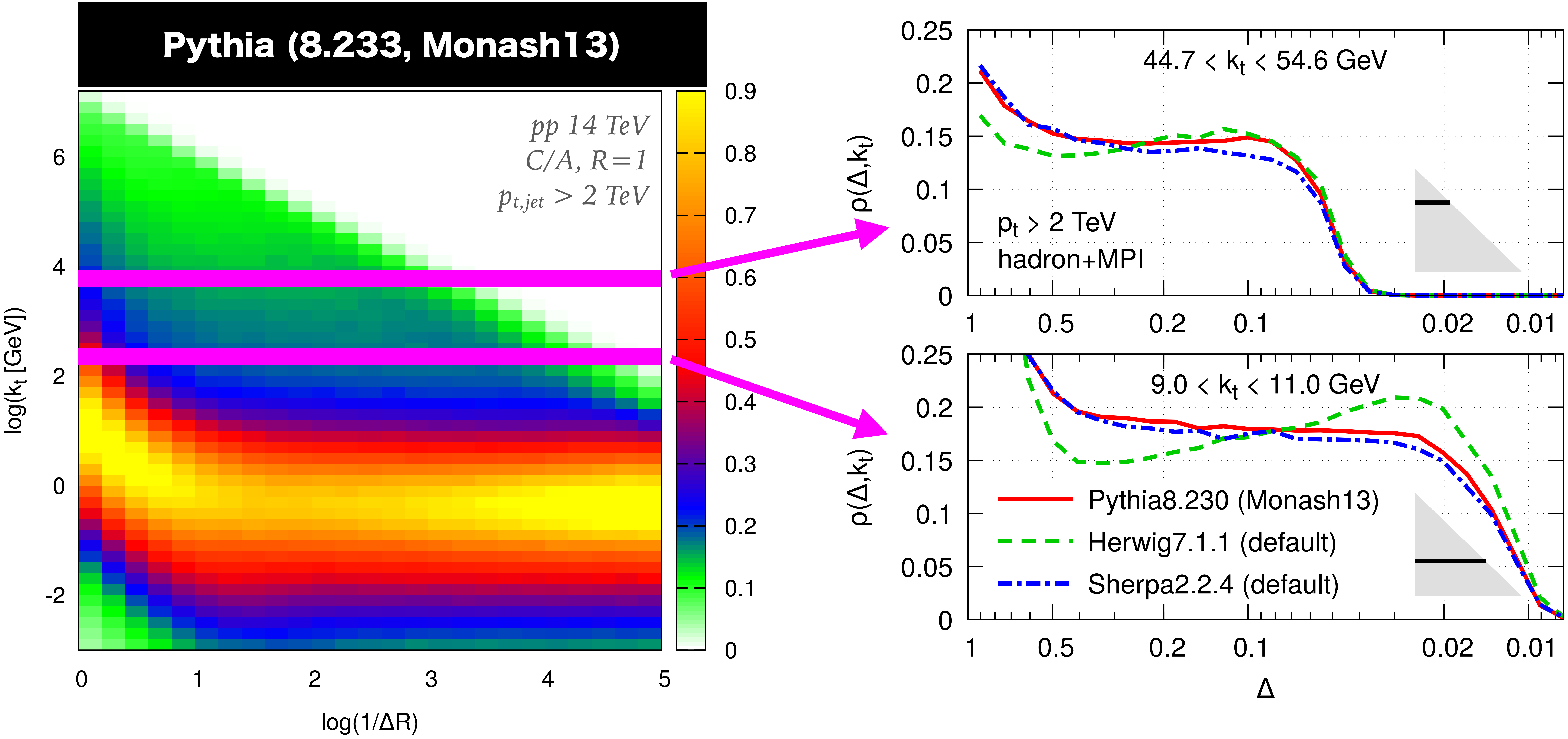
average pp Lund density: hadron level (no underlying event / MPI)

average pp Lund density: hadron level (with underlying event / MPI)





average pp Lund density: cross sections



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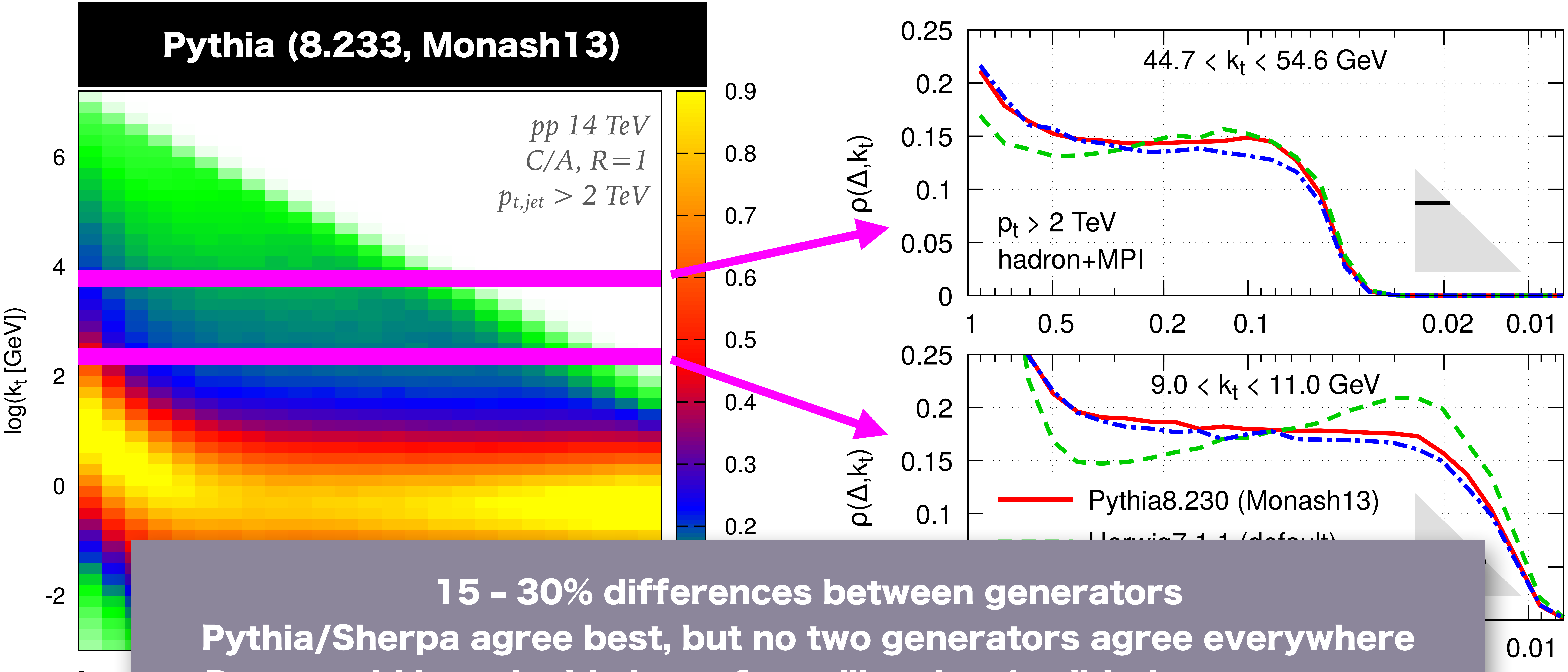
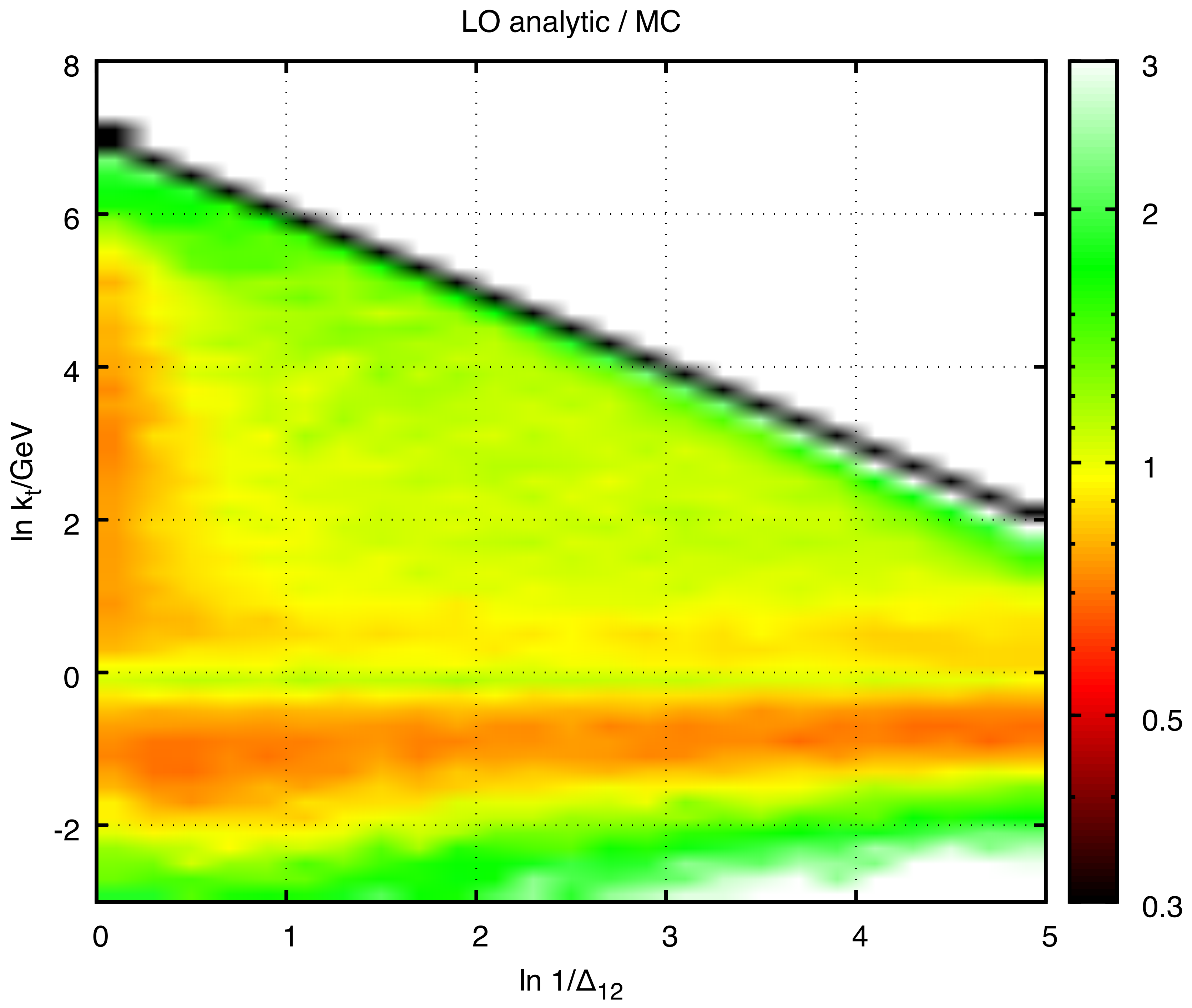


15 – 30% differences between generators
Pythia/Sherpa agree best, but no two generators agree everywhere
Data would be valuable input for calibrating / validating generators

analytic perturbative QCD control

To leading order in perturbative QCD and for $\Delta \ll 1$, one expects for a quark initiated jet

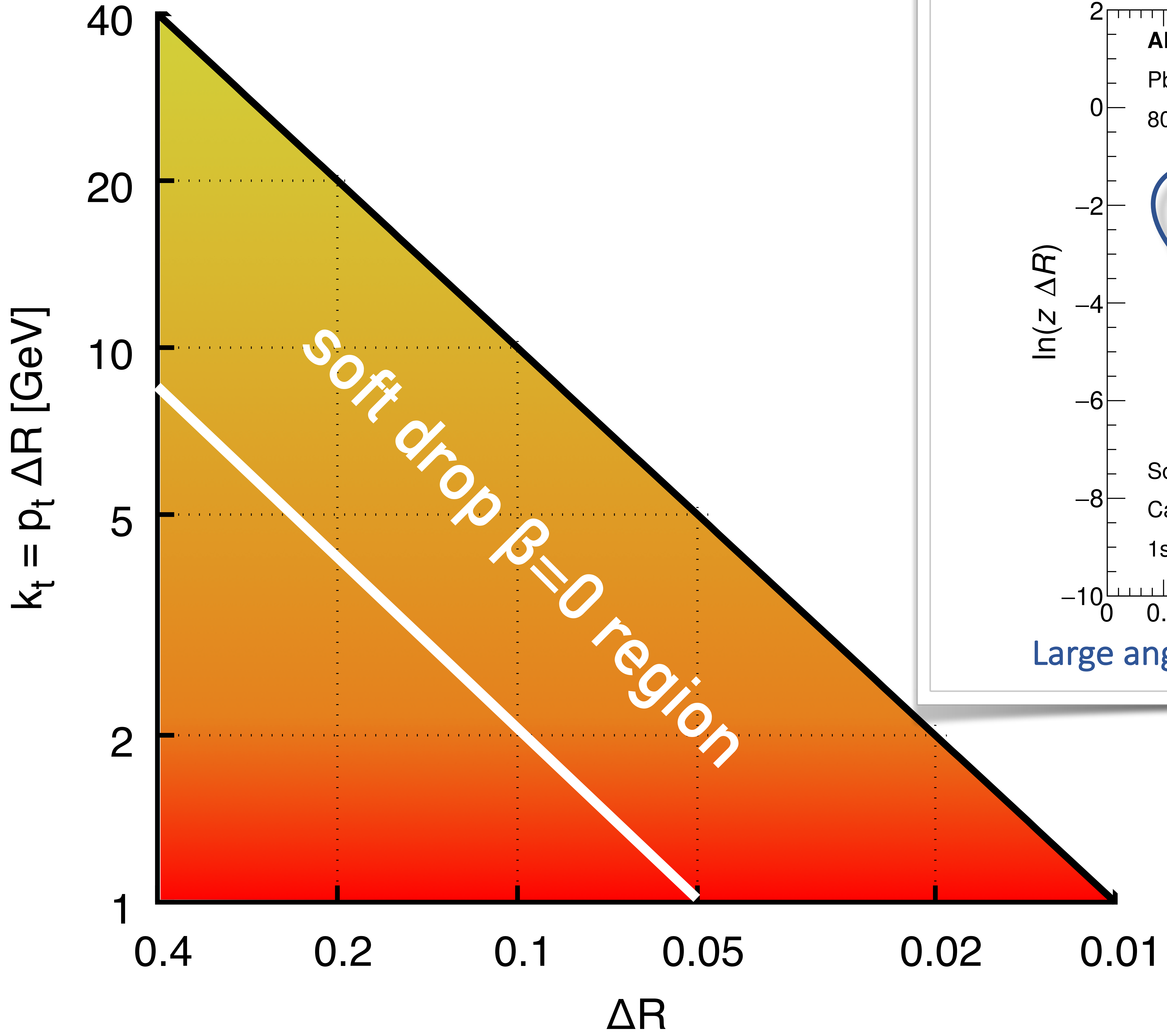
$$\rho \simeq \frac{\alpha_s(k_t) C_F}{\pi} \bar{z}\left(p_{gq}(\bar{z}) + p_{gq}(1-\bar{z})\right), \quad \bar{z} = \frac{k_t}{p_{t,\text{jet}}\Delta}$$

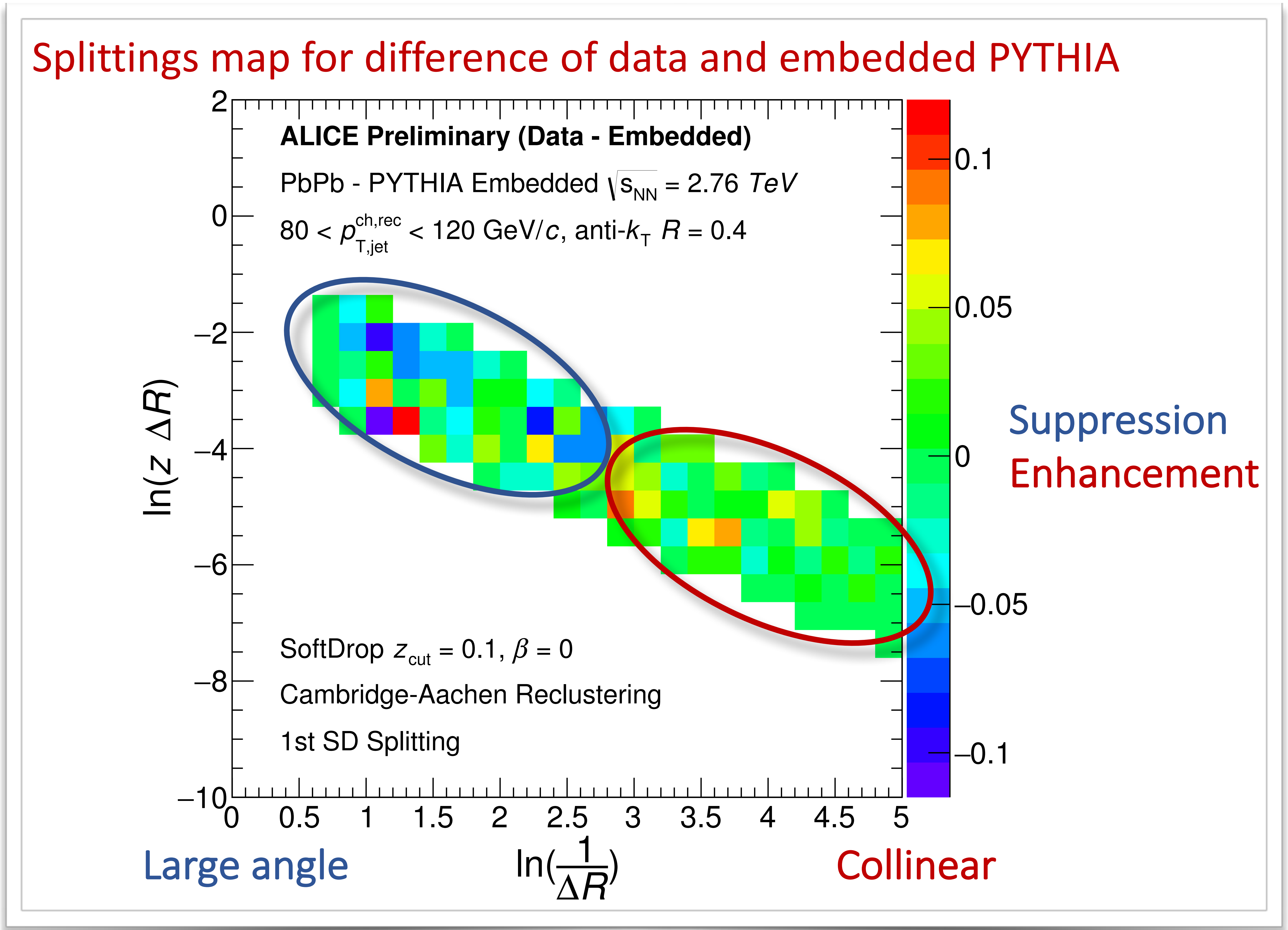


- Lund plane can be calculated analytically.
- Calculation is systematically improvable.

application to HI collisions

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





This is not the average density, but the density of the 1st soft-drop splitting

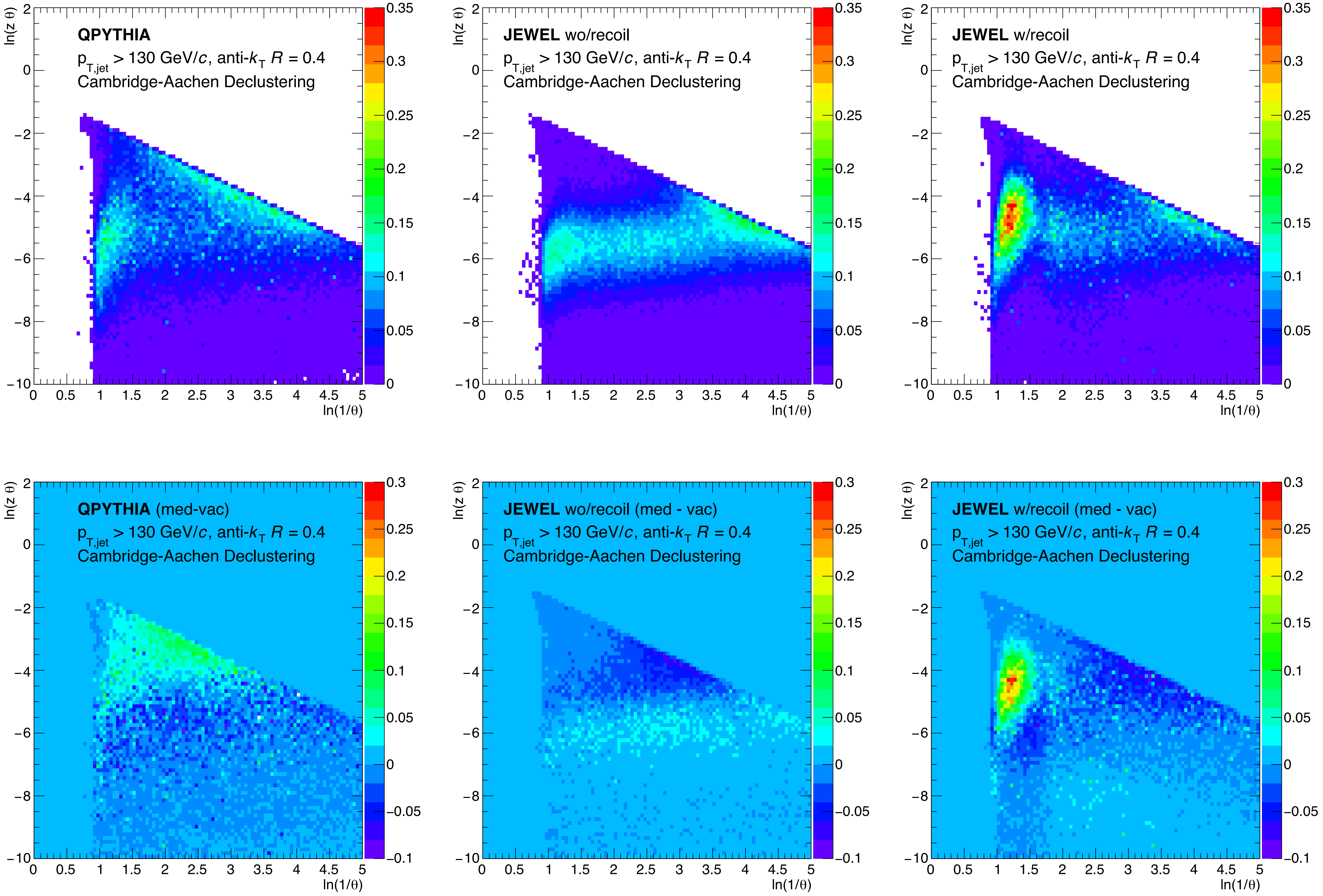


Figure 4: Lund diagram reconstructed from jets generated by QPYTHIA (left column), JEWEL without recoils (middle column) and JEWEL with recoils (right column). The lower panels correspond to the difference of the radiation pattern with and without jet quenching effects. Note that the scale of the z-axes varies between the panels.

HI MC studies

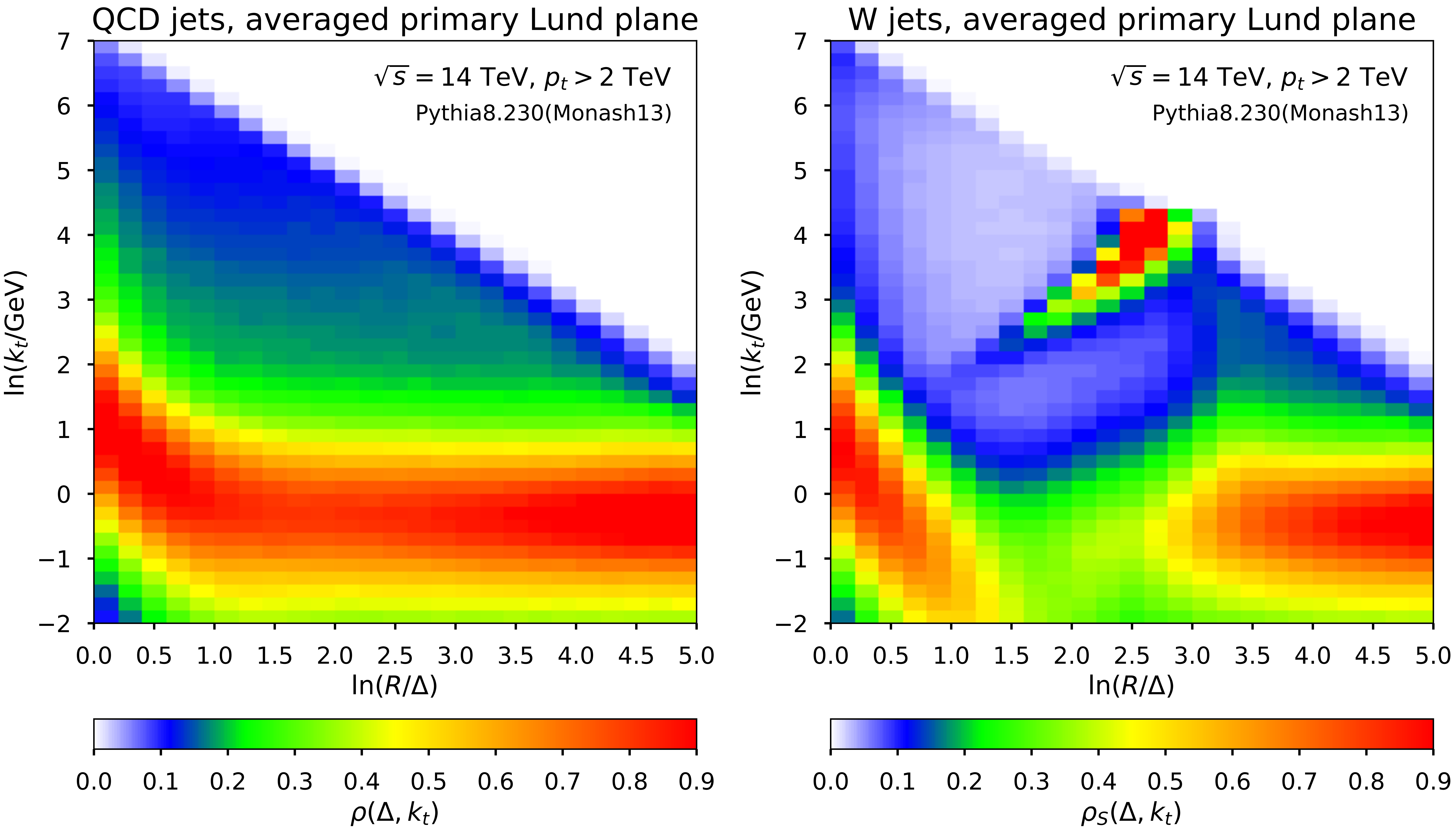
Andrews et al, 1808.03689

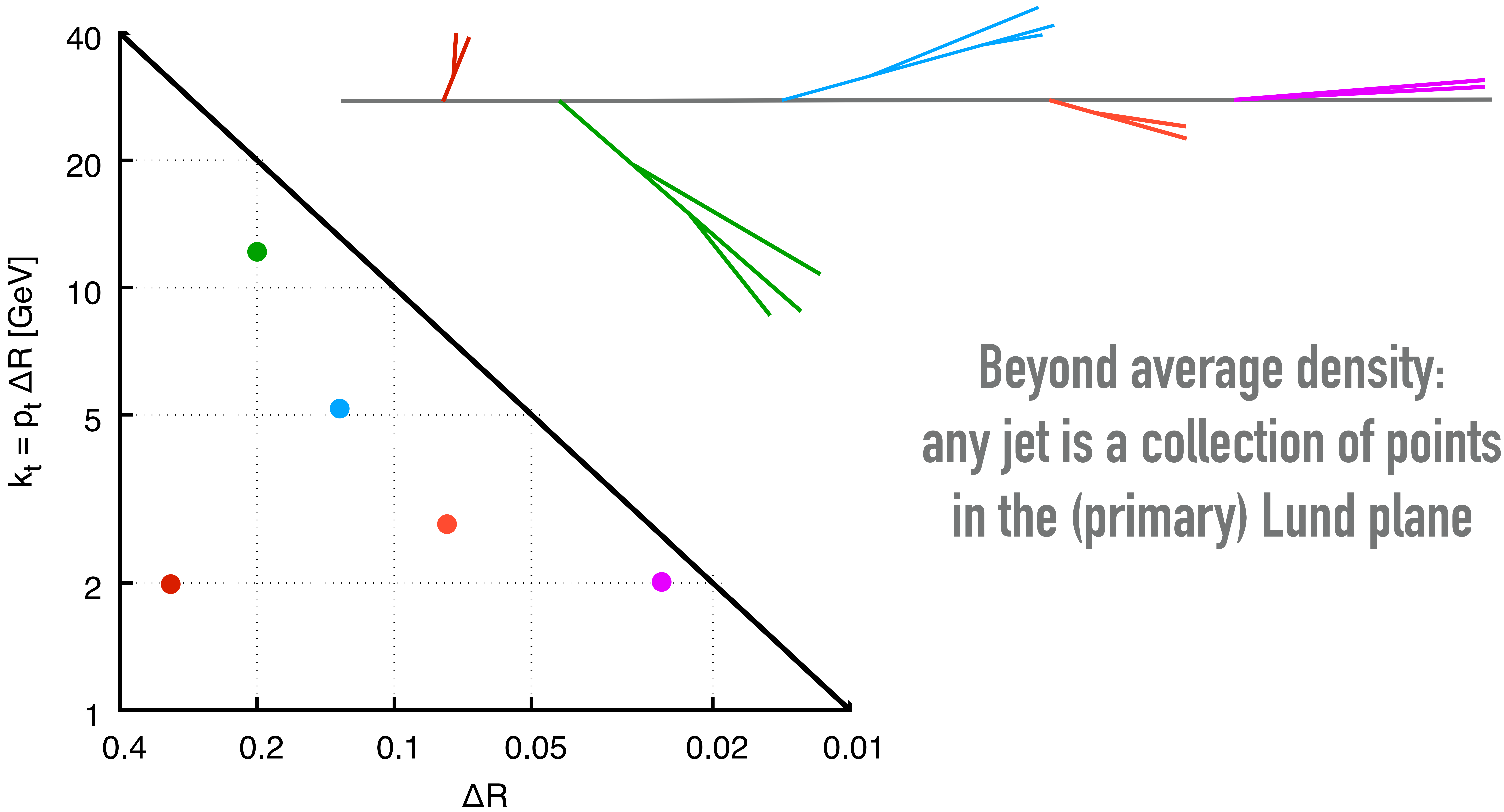
- clear potential for distinguishing between models, with clear physical picture of where the differences arise

application to high-p_t physics

e.g. new-physics searches and Higgs studies

Comparing quark/gluon v. W-induced jets



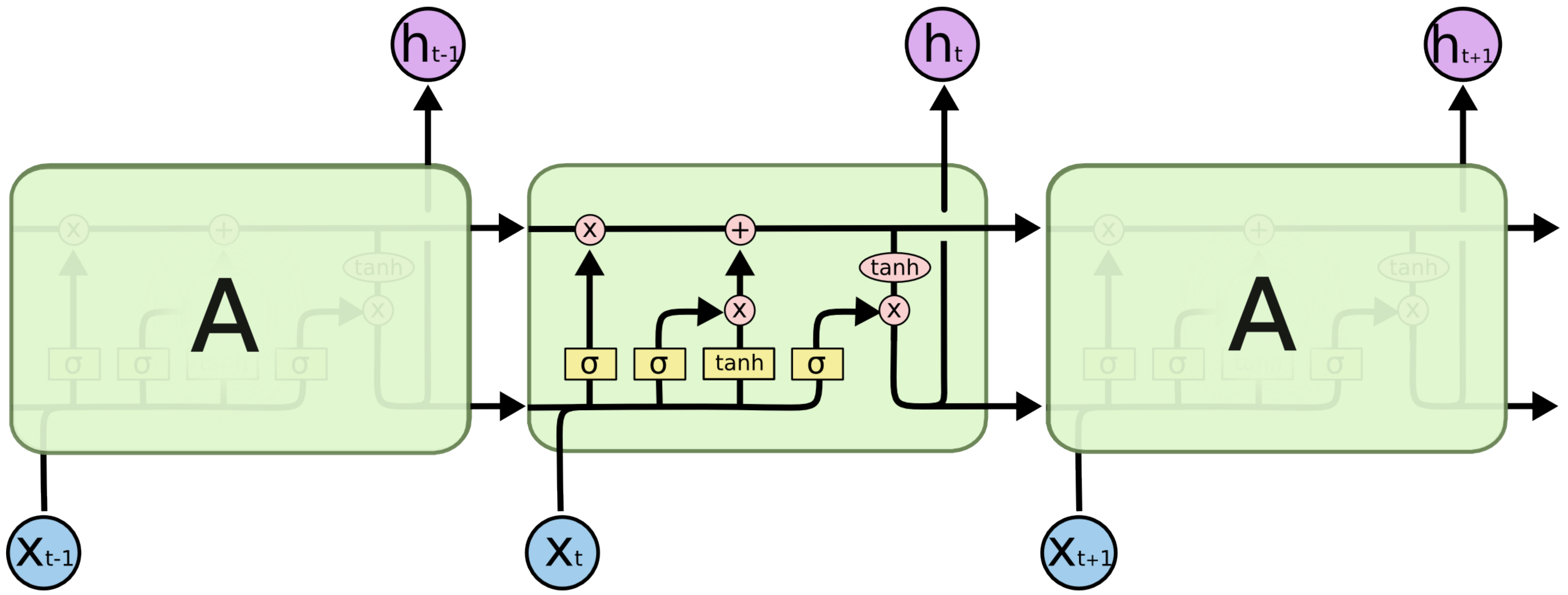


Beyond average density: any jet is a collection of points in the (primary) Lund plane

Lund declustering points as inputs to machine-learning

- Simple recurrent networks unable to handle dependencies that are widely separated in the data.
- LSTM networks designed to have memory over longer periods, by adding four layers for each module and including a no-activation function. [Hochreiter, Schmidhuber (1997)]

long-short-term memory networks (LSTMs) gave us the best performance



Figures from http://colah.github.io/posts/2015-08-Understanding-LSTMs/

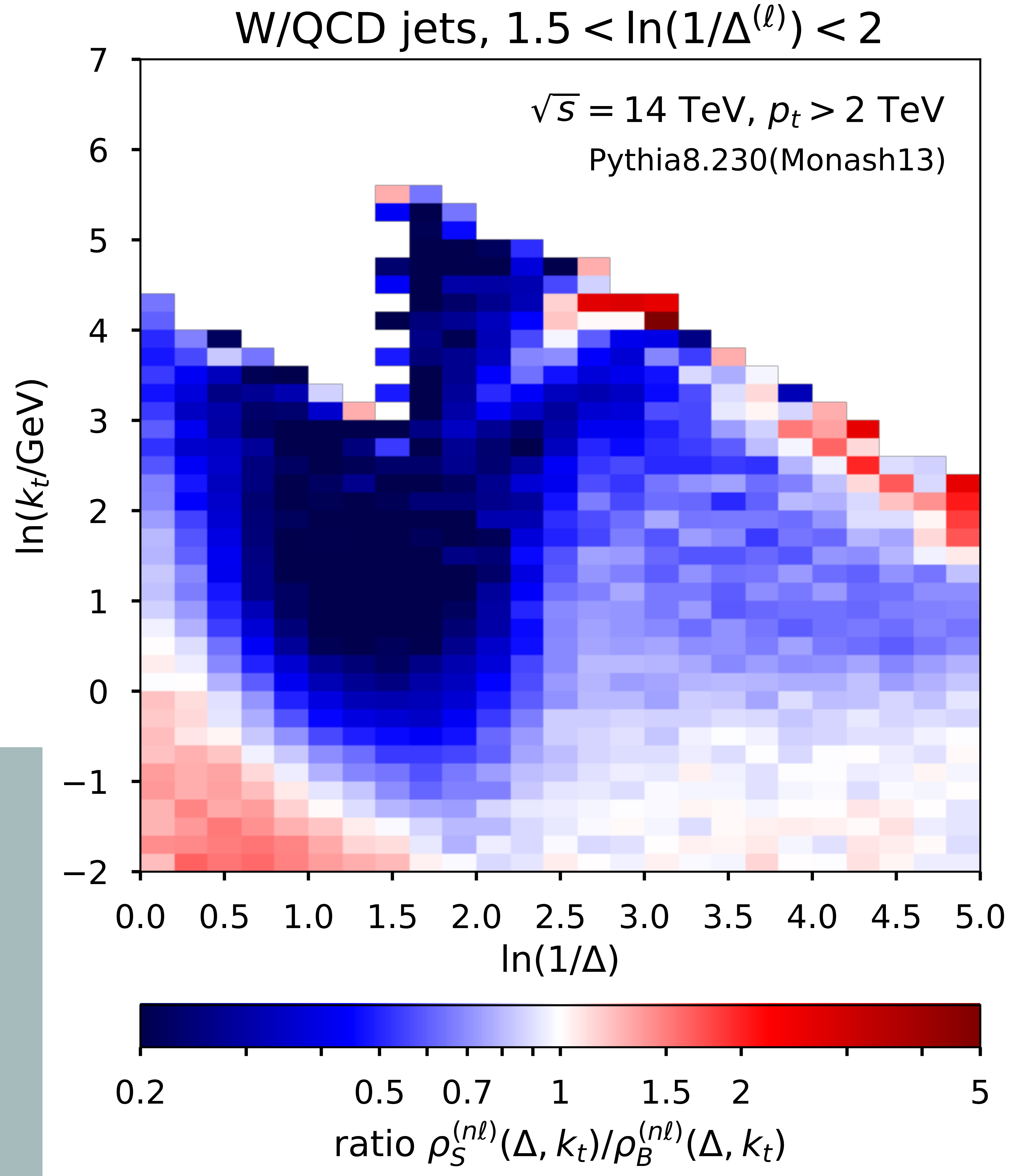
Lund declustering points as inputs to hand-crafted likelihood calculation

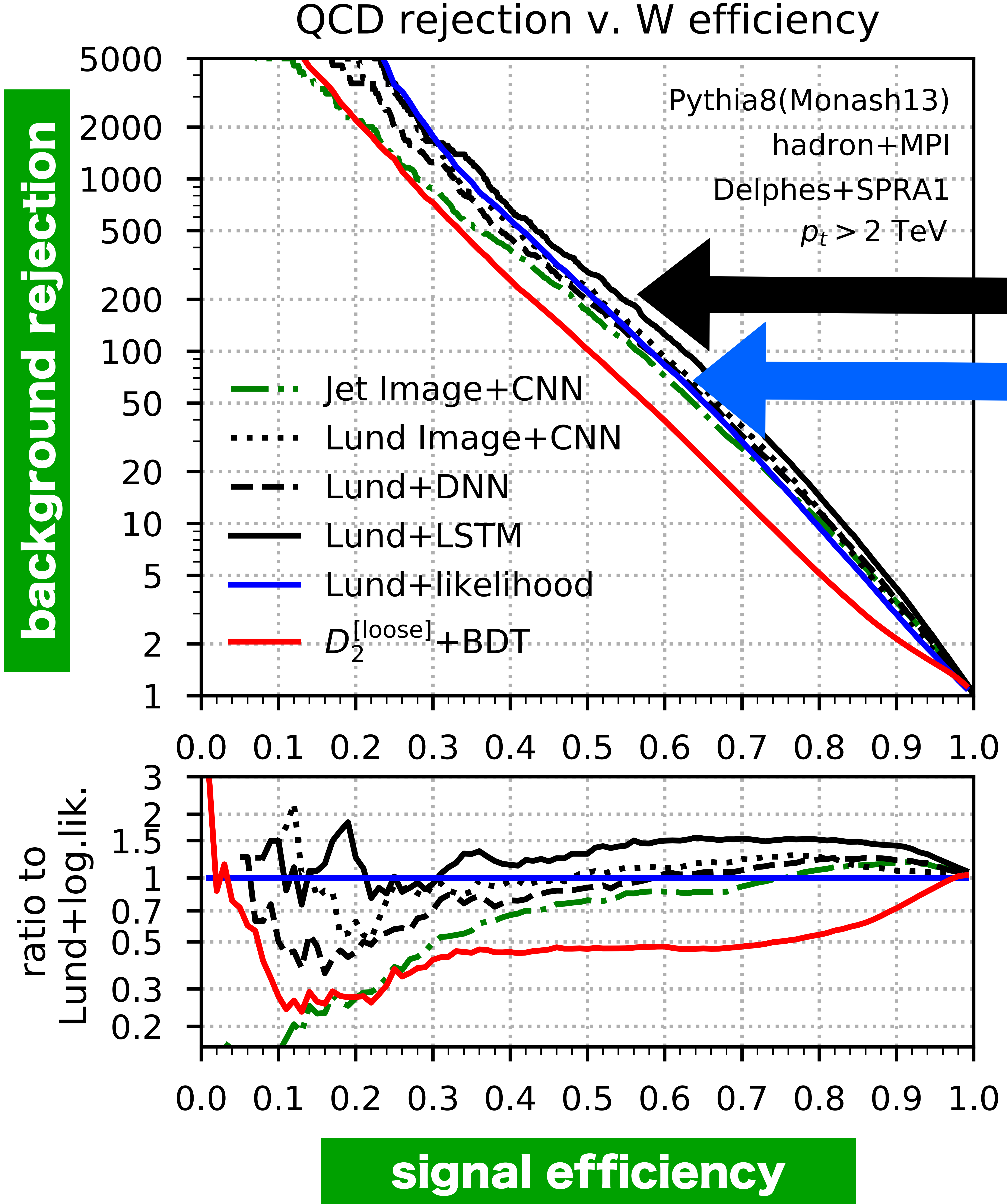
- Identify emission that generates the jet mass (with Soft-Drop)
- Assume all other emissions are independent of each other, i.e. random distribution just set by average density
- Get MC ratio of average densities for W (Signal≡S) v. QCD (background ≡ B) jets
- Build likelihood discriminator

$$\mathcal{L}_{\text{tot}} = \mathcal{L}_{\ell}(m^{(\ell)}, z^{(\ell)}) + \sum_{i\neq\ell} \mathcal{L}_{n\ell}(\Delta^{(i)}, k_t^{(i)}; \Delta^{(\ell)}) + \mathcal{N}(\Delta^{(\ell)})$$

$$\mathcal{L}_{n\ell}(\Delta, k_t; \Delta^{(\ell)}) = \ln\left(\rho_S^{(n\ell)} / \rho_B^{(n\ell)}\right)$$

$$\rho_X^{(n\ell)}(\Delta, k_t; \Delta^{(\ell)}) = \frac{dn^{(n\ell)}_{\text{emission},X}}{d\ln k_t \, d\ln 1/\Delta \, d\ln \Delta^{(\ell)}} \Bigg/ \frac{dN_X}{d\ln \Delta^{(\ell)}}$$





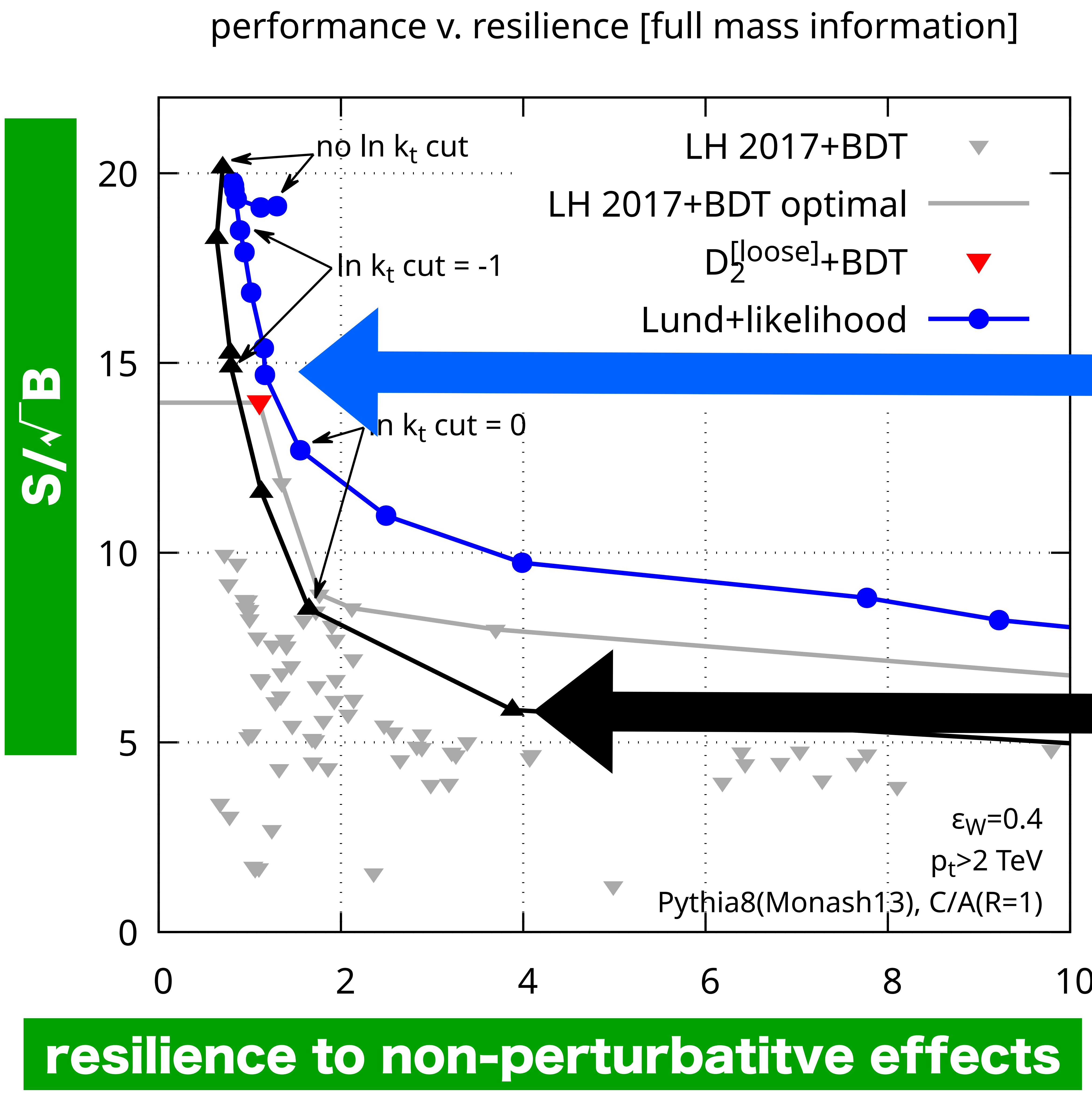
Performance:
background rejection v. signal efficiency

Lund + machine-learning (LSTM)

Lund + likelihood

(gets to within 70-80% of performance of best machine learning)

Performance:
S/√B v. resilience to non-perturbative QCD



$$\zeta = \left(\frac{\Delta\epsilon_W^2}{\langle\epsilon\rangle_W^2} + \frac{\Delta\epsilon_{\mathrm{QCD}}^2}{\langle\epsilon\rangle_{\mathrm{QCD}}^2}\right)^{-\frac{1}{2}}$$

Lund + likelihood
performs better than machine learning when you exclude non-perturbative region (k_t < 1 GeV(

Lund + machine-learning (LSTM)

closing

Conclusions

The QCD radiation in collider events (pp & HI) is a rich source of information, which we're only just starting to tap into.

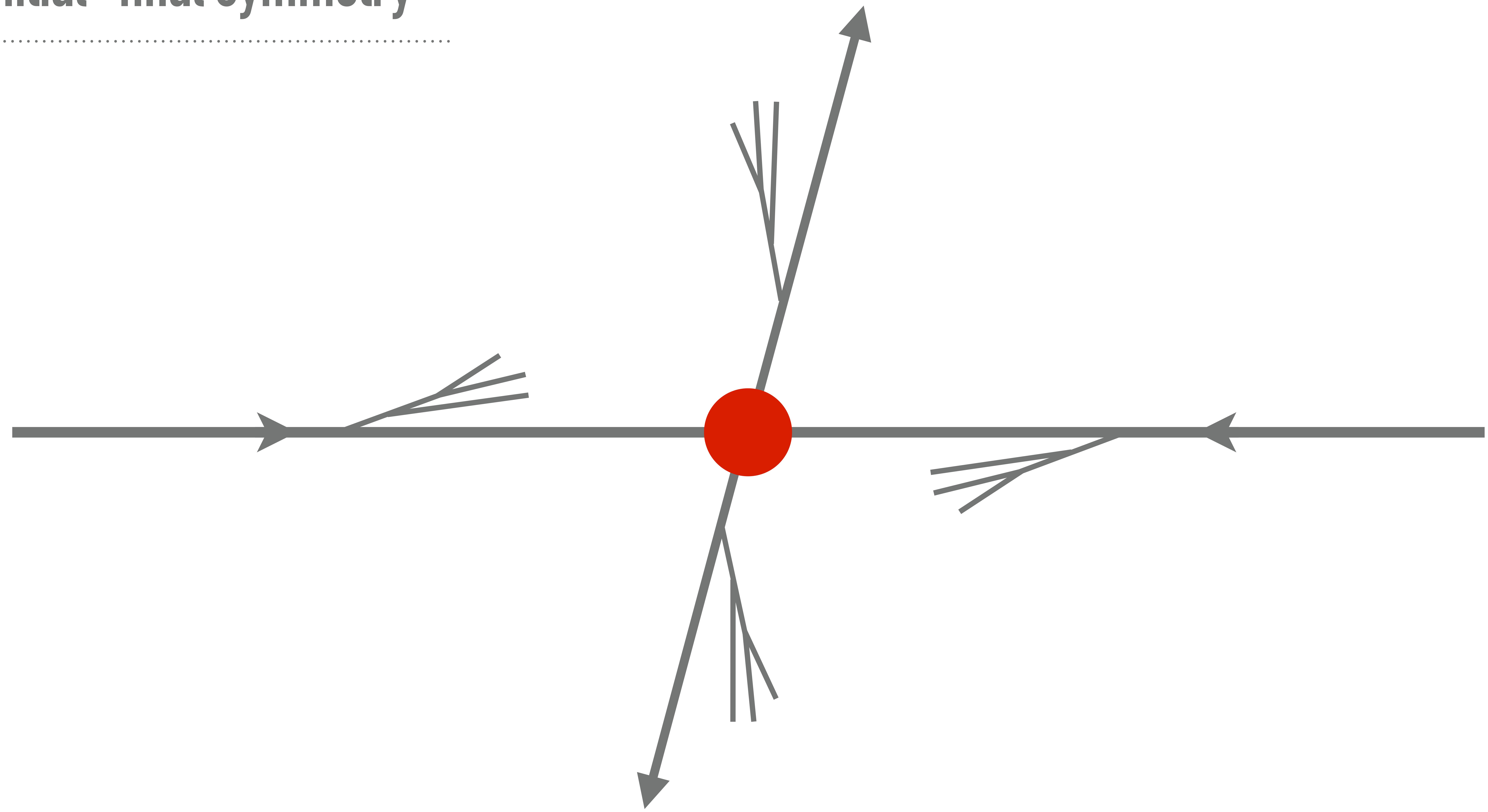
The difficulty is that there's a lot of it: how do we condense it down to something we can understand, measure & exploit quantitatively?

The Lund plane "construction" offers an approach that

- maps transparently onto physically meaningful kinematic regions
- is amenable to calculations in QCD (work in progress)
- provides a powerful input to machine learning, but also can be used almost as effectively in simpler multivariate frameworks.

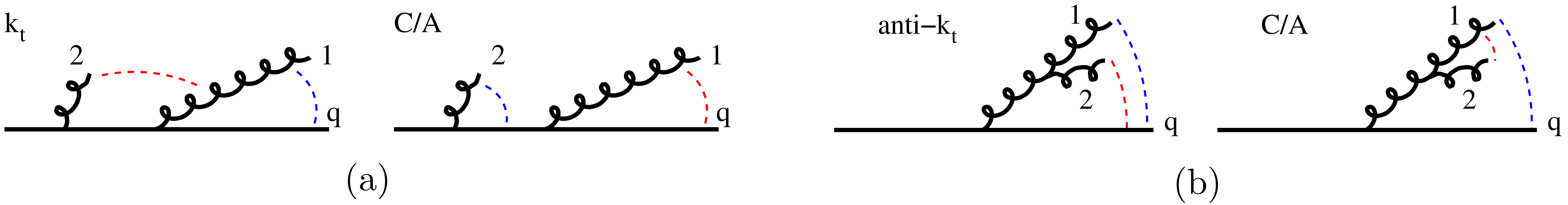
backup

Initial–final symmetry



choice of C/A for declustering

why the C/A algorithm?



why the C/A algorithm?

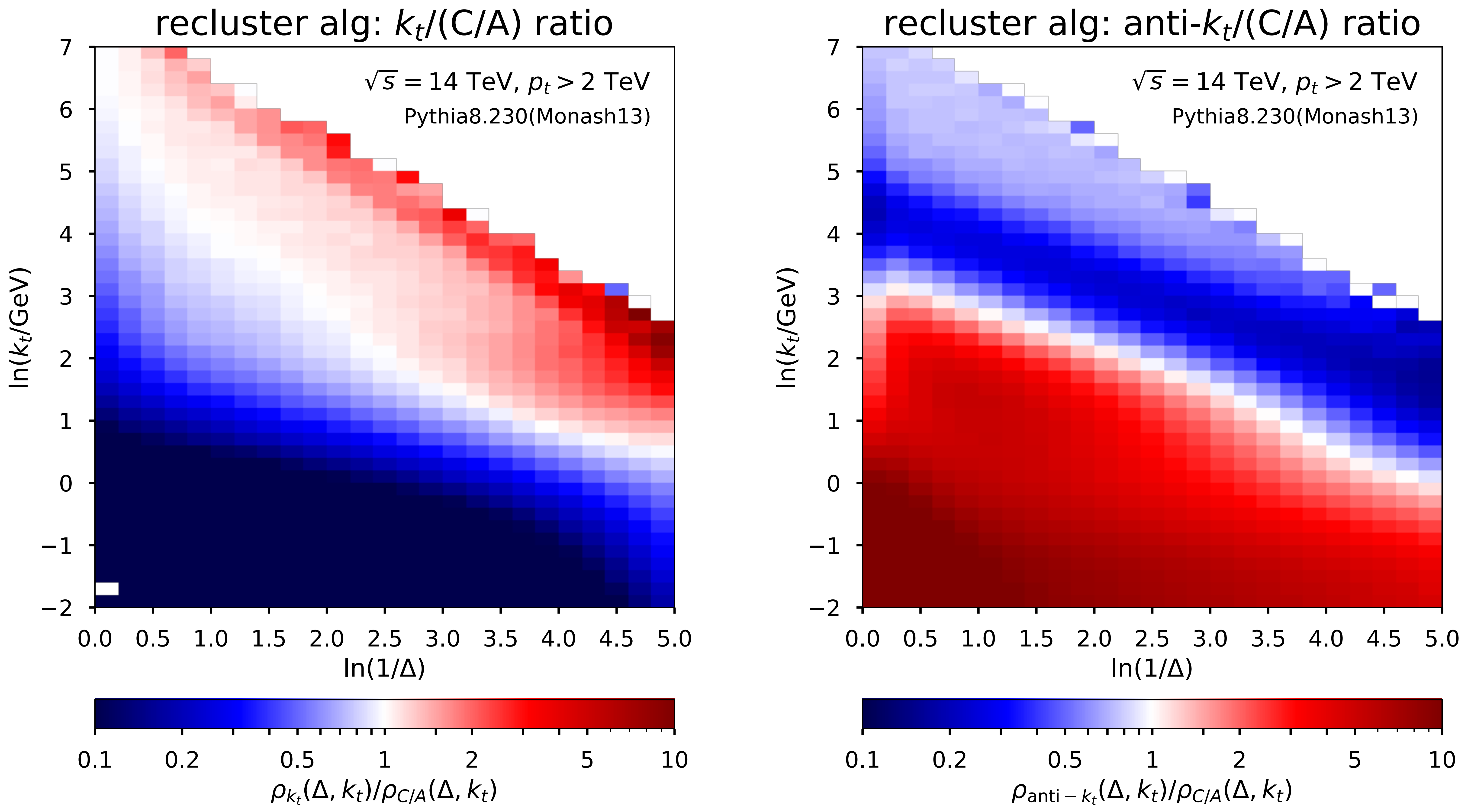


Figure 6: The $\rho(\Delta, k_t)$ results as obtained with k_t (left) and anti-k_t (right) declustering, normalised to the result for C/A declustering.

If you use jet algorithms other than C/A to provide the initial (de)clustering sequence, the jet algorithm itself introduces strong “unphysical” structure

why the C/A algorithm?

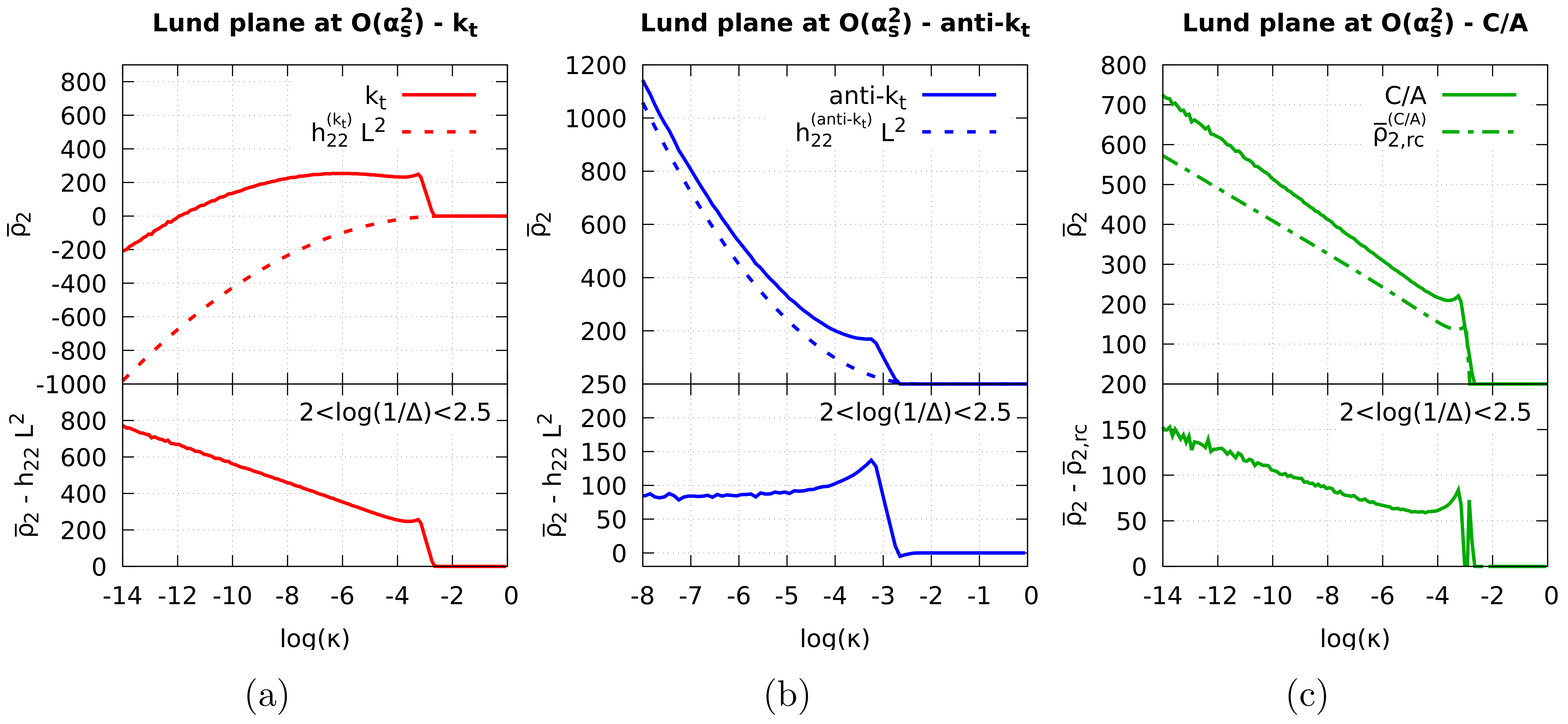


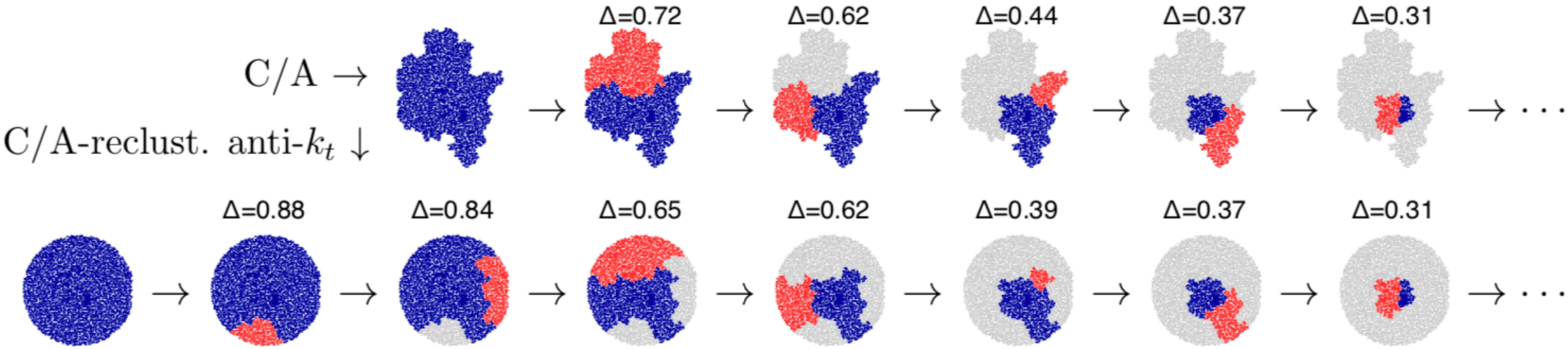
Figure 5: Evaluations with Event2 of the second-order contribution to the Lund plane, in a bin of $\ln 1/\Delta$, as a function of κ, for (de)clustering sequences obtained with the k_t, anti-k_t and C/A jet algorithms. In (a) and (b) the dashed line corresponds to the analytic expectations, Eqs. (2.9) and (2.10) for clustering-induced double-logarithms in the k_t and anti-k_t algorithms. In (c), for the C/A algorithm, which is seen here to be free of double logarithms, the dot-dashed line corresponds to the (single-logarithmic) running coupling correction, Eq. (2.11), illustrating that it dominates the second-order correction.

mathematically, the unphysical structure is driven by double logarithms, $(\alpha L^2)^n$ in the Lund-plane density.

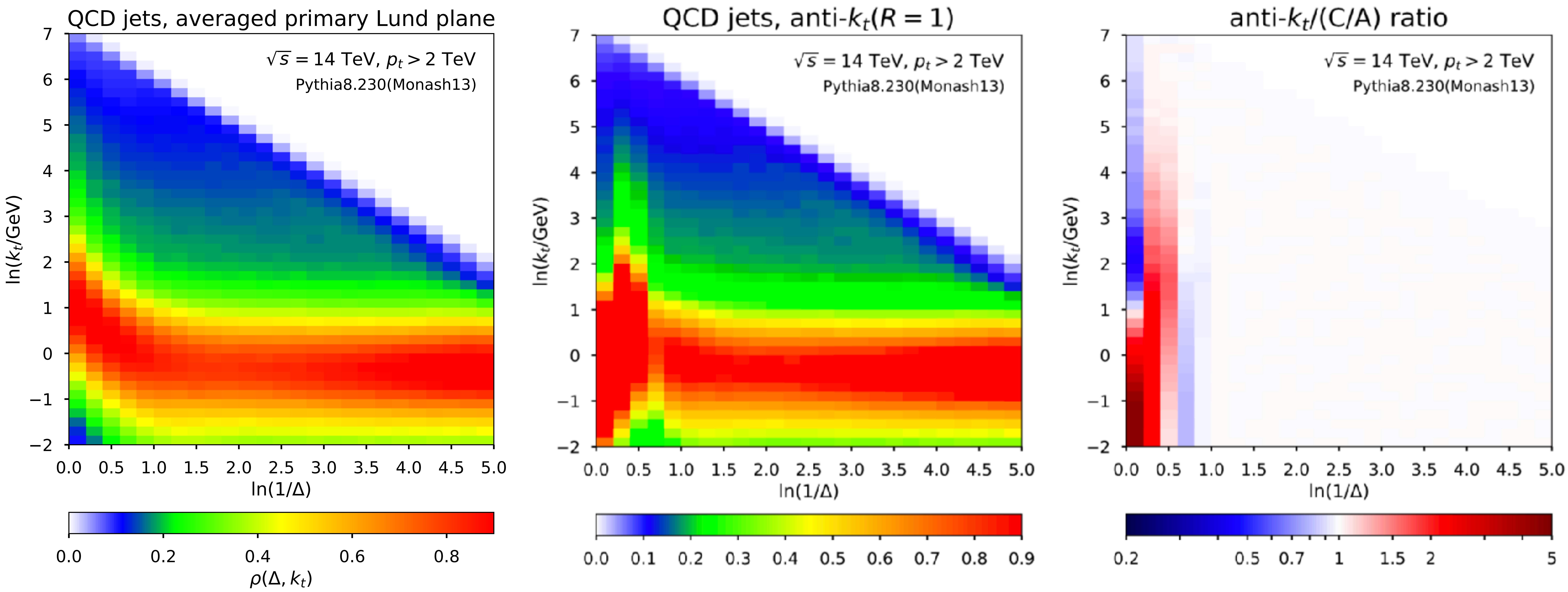
C/A only produces at most single logarithms, $(\alpha L)^n$

choice of original jet alg.

the declustering sequence from C/A v. anti-k_t starting points



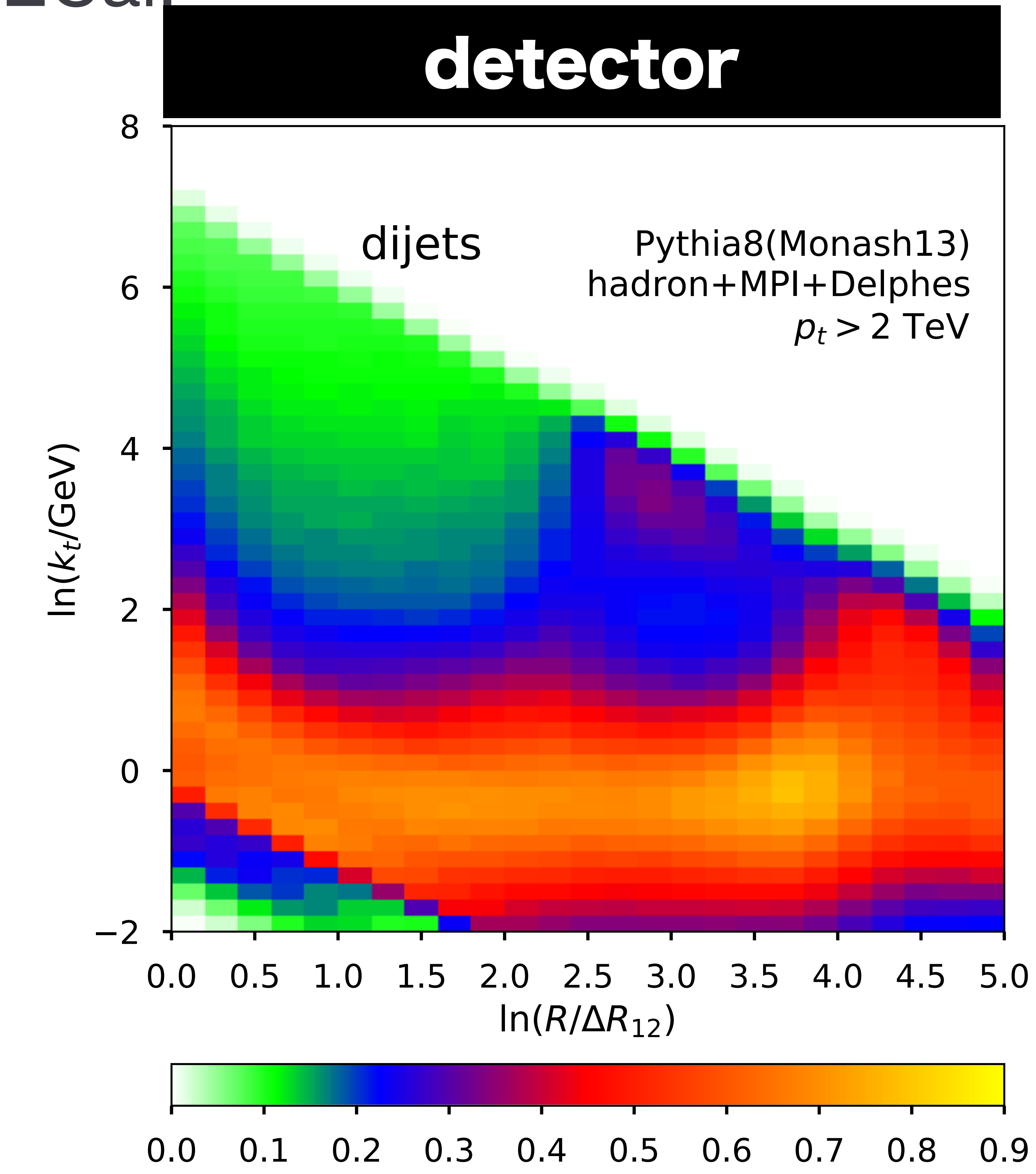
consequence for Lund plane density

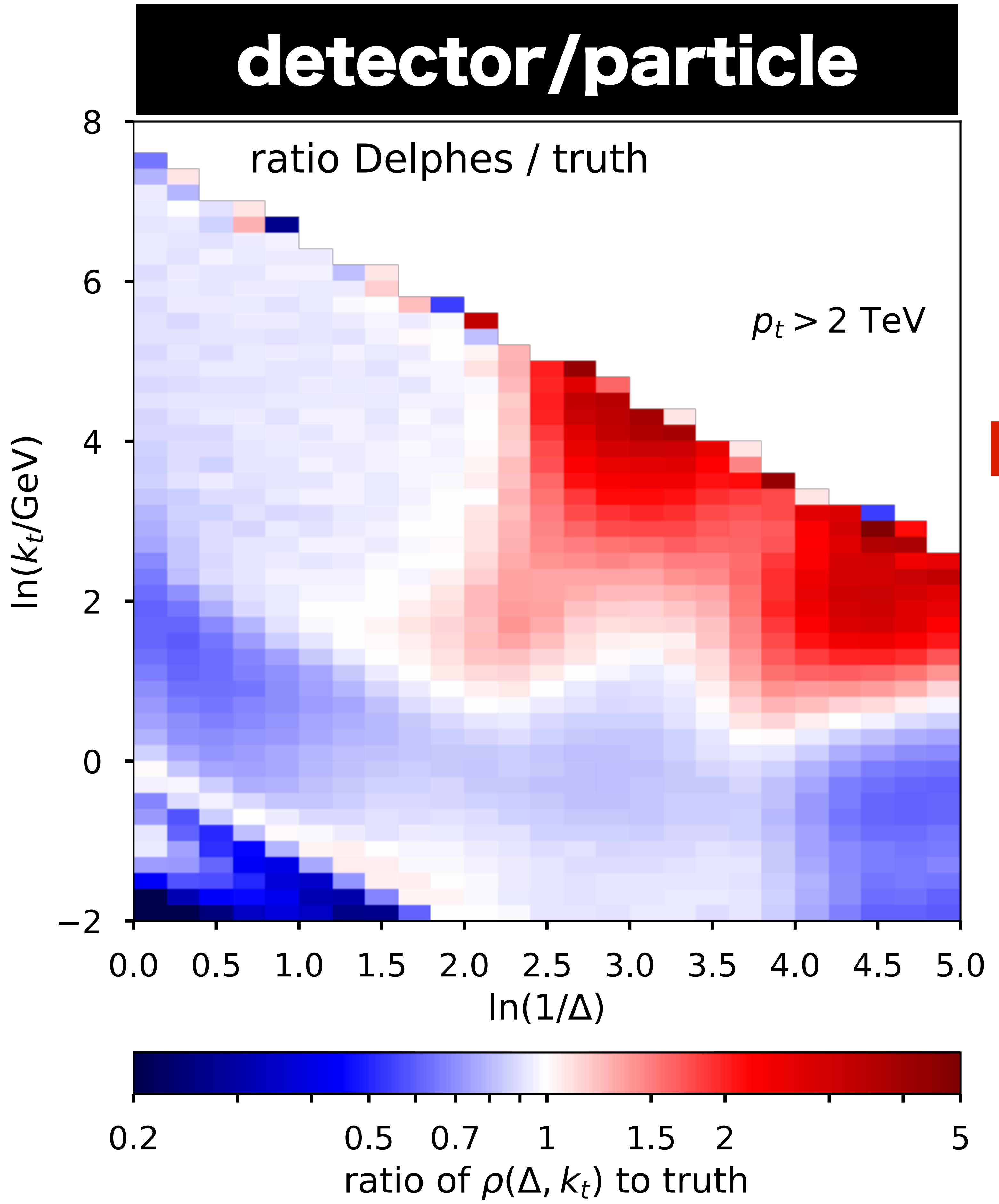


detector effects

Detector effects: with Delphes simulation (+ particle flow)

- Detector effects have significant impact on the Lund plane at angular scales below the hadronic calorimeter spacing.
- Two enhanced regions corresponding to resolution scale of HCal and ECal.





artefacts induced by ECal & HCal granularity

subjet-particle rescaling algorithm (SPRA)

Mitigate impact of detector granularity using a subjet particle rescaling algorithm:

- Recluster Delphes particle-flow objects into subjets using C/A with $R_h = 0.12$.
- Taking each subjet in turn, scale each PF charged-particle ($h^\pm$) and photon (γ) candidate that it contains by a factor f_1

$$f_1 = \frac{\sum_{i \in \text{subjet}} p_{t,i}}{\sum_{i \in \text{subjet}(h^\pm,\gamma)} p_{t,i}},$$

  and discard the other neutral hadron candidates.
- If subjet doesn't contain photon or charged-particle candidates, retain all of the subjet's particles with their original momenta.

Recluster the full set of resulting particles (from all subjets) into a single large jet and use it to evaluate the mass and Lund plane.

not a new idea!

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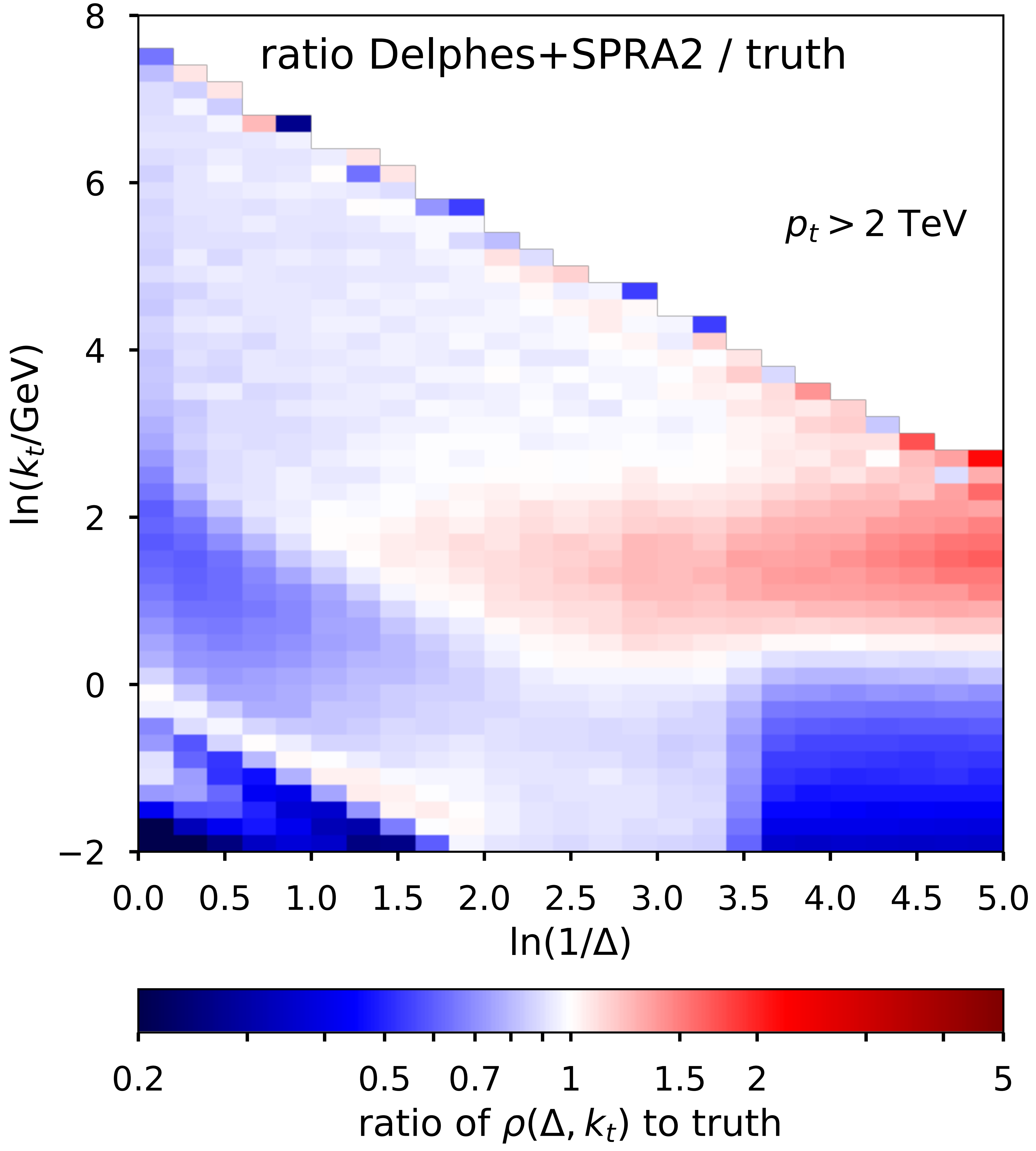
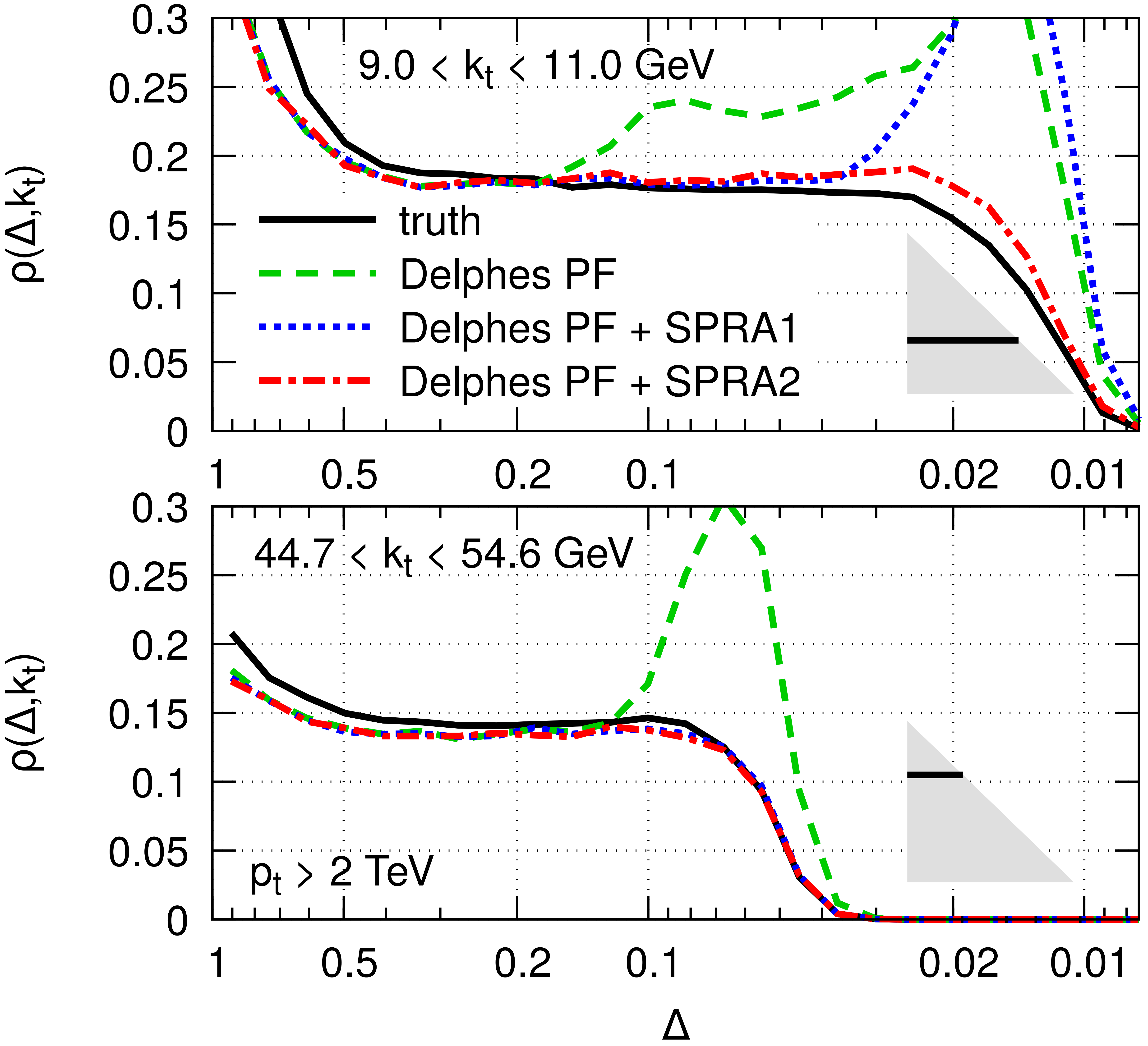
[89] **ATLAS** Collaboration, T. A. collaboration, *Jet mass reconstruction with the ATLAS Detector in early Run 2 data*, .

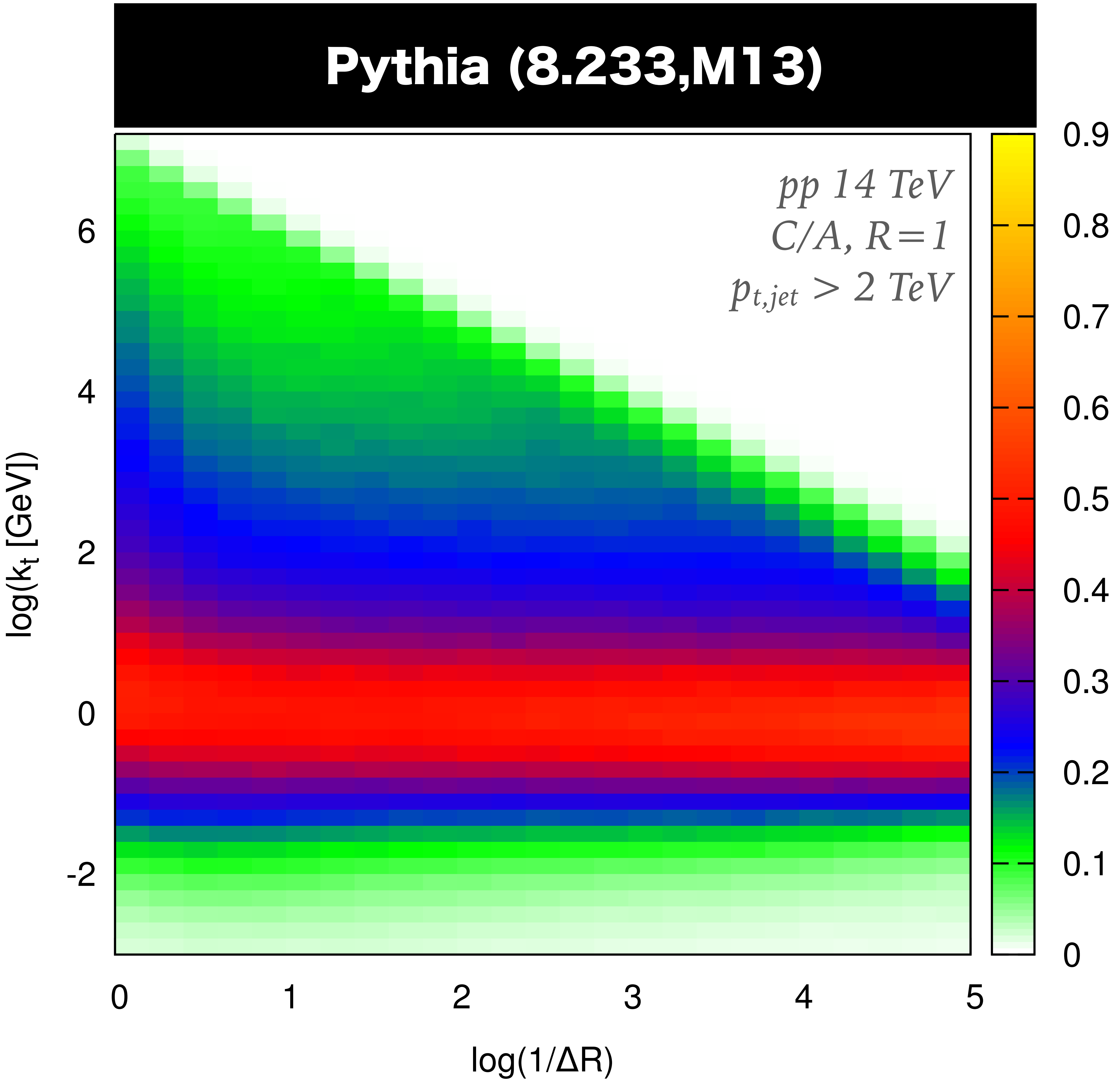
subjet-particle rescaling algorithm (SPRA)

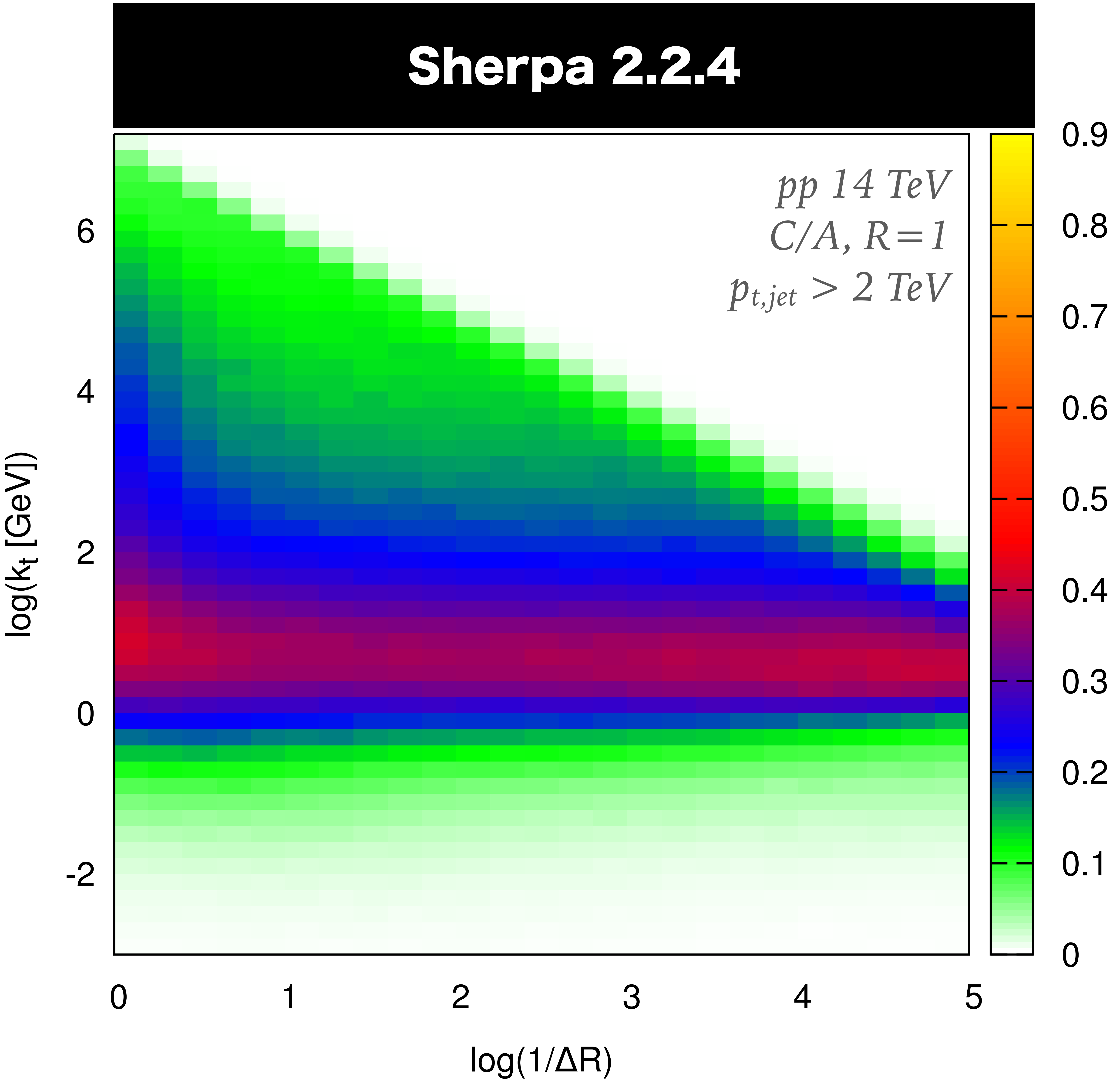




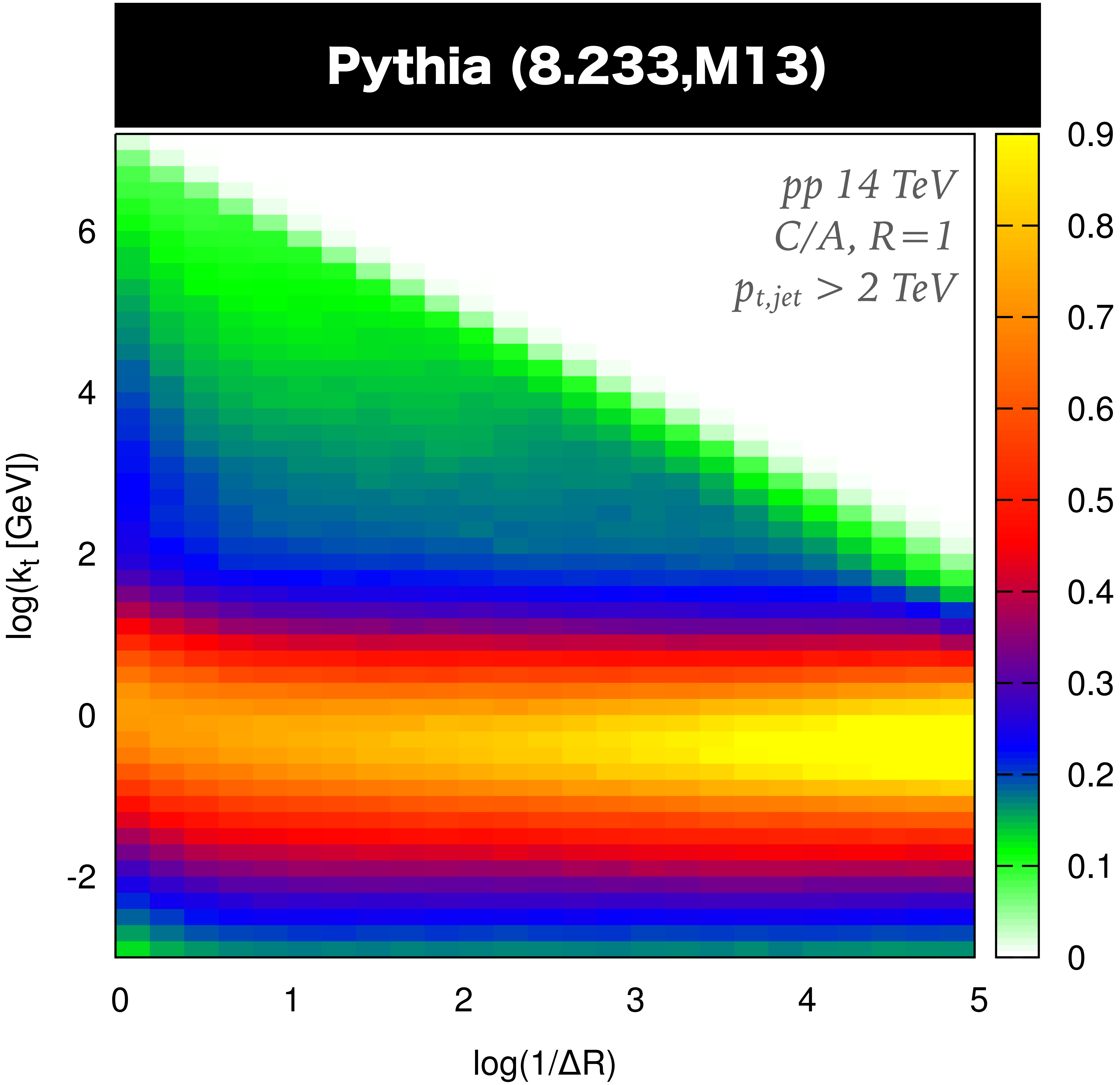
Pythia v. Sherpa

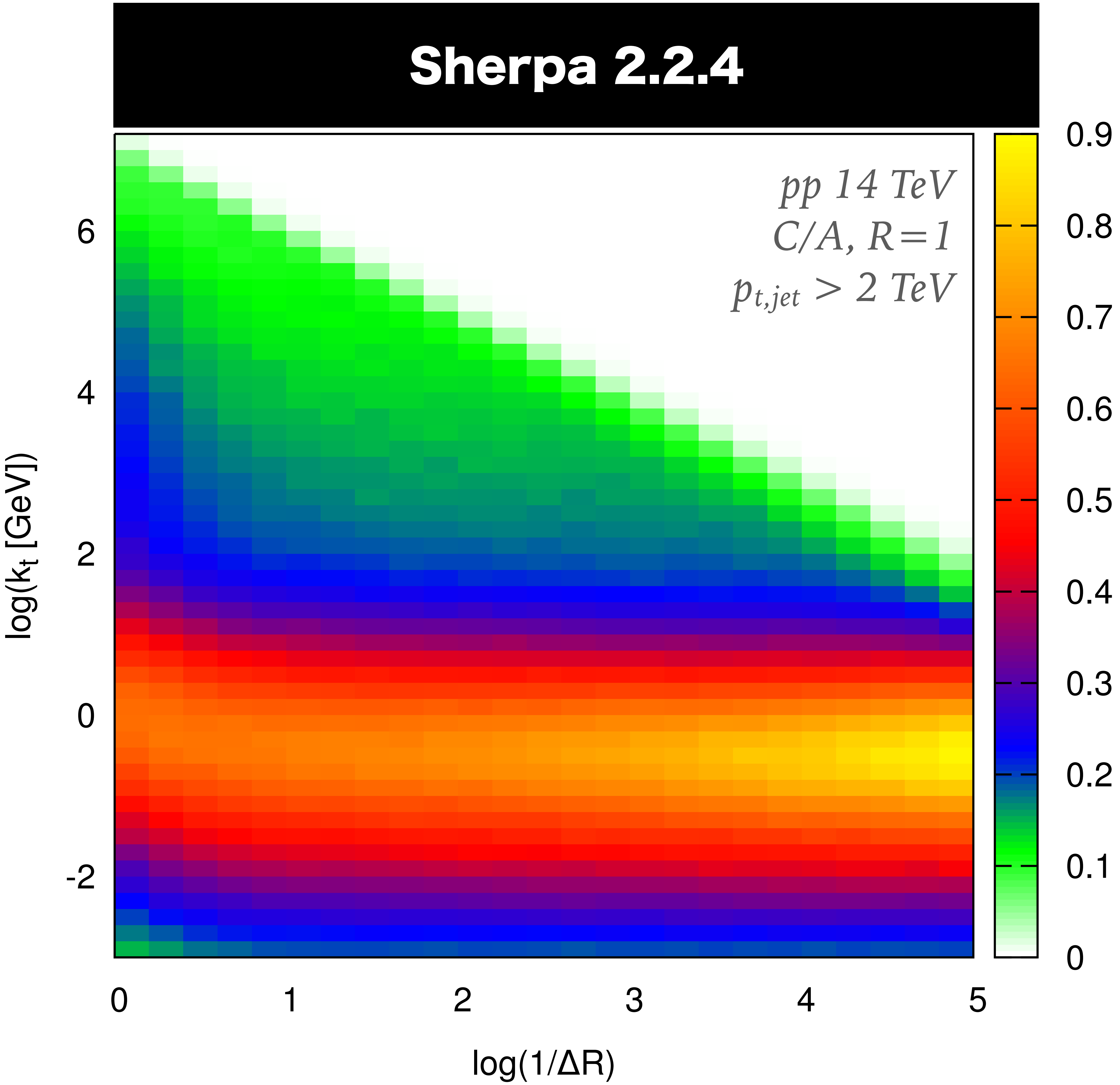
average pp Lund density: parton level





average pp Lund density: hadron level (no underlying event / MPI)





average pp Lund density: hadron level (with underlying event / MPI)