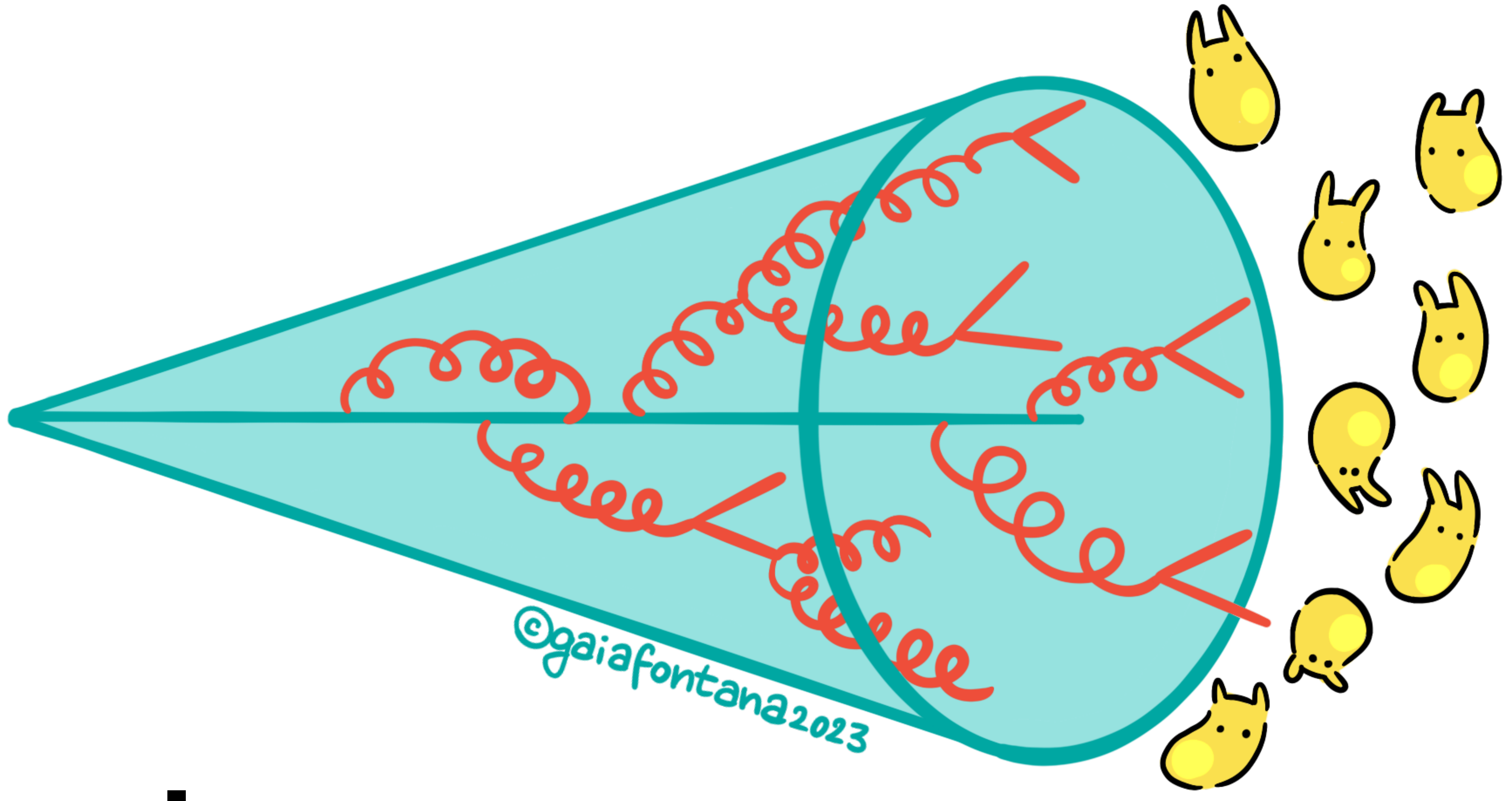
LHCPhysics

Belgrade, 22 - 26 May 2023



Jets and their substructure

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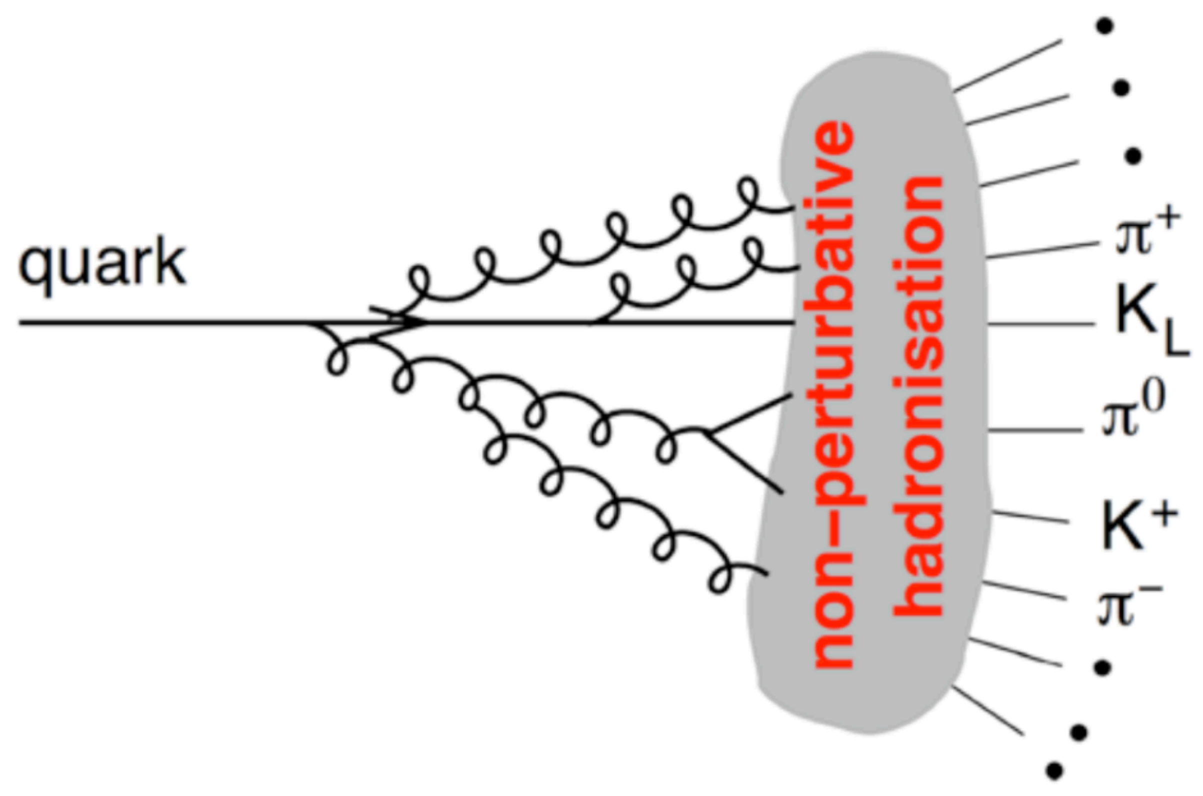
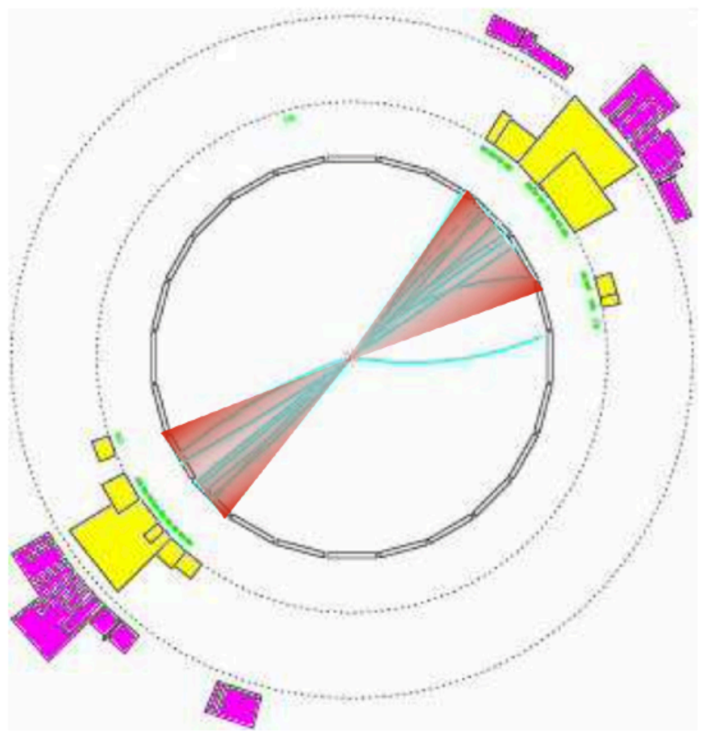
Swiss National Science Foundation

LHCP 2023, Belgrade, 22-26.05.2023

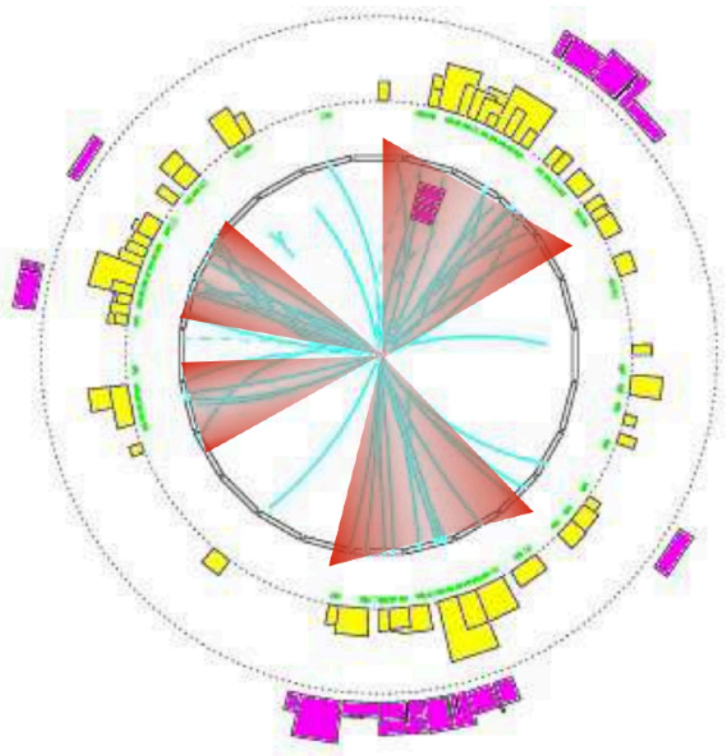
What are jets?

Naive definition: **collimated bunch of hadrons** flying roughly in the same direction





2 clear jets



3 jets?
or 4 jets?

Proper definition: a collection of hadrons defined by means of a **jet algorithm**

“*Jet [definitions] are legal contracts between theorists and experimentalists*”
MJ Tannenbaum

The k_t algorithm and its siblings

from Matteo Cacciari

$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p}) \frac{\Delta y^2 + \Delta \phi^2}{R^2} \qquad d_{iB} = p_{ti}^{2p}$$

p = 1 k_t algorithm

S. Catani, Y. Dokshitzer, M. Seymour and B. Webber, Nucl. Phys. B406 (1993) 187
S.D. Ellis and D.E. Soper, Phys. Rev. D48 (1993) 3160

p = 0 Cambridge/Aachen algorithm

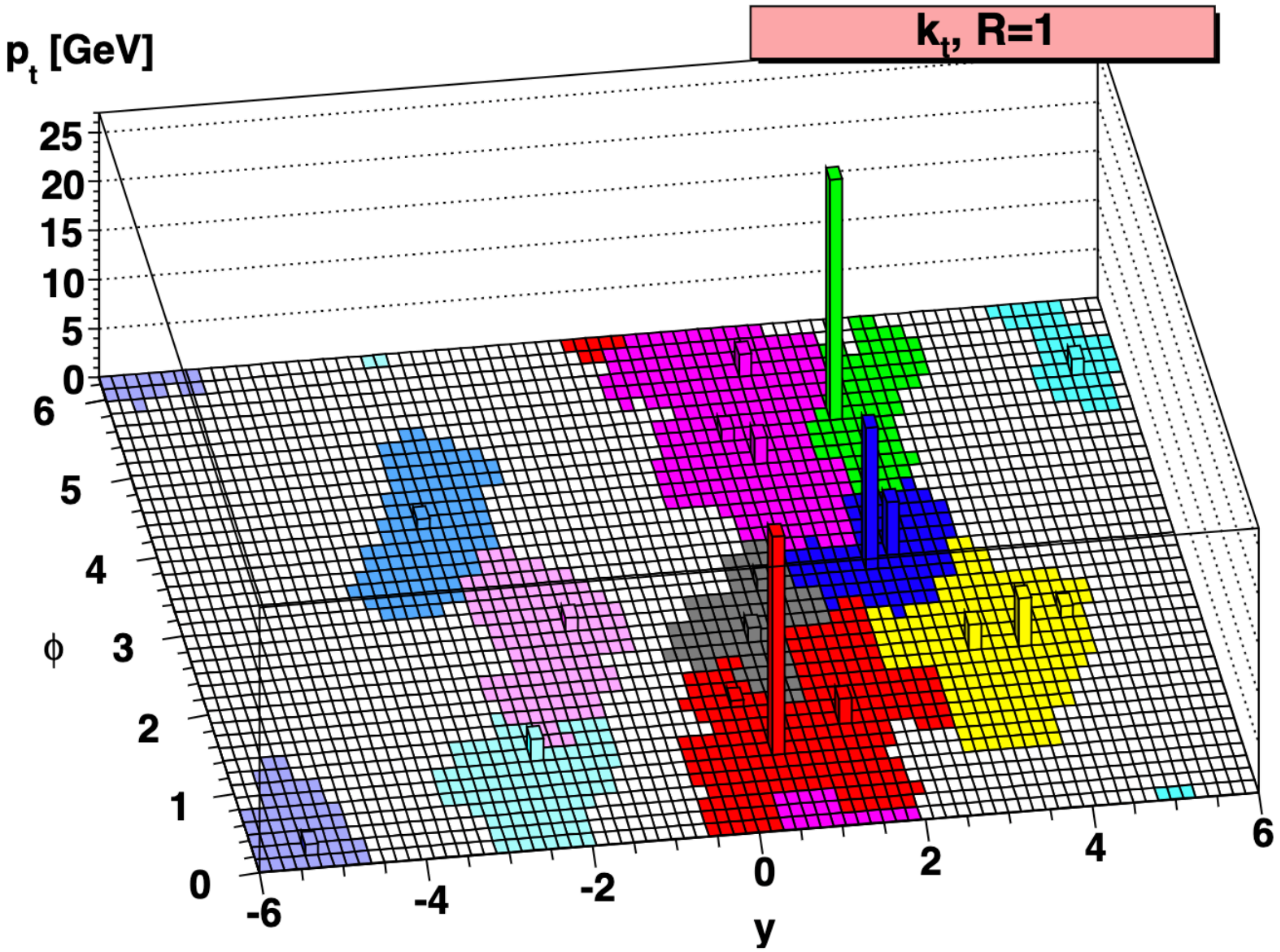
Y. Dokshitzer, G. Leder, S.Moretti and B. Webber, JHEP 08 (1997) 001
M.Wobisch and T.Wengler, hep-ph/9907280

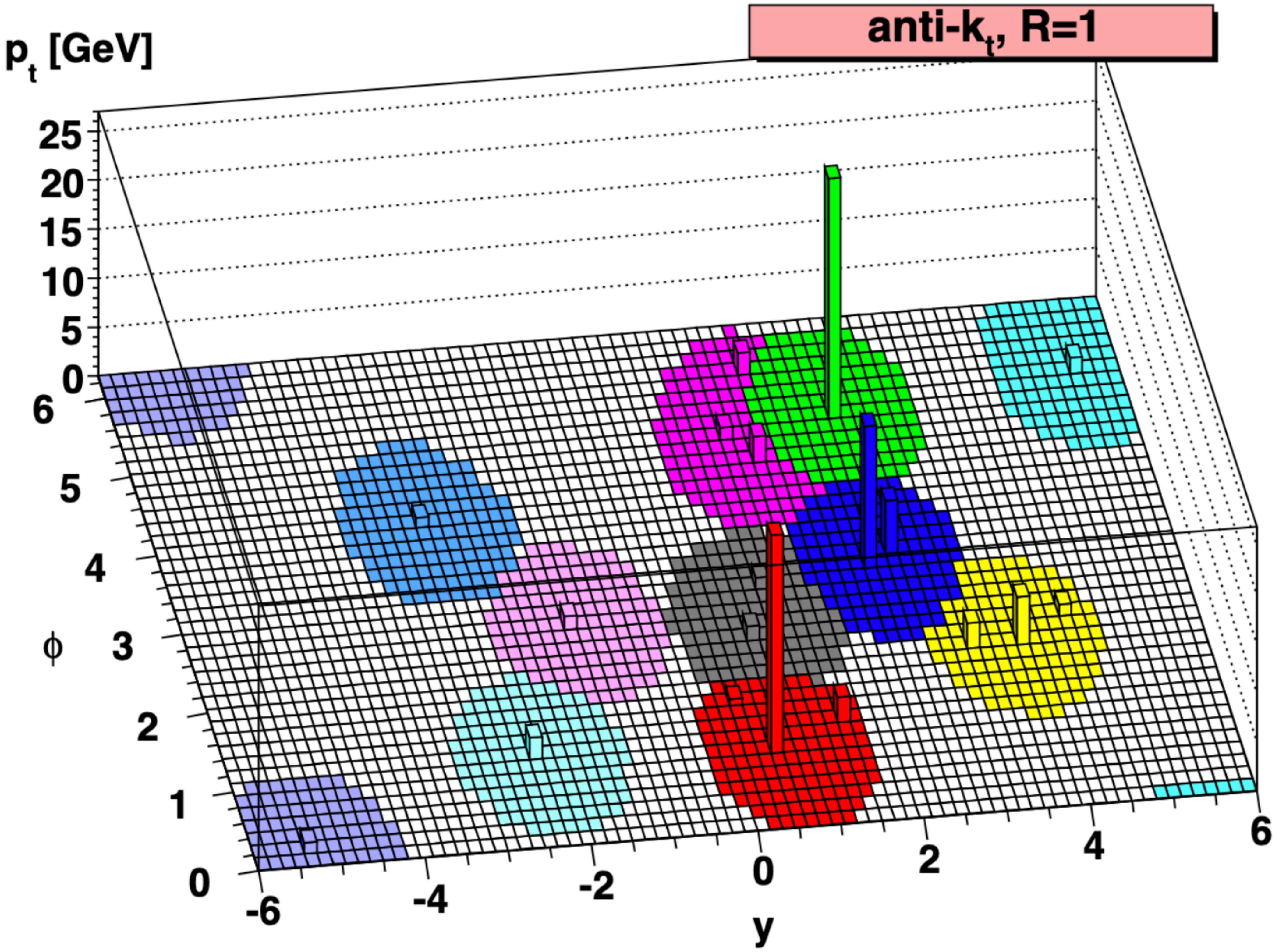
p = -1 **anti-k_t algorithm**

MC, G. Salam and G. Soyez, arXiv:0802.1189

NB: in anti-kt pairs with a **hard** particle will cluster first: if no other hard particles are close by, the algorithm will give **perfect cones**

$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p}) \frac{\Delta y^2 + \Delta\phi^2}{R^2} \qquad d_{iB} = p_{ti}^{2p}$$





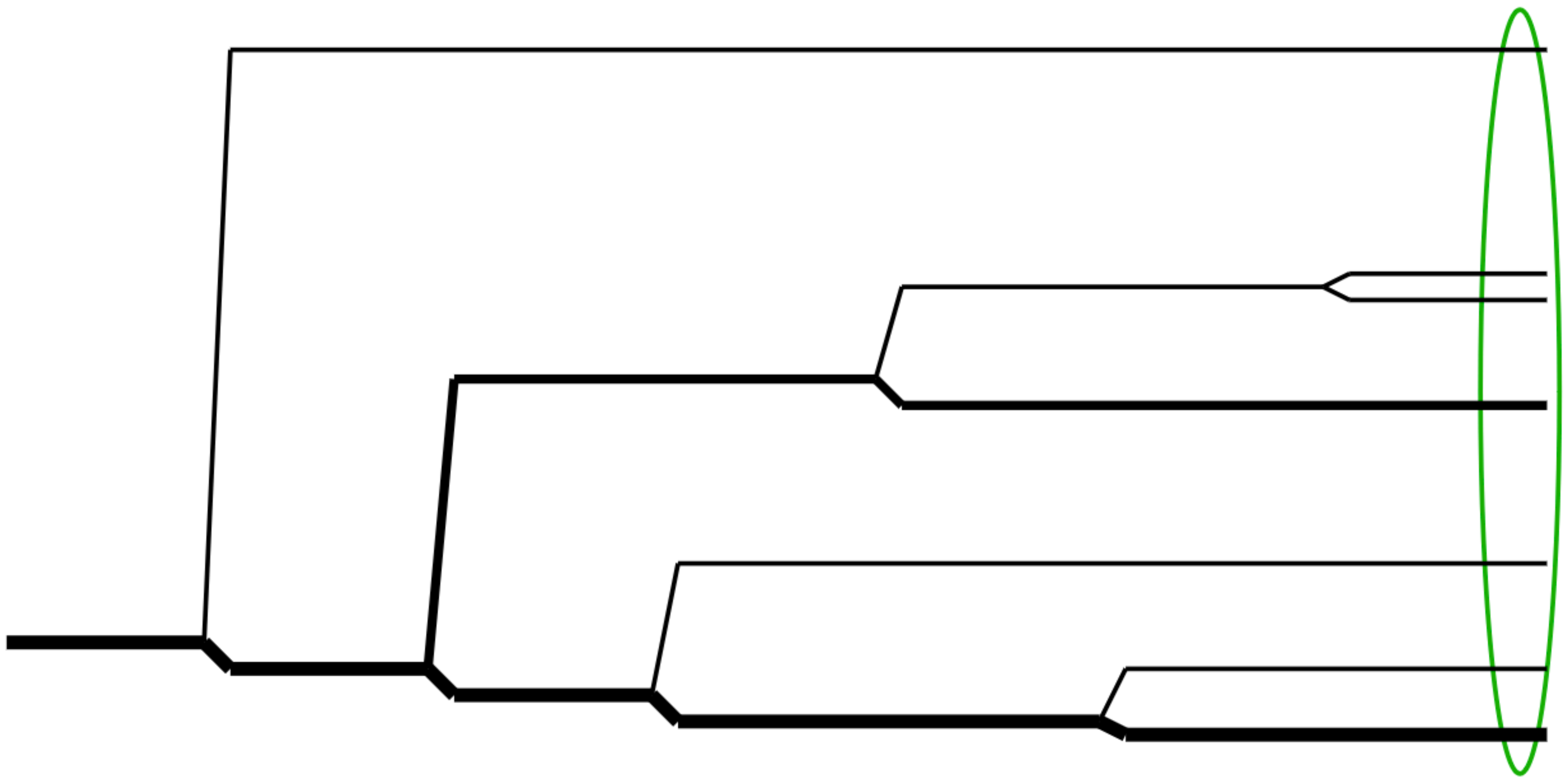
p = 1 k_t algorithm

p = -1 anti-k_t algorithm

$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p}) \frac{\Delta y^2 + \Delta\phi^2}{R^2} \qquad d_{iB} = p_{ti}^{2p}$$

p = 0 Cambridge/Aachen algorithm

Cambridge/Aachen: iteratively recombine the closest pair

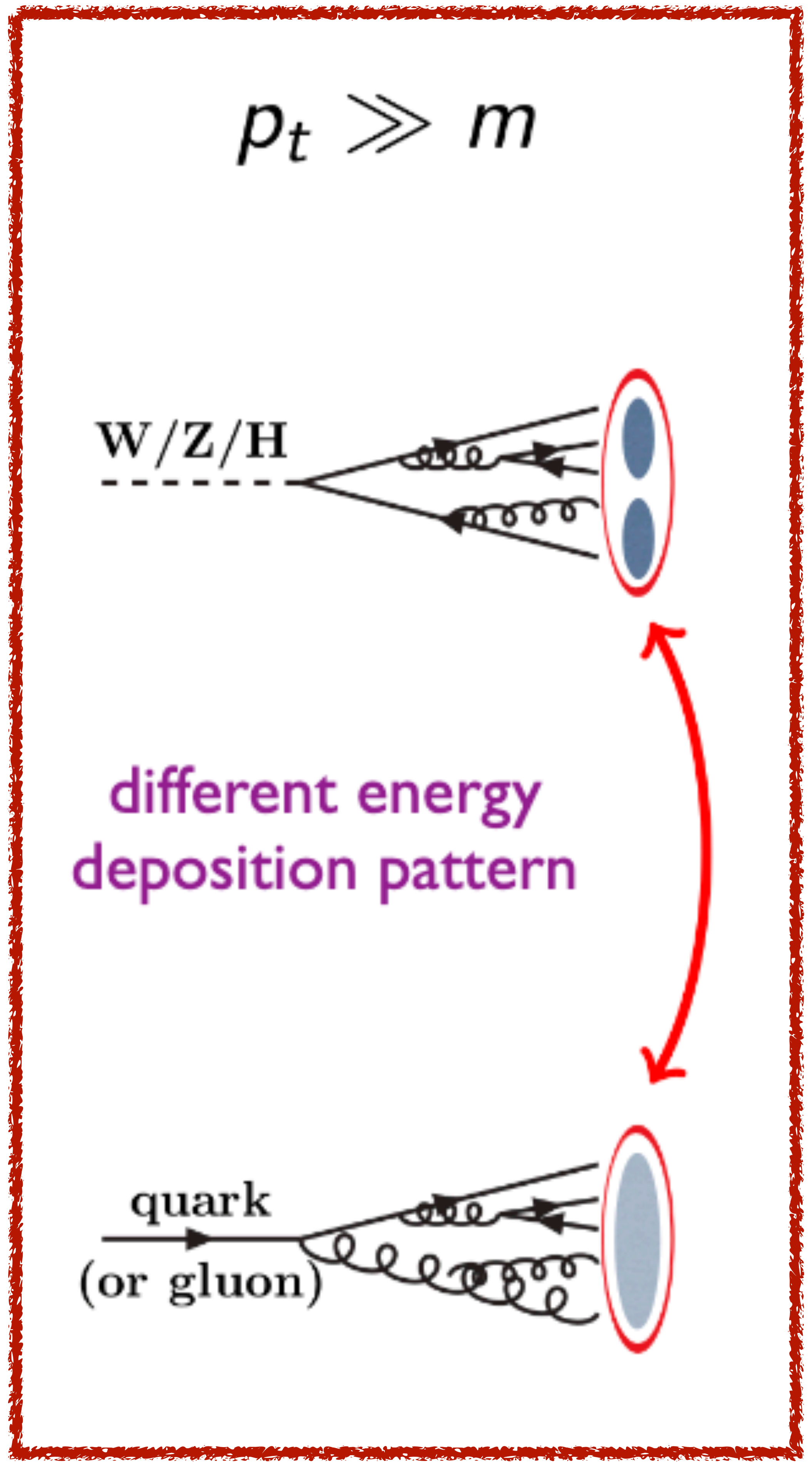


Particularly useful when looking “inside” the jet…

Jet substructure in one slide

from Simone Marzani

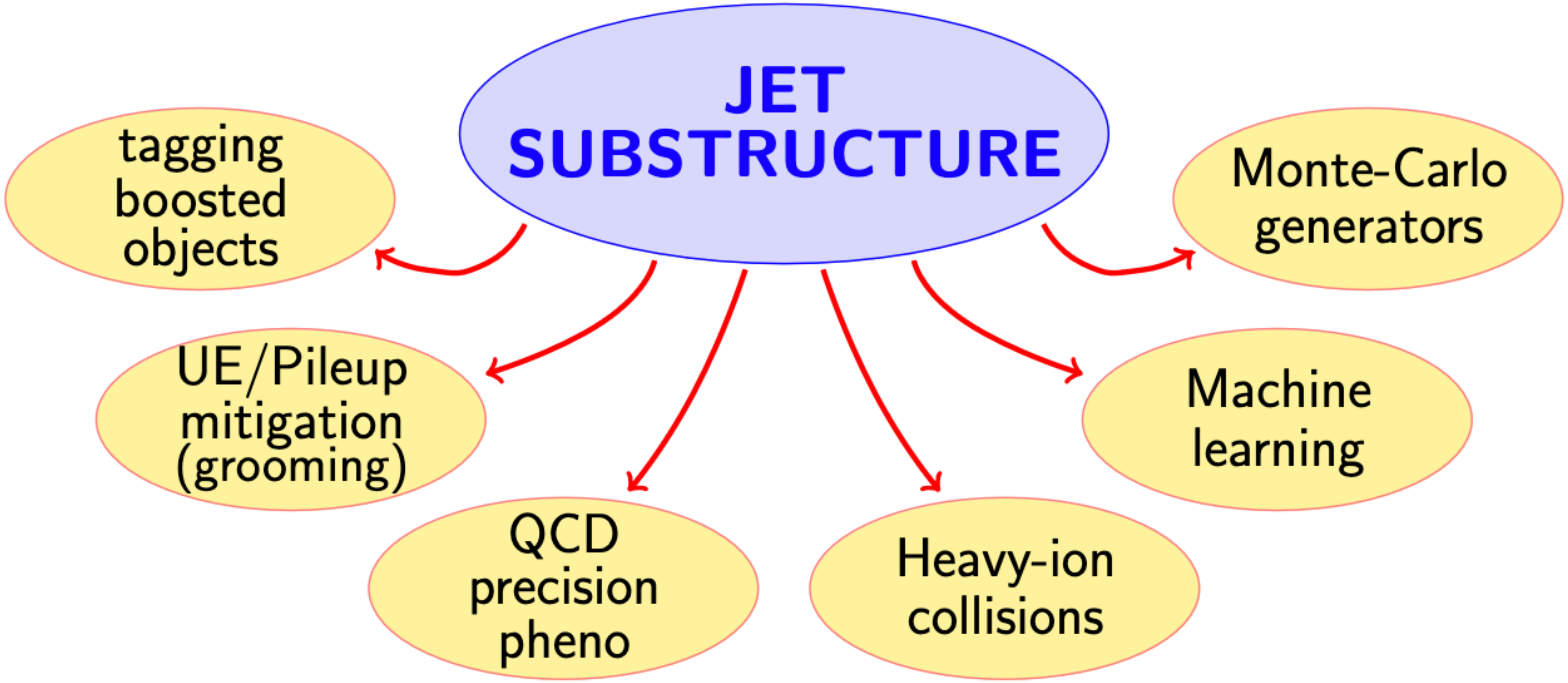
- the two major goals of the LHC
- search for new particles
- characterise the particles we know
- jets can be formed by QCD particles but also by the decay of massive particles (if they are sufficiently boosted)
- how can we distinguish signal jets from background ones?



- the final energy deposition pattern is influenced by the originating splitting
- hard vs soft translates into 2-prong vs 1-prong structure
- picture is mudded by many effects (hadronisation, underlying event, pileup)
- two-step procedure:
  - grooming: clean the jets up by removing soft radiation
  - tagging: identify the features of hard decays and cut on them

Disclaimer

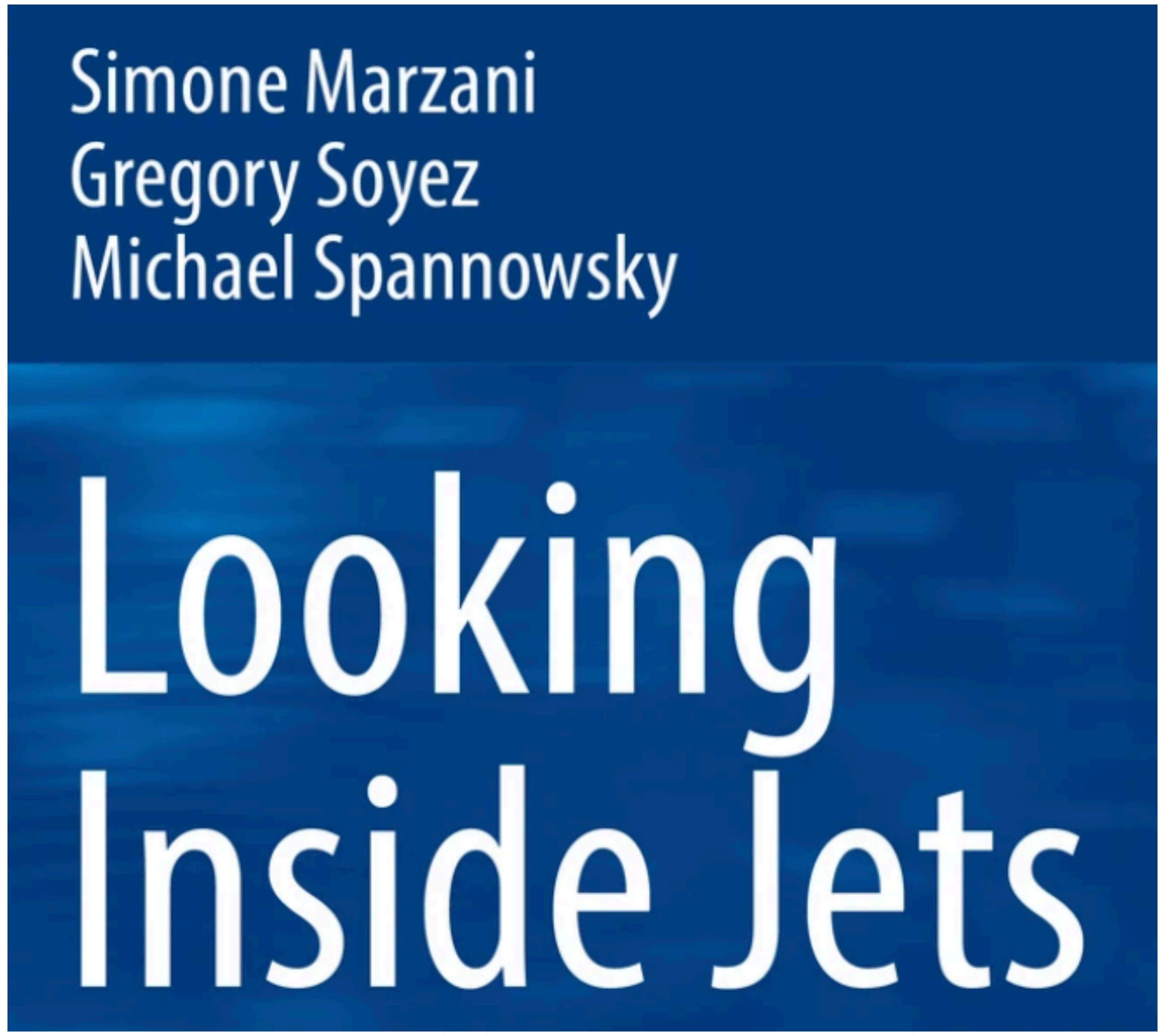
Substructure of jets is a very broad topic, with a lot of recent developments …



from Gregory Soyez

Disclaimer

… a standard topic, with a dedicated textbook!



https://link.springer.com/book/10.1007/978-3-030-15709-8

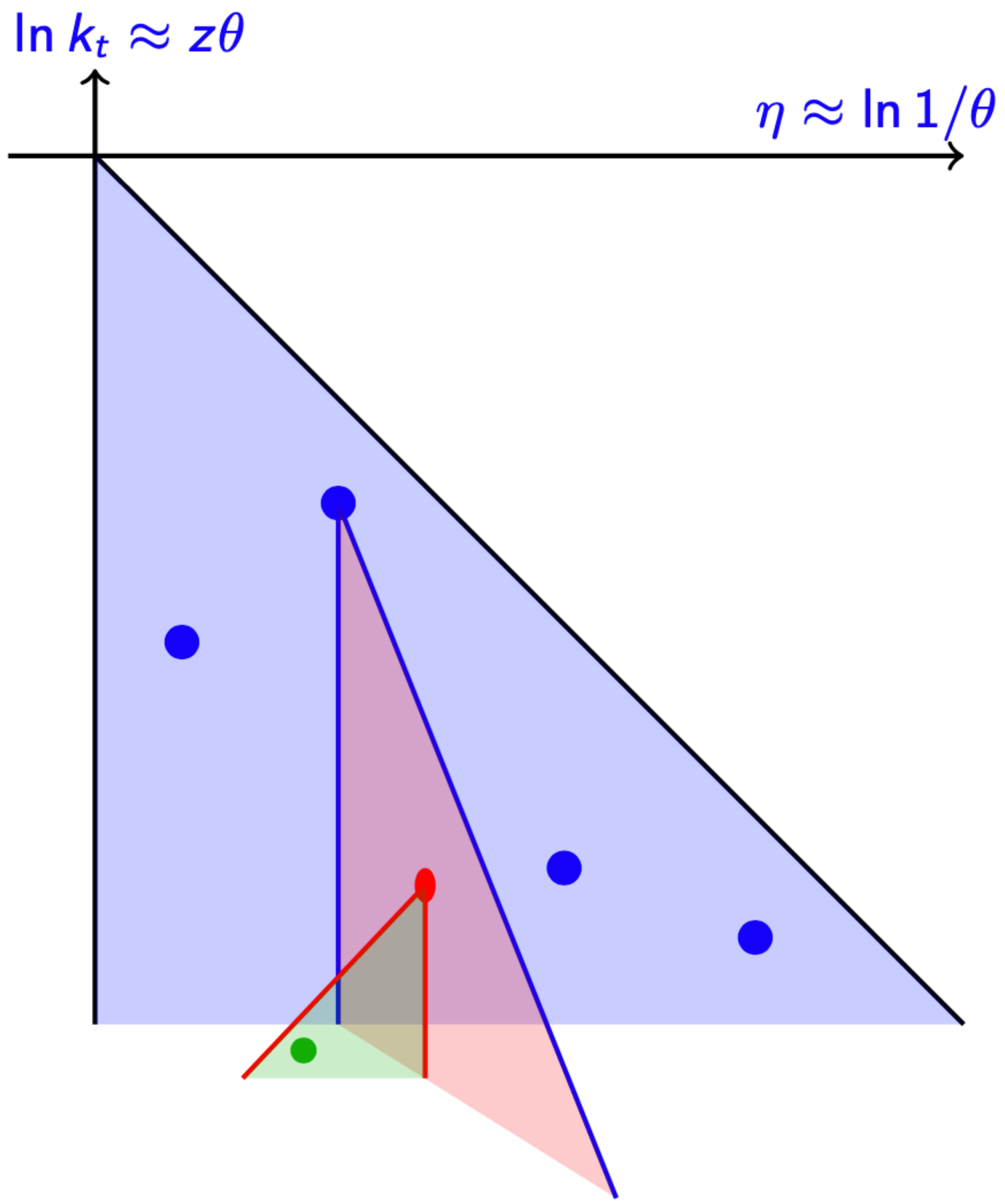
Up-to-date version on the arXiv (1901.10342)

Disclaimer

I will focus on a single tool, adopted in a wide range of applications,

the **Lund plane** [Z. Phys. C43 (1989) 625]

a way of depicting the pattern of QCD radiation, inside a jet or in the whole event



In particular, I will show some examples of:

1) analytic calculations

2) machine learning techniques

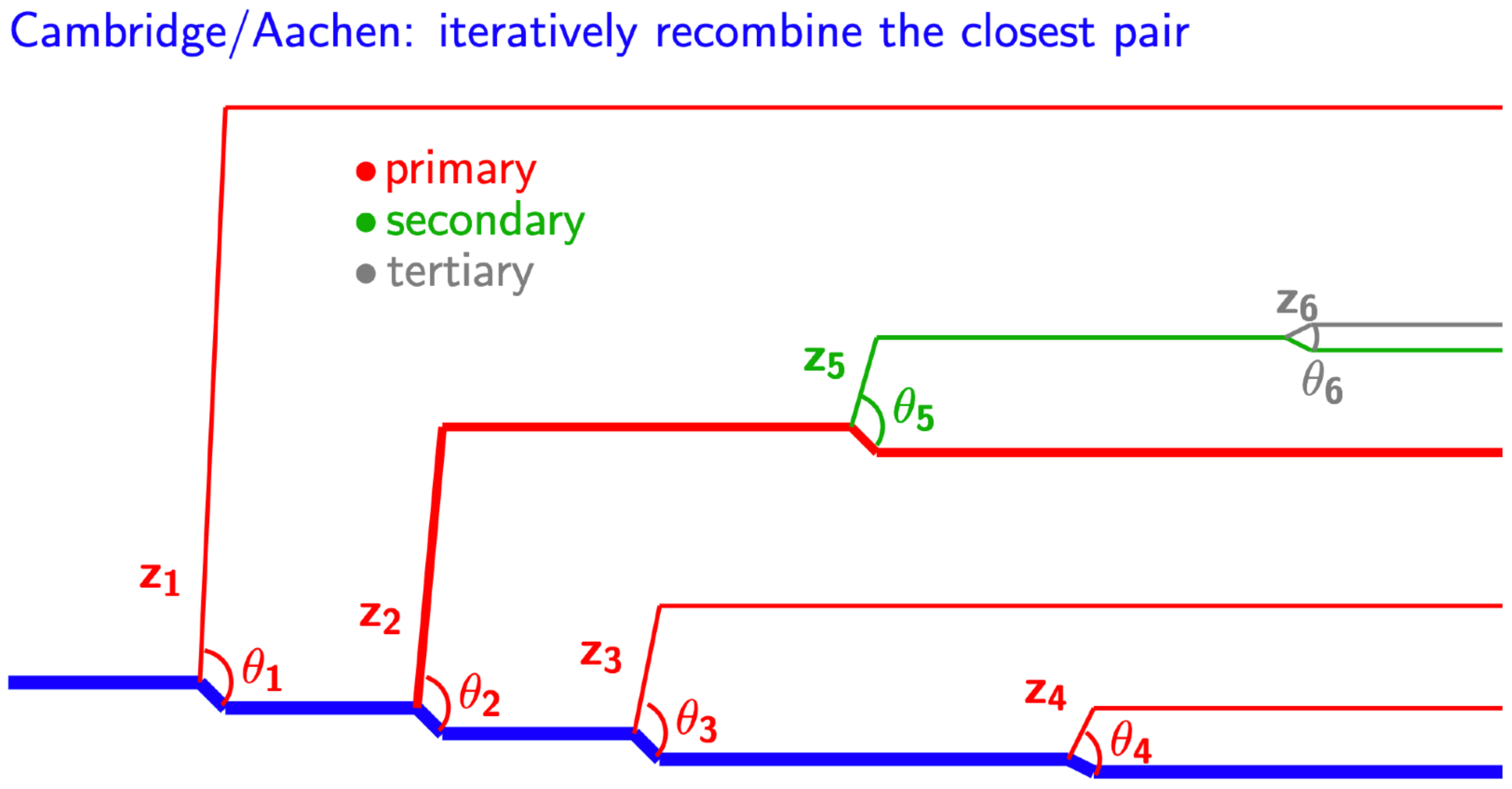
3) heavy quark studies

based on the Lund plane.

Let’s first define it!

The Lund jet plane

[Dreyer, Salam, Soyez (1807.04758)]

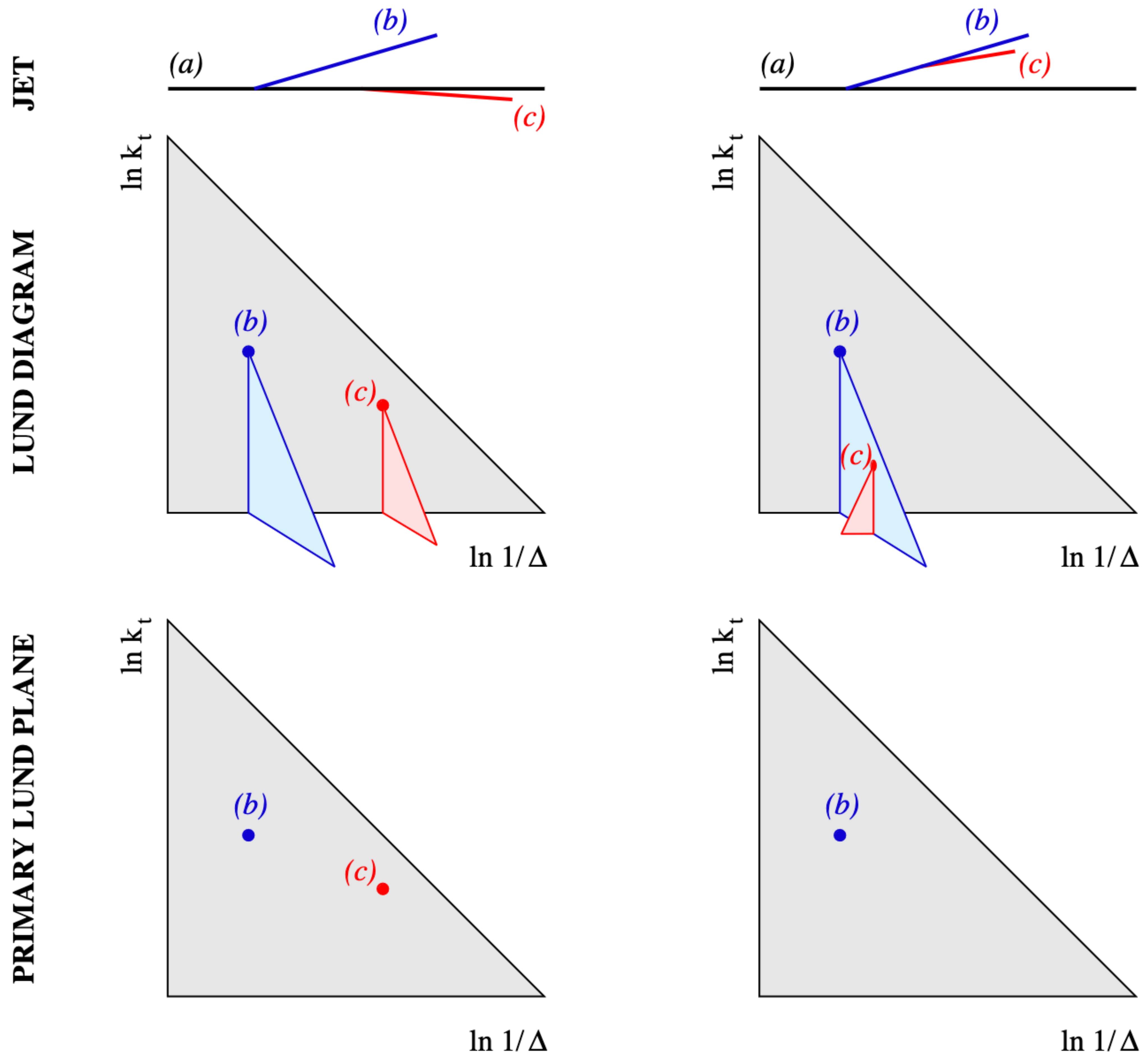


For each step of the declustering, record the variables:

$$\Delta_{ab} = \sqrt{(y_a - y_b)^2 + (\phi_a - \phi_b)^2}, \, k_t = p_{tb}\Delta_{ab}$$

and add a point in the primary, secondary, etc. planes.

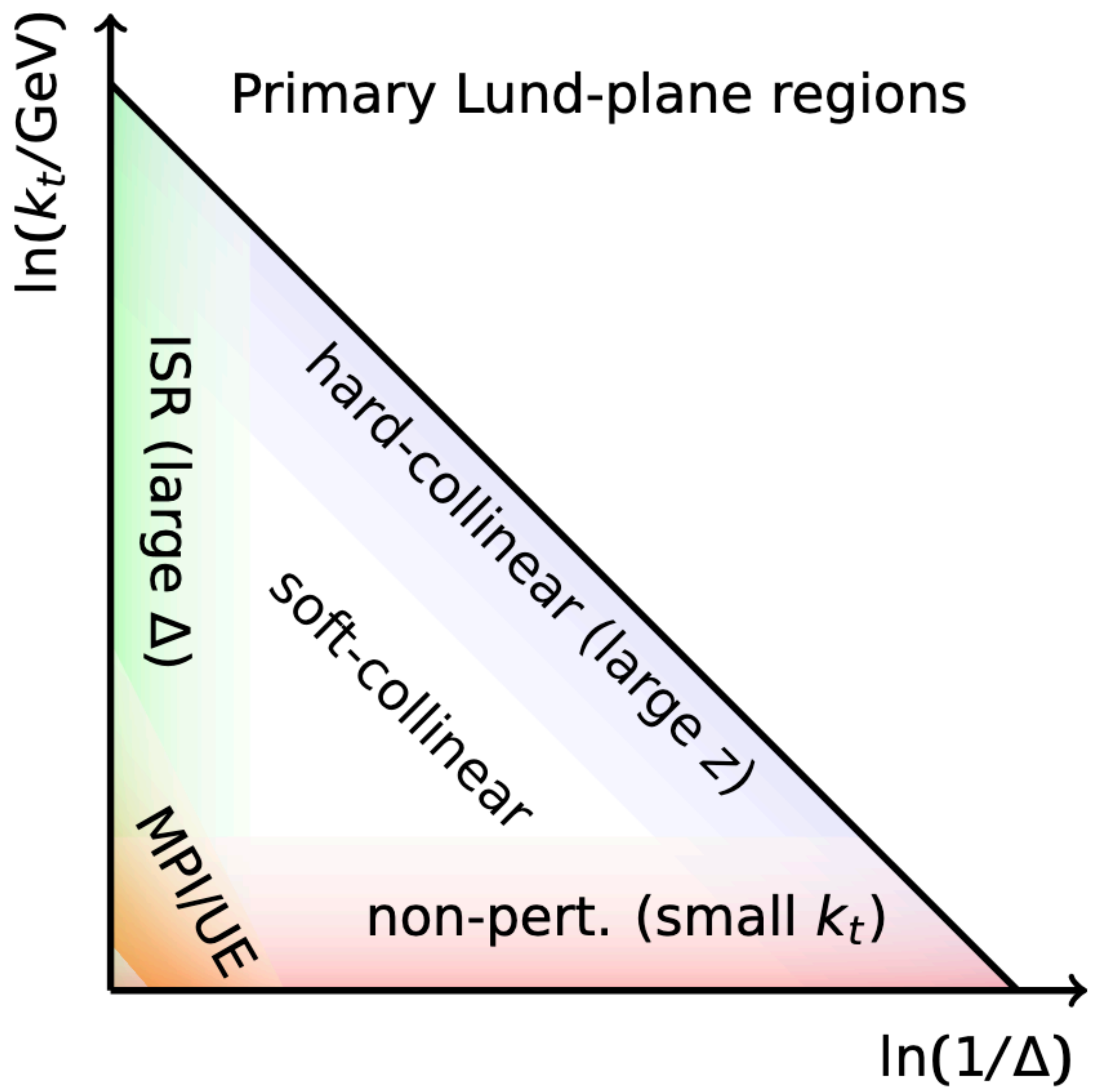
We associate a **kinematic structure to a high-energy jet.**

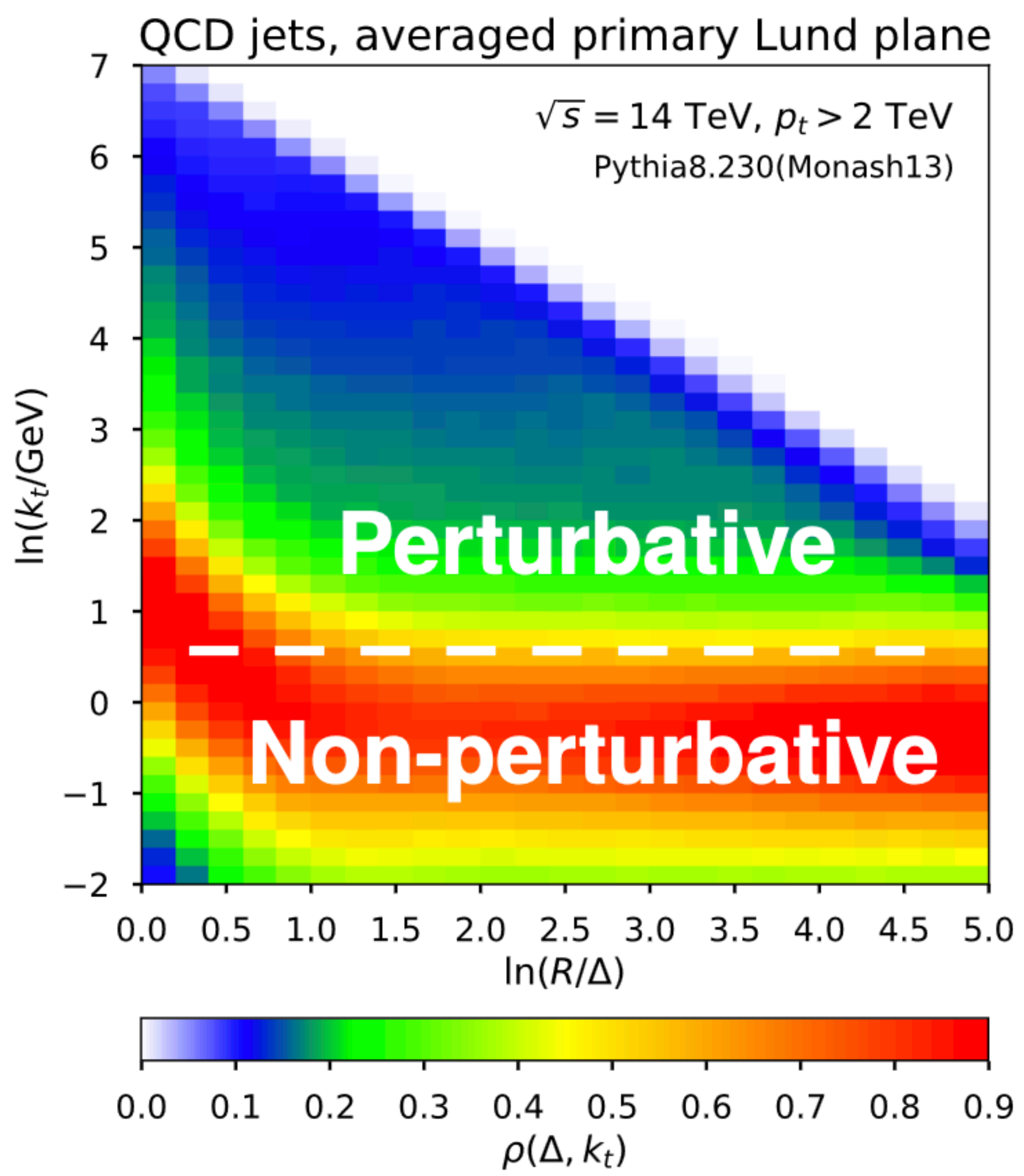


Lund plane & analytics

Lund jet plane density

Simplest observable, defined on the primary Lund plane:





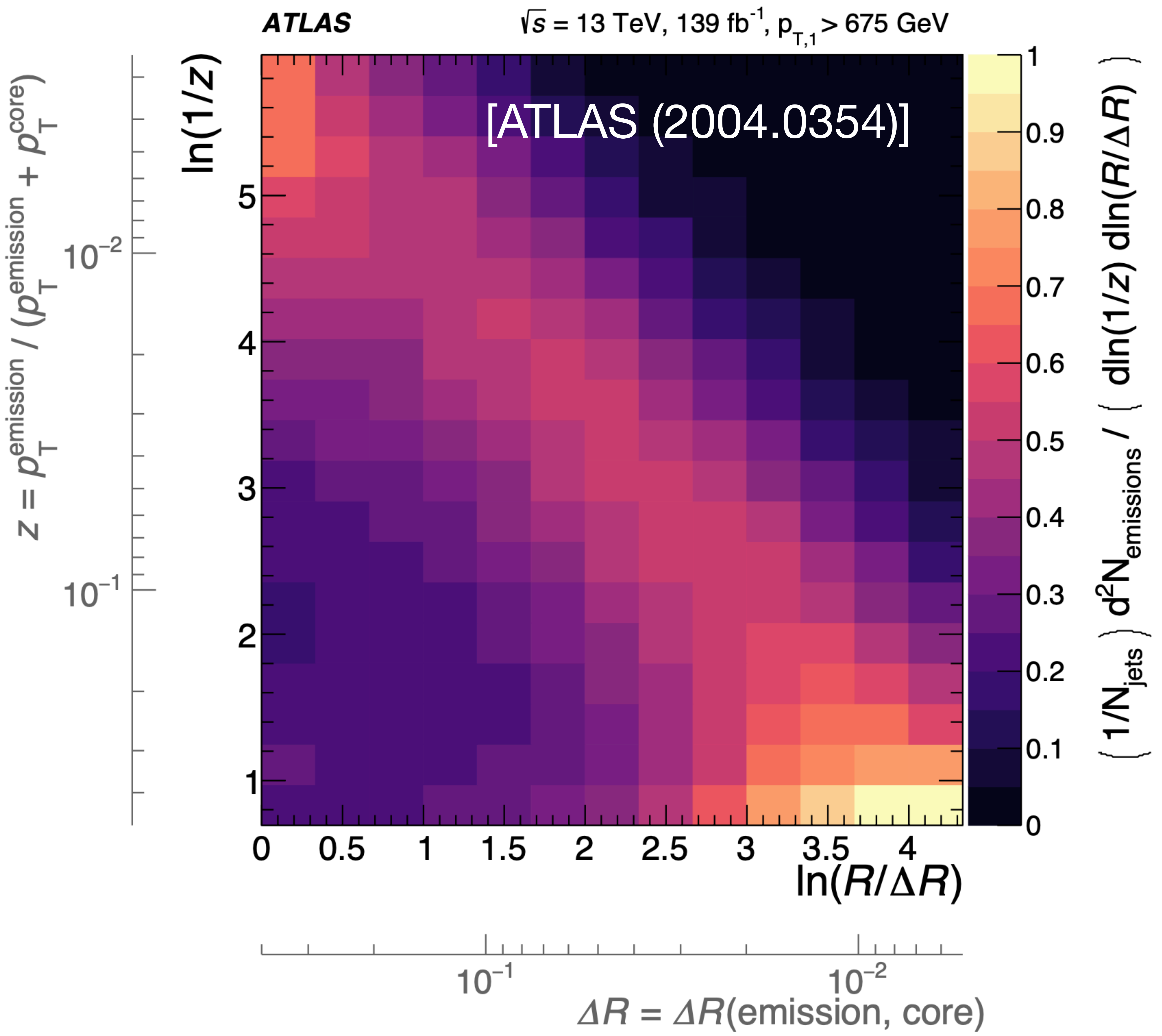
$$\rho(\Delta, k_t) = \frac{1}{N_{jet}} \frac{dn_{\text{emission}}}{d\ln k_t \, d\ln 1/\Delta}$$

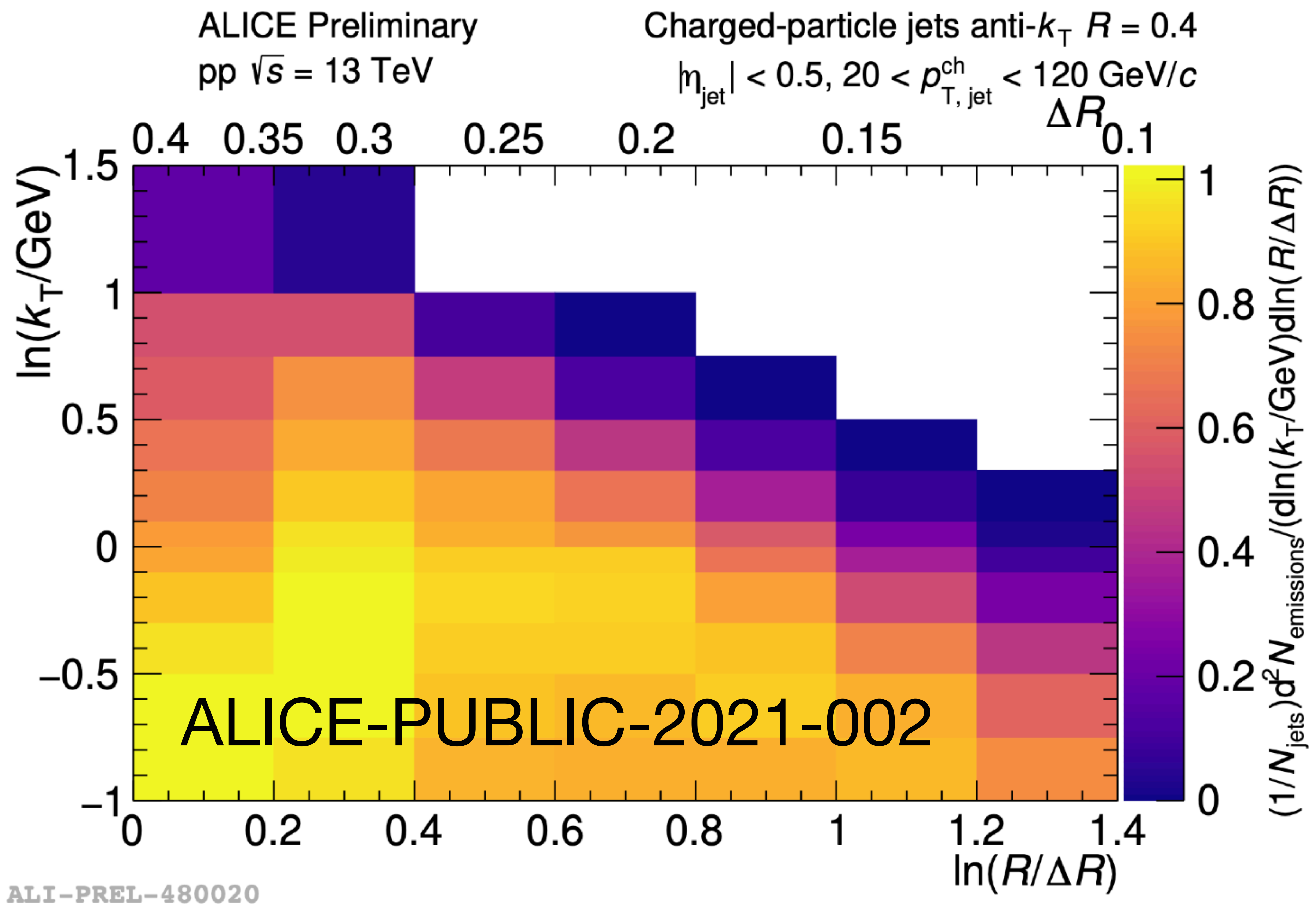
At LO: $\rho_i \simeq \frac{2\alpha_s(k_t)C_i}{\pi}, (C_q = C_F, C_g = C_A)$

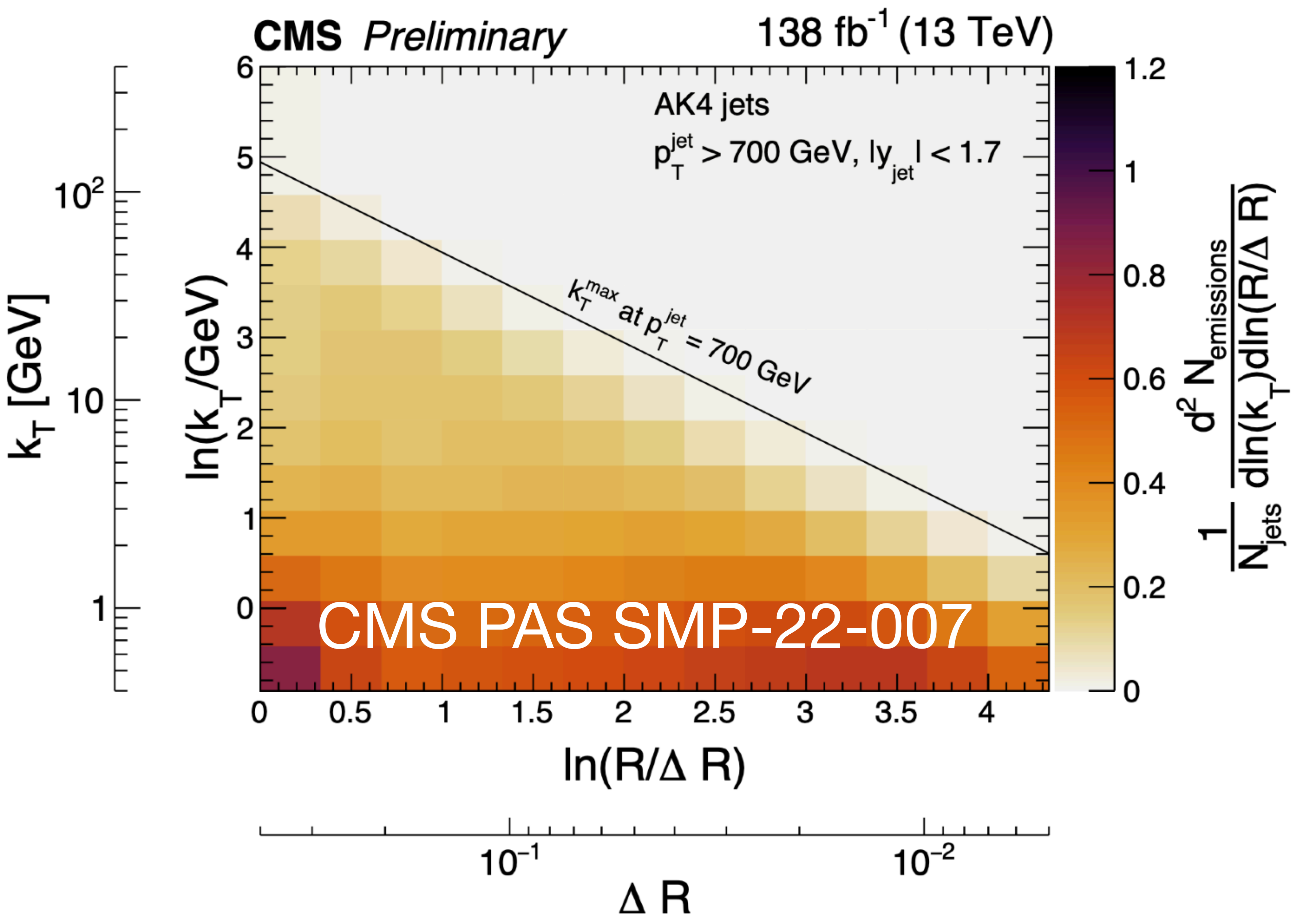
Clear separation between QCD regimes!

Infrared and collinear safe (if we consider a “pixel”)

Lund Plane density measurements

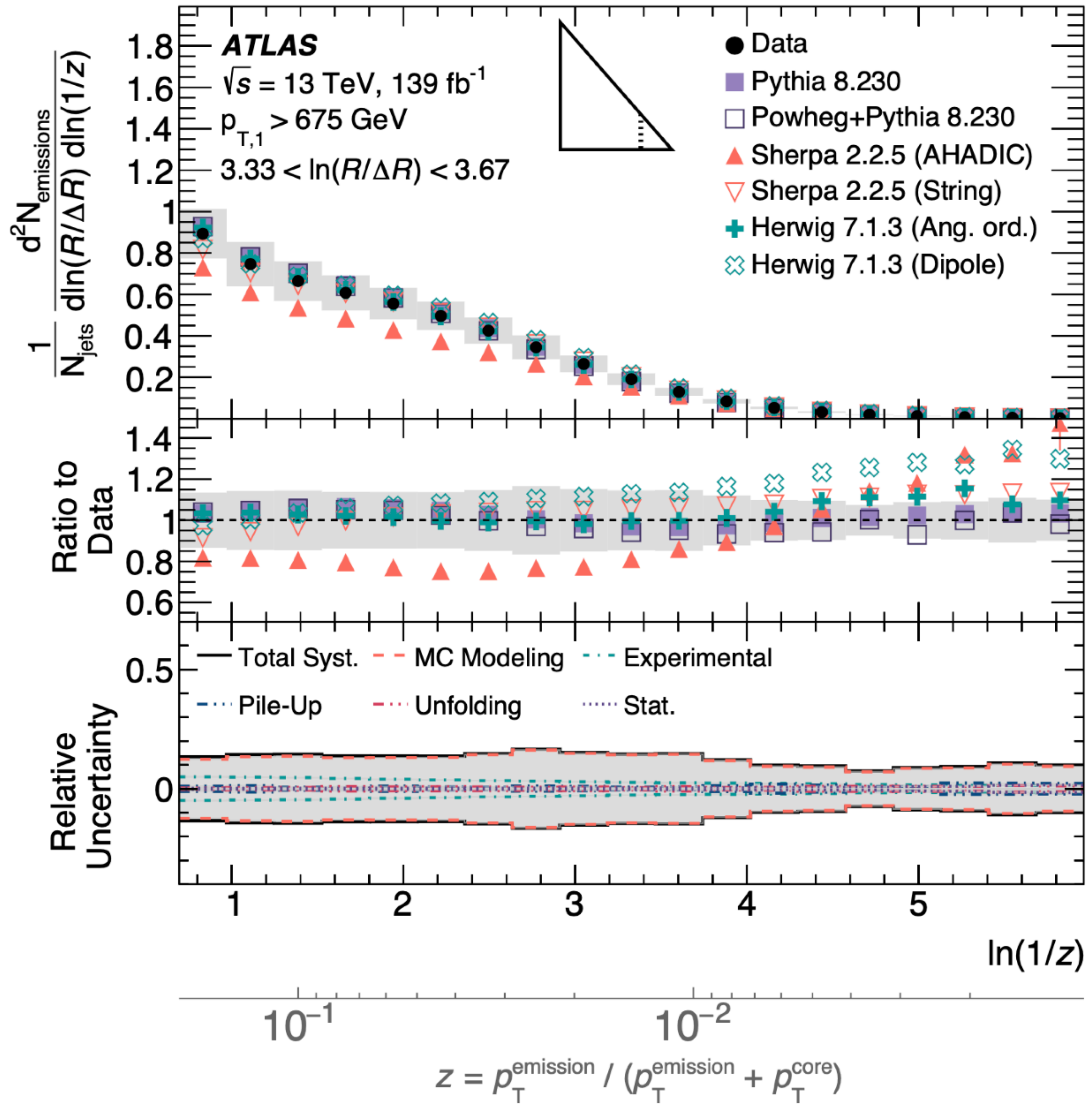


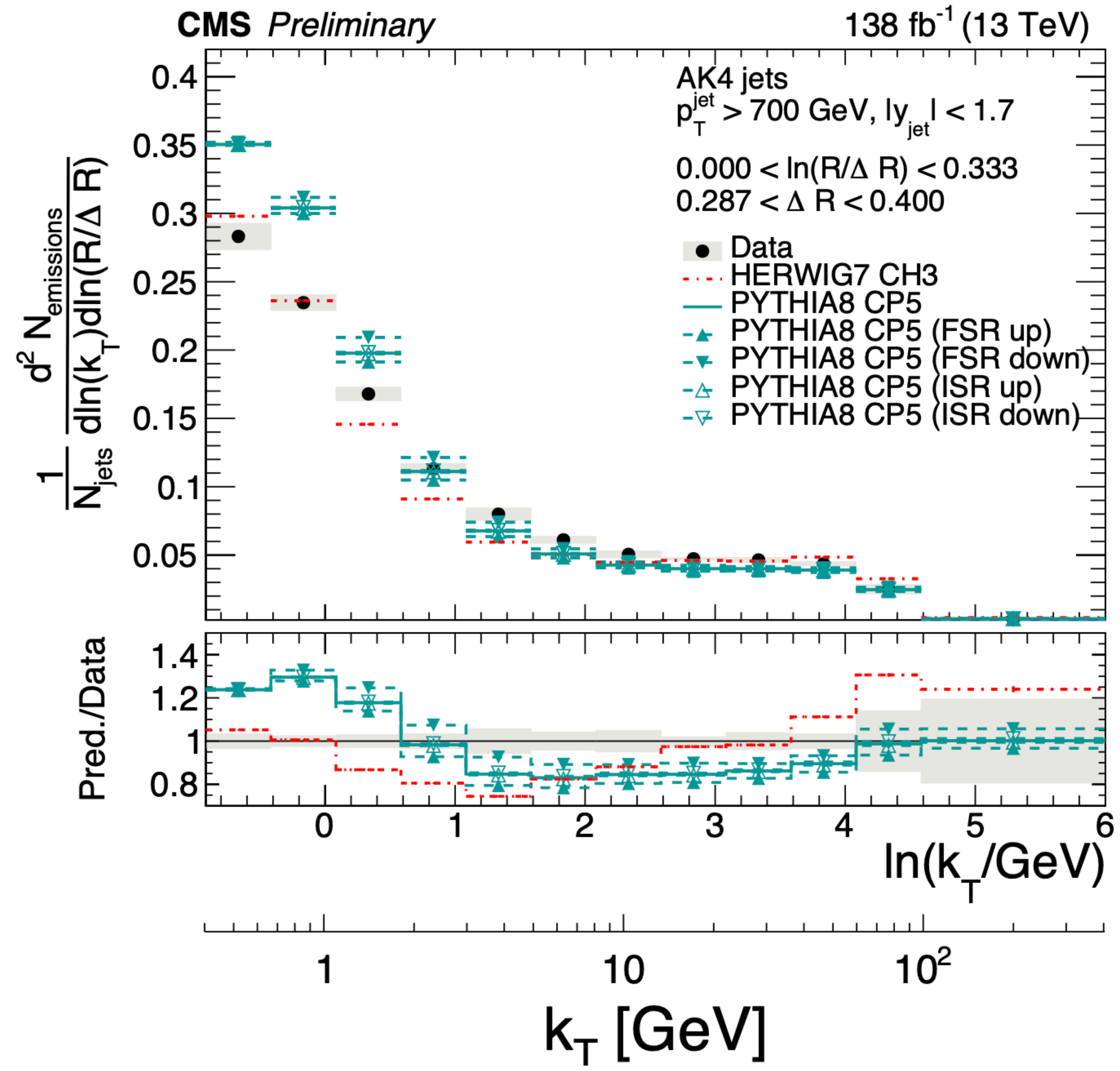


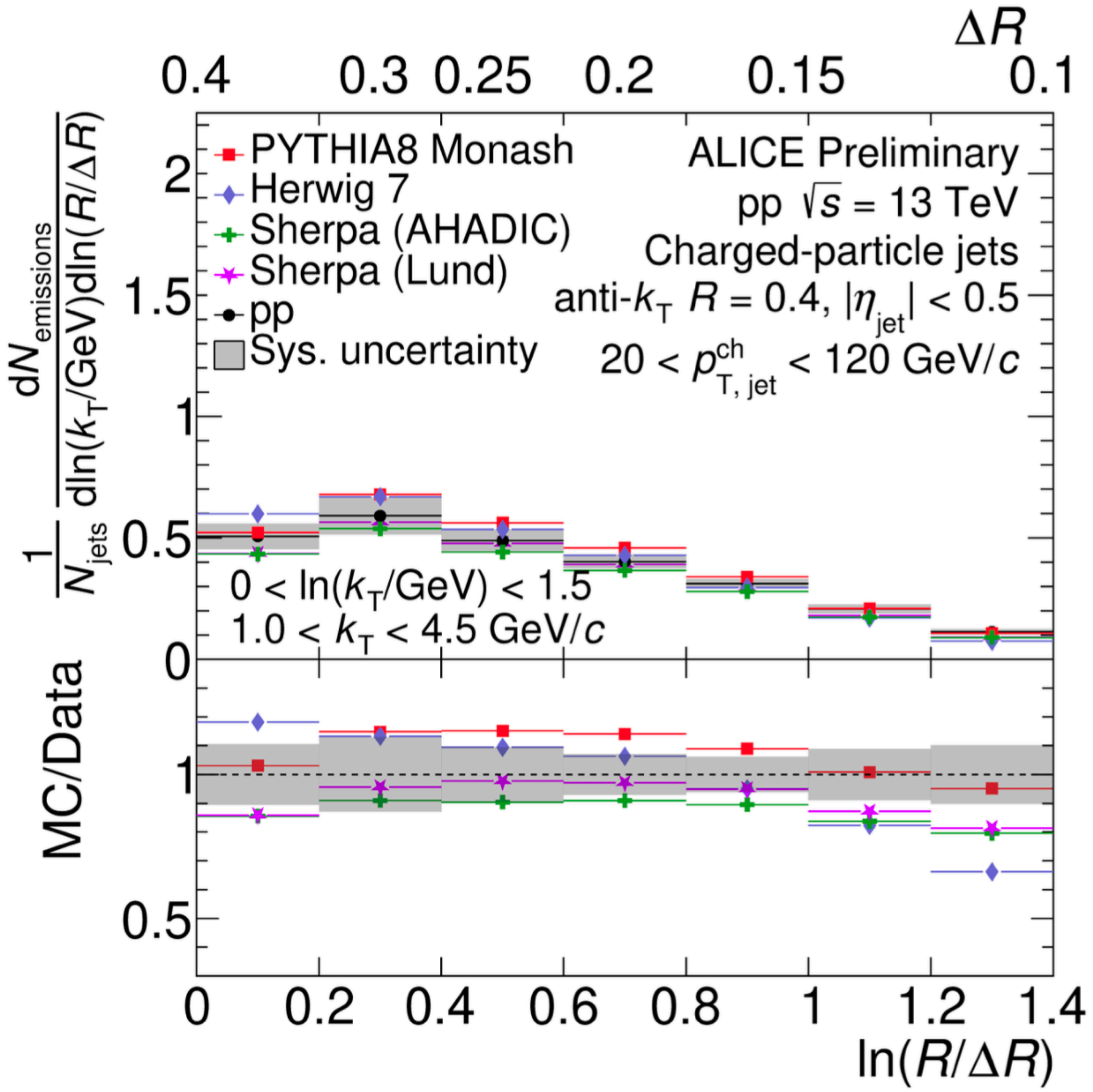


Lund Plane density & MCs

Up to 20-30% difference between Monte Carlo generators in different slices of the plane







Ability of the Lund jet plane to isolate physical effects

→ useful input to both perturbative and non-perturbative model development and tuning

Lund Plane density at all-orders

[Lifson, Salam, Soyez (2007.06578)]

Logarithmically dominant terms with structure:

$$\alpha_s^{n+1} \ln^m \Delta \ln^{n-m} z, \quad 0 \le m \le n, \quad z = \frac{k_t}{p_{t,\mathrm{jet}} \Delta}$$

Their resummation requires to deal with:

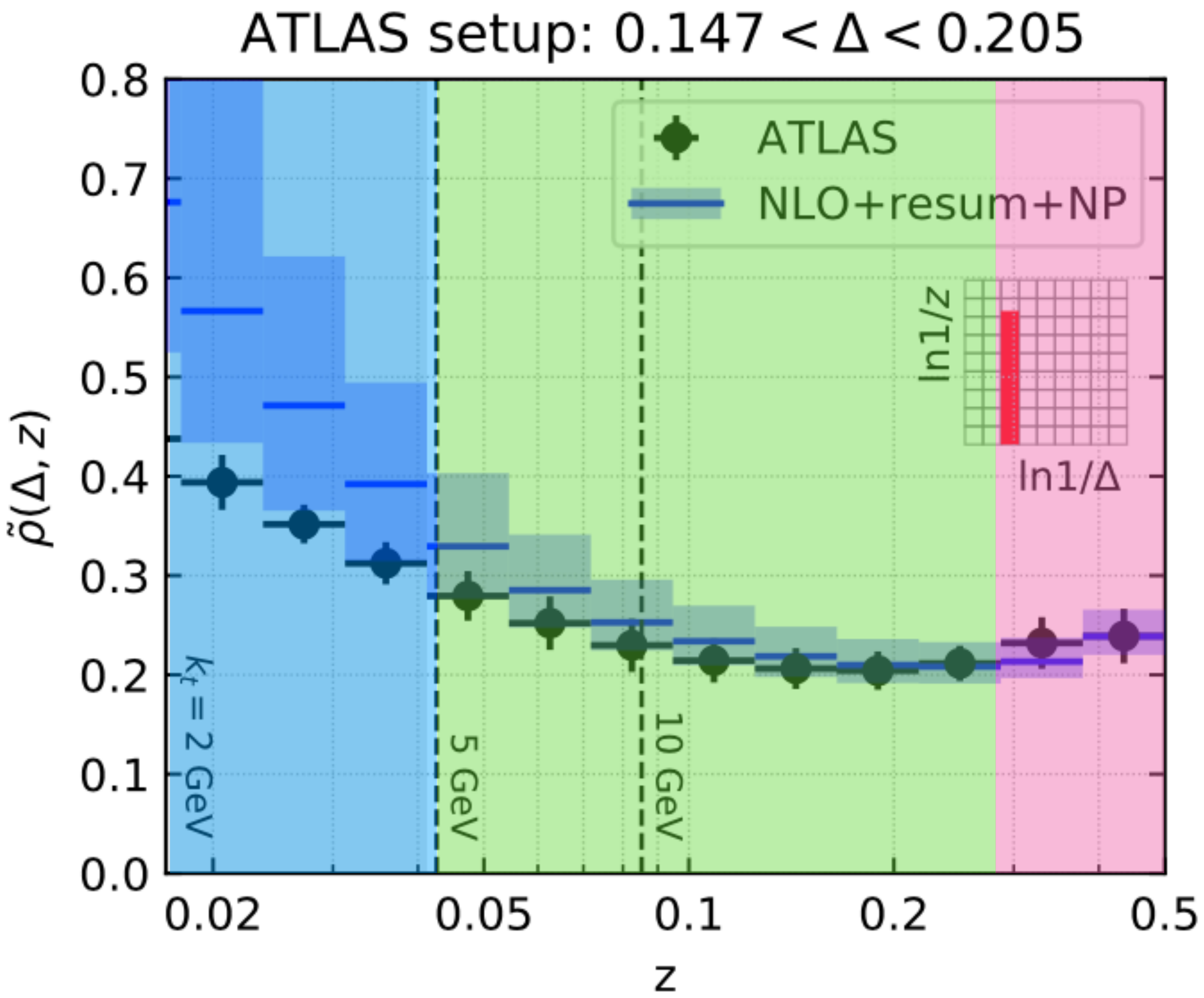
- Running coupling corrections (numerically dominant)
- Hard-collinear logarithms (can change flavour)
- Soft effects (large-angle emissions)
- Clustering logarithms

Non-perturbative estimated through Monte Carlo

Matching to fixed-order NLO

Clear separation of contributions

Non perturbative Resummation NLO



Good agreement with ATLAS data in several slices of the plane

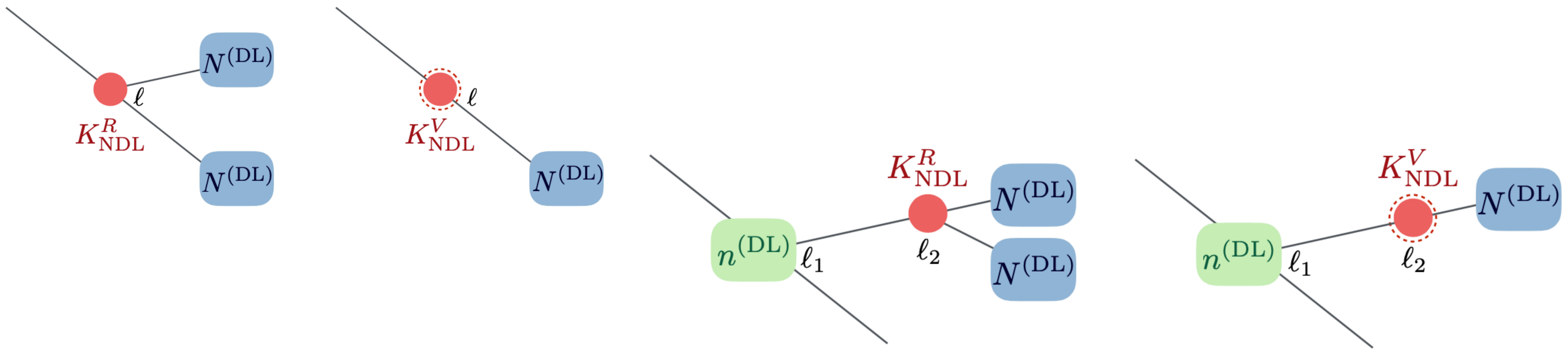
Lund multiplicity at LEP

[Medves, Soto-Ontoso, Soyez (2205.02861)]

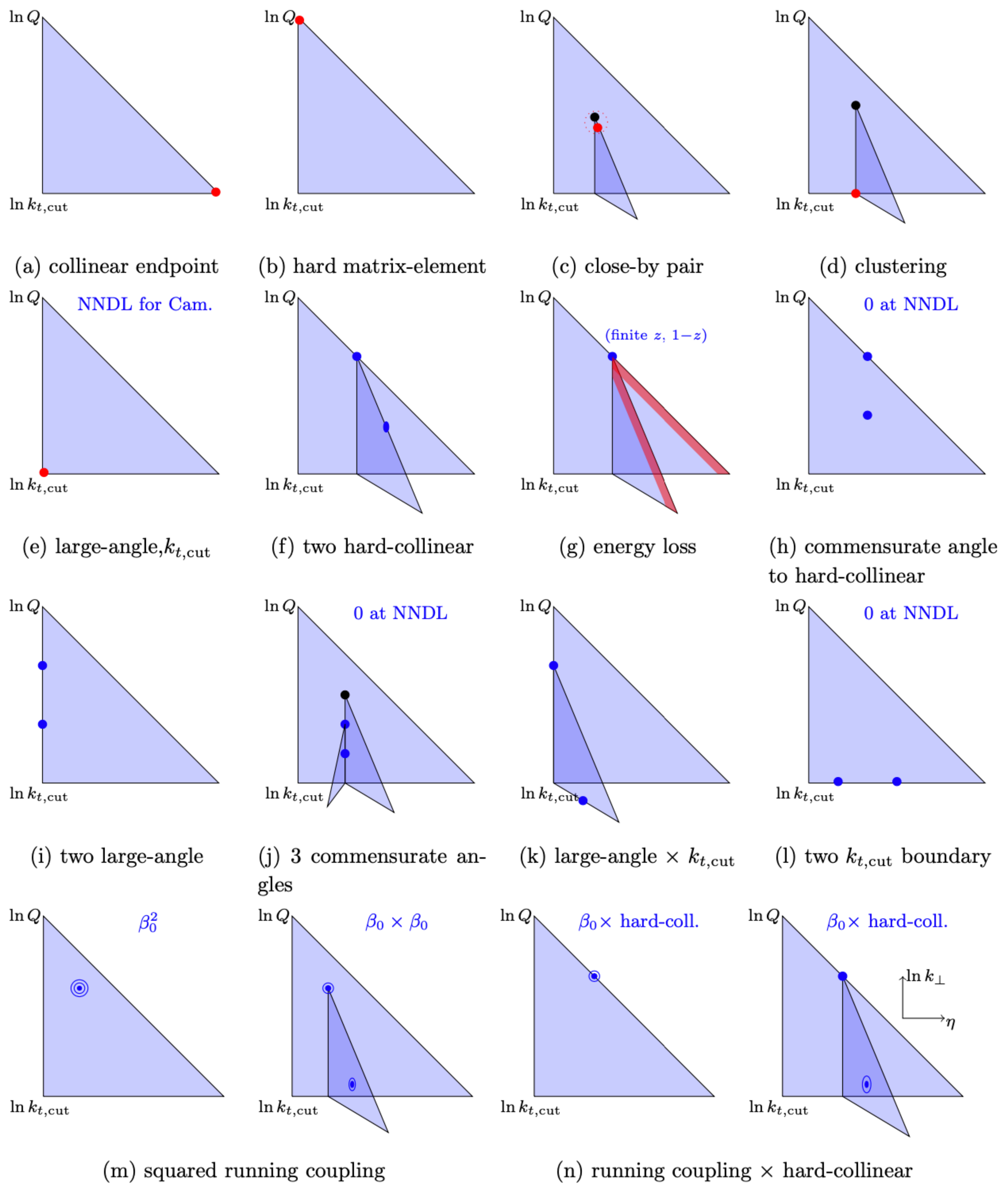
Defined as (average) number of Lund declusterings (in the full tree) with $k_t \geq k_{t,\text{cut}}$

Computed up to NNDL, with $L = \ln(Q/k_{t,\text{cut}})$

$$\langle N(\alpha_s, L)\rangle = \langle N(\alpha_s, 0)\rangle \left[\underbrace{h_1(\alpha_s L^2)}_{\text{DL}} + \underbrace{\sqrt{\alpha_s} h_2(\alpha_s L^2)}_{\text{NDL}} + \underbrace{\alpha_s h_3(\alpha_s L^2)}_{\text{NNDL}} + \dots \right]$$



Novel method: recycle DL results with insertions of NDL or NNDL genuine ingredients

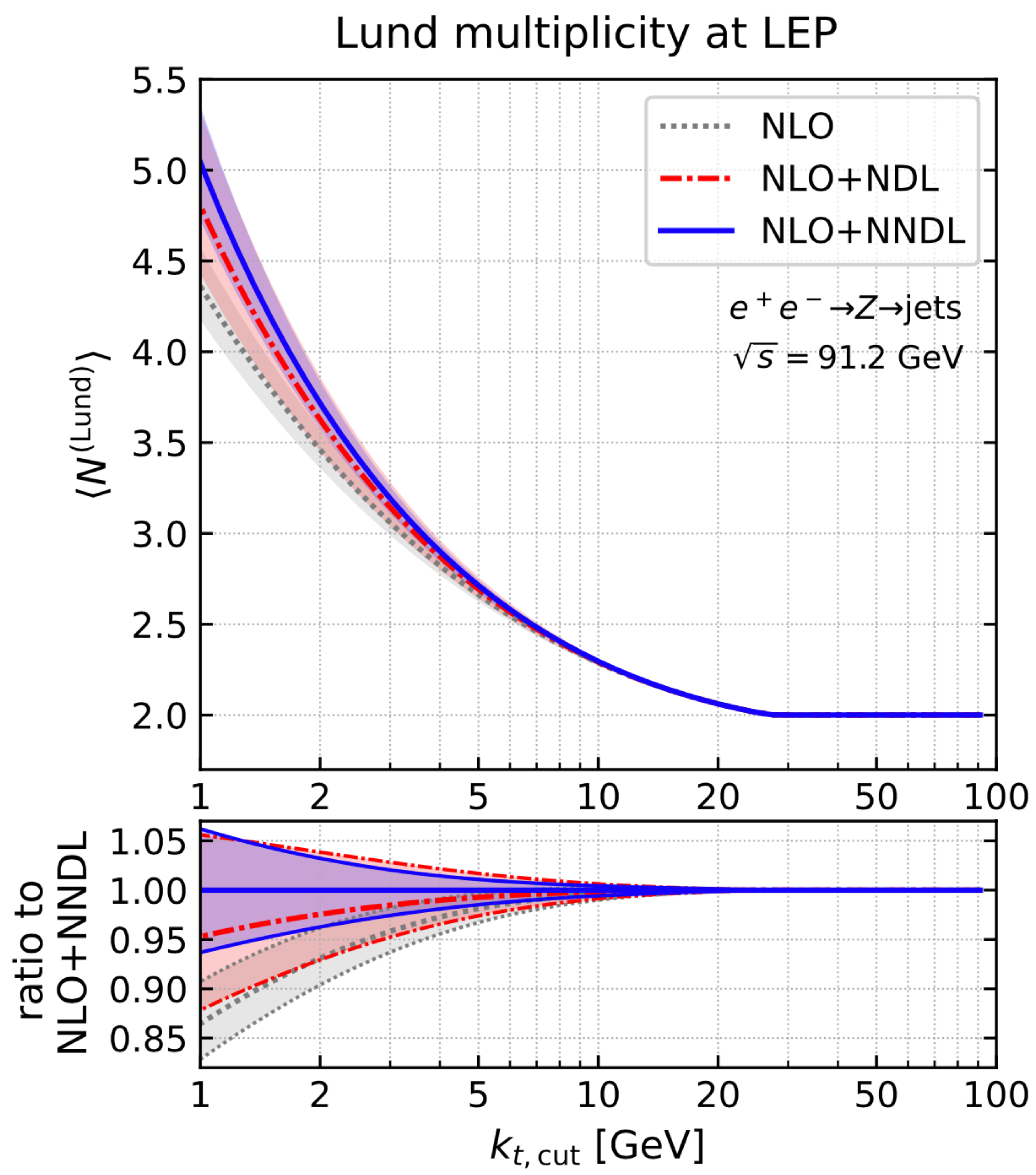


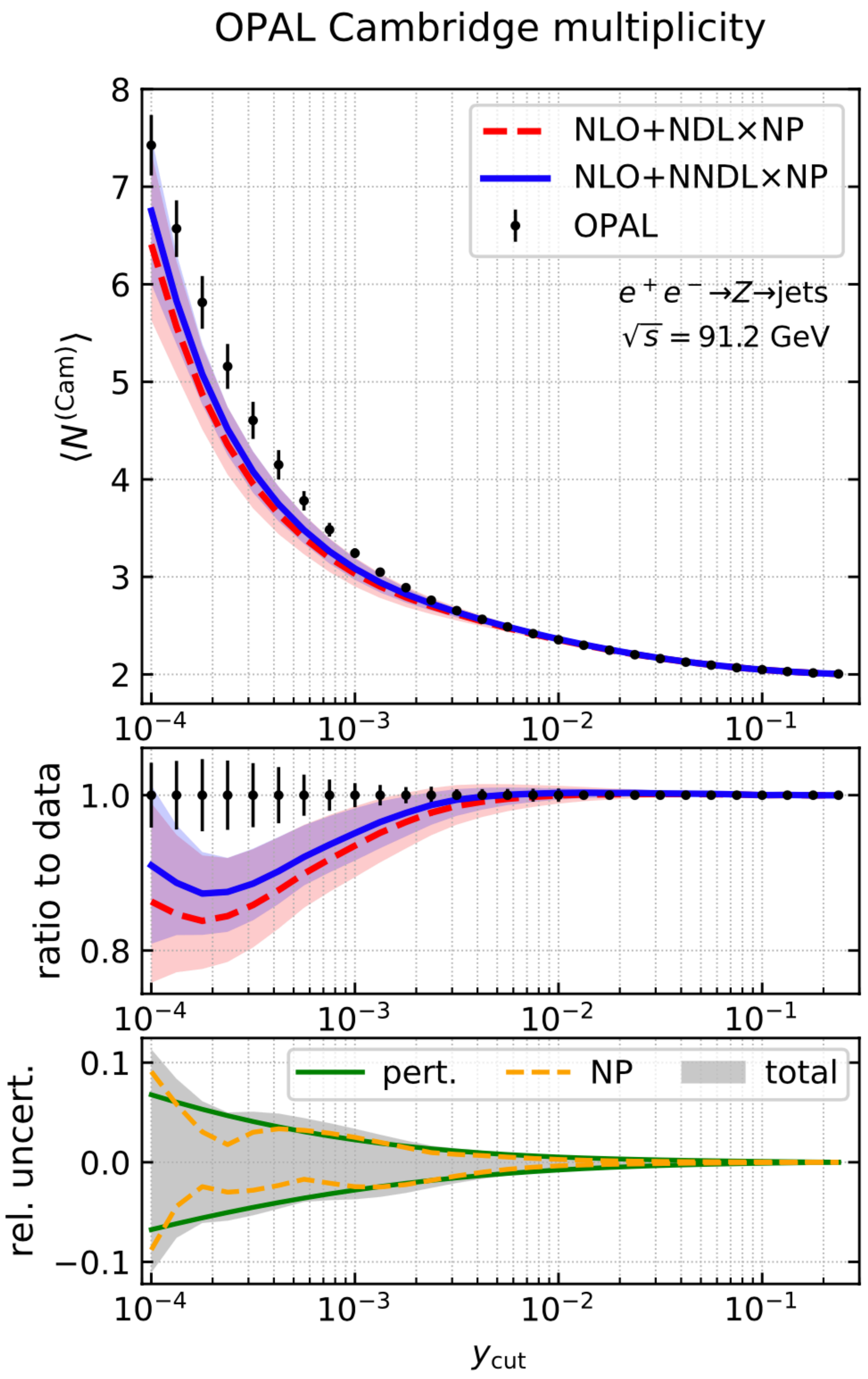
Black dots $\propto \alpha_s L^2$

Blue dots $\propto \alpha_s L$, Red dots $\propto \alpha_s$

Lund multiplicity at LEP…

[Medves, Soto-Ontoso, Soyez (2205.02861)]





… and at the LHC

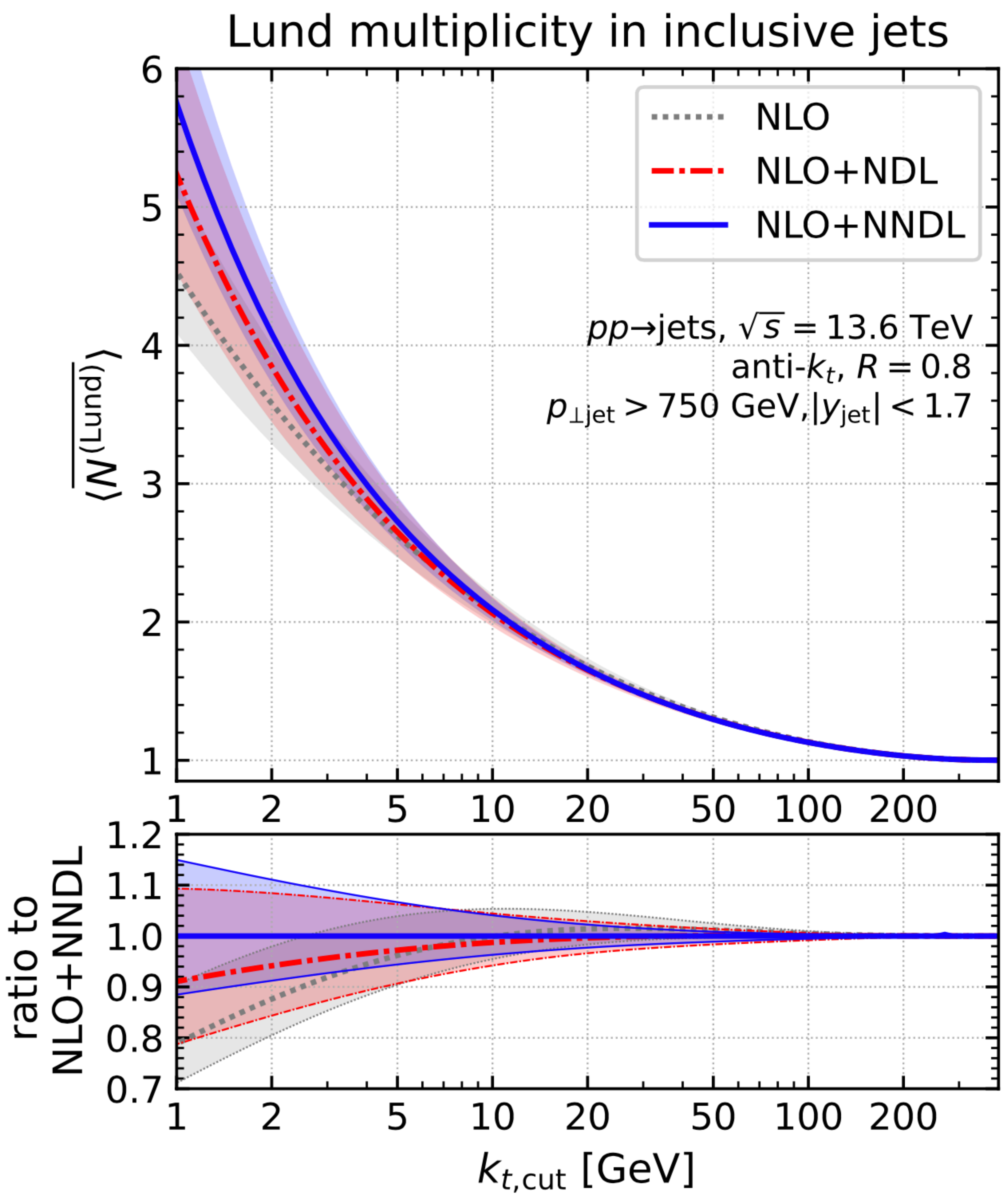
[Medves, Soto-Ontoso, Soyez (2212.05076)]

Counting the mean number of subjects per anti-k_t jet with relative $k_t \geq k_{t,\mathrm{cut}}$

Resummation up to **NNDL** in $L = \ln(p_\perp R / k_{t,\mathrm{cut}})$:

- Universal ingredients from e+e– event-wide result
- Presence of jet radius impacts the large-angle components starting at NDL, with a process dependence (e.g. $Z + \mathrm{jets}$ or dijets)
- Additional presence of experimental fiducial cuts used for the jet analysis in a collider environment.

Precision calculation has the potential to serve as benchmarks to test and develop MC event generators

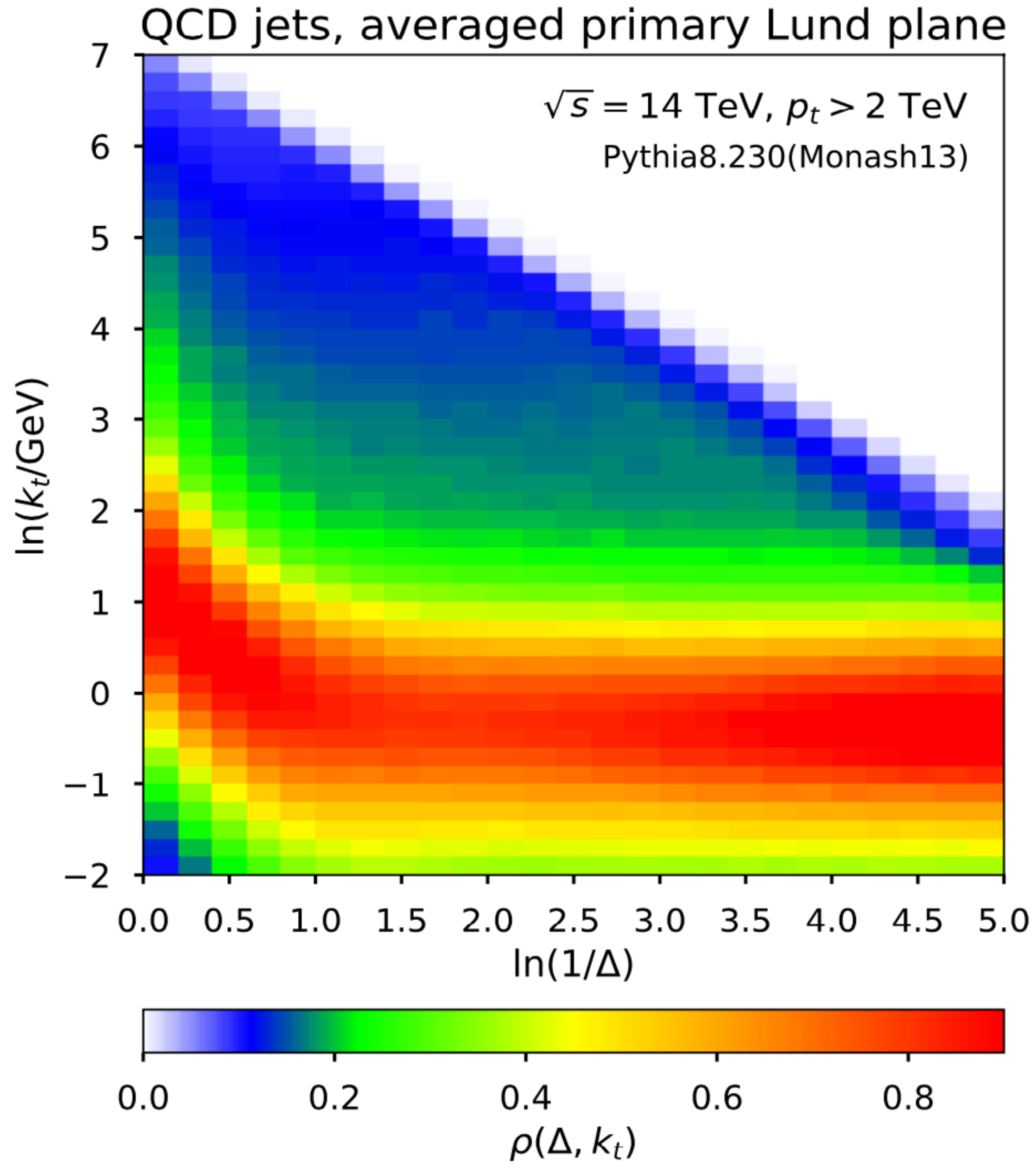


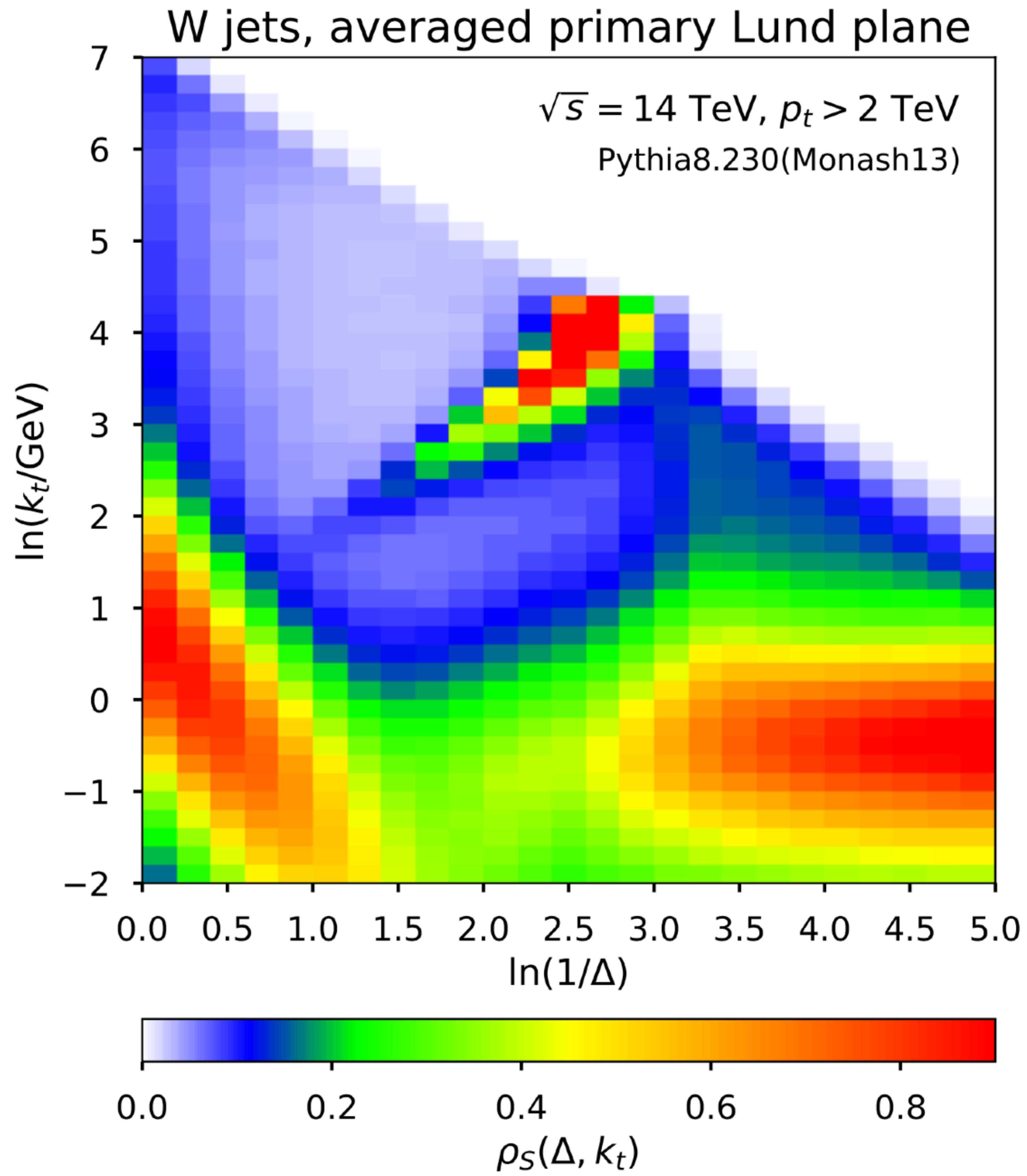
Lund Plane & machine learning

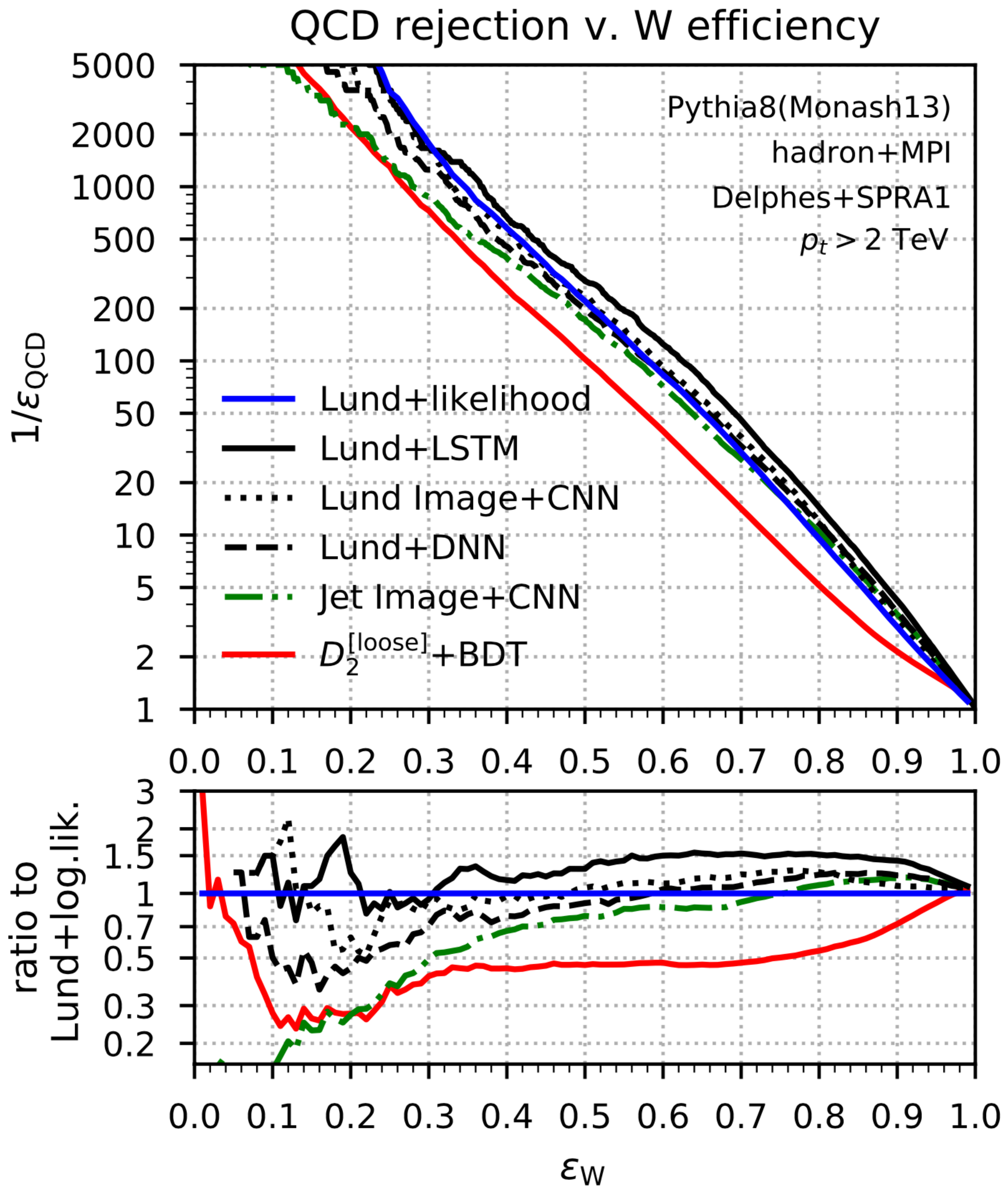
Tagging W decay

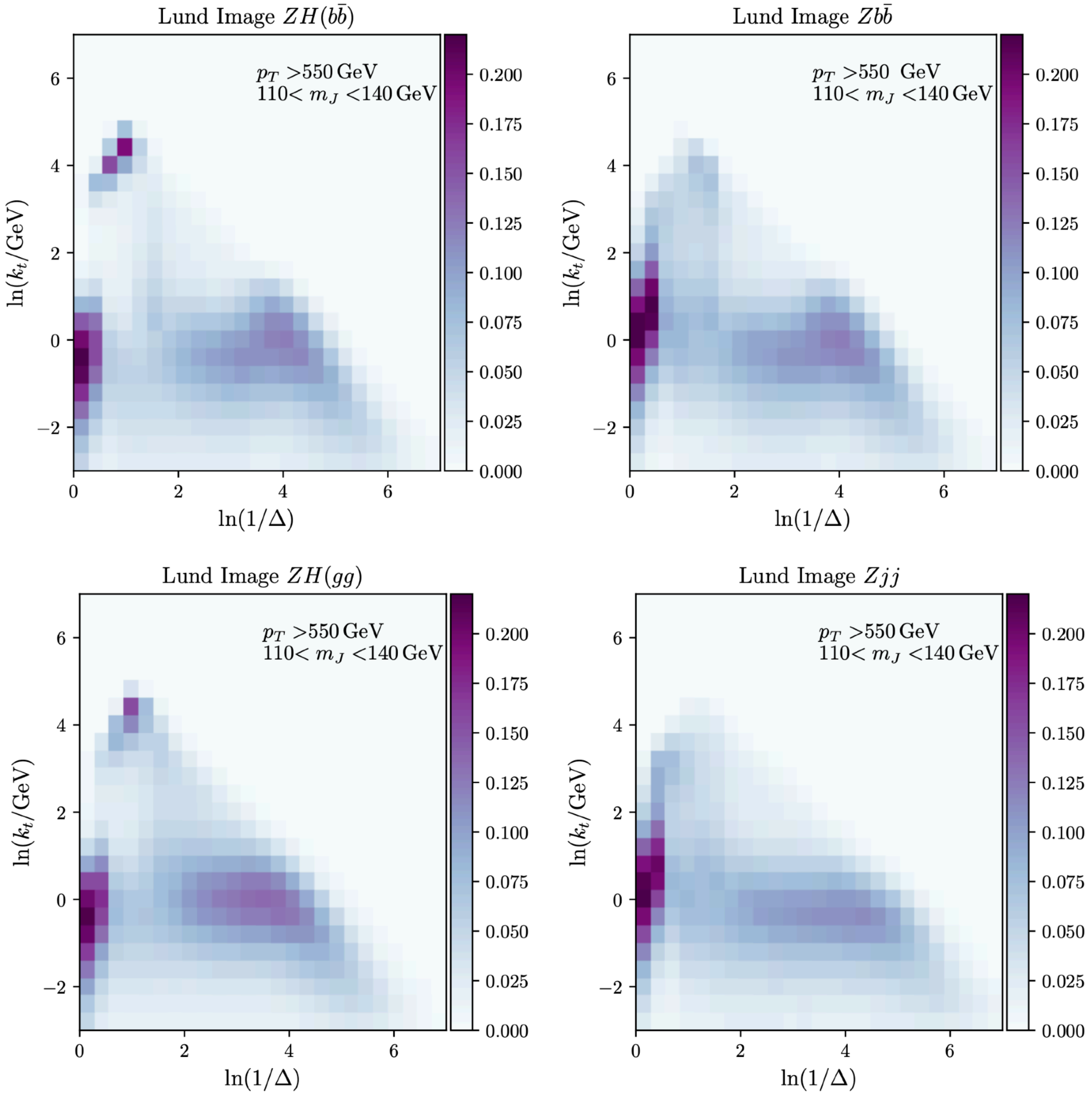
[Dreyer, Salam, Soyez (1807.04758)]

Exploit different structure of primary Lund plane for QCD and signal jets
→ use density to build likelihood,
sequence of declusterings as input to LSTM or DNN,
image as input to CNN





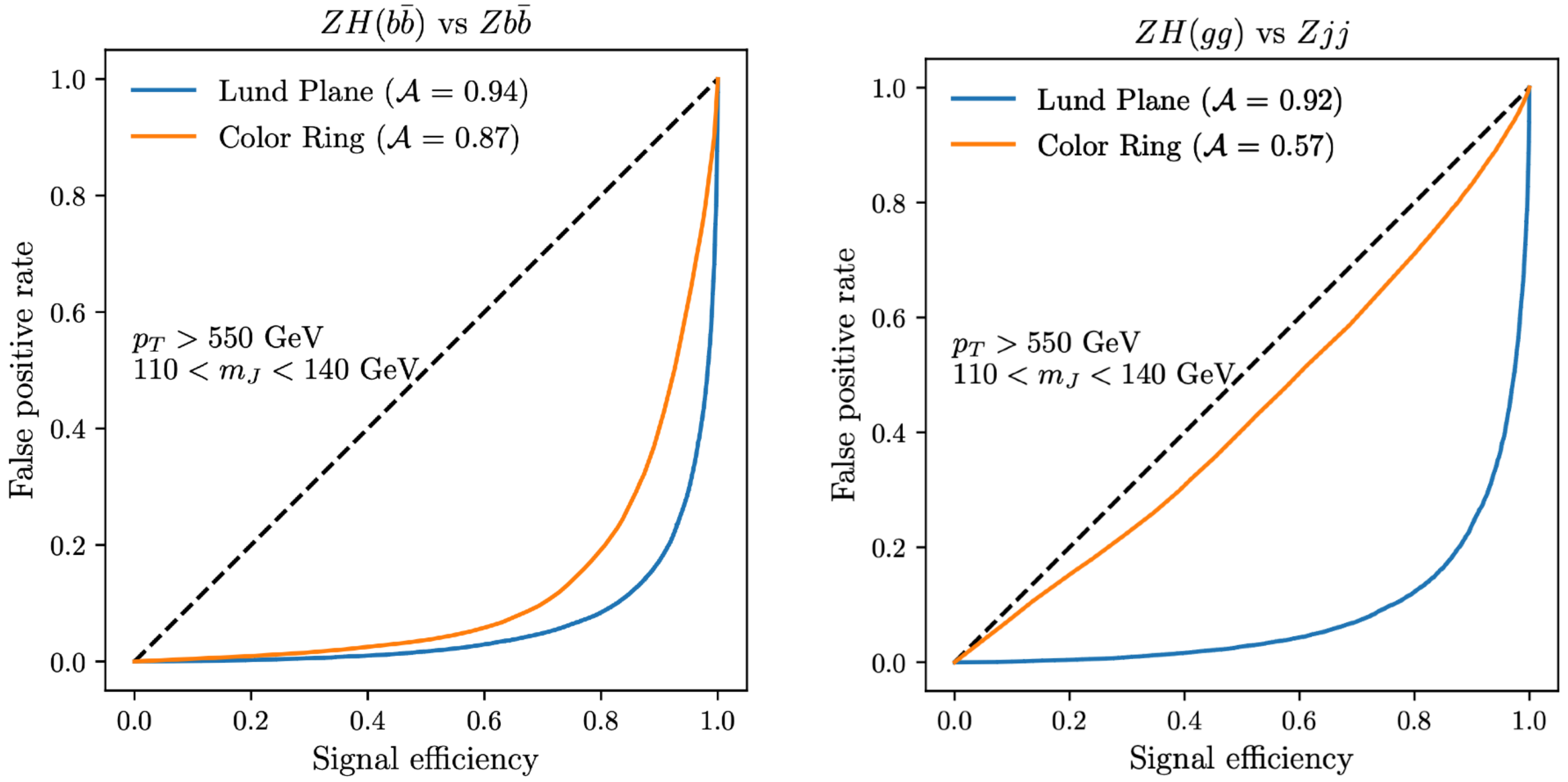




Tagging H decays

[Khosa, Marzani (2105.03989)]
[Cavallini, GS et al. (2112.09650)]

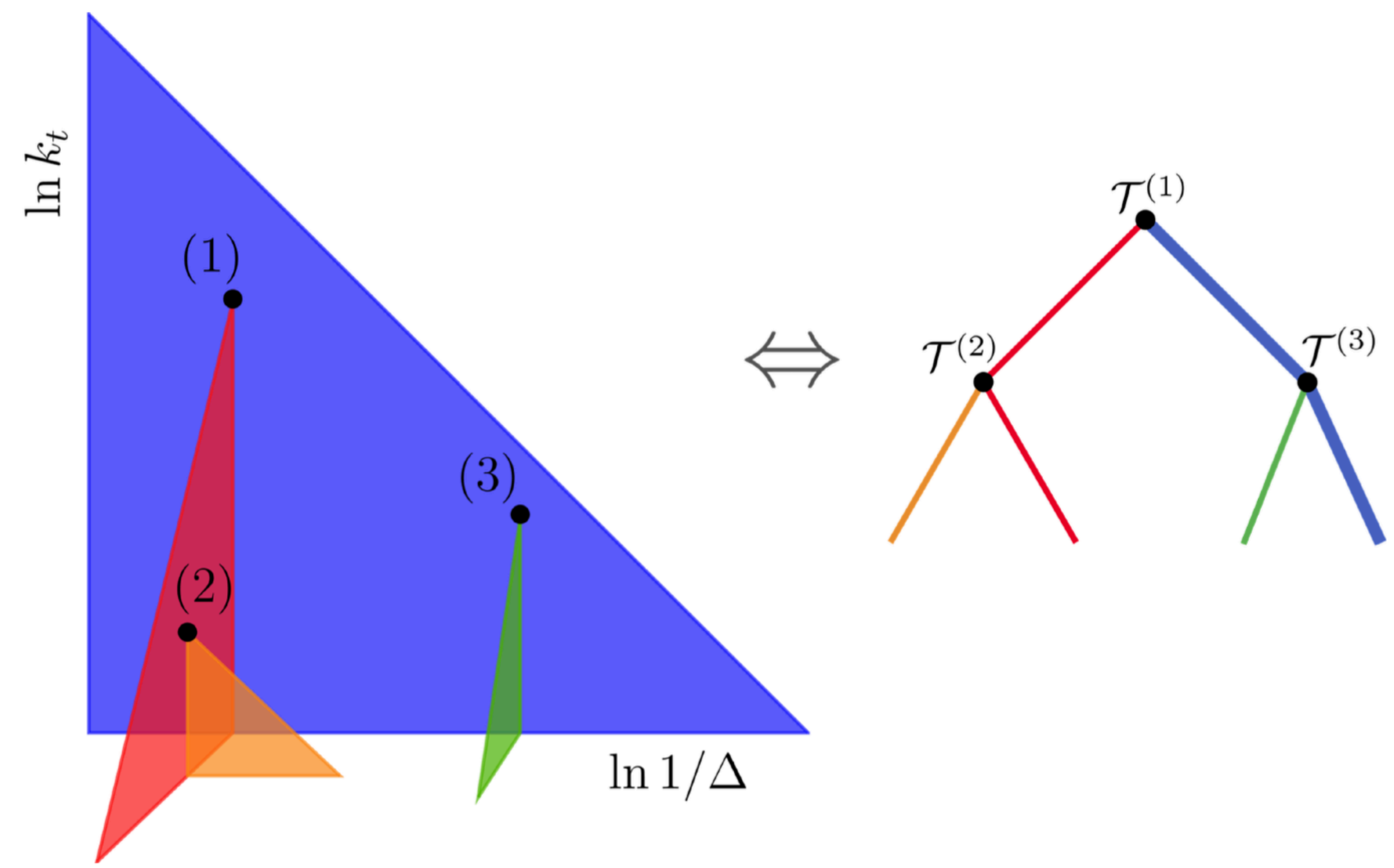
Use CNN trained on primary Lund plane images of $Z(H \to b\bar{b}/gg)$ and $Zb\bar{b}/Zjj$

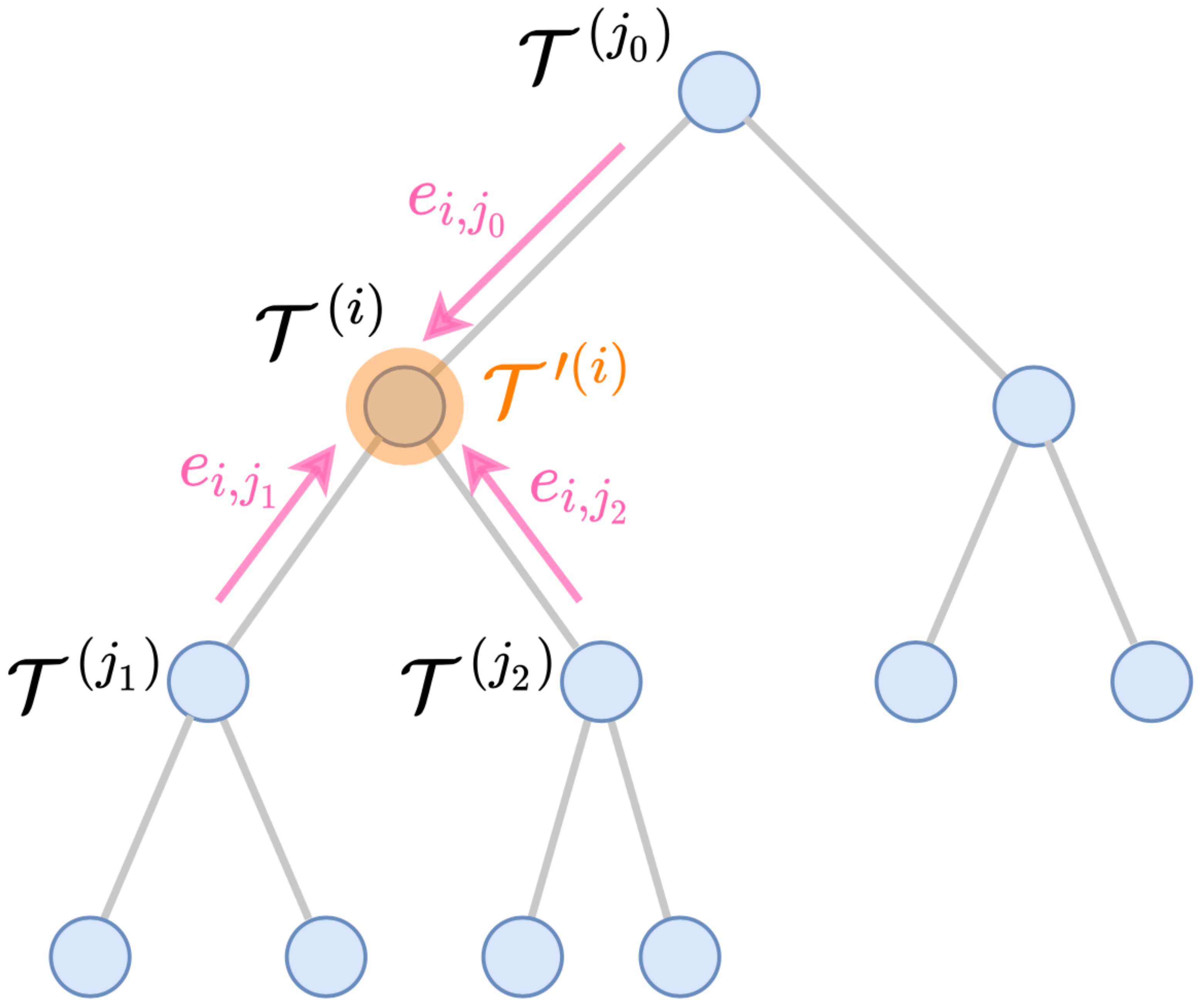


A simple one-variable discriminant (color ring) fails in the $H \to gg$ case, whereas the Lund plane CNN maintains its discrimination power.

Exploit the full Lund plane

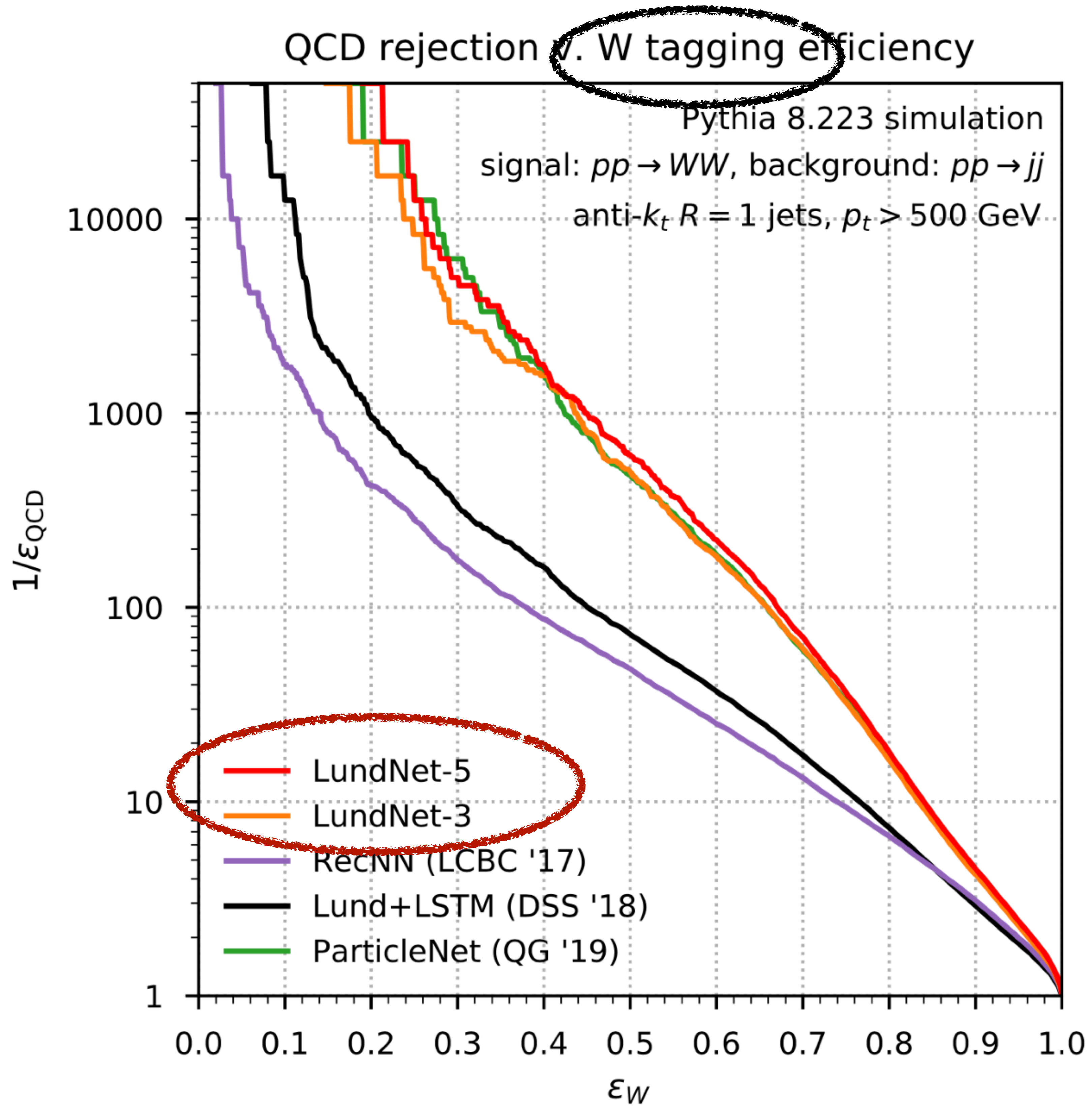
[Dreyer, Qu (2012.08526)]

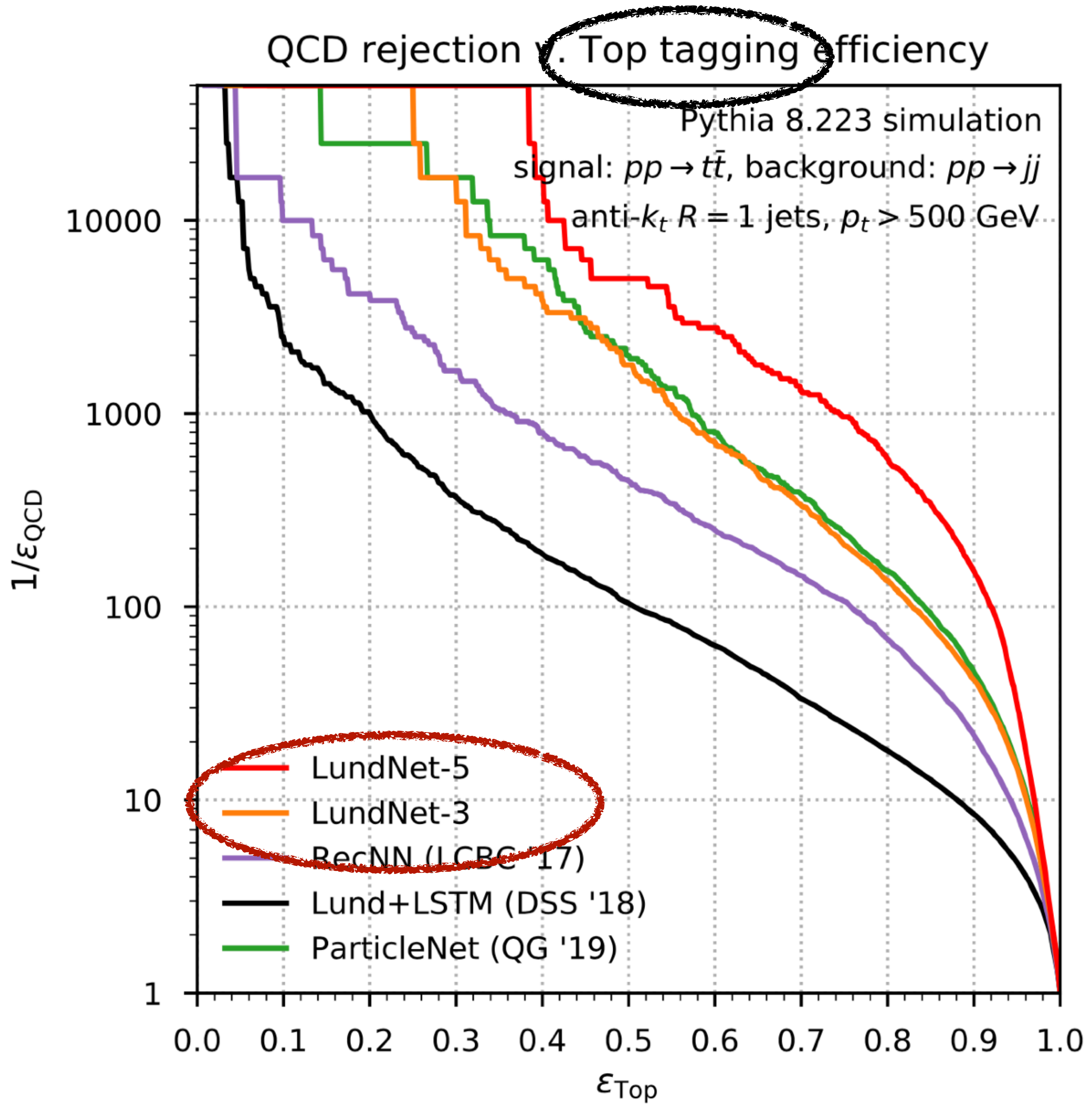


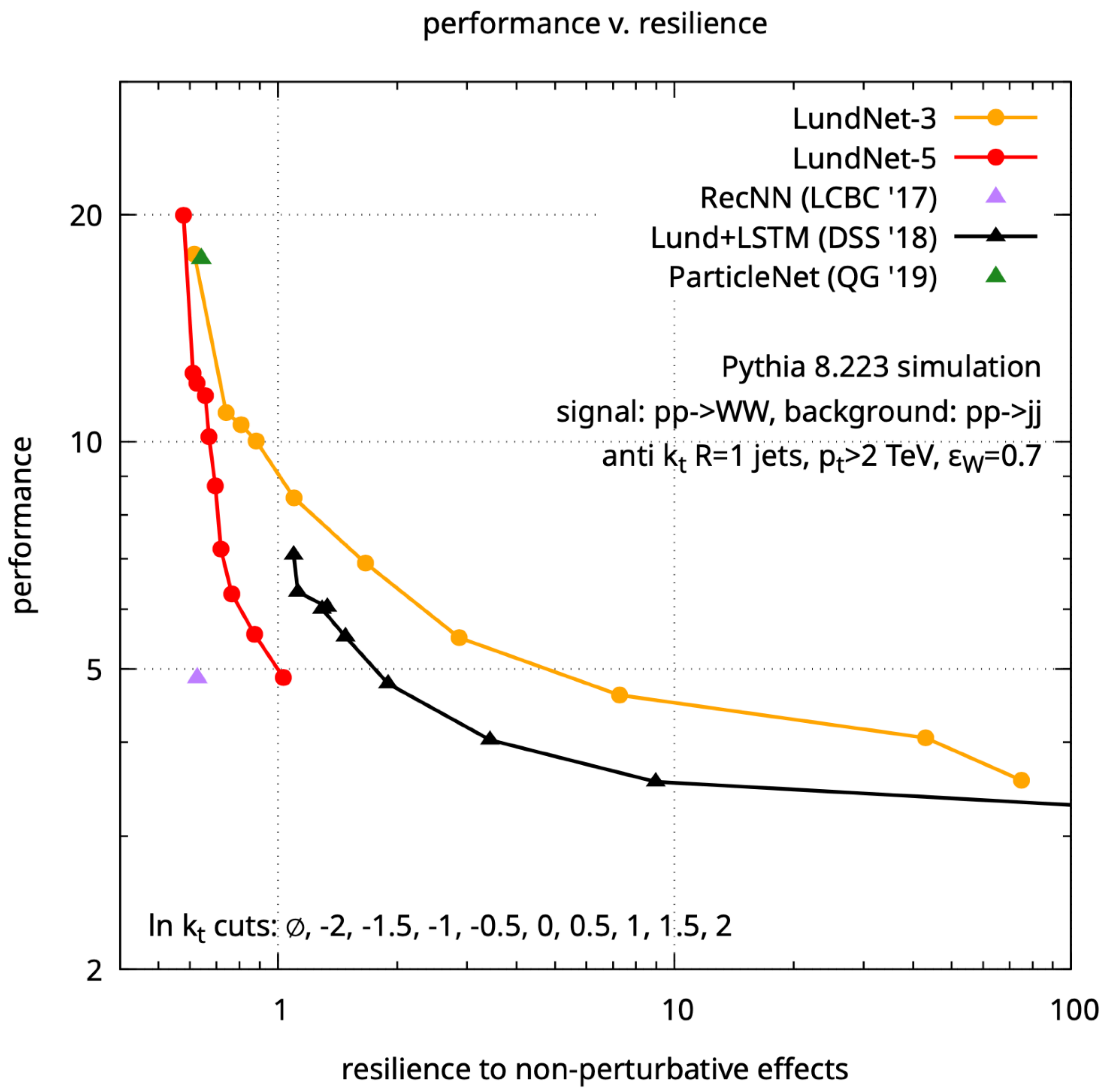


Lund tree as input to a graph NN (GNN), dubbed **LundNet**

State-of-the-art performances







$$\xi_{NP} = \left(\left(\frac{\epsilon^W_{\rm had} - \epsilon^W_{\rm part}}{(\epsilon^W_{\rm had} + \epsilon^W_{\rm part})/2} \right)^2 + \left(\frac{\epsilon^{\rm QCD}_{\rm had} - \epsilon^{\rm QCD}_{\rm part}}{(\epsilon^{\rm QCD}_{\rm had} + \epsilon^{\rm QCD}_{\rm part})/2} \right)^2 \right)^{-1/2}$$

Resilience: degree of insensitivity to potential mismodelling aspects or to specific details of an event sample

Exploit the full Lund plane

[Dreyer, Qu (2012.08526)]

Two variants:

LundNet-3: trained on $(\ln k_t, \ln \Delta, \ln z)$

LundNet-3: trained on $(\ln k_t, \ln \Delta, \ln z, \ln m, \psi)$

m invariant mass of the pair

$$\psi = \tan^{-1}\left(\frac{y_b - y_a}{\phi_b - \phi_a}\right),$$

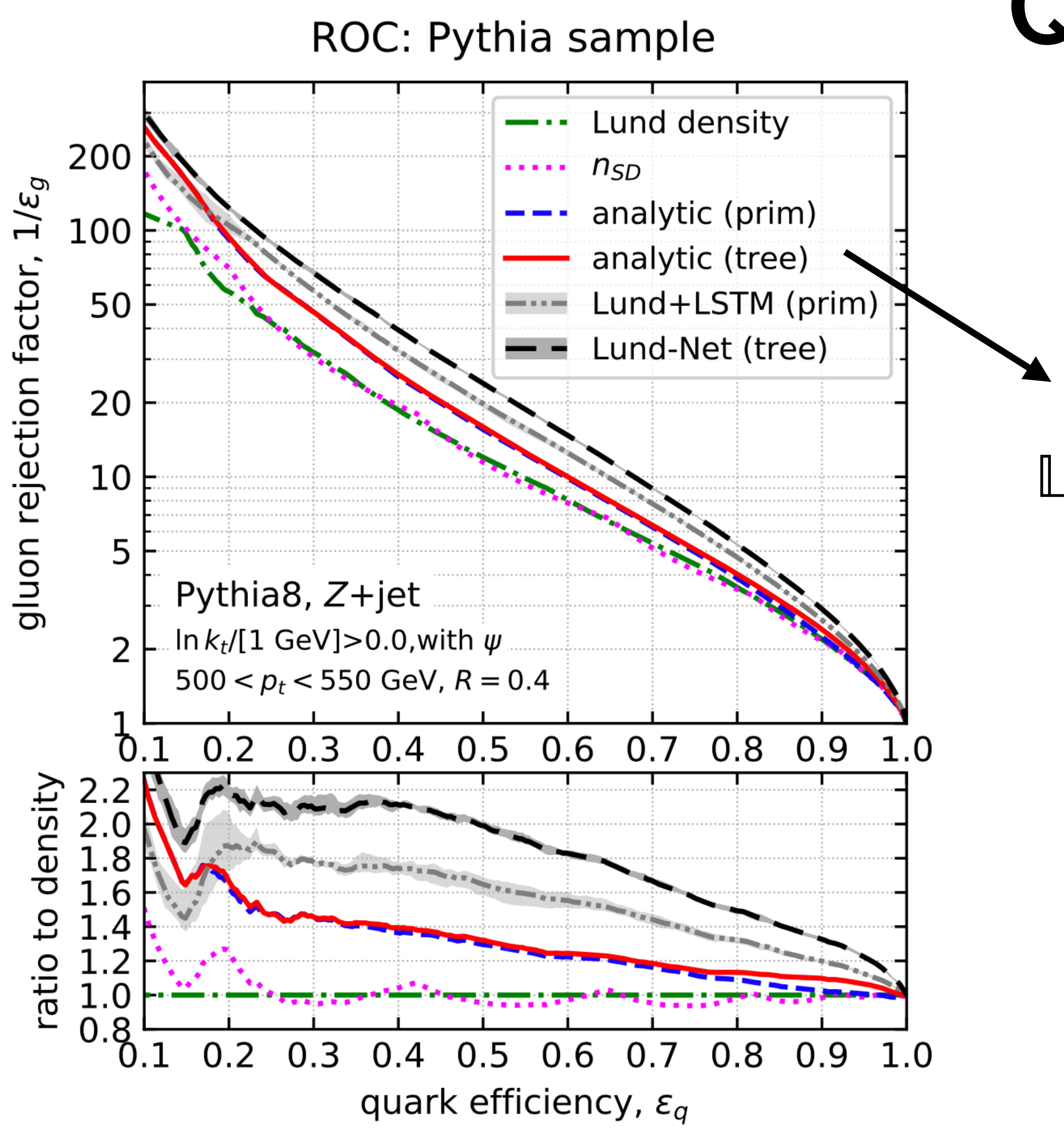
azimuthal angle around subject's axis

LundNet-5 more performant,
but LundNet-3 is more resilient to non-perturbative effects

Is LundNet-5 is extrapolating some information on emissions below the $k_{t,\rm cut}$?

Quark/gluon discrimination

[Dreyer, Soyez, Takacs (2112.09140)]



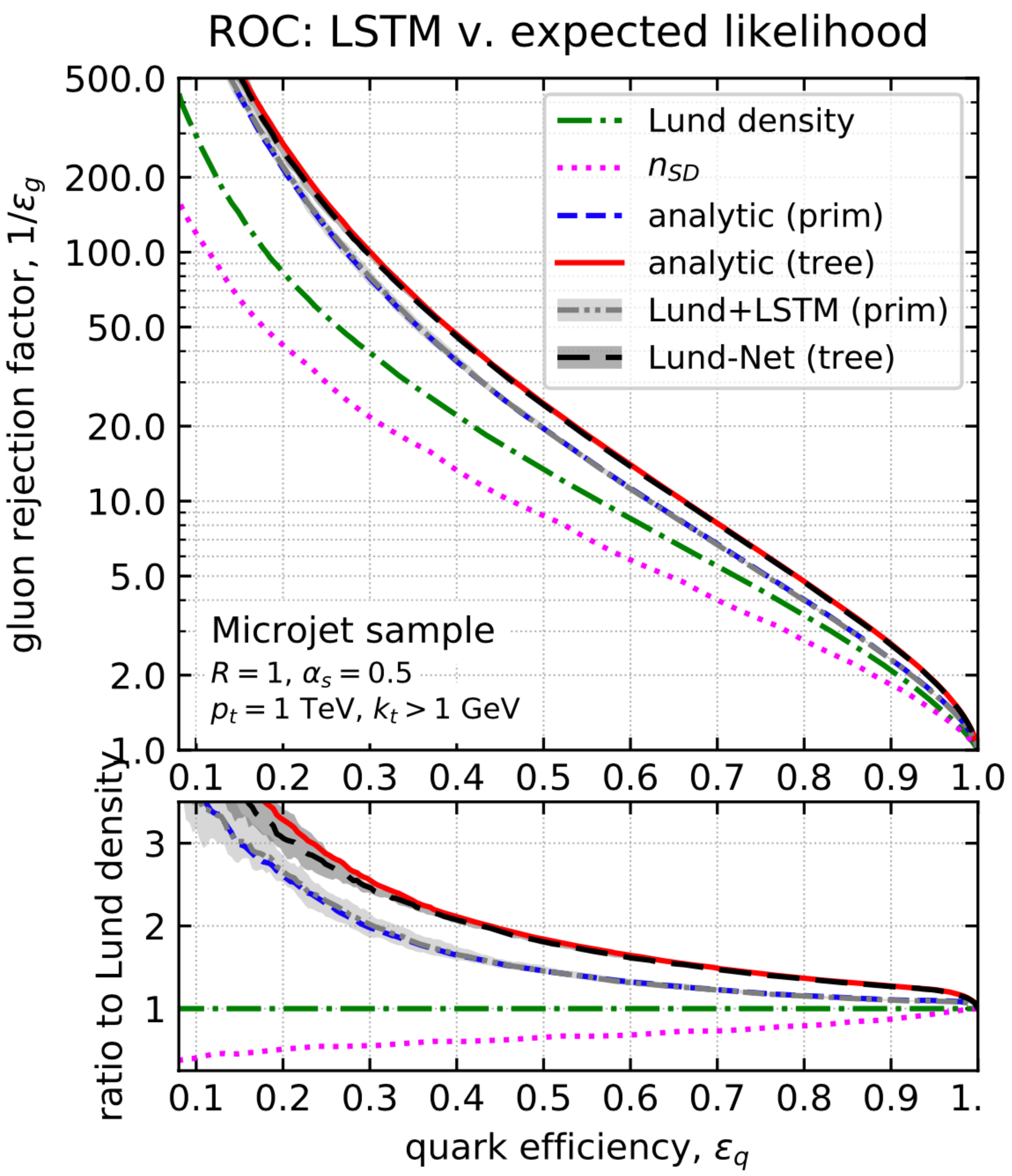
Optimal discriminant: likelihood ratio

$$\mathbb{L} = \frac{p_g(\mathscr{L})}{p_q(\mathscr{L})},$$ with $\mathscr{L}$ the Lund primary tree or full tree

can be **calculated analytically up to single logs**

Gain in performance when considering the full tree (better kinematics and treatment of correlations)

Lund + ML models have better performance than analytics: what are they learning?

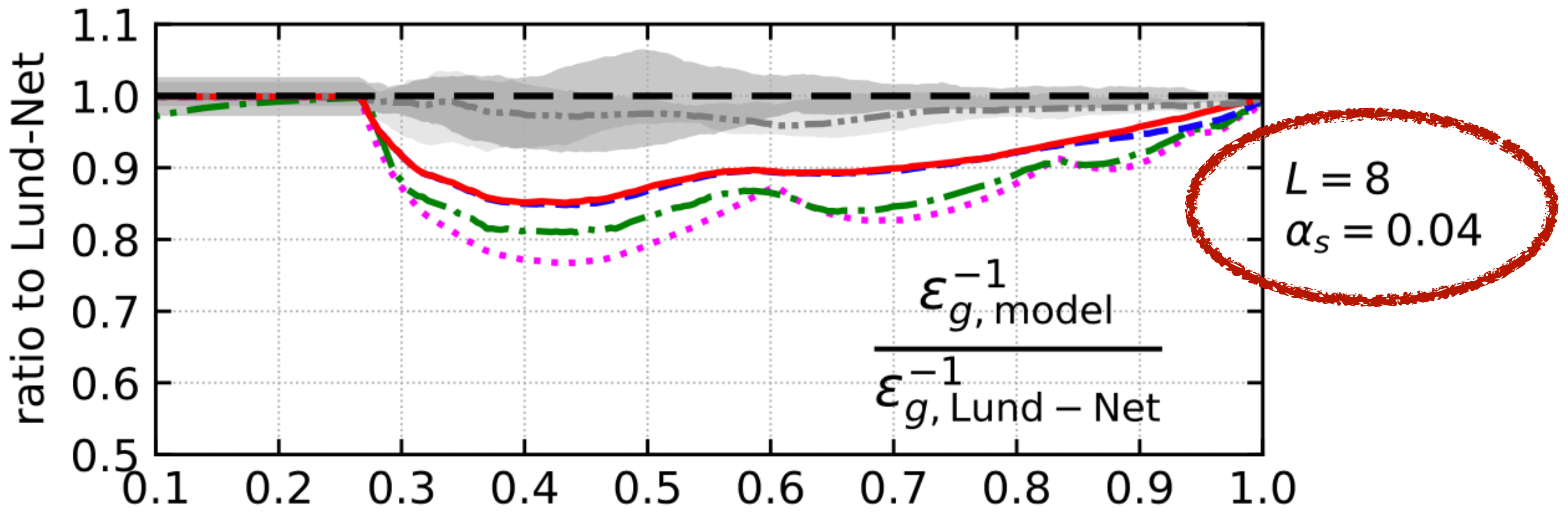


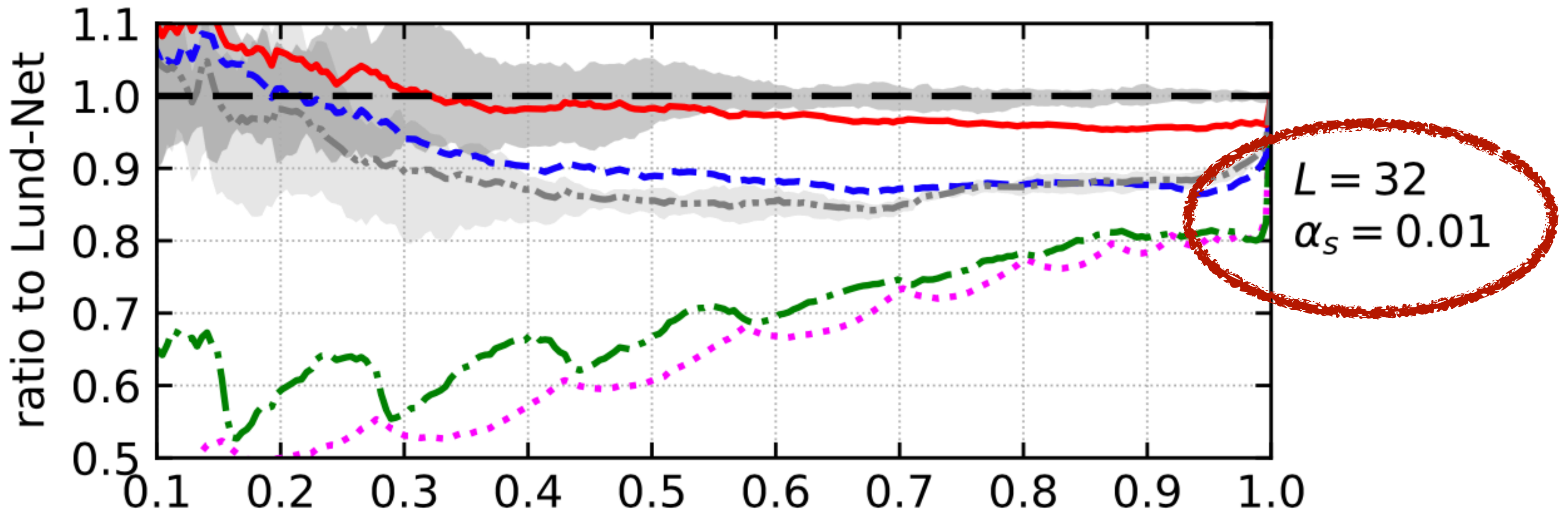
Quark/gluon discrimination

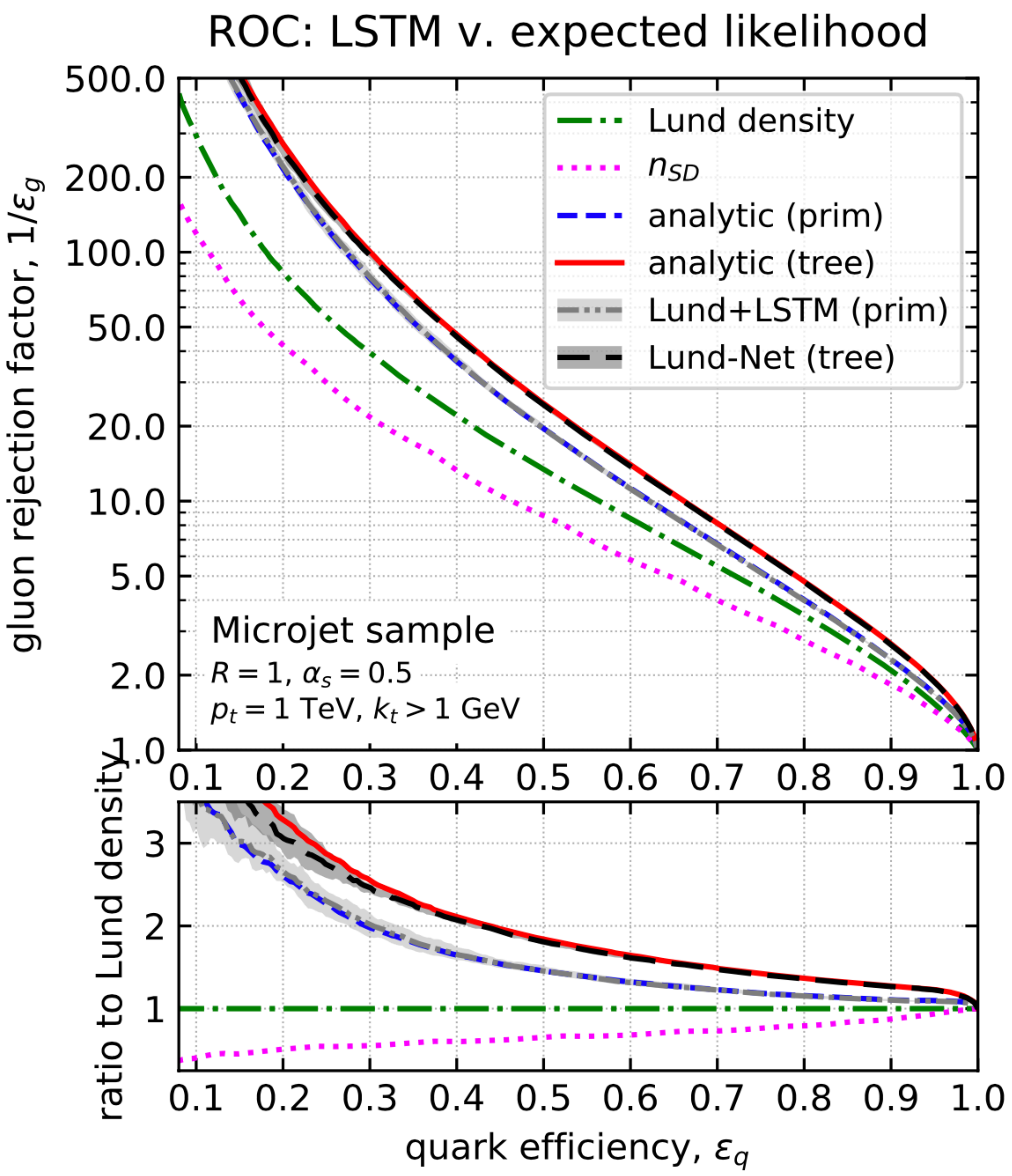
[Dreyer, Soyez, Takacs (2112.09140)]

We can work in a setup in which the analytic approach corresponds to the exact likelihood-ratio discriminant (similarly to [Kasieczka, Marzani, Soyez, GS (2007.04319)]): events generated in the strong strong-angular-ordered limit → ML gives same performance

Moving progressively to the single-logarithmic asymptotic limit, $\alpha_s \to 0$ at fixed as $\alpha_s \ln(Q/k_{t,\text{cut}})$, the difference between the two approaches reduces.







Quark/gluon discrimination

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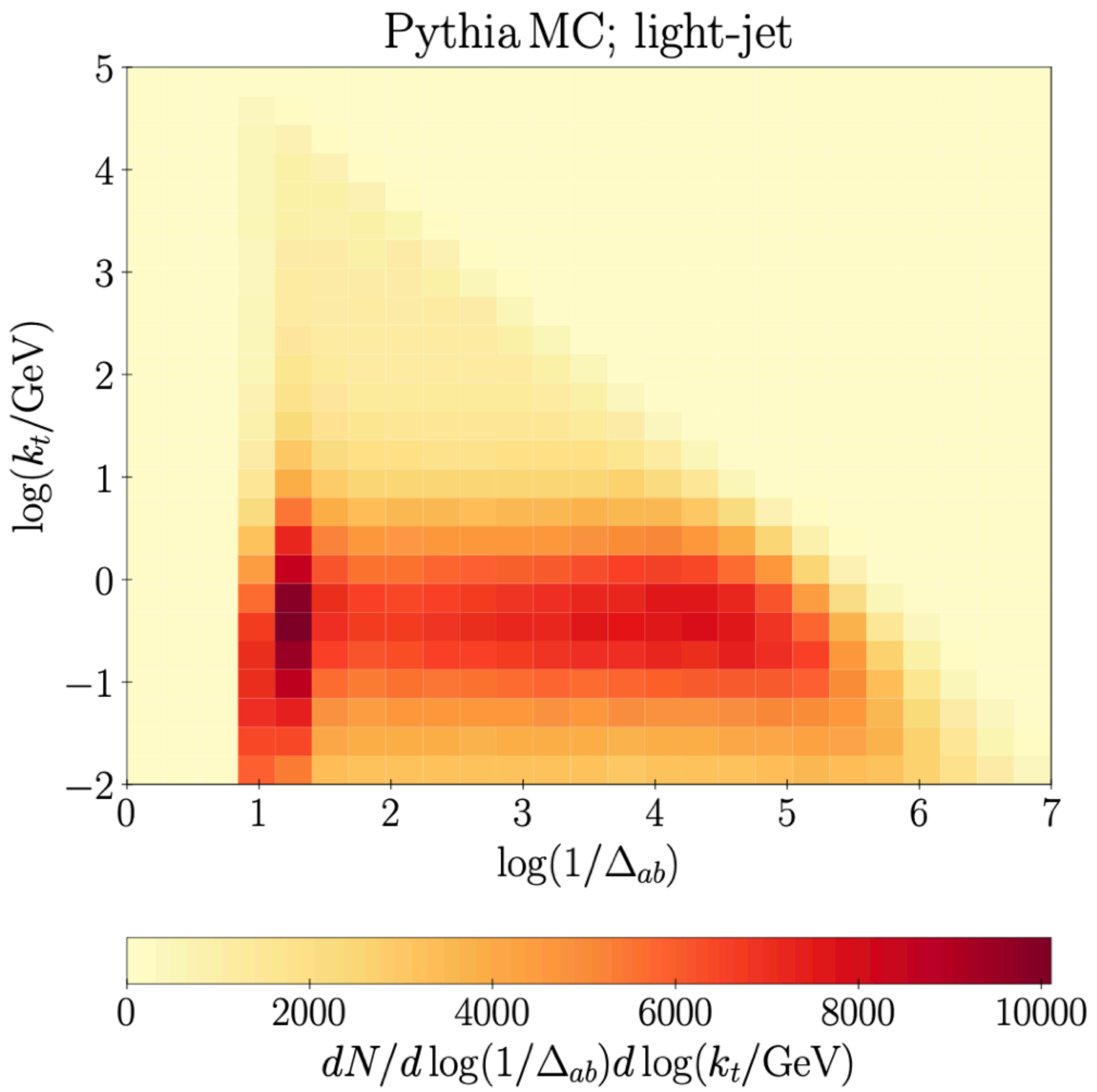
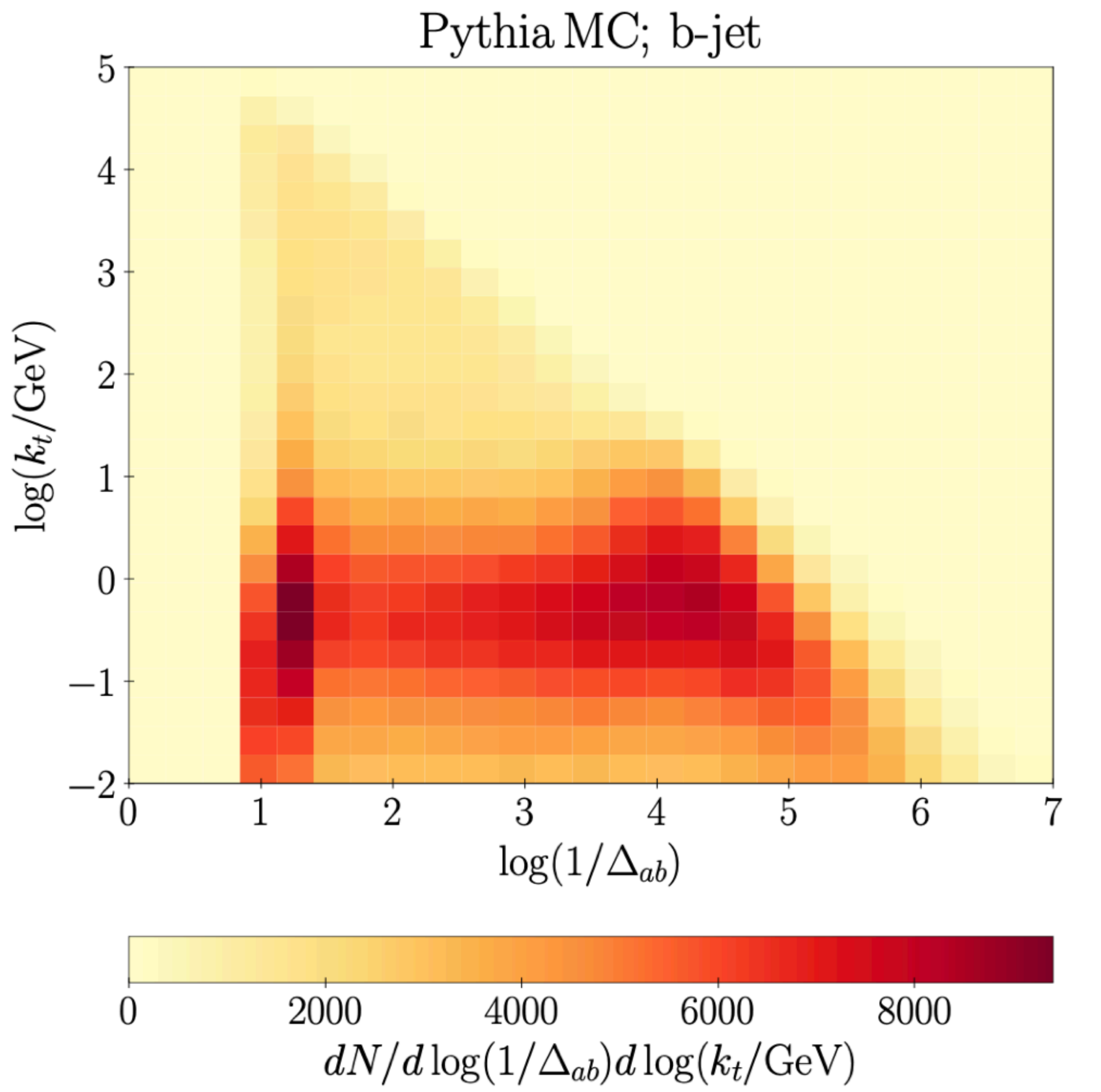
Moving progressively to the single-logarithmic asymptotic limit, $\alpha_s \to 0$ at fixed as $\alpha_s \ln(Q/k_{t,\mathrm{cut}})$, the difference between the two approaches reduces.

Gain in performance for ML come from effects that are not fully under control (subleading effects beyond single logarithms, large-angle soft emissions, non-perturbative effects)

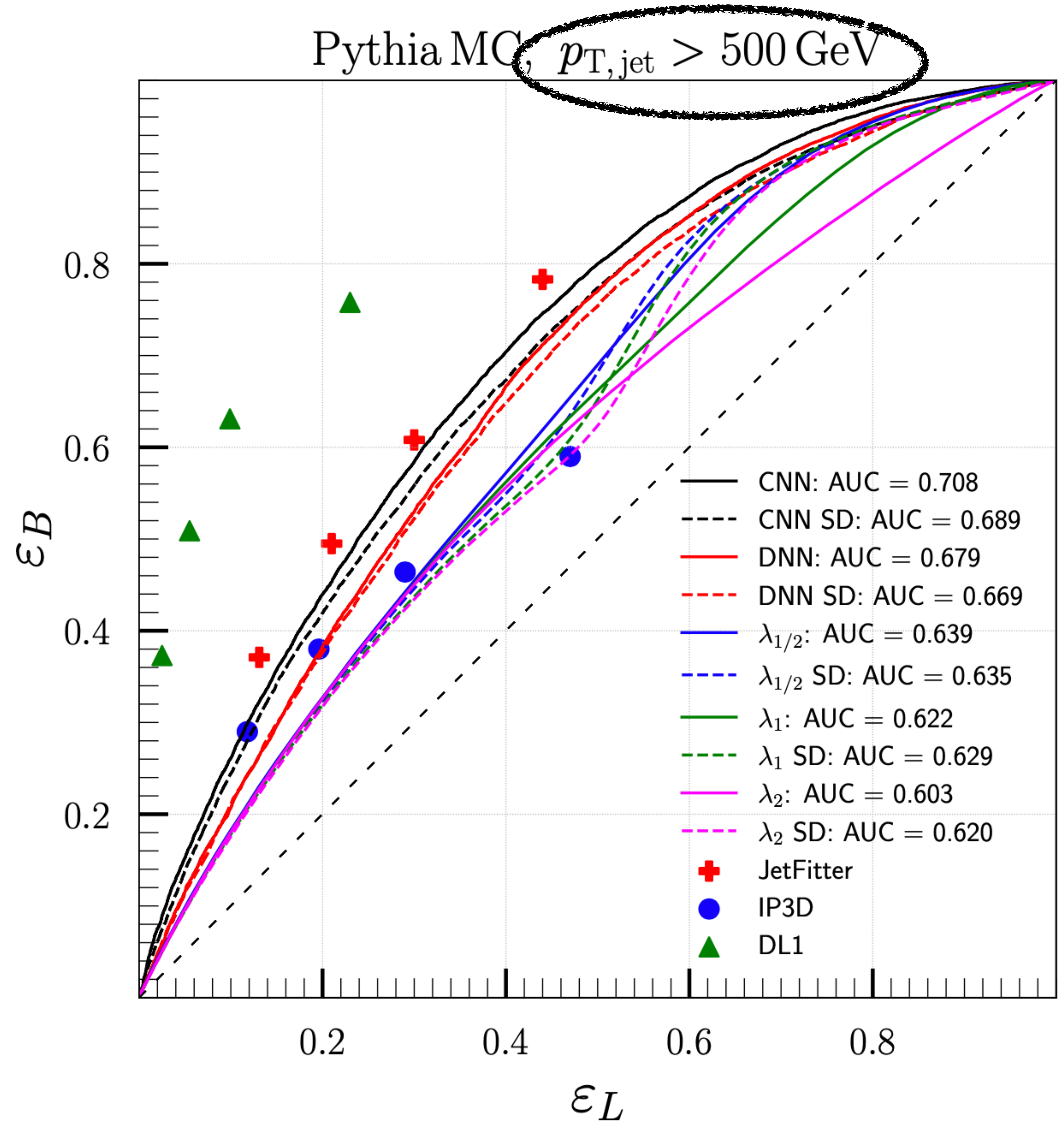
Tagging b-jets

[Fedkevych, Khosa, Marzani, Sforza (2202.05082)]





Study in the boosted region (where b-tagging performance usually degrades)



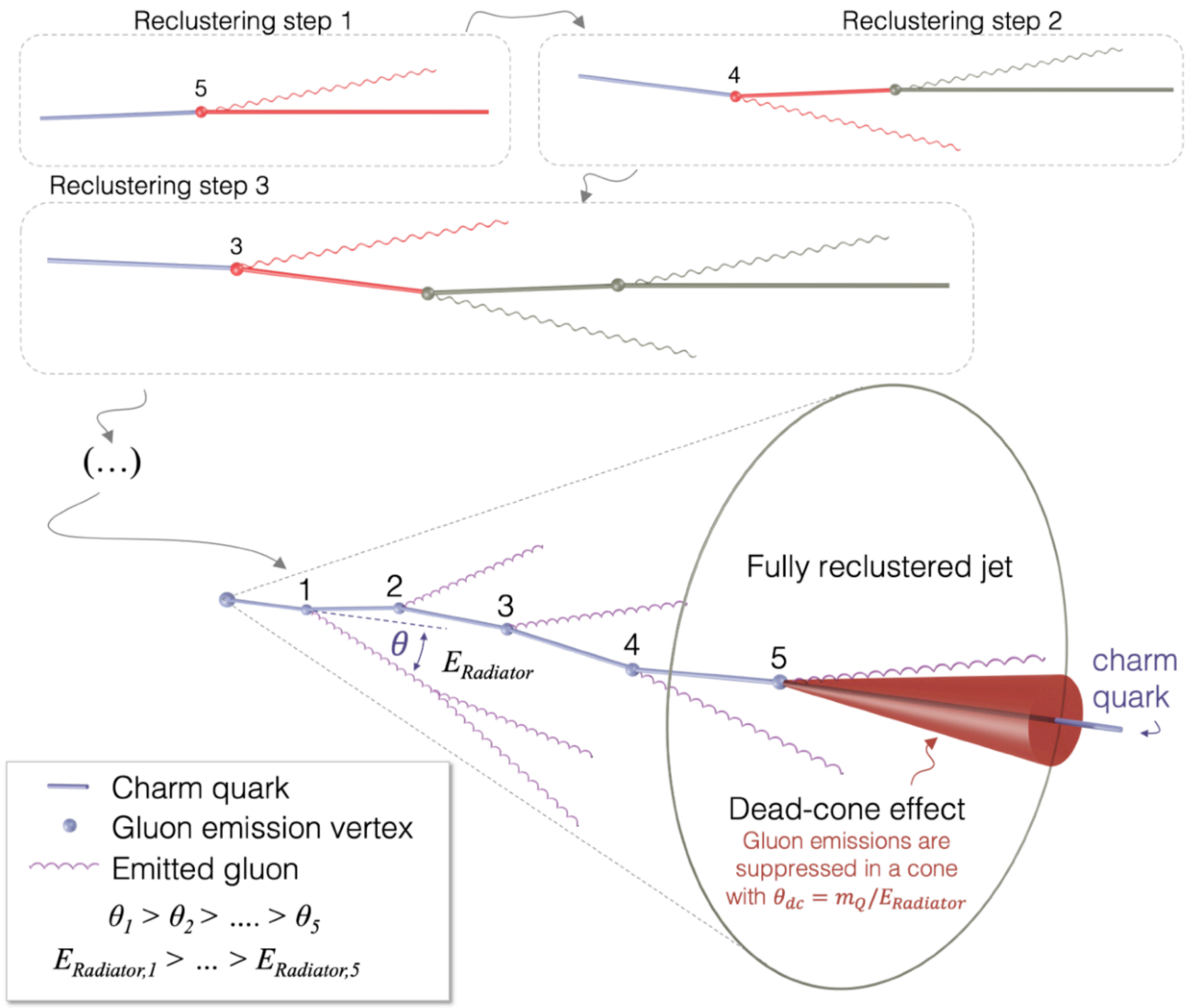
- CNN on primary Lund plane
- DNN is a combination of angularities (single-variable discriminants)
- JetFitter and IP3D are low-level algorithms based on charged particle track reconstruction
- DL1 is a high-level tagger, combining low-level ones

Lund plane CNN has performances similar to dedicated b-tagging algorithms

Lund Plane & heavy quarks

Dead-cone effect

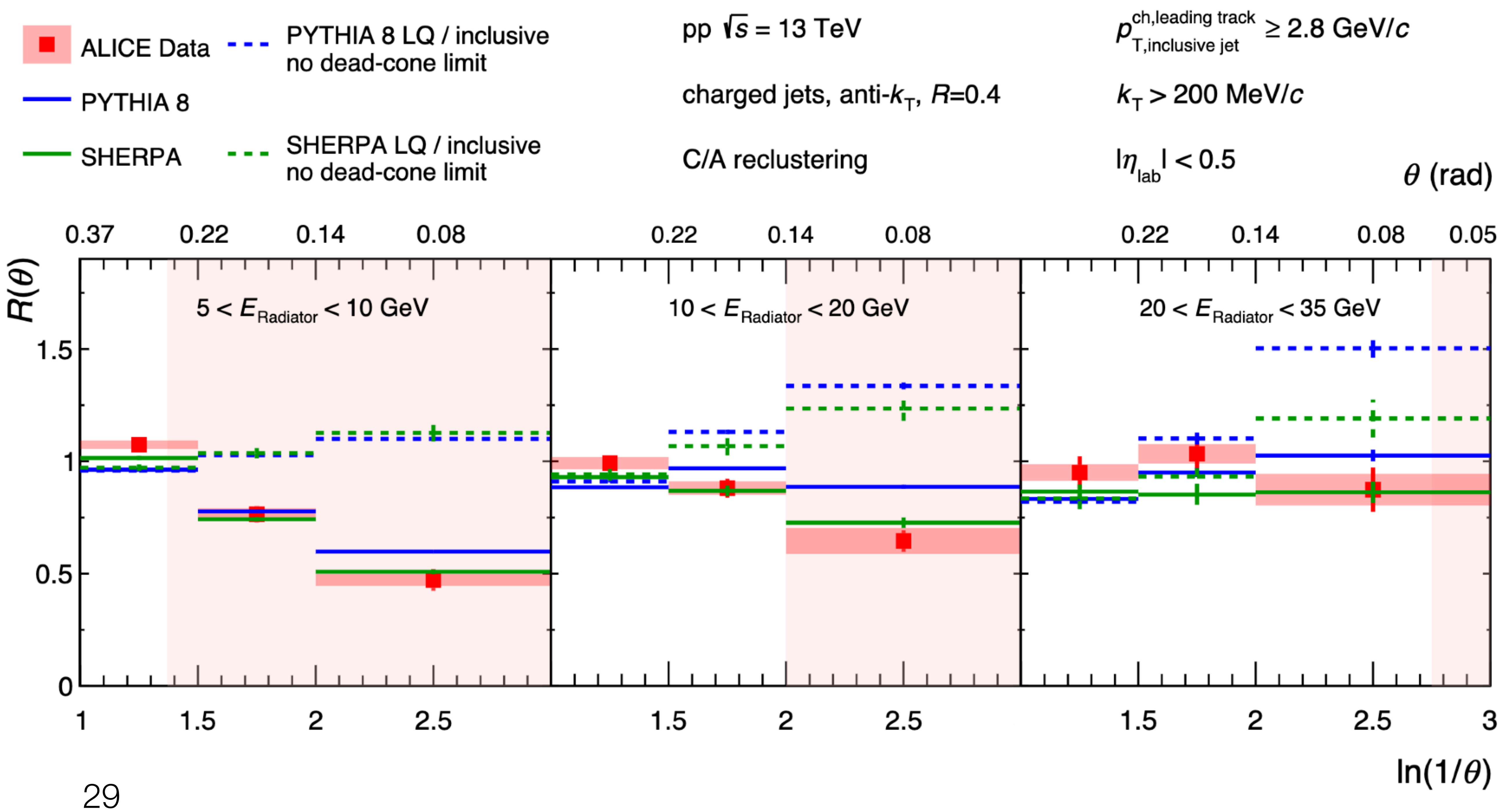
[ALICE (2106.05713) Nature 605 (2022)]



The technique introduced in [Cunqueiro, Ploskon (1812.00102)] is based on a C/A declustering sequence, following the D^0

Observation of dead-cone effect from measurement of angular distribution

$$R(\theta) = \frac{1}{N^{D^0\,\text{jets}}} \frac{dn^{D^0\,\text{jets}}}{d\ln(1/\theta)} \Big/ \frac{1}{N^{\text{inclusive jets}}} \frac{dn^{\text{inclusive jets}}}{d\ln(1/\theta)} \Bigg|_{k_T, E_{\text{Radiator}}}$$

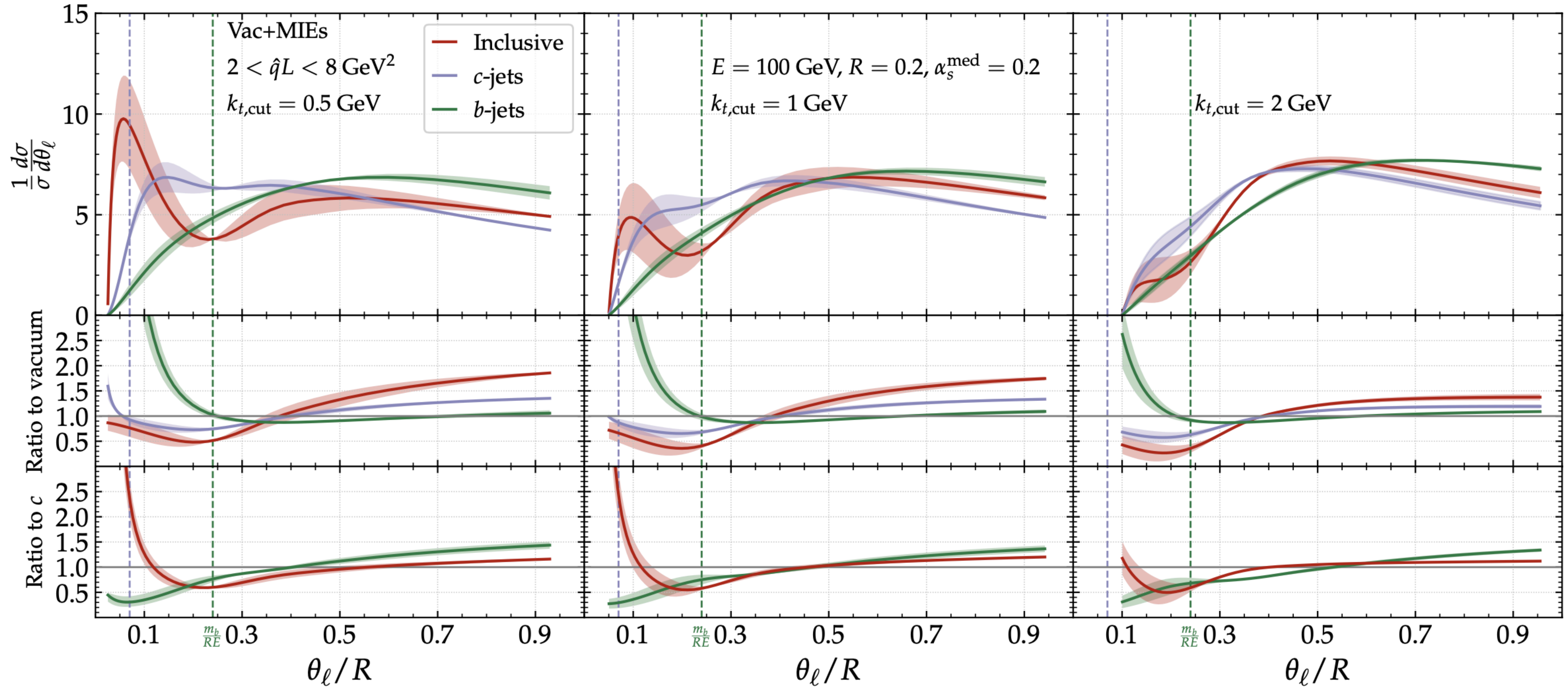


Dead-cone searches in heavy-ion

[Cunqueiro, Napoletano, Soto-Ontoso (2211.11789)]

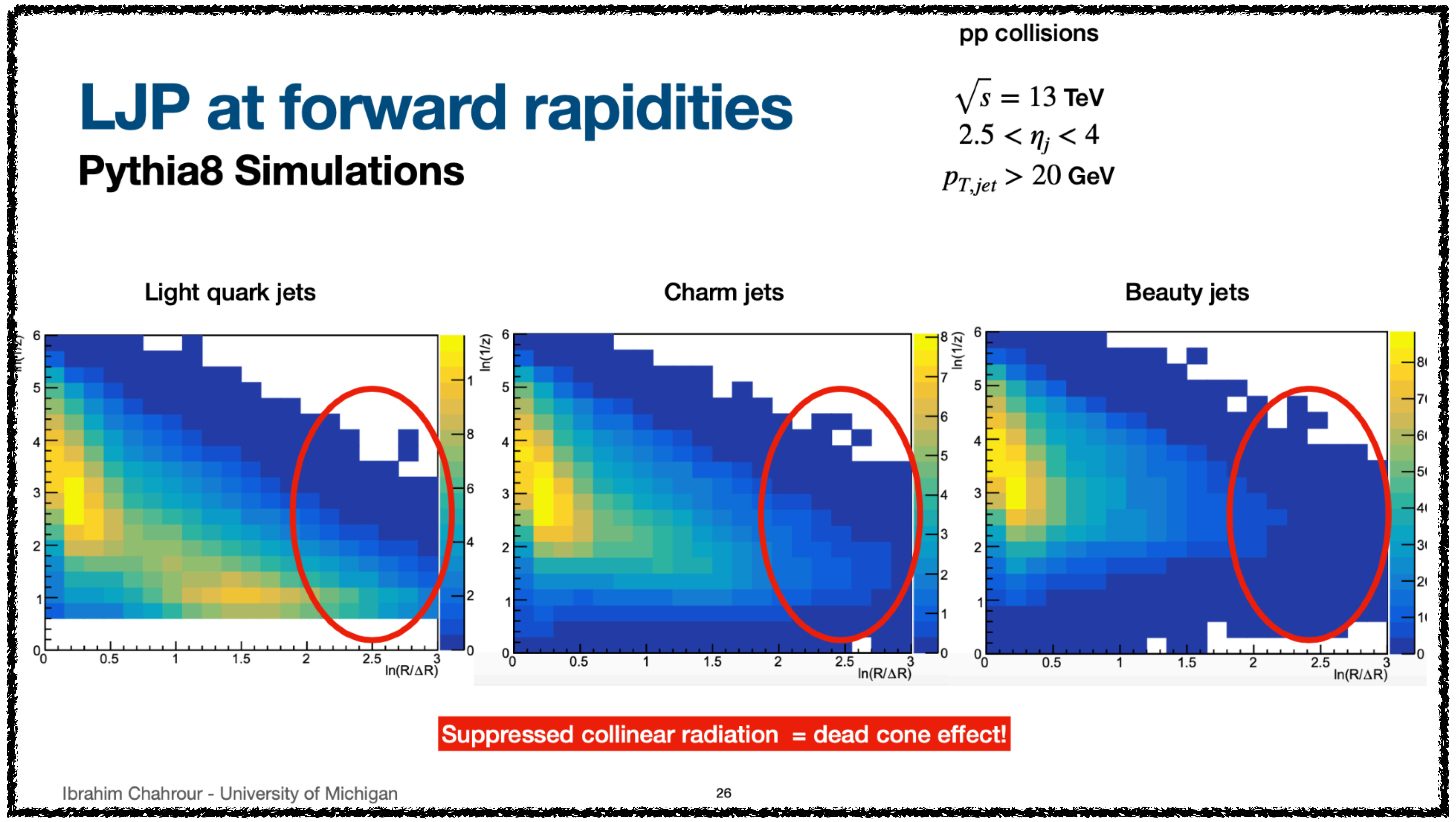
New groomer (Late-k_t), selecting the most collinear splitting above a certain $k_{t,\mathrm{cut}}$

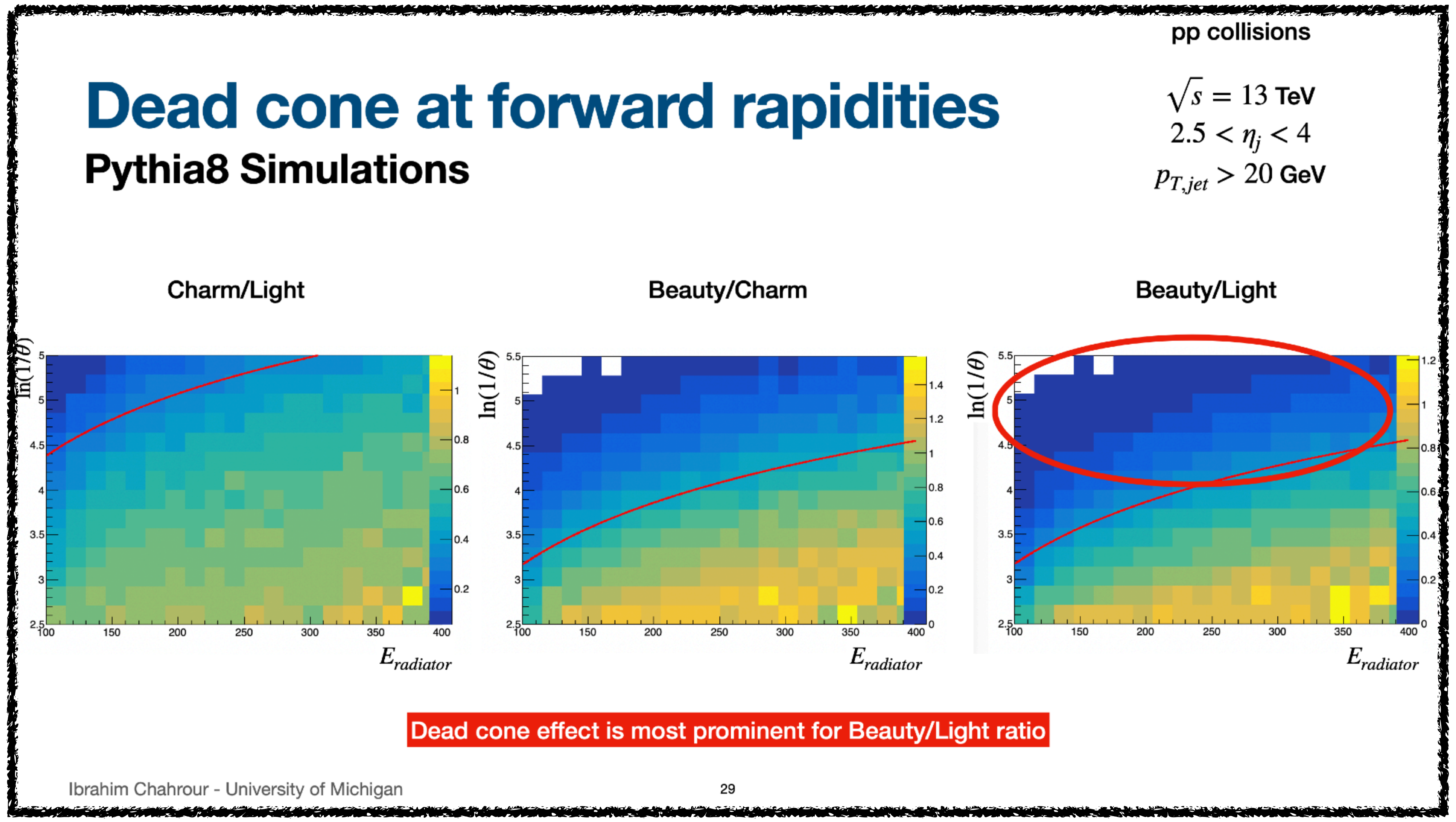
→ suited to heavy-ion environment (reduces the impact of uncorrelated thermal background, typically manifest as fake large angle splittings)



Also LHCb in the game

[slides of Ibrahim Chahrour, on behalf of the LHCb collaboration, DIS2023]





Conclusions and outlook

Lund (jet) plane is a **unique tool** for collider phenomenology:

- Clear separation of perturbative and non-perturbative regimes
  → extraction of strong coupling constant?
- Sensitivity to disparate scales, from few GeV up to several TeV
  → ideal tool for resummation and Parton Showers (PS) studies
- Observables based on Lund plane amenable to calculability up to high orders
  → precise comparisons with data and benchmark calculations
- Lund trees or images as theory-friendly input to machine learning algorithms
  → good performance and resilience at the same time

First Lund Jet Plane Institute

Jul 3 – 7, 2023
CERN
Europe/Zurich timezone

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TH workshop secretariat or workshop organisers

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Jet substructure techniques are now routinely used in collider phenomenology. This specialised workshop evolves around a recent tool called the Lund Jet Plane(s). The main idea is to use the Cambridge/Aachen clustering technique (i.e. a roughly angular-ordered clustering tree) to associate a kinematic structure, akin to the Lund planes used in resummations and in Monte Carlo generators, to a high-energy jet. This structure can then be used in a wide range of applications. The goal of this workshop is to provide a theoretical and experimental overview of these applications and their connections with other tools in the field. A special emphasis will be put on recent developments and on discussions of future potential directions. This includes the following list of topics:

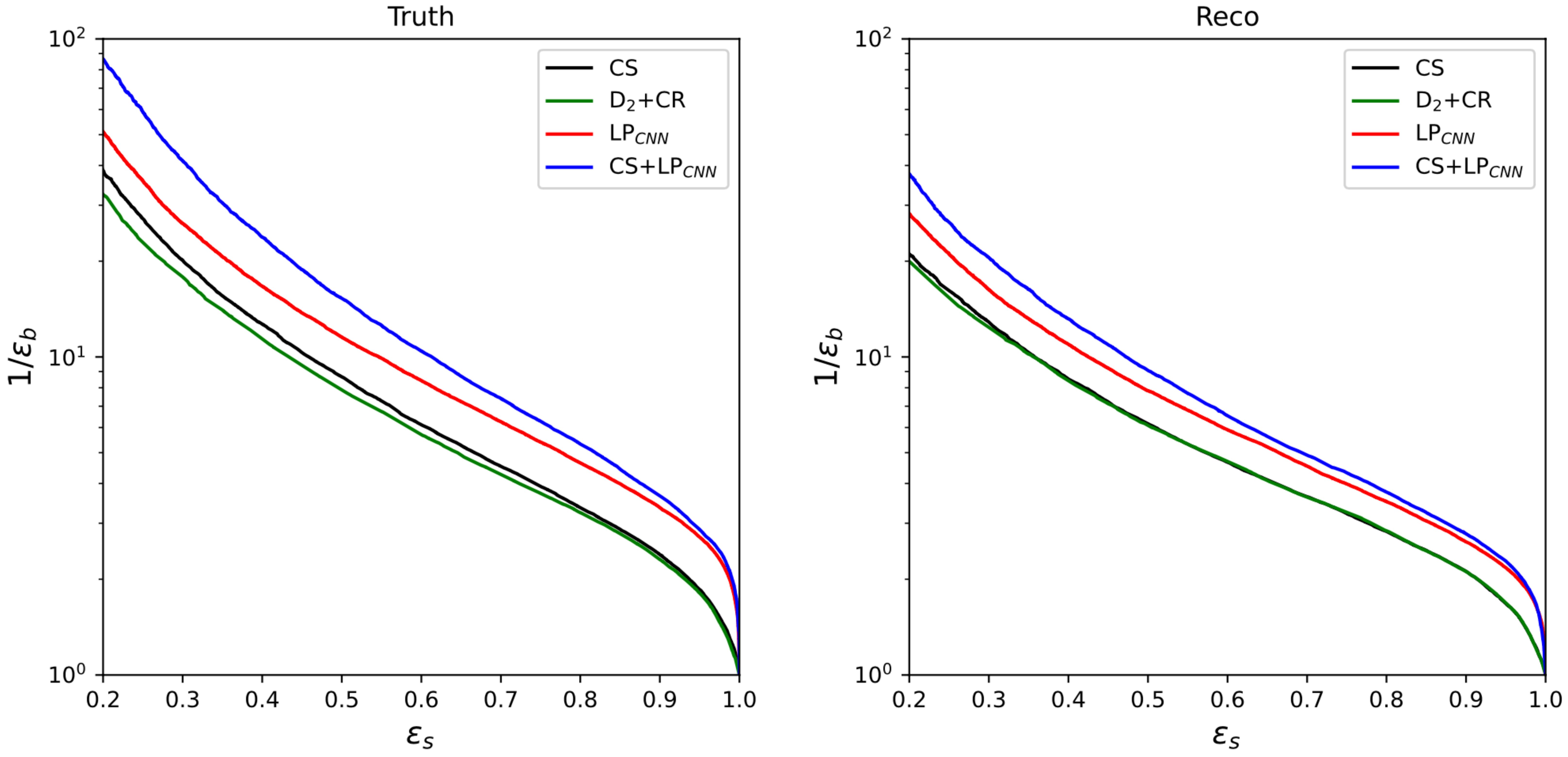
- Constraints on Monte Carlo generators from Lund plane density measurements
- Tagging of light-quarks vs. gluon
- Boosted V/H/t vs. QCD jets discrimination
- Mass effects in the Lund plane (dead cone, heavy flavor tagging)
- Applications to BSM searches
- Studies of the quark-gluon-plasma in heavy-ion collisions
- Jet substructure measurements (generalised angularities, groomed observables,..)
- Machine learning tools (e.g., LundNet, ParticleNet, GNN)
- Lund-plane observables to constrain parton showers with N^kLL resummation
- Strategies to mitigate quark/gluon fraction issues.
- Possible α_s extractions with jet substructure.

BACKUP

[Cavallini, GS et al. (2112.09650)]

“CS” = BDT architecture on high-level color-sensitive variables (CS): pull angle θ_p, components of the pull vector $t_{\|}$ and $t_{\perp}$, color ring $\mathcal{O}$ (CR), D_2

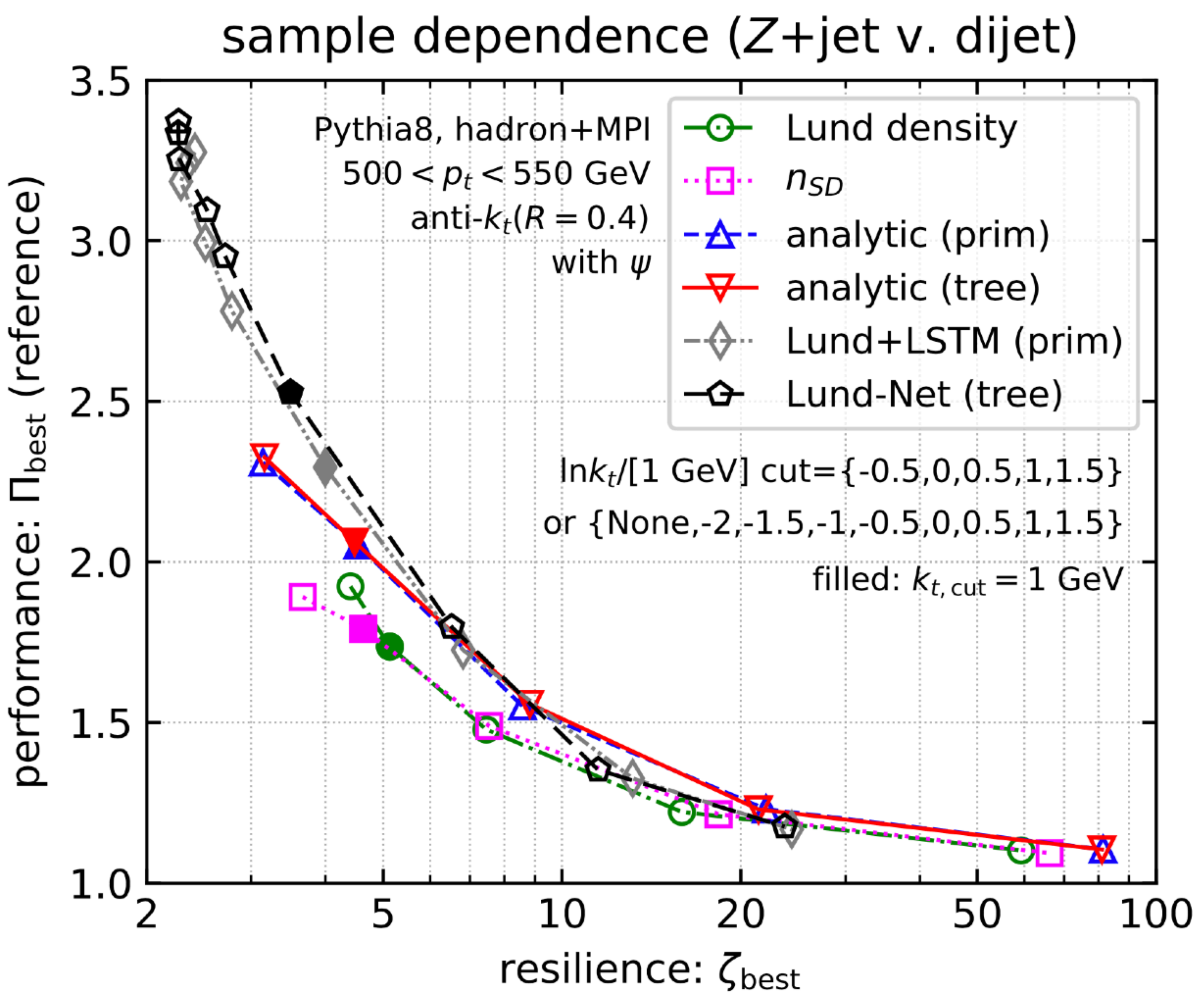
“CS + LP_{CNN}” = BDT combined with CNN trained on Lund plane images

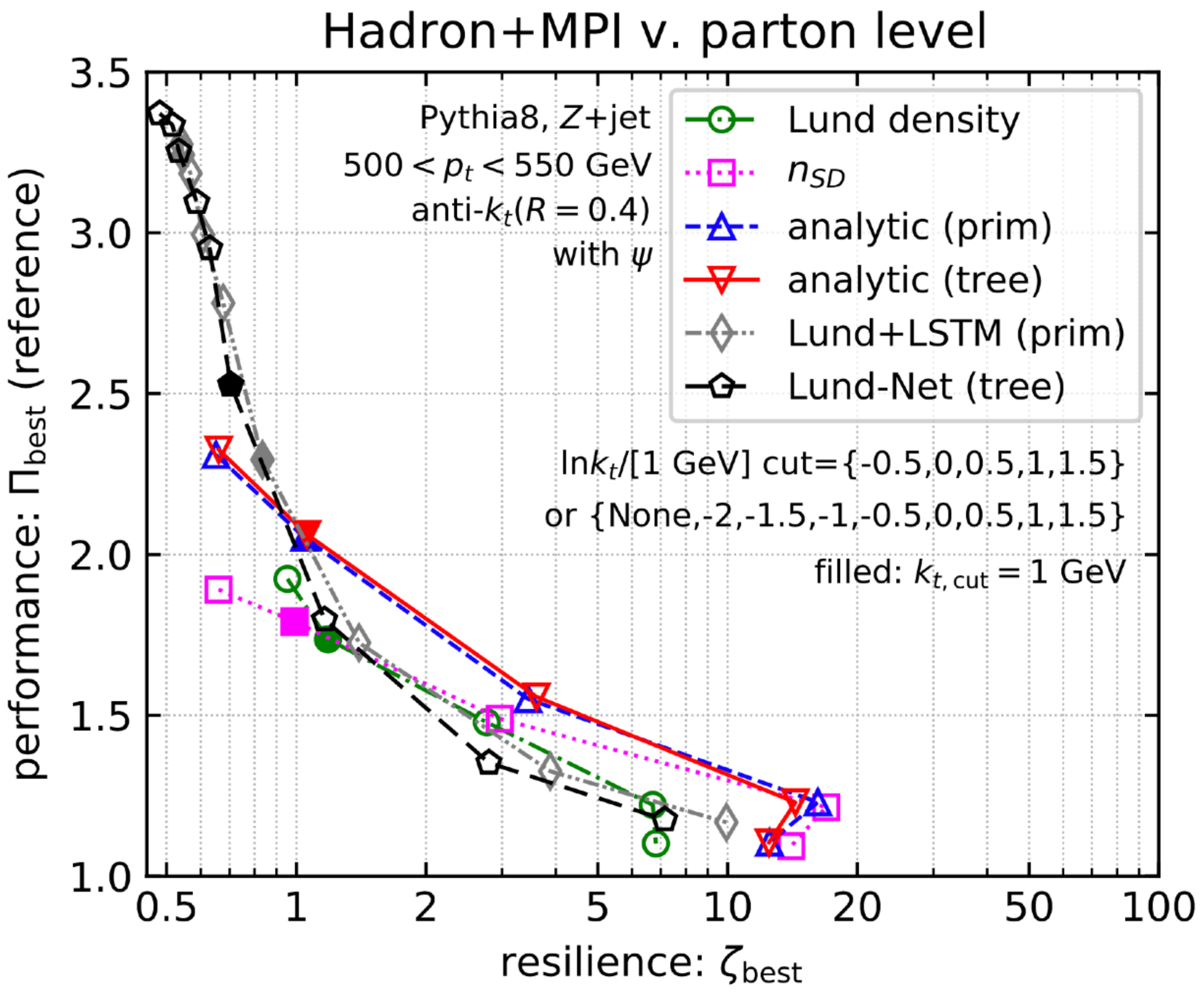


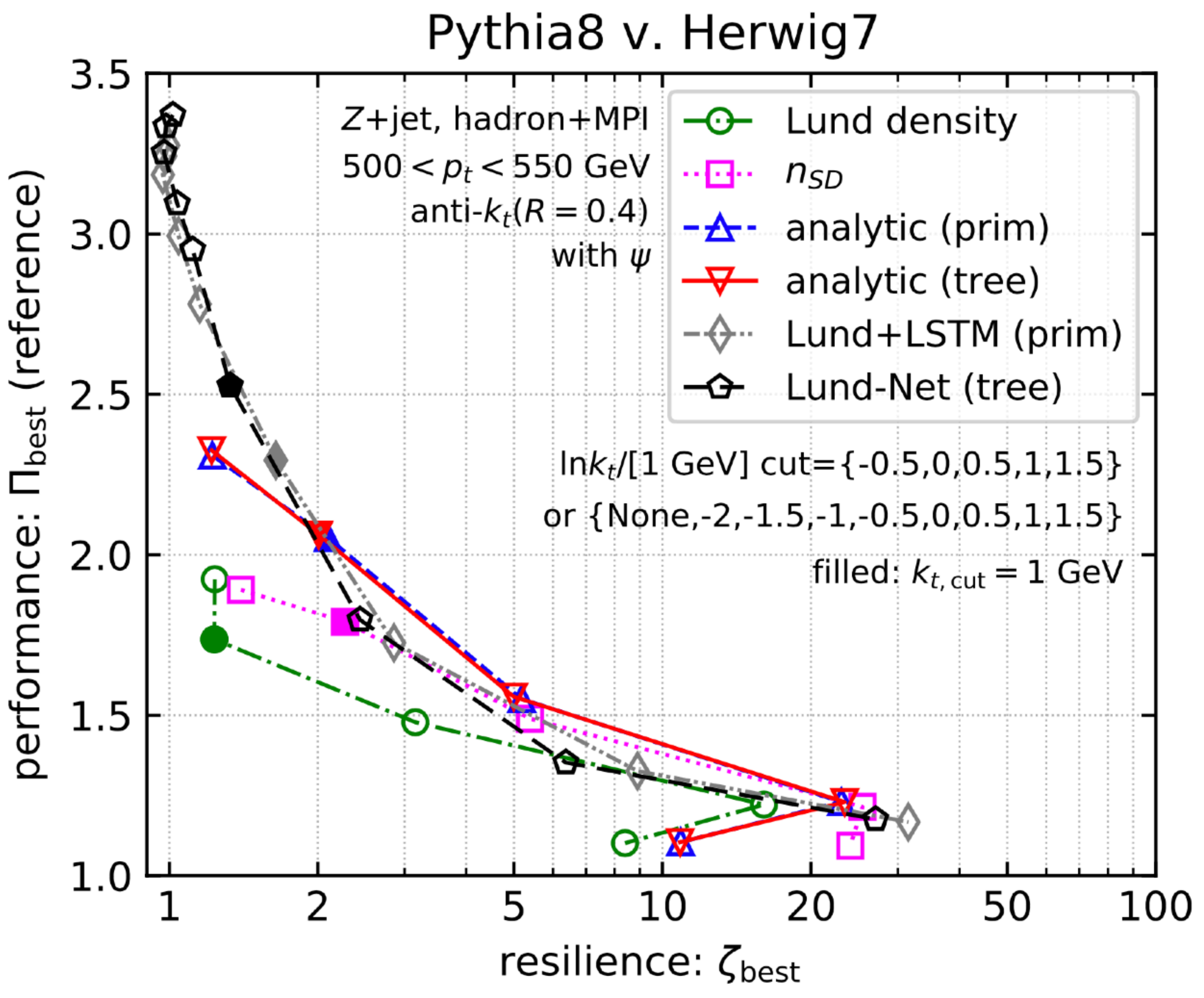
$$\mathcal{O} = \frac{\Delta_{ka}^2 + \Delta_{kb}^2}{\Delta_{ab}^2}$$

Quark/gluon discrimination

[Dreyer, Soyez, Takacs (2112.09140)]

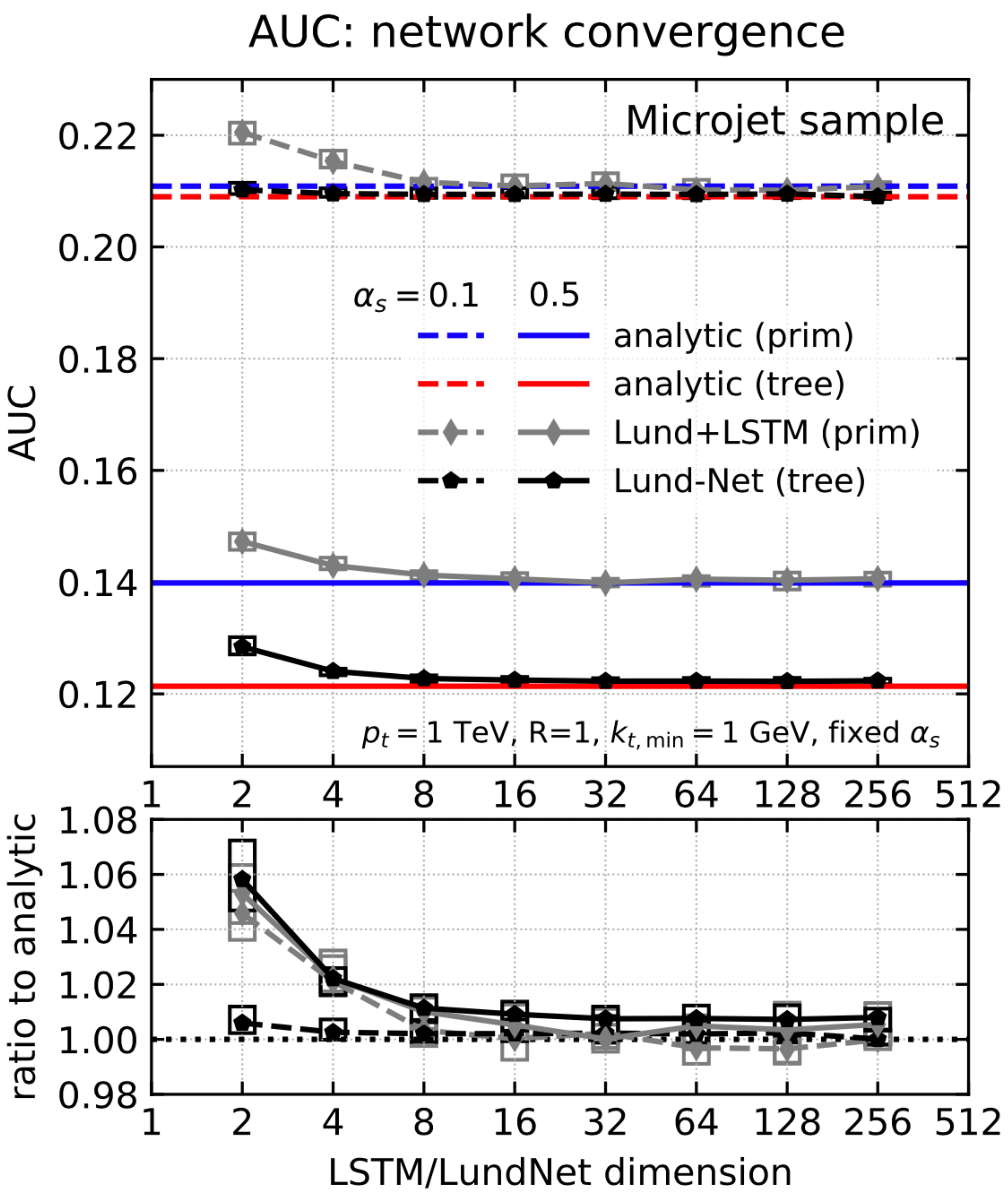






Quark/gluon discrimination

[Dreyer, Soyez, Takacs (2112.09140)]



[Dreyer, Salam, Soyez (1807.04758)]