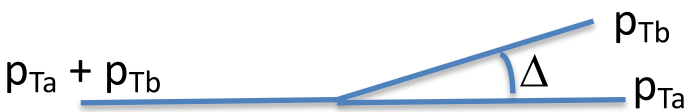

# LUND PLANE AND APPLICATIONS

# Jet Lund diagram

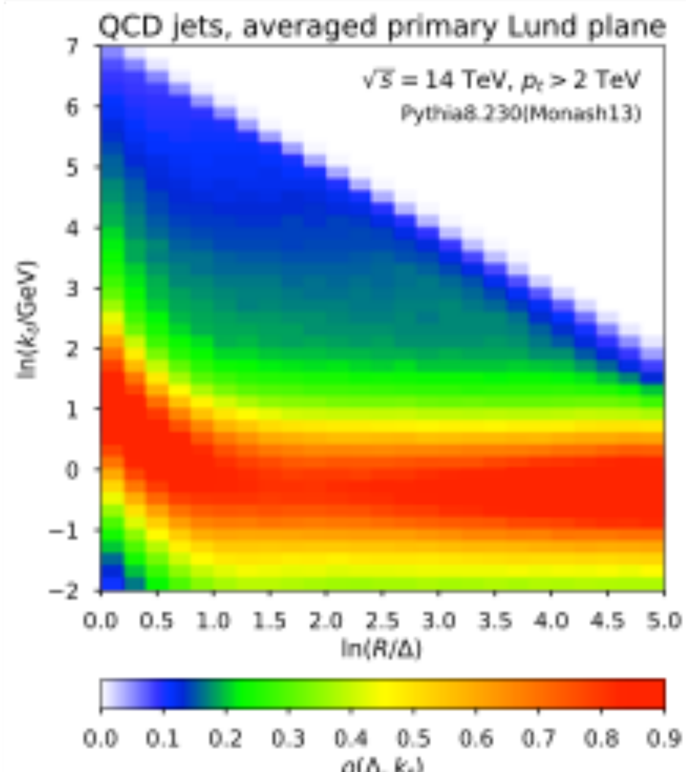
$$p_{T,a} > p_{T,b},\ \kappa = \frac{p_{T,b}}{p_{T,a}+p_{T,b}}\Delta_{ab}$$

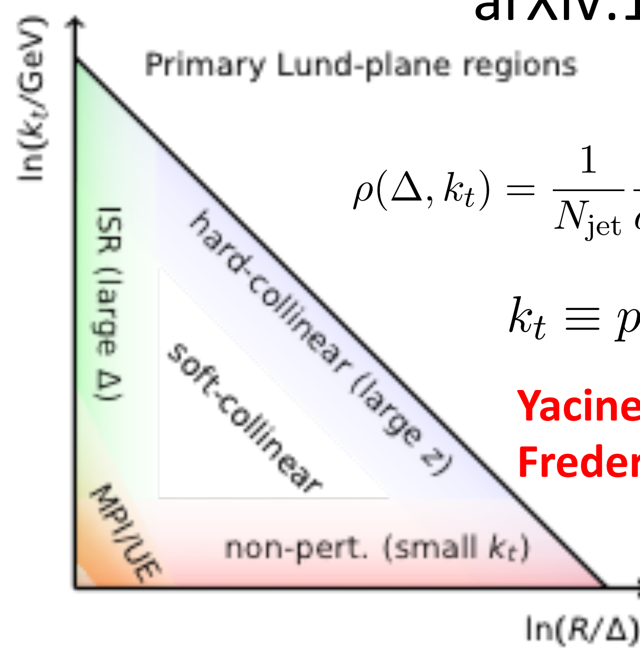



$$\bar{\rho}(\Delta,\kappa) = \frac{1}{N_{\text{jet}}}\frac{dn_{\text{emission}}}{d\ln\kappa\ d\ln 1/\Delta}$$

*Lund diagrams, a theoretical representation of the phase space within jets, have long been used in discussing parton showers and resummations. We point out that they can be created for individual jets through repeated Cambridge/Aachen declustering, providing a powerful visual representation of the radiation within any given jet.*

arXiv:1807.04758




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

$$k_t \equiv p_{tb}\Delta_{ab},$$

**Yacine on Monday…**

**Frederic yesterday…**

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

**Calculable(!)**

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

# Jet Lund diagram

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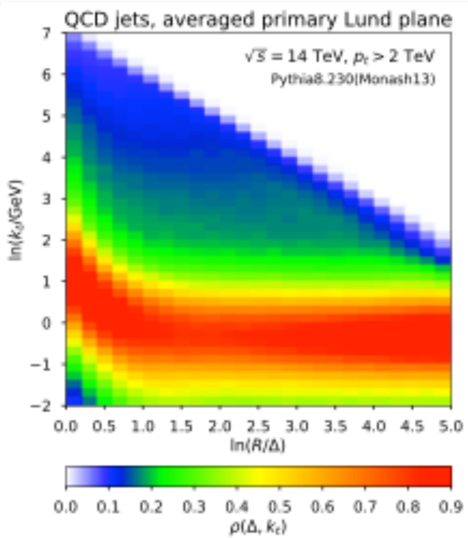
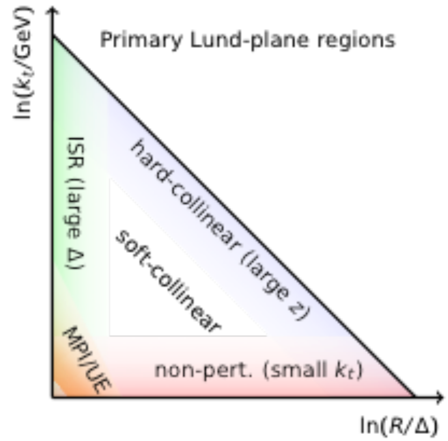
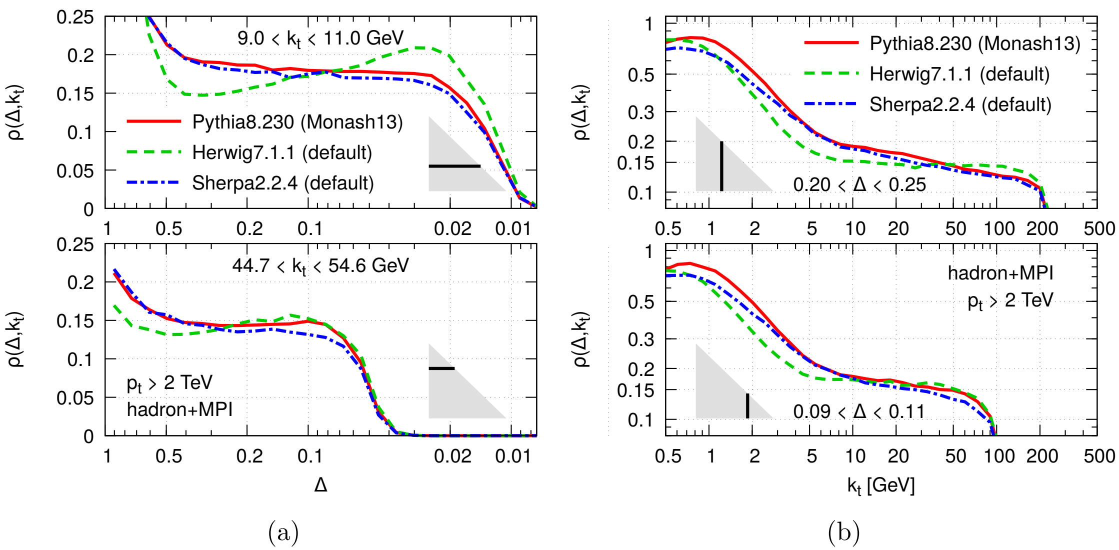
- Comparison of event generators
- Use for ML – jet ID (RHS below: boosted electroweak boson tagging at high momenta)



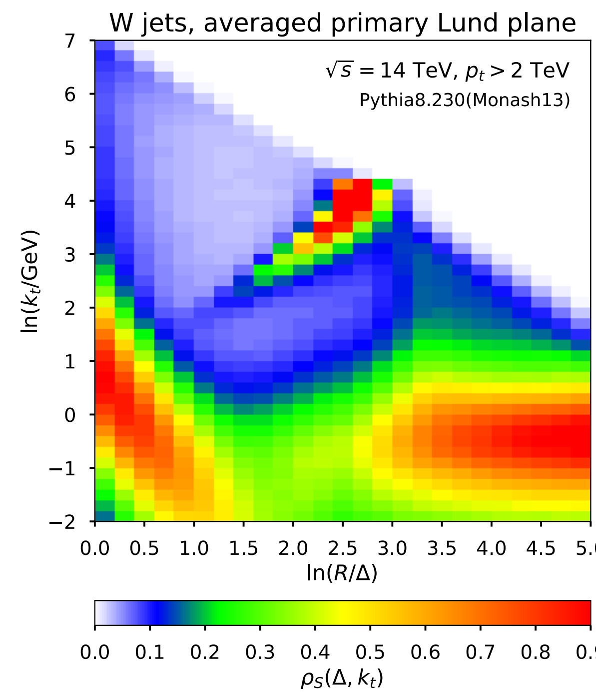
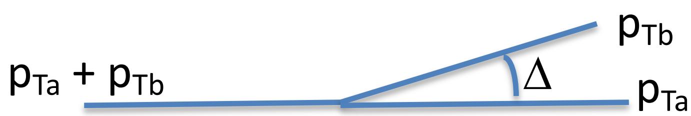
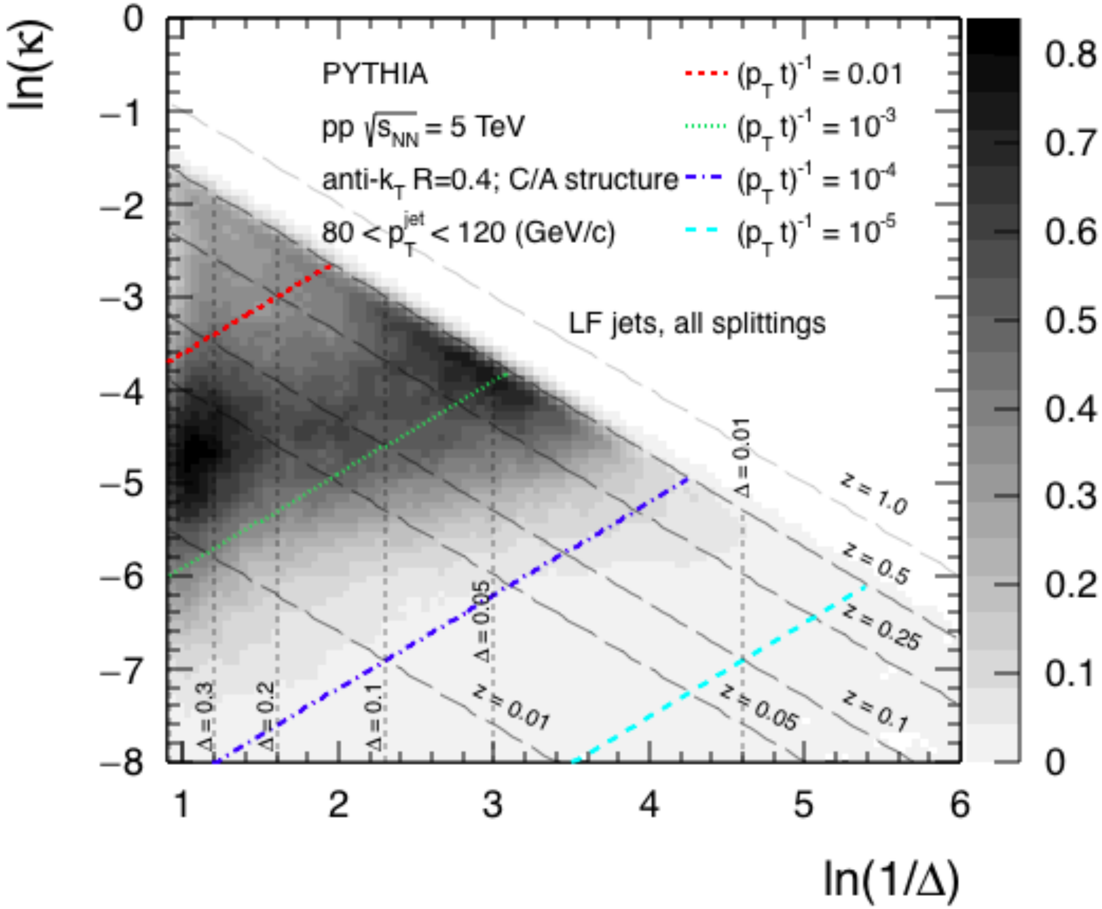




**Figure 3**: Emission density along slices of the Lund plane, at fixed $k_t$ (top) and $\Delta$ (bottom), comparing three event generators.

# Declusterization

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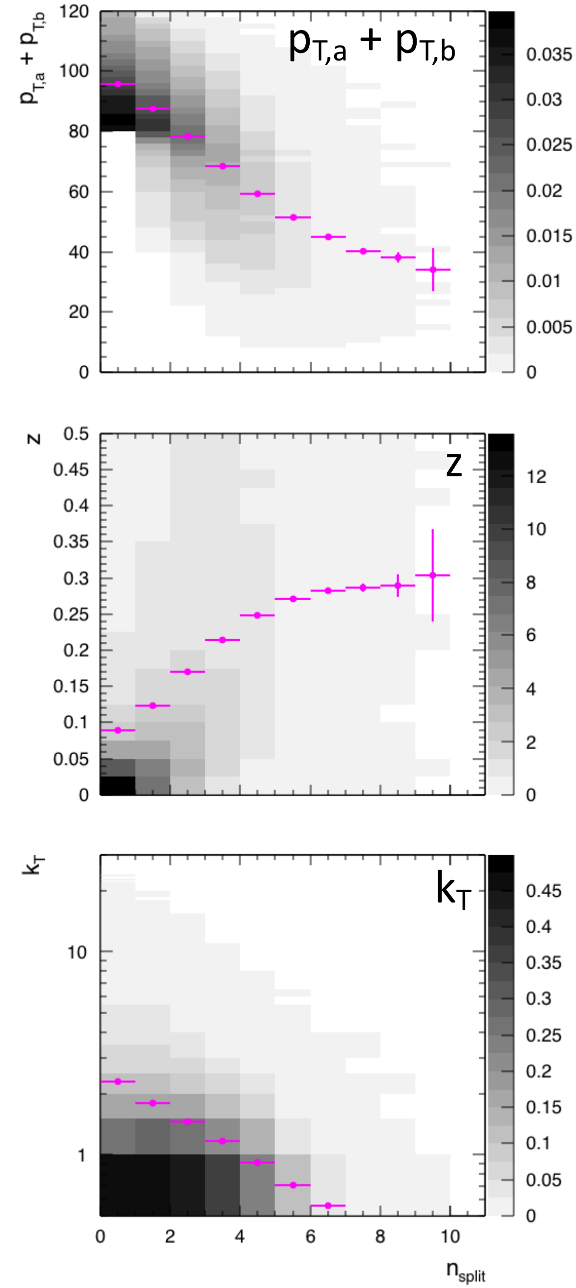




Note: structures from MPI, ISR, FSR,

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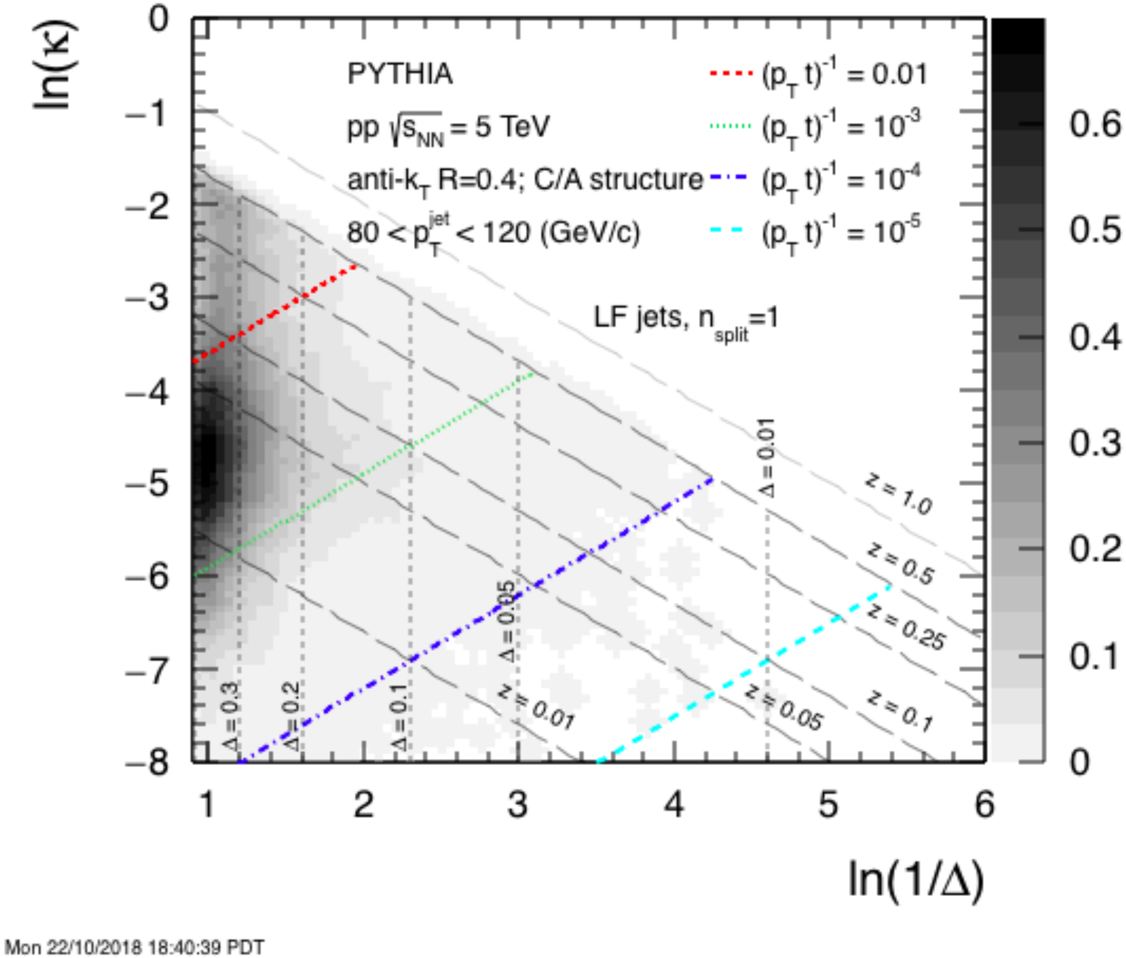


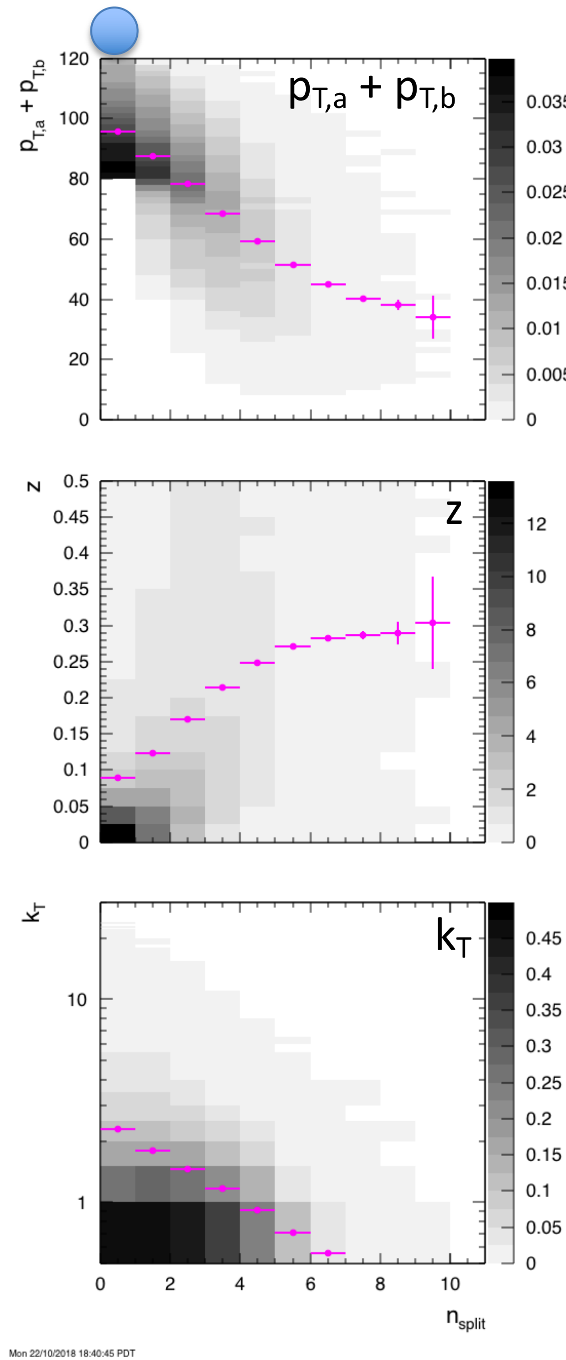

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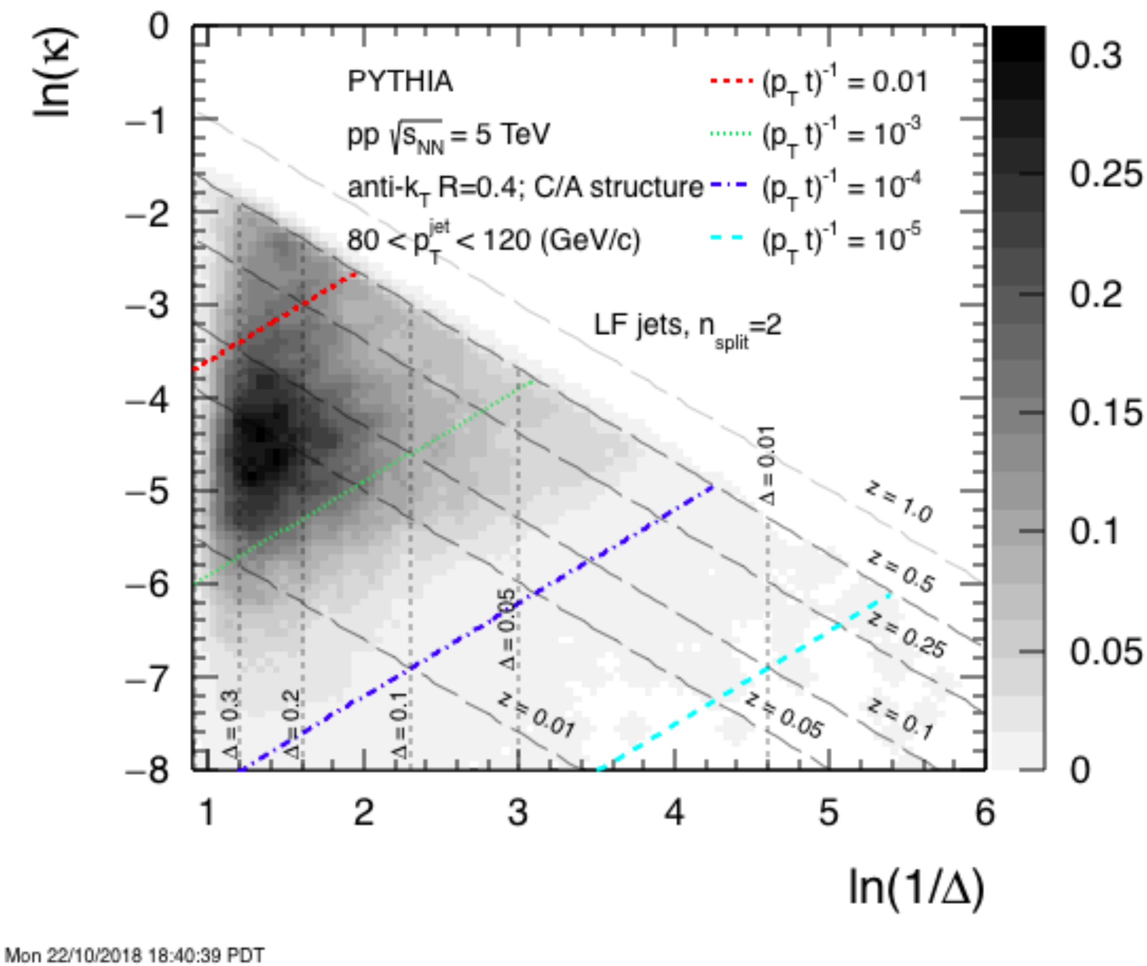


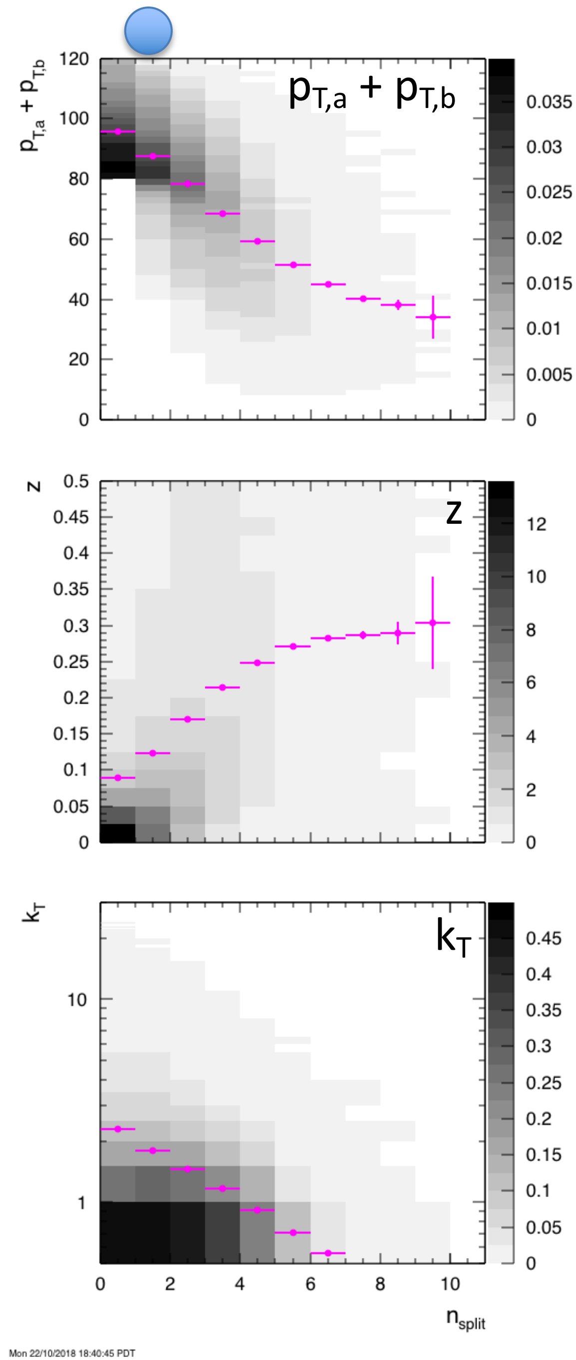

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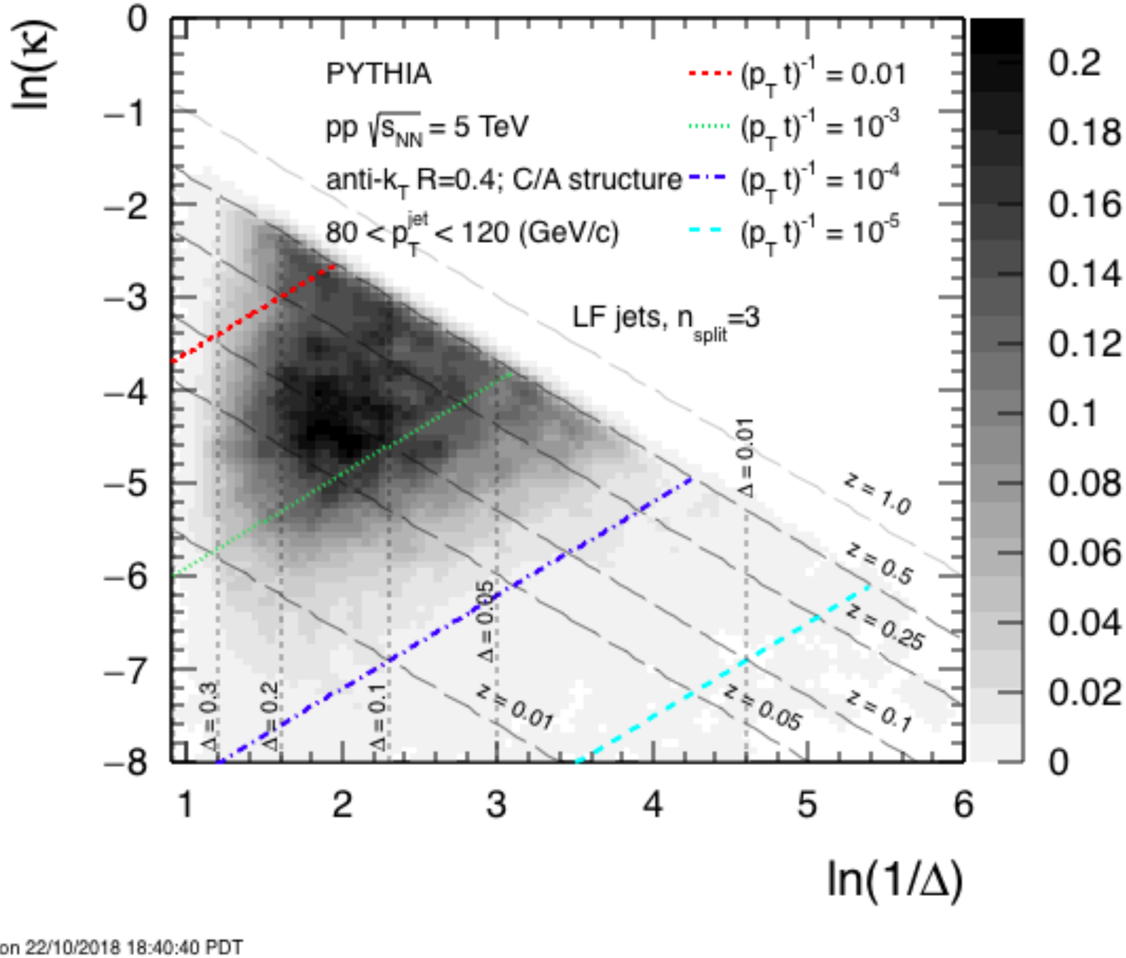


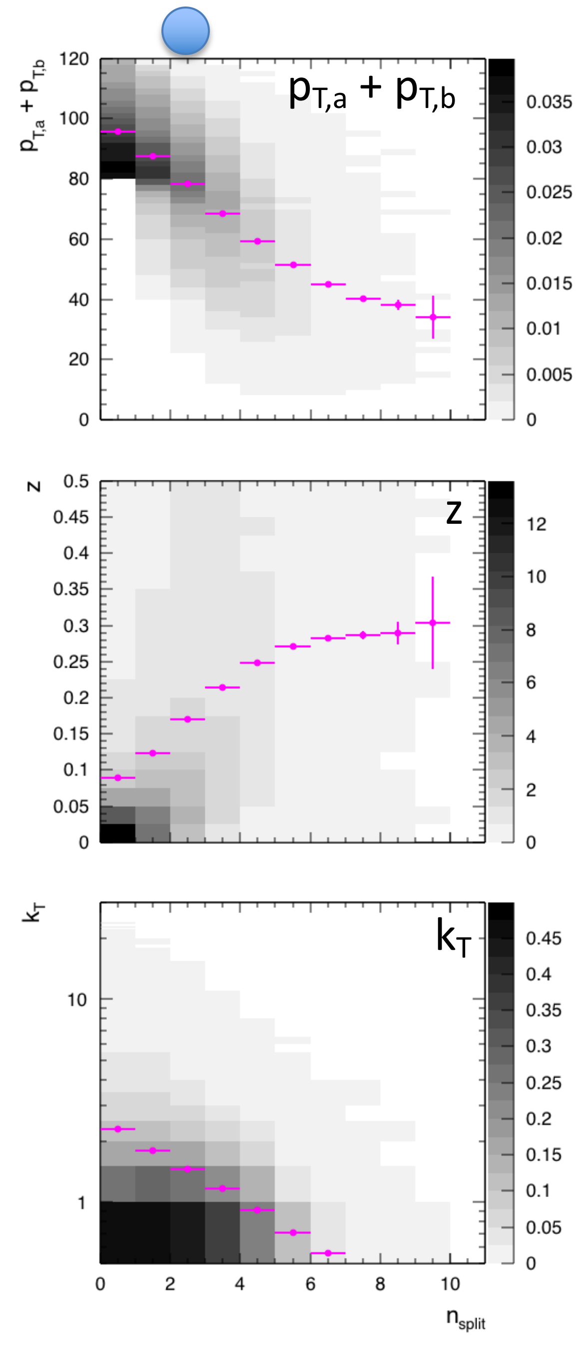

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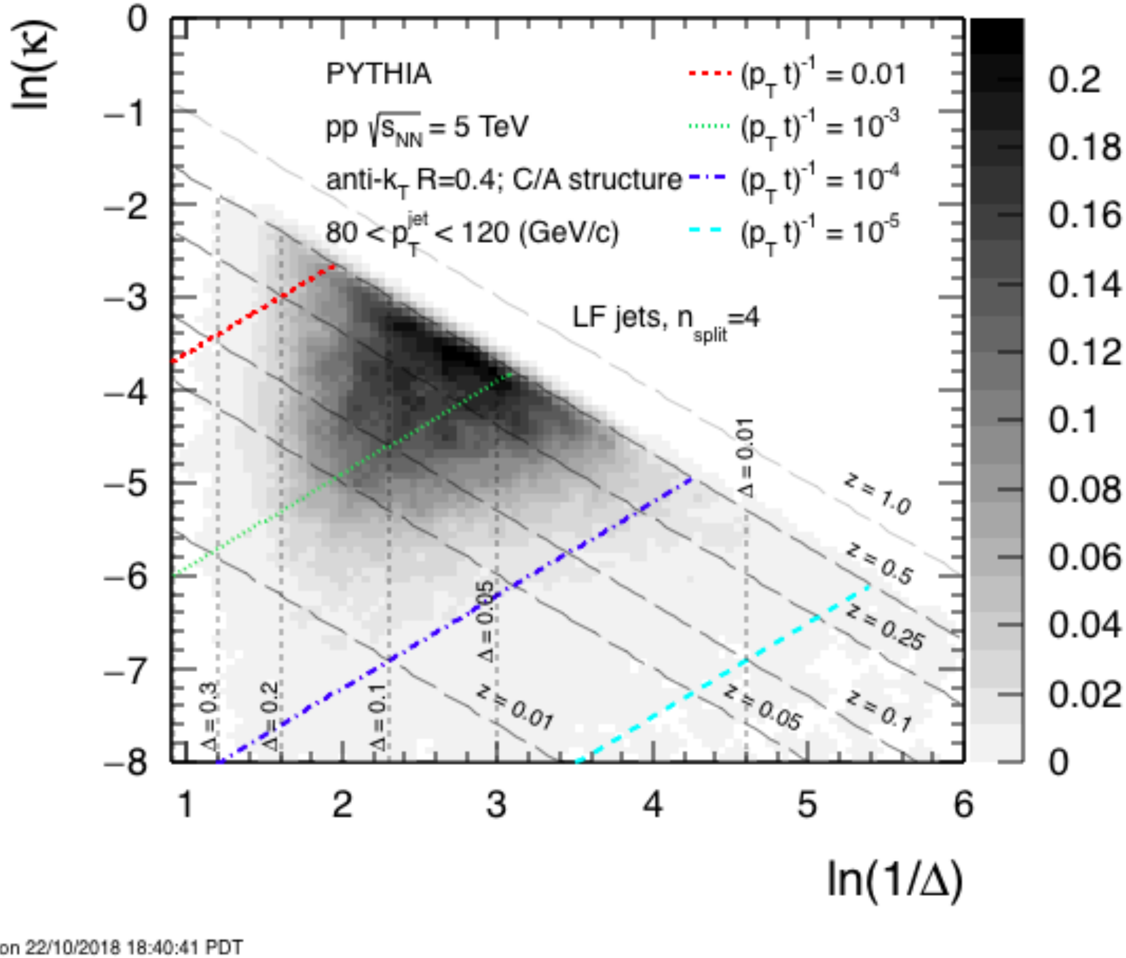


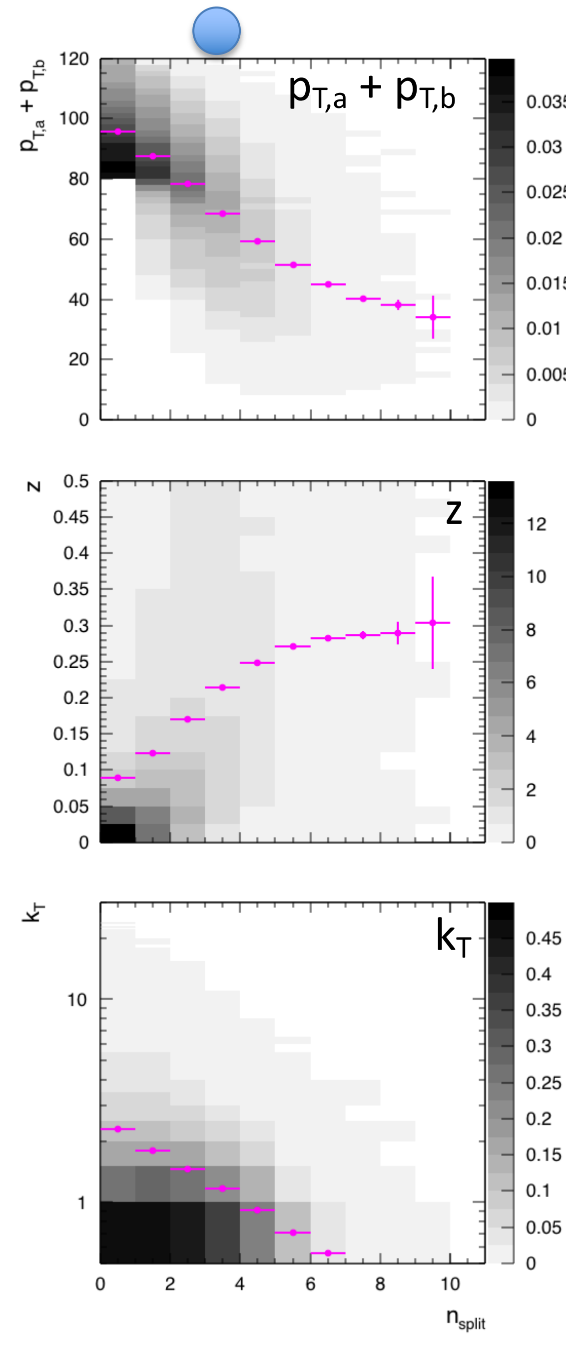

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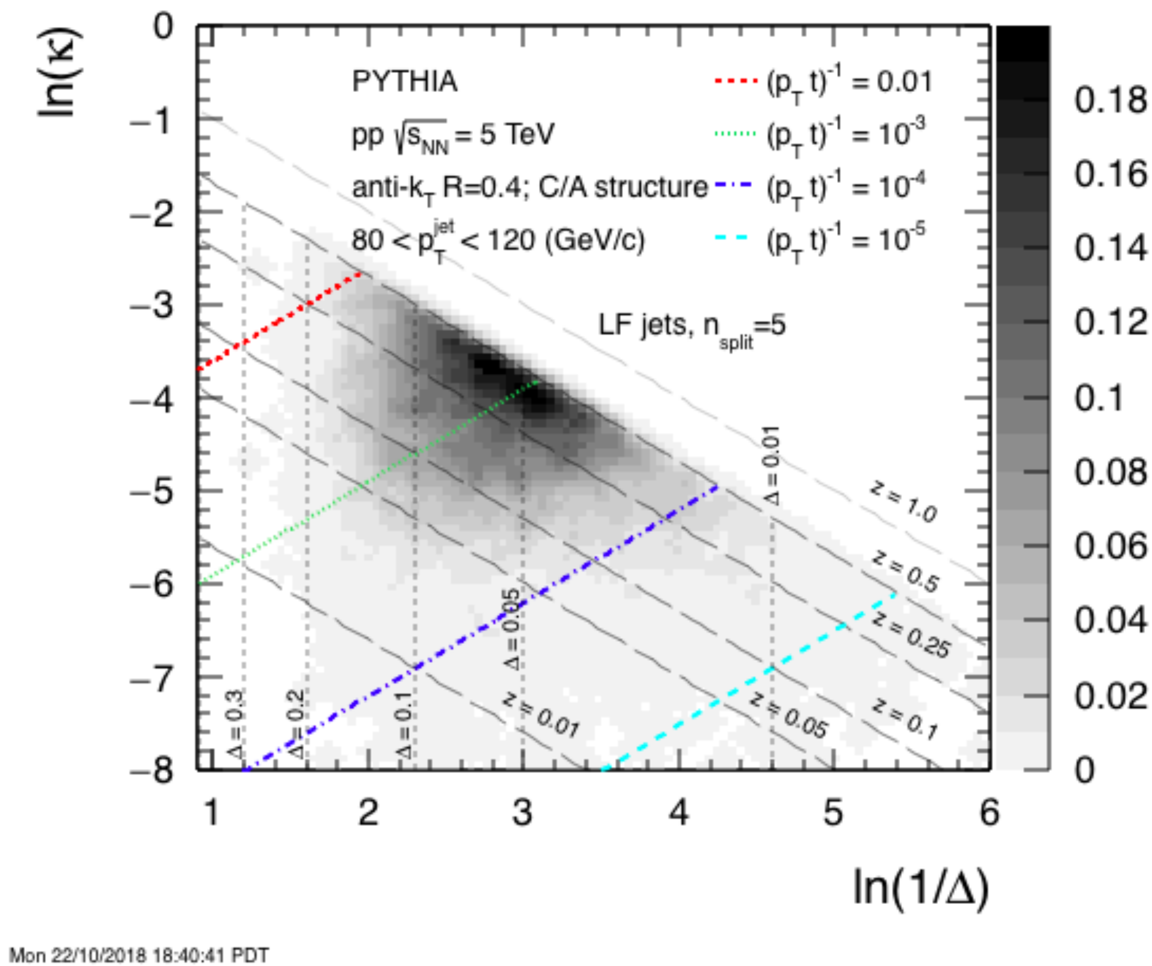


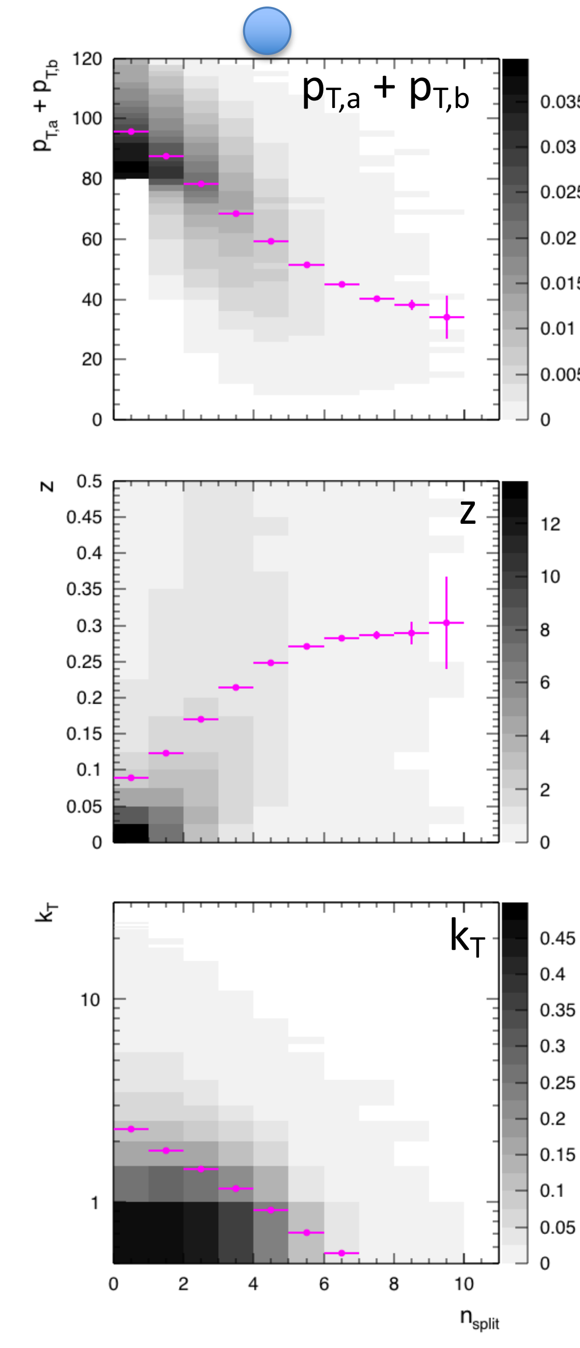

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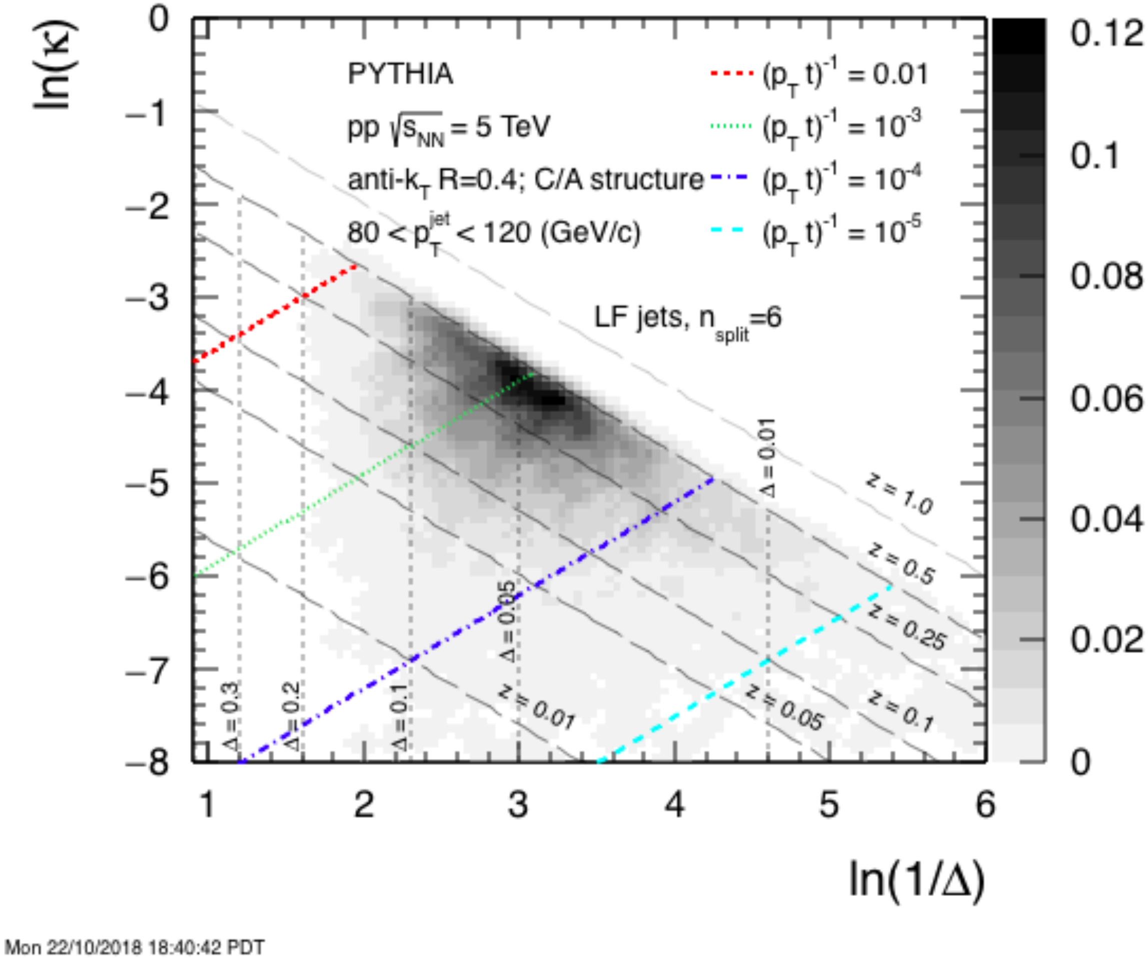


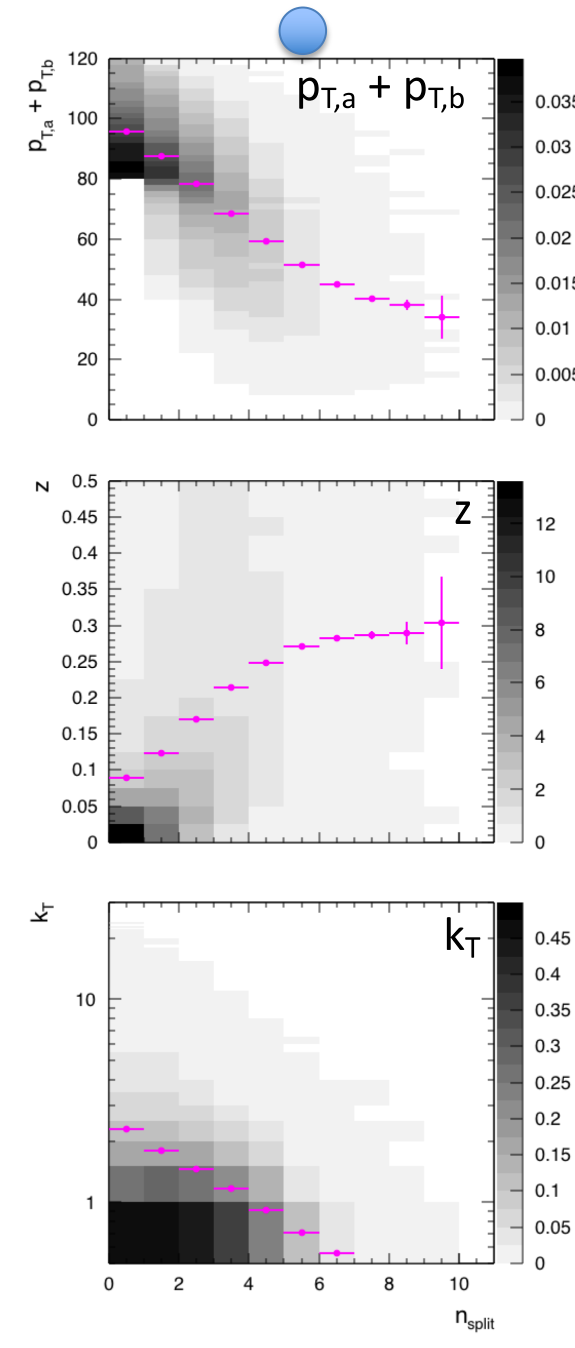

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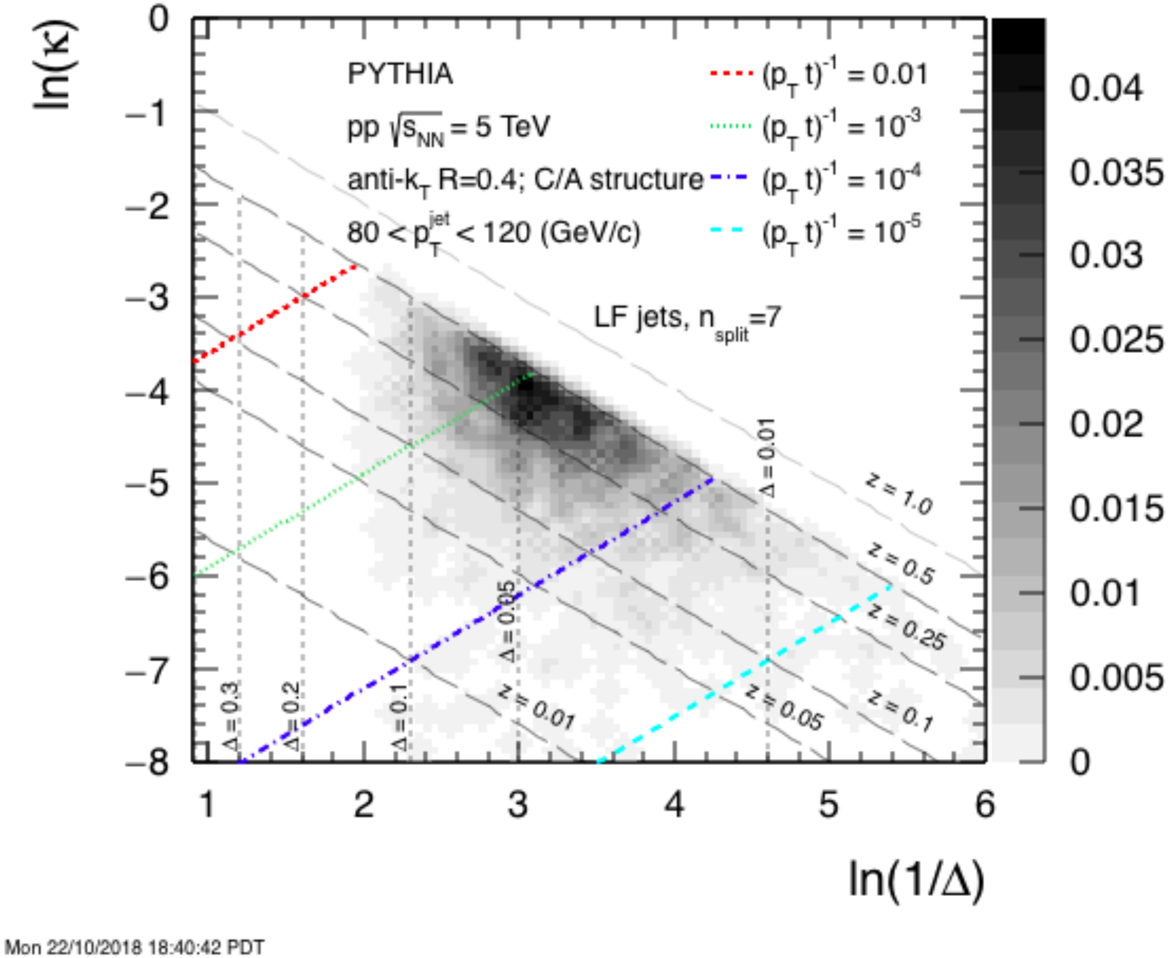


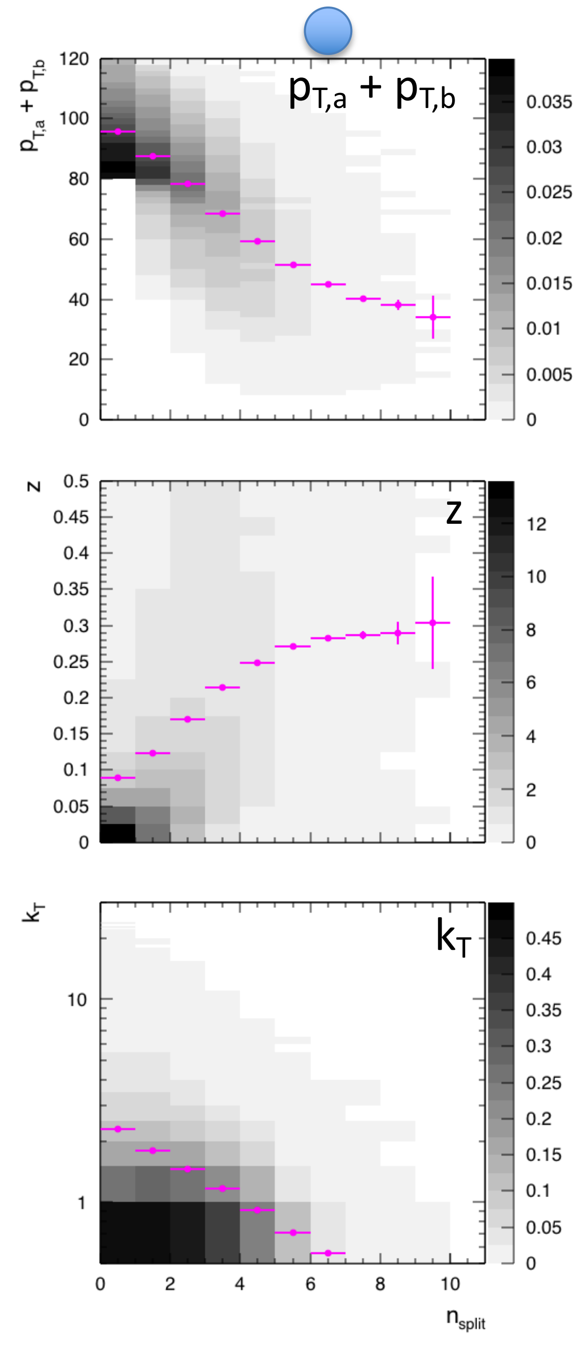

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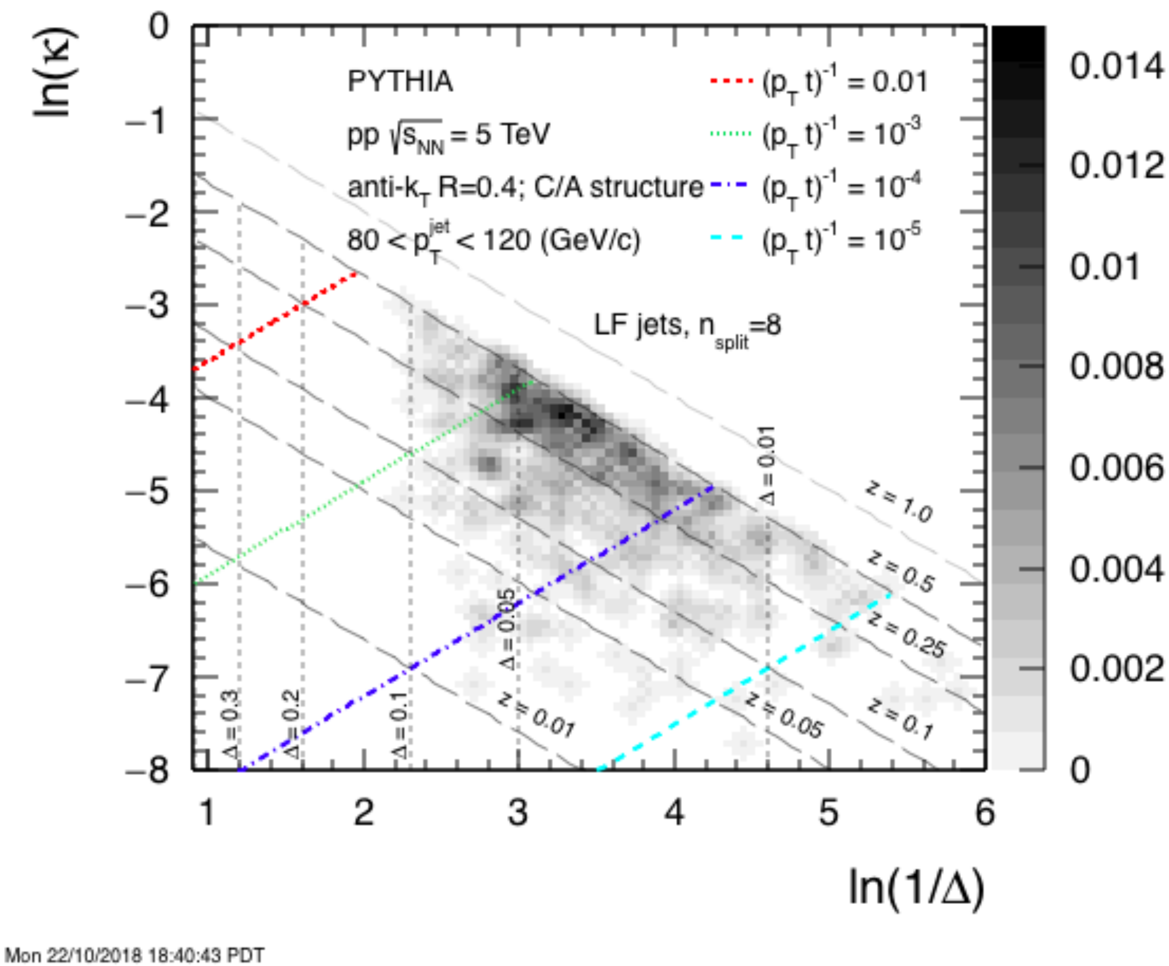


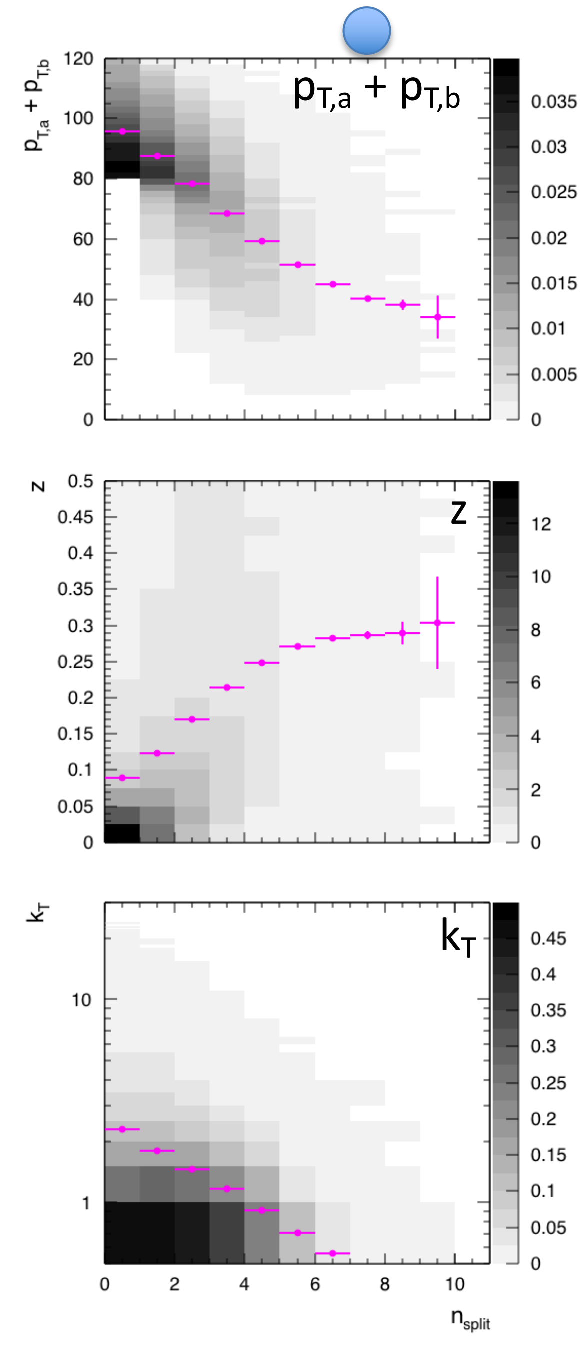

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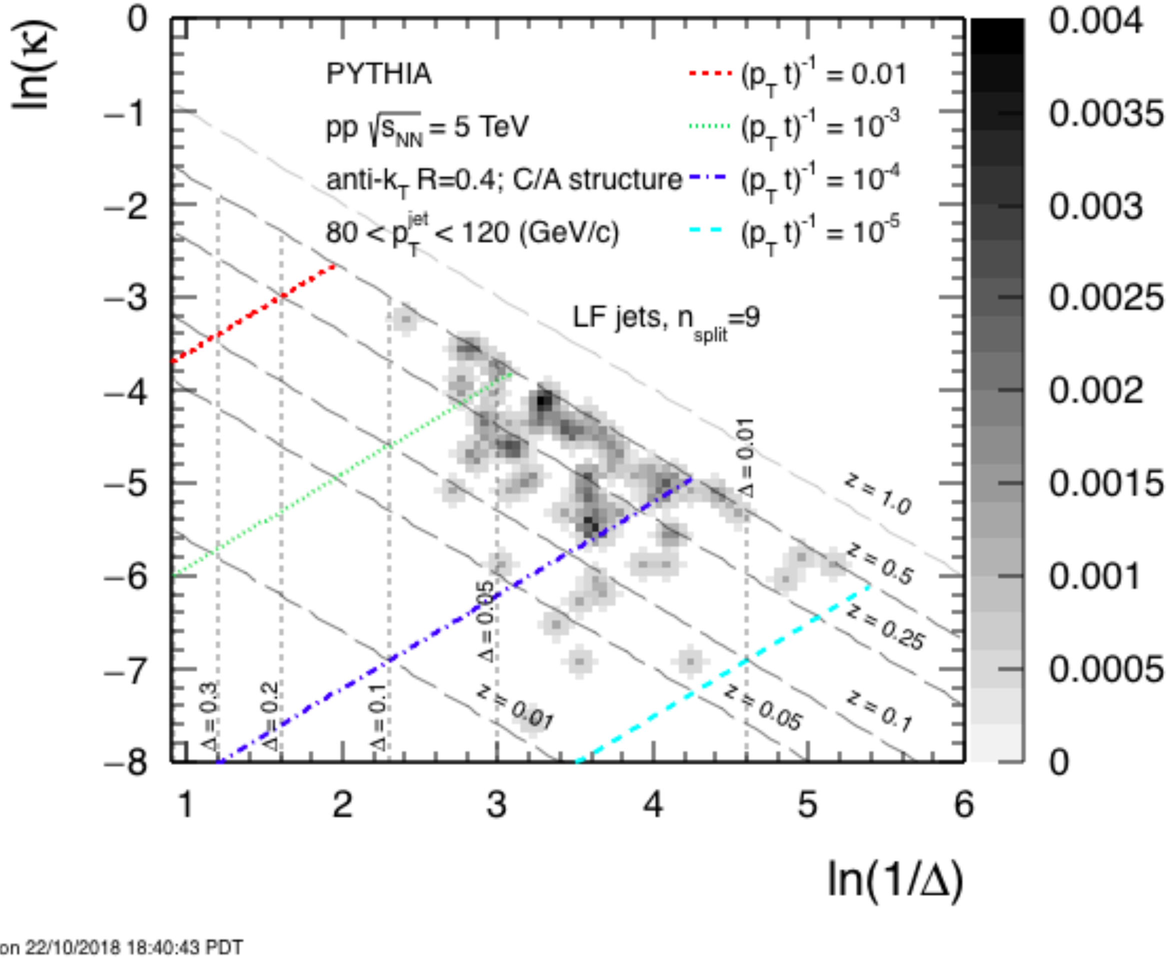


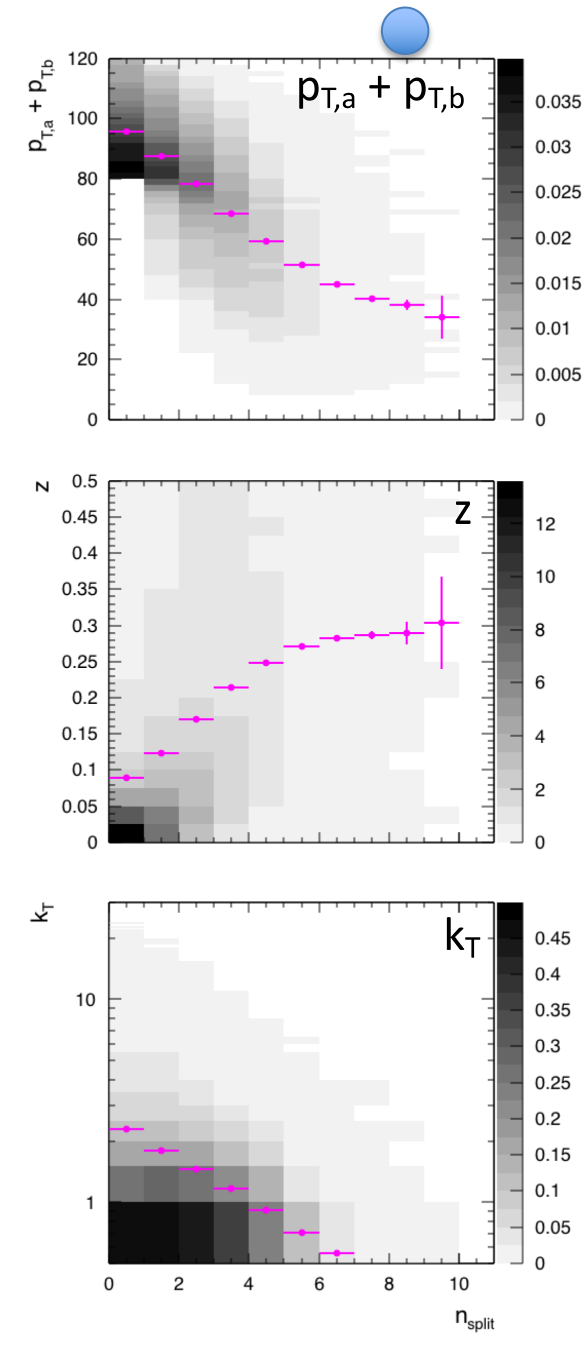

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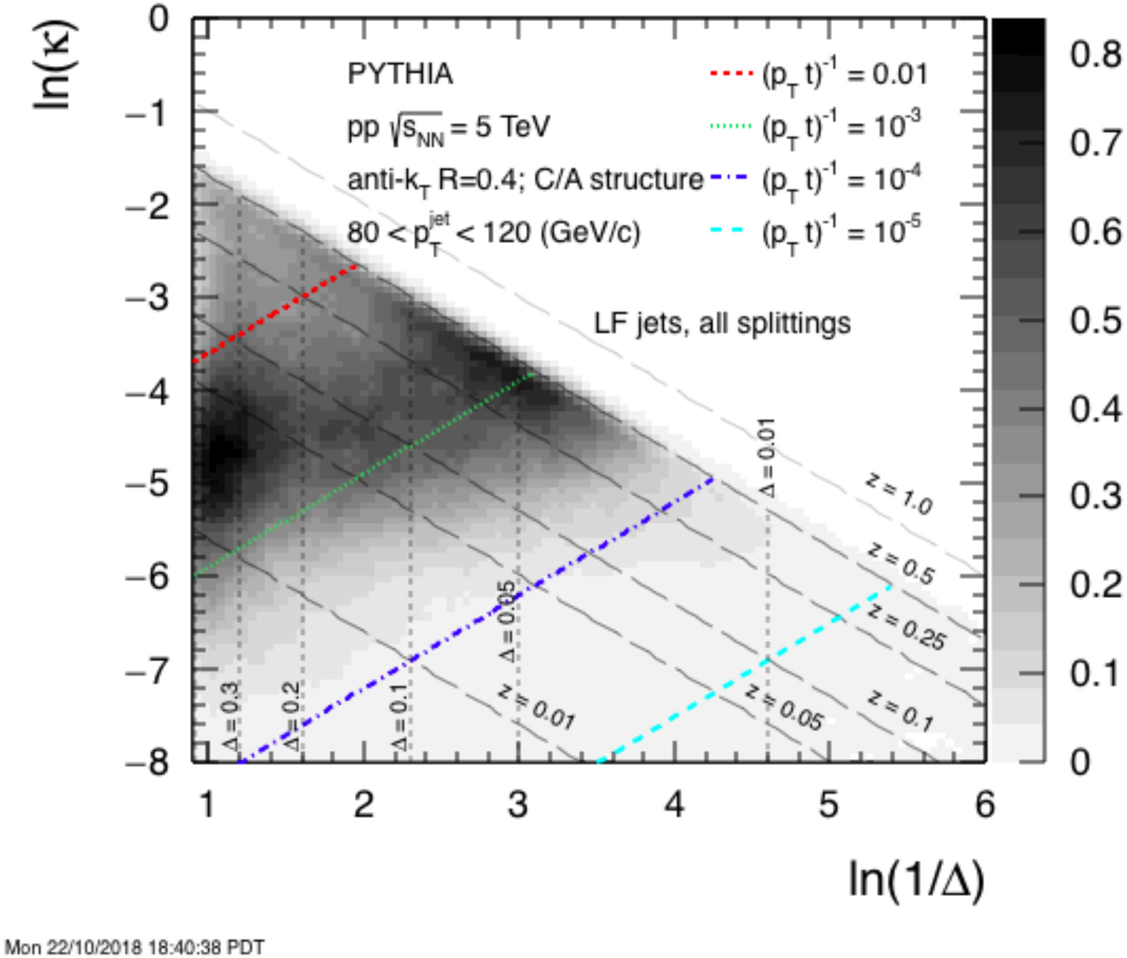


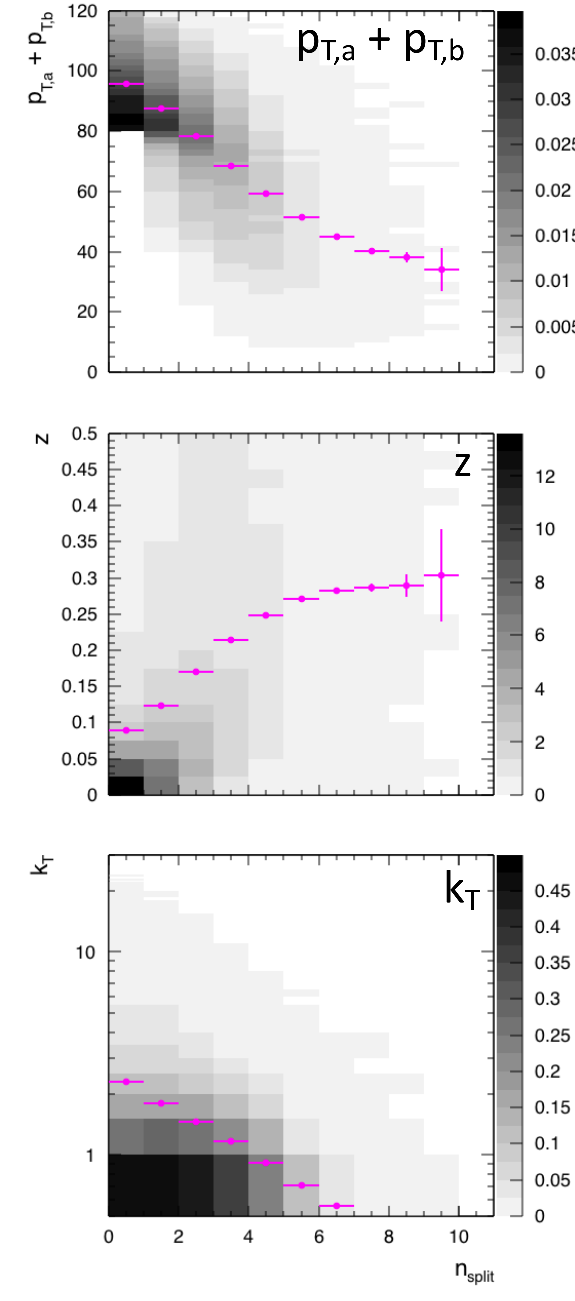

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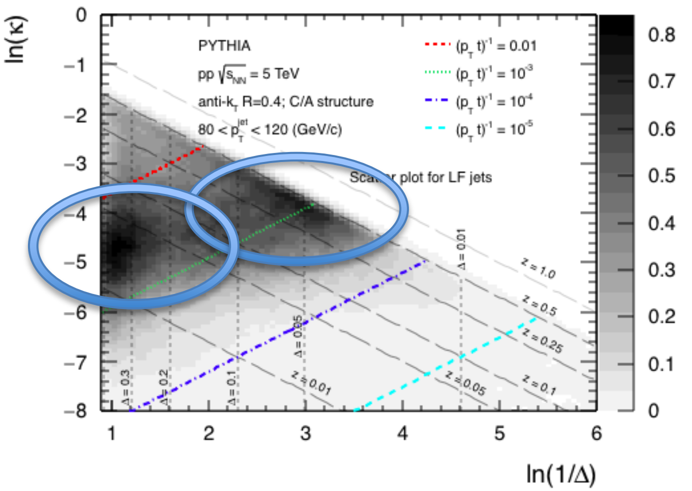


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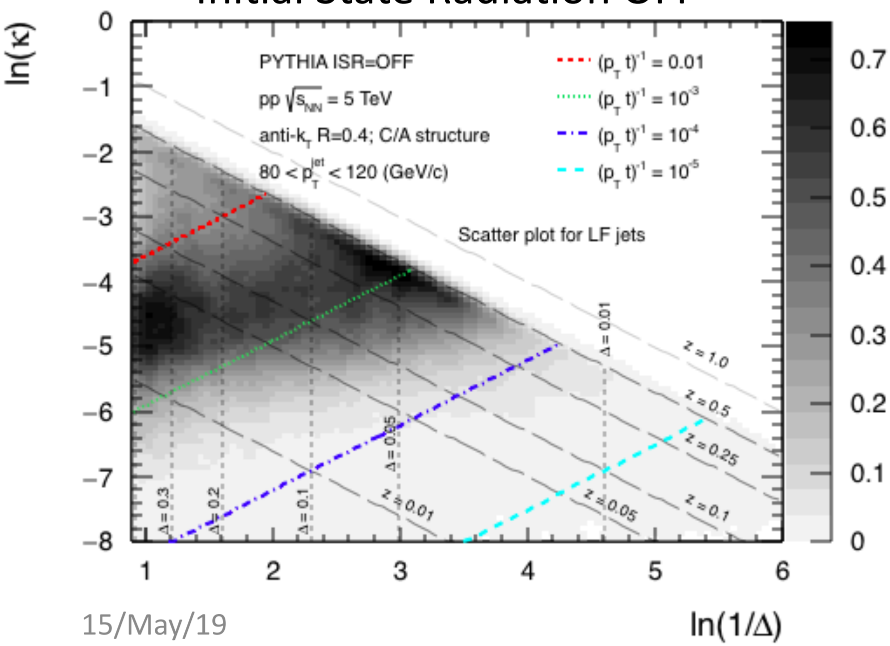
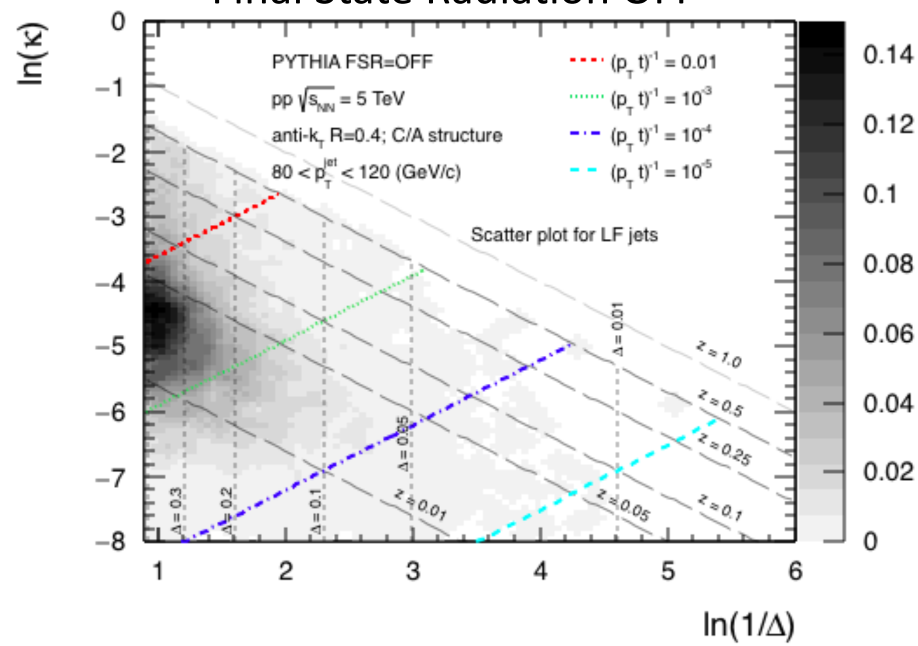
*Expectation: for every R and $p_T$, the phase space should be filled rather uniformly => the local max. at the max. angle is not expected.. The uniform distribution should be a feature of FSR…*
*=> Structures to some degree a feature of UE (IR/MPIs)*

Initial State Radiation OFF




Final State Radiation OFF



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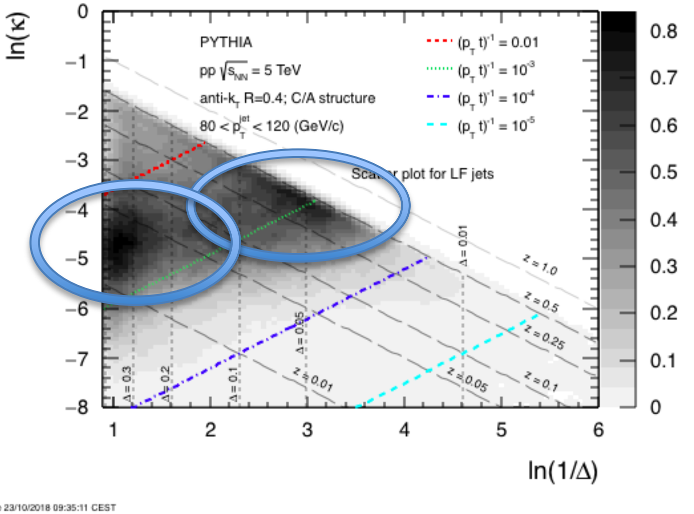
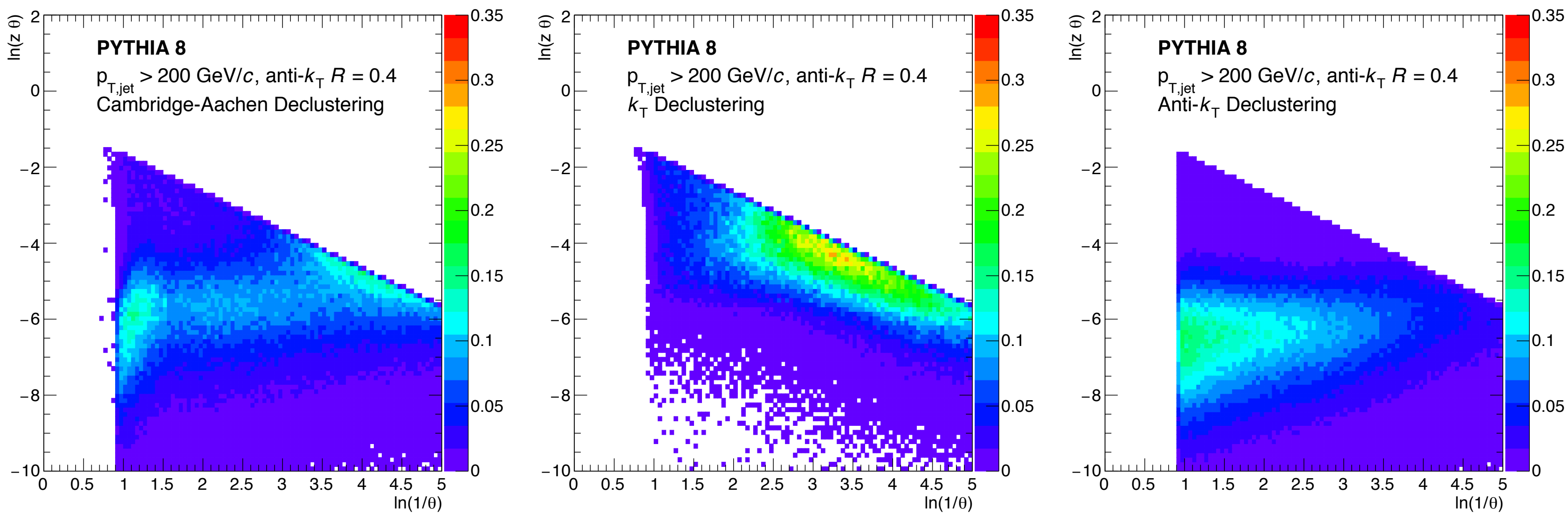



Structures vary with the algorithm used – last year exercise – remember Frederic yesterday…




https://arxiv.org/pdf/1808.03689.pdf

Figure 3: Lund diagrams reconstructed from a sample anti-$k_T$ $R = 0.4$ jets generated by PYTHIA8. Three reclustering strategies were considered: C/A (left), $k_T$(middle), and anti-$k_T$ (right).

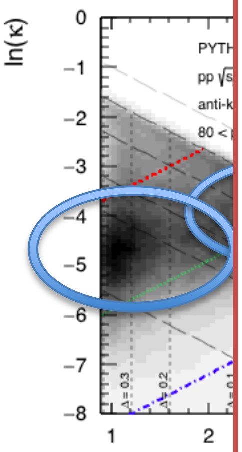
# Jet

## Declustering other jet-algorithm sequences

F. Dreyer

- Choice of C/A algorithm to create clustering sequence related to physical properties and associated to higher-order perturbative structures
- anti-$k_t$ or $k_t$ algorithms result in double logarithmic enhancements

$$\bar{\rho}_2^{(\text{anti-}k_t)}(\Delta,\kappa) \simeq +8C_F\, C_A \ln^2 \frac{\Delta}{\kappa} \qquad \bar{\rho}_2^{(k_t)}(\Delta,\kappa) \simeq -4C_F^2 \ln^2 \frac{\Delta}{\kappa}$$


$$\ldots_{T,b} \ldots + p_{T,b} \; \Delta_{ab}$$

mission

$$d\ln 1/\Delta$$

eric

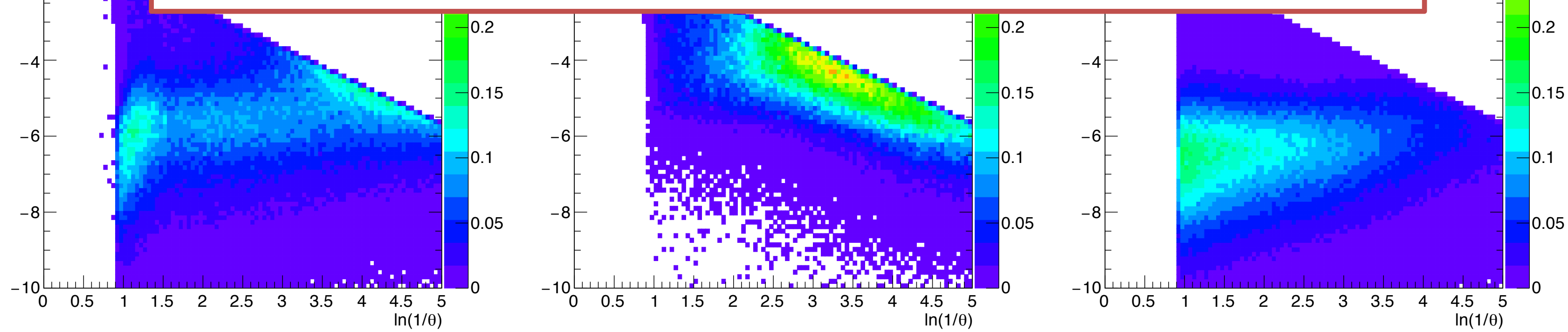


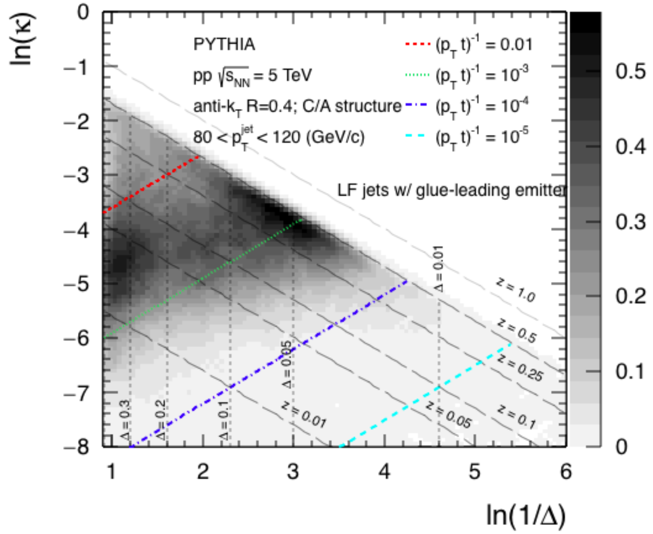

Figure 3: Lund diagrams reconstructed from a sample anti-$k_{\mathrm{T}}$ $R = 0.4$ jets generated by PYTHIA8. Three reclustering strategies were considered: C/A (left), $k_{\mathrm{T}}$(middle), and anti-$k_{\mathrm{T}}$ (right).

# Notes on heavy-quarks

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

$$p_{T,a} > p_{T,b}, \; \kappa = \frac{p_{T,b}}{p_{T,a}+p_{T,b}} \Delta_{ab}$$

## Gluon

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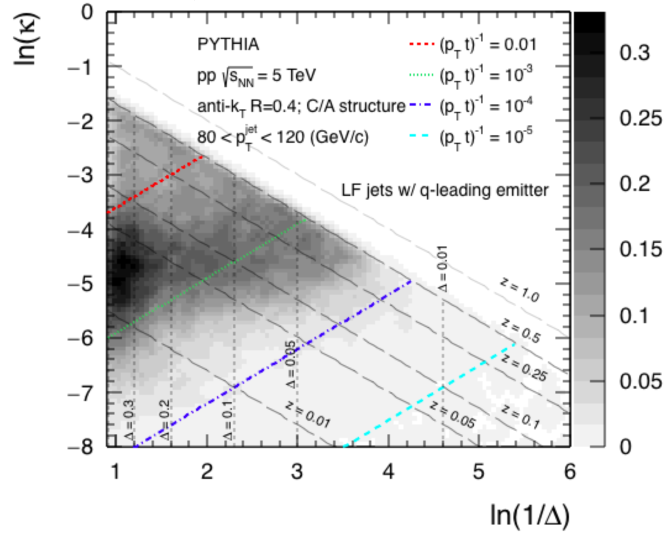
## LF Quark

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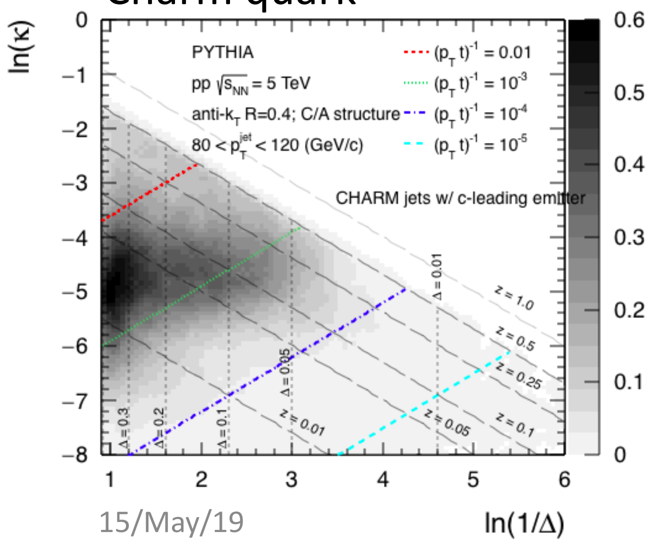
## Charm quark

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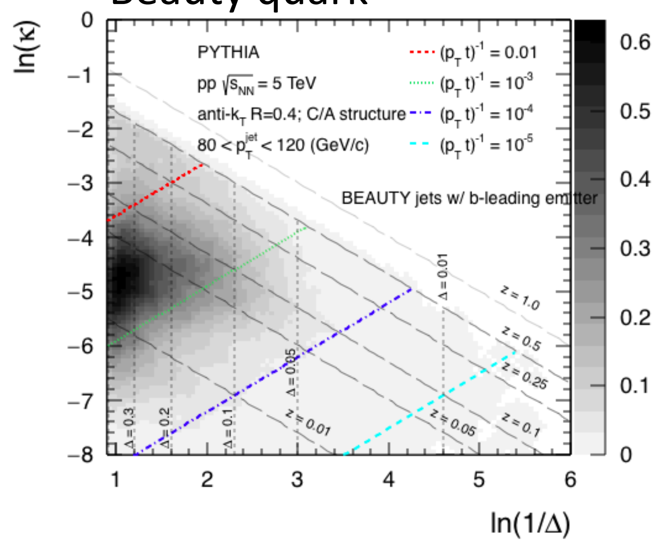
## Beauty quark

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Purely MC exersize – compare LF to HF jets

An approximation:
- use the leading parton within the emitter (follow Q)

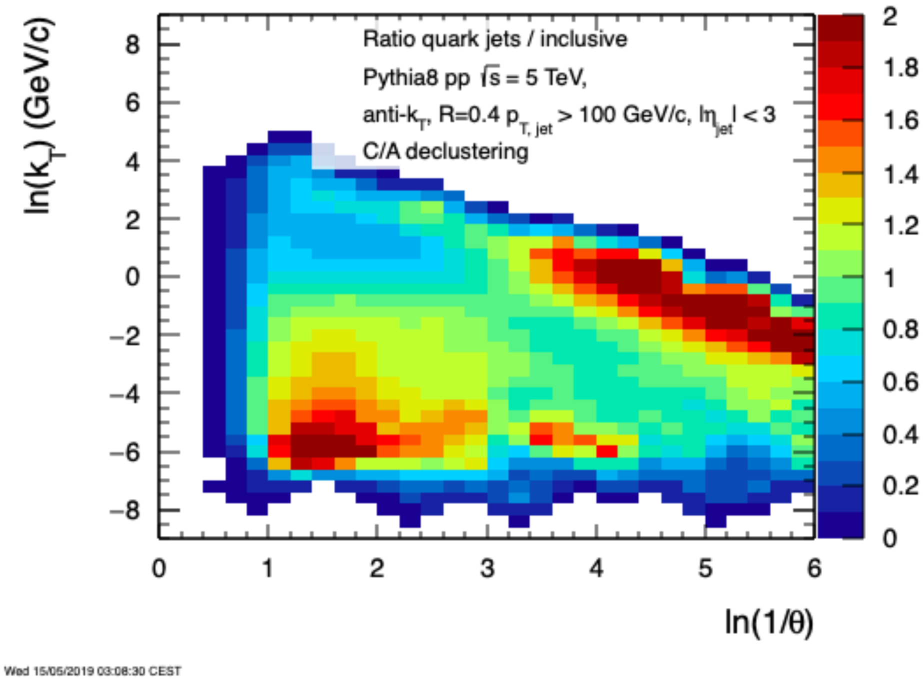
Opportunity? – explore with Machine Learning

Jet quenching – detail studies of mass dependence of energy loss?

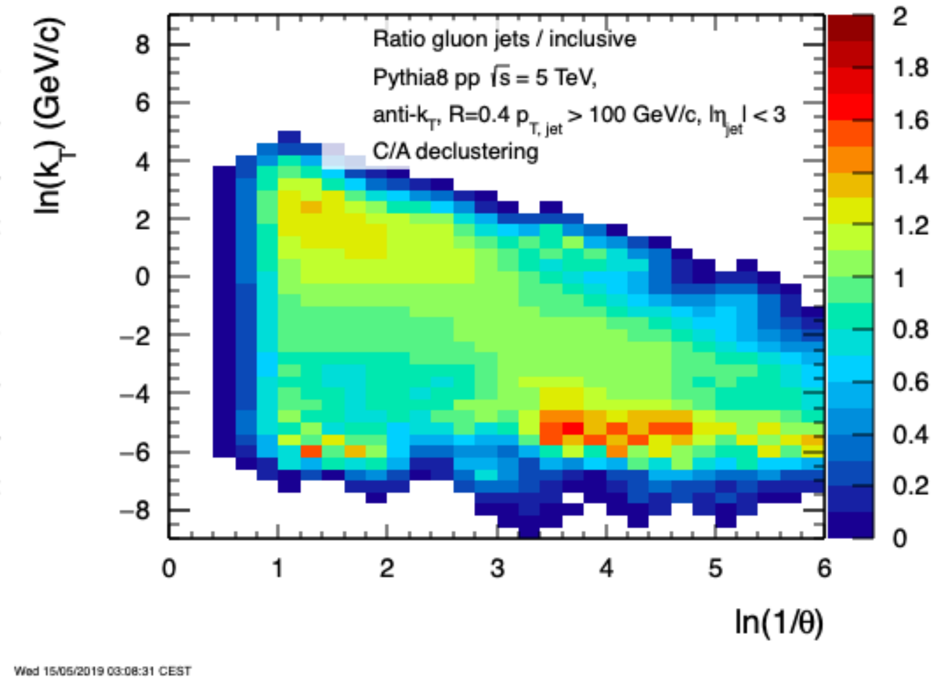
To be learned: gluon splitting contribution…

# Quark and gluon jets…

**Quark / inclusive**




**Gluon / inclusive**

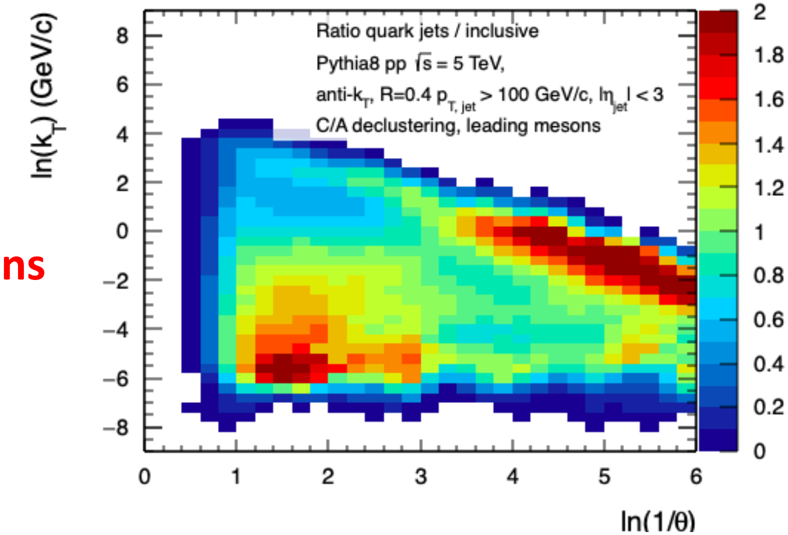


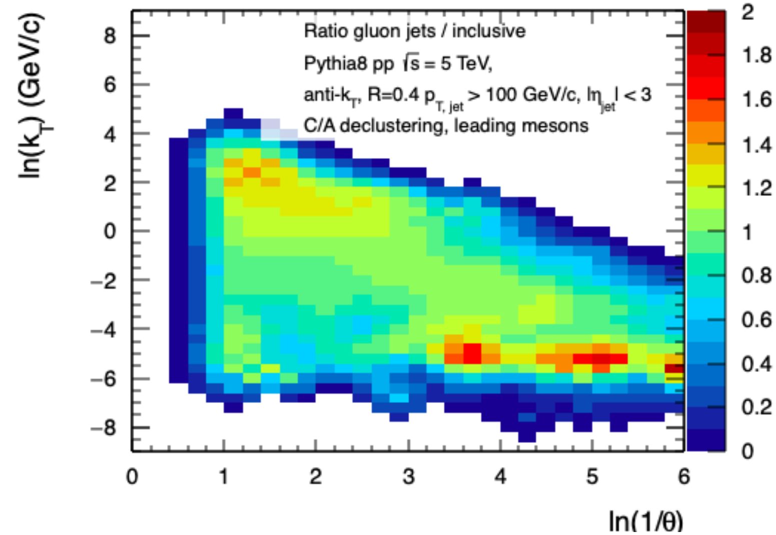

Quark jets as compared to gluons jets: harder fragmentation; more collimated
- To explore: what jet quenching does to such these distributions - what effects measurable / what is calculable? -> Felix et al.?

# Leading mesons and baryons – quark and gluon jets… Ratios for leading mesons and baryons

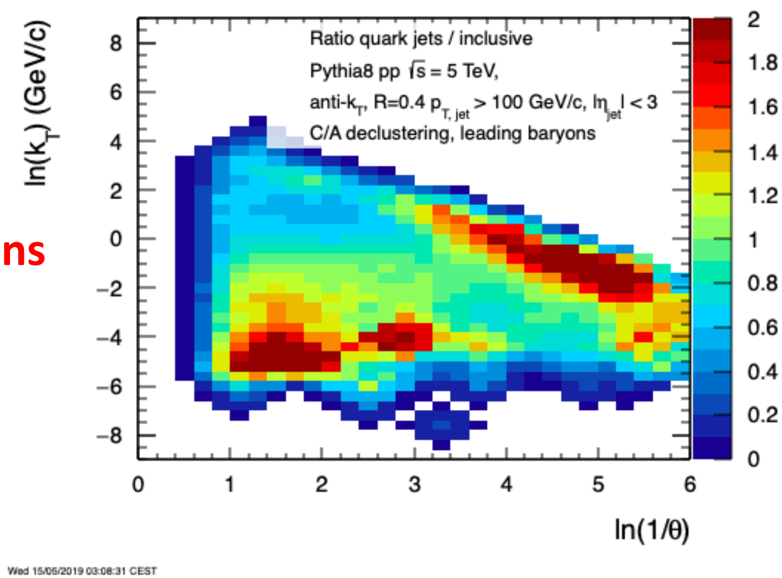
**Quark / inclusive** **Gluon / inclusive**

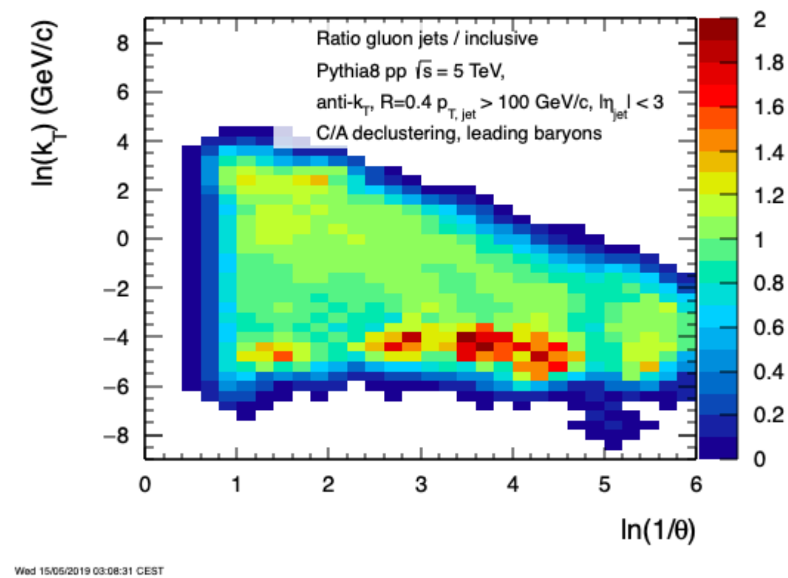
**Lead mesons**




**Lead baryons**



# JET QUENCHING – A QUICK STUDY

https://arxiv.org/pdf/1812.06772.pdf

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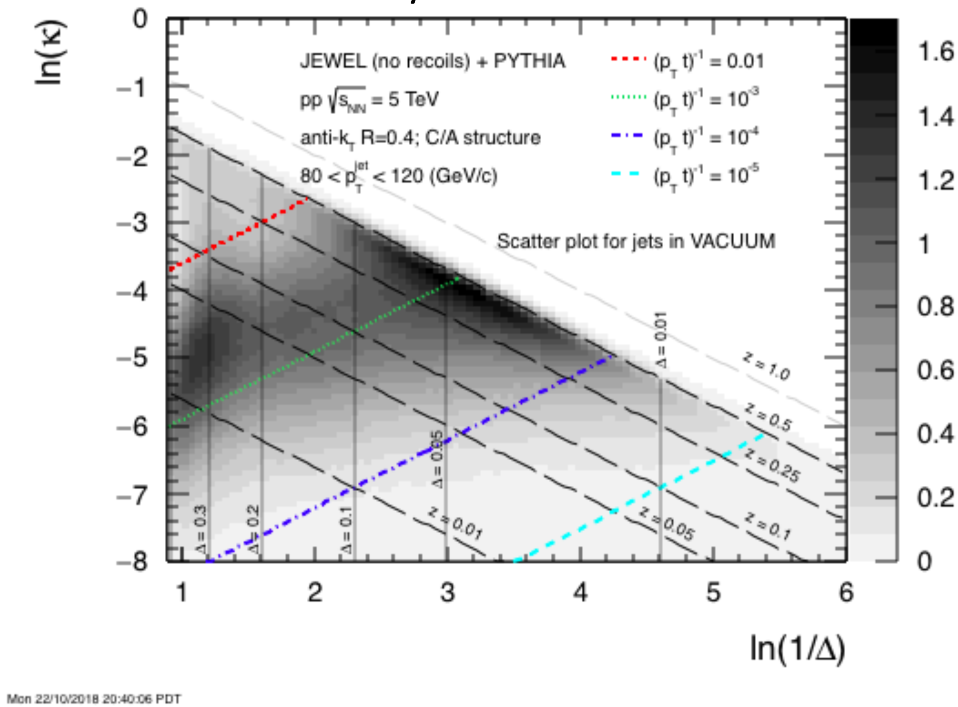
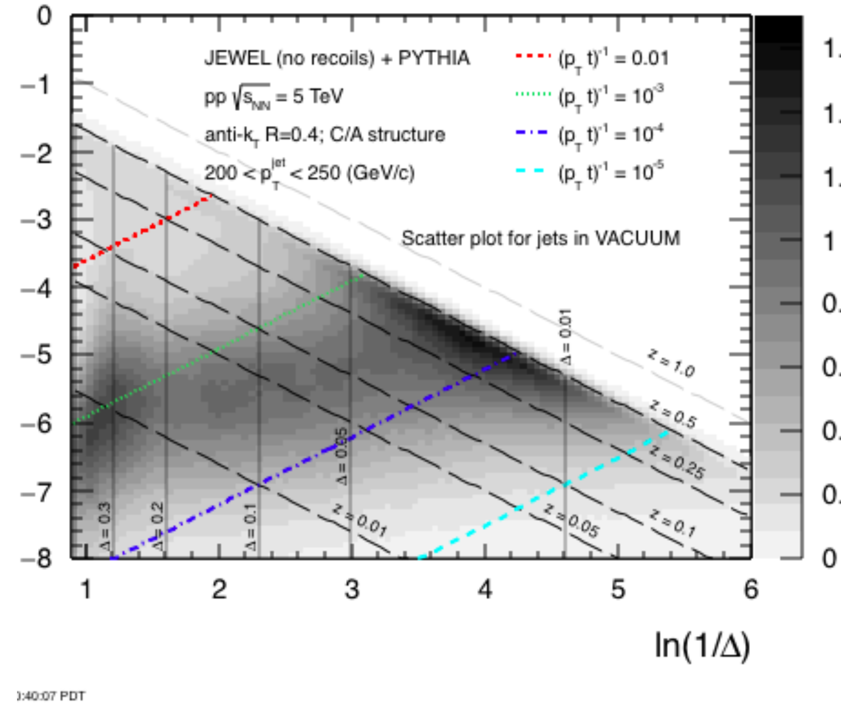
JEWEL + PYTHIA (RECOIL=OFF)
10% most central PbPb at 5 TeV
VACUUM

80-120 GeV/c




200-250 GeV/c



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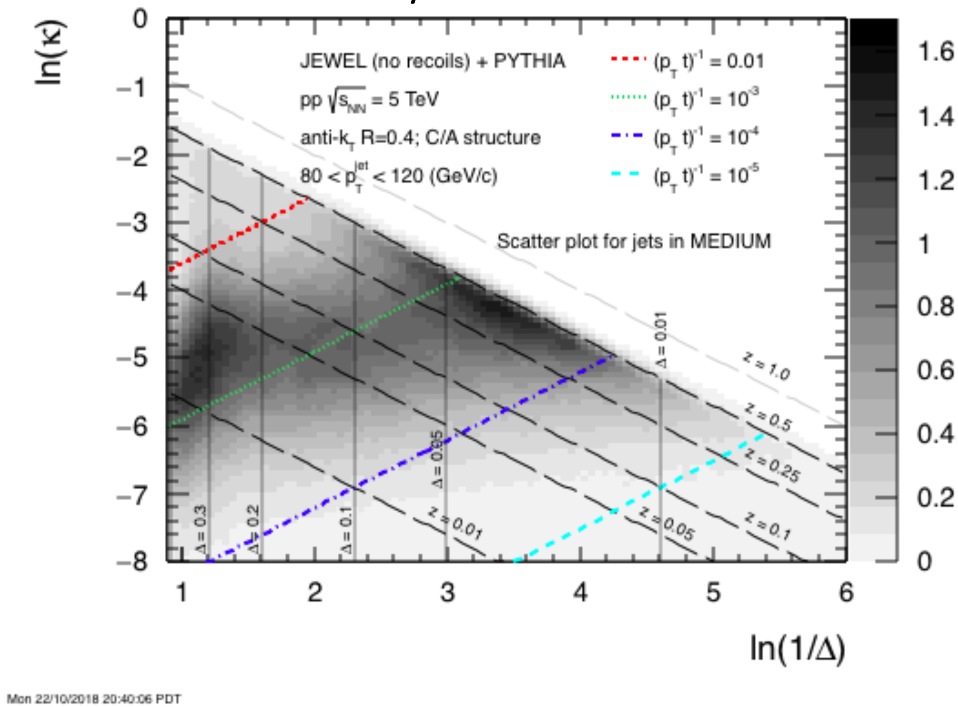


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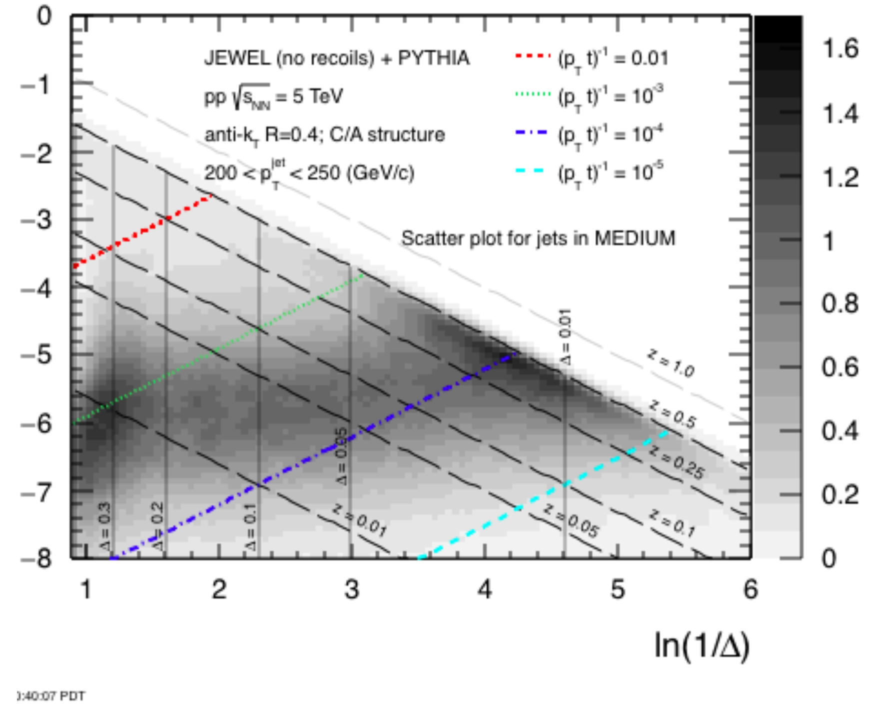

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MEDIUM - VACUUM

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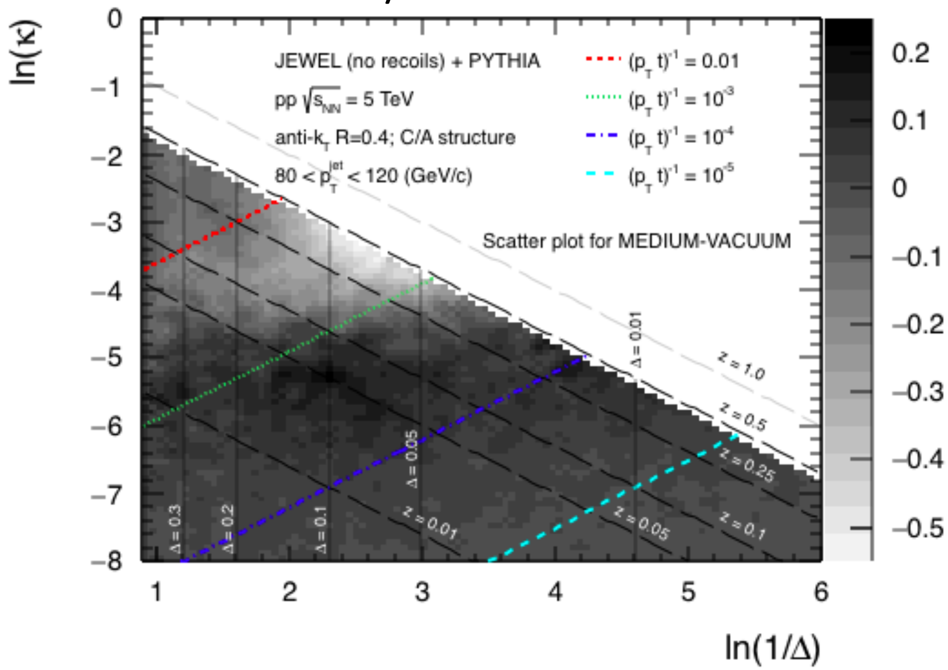


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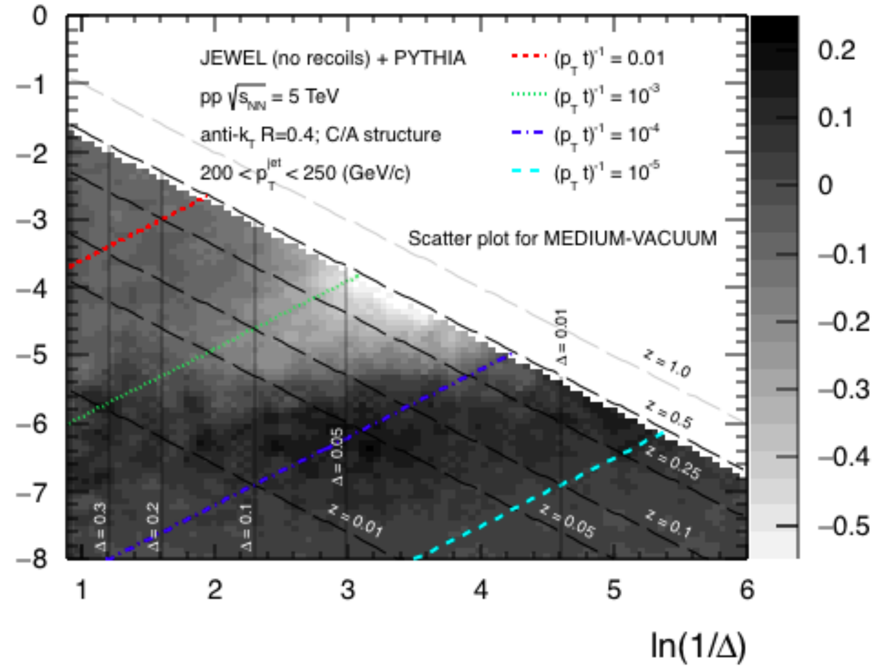
200-250 GeV/c

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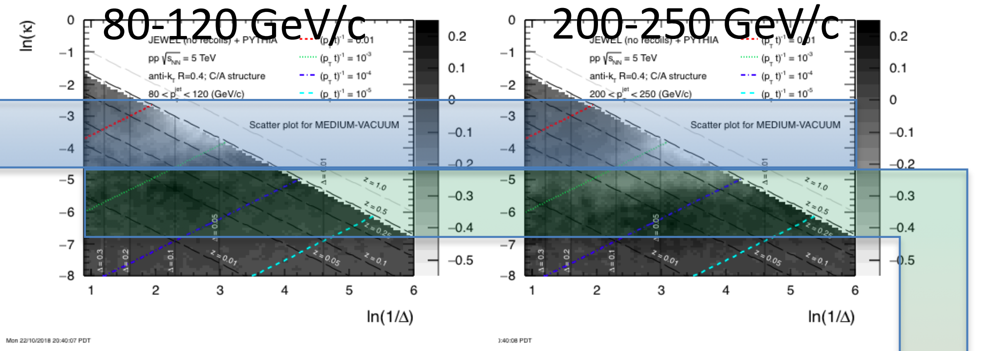
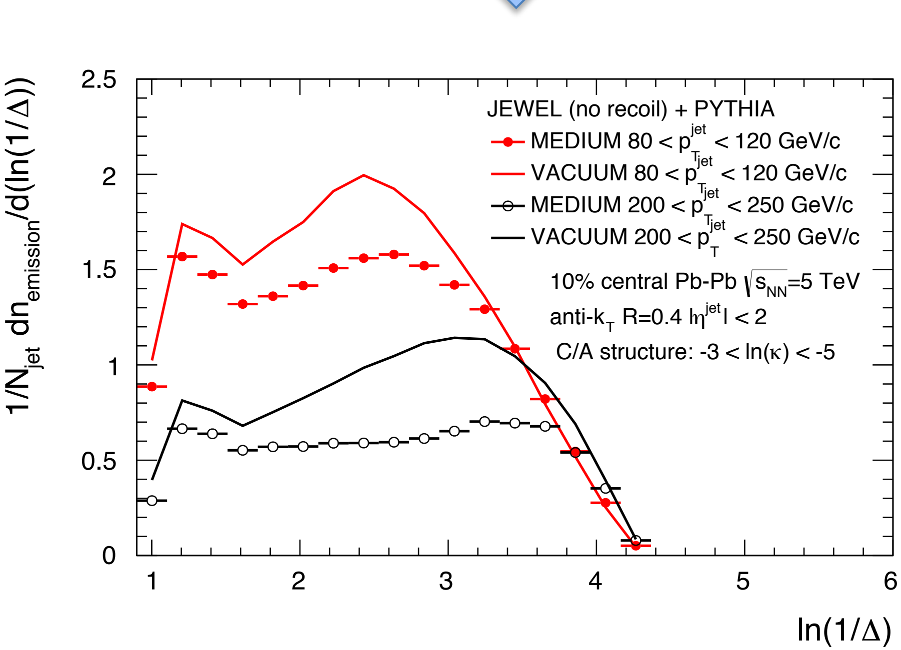
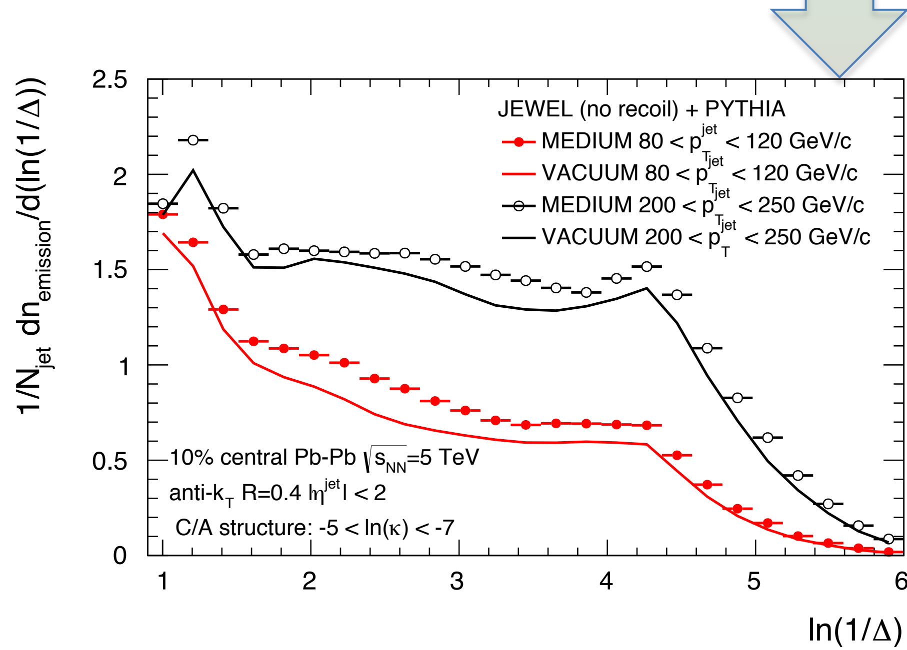
MEDIUM - VACUUM



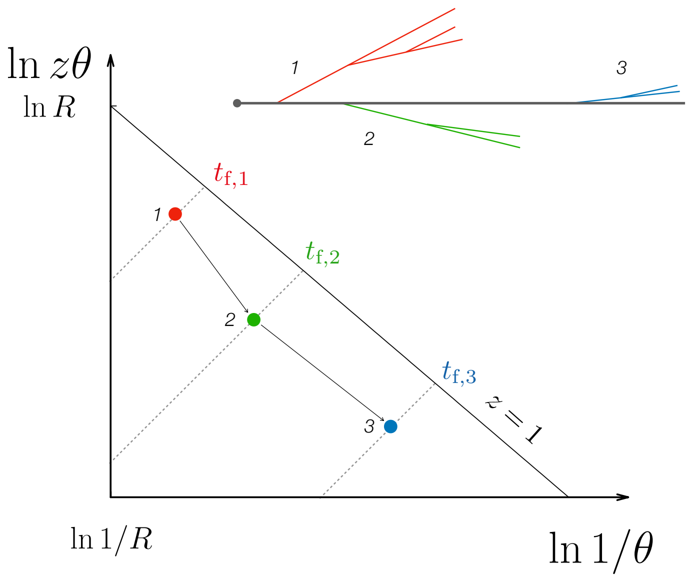
# A reminder from last wshop

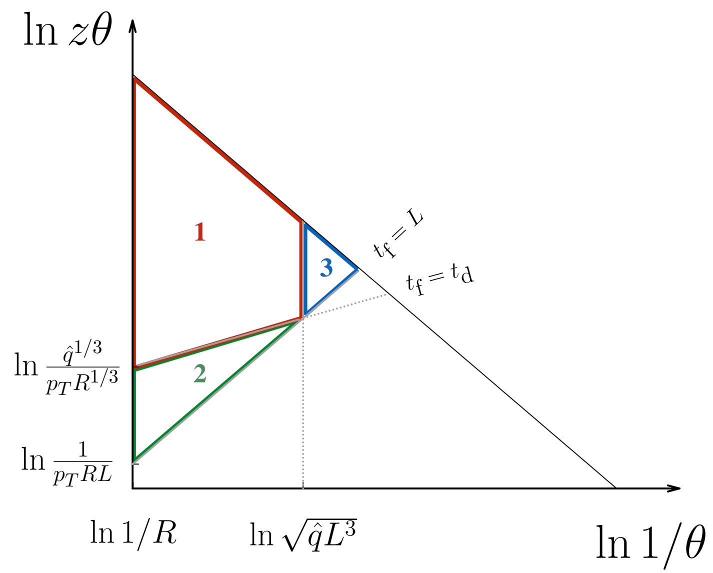
the detector. The characteristic time-scale of the splitting is usually referred to as the *formation time*, and is related to the finite energy resolution, $t_{\mathrm{f}} \sim \Delta E^{-1}$. It is explicitly given by

$$t_{\mathrm{f}} = \frac{2z(1-z)p_{\mathrm{T}}}{k_{\mathrm{T}}^2} = \frac{2p_{\mathrm{T}}}{M^2}\,, \tag{2}$$

where $k_{\mathrm{T}} = z(1-z)p_{\mathrm{T}}\theta$ is the (relative) transverse momentum of the dipole in the small angle limit. This formula can easily be understood as the time-scale for decaying in the rest frame of the parent times its boost factor $\sim (1/M) \times (p_{\mathrm{T}}/M)$.

https://arxiv.org/pdf/1808.03689.pdf



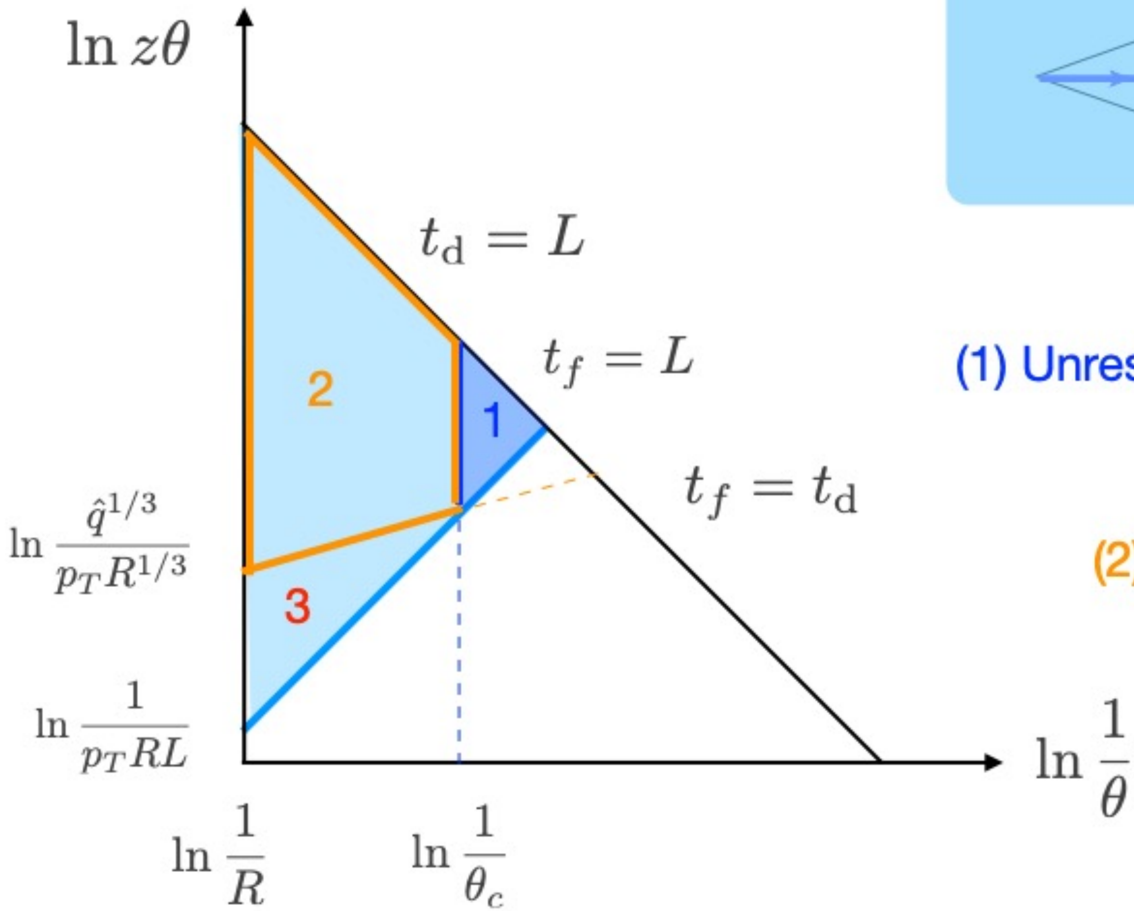

$$\ln z\theta = \ln \frac{1}{\theta} + \ln \frac{1}{p_{\mathrm{T}} t}\,,$$

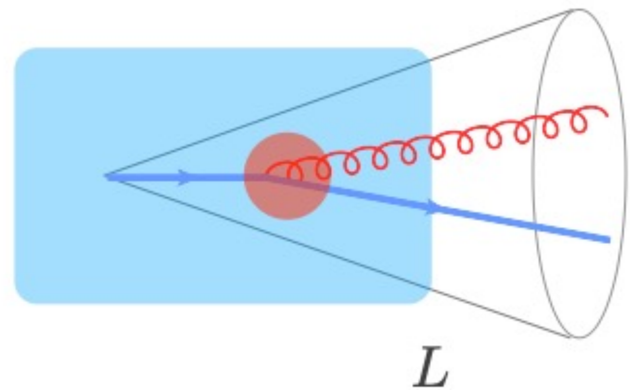
# Back to the Lund plane

[Andrews et al (2018)]

Monday - Yacine

formation time: $t_f = (\omega\theta^2)^{-1}$




(1) Unresolved in medium splitting

$$t_{\rm d} > L$$

(2) Resolved vacuum splitting inside the medium

$$t_f < t_{\rm d} < L$$

(3) Medium-induced radiation

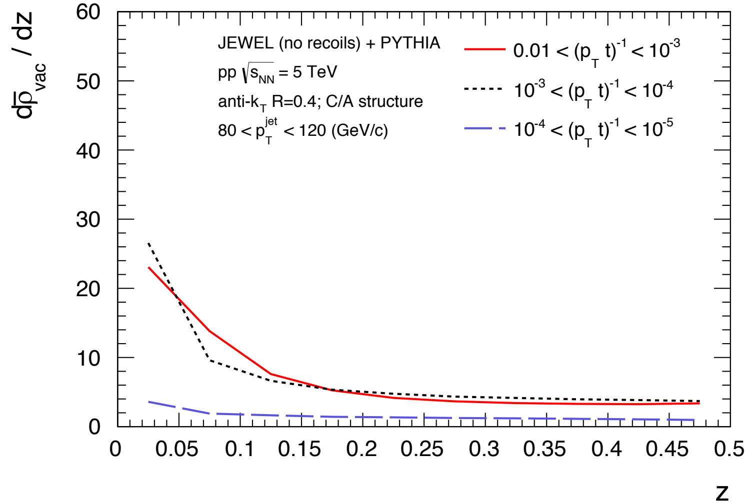
$$t_{\rm d} < t_f < L$$

[See talk by P. Caucal for MC implementation]

# Jet Lund diagram slicing through time

$$p_{T,a} > p_{T,b},\ \kappa = \frac{p_{T,b}}{p_{T,a}+p_{T,b}}\Delta_{ab}$$

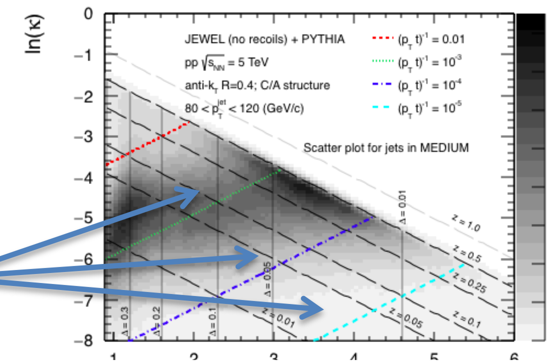
$$\bar{\rho}(\Delta,\kappa) = \frac{1}{N_{\mathrm{jet}}}\frac{dn_{\mathrm{emission}}}{d\ln\kappa\ d\ln 1/\Delta}$$

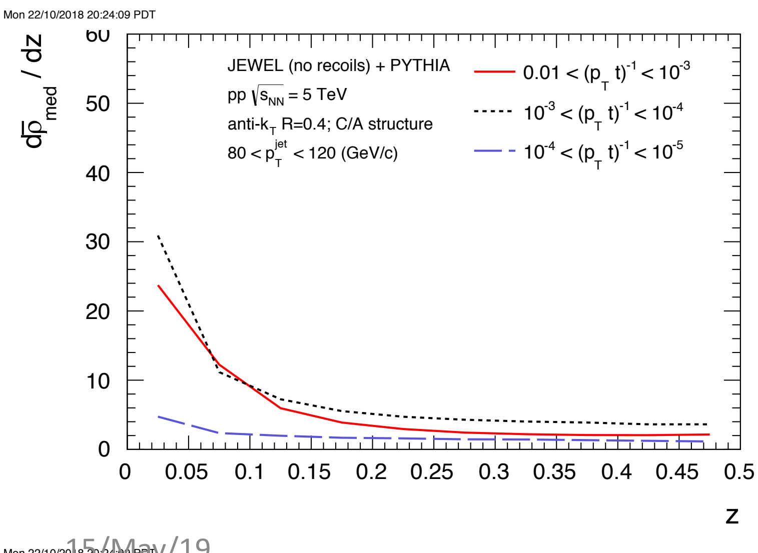


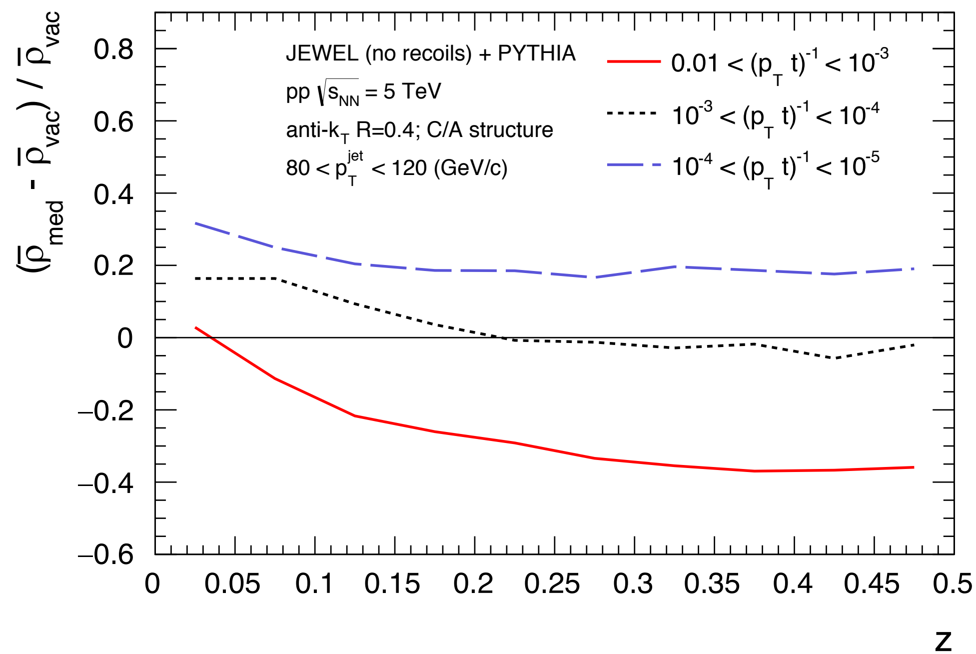

80 – 120 GeV/c

$$\ln z\theta = \ln\frac{1}{\theta} + \ln\frac{1}{p_{\mathrm{T}}t},$$

Slicing along $1/(p_T \times t)$ and projecting along z



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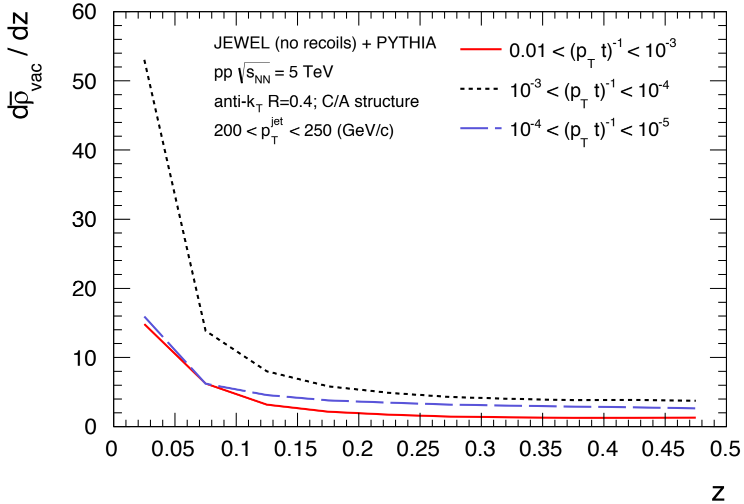


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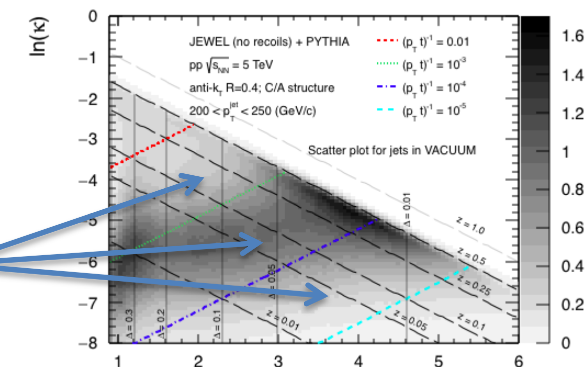
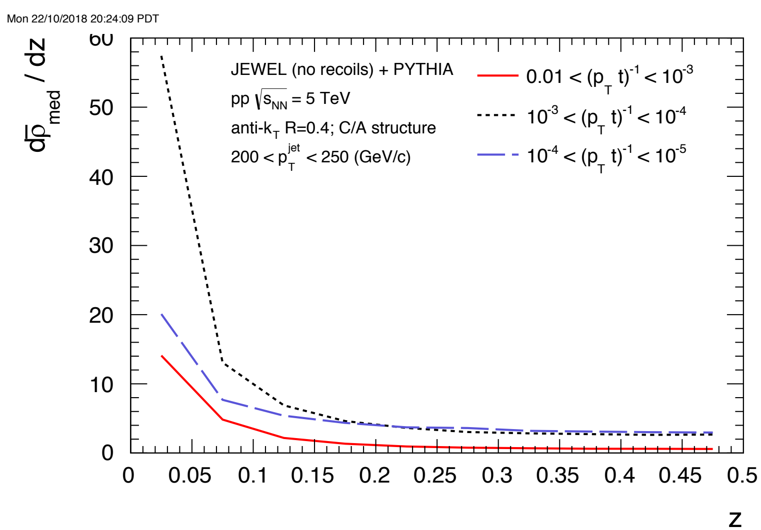
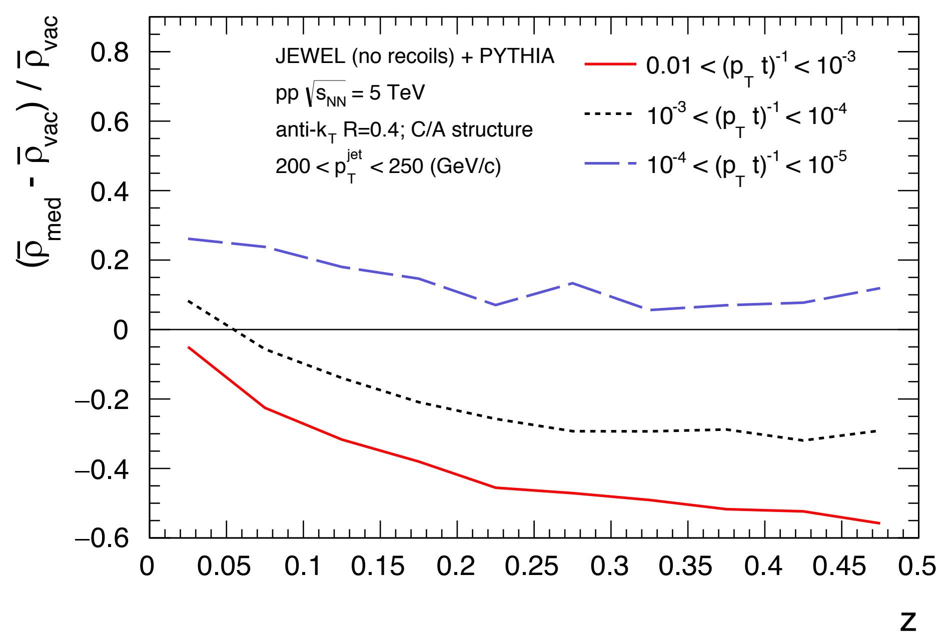



Slicing along $1/(p_T \times t)$ and projecting along z



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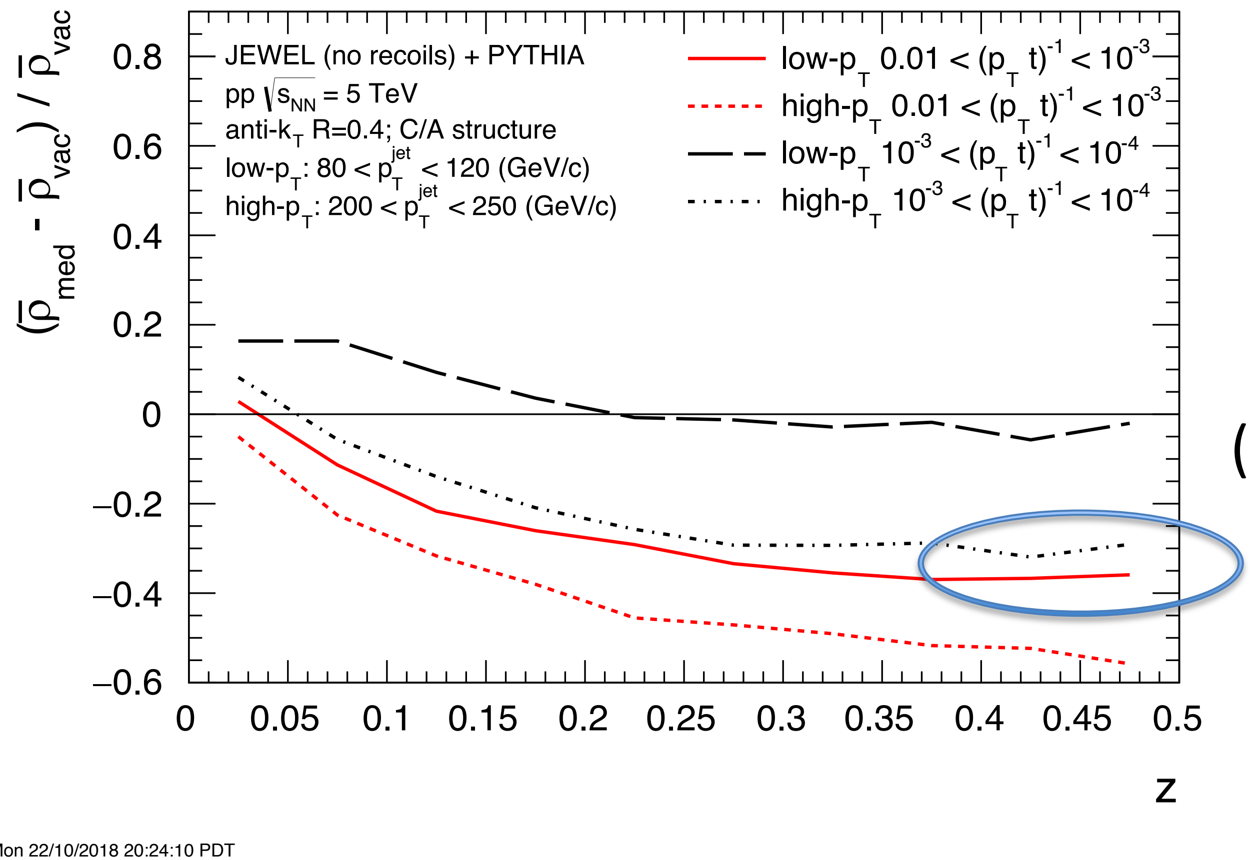


Low- with high-$p_T$ for the similar t

⇔

similar suppression (scaling factor for $p_T$ x t roughly 80/200)

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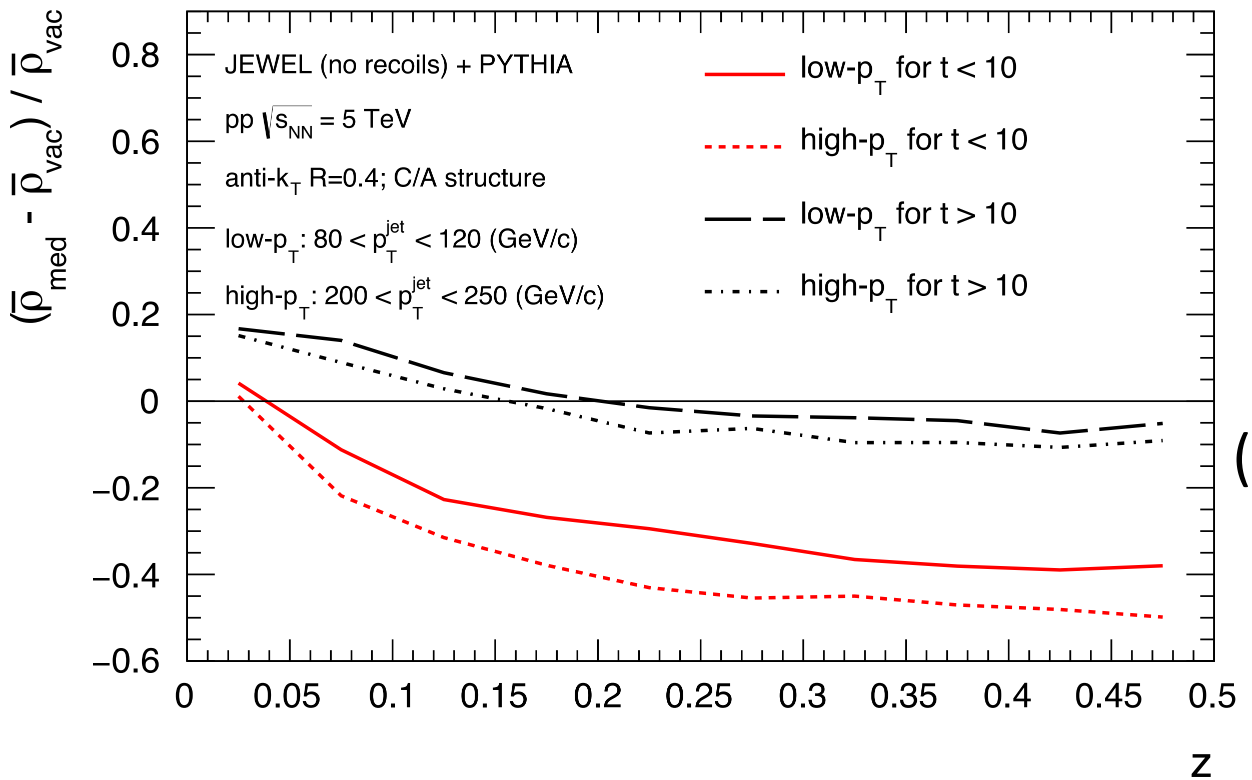



Low- with high-$p_T$ for the similar t

⇔

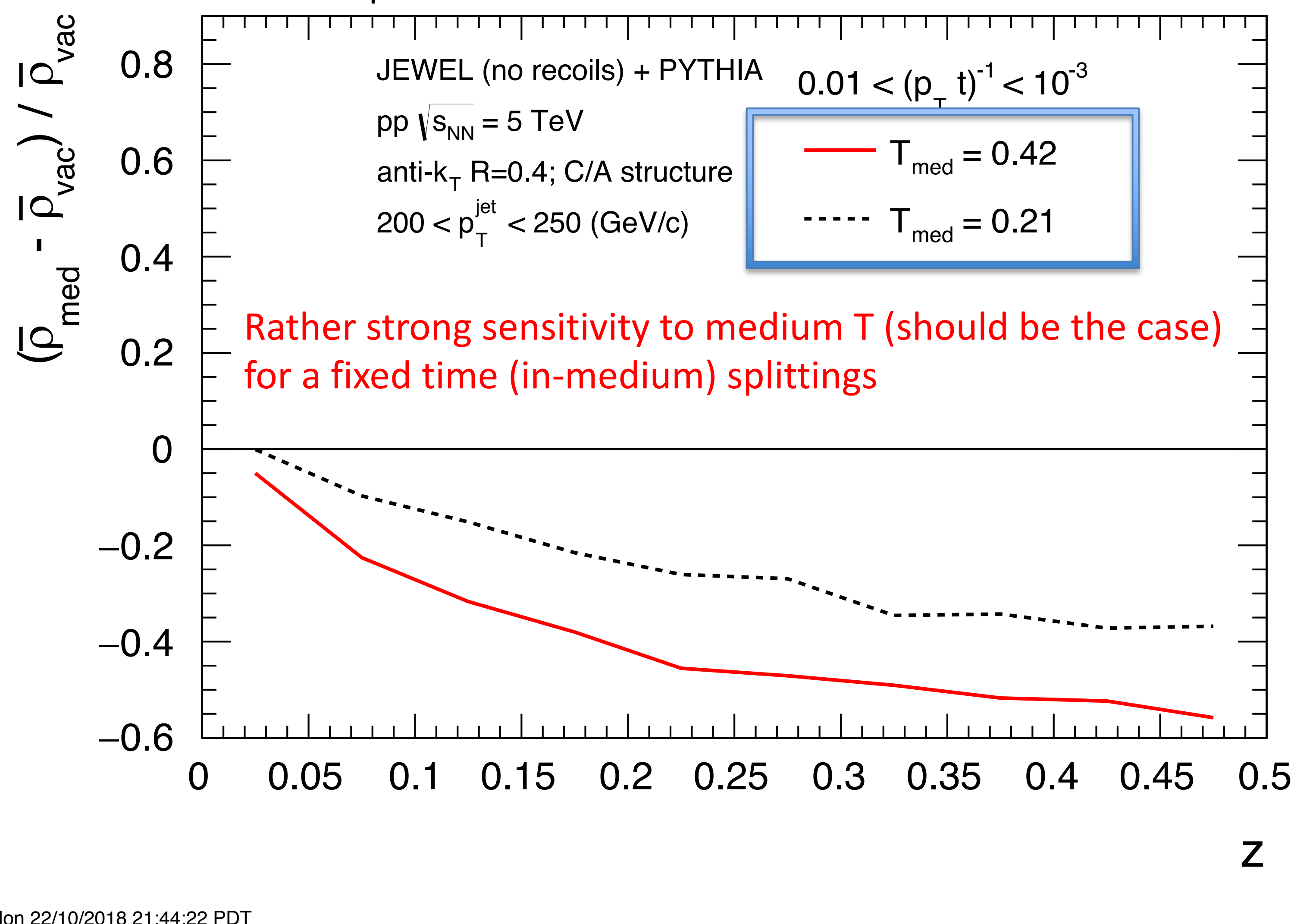
similar suppression (scaling factor for $p_T$ x t roughly 80/200)

Slicing on formation time => similar suppression for similar t

Explore: Mass ($z\theta^2$) slicing?

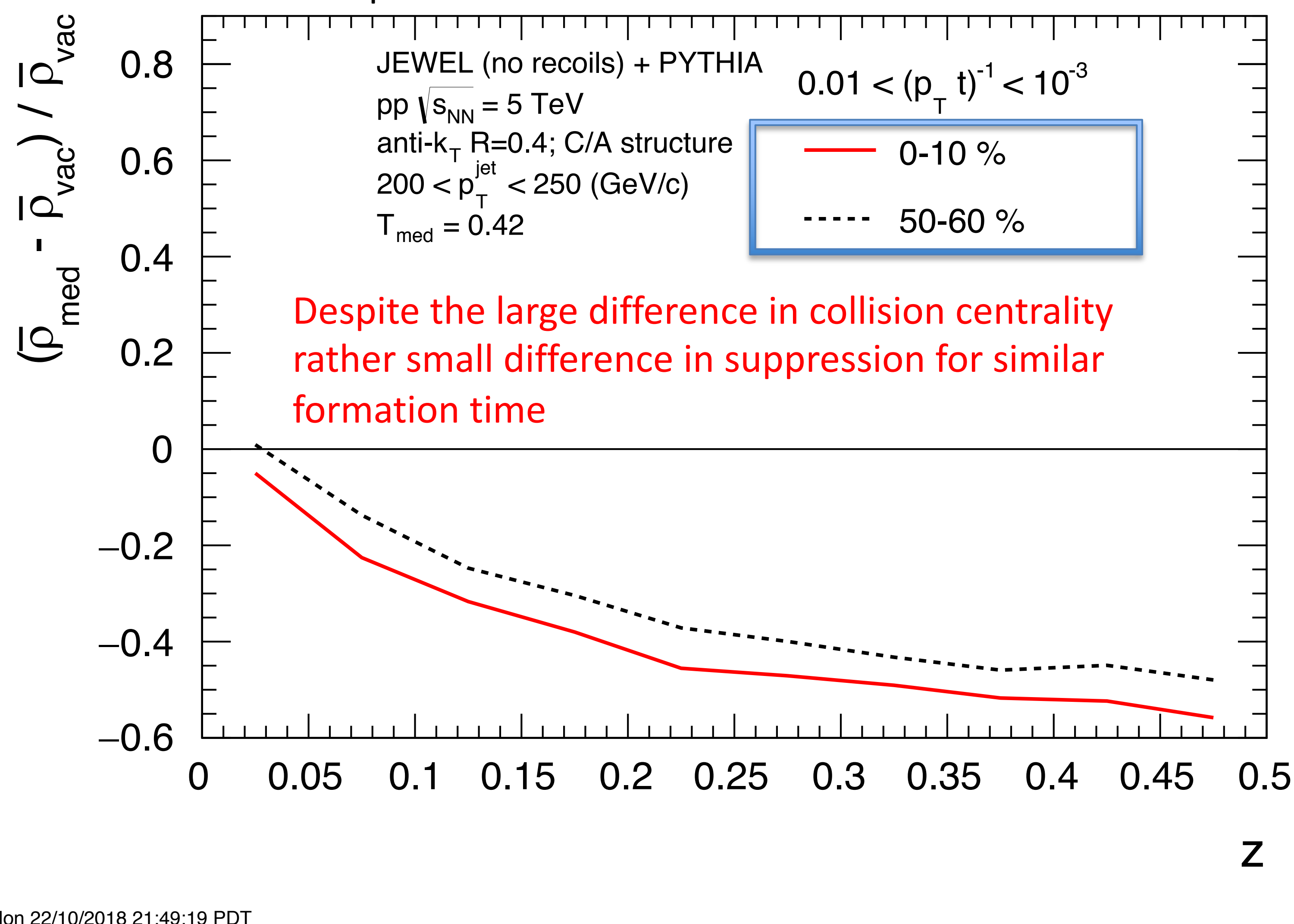
# Sensitivity to medium's Temperature

An example…



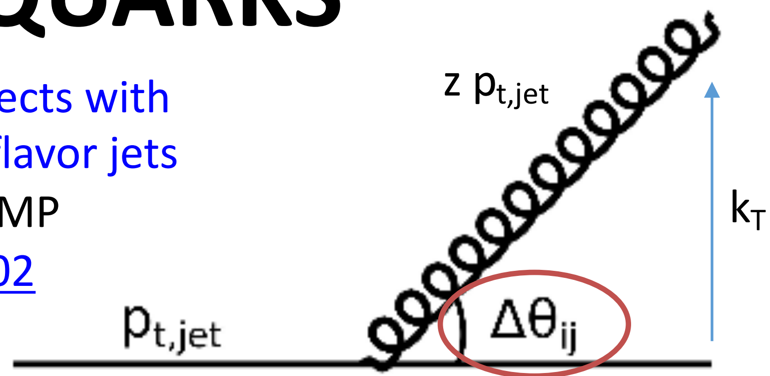
# Sensitivity to medium's L (centrality)

An example…



# ONTO HEAVY QUARKS

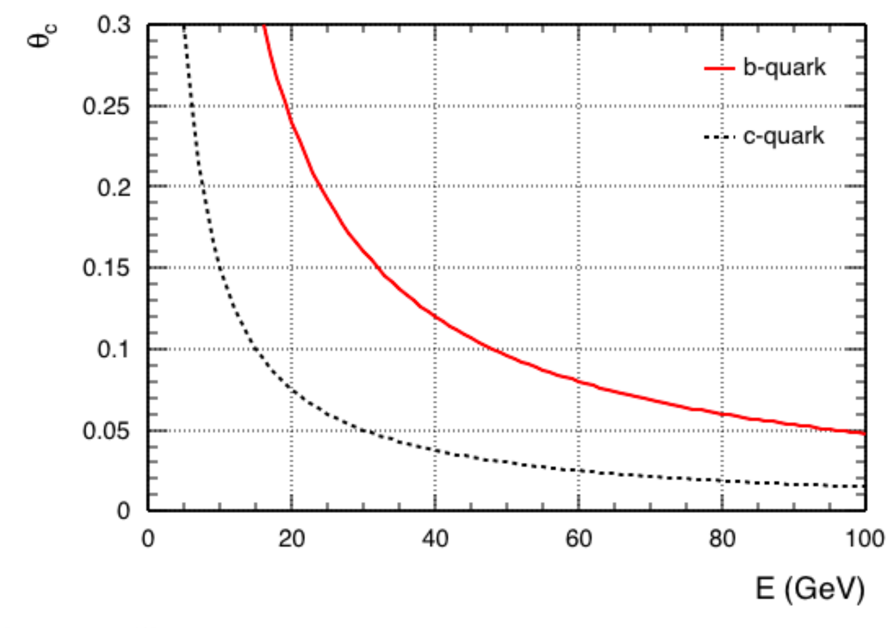
Searching for the dead cone effects with iterative declustering of heavy-flavor jets
Leticia Cunqueiro (ORNL/UTK), MP
[https://arxiv.org/abs/1812.00102](https://arxiv.org/abs/1812.00102)

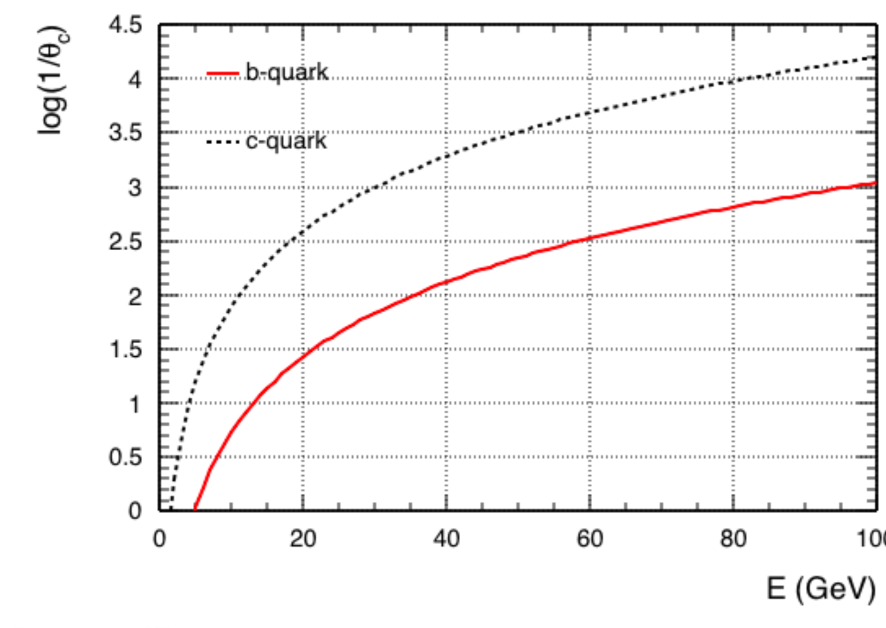



$\boldsymbol{\theta} \sim k_T/zp_{t,jet}$

Hard gluons restricted to radiate outside the dead cone (small $k_T$)

## Dead cone for $\theta < m\,/\,E$



# Heavy-flavor and the dead cone…

- High-energy HF – little dead-cone effect because of m/E small – radiative quark (a la LF) e-loss dominant
- I. Viteev et al. study HF-jets with $z_g$ (standard grooming tech.) => no significant differences as compared to LF jets (high-momentum 140-160 GeV) for HF tagged jet Q->Qg
- QQbar splits in parton shower:
  - I. Viteev – little / no in medium modification
  - Novel techniques in pp on Disentangling Heavy Flavor at Colliders [arXiv:1702.02947] – potentially interesting for AA

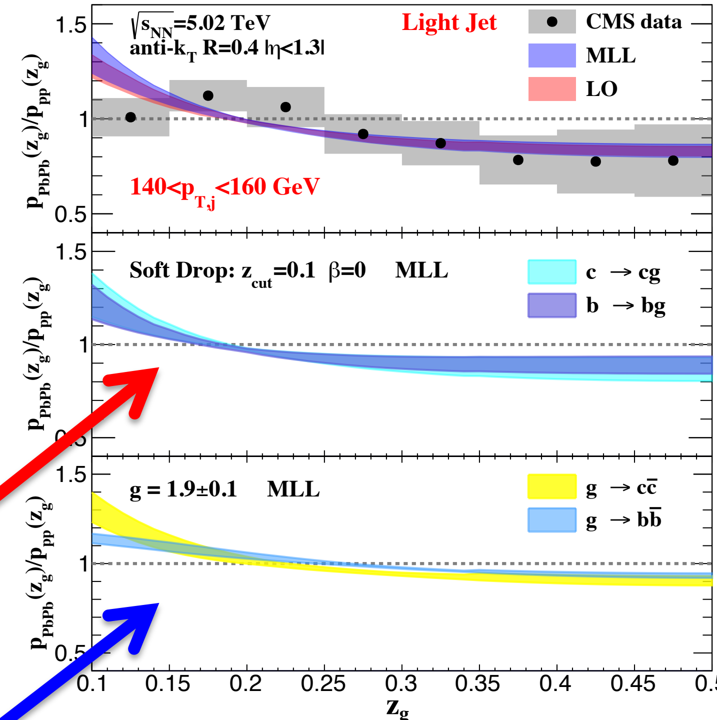



**Figure 2.** The modification of the jet splitting functions in 0-10% central Pb+Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV for the $p_T$ bin $140 < p_{T,j} < 160$ GeV. The upper panels compare the LO and MLL predictions to CMS light jet substructure measurements [12]. The middle and lower panels present the MLL modifications for heavy flavor tagged jet - the $Q \to Qg$ and $\to Q\bar{Q}$, respectively.

# Heavy-flavor and the dead cone…

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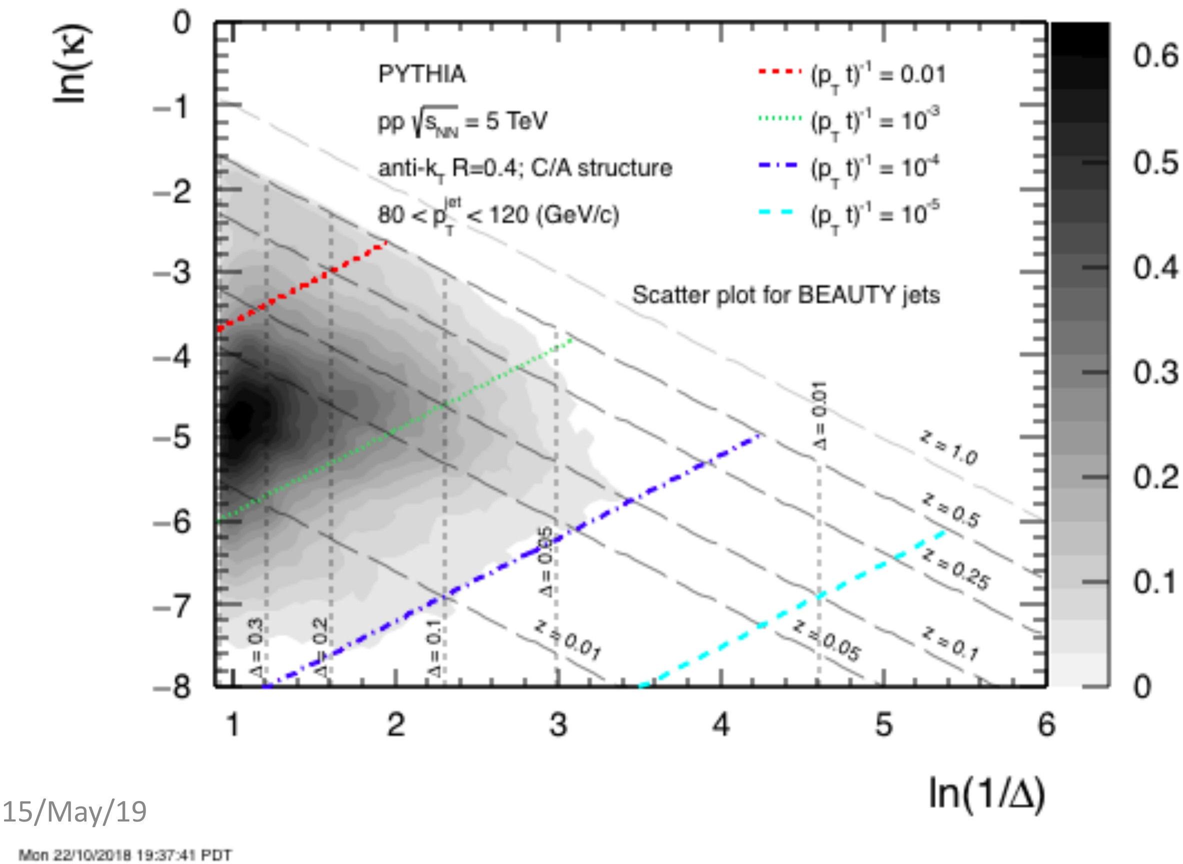
  - Use leading (high-$p_T$) HF-hadron (lepton) for the tag & follow declusterization
- Why $z_g$ (used so far) not good?



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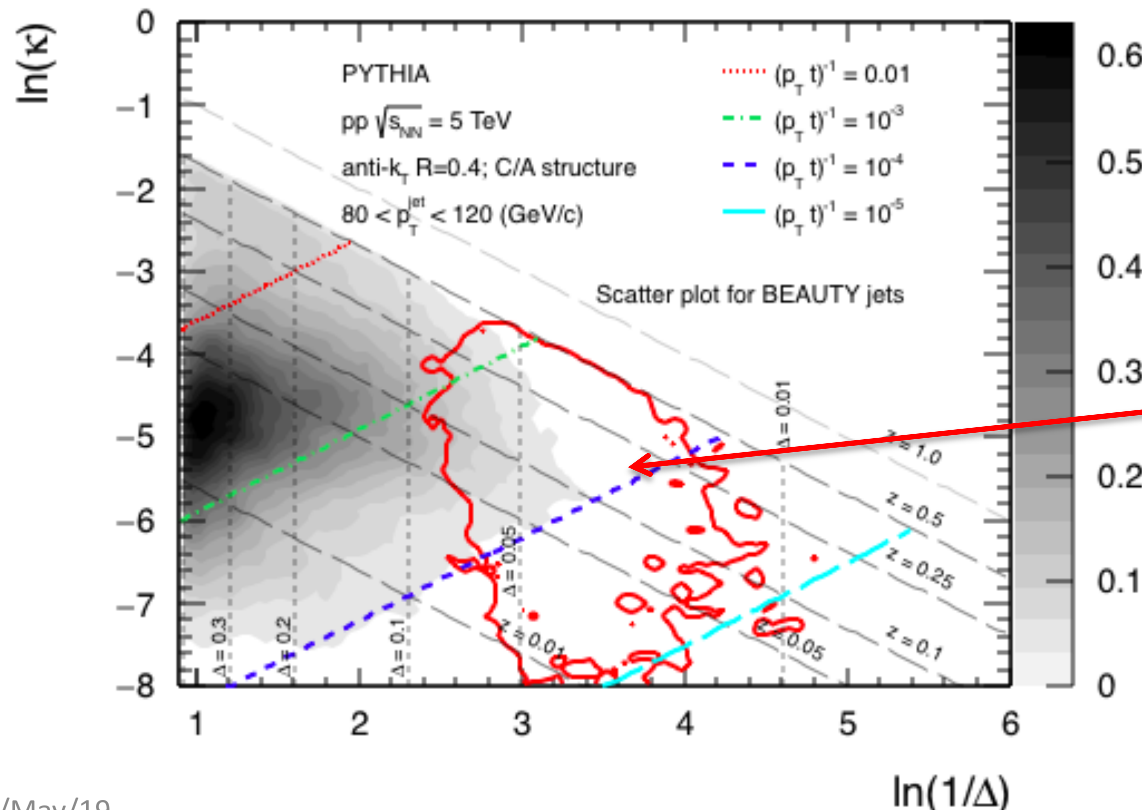


Dead cone
- An approximation
  - $\Delta < m/E$
- Entries that dead cone ought to suppress



Mon 22/10/2018 19:37:42 PDT

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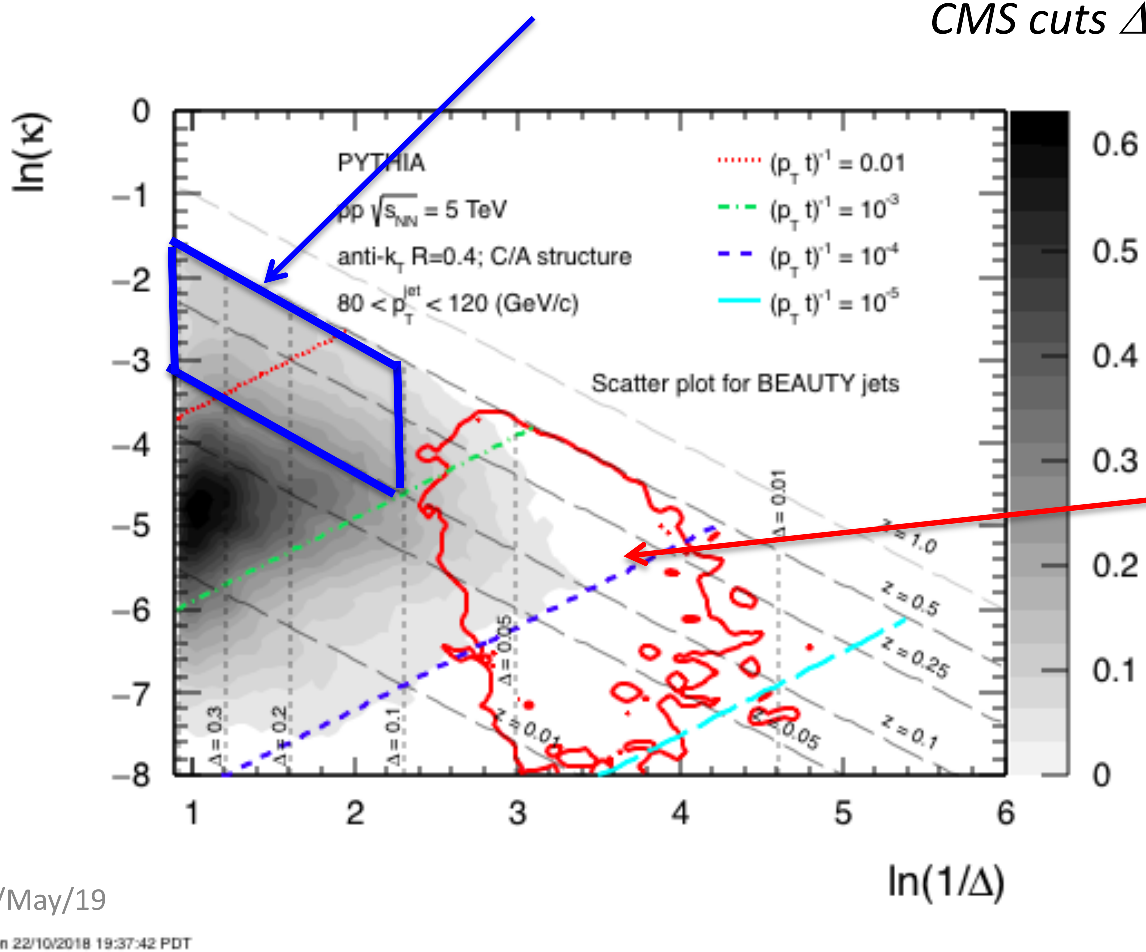
*CMS cuts $\Delta < 0.1$ – ALICE does not*

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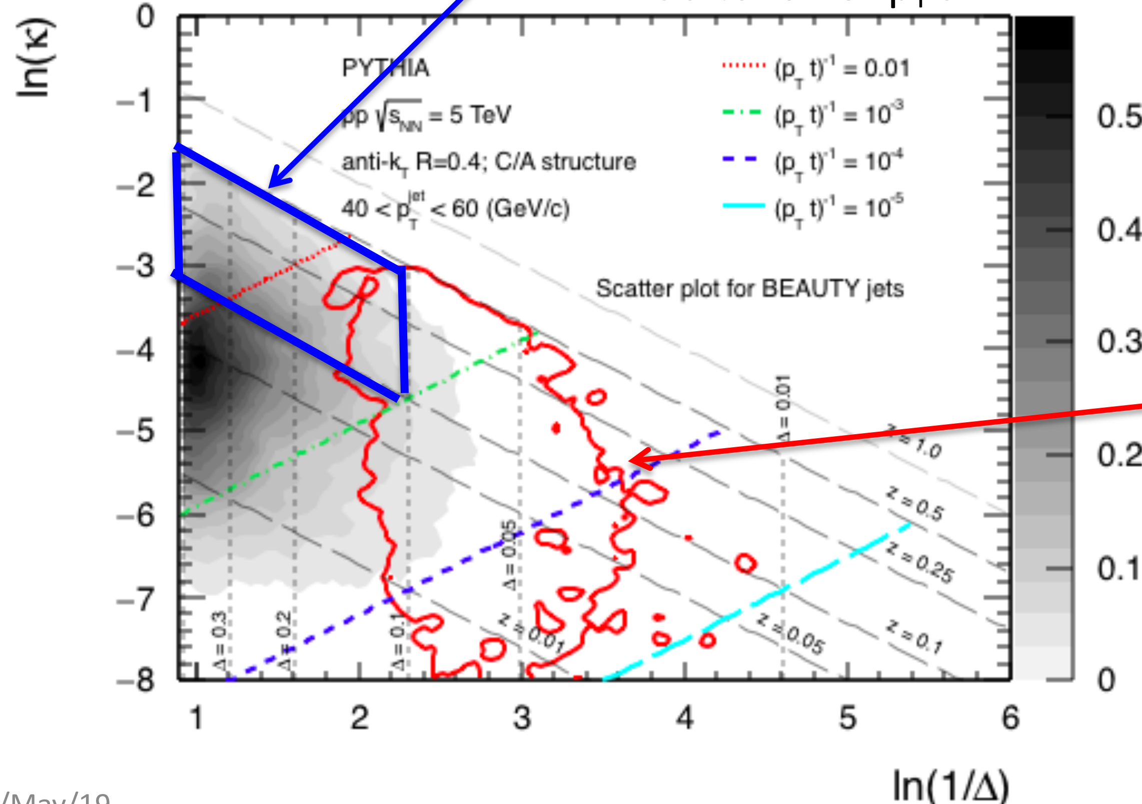
Go to lower $p_T$'s …

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Mon 22/10/2018 19:37:42 PDT

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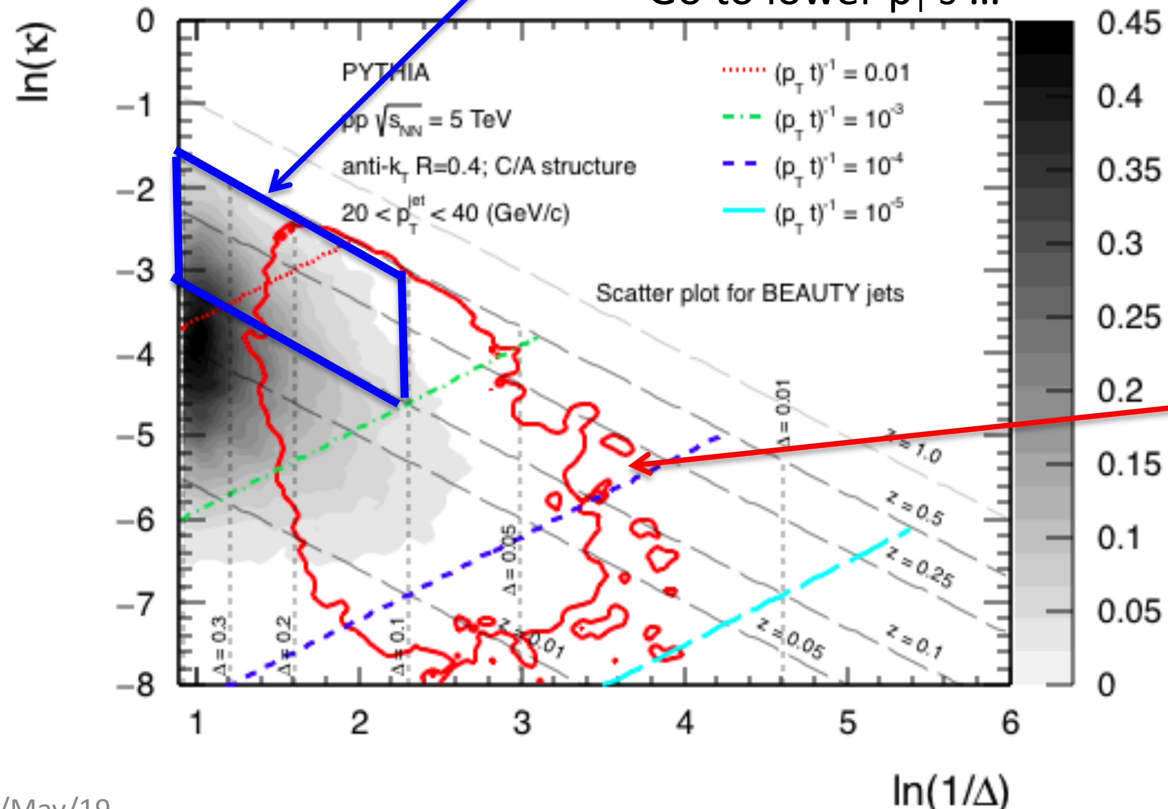


Dead cone
- An approximation
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# Lower pT

**Hai Tao Li**
**There it is!**
**Normalization?(!)**

High-$p_T$

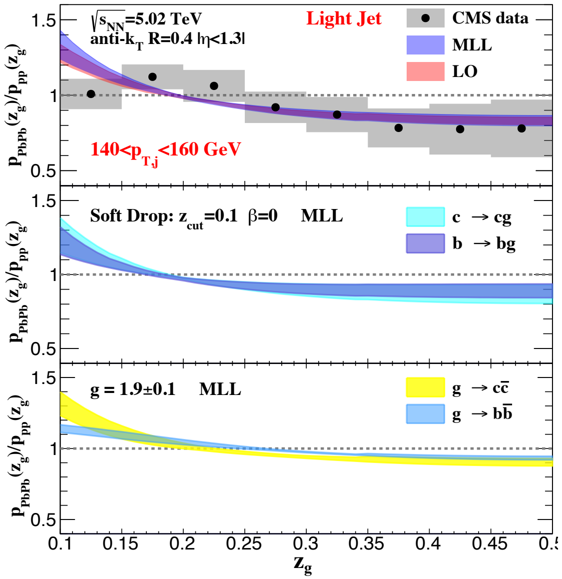
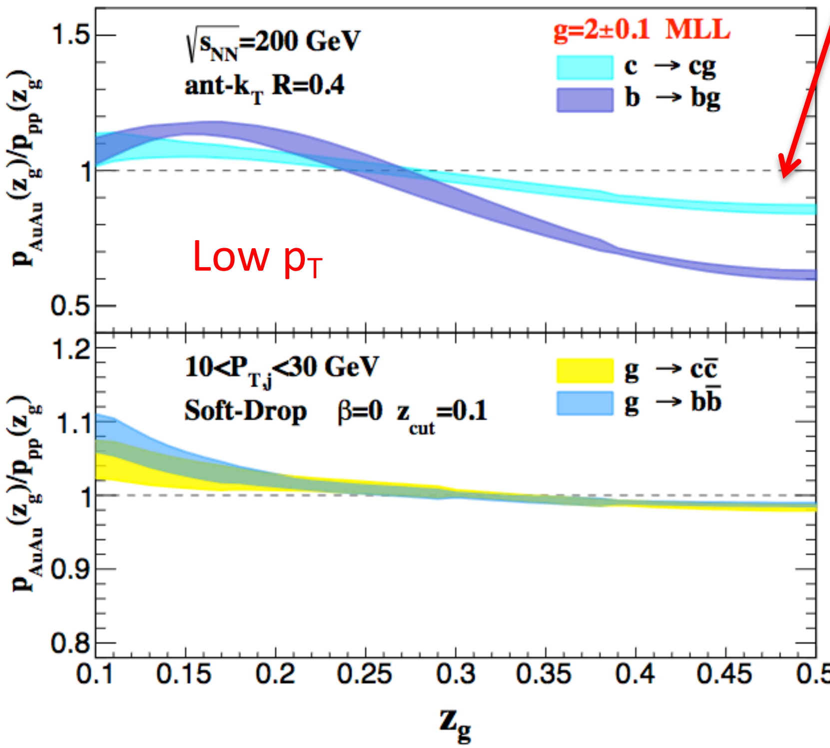



**Figure 2.** The modification of the splitting functions in 0-10% central Pb- collisions at $\sqrt{s_{NN}} = 5.02$ TeV for the $p_T$ $140 < p_{T,j} < 160$ GeV. The upper pa compare the LO and MLL predictions to C light jet substructure measurements [12]. middle and lower panels present the M modifications for heavy flavor tagged jet - $Q \to Qg$ and $\to Q\bar{Q}$, respectively.

Modification of fragmentation functions for gluon and quark

Kang et al 2014

Chien e



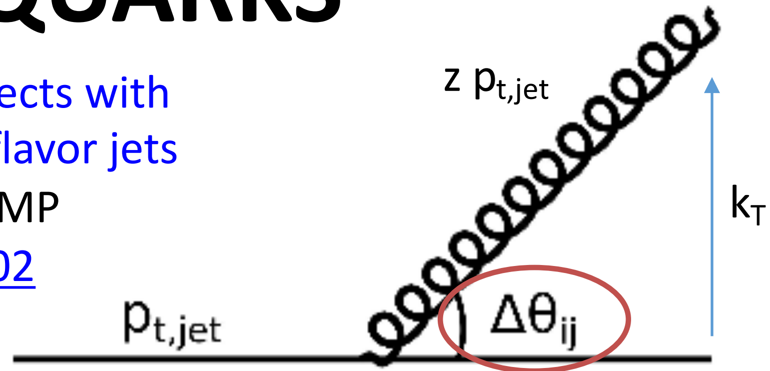

modifications of the jet splitting functions

HTL, Vitev 2018

https://indico.bnl.gov/event/5039/contributions/26256/attachments/21619/29615/b_jet_haitao.pdf

# ONTO HEAVY QUARKS

Searching for the dead cone effects with iterative declustering of heavy-flavor jets
Leticia Cunqueiro (ORNL/UTK), MP
https://arxiv.org/abs/1812.00102

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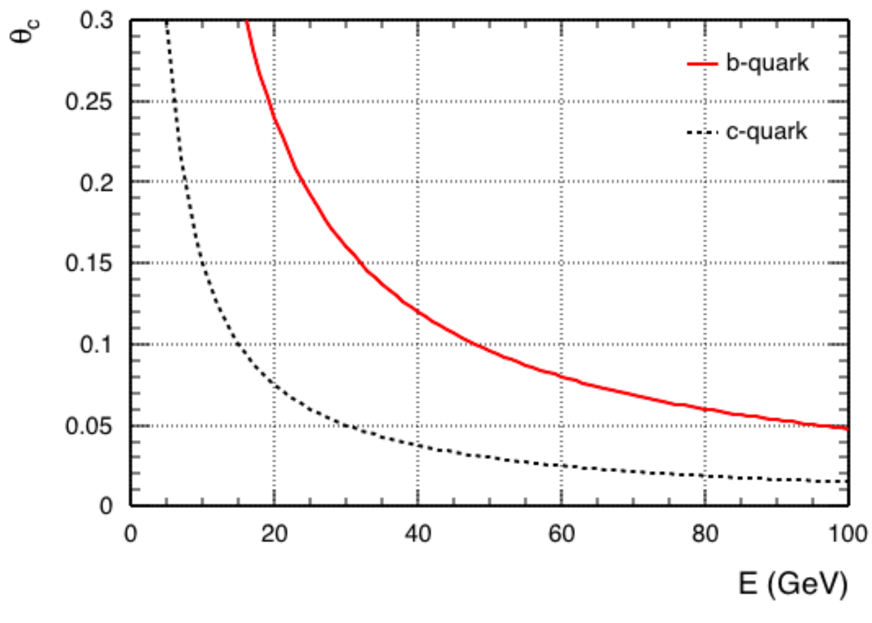
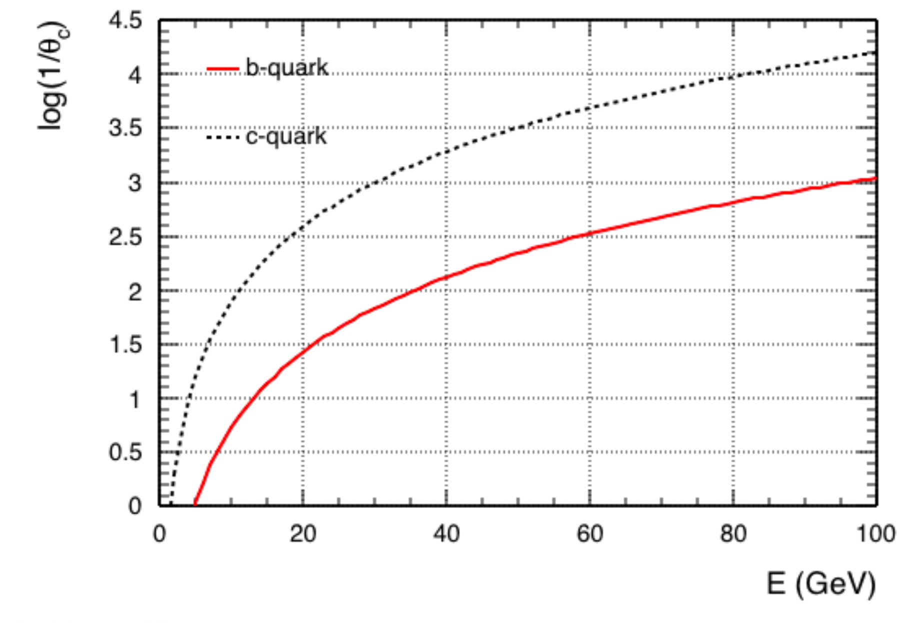
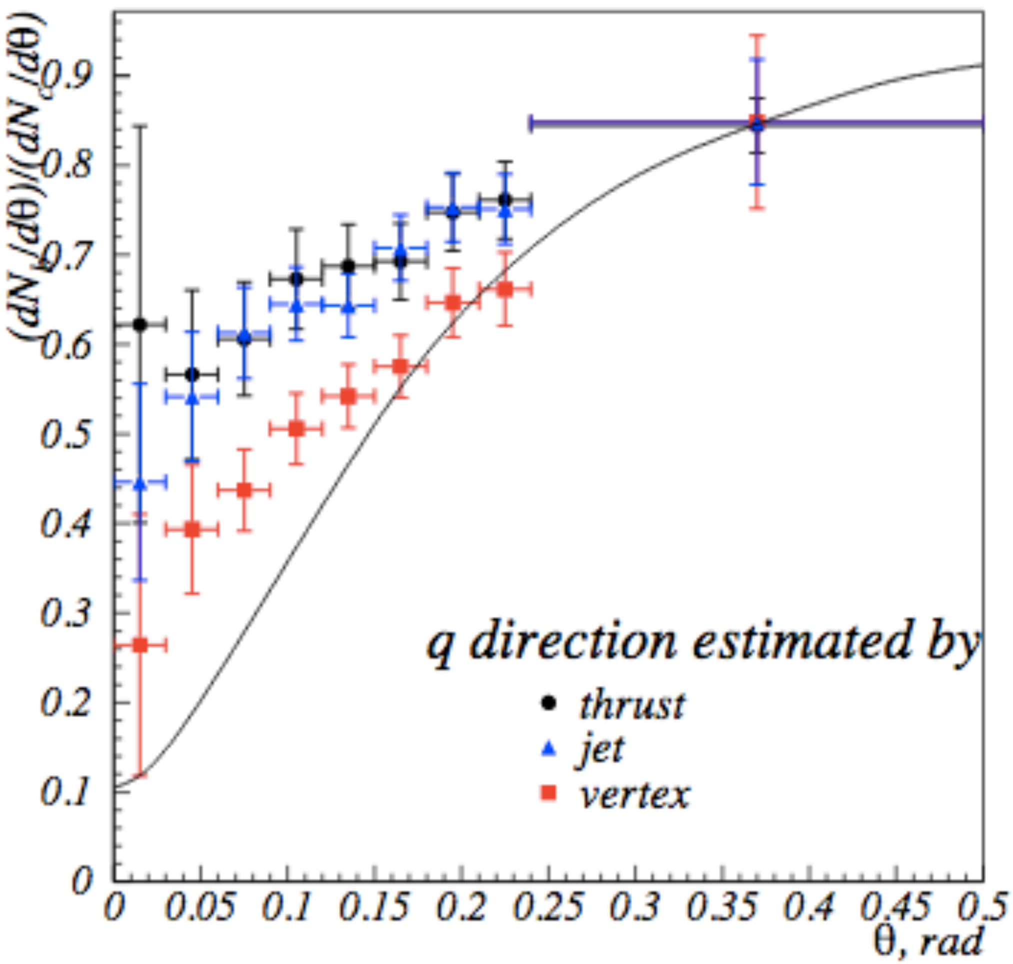


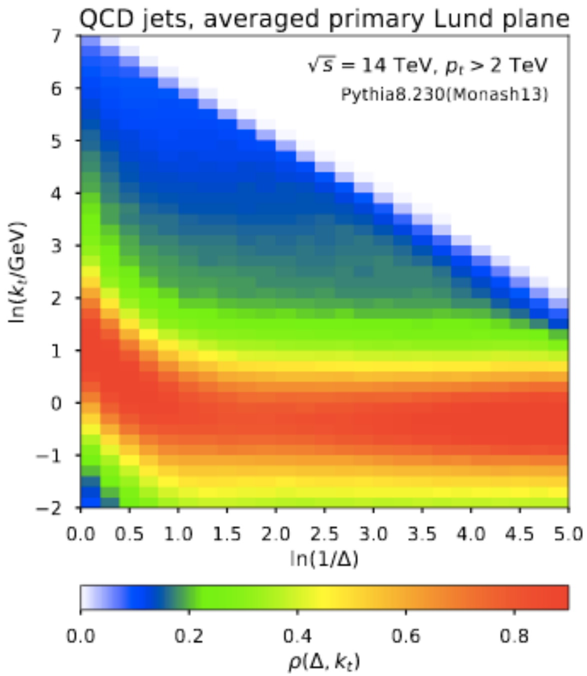



# Dead cone measured?

*Battaglia,Orava,Sami "A study of depletion of fragmentation particles at small angles in b-jets with the DELPHI detector at LEP"*
The first and only attempt of direct dead cone measurement



# The recipe… (1/2 – decluster…)




Dreyer, Soyez,Salam JHEP 1812 (2018) 064

2D map of the jet tree filled via iterative declustering:

-Recluster the jet constituents with CA (a convenient metric for vacuum angular ordered showers)

-Uncluster it step by step, from the prongs that were merged last to the prongs that were merged first.

-Each time, register the scale $k_T$ and the opening angle θ between the subleading and leading prong

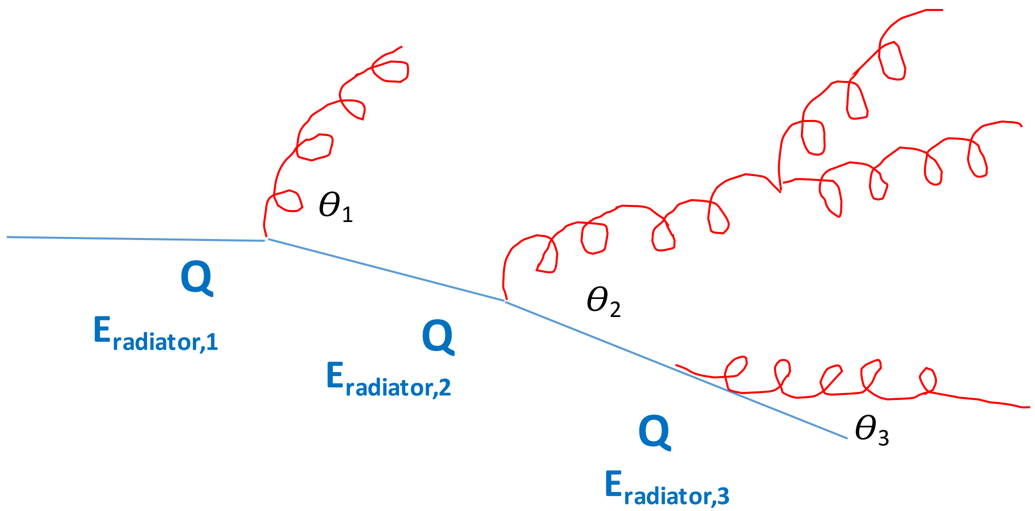
-Always follow the hardest prong

The result is a flat 2D density map (except for the running of the coupling)

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

# Recipe… 2/2 – follow HF

## “tag & follow” heavy-flavors (hardest branch)…




We do the standard declustering process

We follow the prong containing the heavy flavor at each step

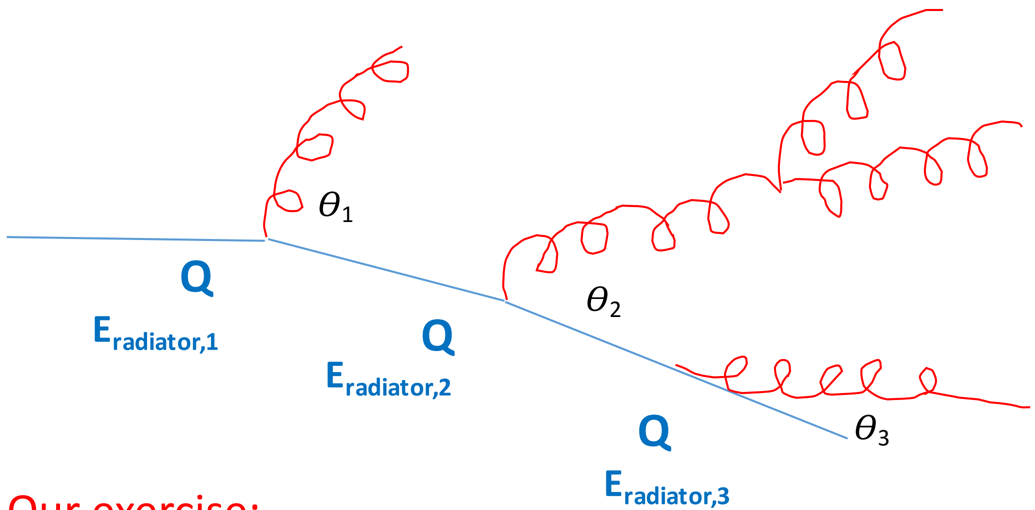
Negligible number of cases where the prong containing the heavy flavor is not the hardest, no ambiguity when comparing to light quarks

At each step of the jet tree we can access the angle of the splitting and the energy of the radiating parent subjet, $E_{radiator}$. For $\theta < m_Q/E_{radiator}$ we expect to see a suppression of splittings.

For low $E_{radiator}$ , which means penetrating the jet to deep levels, the phase space for the dead cone observation grows.

# Recipe… 2/2 – follow HF

## "tag & follow" heavy-flavors (hardest branch)…




We do the standard declustering process

We follow the prong containing the heavy flavor at each step

Negligible number of cases where the prong containing the heavy flavor is not the hardest, no ambiguity when comparing to light quarks

Our exercise:

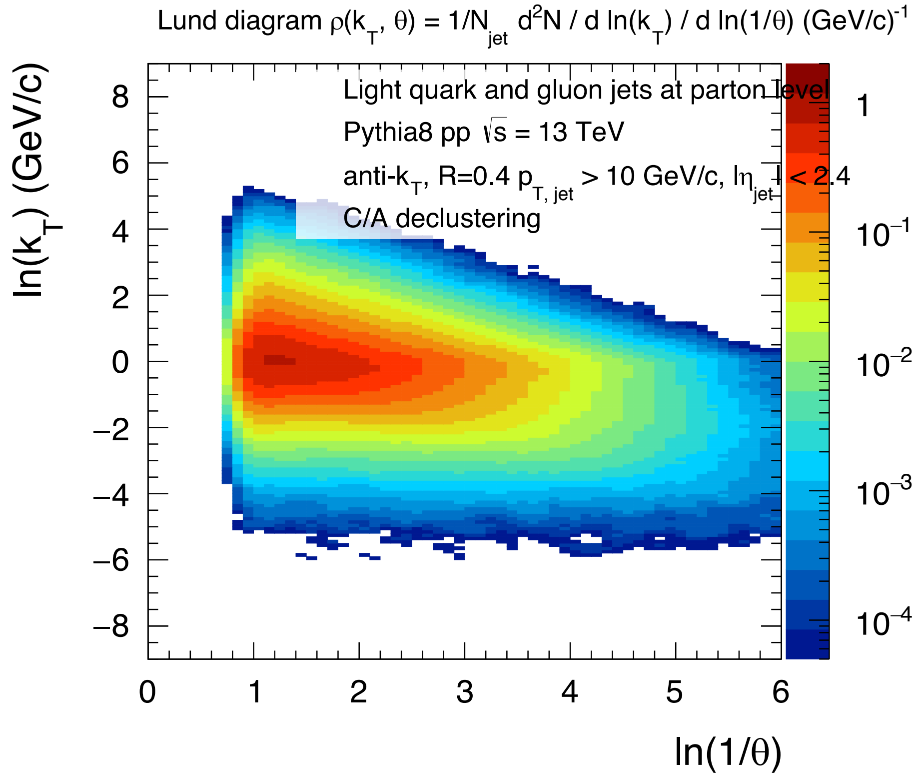
- Pythia8 Tune 4C
- pp collisions at √s=13 TeV
- Select ccbar, bbar production channels
- At parton level the leading prong at each declustering step is the one containing the heavy parton
- At hadron level, we inhibit the decay of the B and D mesons and the leading prong at each declustering step the one containing the heavy meson.
- Anti$k_T$ jets R=0.4, CA reclustering algo

# LF vs HQ – parton level – no UE, no ISR

log(kT) = -2 ⇔ kT = 0.135 GeV
log(kT) = 0 ⇔ kT = 1 GeV

All jets (light quark and gluon)

Parton level

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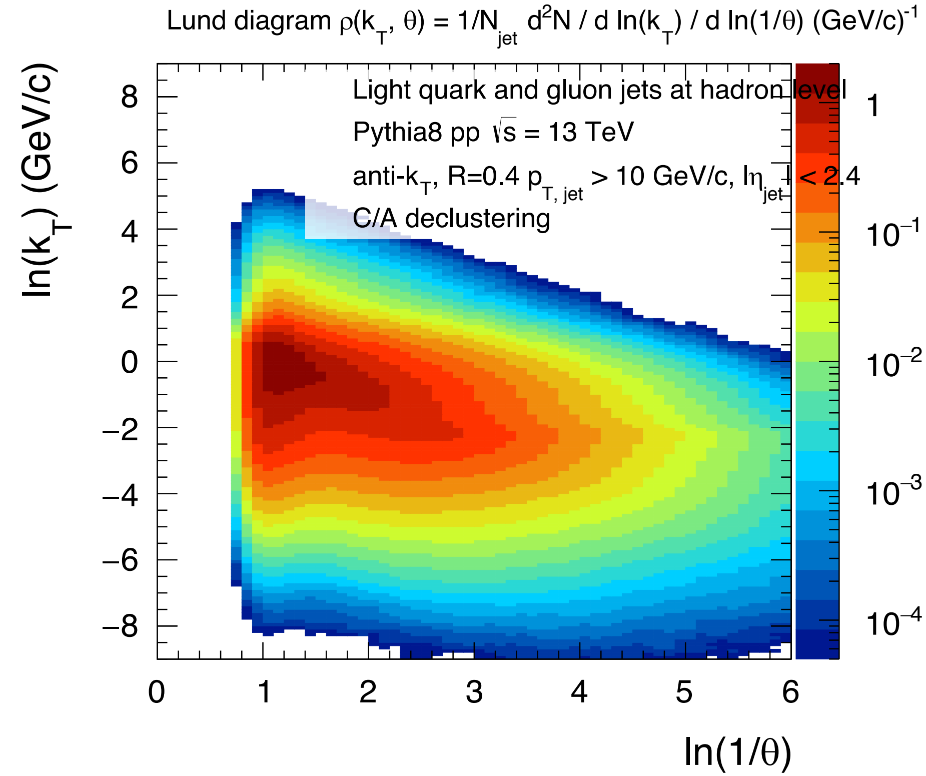
Hadron level

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Hadron level – ALL processes

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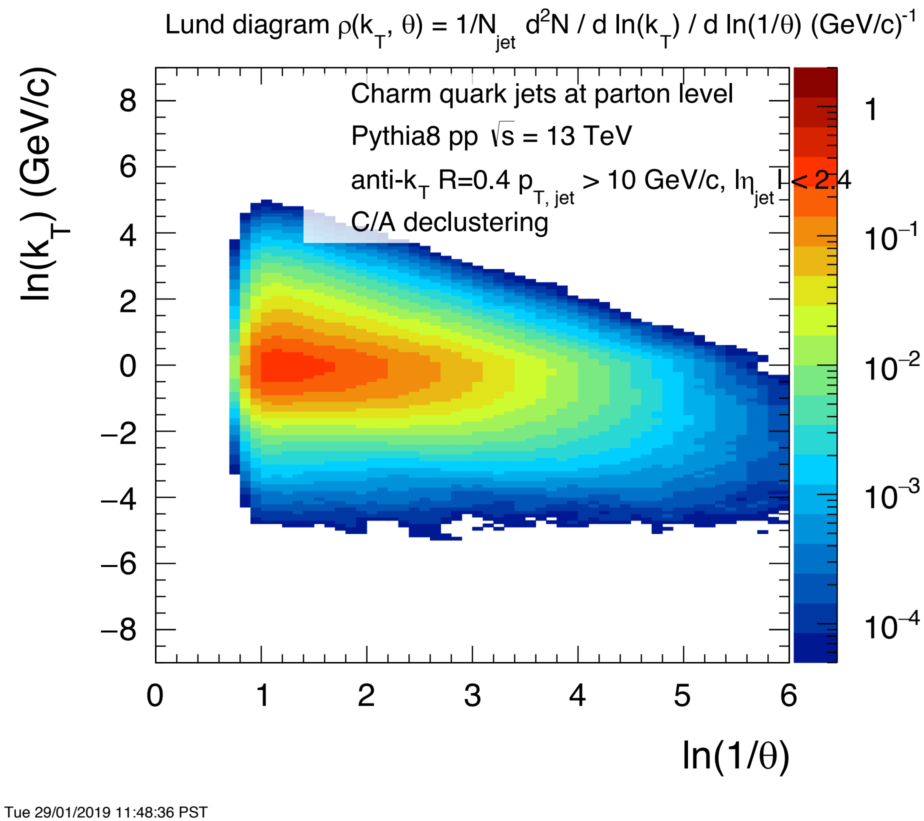
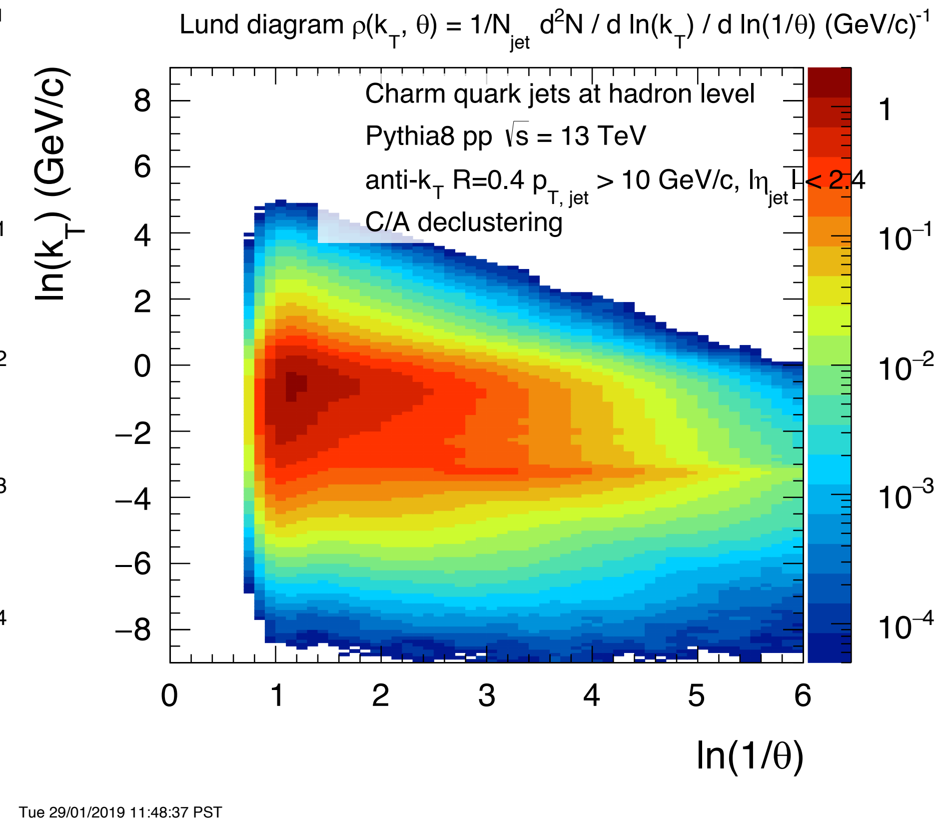
**Charm**

Parton level




Hadron level

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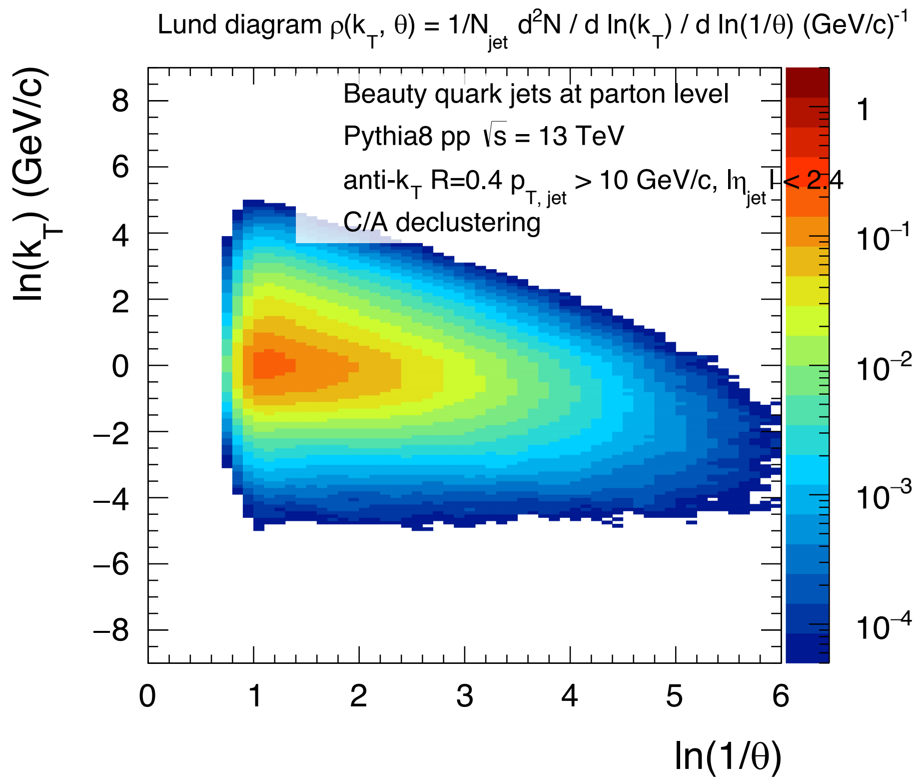
**Beauty**

Parton level

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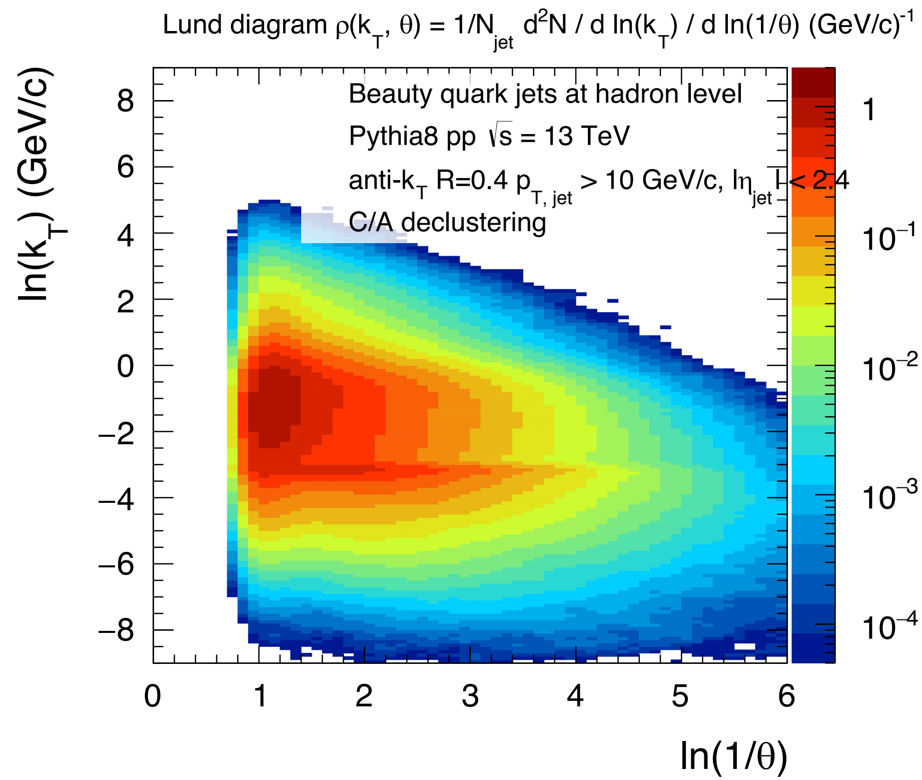


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Hadron level – ALL processes

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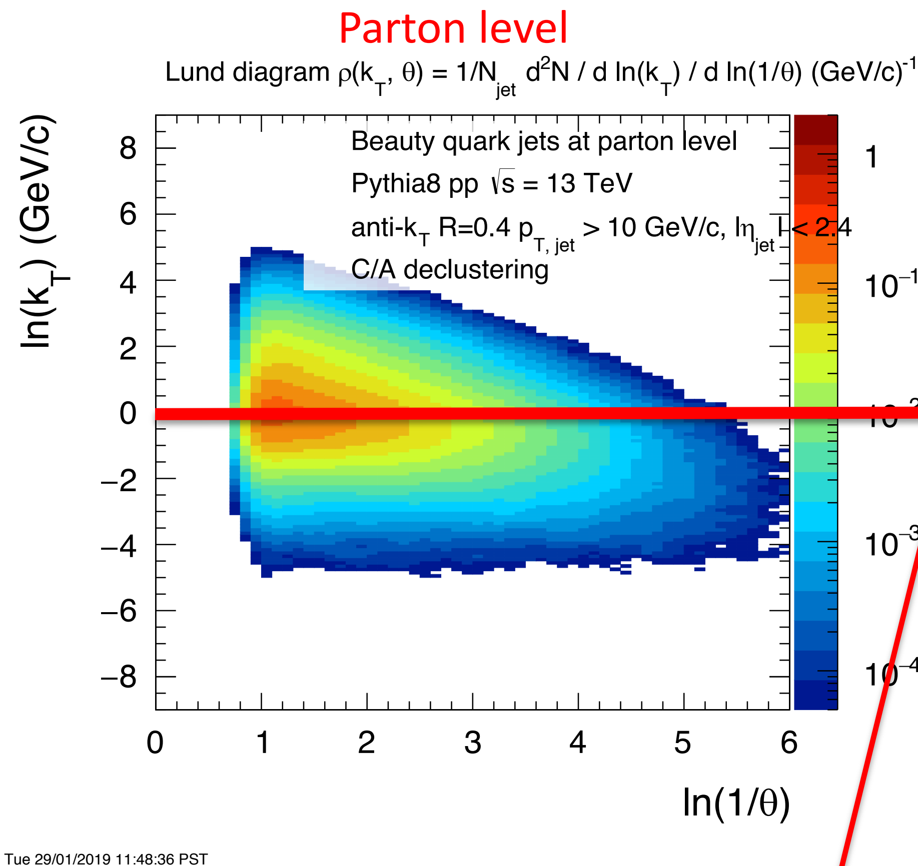
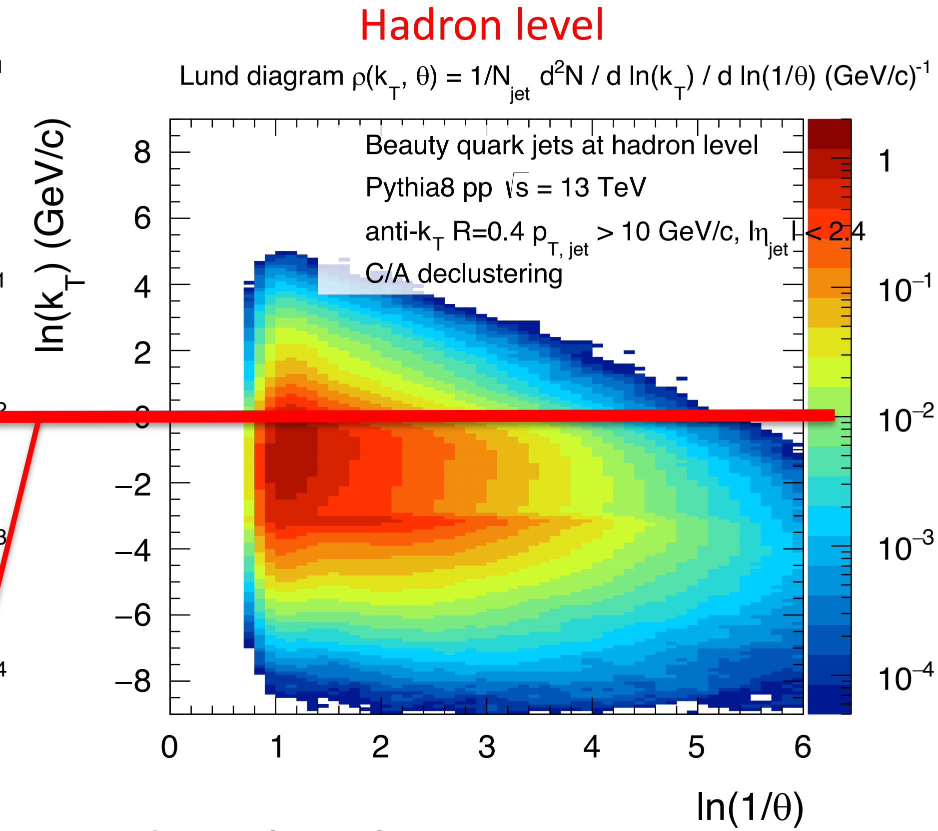



Hadron level – ALL processes

Non-perturbative effects can be removed/isolated by cutting the region $\ln(k_T)<0$

# Dead cone on parton level

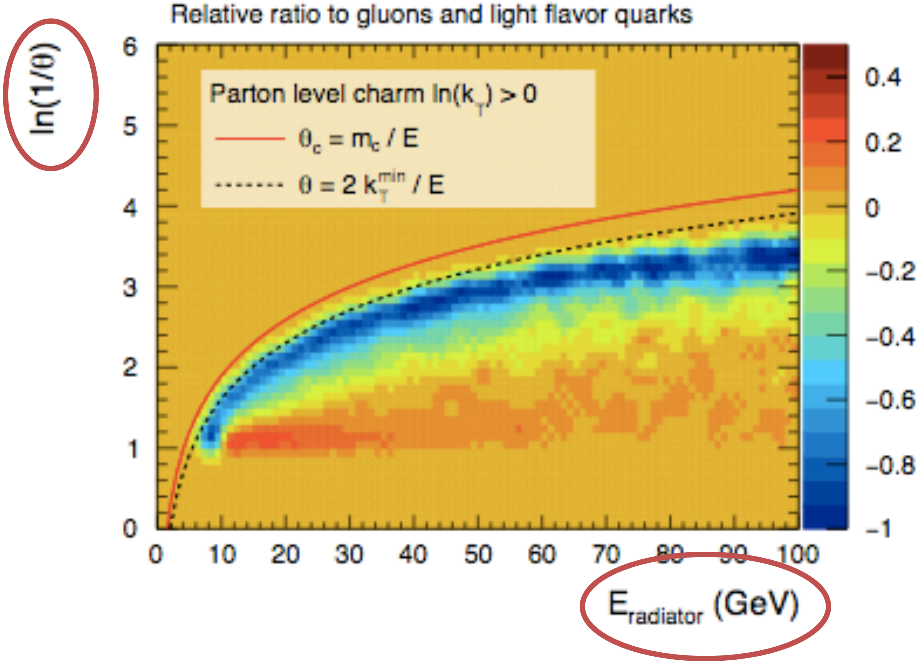
Cut on log(kT) > 0

$$E_{radiator} > 1/(z\theta)$$

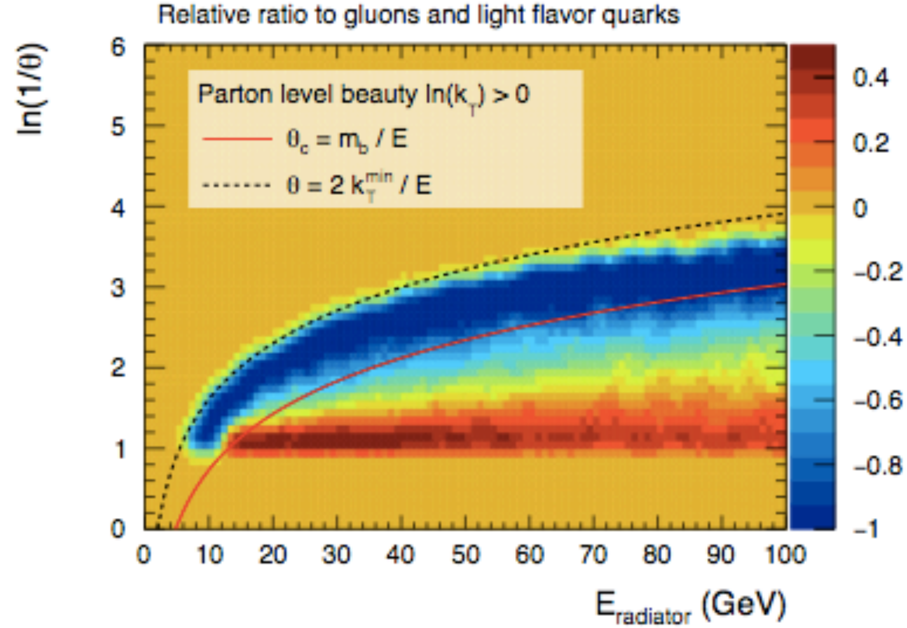
Parton level – no UE, no ISR

**Angle vs. Energy of the radiator**

**charm**




**beauty**




$$Q = \frac{P^{Q}(log(1/\theta), E_{radiator}) - P^{inc}(log(1/\theta), E_{radiator})}{P^{inc}(log(1/\theta), E_{radiator})}$$

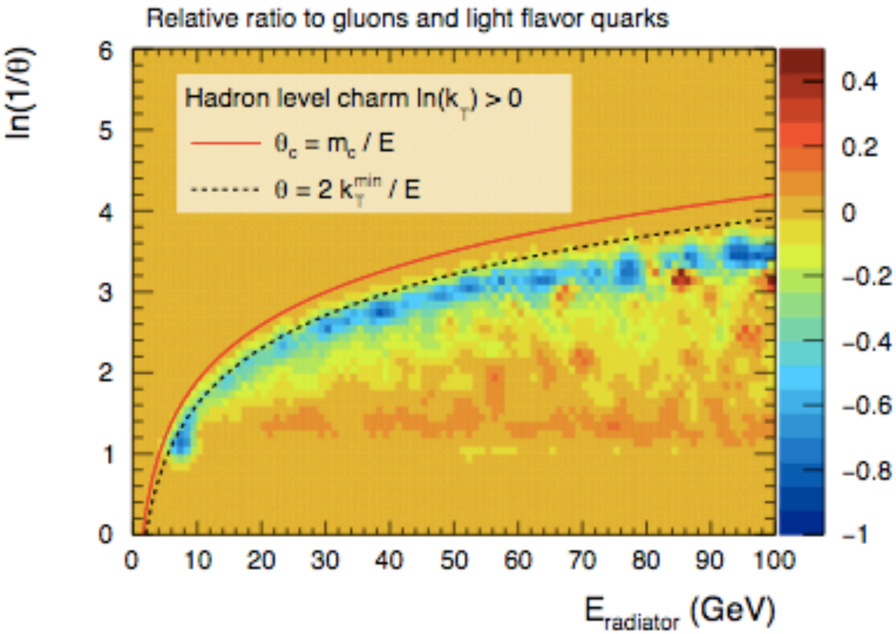
The cut log($k_T$)>$k_T^{min}$ translates into $\boxed{E_{radiator} > k_T^{min}/z\theta}$ The black dashed line corresponds to the kinamtic limit of z=0.5, above which there are no more entries in the inclusive reference

We can identify regions of phase space where $P^Q$ =-1, meaning no radiation off the heavy quark radiator. **The suppression of large angles couples to the suppression of large z**

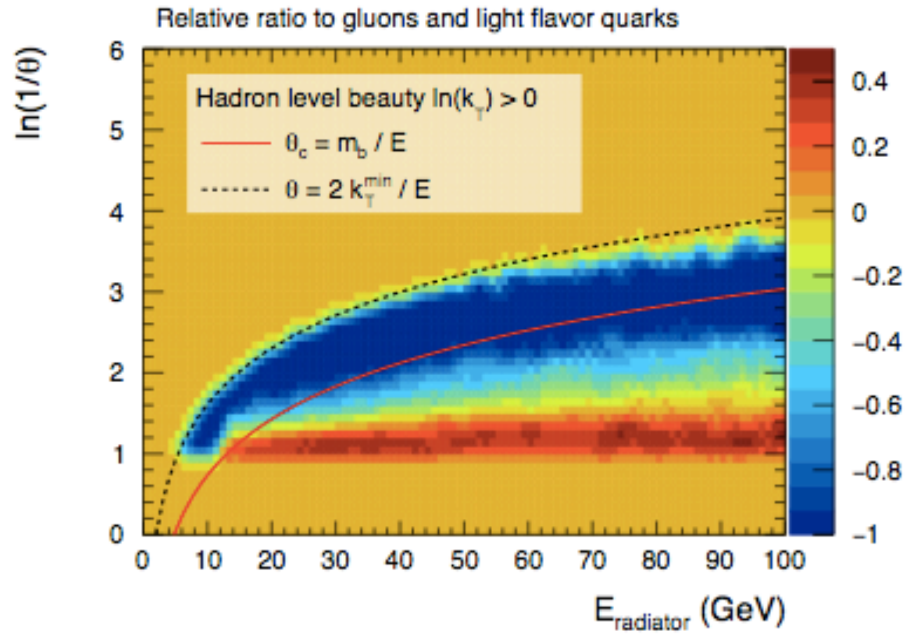
# Dead cone at hadron level

## Hadron level – ALL processes

**charm**




**beauty**




$$Q = \frac{P^{Q}(log(1/\theta), E_{radiator}) - P^{inc}(log(1/\theta), E_{radiator})}{P^{inc}(log(1/\theta), E_{radiator})}$$

At hadron level the effects are smeared but not washed out

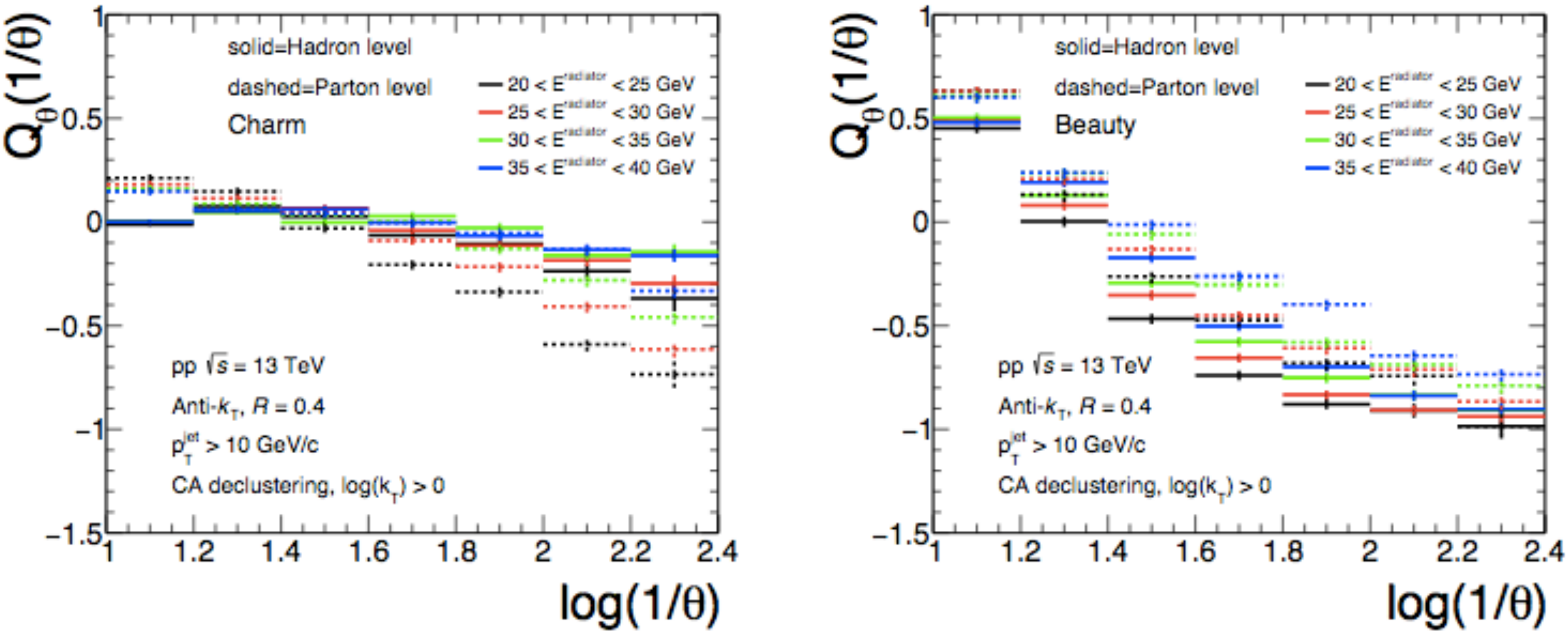
**As expected: the higher $E_{radiator}$ is, the dead cone effects appear at smaller angles.**

**For D jets, the effects appear at measurable angles of ~0.1 rad for radiator energies of 10-30 GeV**

**For B jets, one can go higher in radiator energy and still have effects at angles of the order of 0.1 rad**

# The observable – projections for E

$$Q_\theta = \frac{P^Q(1/\theta) - P^{inc}(1/\theta)}{P^{inc}(1/\theta)}, E_{radiator} \in (E_{min}, E_{max})$$




For $E_{radiator}$=20 GeV,

D-jets are suppressed by 30% relative to inclusive at $\boldsymbol{\theta}$ ~0.1 rad

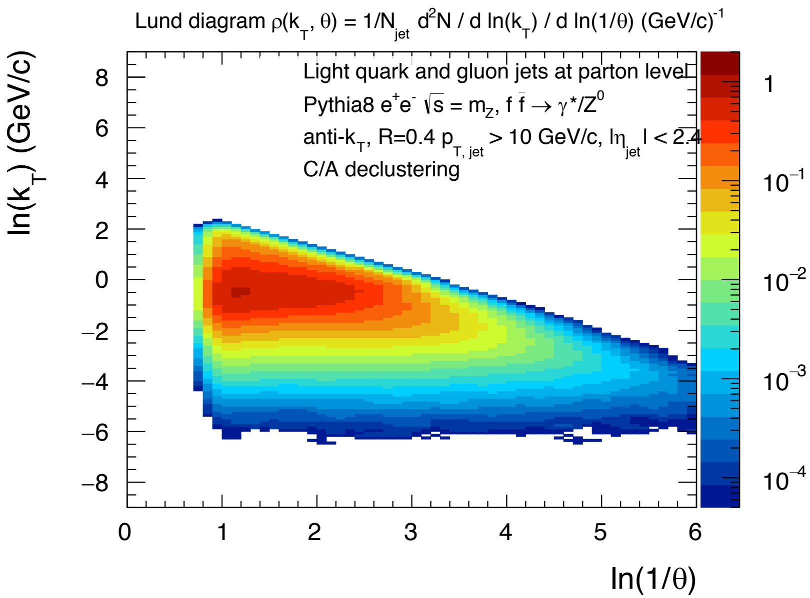
B-jets are suppressed by nearly by 100% relative to inclusive at $\boldsymbol{\theta}$ ~0.1 rad

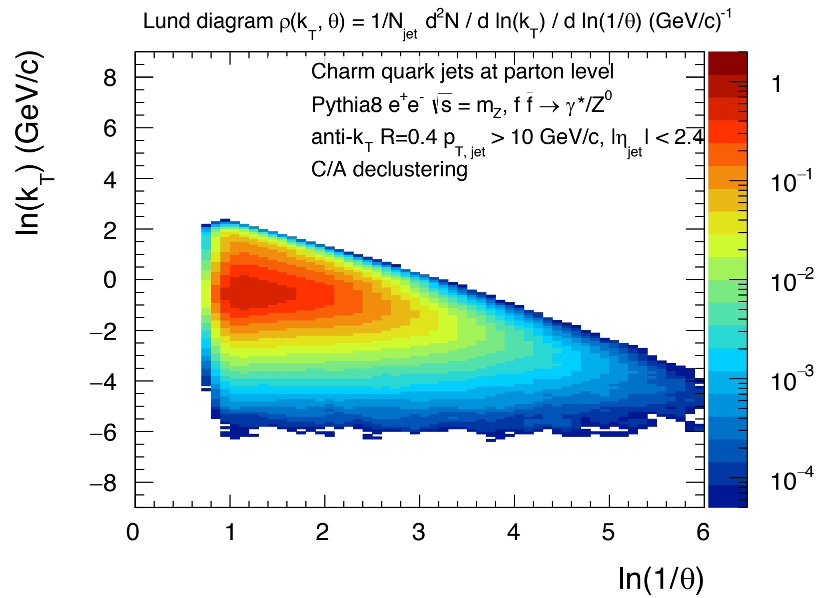


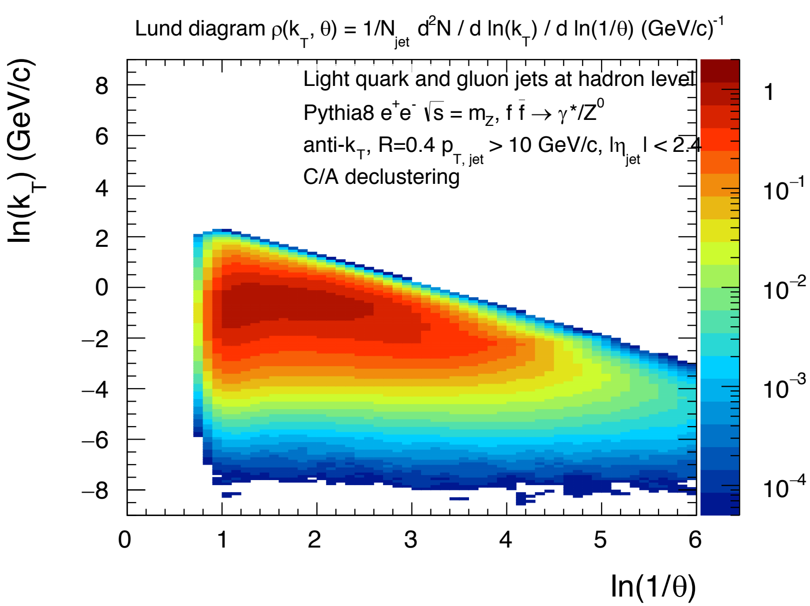
ALICE measurements under way…

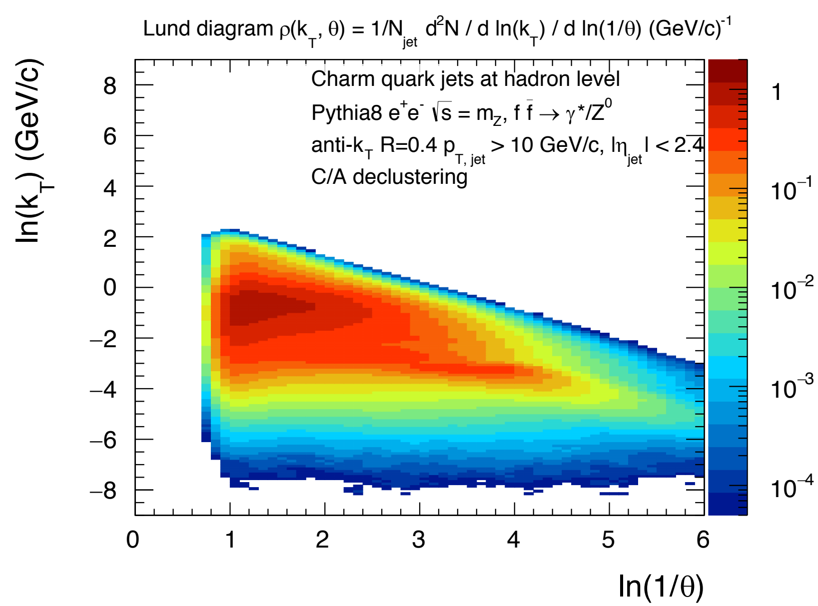
# OUTLOOK: REVISIT LEP, MEASURE AT LHC, … EIC? DETAILED HADRONIZATION STUDIES?

# Outlook : LEP, (eIC…) - charm

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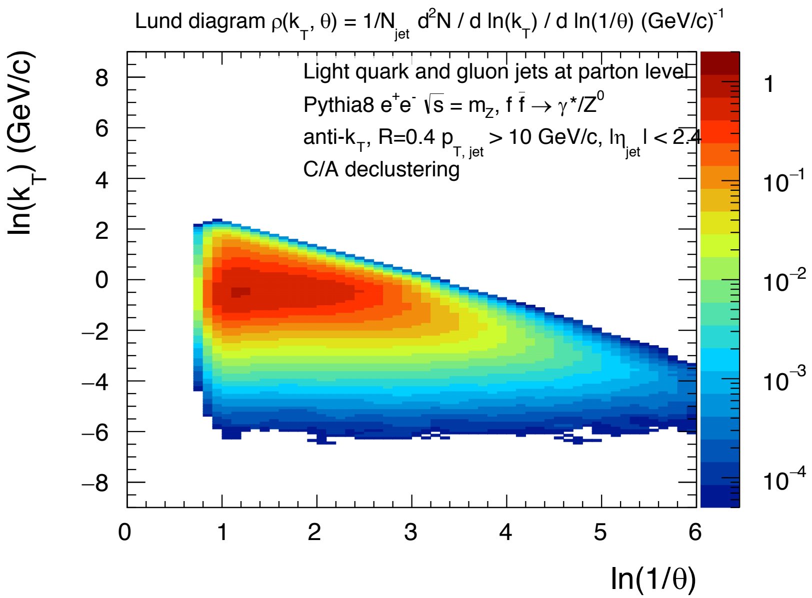
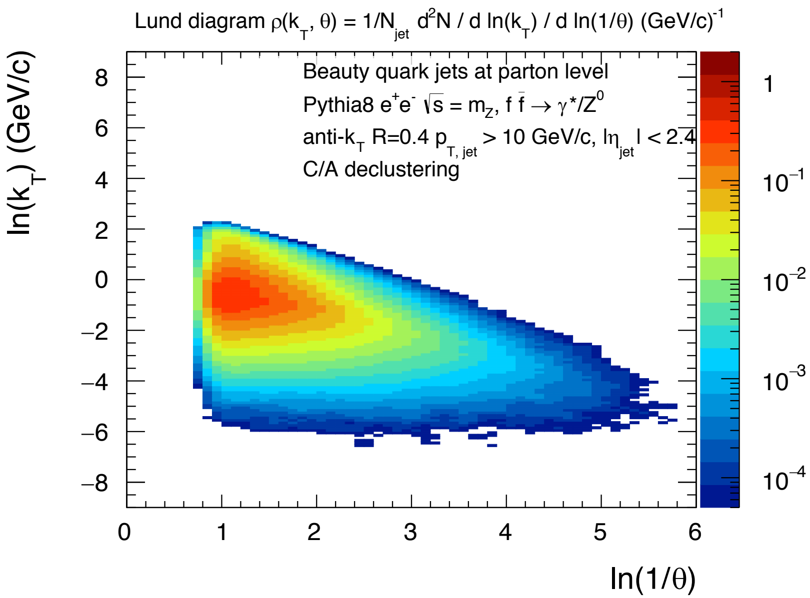
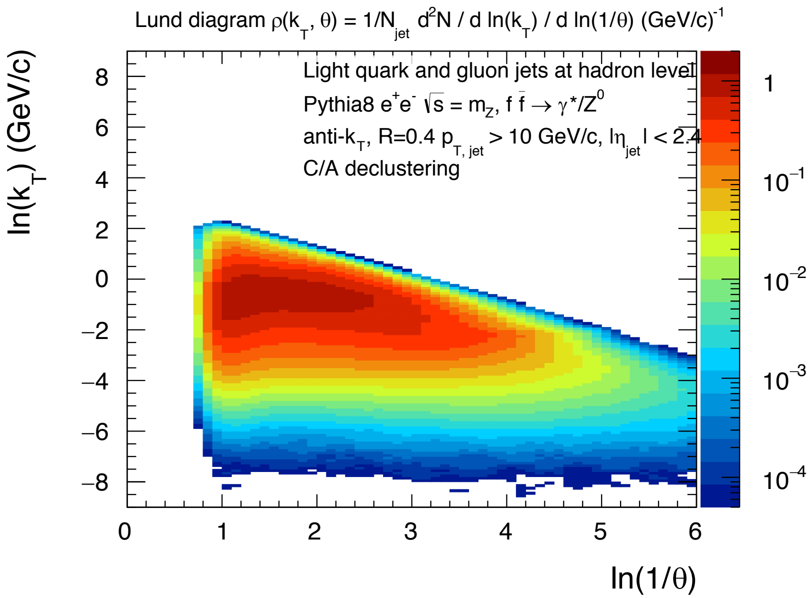
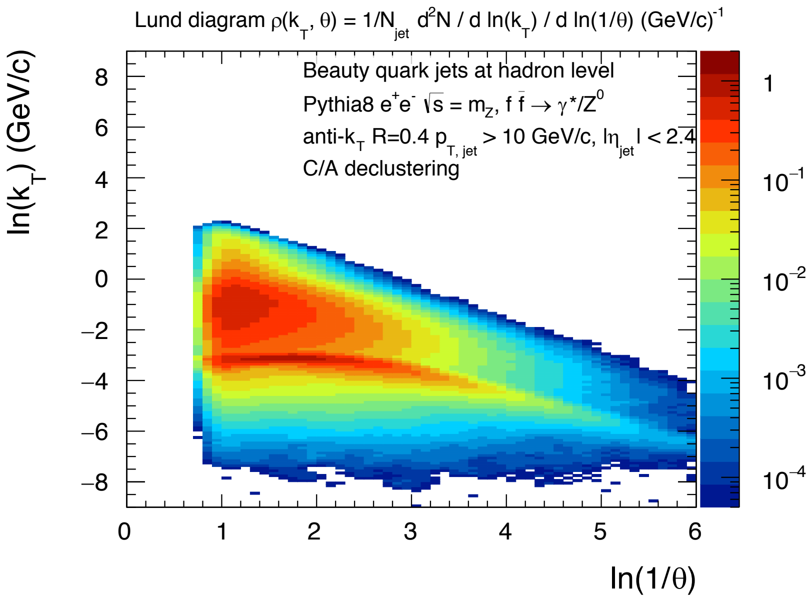
# Outlook : LEP, (eIC…) - beauty

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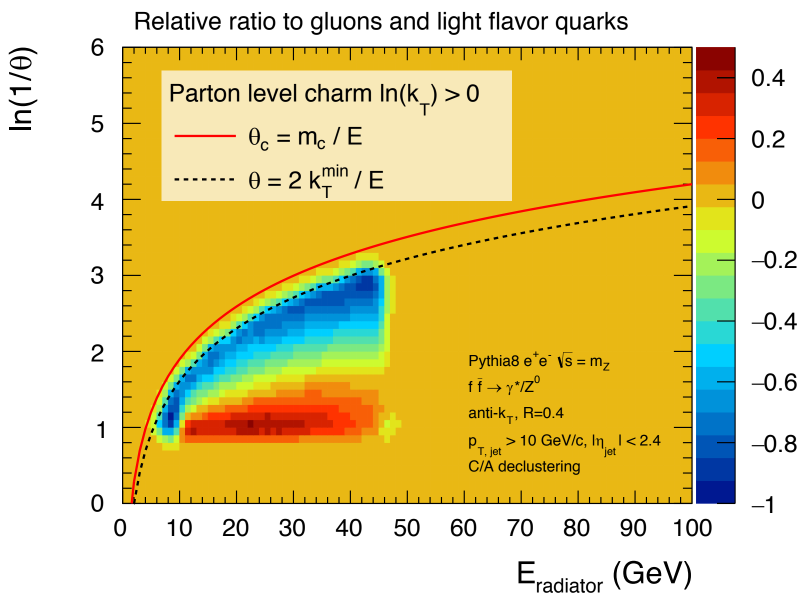
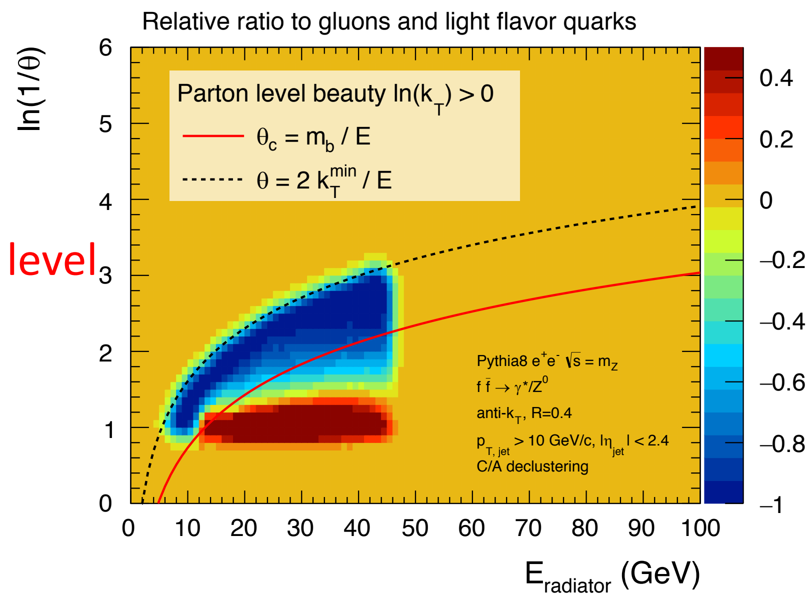
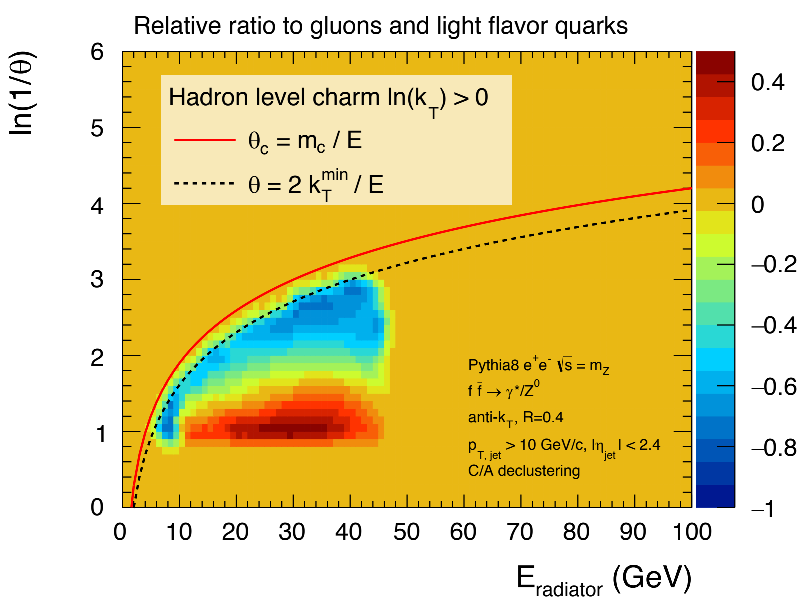
# Outlook : LEP, (eIC…)

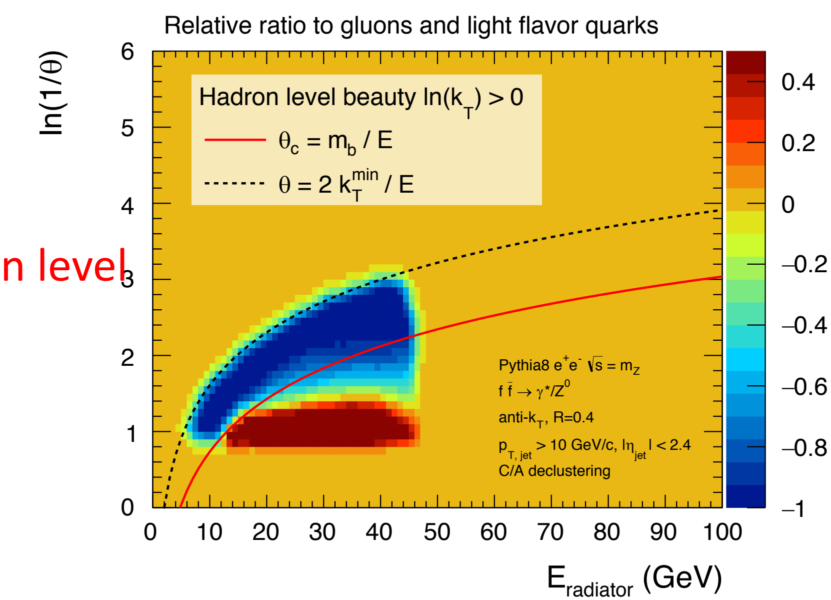



Parton level




Hadron level

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# A comment: kT cut vs. Soft Drop ?

Soft Drop Condition:

$$\frac{\min(p_{t_1}, p_{t_2})}{p_{t_1} + p_{t_2}} > z_{cut} \left( \frac{\Delta R_{12}}{R_0} \right)^{\beta}$$

$$z = \frac{p_{t_2}}{p_{t_1} + p_{t_2}}$$

$$k_T = p_{t_2} \cdot \Delta R_{12}$$

$p_{t_2} > k_{T cut}$ for $R_0 = 1$, $\beta = 1$

# Summary

- Dead cone at the subjet level:
  - rather “simple” conceptually
  - Cut on kT: opportunity to study the effect systematically => constraints on hadronization? (LEP, eIC; hadronic collisions more difficult ISR, MPI,…) – other applications (TBStudied)?
- More applications for de-clustering in considerations (jet classification based on Lund plane - kT)
  - Role for secondary plane (soft branches)?
  - Azimuthal angle? (hadronization, particle decays?)
- Opportunities for heavy-ion collisions – jet modifications, medium response(?), *different* grooming / selection of splittings… - BUT need to choose the ‘right’ observables (not all equally defined/calculable in theory)