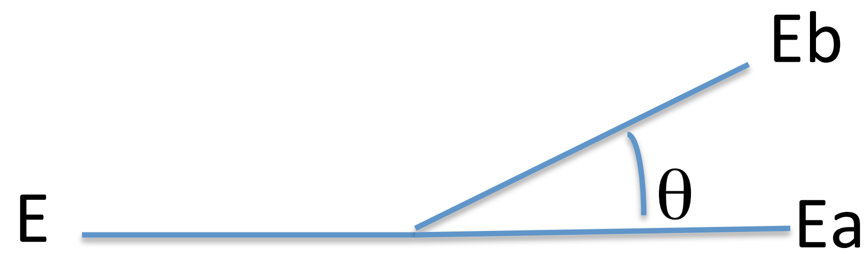
Searching for the dead cone effects with iterative declustering of heavy-flavor jets

Leticia Cunqueiro (ORNL/UTK), MP

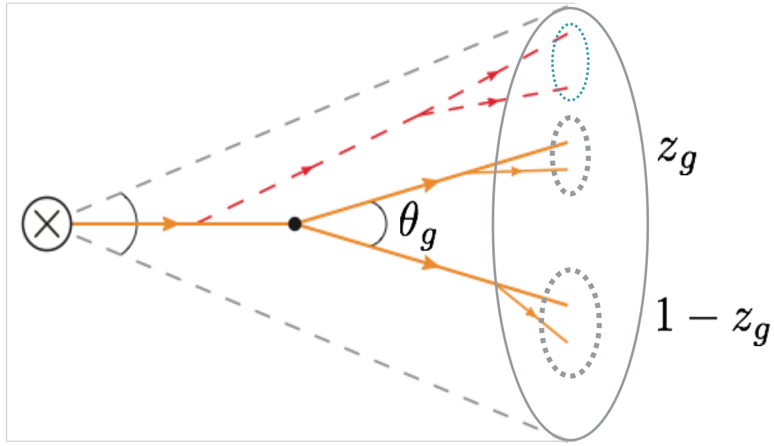
https://arxiv.org/abs/1812.00102

$$\Theta_{d.c.} < m / E$$



Ea > Eb
E = Ea + Eb

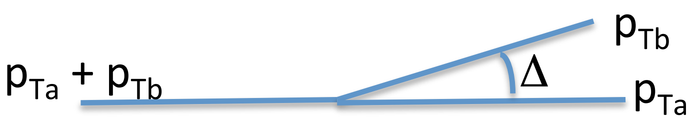
Y.Dokshitzer,V.A.Khoze and S.I.Troyan "On specific QCD properties of heavy quark fragmentation"



JET STRUCTURE

Jet Lund diagram

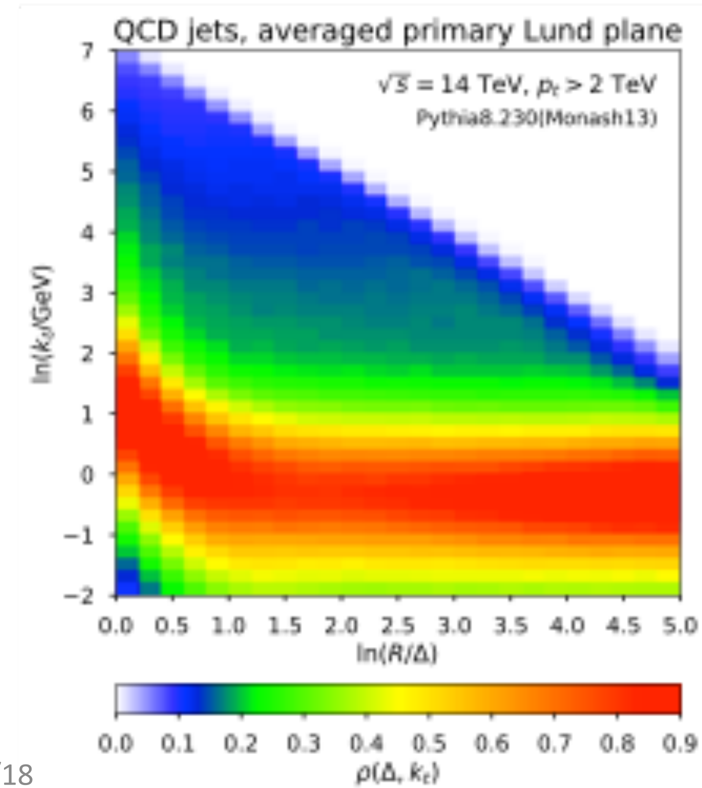
$$p_{T,a} > p_{T,b},\ \kappa = \frac{p_{T,b}}{p_{T,a}+p_{T,b}}\Delta_{ab}$$

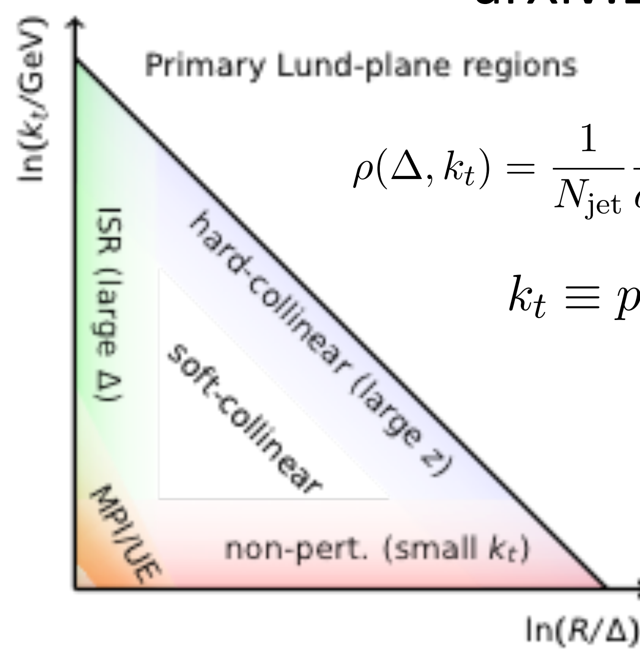


$$\bar{\rho}(\Delta,\kappa) = \frac{1}{N_{\rm jet}}\frac{dn_{\rm emission}}{d\ln\kappa\ d\ln 1/\Delta}$$

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





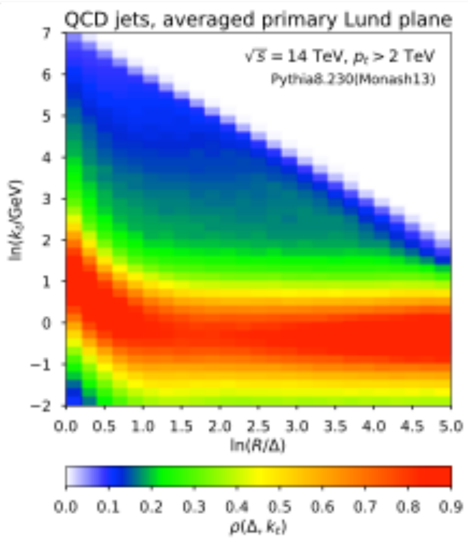
$$\rho(\Delta, k_t) = \frac{1}{N_{\rm jet}}\frac{dn_{\rm emission}}{d\ln k_t\, d\ln 1/\Delta}$$

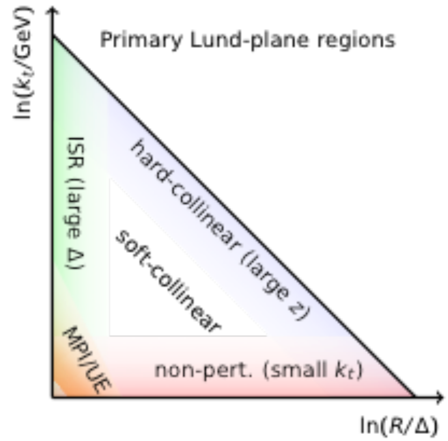
$$k_t \equiv p_{tb}\Delta_{ab},$$

Jet Lund diagram

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

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





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

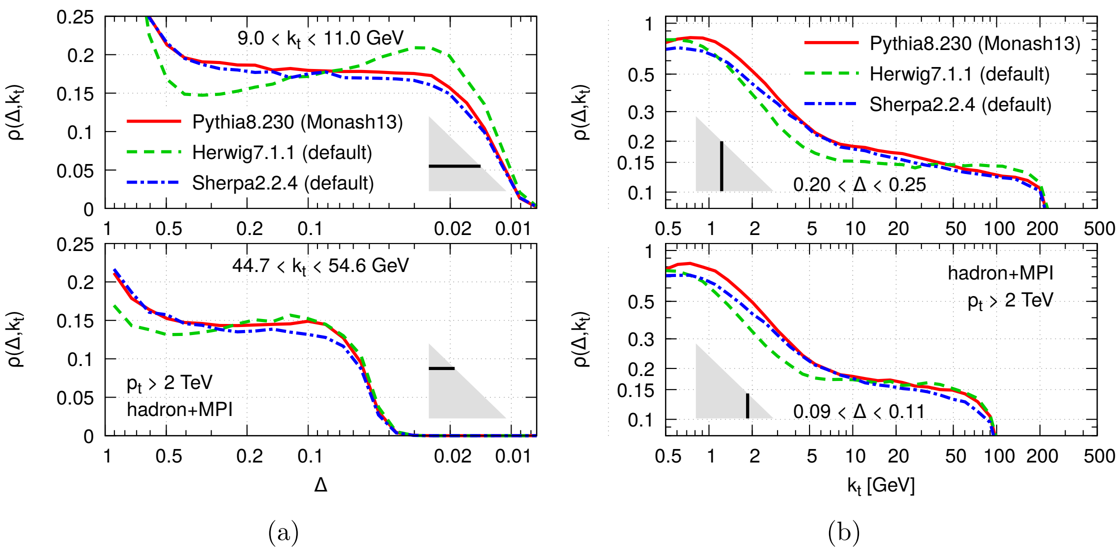
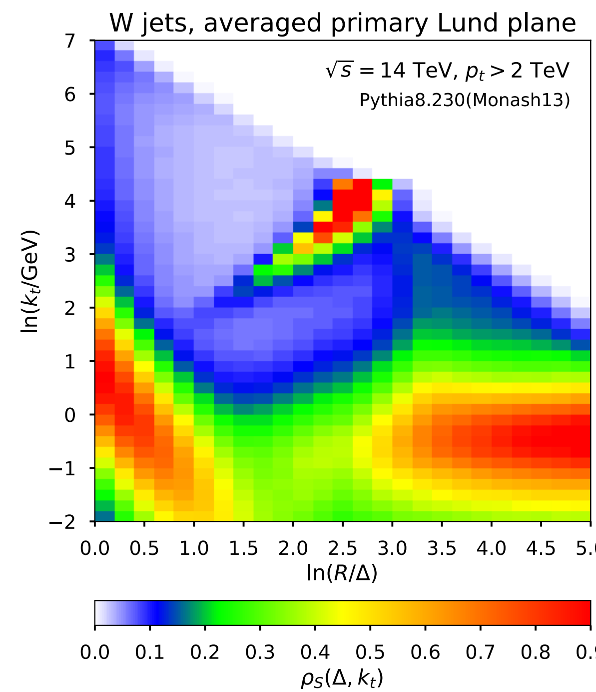
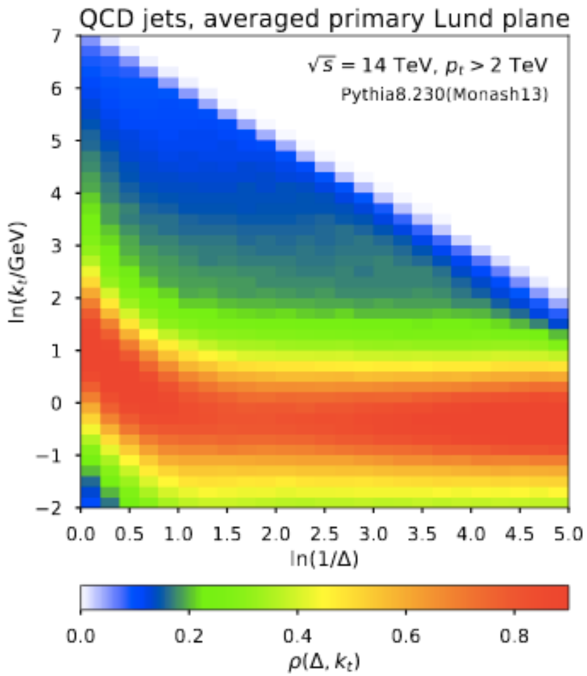


Figure 3: Emission density along slices of the Lund plane, at fixed k_t (top) and Δ (bottom), comparing three event generators.



The recipe… (1/2)



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.

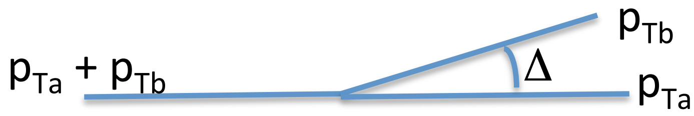
-Each time, register the scale k_T and the opening angle θ between the subleading and leading prong

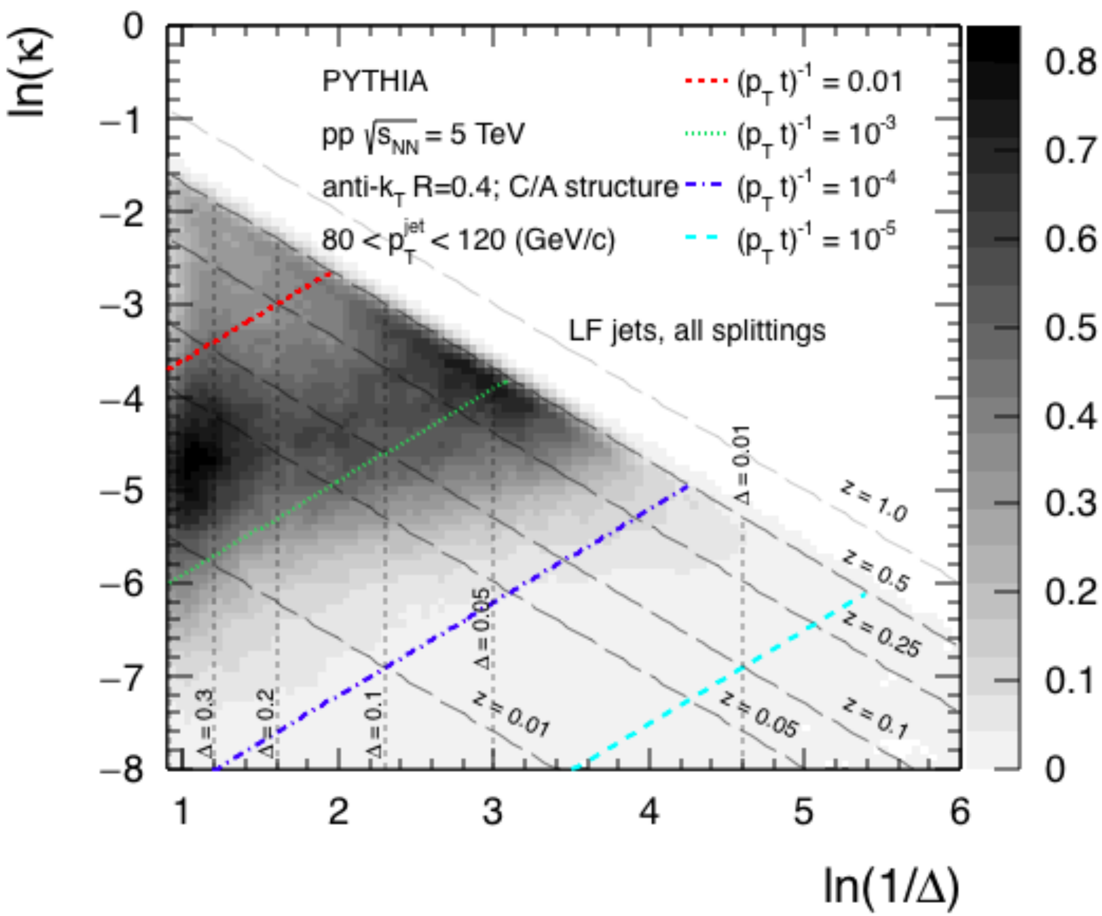
-Always follow the hardest prong

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

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

Declusterization





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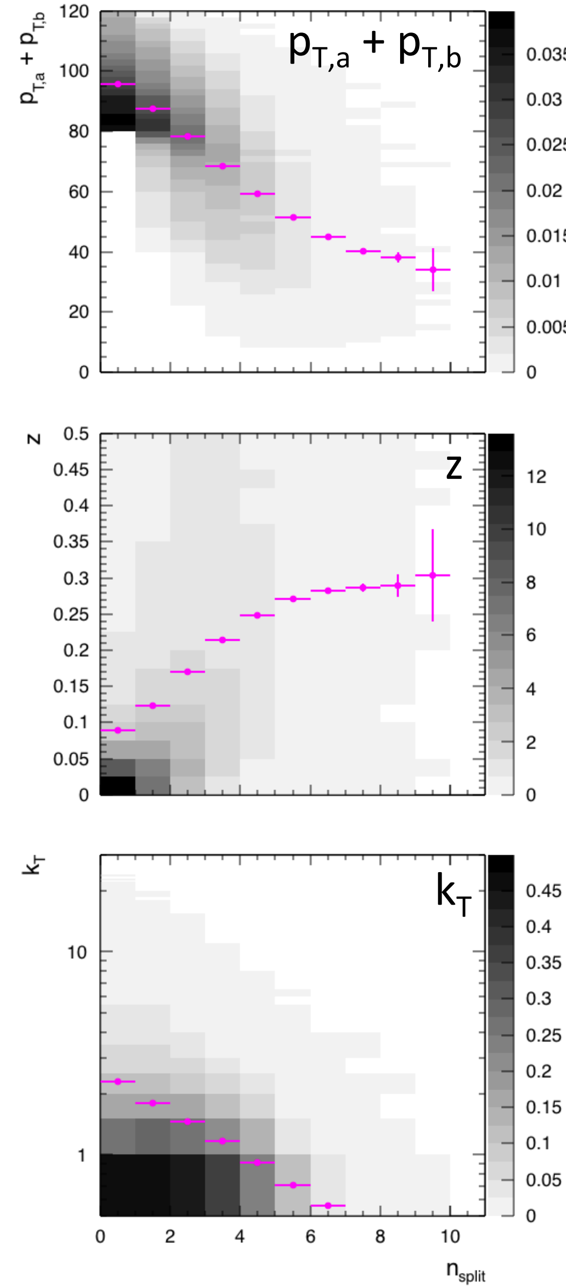

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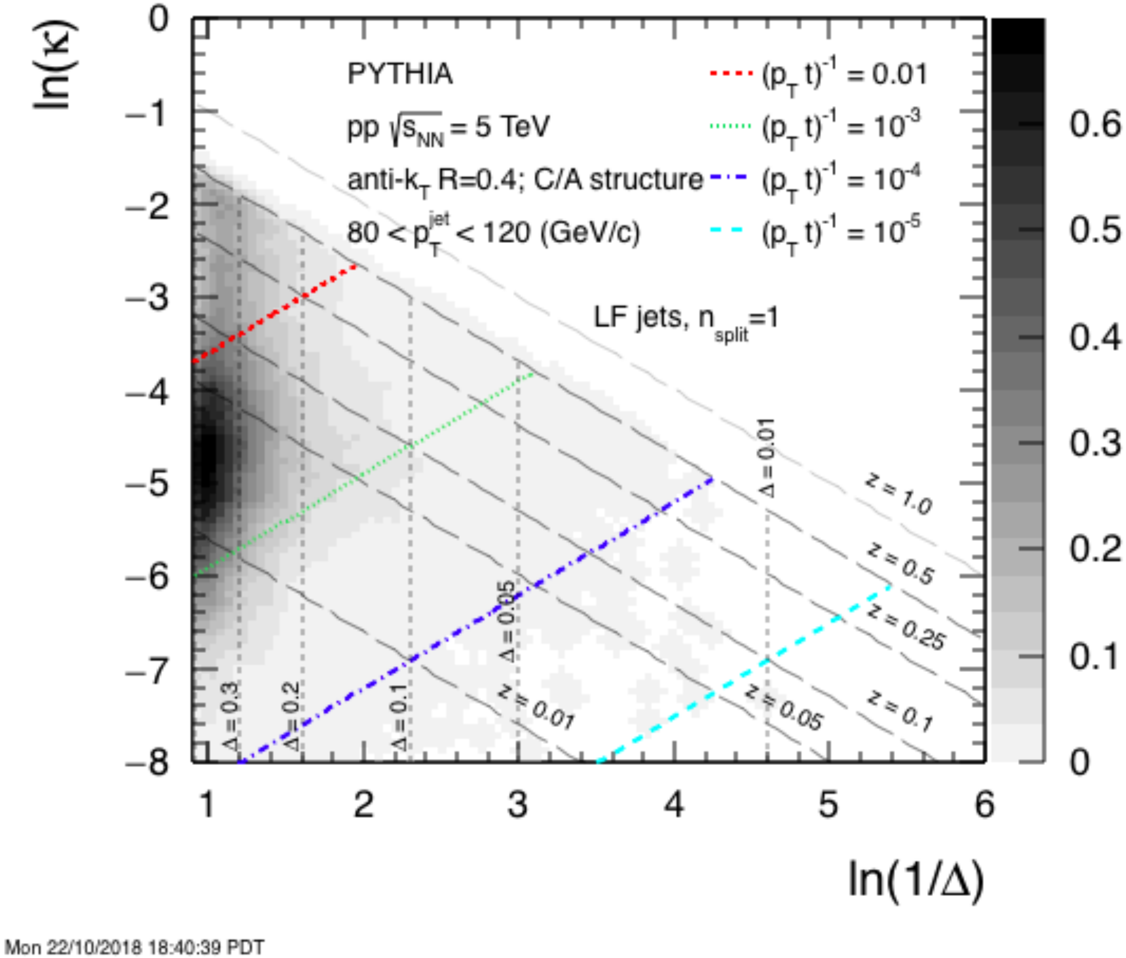
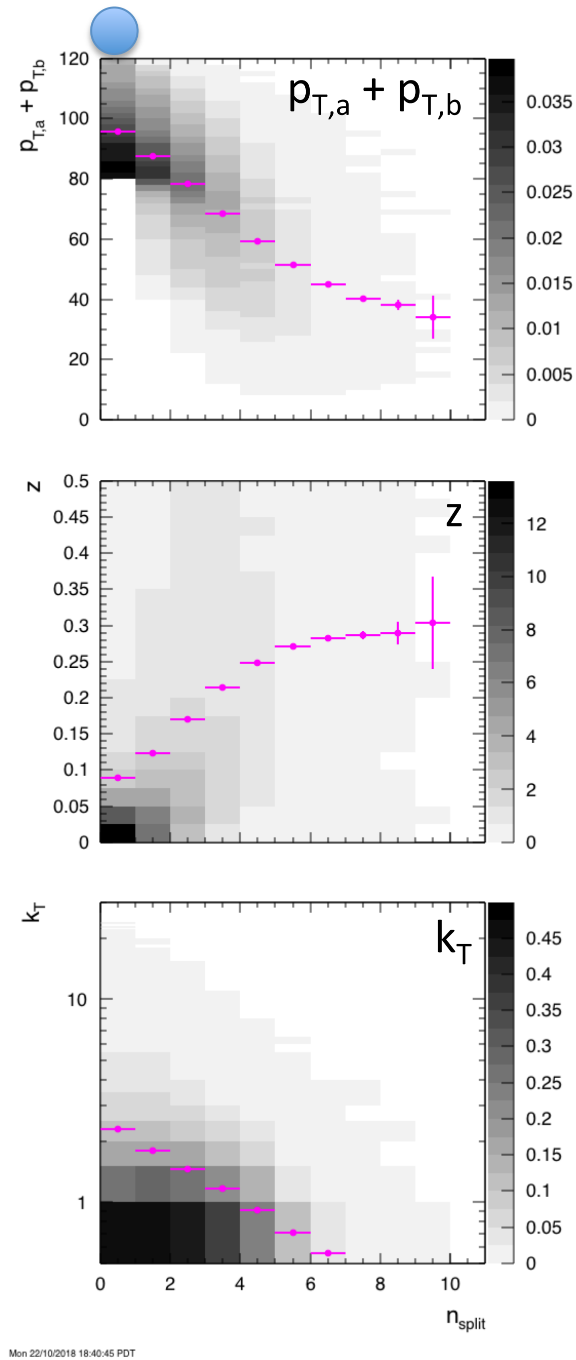
Note: structures from MPI, ISR, FSR,

Declusterization





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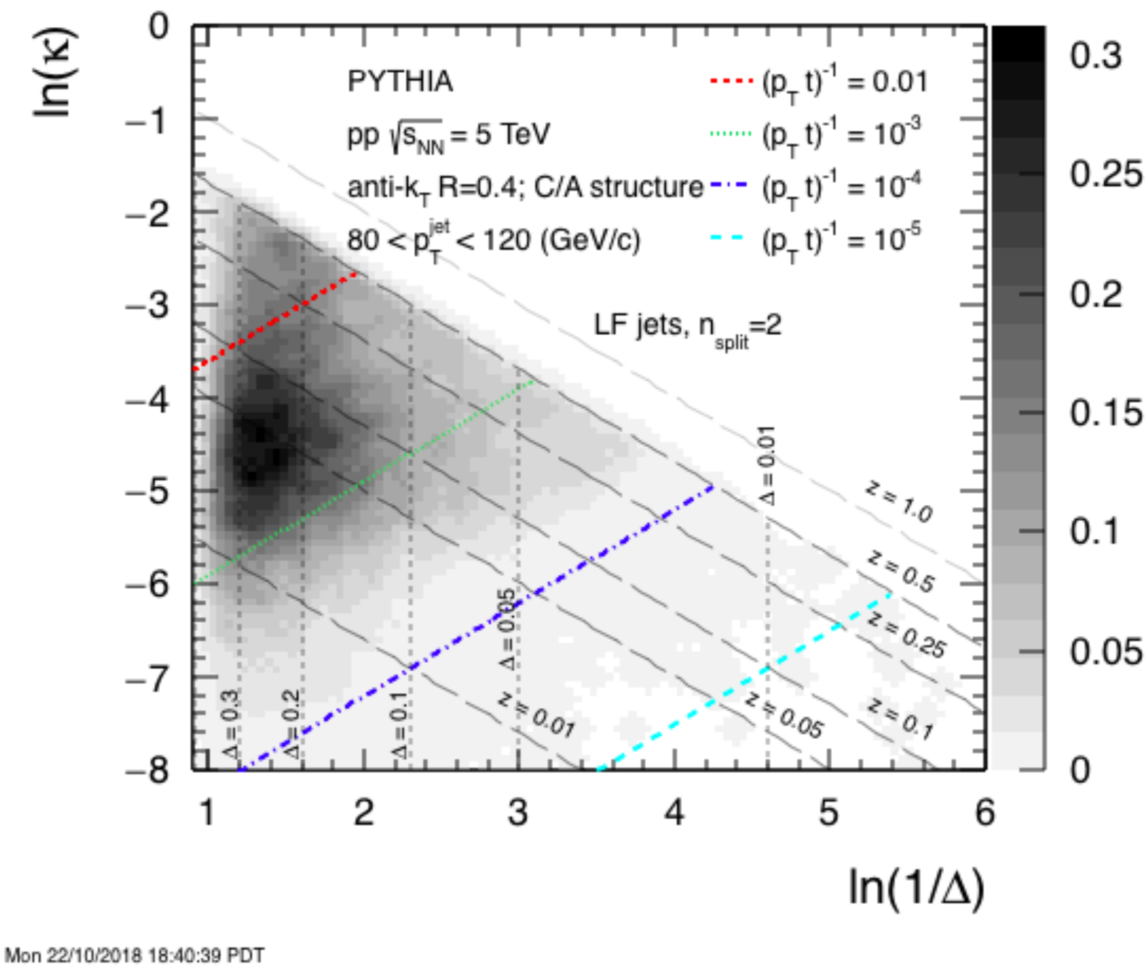

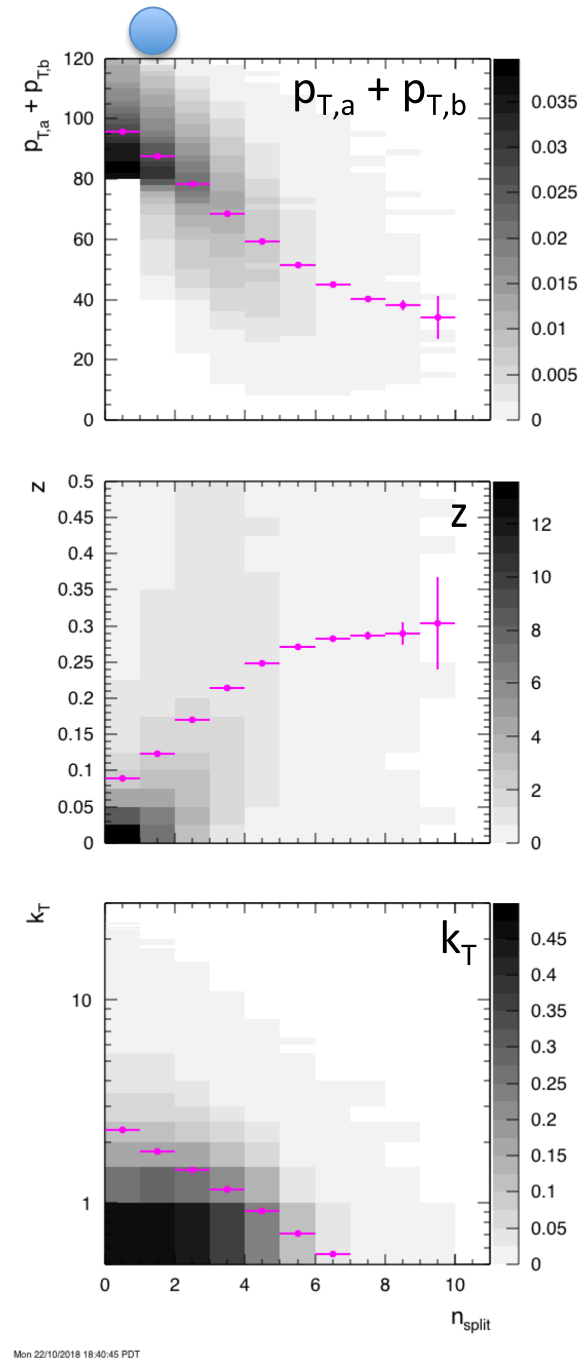

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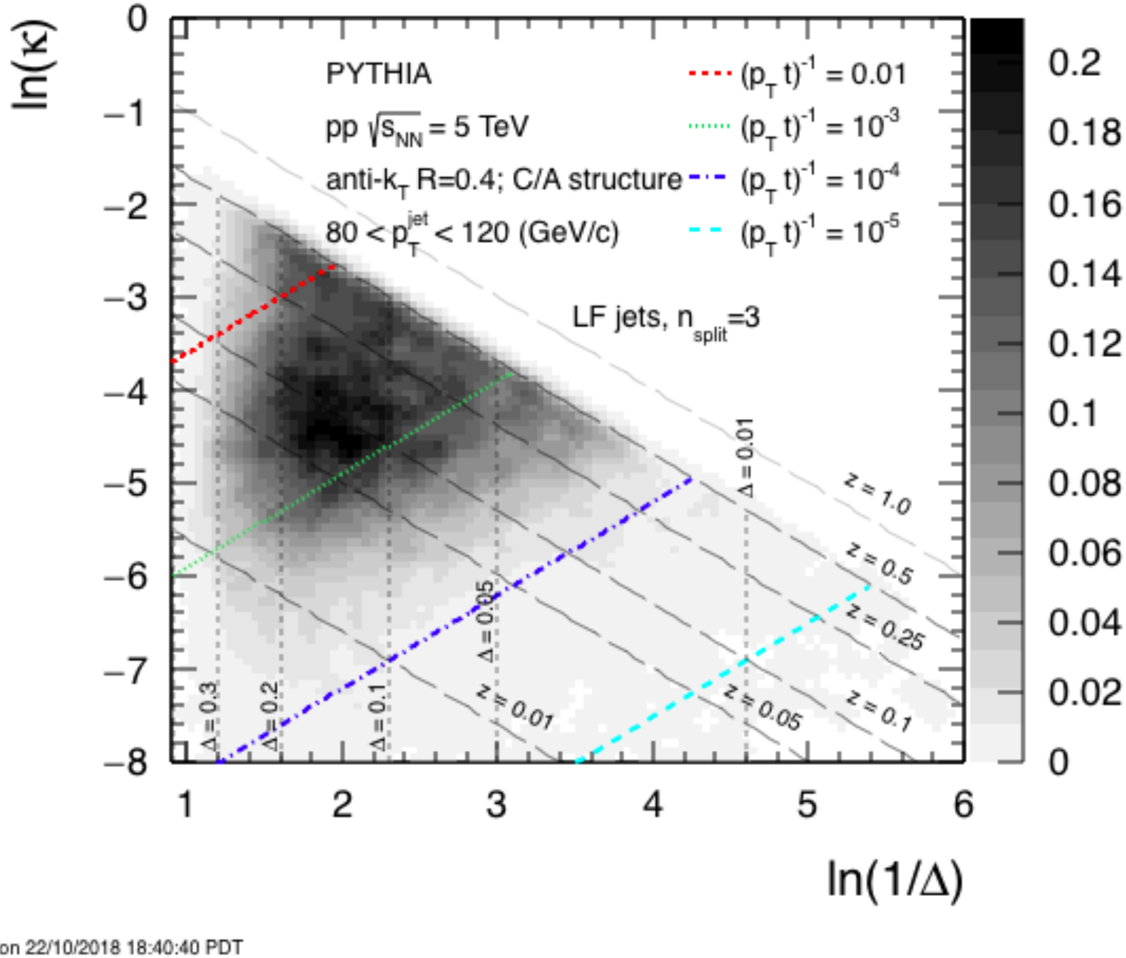

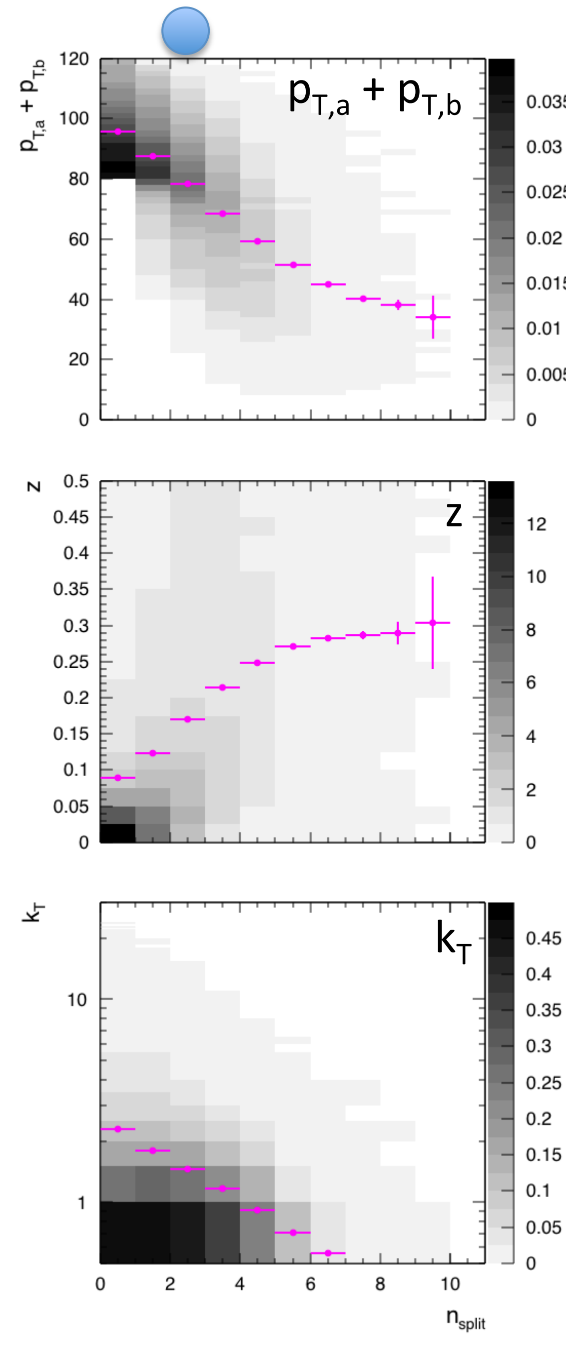

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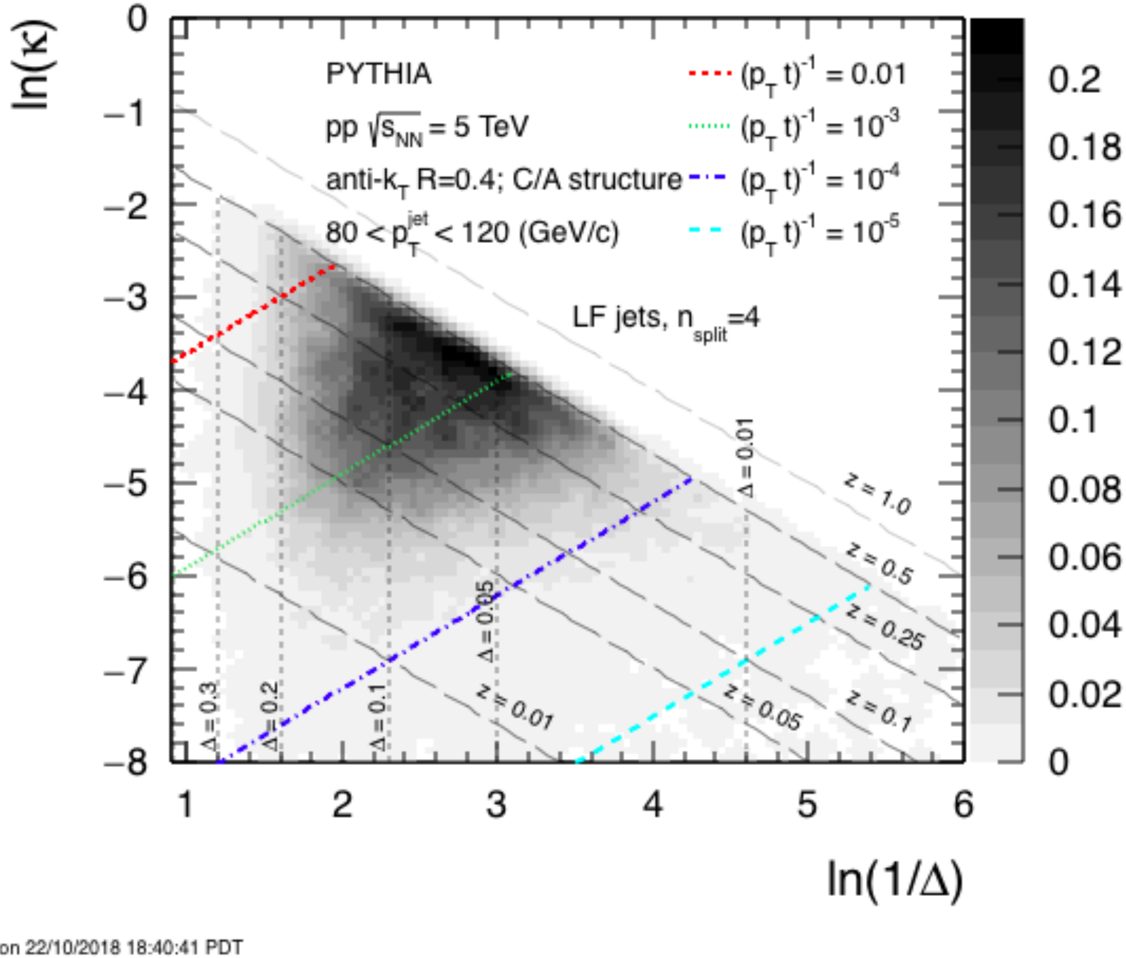

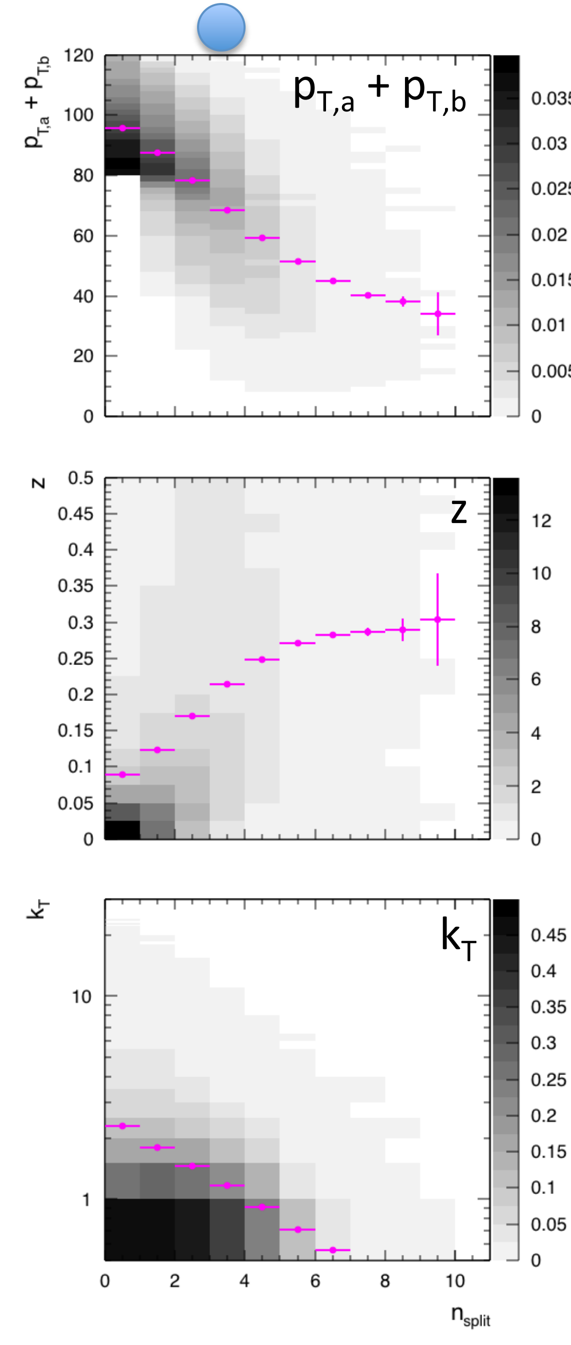

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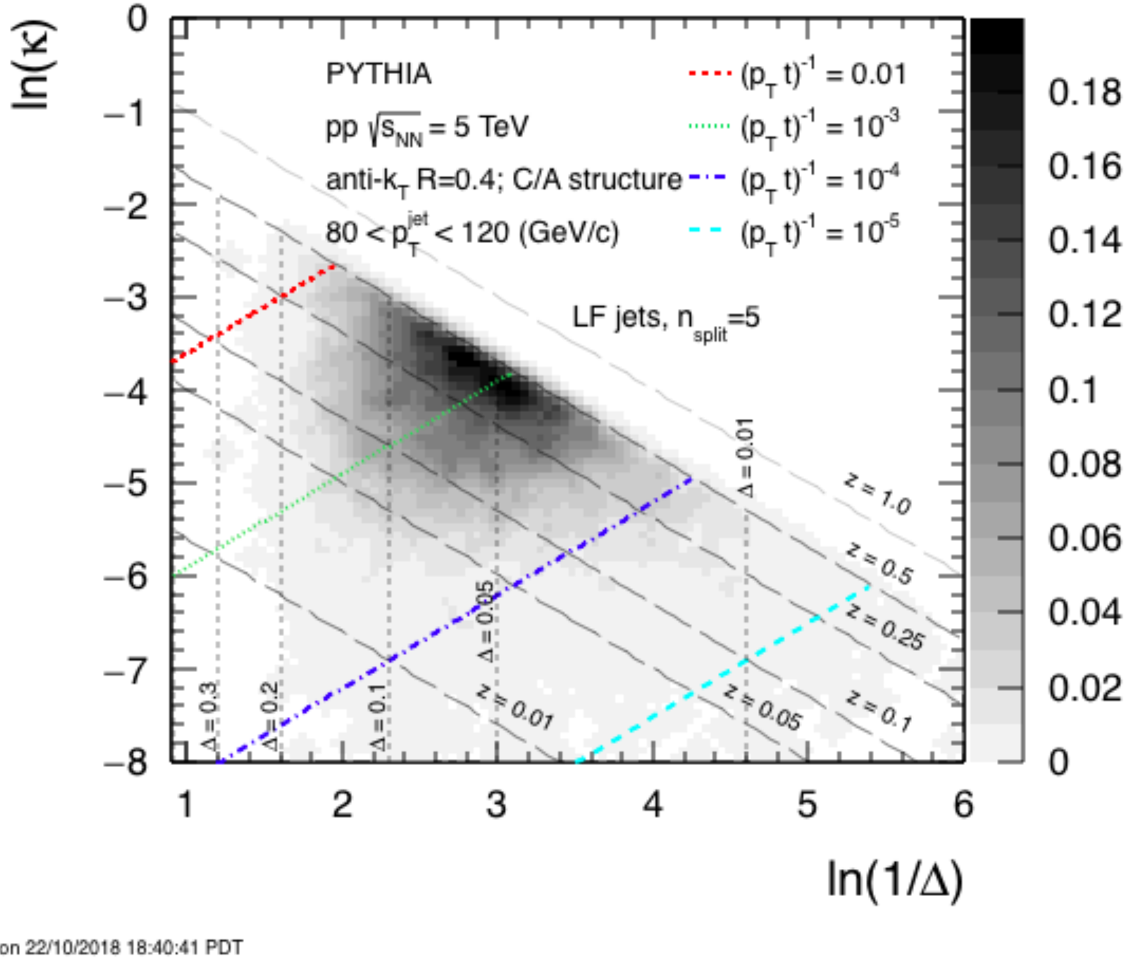

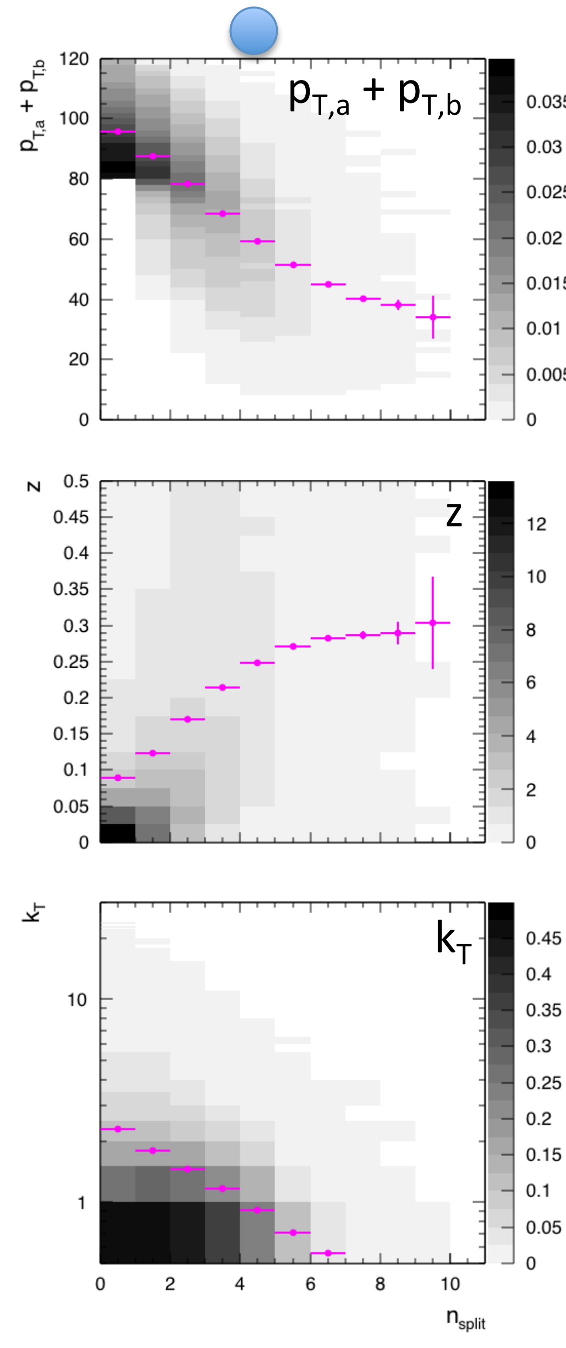

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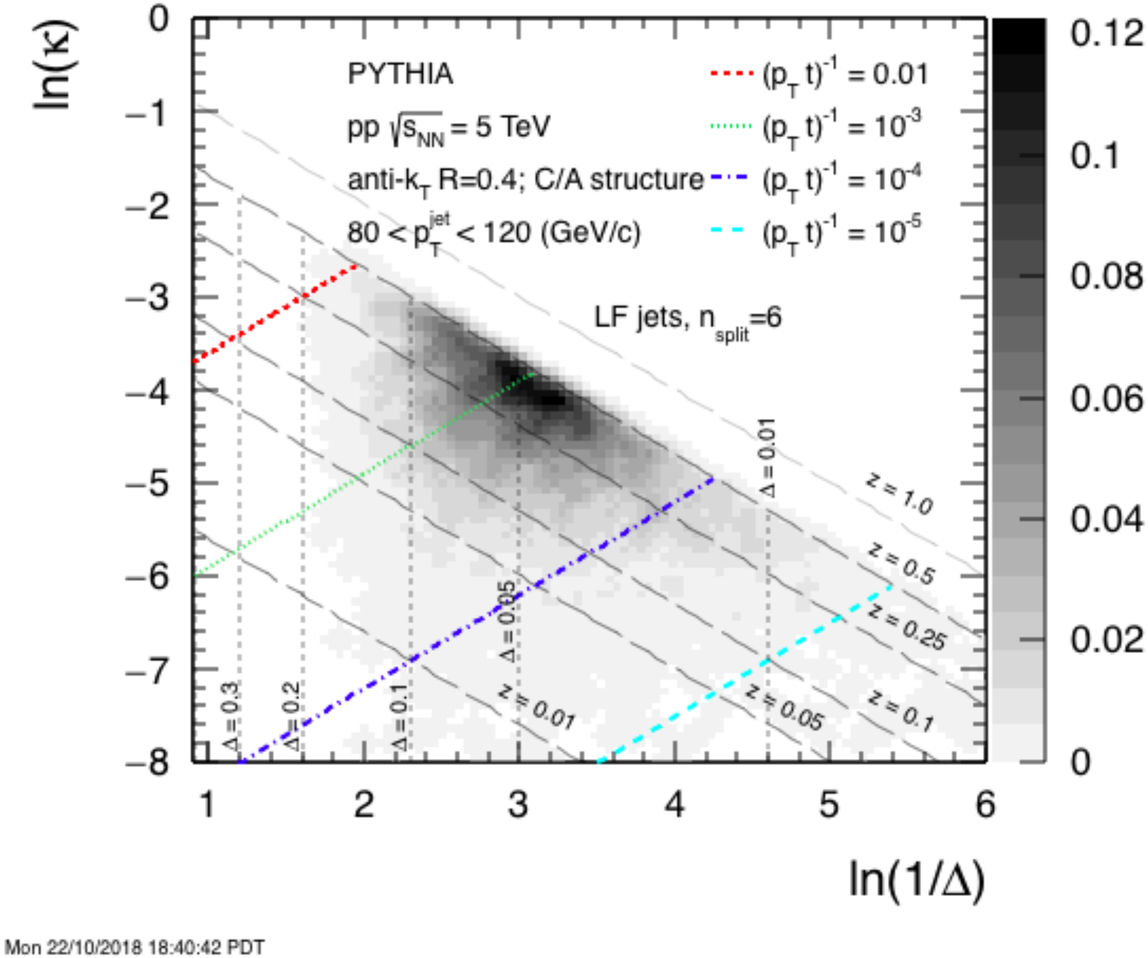

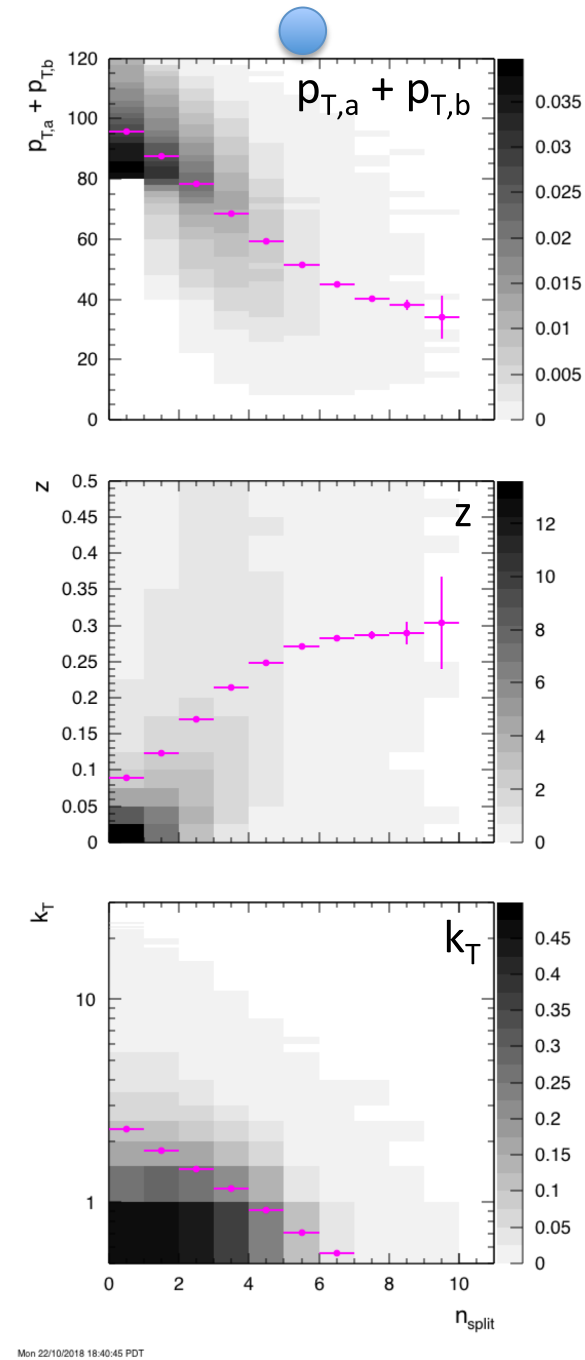

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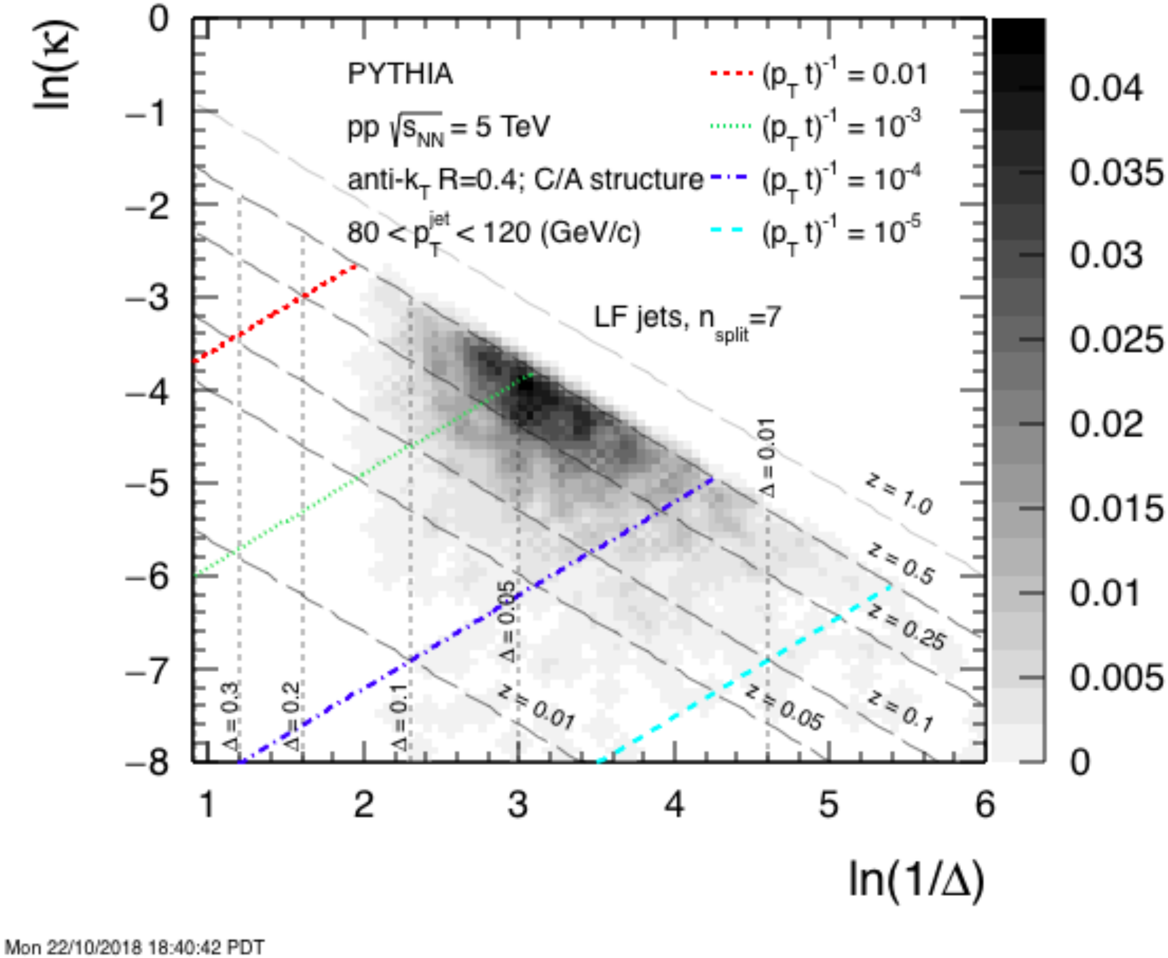

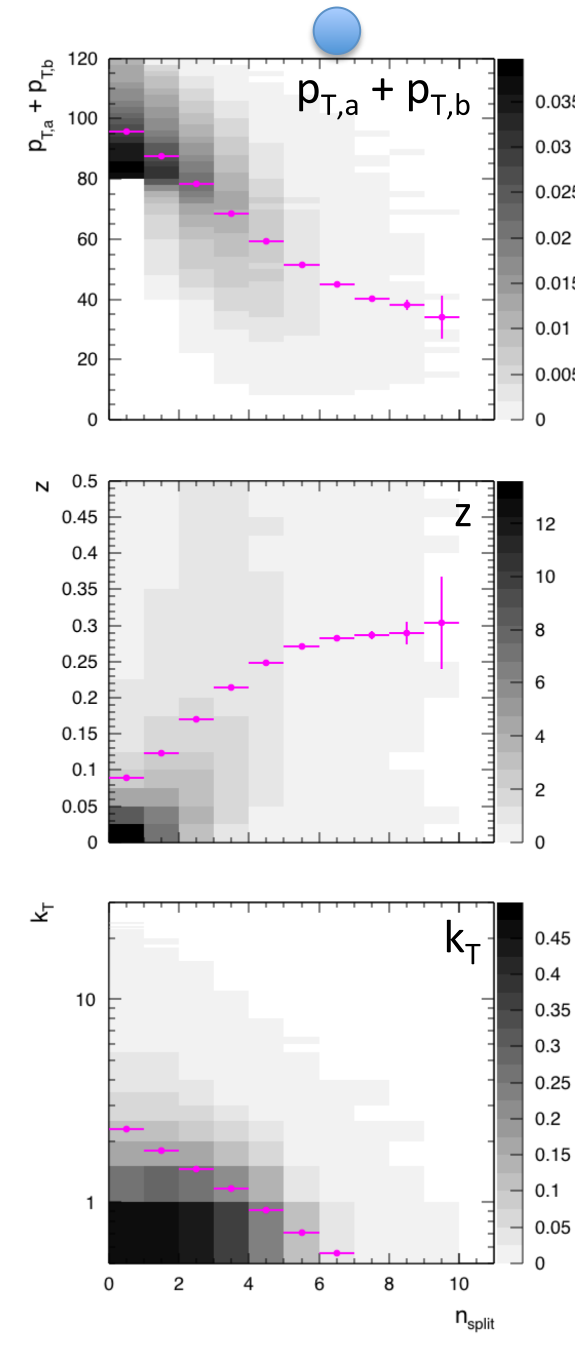

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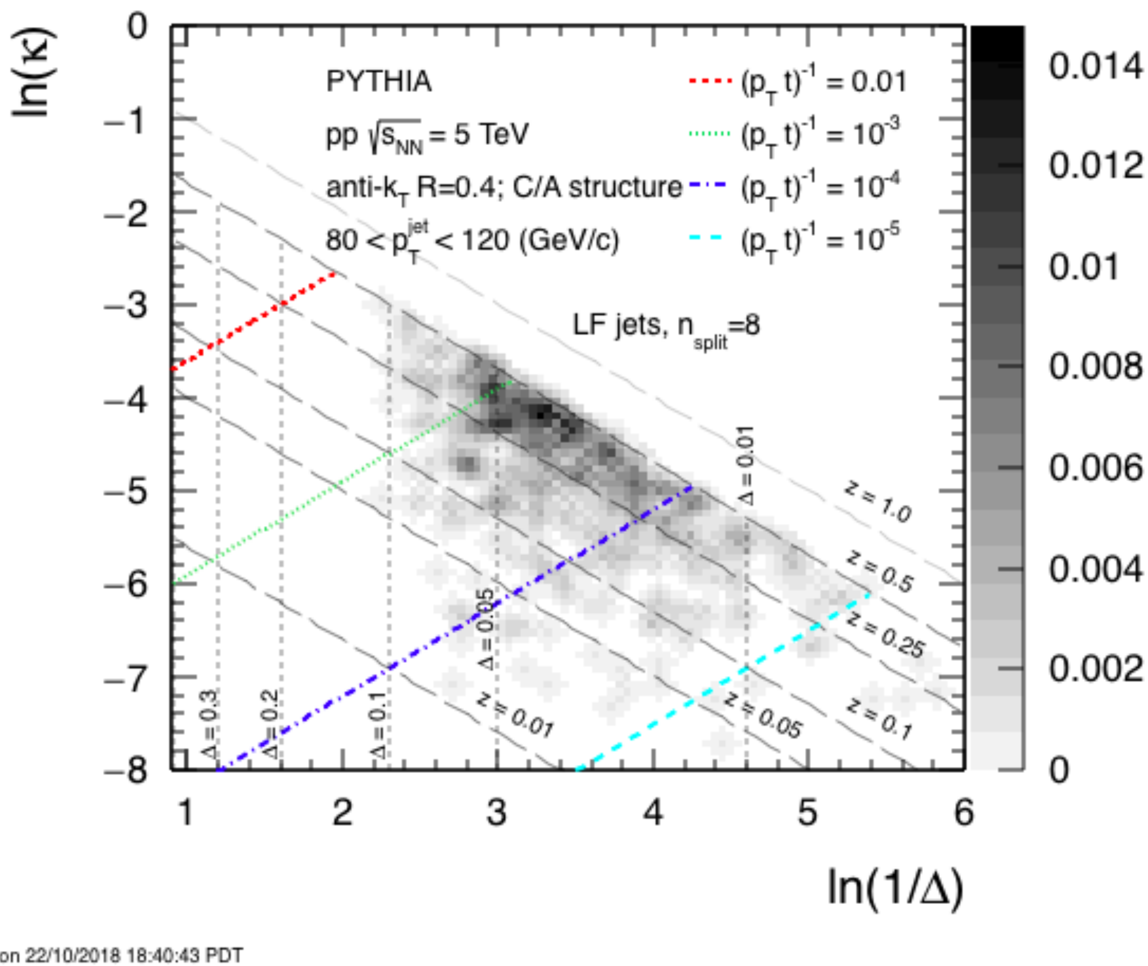

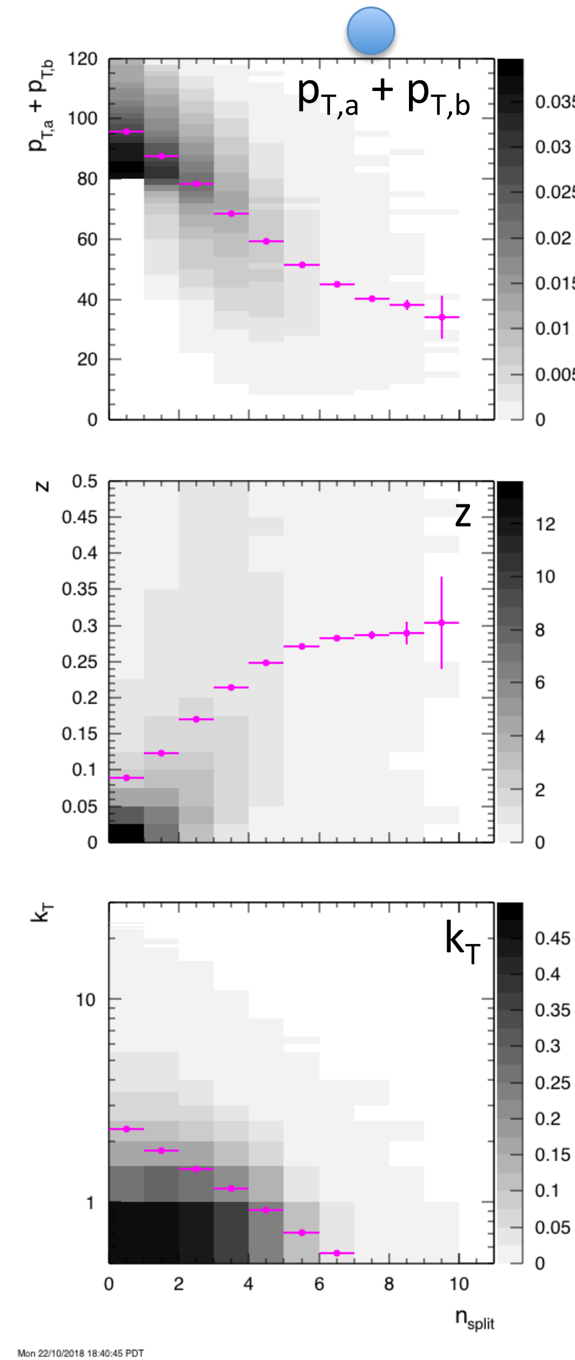

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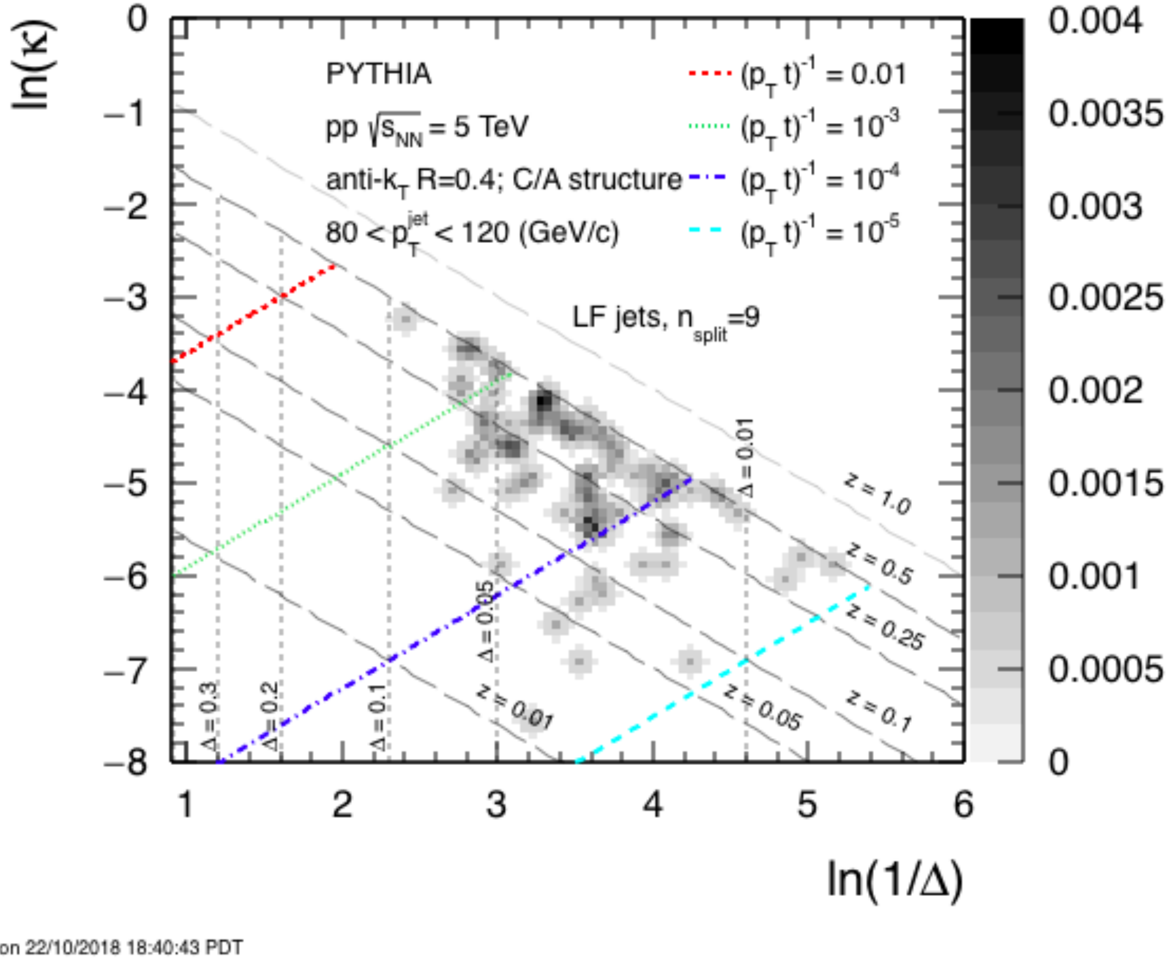

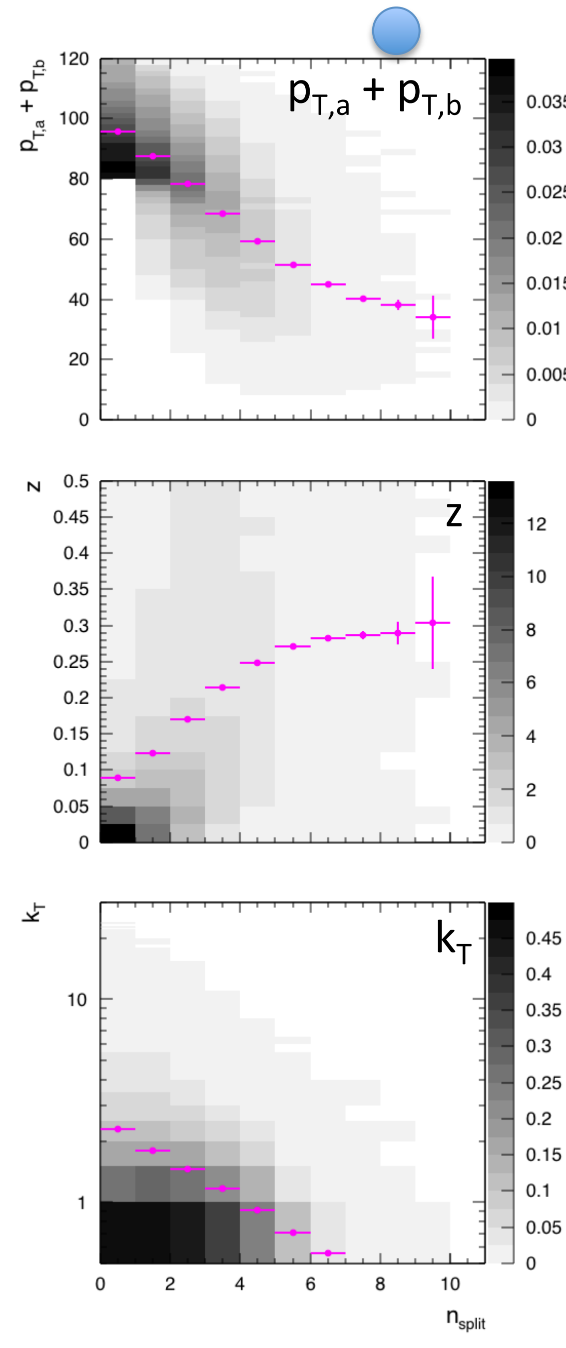

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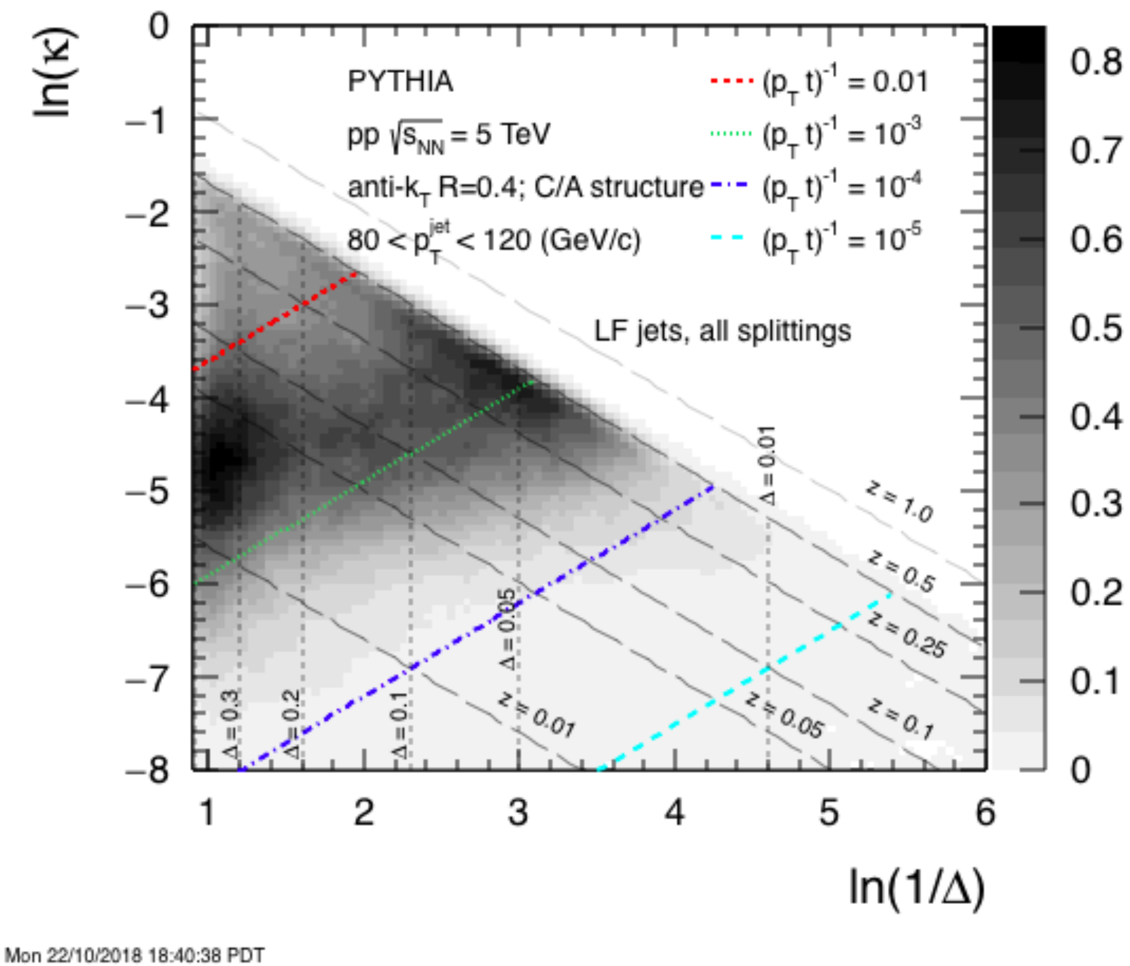

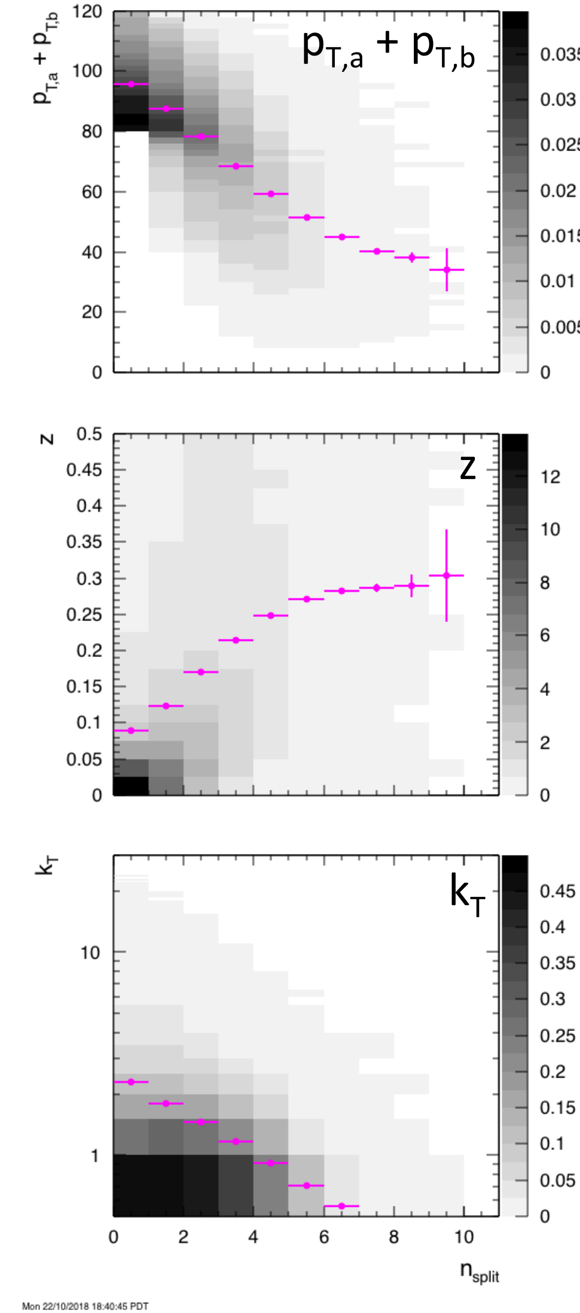

Jet Lund diagram

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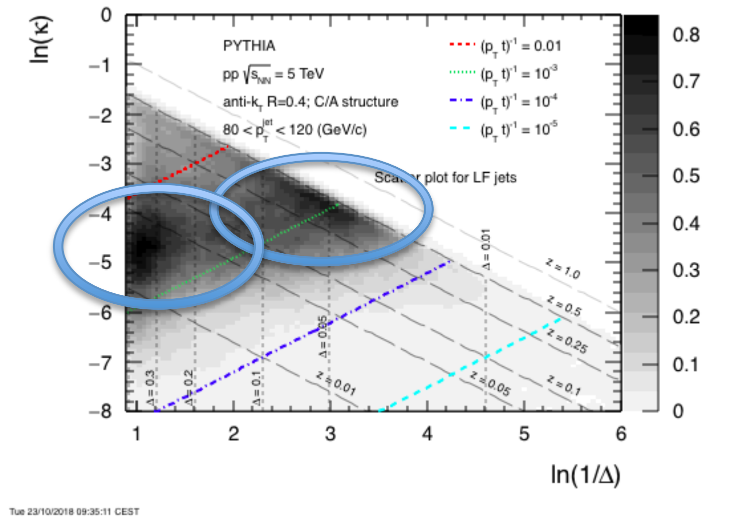
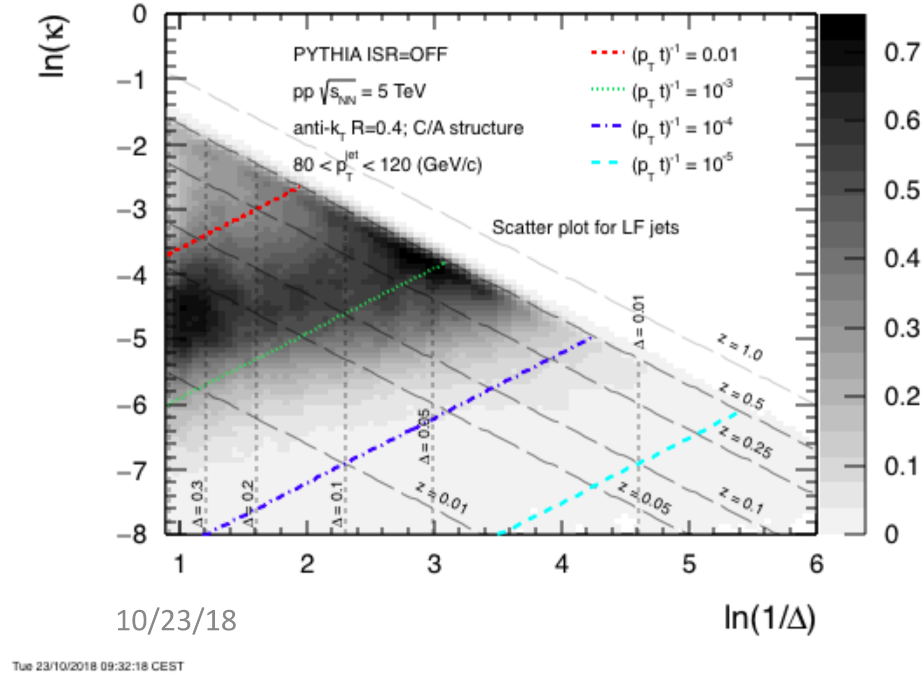


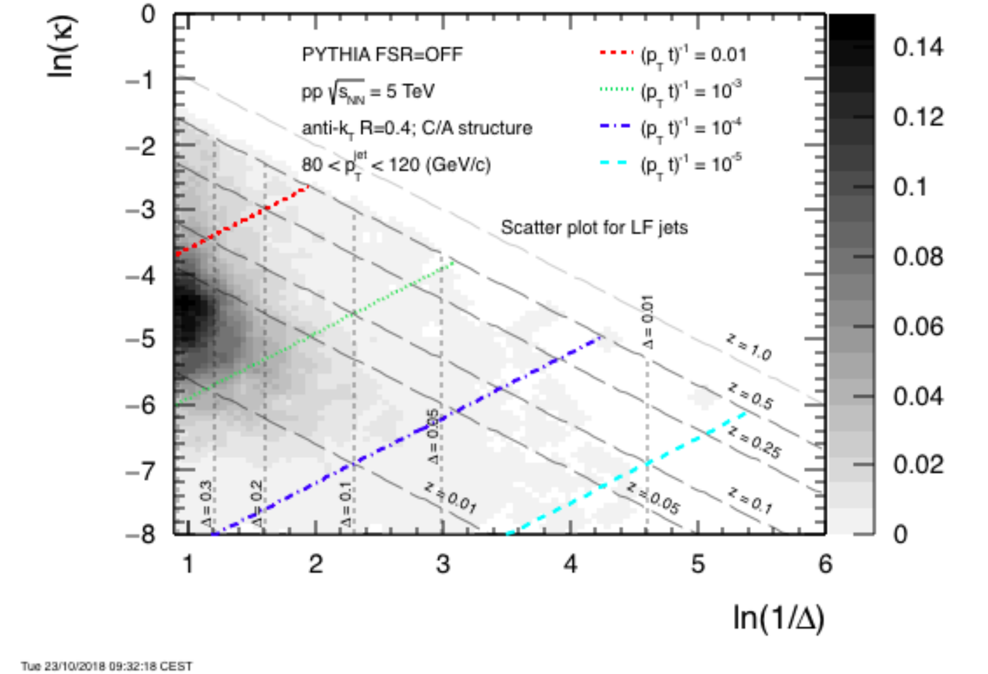
Expectation from theory: for every R and p_T, the phase space should be uniformly filled => the peak at the maximal angle is not expected.. The uniform distribution should be a feature of FSR.

- Potential feature of UE (MPIs) ? – TBD but not a show stopper at this point – treat MC as real data

Initial State Radiation OFF



Final State Radiation OFF



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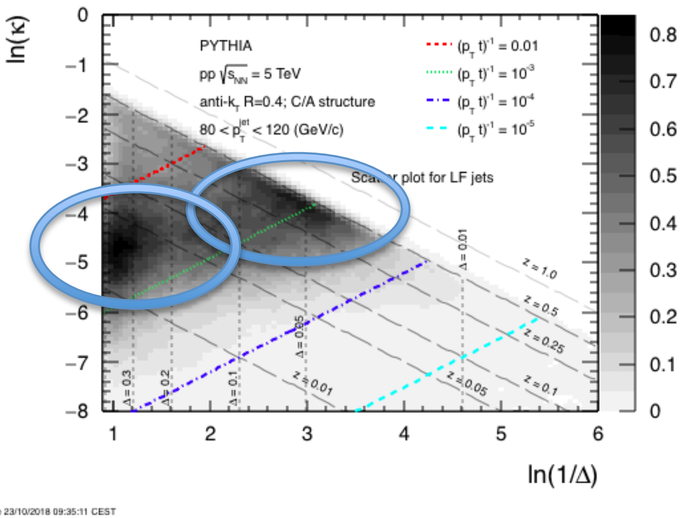


Structures vary with the algorithm used

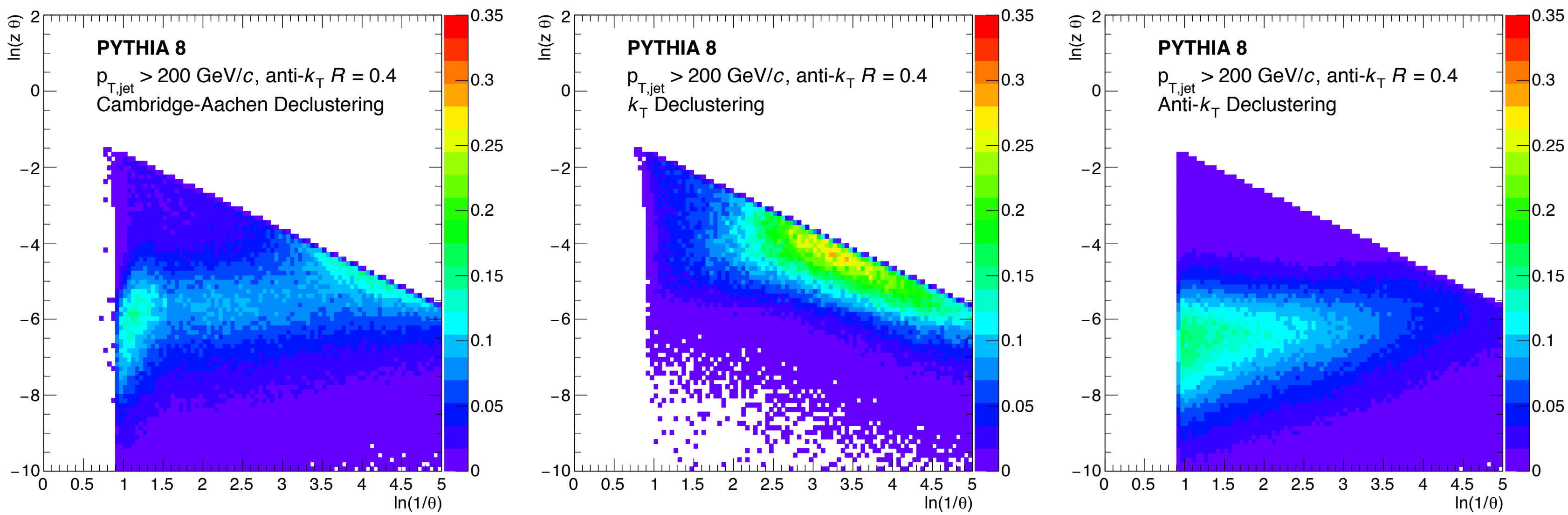
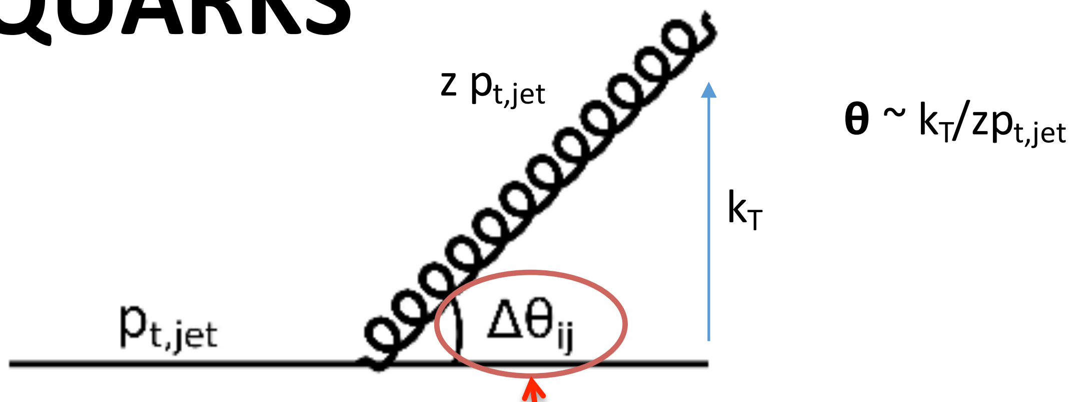


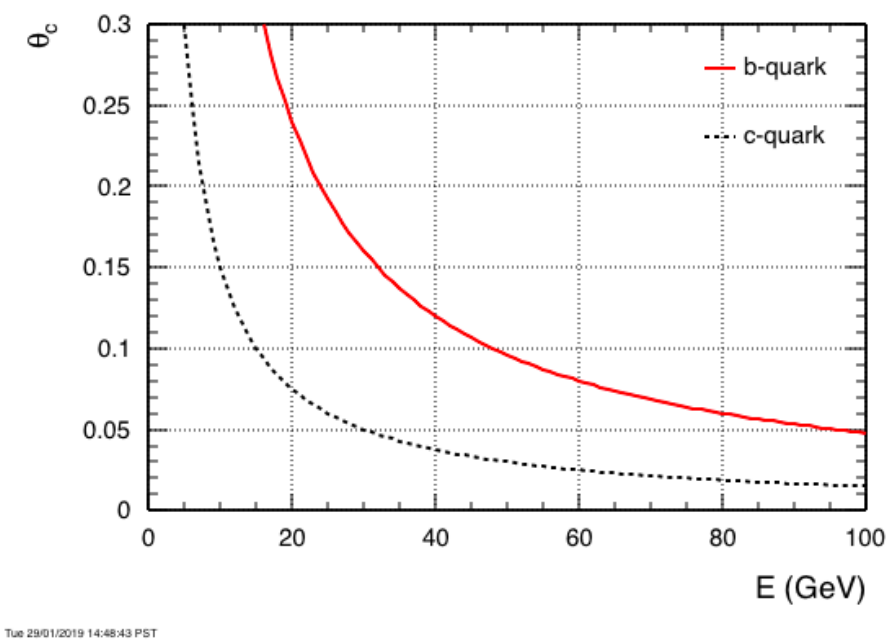
Figure 3: Lund diagrams reconstructed from a sample anti-k_T $R = 0.4$ jets generated by PYTHIA8. Three reclustering strategies were considered: C/A (left), k_T(middle), and anti-k_T (right).

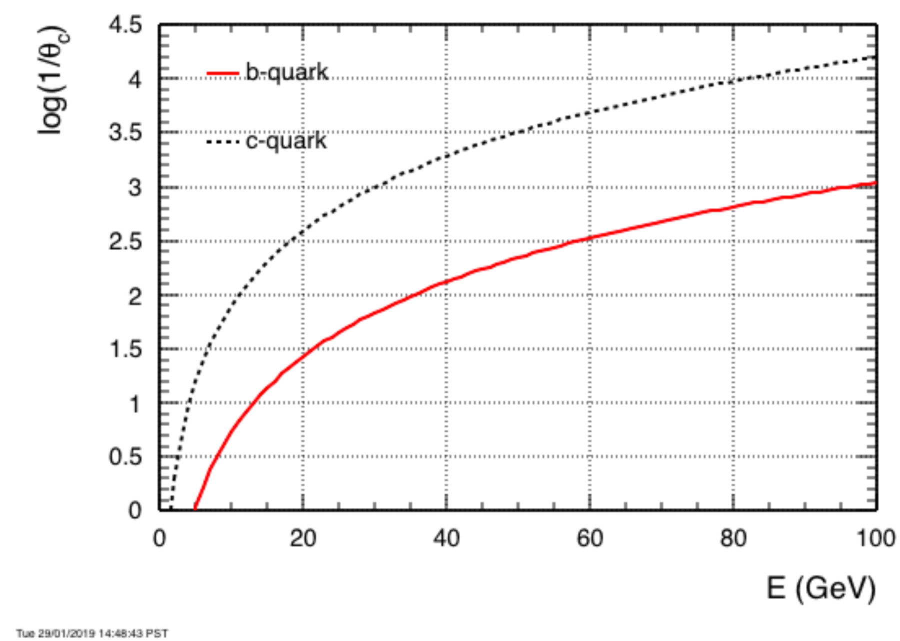
ONTO HEAVY QUARKS

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



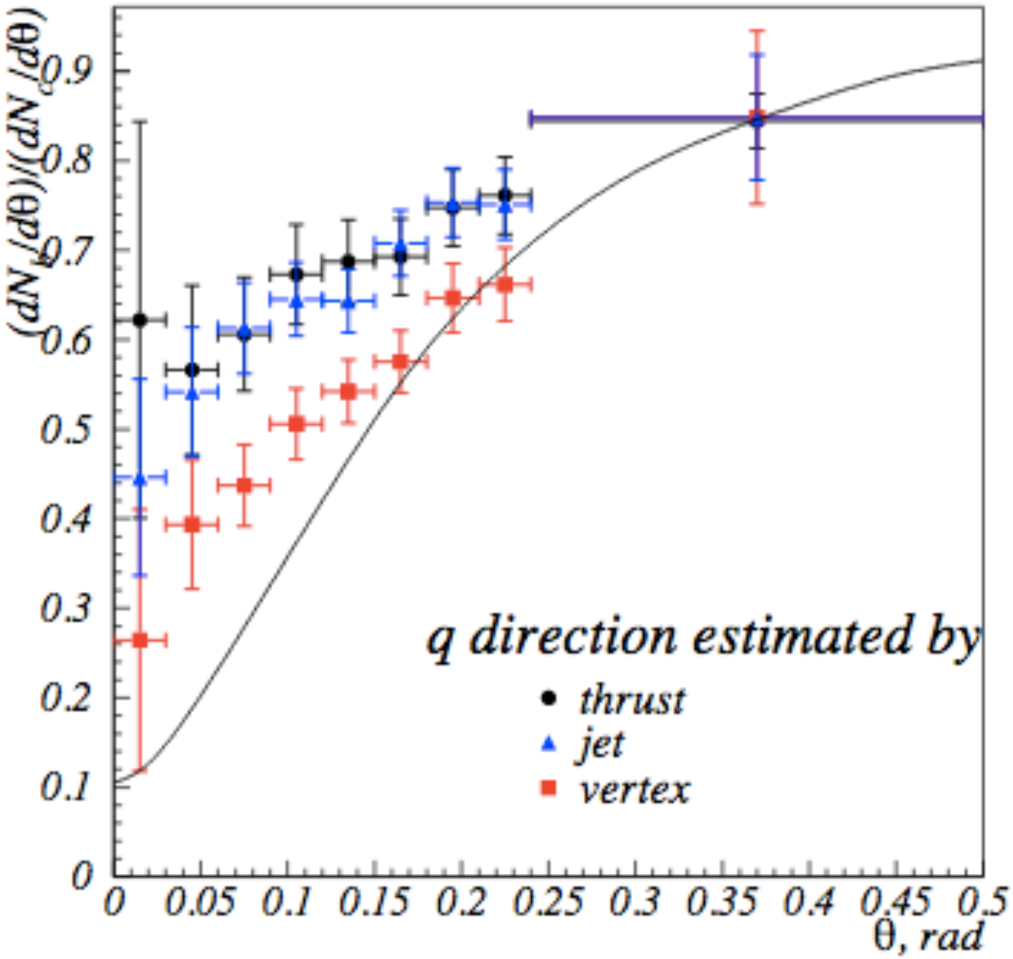
Dead cone for $\theta < m / E$





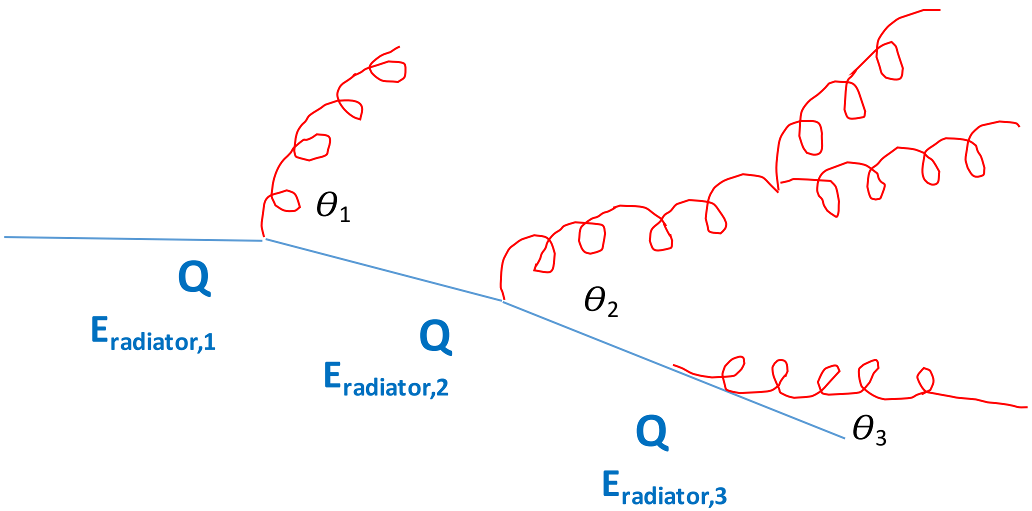
Dead cone measured?

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



Recipe… 2/2

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



We do the standard declustering process

We follow the prong containing the heavy flavor at each step

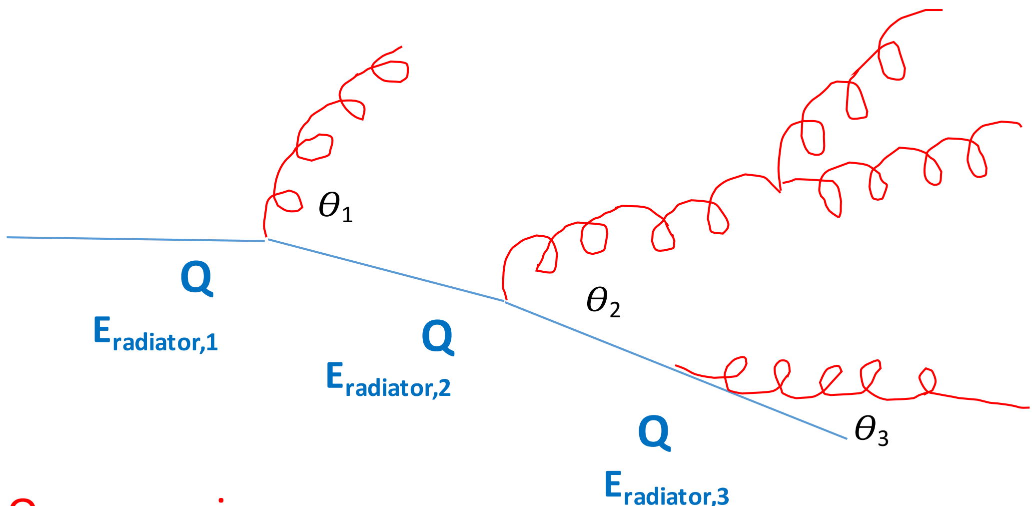
Negligible number of cases where the prong containing the heavy flavor is not the hardest, no ambiguity when comparing to light quarks

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

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



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Our excersize:

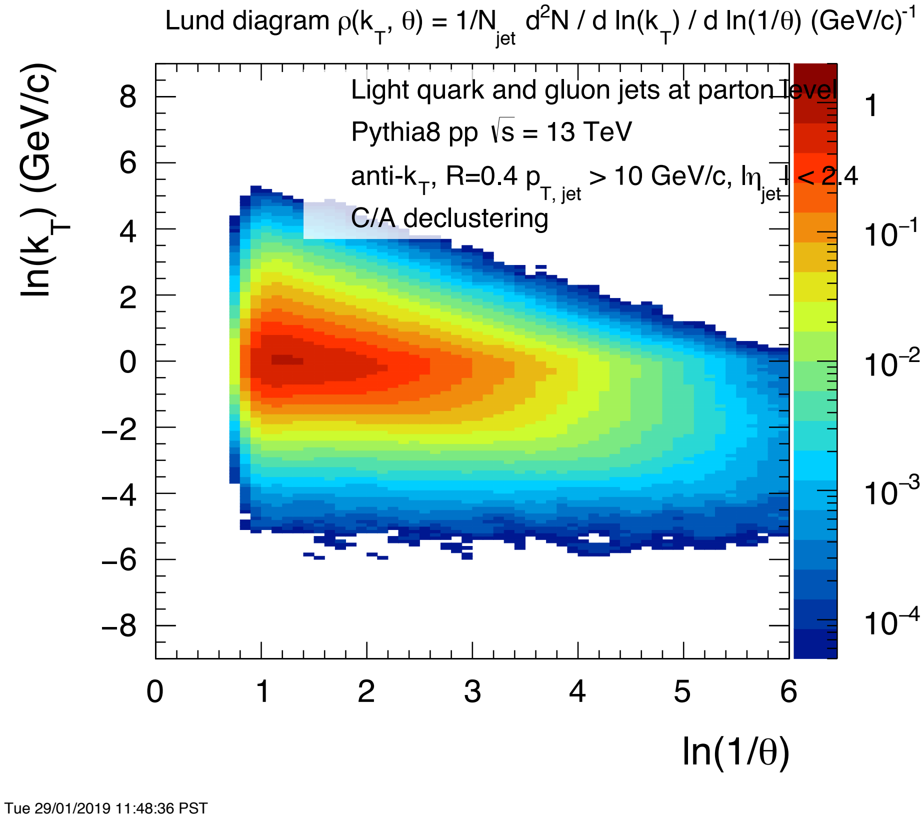
- Pythia8 Tune 4C
- pp collisions at $\sqrt{s}$=13 TeV
- Select ccbar, bbar production channels
- At parton level the leading prong at each declustering step is the one containing the heavy parton
- At hadron level, we inhibit the decay of the B and D mesons and the leading prong at each declustering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

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

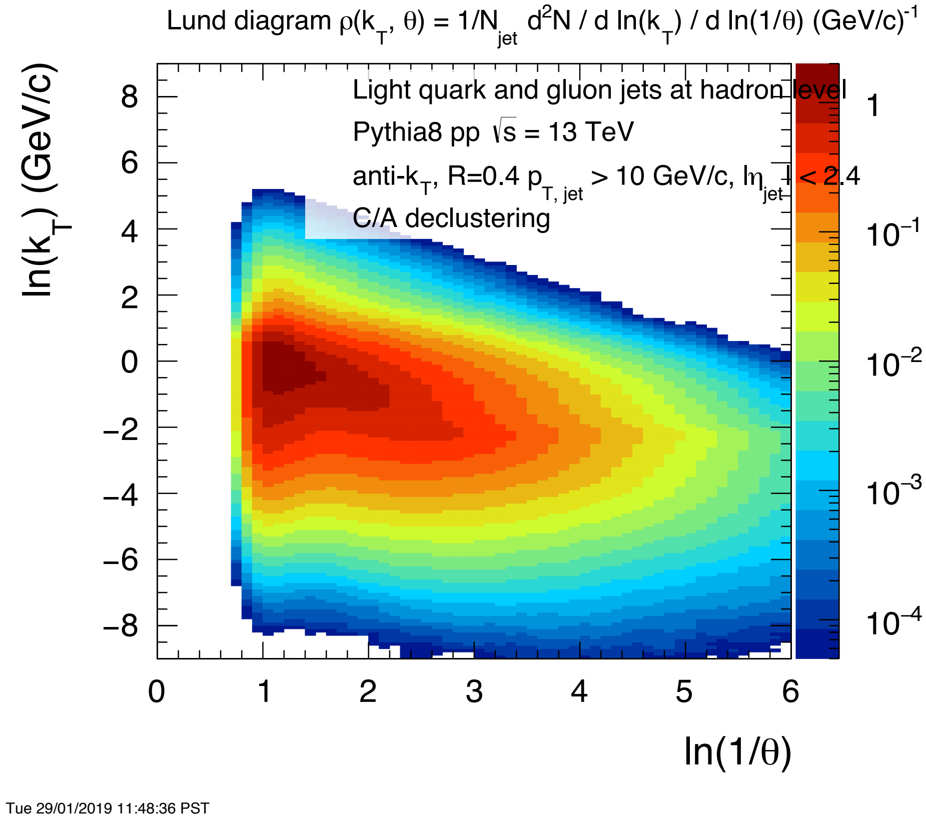
All jets (light quark and gluon)

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

Parton level



Hadron level



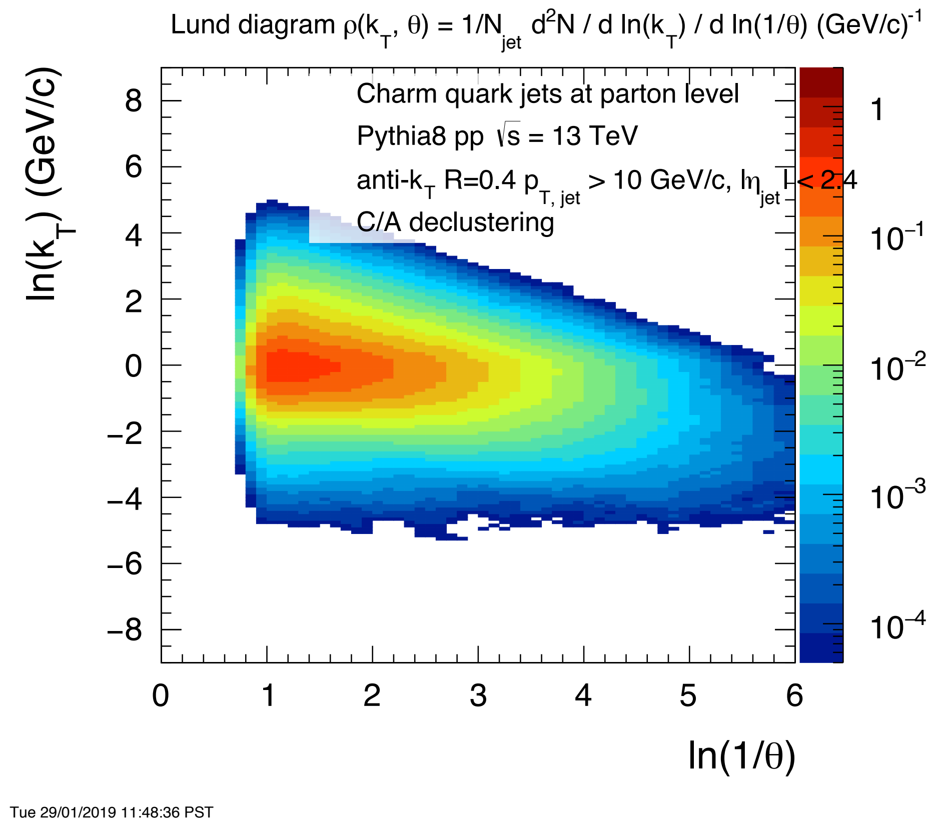
Hadron level – ALL processes

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

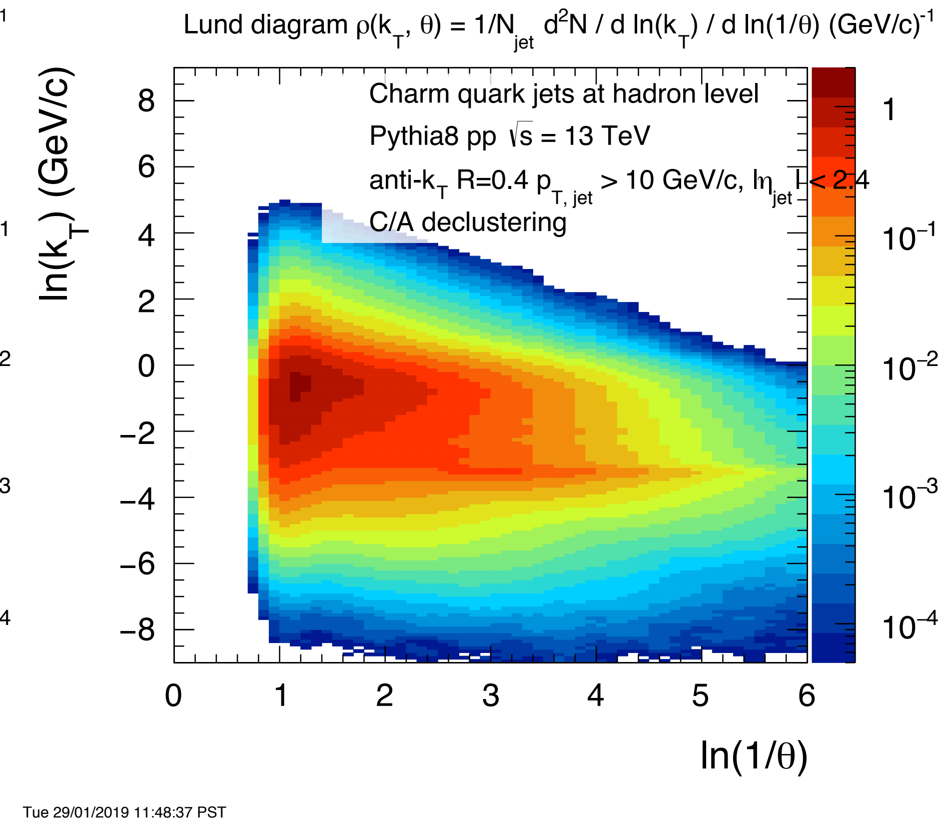
log(kT) = -2 ⇔ kT = 0.135 GeV
log(kT) = 0 ⇔ kT = 1 GeV

Charm

Parton level



Hadron level



Hadron level – ALL processes

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

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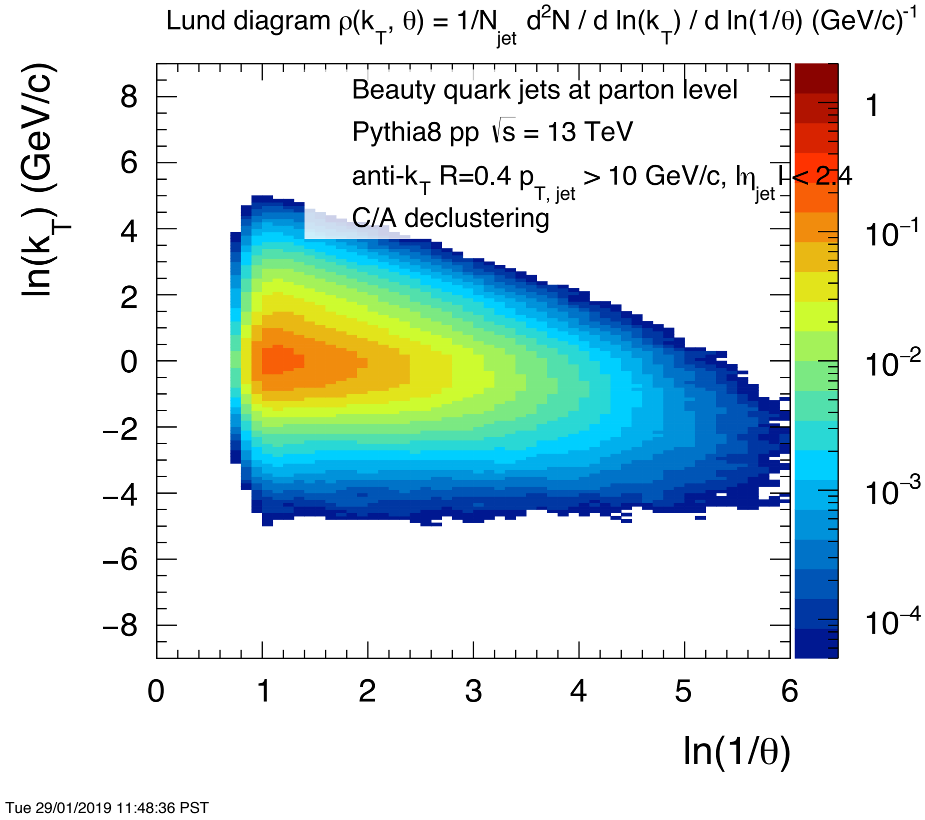
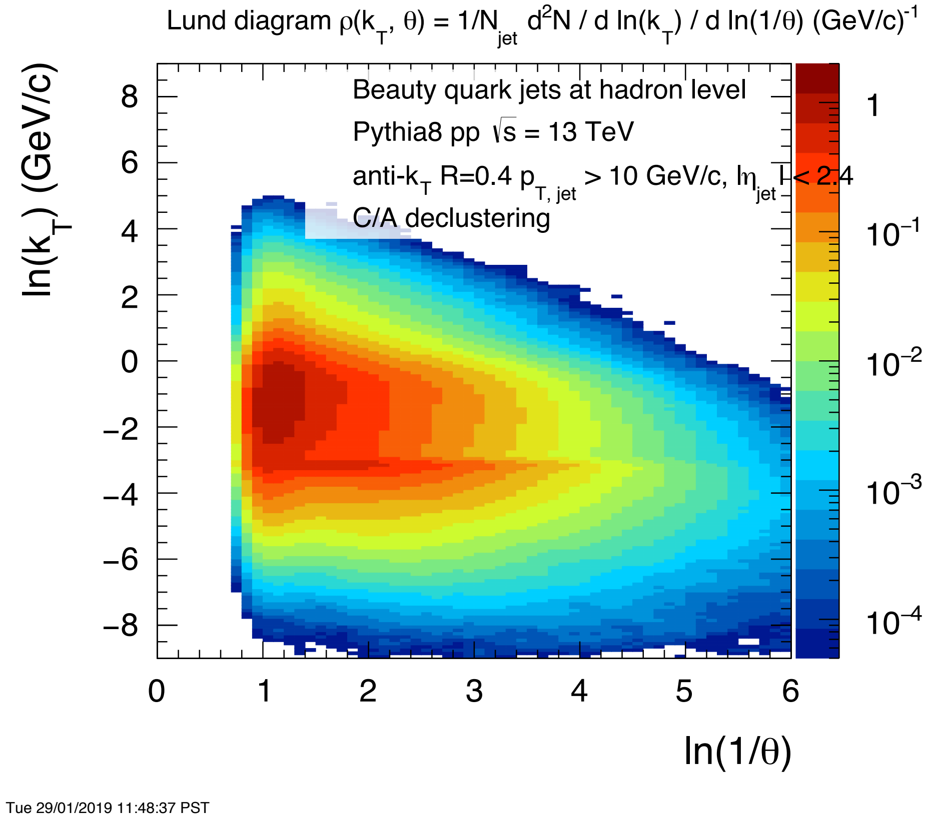
Beauty

Parton level



Hadron level



Hadron level – ALL processes

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

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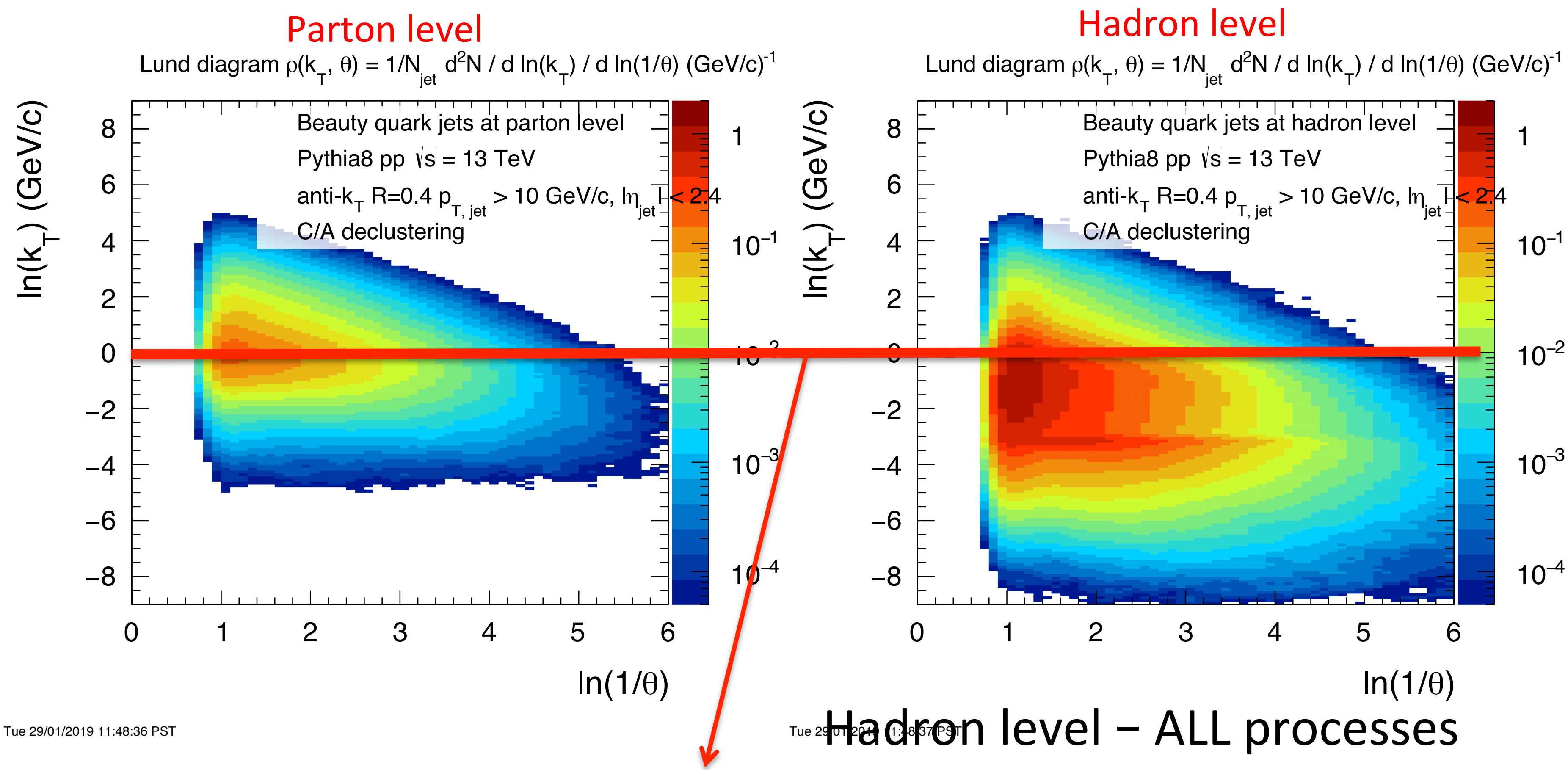


Hadron level – ALL processes

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

Dead cone on parton level

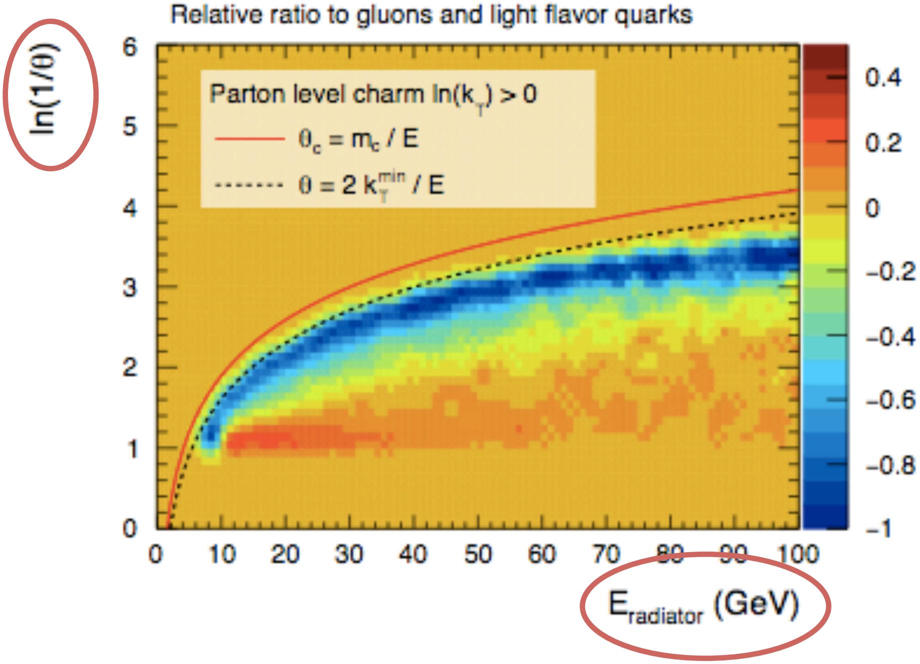
Cut on log(kT) > 0

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

Parton level – no UE, no ISR

Angle vs. Energy of the radiator

charm



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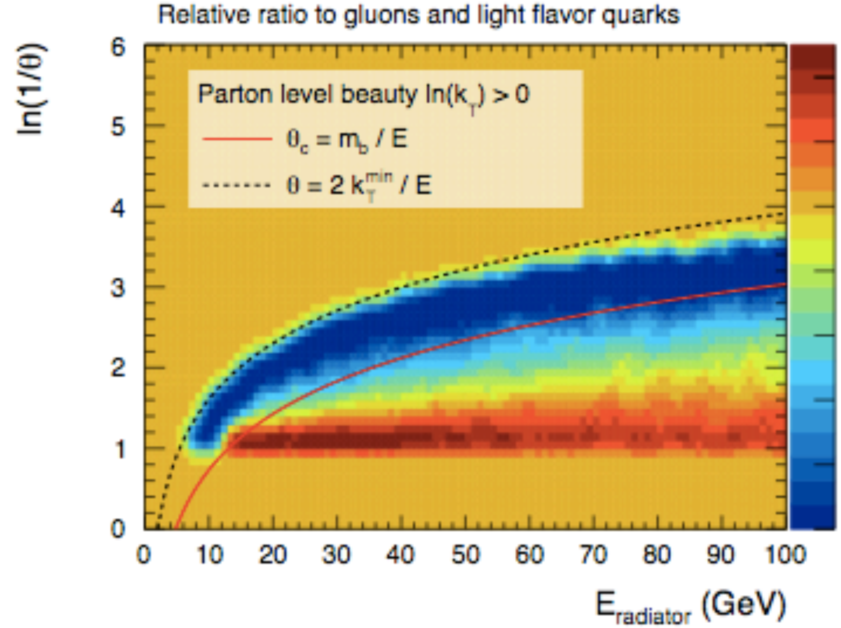


$$Q = \frac{P^{Q}(log(1/\theta), E_{radiator}) - P^{inc}(log(1/\theta), E_{radiator})}{P^{inc}(log(1/\theta), E_{radiator})}$$

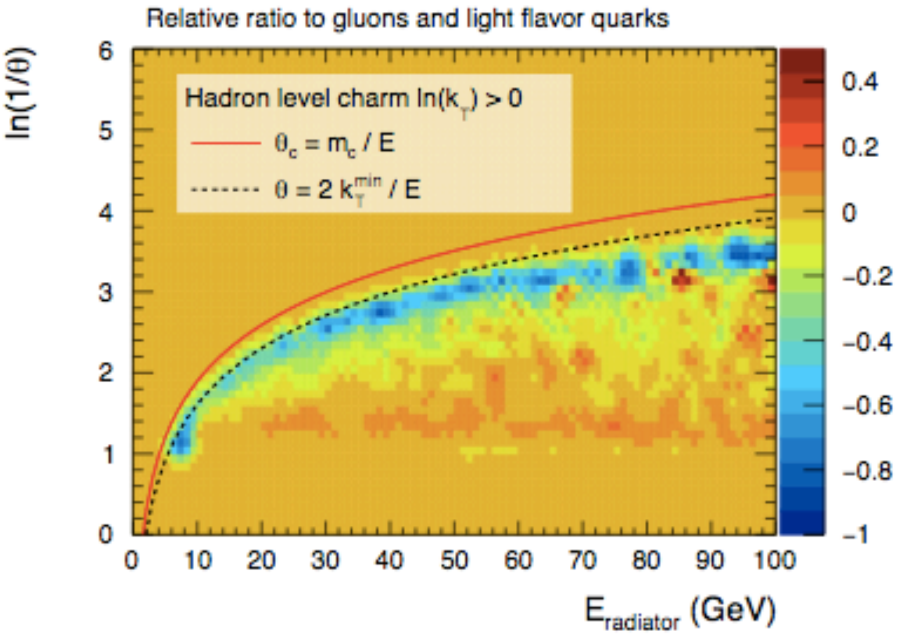
The cut $\log(k_T) > k_T^{min}$ translates into $E_{radiator} > k_T^{min}/z\theta$. The black dashed line corresponds to the kinamtic limit of z=0.5, above which there are no more entries in the inclusive reference

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**

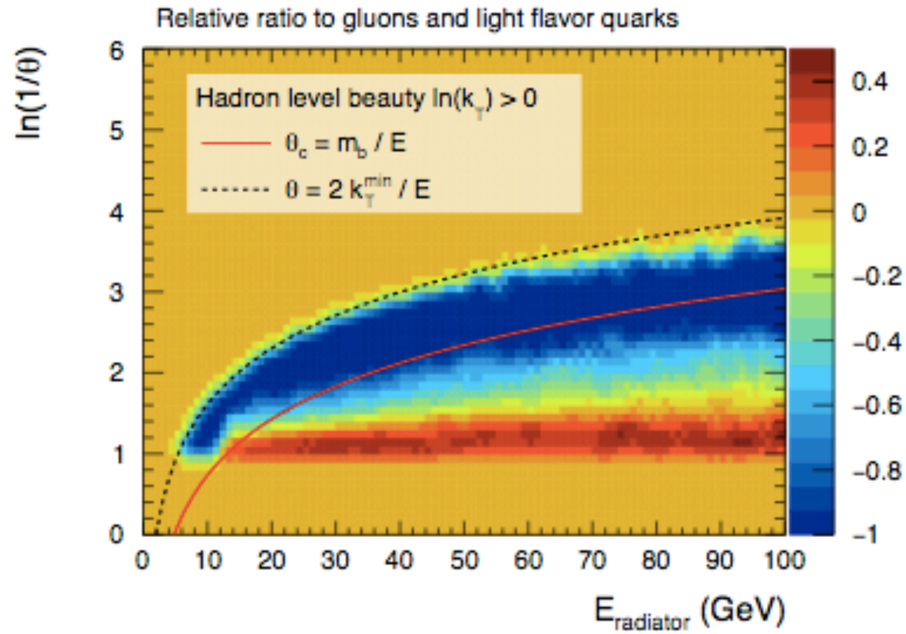
Dead cone at hadron level

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

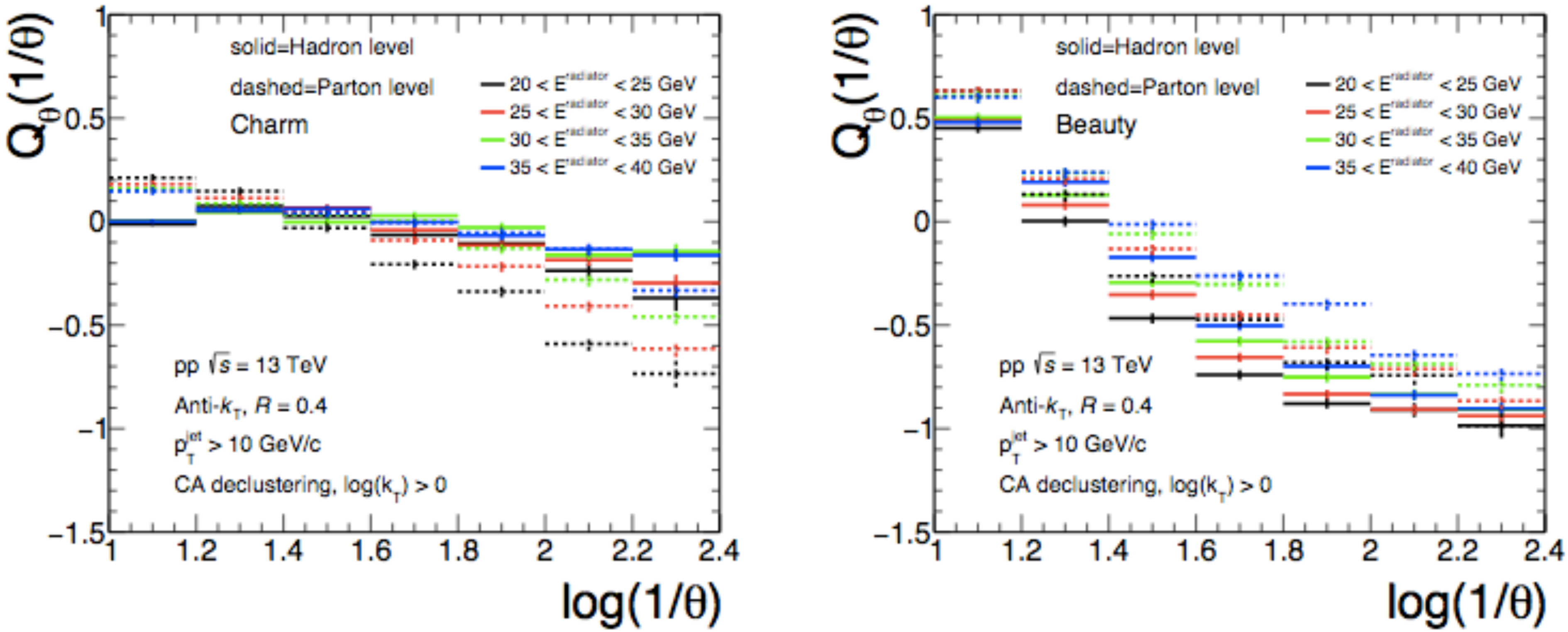
As expected: the higher $E_{radiator}$ is, the dead cone effects appear at smaller angles.

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

SOME NOTES…

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

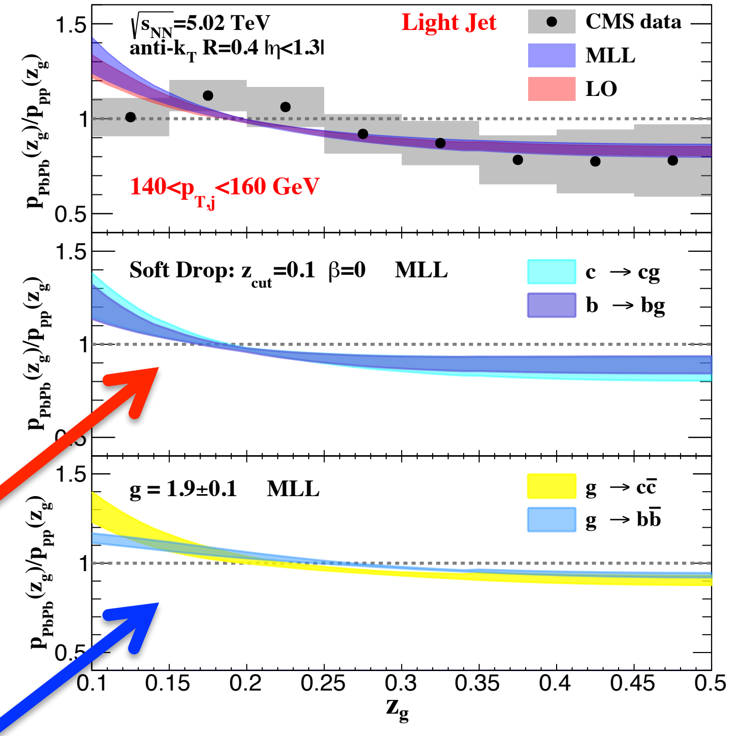
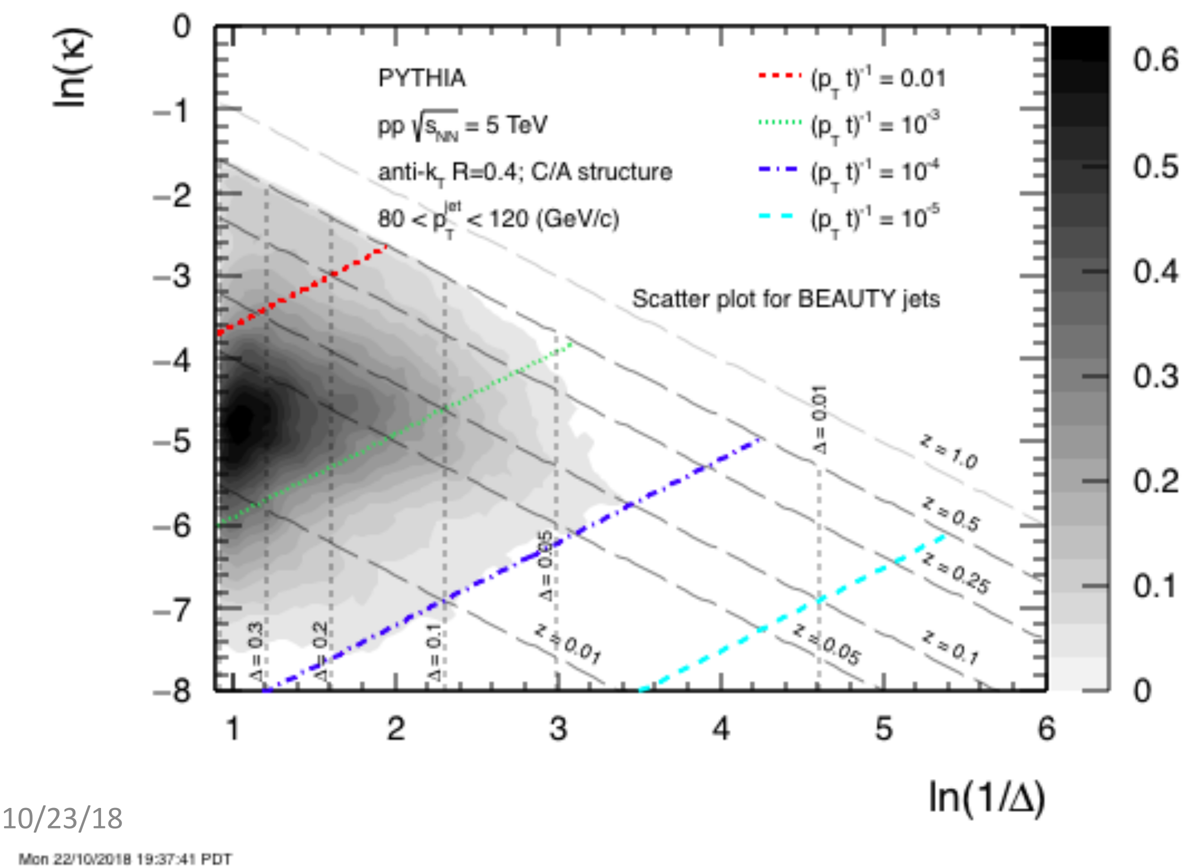


Figure 2. The modification of the jet splitting functions in 0-10% central Pb+Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV for the p_T bin $140 < p_{T,j} < 160$ GeV. The upper panels compare the LO and MLL predictions to CMS light jet substructure measurements [12]. The middle and lower panels present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

Heavy-flavor and the dead cone…

- Can we take a look with Lund diagram?
  - 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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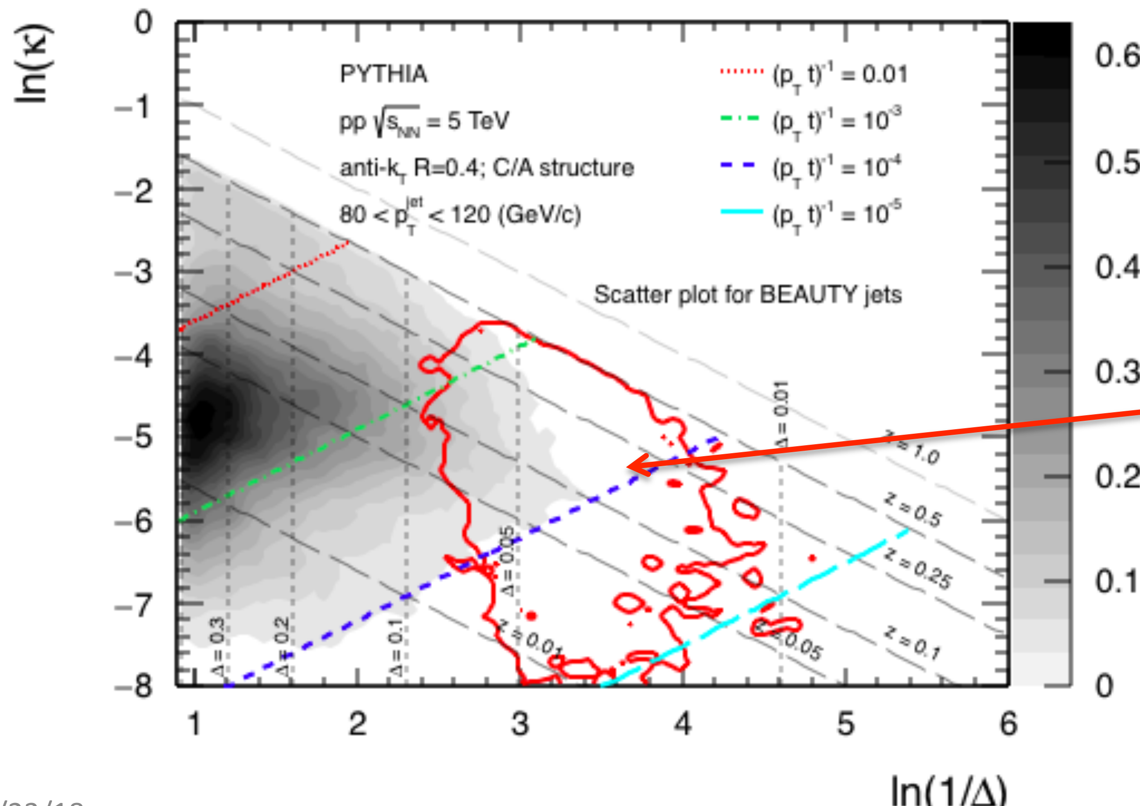

Dead cone
- An approximation
  - $\Delta < m/E$
- Entries that dead cone ought to suppress

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

Heavy-flavor and the dead cone…

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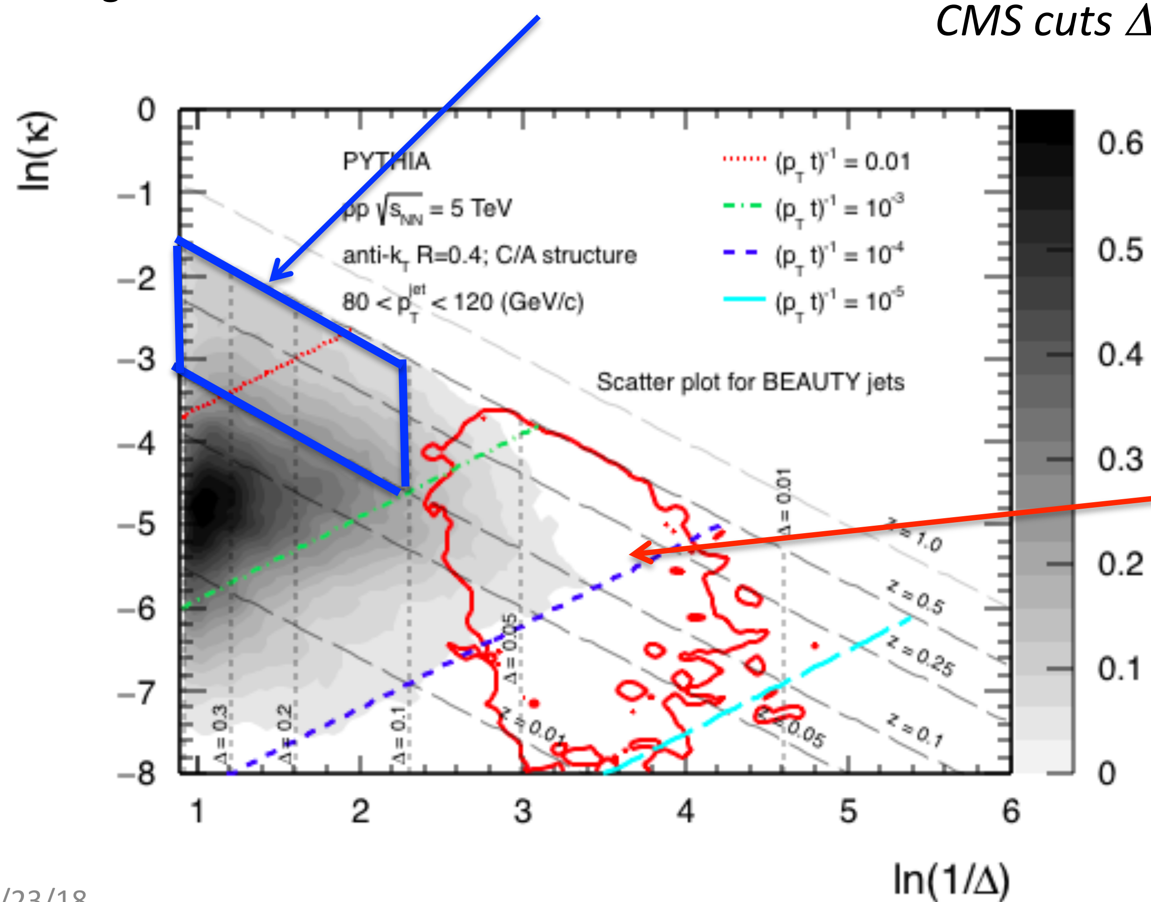
CMS cuts $\Delta < 0.1$ – ALICE does not



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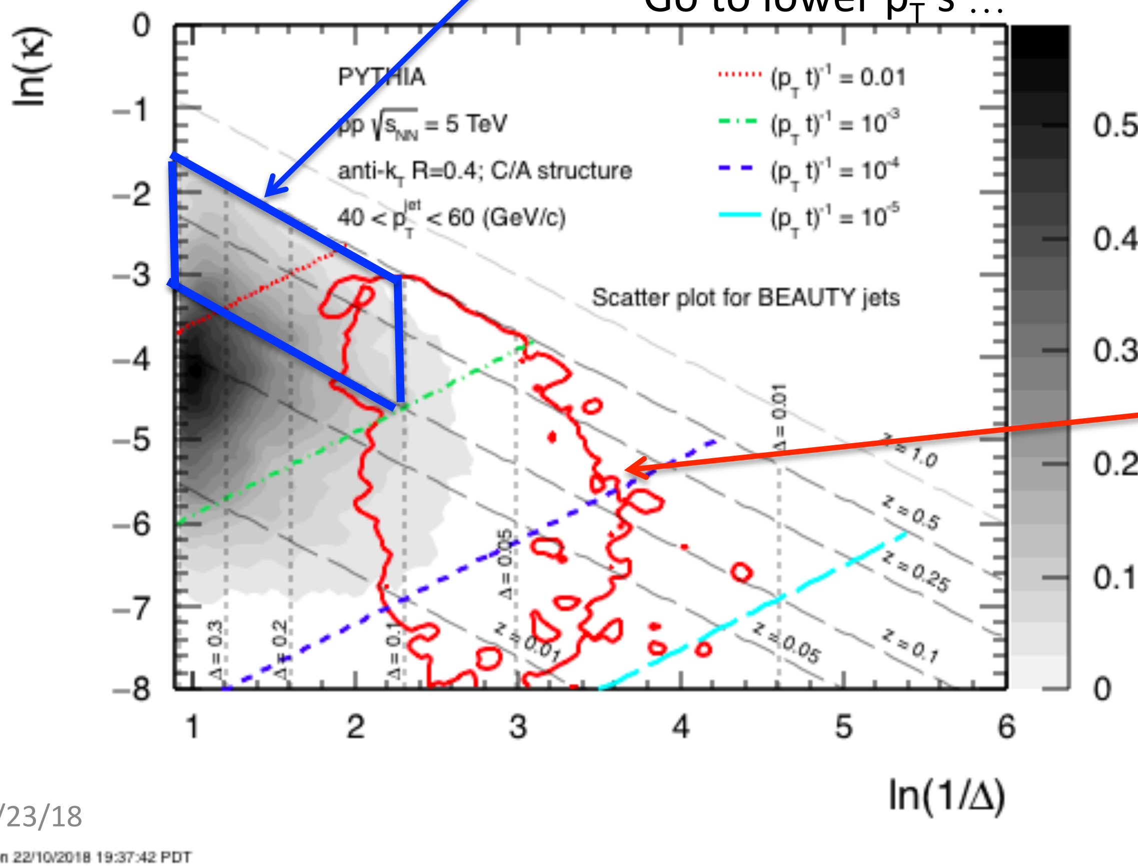
Go to lower p_T's …



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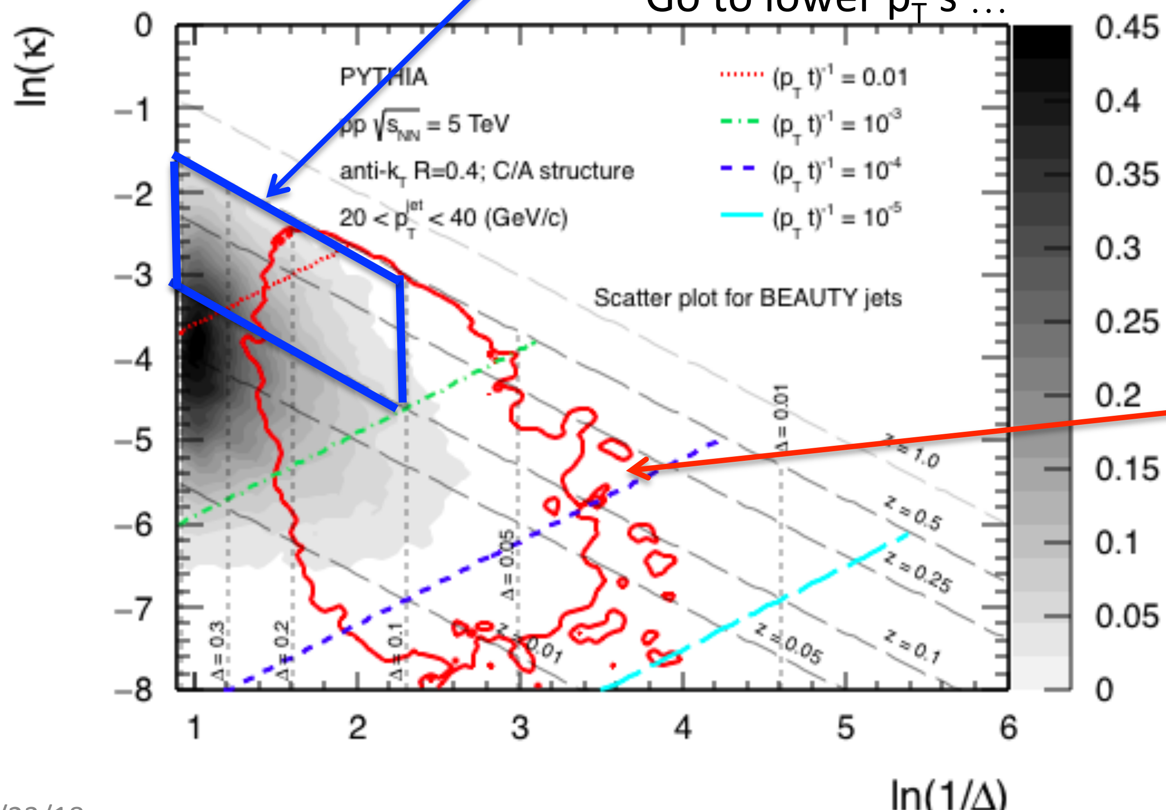

Dead cone
- An approximation
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Lower pT

Hai Tao Li, yesterday…
There it is!
Normalization?(!)

High-p_T

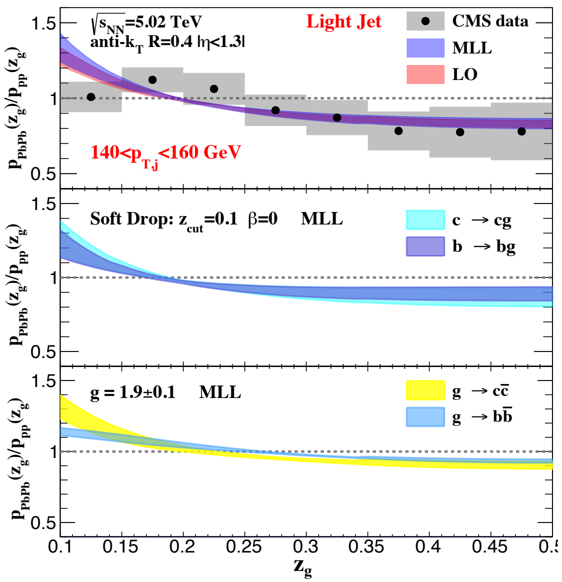
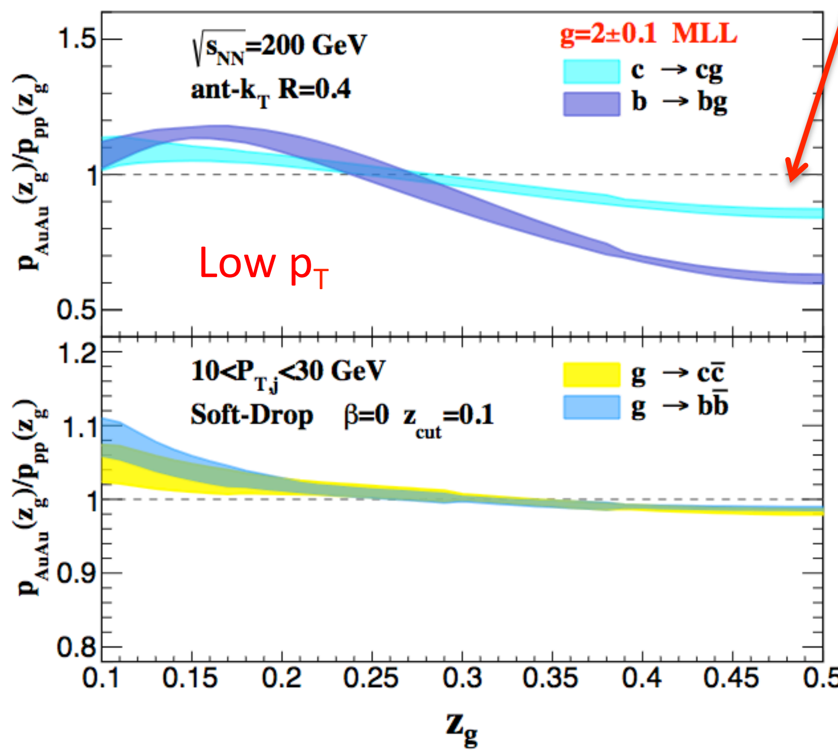


Figure 2. The modification of the splitting functions in 0-10% central Pb-collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV for the p_T $140 < p_{T,j} < 160$ GeV. The upper pa compare the LO and MLL predictions to C light jet substructure measurements [12]. middle and lower panels present the M modifications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



modifications of the jet splitting functions

HTL, Vitev 2018

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

kT cut vs. Soft Drop ?

Soft Drop Condition:

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

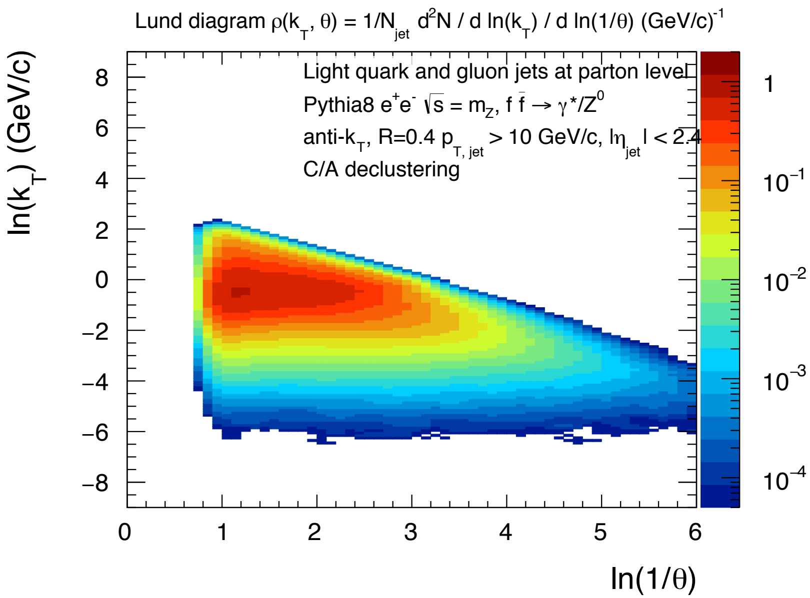
$$z = \frac{p_{t_2}}{p_{t_1} + p_{t_2}}$$

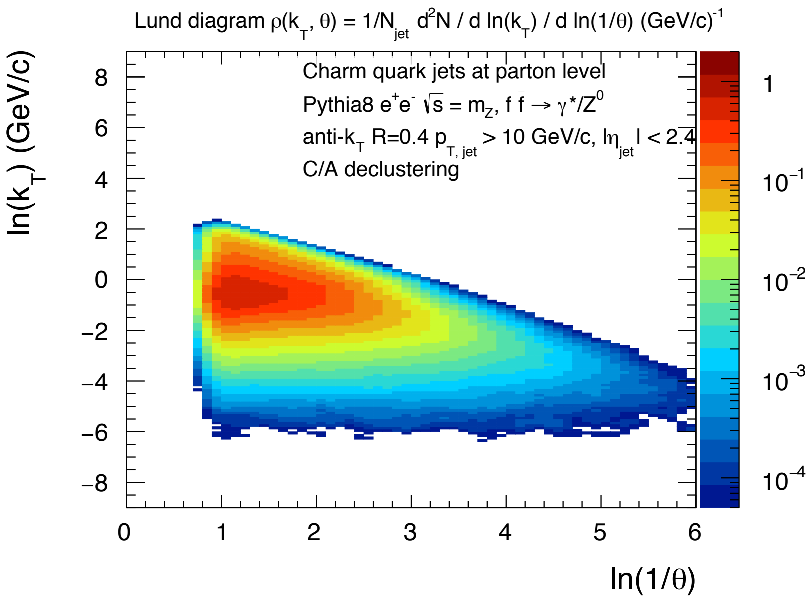
$$k_T = p_{t_2} \cdot \Delta R_{12}$$

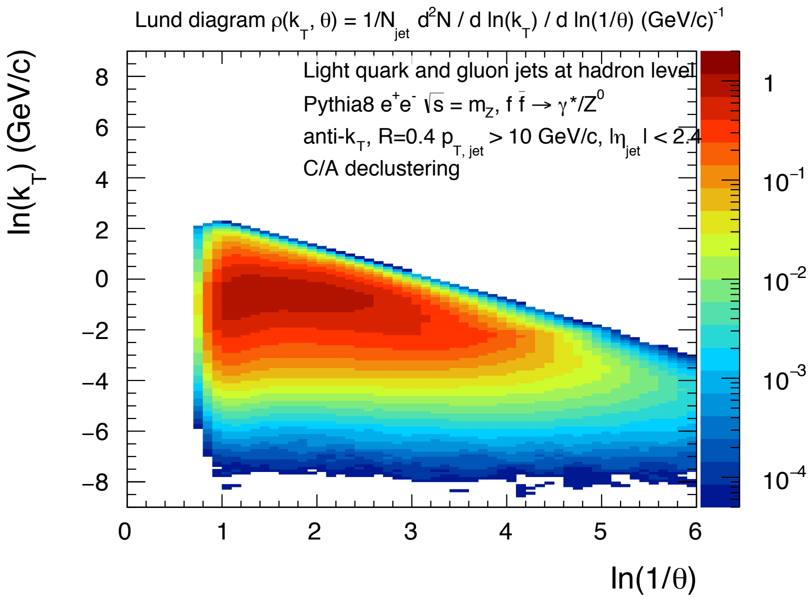
$p_{t_2} > k_{T_{cut}}$ for $R_0 = 1$, $\beta = 1$

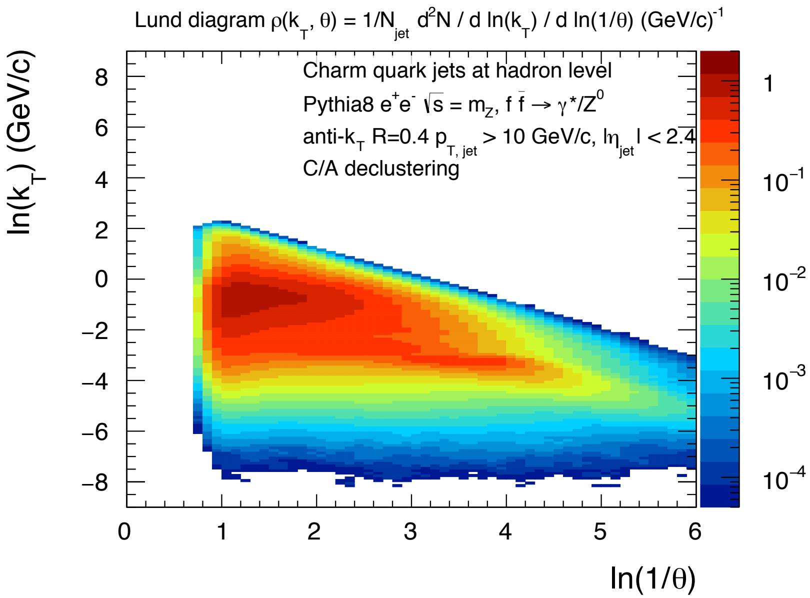
OUTLOOK: REVISIT LEP, MEASURE AT LHC, … EIC? DETAILED HADRONIZATION STUDIES?

Outlook : LEP, (eIC…) - charm









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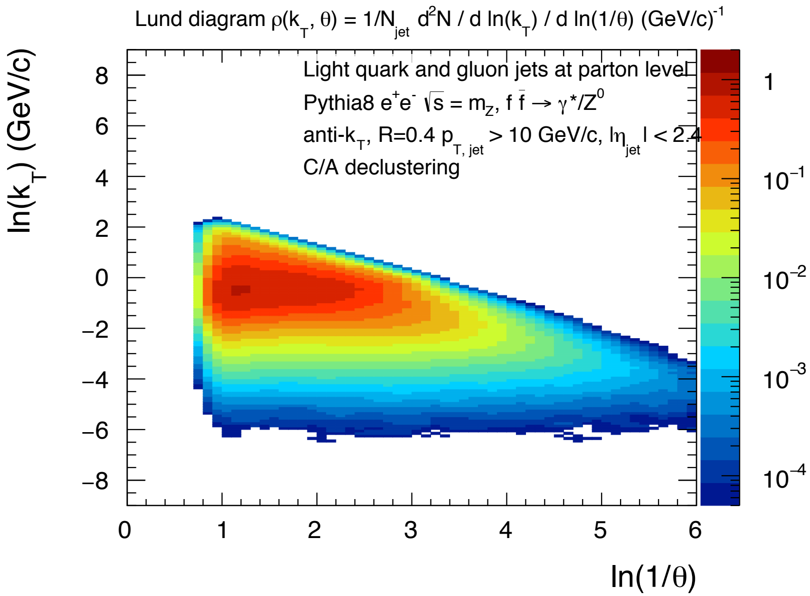
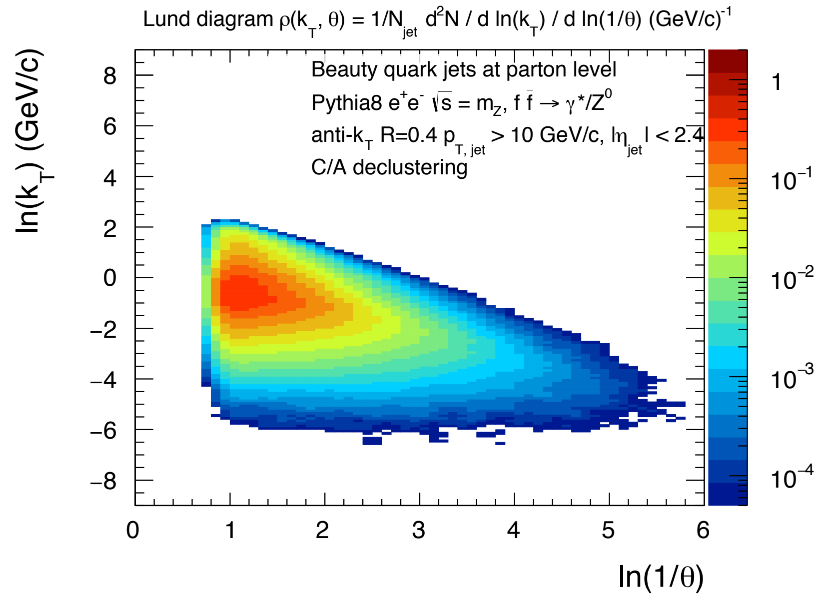
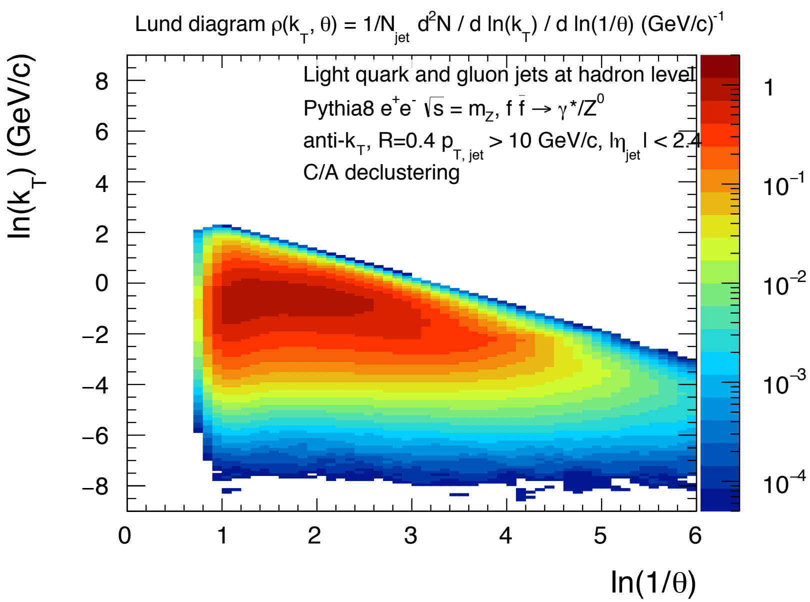
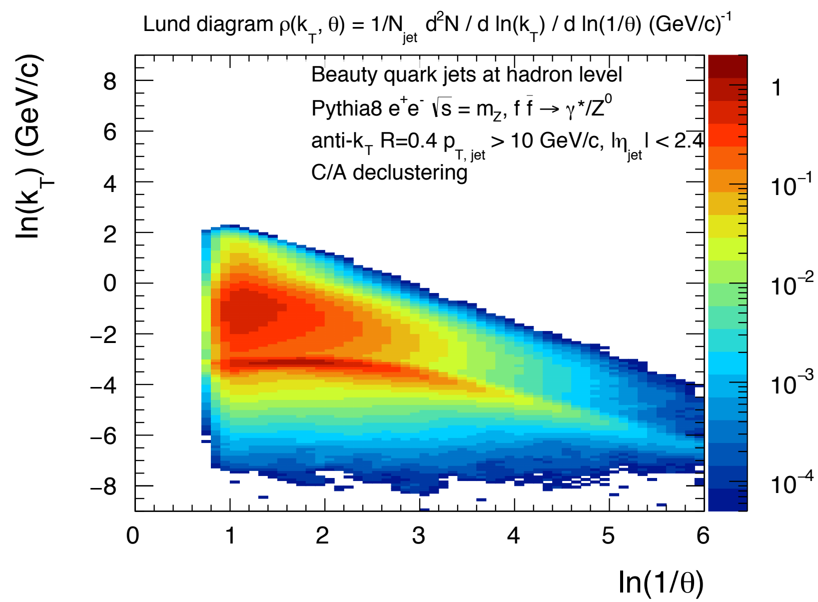
Tue 29/01/2019 10:56:24 PST

Outlook : LEP, (eIC…) - beauty









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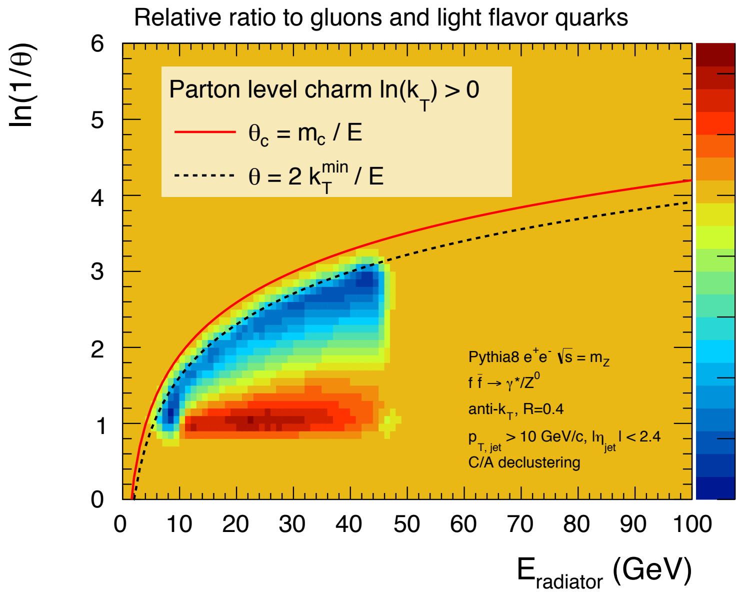
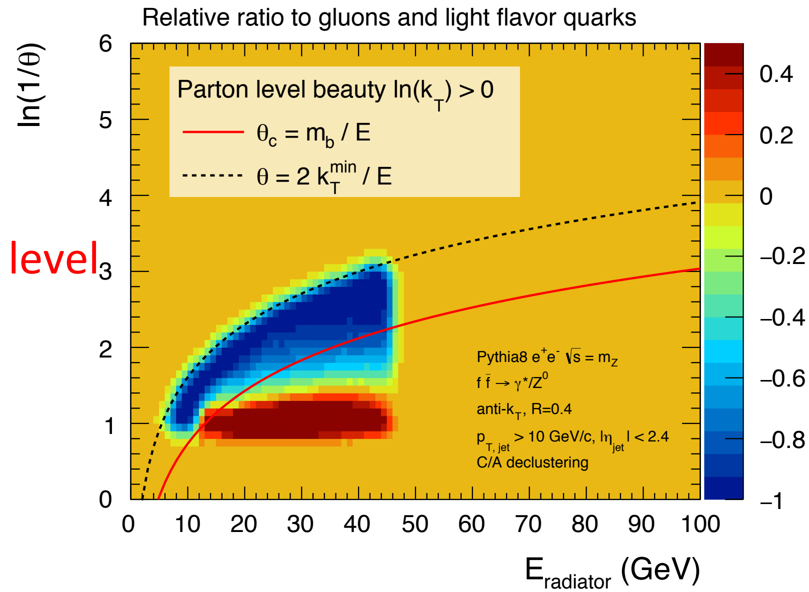
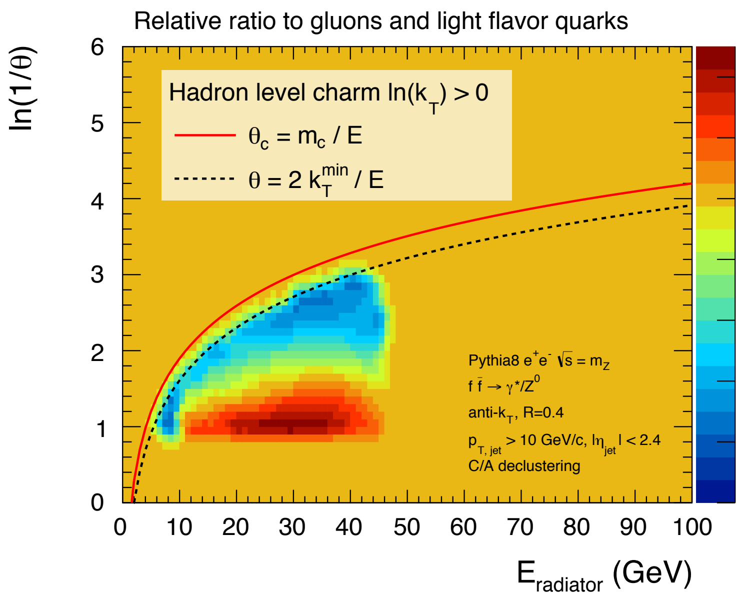
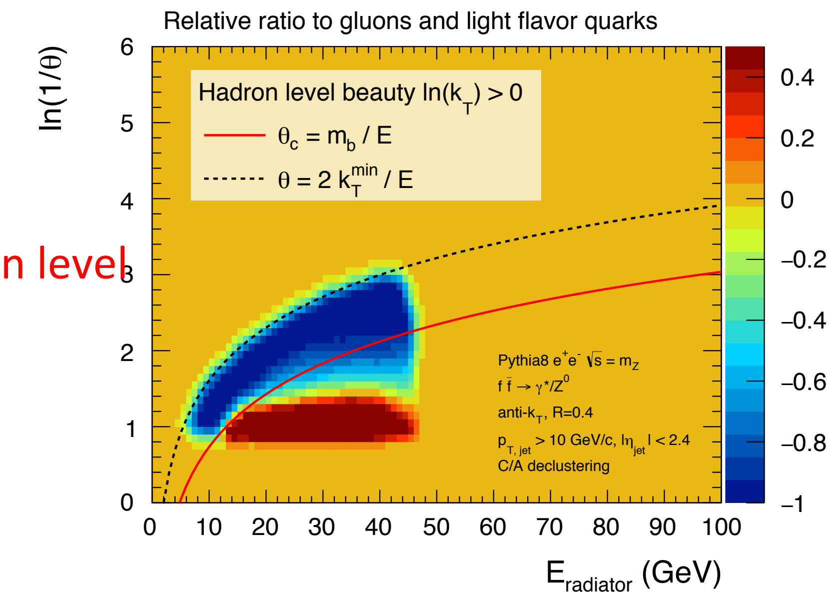




Parton level





Hadron level

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Summary

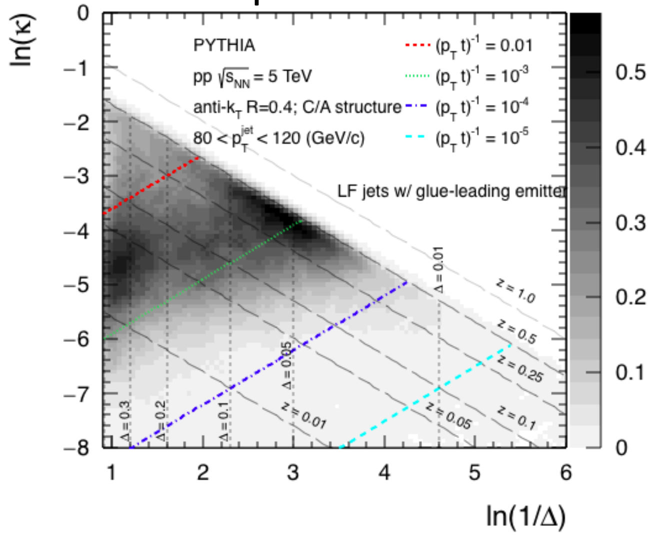
- Dead cone at the subjet level:
  - rather “simple” conceptually
  - Cut on kT: opportunity to study the effect systematically => constraints on hadronization (LEP, eIC; hadronic collisions more difficult ISR, MPI,…)
- More applications for declustering in considerations (jet classification based on Lund plane - kT)
- Last but not least: no grooming, no soft drop, no ΔR cuts… => opportunity for heavy-ion collisions => jet modifications, medium response(?), …

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 splits



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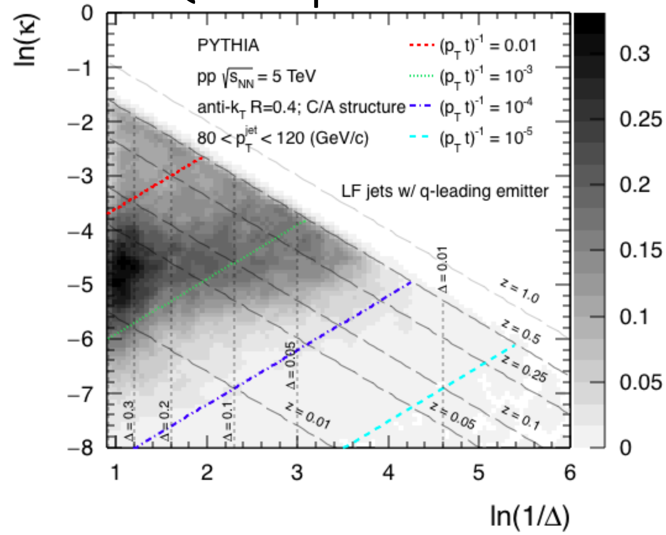
LF Quark splits



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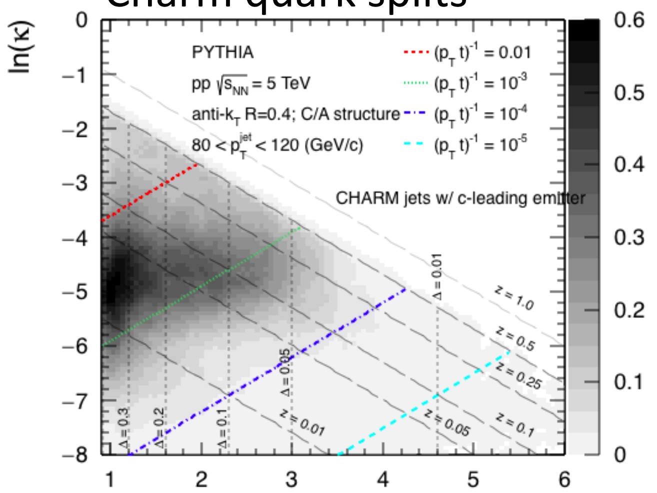
Charm quark splits



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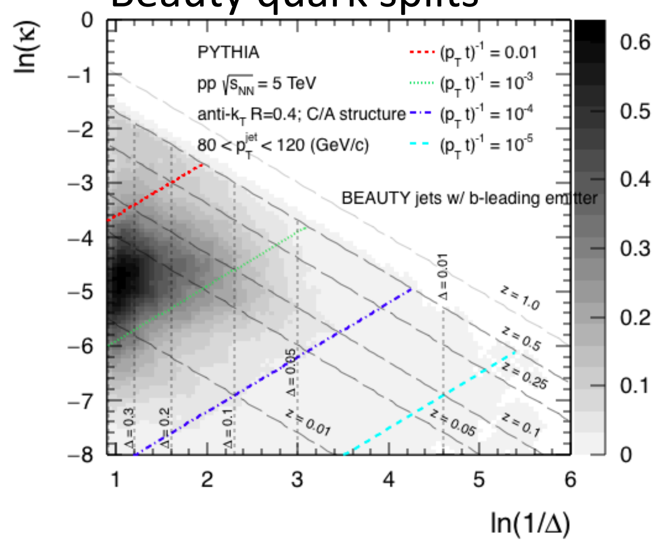
Beauty quark splits



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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 – MC STUDY

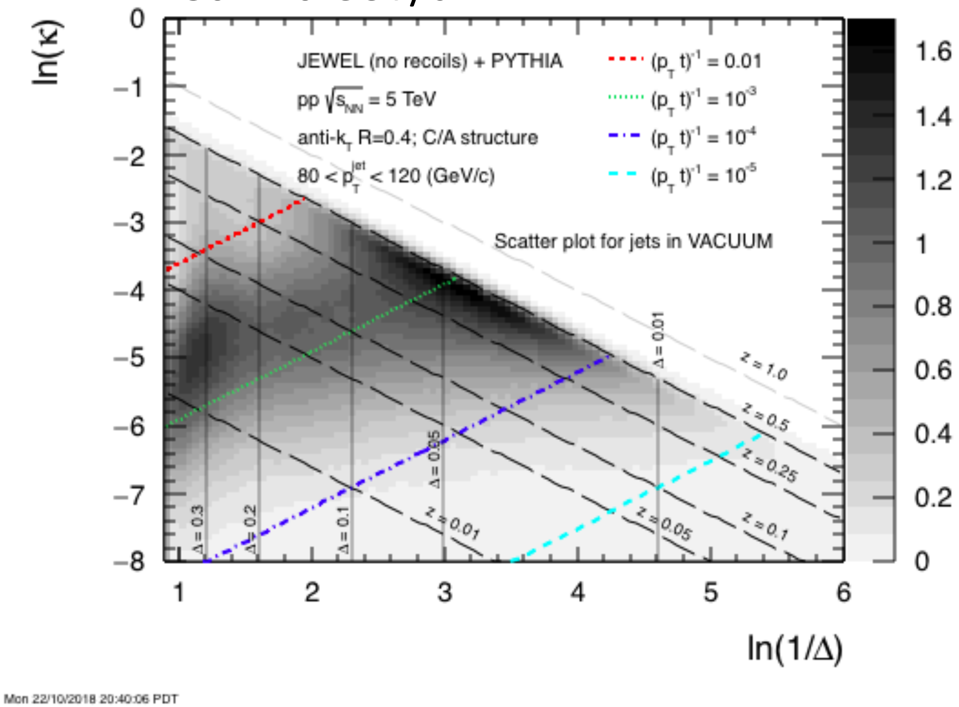
Jet Lund diagram

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

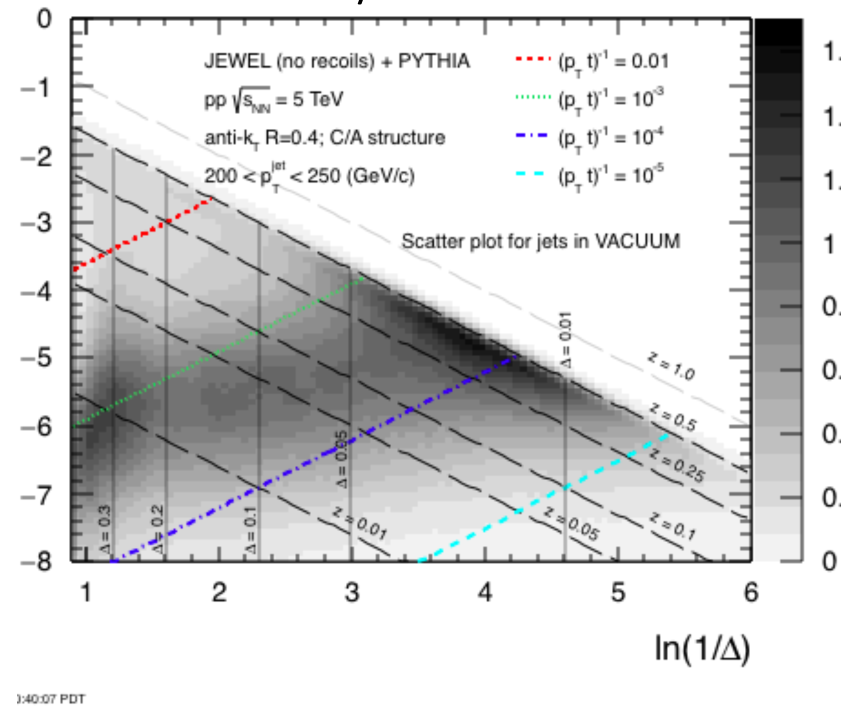
$$\bar{\rho}(\Delta,\kappa) = \frac{1}{N_{\text{jet}}}\frac{dn_{\text{emission}}}{d\ln\kappa\ d\ln 1/\Delta}$$

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

80-120 GeV/c



200-250 GeV/c



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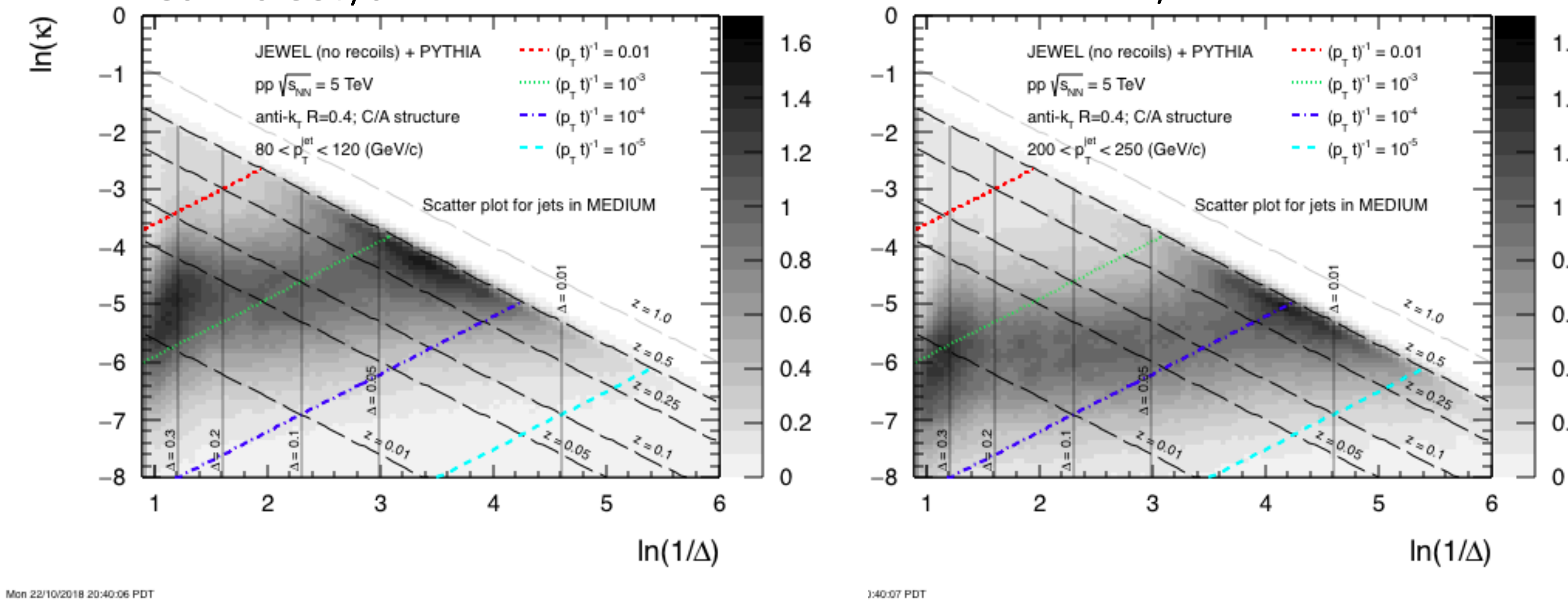

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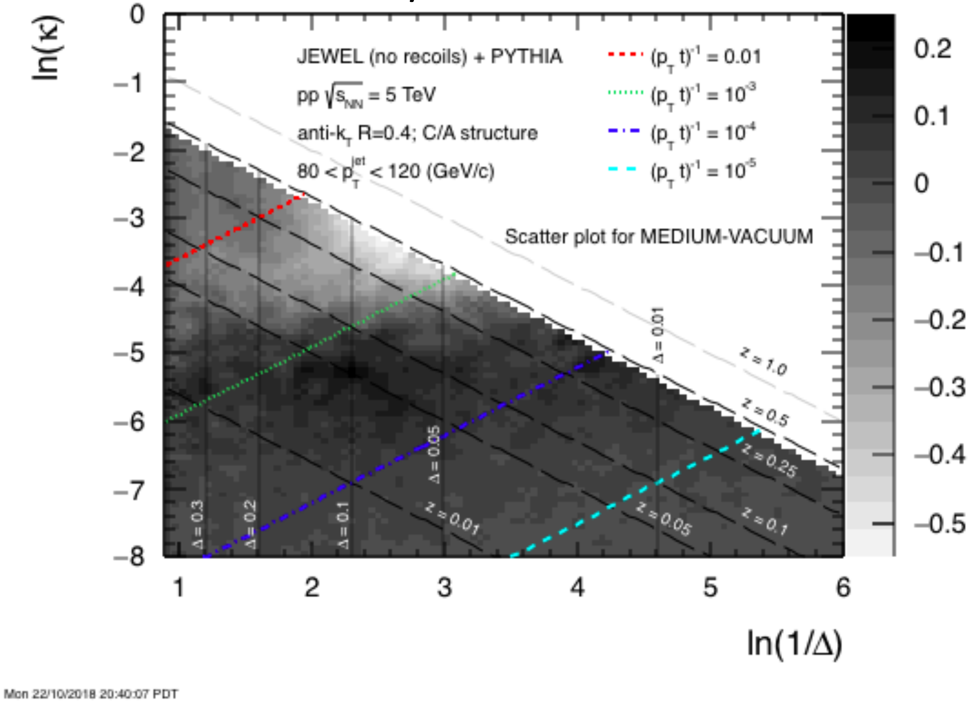

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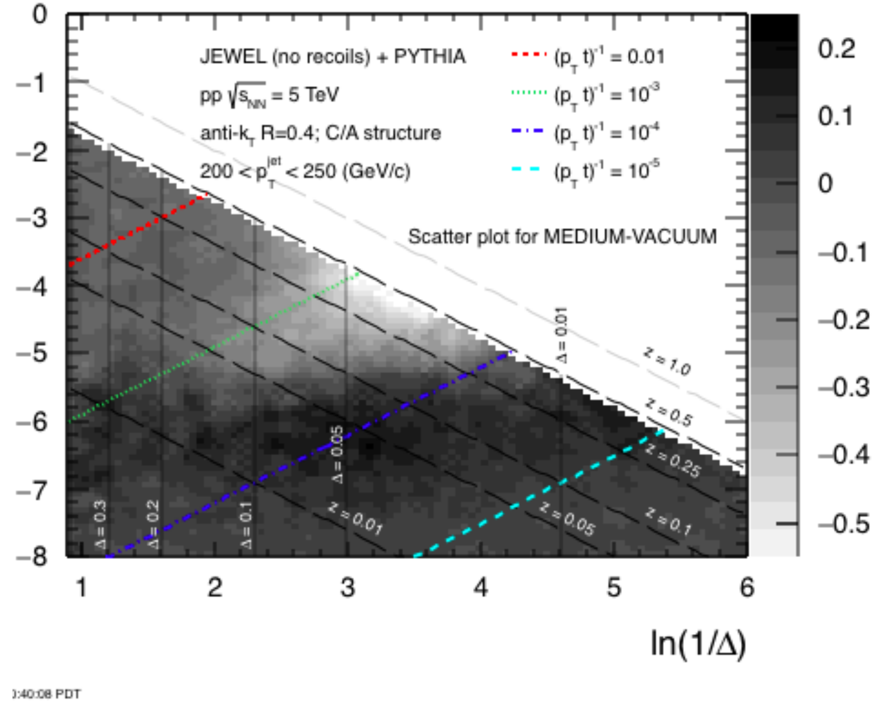

Jet Lund diagram slicing through time

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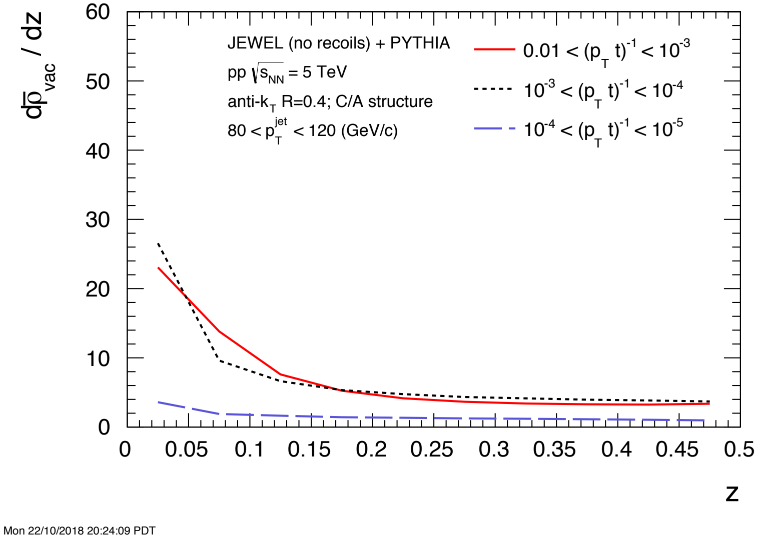
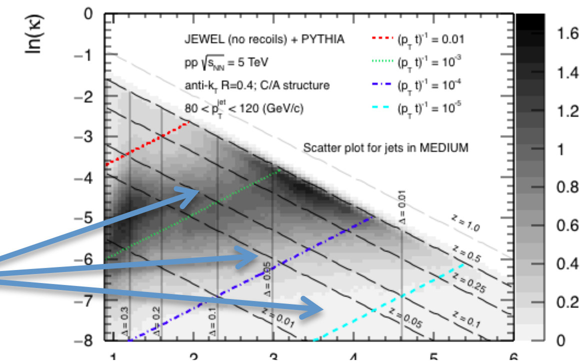
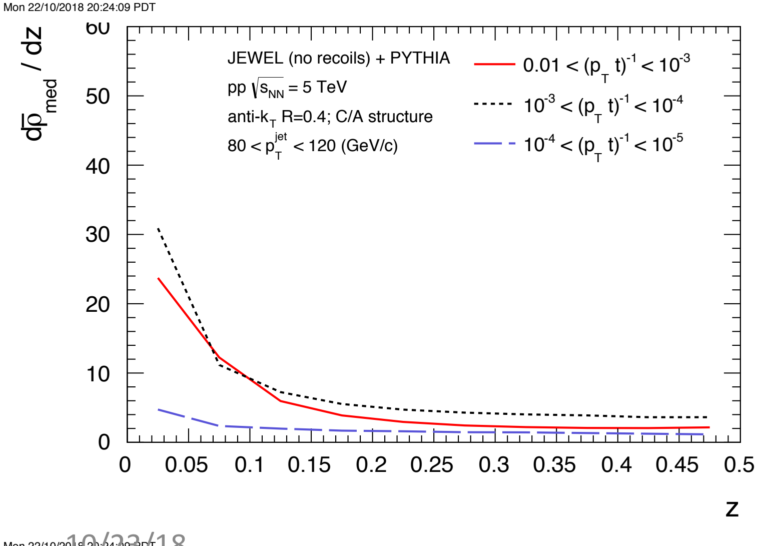
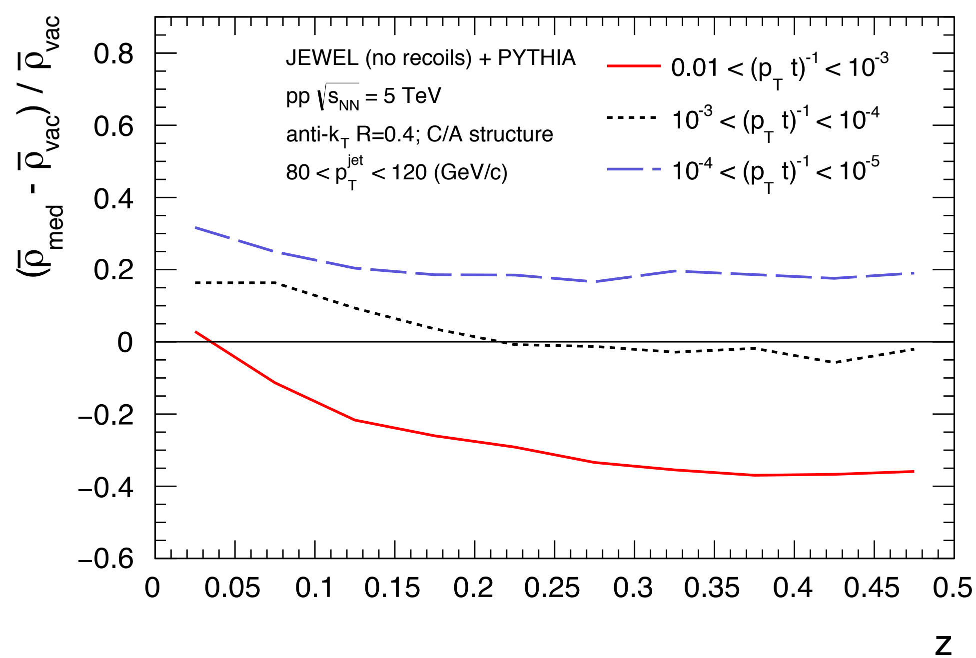


80 – 120 GeV/c



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





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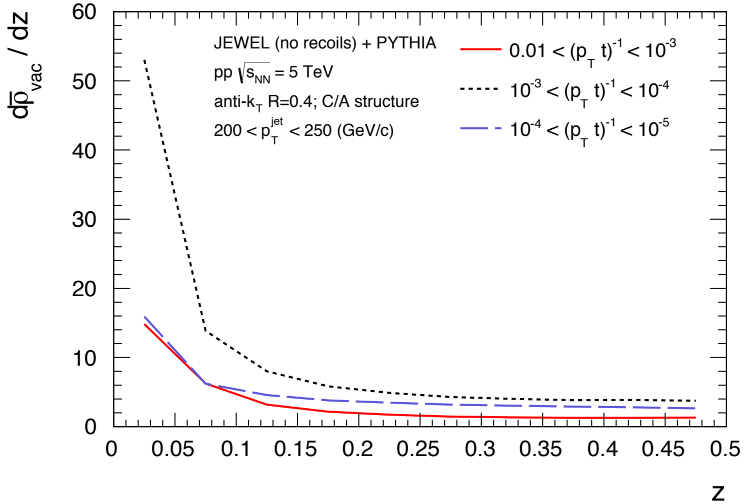

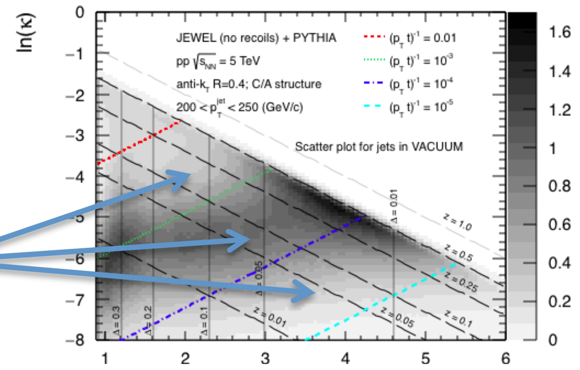

Slicing along $1/(p_T \times t)$ and projecting along z

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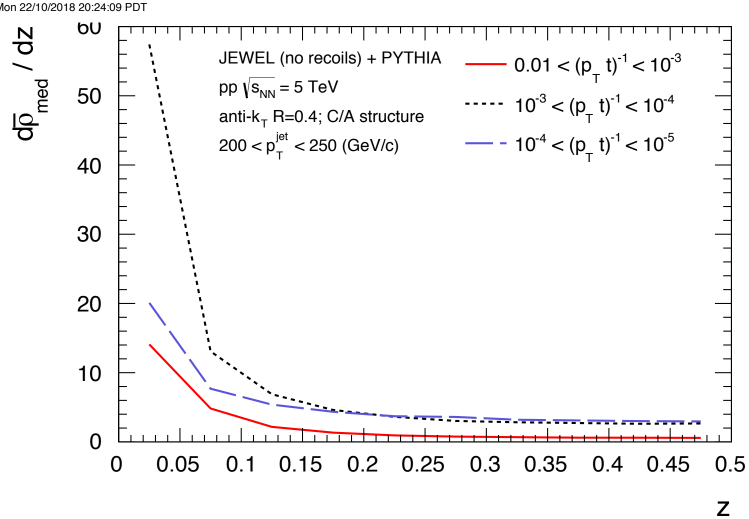

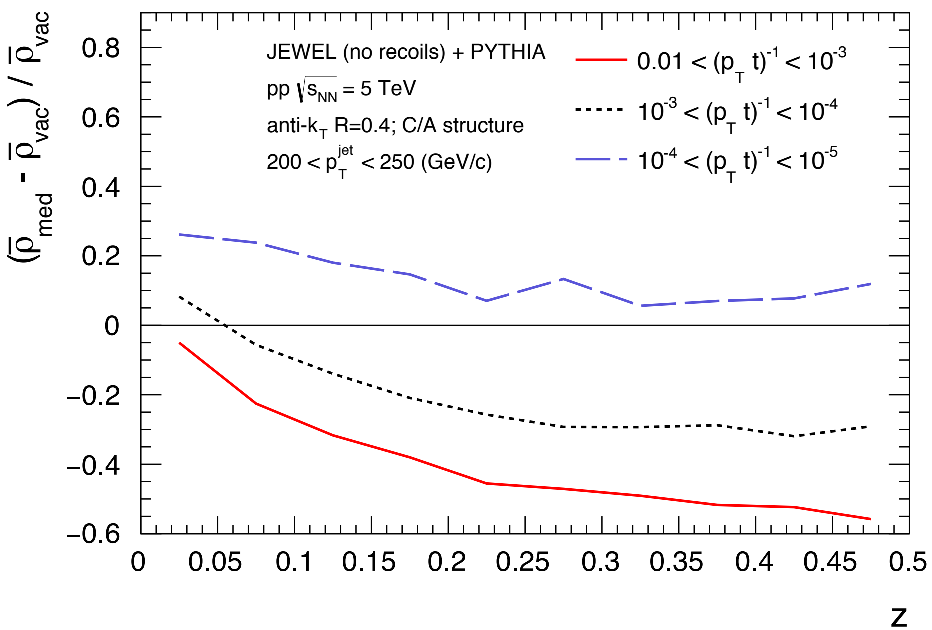

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Jet Lund diagram slicing through time

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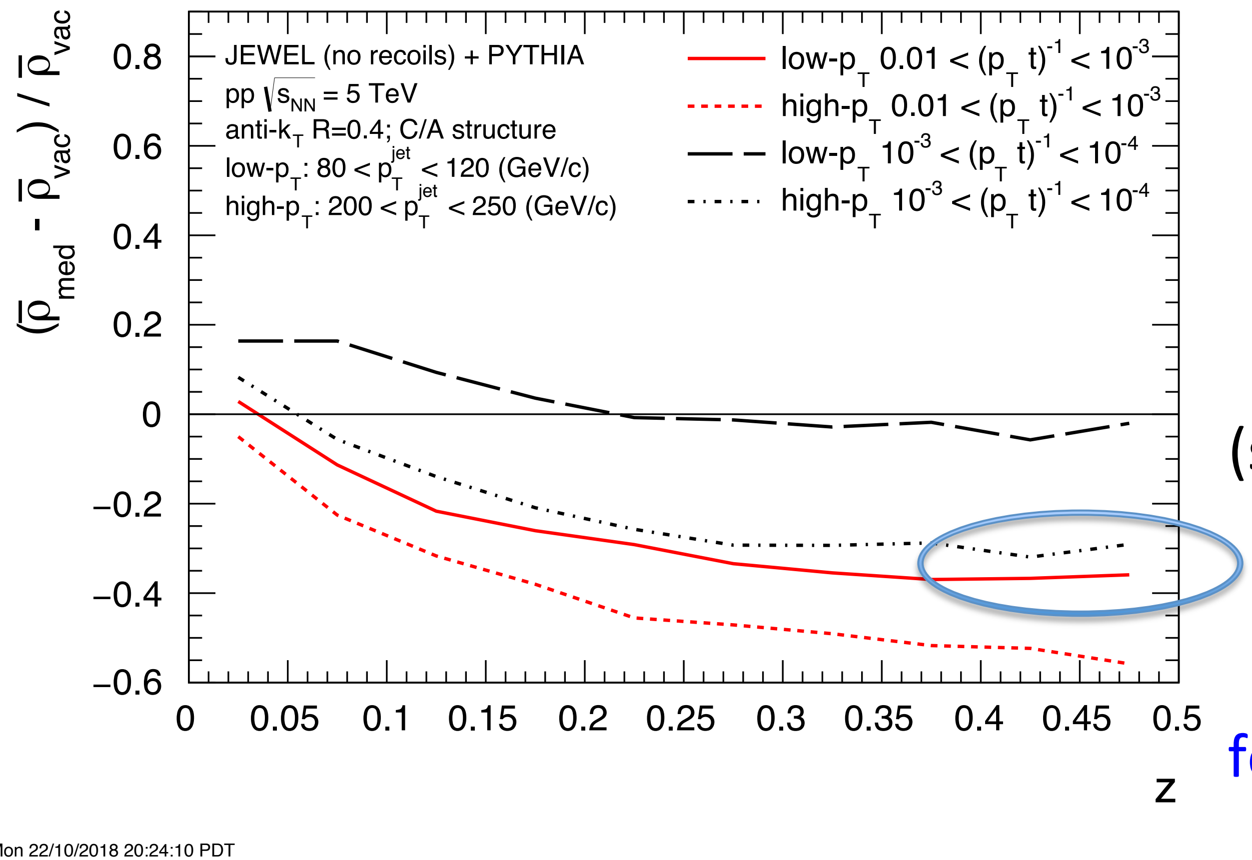


Low- with high-p_T for the similar t

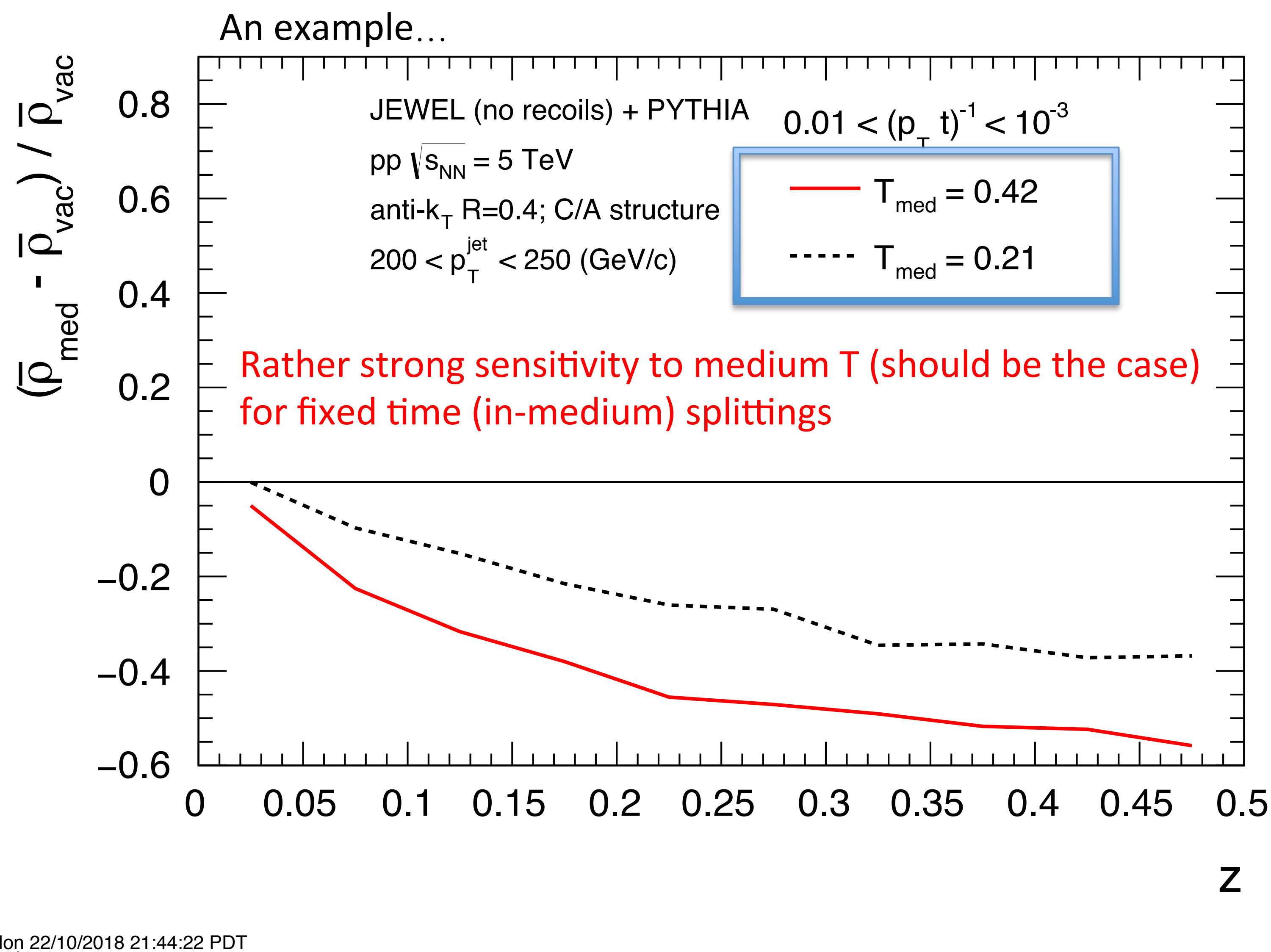
⇔

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

Work on slicing on formation time directly ongoing

Sensitivity to medium's T

An example…



Sensitivity to medium's L (centrality)

An example…