Recent jet results from ALICE and STAR @ RHIC

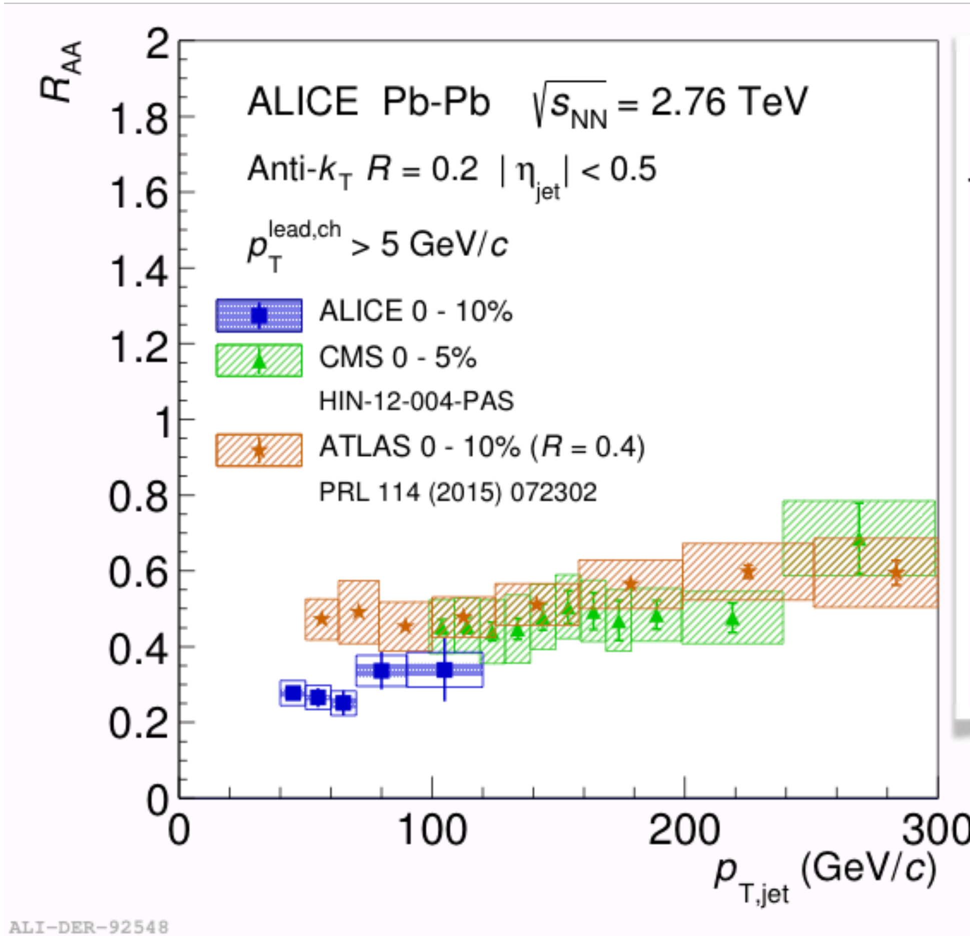
Tons of slides – but most are for your reference - I will not go to details on many of those…

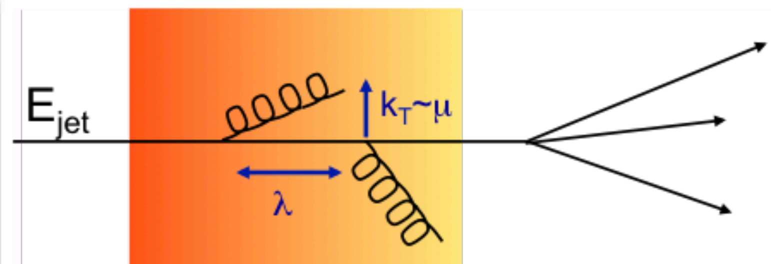
Jets in AA collisions – what's that about?

Jet R_{AA}

$$R_{AA} = \frac{\#(\text{jets observed in AA collision per N-N (binary) collision})}{\#(\text{jets observed per p-p collision})}$$

$R_{AA} < 1$: medium induced out-of-cone radiation





Longitudinal modification:

- out-of-cone: energy lost, loss of yield, di-jet energy imbalance
- in-cone: softening of fragmentation

Transverse modification

- out-of-cone: increase acoplanarity kT
- in-cone: broadening of jet-profile

LHC: Estimates (on average) of about 10-20 (10%) GeV radiated out of cone – similar result at RHIC

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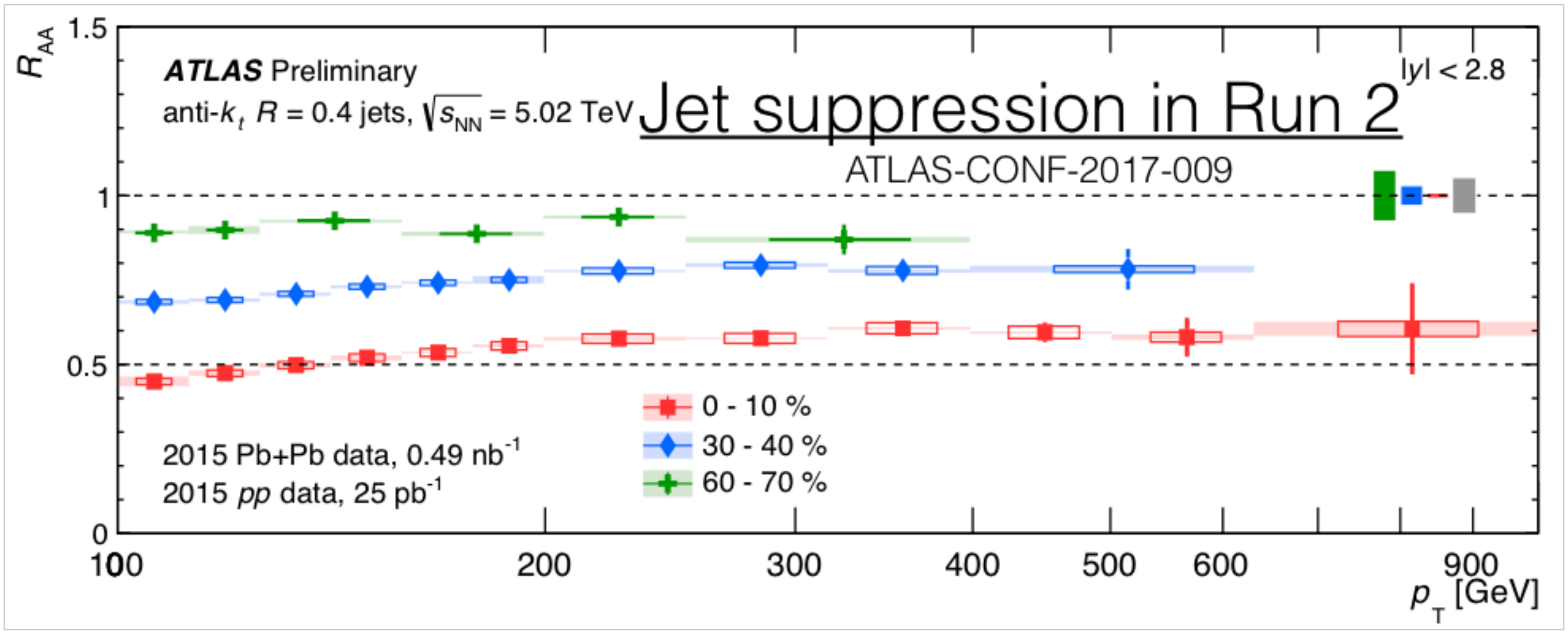

R_{AA} for jets ~0.6 at 0.2 TeV all the way to 1 TeV

<=> a constant "shift" => a TeV jet looses/injects tens (100?) of GeV into the medium

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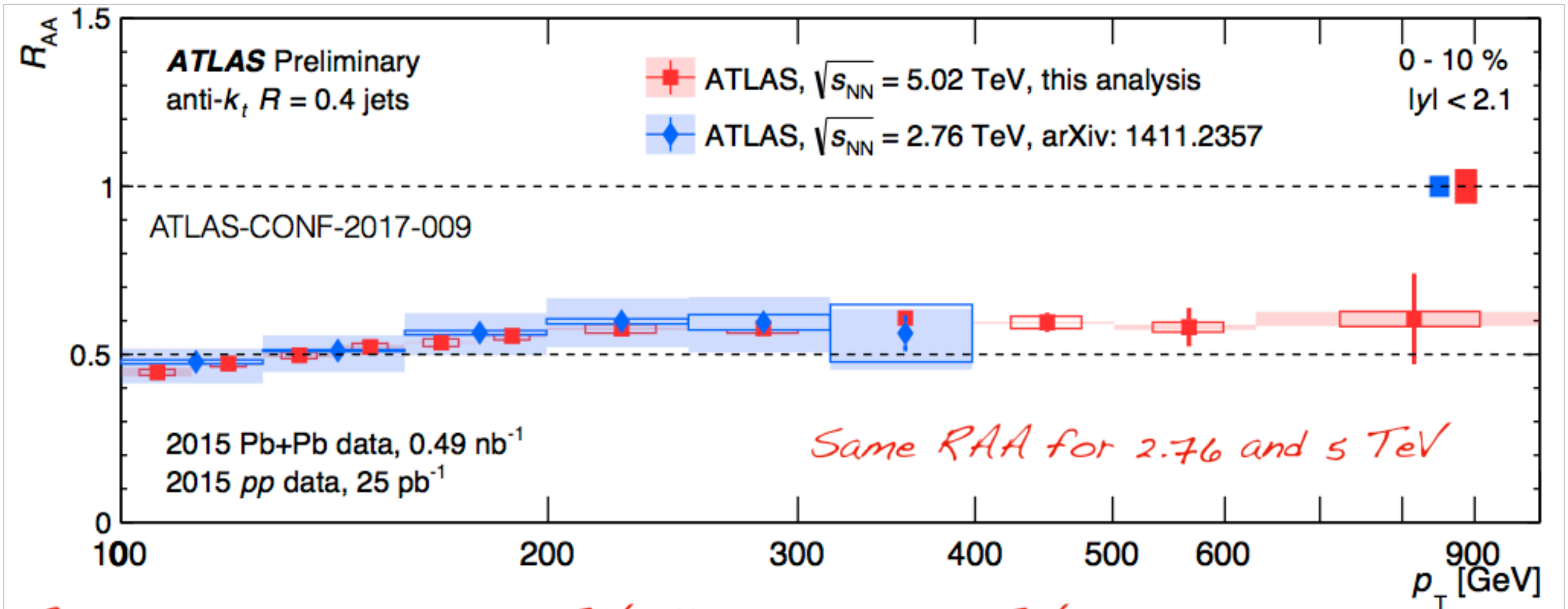

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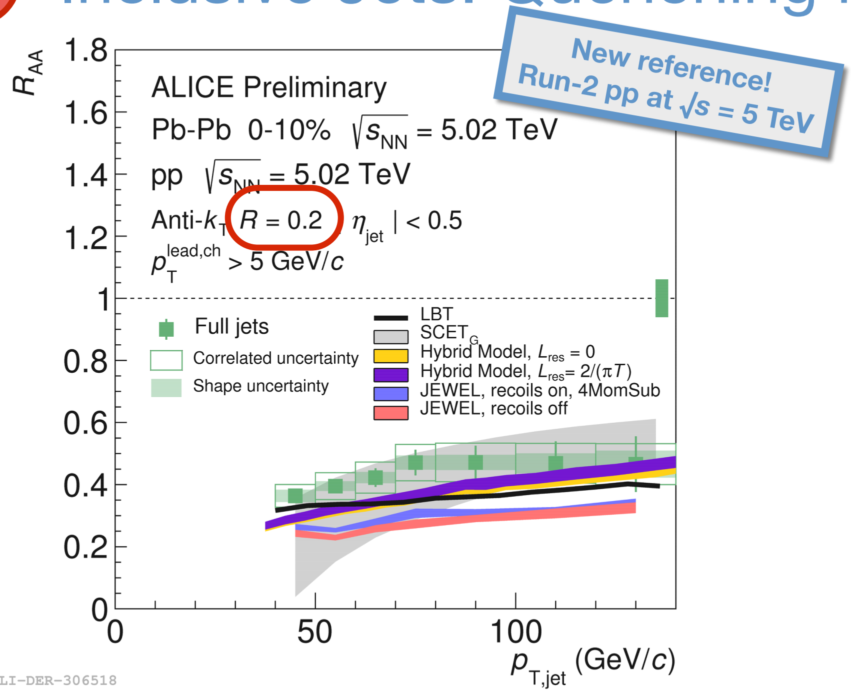
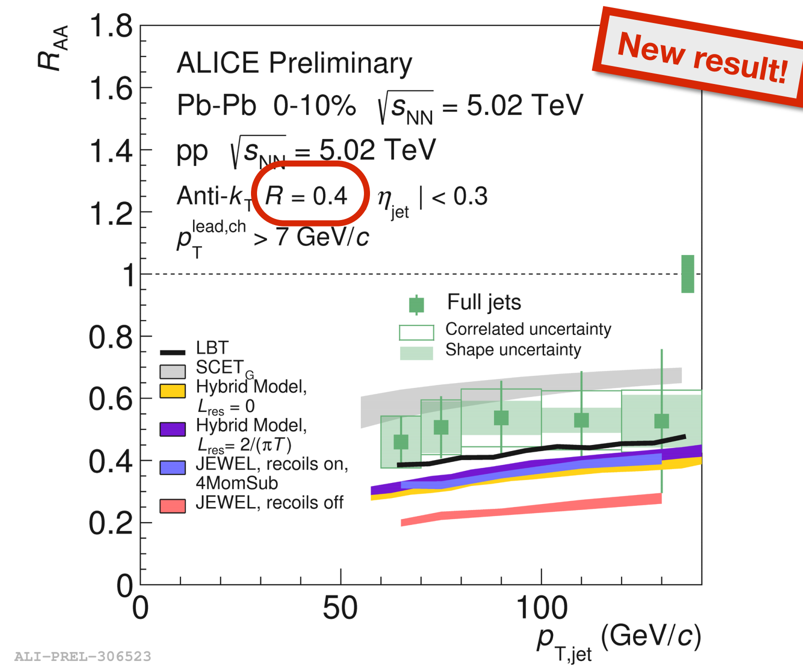
Inclusive Jets: Quenching in Pb–Pb at $\sqrt{s_{NN}}$ = 5 TeV





- Jet quenching measured down to $p_{T,jet}$ = 40 GeV/c
- **New: measured with jet radii up to R = 0.4**
- ***R* dependence probes the angular distribution of medium-induced radiation**
  - Hint of tension with most models at low p_T

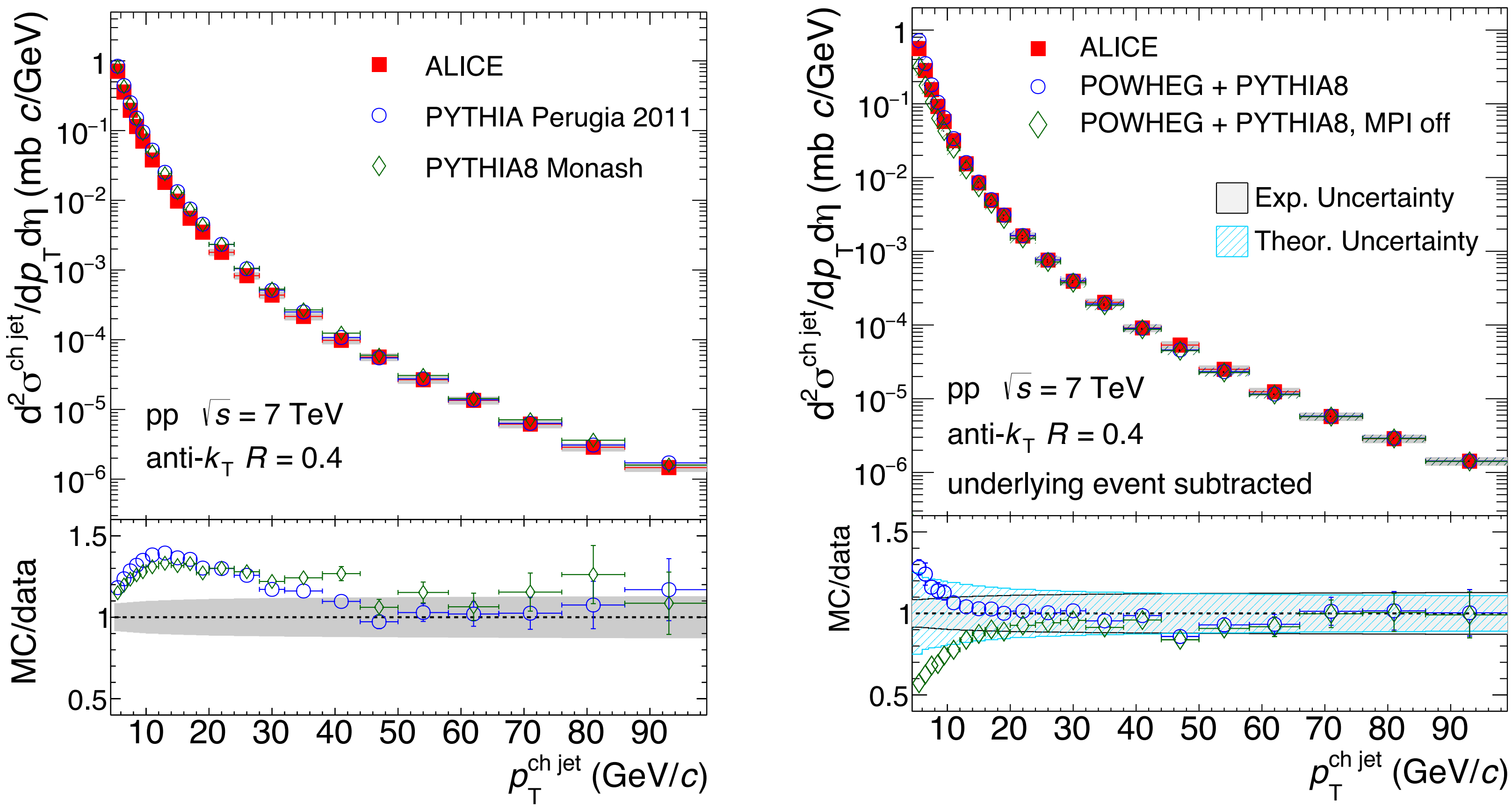
J. Mulligan, Wed, 11h05

(model references in backup)

https://indico.cern.ch/event/634426/contributions/3003545/attachments/1725255/2786826/tdahms_20181001.pdf

ALICE: charged particle jets pp at 7 TeV

https://arxiv.org/pdf/1809.03232v1.pdf



Important for understanding of AA reference (good quality data set)
Interesting deviations at low-pT ?

ALICE: charged particle jets pp at 7 TeV

https://arxiv.org/pdf/1809.03232v1.pdf

Fragmentation for lowest pT jets

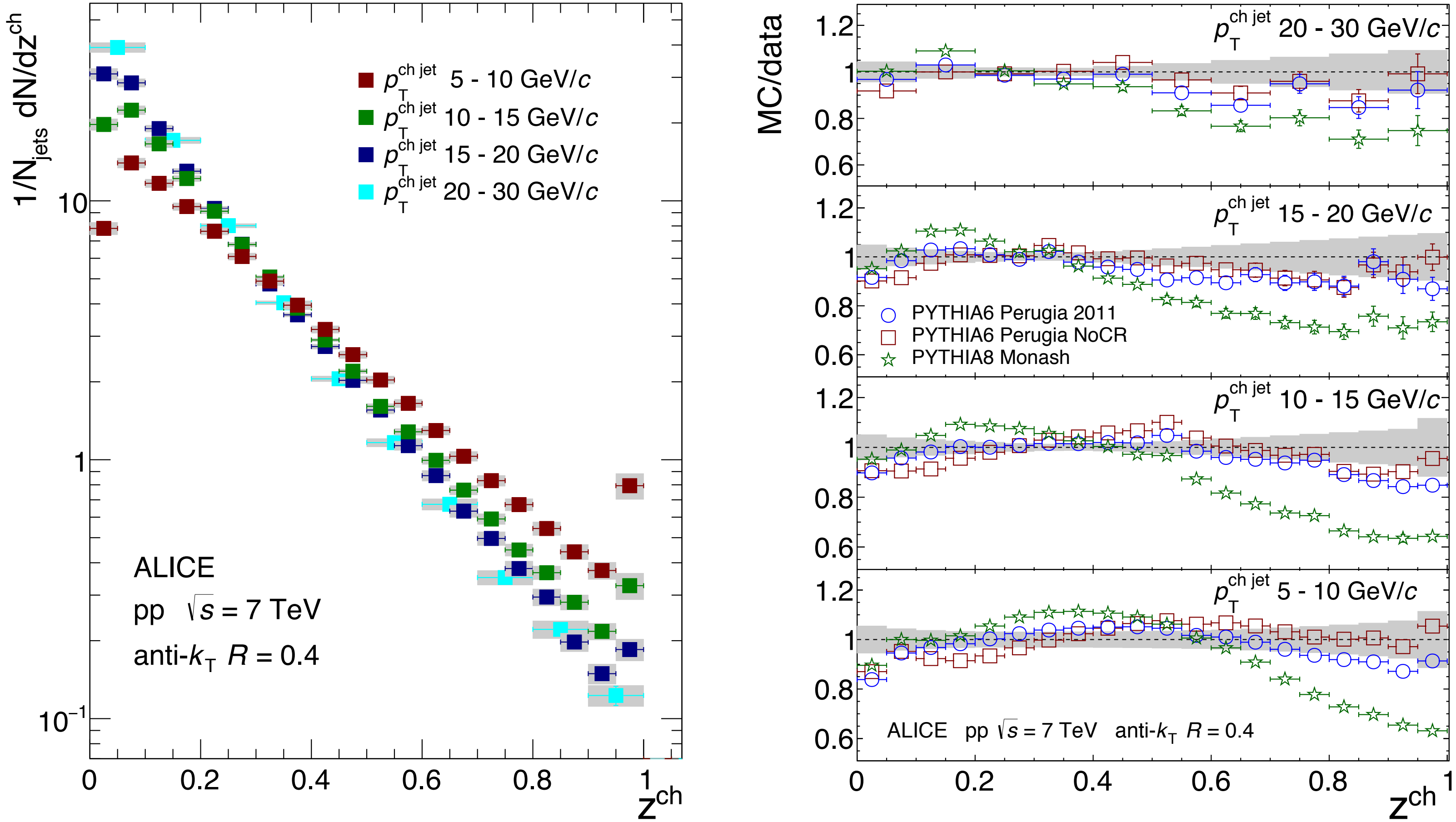


Figure 3: Left panel: Charged particle scaled p_T spectra $F^z(z^{ch}, p_T^{ch\ jet})$ for different bins in jet transverse momentum. Right panel: Ratio of MC distributions to data. The shaded band shows the systematic uncertainty on the data drawn at unity. Error bars represent the statistical uncertainties.

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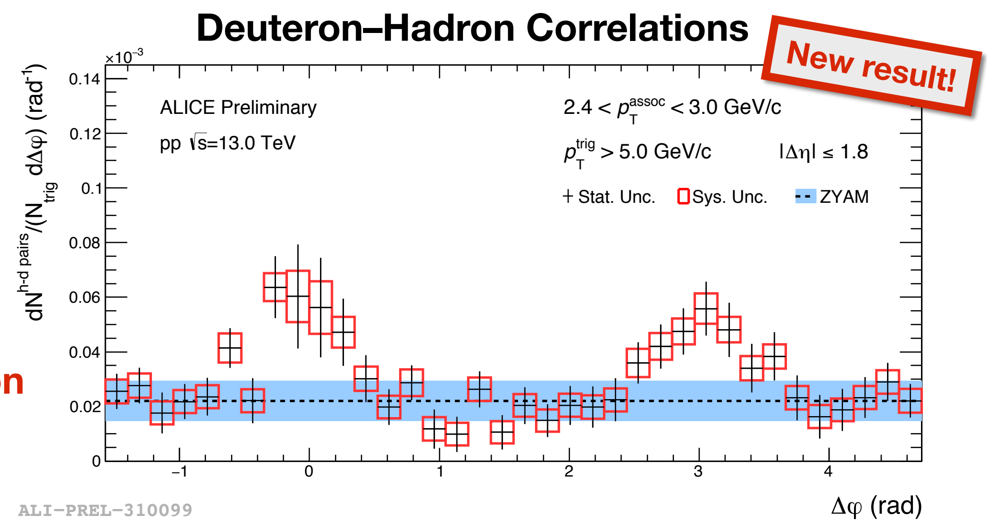
Particle ID in Jets: Deuterons

ALICE

- **Are deuterons created in jets?**
  - e.g. by coalescence of protons and neutrons
  - **directly linked to baryon production in jets**
- If yes, should observe a correlation of deuterons with other hadrons in jet
- **High-p_T deuterons show angular correlation with high-p_T hadrons in pp at $\sqrt{s}$ = 13 TeV**
  - indication that deuterons are also produced in jets (and not only non-composite hadrons)



B. Schaefer, Tue, 12h05

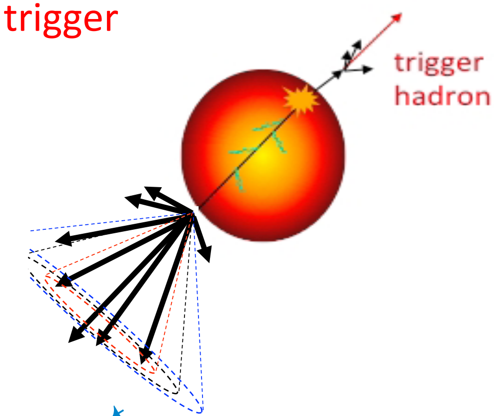
https://indico.cern.ch/event/634426/contributions/3003545/attachments/1725255/2786826/tdahms_20181001.pdf

Hadron-jet coincidences

- Coincidence distributions:
  - Trigger on a hard process (hadron, jet, gamma, Z)
  - Measure correlated energy-momentum distribution recoiling from the trigger

Key assertion:

- Correlations cannot strictly be measured event-by-event
- ensemble-averaged distributions required for strict discrimination of jet-correlated and uncorrelated yields



Analysis procedure:

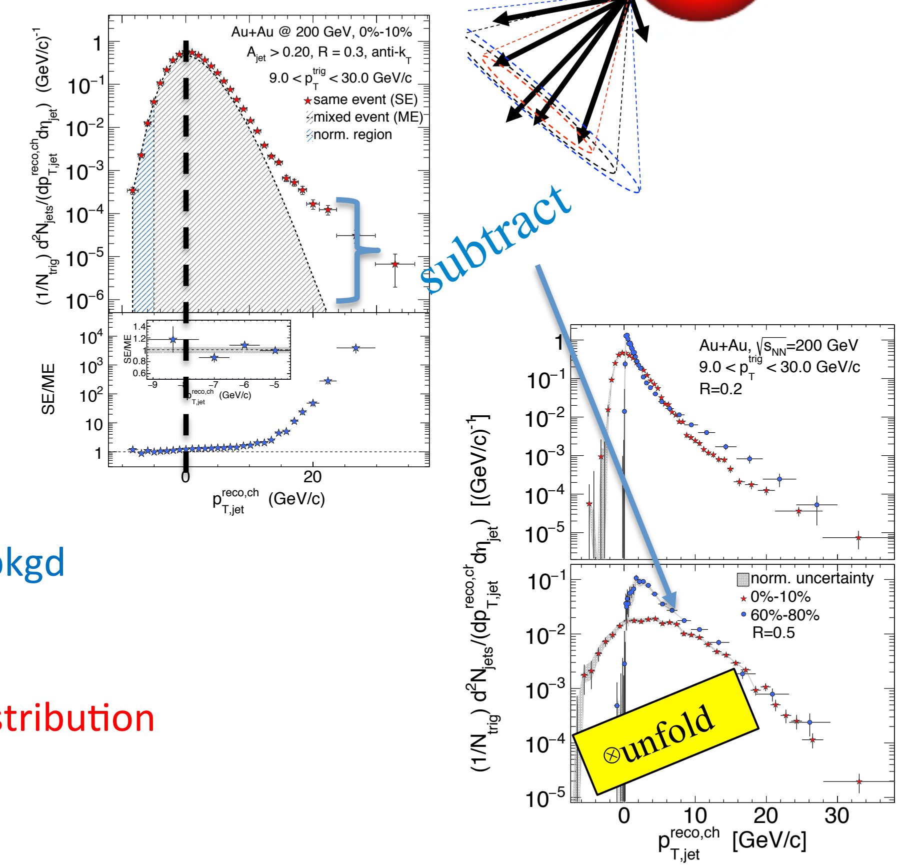
1. E-by-e adjustment of JES (estimated)

$$p_{\mathrm{T,jet}}^{\mathrm{reco,i}} = p_{\mathrm{T,jet}}^{\mathrm{raw,i}} - \rho A_{\mathrm{jet}}^{\mathrm{i}}$$

→ reduces fluctuations for unfolding

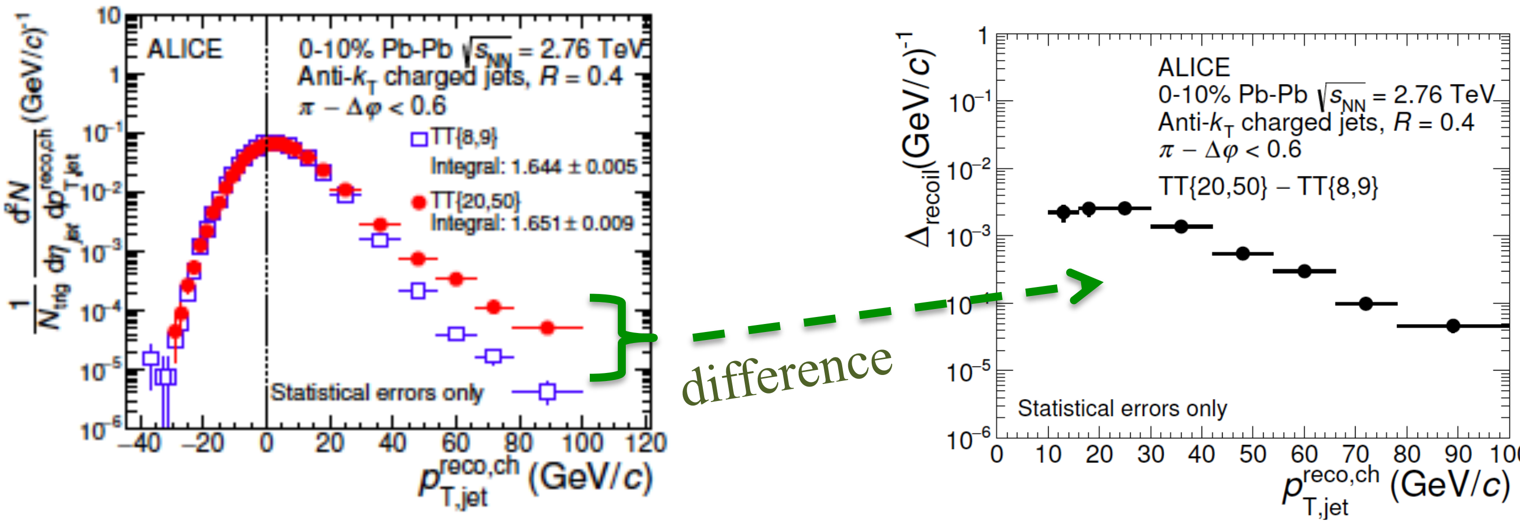
2. Subtract uncorrelated bkgd distribution
→ distribution of correlated yield, p_T is smeared by bkgd

3. Correct p_T-smearing via unfolding of difference distribution



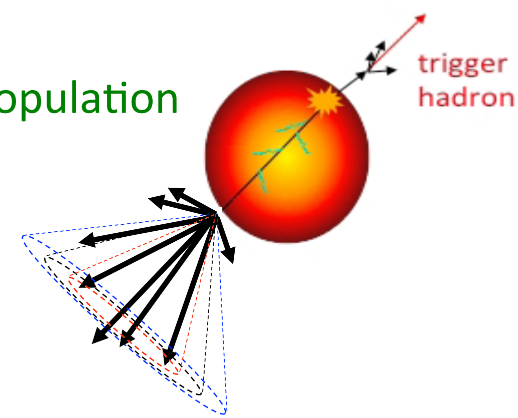
Isolate correlated yield: Δ_{Recoil}

$$\Delta_{Recoil} = \left[\frac{1}{N_{trig}}\frac{dN_{Jet}}{dp_T^{jet}}\right]_{20<p_T^{trig}<50} - c_{Ref}\cdot\left[\frac{1}{N_{trig}}\frac{dN_{Jet}}{dp_T^{jet}}\right]_{8<p_T^{trig}<9} \;;\; c_{Ref}\simeq 0.9-1.0$$



Experimental expression of QCD factorization

- Precise correction for uncorrelated yield w/o biasing signal jet population
- Robust for large R, low p_T^{jet}
- Unfold to particle level (instrumental effects, bkgd fluctuations)



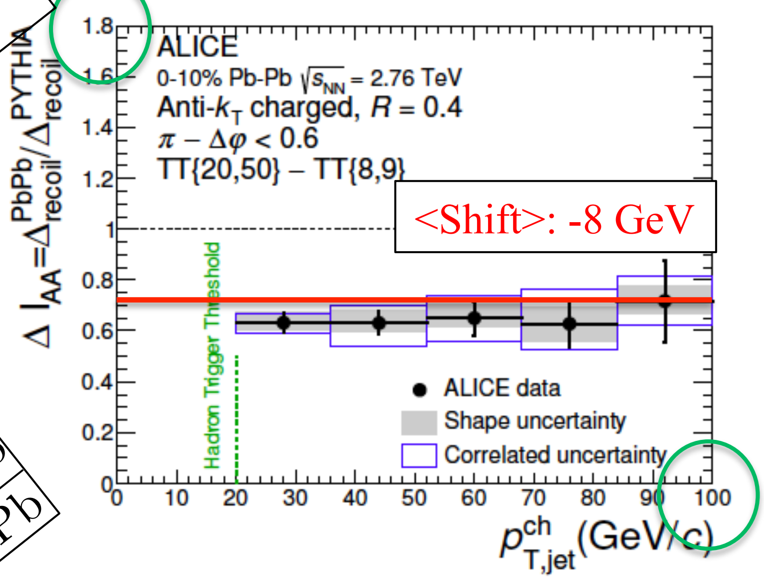
But there is a price:

- **D_{recoil} is not an absolute yield**
- Differential observable: evolution of recoil jet population with evolution in p_T^{trig}
- In the spirit of pQCD: precise characterization of how something changes (think: DGLAP)

Yield suppression → spectrum shift

ALICE, Phys.Lett. B783 (2018) 95

Central Pb + Pb
p + p

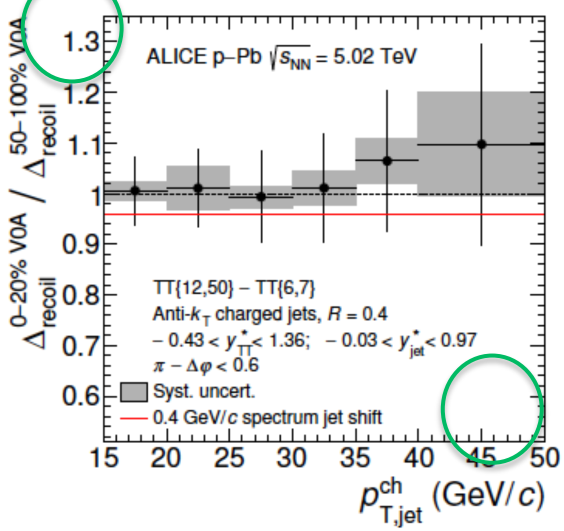


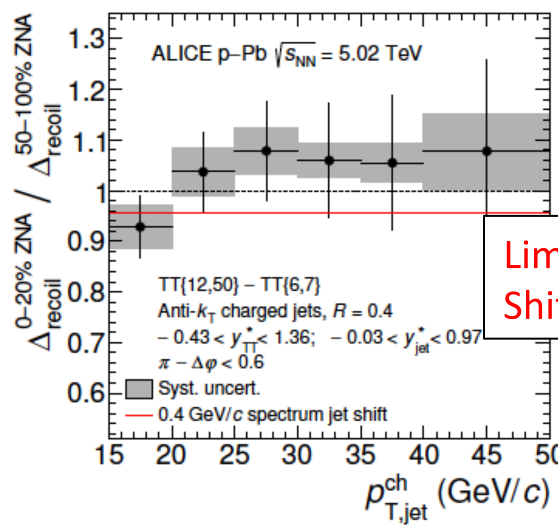
Limit on jet quenching in p+Pb:

Equate spectrum shift with population-averaged energy loss out-of-cone

p+Pb spectrum shift limit (90% CL) is factor 20 smaller than mean shift measured in central Pb+Pb

High EA p + Pb
Low EA p + Pb

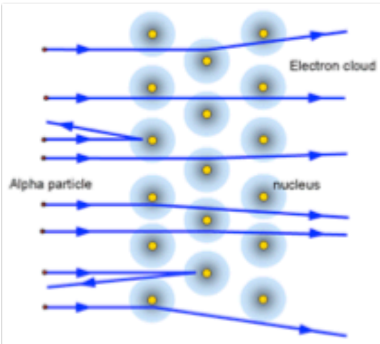




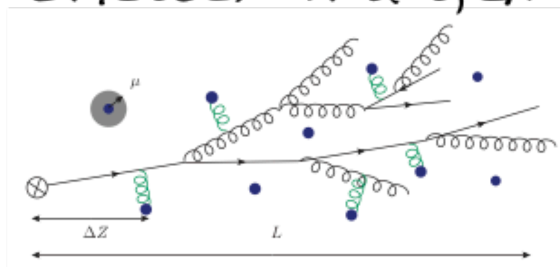
Limit on jet quenching in pA:
Shift limit (90% CL): -0.4 GeV

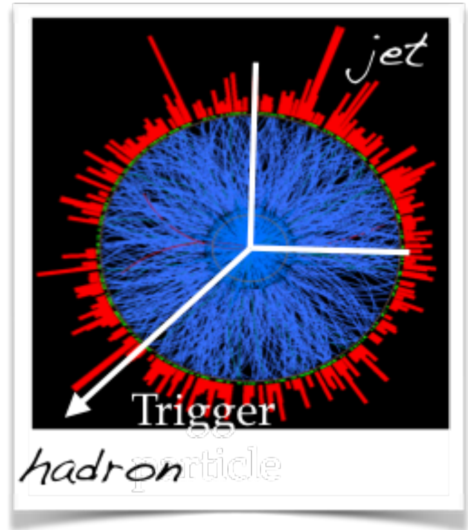
Probing structure of QGP

Jet quenching via hadron-jet coincidences

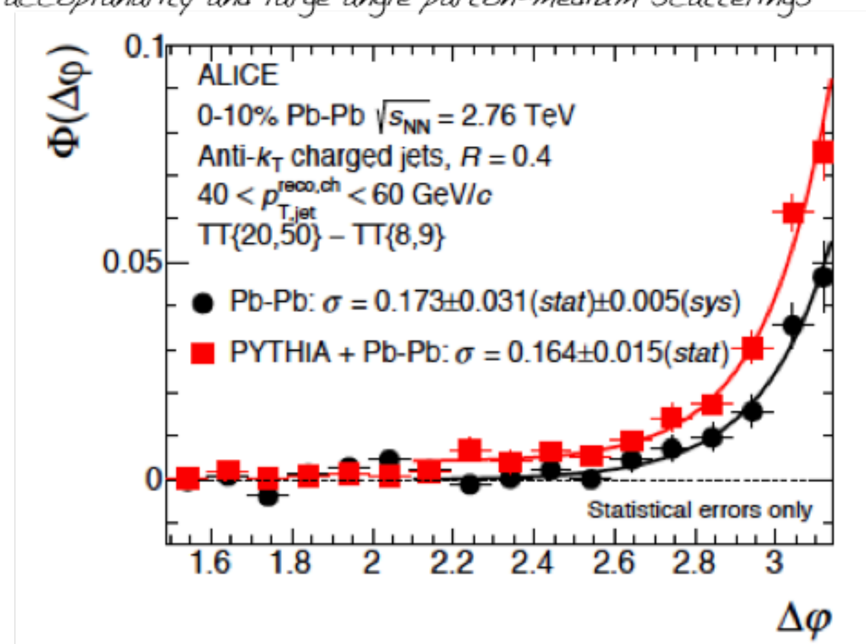


A picture in QCD:
Shower in a QGP





Ratio of azimuthal correlations is sensitive to medium induced accoplanarity and large angle parton-medium scatterings



Azimuthal correlations:

No medium induced accoplanarity (consistent with CMS and ATLAS)

Limit on rate of scatterings – sensitivity to medium homogenity – magnitude of the effect TBD – shower evolution vs. large angle scatterings

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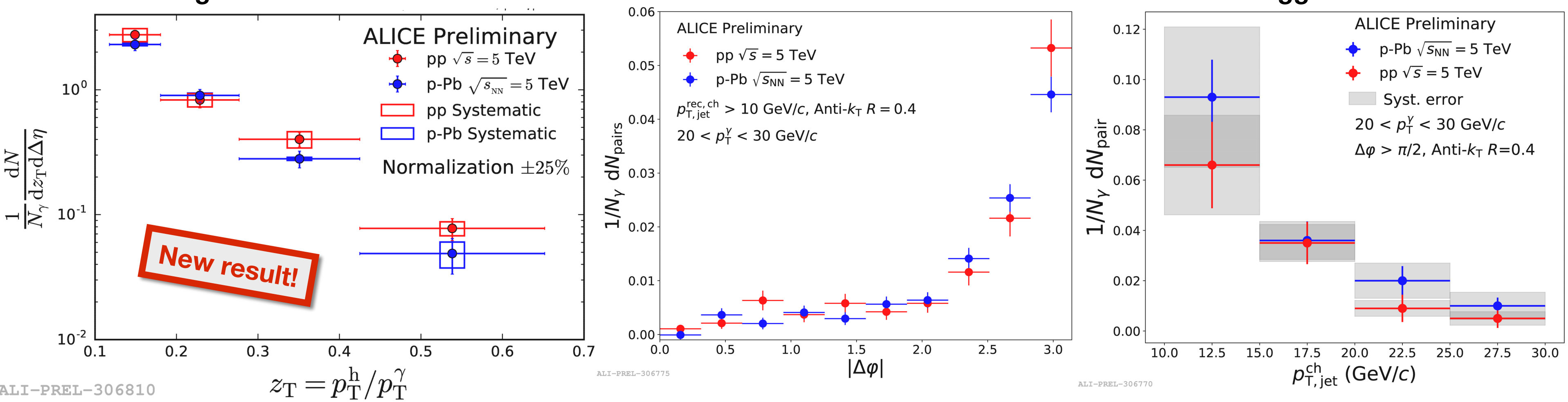
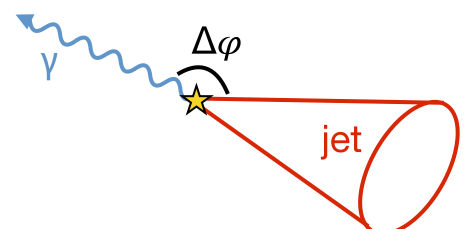
γ–Jet Correlations in pp and p–Pb at $\sqrt{s_{NN}}$ = 5 TeV

ALICE

Fragmentation Function | **Azimuthal Correlation** | **Per-trigger Jet Yield**



- Unique access to low-Q^2 and low-x_{Bj} region
- **As expected: no significant differences between pp and p–Pb in**
  - fragmentation function
  - angular correlations
  - jet yield
- Reference for Pb-Pb measurement



M. Arratia, Tue, 16h25

https://indico.cern.ch/event/634426/contributions/3003545/attachments/1725255/2786826/tdahms_20181001.pdf

Not shown:

hadron fragmentation within jets, radial jet shapes (non ALICE)…

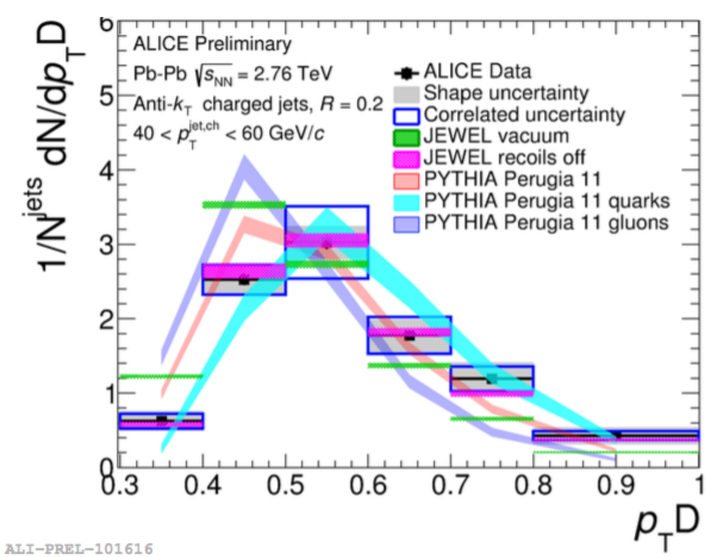
JET SUBSTRUCTURE

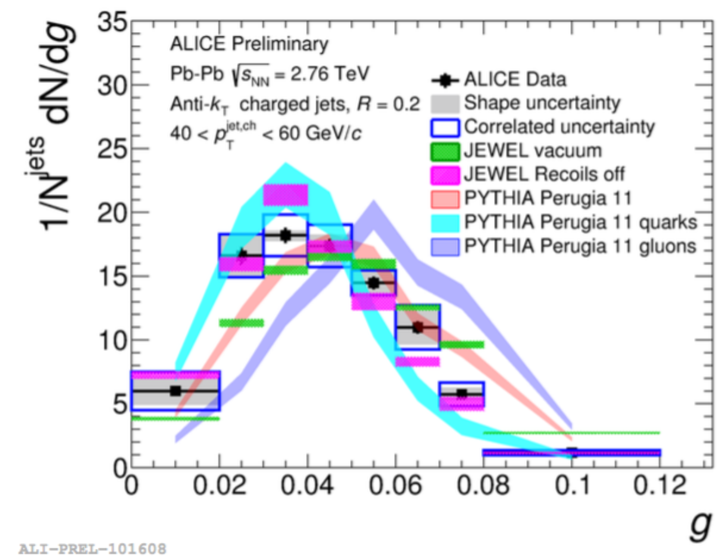
A broad strokes consensus:
MEDIUM vs. PROTON-PROTON: jets in AA more collimated;
more modifications at large angles / in soft particles

ALICE Jet structure - Older results…

$$p_{\mathrm{T}}D = \frac{\sqrt{\sum_i p_{\mathrm{T},i}^2}}{\sum_i p_{\mathrm{T},i}}$$

$$g = \sum_i \frac{p_T^i}{p_T^{jet}}|r_i|$$





Medium: shift towards larger values
=> Bias towards quark jets / harder fragmentation?

Medium: narrower pT weighted jet width
=> a la quark jets…

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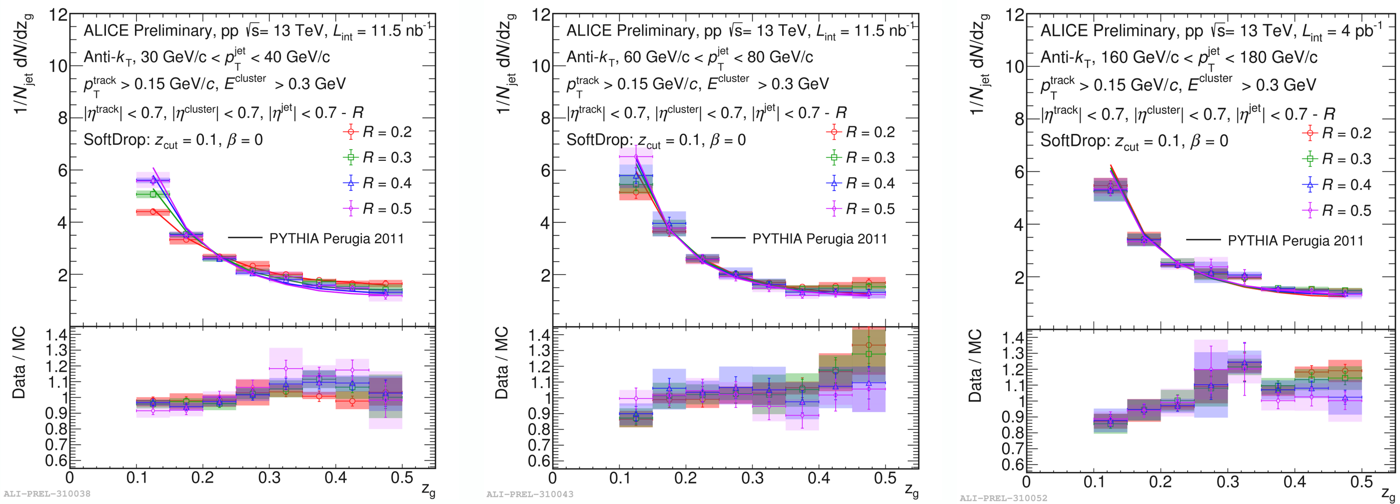
Full Jets : z_g Measurements in Differential p_T^{jet} and Jet Resolution Bins in pp

$30 < p_{T,jet} < 40$ GeV/c | $60 < p_{T,jet} < 80$ GeV/c | $160 < p_{T,jet} < 180$ GeV/c



New Result!

Talk by M. Fasel

- Larger data set at $\sqrt{s}$ = 13 TeV : L_{int} = 11.5 nb^{-1} (Min Bias) L_{int} = 4 pb^{-1} (Triggered)
- Extending data set further by measuring full jets: Charged tracking + EMCal towers.

  - Allows for a more **detailed probing of QCD**:
    Can help constrain non-perturbative effects?

https://indico.cern.ch/event/634426/contributions/3090534/attachments/1728180/2792125/Hard_Probes_Nima_Zardoshti.pdf

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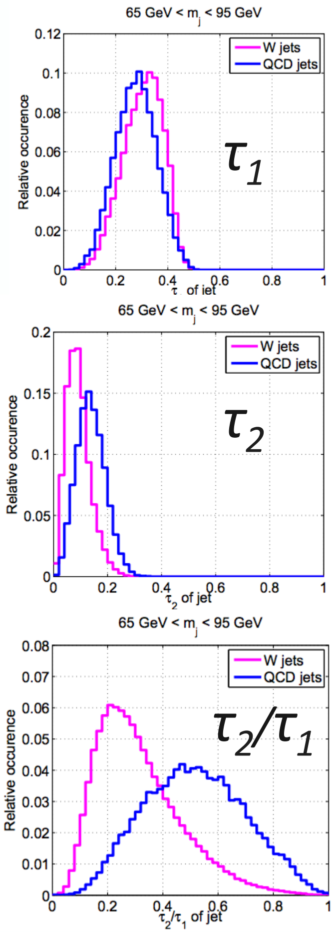
W jets

QCD jets



[Thaler et al, JHEP 1103 (2011) 015]

N-subjettiness

- The N-subjettiness, τ_N, jet shape is a measure of how *N*-pronged a jet's substructure is.
- τ_N is calculated relative to the *N* returned axes.
- Initially developed to tag jets from Higgs decays such as Higgs -> W^+W^-.

$$\tau_N = \frac{\sum_{i=1} p_{T,i} Min(\Delta R_{i,1}, \Delta R_{i,2}, \ldots, \Delta R_{i,N})}{R_0 \sum_{i=1} p_{T,i}}$$

$\Delta R_{i,j}$ -> η-φ distance between track *i* and subjet *j*

$p_{T,i}$ -> p_T of i^{th} jet constituent

R_0 : Jet resolution parameter

- τ_N -> 0 Jet has *N* or fewer well defined cores
- τ_N -> 1 Jet has at least *N*+1 cores
- τ_N/τ_{N-1} -> 0 Jet has *N* cores
- τ_2/τ_1 -> 0 Jet is two-pronged

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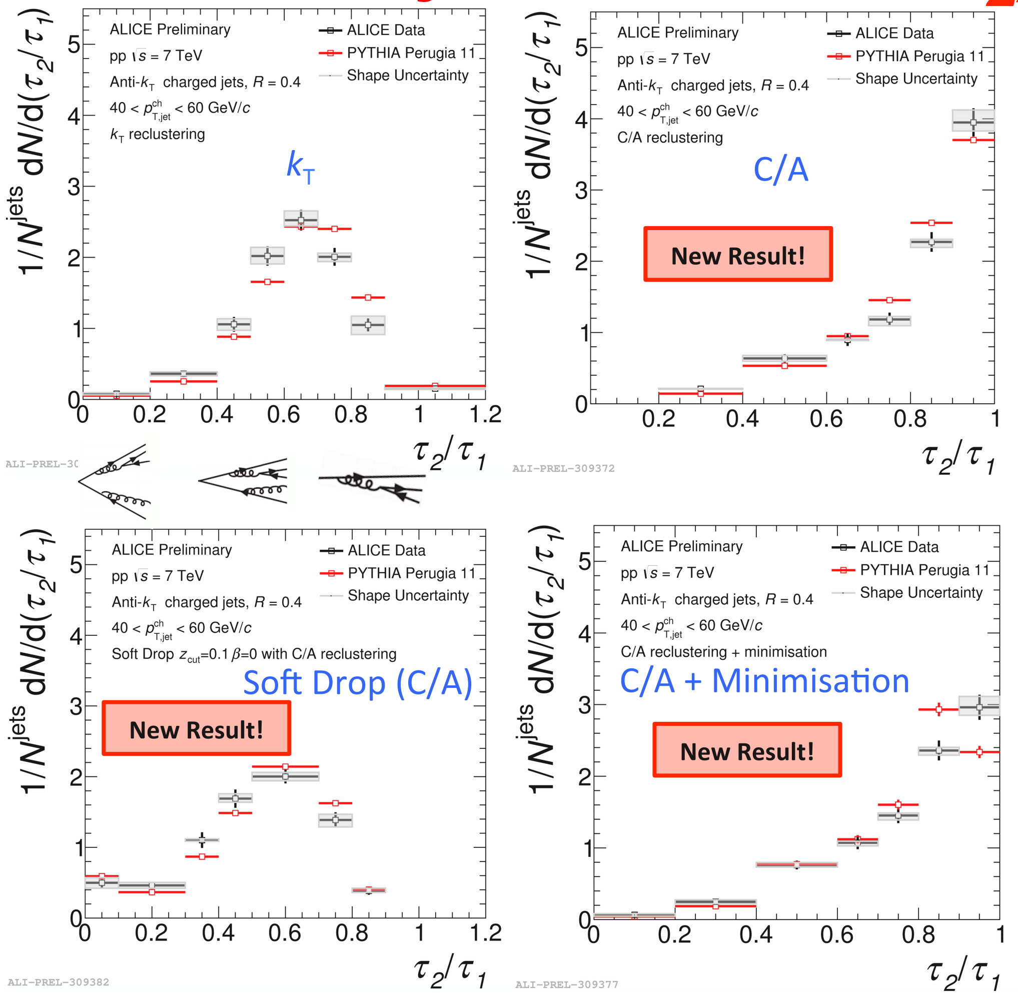
Fully Corrected τ_2/τ_1 Shape in pp



- Alignment of radiation relative to returned axes (τ_2/τ_1) **reasonably well** described by PYTHIA.
- Additional information compared to Lund map: subleading subjet.
- Subleading C/A axis follows soft radiation : jet not expected to be two-pronged relative to this axis.
- The Soft Drop groomer increases the p_T sensitivity of the subleading axis.

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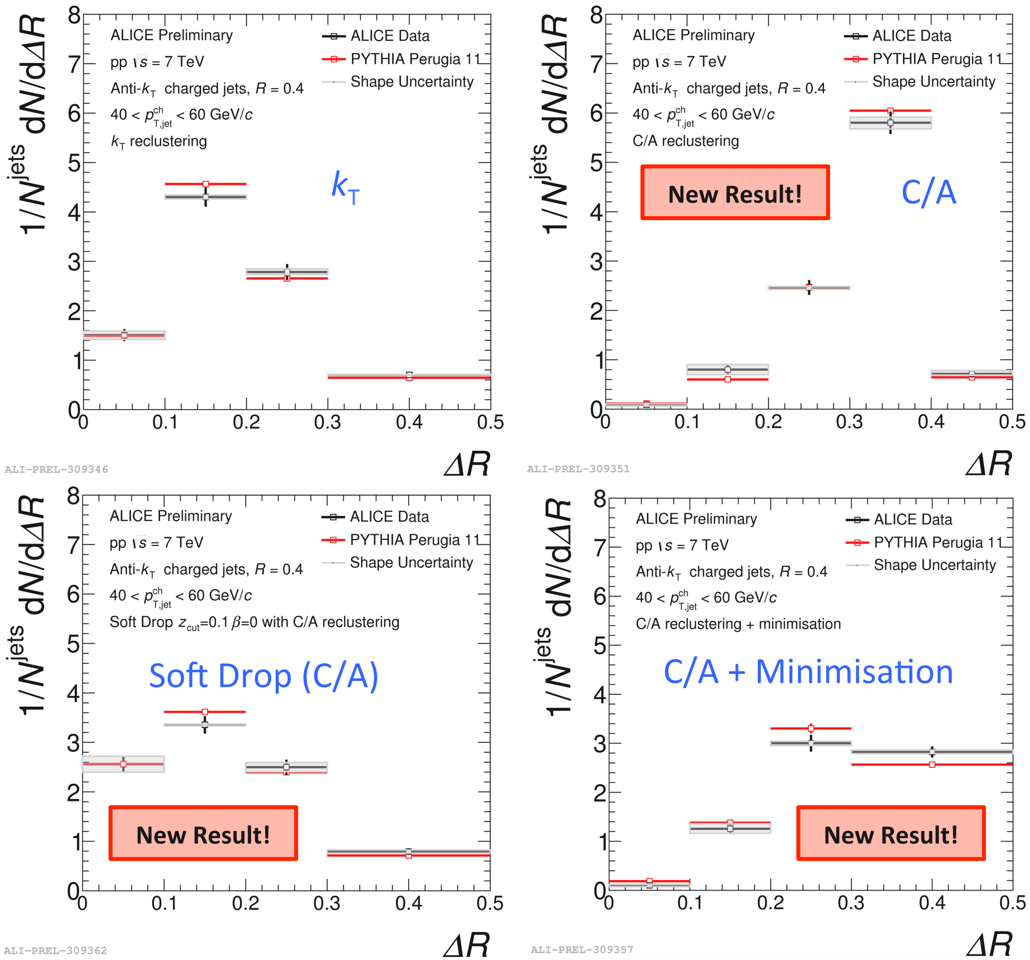
Fully Corrected *ΔR* Shape in pp



- Clean observable describing the distance between different types of splittings in the jet.
- Returned axes (*ΔR*) **well described** by PYTHIA.
- C/A : soft scale acts at large distances from the jet core.
- k_T and Soft Drop: hard splittings primarily in jet core.

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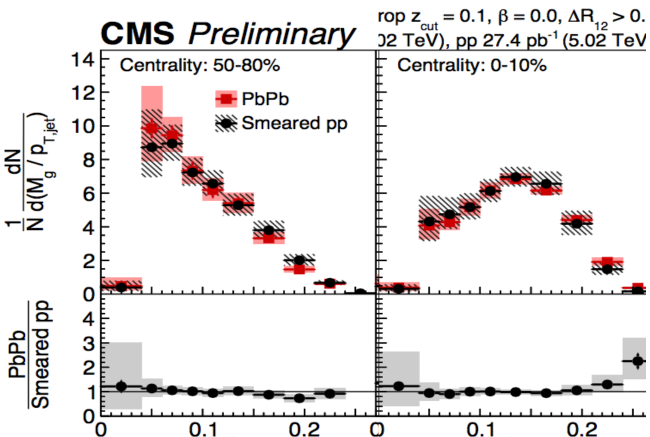
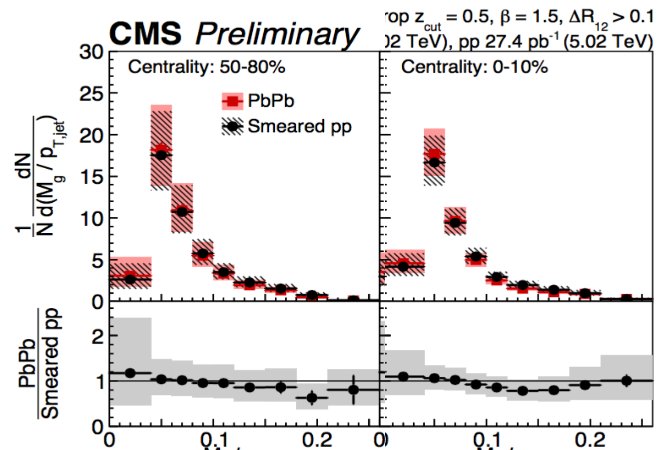
Jet Mass - LHC



Z_{cut}=0.1 β=0

Grooming Independent of angular separation



Z_{cut}=0.5 β=1.5

Grooming for larger angular separation

Groomed:
- No modification to the jet "core"
- Deviations for large angles

NOT Groomed:
- Little to none changes to the mass

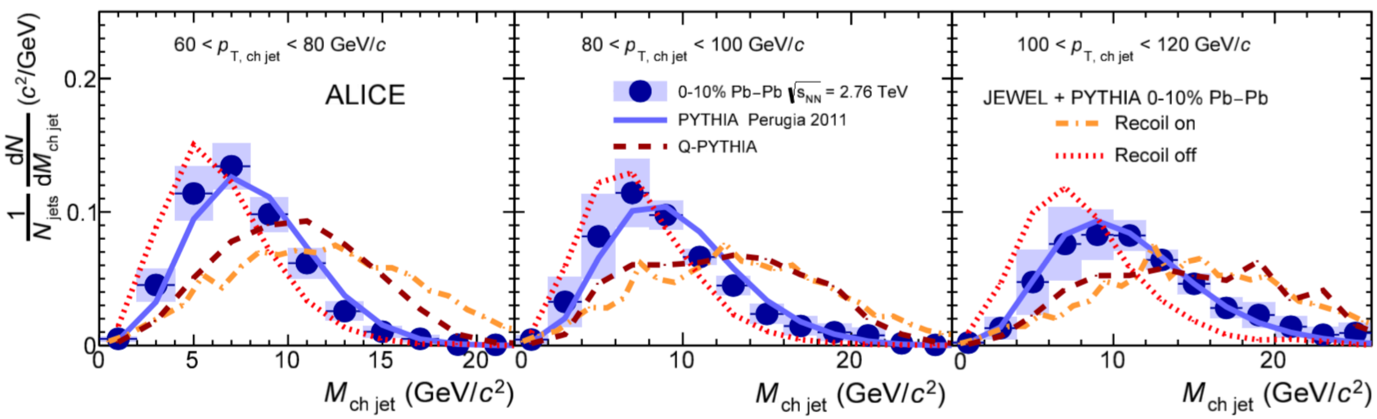
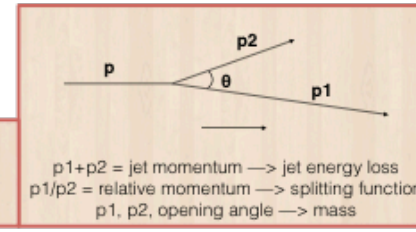


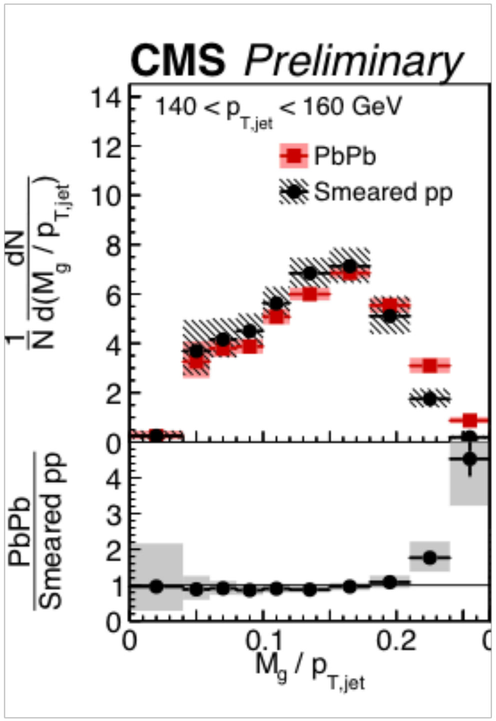
Fig. 10: Fully-corrected jet mass distribution for anti-k_T jets with $R = 0.4$ in the 10% most central Pb–Pb collisions compared to PYTHIA with tune Perugia 2011 and predictions from the jet quenching event generators (JEWEL and Q-PYTHIA). Statistical uncertainties are not shown for the model calculations.

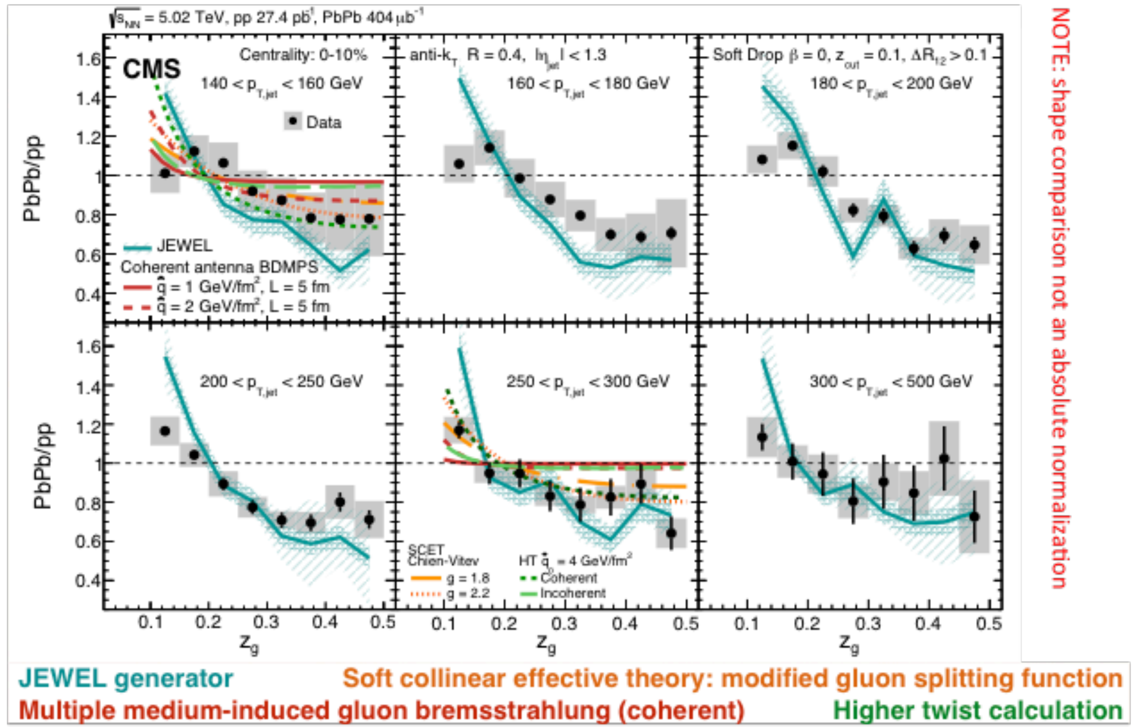
Splitting function in AA

Modifications at large M/p_T for z_{cut}=0.1 & β=0;
No modifications for z_{cut}=0.5 & β=1.5 (jet core)

$$z_g \equiv \frac{\min(p_1,p_2)}{p_1+p_2} > z_{cut}\left(\frac{\Delta R}{R_0}\right)^{\beta}$$

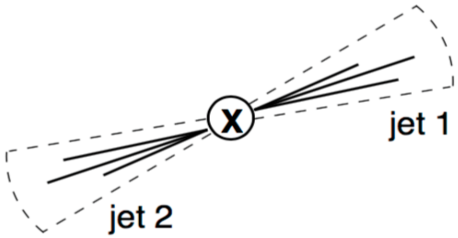






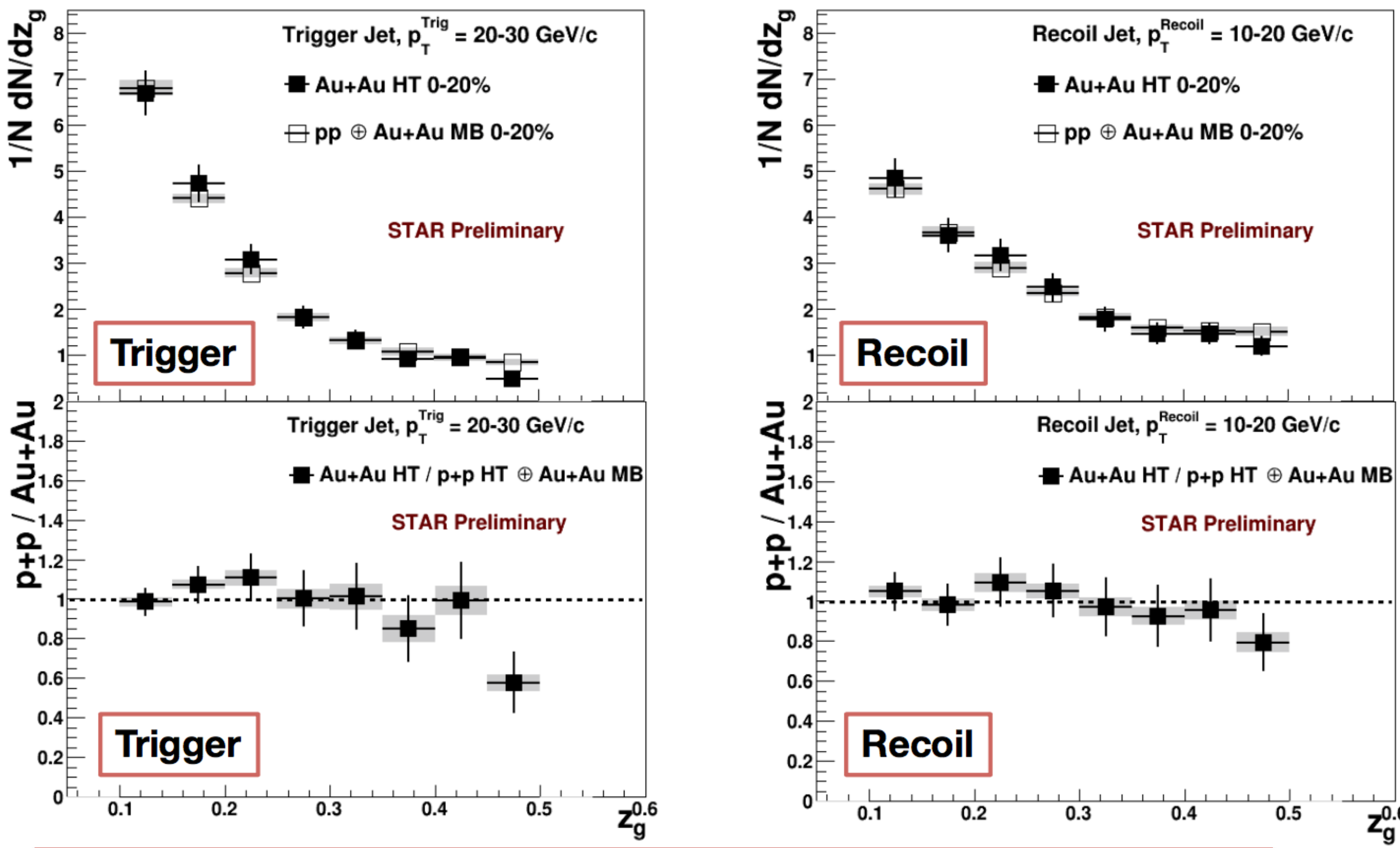
Small modifications to the jet core (no mods. at RHIC)

Distribution of particles to large angles (inducing large jet masses) - increase small z_g [deplete large z_g]



Utilizing Jet Grooming at RHIC with di-jets

Hard Core –Dijet Selection



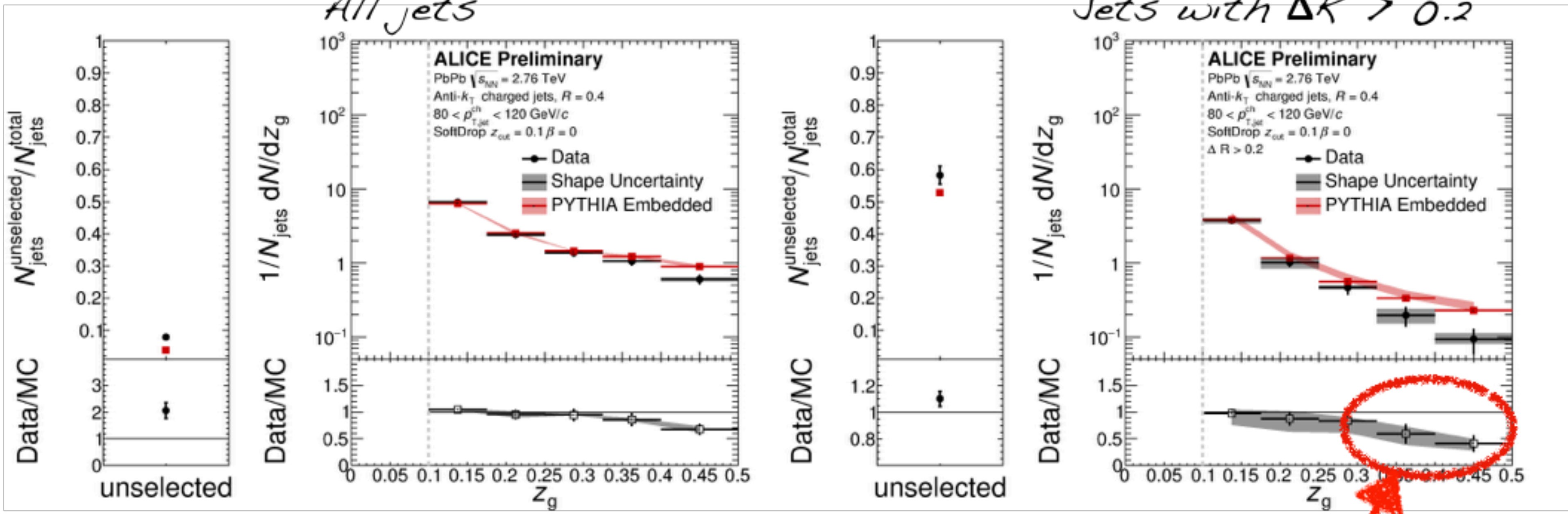
No observable difference in AuAu in comparison to pp

Subtleties: difference (to LHC) in jet selection – a hard fragmentation selection

Subjets - ALICE - absolute normalization

All jets

Jets with ΔR > 0.2



Suppression for large zg (symmetric splittings)

More "unselected" jets in AA;

also increase for larger separation of subjets

Suppression of zg for larger subjet separation

<=> subjets loose energy indepentently

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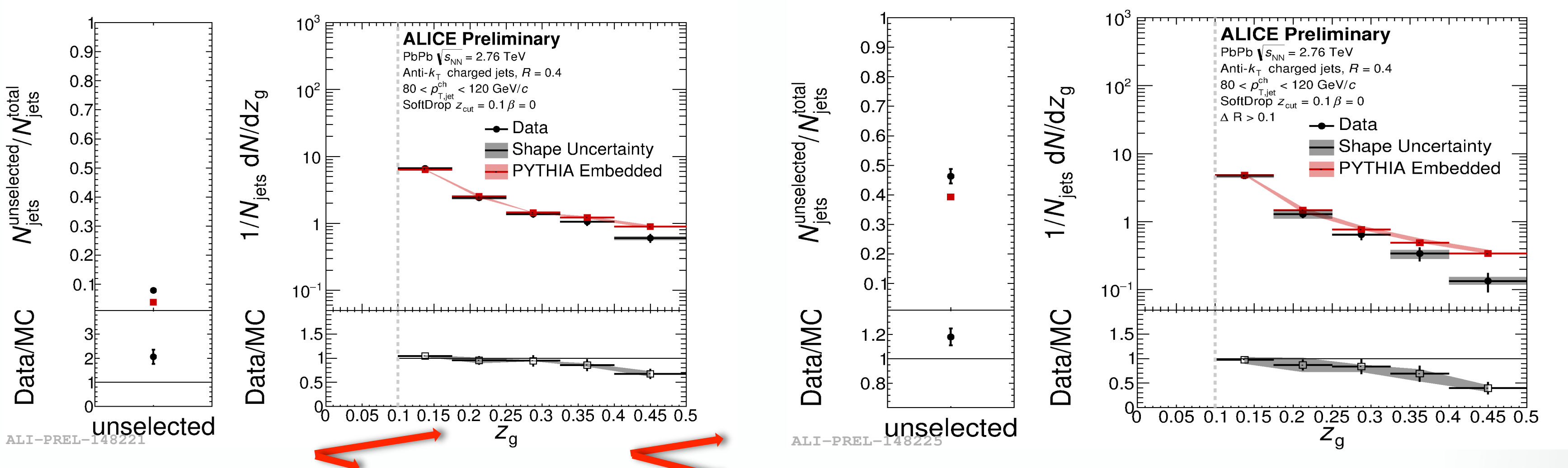
Inclusive z_g Shape in Pb-Pb

No ΔR cut $\qquad\qquad$ ΔR > 0.1 cut



Asymmetric splittings $\qquad$ Symmetric splittings

- **No net enhancement** of splittings passing the Soft Drop criteria observed at ΔR > 0.1 .
- ~ 10 % **reduction** in the number of jets with a splitting that passes Soft Drop.

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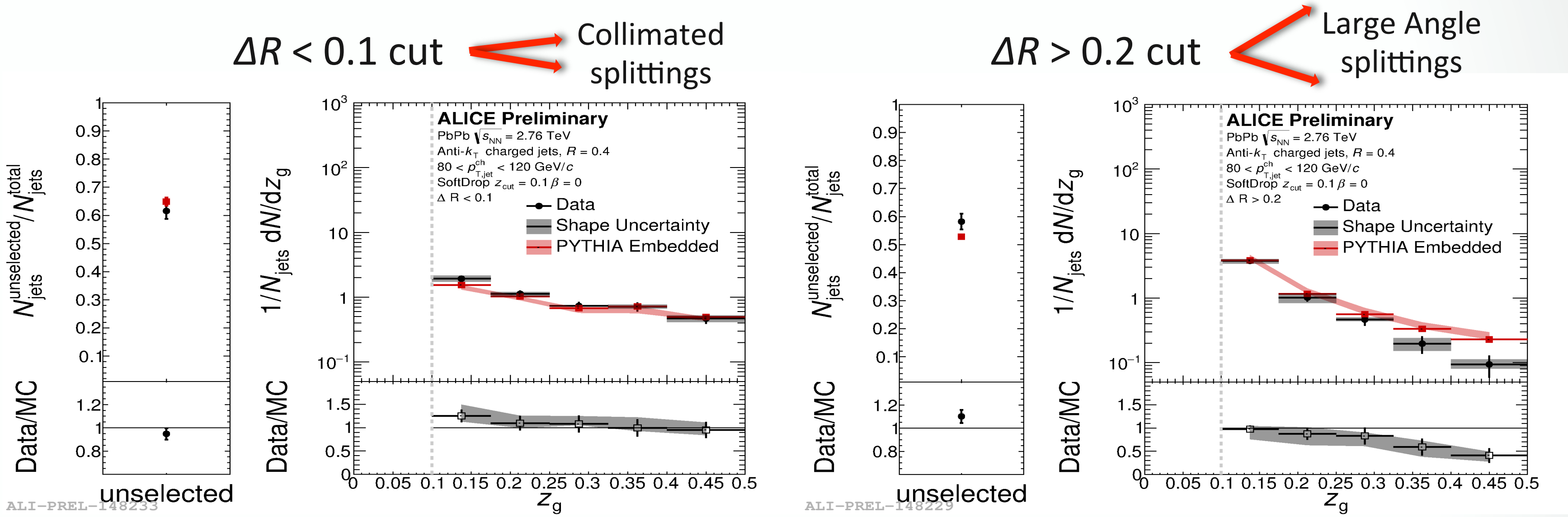
Inclusive z_g Shape in Pb-Pb



- **Collimated** splittings **enhanced**.
- **Large angle** splittings **suppressed**.
- No low z_g enhancement observed at large angles.

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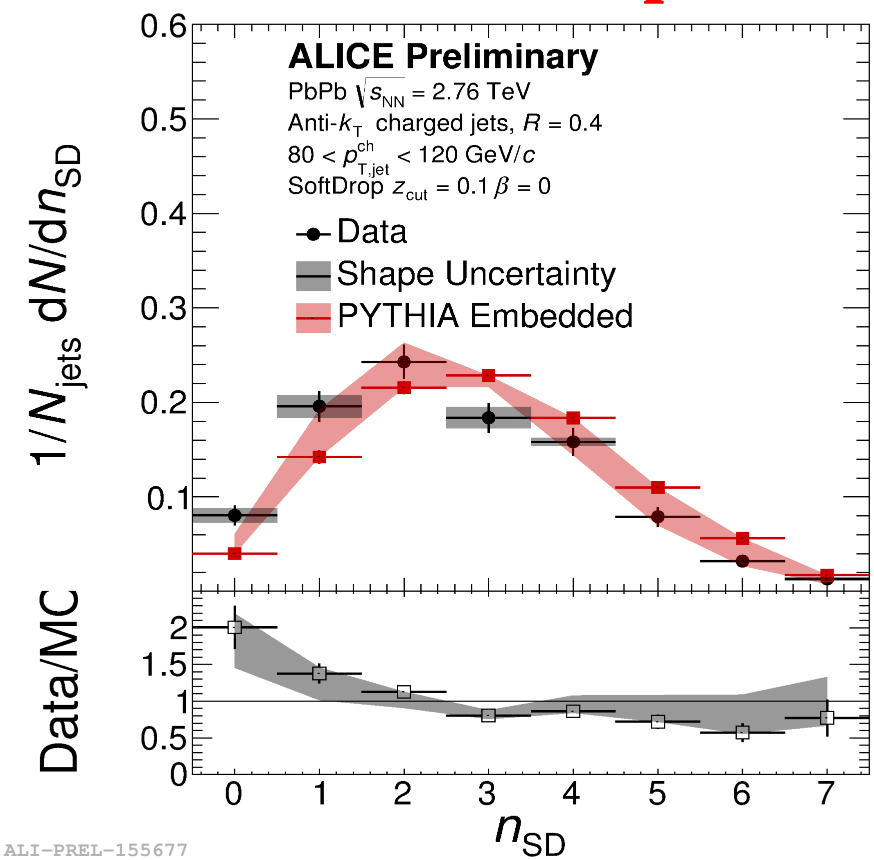
Number of Splittings in the Jet that Satisfying the Soft Drop Condition in Pb-Pb



- **No enhancement** in number of splittings passing Soft Drop.
- Enhancement in number of untagged jets (first bin).
- In contrast to expected correlated medium response or coherent collinear emissions.

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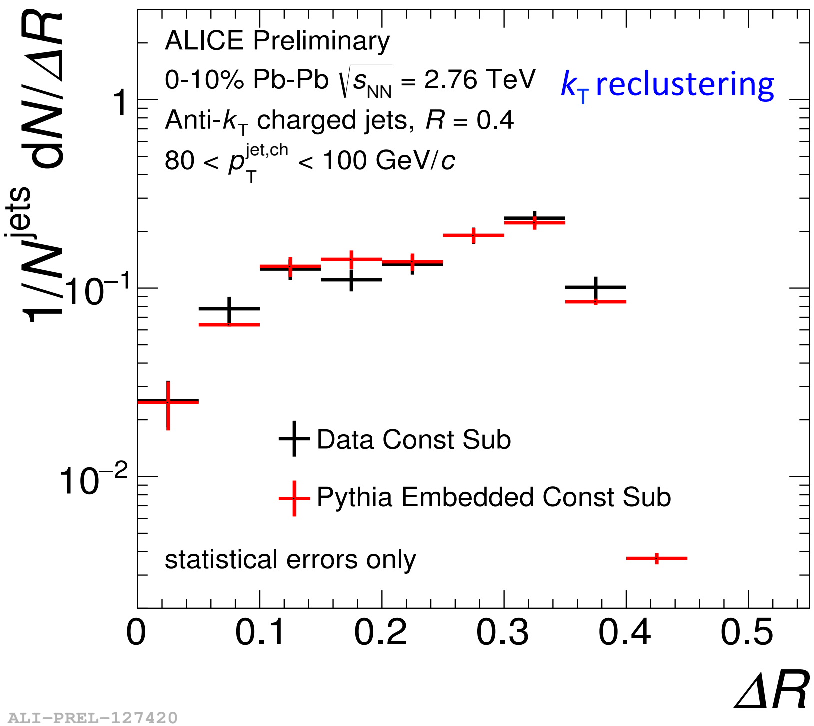
Inclusive *ΔR* Shape in Pb-Pb



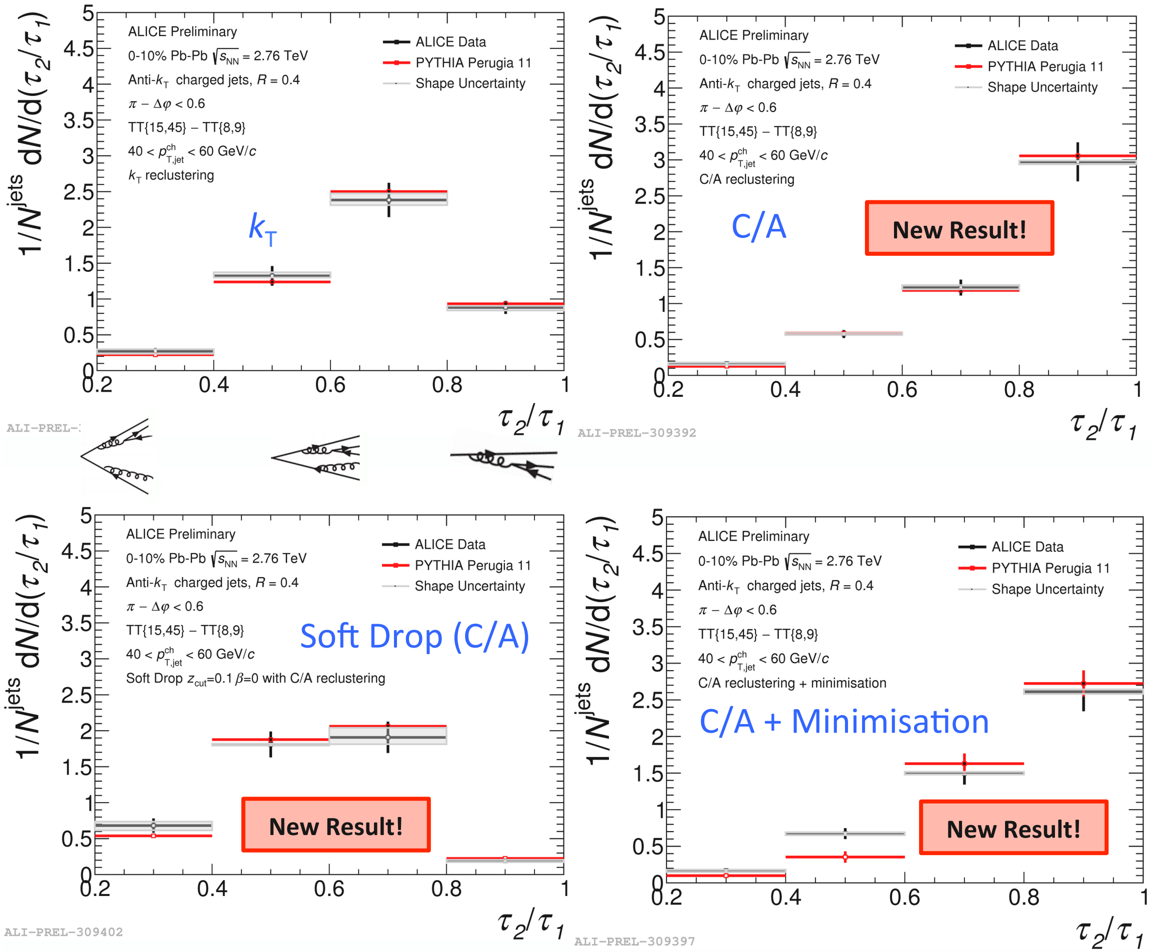
- **No modification** observed within statistical limits.
- Suppression of large *ΔR* would be expected for "resolved" jets.
- Enhancement of low *ΔR* would be expected with medium induced semi-hard radiation.
- Possible modifications can be smeared by the **fake splittings** → reduction of signal to background ratio.
- Need to **reject fake splittings** to uncover potential physics signal.

https://indico.cern.ch/event/634426/contributions/3090534/attachments/1728180/2792125/Hard_Probes_Nima_Zardoshti.pdf

Hard Probes conference October 2018

https://indico.cern.ch/event/634426/

Fully Corrected τ_2/τ_1 Recoil Shape in Pb-Pb



- Alignment of radiation relative to returned axes is similar in Pb-Pb and PYTHIA.
- **No quenching modifications** observed in a variety of different types of splittings.
- k_T and Soft Drop :
  - A shift to larger values expected if jets are "resolved".
  - A shift to lower values expected with medium induced semi-hard radiation.

https://indico.cern.ch/event/634426/contributions/3090534/attachments/1728180/2792125/Hard_Probes_Nima_Zardoshti.pdf

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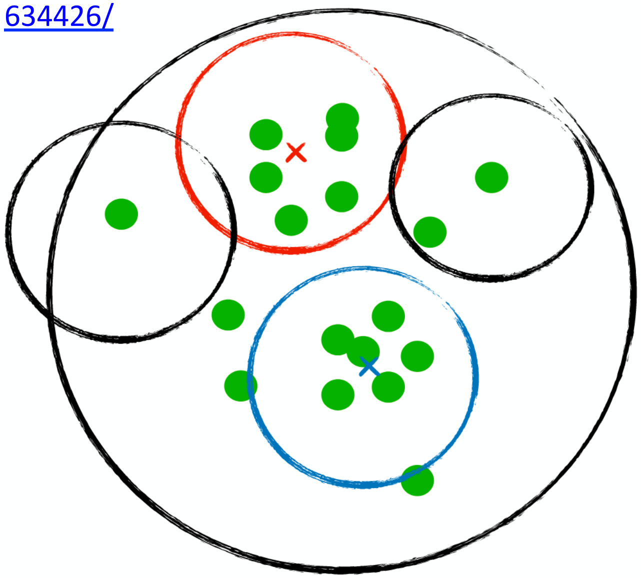
ALICE substructure summary

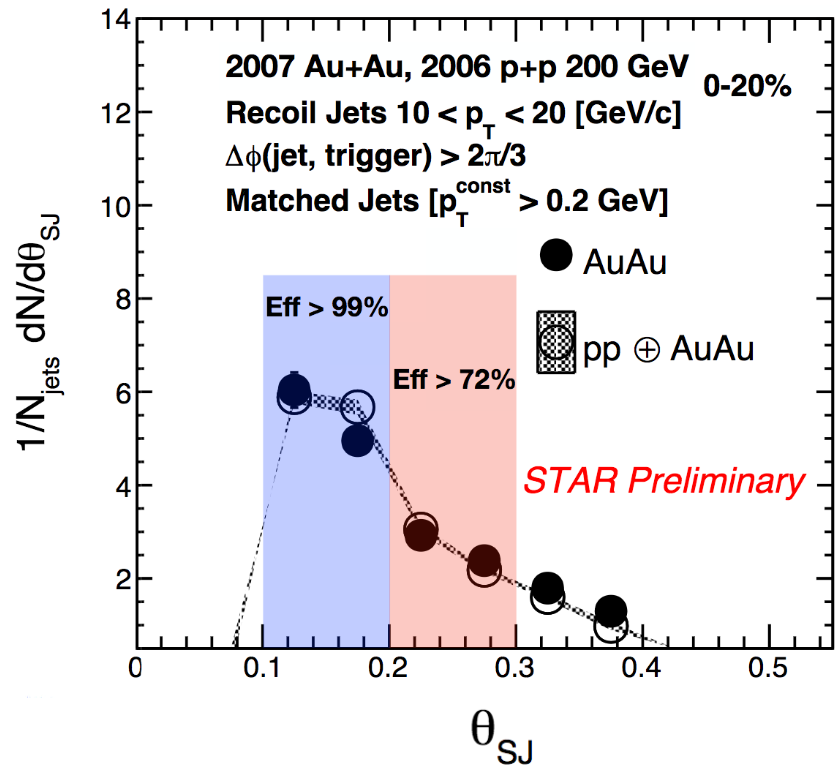
- Reclustering algorithms varied to probe **different scales** in the splittings.
- **No modification** of the the **two-pronged substructure** of jets observed in the medium.
- A **significant modification** of the z_g **distribution** observed in the medium.
- **Large angle splittings** appear **suppressed** in data.
- The **number of hard splittings** are **not enhanced** in data.
- These measurements represent an ongoing effort to systematically investigate jet substructure at ALICE.

https://indico.cern.ch/event/634426/contributions/3090534/attachments/1728180/2792125/Hard_Probes_Nima_Zardoshti.pdf

Jet angular structure with subjets
New from STAR at RHIC

Hard Probes conference
October 2018
https://indico.cern.ch/event/634426/





- Cluster all constituents into anti-k_T jets of smaller radii (R = 0.1)
- Choose leading and subleading subjets
- $z_g = p_T^{SubleadingSJ}/(p_T^{LeadingSJ} + p_T^{SubleadingSJ})$
- $\theta_{SJ} = \Delta R$(LeadingSJ axis, SubLeading SJ axis)

- Interaction of the jet with medium could depend on the jet's angular scale

- Look separately at jets with different θ_{SJ}

https://indico.cern.ch/event/634426/contributions/3003555/attachments/1725349/2786866/HarProbes2018_ver4f.pdf

Majumder, A and Putschke, J Phys Rev C 93 054909
Mehtar-Tani, Y and Tywoniuk, K arXiv:1707.07361

See also: https://arxiv.org/abs/1710.07607

Jet angular structure with subjets New from STAR at RHIC

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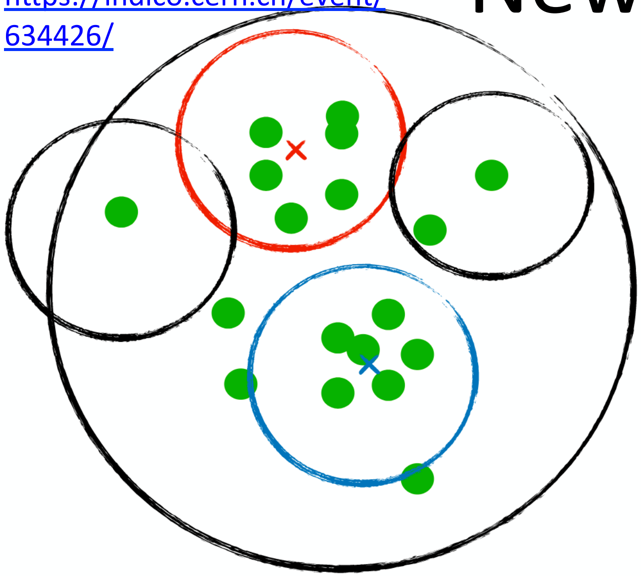
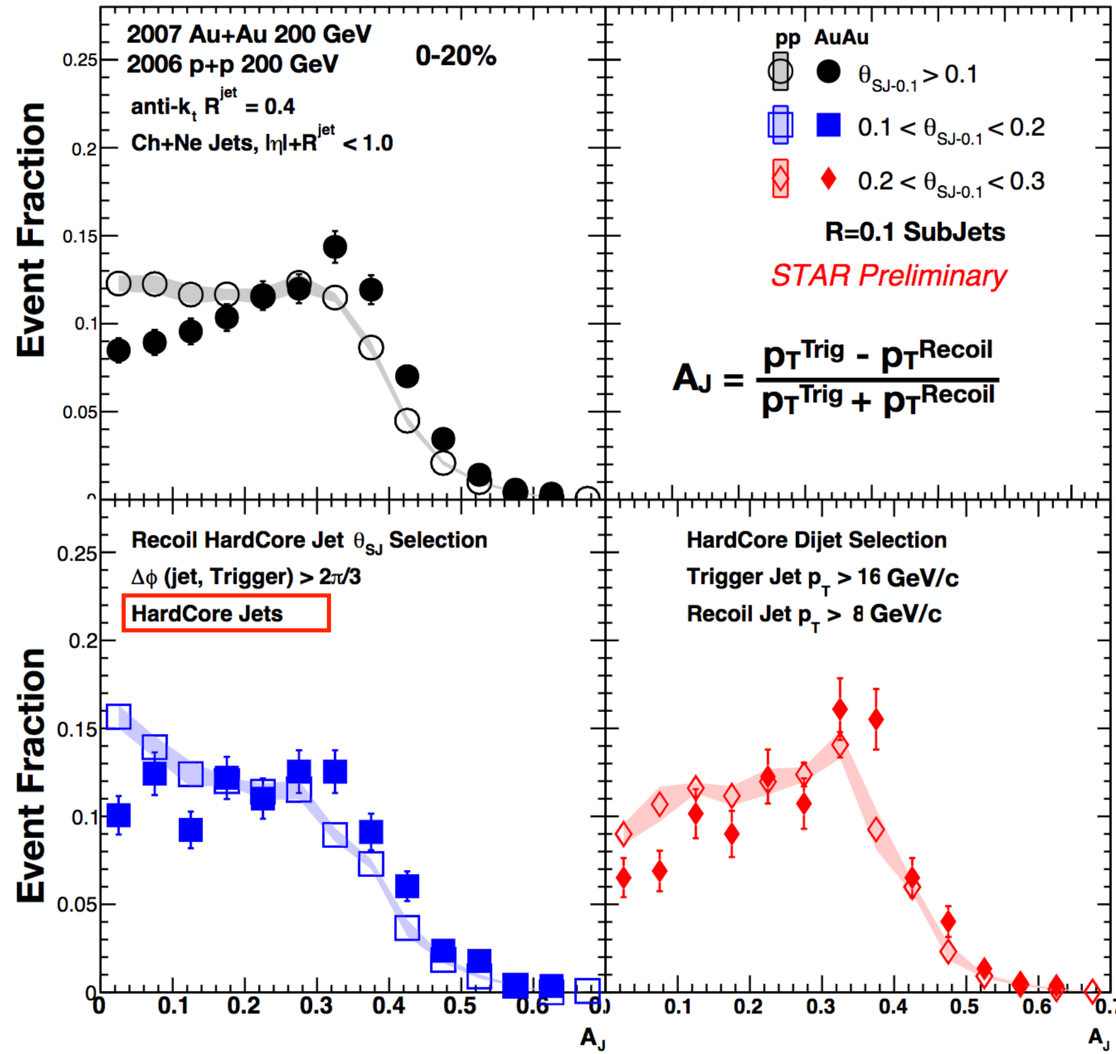


$\theta_{SJ} = \Delta R$(LeadingSJ axis, SubLeading SJ axis)

- ***Hard-core jets*** unbalanced for all θ_{SJ} selections
- No large difference among different θ_{SJ} selections



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Jet angular structure with subjets
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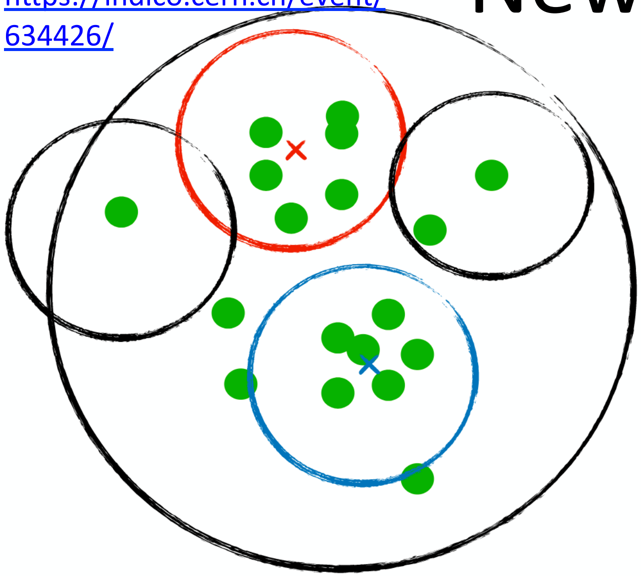
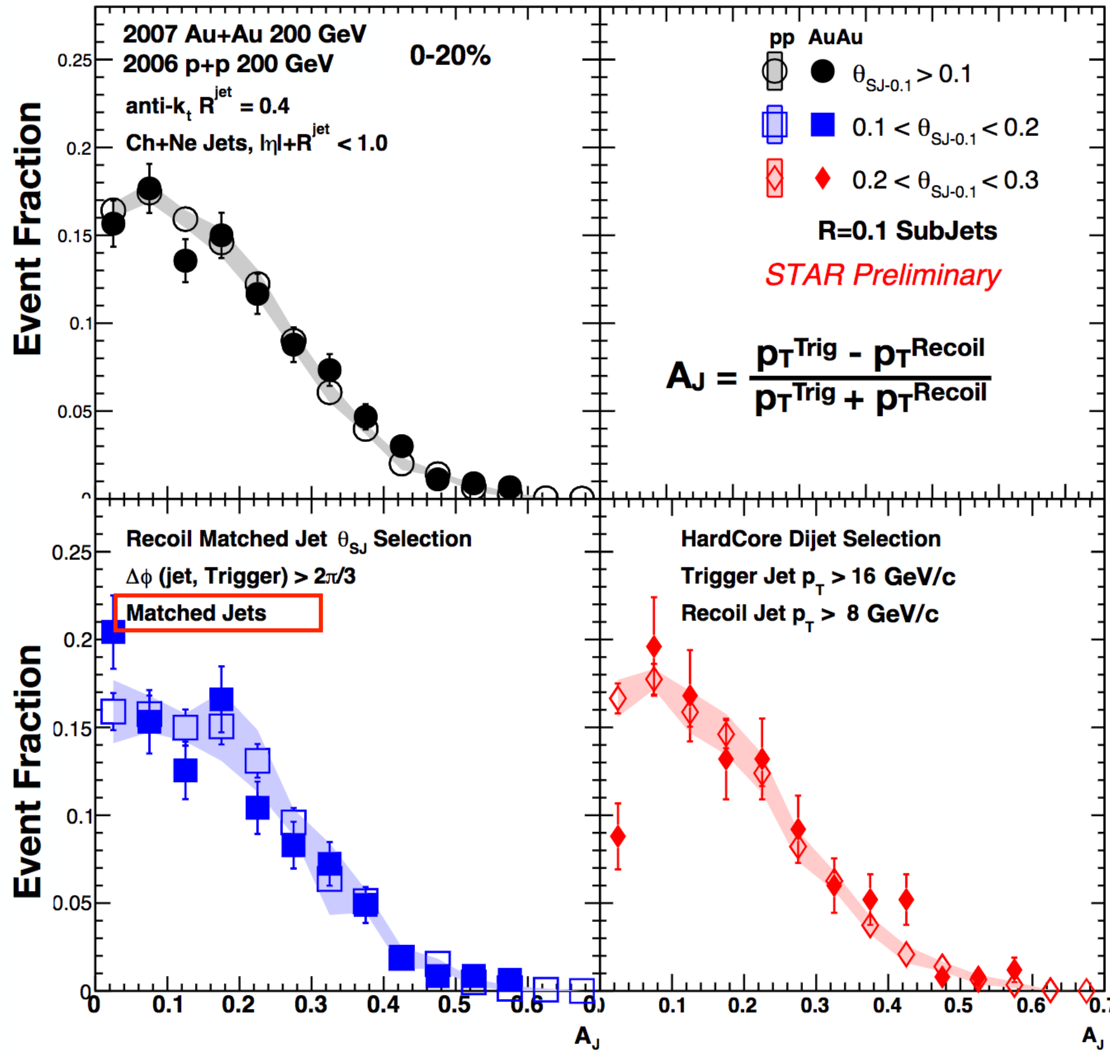
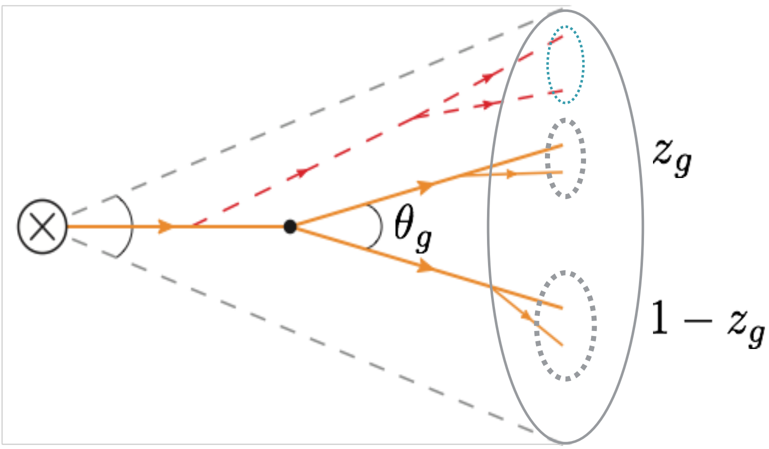




$\theta_{SJ} = \Delta R$(LeadingSJ axis, SubLeading SJ axis)

- ***Matched jets*** (R = 0.4) recover balance (w.r.t p+p) for all θ_{SJ} selections

https://indico.cern.ch/event/634426/contributions/3003555/attachments/1725349/2786866/HarProbes2018_ver4f.pdf

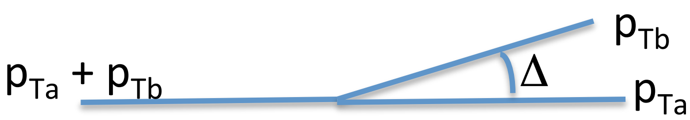


Modifications of jet structure due to **jet**-medium interactions

… ON THE FUTURE OF JET QUENCHING STUDIES

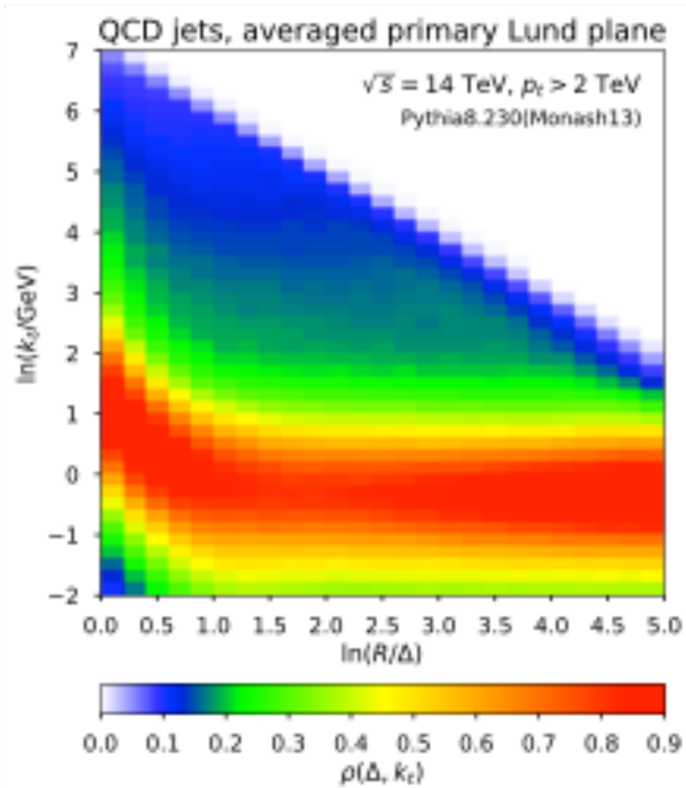
Jet Lund diagram

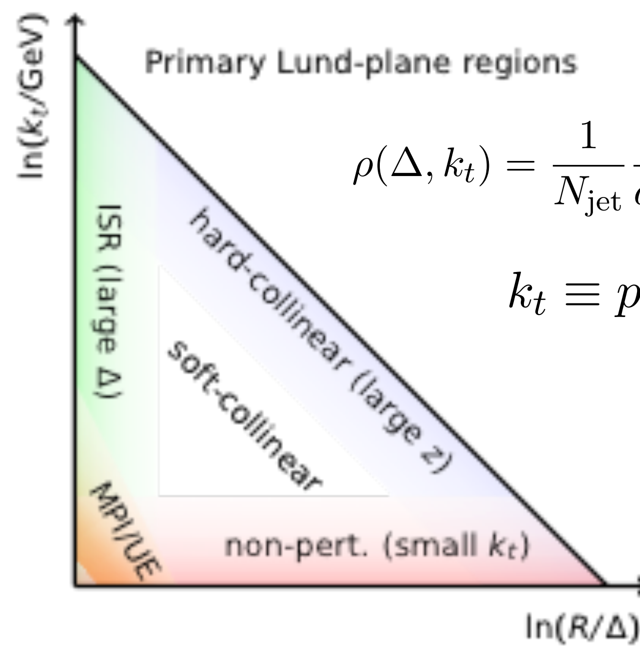
$$p_{T,a} > p_{T,b},\ \kappa = \frac{p_{T,b}}{p_{T,a}+p_{T,b}}\Delta_{ab}$$



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

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





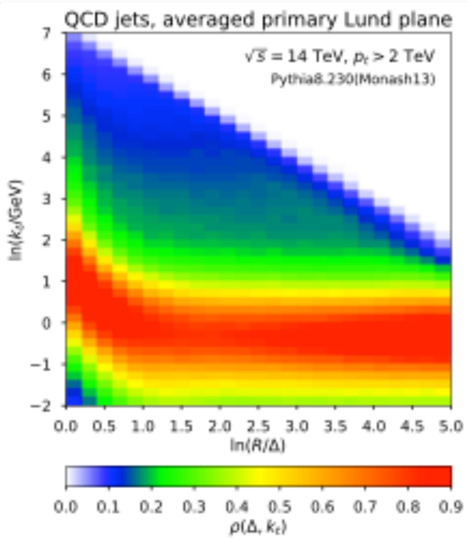
$$\rho(\Delta,k_t) = \frac{1}{N_{\rm jet}}\frac{dn_{\rm emission}}{d\ln k_t\, d\ln 1/\Delta}$$

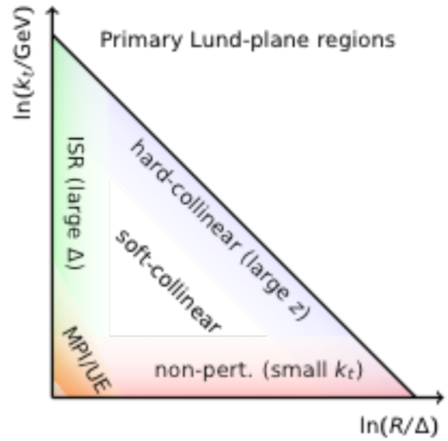
$$k_t \equiv p_{tb}\Delta_{ab},$$

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)

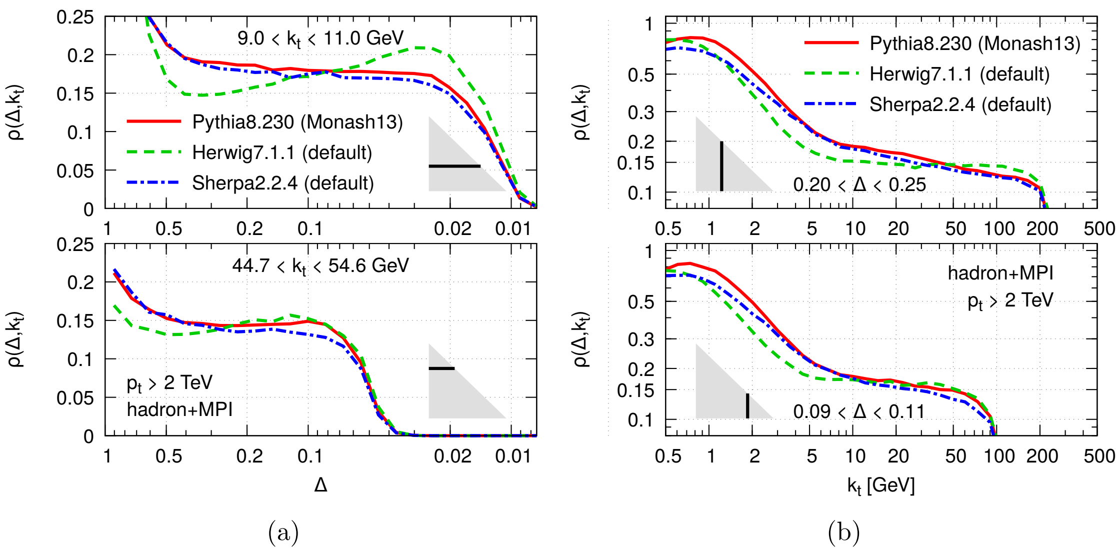
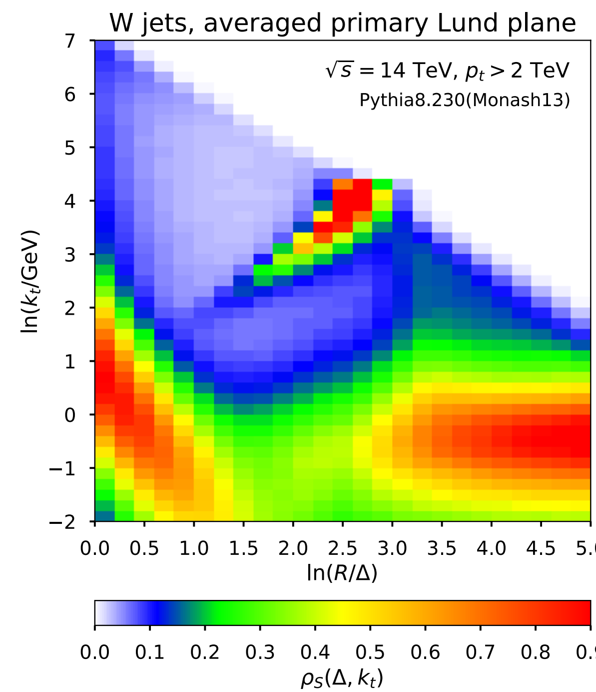


Figure 3: Emission density along slices of the Lund plane, at fixed k_t (top) and Δ (bottom), comparing three event generators.



Jet Lund diagram

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

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

Interesting tool for jet quenching…

arXiv: 1710.07607 [hep-ph]

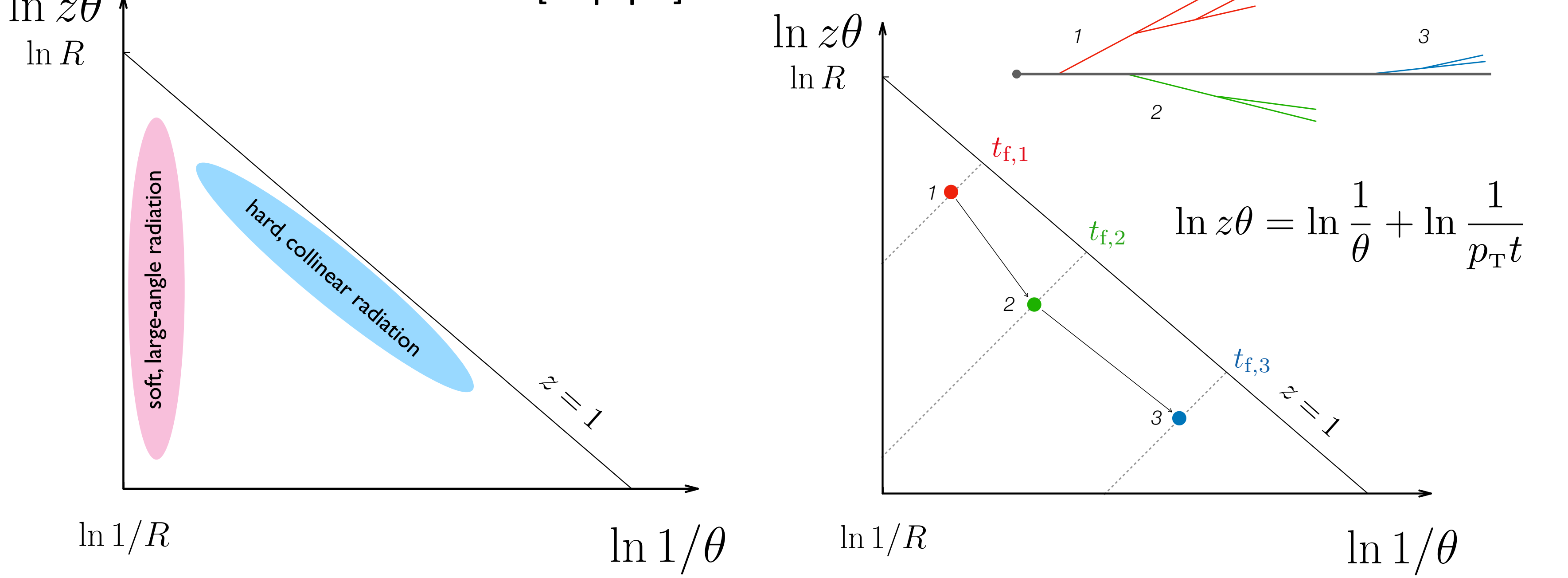


Figure 1: Left: The kinematical Lund plane spanned by $\ln 1/\theta$ and $\ln z\theta$ for jets with opening angle R, see text for details. Right: clustering history with the formation time of *primary* emissions in the kinematical Lund plane.

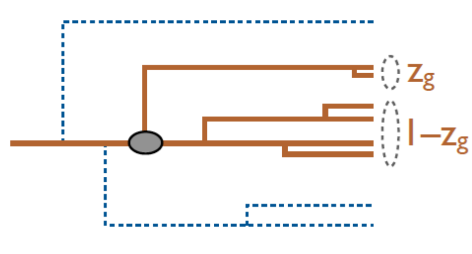
Note: Lund diagram - direct connection to z_g (groomed obs.) worked out

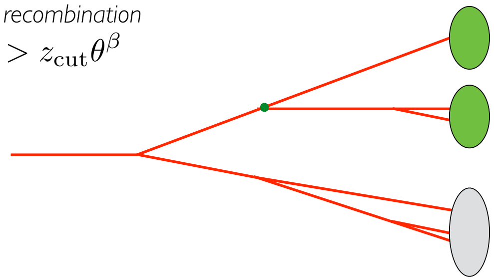
arXiv:1807.04758

z_g and Lund Diagram – a side remark

arXiv:1807.04758

- **p_T distribution of hard subjet (z_g)**
  - Momentum balance of the two hard sub-jets.
  - Observable connected to the hardest splitting.

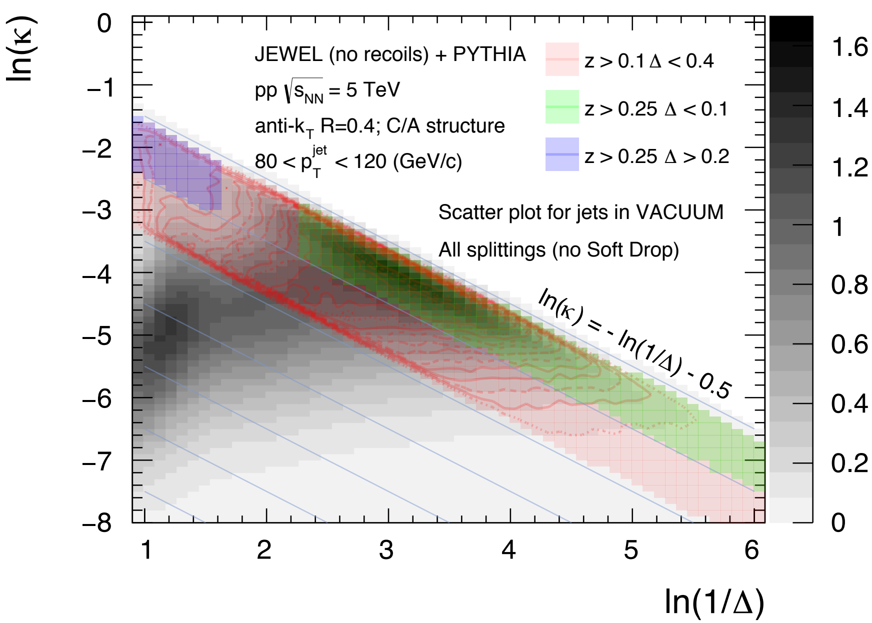




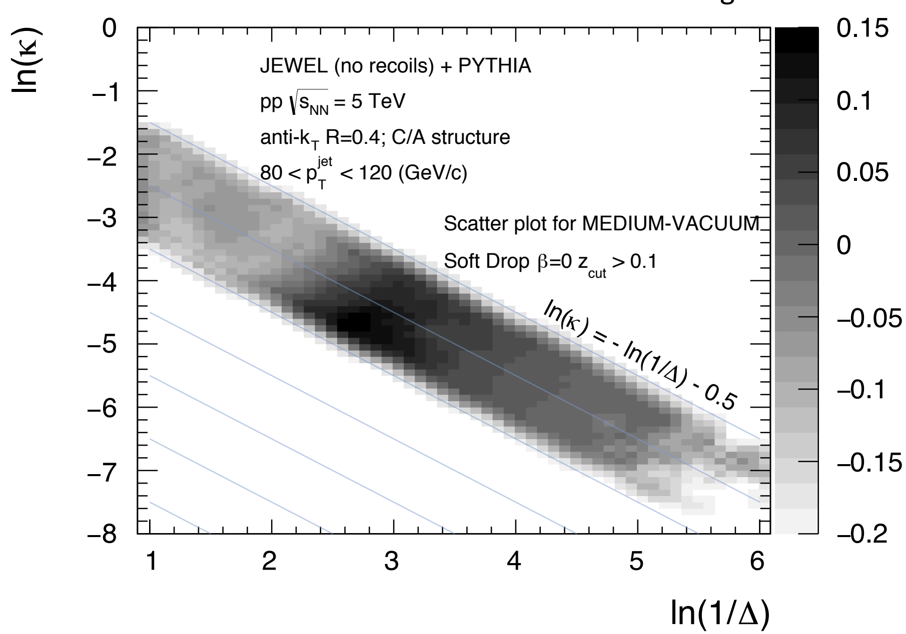
$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}},$$

P(z_g) proportional to splitting function

JEWEL: no Soft-Drop – all splittings



JEWEL: MEDIUM-VACUUM - z_g



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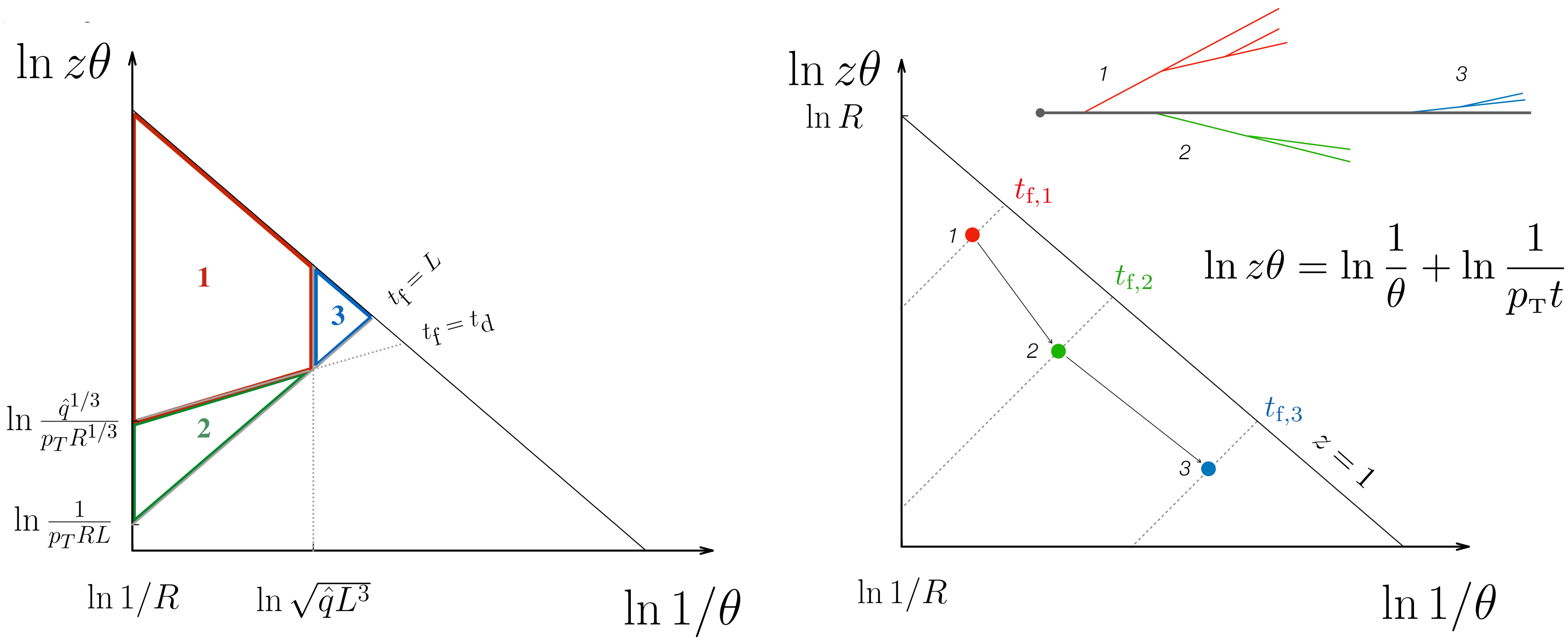
Jet Lund diagram

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

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

Interesting tool for jet quenching…
Tagging time of the splits – "access" to formation time; sensitivity to Length of the medium



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Jet Lund diagram

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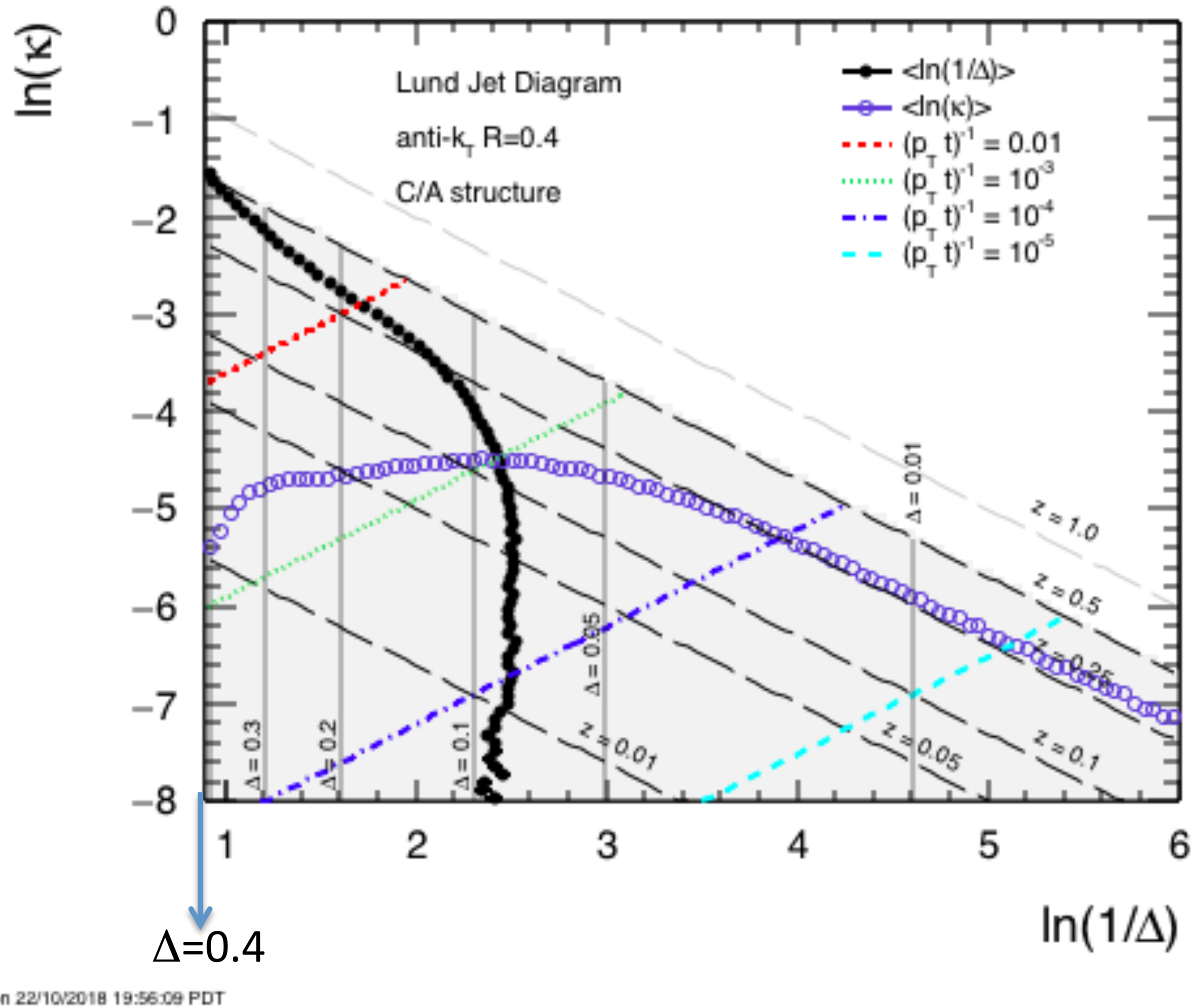
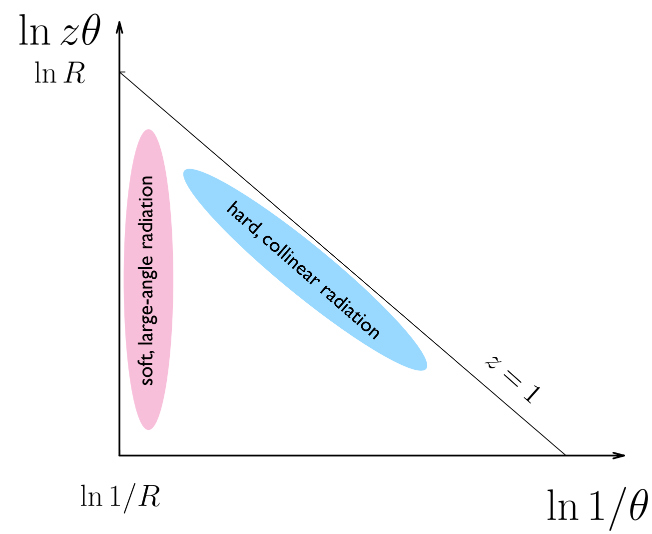
$$\bar{\rho}(\Delta,\kappa) = \frac{1}{N_{\text{jet}}}\frac{dn_{\text{emission}}}{d\ln\kappa\ d\ln 1/\Delta}$$

In this talk:
- Find jet with anti-kT R=0.4
- Recluster with C/A R=1
- Follow hardest branch



Various lines: z, $1/(p_T\ t)$, Δ

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



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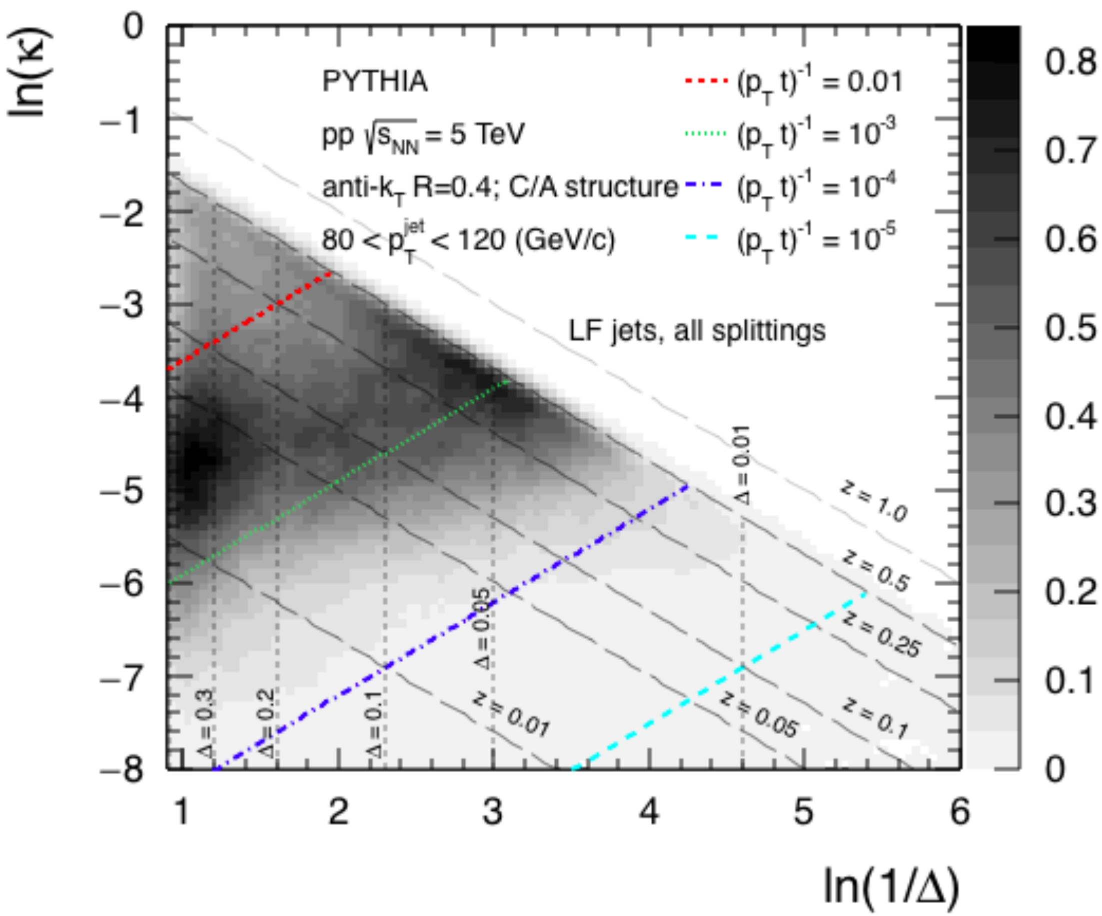

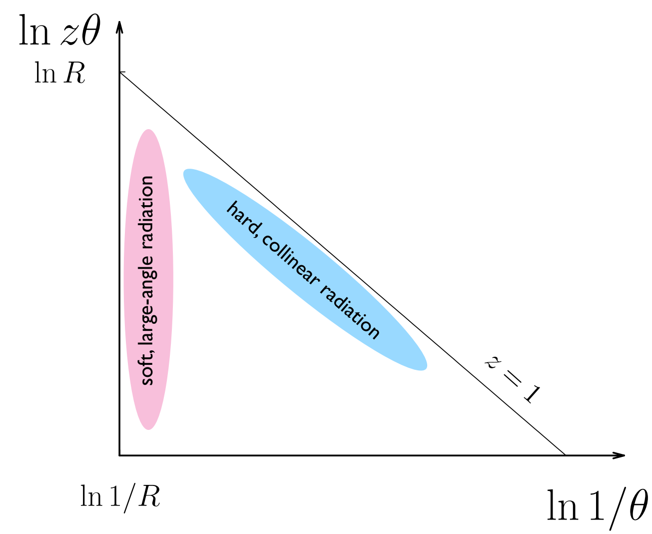

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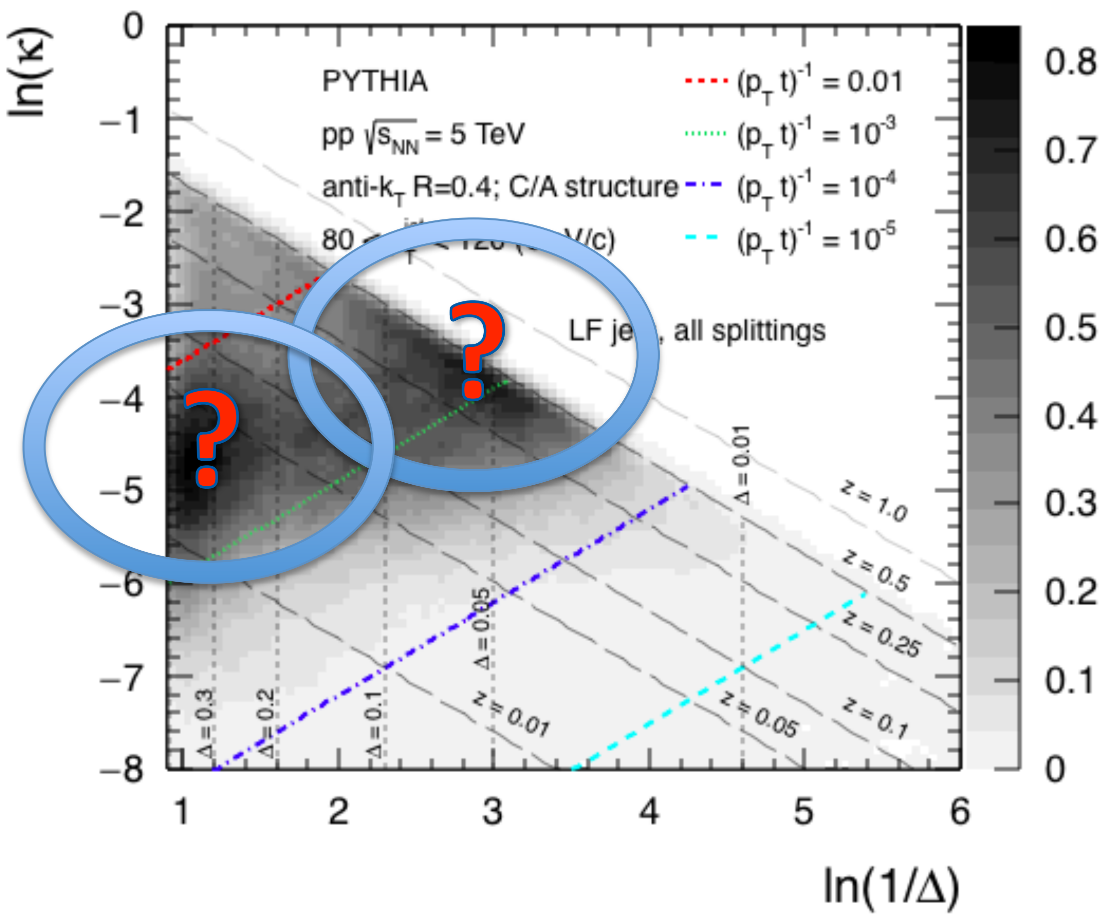

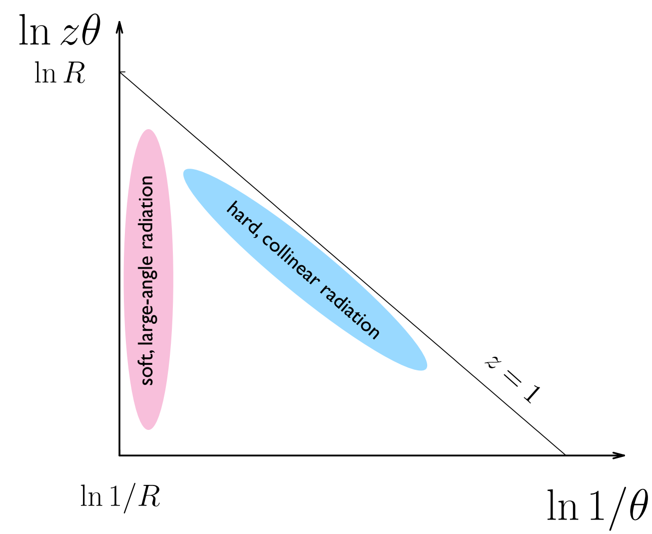

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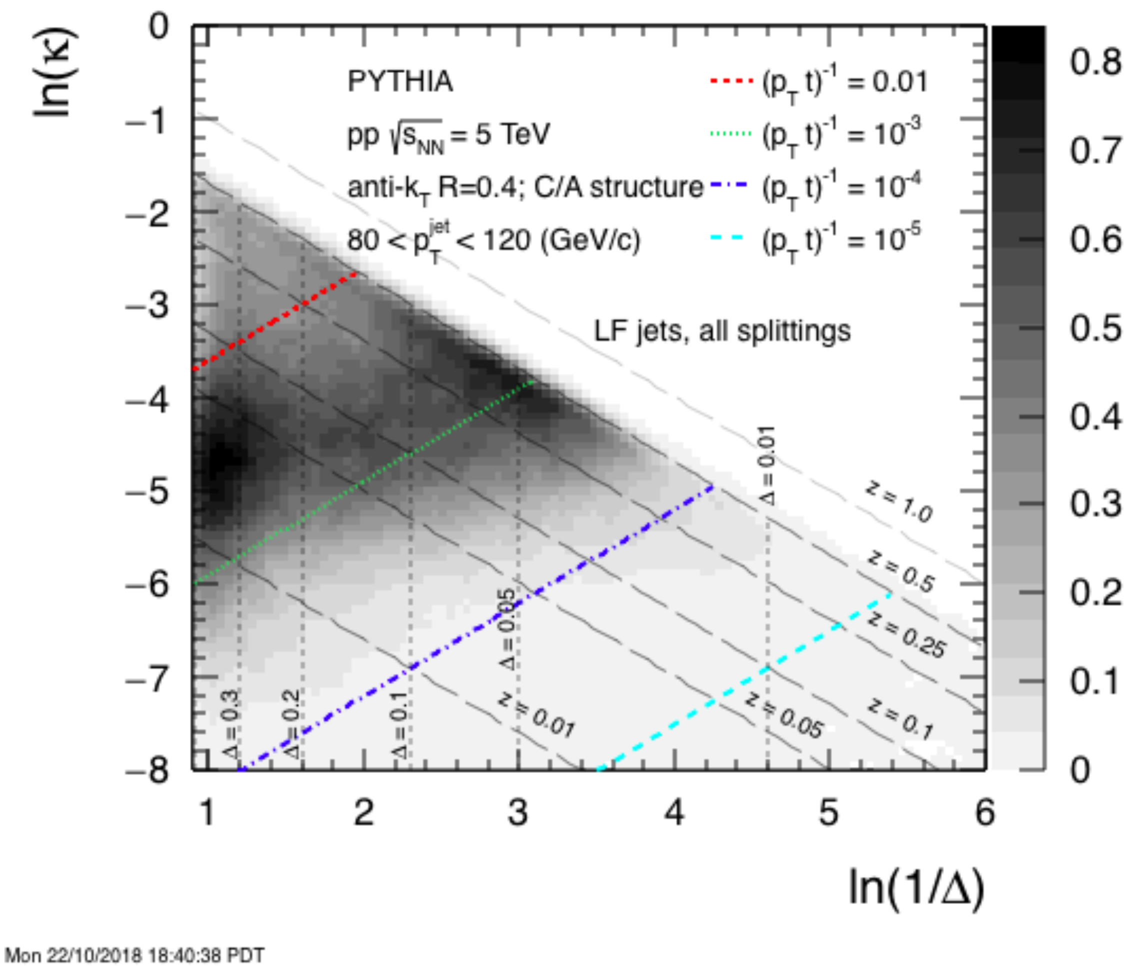

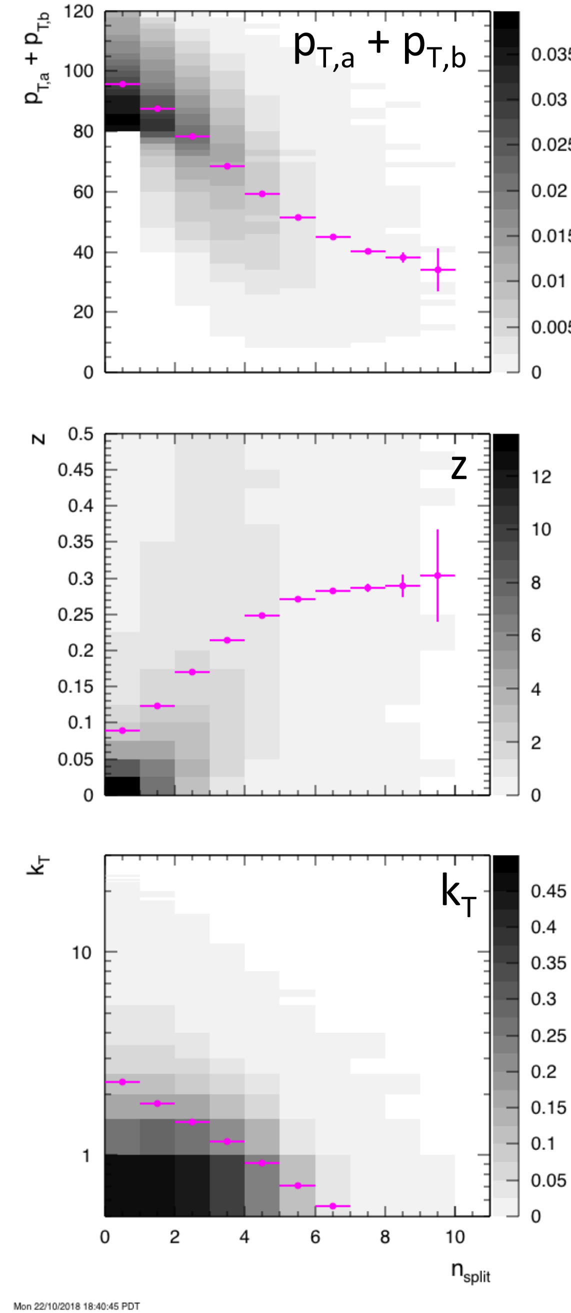

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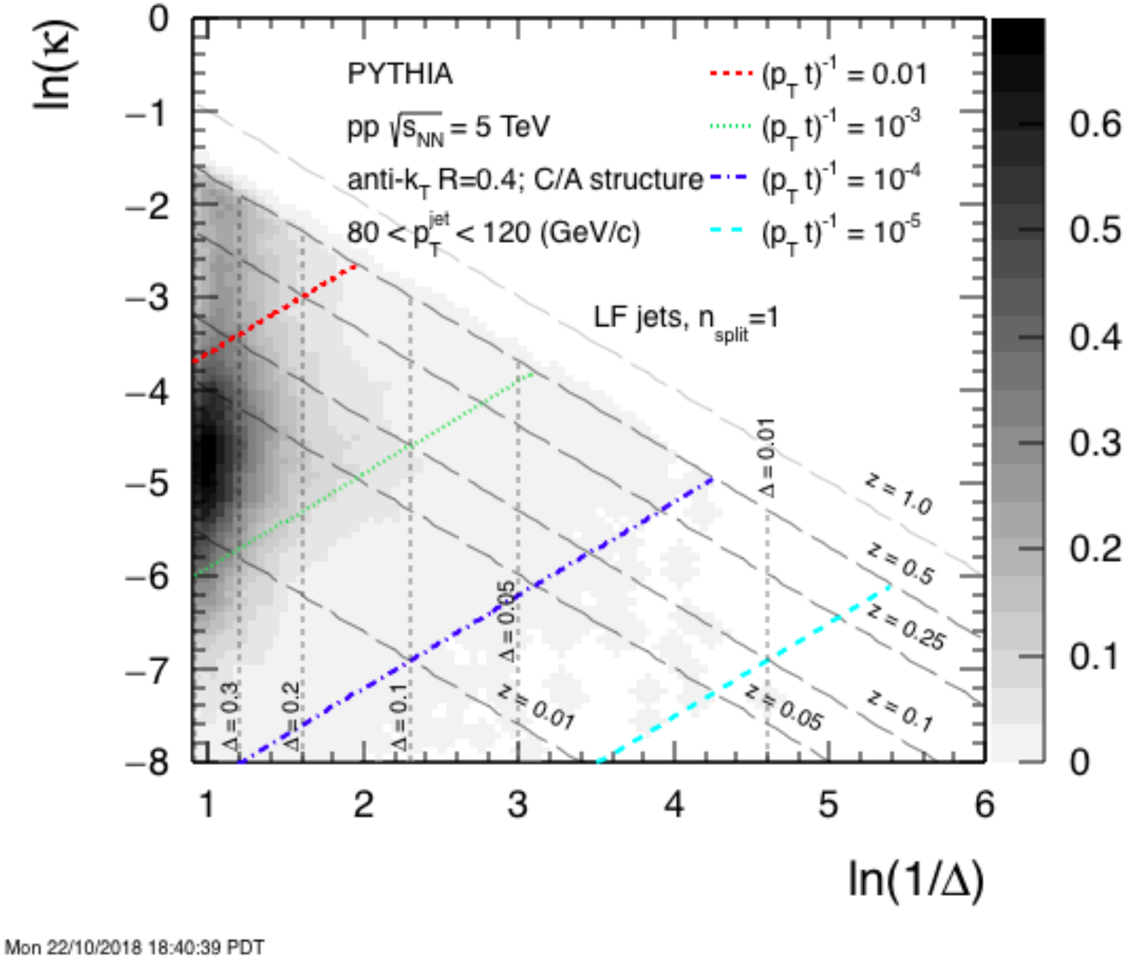

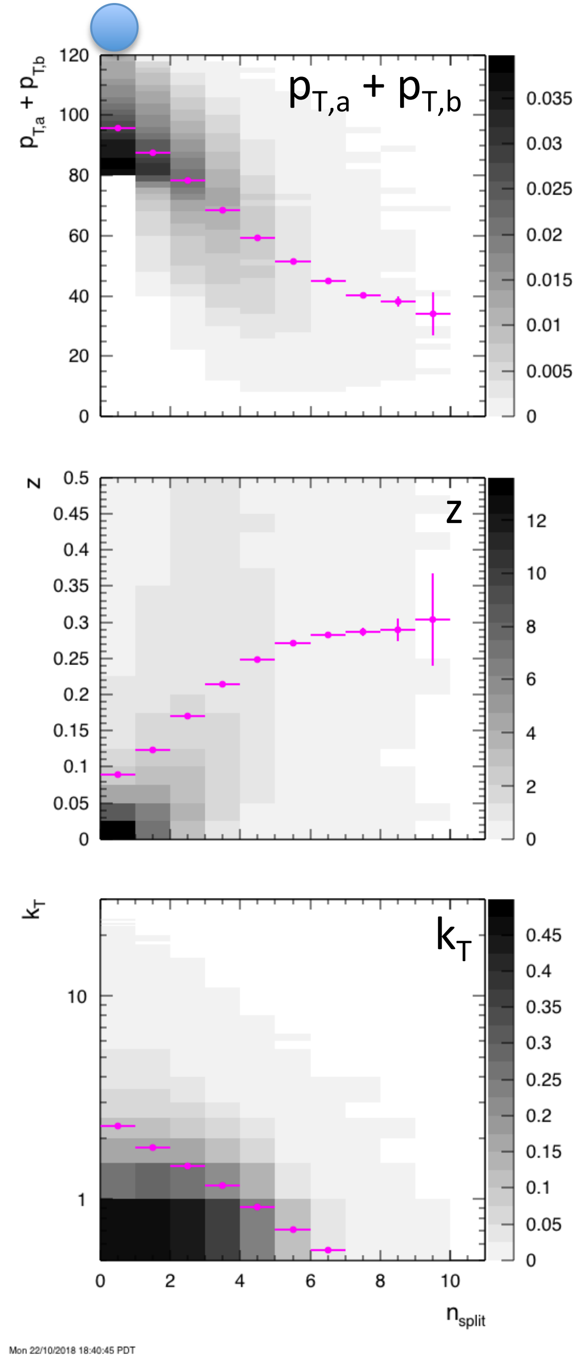

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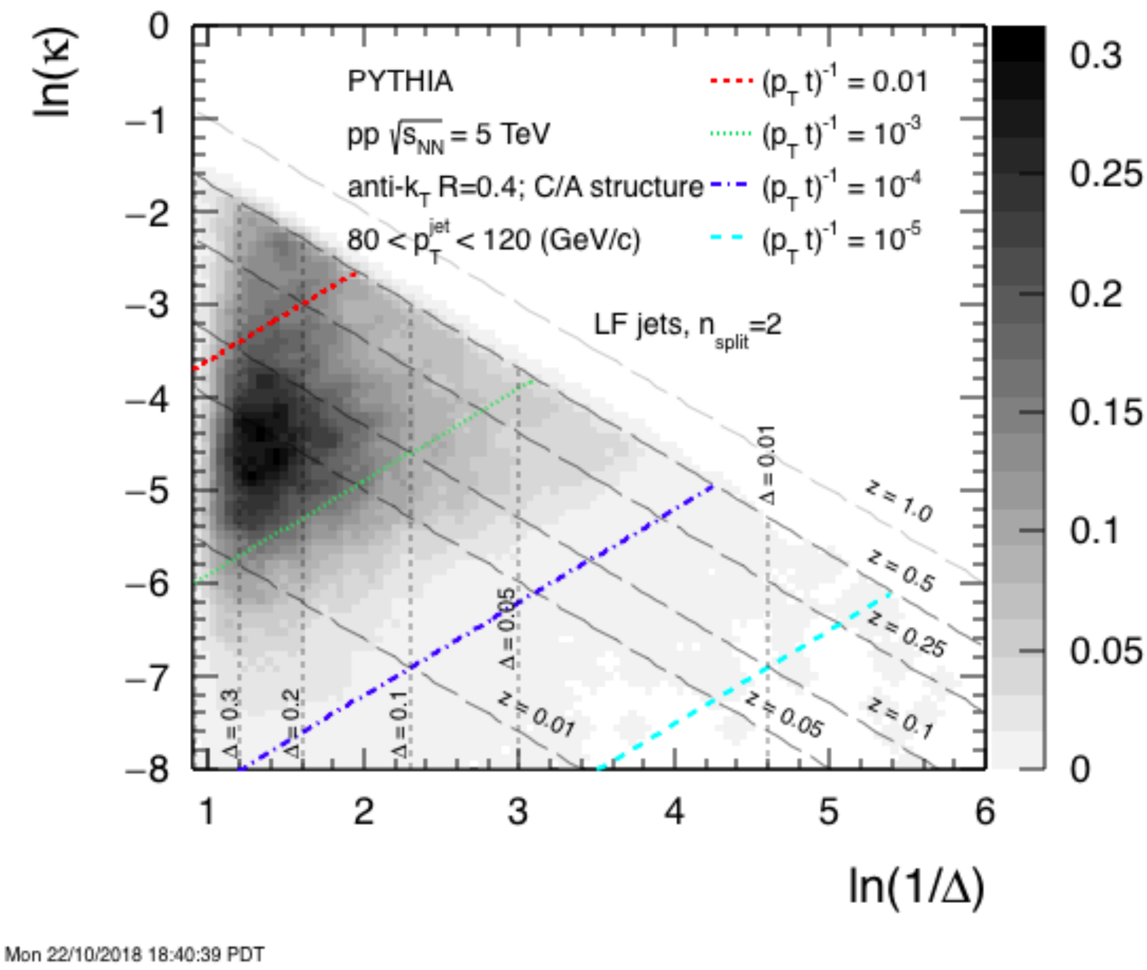

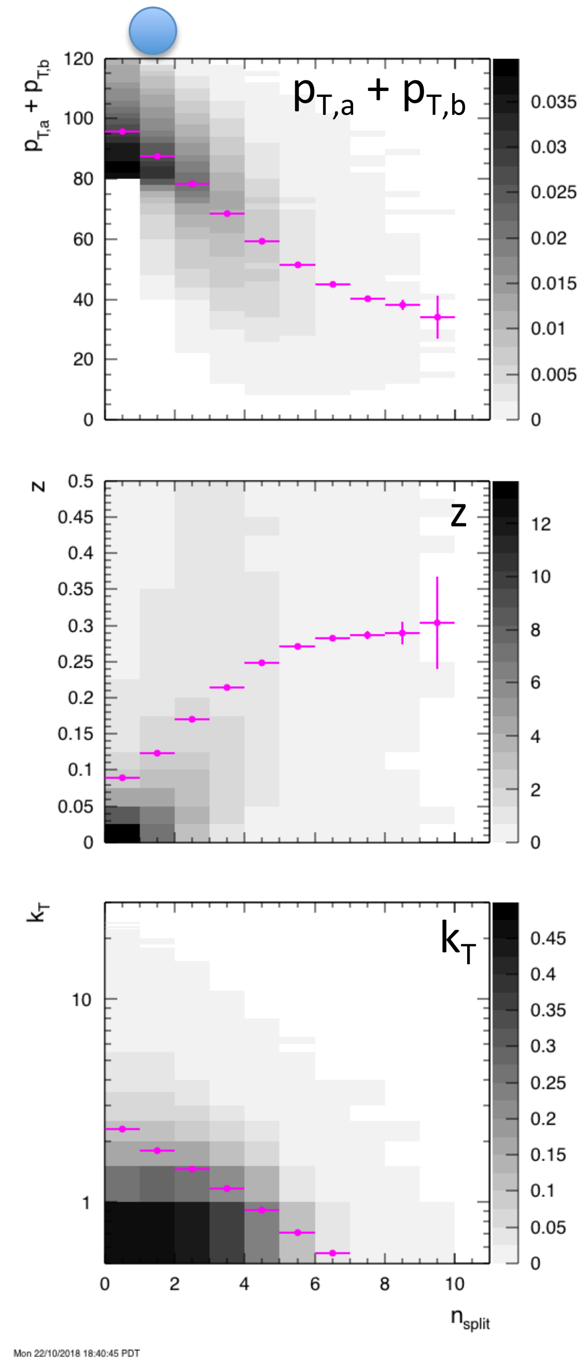

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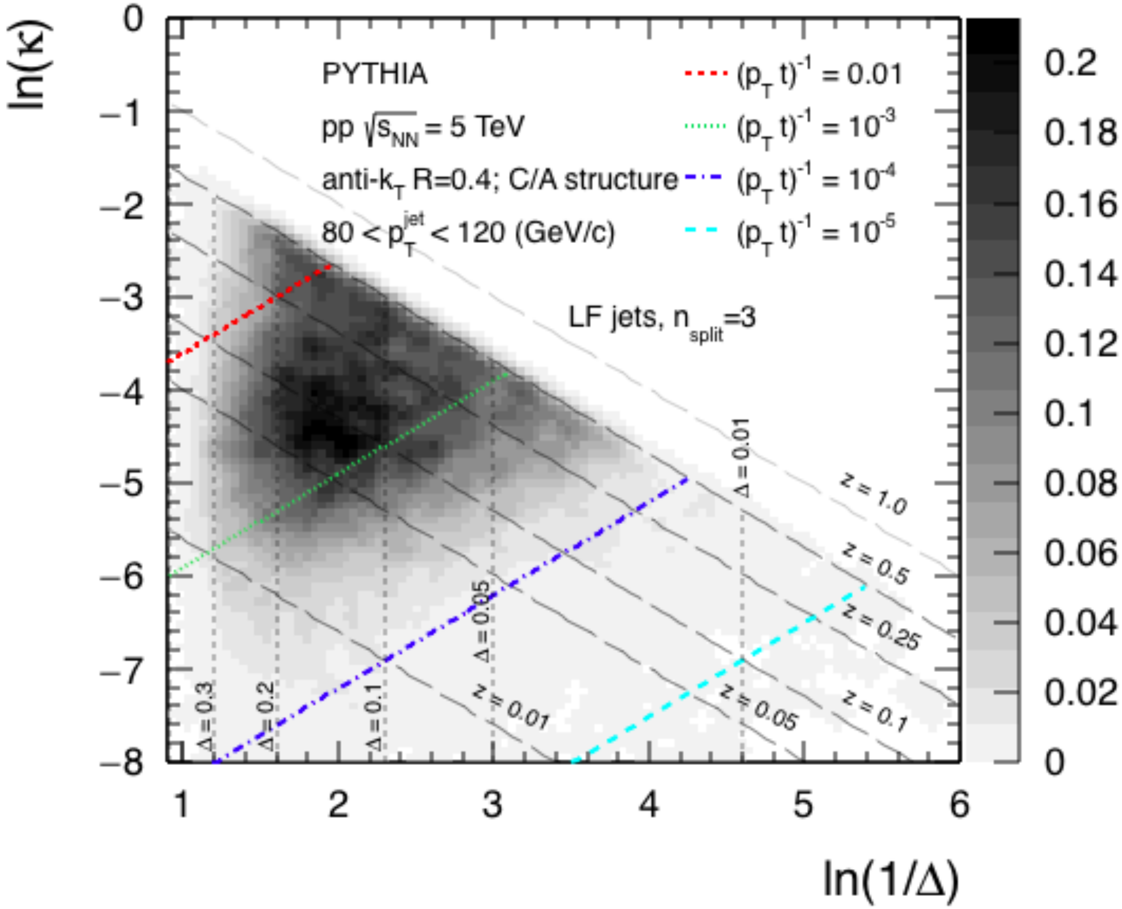

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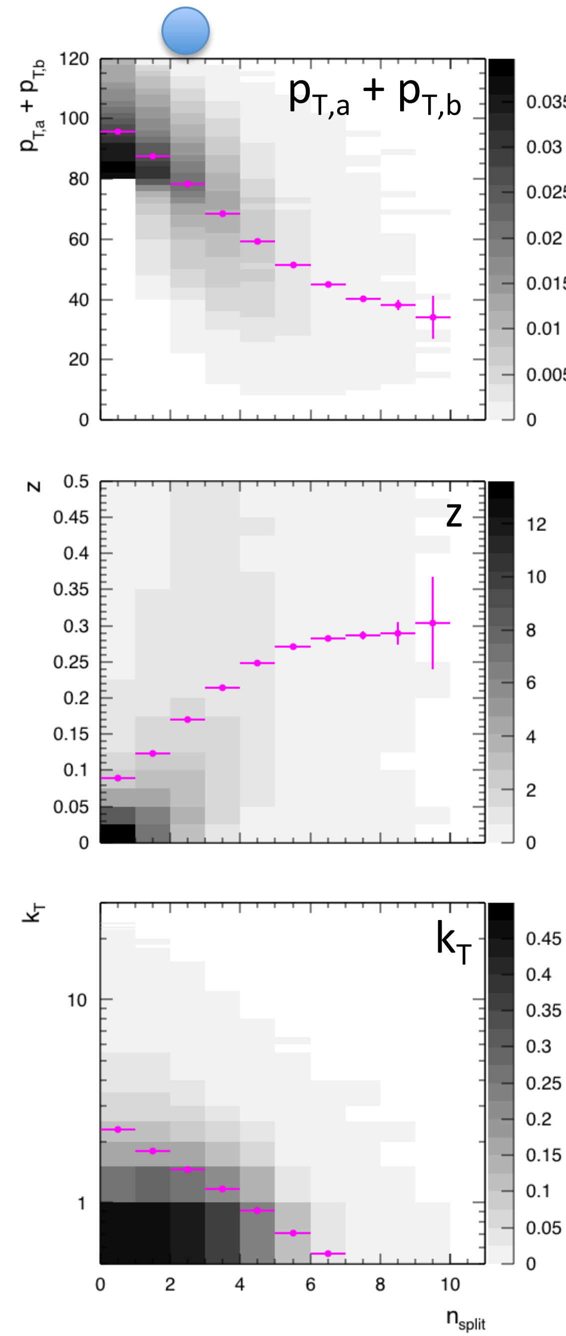

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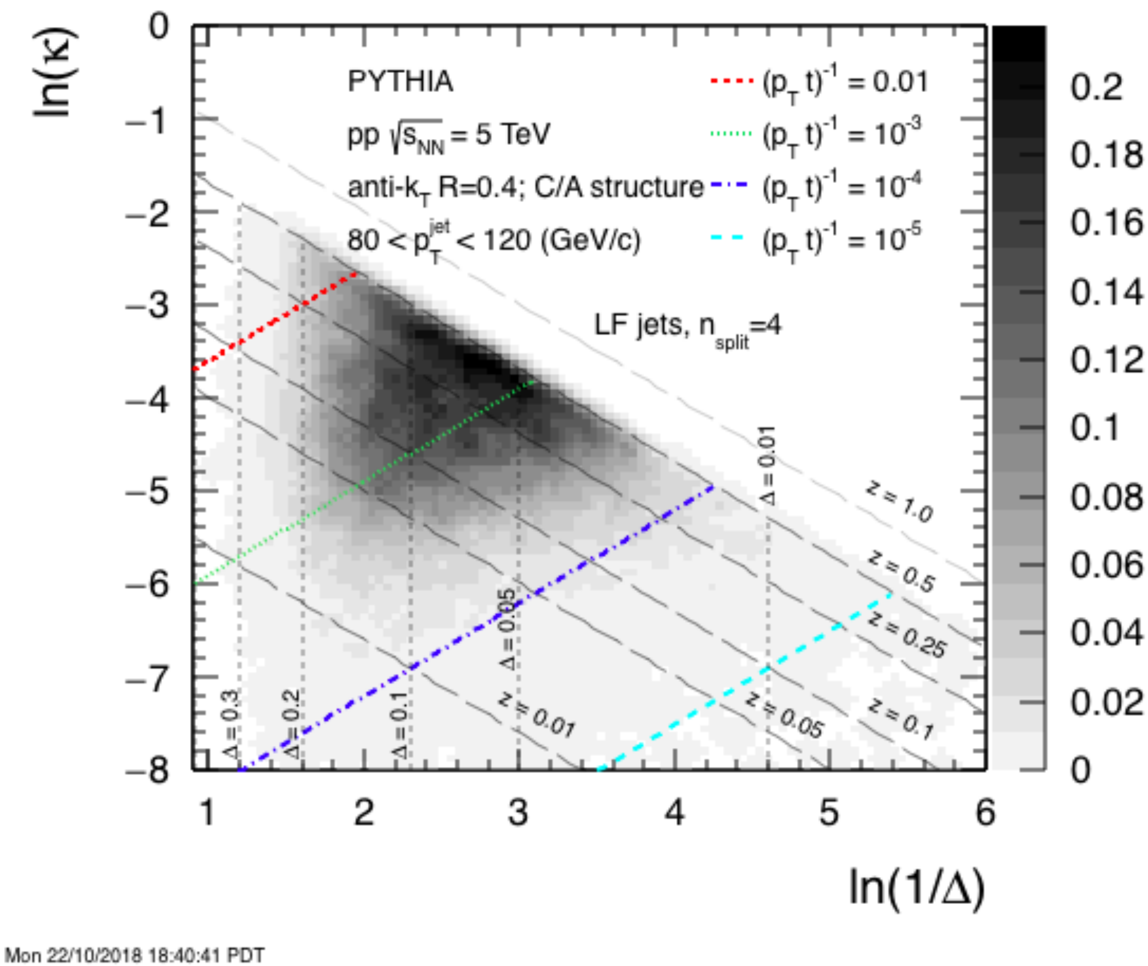

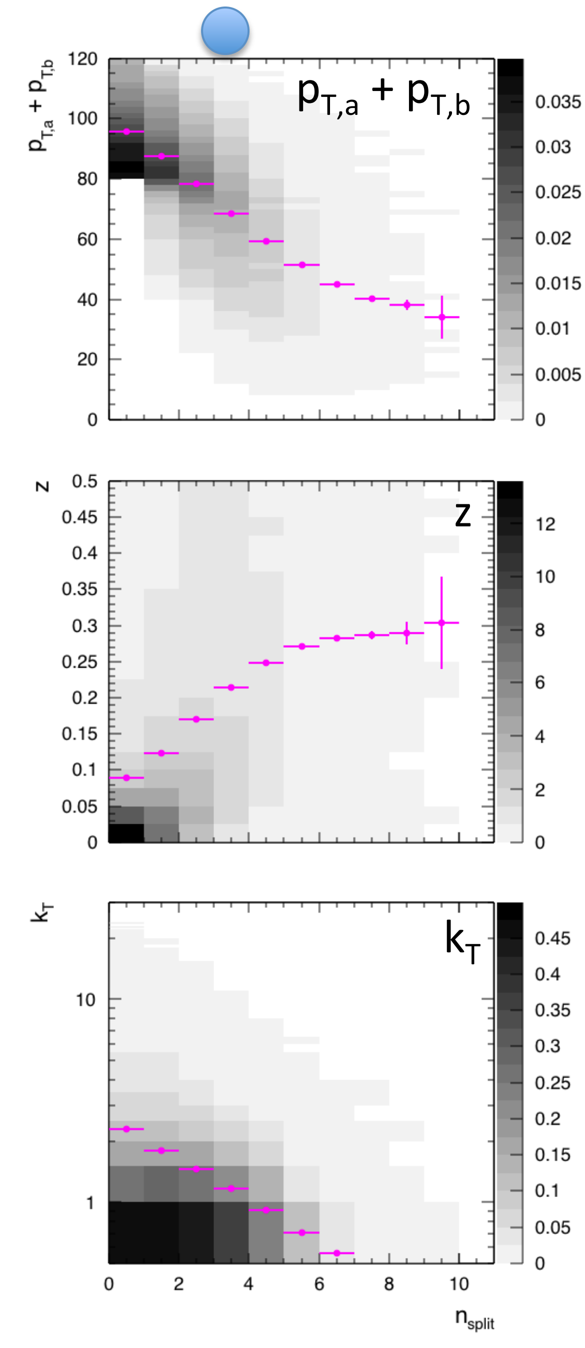

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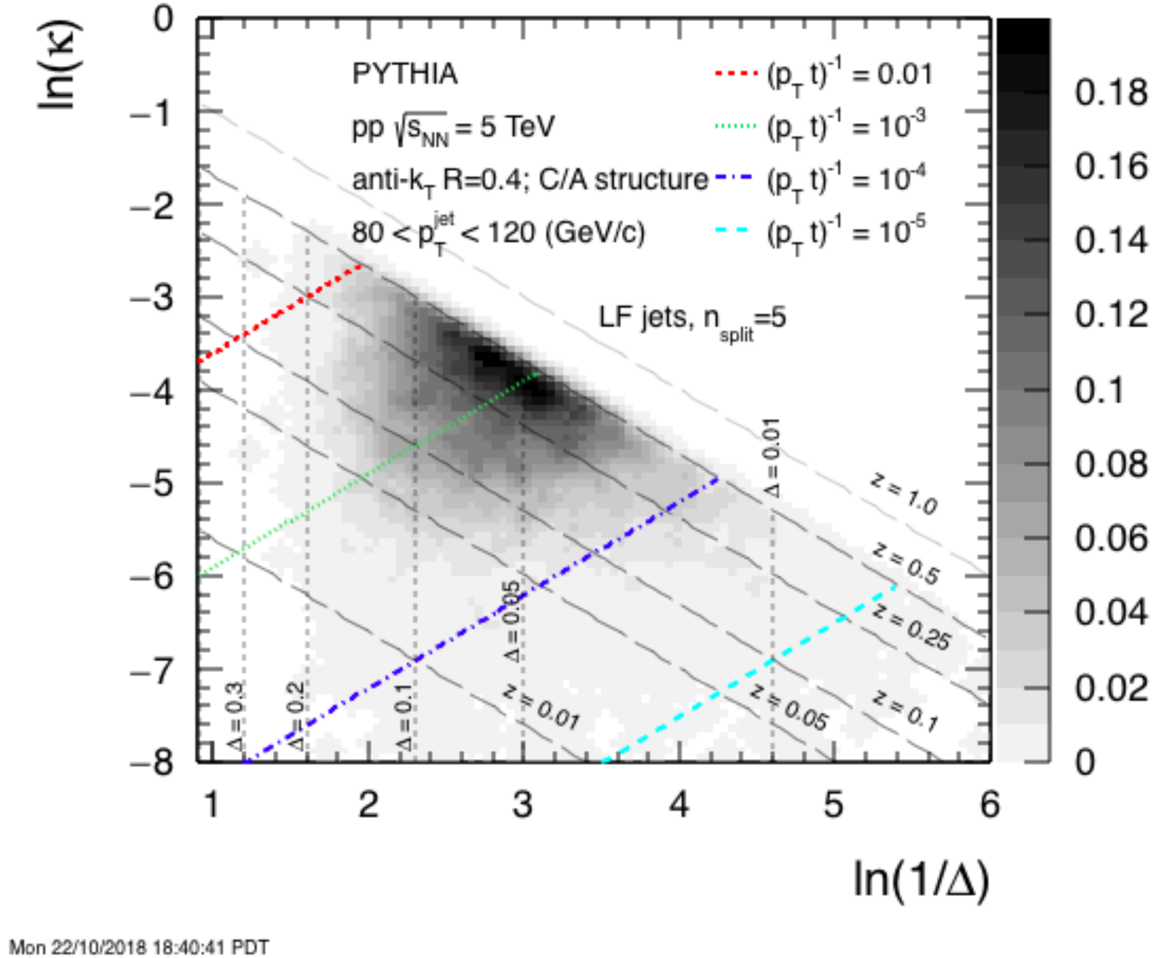

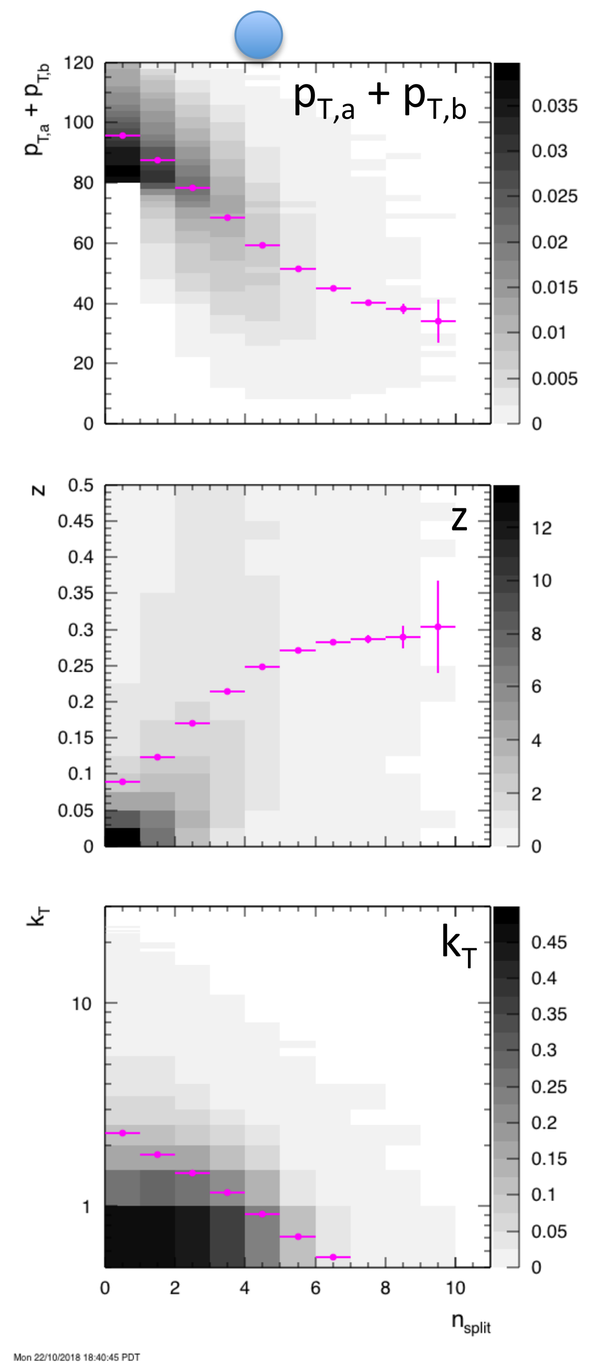

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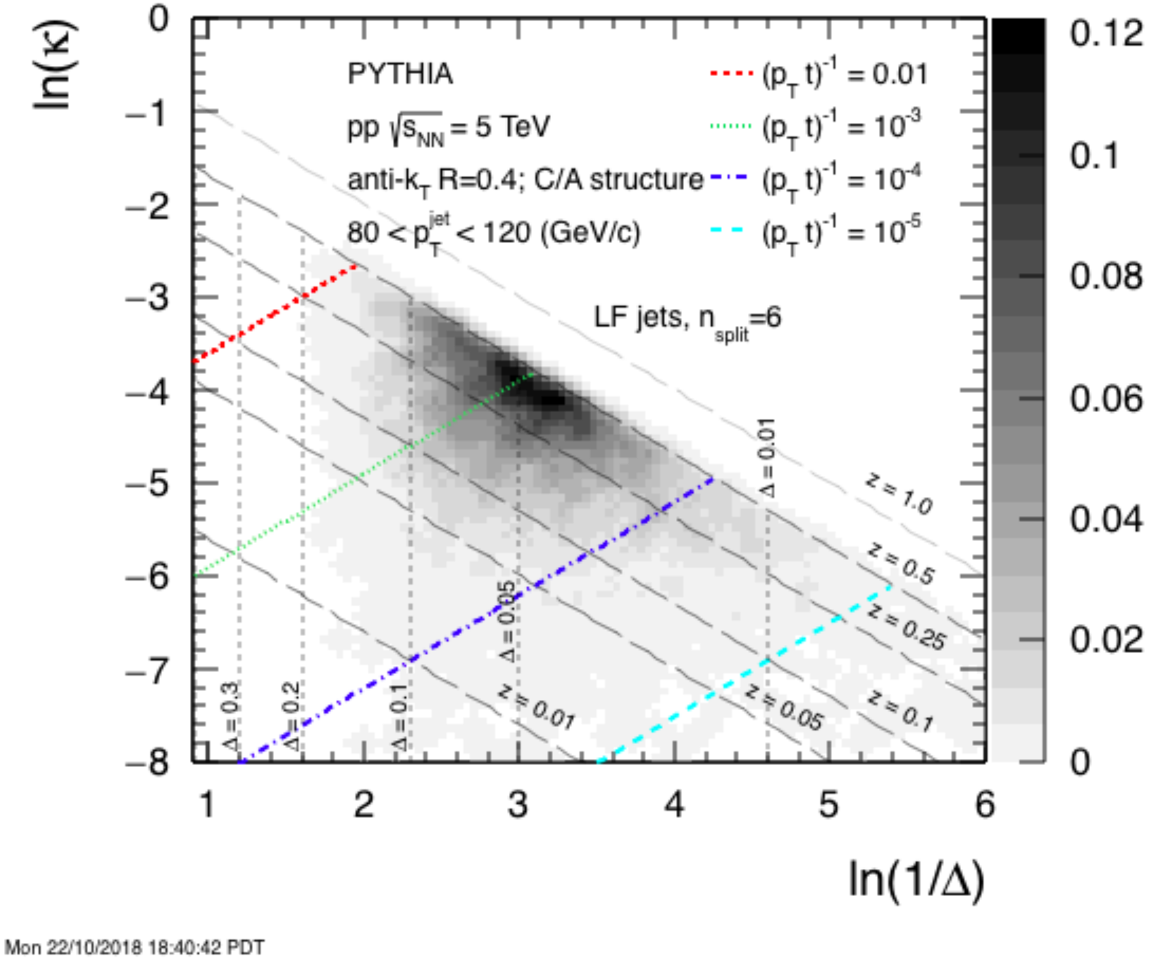

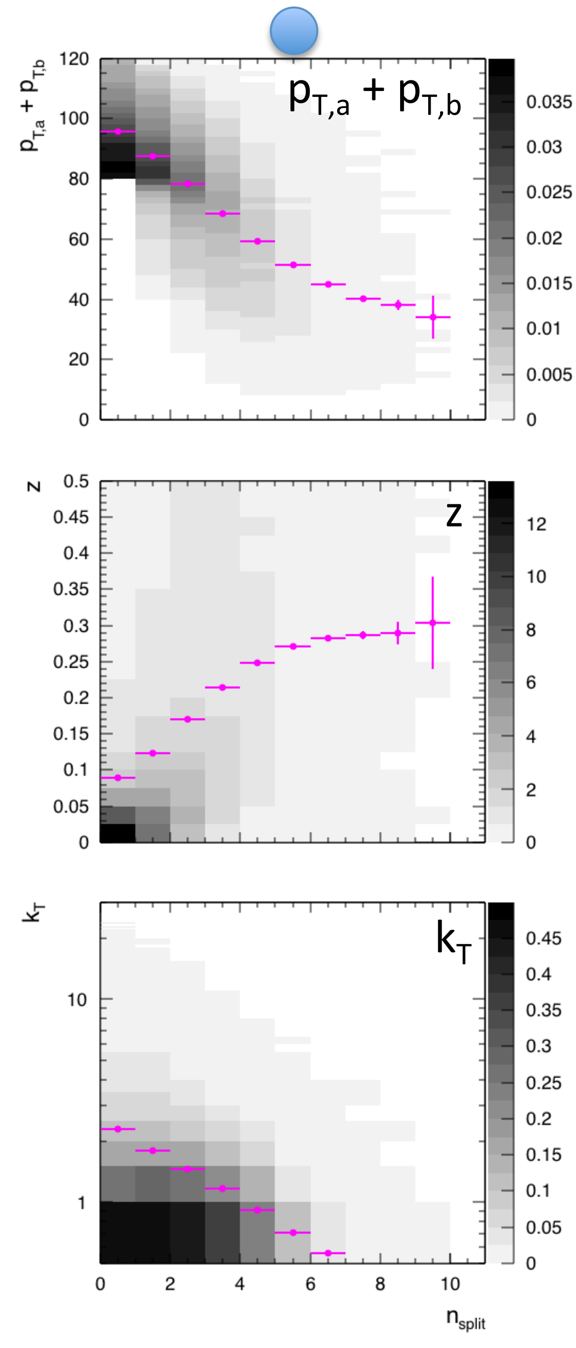

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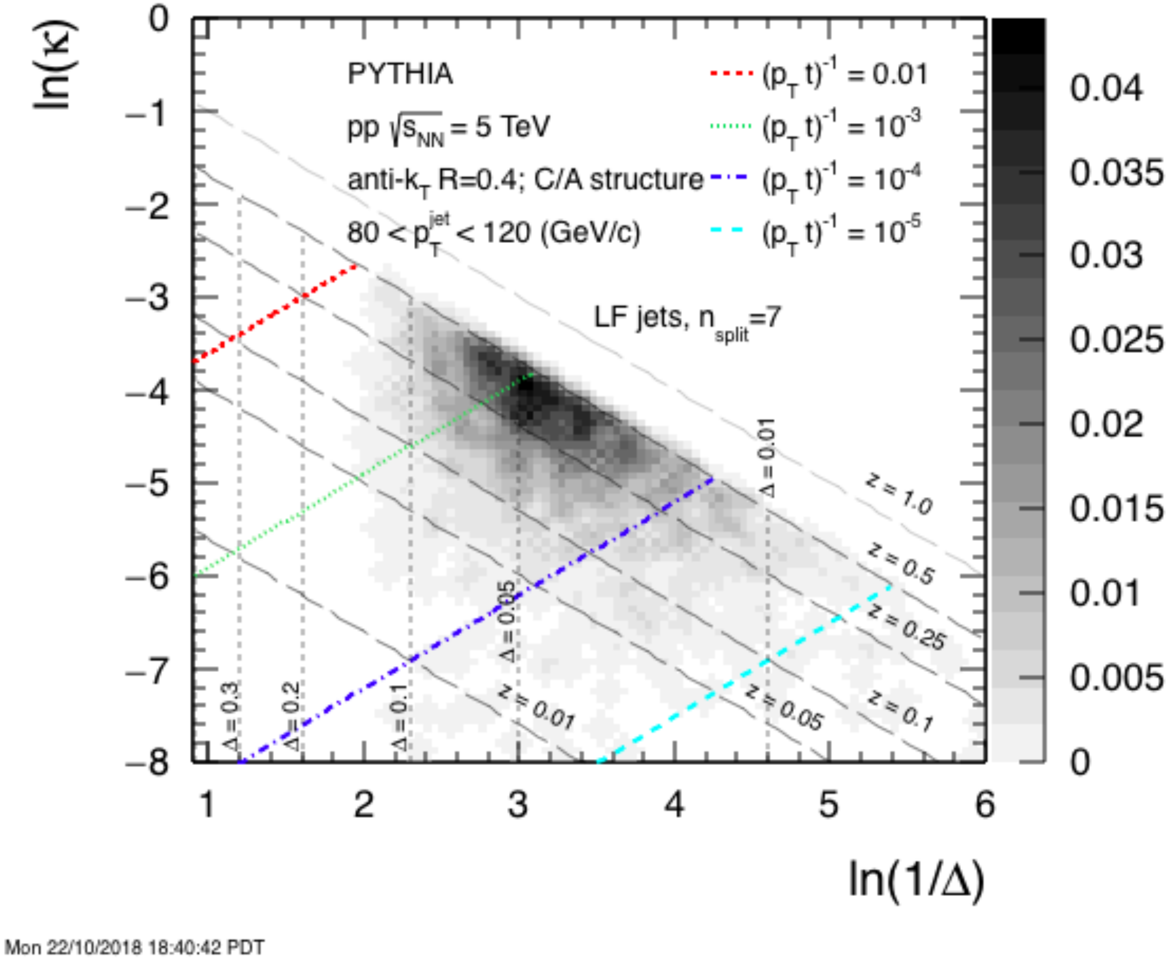

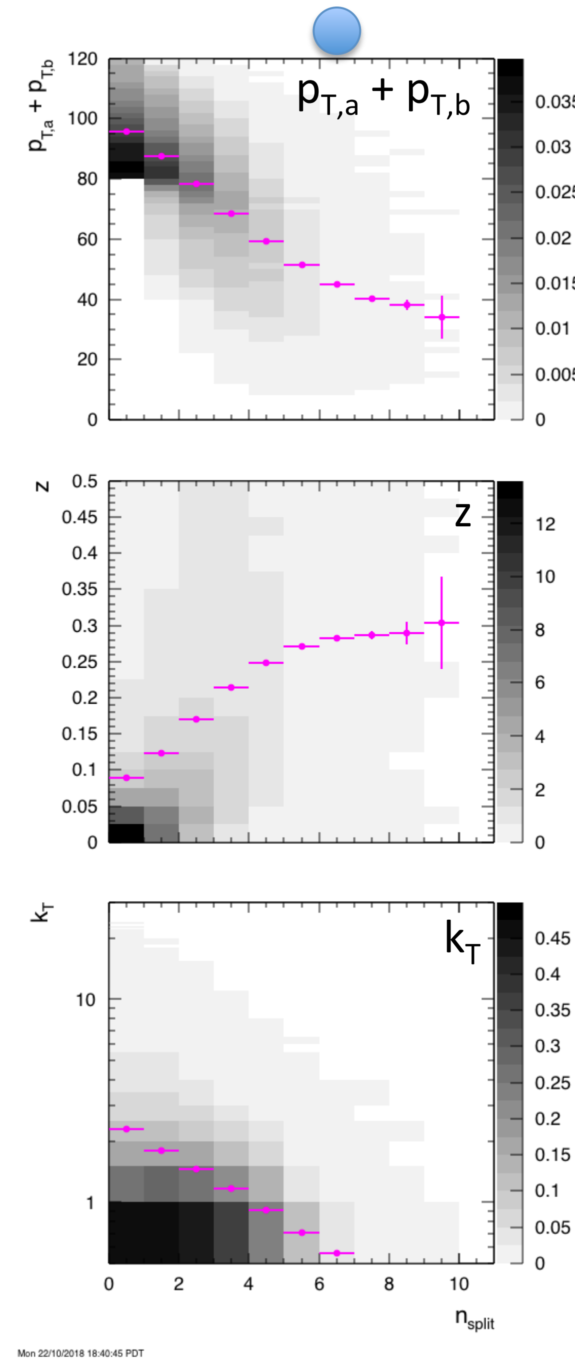

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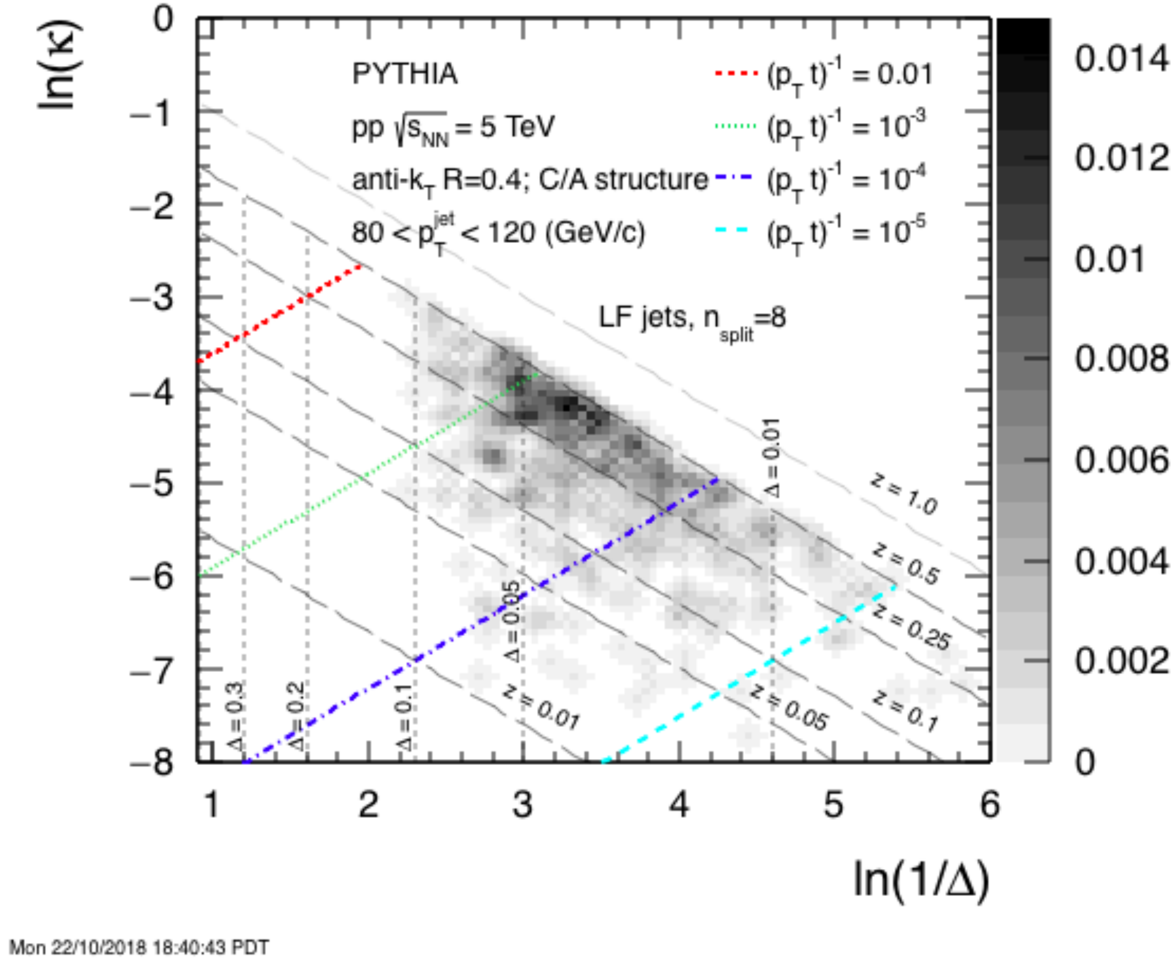

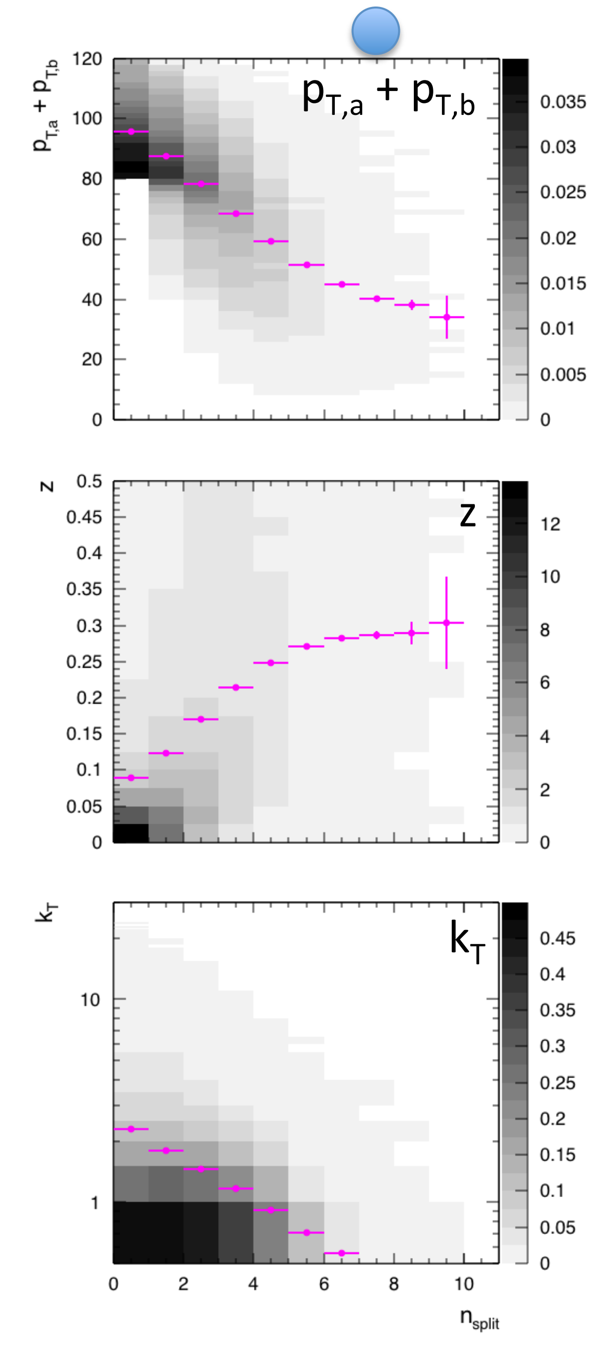

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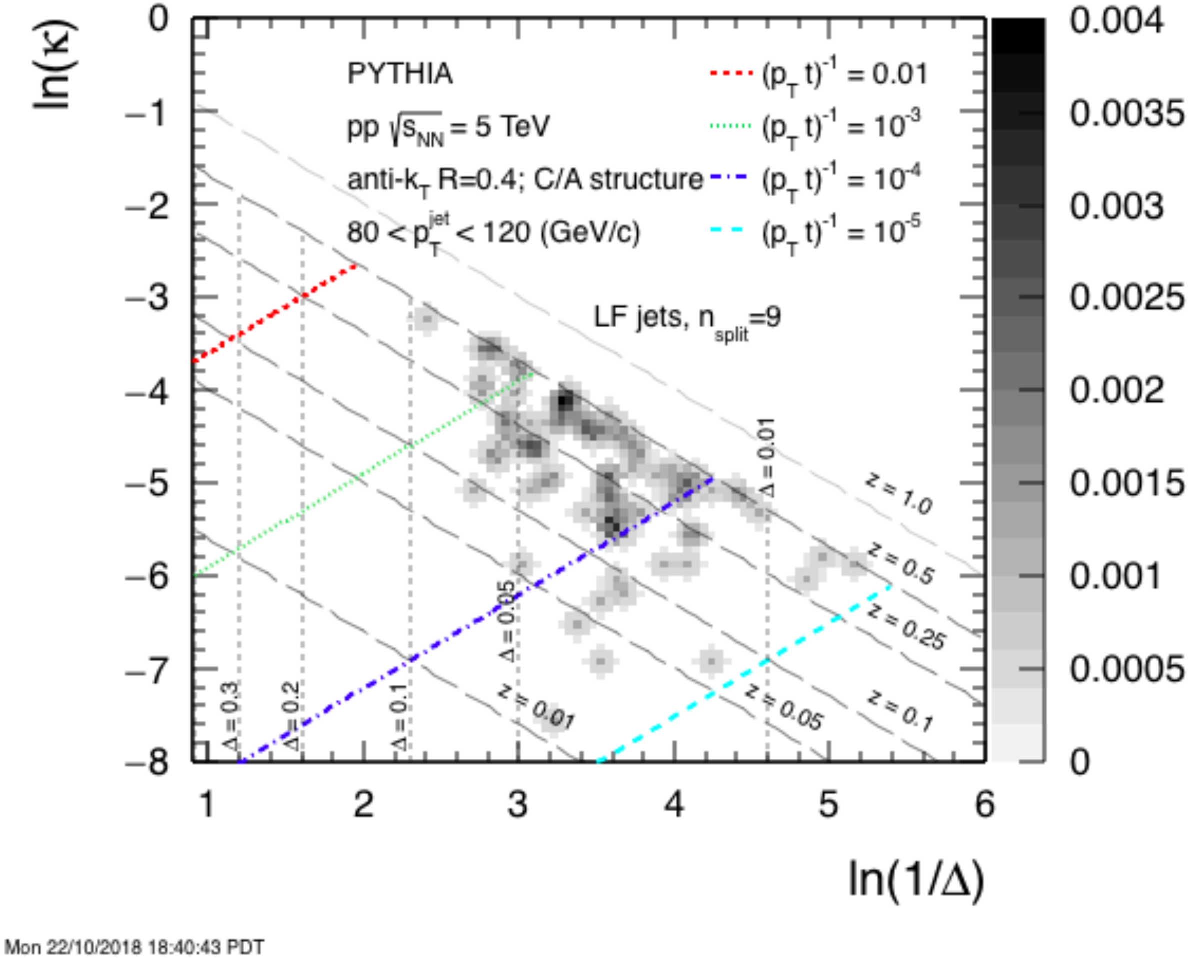

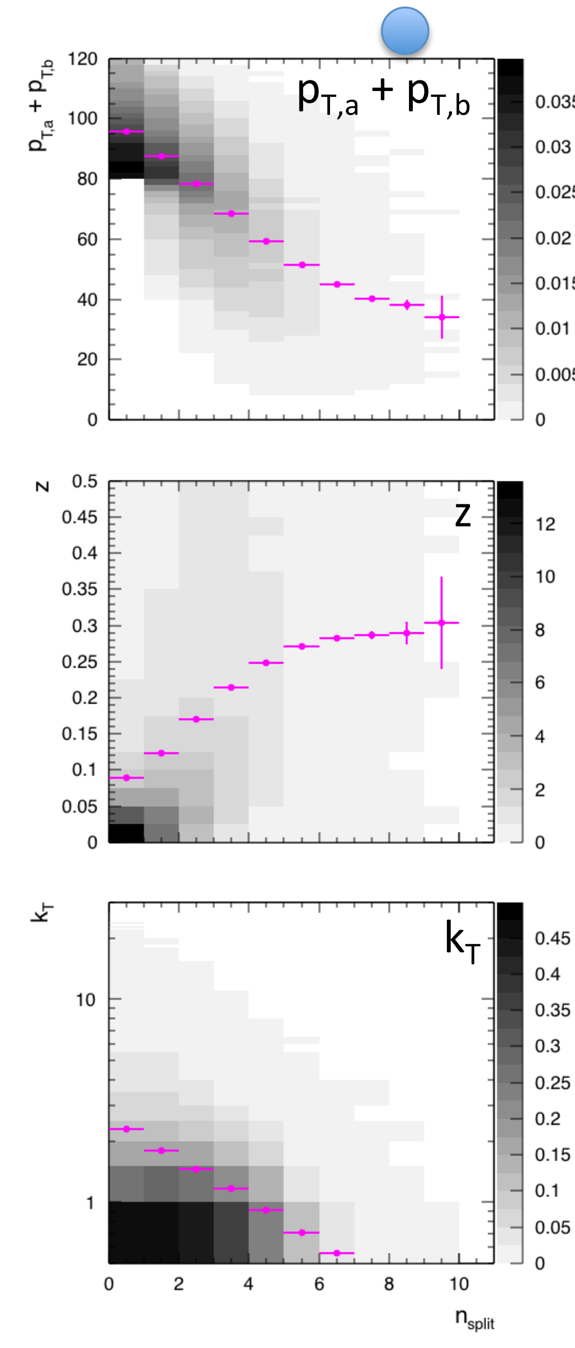

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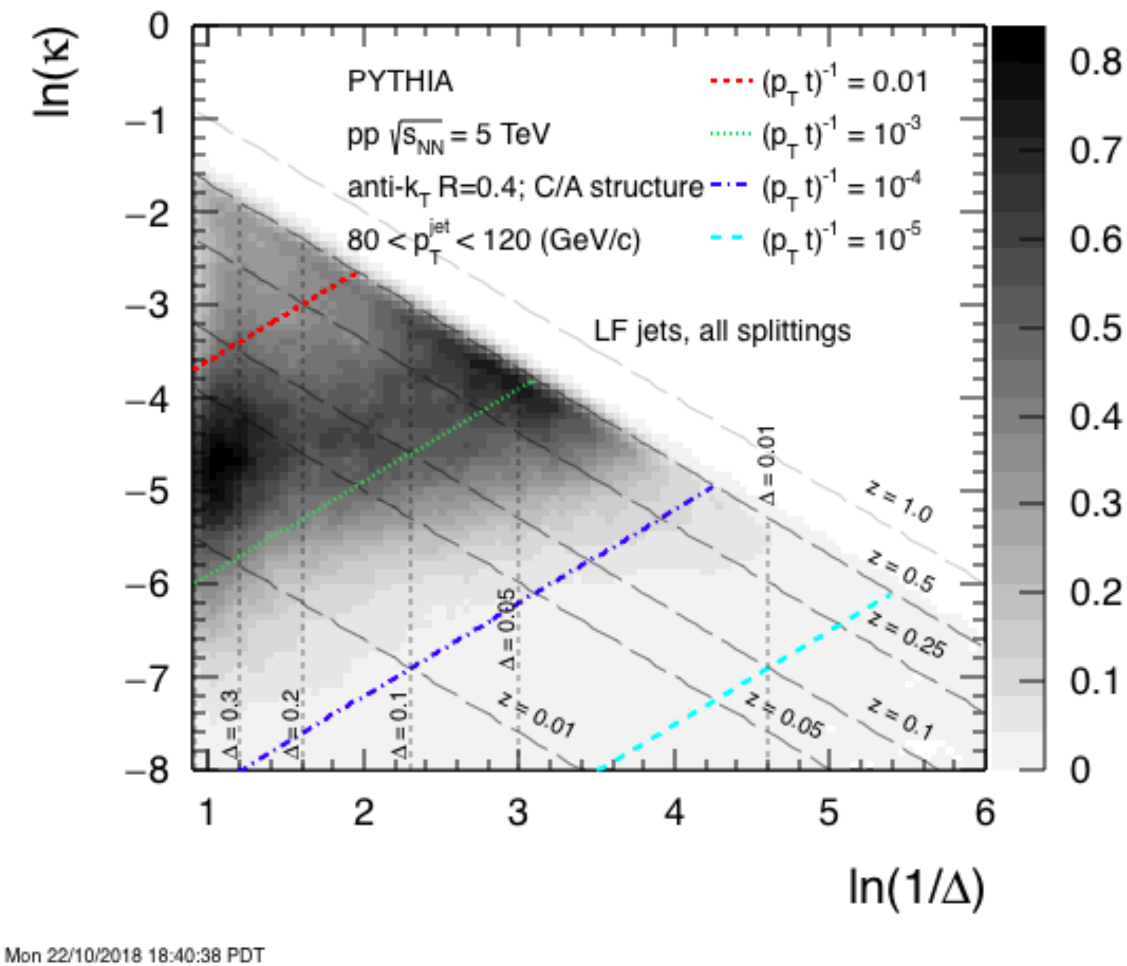

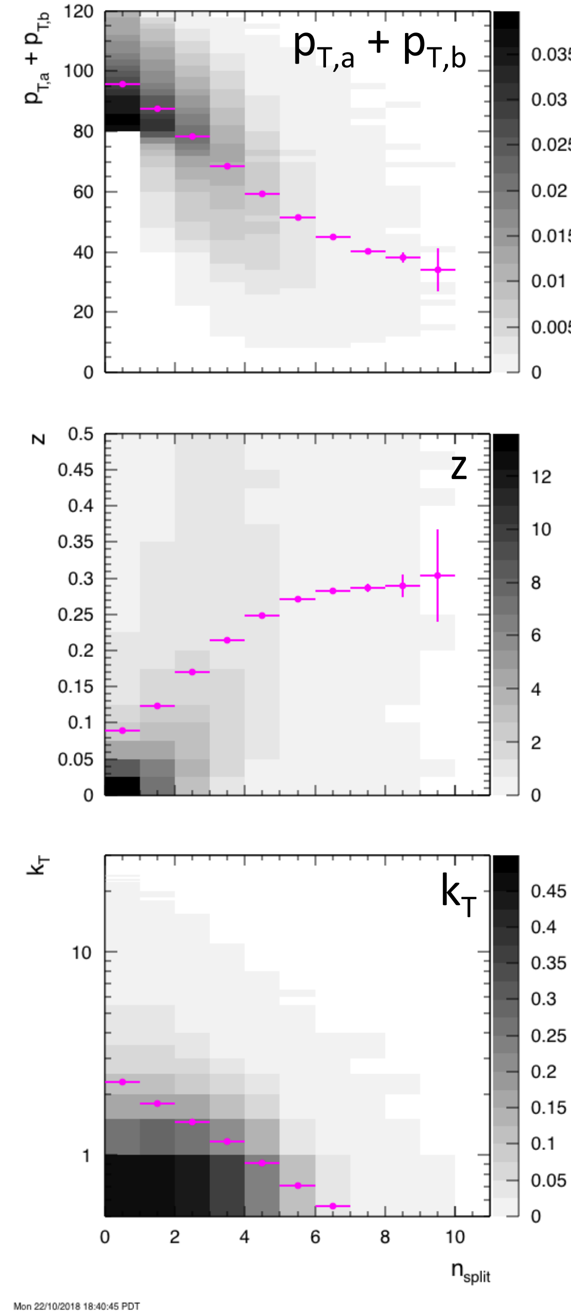

Jet Lund diagram

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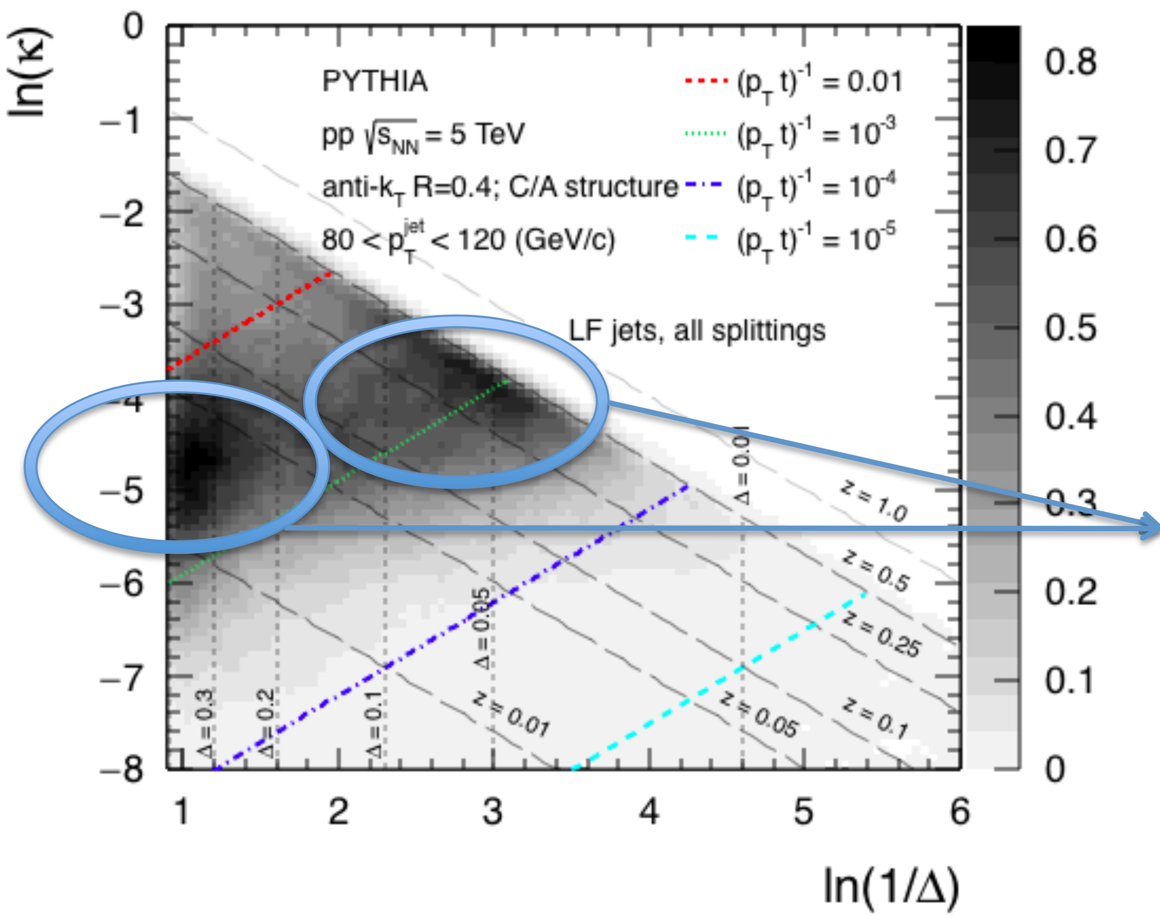

[Another] investigation into what are these?

- Large angle, soft
- Small angle, hard

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Jet Lund diagram

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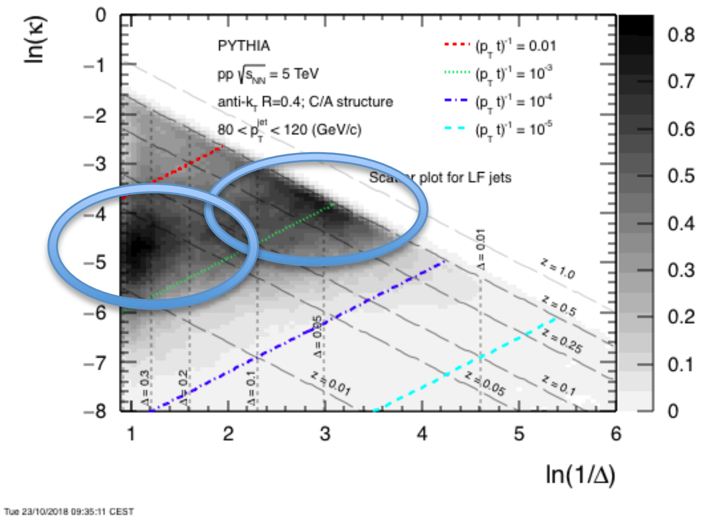
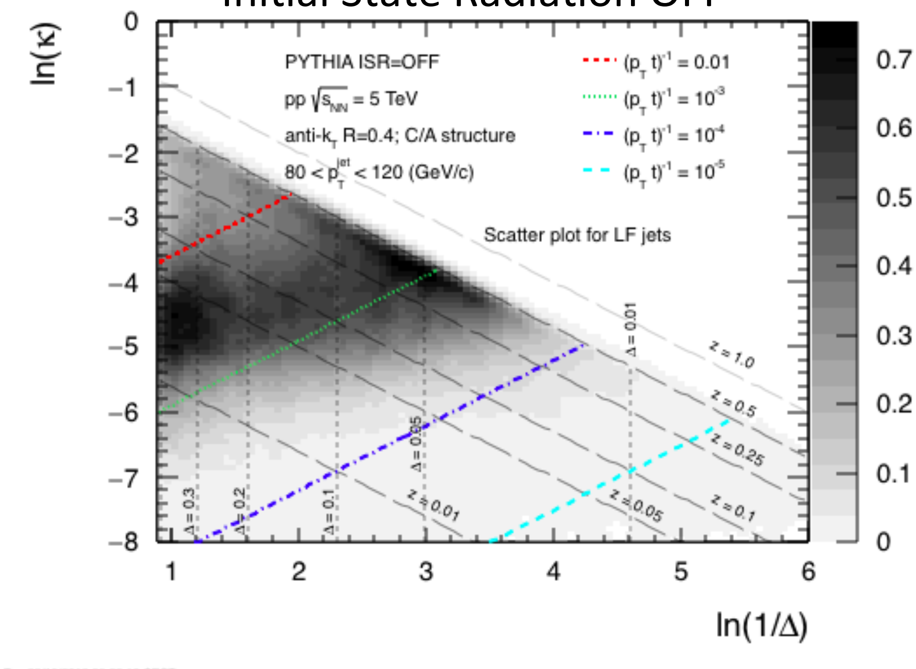


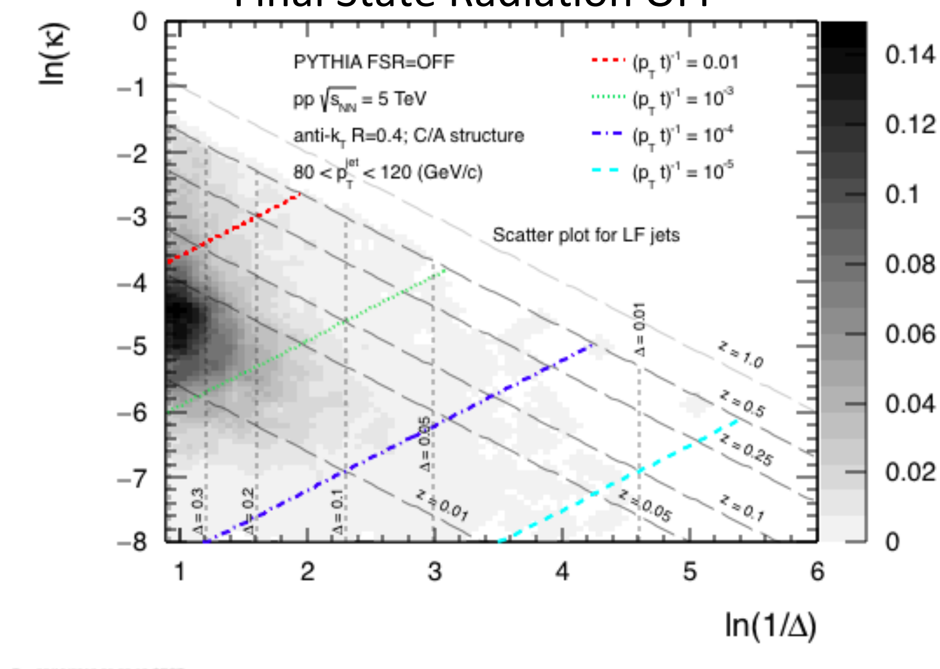
Expectation from theory: for every R and p_T, the phase space should be uniformly filled => the peak at the maximal angle is not expected.. The uniform distribution should be a feature of FSR.

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

Initial State Radiation OFF



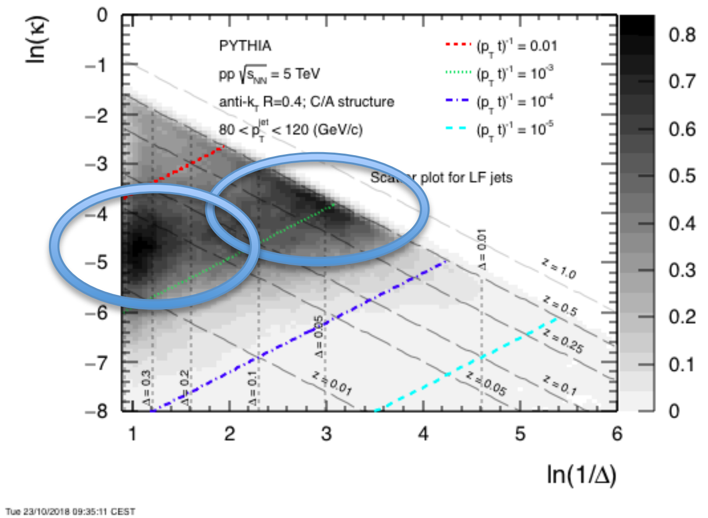
Final State Radiation OFF



Jet Lund diagram

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

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



Structures vary with the algorithm used

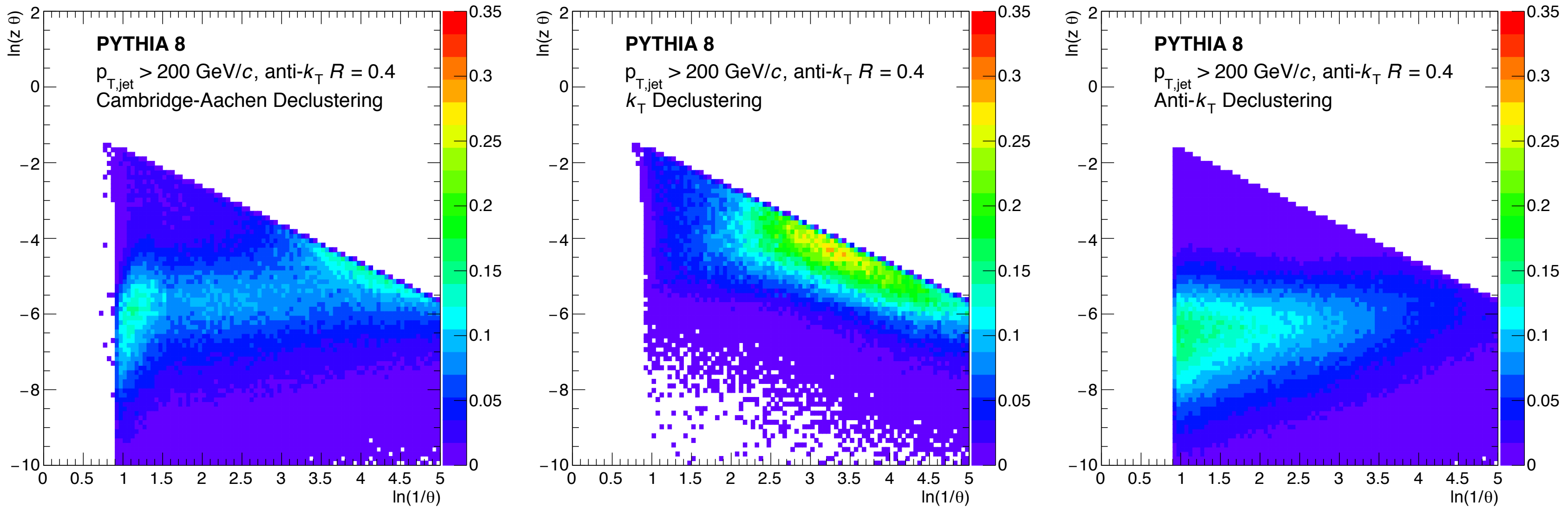


Figure 3: Lund diagrams reconstructed from a sample anti-k_{T} $R = 0.4$ jets generated by PYTHIA8. Three reclustering strategies were considered: C/A (left), k_{T}(middle), and anti-k_{T} (right).

JET QUENCHING – MC STUDY

Jet Lund diagram

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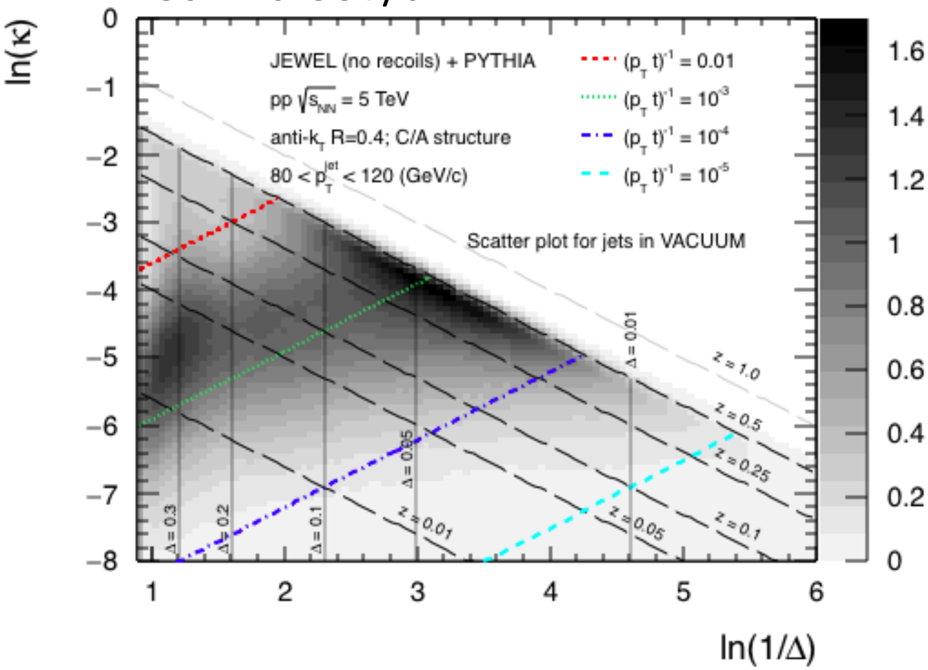
JEWEL + PYTHIA (RECOIL=OFF)
10% most central PbPb at 5 TeV
VACUUM

80-120 GeV/c



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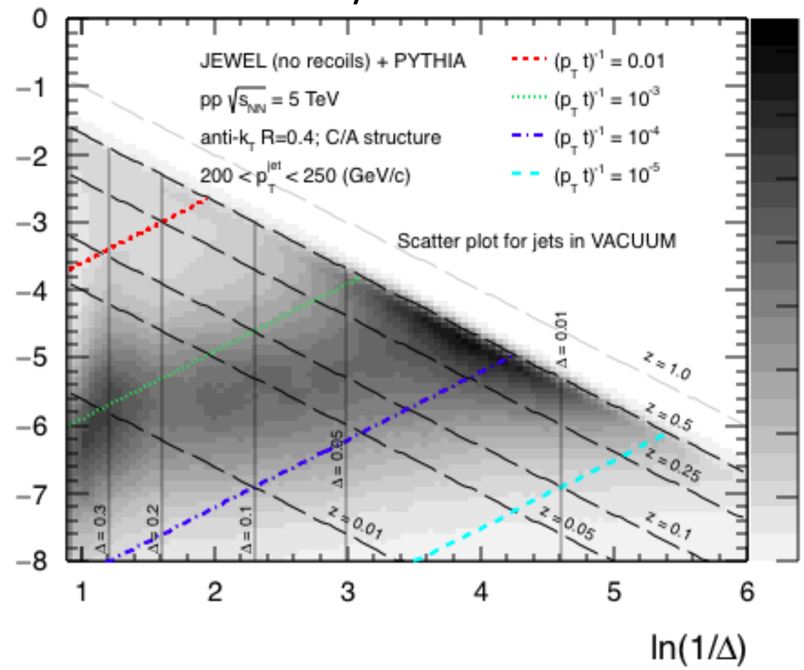
200-250 GeV/c



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Jet Lund diagram

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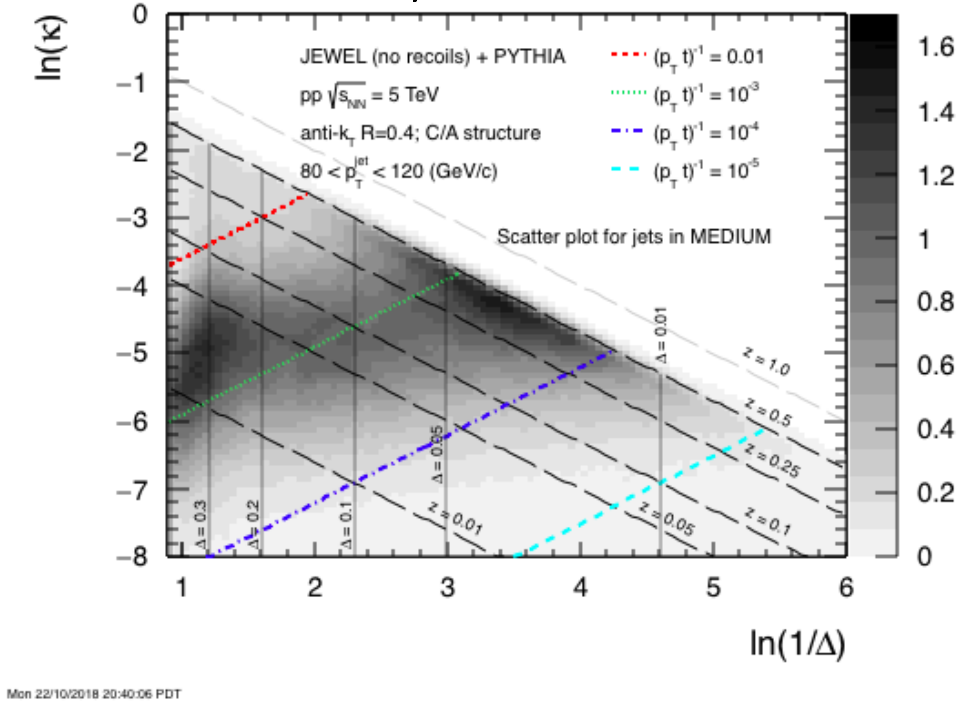
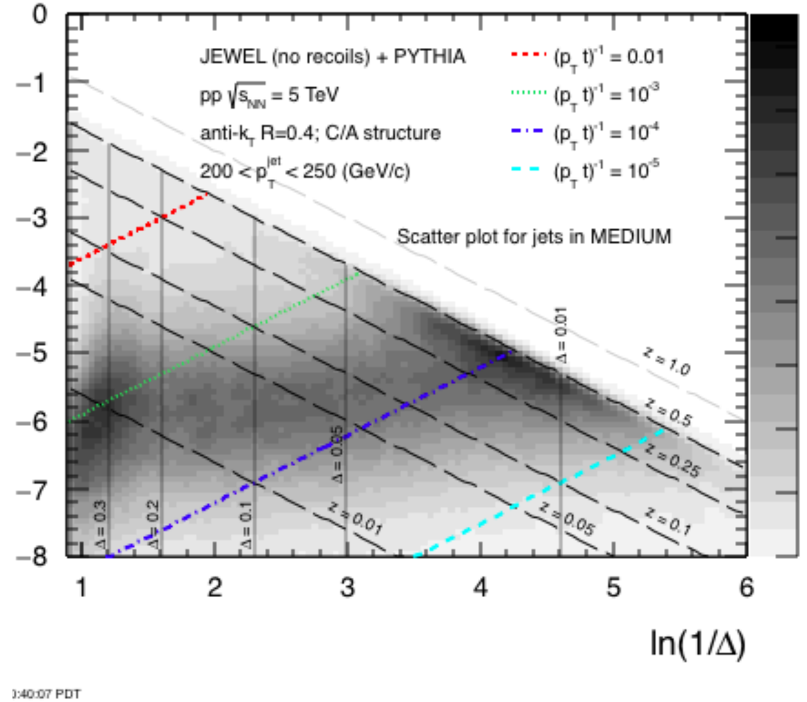
JEWEL + PYTHIA (RECOIL=OFF)
10% most central PbPb at 5 TeV
MEDIUM

80-120 GeV/c



200-250 GeV/c



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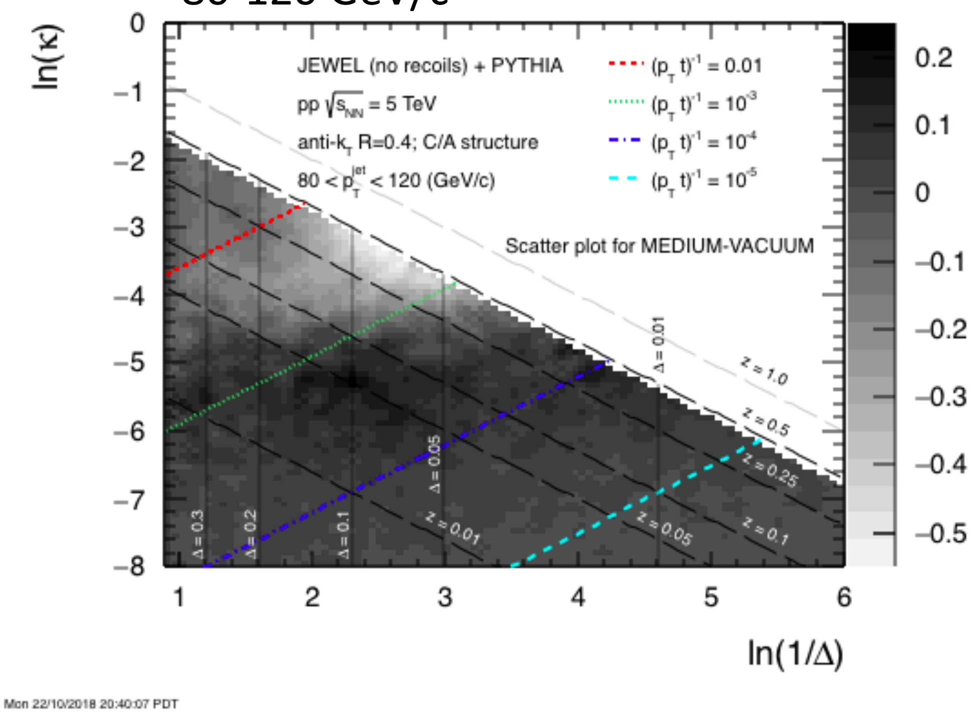
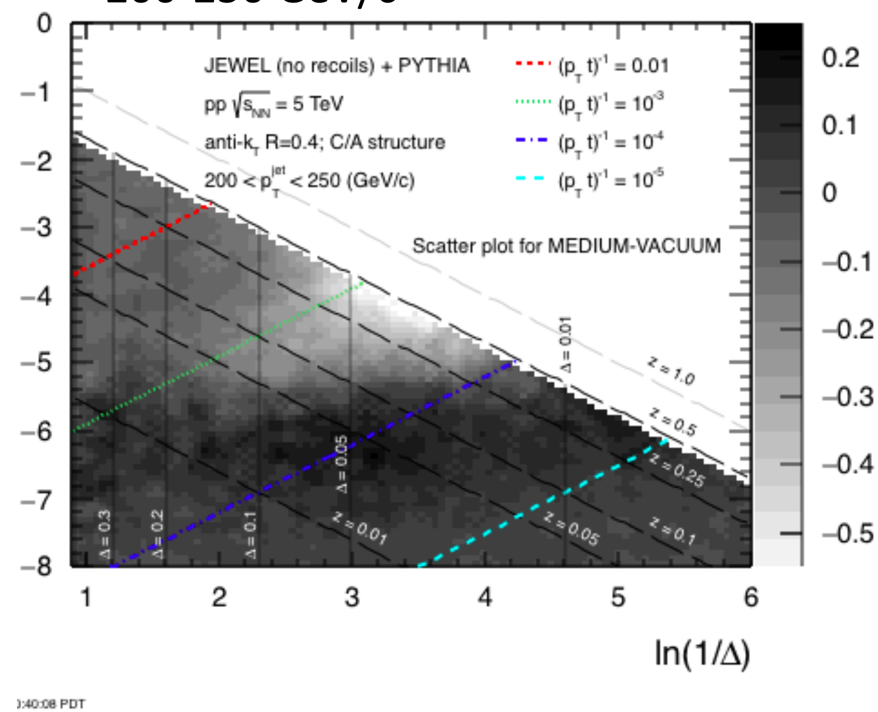
80-120 GeV/c



200-250 GeV/c



Jet Lund diagram slicing through time

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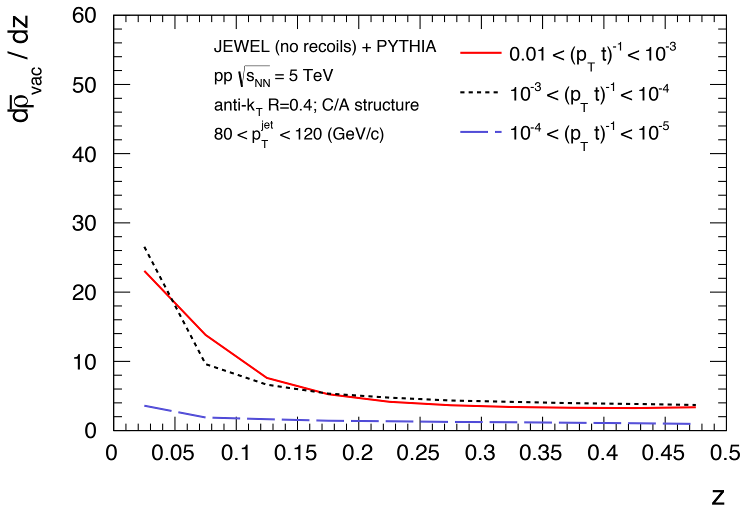
$$\bar{\rho}(\Delta,\kappa) = \frac{1}{N_{\text{jet}}}\frac{dn_{\text{emission}}}{d\ln\kappa\ d\ln 1/\Delta}$$



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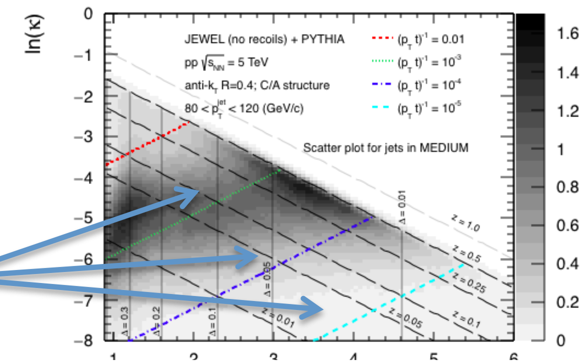
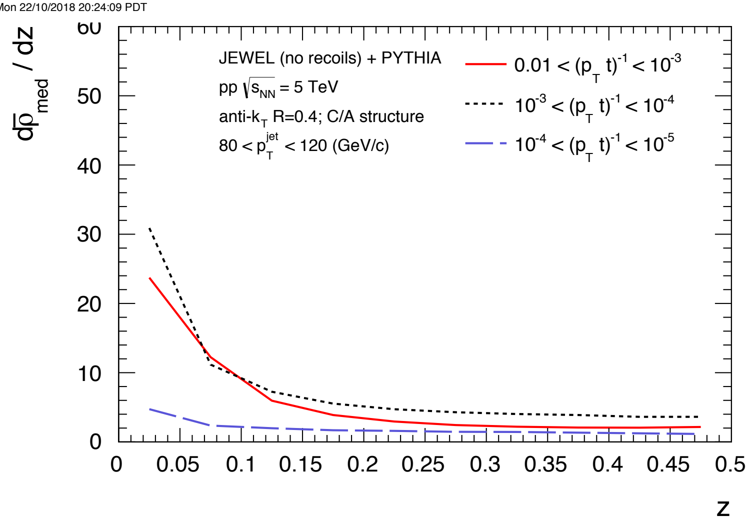
80 – 120 GeV/c

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

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





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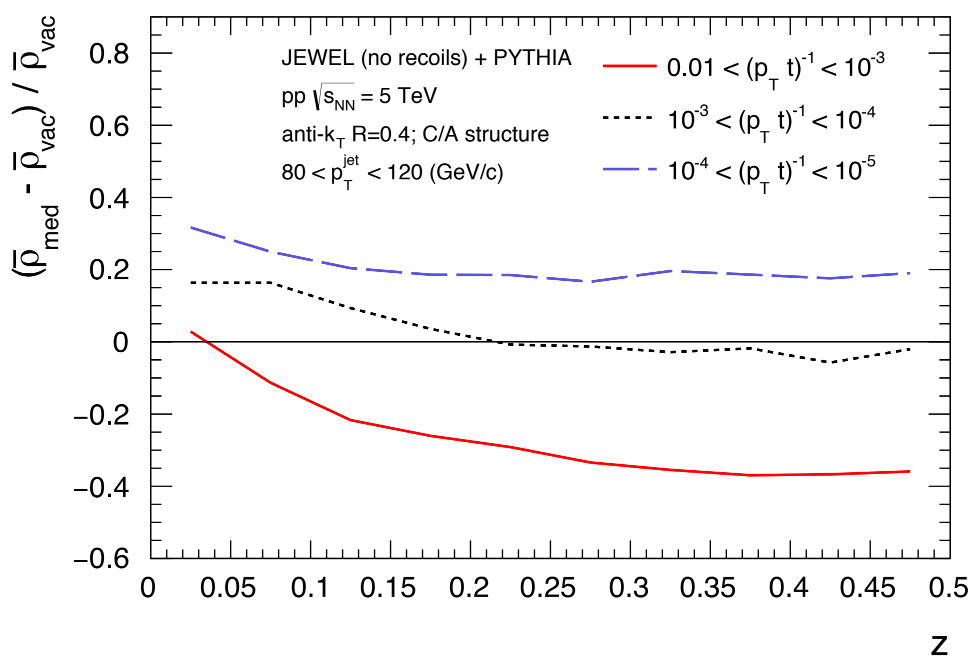

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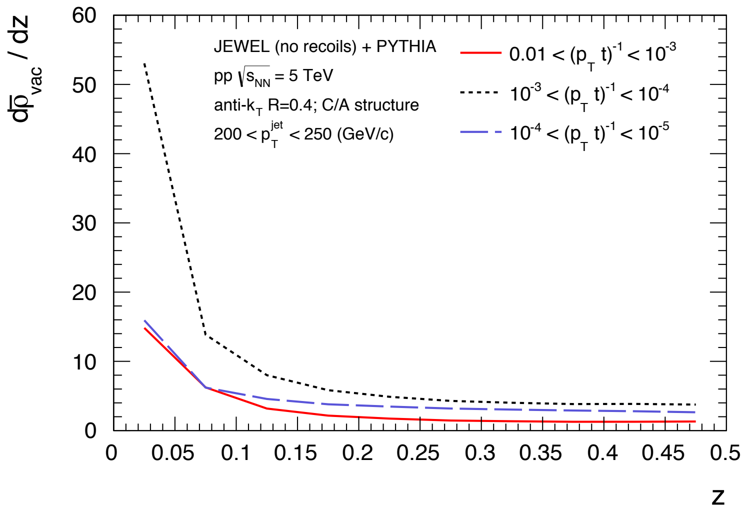

Mon 22/10/2018 20:24:09 PDT

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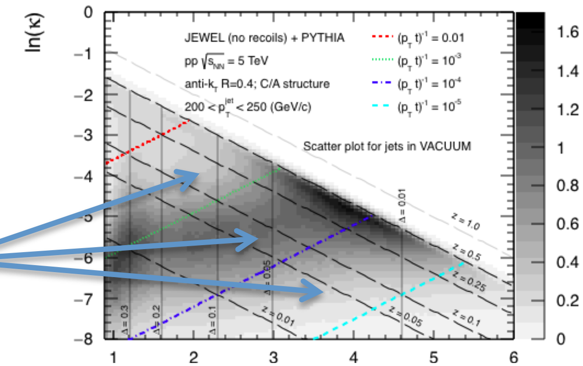
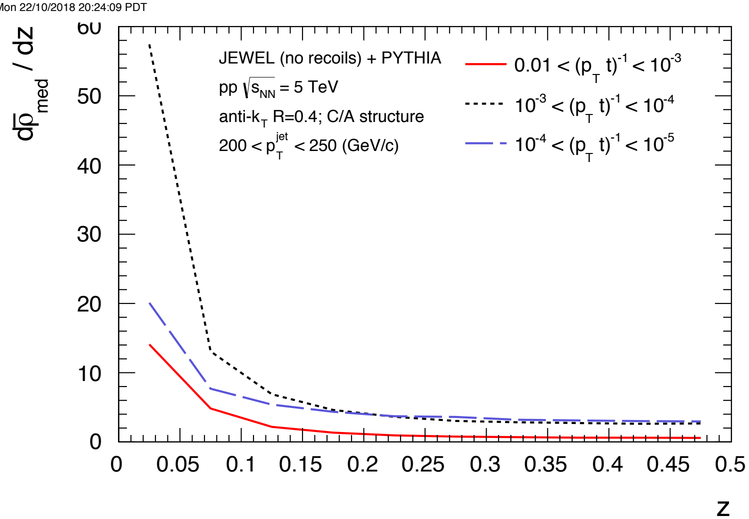
Slicing along $1/(p_T$ x t) and projecting along z





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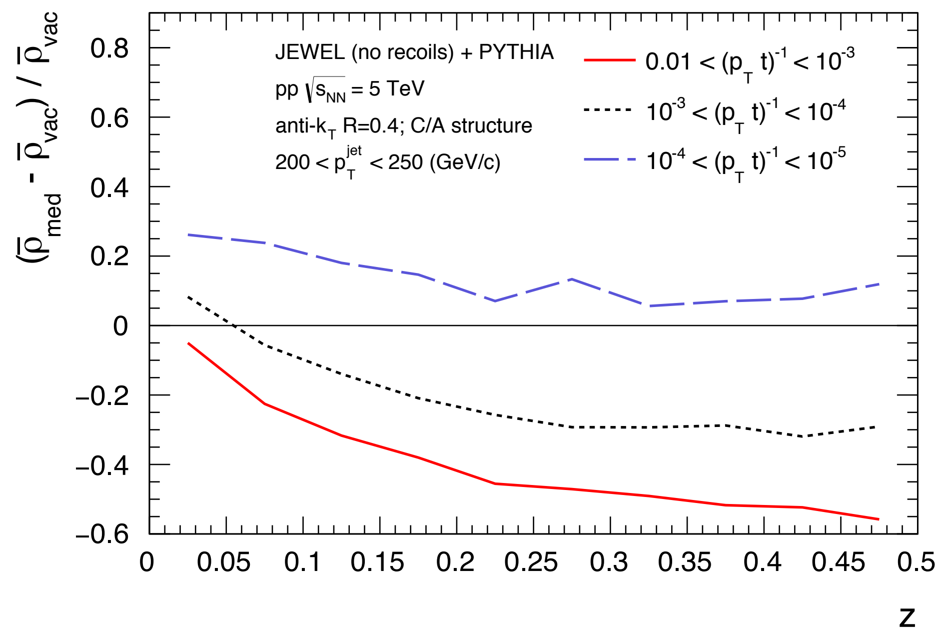

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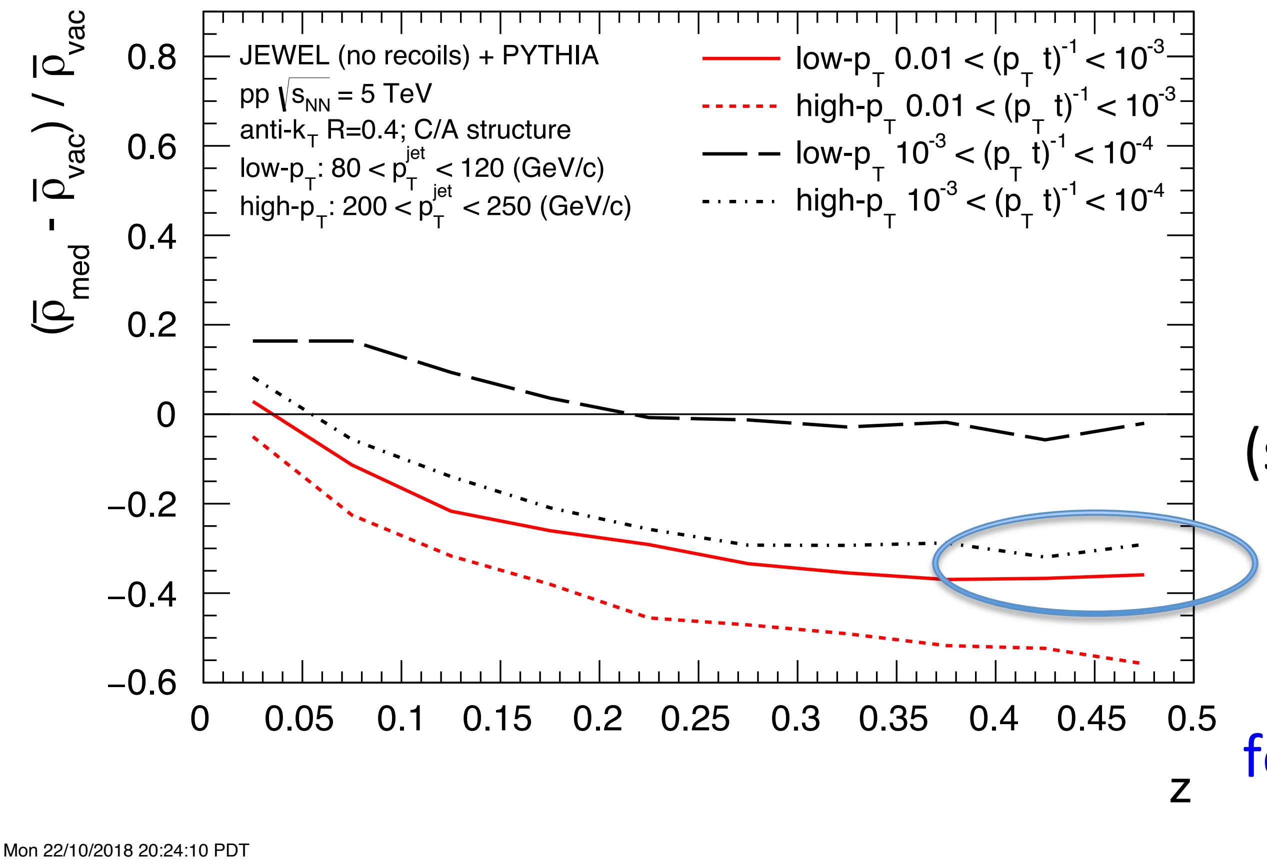

Low- with high-p_T for the similar t

⇔

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

Work on slicing on formation time directly ongoing

Jet Lund diagram slicing through time

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

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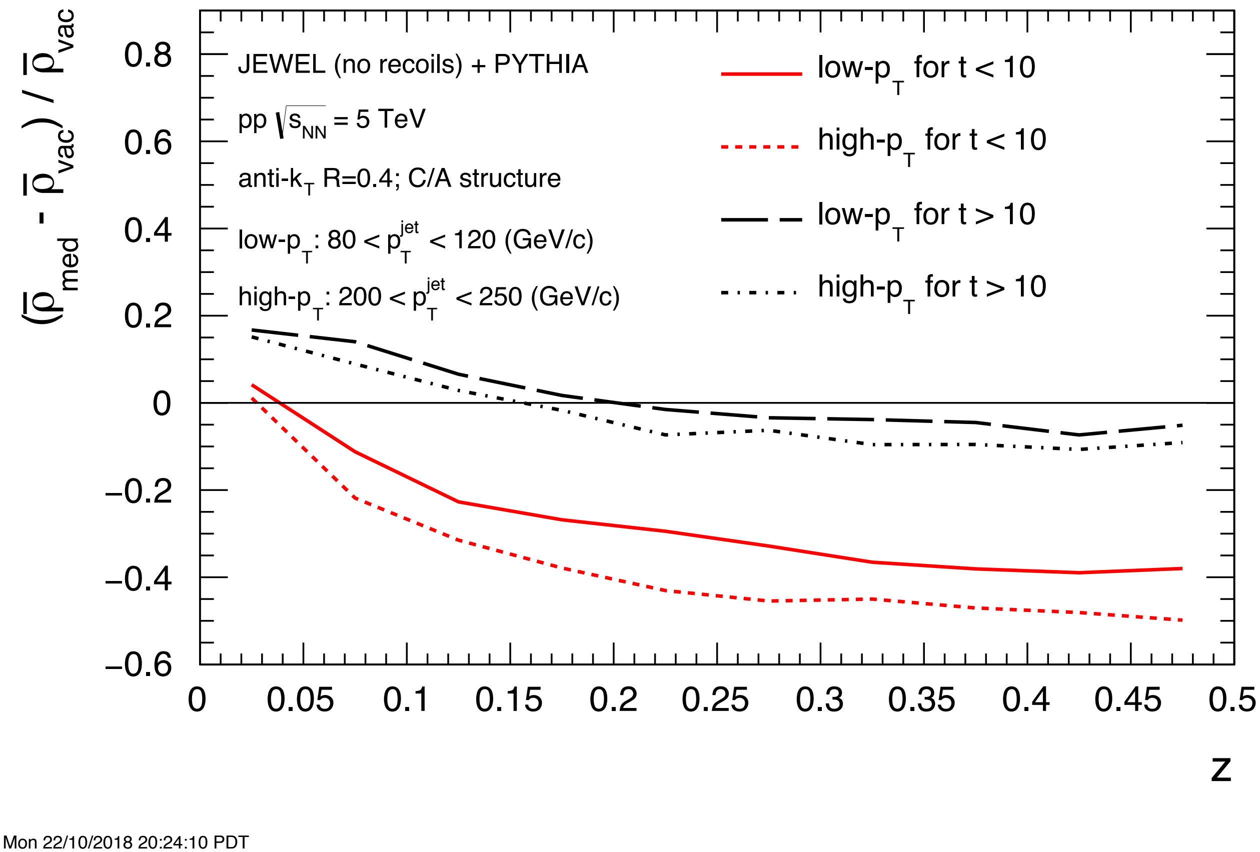


Low- with high-p_T for the similar t

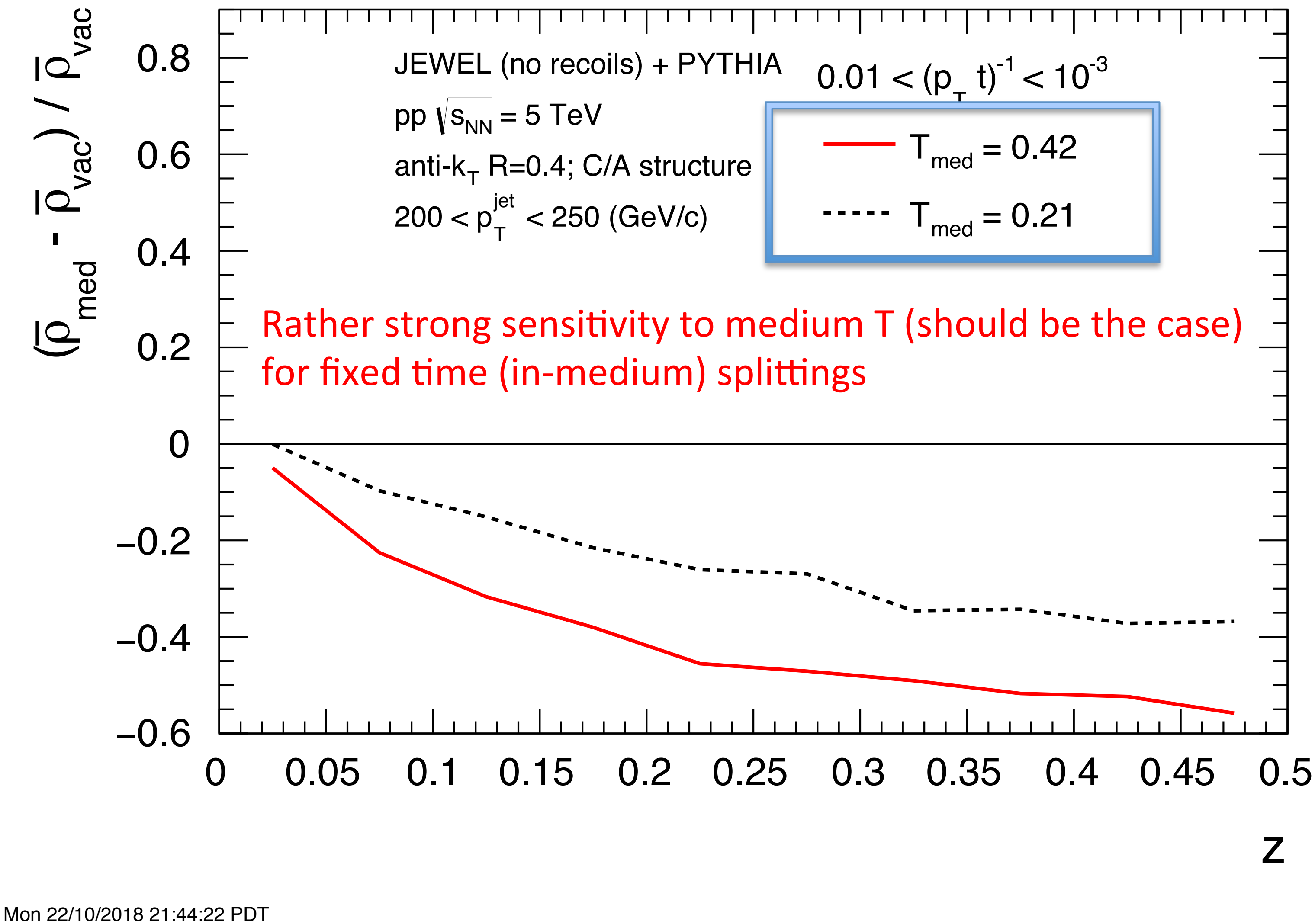
⇔

Early: in-medium

Late: no-medium

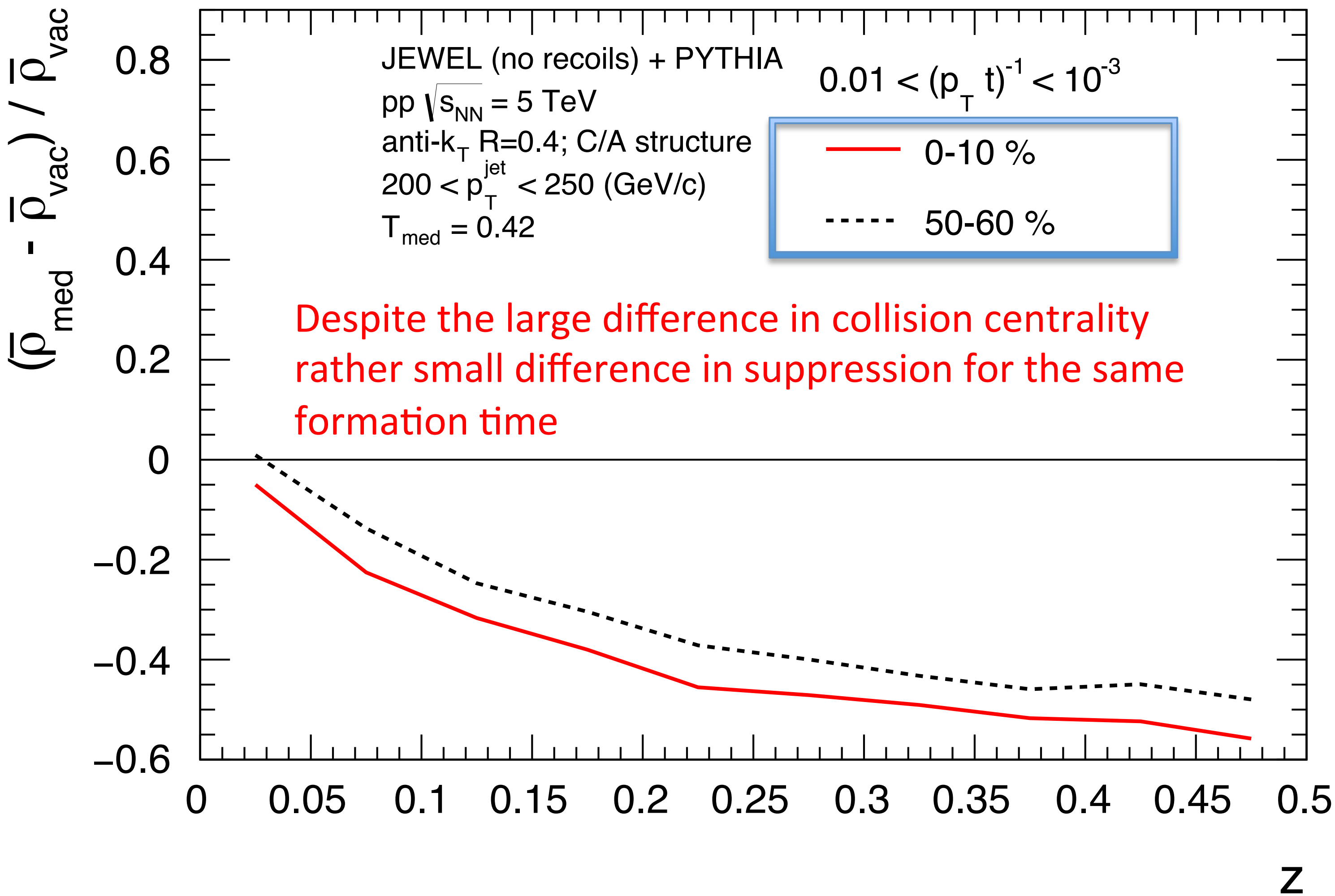
Sensitivity to medium's T

An example…



Sensitivity to medium's L (centrality)

An example…



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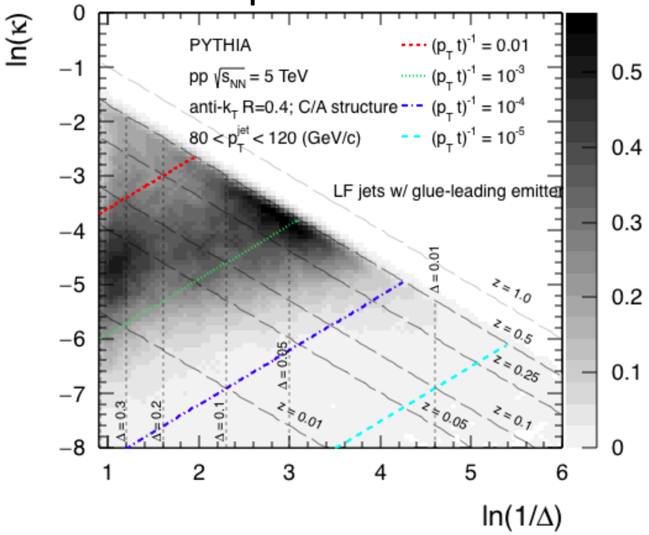
NOTES ON HEAVY QUARKS

Notes on (heavy-)quarks

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

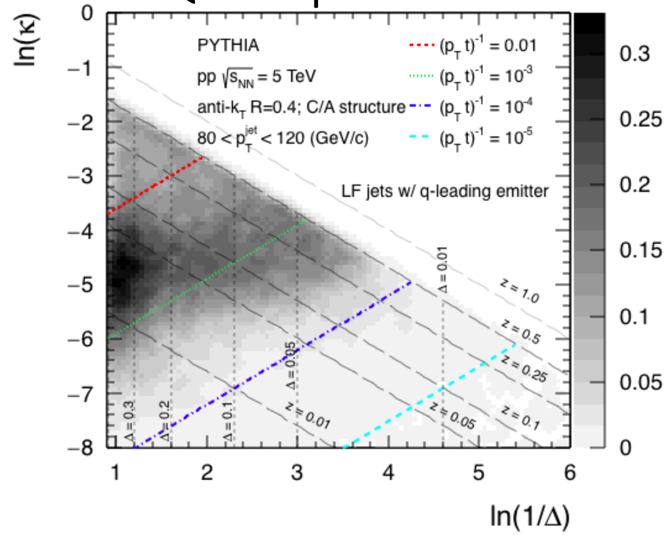
$$p_{T,a} > p_{T,b},\ \kappa = \frac{p_{T,b}}{p_{T,a}+p_{T,b}}\Delta_{ab}$$

Gluon splits



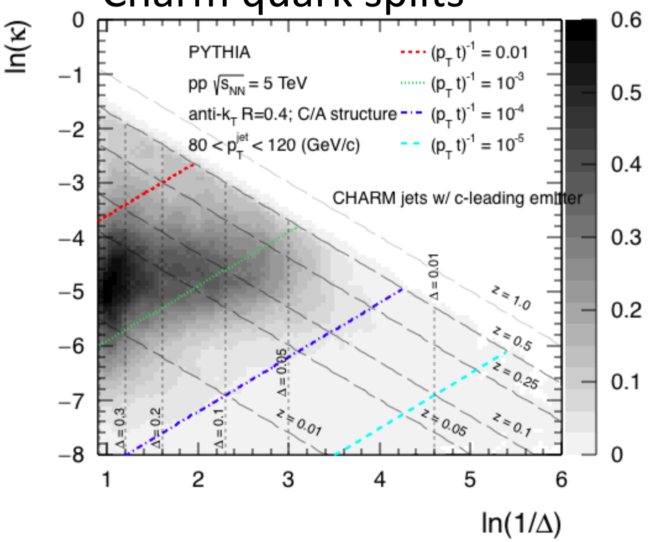
Mon 22/10/2018 19:05:01 PDT

LF Quark splits



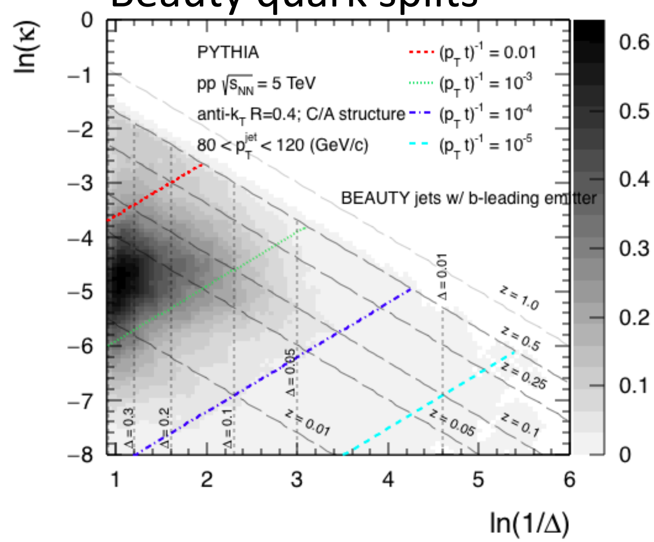
Mon 22/10/2018 19:05:02 PDT

Charm quark splits



Mon 22/10/2018 19:05:03 PDT

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

Dead cone: radiation suppressed 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 studied 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

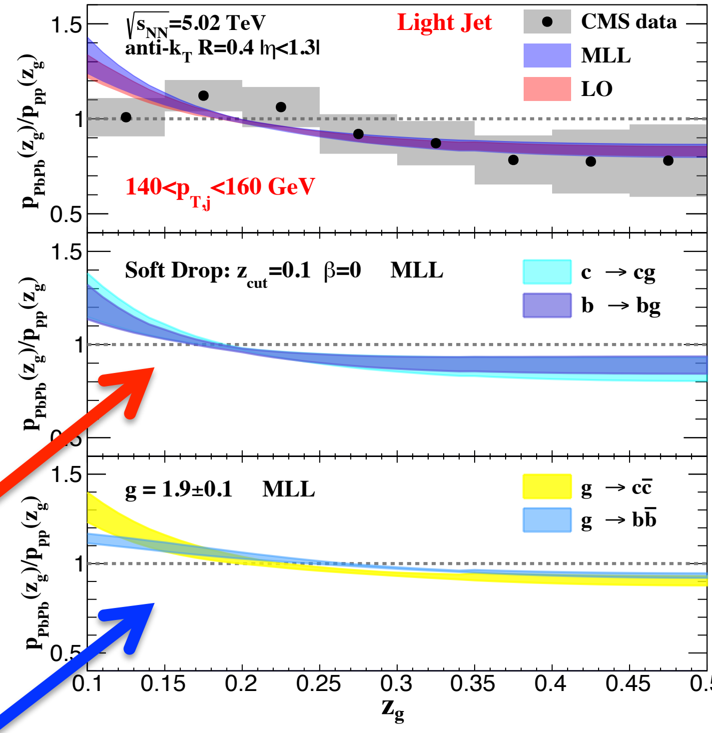
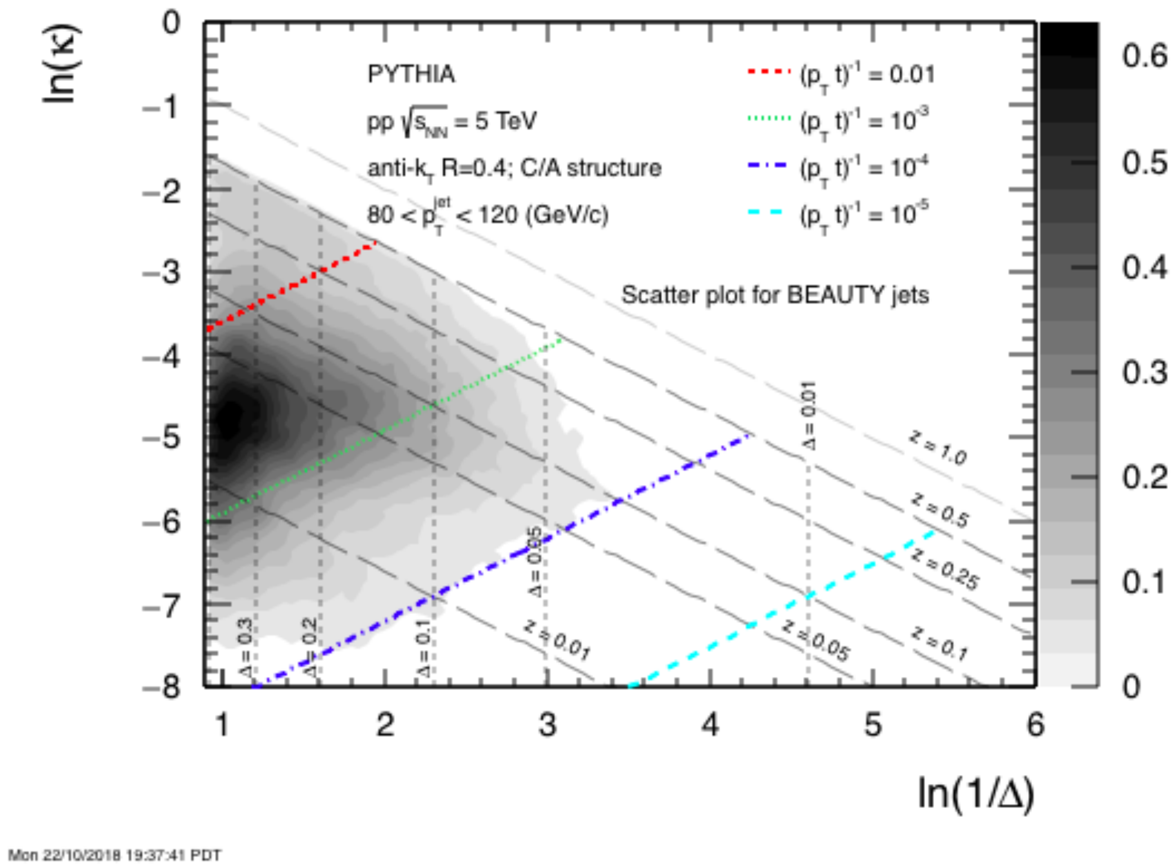


Figure 2. The modification of the jet splitting functions in 0-10% central Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for the p_T bin $140 < p_{T,j} < 160$ GeV. The upper panels compare the LO and MLL predictions to CMS light jet substructure measurements [12]. The middle and lower panels present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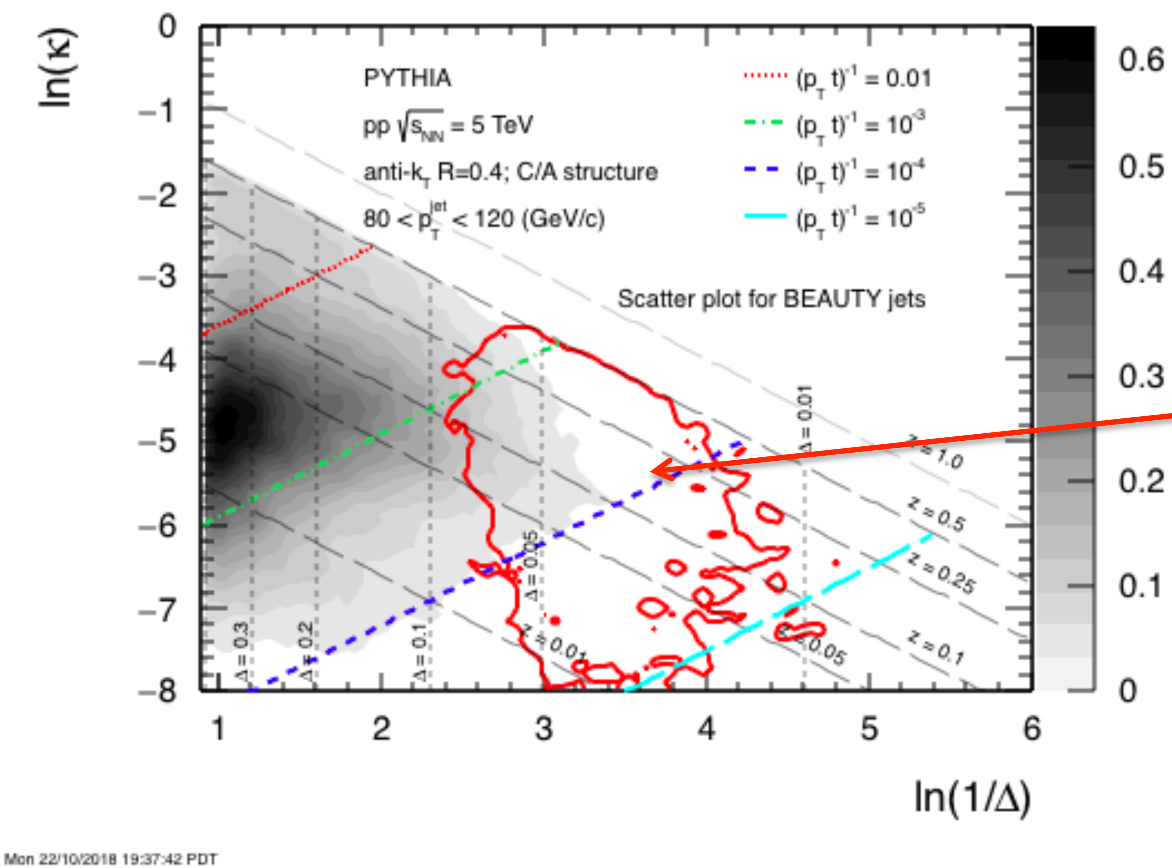
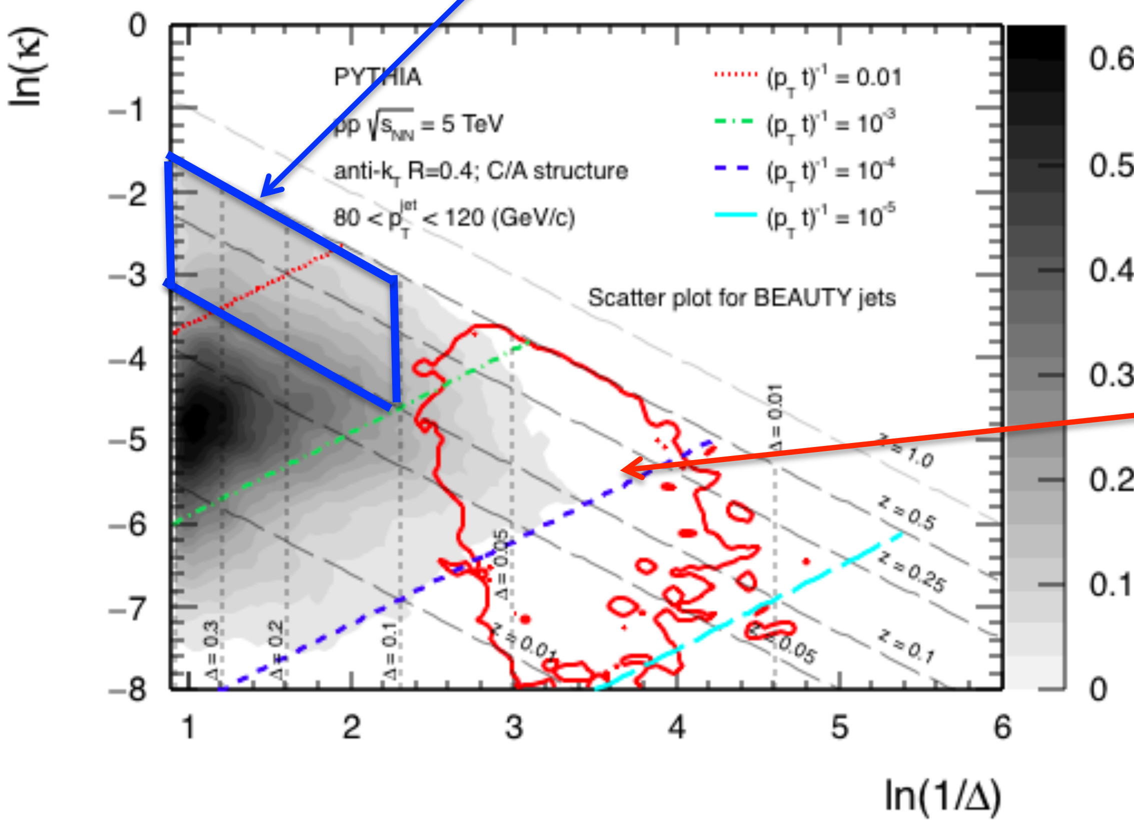


Dead cone
- An approximation
  - $\Delta < m/E$
- Entries that dead cone ought to suppress

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? (even worse separation for higher p_T)

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



Dead cone
- An approximation
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Mon 22/10/2018 19:37:42 PDT

Heavy-flavor and the dead cone…

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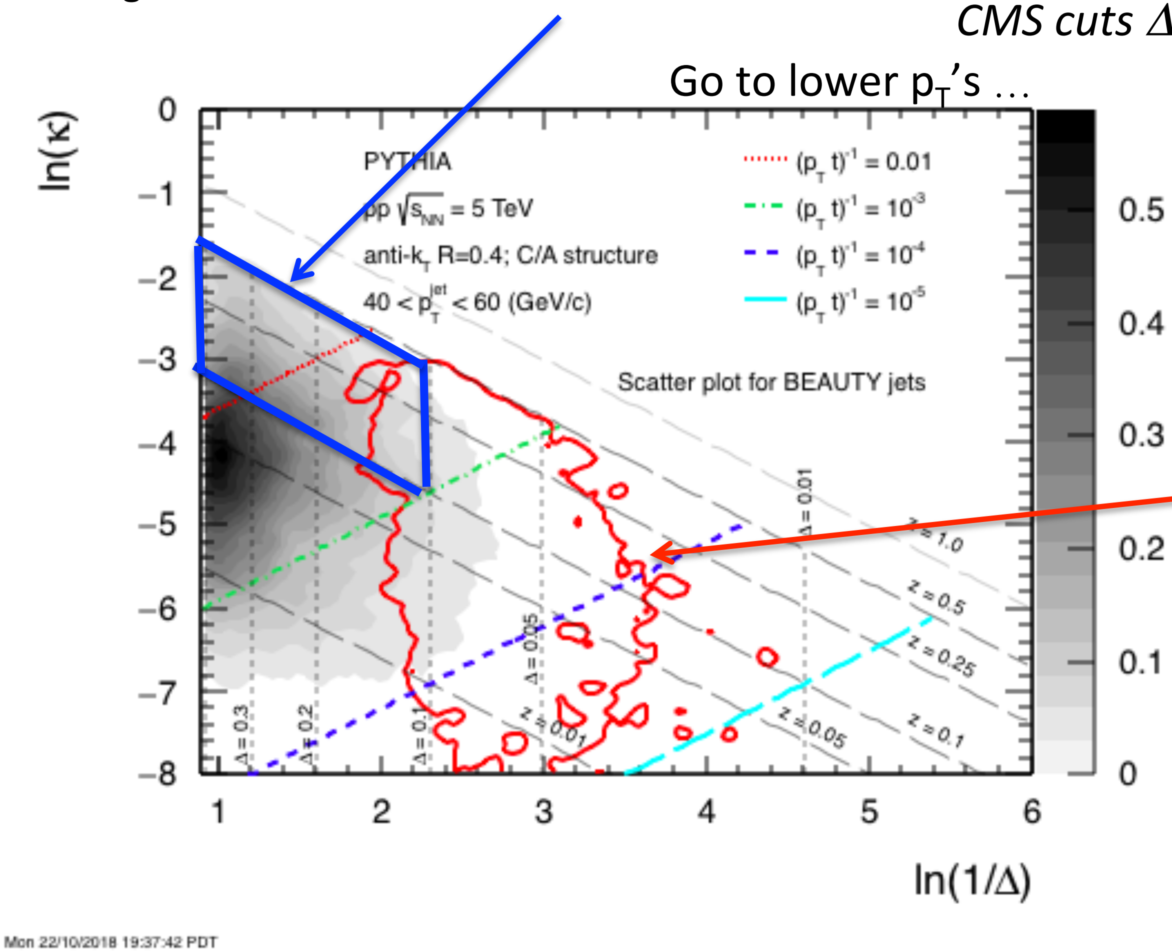
CMS cuts $\Delta < 0.1$ – ALICE does not

Go to lower p_T's …



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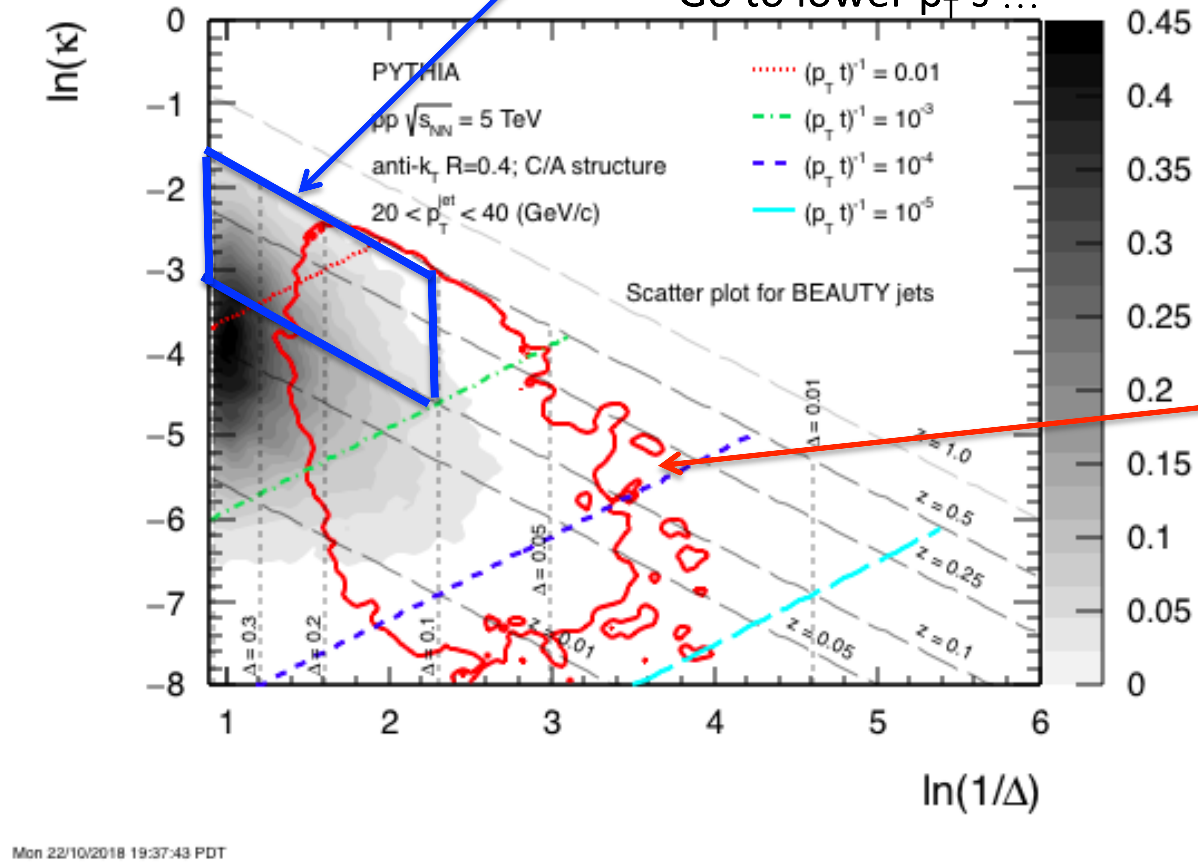

Dead cone
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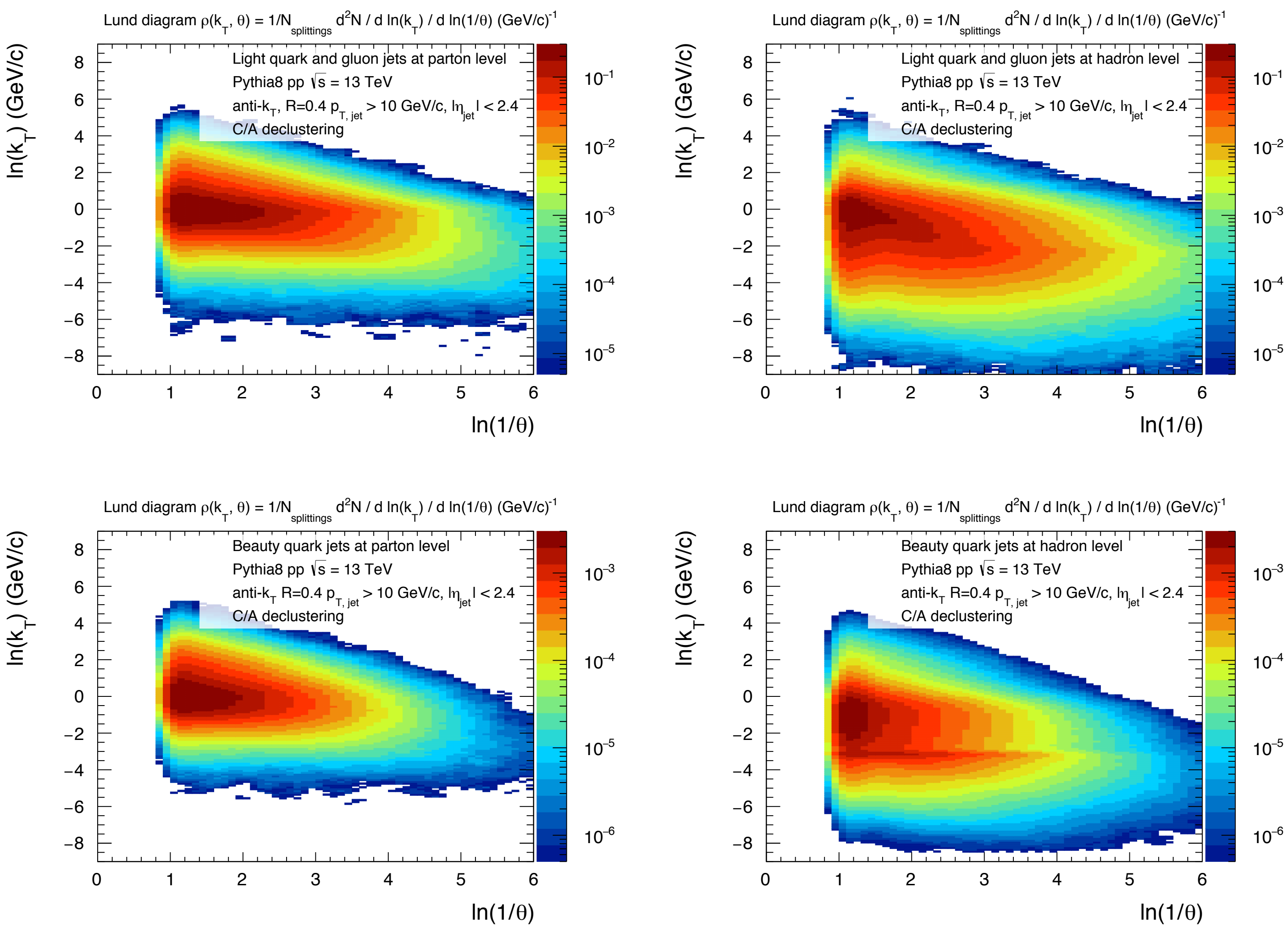
Searching for the dead cone (PYTHIA)



Light-flavor

Dead cone:
radiation
suppressed for
$\theta < m/E$

b-jets

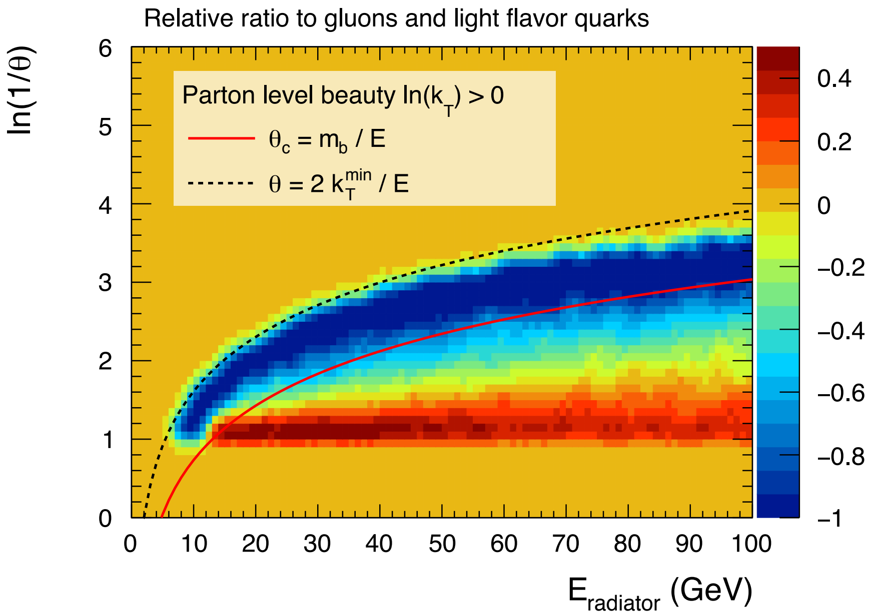
Lund with C/A
Cut Lund non-perturbative region log(kt) < 0
Project onto E_{radiator}

https://arxiv.org/abs/1812.00102

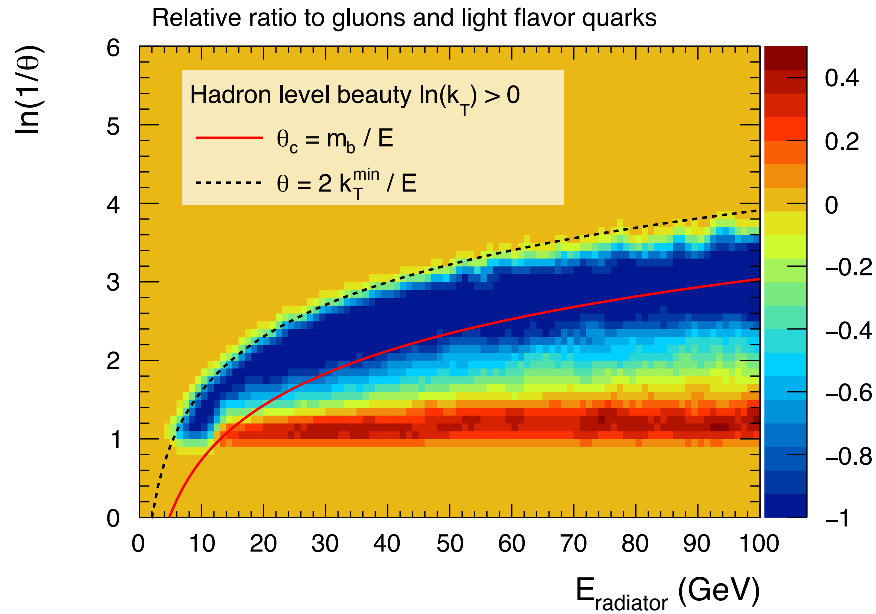
Searching for the dead cone

Ratio: b-jets / LF

Parton level



Hadron level – measurable effect(?)



Lund with C/A
Cut Lund non-perturbative region log(kt) < 0
Project onto E_{radiator}

Dead cone:
radiation suppressed for
$\theta < m/E$

Summary

- Lots of activity on jets in AA (and pp – as the reference)
- Strong focus on jet substructure, declustering => a direction seen as a way towards in-medium parton shower studies (more in-depth?) – still somewhat on a learning curve…
- Quark vs. gluon energy in-medium radiation is likely to be a one of the most interesting items – (one of the most important predictions) – looking forward to high-precision photon/Z-jet coincidences; heavy-flavor jets
- RHIC vs. LHC – luxury but very useful comparison and contrast
- New ideas: leading subjets (https://arxiv.org/abs/1710.07607); automated substructure observables discovery (https://arxiv.org/abs/1810.00835)

ADDITIONAL MATERIAL

Searching for the Dead Cone

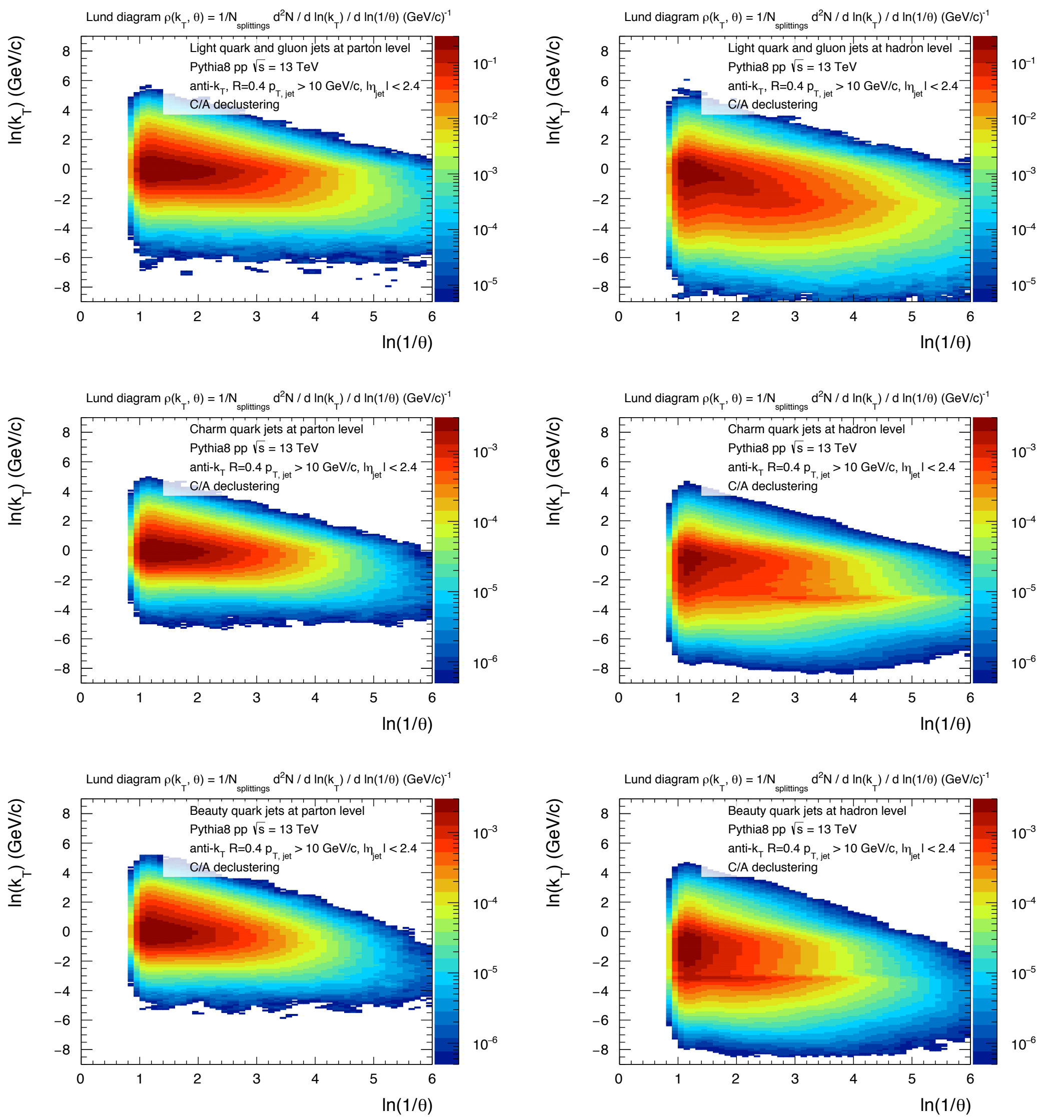


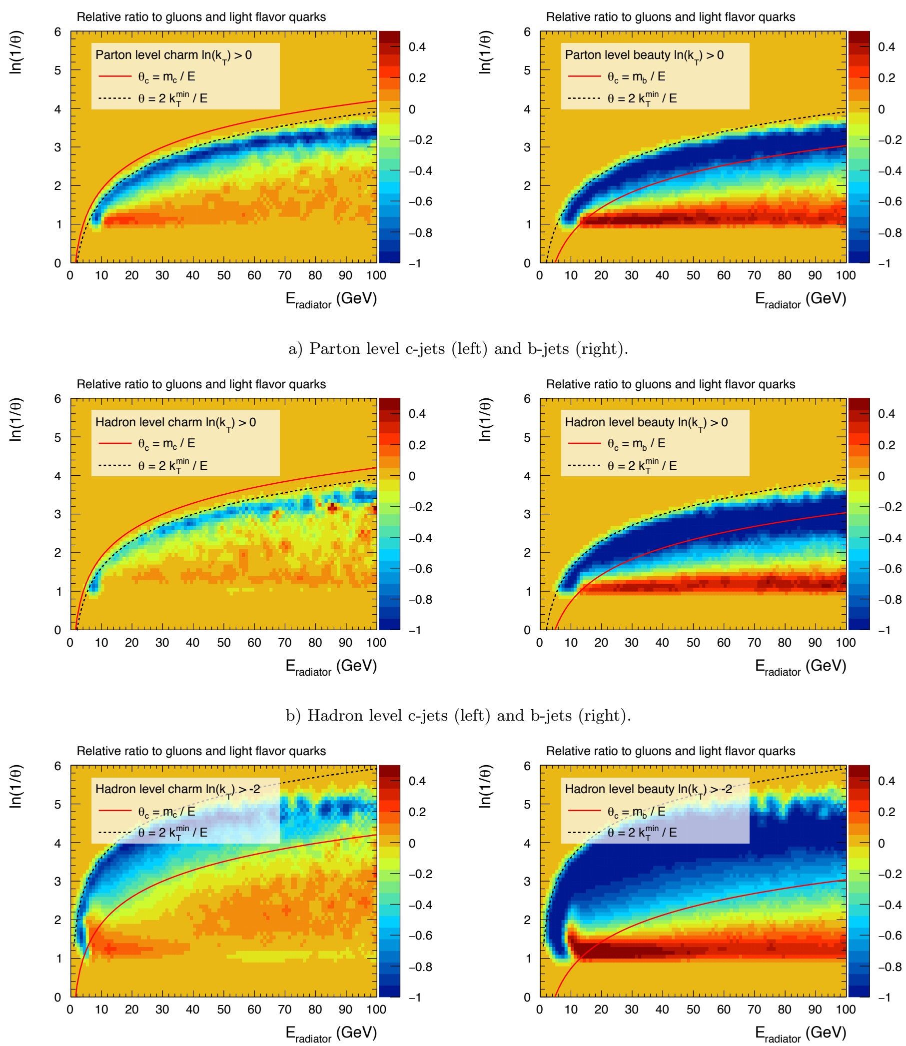
FIG. 1: Left column: Lund diagrams for charm and beauty and inclusive jets at parton level and UE switched off, for low momentum jets of $10 < p_{T,jet} < 40$. Right column: Same plots but at hadron level.

Lund with C/A

Cut Lund non-perturbative region log(kt) < 0

Project onto E_{radiator}

Searching for the Dead Cone



a) Parton level c-jets (left) and b-jets (right).

b) Hadron level c-jets (left) and b-jets (right).

c) Hadron level with a relaxed cut on k_T - demonstration of the impact of non-perturbative effects

FIG. 2: Relative difference for heavy flavor and inclusive jets of the correlation of the splitting angle and the energy of the radiator. The red curves correspond to the critical angle $\theta_C = m_Q/E$.

Lund with C/A

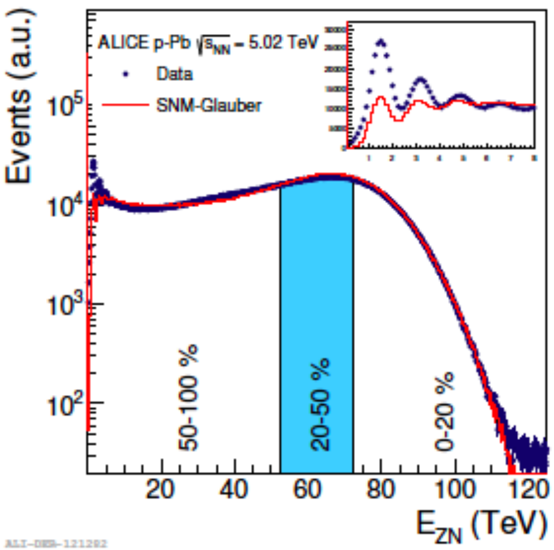
Cut Lund non-perturbative region log(kt) < 0

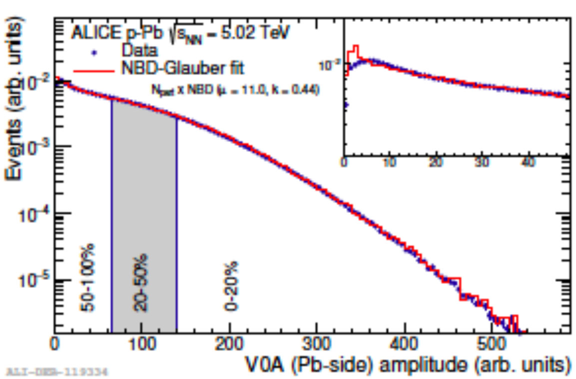
Project onto E_{radiator}

Δ_{recoil} application: jet quenching in p+Pb

ALICE, Phys.Lett. B783 (2018) 95

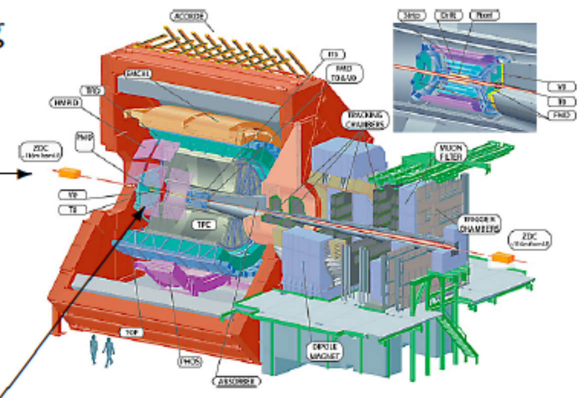
Event activity (a.k.a. "centrality) in p+Pb @ 5.02 TeV





Pb-going direction

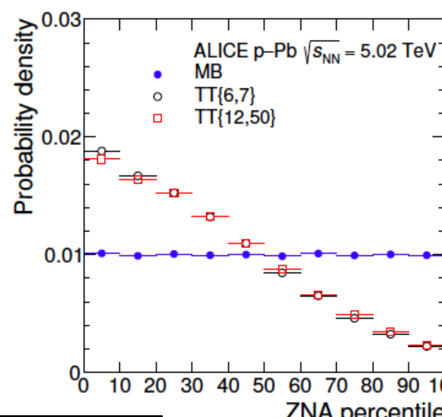
ZNA

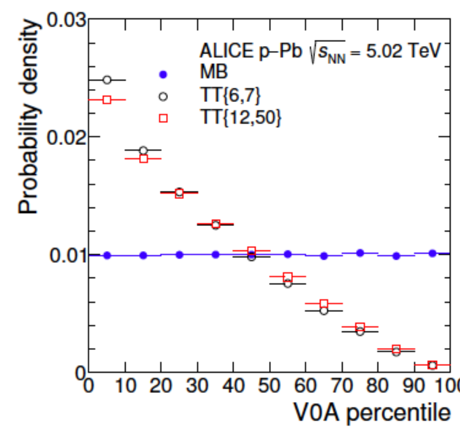


V0A

$\eta \in (2.8, 5.1)$

EA bias due to high p_T trigger
→ does EA measure "centrality"?





High EA

Low EA

Hard Probes conference October 2018
https://indico.cern.ch/event/634426/

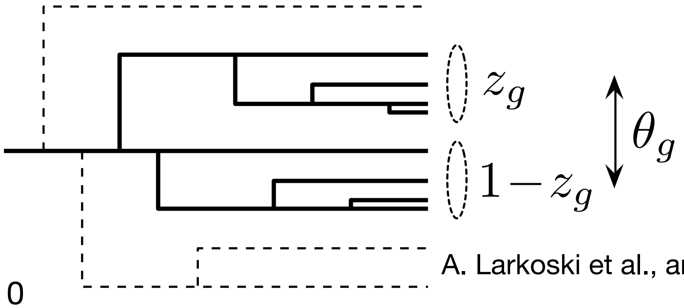
Jet Structure: Splitting Function

ALICE

- **Study QCD 1→2 splitting function in pp**
  - momentum fraction z_g carried hard jet component after removing soft jets with momentum fraction z

$$z = \frac{\min(p_{T,1};\, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$

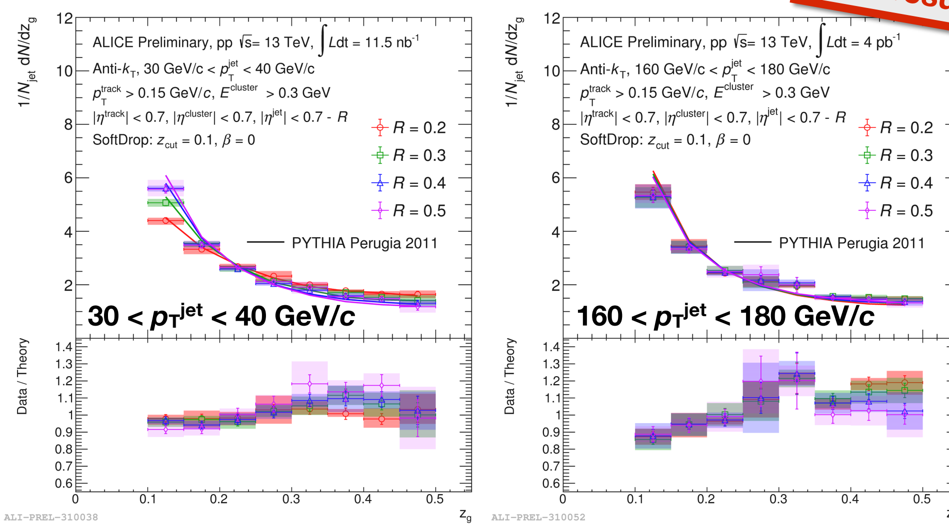
here: $z_{cut} = 0.1$, $\beta = 0$



A. Larkoski et al., arXiv:1704.05066

New result!

- **No dependence on jet p_T (as expected)**
  - probe now high-p_T jets (180 GeV/c)
- **Depends on jet cone radius at low p_T → points to non-perturbative effects**
- Studied out to $R = 0.5$



M. Fasel, Wed, 9h40

https://indico.cern.ch/event/634426/contributions/3003545/attachments/1725255/2786826/tdahms_20181001.pdf

Hard Probes conference October 2018
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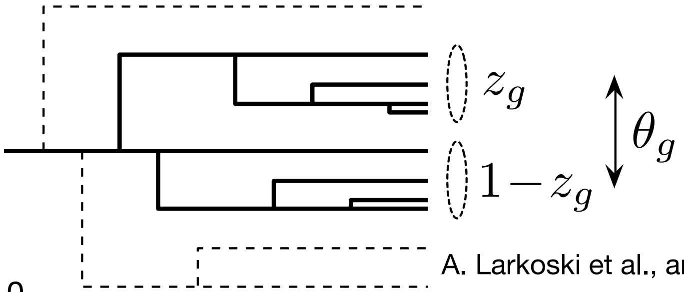
- **Study QCD 1→2 splitting function in pp**
  - momentum fraction z_g carried hard jet component after removing soft jets with momentum fraction z

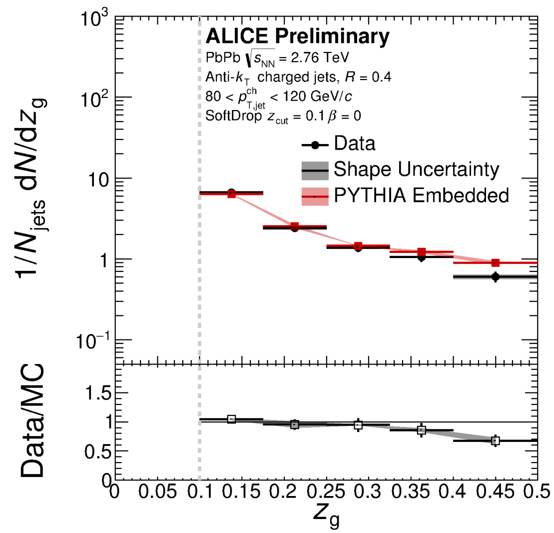
$$z = \frac{\min(p_{T,1}; p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$

here: $z_{cut} = 0.1$, $\beta = 0$



A. Larkoski et al., arXiv:1704.05066

- **No dependence on jet p_T (as expected)**
  - probe now high-p_T jets (180 GeV/c)
- **Depends on jet cone radius at low p_T → points to non-perturbative effects**
- Studied out to $R = 0.5$



M. Fasel, Wed, 9h40

https://indico.cern.ch/event/634426/contributions/3003545/attachments/1725255/2786826/tdahms_20181001.pdf

Hard Probes conference October 2018
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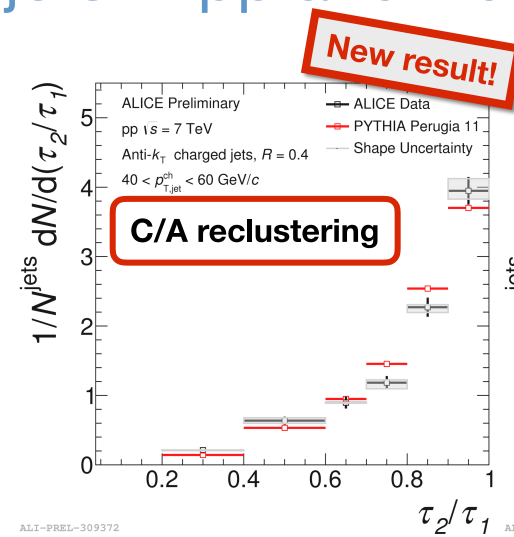
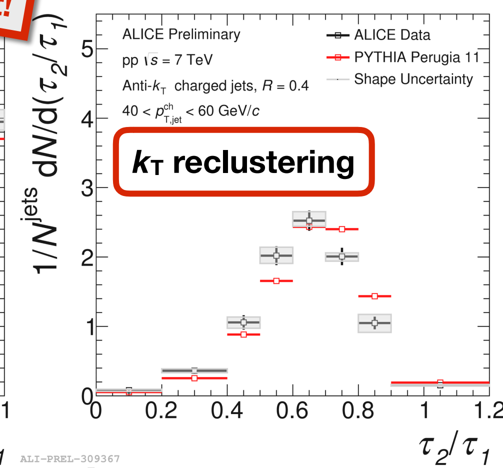
Jet Structure: Sub-jets in pp and Pb–Pb

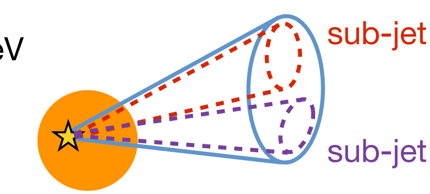
- Study number of sub-jets within jets
  - Quantify how pronounced *N* prongs are in a jet

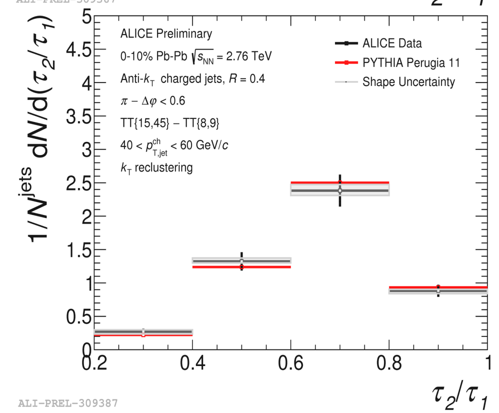
$$\tau_N = \frac{\sum_i p_{\mathrm{T},i} \min(\Delta R_{1,i},\, \Delta R_{2,i}, \ldots \Delta R_{N,i})}{R \sum_i p_{\mathrm{T},i}}$$

  - $\tau_N \to 0$: *N* or less cores
  - $\tau_N \to 1$: at least *N*+1 cores
  - $\tau_2/\tau_1 \to 0$: jet has 2 prongs
- Different structures probed by different reclustering algorithms (e.g. C/A or k_T)
- **Splitting of sub-jets in pp described by PYTHIA**
  - use PYTHIA for energy extrapolation: 7 TeV → 2.76 TeV
- **Very similar sub-jet structure in Pb–Pb**
  → In-medium jet core remains vacuum-like
  - more pp data needed to quantify









N. Zardoshti, Thu, 14h40

https://indico.cern.ch/event/634426/contributions/3003545/attachments/1725255/2786826/tdahms_20181001.pdf