Measurement of the Lund jet plane density at 13 TeV with CMS

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XXXVI Reunión Anual de la División de Partículas y Campos
Sep 8-10 2022

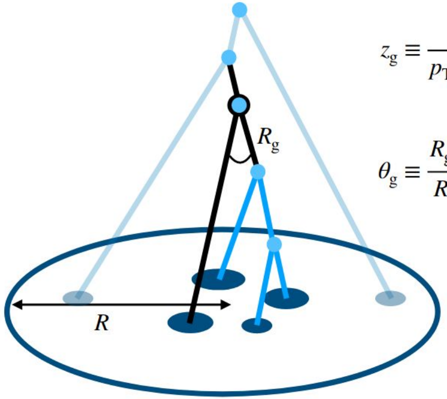
Jet substructure

- Main idea: organizing jet constituents 4-momenta into intelligible and transparent observables.

  Resilience to soft radiation.

- Experimental precision to challenge state-of-the-art pQCD calculations and constrain parton shower & hadronization models of MC generators.

- *A field in rapid development!*



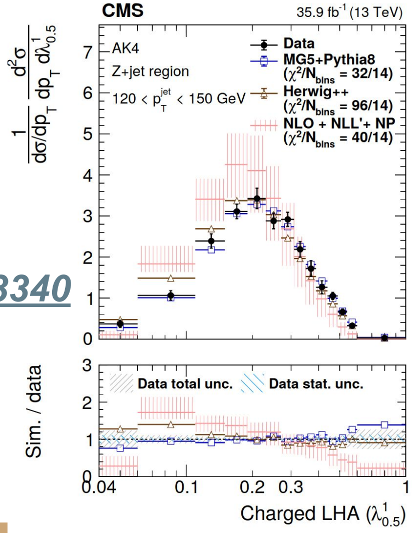
$$z_g \equiv \frac{p_{T,\mathrm{subleading}}}{p_{T,\mathrm{leading}} + p_{T,\mathrm{subleading}}}$$

$$\theta_g \equiv \frac{R_g}{R} \equiv \frac{\sqrt{\Delta y^2 + \Delta\varphi^2}}{R}$$

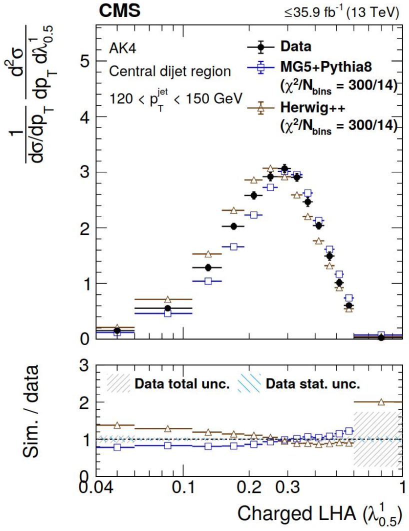
Soft drop grooming (algorithm to find the 1st hard subjet)

Additional inputs for V/H/t vs q/g jet discrimination.

Z+jet, quark enriched



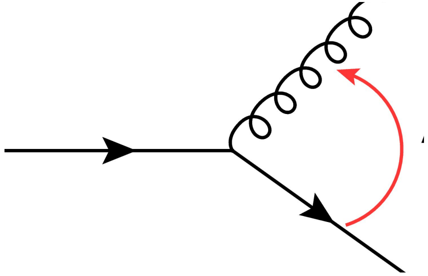
Dijet, gluon enriched



arXiv:2109.03340

Lund diagrams: a 2D representation of the phase-space of 1→2 splittings

F. Dreyer, G. Salam, G. Soyez, JHEP12(2018)064

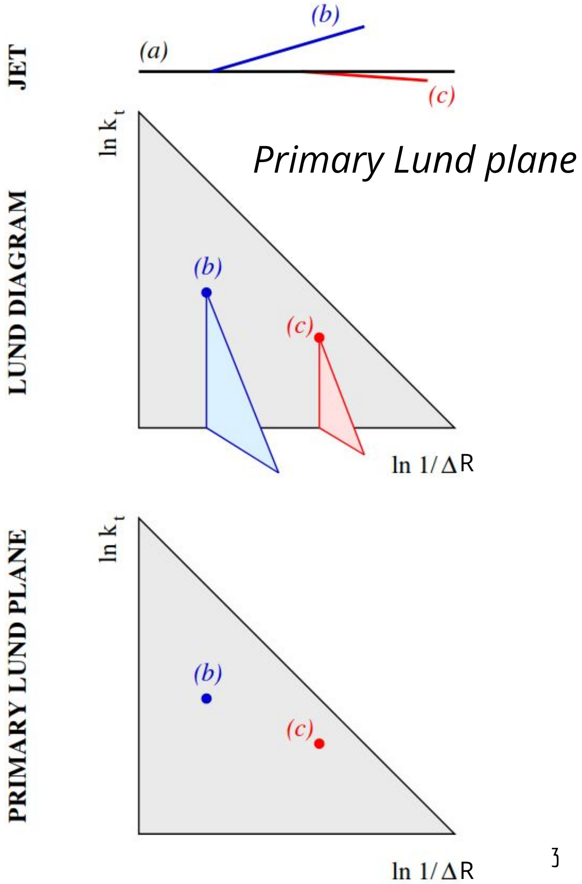


splitting angle

$$\Delta R = \sqrt{(y_{\rm soft} - y_{\rm hard})^2 + (\phi_{\rm soft} - \phi_{\rm hard})^2}$$

relative transverse momentum

$$k_{\rm T}$$



Used for parton shower and jet substructure techniques developments.

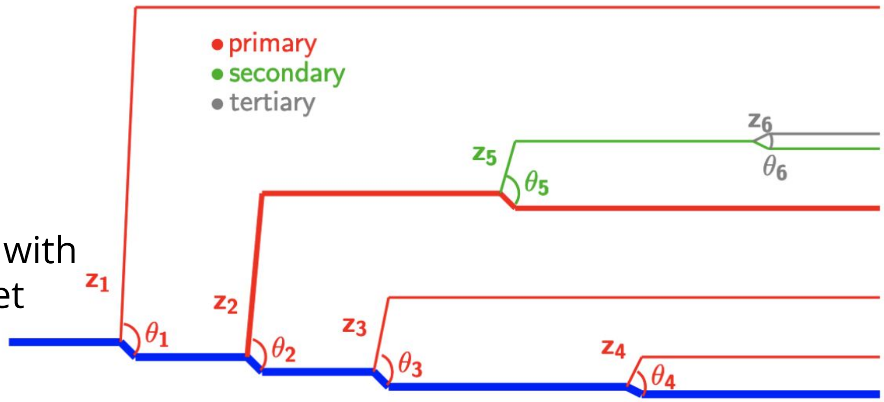
Experimental proxy for them can be constructed with iterative declustering techniques.

Constructing the primary Lund jet plane

Recipe proposed by F. Dreyer, G. Salam, G. Soyez, JHEP12(2018)064

Gregory Soyez' sketch

Start with C/A jet



Cambridge–Aachen declustering

large angles → small angles

Iterate until the **core** is a single particle.

We recluster the constituents of an anti-kT jet using the Cambridge–Aachen (C/A) algorithm.

C/A sequentially combines the closest pairs of particles (or proto-jets) at each step of the clustering process (small → large angles).

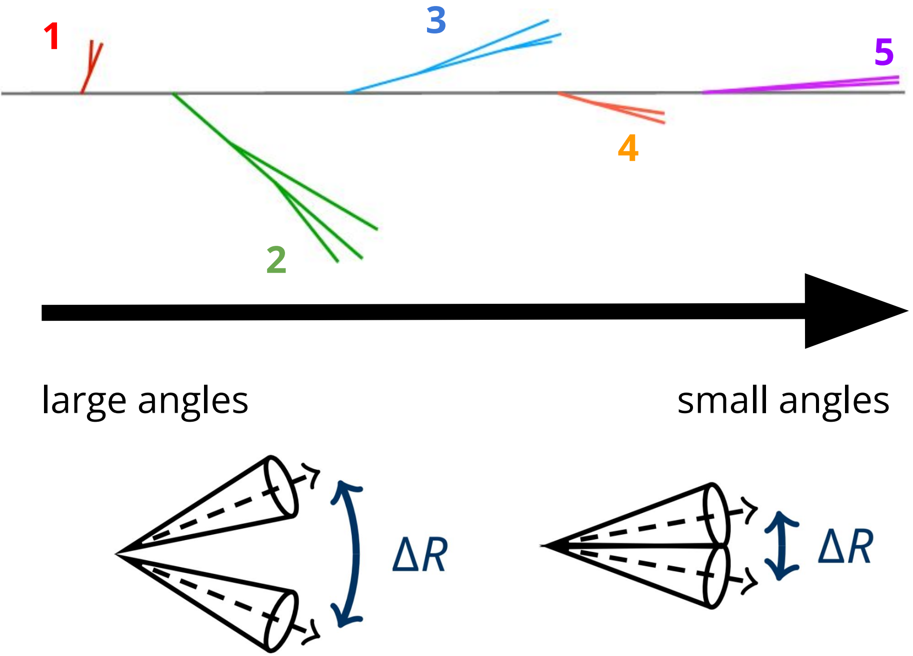
Then, the C/A jet is declustered iteratively (large → small angles).

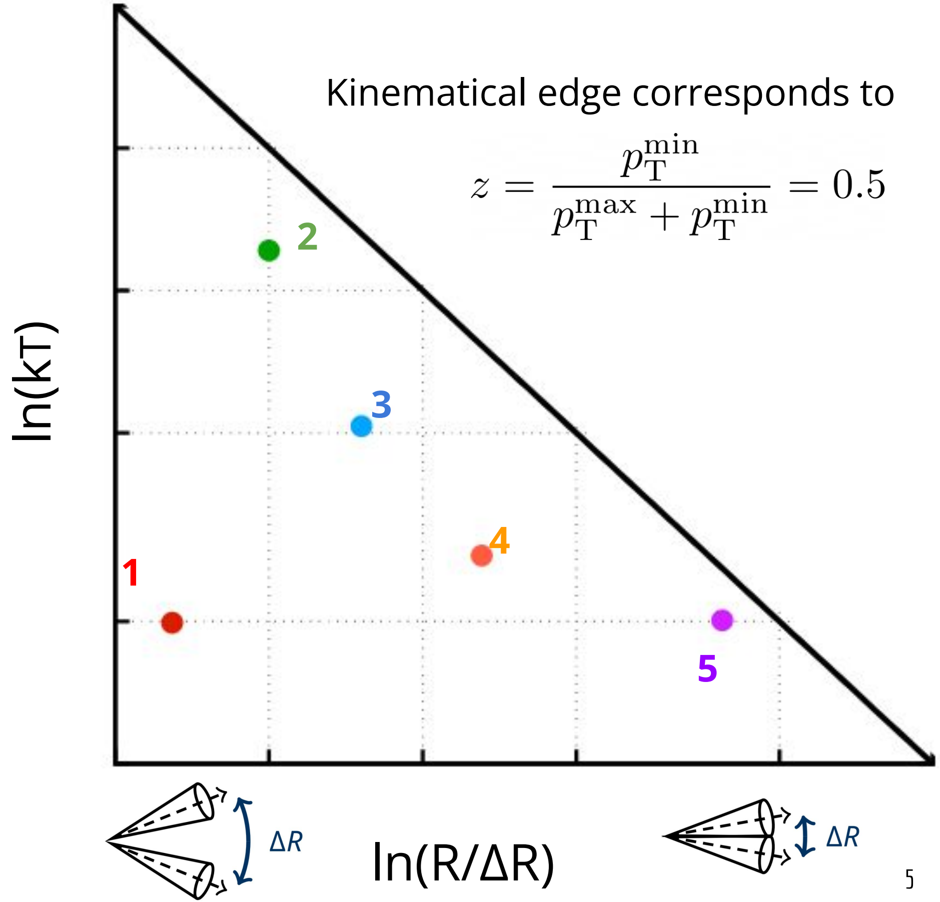
The transverse momentum and splitting angle of the soft prong (**emission**) relative to the hard prong (**core**) are extracted at each declustering iteration,

$$\Delta R = \sqrt{(y_{\rm soft} - y_{\rm hard})^2 + (\phi_{\rm soft} - \phi_{\rm hard})^2}$$

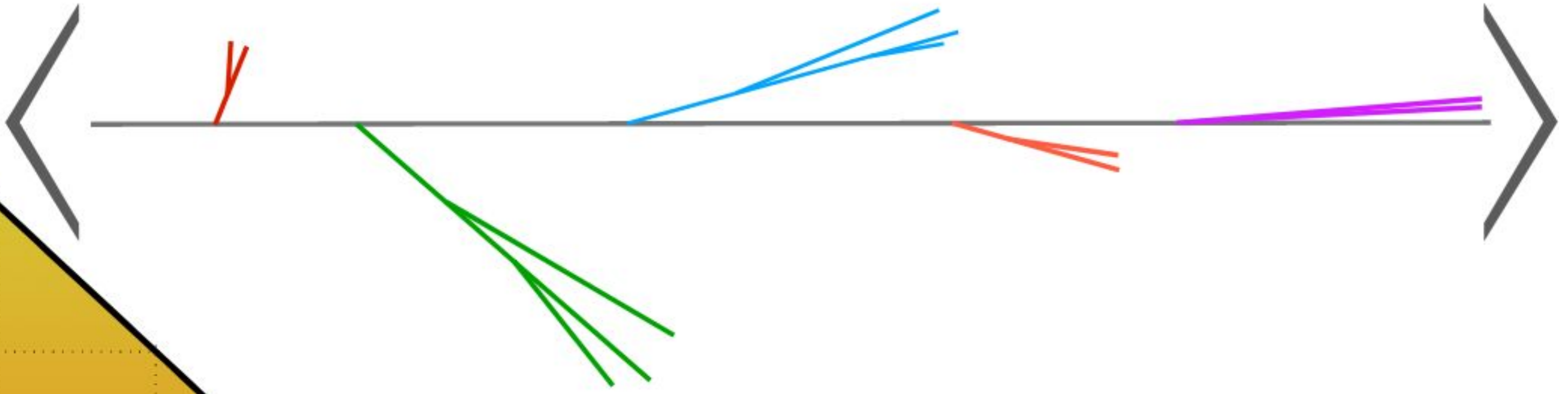
$$k_{\rm T} = p_{\rm T} \Delta R$$

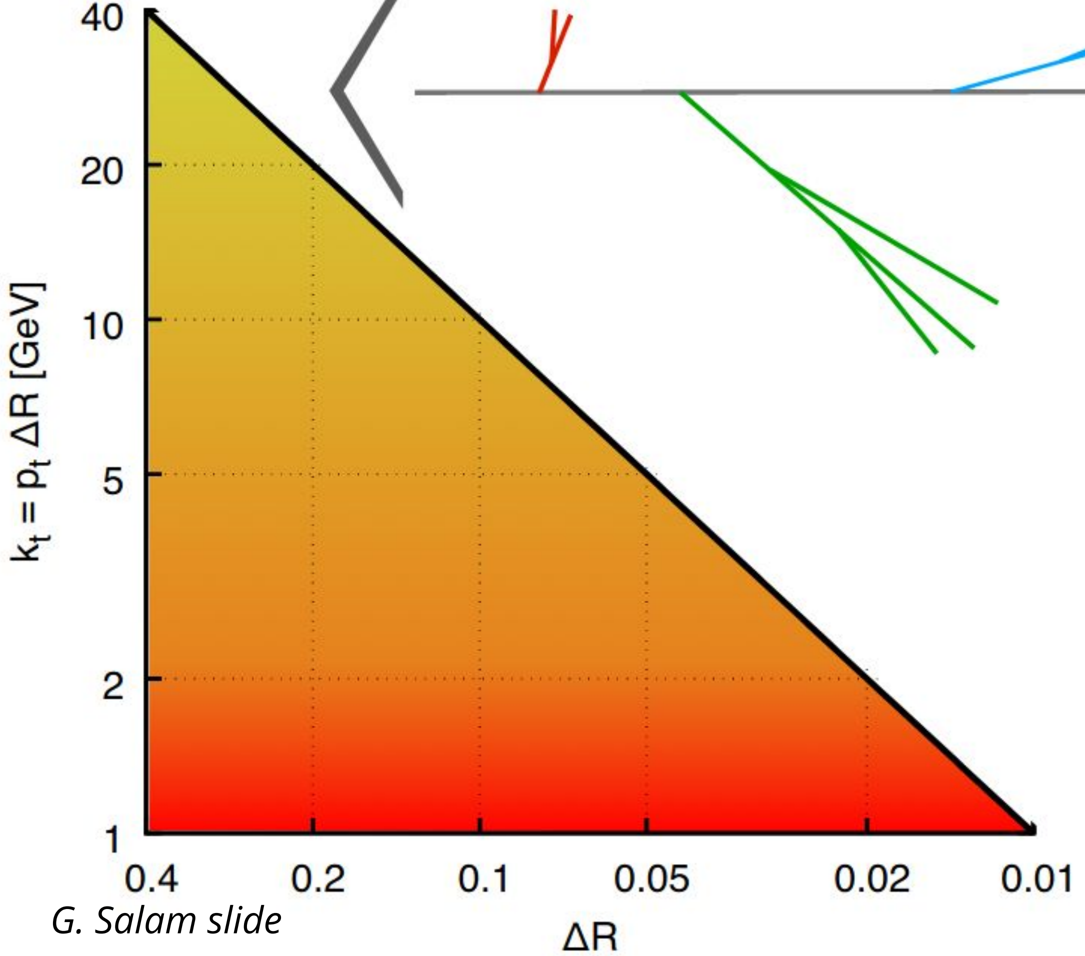
A specific jet is represented as a number of points in the Lund plane





Gavin Salam's slide





G. Salam slide

average over many jets:

Lund plane density

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

constructing the Lund plane

The Lund plane density

Different mechanisms contributing to jet formation can be isolated in the Lund plane F. Dreyer, G. Salam, G. Soyez, JHEP12(2018)064

Main observable is the 2D emission density:

$$\frac{1}{N^{\text{jets}}} \frac{d^2 N_{\text{emissions}}}{d\ln(k_T) d\ln(R/\Delta R)}$$

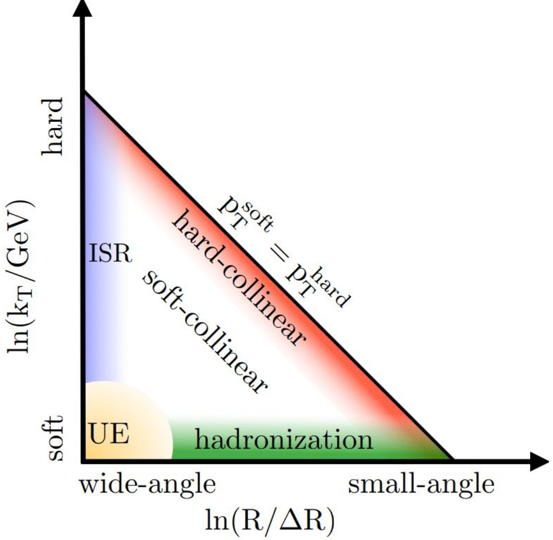
At LO in the soft- and collinear limit of pQCD, the Lund plane is proportional to αS

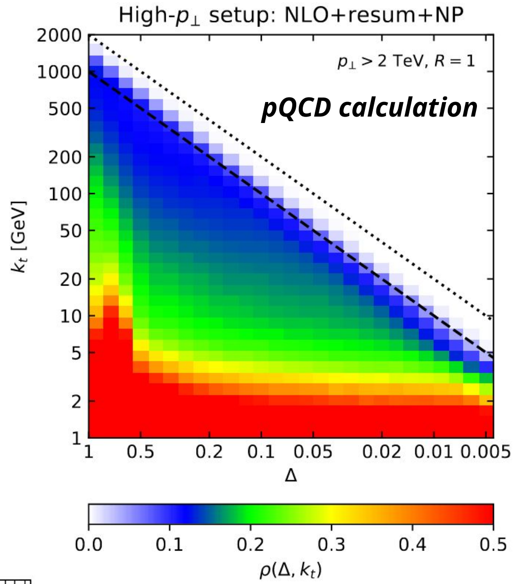
$$\frac{1}{N^{\text{jets}}} \frac{d^2 N_{\text{emissions}}}{d\ln(k_T) d\ln(R/\Delta R)} \simeq \frac{2}{\pi} C_R \alpha_s(k_T)$$

→ **the running of** αS(kT) **sculpts the Lund plane density.**

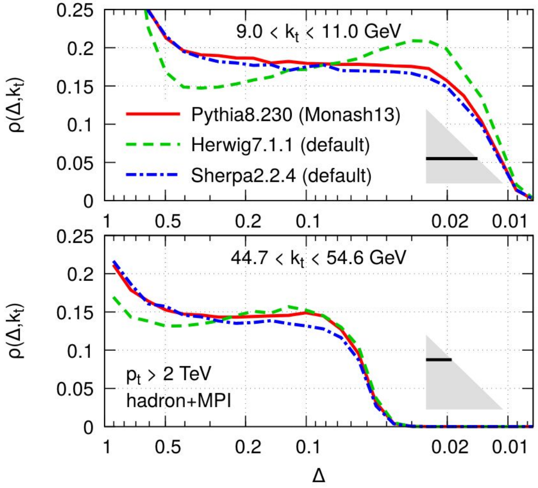
CR = CF = 4/3 for quark jets and CR = CA = 3 for gluon jets.

Can be used to **constrain MC** generators and is **amenable to analytical pQCD calculations**.





A. Lifson, G. Salam, G. Soyez, JHEP10(2020)170



Previously measured by ATLAS and ALICE Collaborations.

Measuring it for the first time in CMS (SMP-22-007, under review)

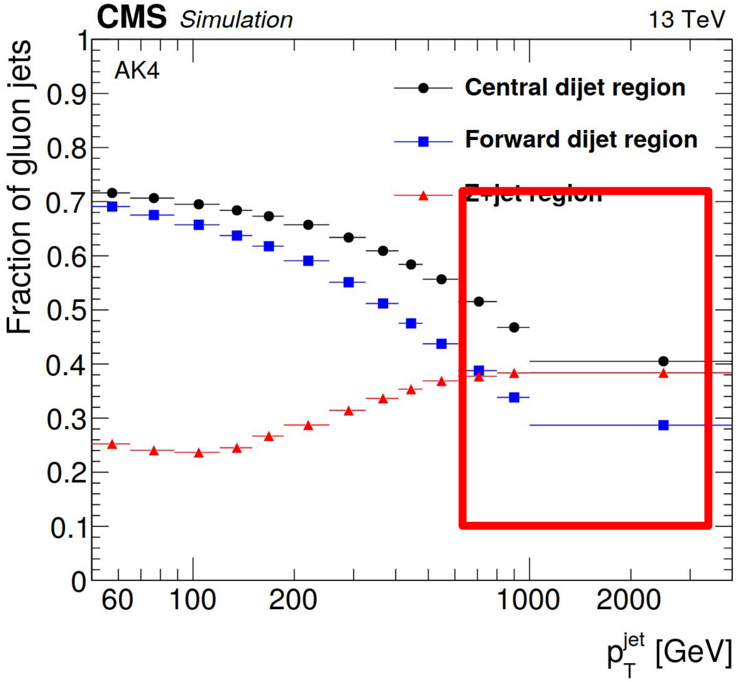
F. Dreyer, G. Salam, G. Soyez, JHEP12(2018)064

Run-2 analysis

- 13 TeV pp collisions, 138 fb-1 of data.
- anti-kT *R = 0.4* and *R = 0.8* jets with pileup mitigation.
- Lund plane is extracted for **jets with pT > 700 GeV and |y| < 1.7**
- Jet substructure using **charged-particles inside the jet with pT > 1 GeV and |η| < 2.5** (***better angular and momentum resolution***).
- Jets are ungroomed (we want to see everything!)

We focus on high-pT jets to allow enough phase space for perturbative splittings (kTmax = ½ pTjet ΔR).

About 60-70% of the jets are quark-jets w/ our selection.



CMS, arXiv:2109.03340

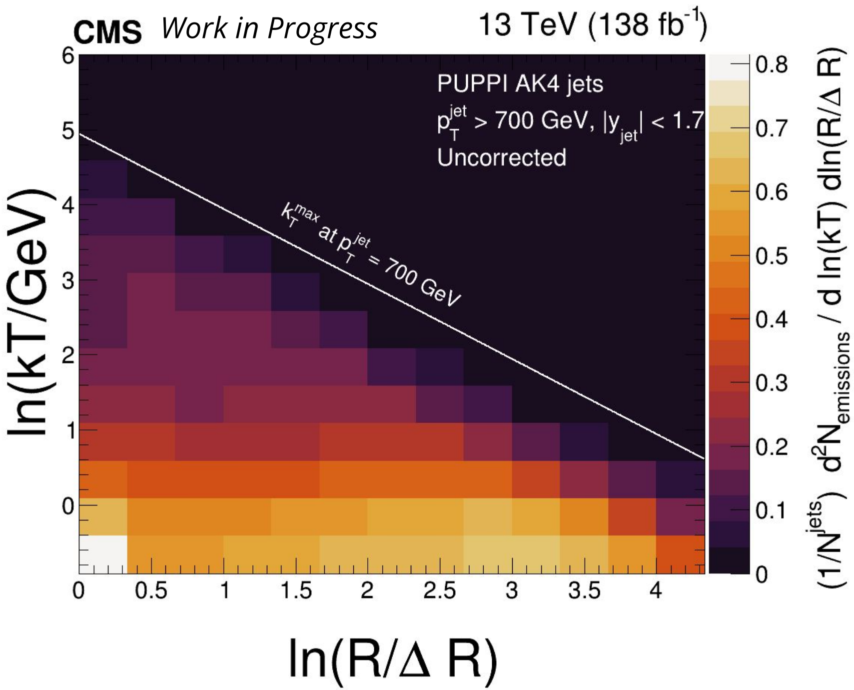
Detector-level Lund jet planes

Kinematic range for measurement:

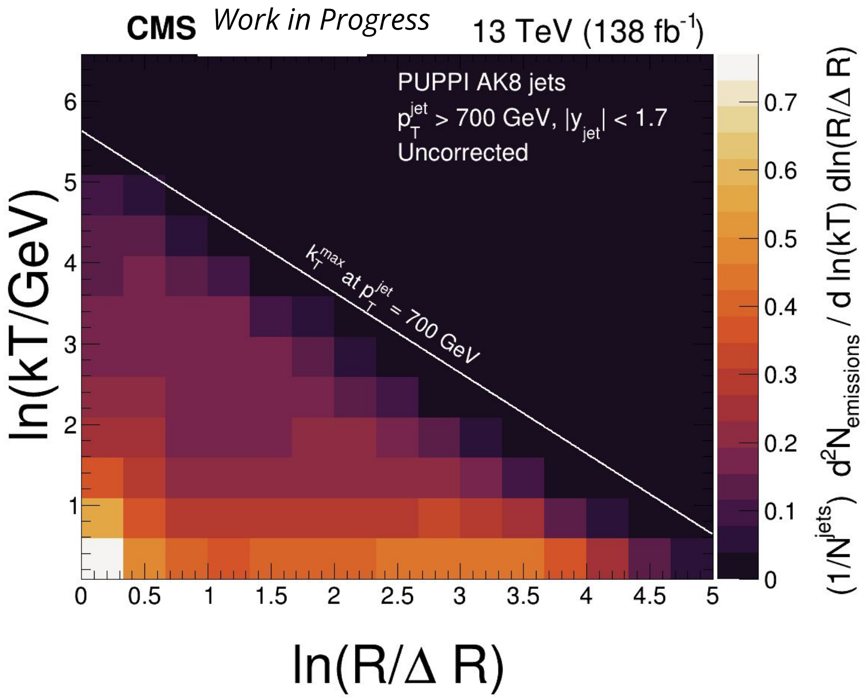
$0.005 < \Delta R < 0.8$
(~pixel pitch)

$0.4 < k_T < 280$ GeV
(for pTjet = 700 GeV)

R=0.4



R=0.8



Unfolding the Lund plane to stable charged-particle level

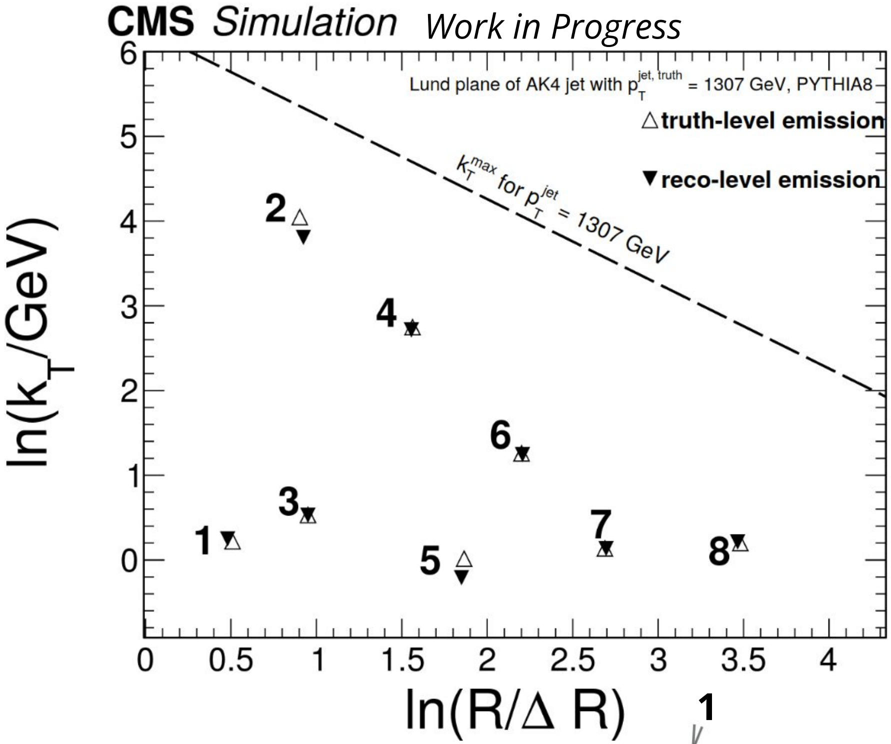
$$\frac{1}{N^{\text{jets}}} \frac{\mathrm{d}^2 N_{\text{emissions}}}{\mathrm{d}\ln(k_T)\,\mathrm{d}\ln(R/\Delta R)}$$

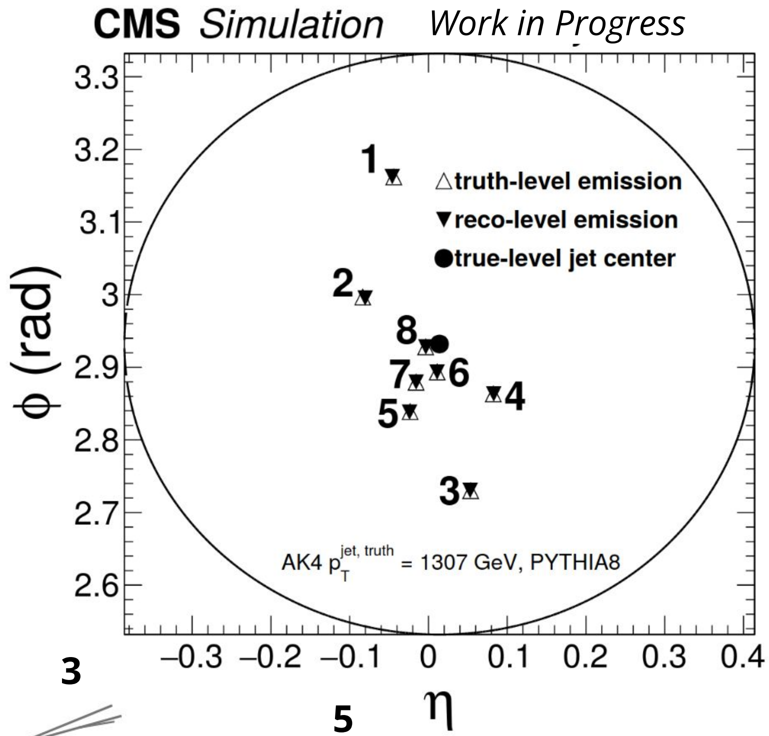
1D unfolding for number of jets for normalization ("bookkeeping")

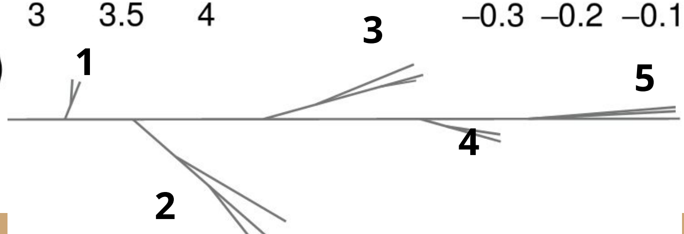
3D unfolding for for number of emissions (substructure)

Corrections derived with uniquely matched truth-level and det-level splittings.

Geometrical matching with window $\Delta R = \sqrt{(\eta_{\mathrm{true}} - \eta_{\mathrm{det}})^2 + (\phi_{\mathrm{true}} - \phi_{\mathrm{det}})^2} < 0.1$







Unfolding the Lund plane to stable charged-particle level

1. Apply matching purity corrections to raw Lund plane (LP*purity).

2. **3D unfold** purity-corrected Lund plane (pTjet, kT, ΔR)
   + **1D unfolding** of jet pT for normalization purposes.

   We use **iterative Bayesian unfolding**. **PYTHIA8 CP5** (nominal) and **HERWIG7 CH3** are used to construct response matrices.

3. Apply matching efficiency corrections (LP*1/efficiency). **This is the fully corrected Lund jet plane.**

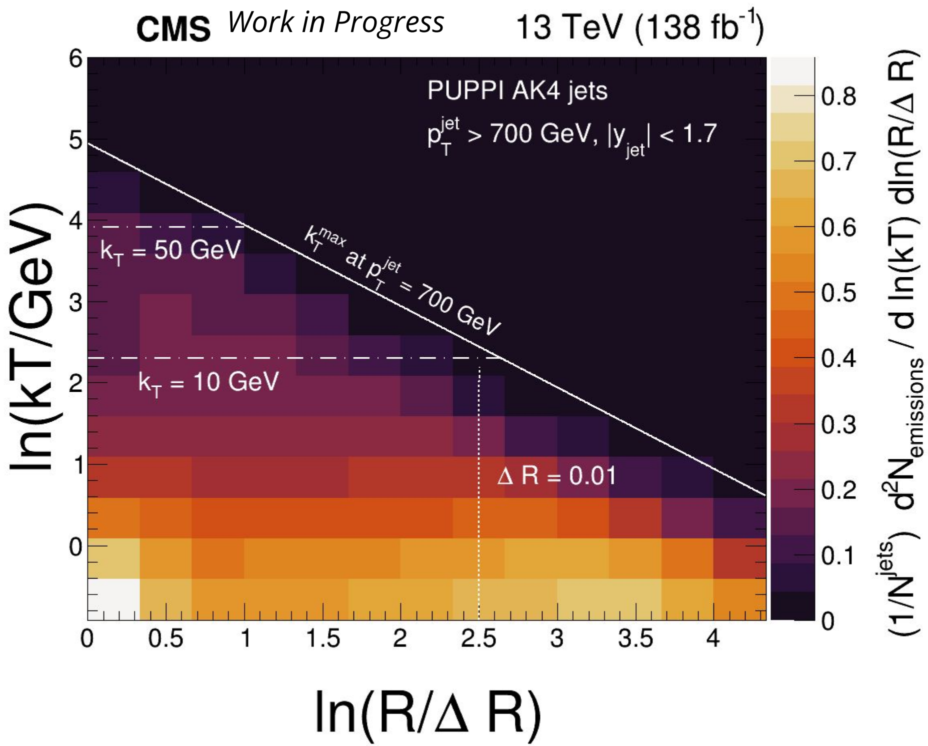
$$\frac{1}{N^{\text{jets}}} \frac{\mathrm{d}^2 N_{\text{emissions}}}{\mathrm{d}\ln(k_T)\,\mathrm{d}\ln(R/\Delta R)}$$

1D unfolding of pTjet spectra for normalization

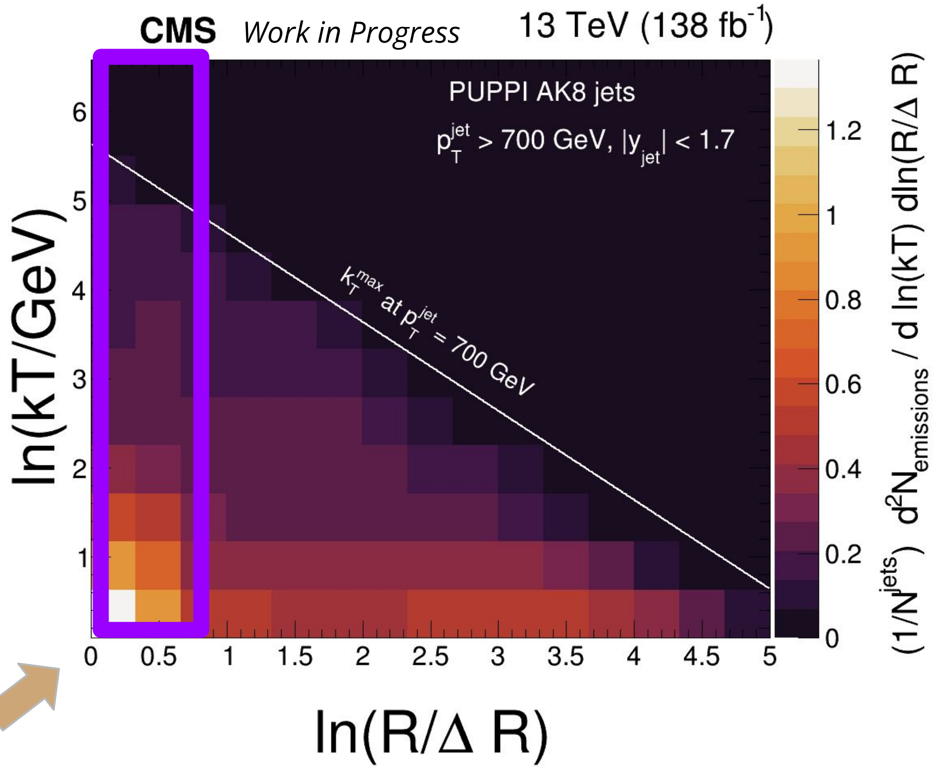
3D unfolding for for Nemissions (substructure)

Fully corrected Lund planes

R=0.4

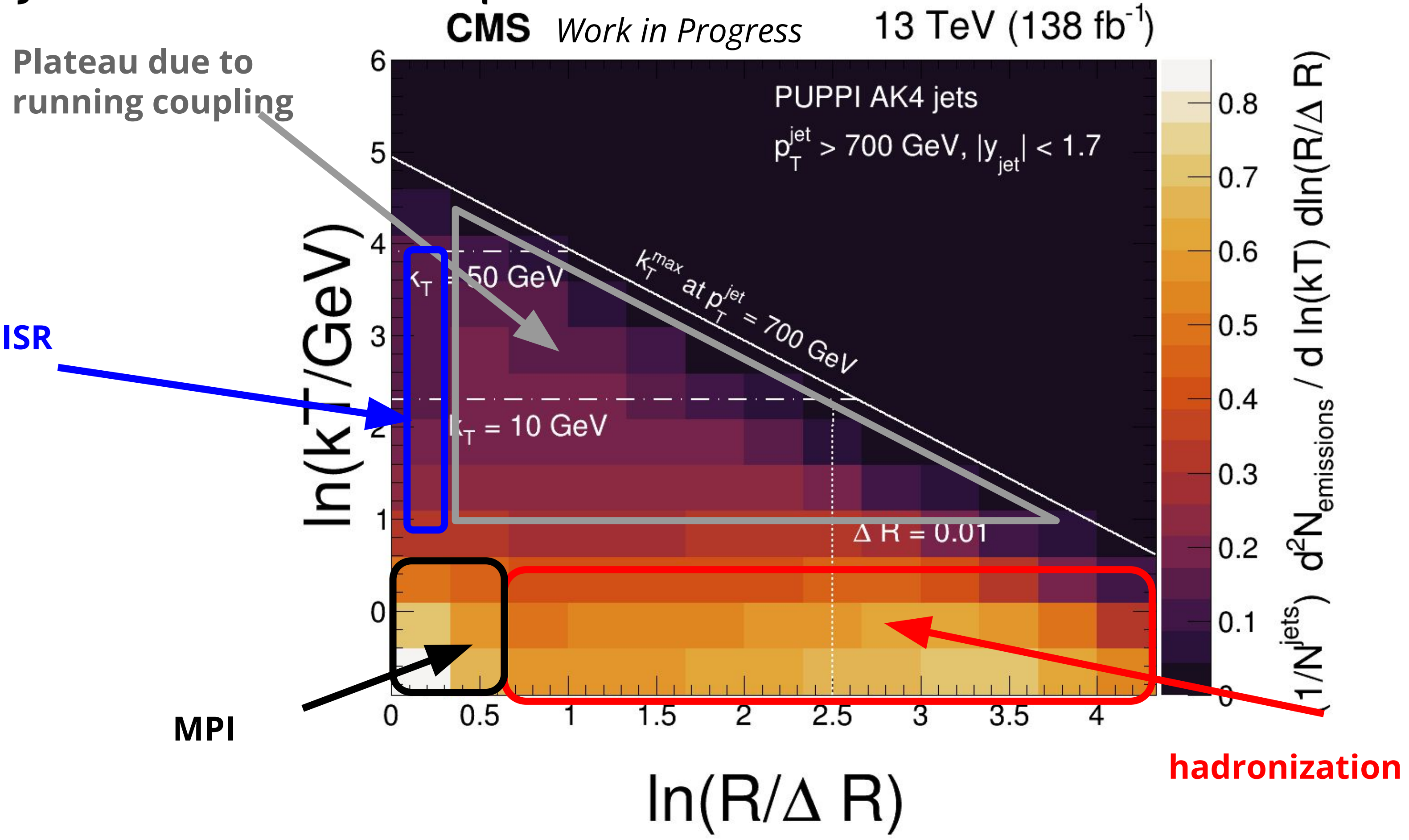


R=0.8



Accessible only with R =0.8

Fully corrected Lund plane



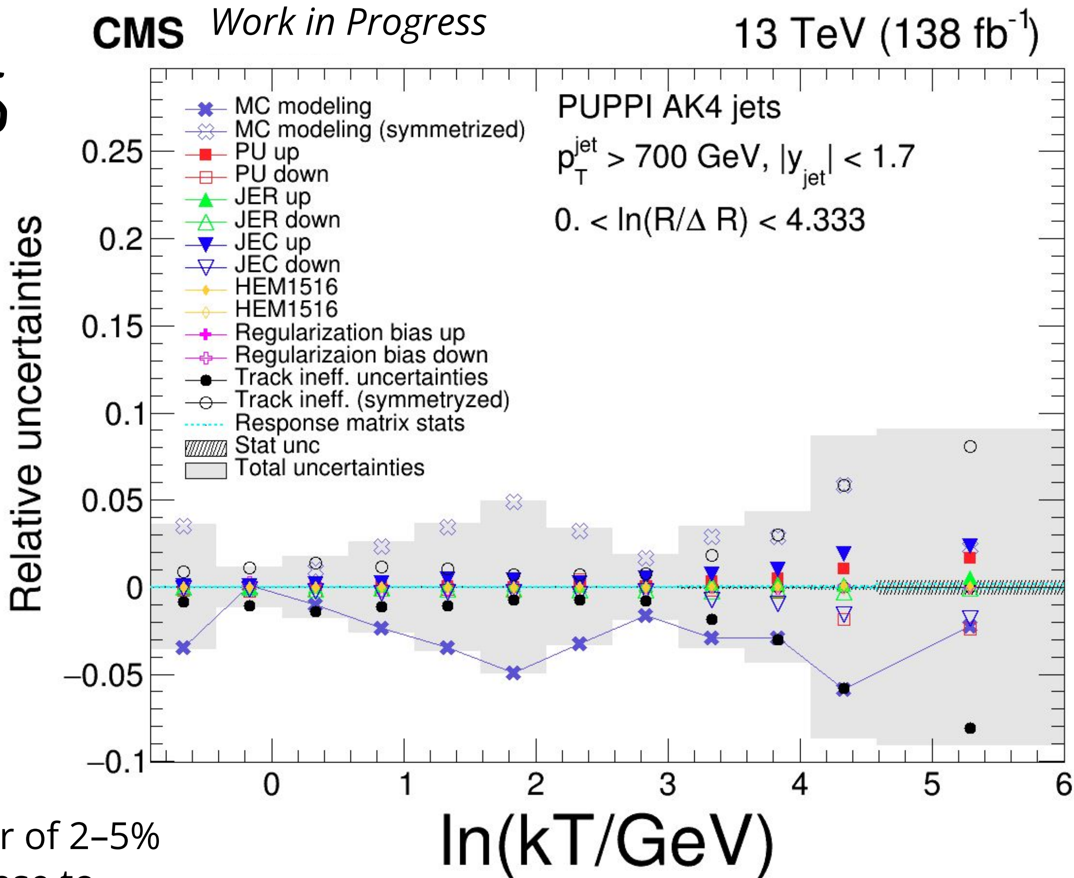
Systematic uncertainties

Dominant (2–10%):

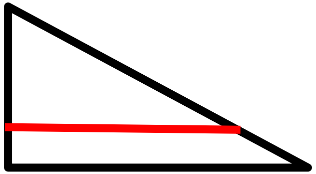
- **MC modeling (herwig7 vs pythia8)**
- **Track inefficiency uncertainties**

Subleading (< 1%):

- **Response matrix stats**
- **Regularization bias**
- **Pileup reweighting uncertainties**
- Jet energy corrections (**JEC**) and resolution uncertainties (**JER**)
- **HEM15/16 module malfunction in 2018**

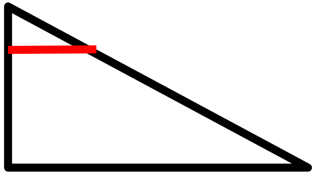


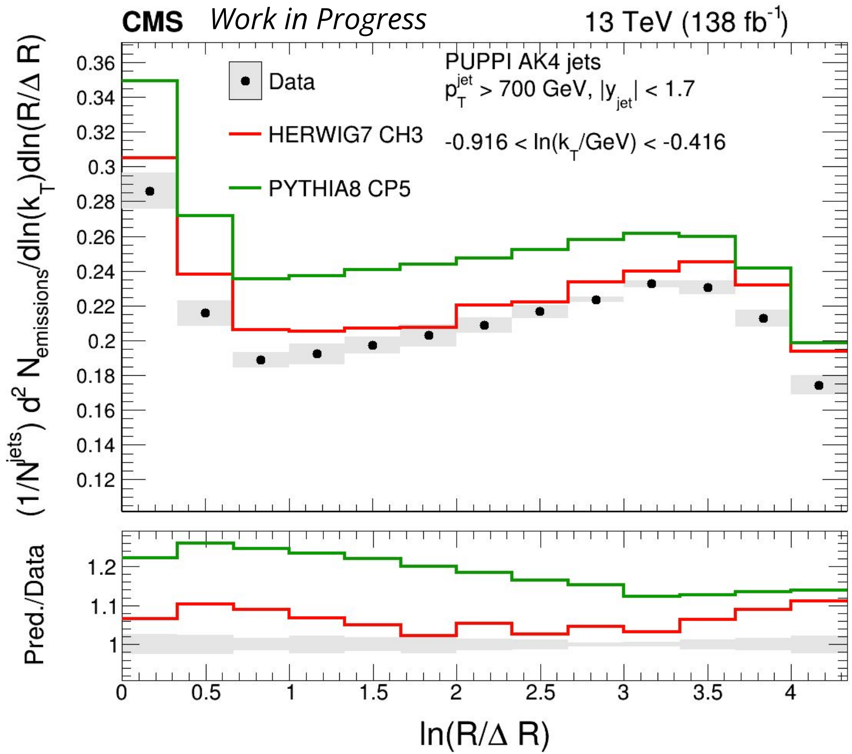
Total experimental uncertainties are of the order of 2–5% throughout (most of) the Lund plane; they increase to 10% at the kinematic edge of the Lund plane (z = 0.5).

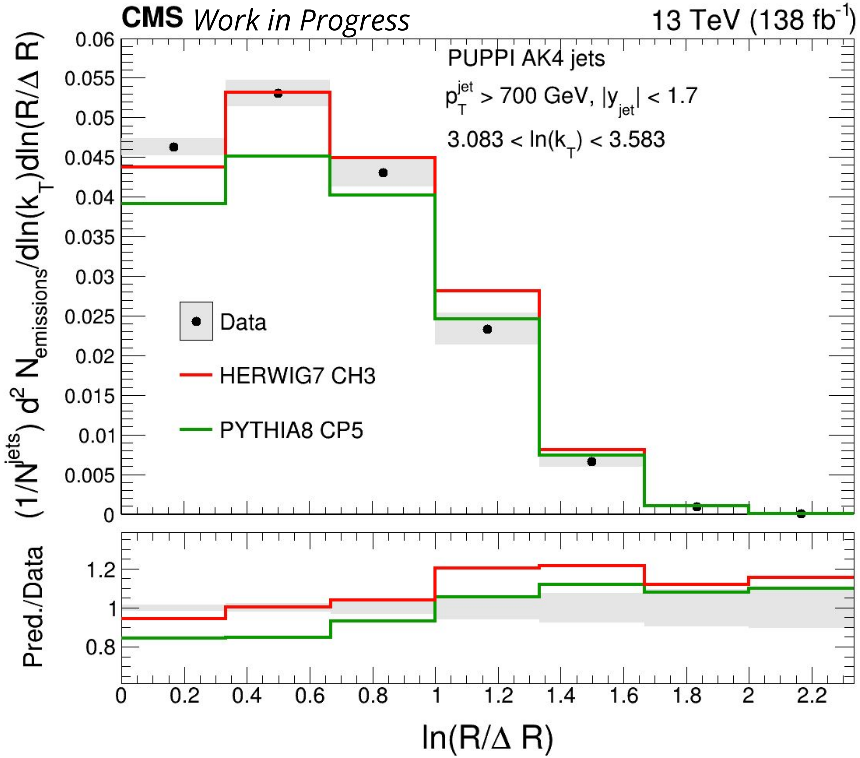


Low-kT
(nonperturbative region)

High-kT
(perturbative region)

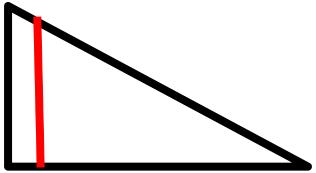


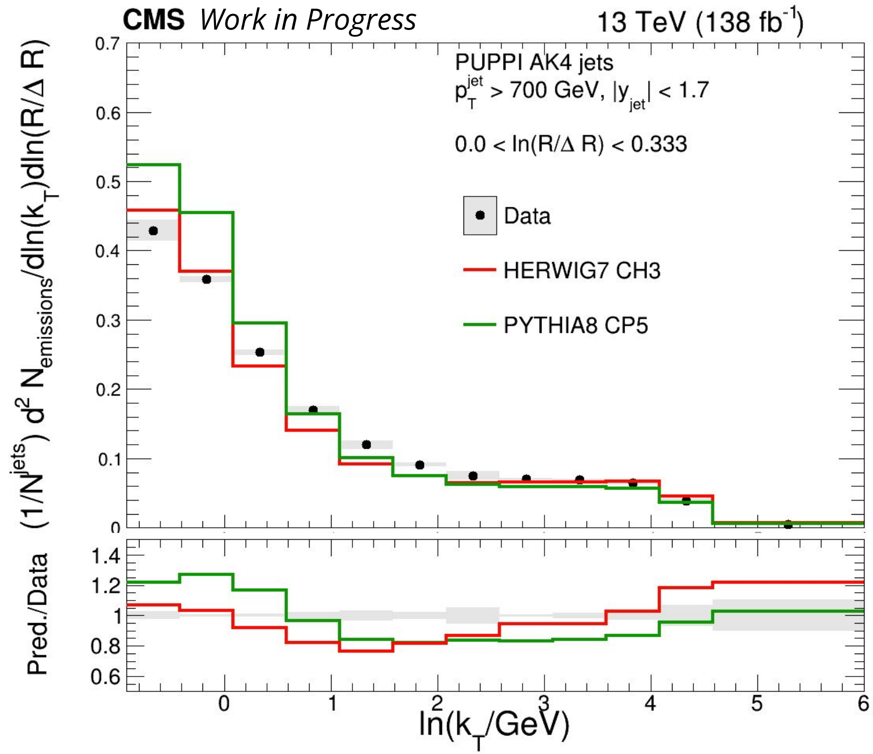




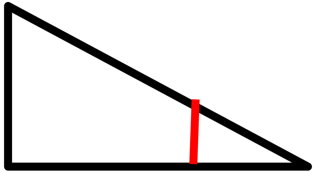
PYTHIA8 generates more splittings in nonperturbative region by 10-20%.

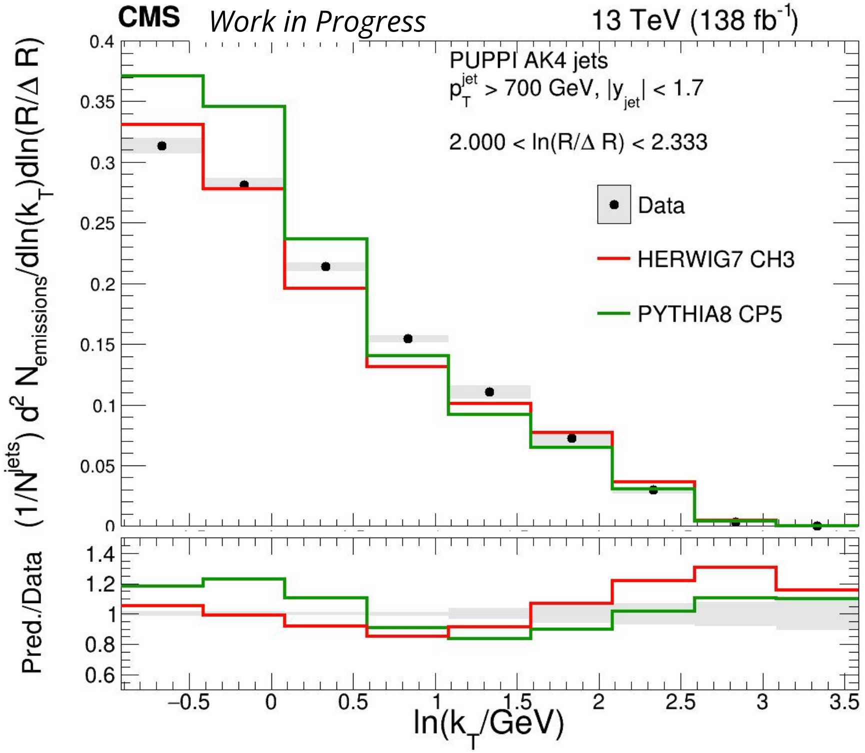
Wide angles





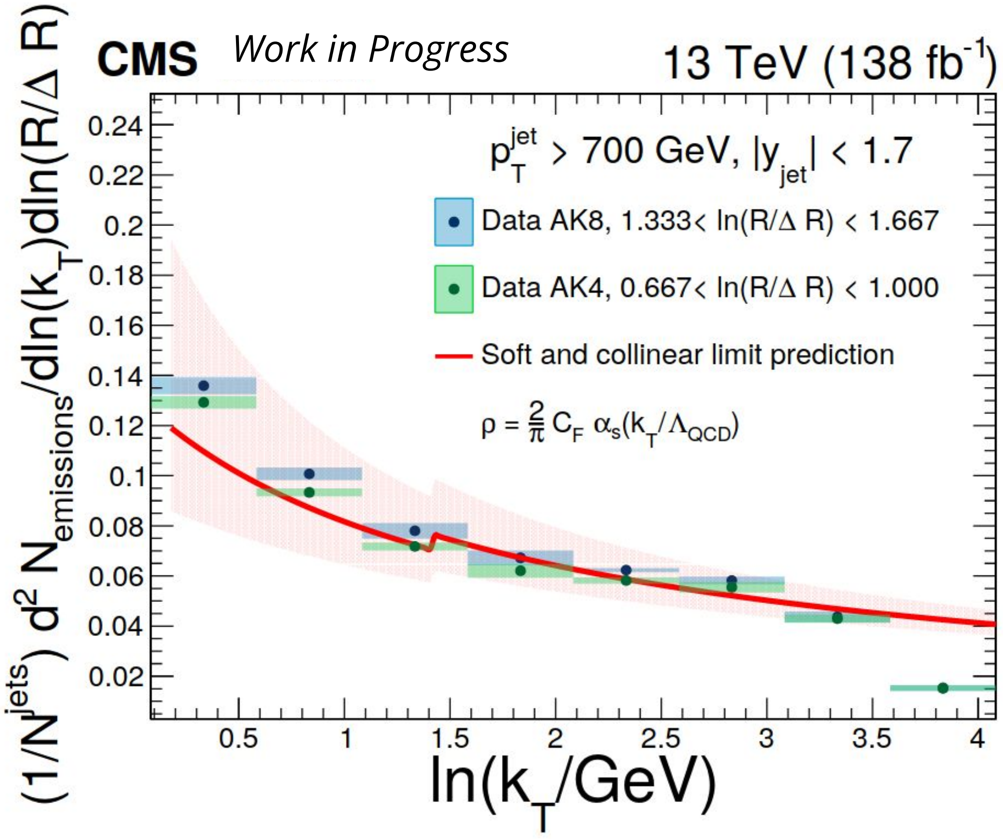
Small angles
(collinear limit)





Strong constraints on parton shower & hadronization in H7 and P8

Running coupling in the jet radiation pattern



Recall LO pQCD prediction,

$$\frac{1}{N^{\text{jets}}}\frac{\mathrm{d}^2 N_{\text{emissions}}}{\mathrm{d}\ln(k_T)\mathrm{d}\ln(R/\Delta R)} \simeq \frac{2}{\pi} C_R \alpha_s(k_T)$$

naïve LO prediction with 1-loop β-function, n_f = 5, and Λ_{QCD} = 0.2 GeV, $C_R = C_F$ = 4/3 yields reasonable description of data.

In principle, one could extract α_S from the Lund plane.

Summary & prospects

- Jet radiation pattern mapped to Lund plane for R = 0.4 and R = 0.8 jets. Running of α_S sculpts the emission density.

- Strong constraints on MC generators in perturbative and nonperturbative regions.

- Plans for a comparison with NLO+LL+NP analytical calculations.

- Planning to go for a public conference note this Fall.

BACK-UP

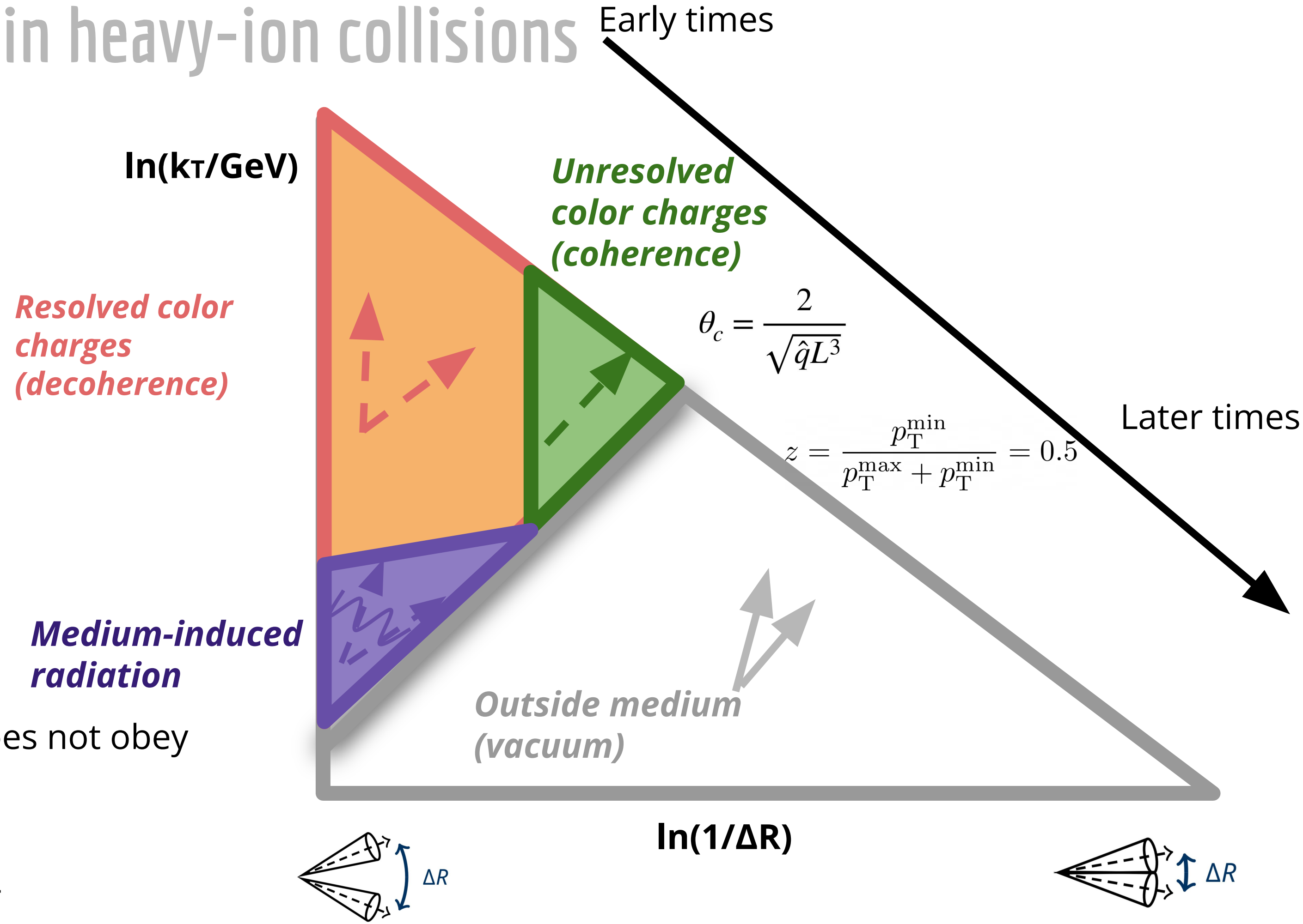
Lund jet plane in heavy-ion collisions

Can it be measured in AA collisions?

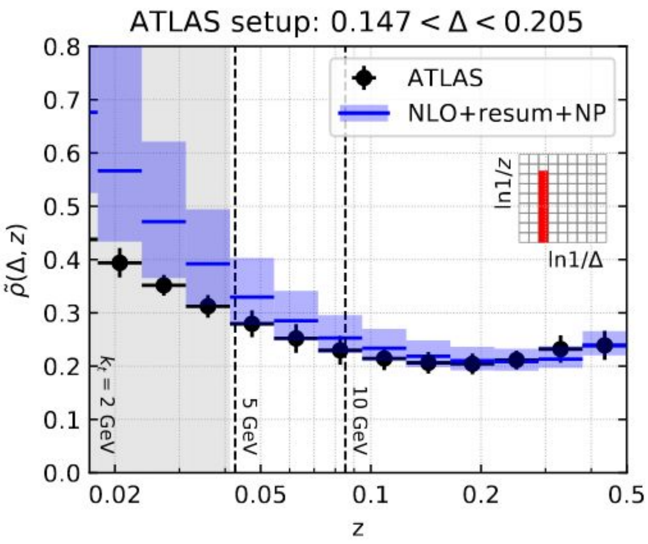
More challenging due to UE

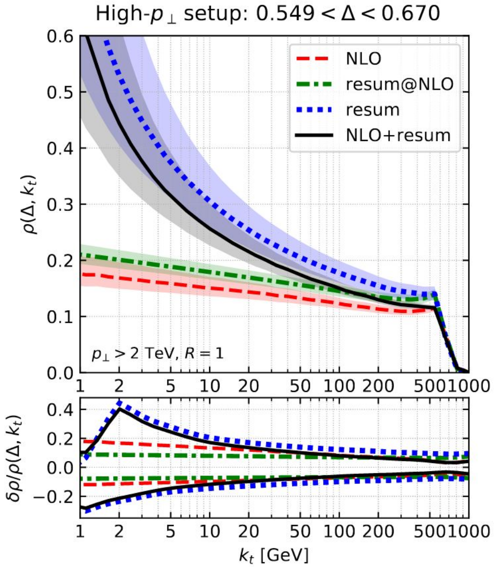
Density of emissions does not obey vacuum rules

$$dP^{\mathrm{mie}} = \frac{\alpha_s^{\mathrm{med}} C_i}{2\pi} \frac{dI}{d\omega d^2 k_t}$$



In contact with theorists for NLO+LL+NP calculations for paper





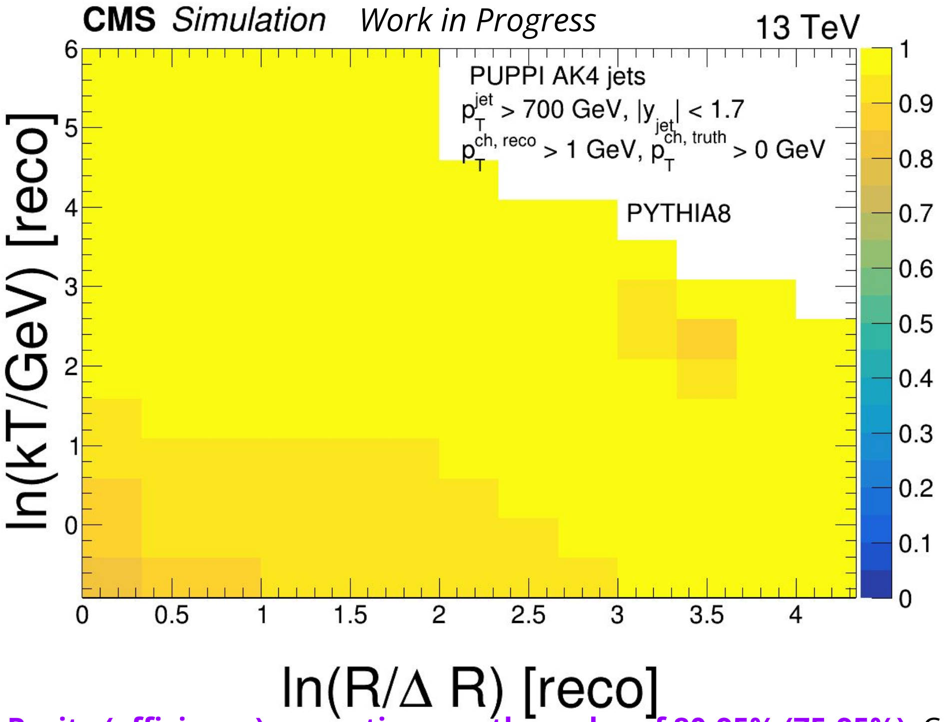
A. Lifson, G. Salam, G. Soyez, JHEP10(2020)170

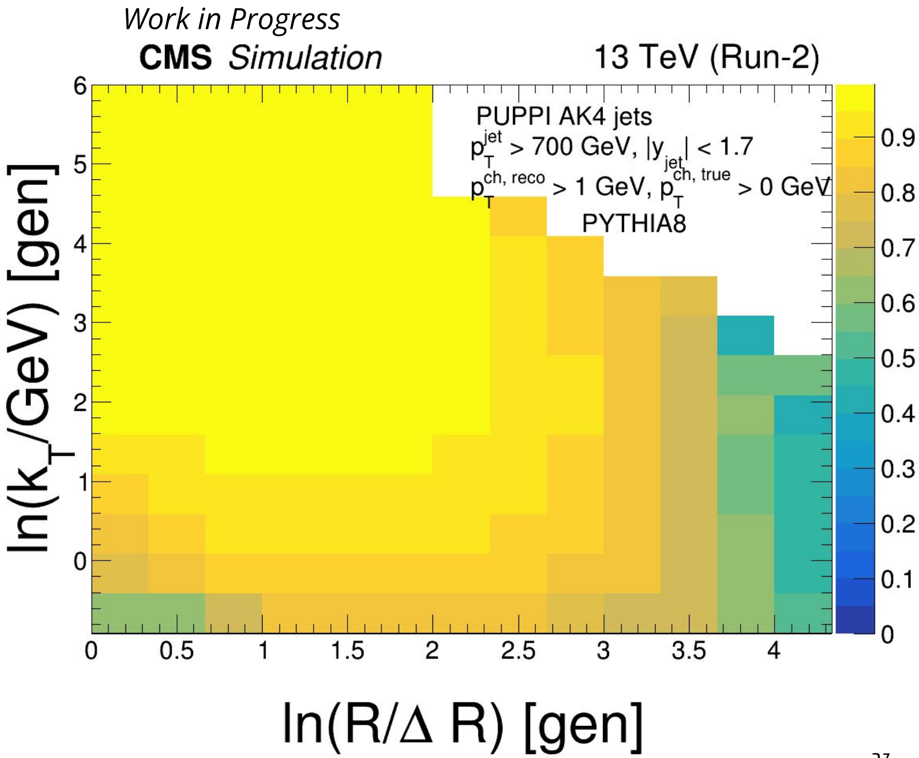
Existing calculations are precise within 5-7% in perturbative region.

Purity and efficiency corrections

$$\text{purity} = \frac{n^{\text{matched}}_{\text{reco}}\big(\ln(k_T), \ln(R/\Delta R)\big)}{n^{\text{all}}_{\text{reco}}\big(\ln(k_T), \ln(R/\Delta R)\big)}$$

$$\text{efficiency} = \frac{n^{\text{matched}}_{\text{truth}}\big(\ln(k_T), \ln(R/\Delta R)\big)}{n^{\text{all}}_{\text{truth}}\big(\ln(k_T), \ln(R/\Delta R)\big)}$$

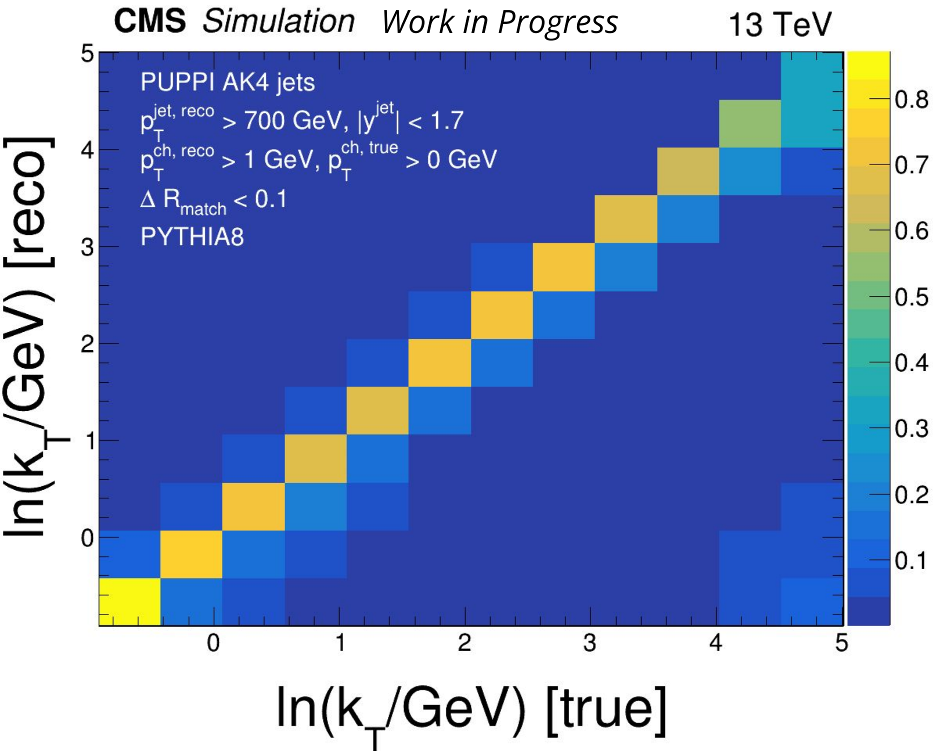


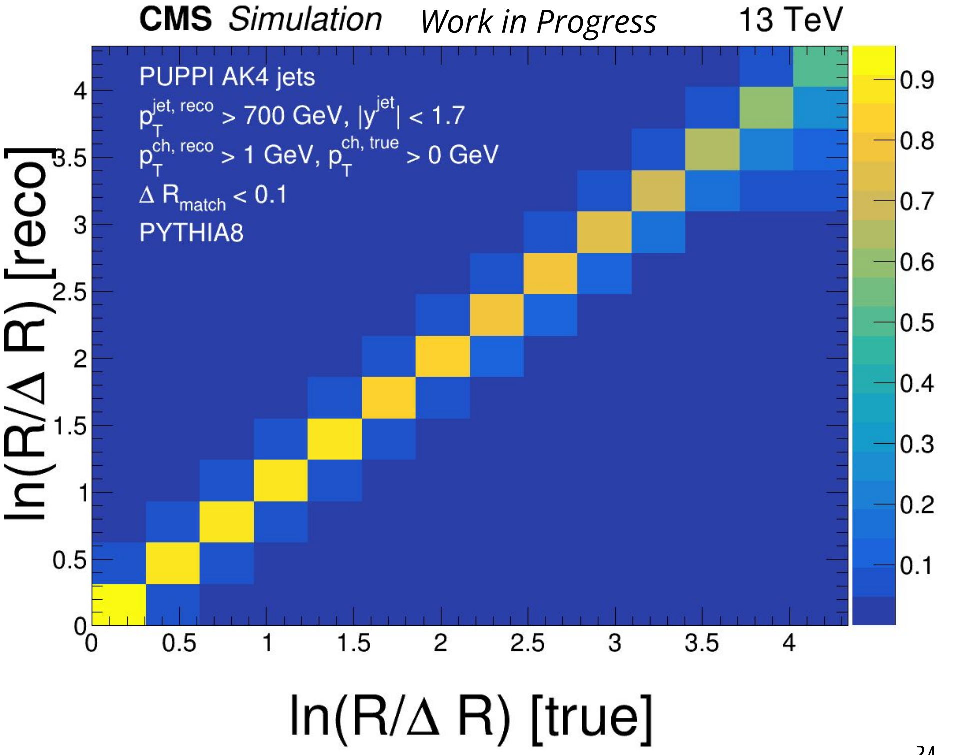


Purity (efficiency) corrections on the order of 80-95% (75-95%). Corrections w/ PYTHIA8 and HERWIG7 are the same within 1-3%.

Response matrices (1D projections)

Nearly diagonal response in ln(kT) and ln(R/ΔR). Losses at high kTtrue due to tracking inefficiencies. Mismatches at high kT true.





Systematic uncertainties (AK8 jets)

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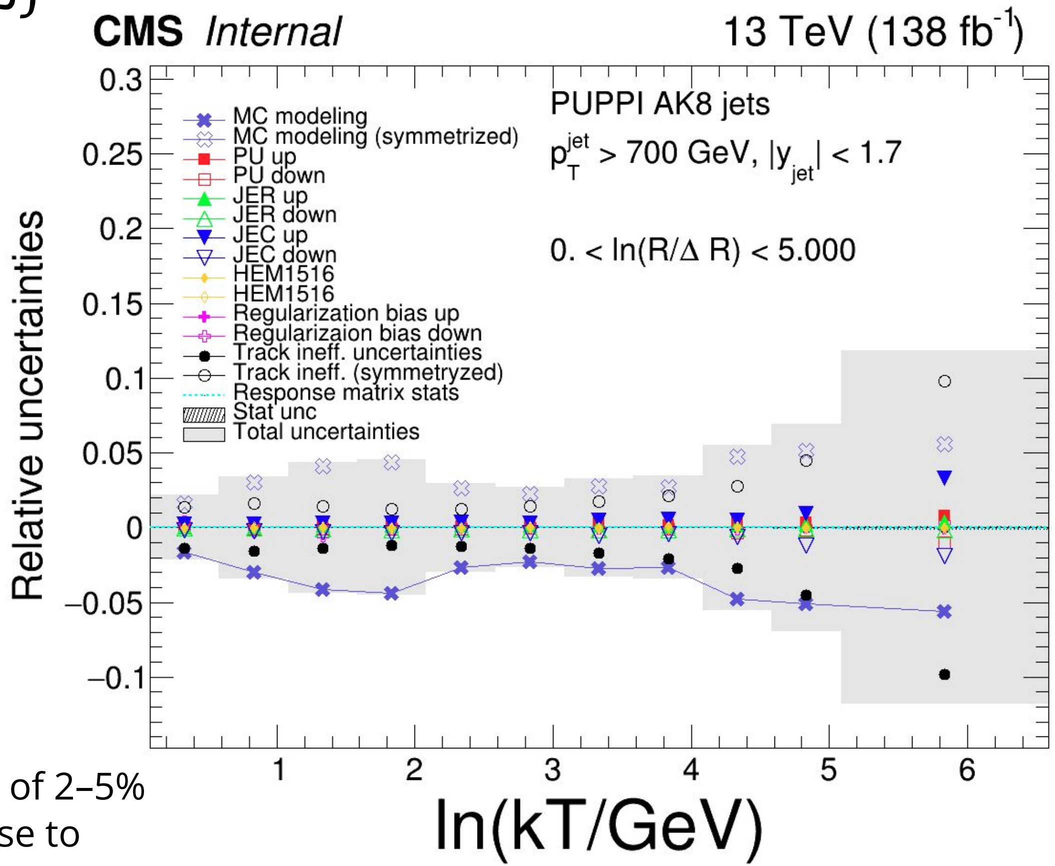
- **MC modeling (herwig7 vs pythia8)**
- **Track inefficiency uncertainties**

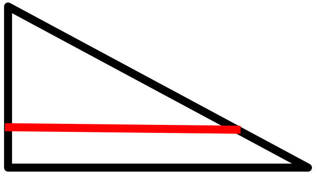
Subleading (<~ 1%):

- **Response matrix stats**
- **Pileup reweighting uncertainties**
- **Regularization bias**
- Jet energy corrections (**JEC**) and resolution uncertainties (**JER**)
- **HEM15/16 issue (2018 data)**



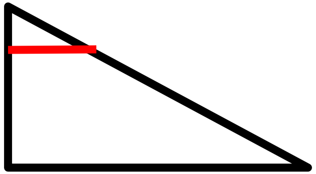
Total experimental uncertainties are of the order of 2–5% throughout (most of) the Lund plane; they increase to ~12% at the kinematic edge of the Lund plane (z = 0.5).

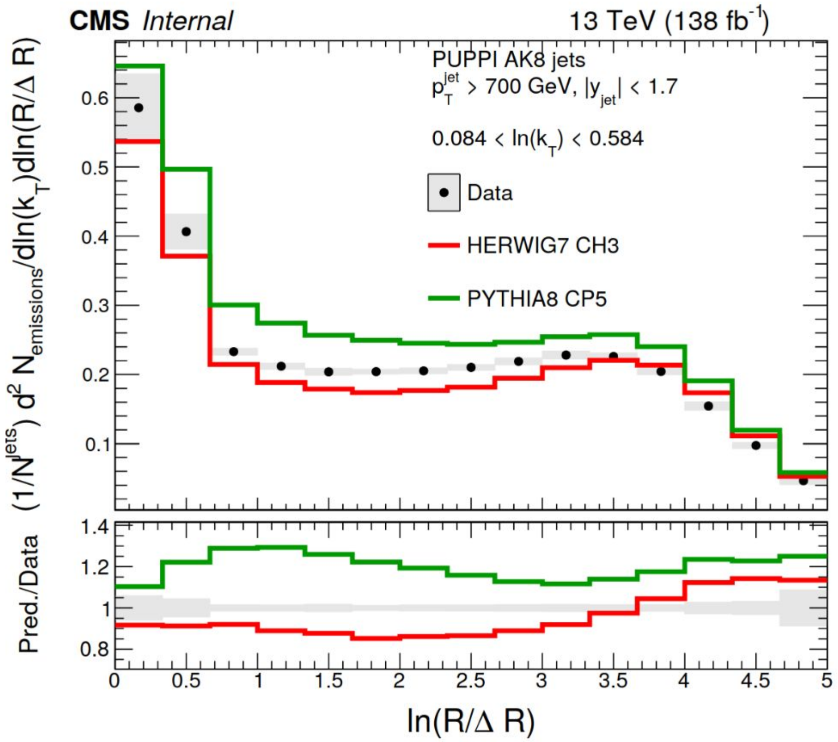
R=0.8 results

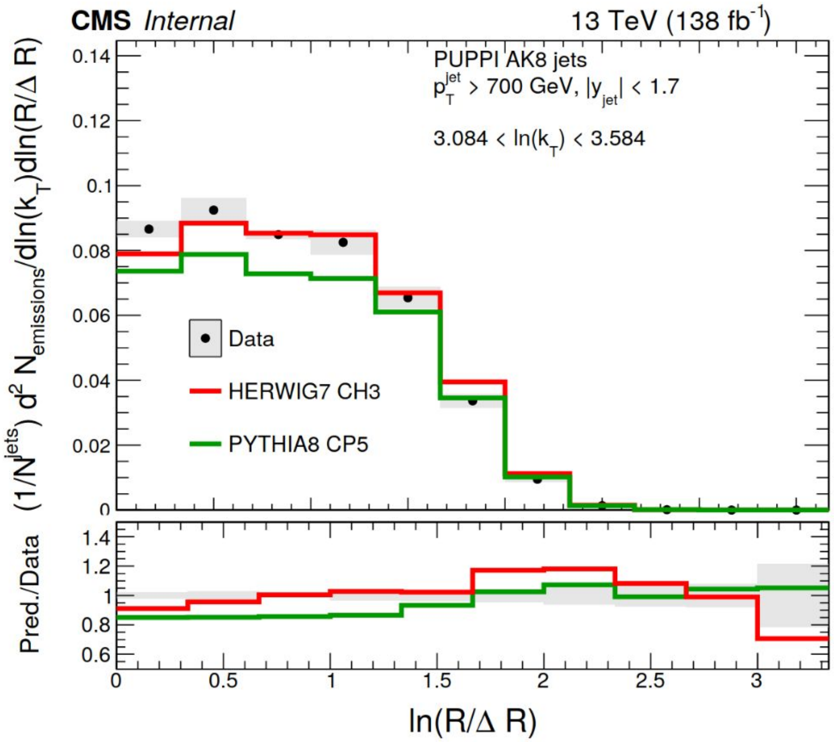


Low-kT
(nonperturbative region)

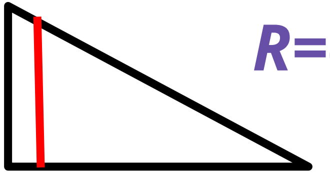
High-kT
(perturbative region)





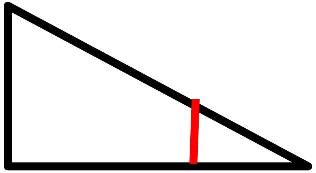


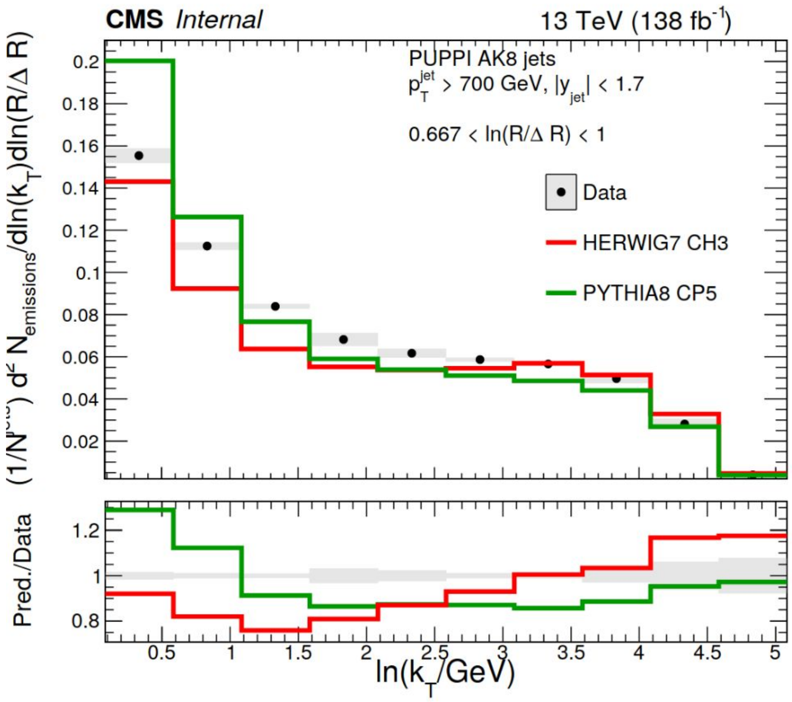
Wide angles

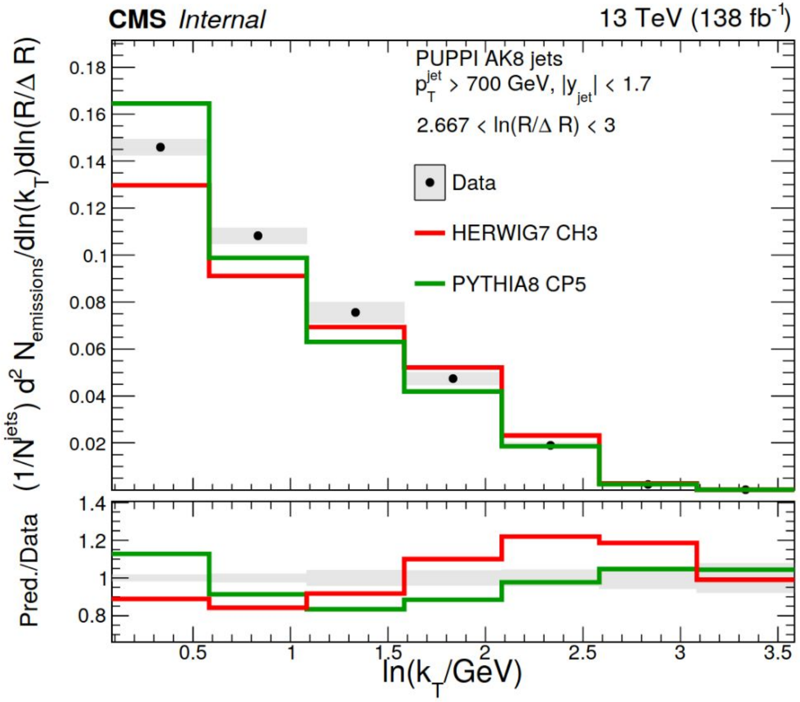


R=0.8 results

Small angles (collinear limit)





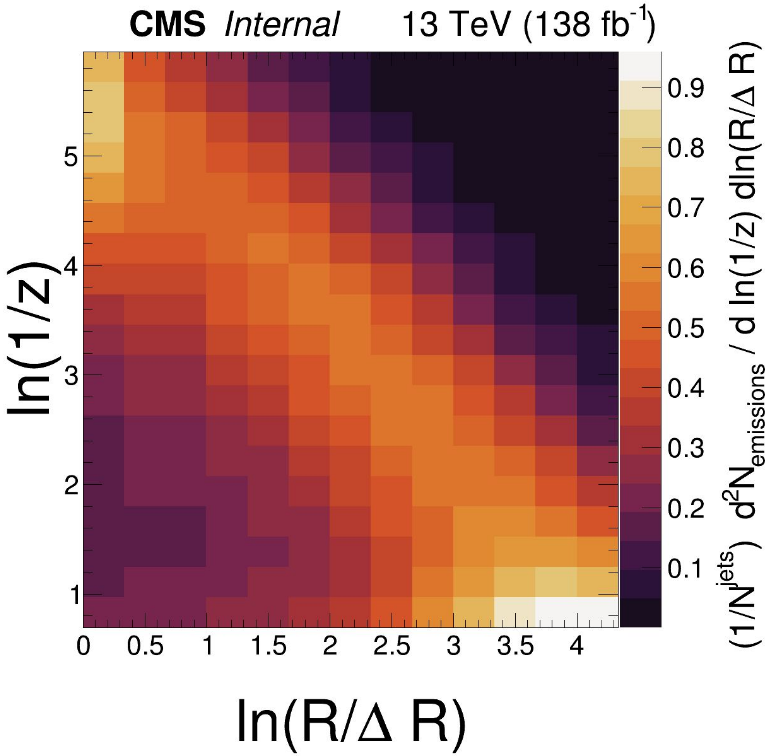


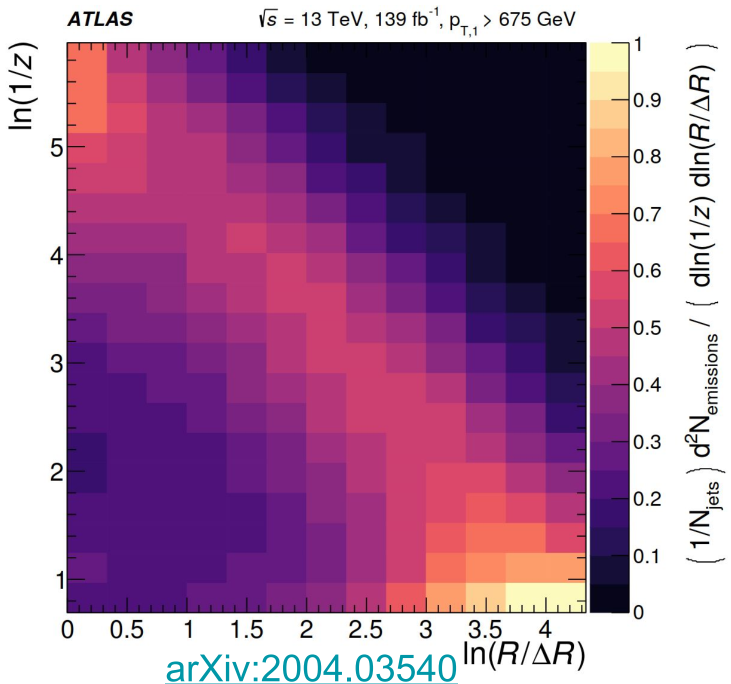
Strong constraints on parton shower & hadronization in H7 and P8

Comparison with ATLAS measurement (ln(1/z) vs ln(R/ΔR))

Unfolded Lund plane

z=pTsoft/(pTsoft+pThard)



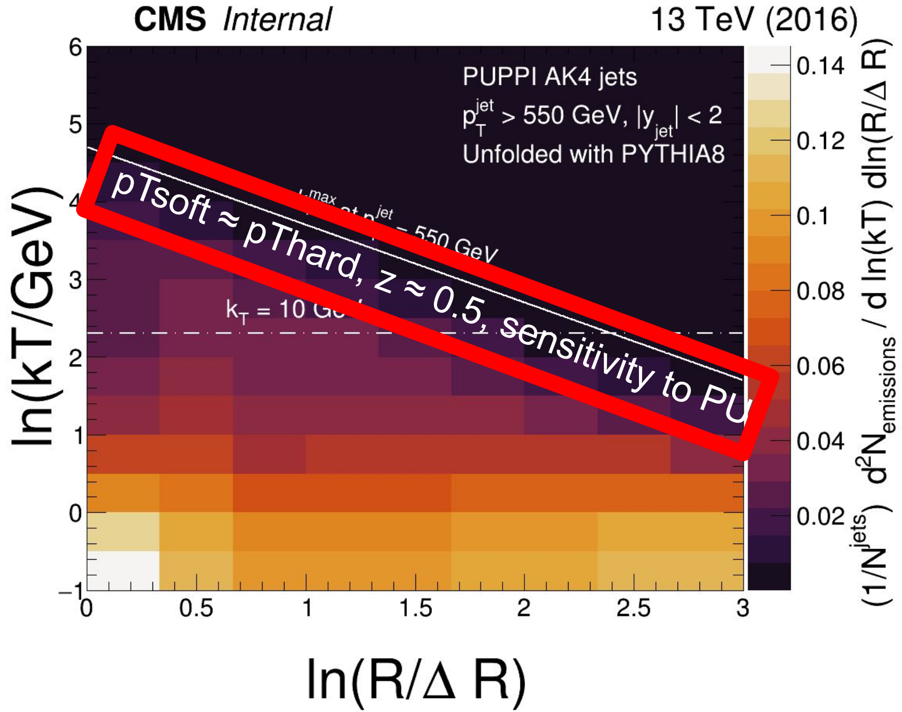


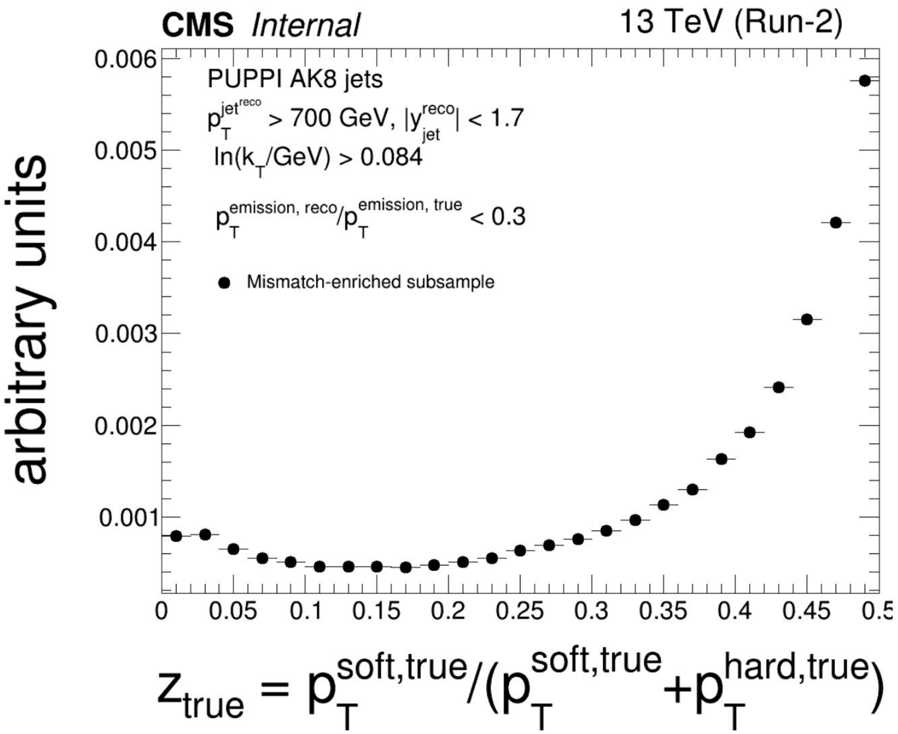
arXiv:2004.03540

We match ATLAS' jet selection (pTjet1 > 675 GeV, pTjet2/pTjet1 > 2/3, |**η**Jet| < 2.1 , R = 0.4)

Mismatches are more likely to occur when pTsoft ≈ pThard

Mismatches cumulate at zTruth = pTsoft/(pTsoft+pThard) ≈ 0.5, **which is the edge of the Lund plane.**

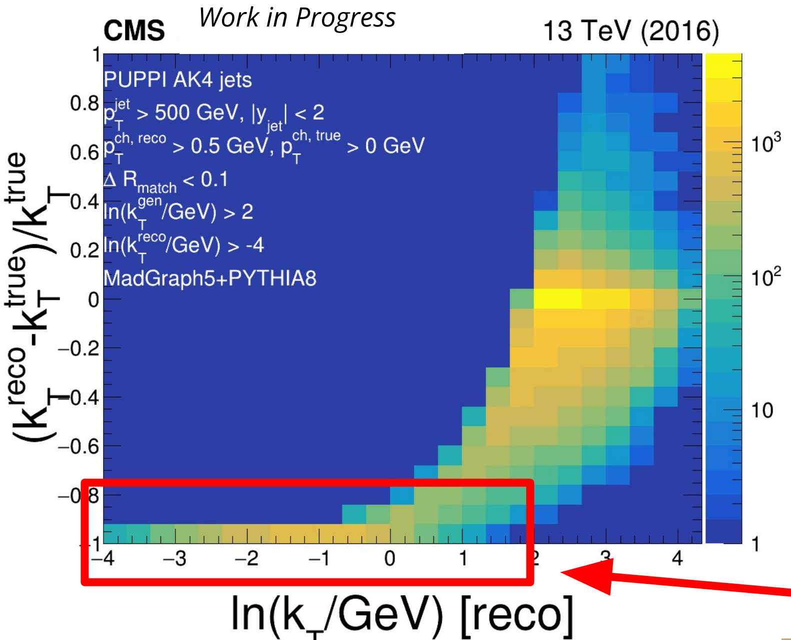




Mismatched splittings

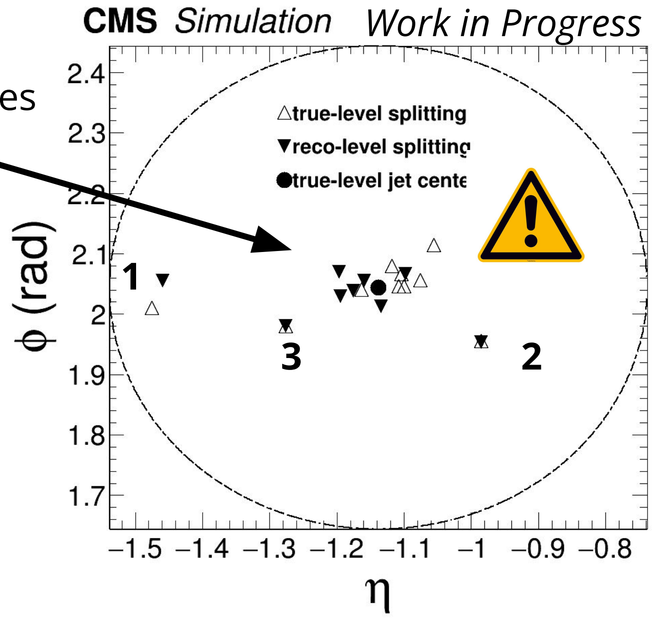
2% of the splittings are wrongly matched. Large angle, high-kT true splittings might be mismatched to small angle, low-kT det-level splittings. ***The reco-level C/A tree history diverges from the truth-level C/A tree history.***

Mismatches are irreducible and need to be modelled in the response matrix.



mismatches

example of mismatches

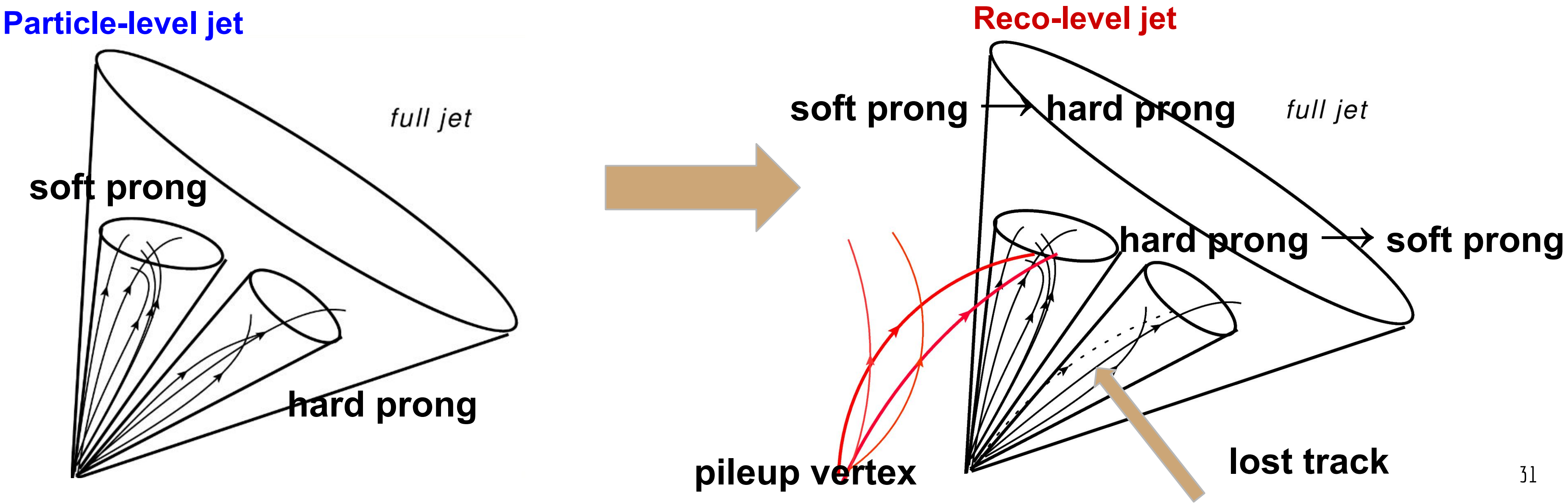


Mismatches are more likely to occur when pTsoft ≈ pThard

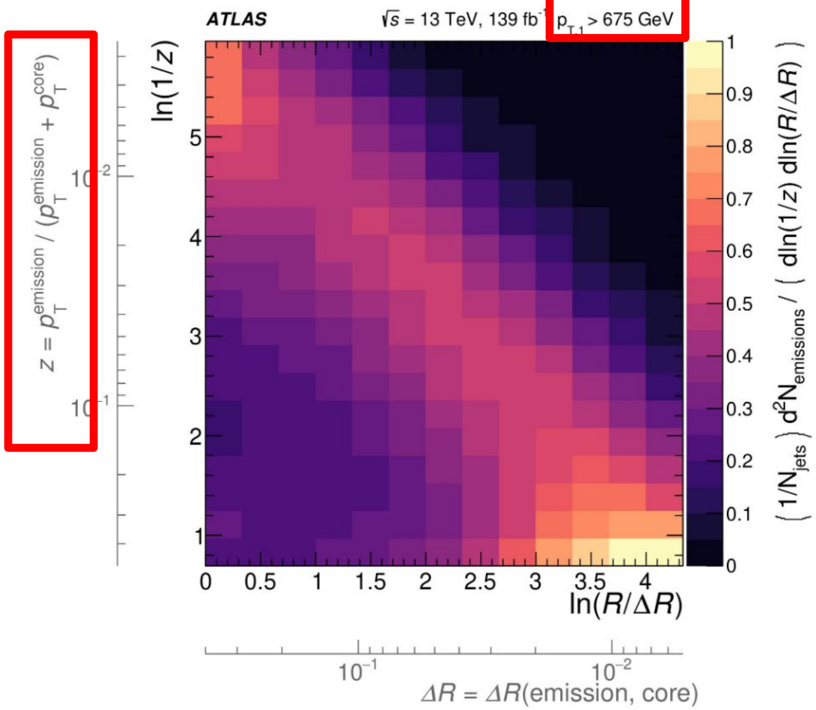
Pileup tracks that are not successfully removed by PUPPI will be clustered.

If pTsoft ≈ pThard at truth-level, **the soft prong could be promoted to hard prong at reco-level.**

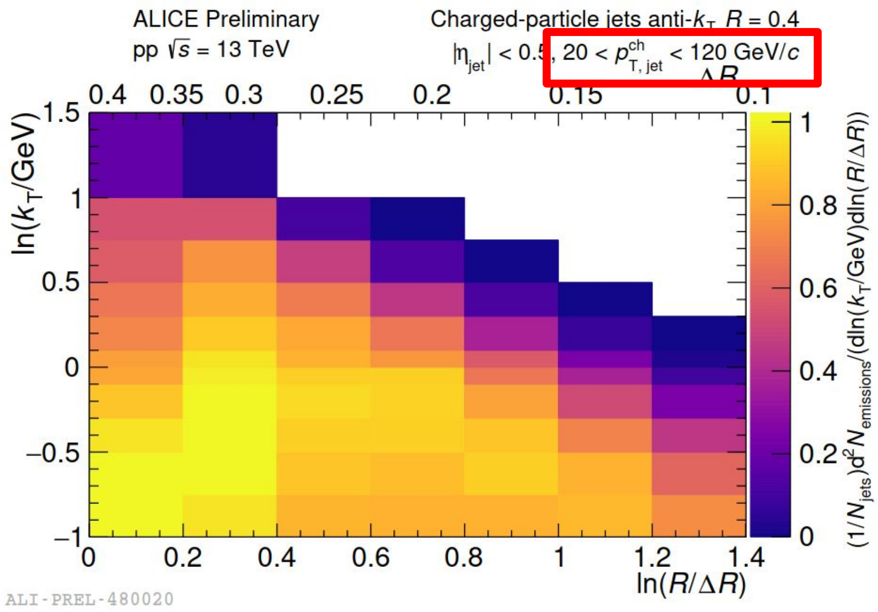
Also, due to tracking inefficiencies, **the hard prong can be demoted to soft prong at reco-level.**



Existing measurements by ATLAS and ALICE



https://arxiv.org/abs/2004.03540



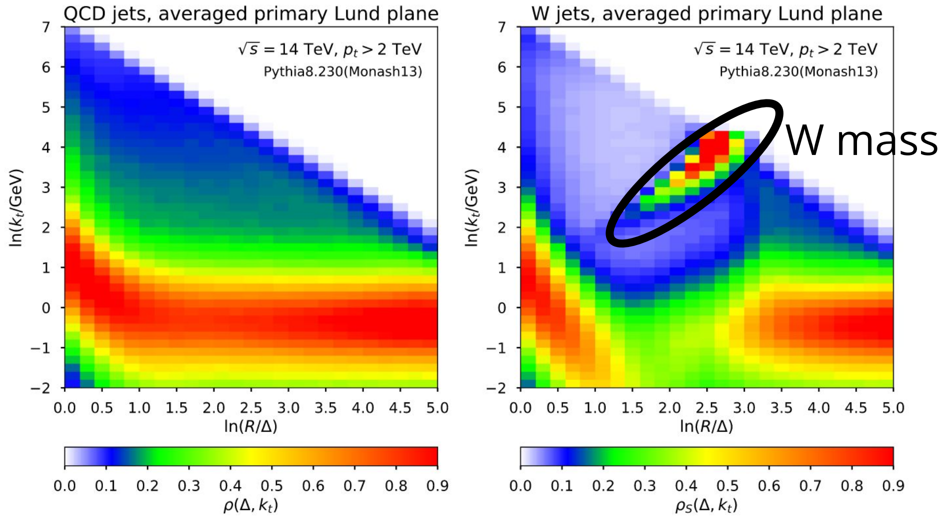
https://cds.cern.ch/record/2759456

ATLAS used the ln(1/z) vs ln(1/ΔR) representation using pT > 675 GeV AK4 jets. Separation of perturbative and nonperturbative regions is more difficult in this picture.

ALICE used AK4 jets with 20 < pTjet < 120 GeV using the ln(kT) vs ln(1/ΔR) representation. Sensitivity to low-kT splittings at wide angles.

Lund plane can be used as a tagger: W-jet vs QCD jet

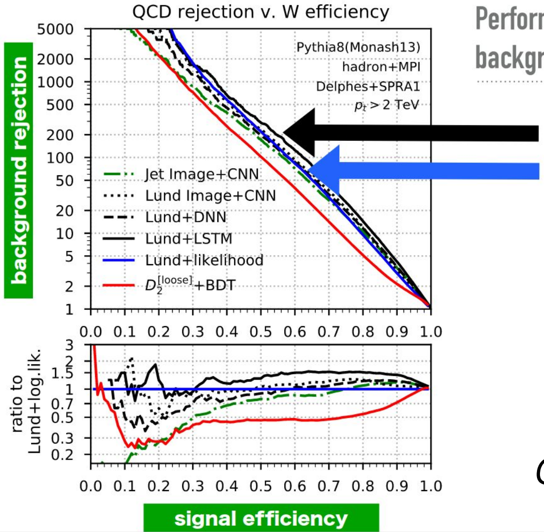
F. Dreyer, G. Salam, G. Soyez, JHEP12(2018)064



Invariant masses manifest as diagonal cuts in the LP.

Large angle, hard splittings suppressed due to color-singlet nature of W boson.

Excellent bkg rejection vs signal efficiency performance (possibly better than mass + jet-shape discriminators).



Performance: background rejection v. signal efficiency

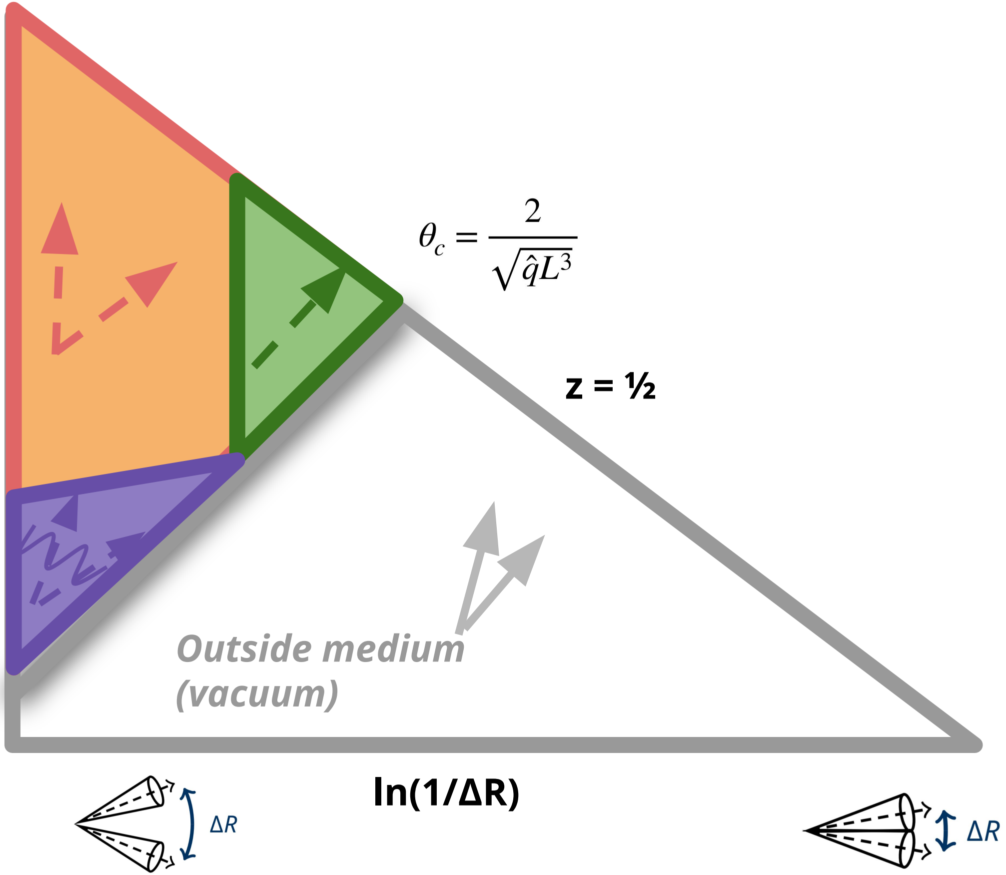
Lund + machine-learning (LSTM)

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

Gavin Salam's slide

Can we access the basic building blocks of medium-induced radiation as we do in pp?

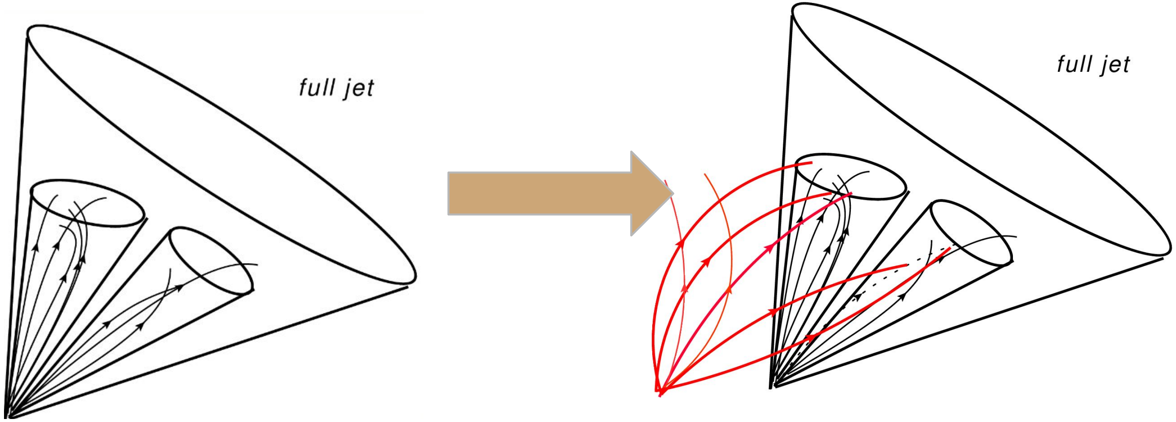
Can we measure the full Lund plane in AA?

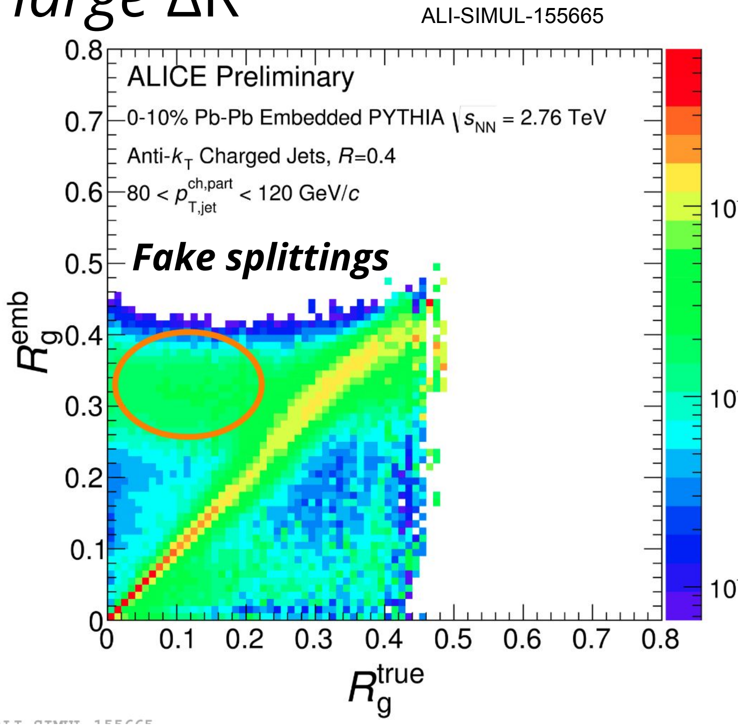


$$dP^{\rm mie} = \frac{\alpha_s^{\rm med} C_i}{2\pi} \frac{dI}{d\omega d^2 k_t}$$

Fake splittings due to UE in AA collisions at large ΔR

Subjets w/o UE (no embedding) **Subjets w/ UE (embedded)**





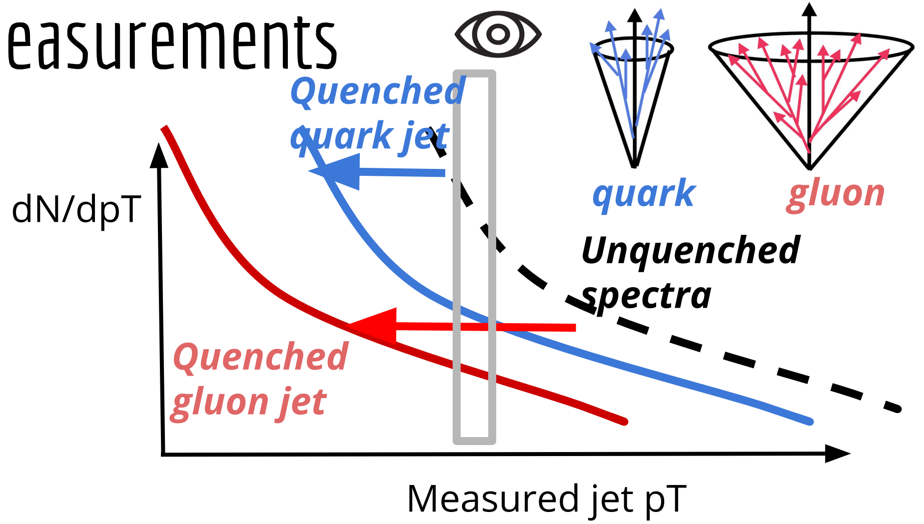
Strategies to mitigate large UE:

- Analyze one sufficiently hard emission (grooming). One can then use tighter grooming conditions (large z_{cut}).
- Increase jet pT.
- Lund jet plane at small ΔR ≪ R
- Heavy-flavor subjets; ensures subjet is not from uncorrelated background.

Correspondence with true emissions is lost
→ ***not unfoldable at large angles***

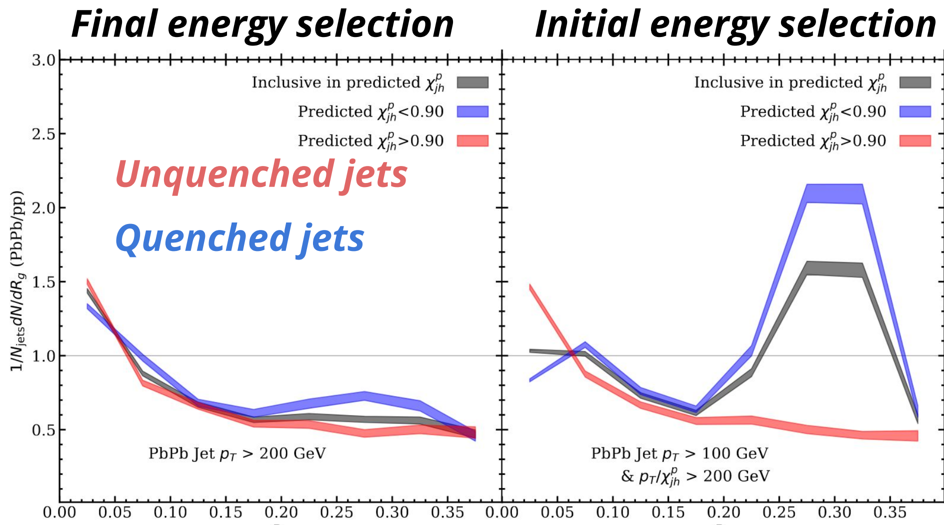
Other issues in *AA* jet declustering measurements

- ***Kinematical bias;*** broad early hard vacuum showers → jet is more quenched.
- Quark/gluon fraction not well-known in AA collisions.
- Medium-response may have an effect at large angles (subject to modeling)



Some of these effects can be mitigated with quark-enriched samples (V-jet, HF-tagged jets), ***which are statistically hungry***. Will benefit greatly from upcoming Run-3 data.

See Bharadwaj's talk on γ+jet substructure.



Du, Pablos, Tywoniuk, JHEP 21 (2020), 206

Jet grooming in AA collisions

Advantages:

✅ Suppression of UE and non perturbative effects with increasingly large zCut.

✅ Calculable with pQCD techniques.

✅ Can be unfolded.

Disadvantages:

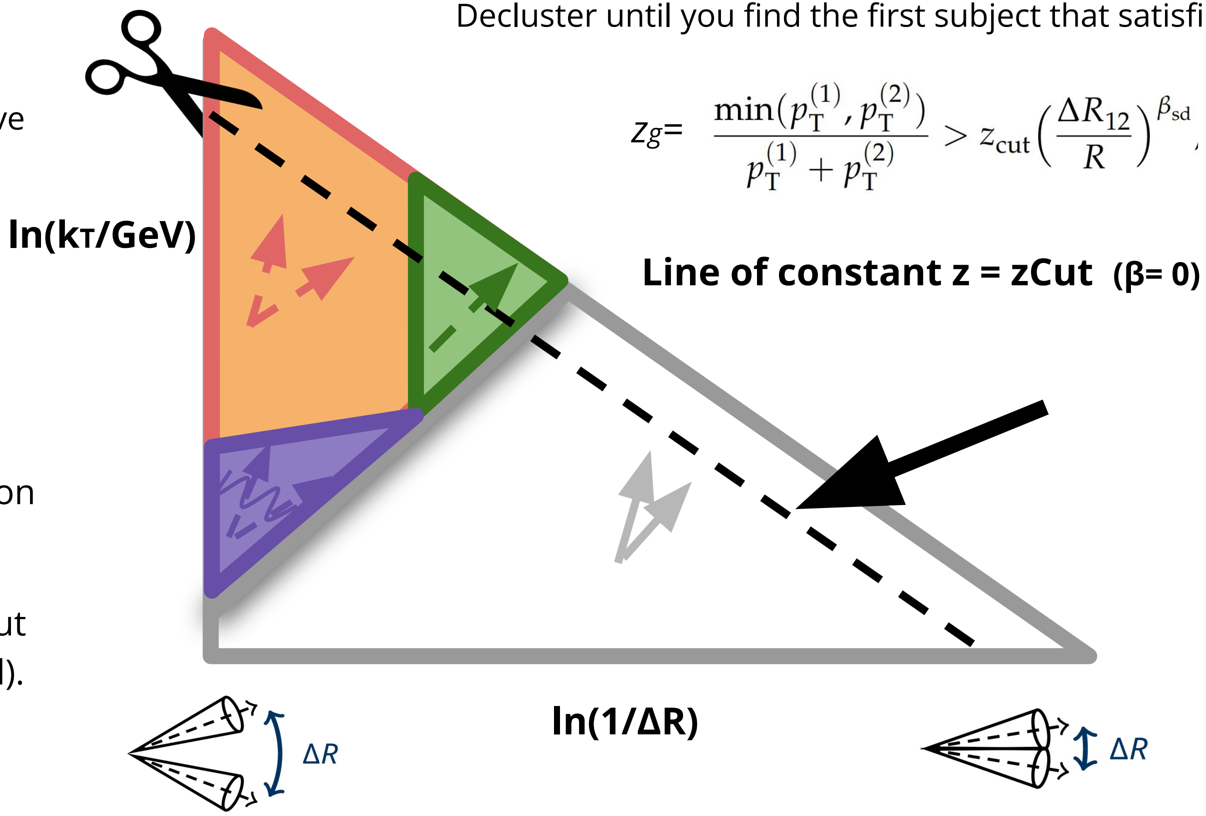
❌ Information loss (exactly one emission per jet).

❌ Reduction of phase-space due to zCut (highly asymmetric subjets are removed).

Soft drop grooming:

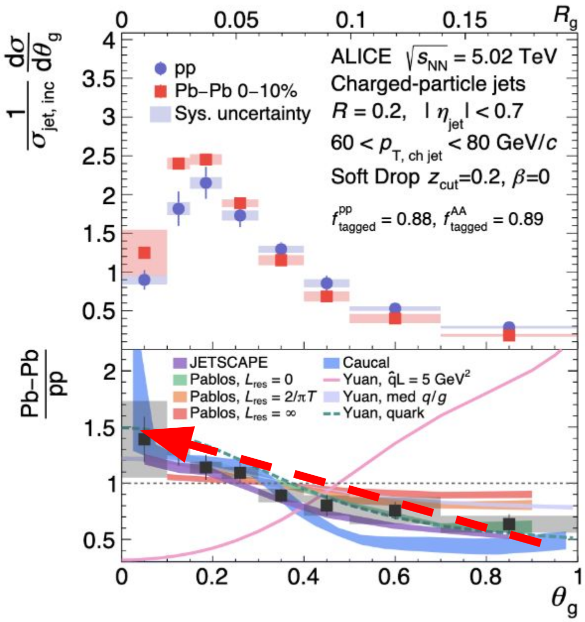
Decluster until you find the first subject that satisfies

$$z_g = \frac{\min(p_T^{(1)}, p_T^{(2)})}{p_T^{(1)} + p_T^{(2)}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R}\right)^{\beta_{\text{sd}}},$$



Groomed observables (one hard emission)

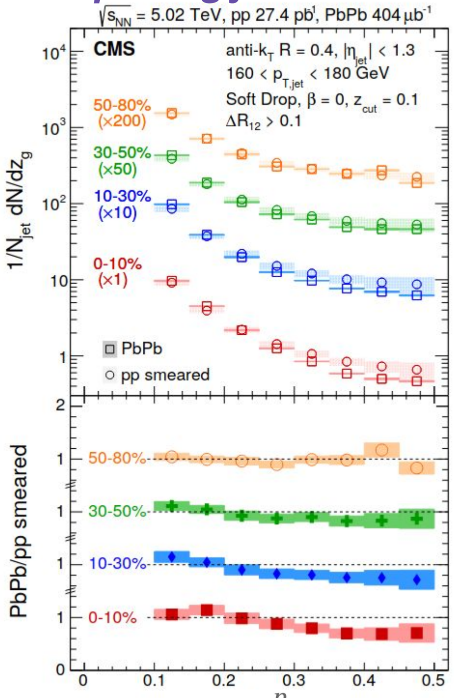
Resolution length of QGP



[ALICE, PhysRevLett.128.102001](#)

Narrowing due to decoherence effects?
Or survivor bias?
See Bharadwaj's talk.

Splitting function

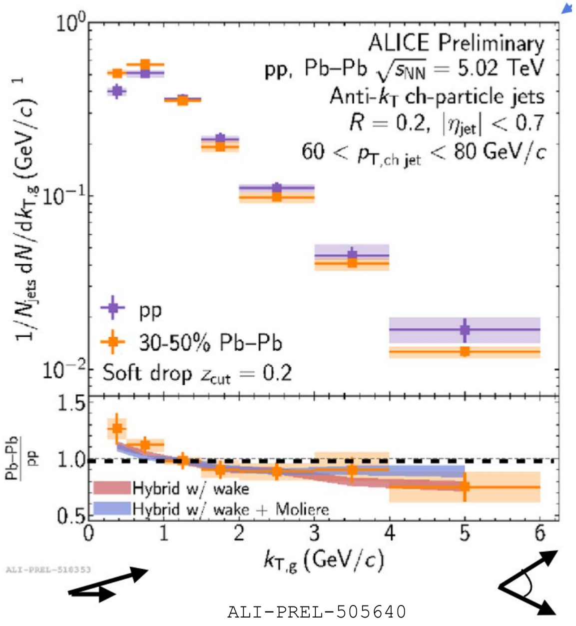


$$z_g = \frac{p_{T2}}{p_{T1} + p_{T2}}$$

CMS, [arXiv:1708.09429](#)

Could we be cutting away
in-medium splittings with zCut cut?

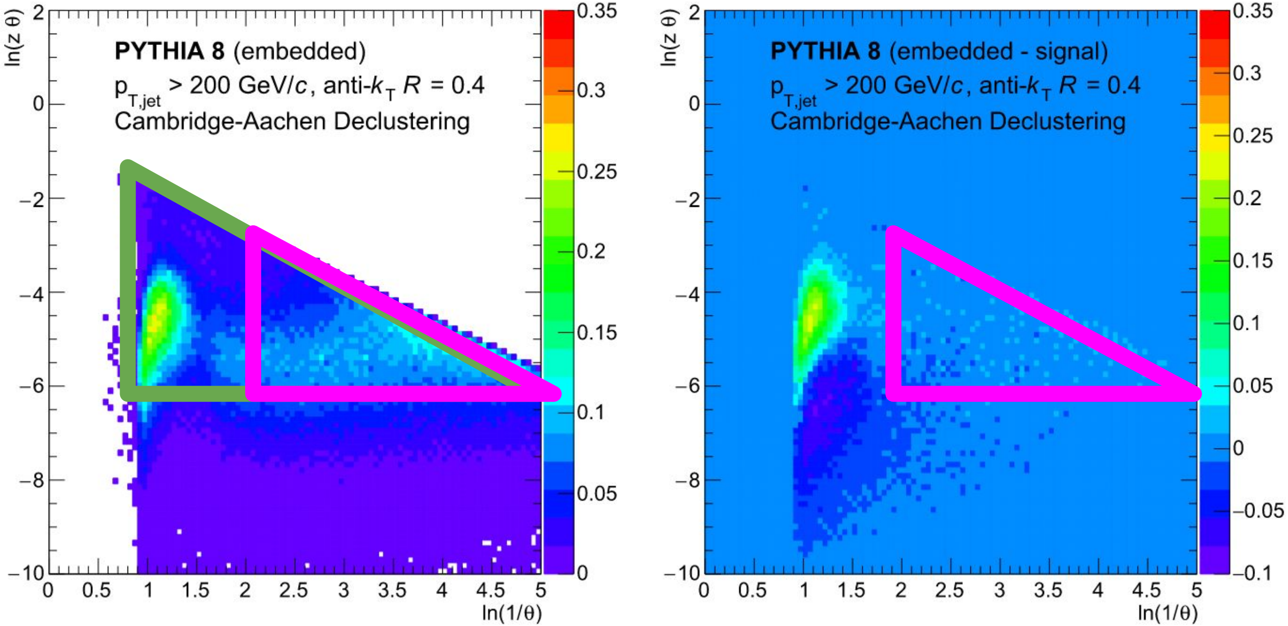
Hard kicks from quasi-particles? (Molière scatterings)



Dynamical kT grooming (hardest subjet)

Primary Lund plane at small angles?

Novel tools and observables for jet physics in heavy-ion collisions, arXiv:1808.03689



Large UE background in *AA* collisions is absent at small angles 2 < ln(1/*ΔR*) < 5.4 (0.005 < *ΔR* < 0.1).

Loss of phase-space can be ***compensated with higher jet pT***, but sacrifices quenching effects.

Green region is dominated by UE (medium-response might contribute here too)

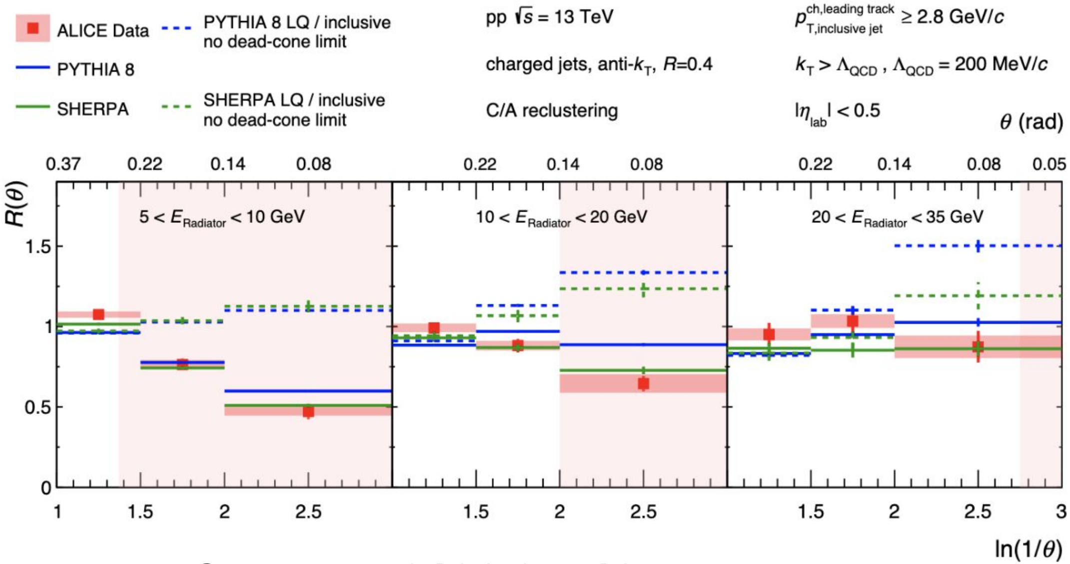
Embedded vs non-embedded substructure is the same for ΔR < 0.1. ***Unfolding-safe region at small angles.***

Dead cone region to study medium-induced radiation effects

Small angles is sensitive to mass effects + UE is suppressed.

Color factors fixed by HF tagging.

Main challenge: ***contamination of B/D-hadron decays.***



***ALICE*, arXiv:2106.05713**

Direct observation of dead cone effect by ALICE using iterative declustering techniques in D-jets (pp collisions)