# Measurement of the Lund jet plane density at 13 TeV

**Cristian Baldenegro***, Leticia Cunqueiro†, Matthew Nguyen*

***LLR-École Polytechnique, †Sapienza Università di Roma**

**Rencontres QGP France 2022**

Laboratoire Leprince-Ringuet

ÉCOLE POLYTECHNIQUE

IP PARIS

SAPIENZA UNIVERSITÀ DI ROMA

CMS

erc

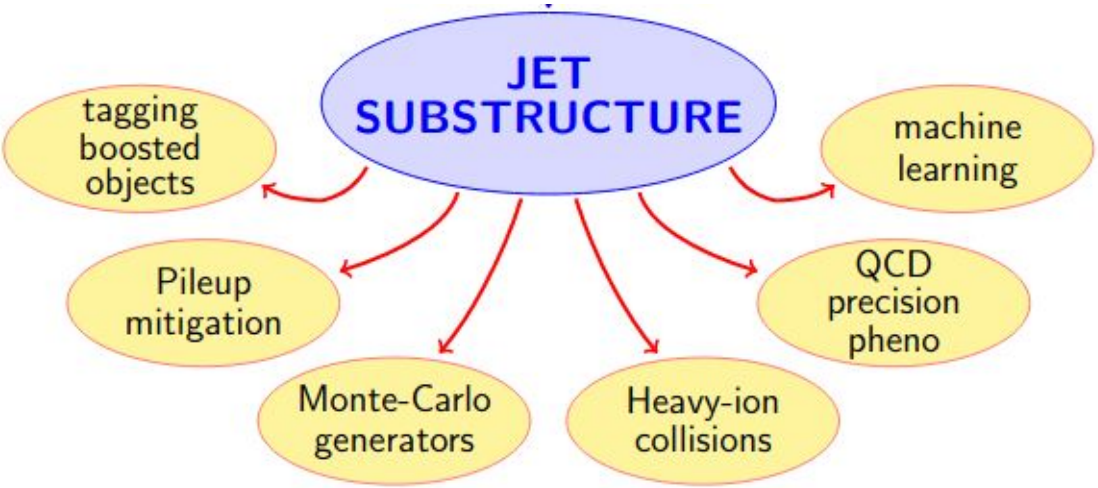
# Jet substructure

- New insights on the strong force by analyzing the radiation pattern inside jets
(***in vacuum and in medium***).

- Experimental precision to challenge pQCD analytical calculations and constrain Monte Carlo generators.

- Classification of jets by flavors (quark jet vs gluon jet, W/Z/H jet vs QCD jets, …)

- Access medium modifications of the parton shower, color coherence effects, energy loss.

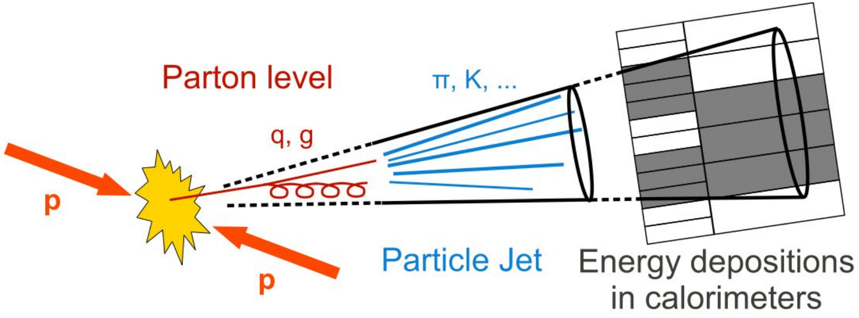


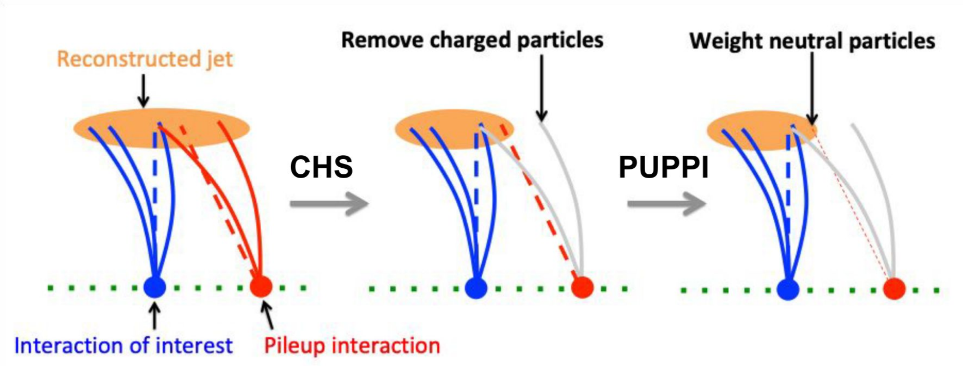

*sketch by Gregory Soyez*

# Jet reconstruction in CMS

Particle-flow (PF) candidates are clustered into jets with anti-kt algorithm, (R = 0.4 & 0.8 are the std distance parameters)

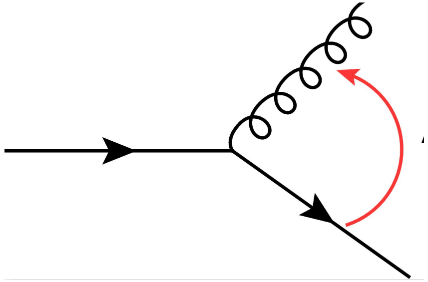
**P**ileU**p** **P**er **P**article **I**dentification **(PUPPI)** algorithm: remove tracks not associated to PV, weigh down neutral clusters not close to PV tracks.



# Lund diagrams

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



splitting angle

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

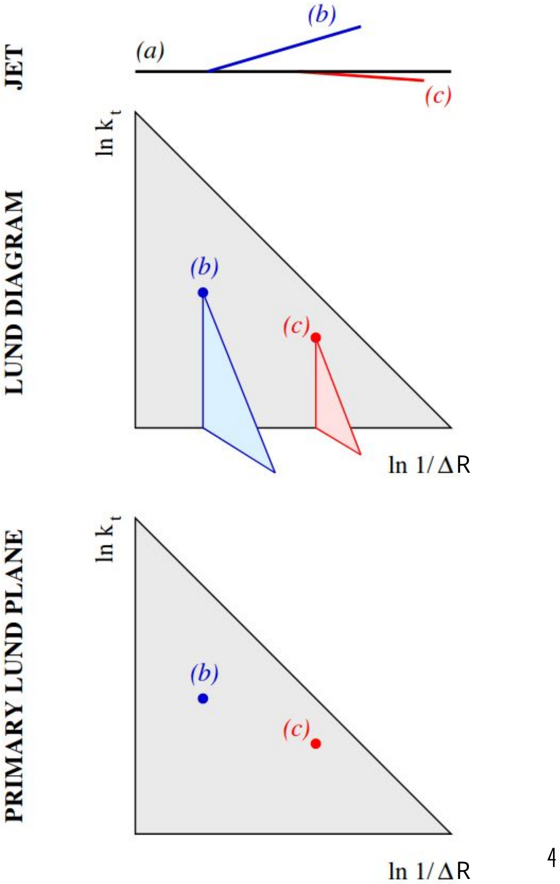
relative transverse momentum

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

They are used for parton shower and jet substructure techniques developments.

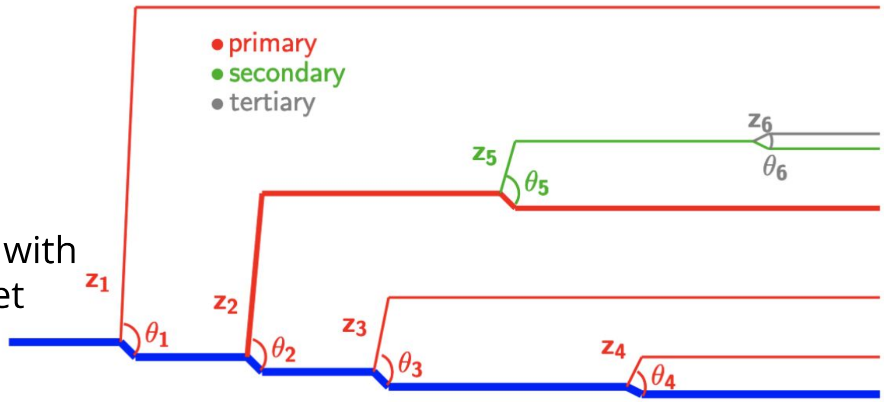
Theoretical Lund diagrams are constructed with partons. However, we can construct an experimental proxy of them using iterative jet declustering techniques.

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



# Constructing the primary Lund jet plane

*Gregory Soyez' sketch*




Start with C/A jet

Cambridge–Aachen declustering

large angles → small angles

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

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

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

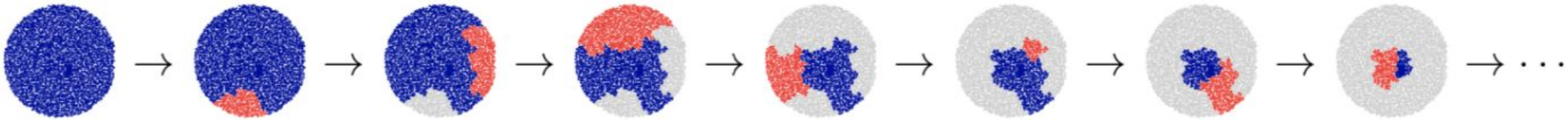
C/A sequentially combines the closest pairs of particles (or proto-jets) at each step of the clustering process (small → large angles).

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,

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

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



# The Lund jet plane

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

Measurement of a per-jet double-differential cross section:

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

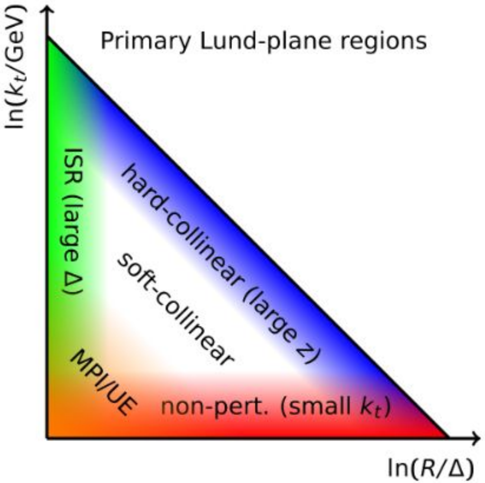
At LO in the soft- and collinear limit of pQCD, it is proportional to αS

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

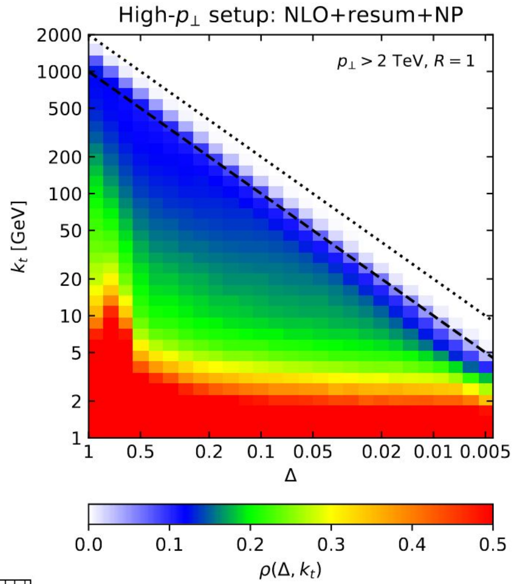
→ **the running of** αS(kT) **sculpts the Lund plane.**

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

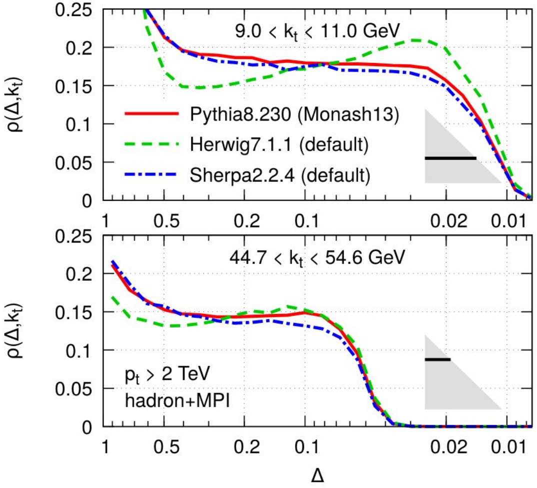
The Lund jet plane can be used to constrain MC generators and is amenable to analytical pQCD calculations.




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




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



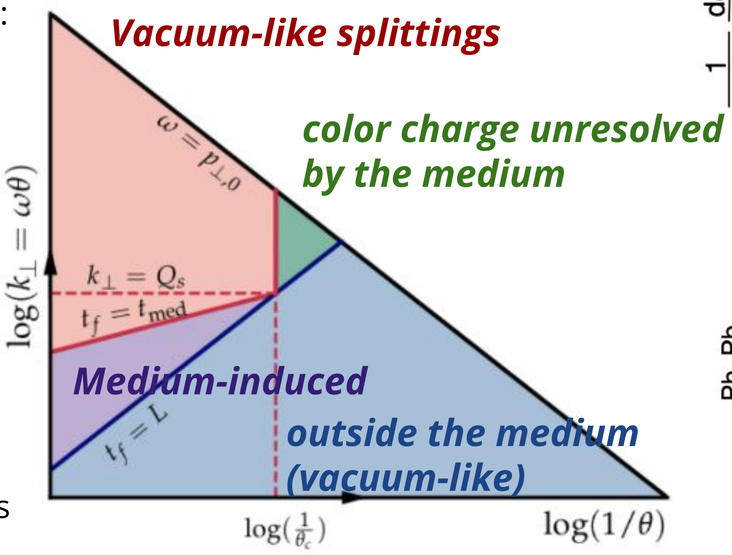
# Lund jet plane in heavy-ion collisions

Potential sensitivity to several effects:

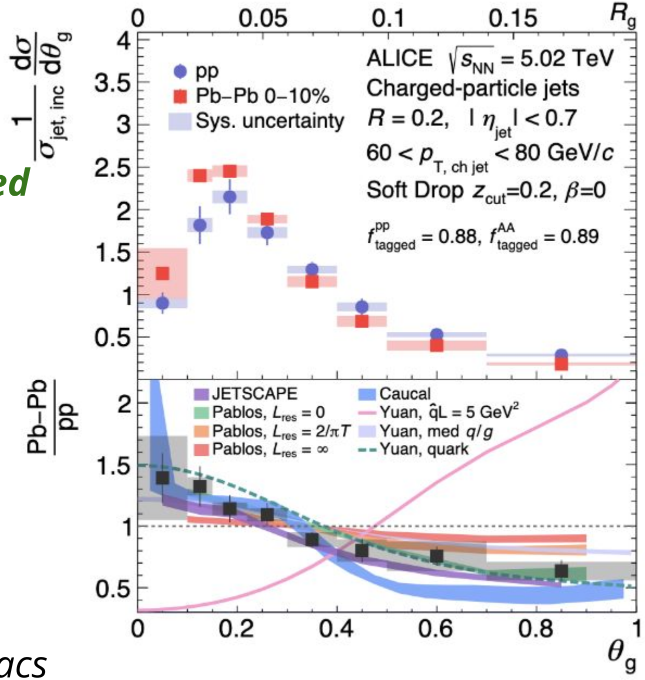
- Color coherence effects
- Evolution in time of the parton shower
- Sensitivity to modifications of the splitting function

***Difficult to measure the full Lund plane due to large uncorrelated bkg.***

→ Lund plane has been analyzed in regions where the underlying event is under control.

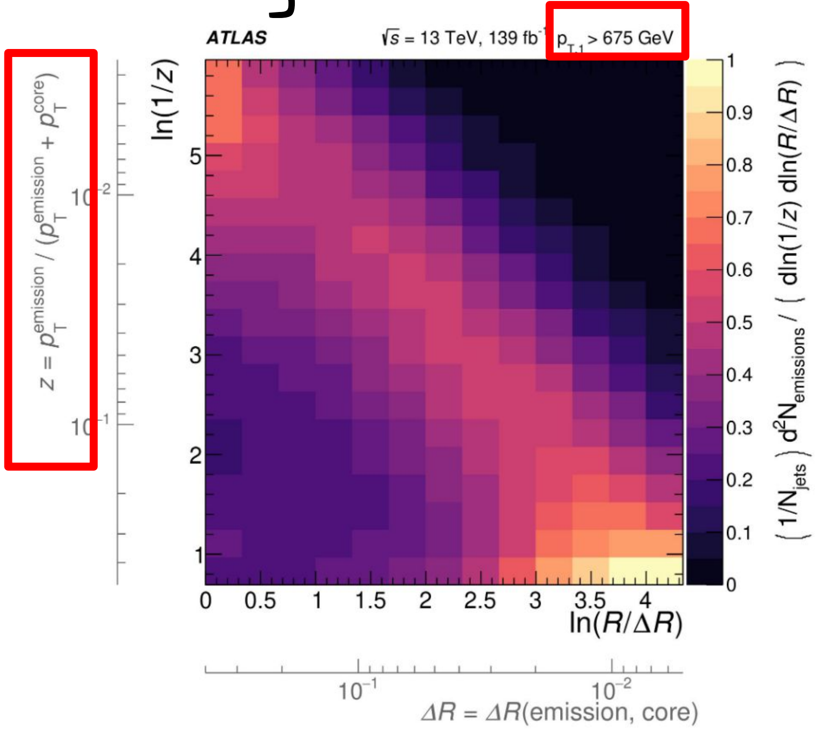



*sketch from P. Caucal, A. Soto, A. Takacs*
***arXiv:2111.14768***

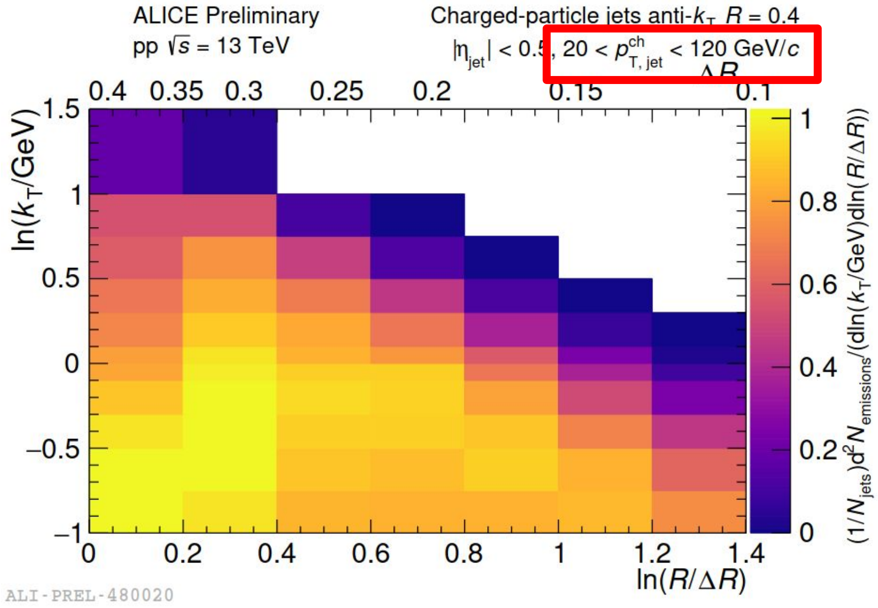



***ALICE Coll, PhysRevLett.128.102001***

# 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.

# Run-2 analysis

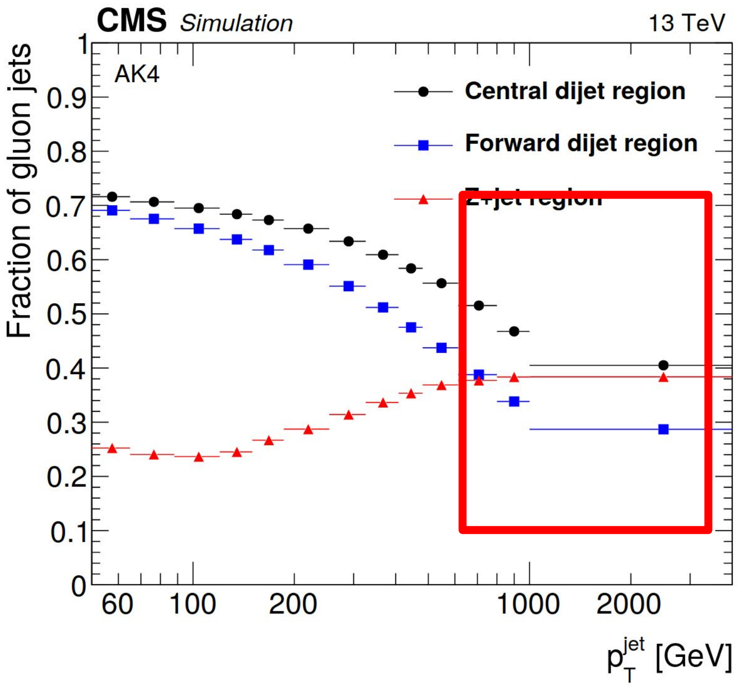
Data sample & event selection:

- 13 TeV pp collisions, 138 fb-1 of data.
- Unprescaled inclusive jet trigger (fully efficient at pT ~ 600 GeV).
- PUPPI anti-kT R = 0.4 jets.
- Lund plane is extracted for **jets with pT > 700 GeV and |y| < 1.7.**
- Jet substructure using **charged-particles inside the jet with pT > GeV and |η| < 2.5** (***better angular and momentum resolution***).
- Jets are ungroomed (we want to see everything!)

10 M jets with these characteristics in Run-2.

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

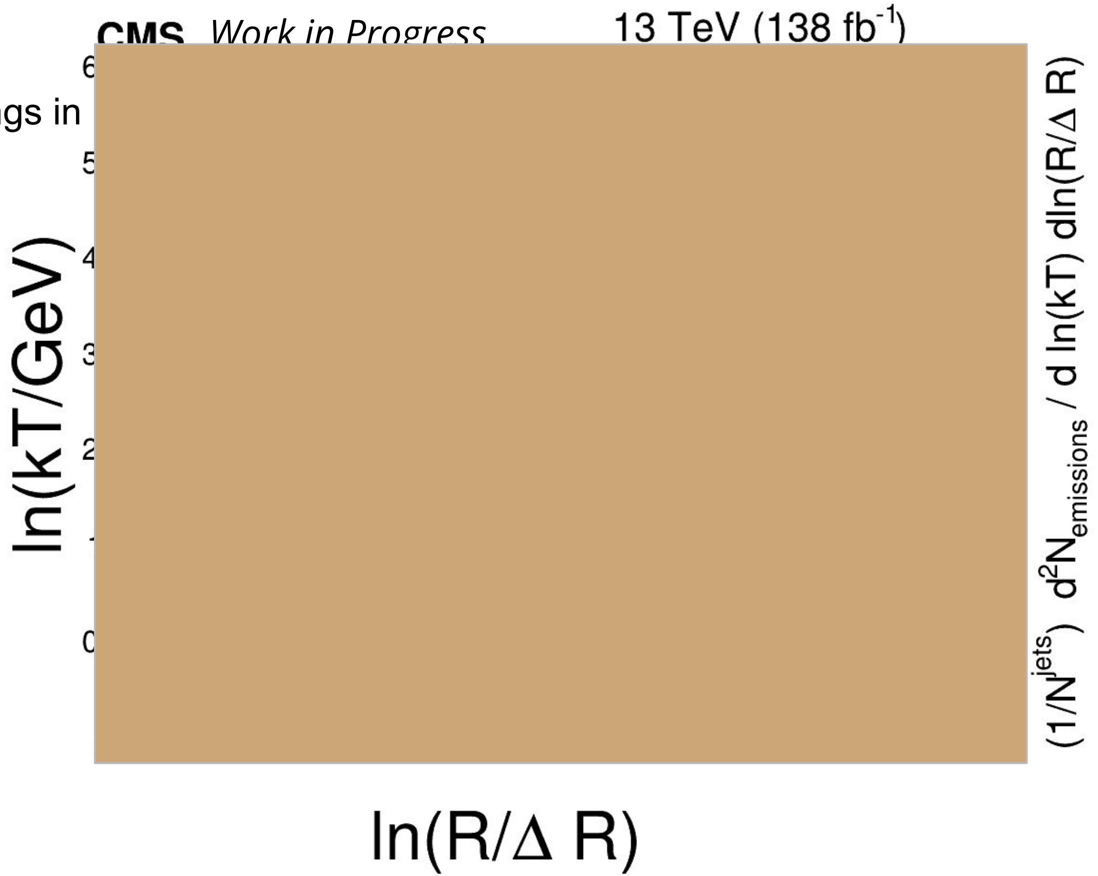
About 50-70% of the jets are quark-jets




**CMS measurement**, *arXiv:2109.03340*

# Detector-level Lund jet plane

60 M splittings in Run-2




***Kinematic range for measurement:***

$0.005 < \Delta R < 0.4$

(~pixel pitch)

$0.4 < kT < 150$ GeV

# Unfolding the Lund plane to stable charged-particle level

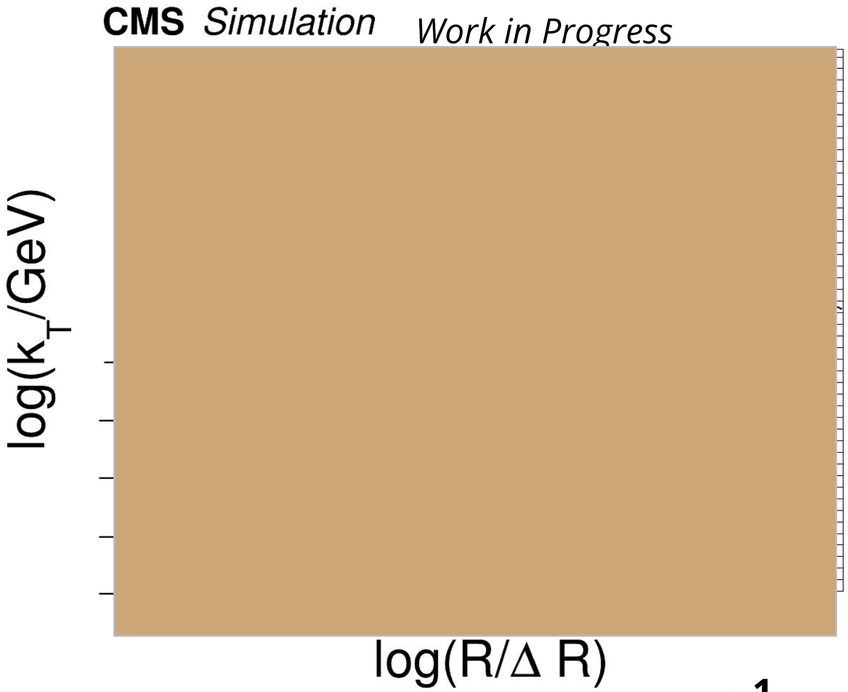
$$\frac{1}{N^{\text{jets}}}\frac{\mathrm{d}^2 N_{\text{emissions}}}{\mathrm{d}\ln(k_T)\,\mathrm{d}\ln(R/\Delta R)}$$

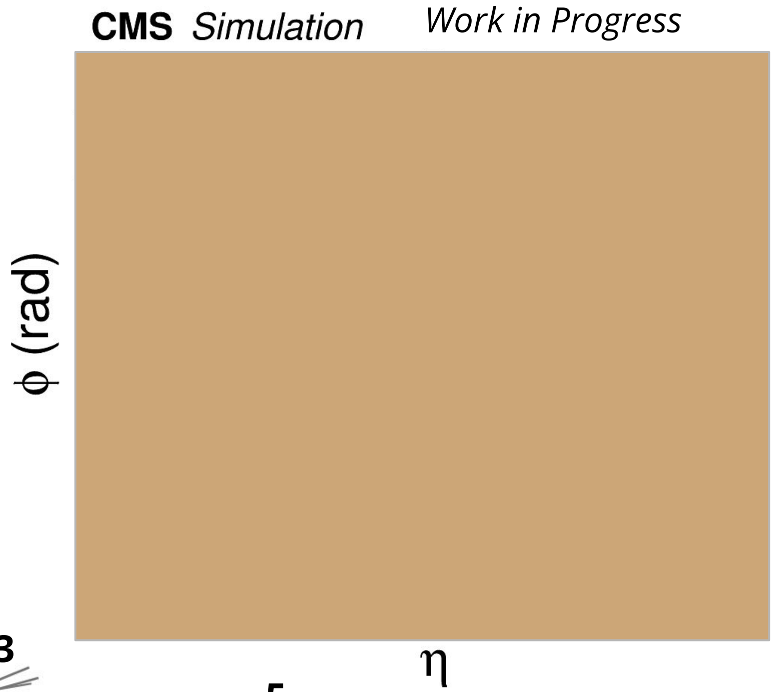
**1D unfolding for number of jets for normalization ("bookkeeping")**

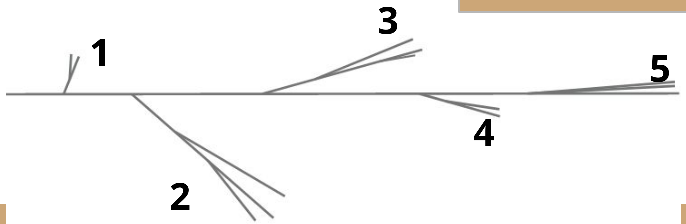
**3D unfolding for for number of emissions (substructure)**

The response matrix is built with geometrically matched truth-level and det-level splittings. Only uniquely matched pairs are considered.

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



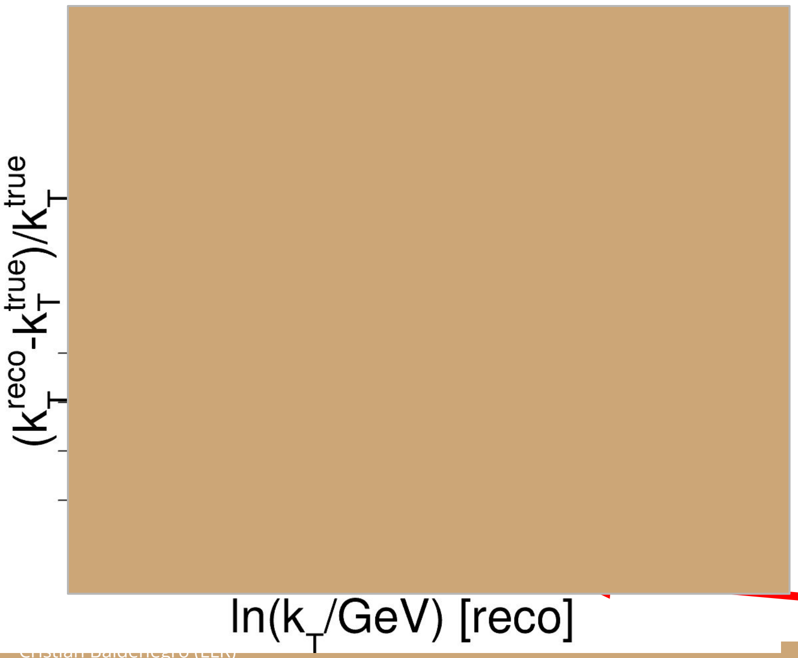



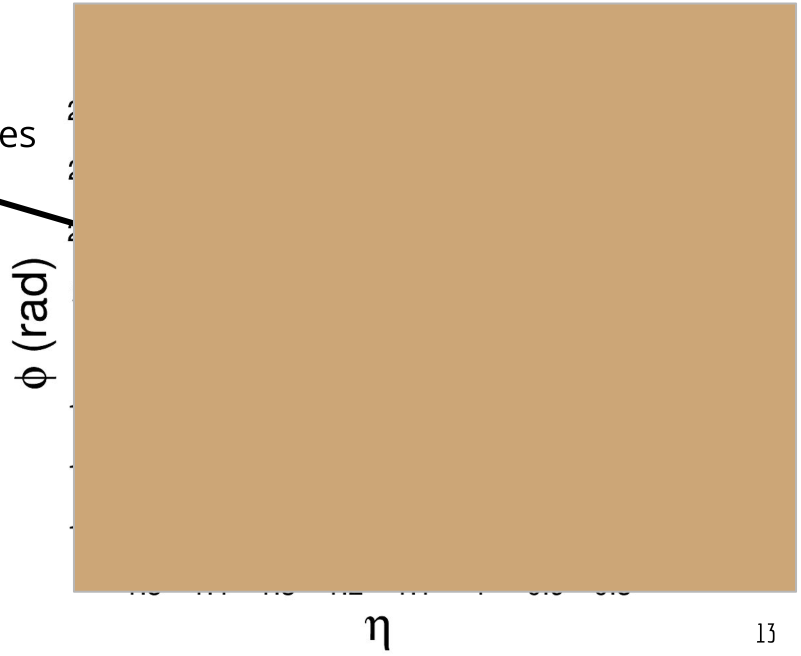



# Mismatched splittings

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.***



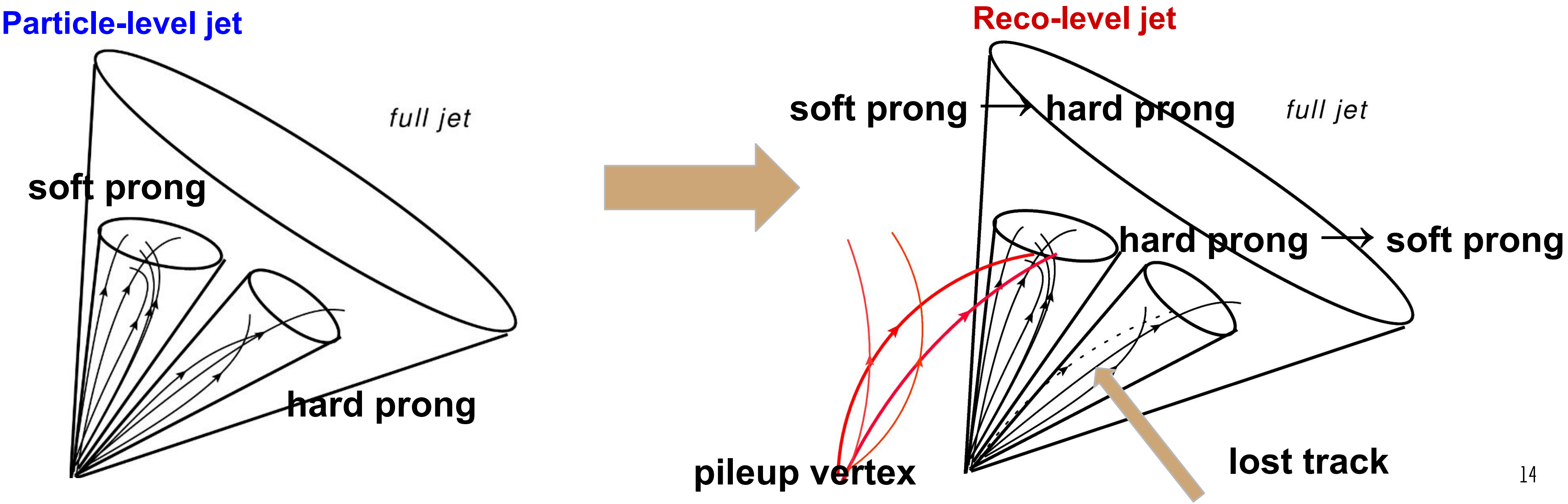



# Mismatches are more likely to occur when pTsoft ≈ pThard

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.**

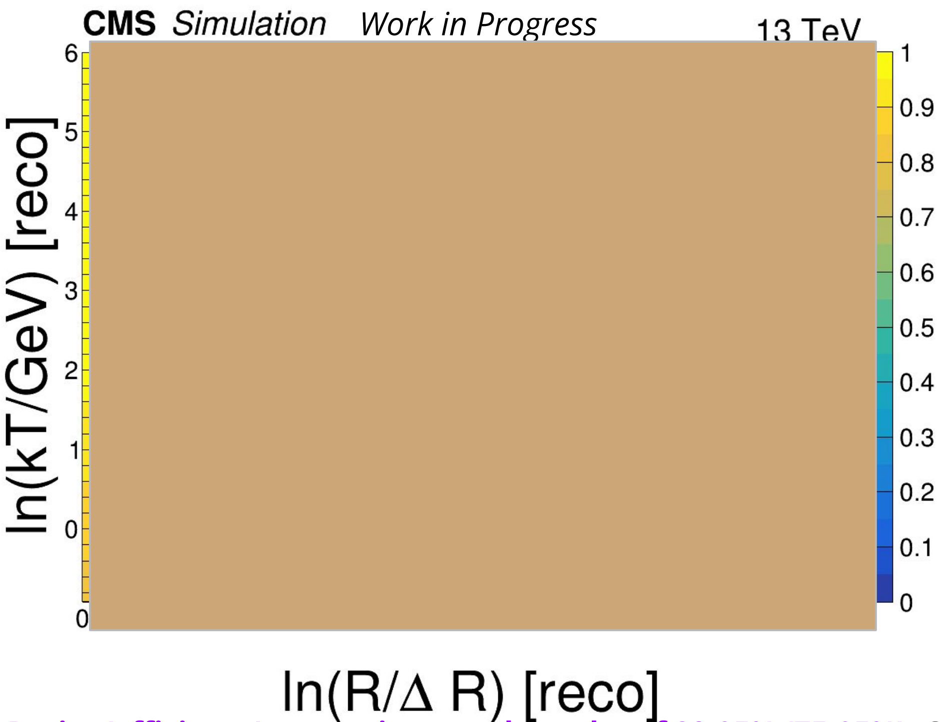
Also, due to tracking inefficiencies, **the hard prong can be demoted to soft prong at reco-level.**

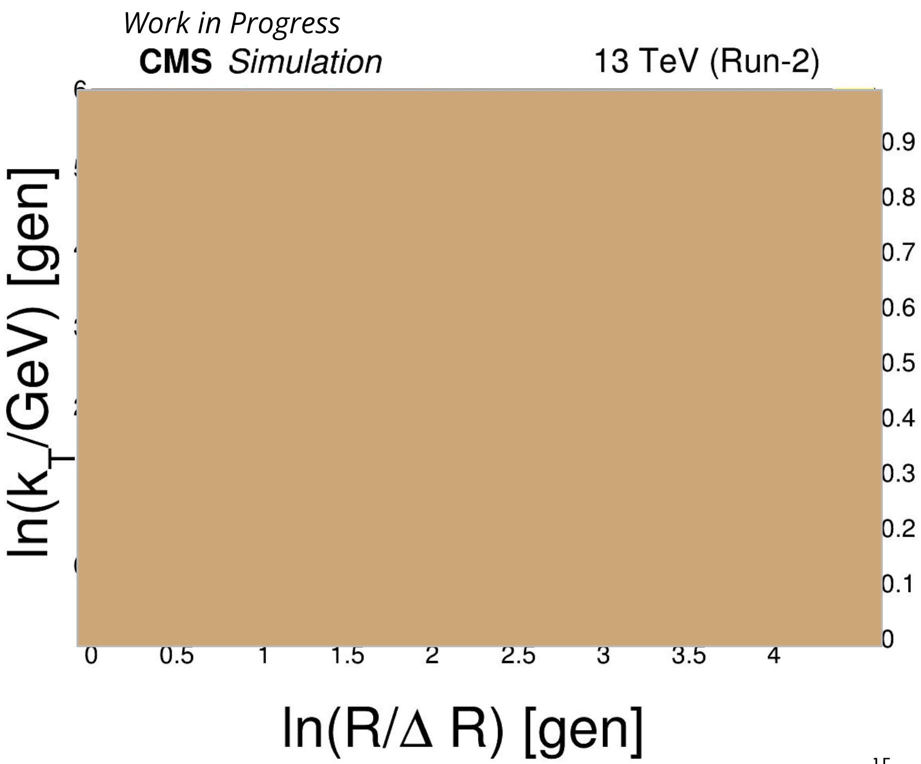


# Purity and efficiency corrections

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

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

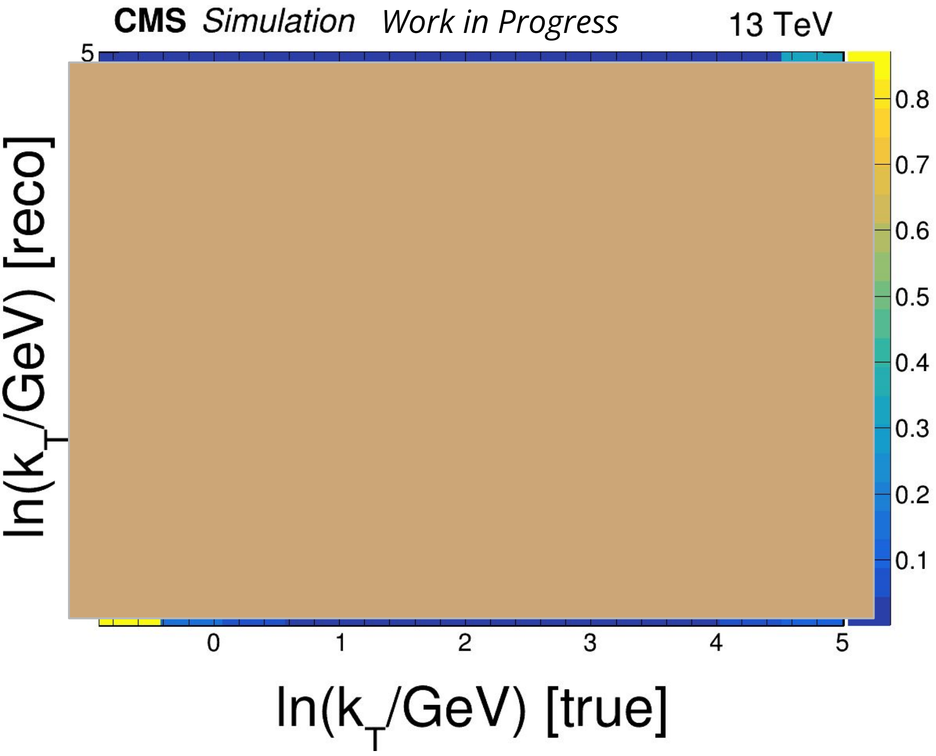


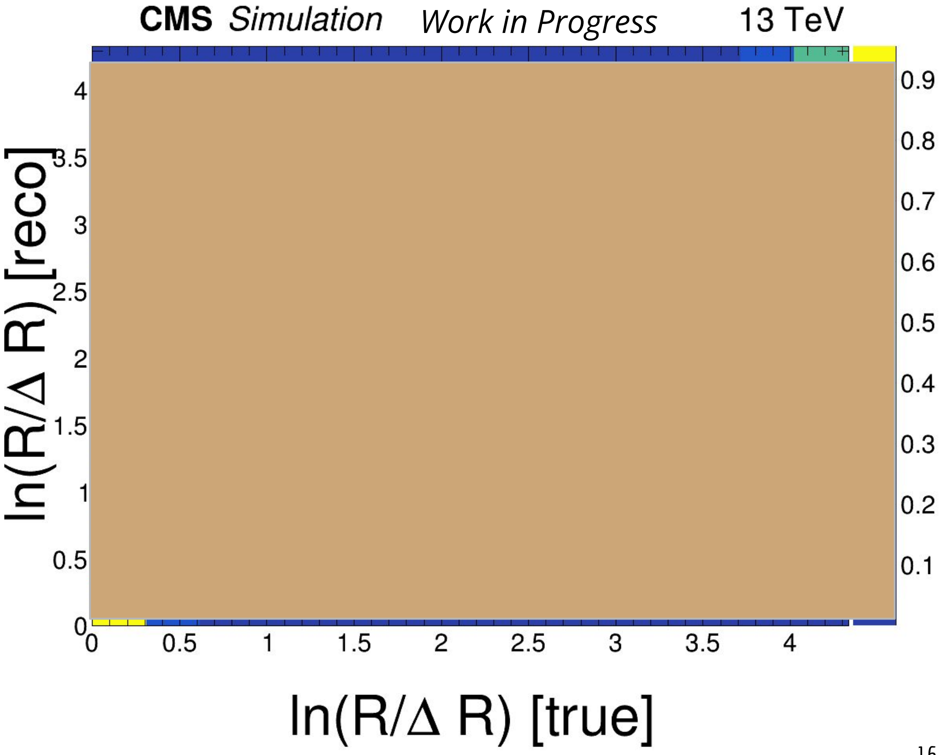




**Purity (efficiency) corrections on the order of 80-95% (75-95%).** Corrections w/ PYTHIA8 and HERWIG7 are the same within 1-3%.

# 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.



# Unfolding the Lund plane to stable charged-particle level

1. Apply 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.

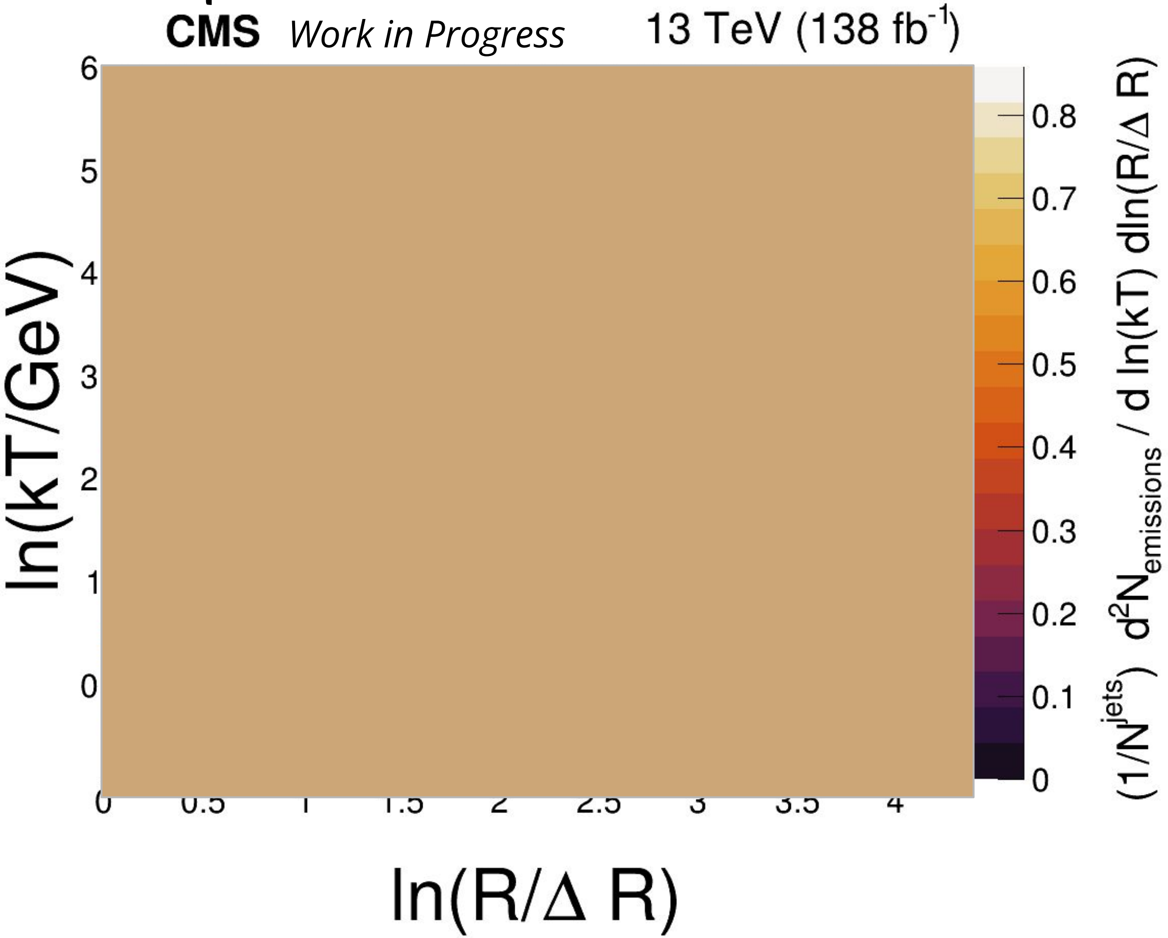
3. Apply efficiency corrections (LP*1/efficiency).
   **This is the fully corrected Lund jet plane.**

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

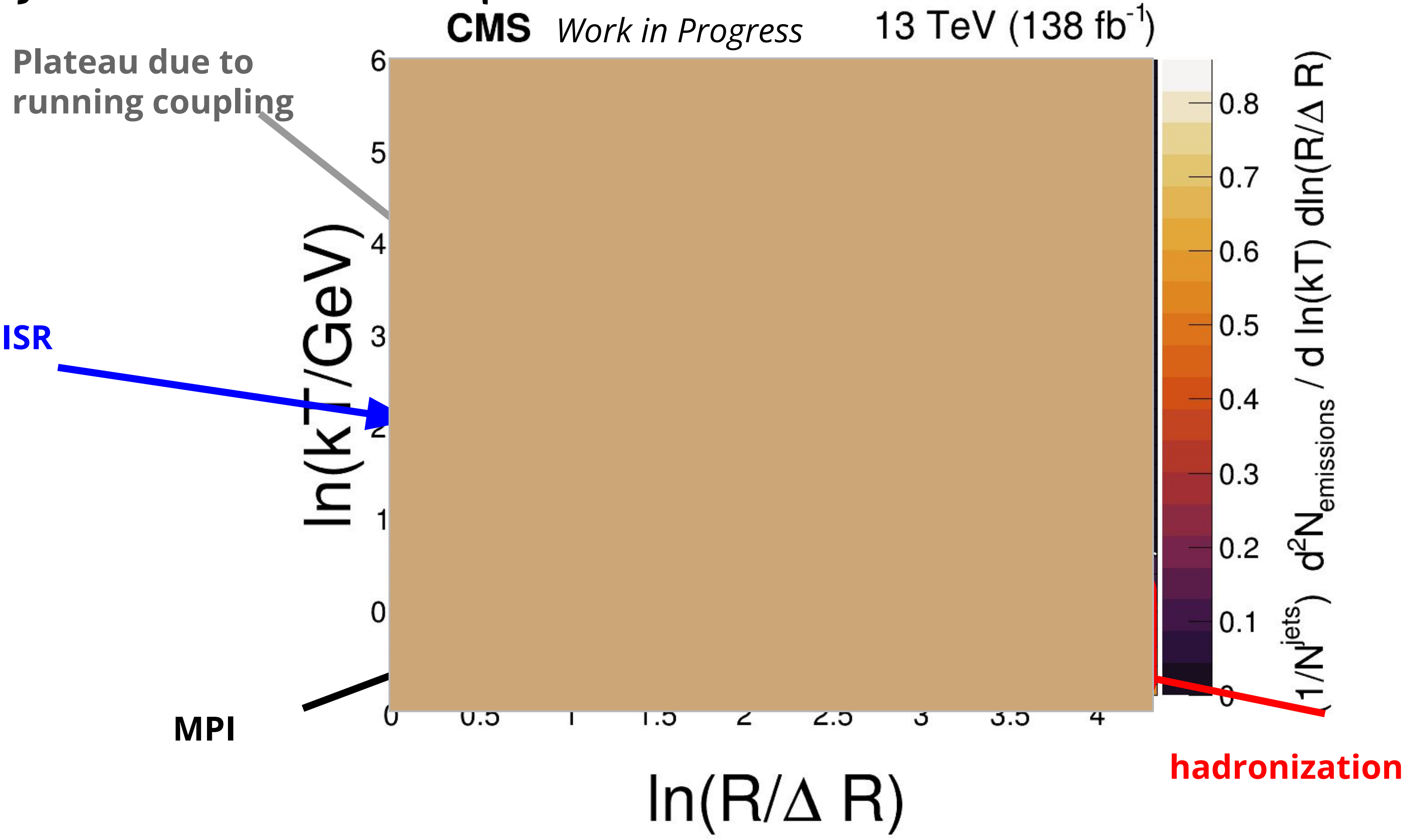
**1D unfolding of pTjet spectra for normalization**

**3D unfolding for for Nemissions (substructure)**

# Fully corrected Lund plane



# Fully corrected Lund plane



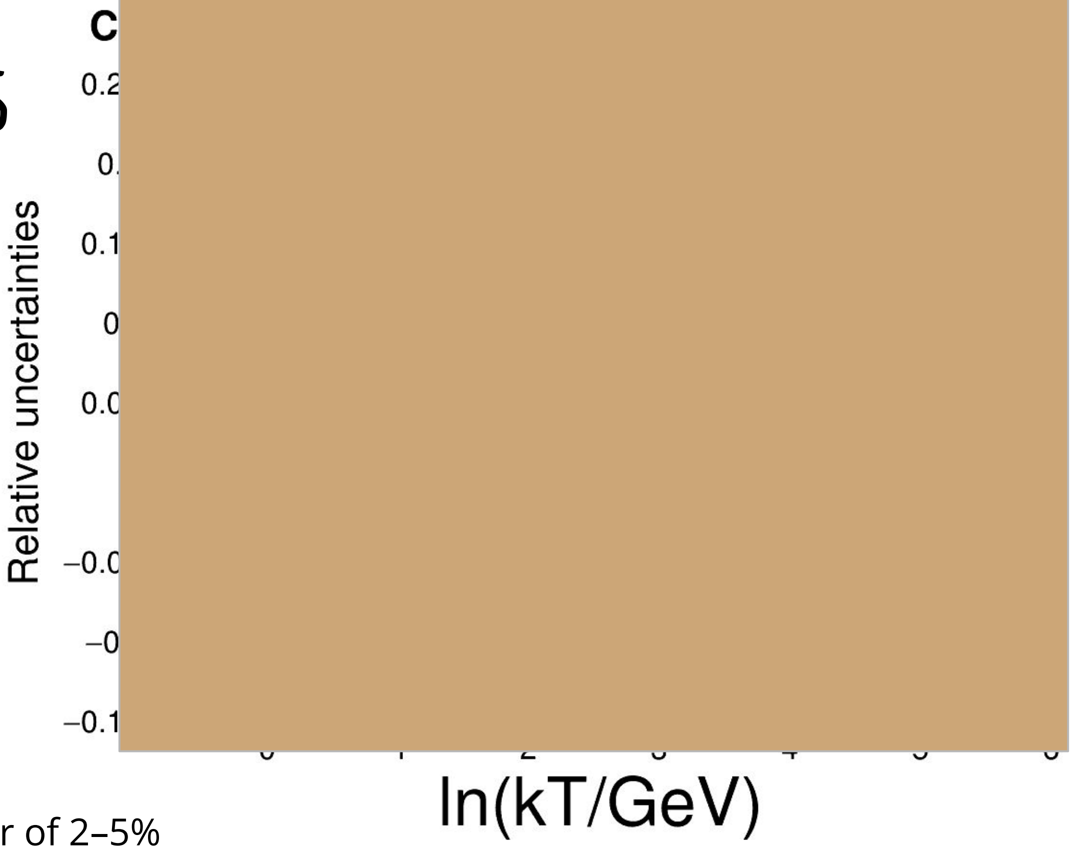
# Systematic uncertainties

Dominant (2–10%):

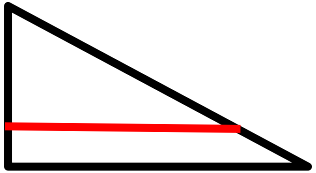
- **MC modeling (herwig7 vs pythia8)**
- **Pileup reweighting uncertainties**
- **Track inefficiency uncertainties**

Subleading ( < 1%):

- **Response matrix stats**
- **Regularization bias**
- Jet energy corrections (**JEC**) and resolution uncertainties (**JER**)

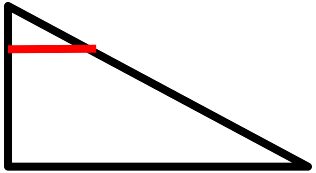


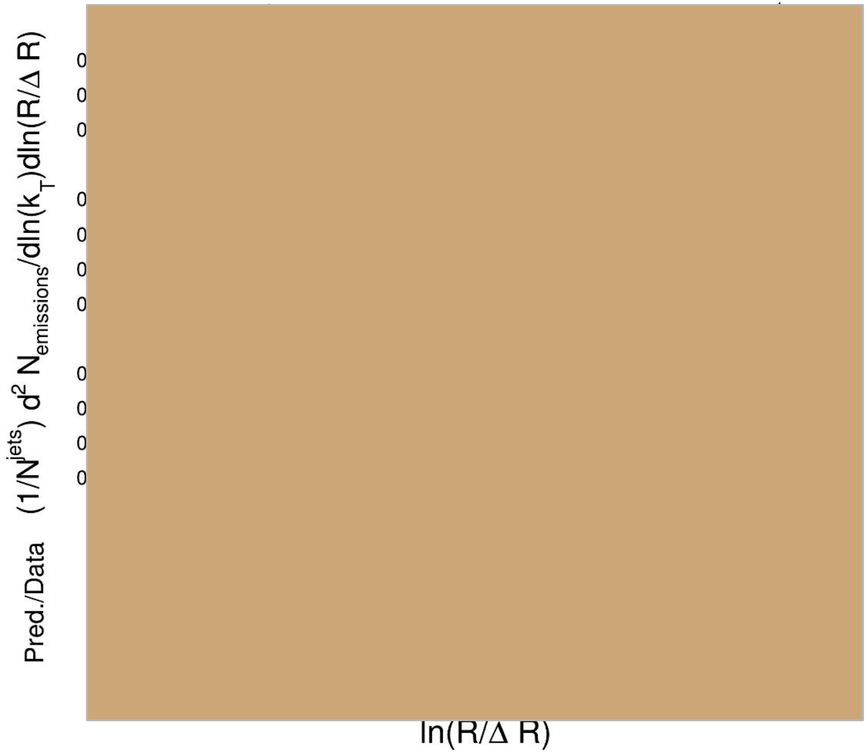

Total experimental uncertainties are of the order of 2–5% throughout (most of) the Lund plane; they increase to 10% at the kinematic edge of the Lund plane (z = 0.5).

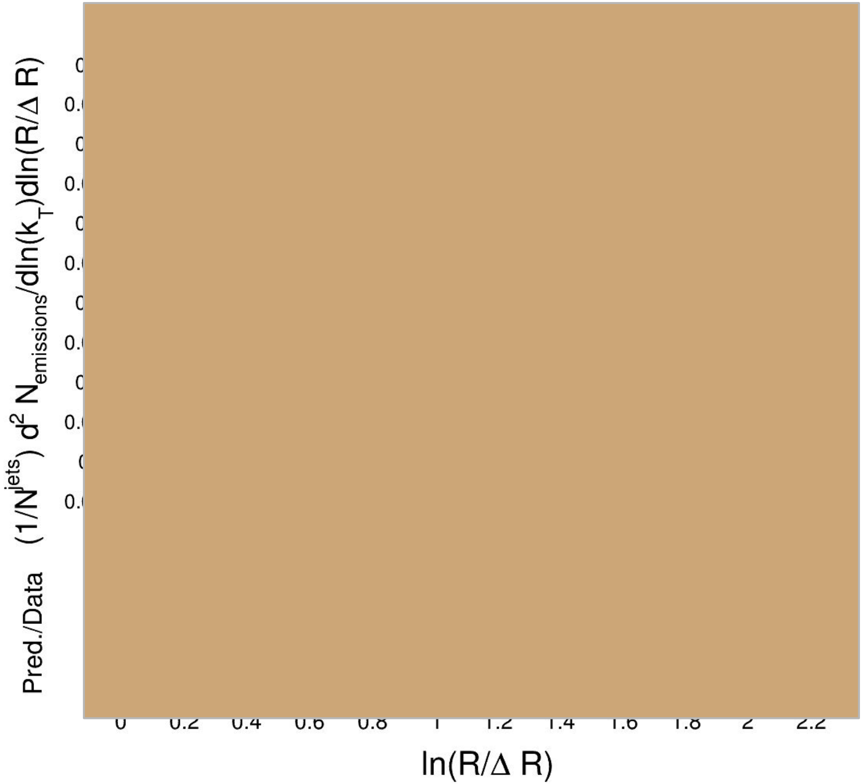


Low-kT
(nonperturbative region)

High-kT
(perturbative region)

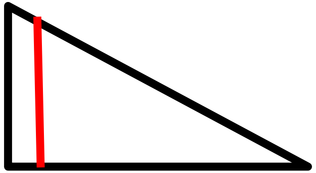


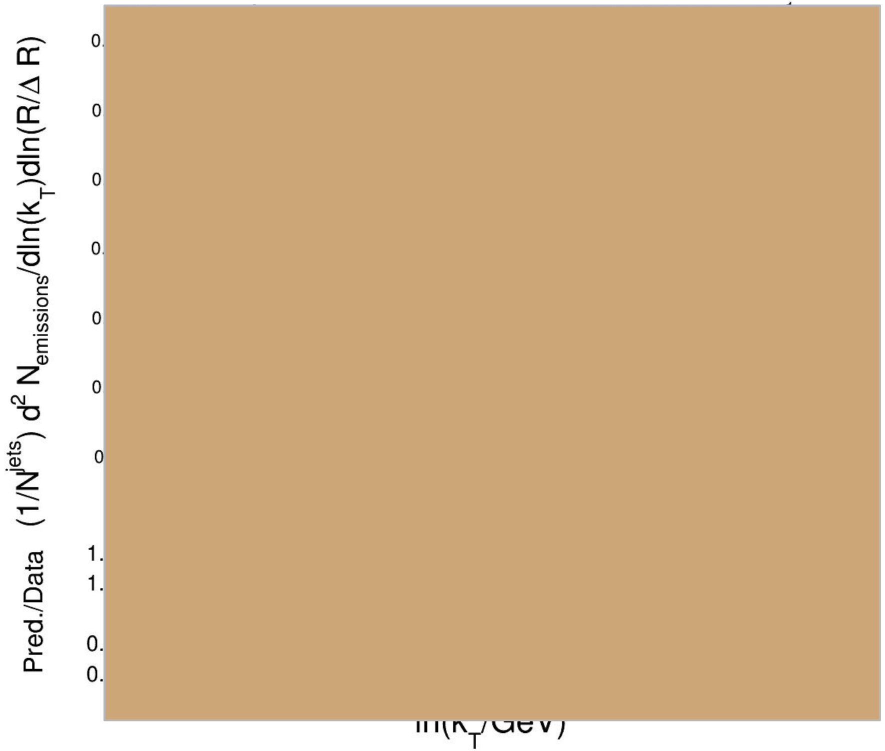


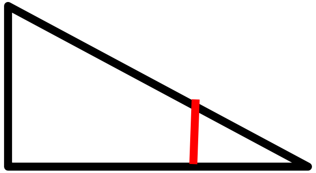

**PYTHIA8 generates more splittings in nonperturbative region by 10-20%.**

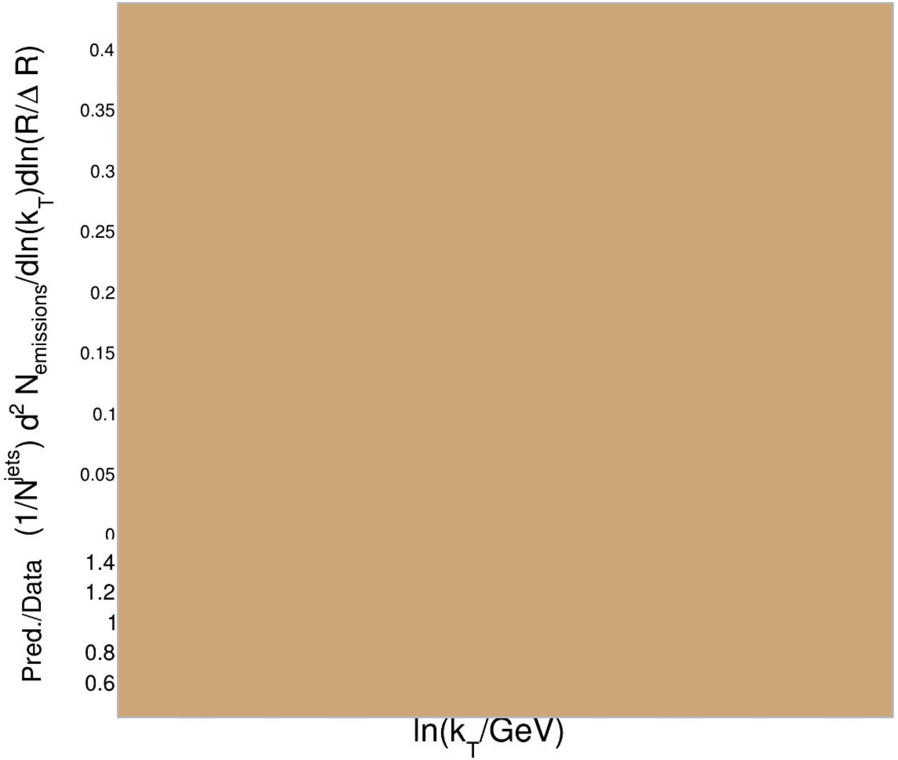
Wide angles





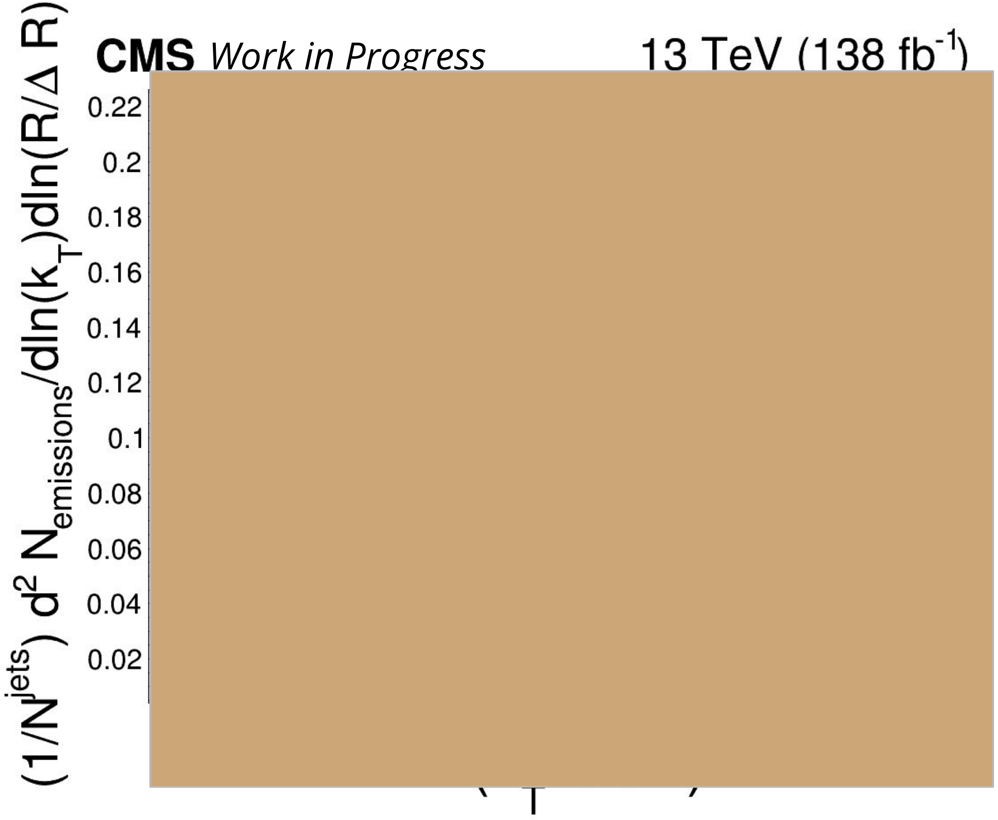

Small angles
(collinear limit)






**Strong constraints on parton shower & hadronization in H7 and P8**

# Running coupling in the jet radiation pattern




Lund jet plane can in principle be used for αS extraction.

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

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 $\Lambda_{QCD}$ = 0.2 GeV yields reasonable description of data.

# Summary & prospects

- Experimental uncertainties 1-10% throughout the Lund plane.

  Model uncertainties dominate for most of the Lund plane; pileup modeling and tracking reco uncertainties dominate in kinematic boundary.

- Strong constraints on MC generators in perturbative and nonperturbative regions. Most recent PYTHIA8 and HERWIG7 tunes do not describe the jet substructure.

- Direct sensitivity to the running of alphaS.

- Looking forward to comparing with analytical calculations.

- Planning to go for a public analysis note in Fall 2022.