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

Cristian Baldenegro*, Leticia Cunqueiro†, Matthew Nguyen*

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

Assemblée Générale du GDR QCD, Île-d'Oléron
May 23-25 2022

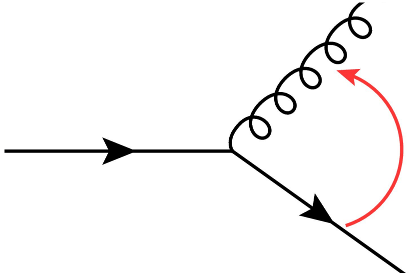
Laboratoire Leprince-Ringuet

SAPIENZA UNIVERSITÀ DI ROMA

Lund diagrams

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

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

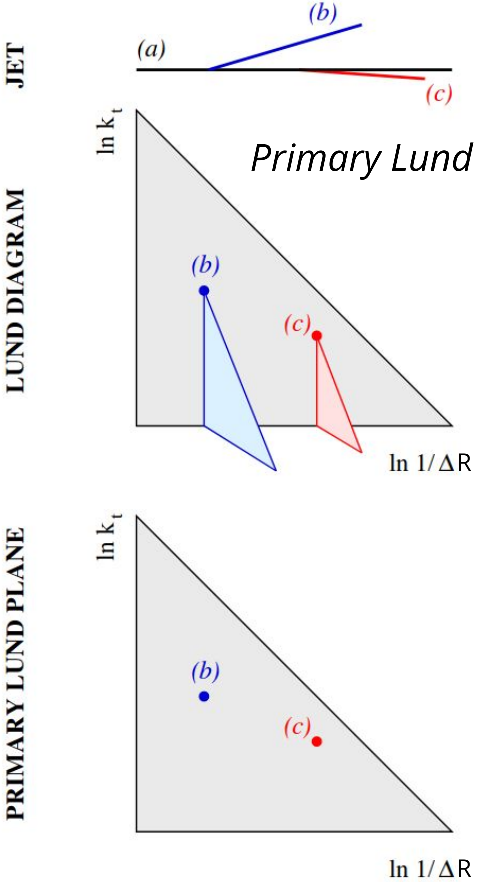


splitting angle

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

relative transverse momentum

$$k_{\mathrm{T}}$$



Primary Lund plane

Historically used for parton shower developments and resummation techniques.

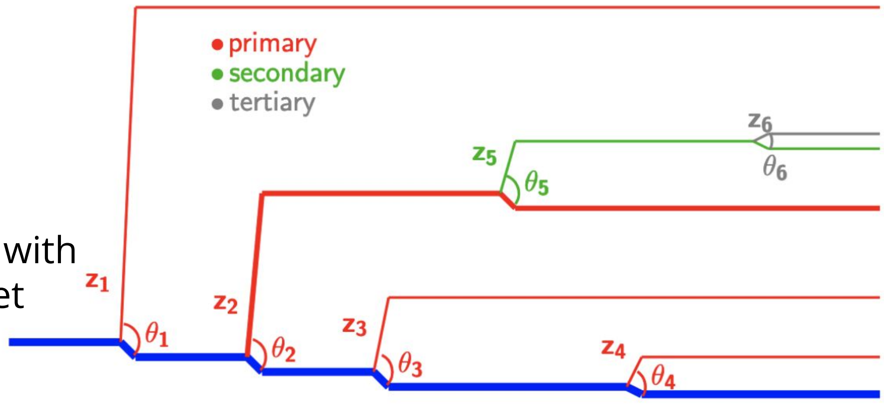
Theoretical Lund diagrams are constructed with partons. However, we can construct an experimental proxy of them using iterative jet declustering techniques.

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).

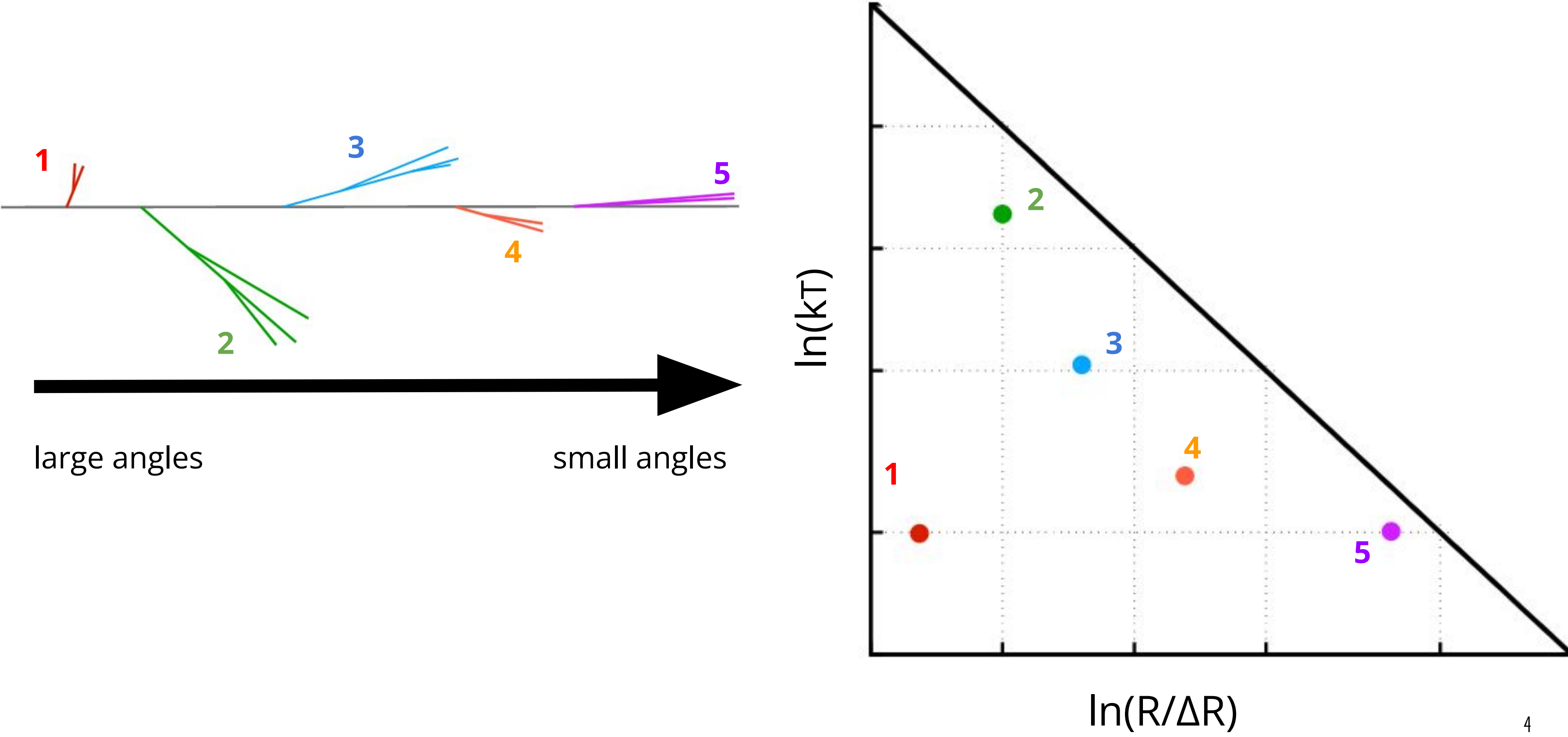
Then, the C/A jet is declustered iteratively (large → small angles).

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



The Lund jet plane density

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

Measurement of emission density as a per-jet double-differential cross section:

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

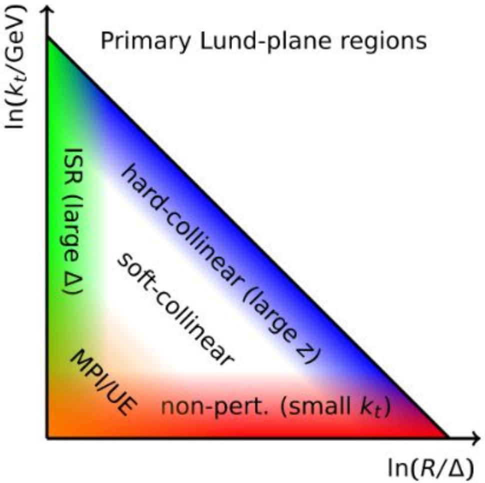
At LO in the soft- and collinear limit of pQCD, it is proportional to α_S

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

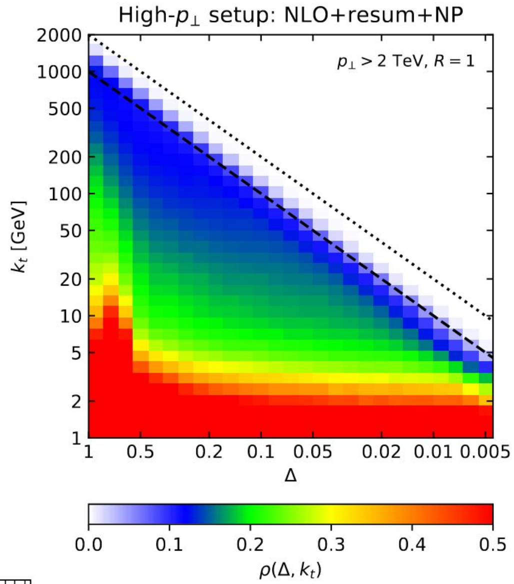
→ **the running of** $\alpha_S(k_T)$ **sculpts the Lund plane.**

$C_R = C_F = 4/3$ for quark jets and $C_R = C_A = 3$ for gluon jets.

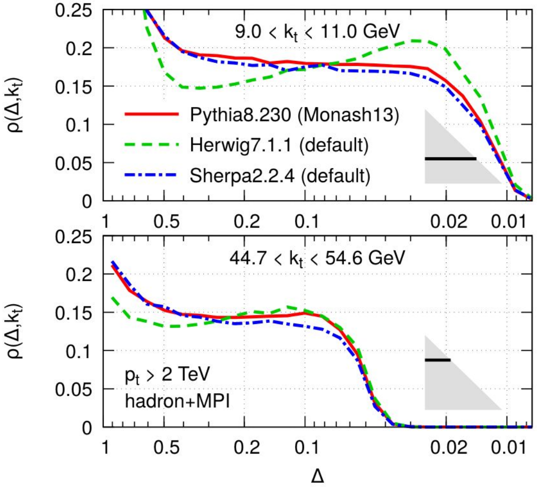
The Lund jet plane can be used to constrain MC generators and is amenable to analytical pQCD calculations. Also, can be used to understand the QGP.



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



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



Existing measurements by ALICE and ATLAS

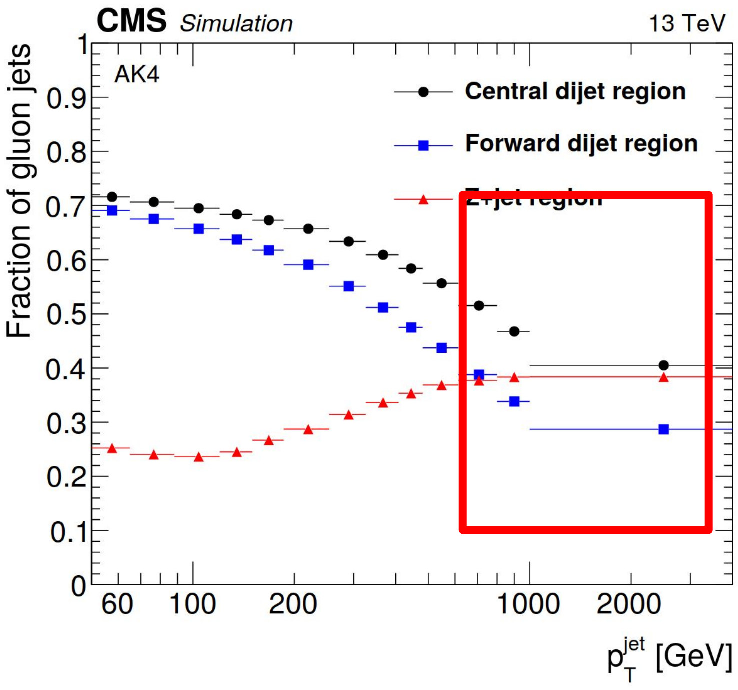
Run-2 analysis

Data sample & event selection:

- 13 TeV pp collisions, 138 fb-1 of data.
- anti-kT *R = 0.4* and *R = 0.8* jets with pileup mitigation (PUPPI algorithm)
- 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!)

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 measurement, ***arXiv:2109.03340***

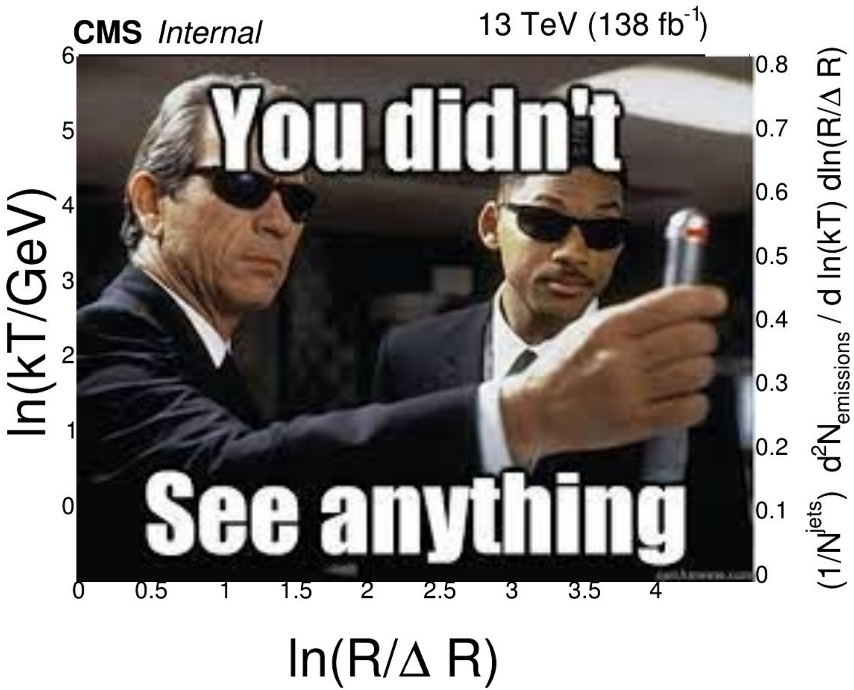
Detector-level Lund jet planes

Kinematic range for measurement:

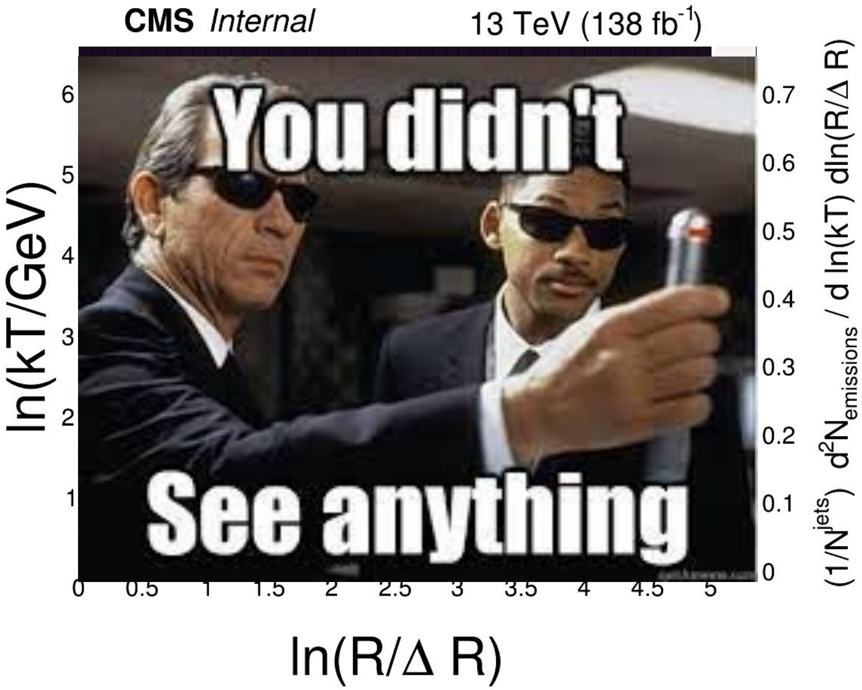
0.005 < ΔR < 0.8
(~pixel pitch)

0.4 < kT < 280 GeV
(for pTjet = 700 GeV)

R=0.4



R=0.8



Unfolding the Lund plane to stable charged-particle level

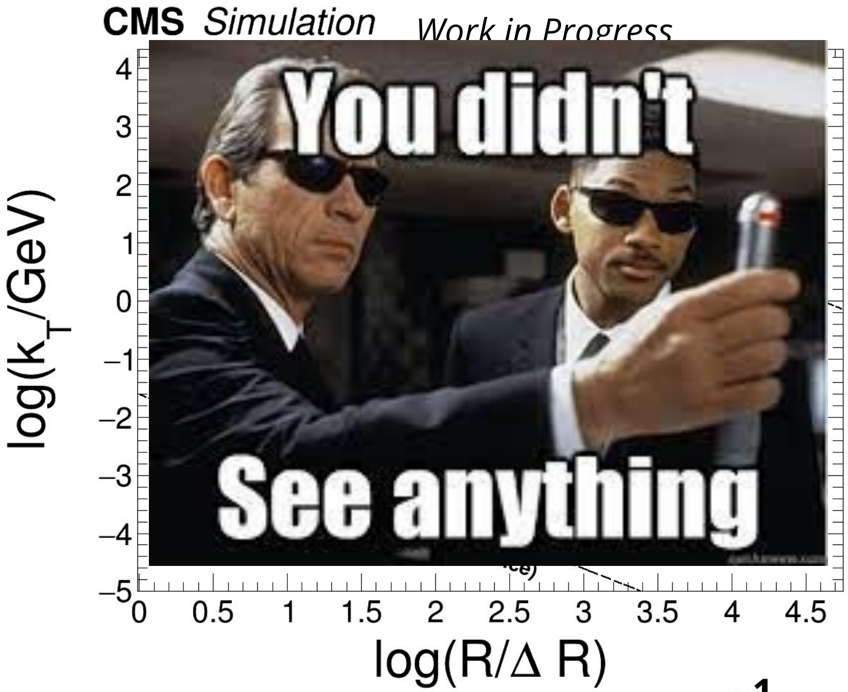
$$\frac{1}{N^{\text{jets}}}\frac{\mathrm{d}^2 N_{\text{emissions}}}{\mathrm{d}\ln(k_T)\,\mathrm{d}\ln(R/\Delta R)}$$

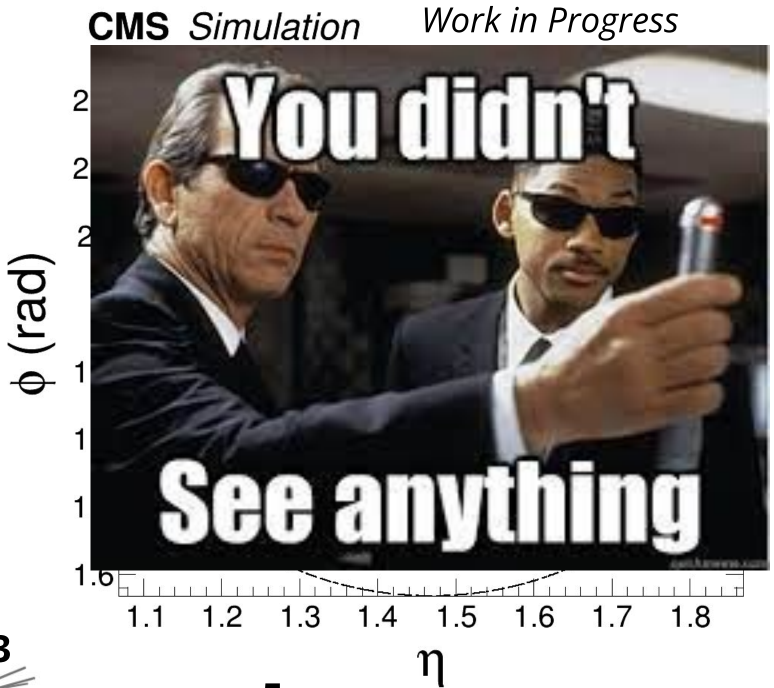
1D unfolding for number of jets for normalization ("bookkeeping")

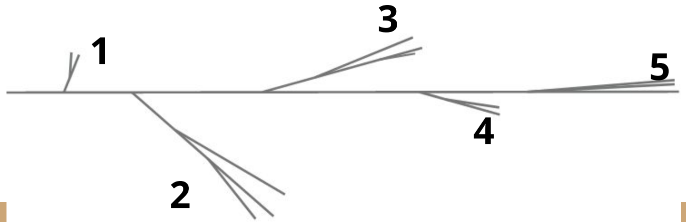
3D unfolding for for number of emissions (substructure)

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

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



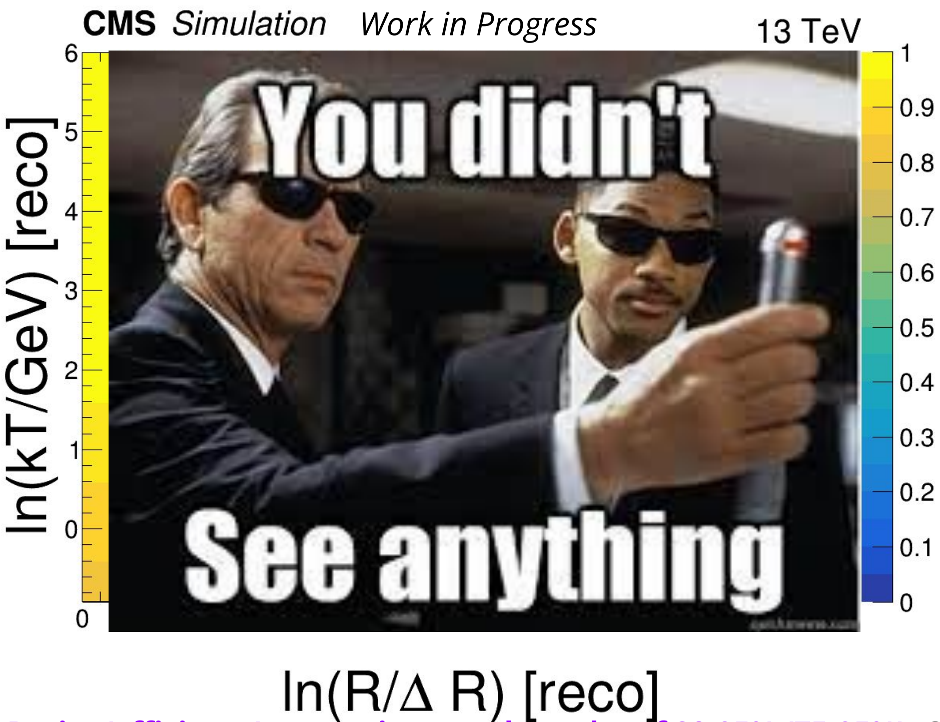


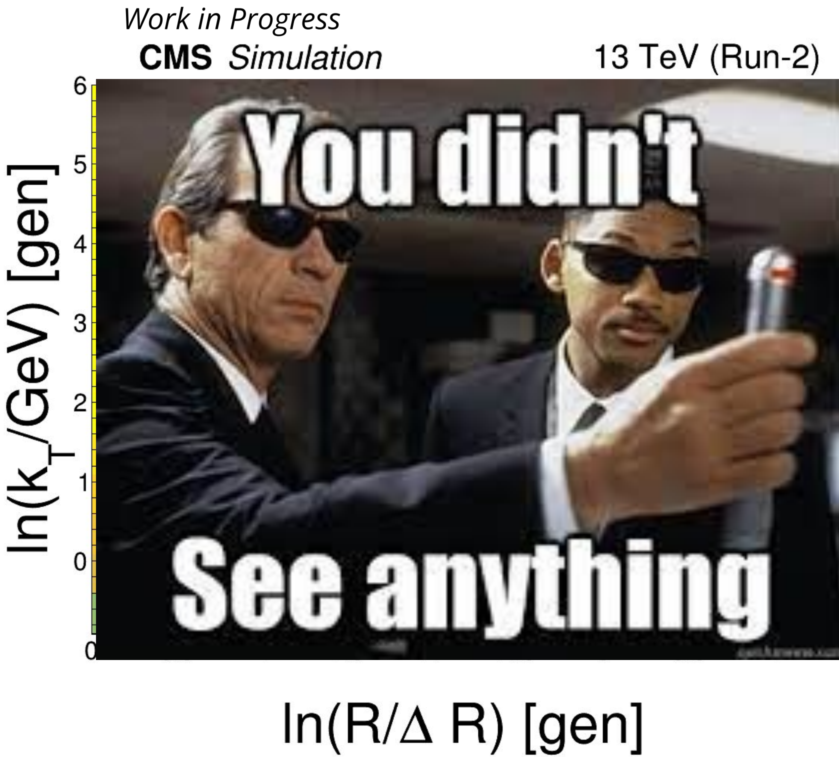


Purity and efficiency corrections

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

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

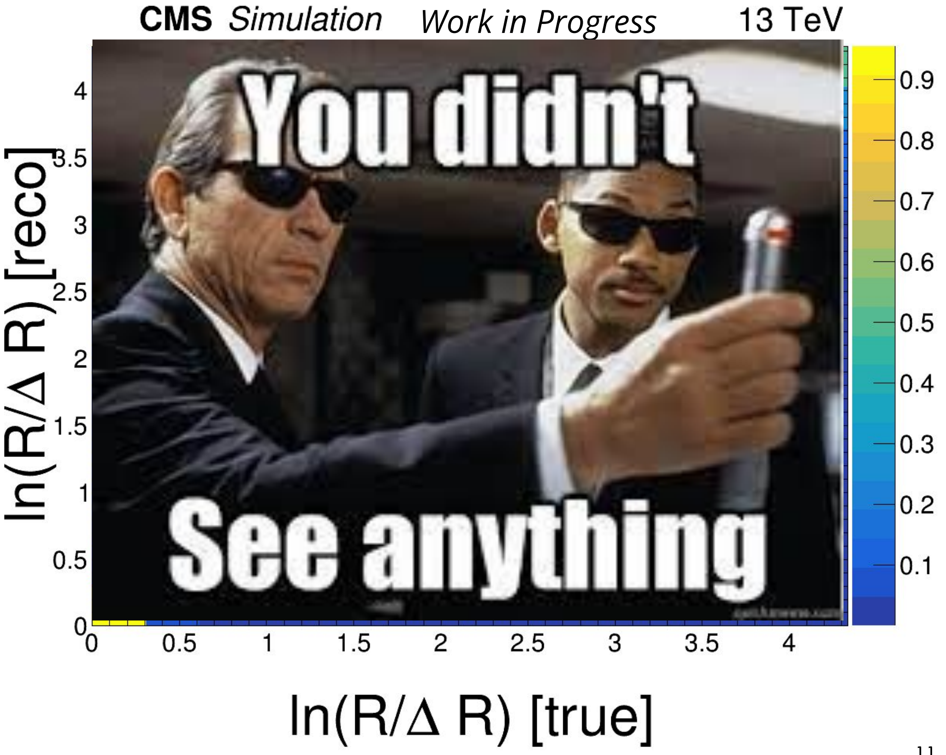




Purity (efficiency) corrections on the order of 80-95% (75-95%). Corrections w/ PYTHIA8 and HERWIG7 are the same within 1-3%.

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.



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.

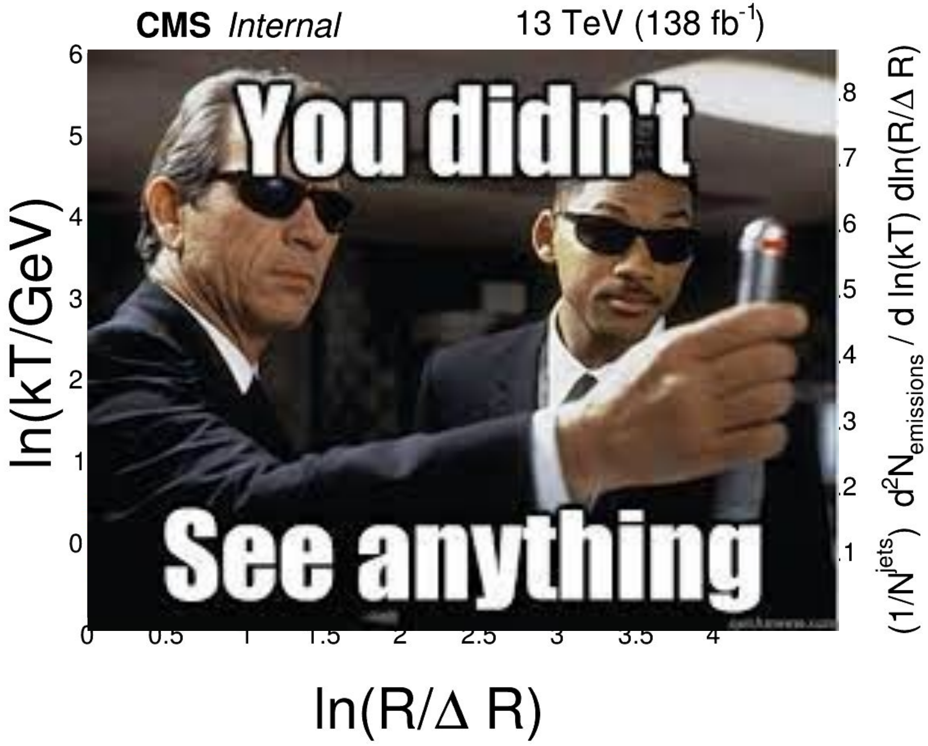
$$\frac{1}{N^{\text{jets}}}\frac{\mathrm{d}^2 N_{\text{emissions}}}{\mathrm{d}\ln(k_T)\,\mathrm{d}\ln(R/\Delta R)}$$

1D unfolding of pTjet spectra for normalization

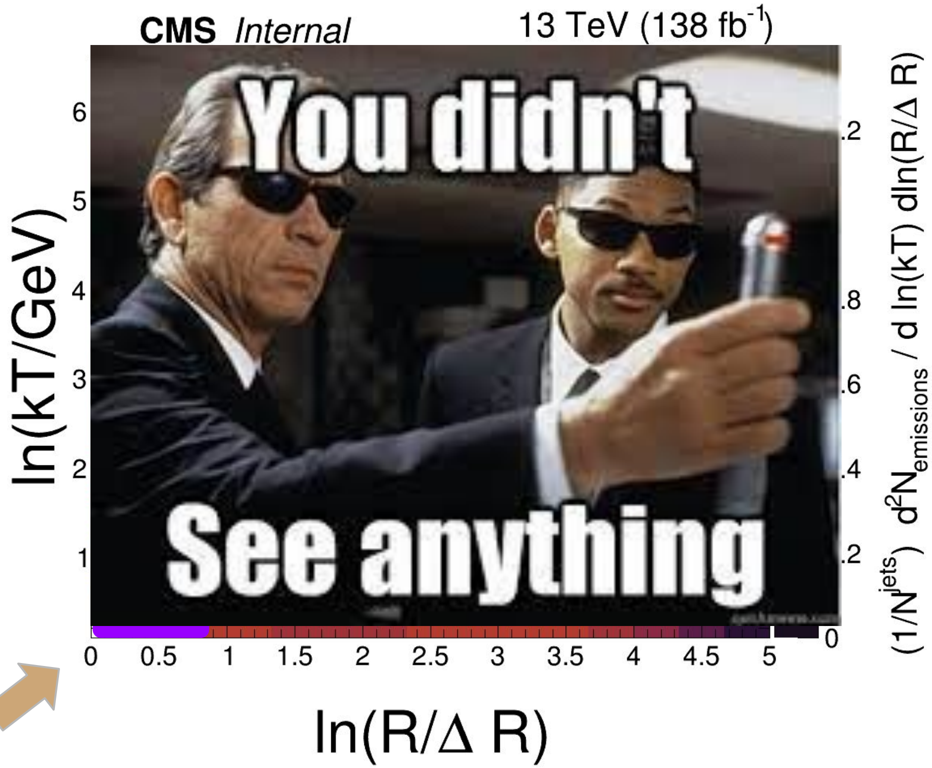
3D unfolding for for Nemissions (substructure)

Fully corrected Lund planes

R=0.4



R=0.8

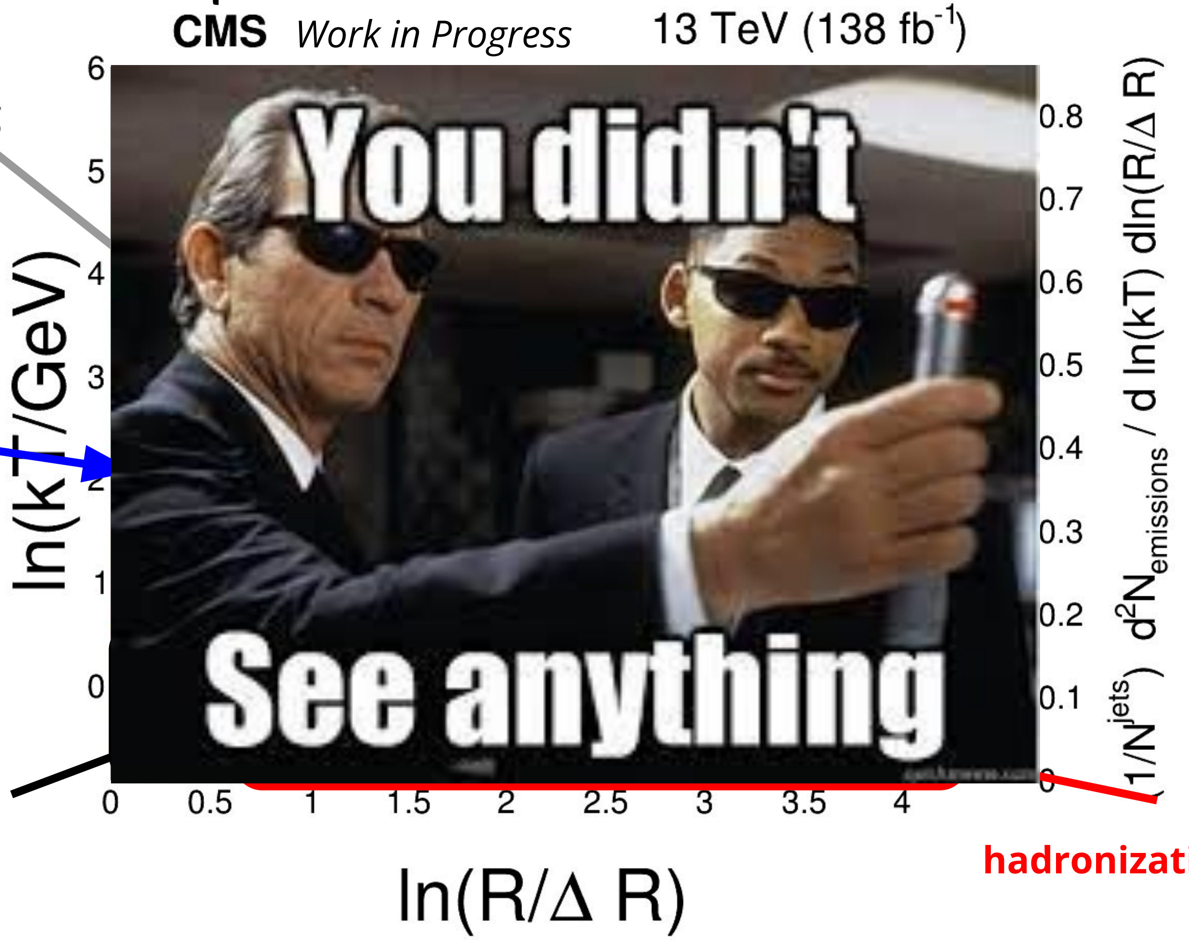


Accessible only with R =0.8

Fully corrected Lund plane

Plateau due to running coupling

ISR



MPI

hadronization

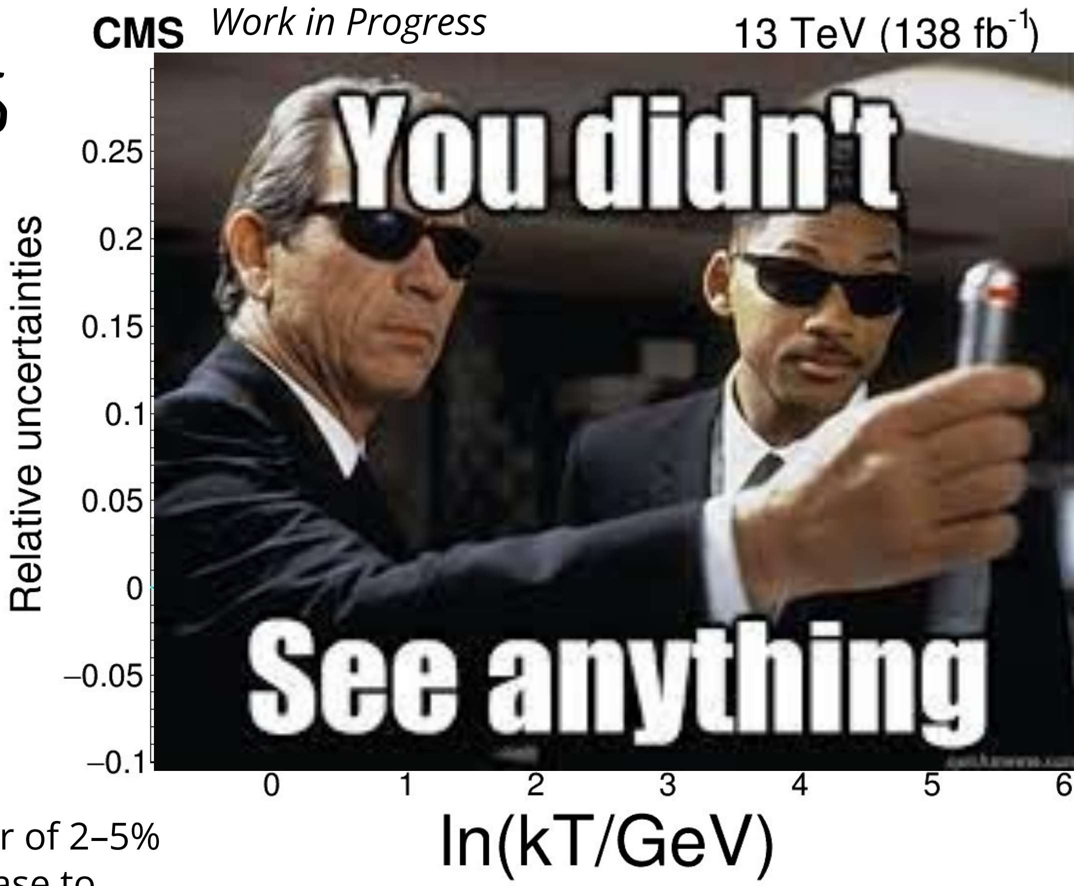
Systematic uncertainties

Dominant (2–10%):

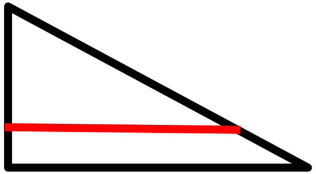
- **MC modeling (herwig7 vs pythia8)**
- **Track inefficiency uncertainties**

Subleading (< 1%):

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

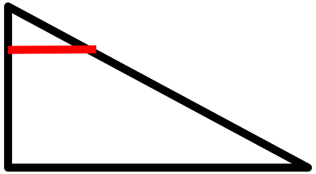


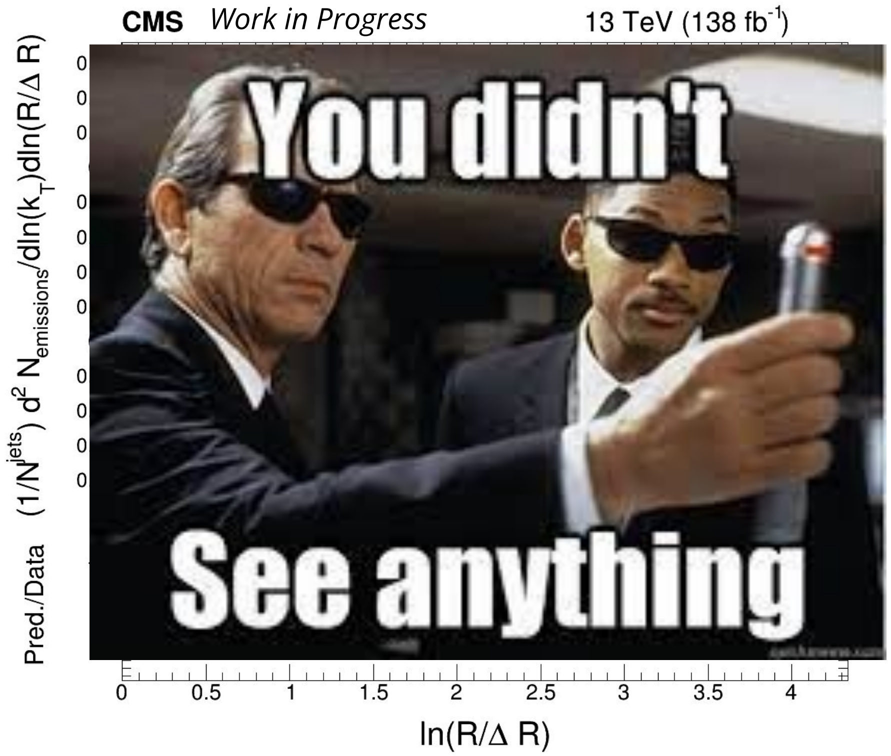
Total experimental uncertainties are of the order of 2–5% throughout (most of) the Lund plane; they increase to 10% at the kinematic edge of the Lund plane (z = 0.5).



Low-kT
(nonperturbative region)

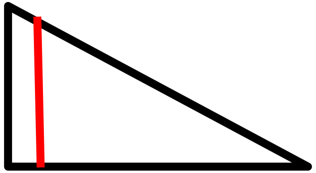
High-kT
(perturbative region)



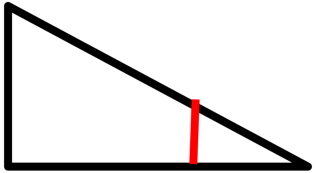


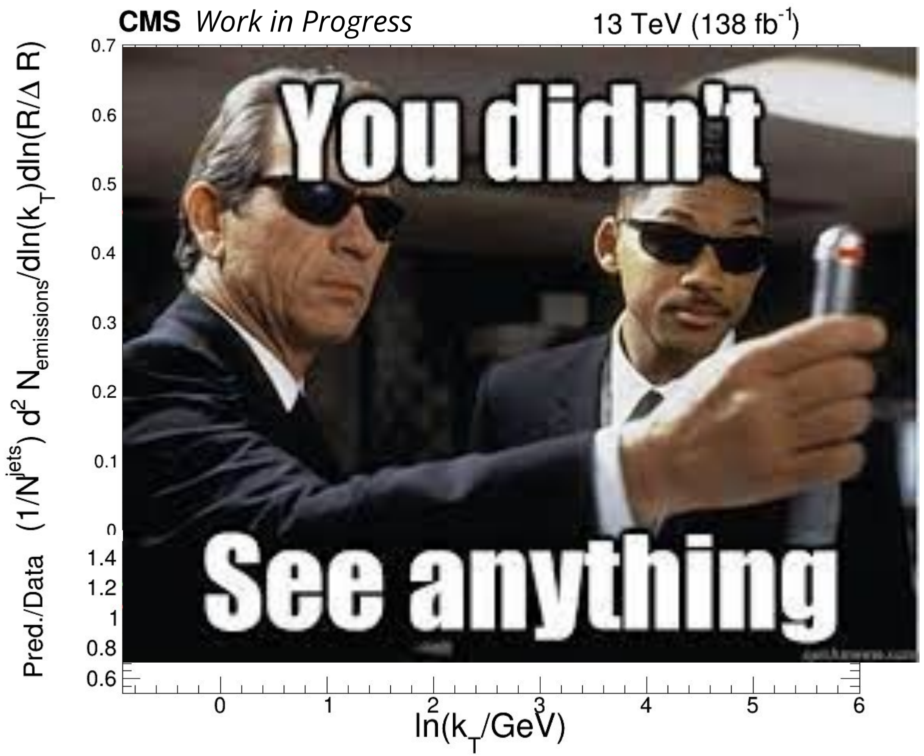
PYTHIA8 generates more splittings in nonperturbative region by 10-20%.

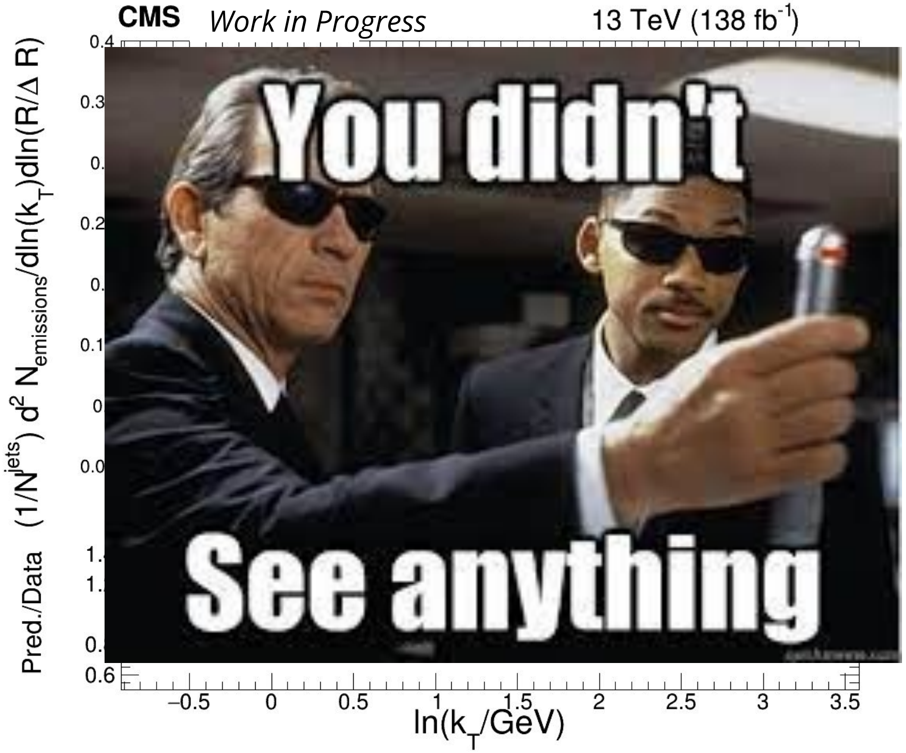
Wide angles



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 $\Lambda_{QCD} = 0.2$ 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

- Lund jet plane measured for R = 0.4 and R = 0.8 jets in CMS.
- Experimental uncertainties 1-10% throughout the Lund plane.
- Strong constraints on MC generators in perturbative and nonperturbative regions. HERWIG7 describes substructure better than PYTHIA8.
- Running of α_S directly on jet substructure.
- Plans for a comparison with NLO+LL+NP analytical calculations.
- Planning to go for a public conference note this Fall.