The Lund jet plane in PbPb collisions and other applications

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Sapienza
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Outline

Jets, substructure and the primary Lund jet plane

The primary Lund jet plane in pp collisions

The primary Lund jet plane in heavy-ion collisions

Conclusions and outlook

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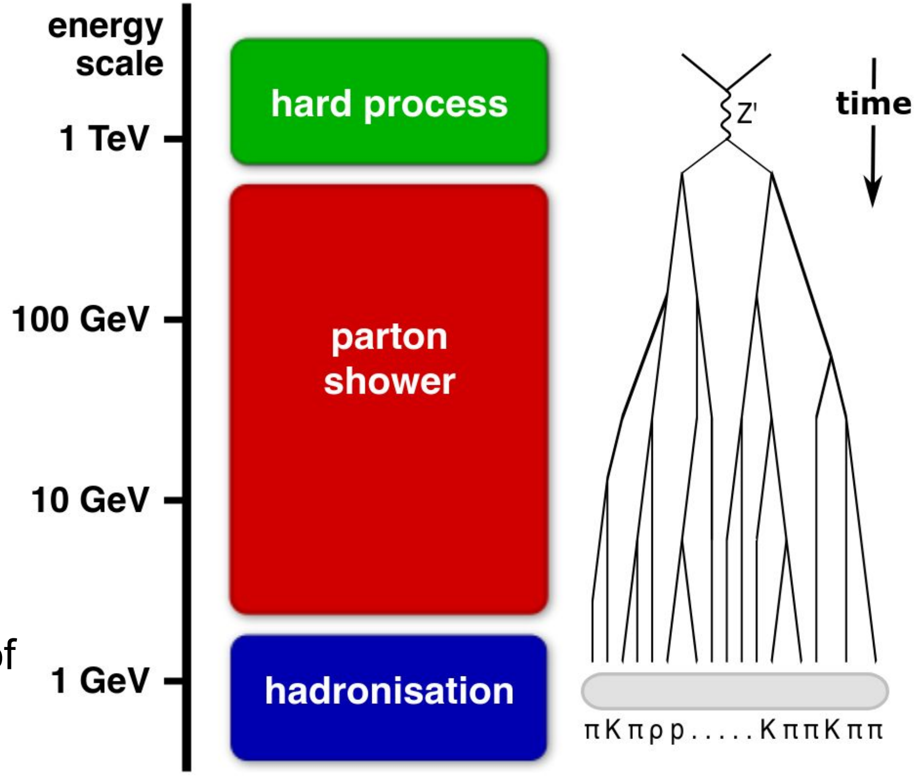
Jets in particle colliders

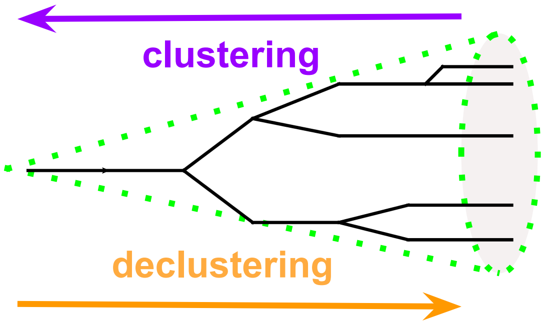
- In particle colliders, partons undergo a multi-scale parton shower evolution
- Make use of the detected hadrons to reconstruct the parton initiator of the jet
- Multiple ways of combining the particles together – jet finding algorithms
- Jet reconstruction algorithms have been employed and tested extensively
- Can also be used to probe the dynamics of the parton shower

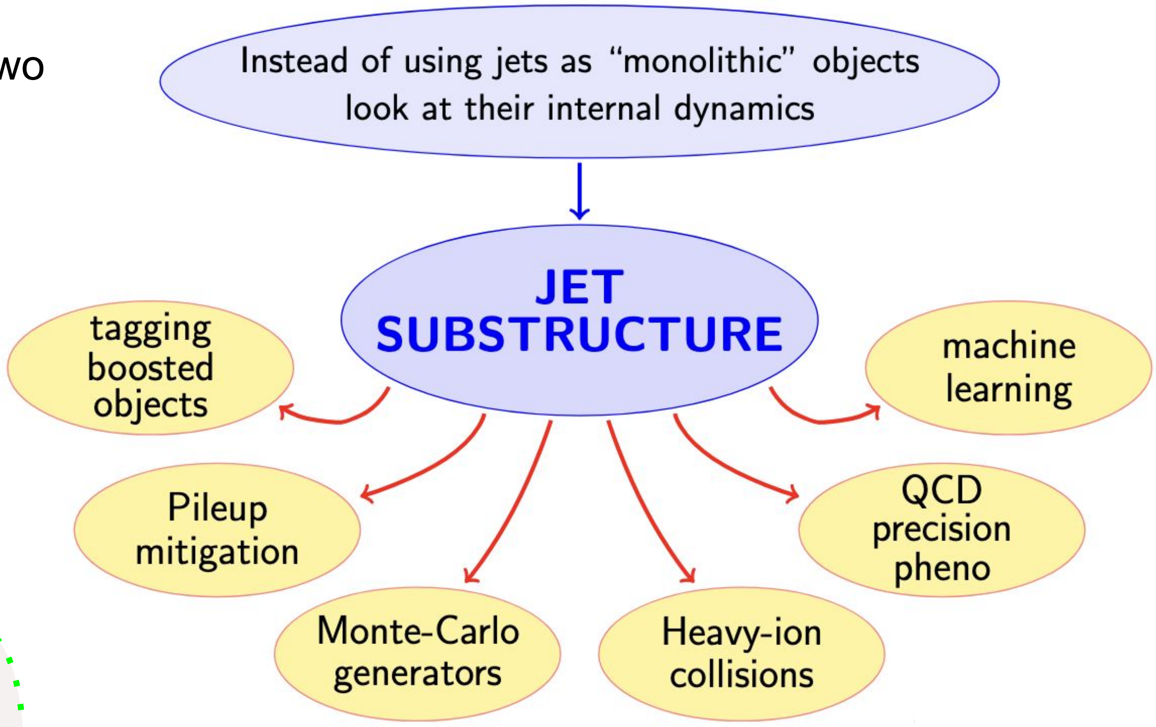


Sketch by G. Salam

Exploring intra-jet dynamics

- Can study internal structure in two complementary methods:
  - ➢ Jet shape observables like generalised angularities, Energy-Energy correlators
  - ➢ <u>Parton shower clustering history</u> – undoing the clustering in order

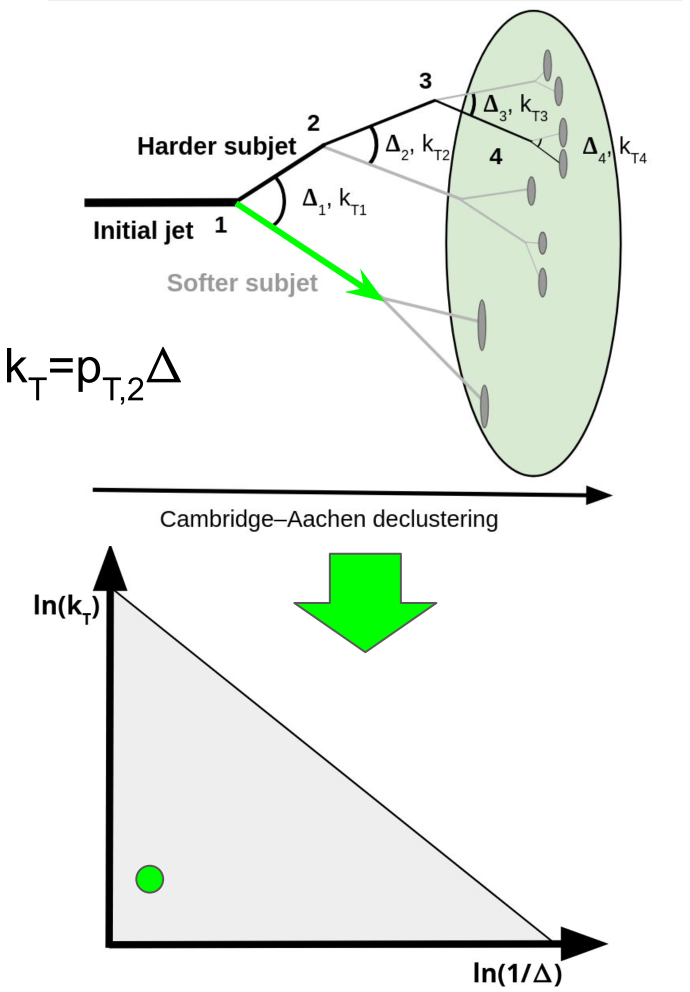




Sketch by G. Soyez

The primary Lund jet plane (PLJP)

- The primary Lund jet plane (PLJP) is a representation of the emissions within a jet
- Formed by combining the jet constituents into a clustering tree using the Cambridge–Aachen algorithm (only angle dependence in clustering, combining closest particles first)
- Retrace back the splittings, following the **primary** (higher p_T) branch
- Record each emission's angle (Δ) and momentum relative to the emitter ($\mathbf{k_T}$)



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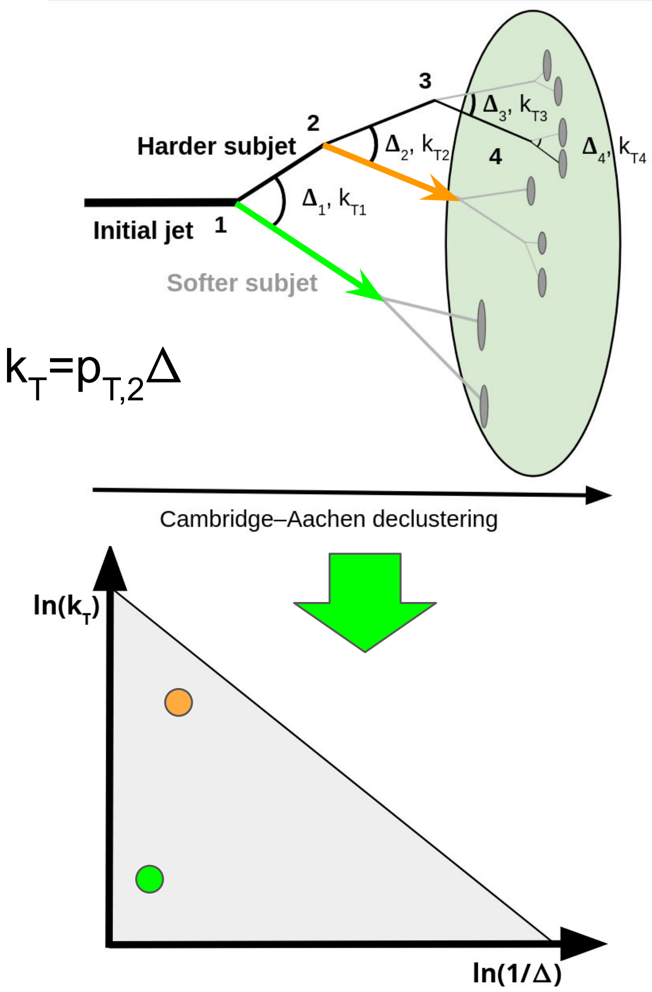

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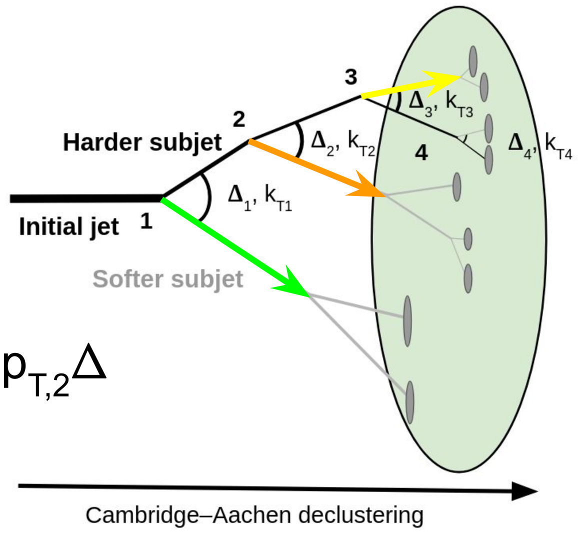
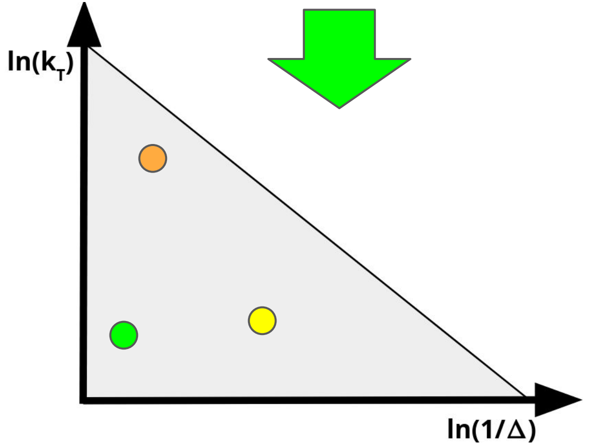


$k_T = p_{T,2}\Delta$



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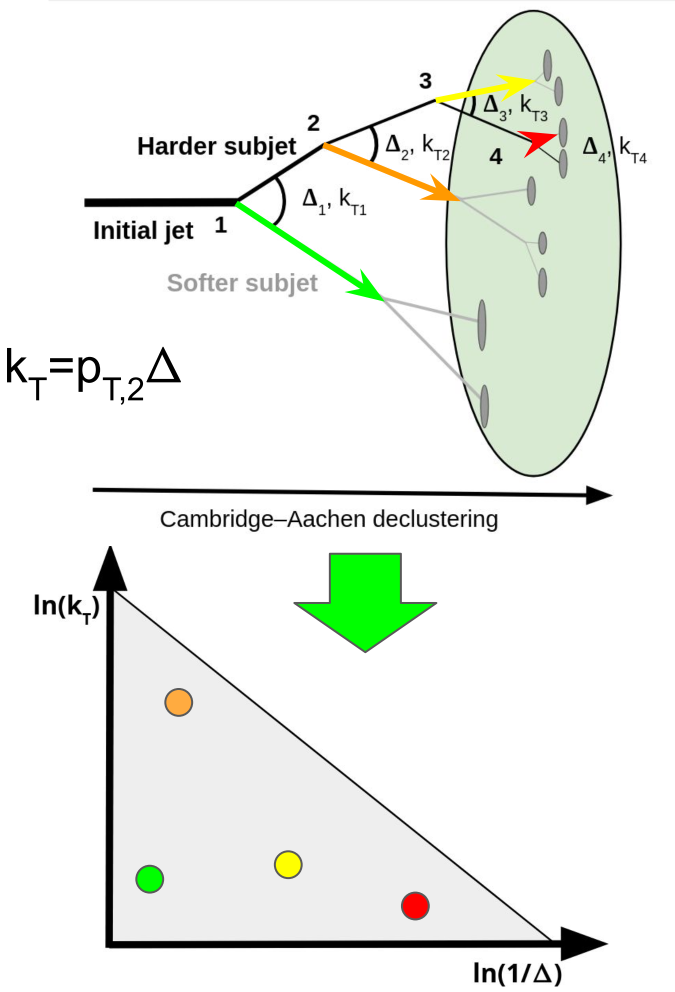

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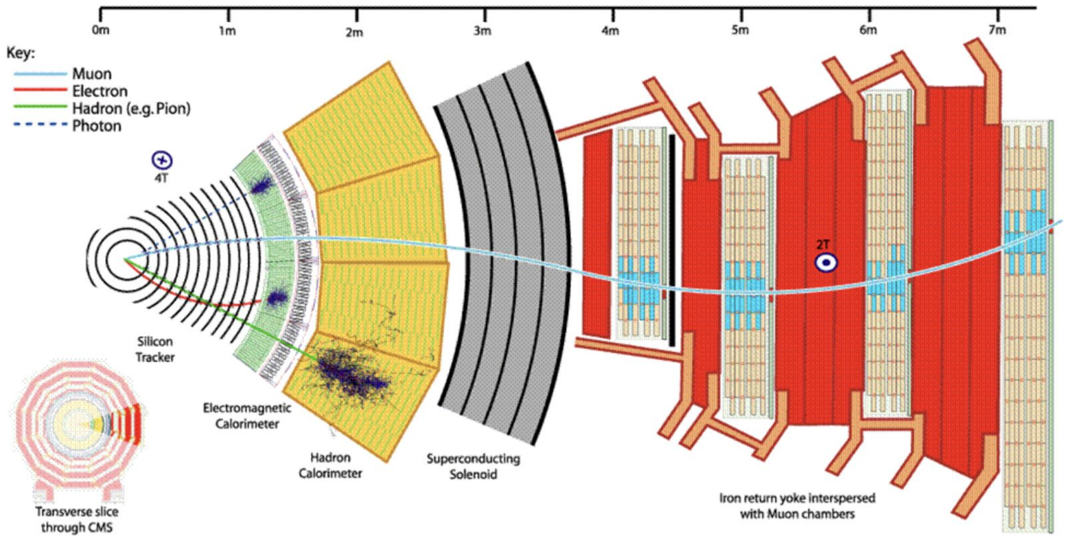
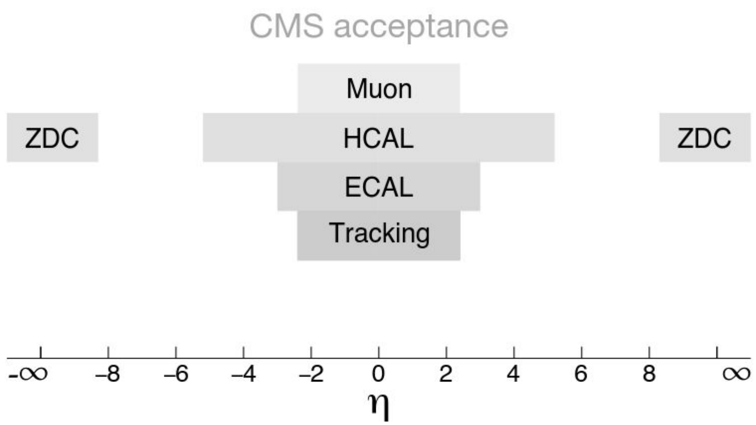
The CMS detector



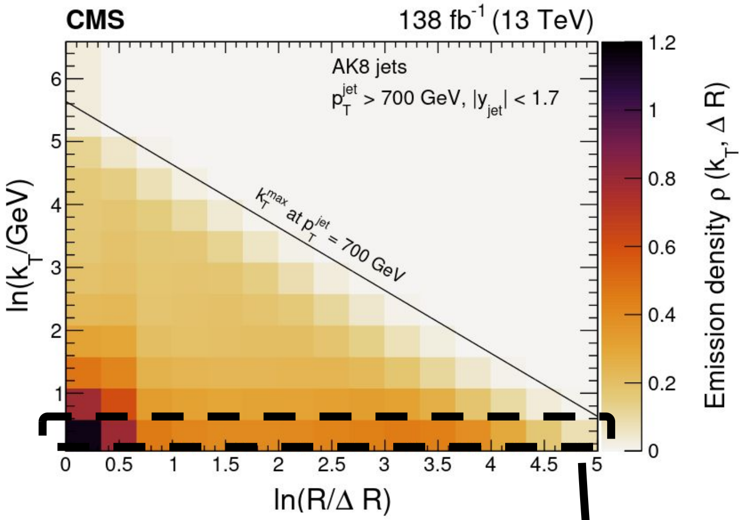


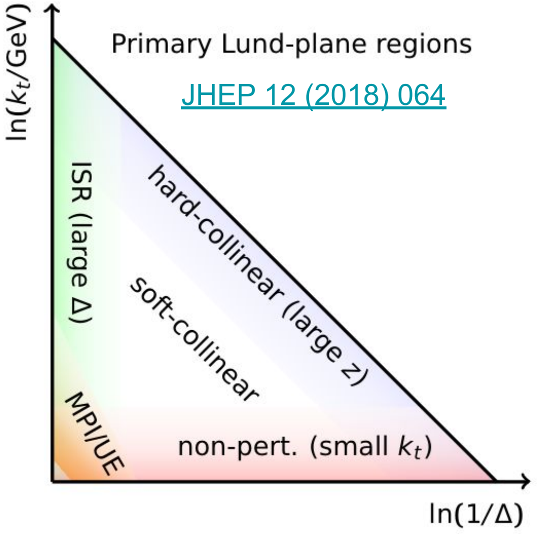
sketch by J. Wang

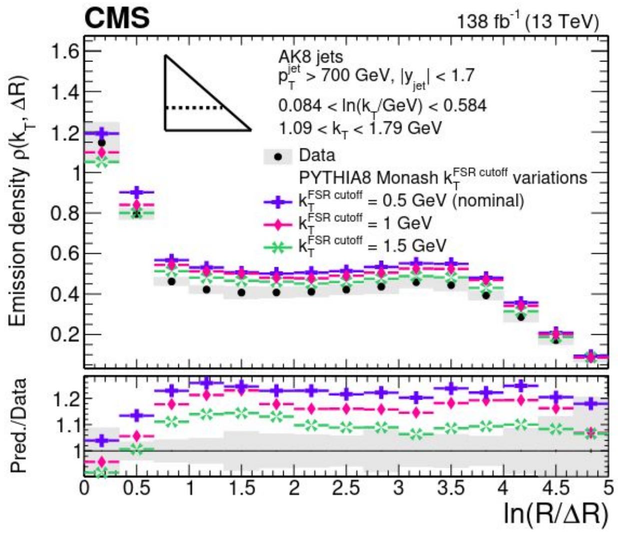
- Full azimuthal coverage for all subdetectors
- Wide pseudorapidity coverage: tracker up to $|\eta|<2.4$
- Good resolution due to magnetic field and detector granularity
- High rate DAQ system: 20 GB/s

The PLJP in pp collisions

- Measured in 13 TeV pp collisions [JHEP 05 (2024) 116](#) [PRL 124](#)
- Different regions of the plane are sensitive to different physical processes
- Modular tool for providing constraints on current models and calculations

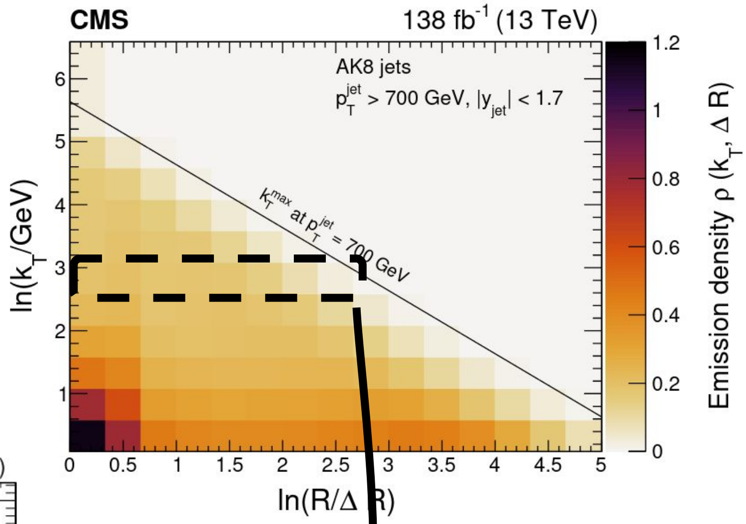


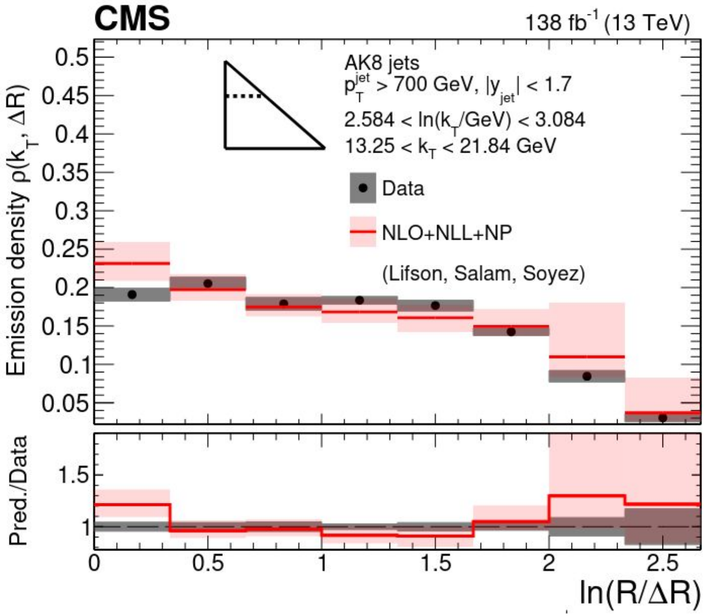




The PLJP in pp collisions

- Measured in 13 TeV pp collisions [JHEP 05 (2024) 116](#) [PRL 124 (2020) 22](#) [EPS-HEP2021 (2022) 364](#)
- The PLJP is also theoretically calculable [JHEP 10 (2020) 170](#)
- Consistency between predictions and data within uncertainties

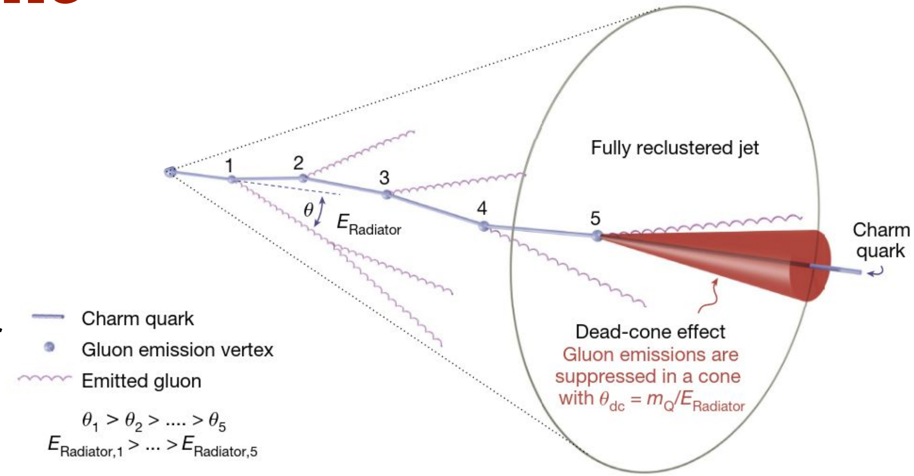


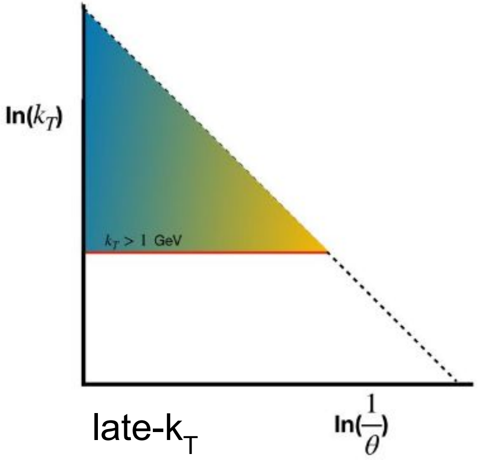


Quark mass and the Lund plane

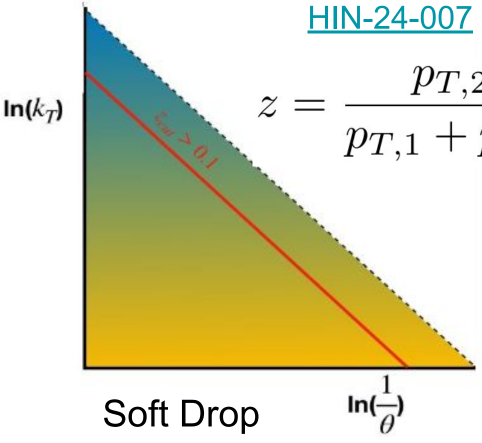
[Nature 605, 440-446 (2022)]

- The dead cone – a cone of size m_Q/E_Q around a quark in which gluon emissions are suppressed
- Scan the Lund plane in the region sensitive to the quark mass by selecting hard and collinear emissions
- Different algorithms are employed, [late-k_T] and [Soft Drop]

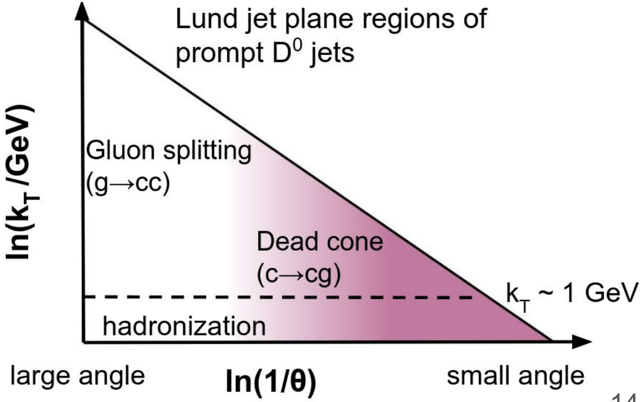




[HIN-24-007]

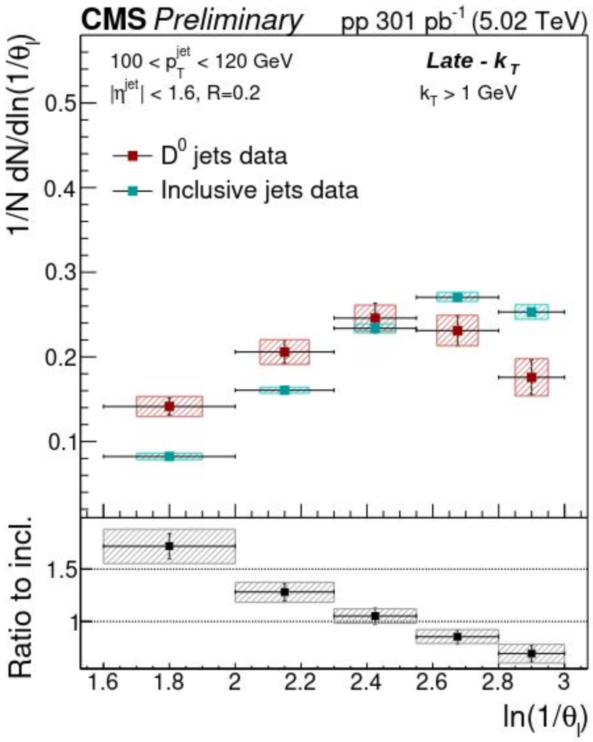


$$z = \frac{p_{T,2}}{p_{T,1} + p_{T,2}}$$



Lund plane and heavy flavours

- Observe a shift towards large angles in D and b jets compared to inclusive jets
- Direct consequence of quark mass
- Inputs for better understanding of heavy-flavour parton showers
- Baseline for heavy-ion studies



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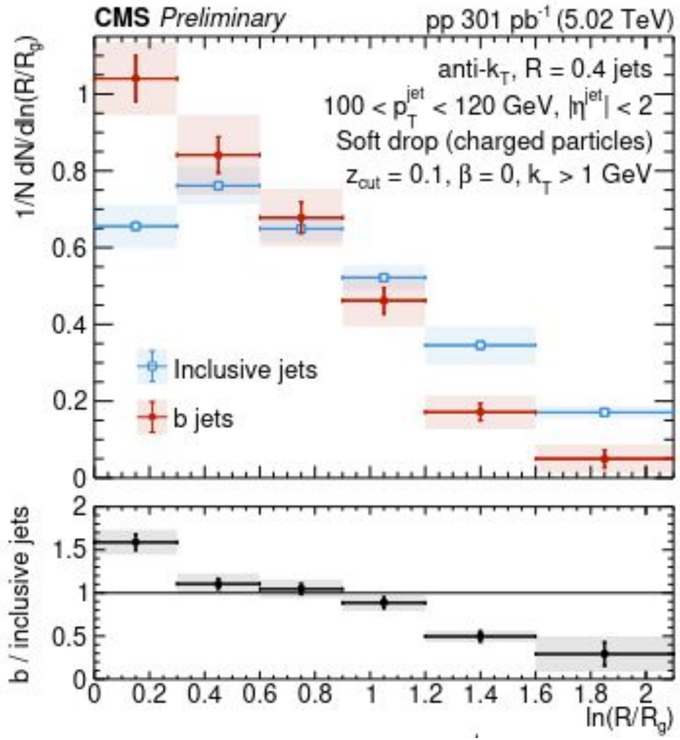
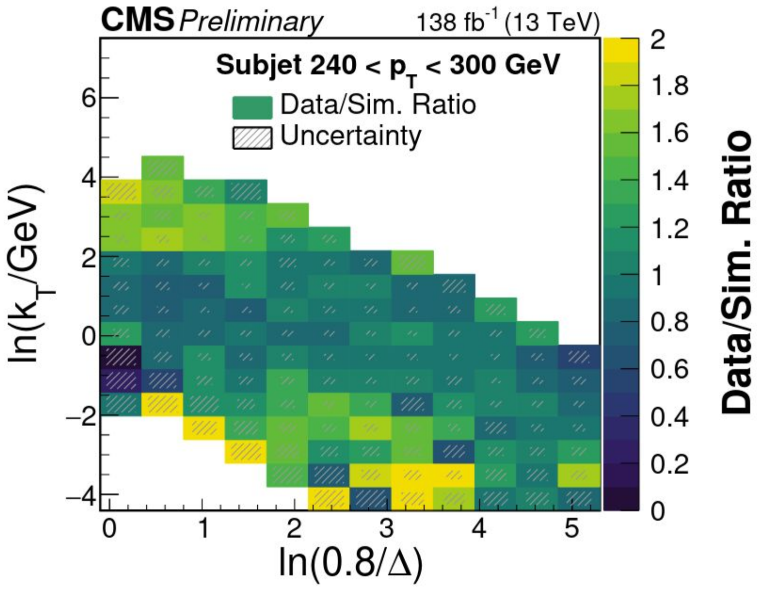


HIN-24-005

Example application of the Lund plane

JME-23-001

- Often boosted large-R jet substructure not well modelled in MC, calibrated using data samples of W boson and top quark jets
- What about jets with more prongs which are not as abundantly available in data?
- Use the primary LJP as a proxy for the parton shower, defining a jet reweighting procedure based on the emissions within each prong of a jet from boosted W bosons



Example application of the Lund plane

JME-23-001

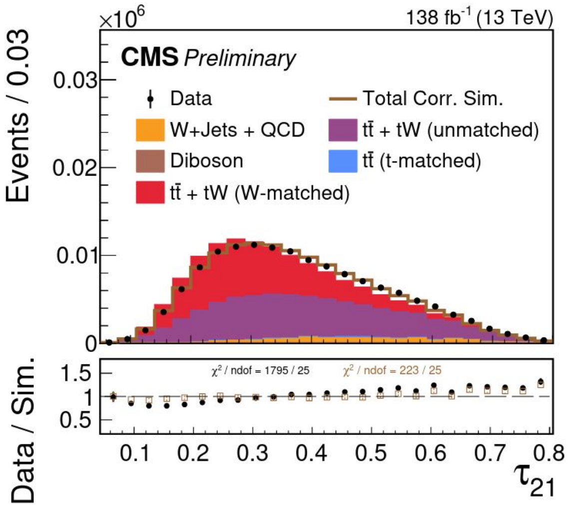
- Examine effect on observables not directly related to the PLJP – *N*-subjettiness:

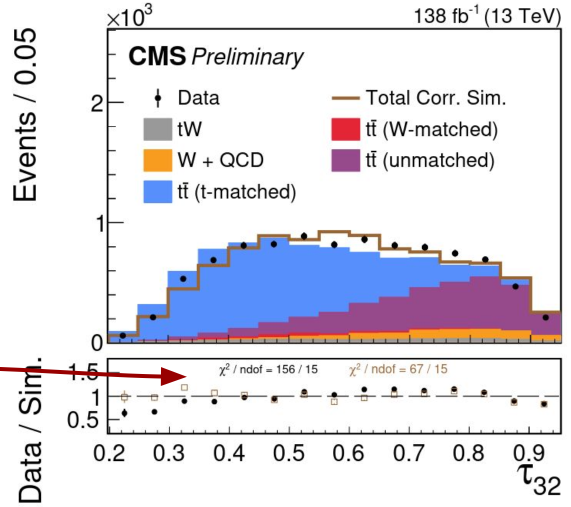
$$\tau_N = \frac{1}{p_T^{\text{jet}} R^{\text{jet}}} \sum_i p_T^i \min(\Delta^{i,1}, ..., \Delta^{i,N})$$

N – number of subjet axes

$\Delta^{i,N}$ – distance between particle i and axis N

- Ratio $\tau_{21}=\tau_2/\tau_1$ expected to be smaller in W-jets than in background
- Validated W-jet-based reweighting in top quark jets
- Observe improvement in data-MC agreement

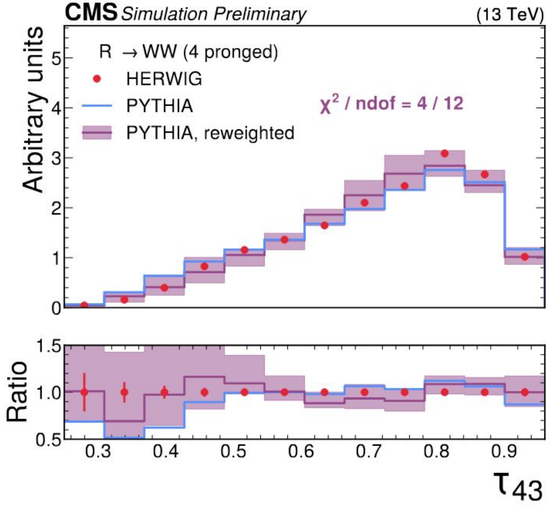


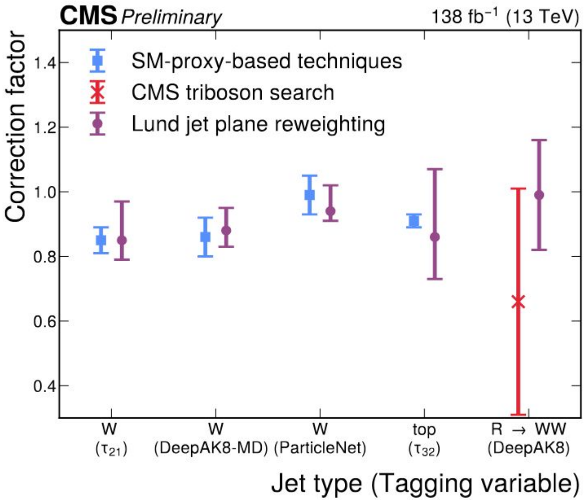


Example application of the Lund plane

JME-23-001

- Applied method to jets with ≥ 4 prongs, for which there are no standard candles in data
- Observe good performance in MC-to-MC reweighting
- Method provides robust substructure calibration of jets with more than three prongs for the first time
- Already implemented in measurements:
  - ➢ EXO-22-026: Search for resonance decaying to jets with anomalous substructure
  - ➢ HIG-23-012: Search for boosted H→WW





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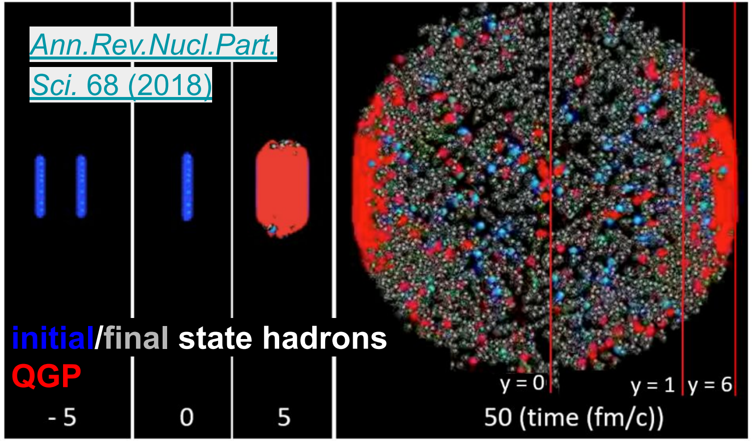
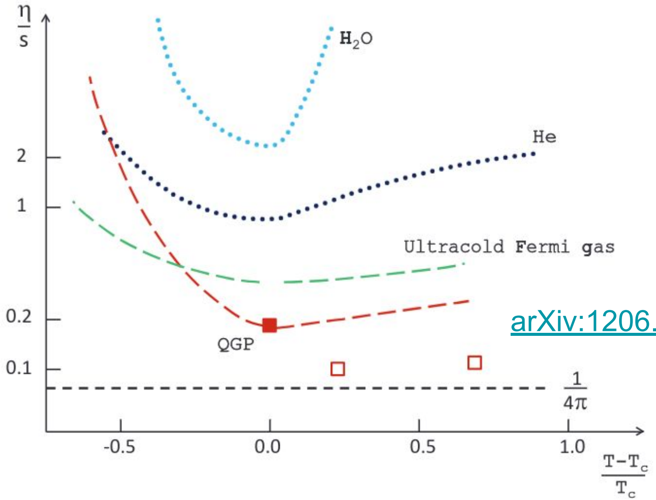
Heavy ion collisions and the QGP

- Heavy ion collisions lead to the creation of quark-gluon plasma (QGP)
- Hot, near perfect fluid of deconfined strongly interacting quarks and gluons
- As system expands and cools, it transitions to hadronic matter
- The main goal of the heavy-ion programme is to study the properties of the QGP

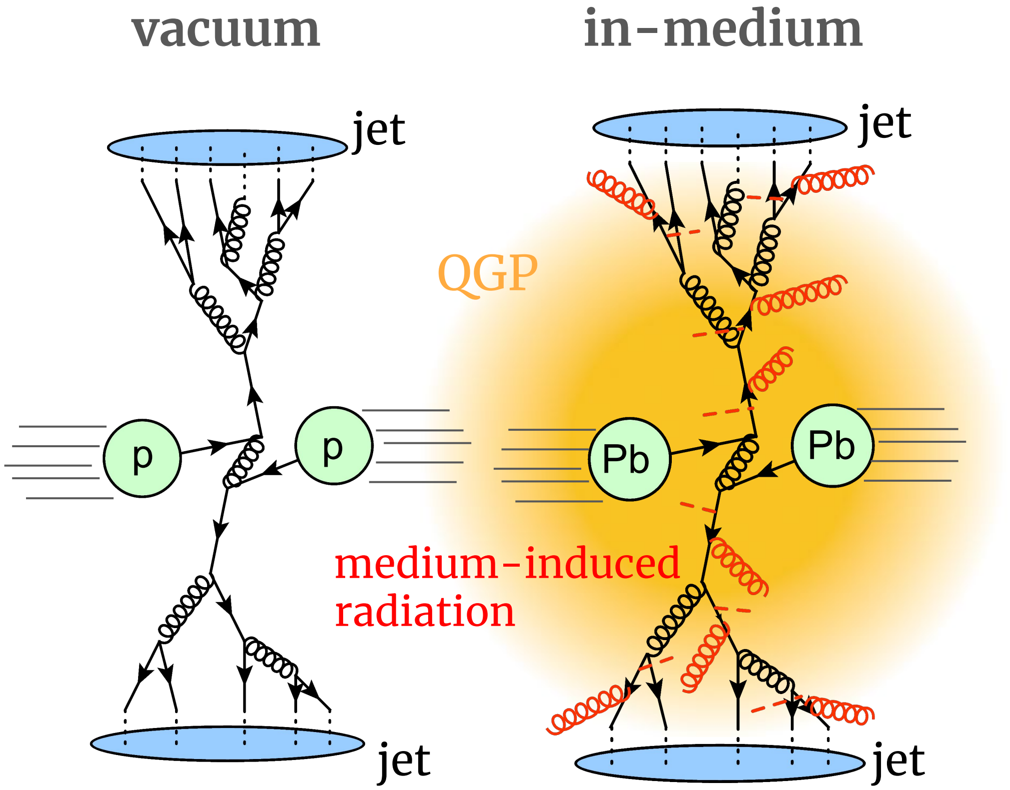




arXiv:1206.3581

Jets as QGP probes

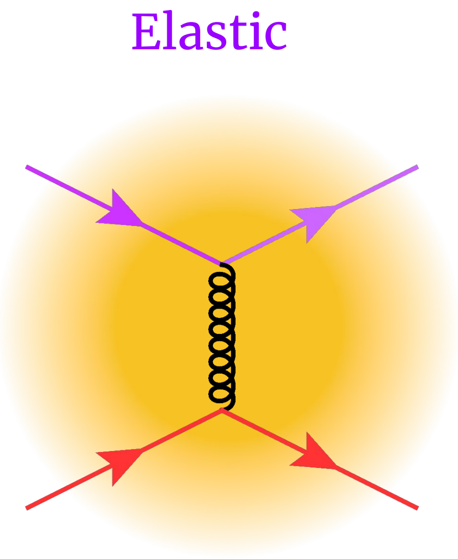
- Jets as coloured objects interact with the QGP while propagating through it
- Multi-scale interaction between jet and medium lead to the modification of jet rates and radiation pattern relative to pp (vacuum) – quenching
- Compare results of jet observables between systems to isolate different physics mechanisms and extract microscopic properties of the QGP

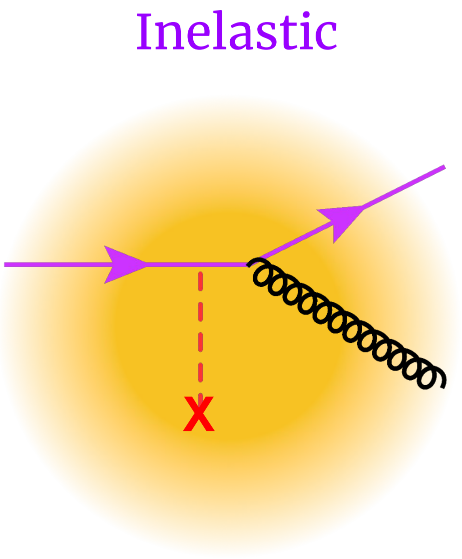


Jet-medium interactions

Weakly coupled description consisting of

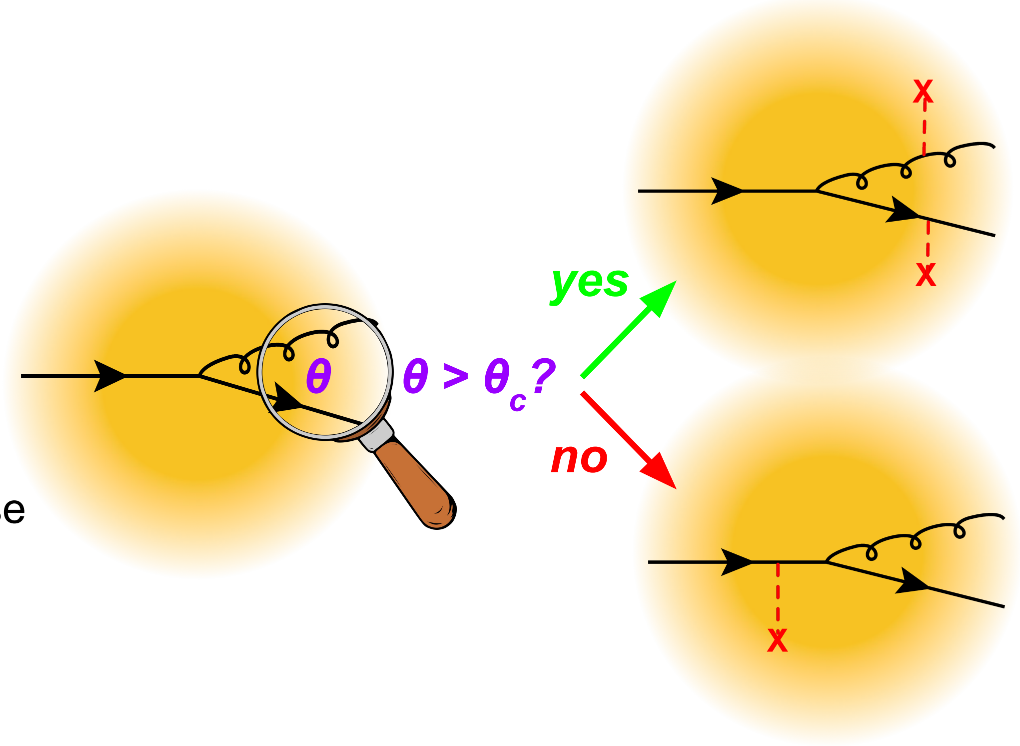
- **Collisional energy loss** through elastic scattering – probe the QGP (pseudo-)particles
  - ➢ dominates at low momenta
- **Radiative energy loss** through **inelastic scattering** within medium
  - ➢ dominates at high momenta





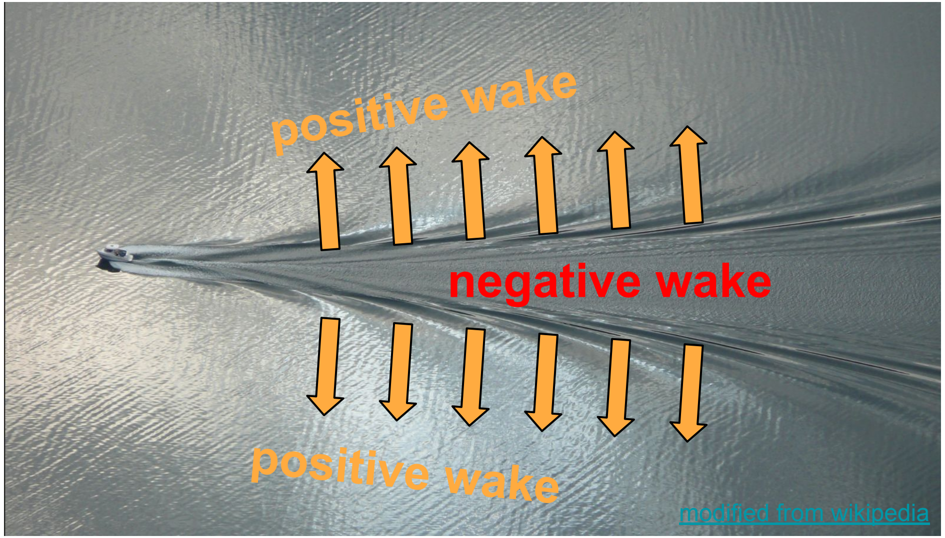
Colour coherence

- Expect medium to have an associated colour coherence angle $\boldsymbol{\theta_c}$:
  - ➢ **below it**, the medium can not resolve separate sources – they act as a **single emitter**
  - ➢ **above it**, the medium resolves them and they lose energy **incoherently** – more quenching



Medium response

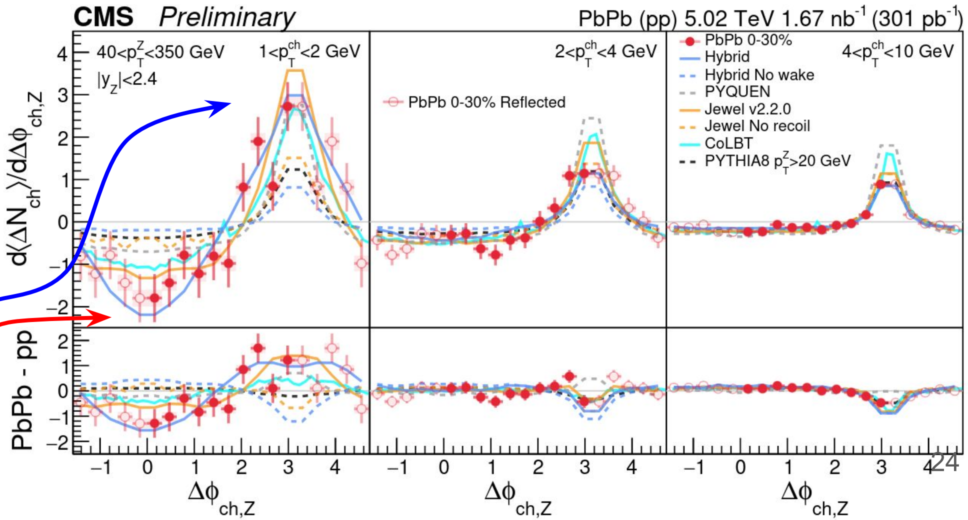
- Propagating jet drags the medium
- Development of **diffusion wake**
- Negative wake behind propagating particle – due to displaced medium



- First direct observation of medium response in Z-jet system

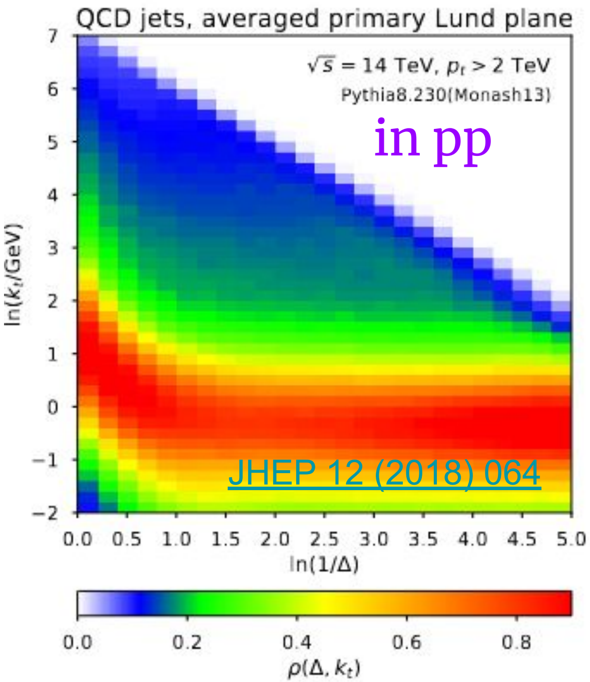
HIN-23-006

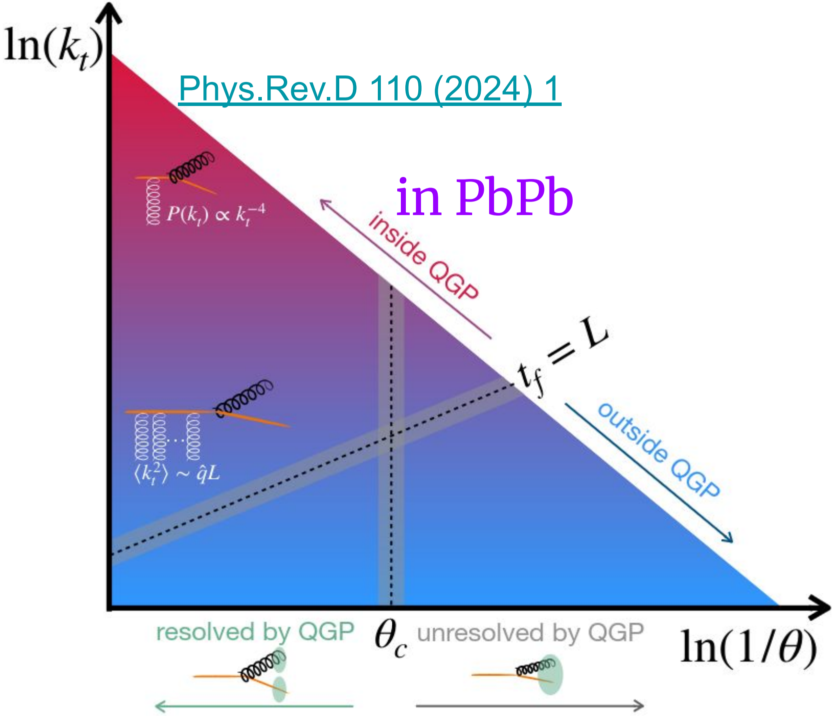
particles in direction of jet
particles in direction of Z



$\Delta\Phi_{ch,Z}$ – azimuthal angle between charged particles and Z boson

The PLJP in PbPb collisions





At LO in soft and collinear limit,
density of the PLJP dependent only on $\alpha_s(k_T)$:

$$\rho(ln(k_T), ln(1/\Delta)) \simeq \frac{2}{\pi} C_F\ \alpha_s(k_T)$$

Additional features due to interaction with the medium!

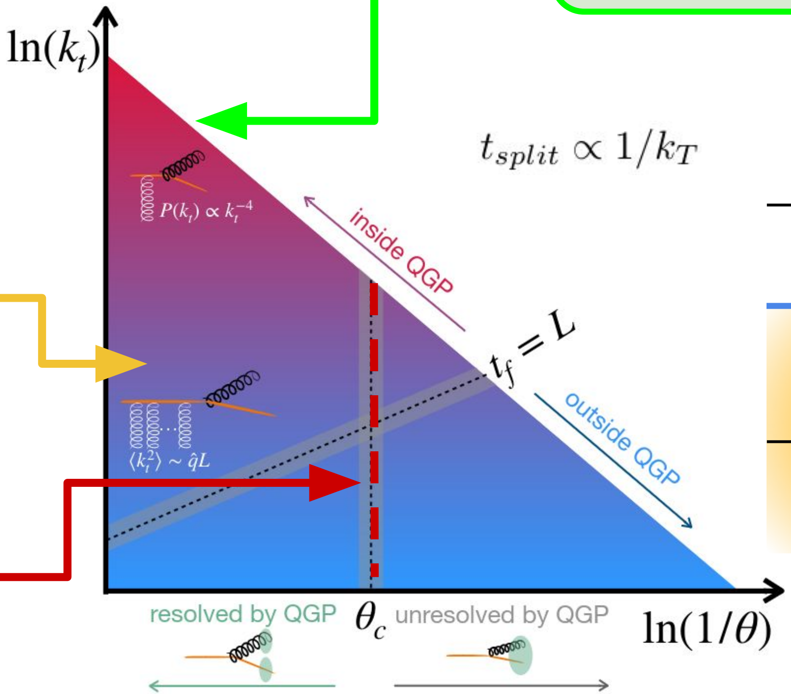
The jet Lund plane in PbPb

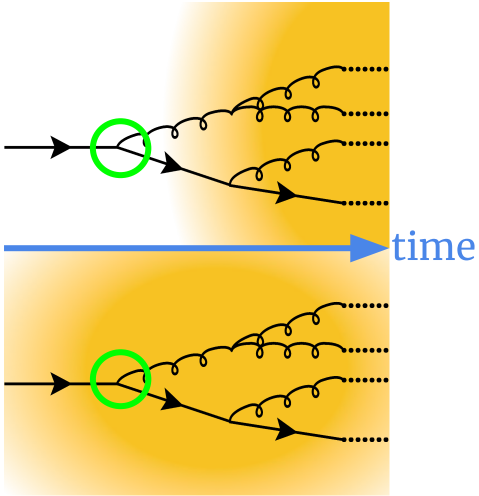
- Different effects due to QGP manifest in different regions of the Lund plane [Phys.Rev.D 110 (2024) 1]

Expect vacuum-like emissions and elastic scattering at high k_T

Medium induced and underlying event combinatorial background

Colour coherence: below θ_c, particles act as a single source – less quenching





Measurement approach

- Select energetic jets (**p_T>200 GeV**, R=0.4, |η|<2) in central PbPb collisions to suppress non-perturbative effects
- Scan LP from top to bottom and inspect angular distribution of emissions, allows for:
  - ➢ k_T-ordered scan
  - ➢ Could constrain assumption of vacuum-like and in-medium factorisation
  - ➢ Gradual onset of colour coherence according to jet quenching models
- Report particle-level angular distribution by unfolding in 3D - Δ, k_T, jet p_T

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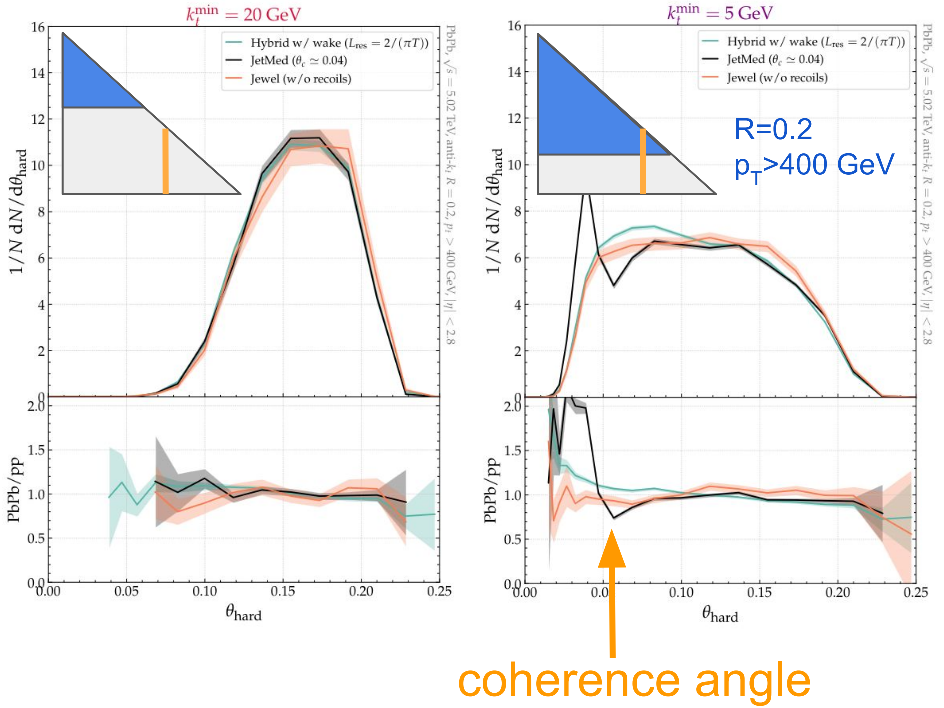
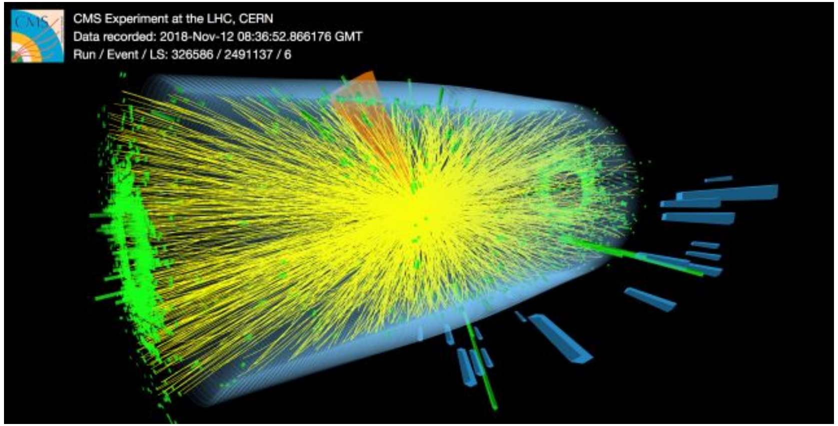
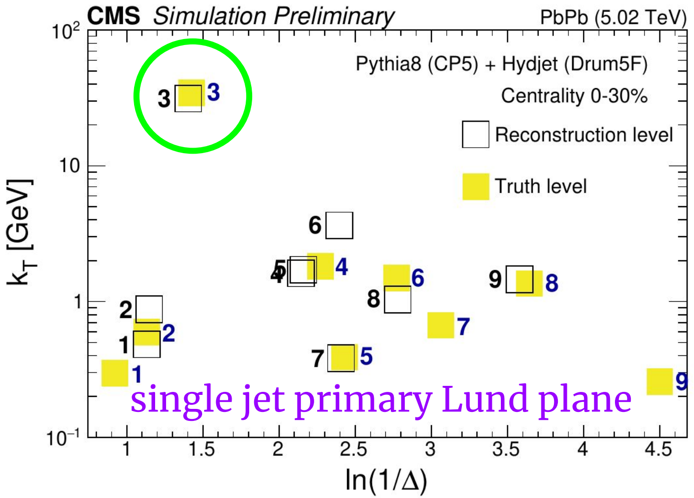
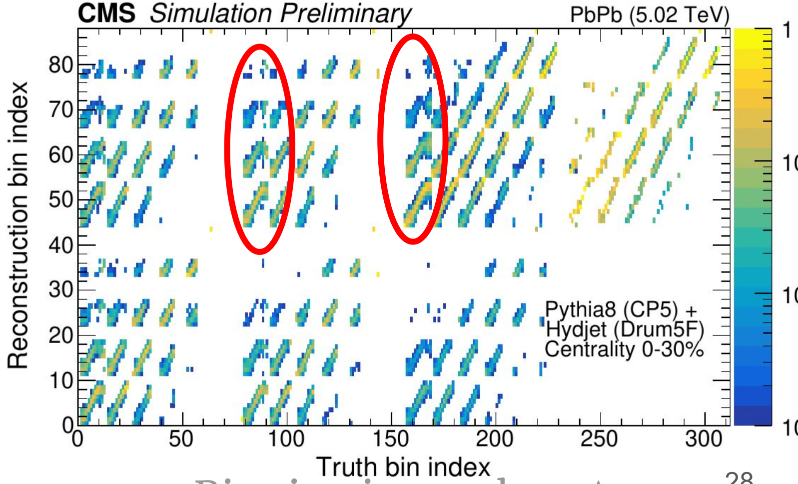


unfolding – removal of detector and physics backgrounds from “true” distributions

Challenges in PbPb: UE





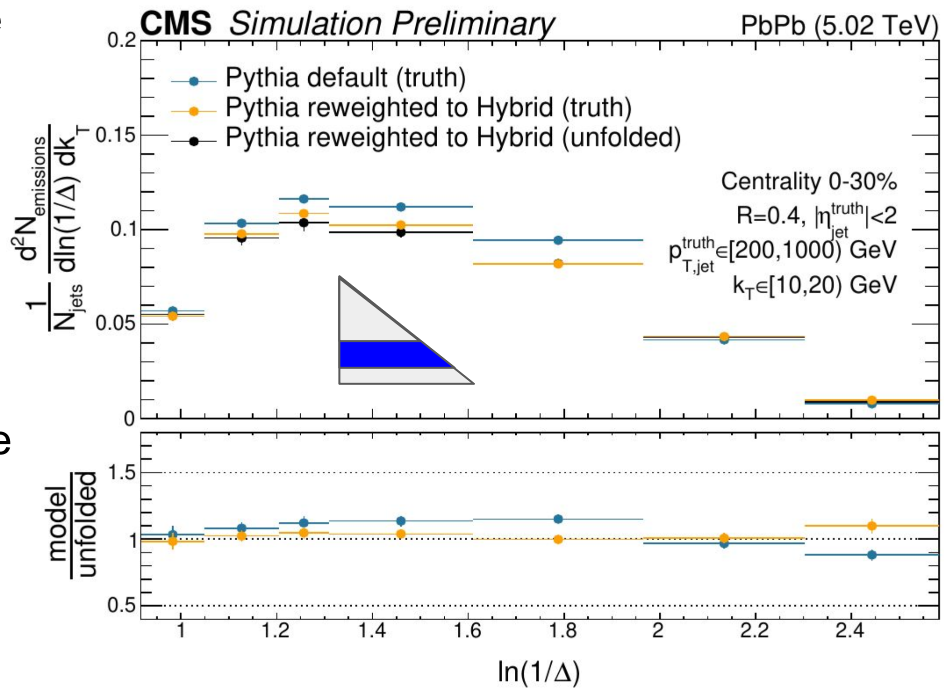


Binning in p_T x k_T x Δ

- Large PbPb underlying event and detector effects distort truth-reco correspondence of emissions
  - ➢ Only use the **hardest splitting at detector and truth level**
  - ➢ Restrict measurement to moderate values of k_T to suppress **combinatorial background**

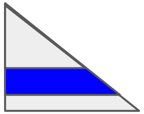
Challenges in PbPb: Prior uncertainty

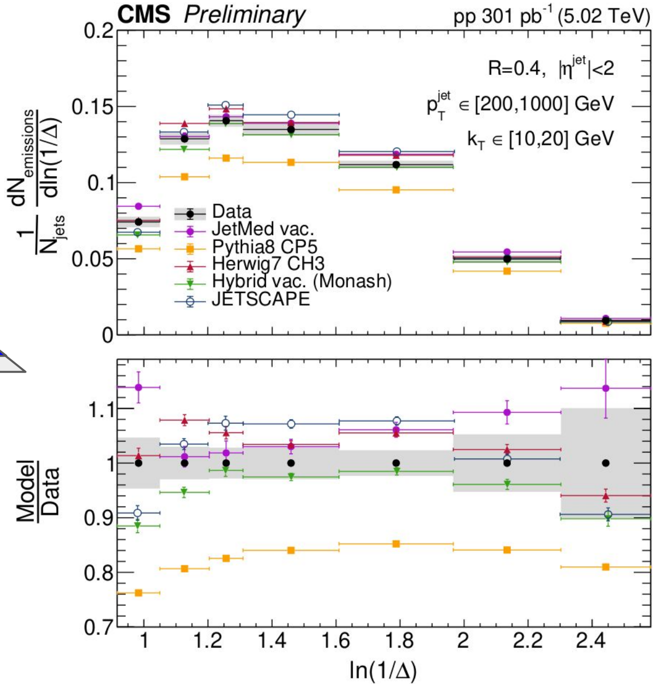
- Need to estimate prior uncertainty of the unfolding procedure
- Several jet quenching models available, no favoured one among them
- Employ procedure similar to the one used in large-R multi-prong jets
- Reweigh the particle level radiation pattern of PYTHIA8 jets to match the one of a model which includes quenching
- Use the reweighted sample as an alternative prior to extract prior dependence of result

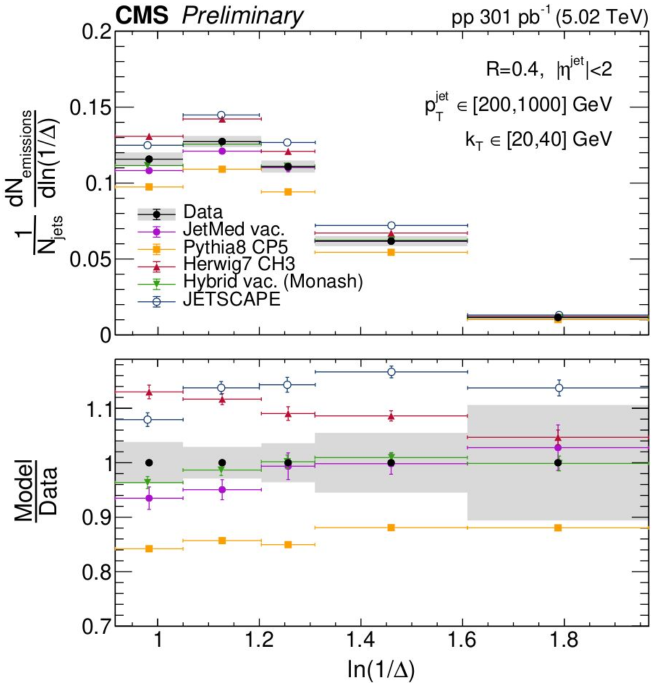


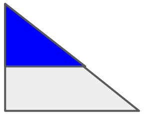
Model comparison of pp distributions

- Compare with commonly used pp model predictions, as well as vacuum predictions of quenching models
- In general data agrees more with models containing higher values of α_S (also seen in other substructure studies, like JHEP 05 (2024) 116)
- Vacuum predictions of some quenching models in disagreement, but interested in the PbPb/pp ratio where pp baseline offset is cancelled out



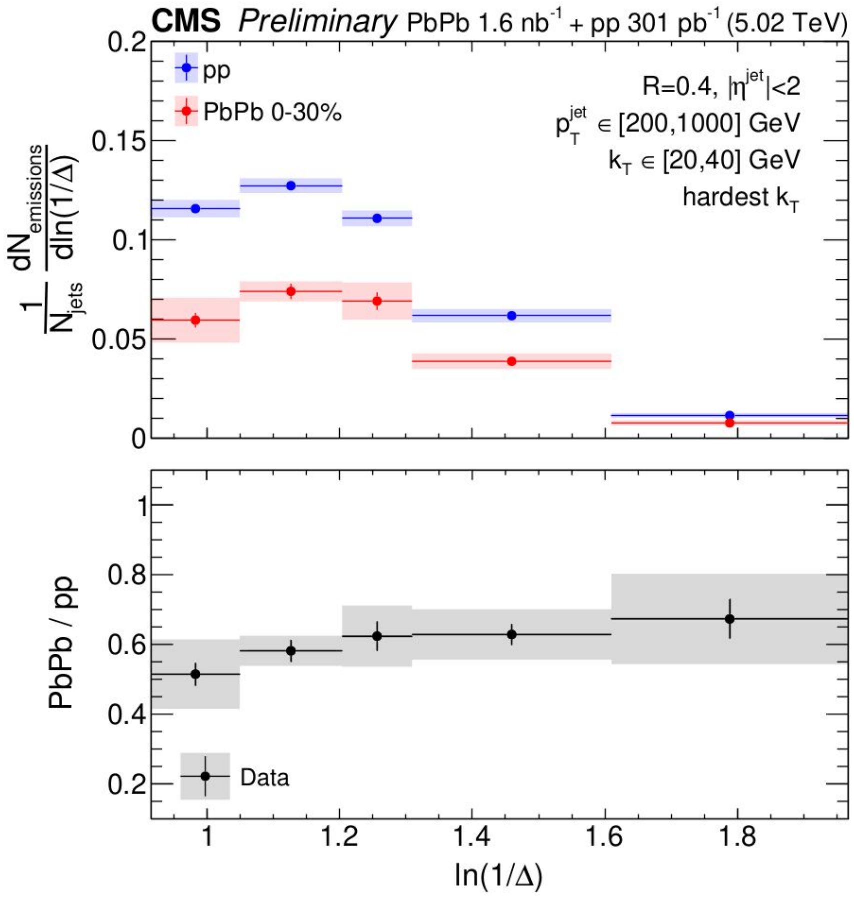






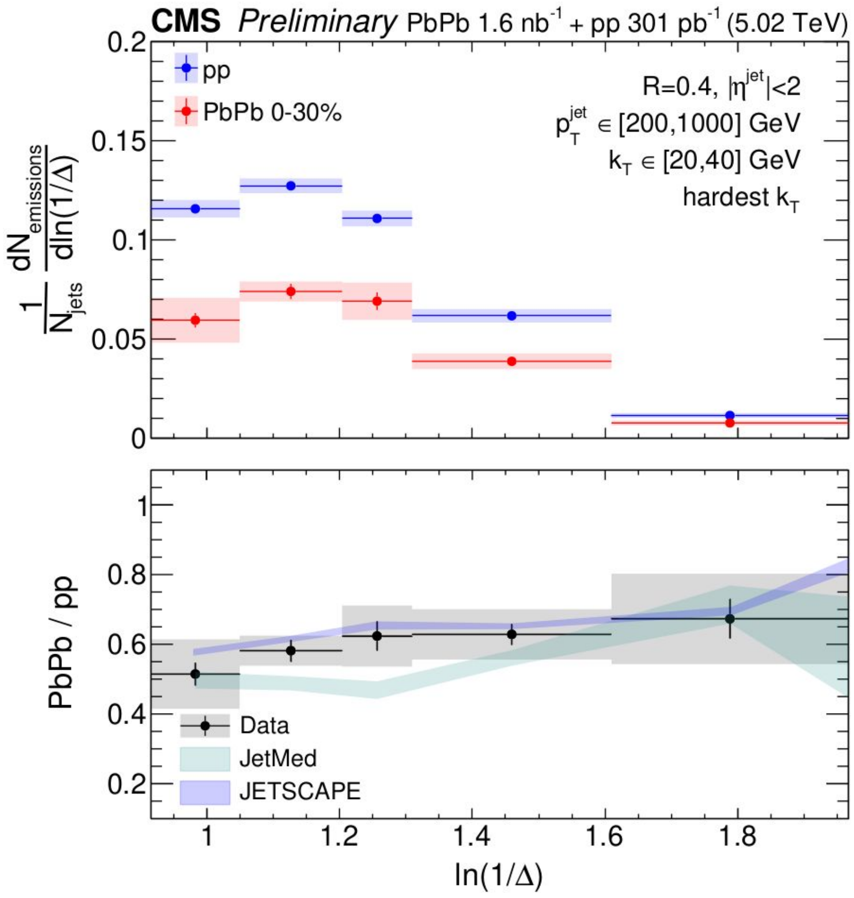
PbPb / pp ratio distribution

- Ratio less than unity – emissions are softened inside medium and are pushed towards lower values of k_T
- Angular structure of hardest emissions consistent between PbPb and pp within uncertainties at highest k_T – possible sign of vacuum emissions



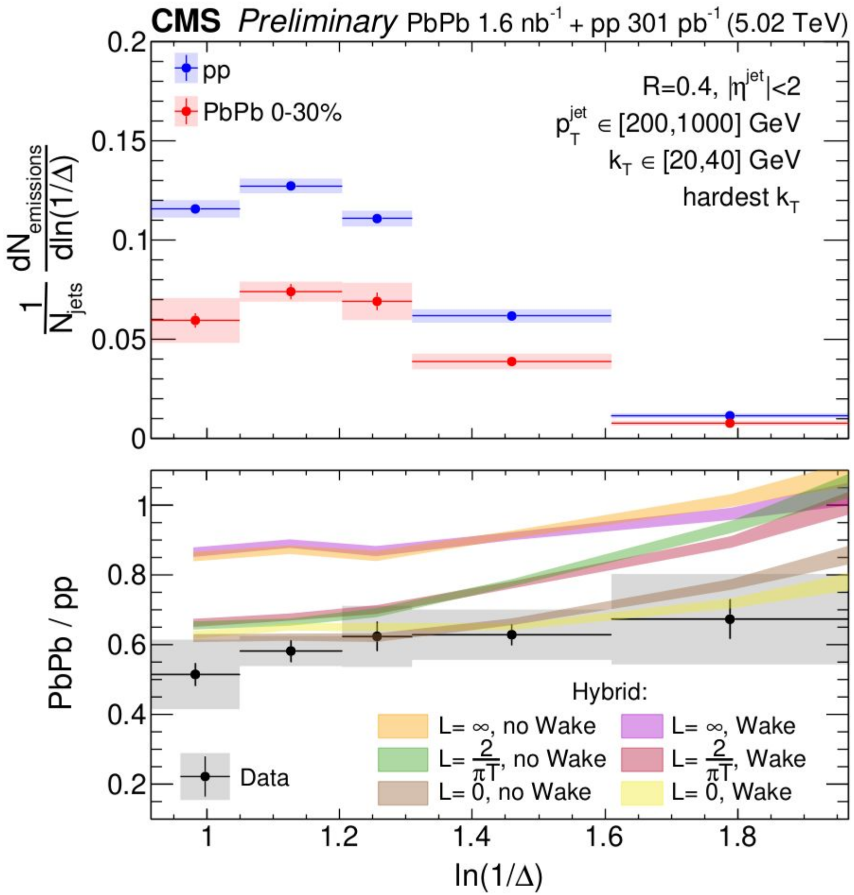
Comparison with models: JetMed, JETSCAPE

- Compared ratio to predictions of models including quenching
- JetMed – pQCD parton shower factorised into vacuum and emissions within a brick medium, with implementation of a coherence angle
- JETSCAPE – a multi-stage parton shower combining the MATTER and LBT models for high and low virtuality partons respectively



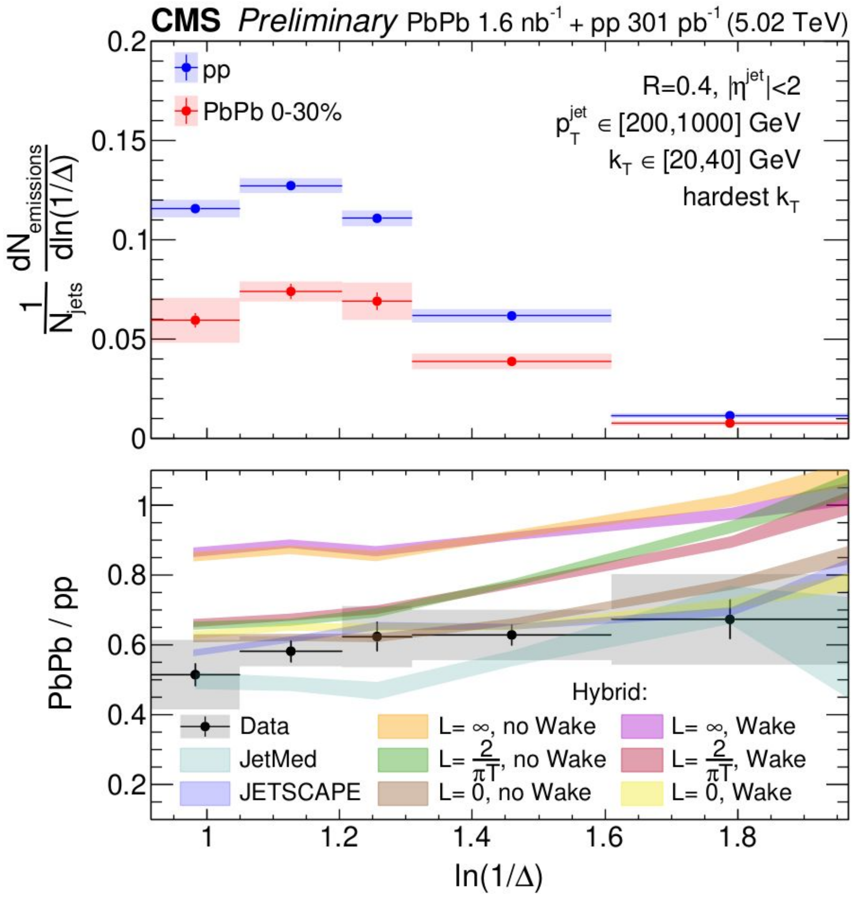
Comparison with models: Hybrid

- Compared ratio to predictions of models including quenching
- Hybrid – a hybrid model using weak coupling for the generation and evolution of the parton shower, and strong coupling to estimate medium interactions. Provides predictions with:
  - ➢ Different values of medium resolution length L, above which two subjets act as independent emitters; In the fully coherent case jets experience less quenching
  - ➢ Inclusion/exclusion of the backreaction of the medium (wake)

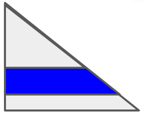


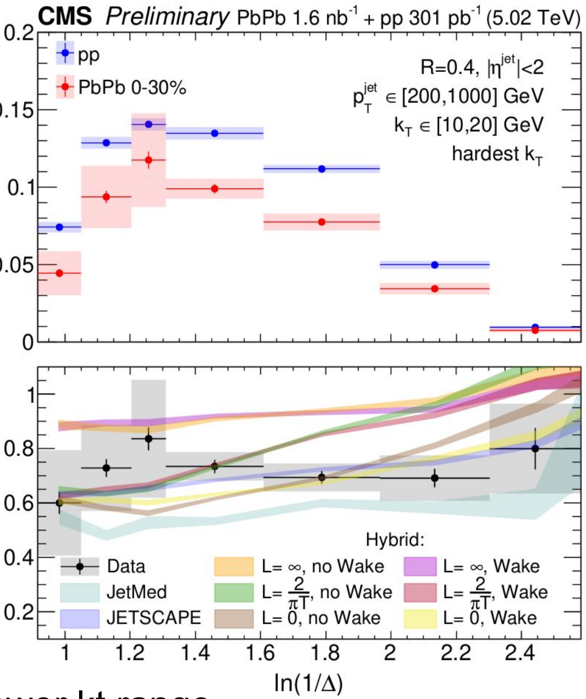
PbPb / pp ratio compared to models

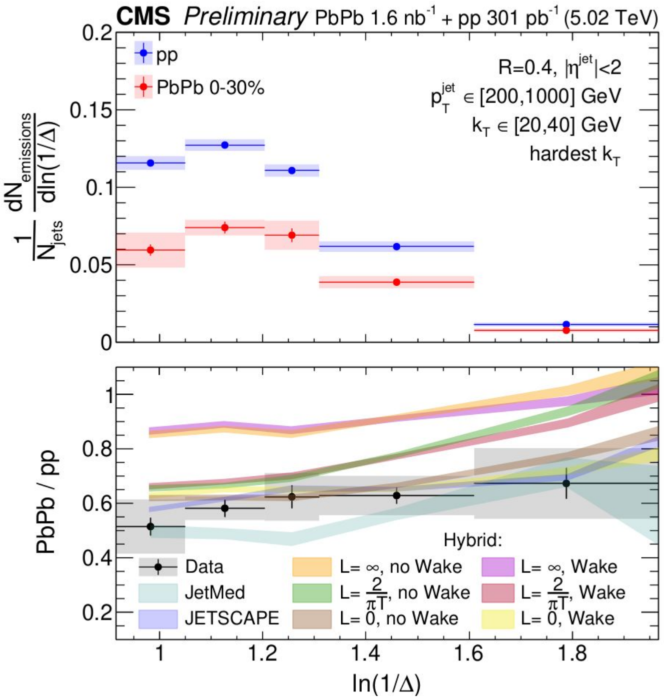
- The predictions by JETSCAPE and Hybrid best describe the data
- Observable largely independent of wake for all resolution lengths
- Ratio most consistent with fully incoherent energy loss case (L=0)

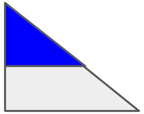


Probing lower k_T values









- Also probed lower kt range
- Able to reach smaller angles due to kinematics
- Modelling prior uncertainties become sizable at high angles
- Unable to reach k_T<10 GeV values because of the underlying event background

For lower values of k_T with different selections, see CERN-EP-2024-238

Outline

Jets, substructure and the primary Lund jet plane

The primary Lund jet plane in pp collisions

The primary Lund jet plane in heavy-ion collisions

Conclusions and outlook

Summary

- The PLJP in pp is a powerful tool to test the parton shower
  - ➢ Modular constraint on models and calculations
  - ➢ New interesting applications for boosted jet topologies
  - ➢ Used in exposing quark mass effect on the parton shower
- The PLJP in heavy-ions:
  - ➢ Probes effects of QGP on the parton shower
  - ➢ First k_T-scan of the PbPb Lund plane to probe different stages of jet evolution and QGP scales
  - ➢ First hints of factorisation of vacuum-like emissions in medium-modified jets

Prospects for future measurements

- Extend heavy-flavour studies to medium-modified jets
  - ➢ Interplay between coherence angle and the dead cone
- Access harder jets and higher values of k_T
  - ➢ More vacuum-like emissions
- More differential Lund Plane based substructure measurements in jet-boson events to control energy loss

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Thank you for listening!

BACKUP SLIDES

Hardest split k_T and JERC

- Jet 4-momentum is corrected by the application of **JEC** and **JER**
- Jet 4-momentum no longer sum of constituents' (used to extract k_T)!
- Interested in hardest emission in jets – chosen emission can carry considerable fraction of momentum

$$k_{\mathrm{T}}^{\mathrm{max}} = \frac{1}{2}\Delta R p_{\mathrm{T}}$$

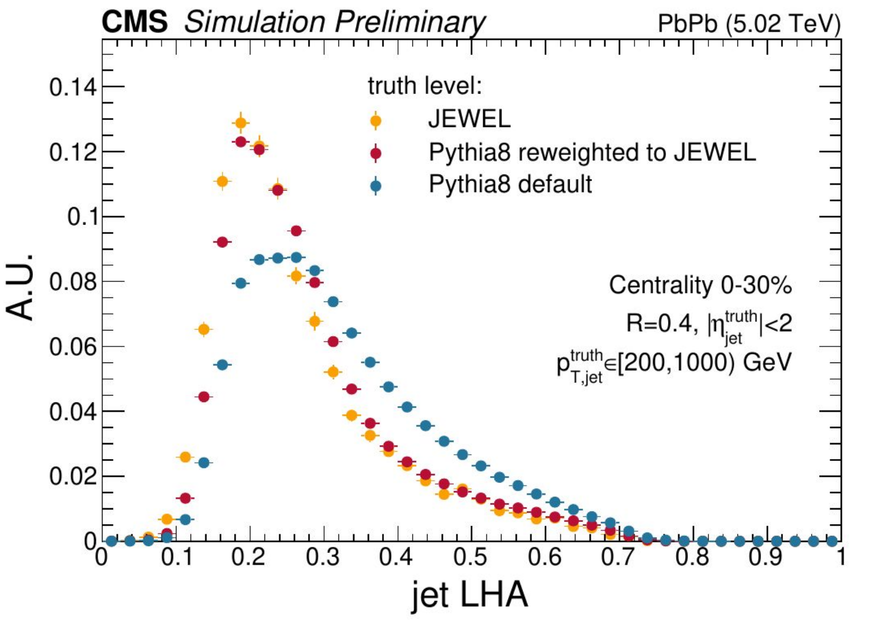
- Scale detector level k_T by the same factor p_T is scaled/smeared by **JEC** and **JER** (and their uncertainties)

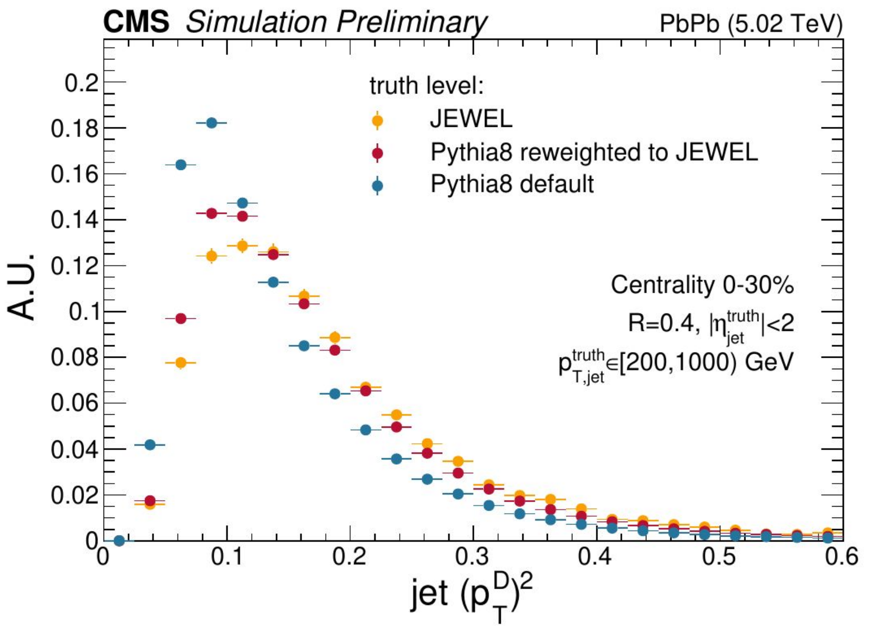
PYTHIA8 reweighting using JEWEL

- Test impact of reweighting on observables not directly connected to the PLJP
  - ➢ Jet angularities
- Normalised distributions of $\lambda_{0.5}^{1}$ (Les Houches angularity, **LHA**) and λ_{0}^{2} (momentum dispersion, **$(p_T^D)^2$**)

$$\lambda_\beta^\kappa = \Sigma_i (p_{T,i}/p_{T,jet})^\kappa (\Delta R_i/R)^\beta$$

sum over all jet constituents i with momentum $p_{T,i}$ and distance to jet axis ΔR_i



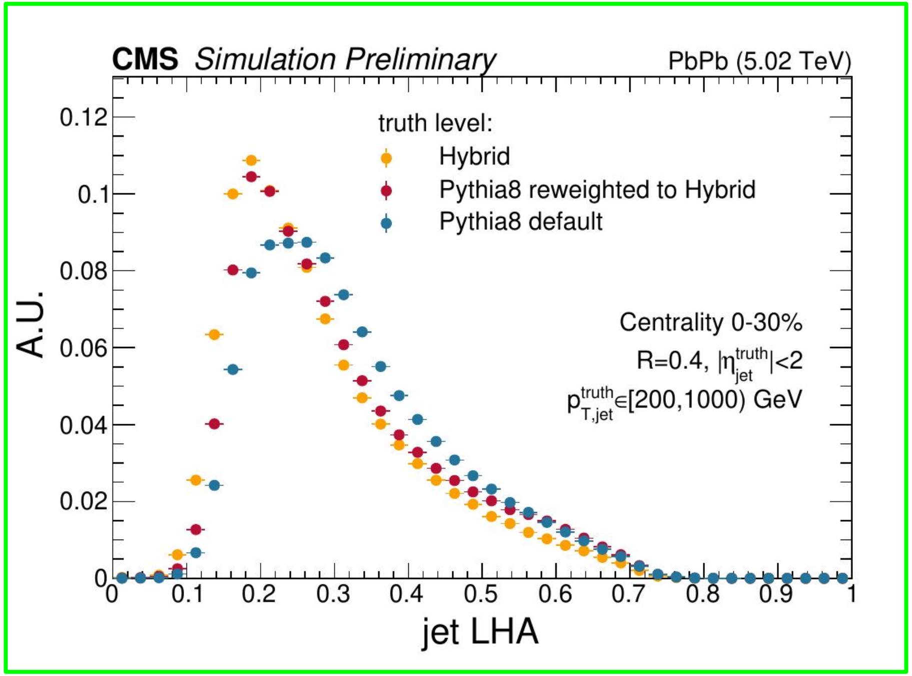


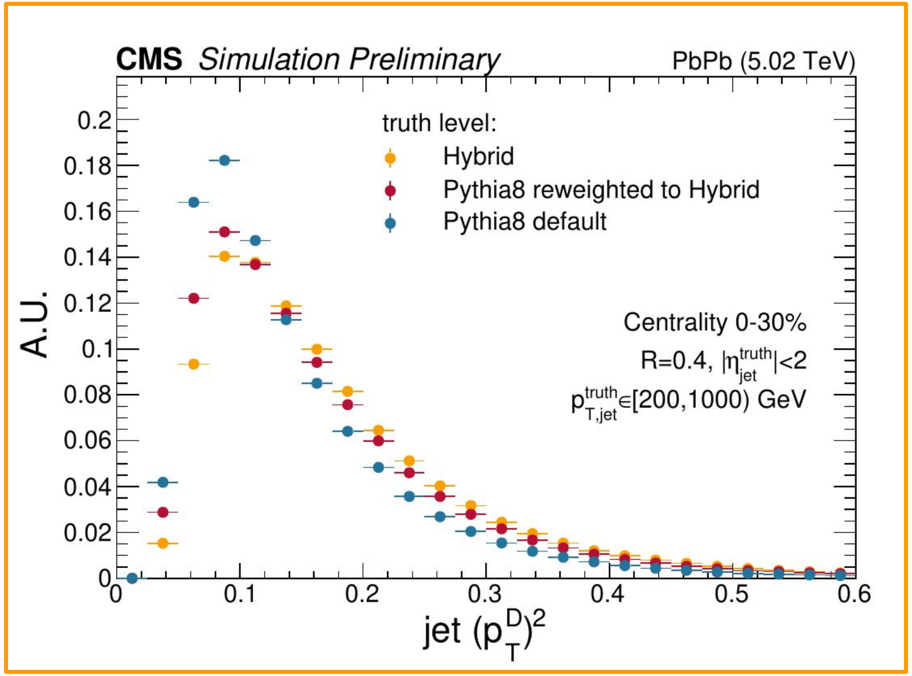
PYTHIA8 reweighting using Hybrid

- Test impact of reweighting on observables not directly connected to the PLJP
  - ➢ Jet angularities
- Normalised distributions of $\lambda_{0.5}^{1}$ (Les Houches angularity, **LHA**) and λ_0^{2} (momentum dispersion, **$(p_T^D)^2$**)

$$\lambda_\beta^\kappa = \Sigma_i (p_{T,i}/p_{T,jet})^\kappa (\Delta R_i/R)^\beta$$

sum over all jet constituents i with momentum $p_{T,i}$ and distance to jet axis ΔR_i





Estimate of prior uncertainty (Hybrid)

- Take the reweighted PYTHIA8 distribution and unfold it using the default PYTHIA8 prior and compare to the two particle level distributions in two different k_T bins
- **Small non-closures** observed