

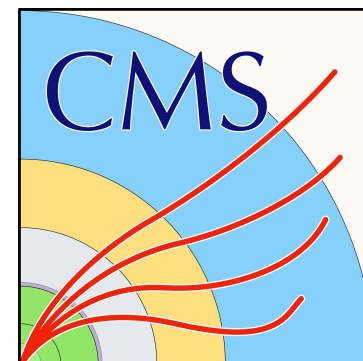
Recent jet substructure measurements in CMS

QCD@LHC 2026

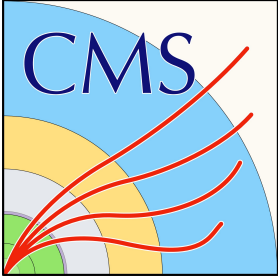
Attila Rád1



ELTE



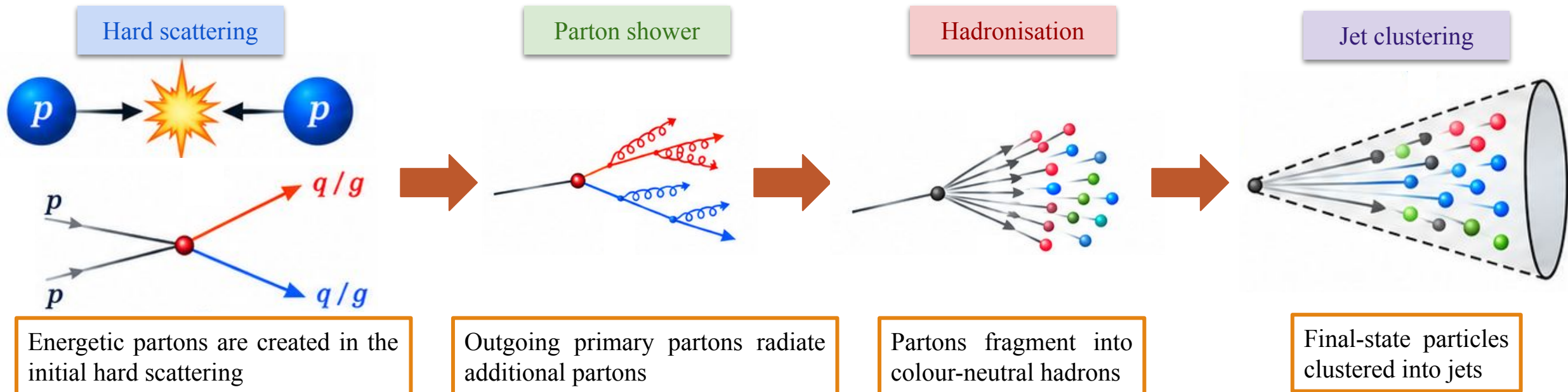
Outline



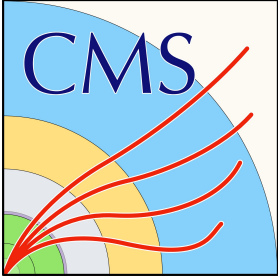
- Time evolution of the proton-proton collisions
- Jet substructure observables
- Focusing on complementary CMS measurements:
 - angular correlations induced by gluon polarisation
 - dead-cone effects in b-jets
 - Z+jet mass cross-section measurements with grooming
 - Four-point energy-energy correlators probing multi-particle angular information

Proton-proton scattering time evolution

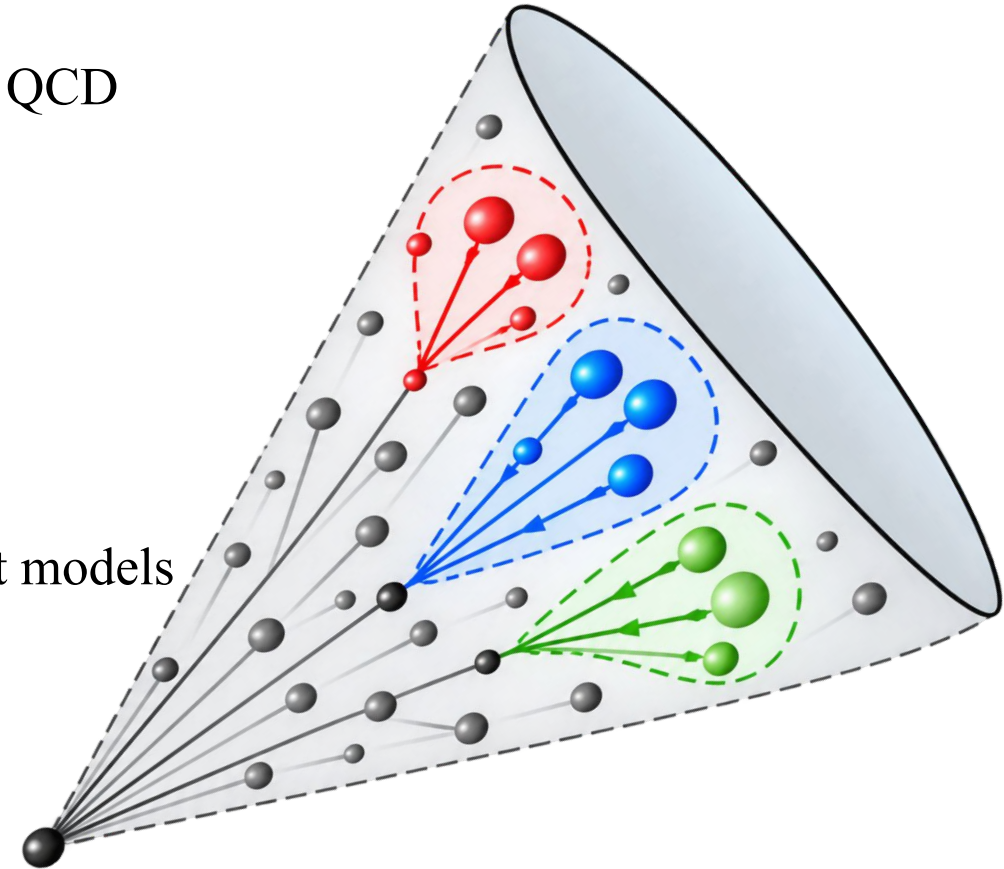
- QCD governs the strong-interaction dynamics of proton-proton collisions
- A measured jet contains information from several stages of the event evolution:
 - hard scattering
 - perturbative parton shower
 - non-perturbative hadronisation
- Different jet-related observables can probe different stages of this evolution



Jet substructure



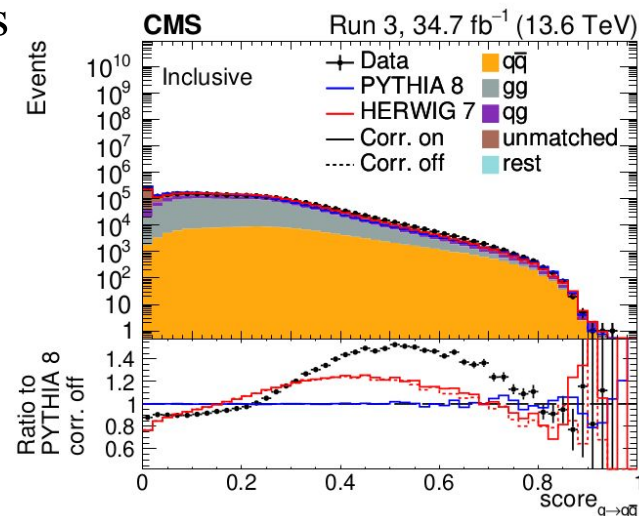
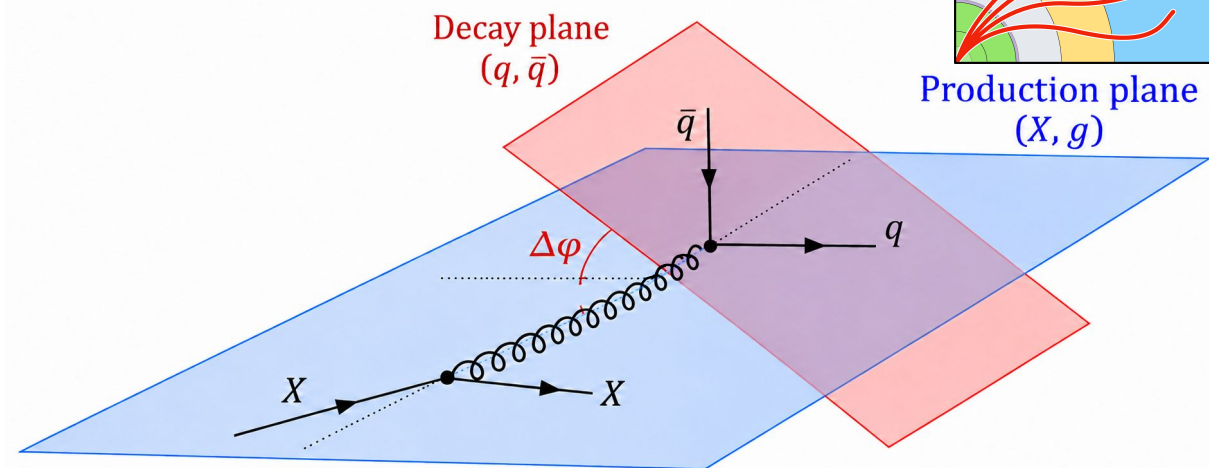
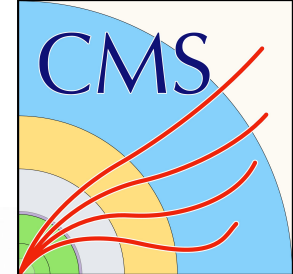
- Jets have an internal structure that carries information about their origin and evolution
 - it links reconstructed particles to the initiating parton and the QCD shower
- Jet substructure observables can
 - discriminate quark- and gluon-enriched jets
 - test perturbative and nonperturbative QCD
 - constrain parton-shower, hadronisation, and underlying-event models in Monte Carlo generators
 - identify boosted hadronic decays of W, Z, H, and top quarks



Gluon polarisation inside jets

- A gluon emission followed by its subsequent splitting defines two planes:
 - production plane: $X \rightarrow X + g$
 - decay plane: $g \rightarrow q\bar{q}$
- $\Delta\phi$: azimuthal angle between the two splitting planes
- Helicity interference of the intermediate gluon produces a non-uniform modulation in $\Delta\phi$
- The signal is clearest for $g \rightarrow q\bar{q}$, but this topology is rare
- Experimental strategy: decluster high- p_T AK8 dijet events with the C/A algorithm.
 - find the highest- k_T splittings on the primary and the secondary branches
 - use a four-class DNN to enrich $g \rightarrow q\bar{q}$ topology
 - measure $\Delta\phi$ and compare showers with and without gluon-spin correlations

arXiv:2603.03689

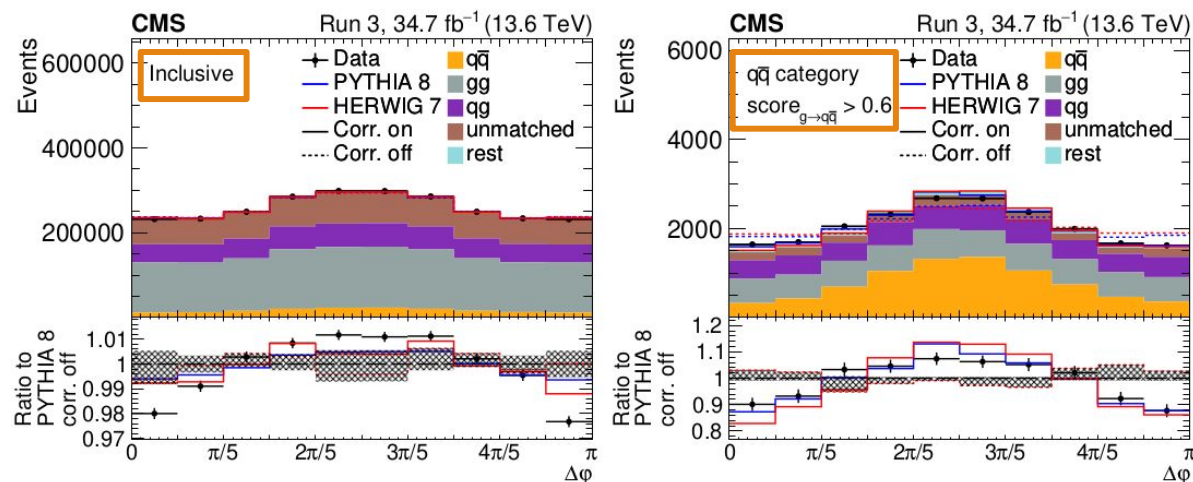
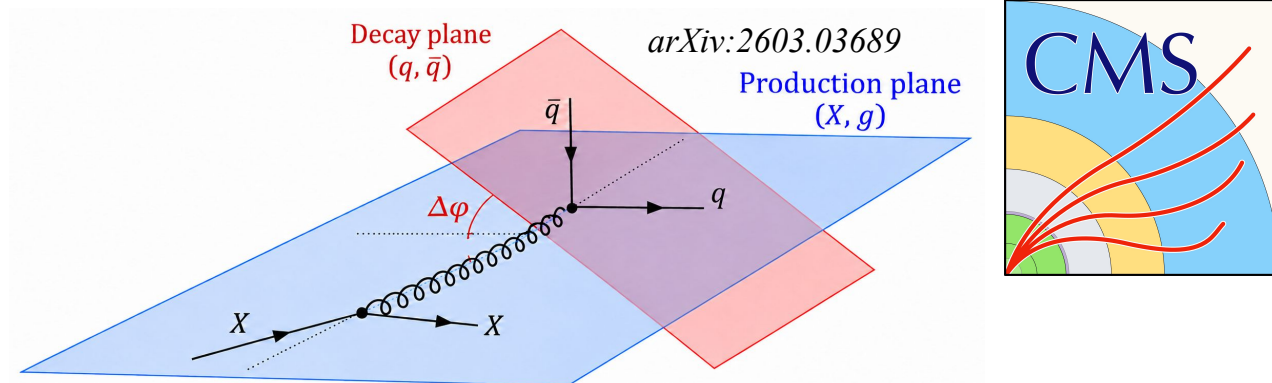


Four-class DNN: qg , gg , $q\bar{q}$, unmatched

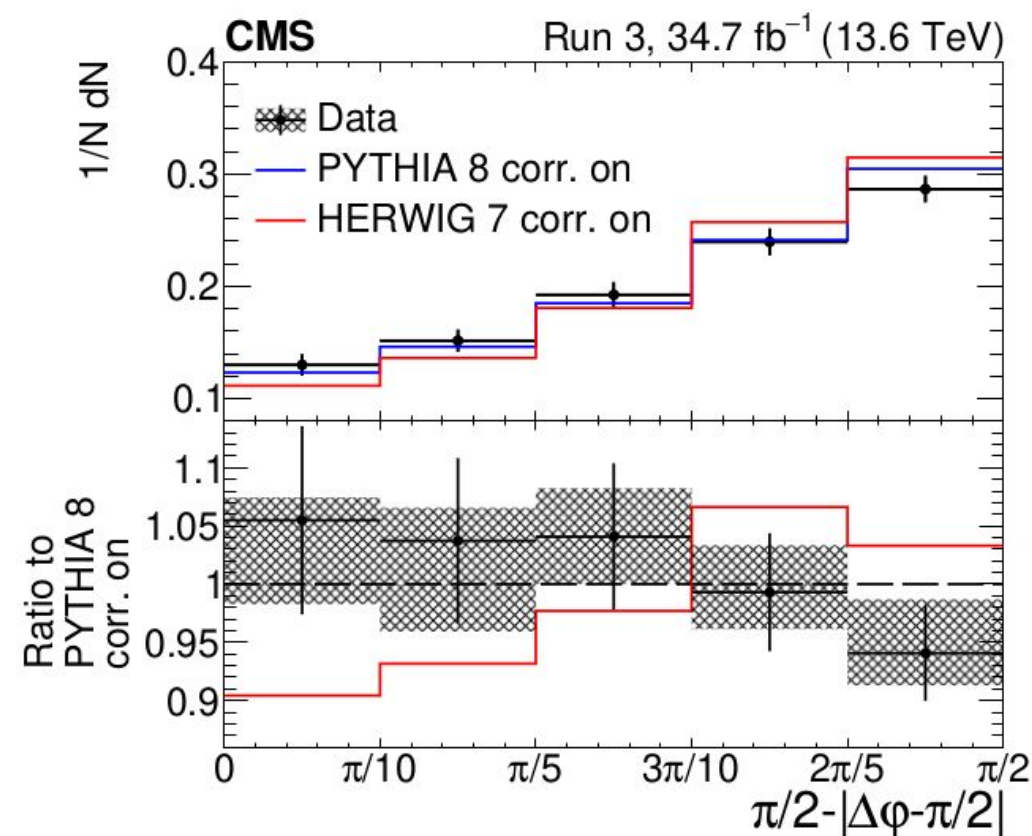
Required score for $g \rightarrow q\bar{q} > 0.6$

Gluon polarisation results

- The inclusive effect is small, enriched quark pair decay category with $\sim 38\%$ purity.

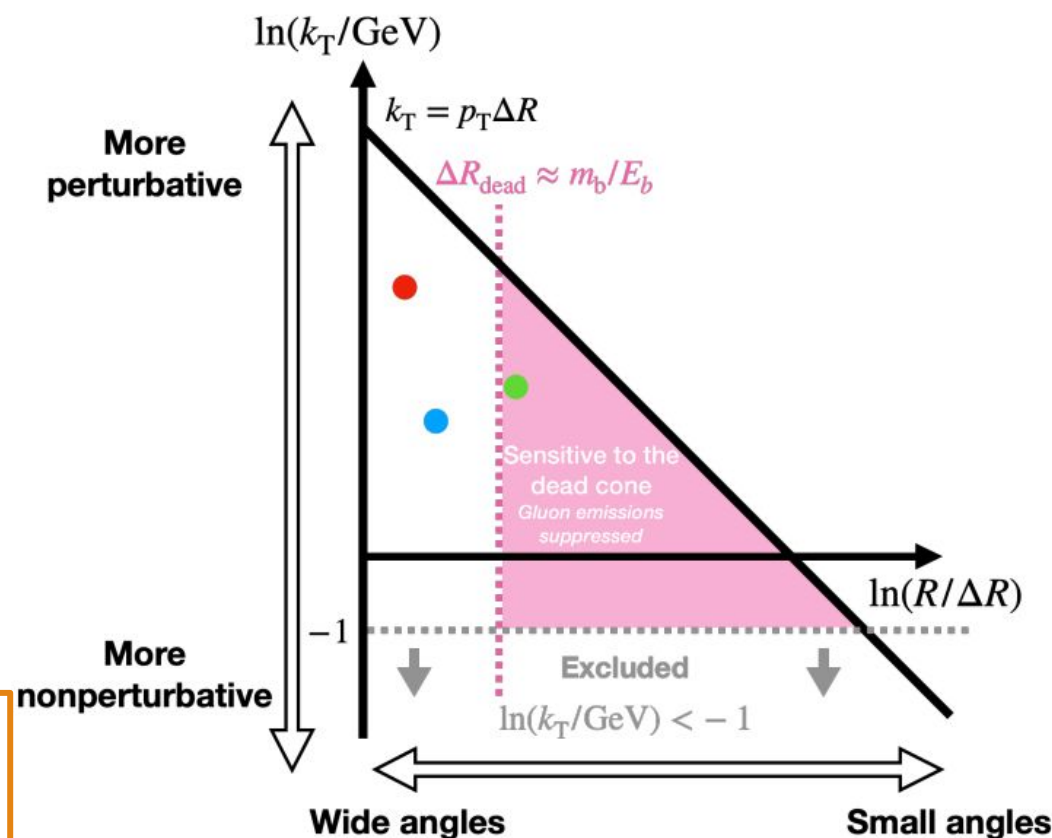
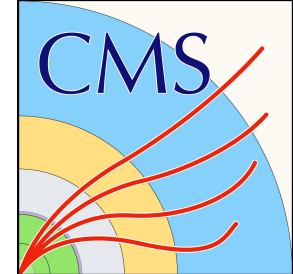
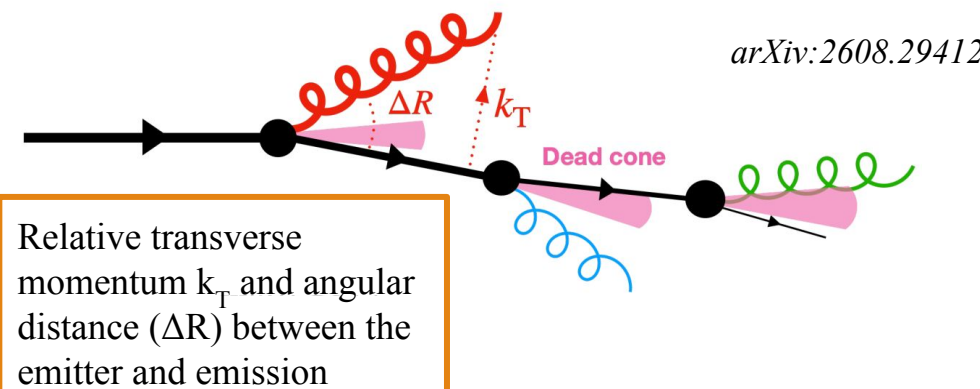


- Data disfavour the correlation-off hypothesis by 6.8σ , Pythia with the correlation effect is within uncertainties
- Unfolded observable: $\pi/2 - |\Delta\phi - \pi/2|$, exploiting symmetry around $\pi/2$
- The observed modulation is slightly smaller than the predictions
- Gluon spin information survives hadronisation in high-energy jets



Dead-cone effect in b-jets

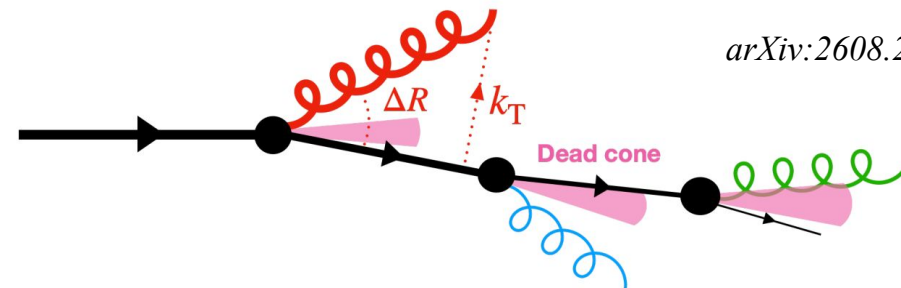
- For a massive quark, nearly collinear gluon emissions are suppressed within $\Delta R_{\text{dead}} \approx m_b/E_b$
- The effect is sizeable for b quarks at moderate energies
- Angle-ordered C/A declustering constructs a Lund jet plane proxy for the shower
 - measured angular emission density vs angular ordinate: $\rho(\Delta R) = (1/N_{\text{jet}}) dN_{\text{em}} / d \ln(R/\Delta R)$
- Event selection: $t\bar{t}$ events with opposite-sign $e \mu +$ at least two jets
 - A tag-and-probe selection gives a high-purity b-jet sample without using the tagged jet for the study



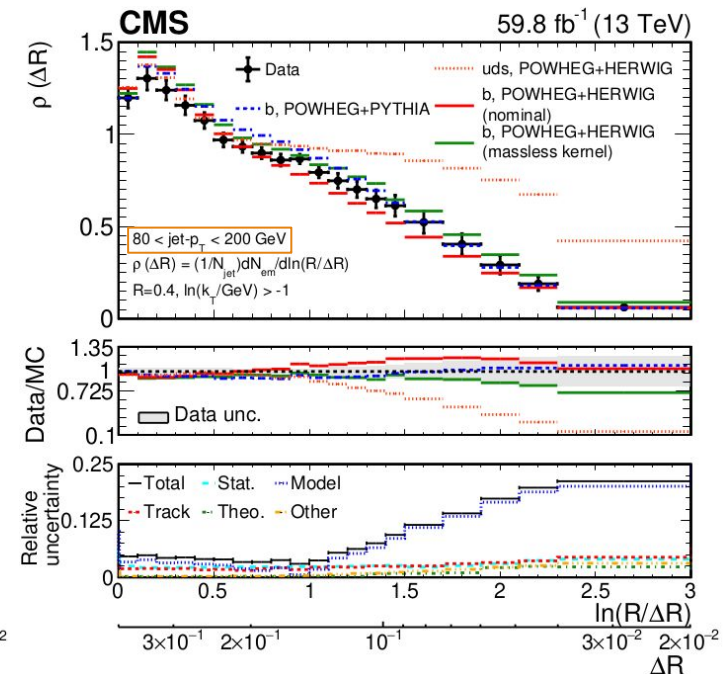
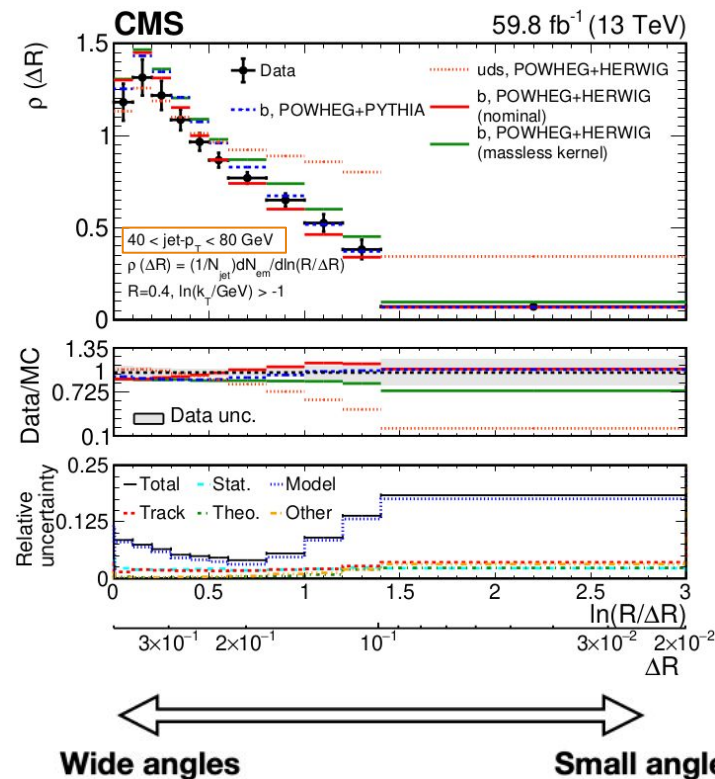
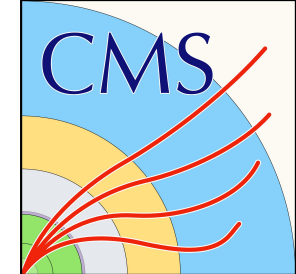
A minimum k_T requirement suppresses very soft, non-perturbative emissions.

Dead-cone effect results

- Unfolded $\rho(\Delta R)$ distributions are measured in two b-jet p_T intervals: 40-80 and 80-200 GeV
- Key comparison: nominal b showering versus a massless-kernel Herwig sample
 - The massless model predicts too many collinear emissions
- Light-quark predictions also overestimate the small-angle emission density
 - heavy- and light-quark jets have different collinear radiation patterns
- The result benchmarks heavy-flavour shower modelling



arXiv:2608.29412

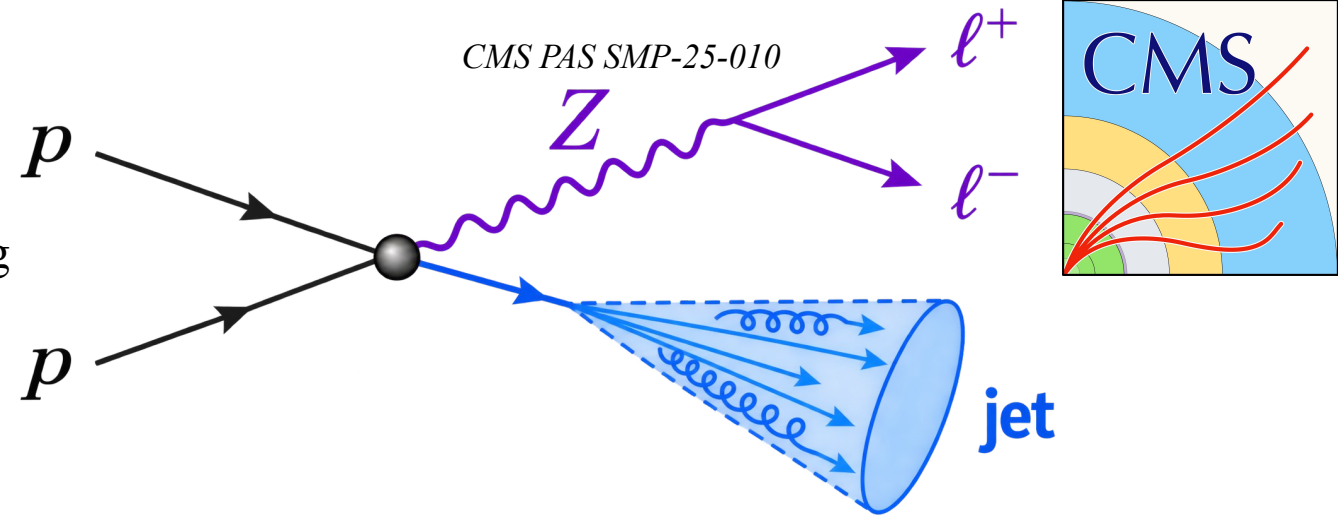


The lower- p_T bin gives 4.3 σ evidence against the shower model without the dead-cone effect

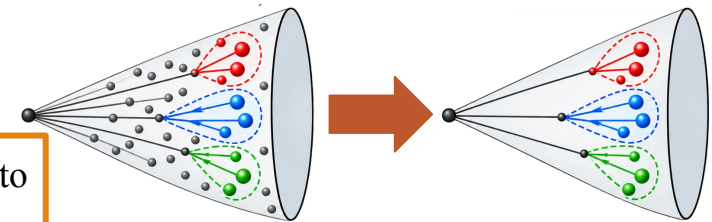
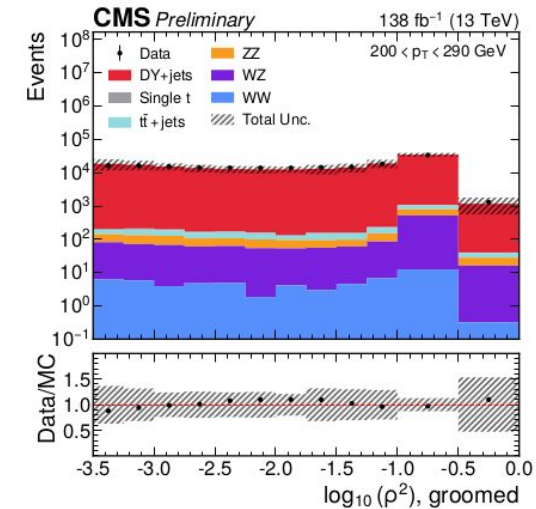
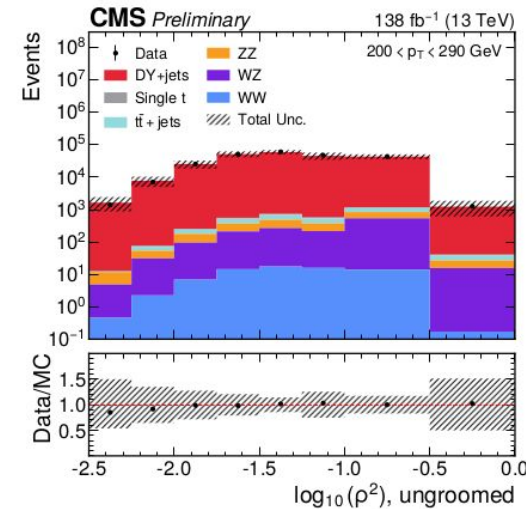
At larger jet p_T the dead cone is narrower

Z+jet mass spectrum

- The Z boson provides a clean reference for the recoiling jet.
- Back-to-back topology: $|\Delta\phi(Z, \text{jet})| > \pi/2$ and p_T asymmetry < 0.3 .
- Dominant production channels $gq \rightarrow Zq$ and $q\bar{q} \rightarrow Zq$ make the leading jet quark-enriched.
 - leading jet is about 70% quark-initiated for single-jet events
- Jet mass is sensitive to hard splittings, soft radiation, hadronisation and the underlying-event
- Comparing groomed and ungroomed mass separates perturbative evolution from soft, non-perturbative effects



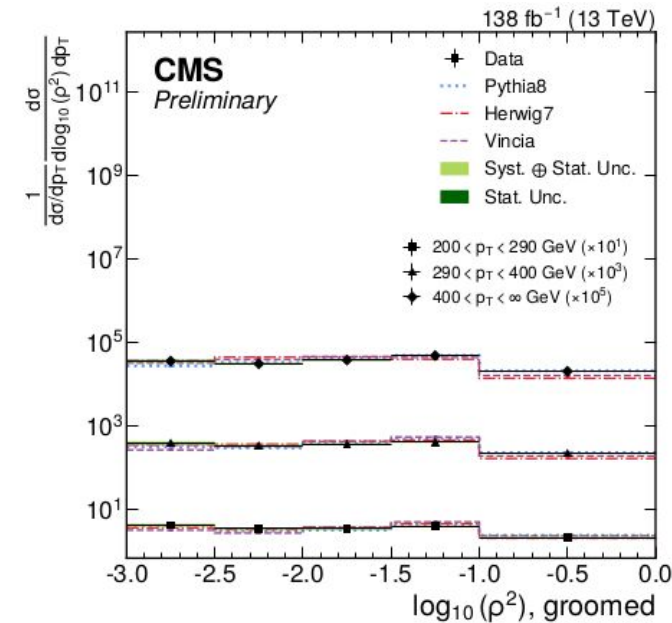
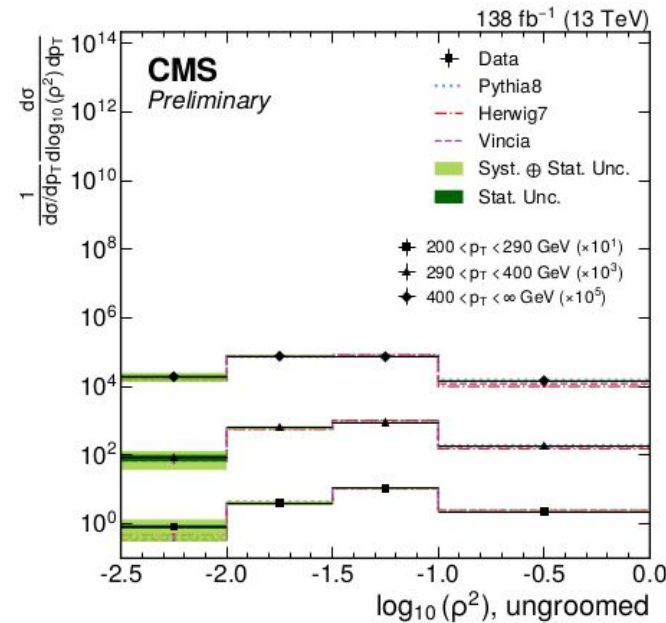
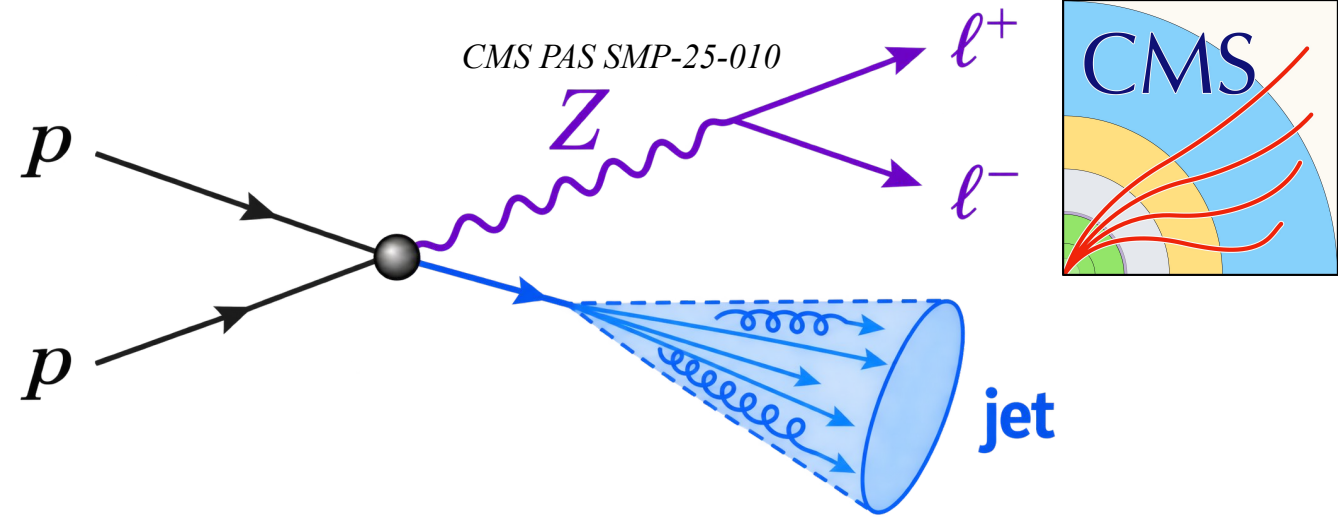
$$\rho = \frac{m}{p_T R}$$



Grooming based on soft drop to isolate the core of the jets

Z+jet mass spectrum results

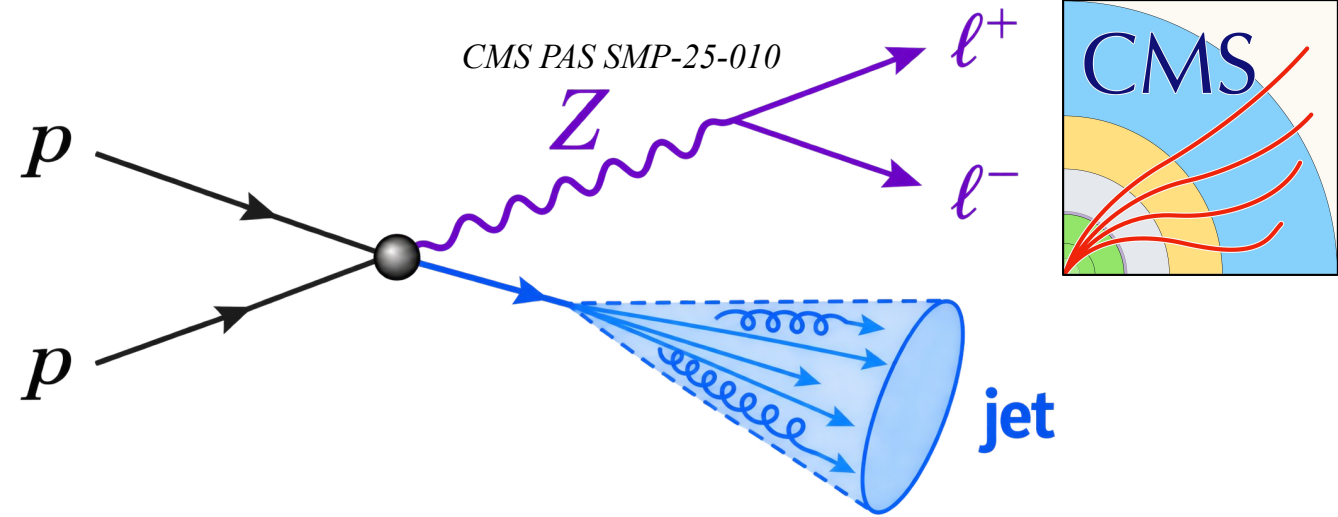
- Grooming shifts the spectrum to lower mass by removing soft wide-angle radiation.



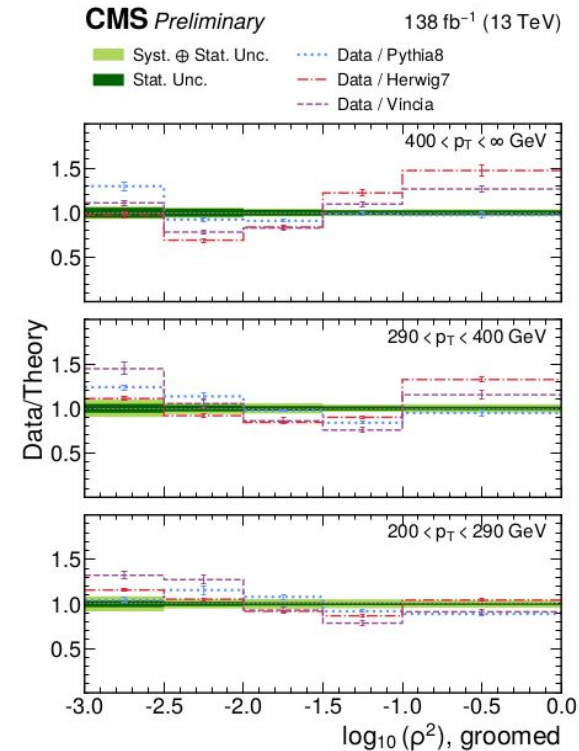
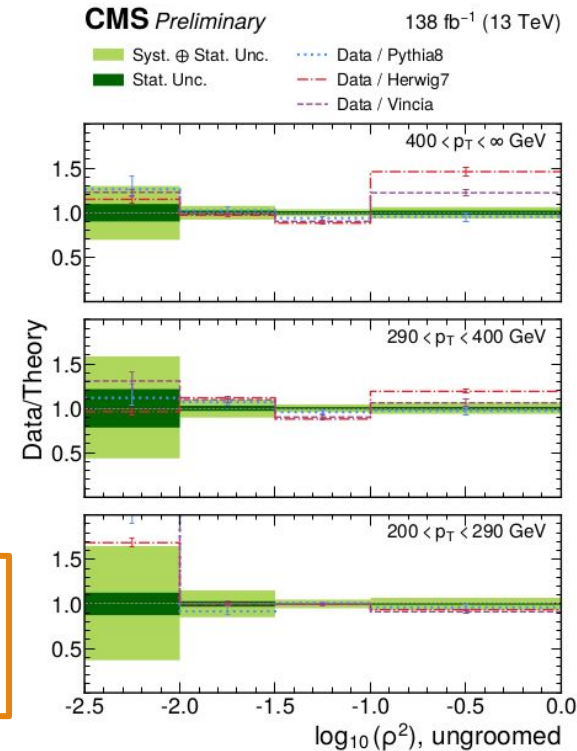
Results in several single jet p_T regions

Z+jet mass spectrum results

- Grooming shifts the spectrum to lower mass by removing soft wide-angle radiation.
- Pythia describes the unfolded spectra across most of the range
- Herwig and Vincia show larger deviations, especially in the ungroomed mass peak and high-mass region
- The result provides a quark-enriched benchmark for shower, hadronization, and tuning studies



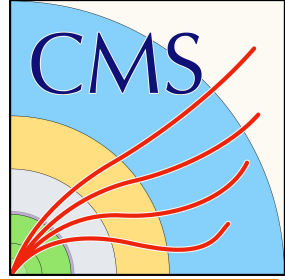
Ratios between data and predictions in several single jet p_T regions



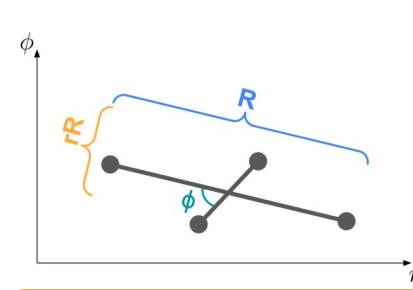
Four-point energy-energy correlators

- N-point EECs measure momentum-weighted angular correlations among N jet constituents
- The four-point EEC is the lowest order with genuine sensitivity to gluon spin, non-trivial colour structure and detailed angular dynamics
 - previously measured two/three-point projections probe bulk angular scaling, but not the full angular structure
- The full four-point space is five-dimensional, this analysis focuses on three 3D subspaces ([arxiv:2607.07792](https://arxiv.org/abs/2607.07792))
- $Z \rightarrow \mu\mu$ provides a clean trigger and low background contamination
- AK8 jets with $p_T > 50$ GeV and $|\eta| < 1.7$ are used, EECs are computed from charged constituents

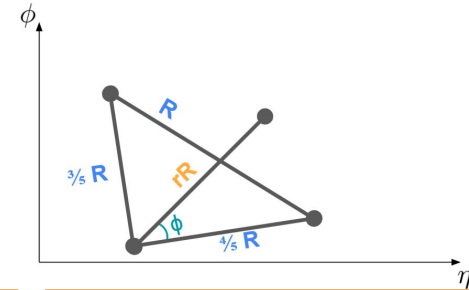
CMS PAS SMP-25-009



R: system scale
r: leg-length ratio
 ϕ : orientation angle

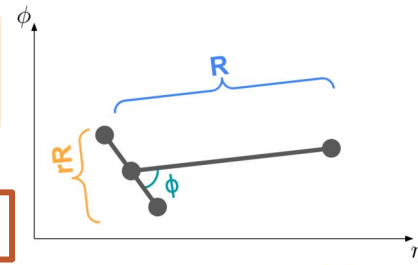


dipole: two line segments sharing a midpoint

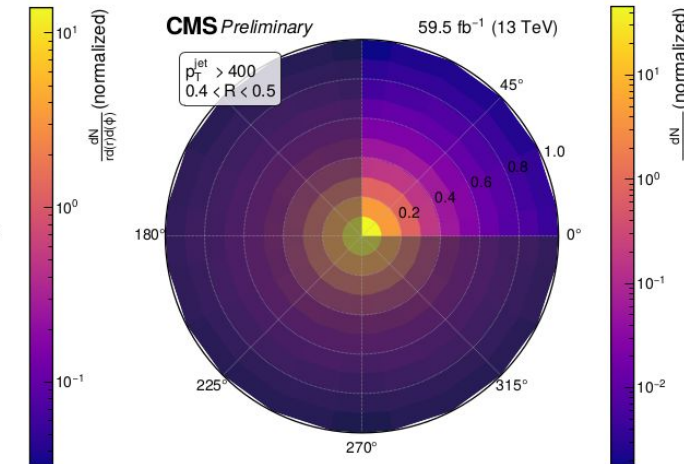
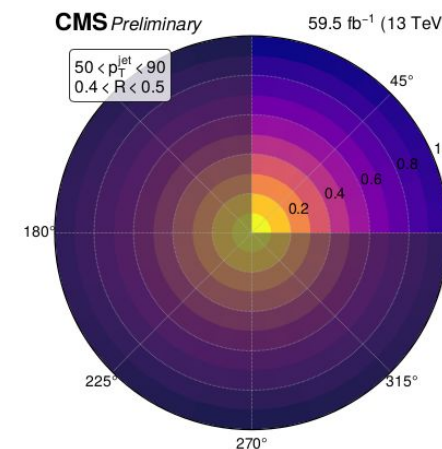


triangle: 3 particles forming a 3-4-5 triangle + 1 moving around it

tee: T-shaped four-particle geometry



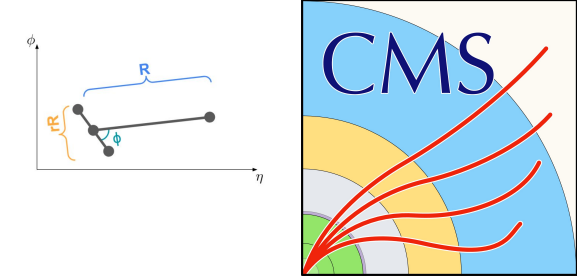
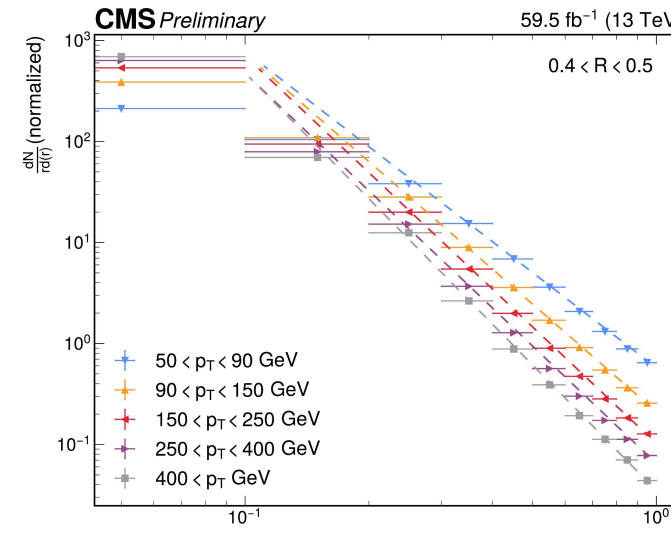
tee configuration unfolded particle-level distributions



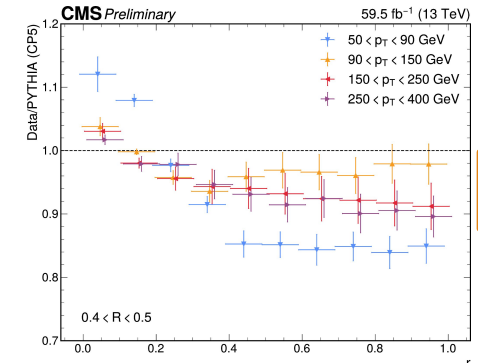
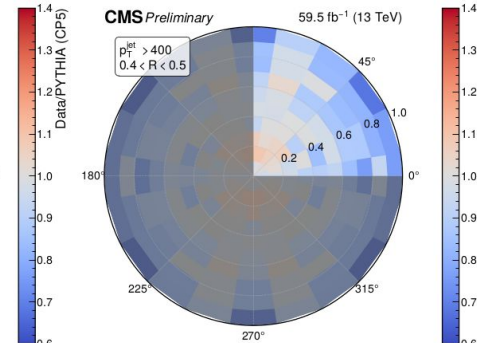
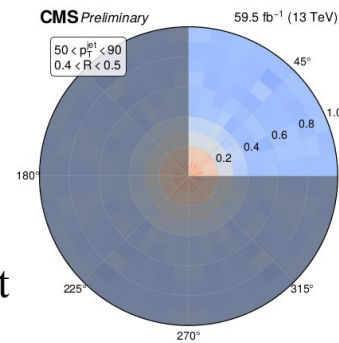
Energy correlator results

- Tee radial profile: power-law behaviour in the perturbative region, with flattening at small r indicating non-perturbative sensitivity
- Both Pythia CP5 and Herwig CH3 are disfavoured across all three subspaces.
- Pythia p_T -ordered shower better describes widely separated multi-parton configurations (larger r)
- Herwig hadronisation model captures the nonperturbative behaviour in the $r \rightarrow 0$ collinear limit better

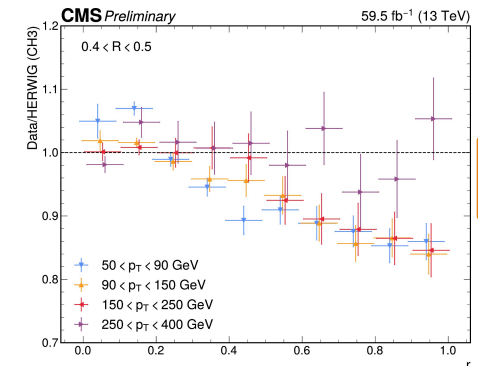
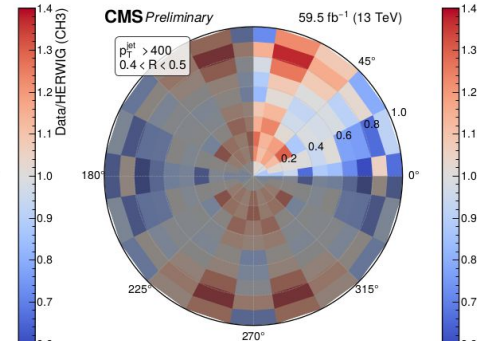
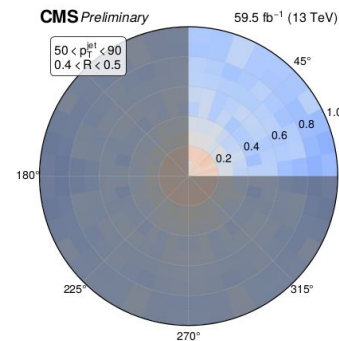
Ratio between data and predictions for selected jet p_T and size bins



Radial profile: integrated over ϕ

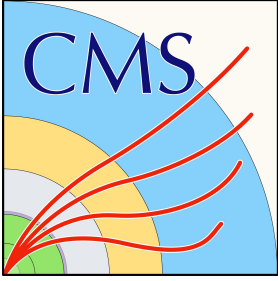


Pythia



Herwig

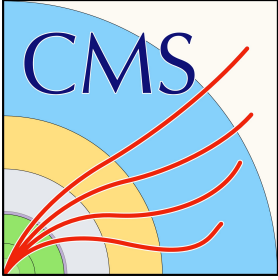
Summary



- Four complementary CMS measurements probe different aspects of jet evolution
 - gluon spin correlations test whether parton showers include polarisation effects
 - the b-jet dead cone tests heavy-quark mass effects in shower kernels
 - Z+jet mass spectra separate perturbative mass evolution from soft contamination
 - 4-point EECs access spin, colour and multi-point angular dynamics beyond 2/3-point projections
- Together they provide information from parton evolution through to hadronisation
 - precision substructure observables are tuning handles for spin, colour, and shower modelling

Thank you

References



- CMS Collaboration, “Measurement of angular correlations inside jets induced by gluon polarization in proton-proton collisions at $\sqrt{s} = 13.6$ TeV”, [*arXiv:2603.03689*](#)
- CMS Collaboration, “Evidence for the dead-cone effect in bottom quark initiated jets produced in proton-proton collisions at $\sqrt{s} = 13$ TeV”, [*arXiv:2608.29412*](#)
- CMS Collaboration, “Measurement of double-differential groomed and ungroomed jet mass cross sections in Z+jet events at $\sqrt{s} = 13$ TeV with the CMS detector”, [*CMS PAS SMP-25-010*](#)
- CMS Collaboration, “Measurement of four-point energy-energy correlator subspaces in Z+jets events”, [*CMS PAS SMP-25-009*](#)