Jet substructure measurements at CMS

ICHEP 2024: 42nd International Conference on High Energy Physics

18 – 24 July 2024, Prague (Czech Republic)

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on behalf of the CMS Collaboration

CMS

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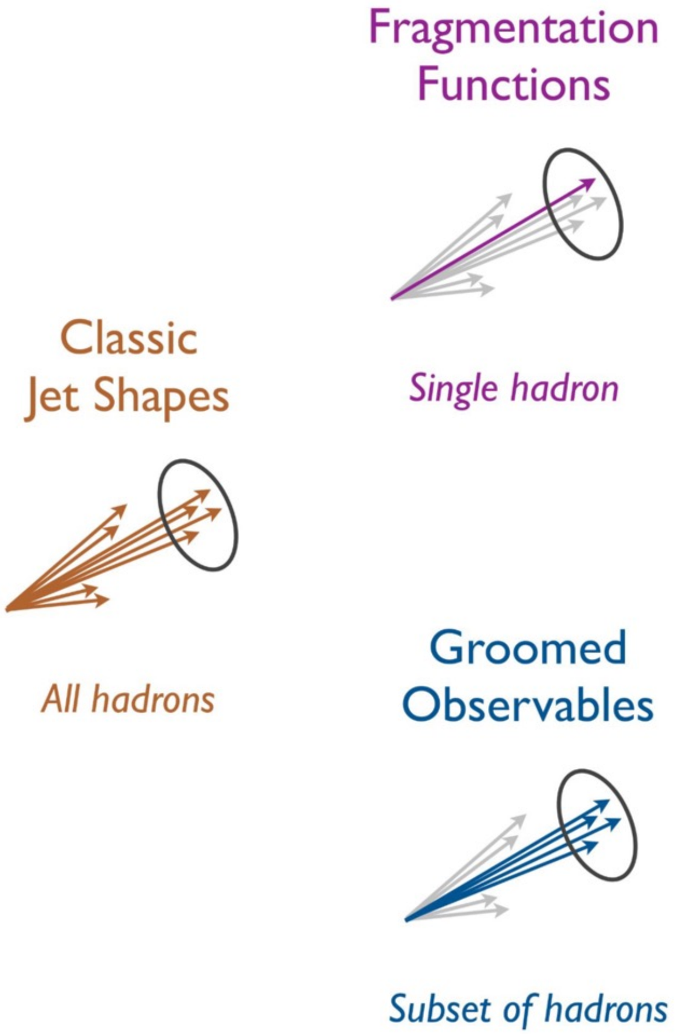
Introduction

What is jet substructure?

- Jet constituents are mapped onto physically meaningful observables
- Provides numerous innovative ways to probe the Standard Model in extreme regions of phase space
- Experimental precision to challenge state-of-the-art pQCD analytical calculations and to constrain parton shower and hadronization model of MC generators

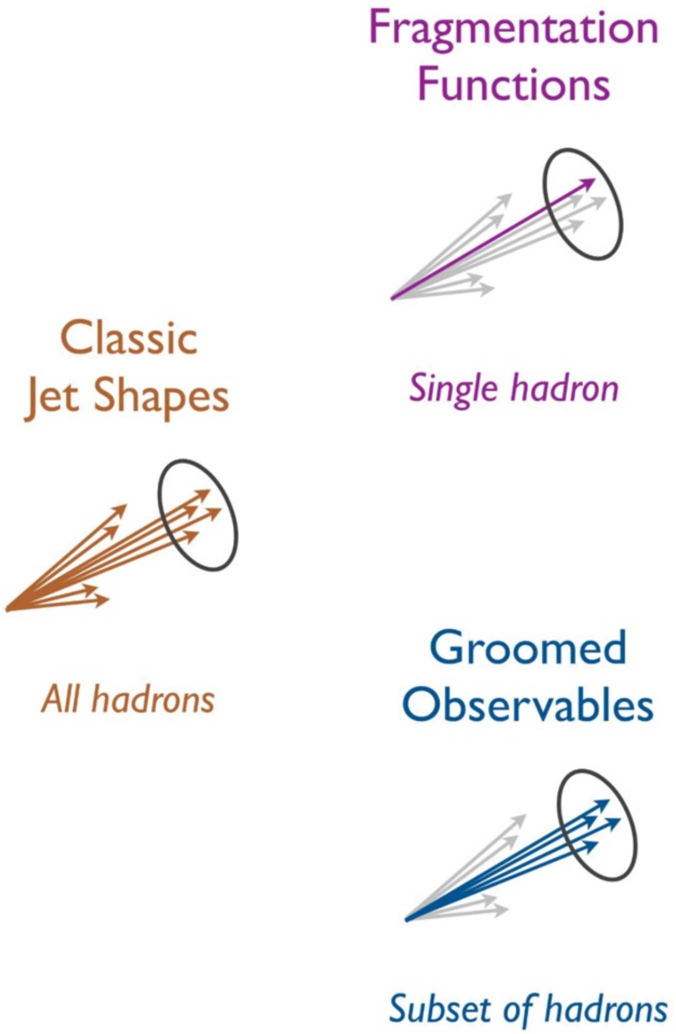


Outline

In this talk:

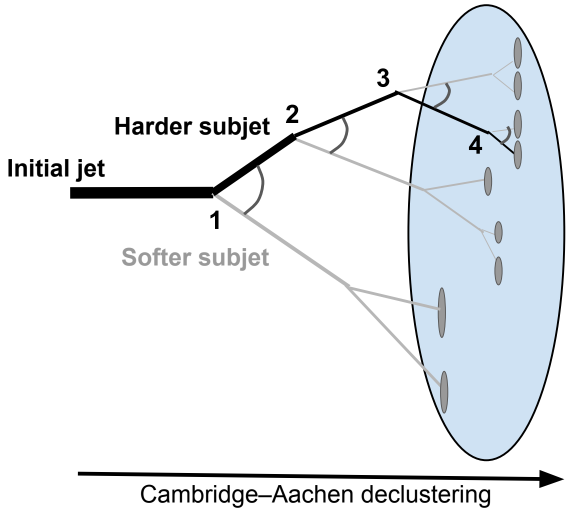
- Measurement of the primary Lund jet plane density in proton-proton collisions at $\sqrt{s}$ = 13 TeV
  JHEP 05 (2024) 116

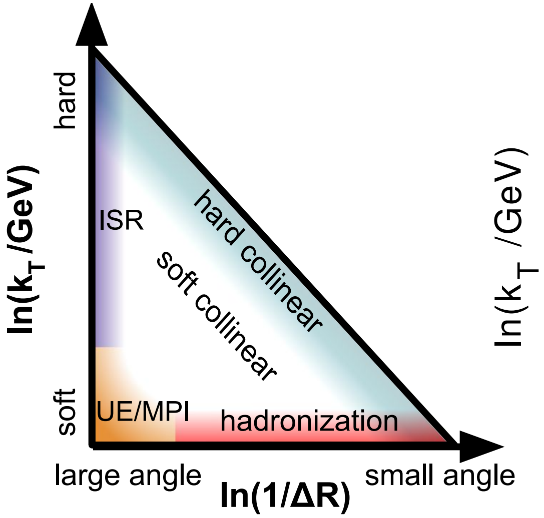
- Measurement of energy correlators inside jets and determination of the strong coupling $\alpha_S(m_Z)$
  SMP-22-015, accepted by PRL

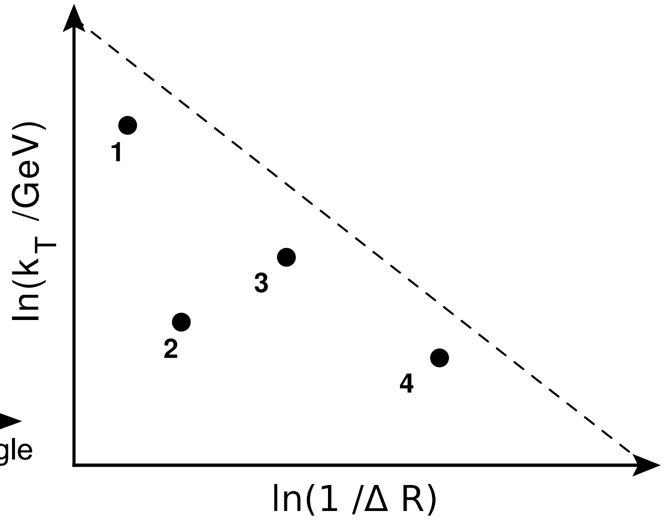


Primary Lund jet plane

- 2D representation of the phase-space of $1 \rightarrow 2$ splitting
- Internal structure of jets – iterative jet declustering using the Cambridge-Aachen algorithm
- **Primary Lund jet (PLJ) plane** - emissions obtained by declustering the harder subjet at each step of the declustering process
- Provides information about the radiation pattern of the jet

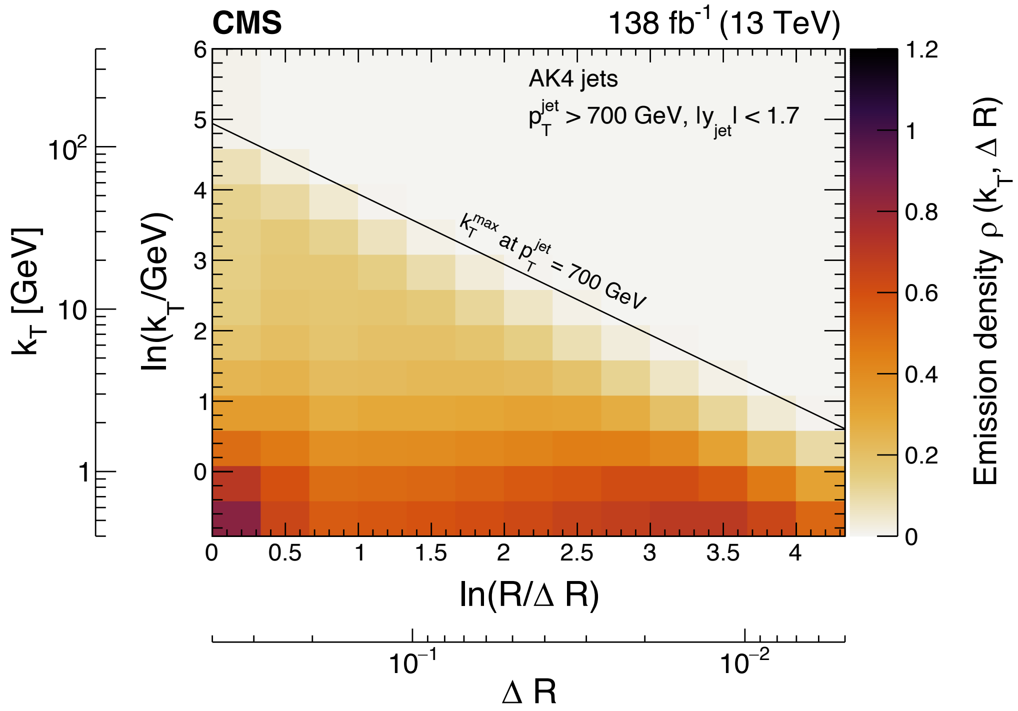


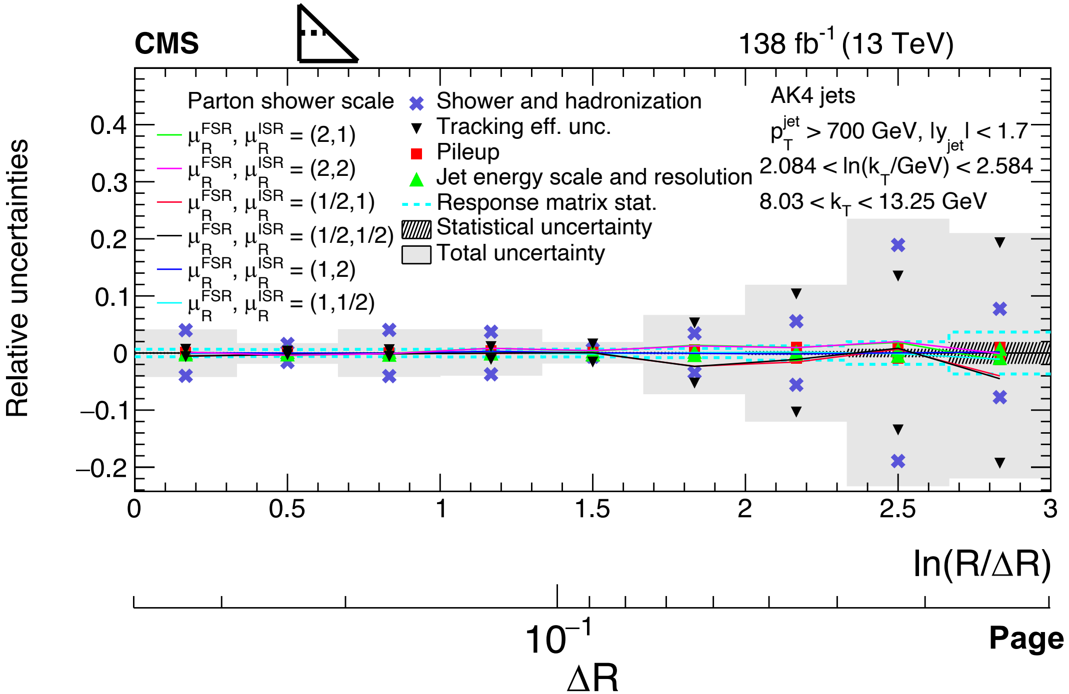




Primary Lund jet plane

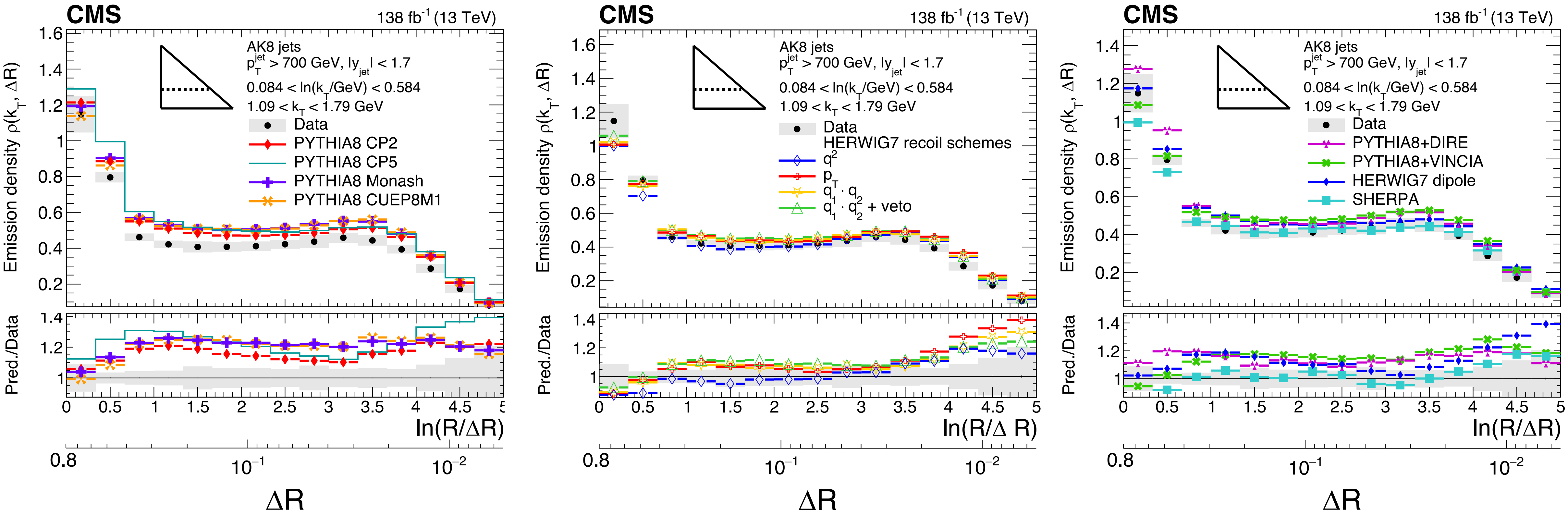
- Measurement based on full Run 2 dataset
- Inclusive jet selection
  - Jet p_T > 700 GeV and $|y|$ < 1.7
  - anti-k_T with small R=0.4 and large R=0.8
- Charge particle of the jet are used for LJP
- Unfolding by D'Agostini method to particle level
- Systematic uncertainties:
  - Shower and hadronization: 2-7% in bulk
  - Tracking eff.: 1-2% in bulk, 10-20% at edge
  - Subleading components (< 1%):
    - Parton shower scale, Jet energy scale and resolution, pileup





Primary Lund jet plane

- Comparison of unfolded LJP density with various MC predictions
  - Different parton showers, hadronization, colour reconnection, and underlying event effects
- Differences between data & MC of the order of 10-20%
- Better agreement with Herwig7 and Sherpa – predictions based on cluster fragmentation model



Energy correlators inside jets

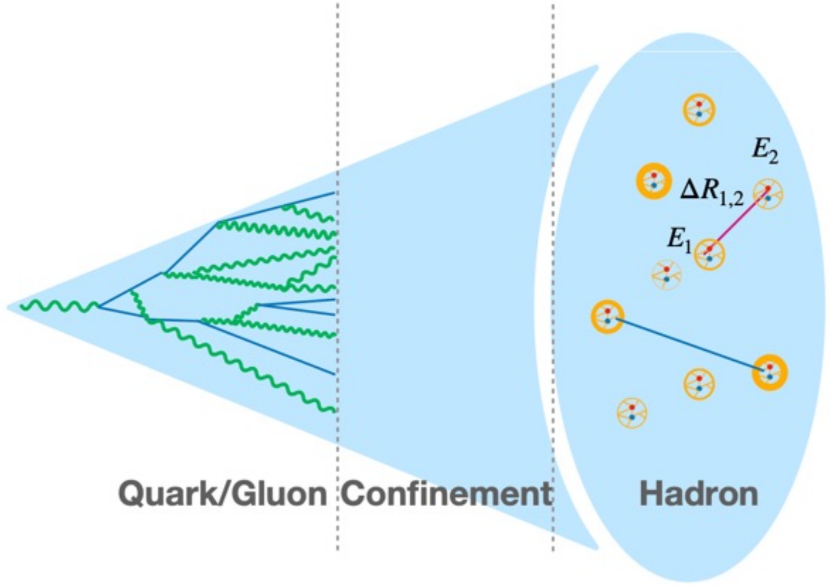
- Multiparticle energy correlators describe the correlations of kinematic properties of particles within the jet
- Two and three-particle energy correlators

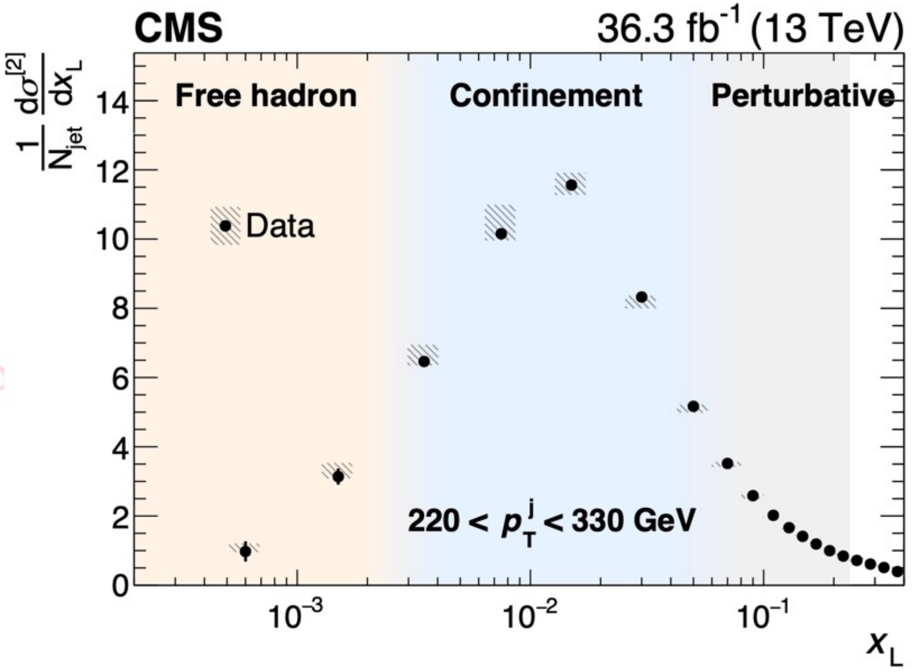
$$E2C = \sum_{i,j}^{n} \int d\sigma \frac{E_i E_j}{E^2} \delta(x_L - \Delta R_{ij})$$

$$E3C = \sum_{i,j,k}^{n} \int d\sigma \frac{E_i E_j E_k}{E^3} \delta\left(x_L - max(\Delta R_{ij}, \Delta R_{ik}, \Delta R_{jk})\right)$$

x_L - the largest distance ΔR_{ij} between constituents

- Mapping out different stages of jet formation:
  - Small angle is dominated by hadronization
  - Large angle is dominated by short distance physics

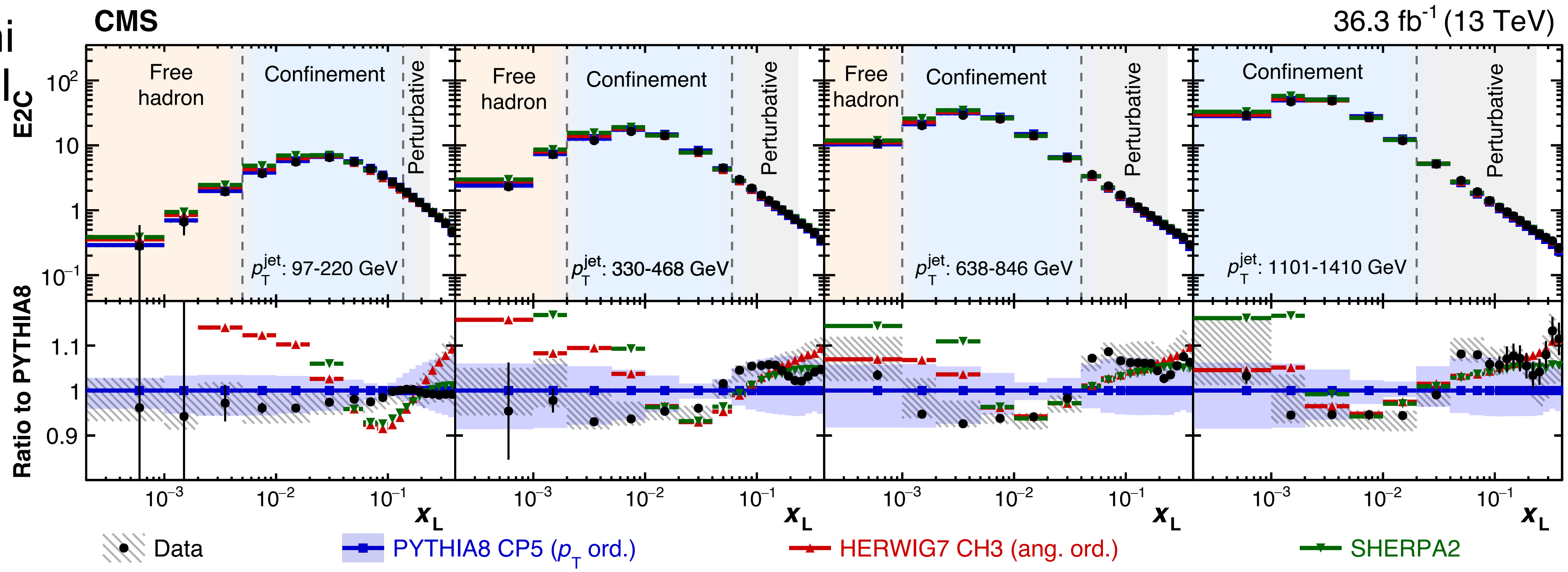




Energy correlators inside jets

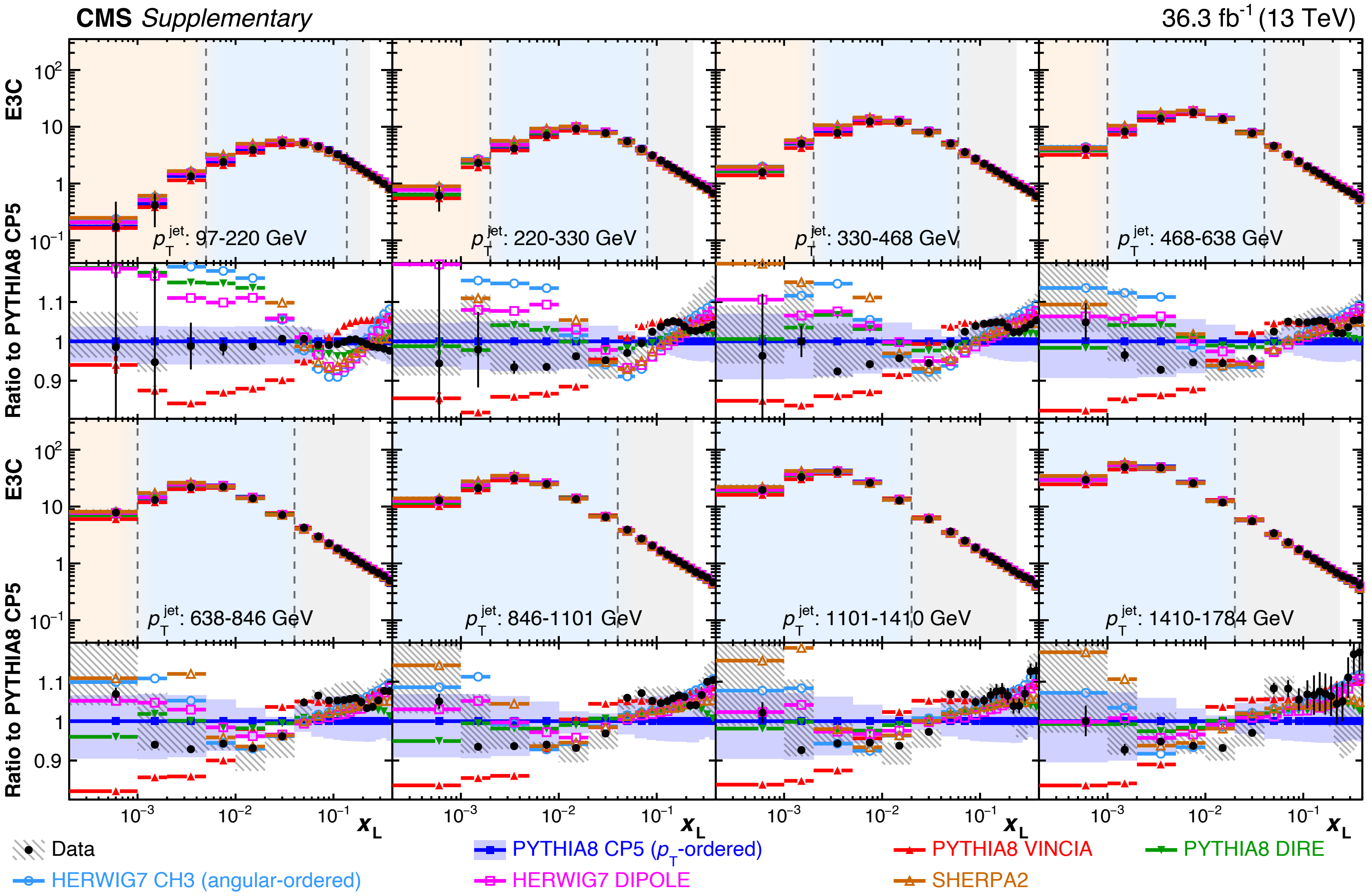
- Measurement based on 2016 dataset: 36.3 fb^{-1}
- Inclusive dijet selection
  - PF CHS jet, anti-k_T with R=0.4 and $|\eta|$ < 2.1, 8 p_T region in 97 – 1784 GeV
  - Neutral & charged particles with p_T > 1 GeV
  - All particles included, direct comparison with theoretical calculation

- Unfolding by D'Agostini method to particle level
- Key feature of this analysis: statistical correlations
  - EnC is a multi-entry distribution for every jet



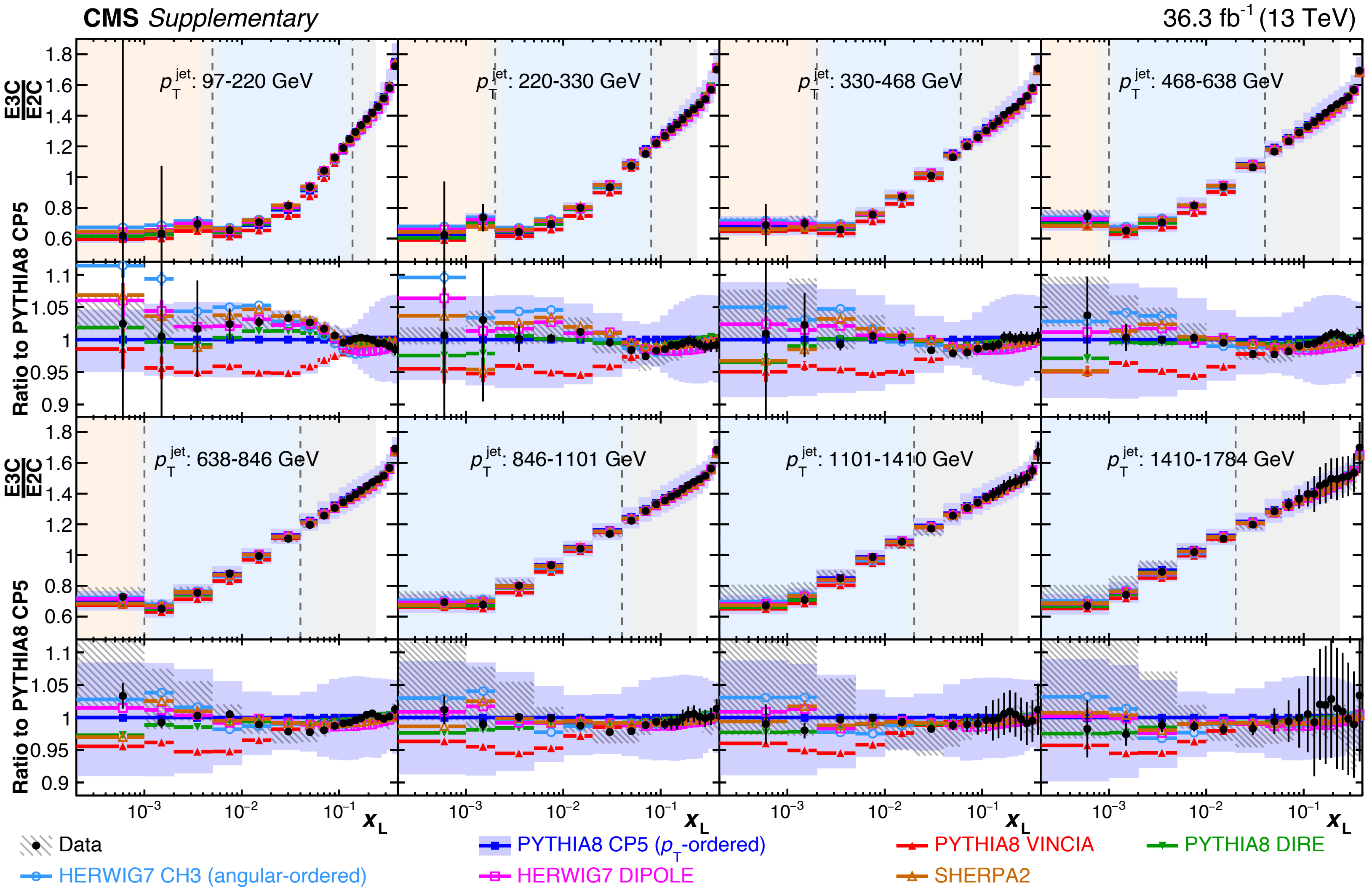
Energy correlators inside jets

- Experimental syst. unc.:
  - Unfolding model
  - Neutral, photon, charged particle energy scale
  - Jet energy scale and resolution
  - Pileup, tracking eff.
- Theory syst. unc.:
  - QCD scale in parton shower
  - QCD scale in hard scattering
  - Underlying event + PS tune
  - PDF
- Differences between data & MC of the order of 10%



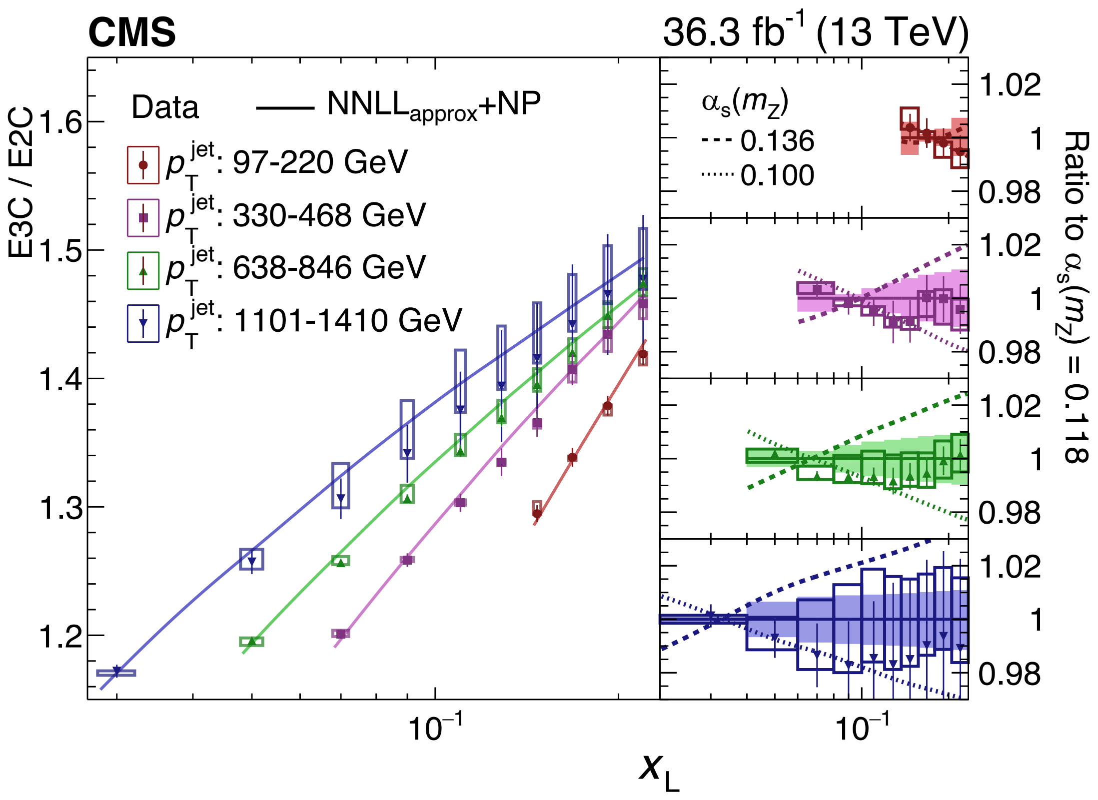
Energy correlators inside jets

- Benefit of taking ratio
  - Exp. syst.: ~8% → ~ 3%
- Data/MC difference reduced
  - ~10% → ~ 3%
- Better agreement with models
- Slope of E3C/E2C decreases with increasing jet p_T



Energy correlators inside jets

- Ratio of E3C and E2C as a function of x_L can be used to extract the strong coupling $\alpha_S(m_Z)$
- Theoretical predictions of the ratio at NLO + $\text{NNLL}_{\text{approx}}$
- Most precise extraction of $\alpha_S(m_Z)$ with jet substructure
$$\alpha_S(m_Z) = 0.1229^{+0.0040}_{-0.0050}$$
- More details in Patrick's talk



Conclusion

- Jet substructure measurements explore the basic building blocks of QCD
- Jet substructure measurements can be used to improve MC event generators
- Jet substructure measurements can be used to determine the strong coupling $\alpha_S(m_Z)$
- More measurements are coming. Stay tuned!