Inclusive and heavy-flavour jet substructure with CMS

Leticia Cunqueiro for the CMS Collaboration

European Research Council
Established by the European Commission

Flavoured jets at the LHC, Durham
June 11th, 2024

Outline

- Two recent measurements of inclusive jet substructure at CMS: The primary Lund plane density and the Energy Correlators
  Prospects for heavy flavour jets

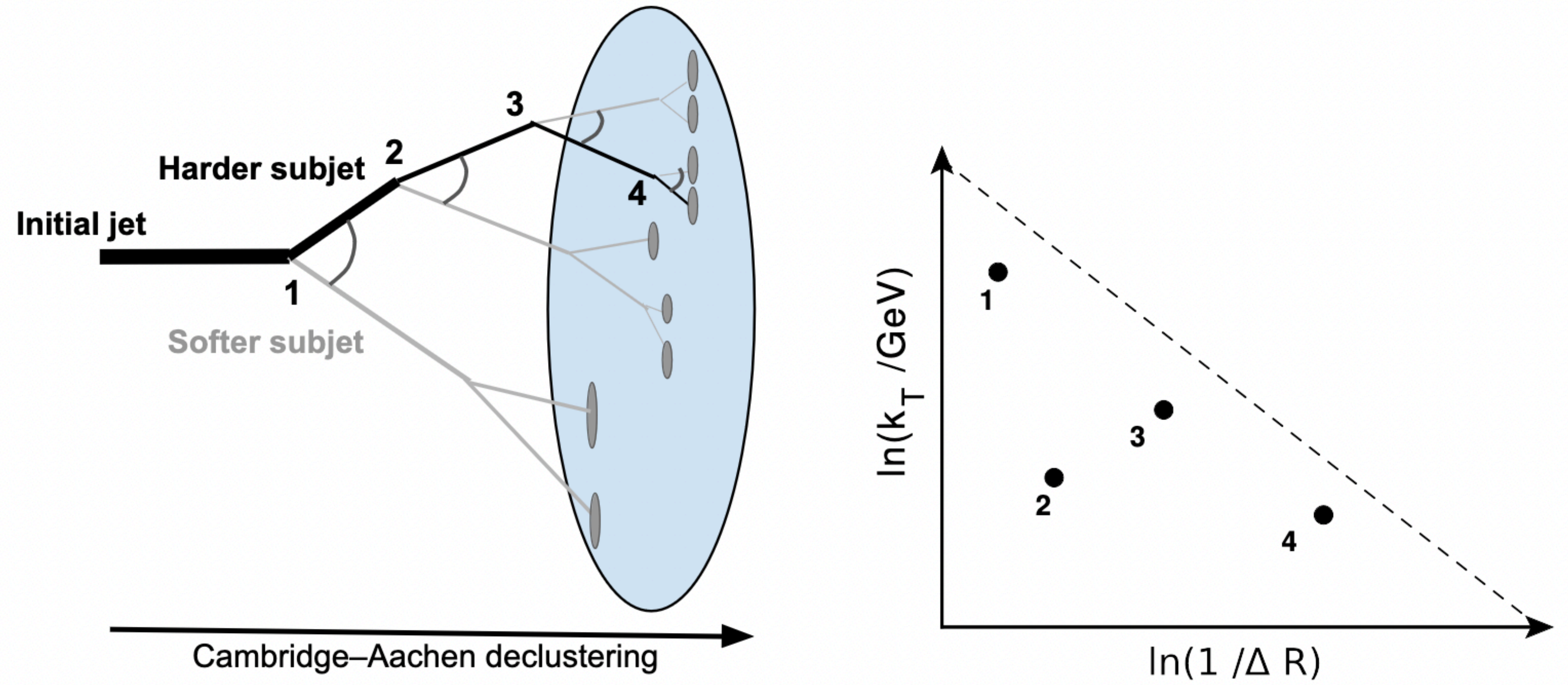
- The experimental measurement of heavy flavour jet substructure that is sensitive to the c/b quark mass needs:

  Heavy flavour jet selection
  Treatment of decay products
  Suppression of hadronisation effects

- Flavoured algorithms

Two recent measurements of jet substructure with CMS

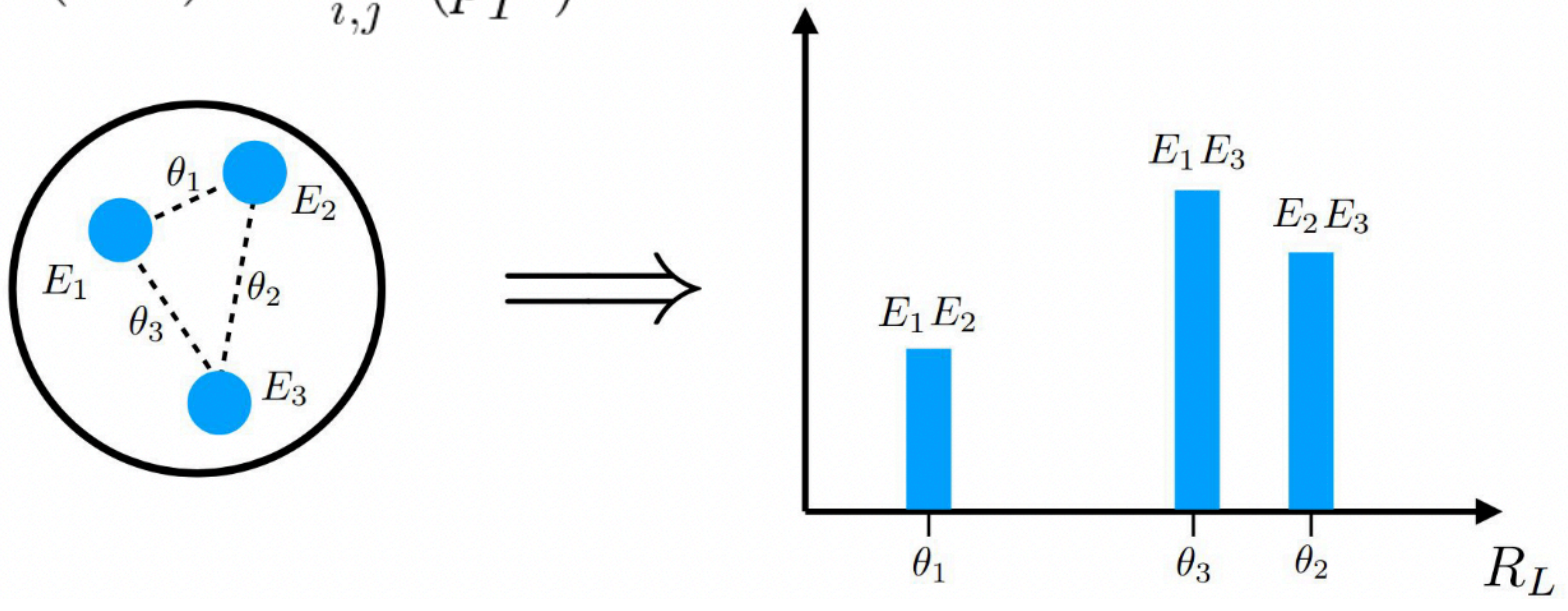
Using the jet tree



Hierarchical structure of jet constituents by undoing the clustering history

Using the energy flow

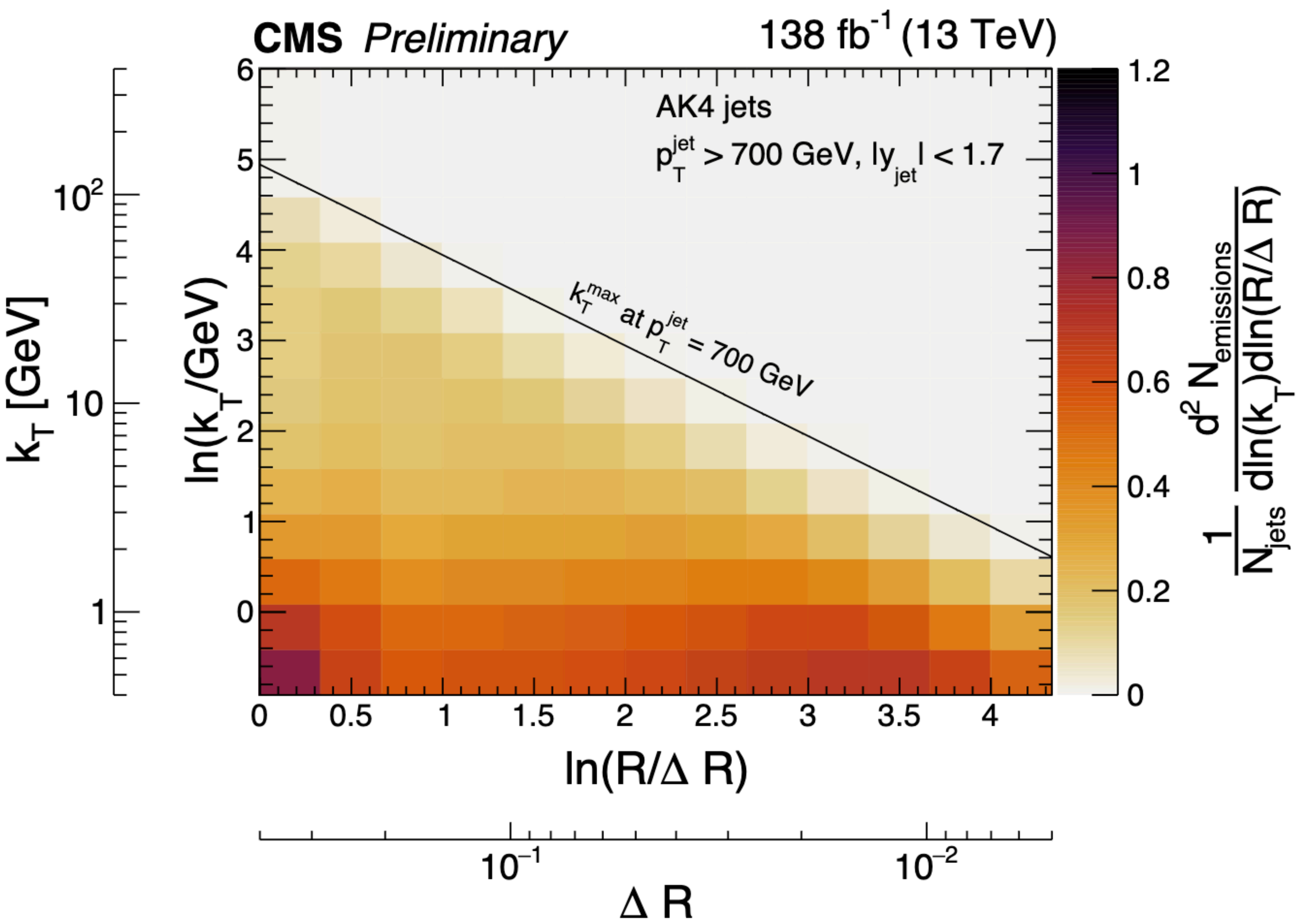
$$\frac{d\Sigma}{d(\Delta R)} = \sum_{i,j} \frac{p_T^i p_T^j}{(p_T^{jet})^2} \delta(\Delta R_{ij} - \Delta R)$$

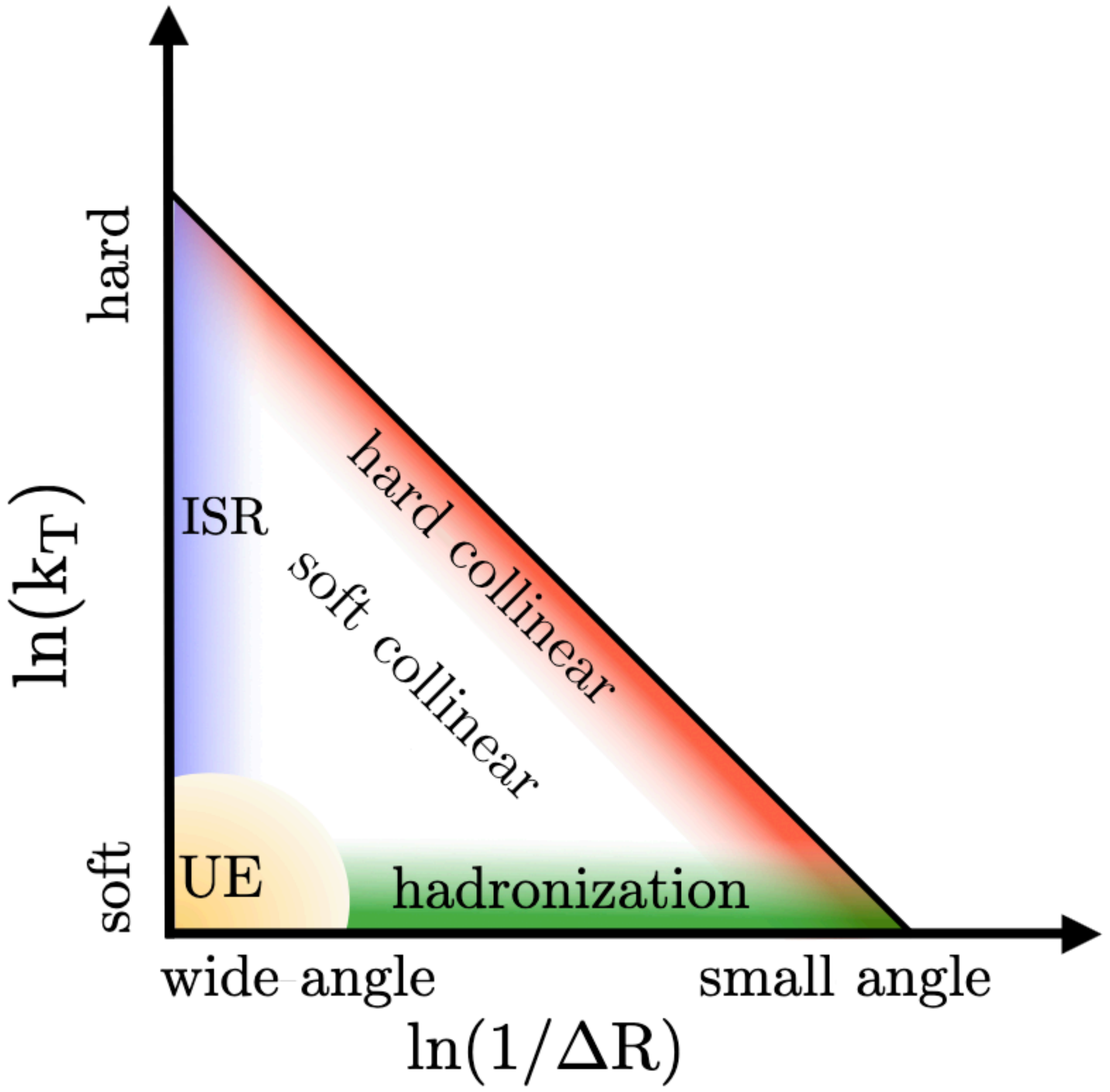


N-point correlation function measured as energy-weighted N-way correlation between configurations of particles

[CMS, JHEP 05 (2024) 116](#)

The primary Lund plane density

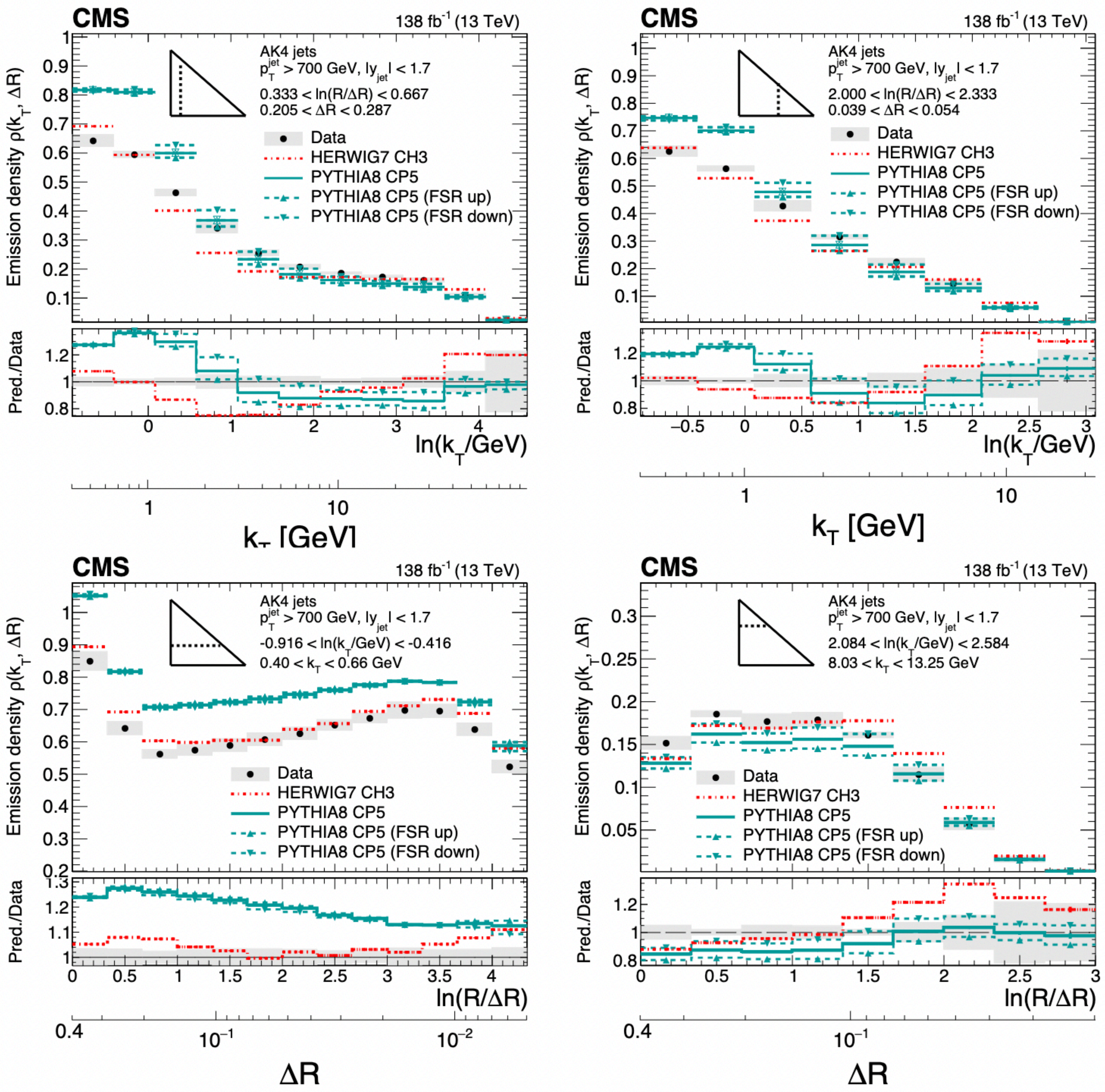




Possibility to access the building blocks of the parton shower, in pp and PbPb collisions

CMS, JHEP 05 (2024) 116

The primary Lund plane density



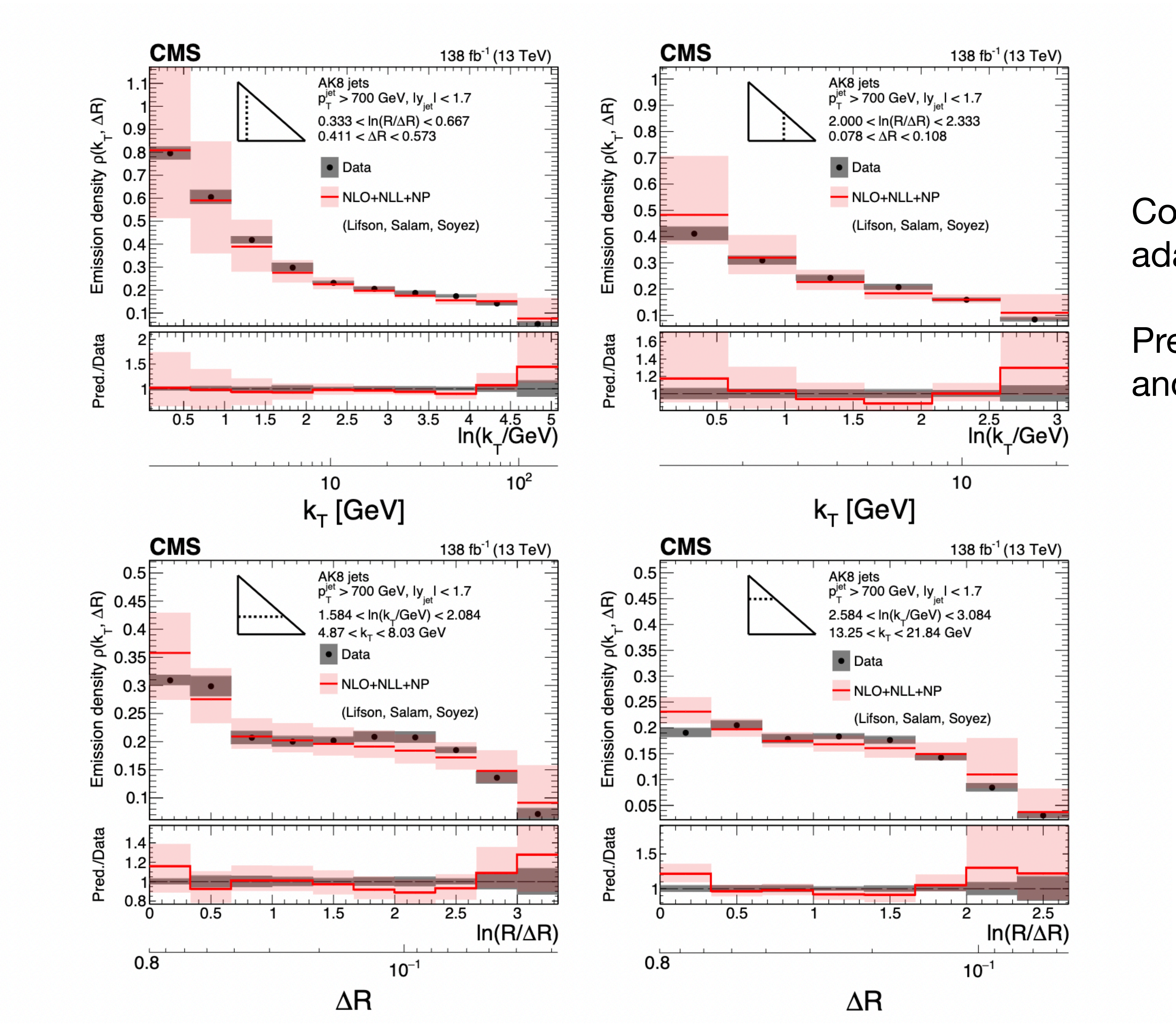
Modular constraint to MC calculations

As an example, see comparison between Herwig7 CH3 and Pythia8 CP5 :

In the nonperturbative region, Pythia overestimates the number of emissions and Herwig describes better the data
In the perturbative region, sensitivity to FSR scale variations

Check the paper for extensive comparisons to models and tests of the sensitivity to recoil schemes, hadronisation scale cutoff etc

The primary Lund plane density

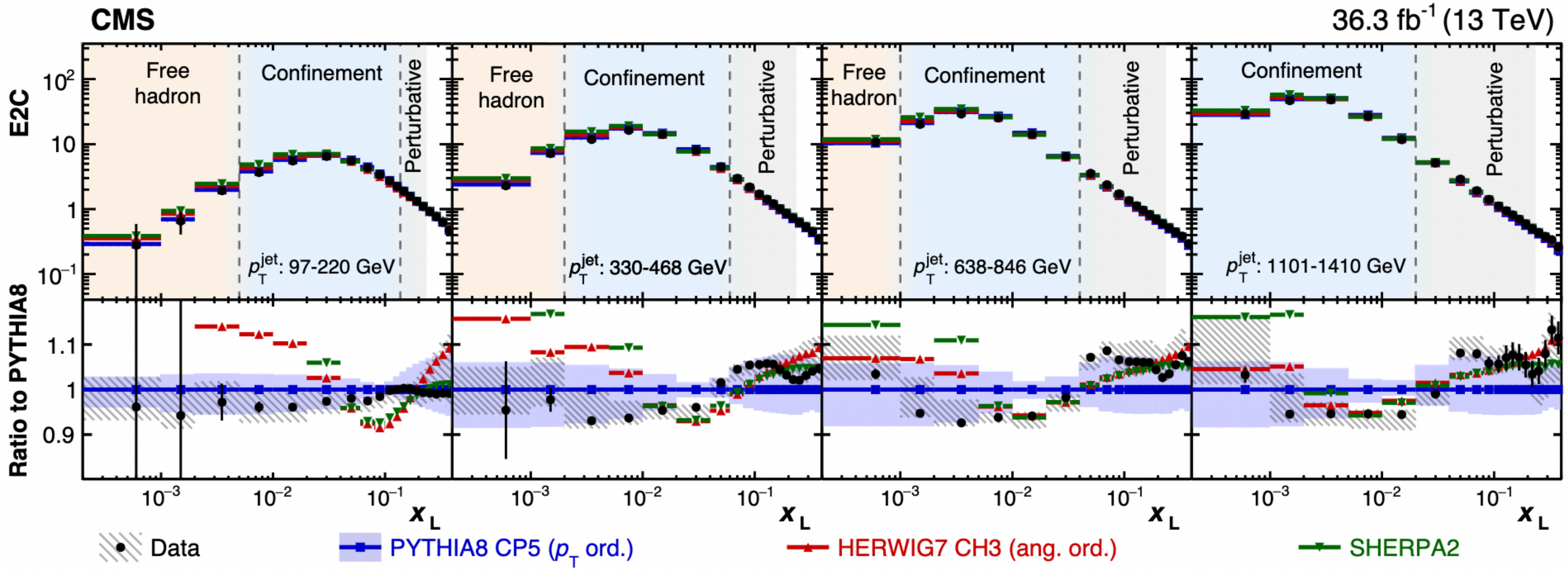


Comparison to NLO+NLL+NP analytical calculations adapted from *Lifson et al, JHEP 10 (2020) 170*

Predictions in agreement with the data within theoretical and experimental uncertainties

[CMS, 2402.13864 [hep-ex]](https://arxiv.org/abs/2402.13864)

Energy correlators



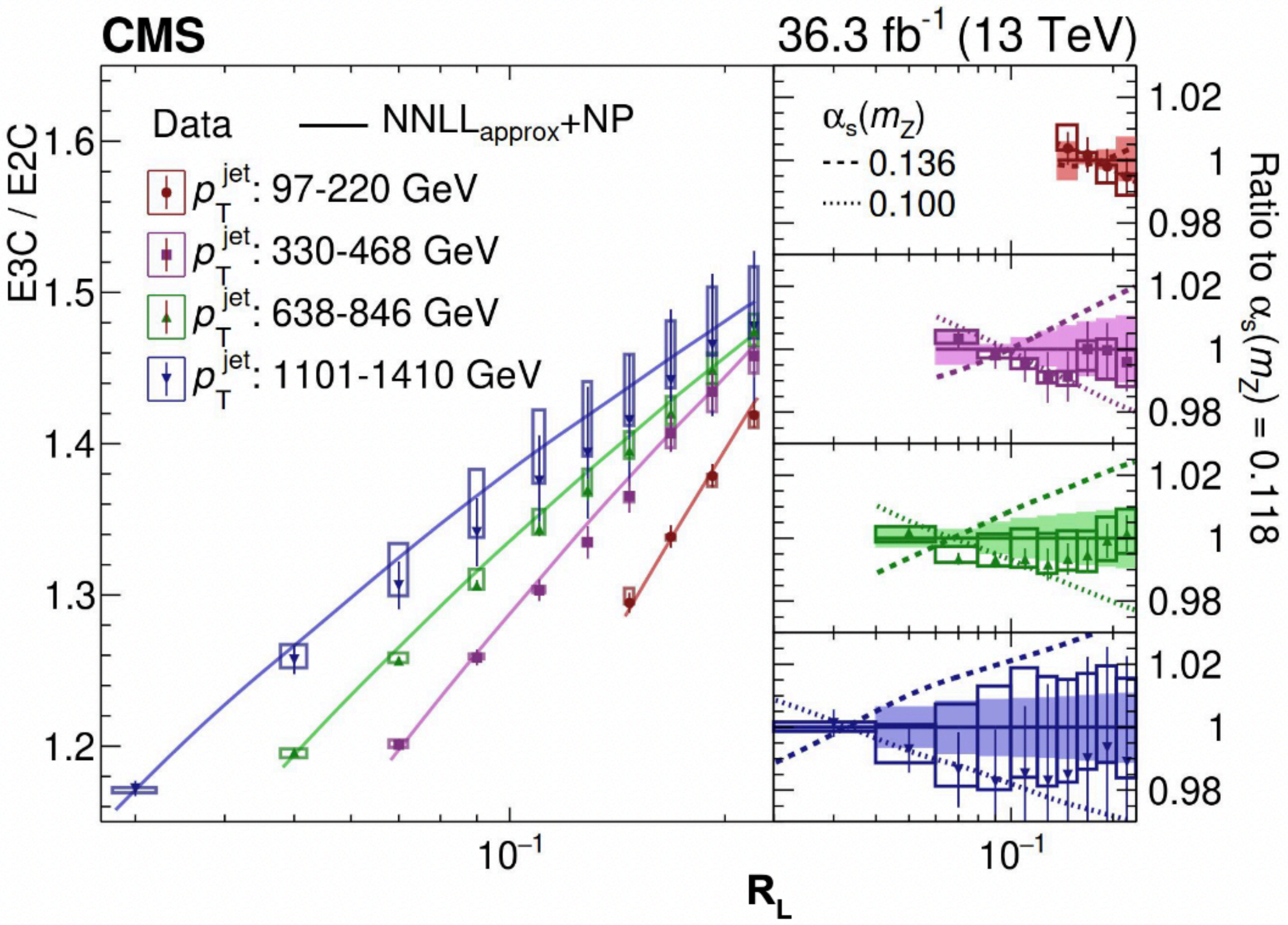
Small angles, E2C ~x_L as expected from uniform distribution of free hadrons

Intermediate angles: crossover between nonperturbative and perturbative regimes

Large angles, perturbative domain

CMS, 2402.13864 [hep-ex]

Energy correlators



Systematics cancel out in the ratio E3C to E2C

Ratio in the perturbative region proportional to α_S

Comparisons to NLO+ NNLL +NP allow for the most precise value of the strong coupling constant using jet substructure:

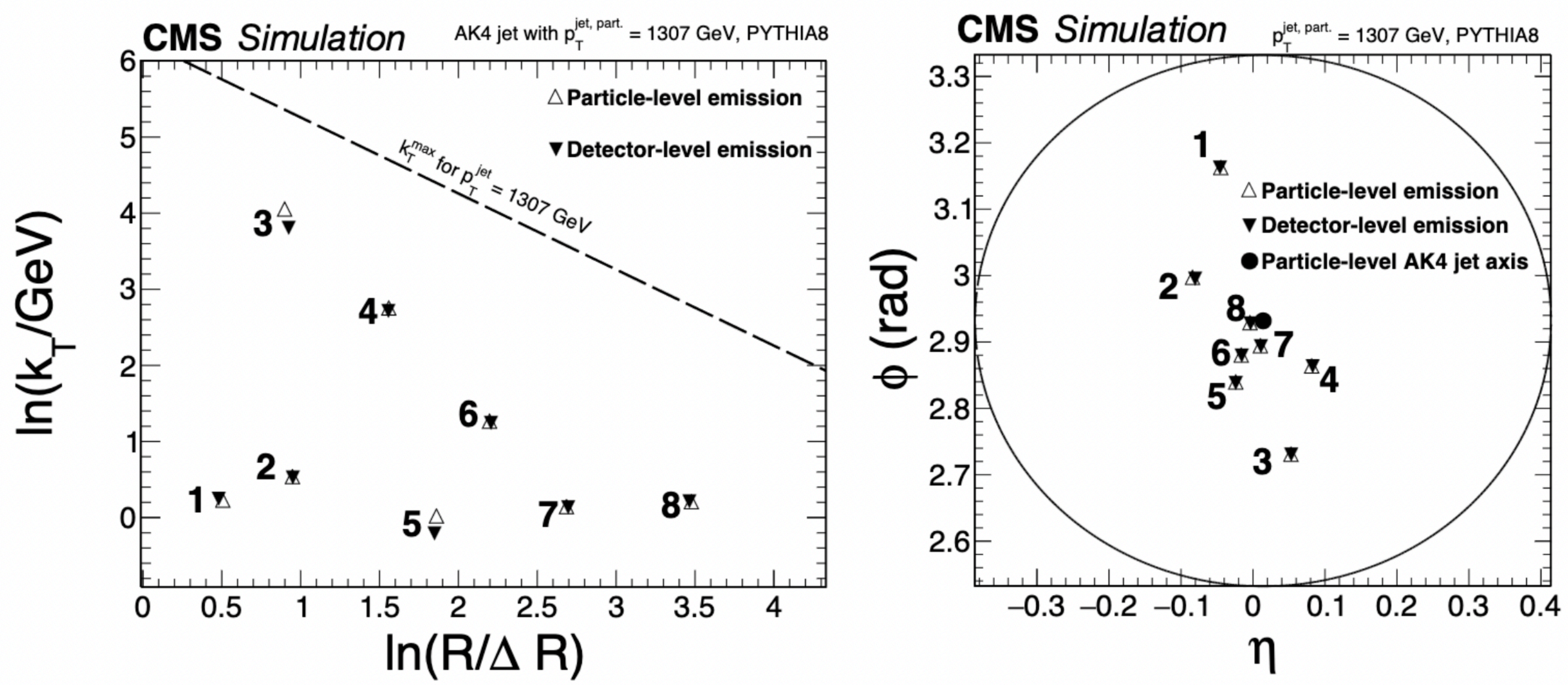
Result: $\alpha_S = 0.1229^{+0.0014(stat.)+0.0030(theo.)+0.0023(exp.)}_{-0.0012(stat.)-0.0033(theo.)-0.0036(exp.)}$

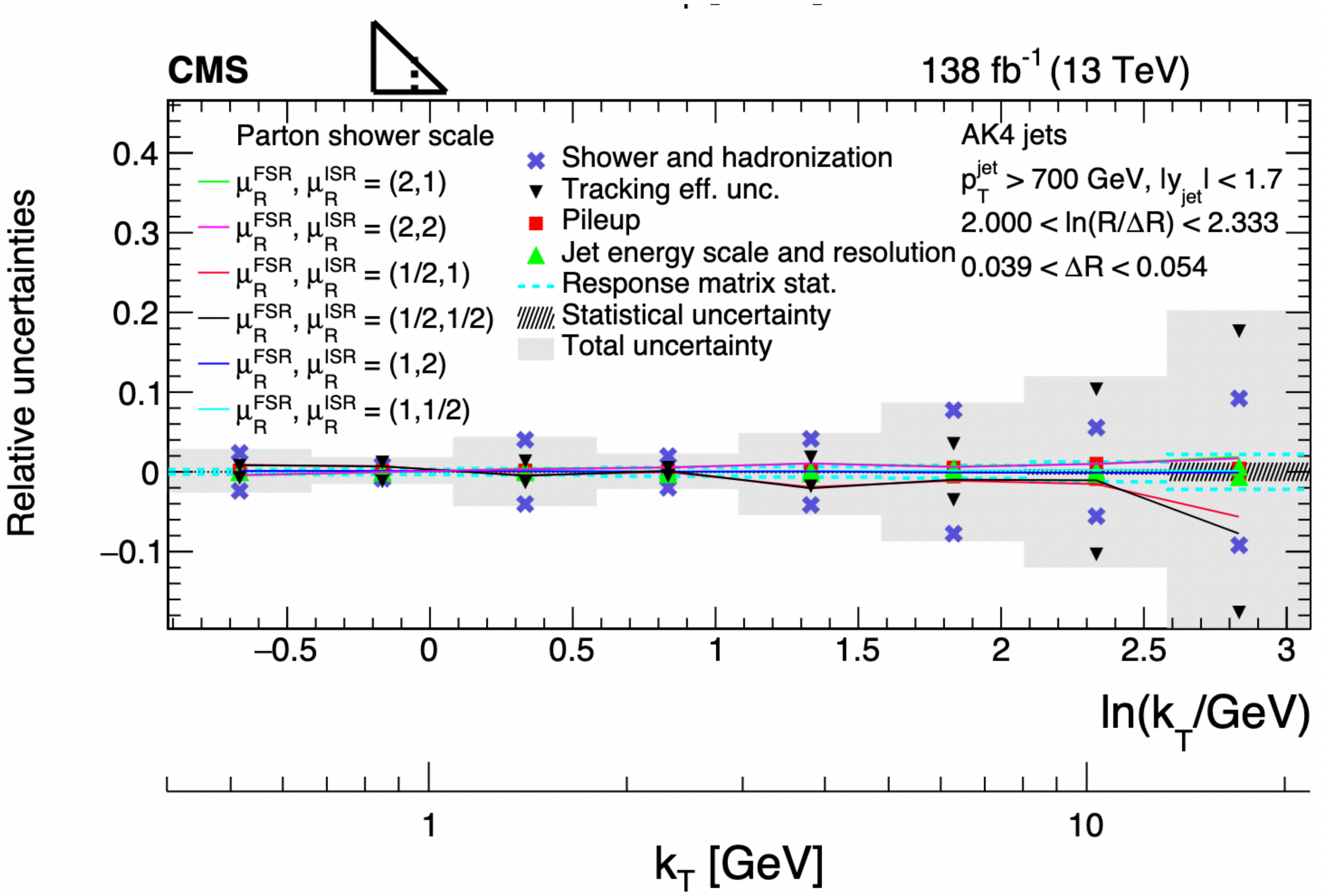
uncert ~4%, most precise using jet substructure today

[CMS, JHEP 05 (2024) 116](https://doi.org/10.1007/JHEP05(2024)116)

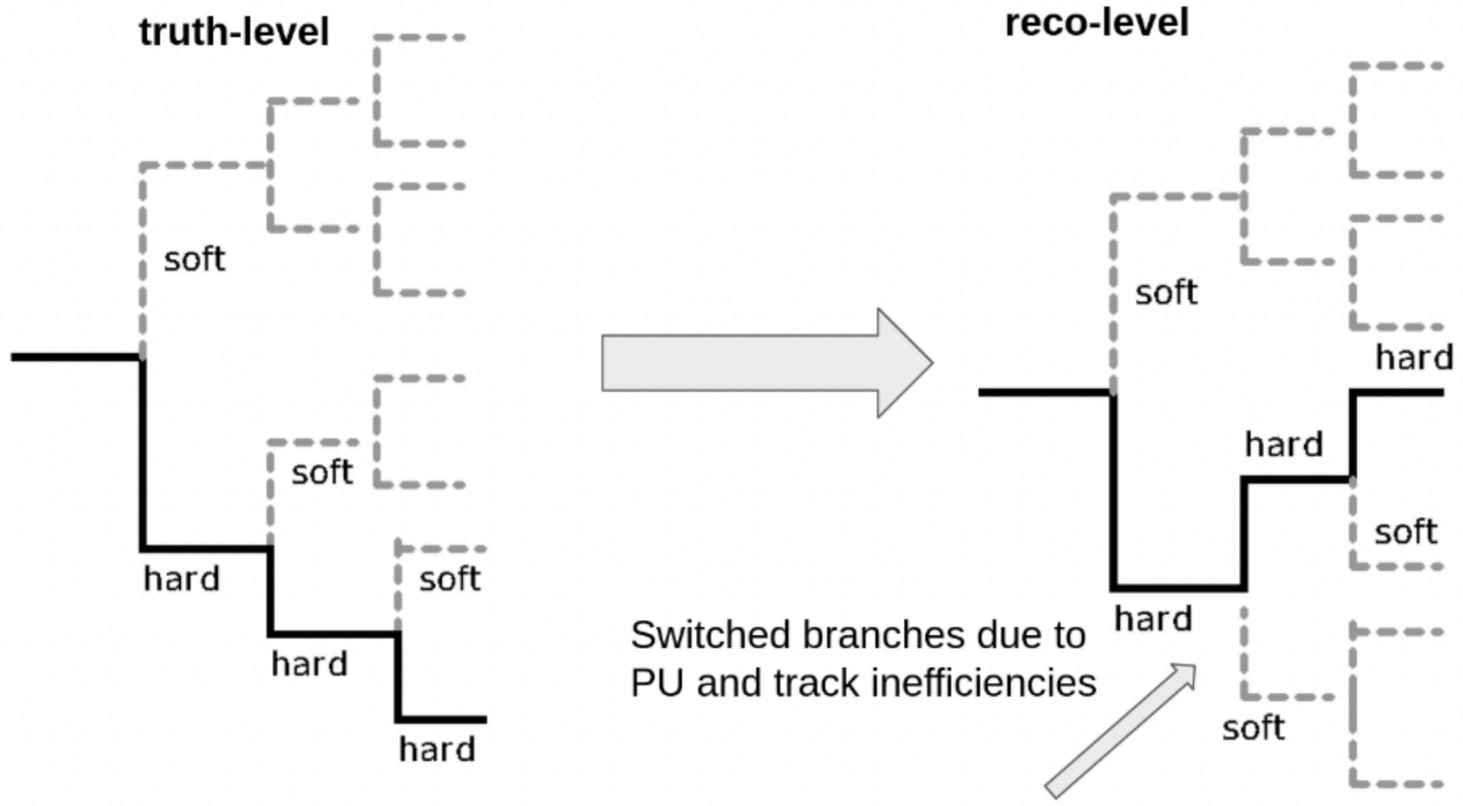
Technical challenges in these 2 measurements

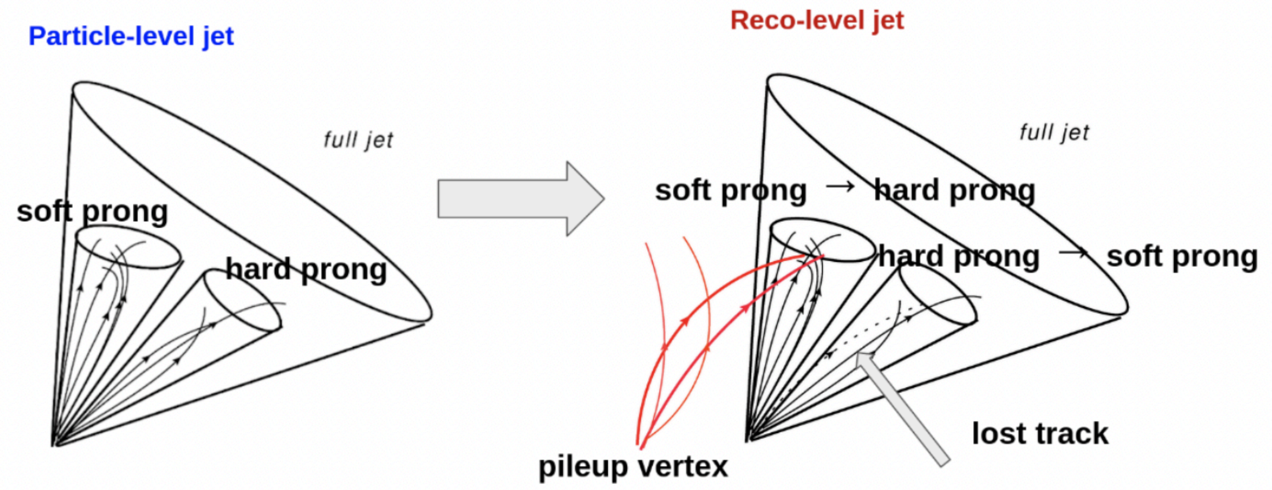
Flat geometrical matching of prongs





Residual mismatches, induce offdiagonalities in the response





In the high k_T perturbative domain:
track. eff. uncert ~20%
model uncert ~10%

[CMS, 2402.13864 [hep-ex]]

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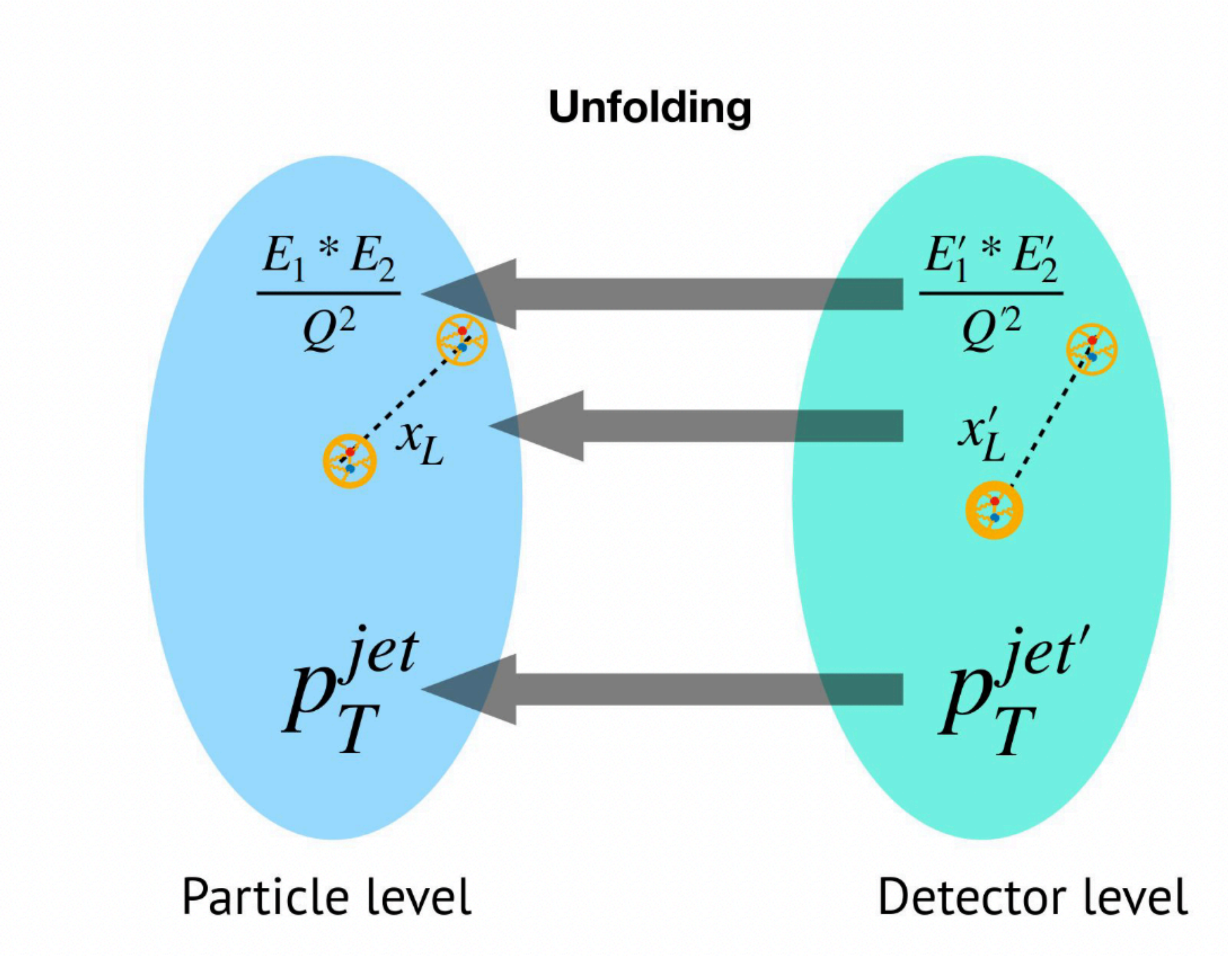

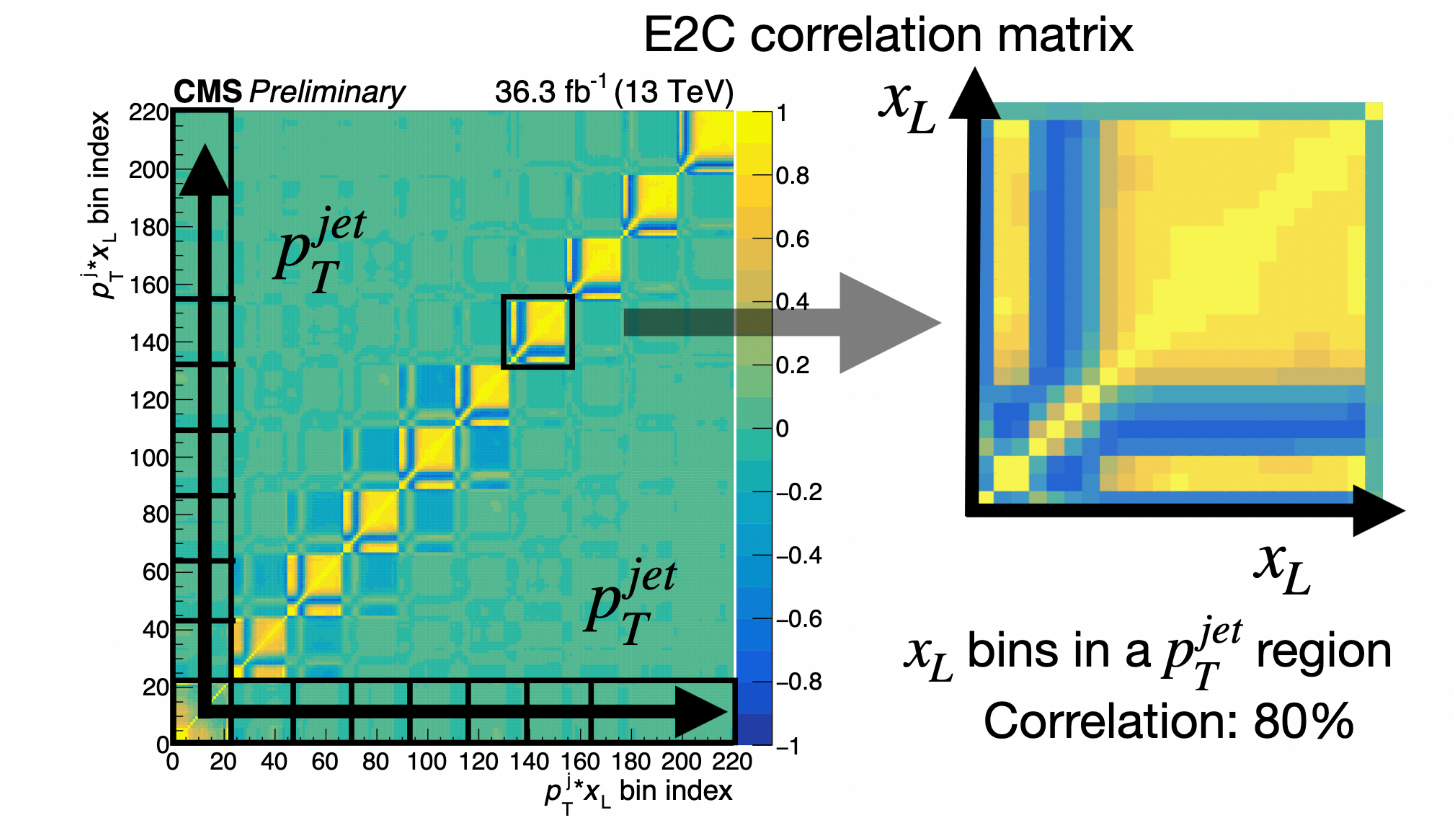

3-dimensional unfolding of jet p_T, x_L and weight (4400 bins)
Multi entry distribution for every jet, statistical correlations important

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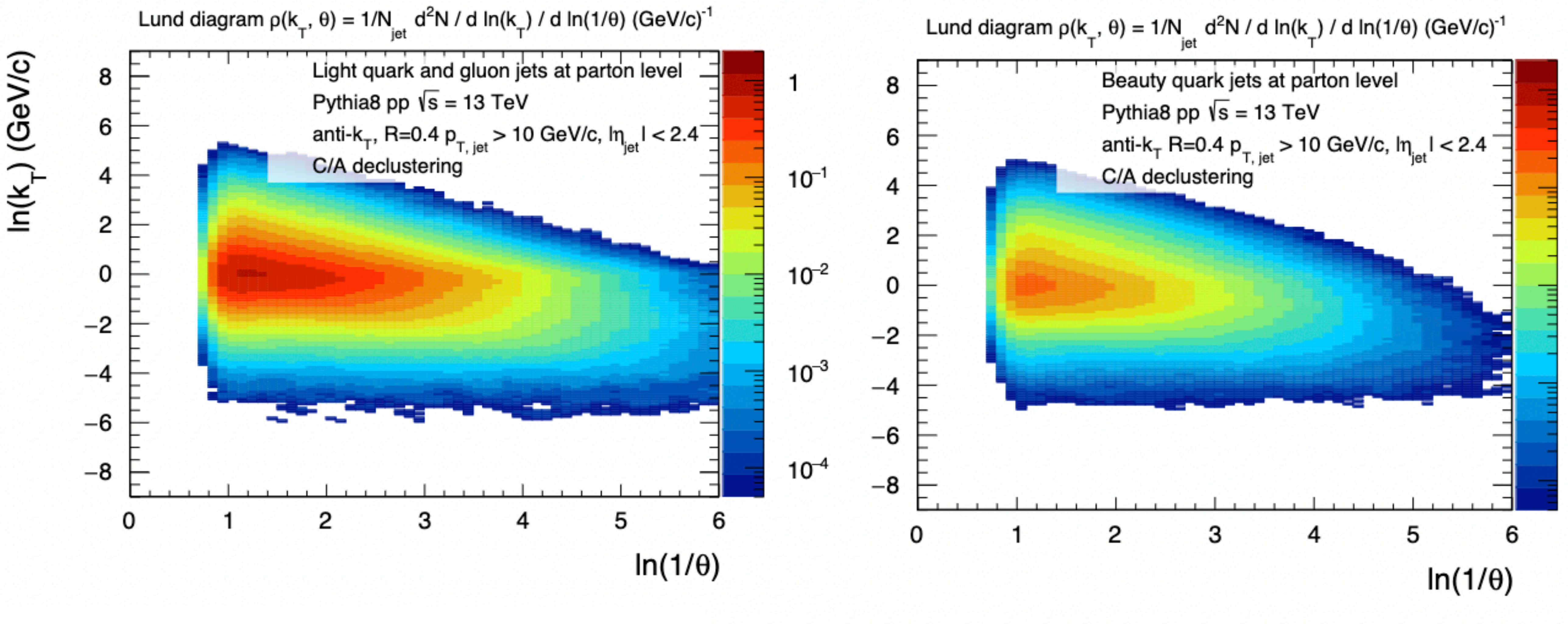
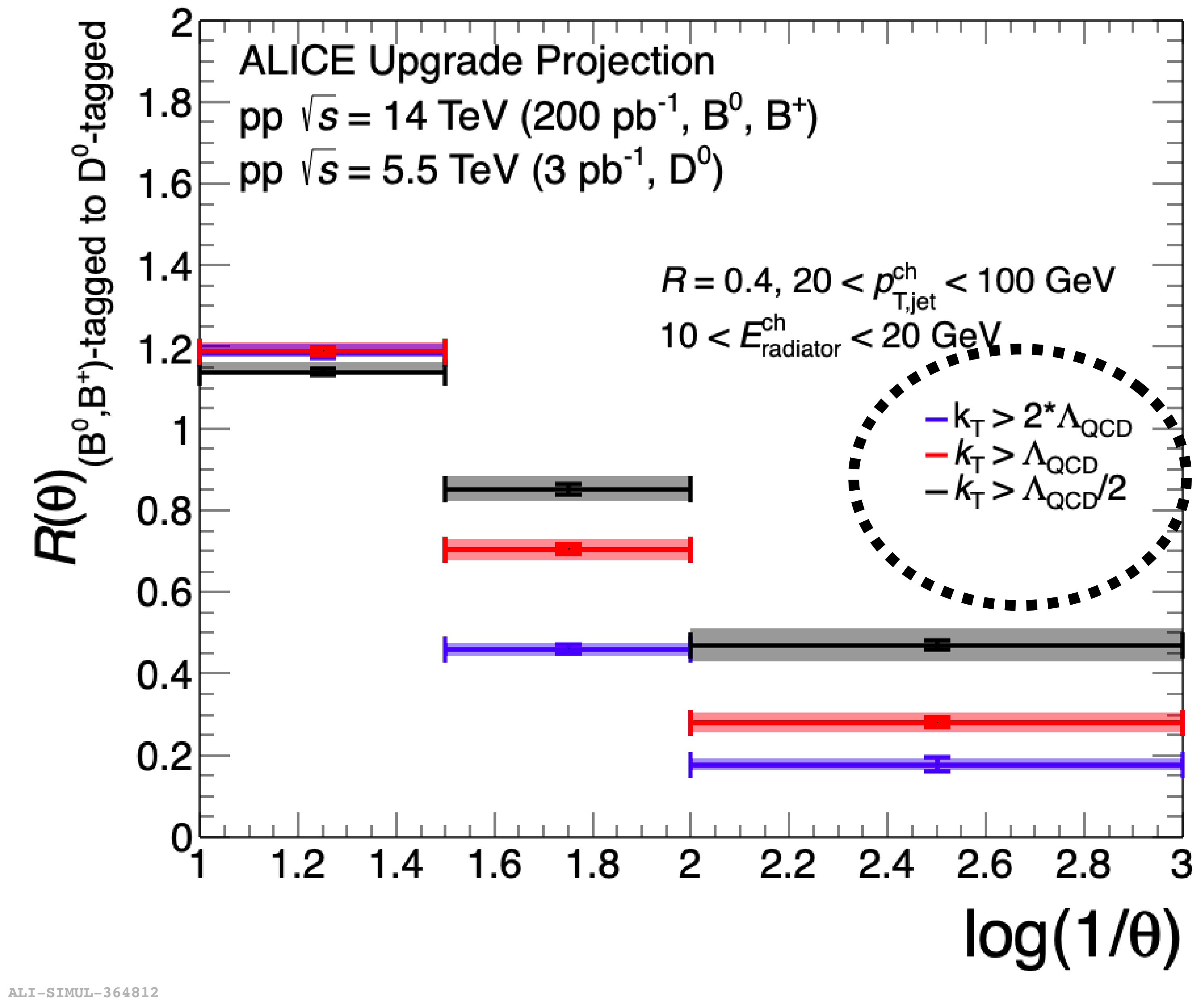
The Lund plane for heavy flavours





The first prongs that were combined by the Cambridge-Aachen algorithm are the most sensitive to mass effects LCM,Ploskon Phys.Rev.D 99 (2019) 7

The Pythia primary Lund plane density plots above show even by eye a suppression of low-angle emissions in b-jets compared to inclusive jets

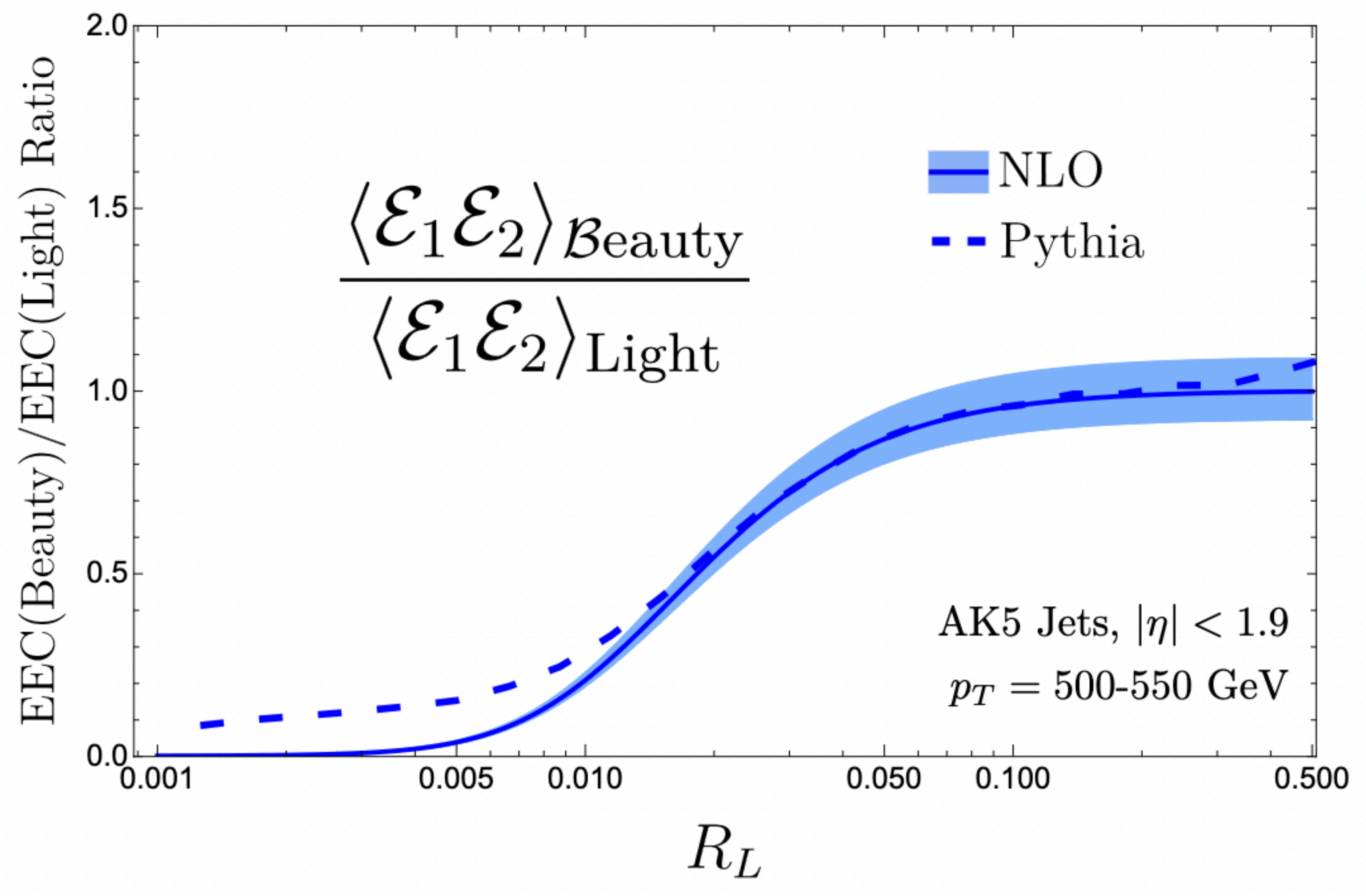
See ALICE's result, first to exploit iterative decluttering to directly observe the dead con in D-tagged jets in 2019 ALICE, Nature 605, 440-446 (2022)

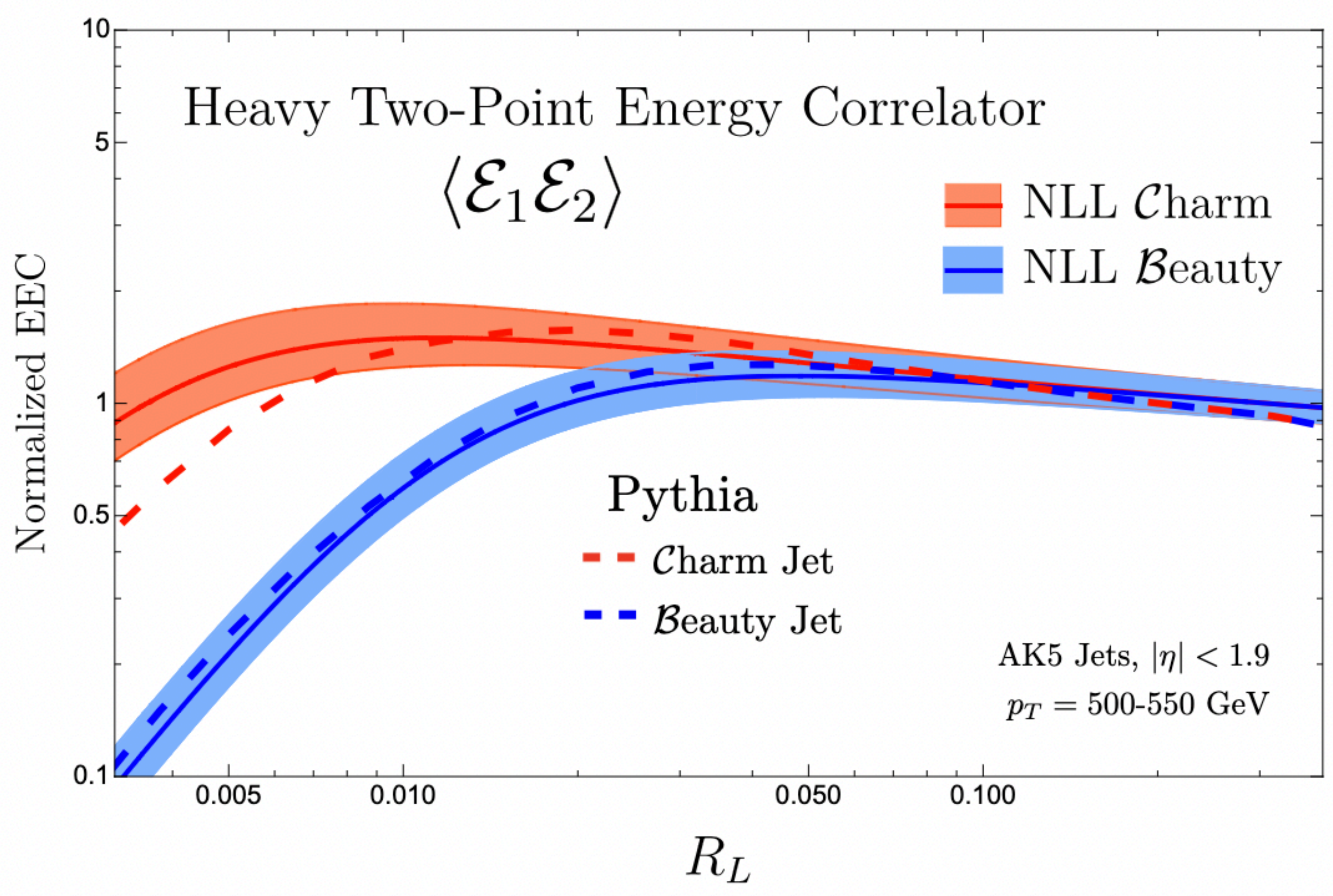
Possibility of a quark mass scan

Projections for Lund plane ratios using fully reconstructed B and D hadron jets

D-jets as reference are ideal ->factor out color effects, ratio just sensitive to quark mass

The EECs for heavy flavours





First NLL calculation of a heavy-flavoured jet substructure observable in pp collisions
Clear suppression of small angles for b-jets, same scaling behaviour as massless for large angular scales

Craft, Lee, Mecca, Moult, [2210.09311]

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Heavy flavour jet selection: tag the jet with a fully reco B/D hadron as constituent

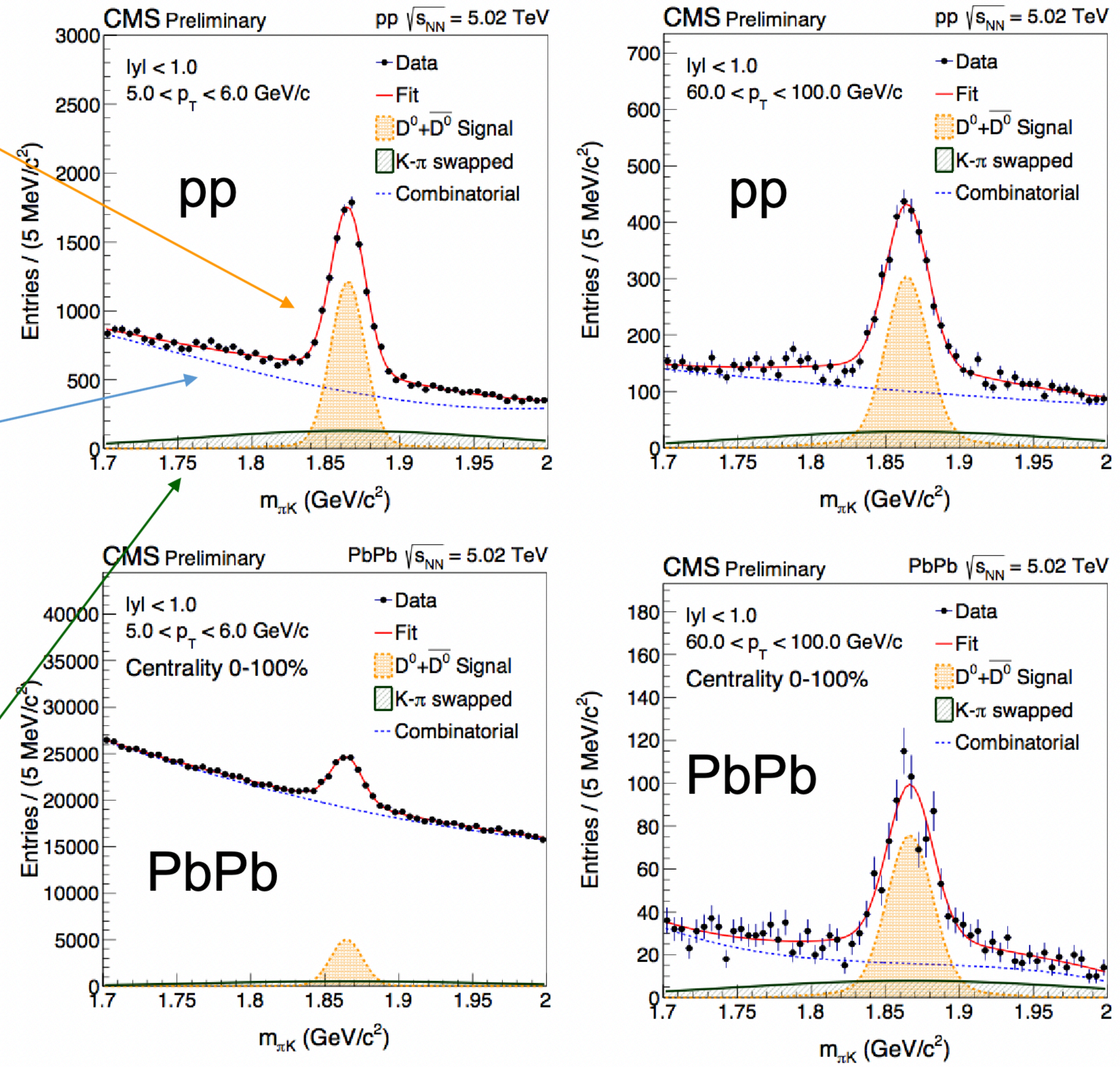
D meson invariant mass fits in pp and PbPb collisions

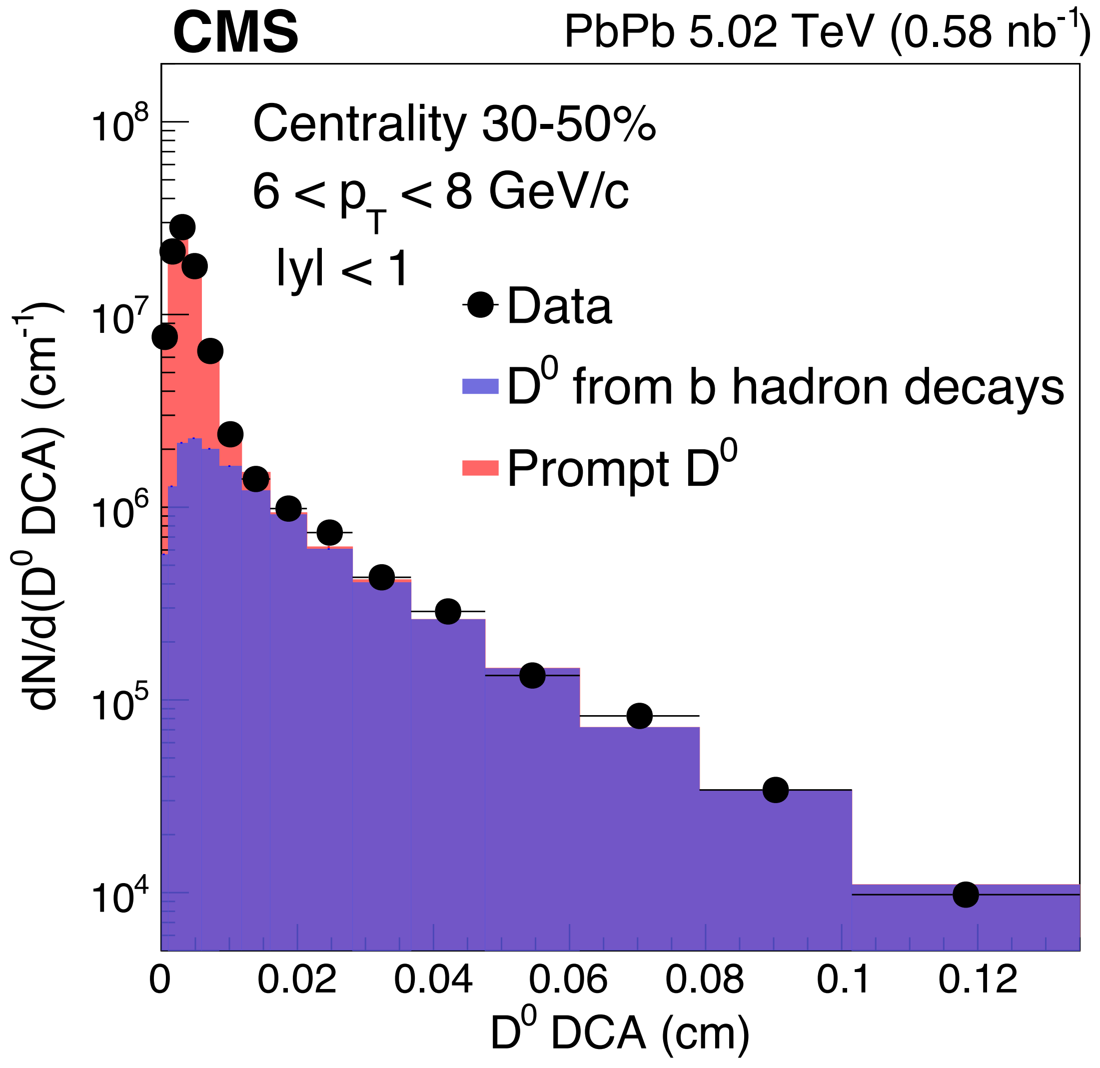
5 < p_T < 6 GeV/c | **60 < p_T < 100 GeV/c**

Double Gaussian for $D^0 \rightarrow K\pi$ signal

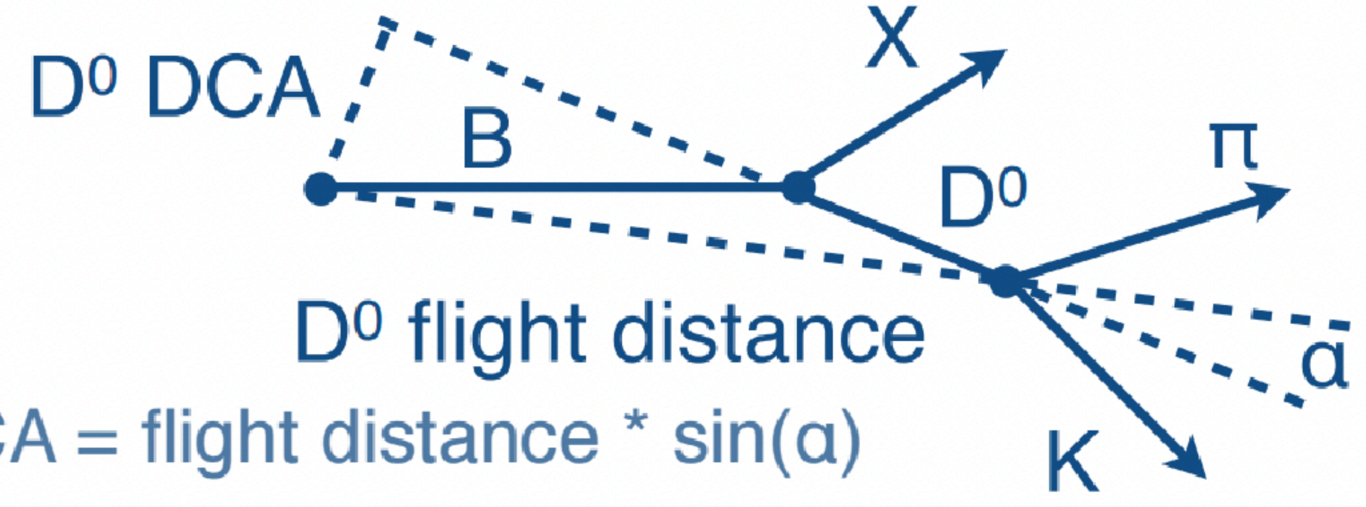
3rd order polynomial for combinatorial background

Gaussian shape for swapped mass hypothesis





Data-driven extraction of non-prompt fractions using DCA or DCA significance in pp and PbPb collisions



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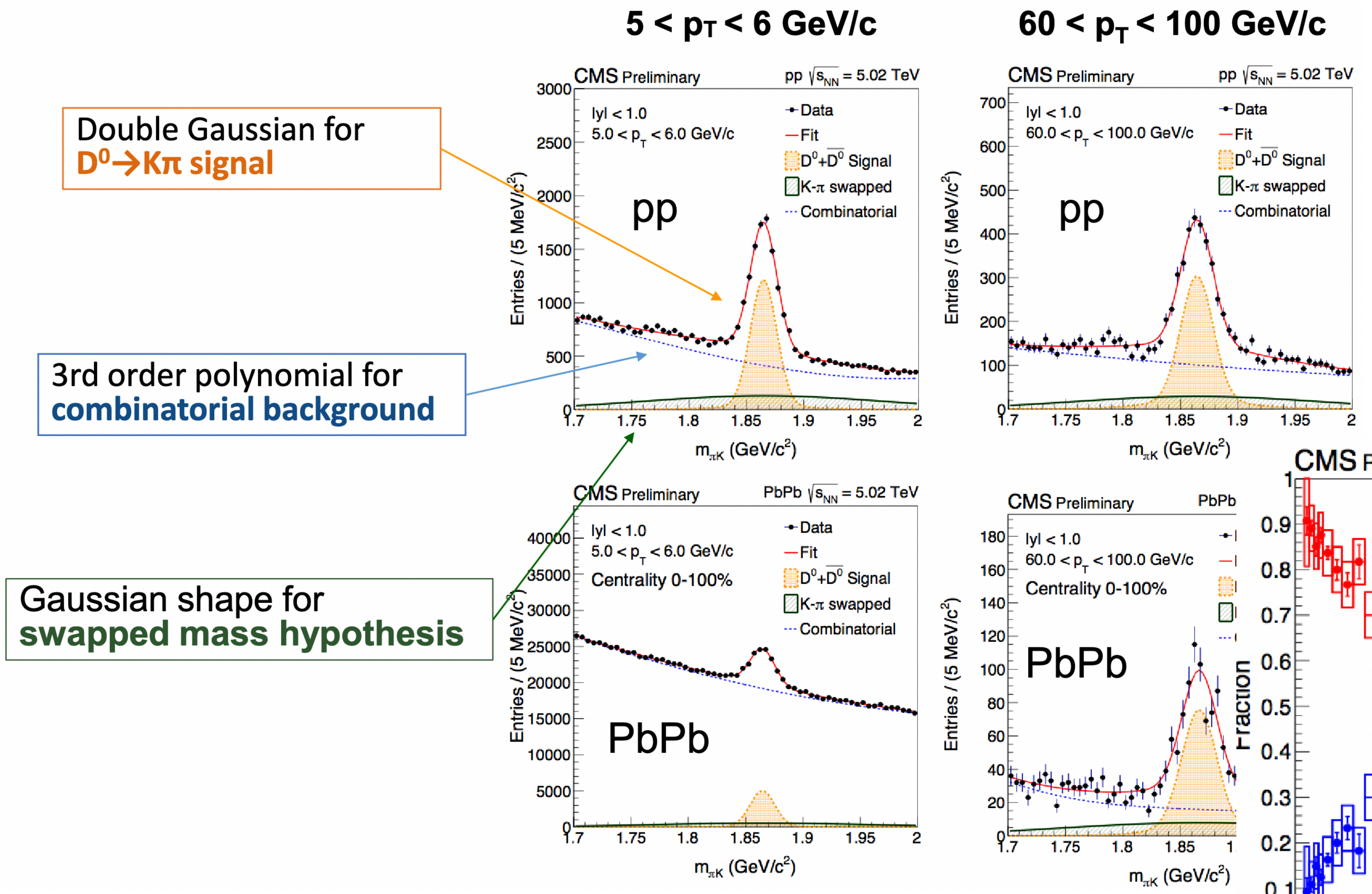

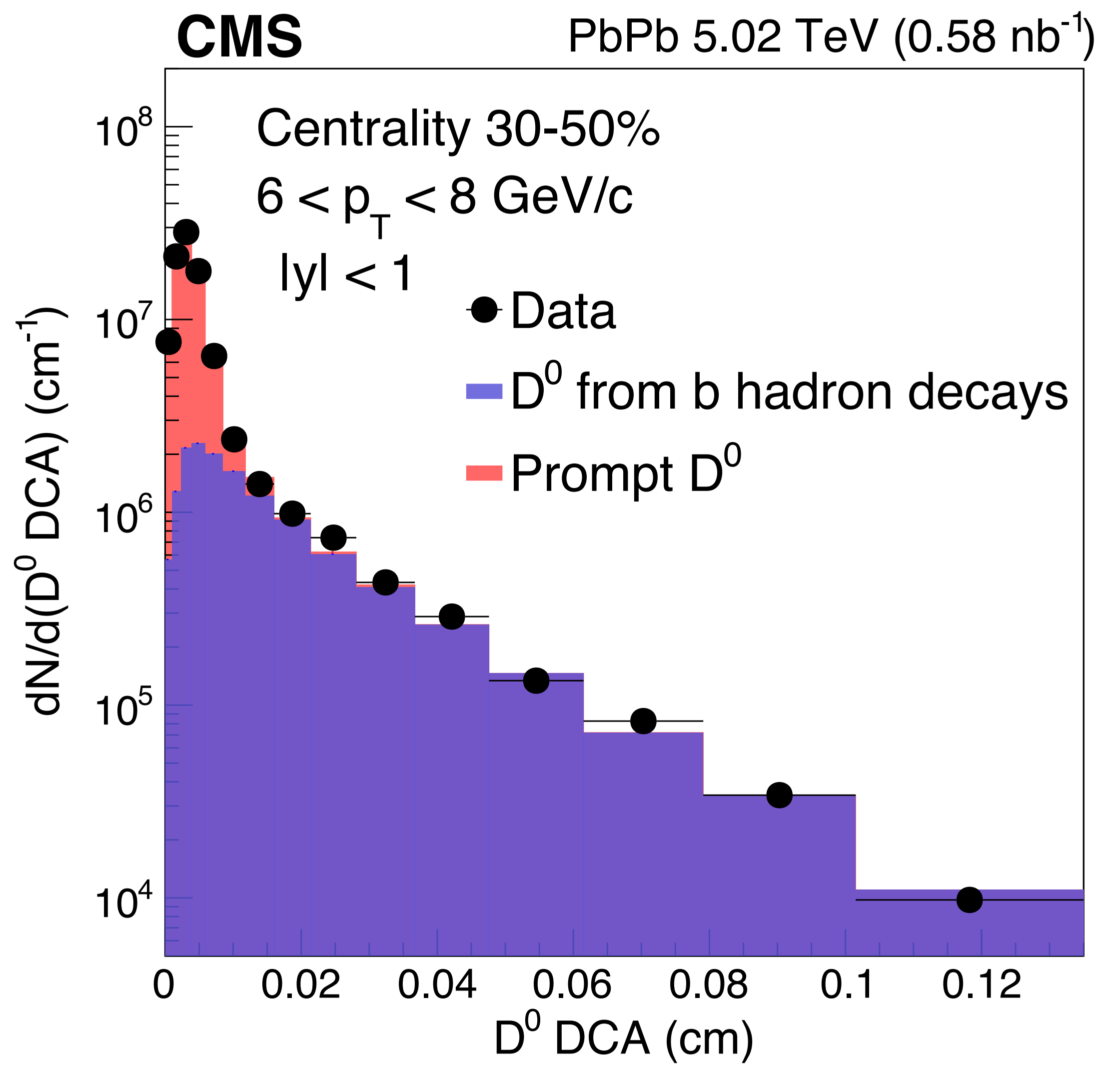

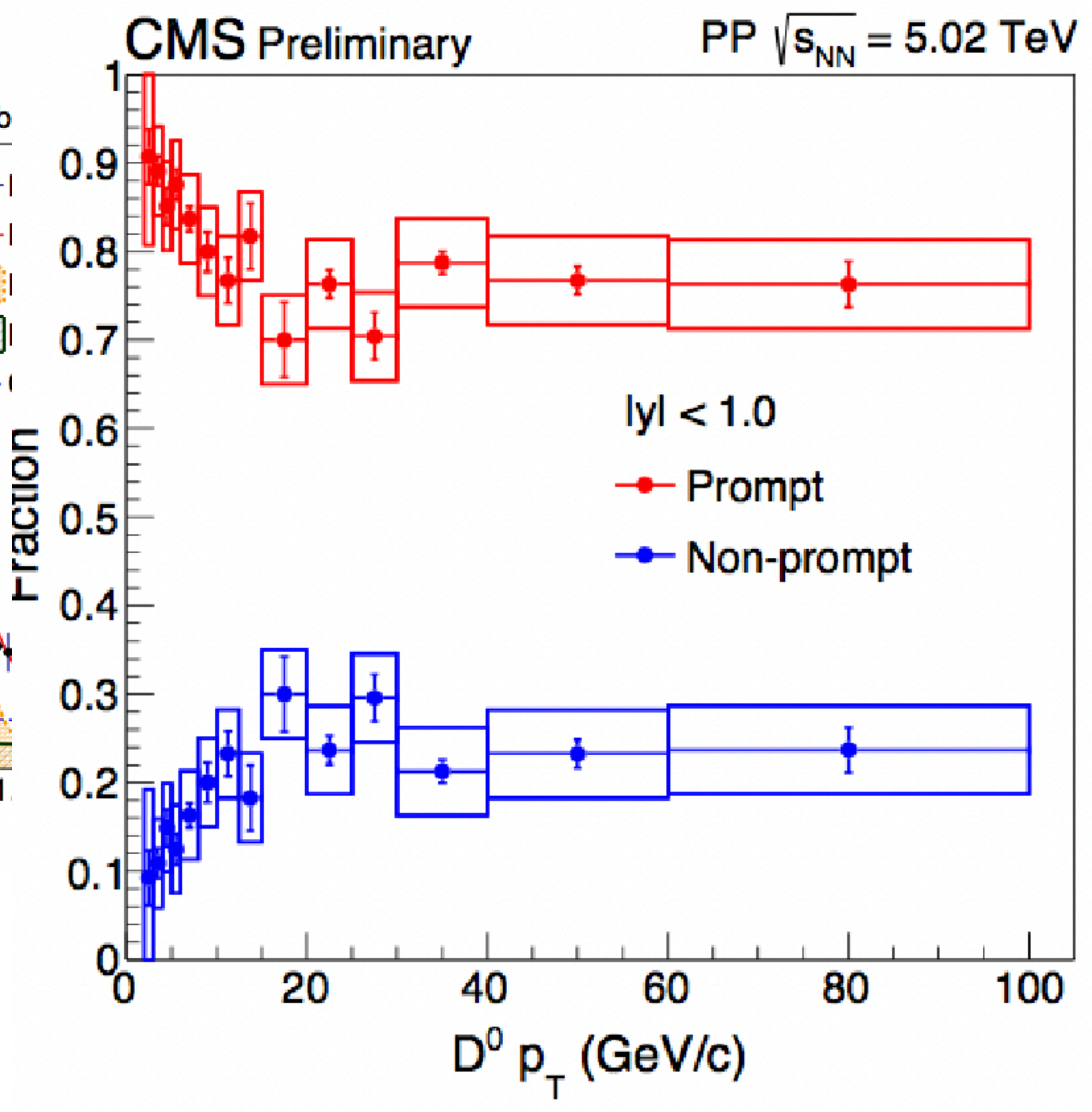

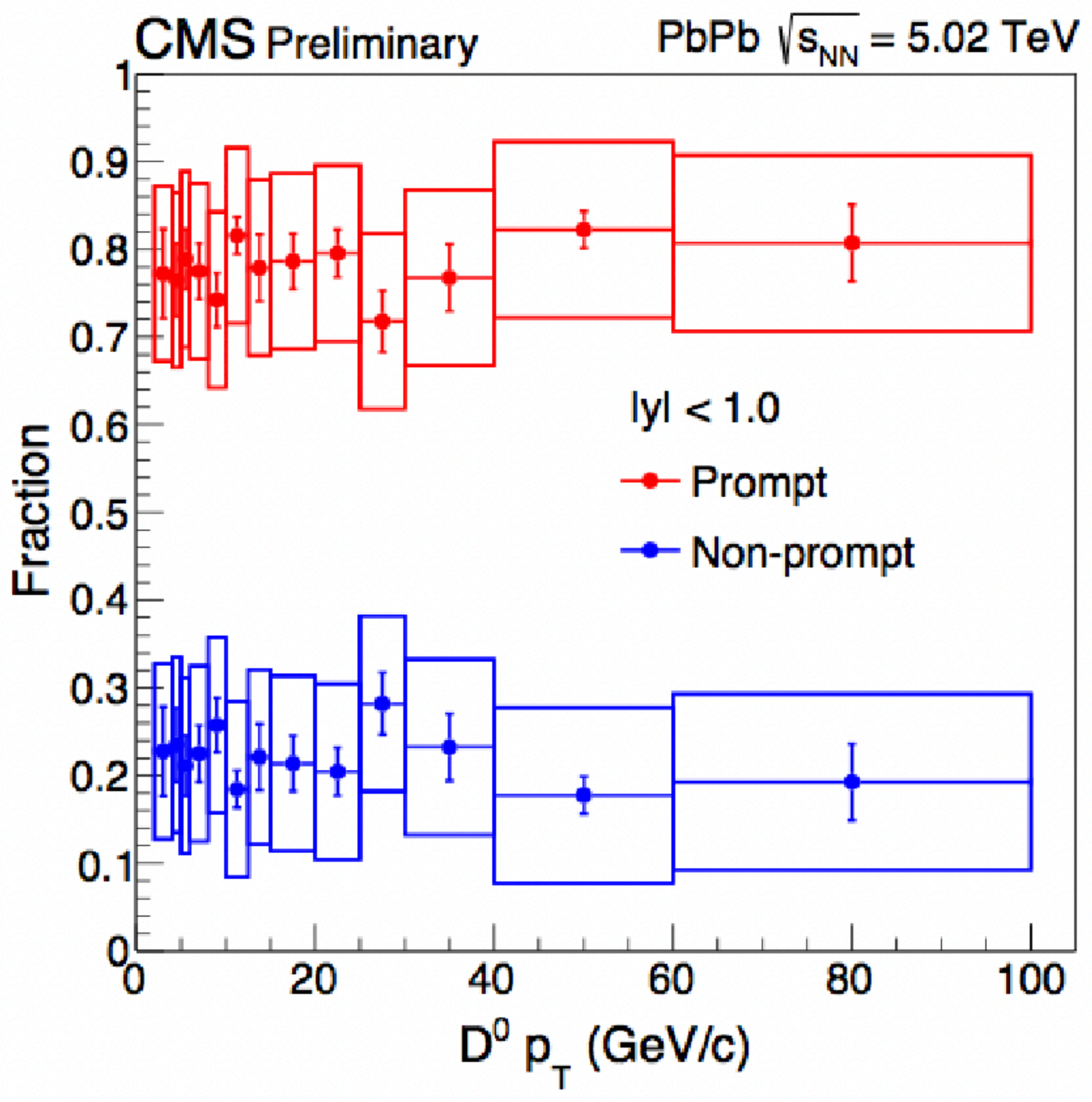

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[CMS,Phys.Rev.Lett. 125 (2020) 10](#)

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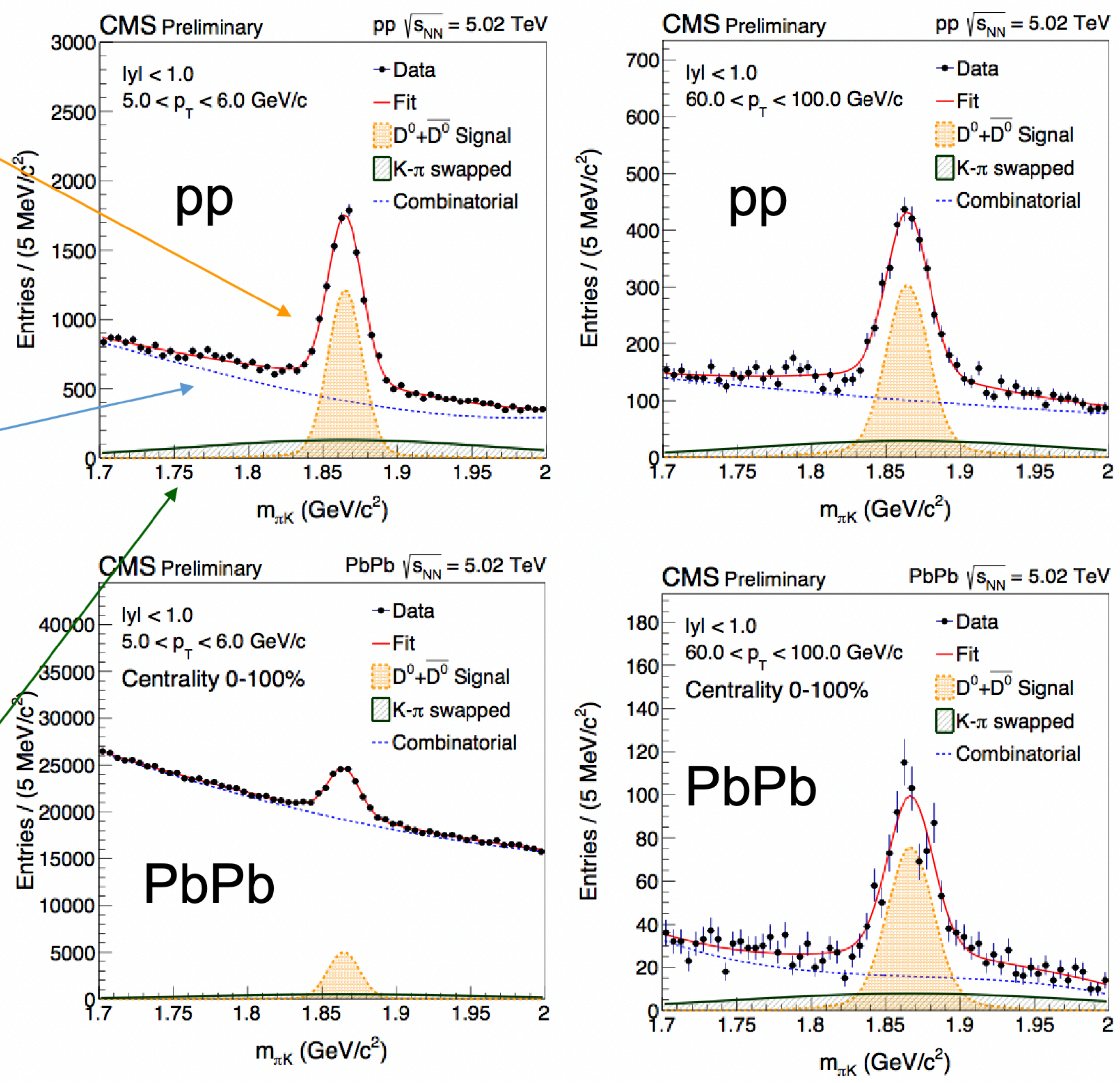
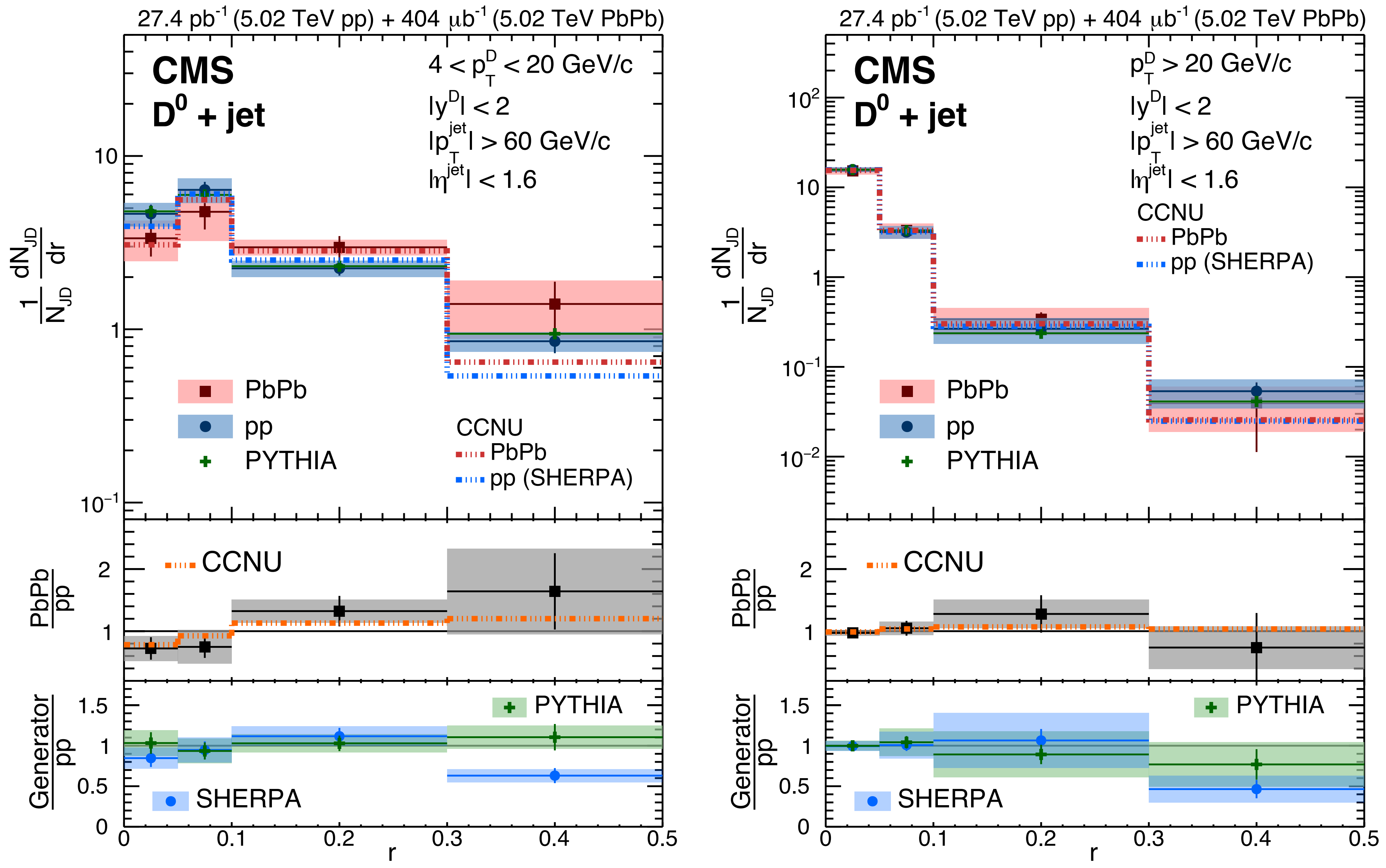
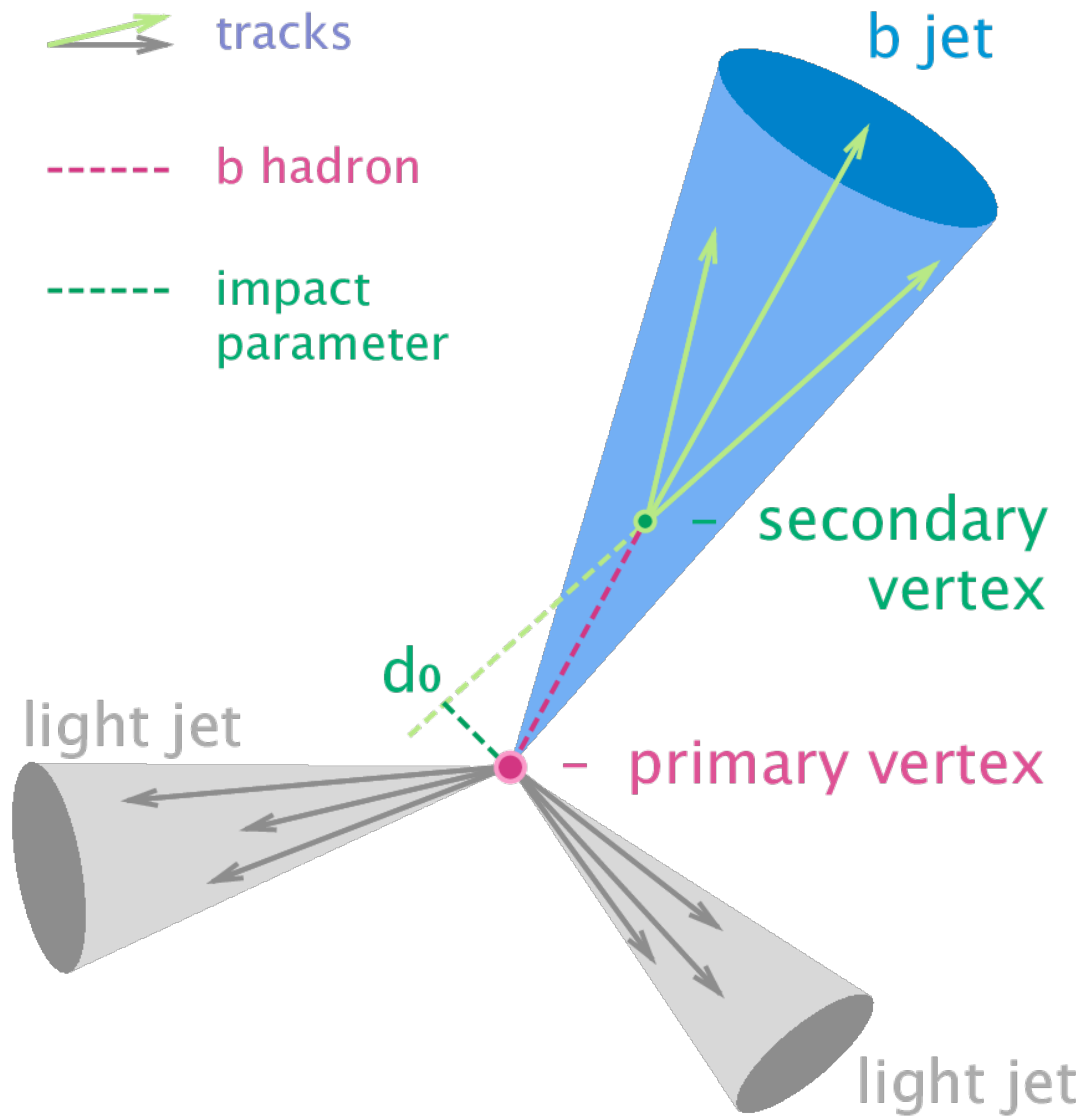




An example: distance between the D meson and the jet axis in pp and PbPb collisions (Searching for charm quark diffusion effects in the QGP)

Heavy flavour jet selection: c/b- tagging



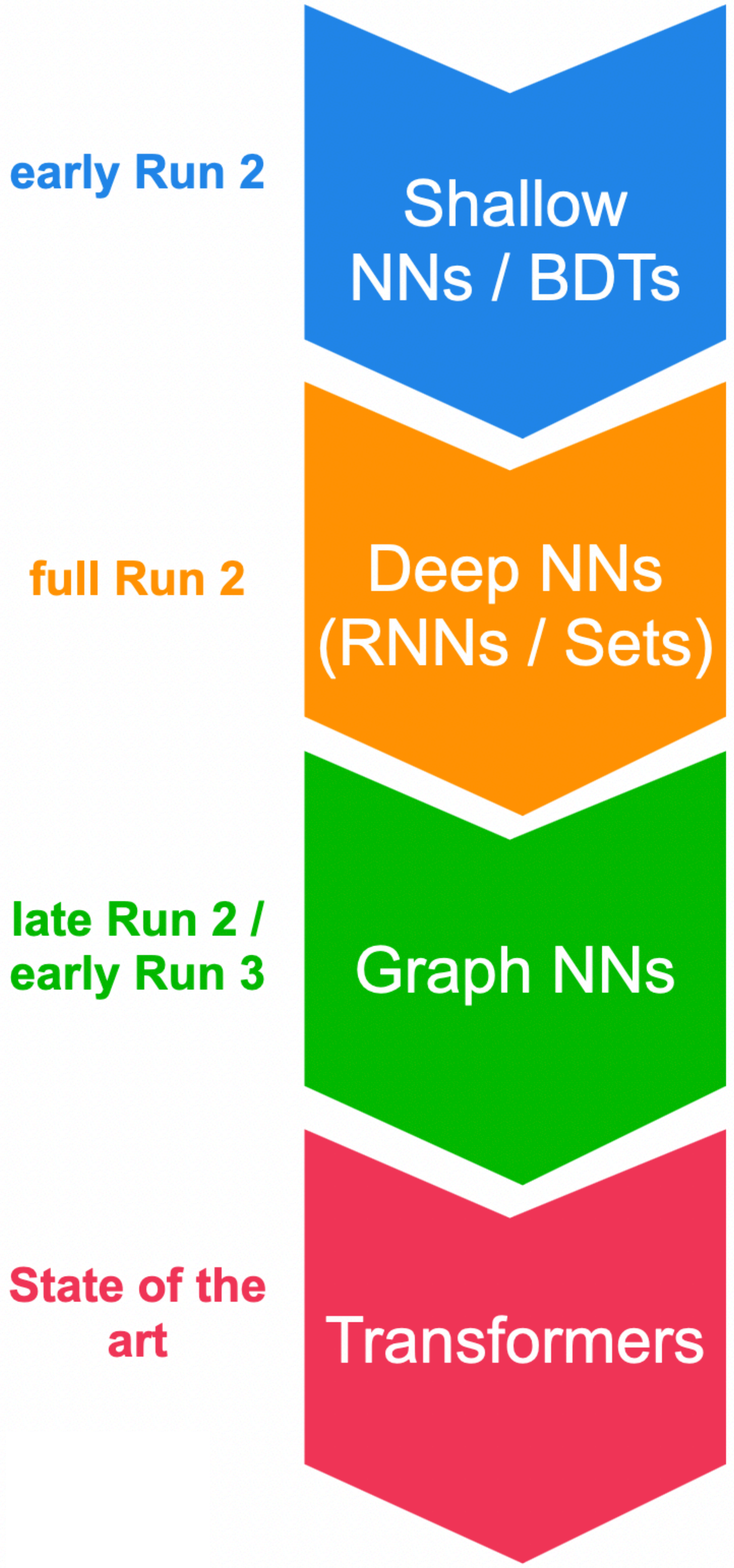
Exploiting properties of the reconstructed secondary vertex or displace tracks or semi-leptonic decay modes:

- Sizable lifetime of c/b-hadrons ~1.5 ps
- Traverse a short distance within the detector systems (~few mm to cm)
- Tracks are displaced relative to the primary vertex of the collisions
- In approx. 20%(10%) of the cases, a lepton is present in the decay chain of a heavy b(c) hadron.

Multidifferential heavy flavour jet substructure measurements benefit from enhanced stats of b/c tagged jets as compared to fully reco b/c-hadron-tagged jets

Heavy flavour jet selection: c/b- tagging

FTAG history



CMS

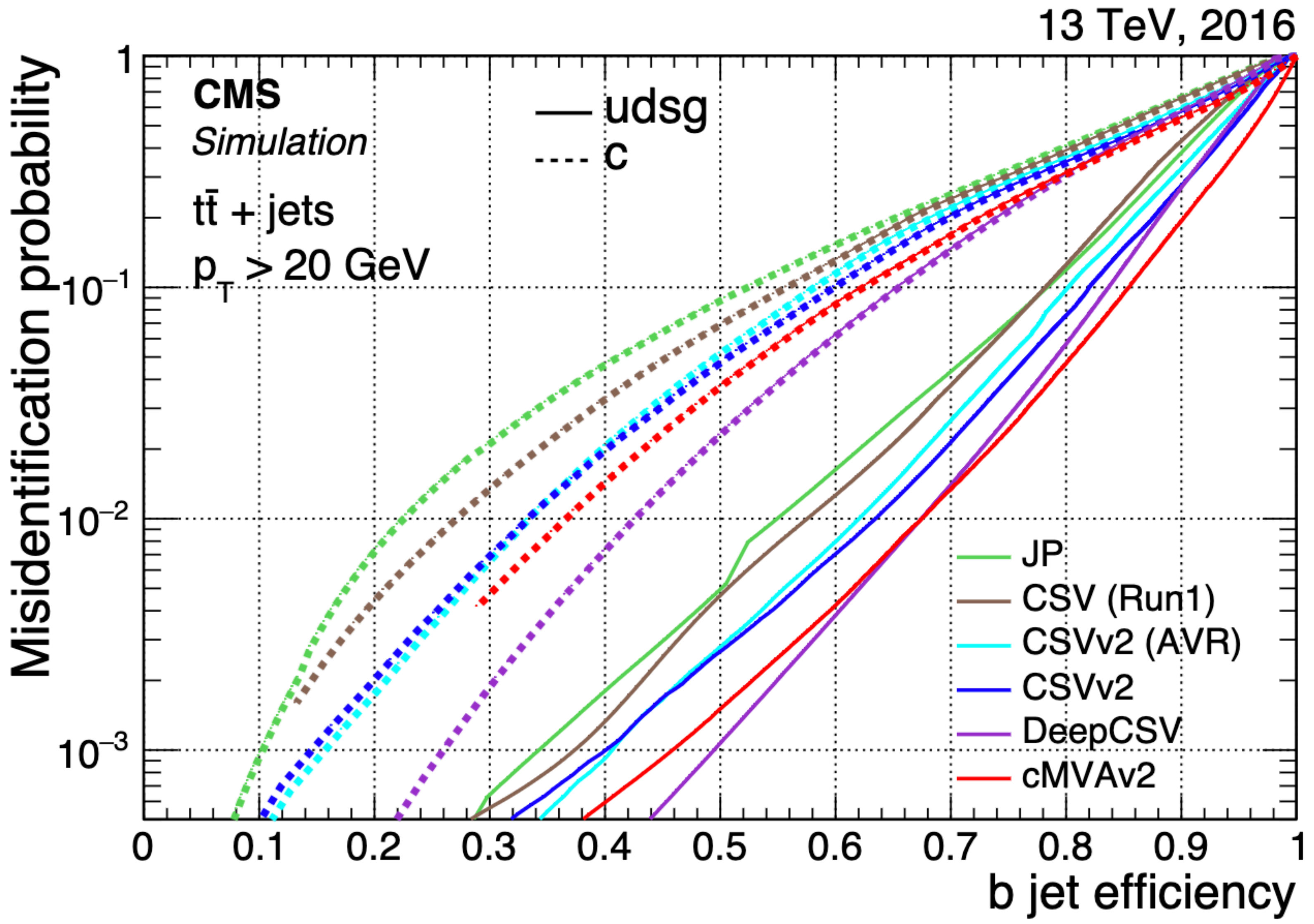
DeepCSV

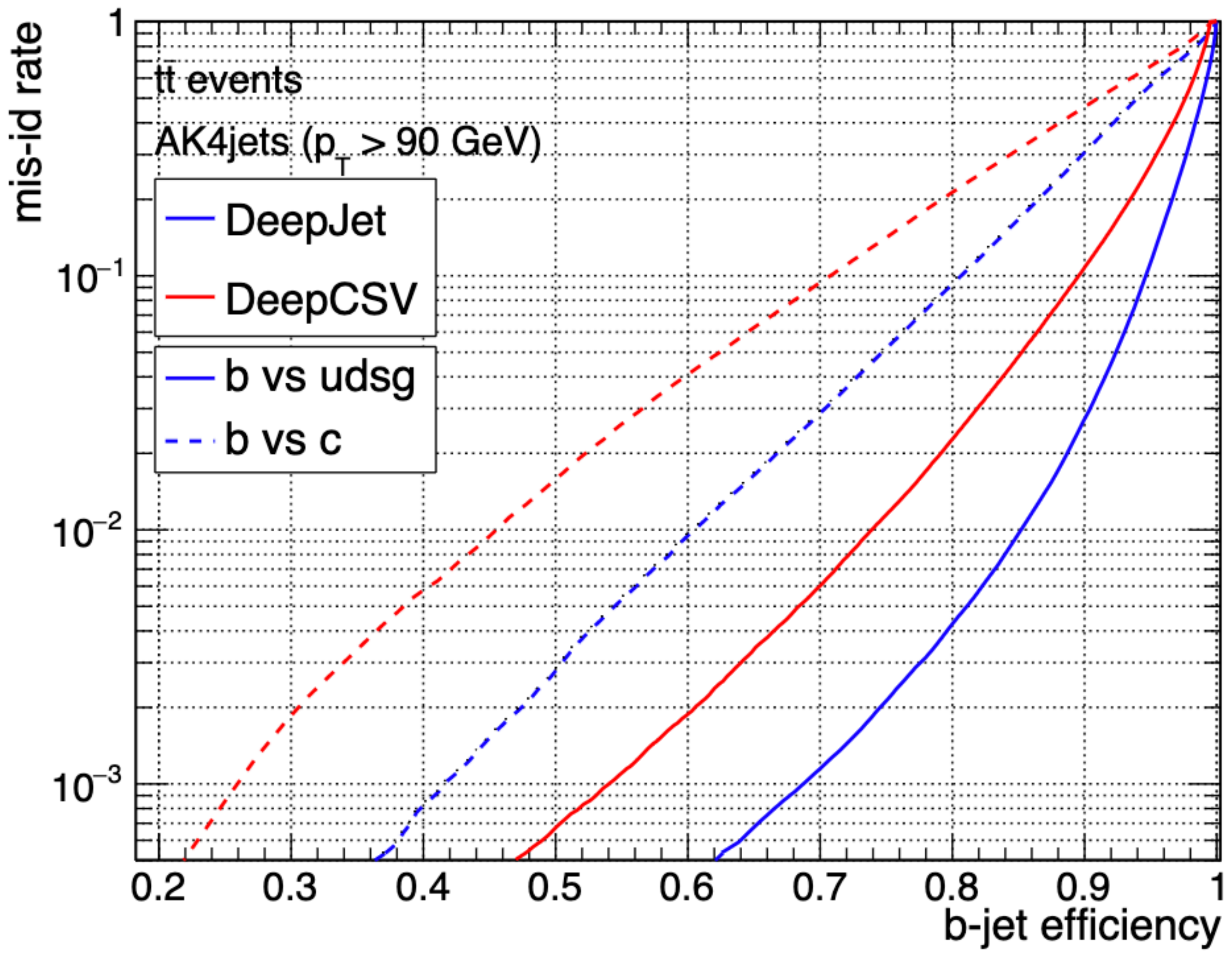
DeepJet — ⭐ Triumph for the Run 2 HH analyses

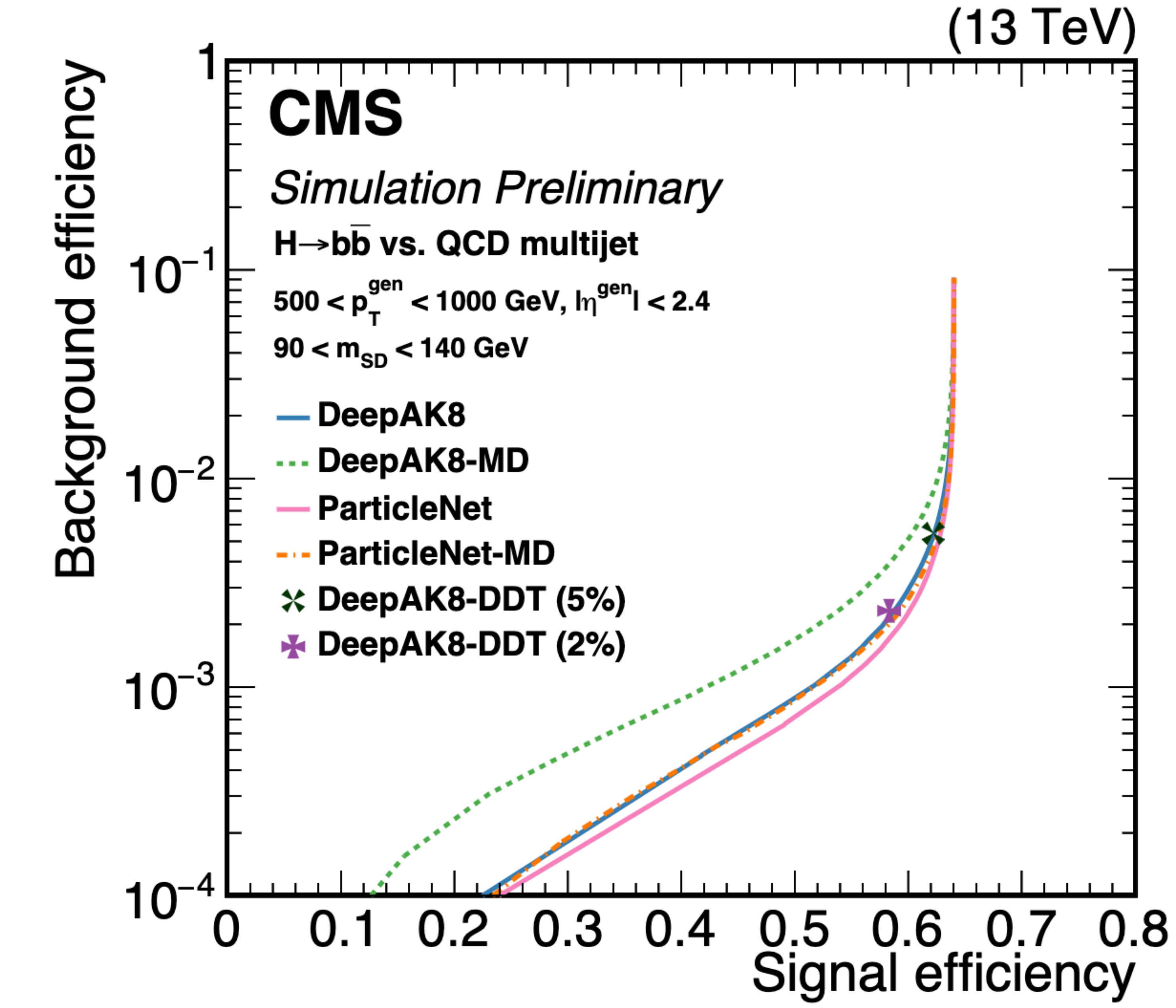
ParticleNet — ⭐ In boosted CMS HH analyses; ⭐ Run 3 triggers

ParticleTransformer (ParT)

Heavy flavour jet selection: c/b-tagging







Early Run2: Efficiency to correctly identify b jets in resolved ttbar events is 68% at a misidentification probability for light-flavour jets of 1%
(improvement of 15% relative to Run1)

[CMS PAS BTV-22-001]

DeepJet does not rely on a selection of jet consituents and overcomes previous limitations on purity and number of inputs

[Bols et al, JINST 15 (202) 12]

ParticleNet: jets treated as particle clouds

[CMS, JINST 13 (2018) 05]

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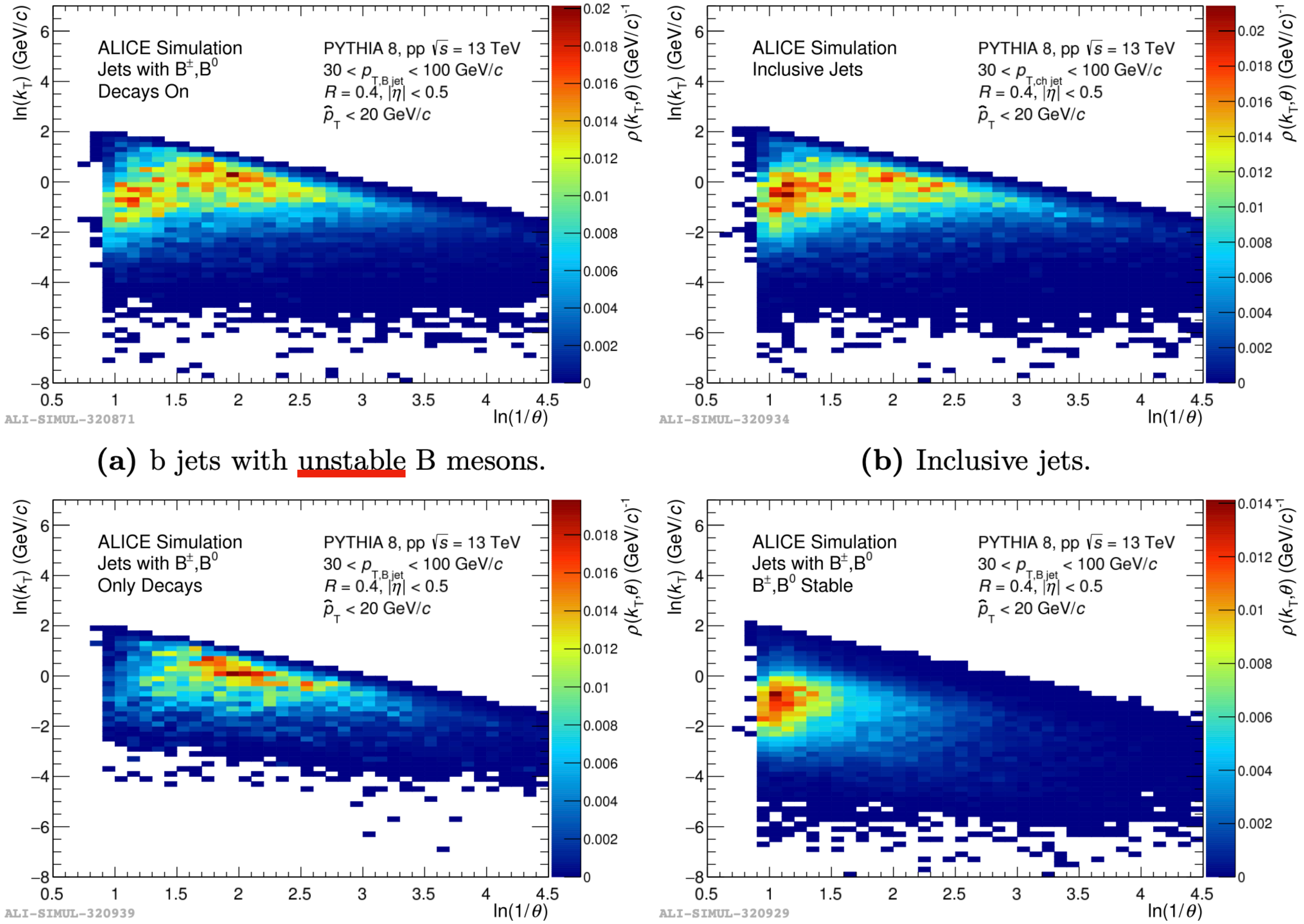
Decays and quark mass effects



(a) b jets with unstable B mesons.

(b) Inclusive jets.

(c) B-meson decays.

(d) b jets with stable B mesons.

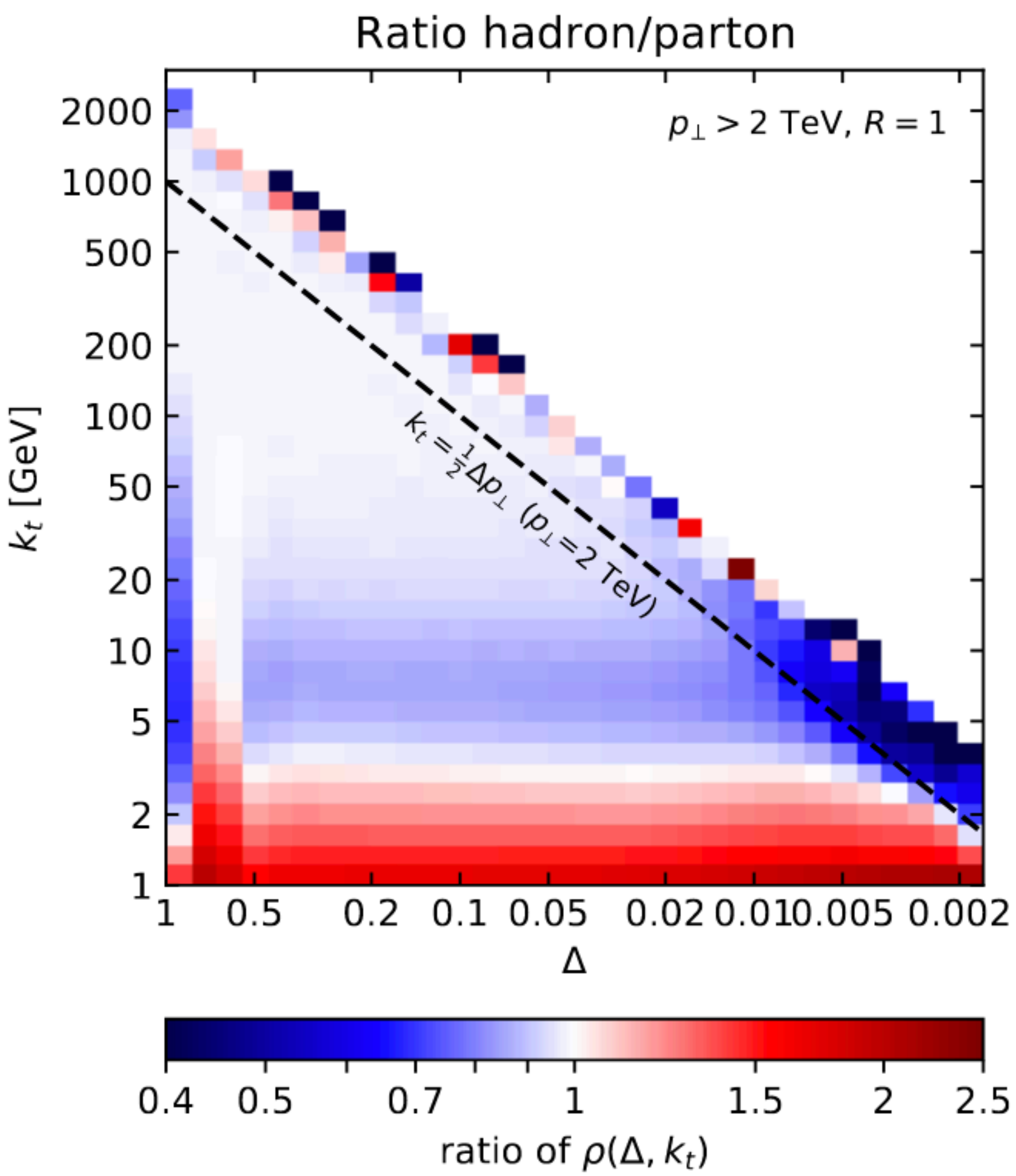
Katharina Garner, Phd Thesis 2019

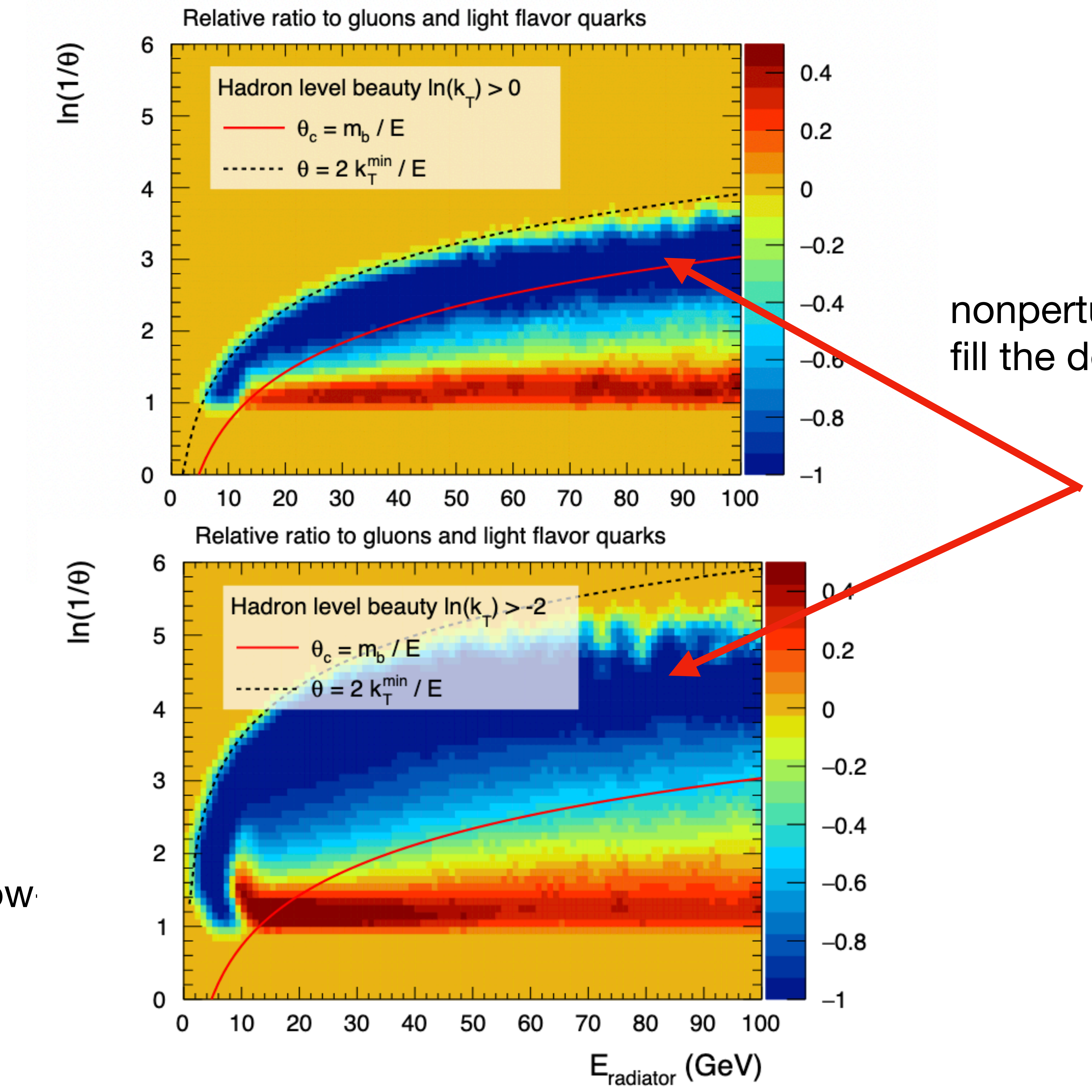
The b-tagged jet contains the b-hadron decay products as constituents

If a jet tree is built, the decays will create extra splittings, dominantly at small angles, darkening quark mass effects (equivalently, the decays will contribute to the small-angle side of the EEC)

Strategies to treat the decays are needed

Hadronisation and quark mass effects





nonperturbative splittings fill the dead cone

Hadronisation naturally dominates the low

Lifson, Salam, Soyez, JHEP 10 (2020)

LCM,Ploskon Phys.Rev.D 99 (2019) 7

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Flavoured algorithms

Consider the case where we can reconstruct or tag all heavy flavour hadrons in a jet

We can imagine three possible flavour recombination schemes (*Caola et al, Phys.Rev.D 108,094010 (2023)*):

1. **Net-flavour summation**: If there's a B and a $\bar{B}$, then there's zero flavour in the recombination
   (resolves collinear unsafety for g->qqbar, good theoretical motivation)
2. **Any flavour**: any recombination that involves nonzero flavour yields a flavoured result. The above case would yield nonzero flavour
   (logarithmically sensitive to quark mass, IRC safety issues at higher orders)
3. **Flavour modulo-2 scheme**: if B and $\bar{B}$ cannot be distinguished experimentally, $b\bar{b}, bb, \bar{b}\bar{b}$ are equivalent and flavourless
   (IRC safety issues at higher orders)

2) close to current experimental CMS c/b-tagging approaches

Flavoured algorithms and jet substructure

Flavoured algorithms for heavy flavour jets is still unexplored in CMS

If we consider what is needed for broad usage of a jet flavor algorithm, we can identify at least four criteria that are necessary, or at least highly desirable:

(i) *IRC safety*. Both the kinematics and the flavors of any hard jets should be IRC safe.

(ii) *Preserved kinematics*. For a given member of the generalized-k_t algorithm family, the flavor algorithm should not modify the jets' kinematics.

(iii) *Multiscale flavor resolution*. The flavors of the pseudojets should be well defined at any step of the clustering, so as to leave open the possibility of using flavor information with the full cluster sequence, e.g., for jet substructure studies.

Caola et al, Phys.Rev.D 108,094010 (2023)

Some experimental approaches require the HF hadron to be in the leading prong at each declustering step or in the selected splitting (see ALICE's dead cone measurement)

Other substructure measurements b-tag the jet but not the leading prong of the selected splitting, see *CMS, Phys.Rev.D 98 (2018) 9*

Summary

Many lessons from inclusive jet substructure measurements

Interesting prospects for heavy flavour jet substructure

- Techniques at place to efficiently select heavy flavour jets
- Decay products impact substructure, need treatment
- New algorithms to achieve not only kinematic but also flavour IRC safety

Stay tuned for the upcoming new CMS results on heavy flavour jet substructure!