Energy-energy correlators inside aggregated b jets

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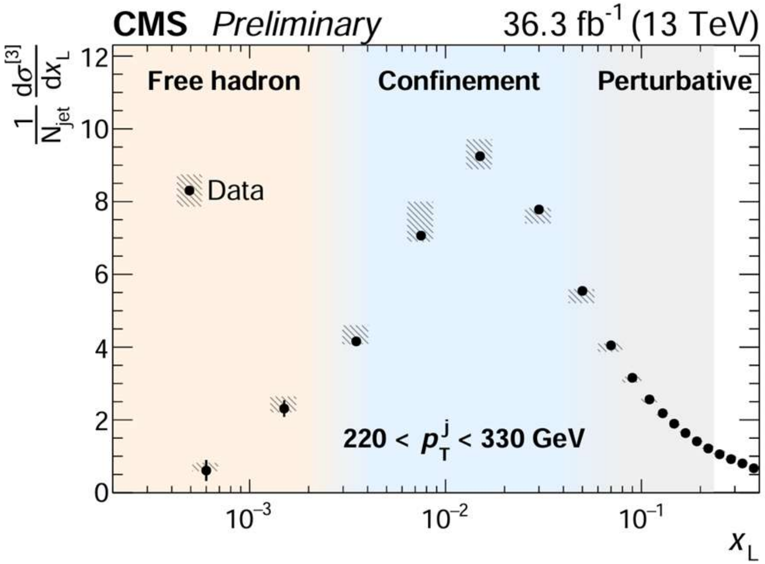
Overview

- Introduction
  - Jets
  - What are EECs?
  - Why EECs?
  - Heavy ion collisions and QGP
- This analysis:
  - Aggregation
  - Signal extraction
  - Unfolding
  - Further corrections
  - Results
- Further analysis developments
- Conclusion



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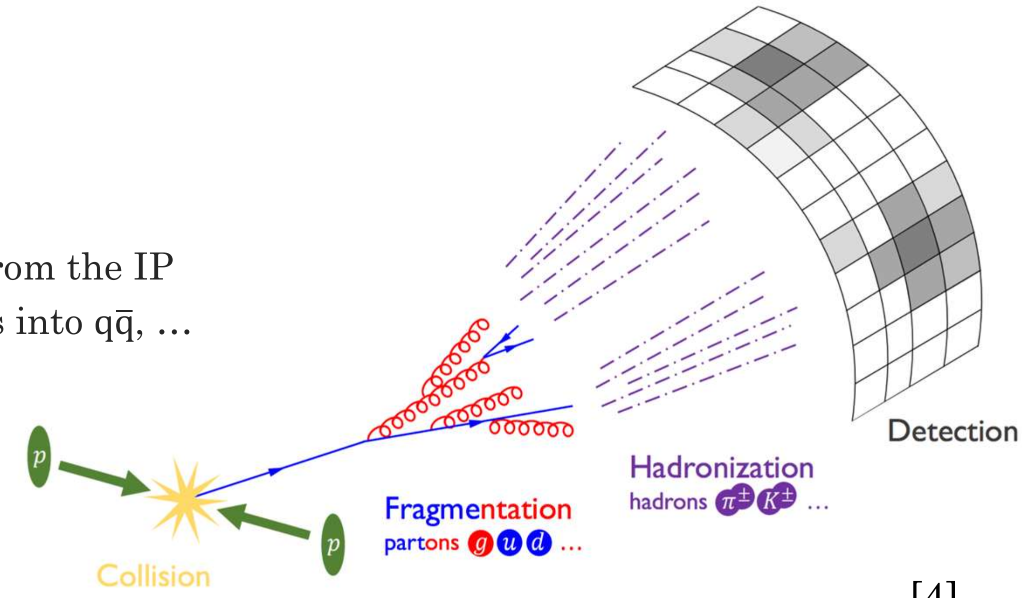
Introduction

Jets

- Jets are collimated flows of hadrons
- Produced by a parton shower:
  - α_S increases as the quark moves away from the IP
  - The quark radiates a gluon, which splits into $q\bar{q}$, …
  - Partons hadronise

  →Jets are observed
- Heavy-quark jets:
  - Parton showers are mass dependent
  - Higher quark mass changes the shower
  - Low-angle radiation is suppressed

  → Dead-cone effect



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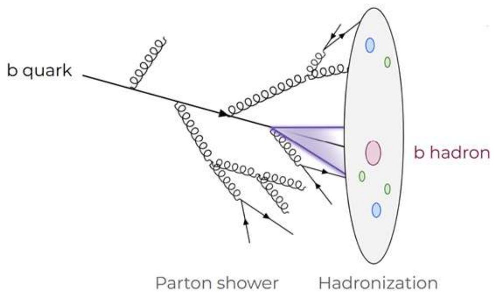

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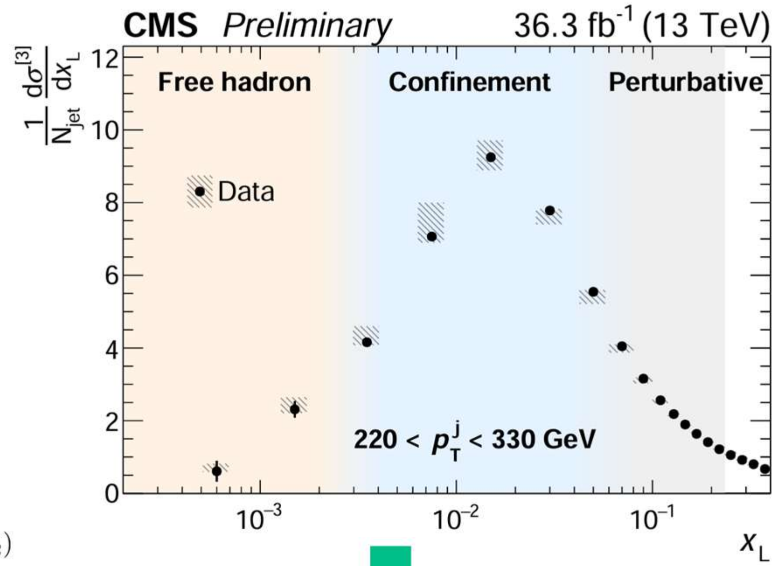
What are EECs?

- Energy-energy correlators (EECs) are observables correlating particles

$$EEC = \frac{d\sigma^{[N]}}{dx_L} = \sum_{i_1,i_2,\ldots i_N}^{n} \int d\sigma\, \delta(x_L - \max(\Delta R_{i_1,i_2}, \ldots \Delta R_{i_{N-1},i_N}))\Pi_{a=1}^{N}\frac{E_{i_a}}{E} \qquad [1]$$

  - Correlate particles inside a jet
  - Angular distance: $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$
  - Exist as 2-point, 3-point, … N-point

- Clear separation of time evolution regions:
  - Perturbative (free quarks, gluons)
  - Confinement
  - Free hadron



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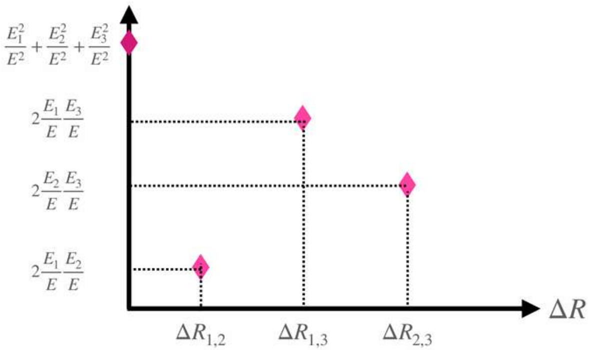

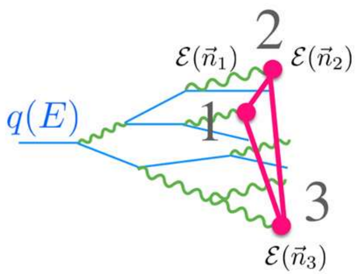

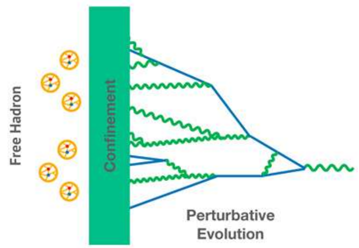

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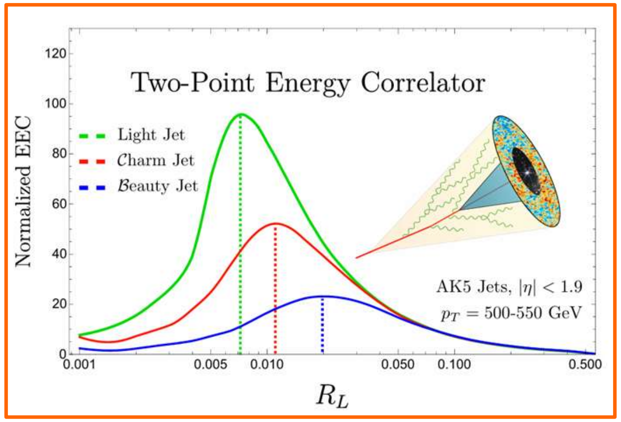
Why EECs?

- Understand QCD dynamics
- Jet substructure
- Well defined and calculable in perturbative QCD, experimentally clear
- Infrared and collinear safe

Possible studies:

- Effect of jet flavour
  - b-jets: dead cone and B hadron decay (this analysis)
- Effect of jet energy
- Extraction of α_S
- Heavy ions: properties and effects of QGP



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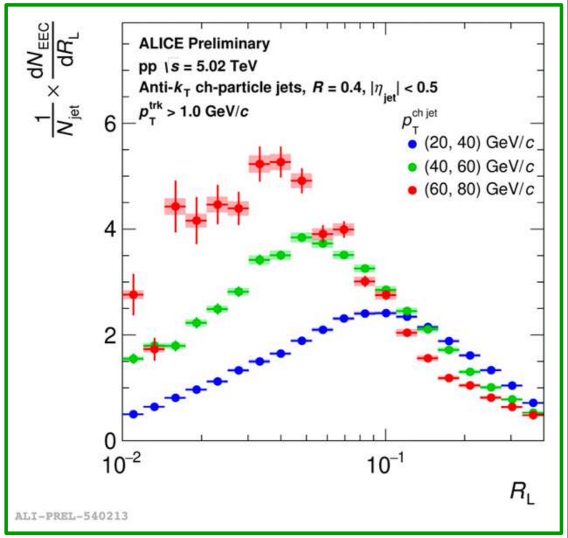

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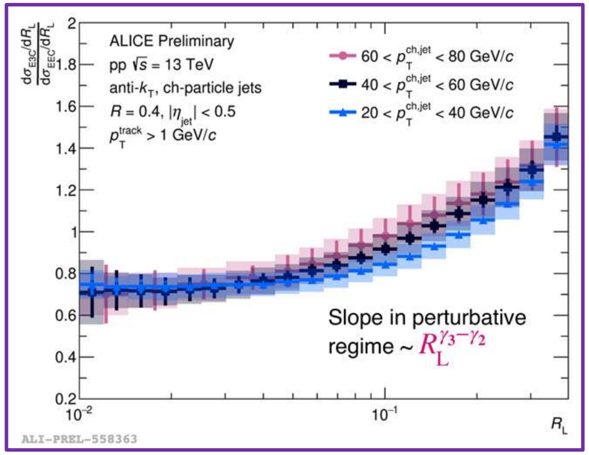

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Heavy ion collisions at CMS

- At LHC: PbPb or small ions collisions 1 month per year
- Heavy ions contain many protons and neutrons
- Their collisions free large amount of energy

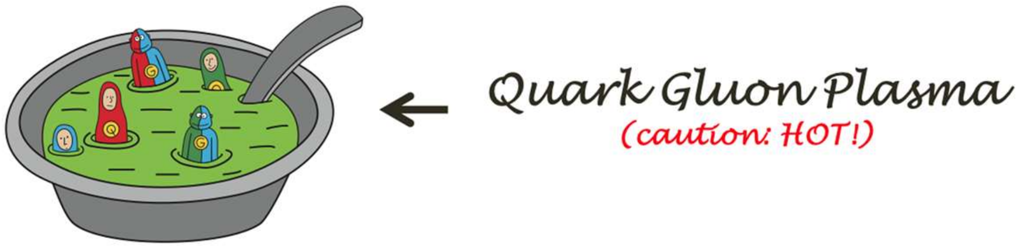
→Access the quark-gluon plasma (QGP)

QGP:

- Quark "soup"
- Hot and dense matter
- Quarks and gluons are deconfined

→Present in the first moments of the Big Bang

→Important for the study of QCD confinement



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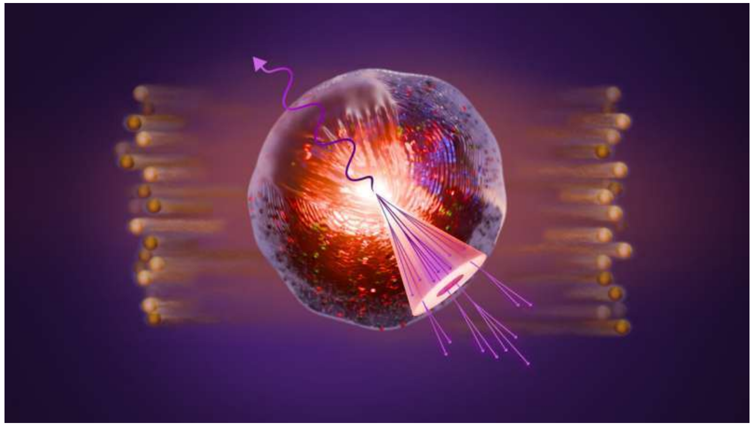
Study of jets in QGP

- QGP has many effects
- Study:
  - Jet energy loss
  - Jet constituents and QGP interactions

with:
  - Jet substructure observables
  - Energy-energy correlators



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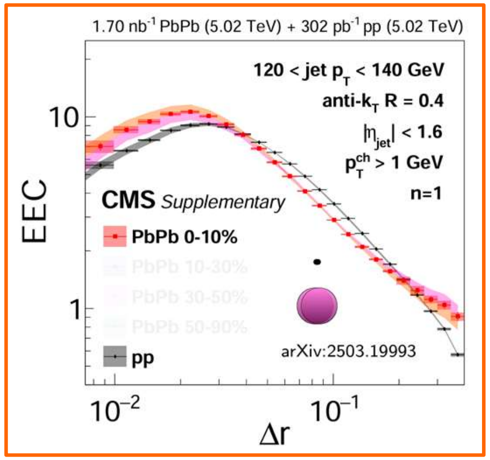
Jet quenching



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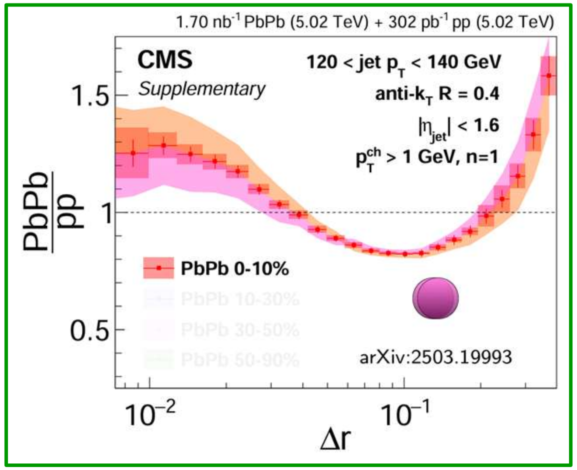
Jet narrowing



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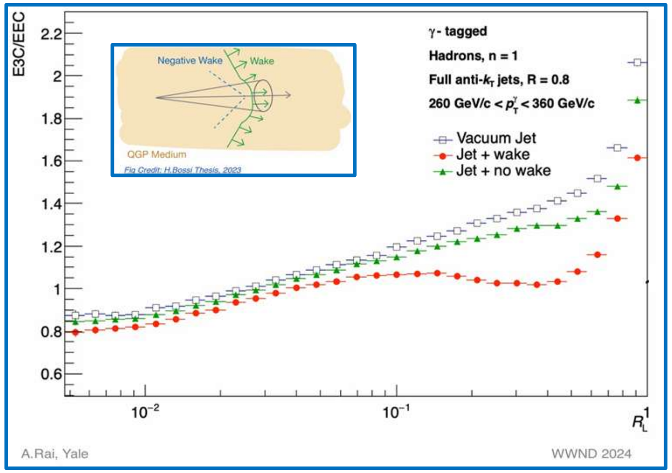
Wake effect



Our analysis: EEC inside b-jets

EEC analysis and event selection

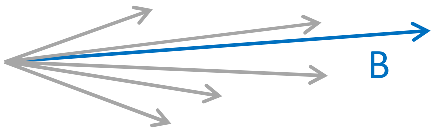
Focus on 2-point EEC inside b-jets with a single B hadron:

→Access different energies

→Study energy loss effects

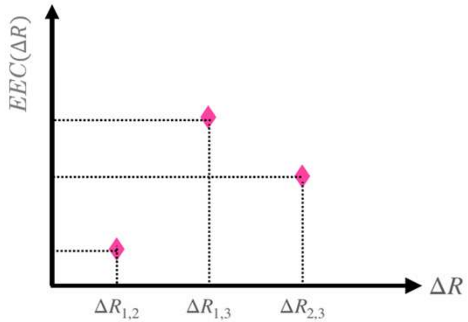
→Heavy quarks produced before QGP, they experience its full evolution

→Study B hadrons



Samples:

- pp CMS dataset at 5.02 TeV
- MC simulations made with Pythia 8
  - Gen: generated events
  - Reco: generated events passed through the simulated detector

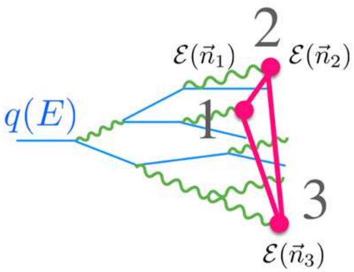


Jet selection:

- b-tagged jets
- 100 GeV $< p_{T,jet} <$ 120 GeV
- $|\eta| < 1.6$

Particle selection:

- charged particles within b jets
- $p_{T,track} > 1$ GeV
- Pair different particles



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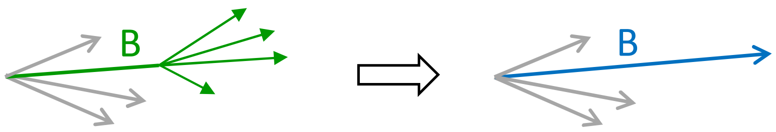
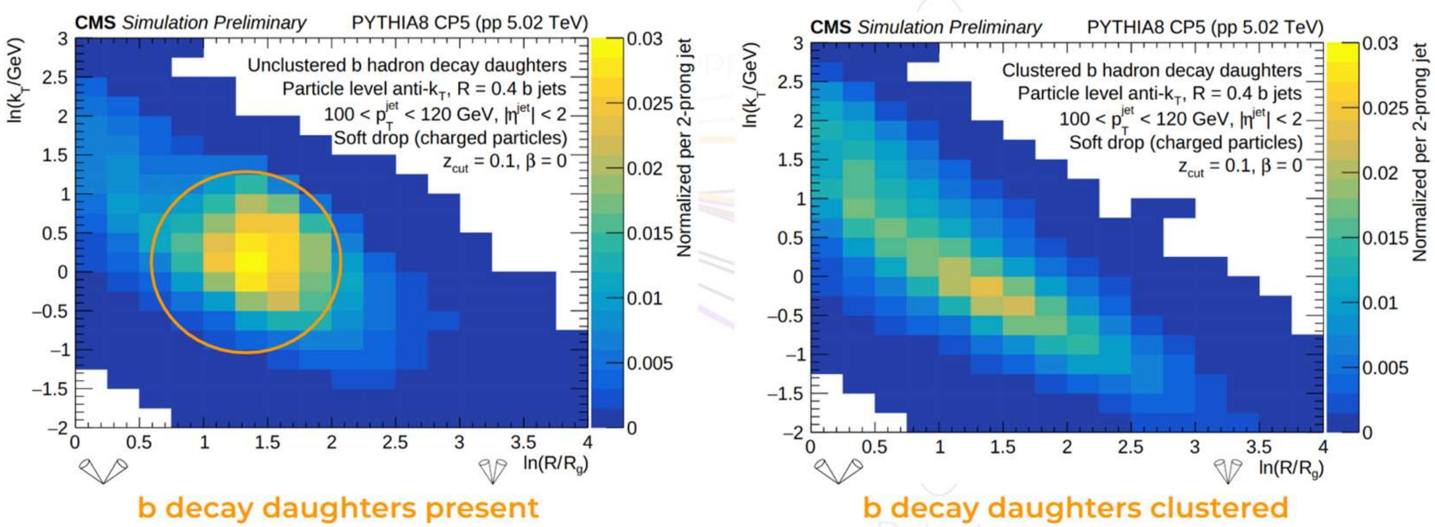
Effect of B hadron decay

- Some tracks come from B hadron decays
- Aggregation: cluster tracks from B to a single particle, use a BDT score
- In Lida's PhD analysis: big effect





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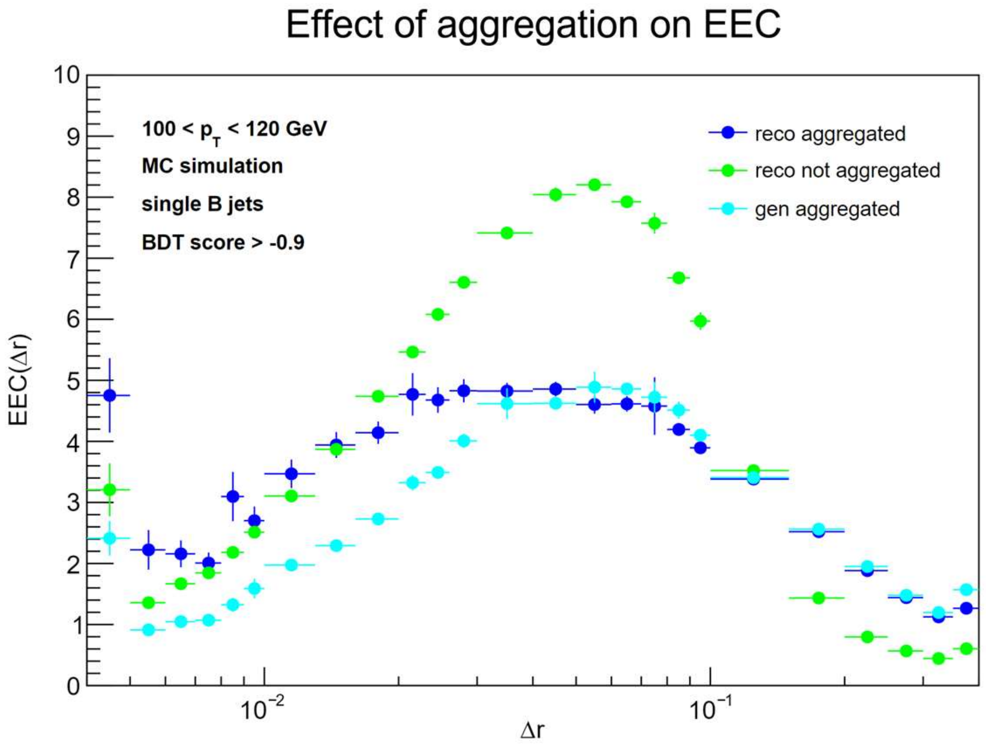
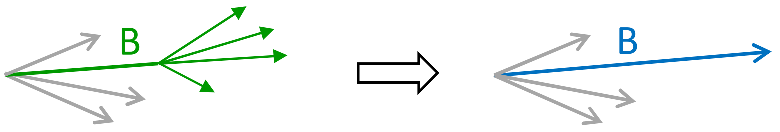
- Does it also have an effect on the EEC distribution?

Effect of B hadron decay

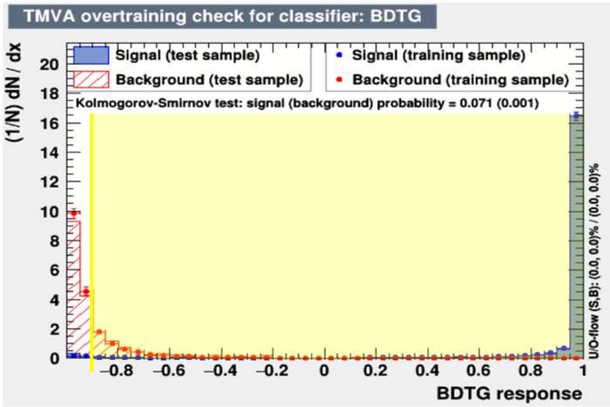
- Also EEC shows a difference whether the tracks coming from a B hadron decay inside the b-jet are aggregated or not

- It has to be considered!





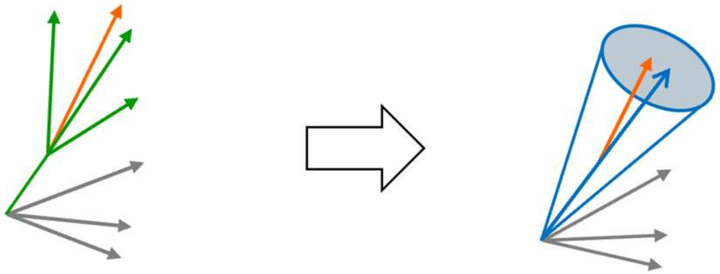
BDT working point



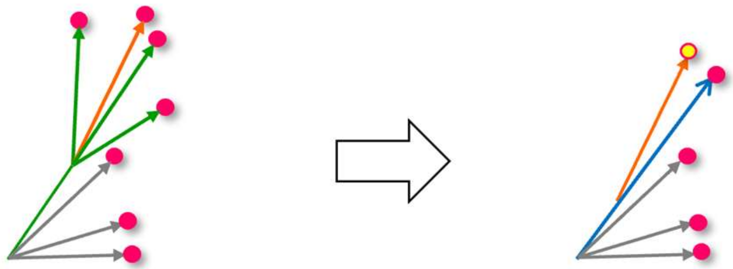
Our working point: get as much signal as possible

Effect of missing one decay particle:

Subjet definition:



EEC:



EEC: finding every decay product seems more important than rejecting the fakes

→ Optimisations can be implemented, e.g. neural networks

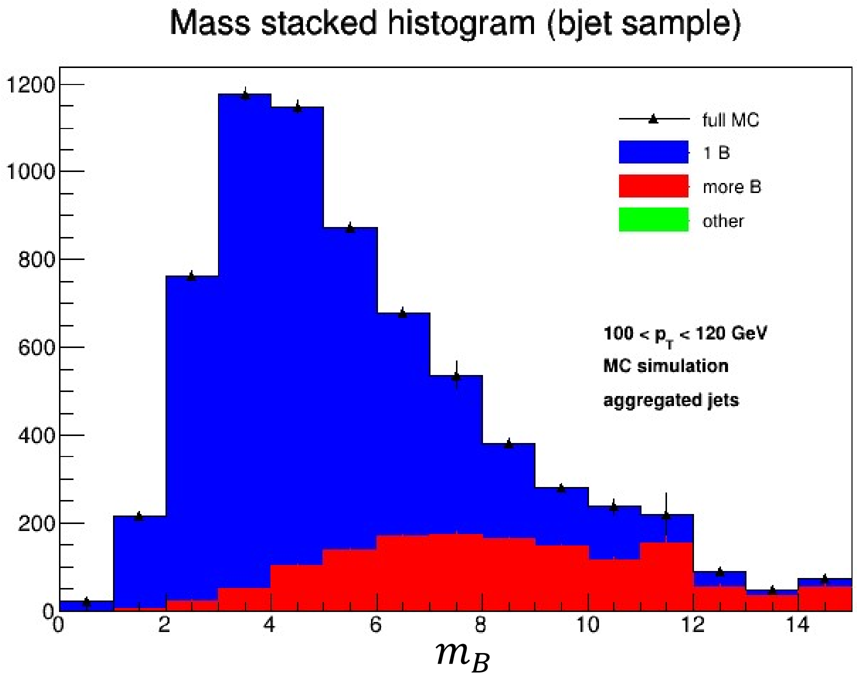
BDT score and signal extraction

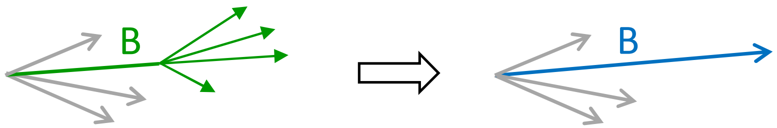
BDT score does not tell us which B is the parent

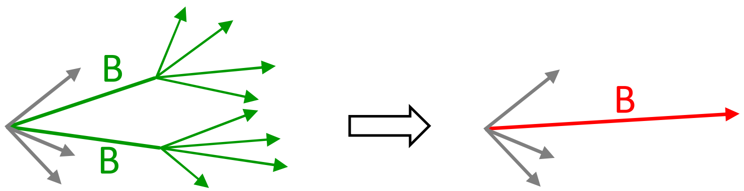
→ no separation between single B and more B hadrons

Extract signal with a template fit

- Separate:
  - signal (single B) jets
  - 2-or-more-B jets
  - non-B jets
- Background will have a different partially reconstructed B-hadron mass m_B distribution than the signal

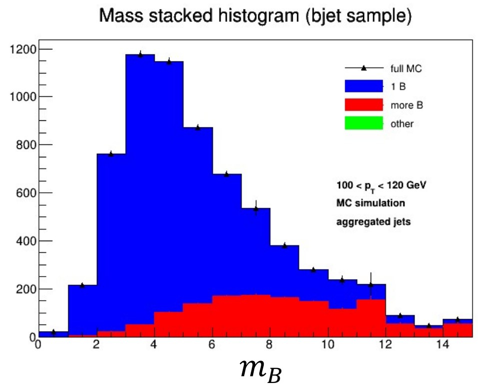


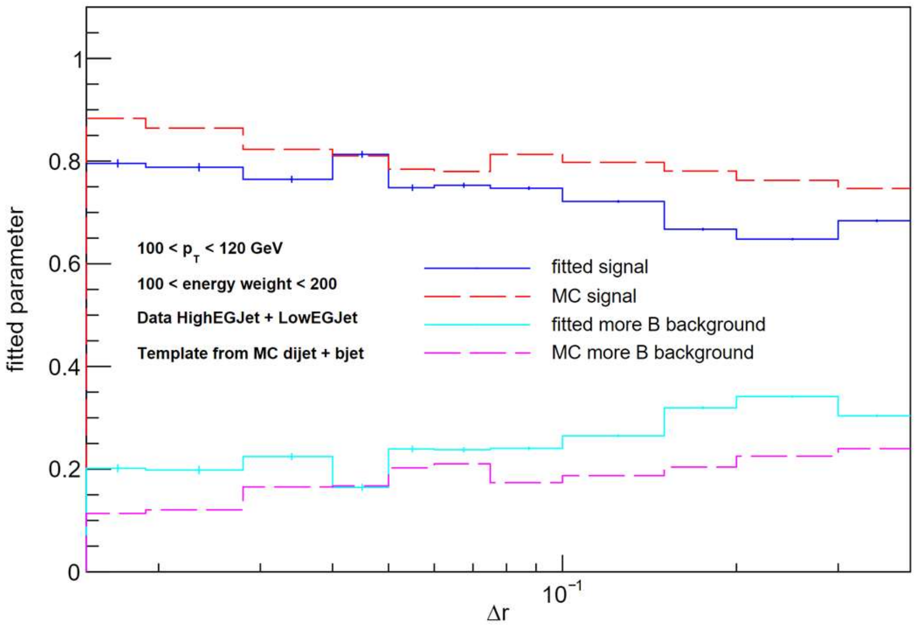




Template fit

- 4D template fit (m_B, Δr, weight, jet p_T)
- Discriminating variable: m_B
- Fit: signal fraction
- Templates from MC: 1-B and more-B, other background negligible





Unfolding

- We are studying EEC in a p_T window
- Account for p_T bin migration and detector effects with unfolding
- Response matrix

Particle level

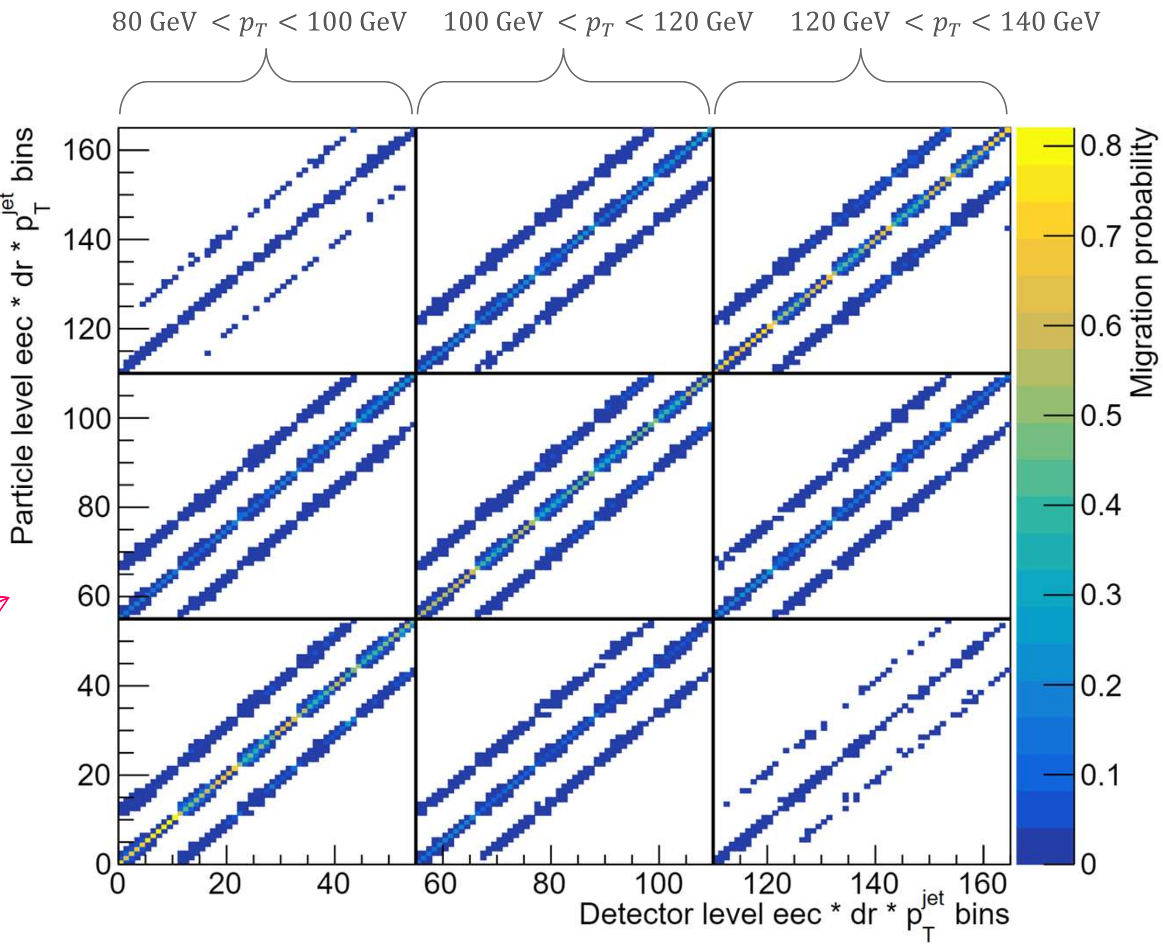
$$\nu_i = \sum_{j=1}^{M} R_{i,j}\mu_j$$

Detector level

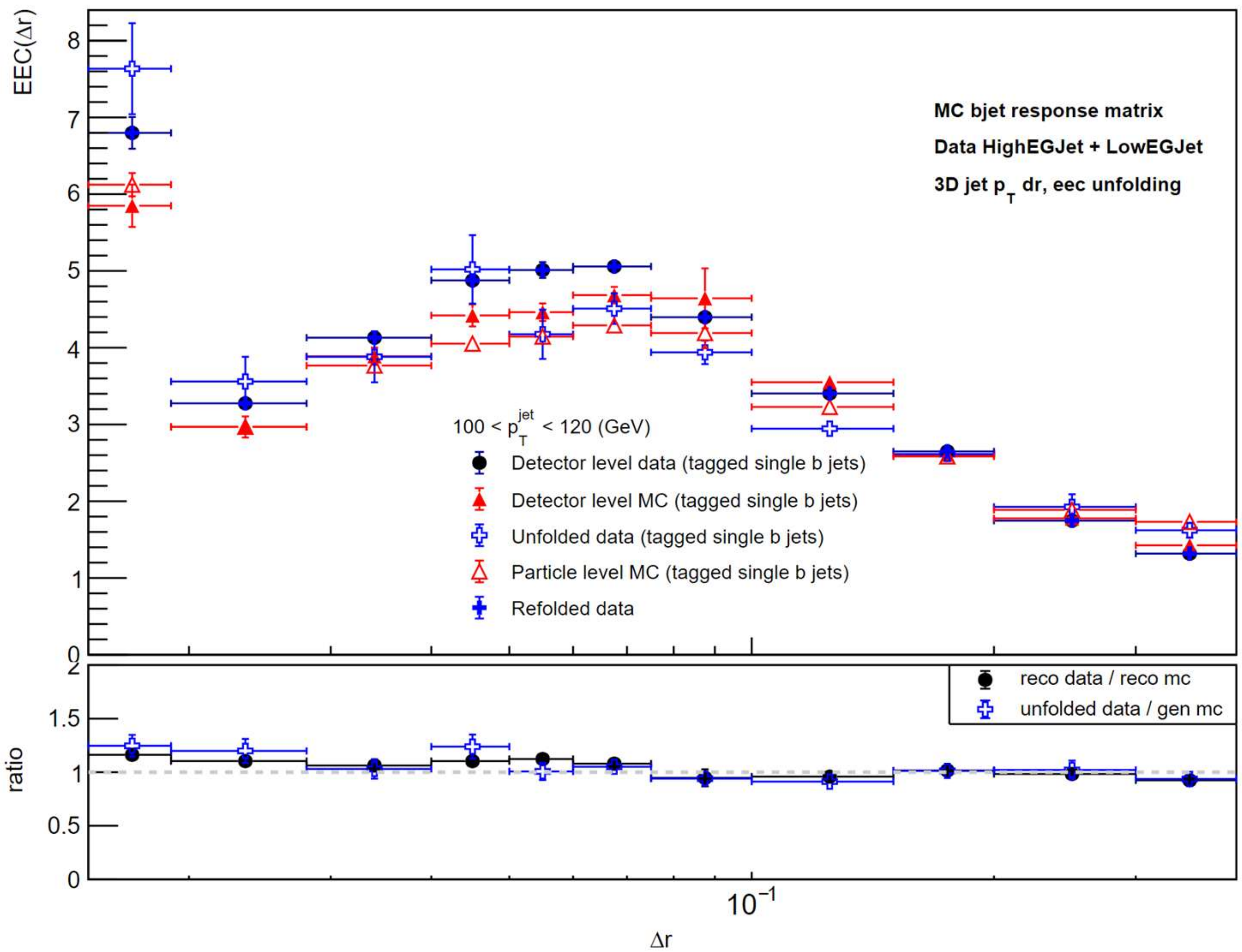
- Δr, EEC and jet p_T are correlated

→ Do 3D unfolding

- Unfolding with RooUnfold matrix inversion (no regularisation)



Results after unfolding



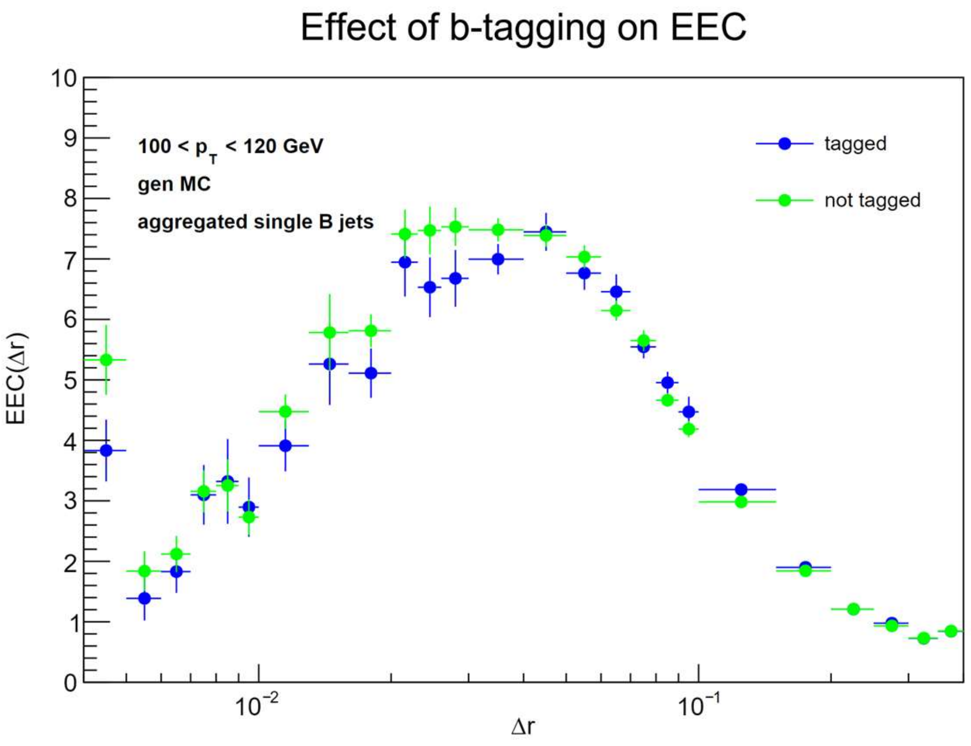
Further corrections

Correct for other effects not taken into account by the template fit and unfolding:

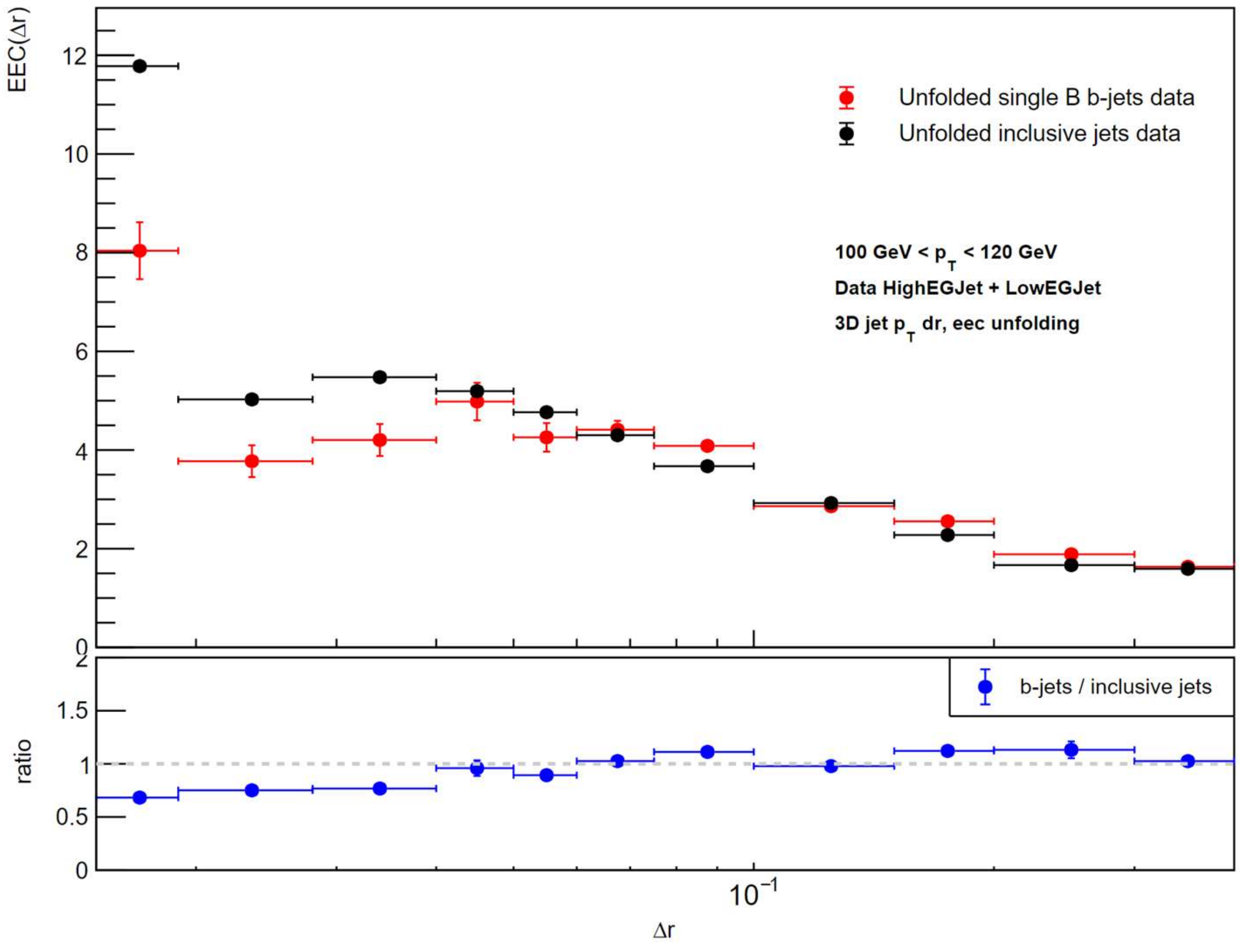
- b-tagging efficiency from gen MC
  →untagged EEC/tagged EEC
- Track reconstruction efficiency
- …

For now only the b-tagging correction

is implemented

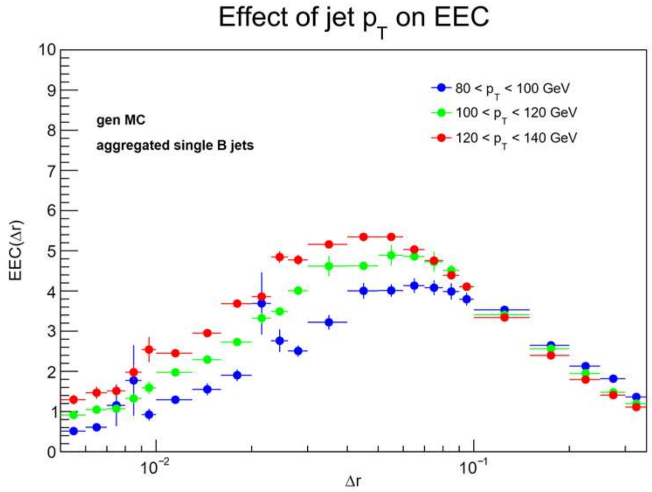


Comparing to inclusive jets



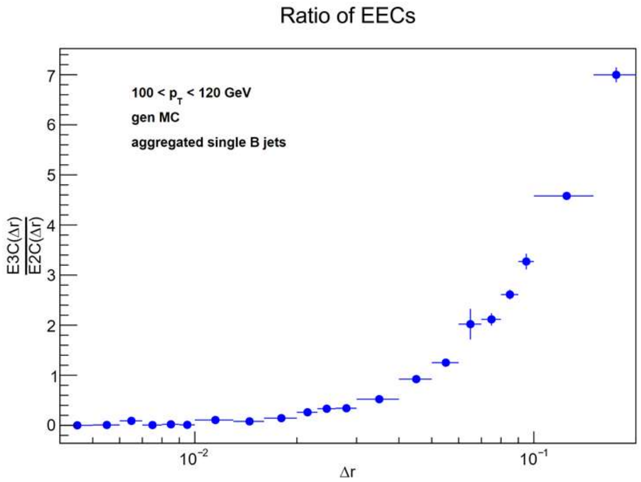
Future development of the analysis

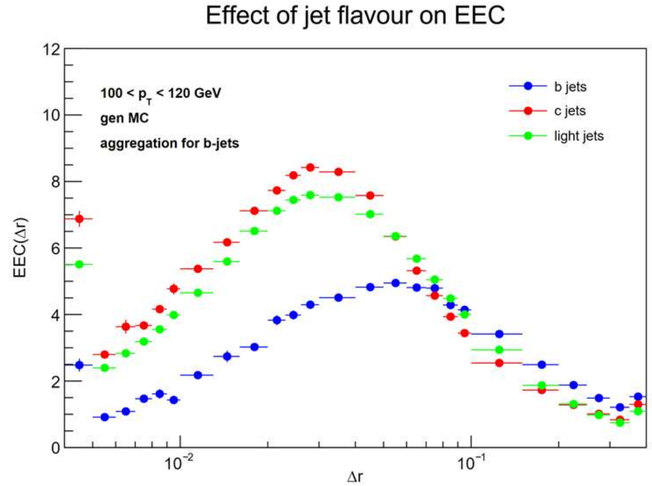
→ Eventually: analyse heavy ions data and compare to this pp analysis



Other studies:

- EECs with higher weight exponent ($n = 2, \ldots$)
- Distribution in different p_T windows
- Distribution for different jet flavours
- Ratio E3C/E2C





Conclusion

- EECs are very interesting observables: they are sensitive to the QCD evolution and can be used to investigate QGP

- EECs show a difference when B hadron decays products are aggregated

  → B decays have to be considered

- 3D unfolding necessary because of the correlations

- EEC b-jets analysis is feasible

- Many interesting evolutions of the EEC analysis for CMS heavy ions:
  - Flavour, jet p_T, QGP effects

Thank you!

References

[1] Zhen Lin, Chenfeng Lu, Renqi Pan, Yuekai Song, M. Xiao, and Yulei Ye, *Color confinement and asymptotic freedom using energy correlators inside jets,* CMS Draft Note, 25.07.2023

[2] Lida Kalipoliti, *CMS overwiev*, Rencontres QGP France, Bagnoles de l'Orne, 20 May 2025

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[4] Eric M. Metodiev, The Fractal Lives of Jets, https://www.ericmetodiev.com/post/jetformation/

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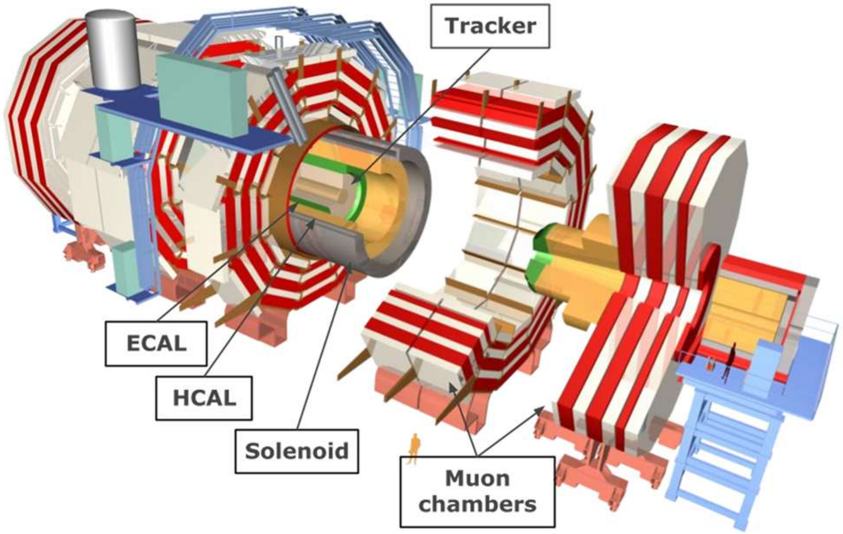
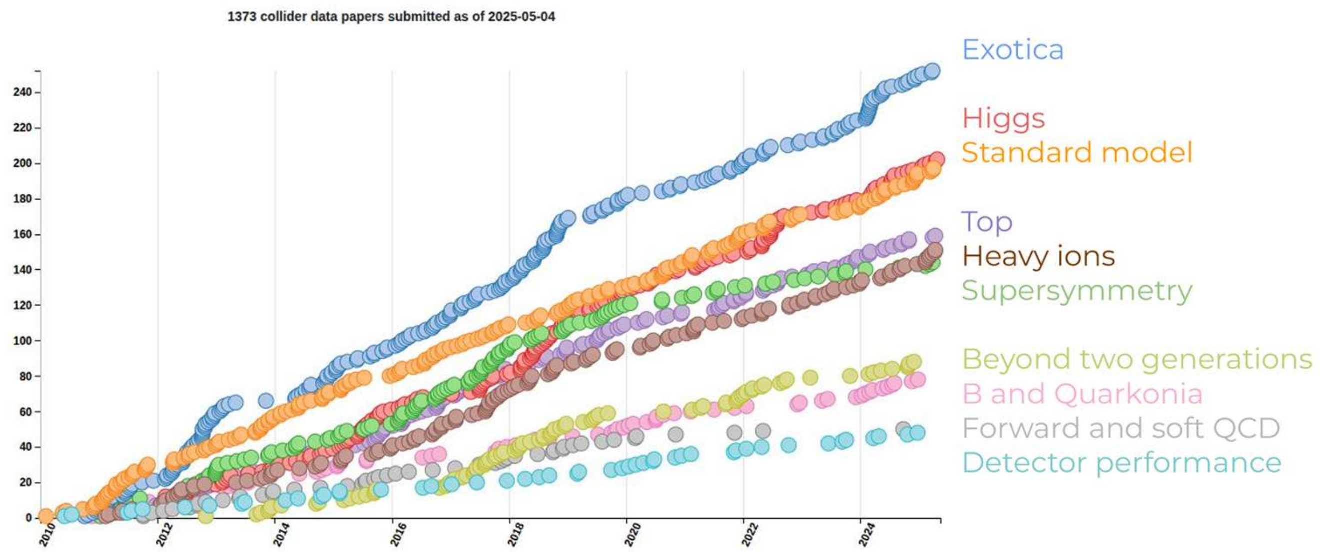
[13] Jussi Viinikainen, *The first measurement of energy-energy correlator of jets in PbPb collisions at CMS,* Vanderbilt University for the CMS Collaboration Quark Matter 2025

Backup slides

The CMS experiment

- Experiment located at the LHC at CERN
- 4π hermetic calorimeter
  - Tracking
  - Electromagnetic calorimeter (ECAL)
  - Hadronic calorimeter (HCAL)
  - 4T magnetic field
  - Muon detectors
- Many physics interests





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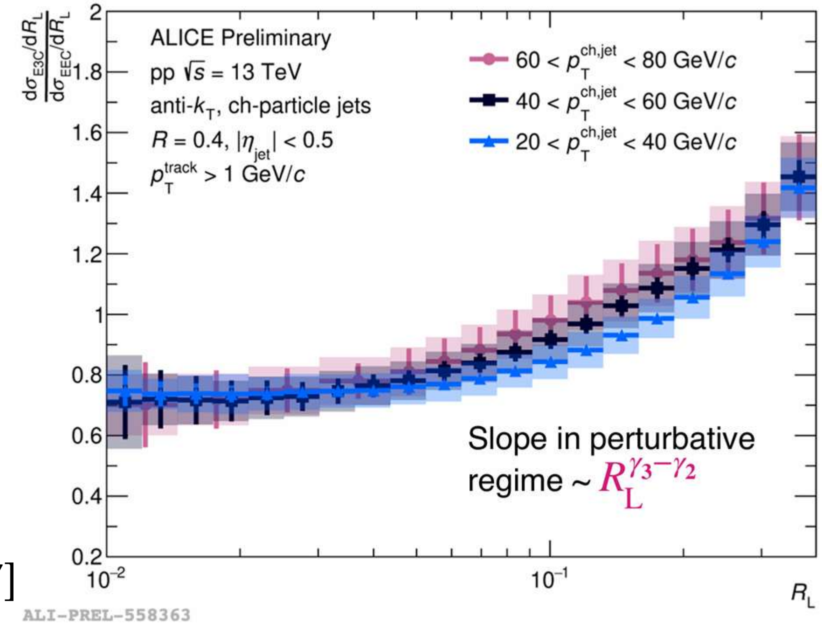
Extraction of α_S

- The ratio E3C/E2C is directly proportional to α_S

$$EEC = \frac{d\sigma^{[N]}}{dx_L} = \sum_{i_1,i_2,\ldots i_N}^{n} \int d\sigma\, \delta(x_L - \max(\Delta R_{i_1,i_2}, \ldots \Delta R_{i_{N-1},i_N}))\Pi_{a=1}^{N} \frac{E_{i_a}}{E}$$

- Three time evolution regions also visible
- Measuring at different energy one sees the expected behaviour of α_S



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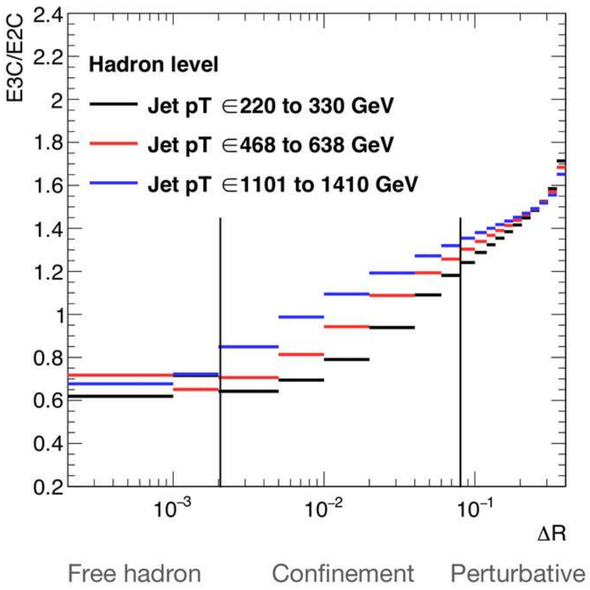

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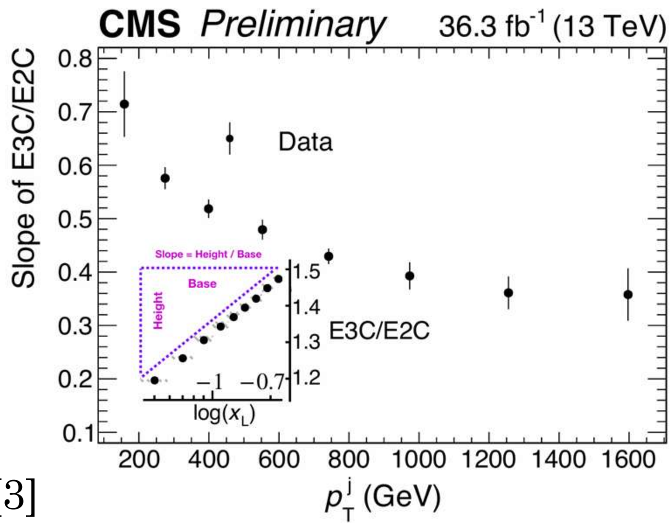

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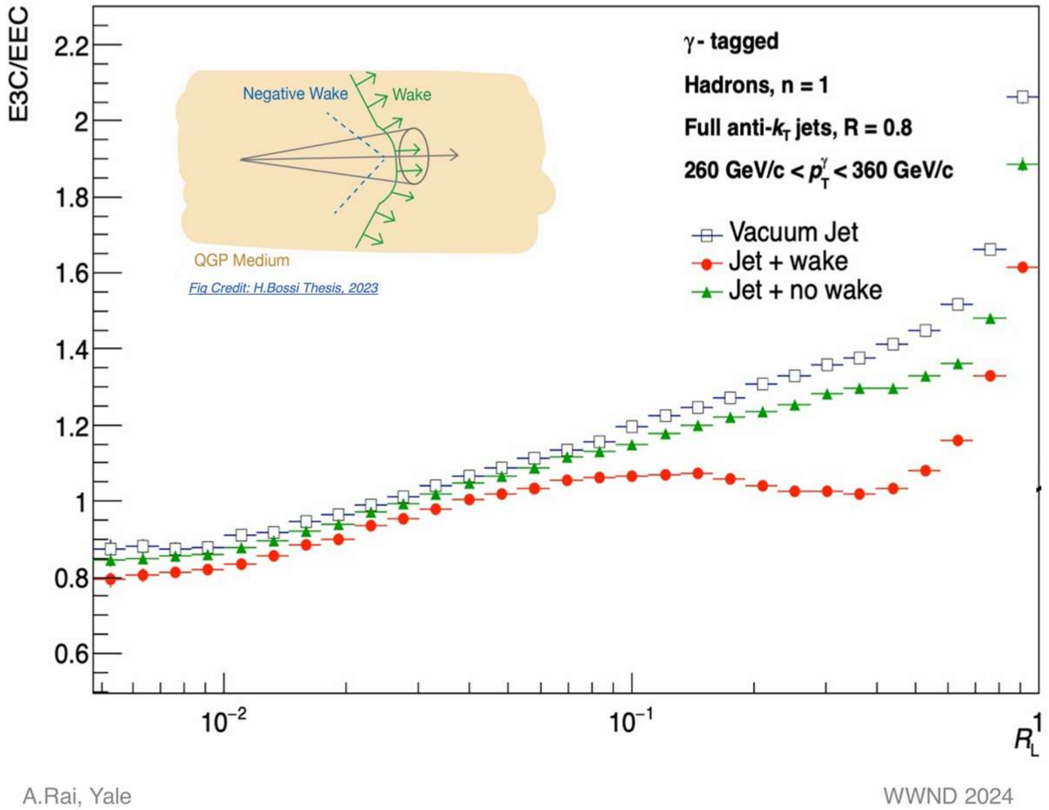
Heavy ions

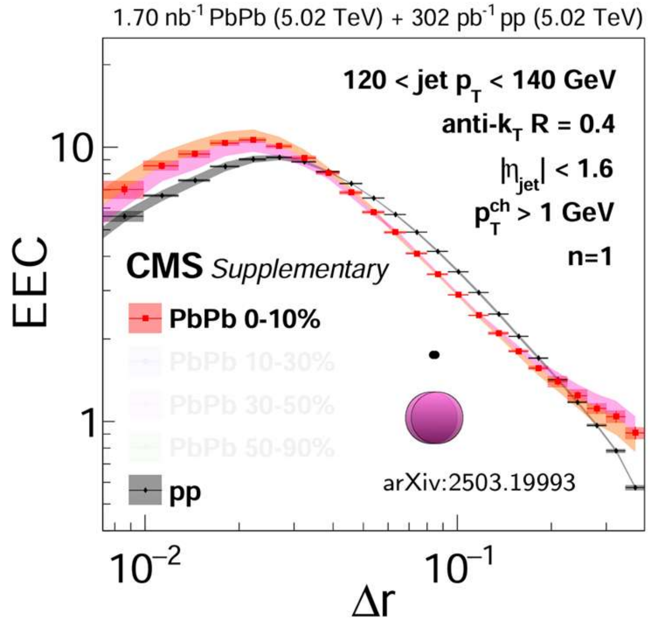
- See the effect of QGP and related phenomena
  - Wake: hadrons from the wake end up in the final jets

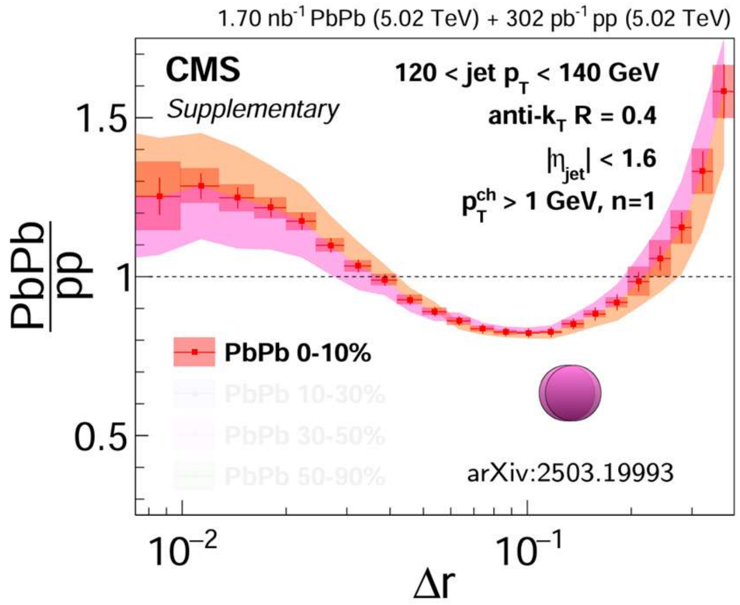


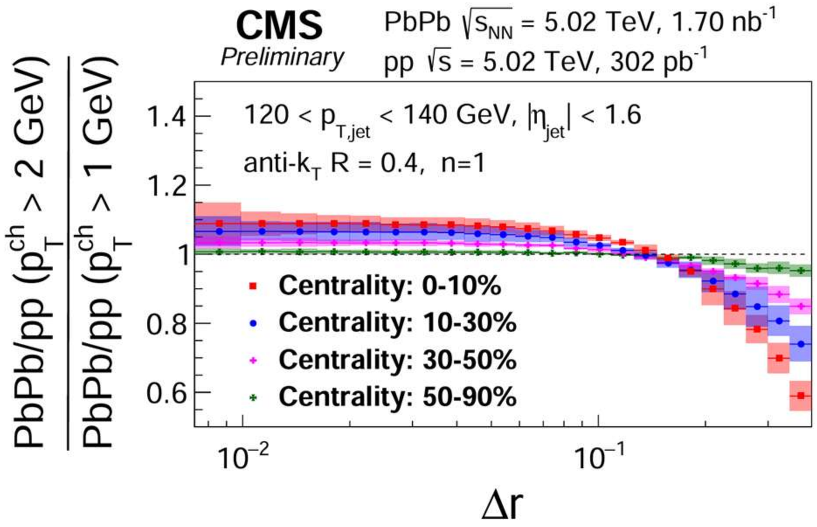
[10]

Heavy ions

- See the effect of QGP and related phenomena
  - Jet quenching
- Look at EEC ratios in heavy ions vs pp
  - Narrowing of the jets, coherence
  - Ratio of ratios: universal scaling for free hadrons







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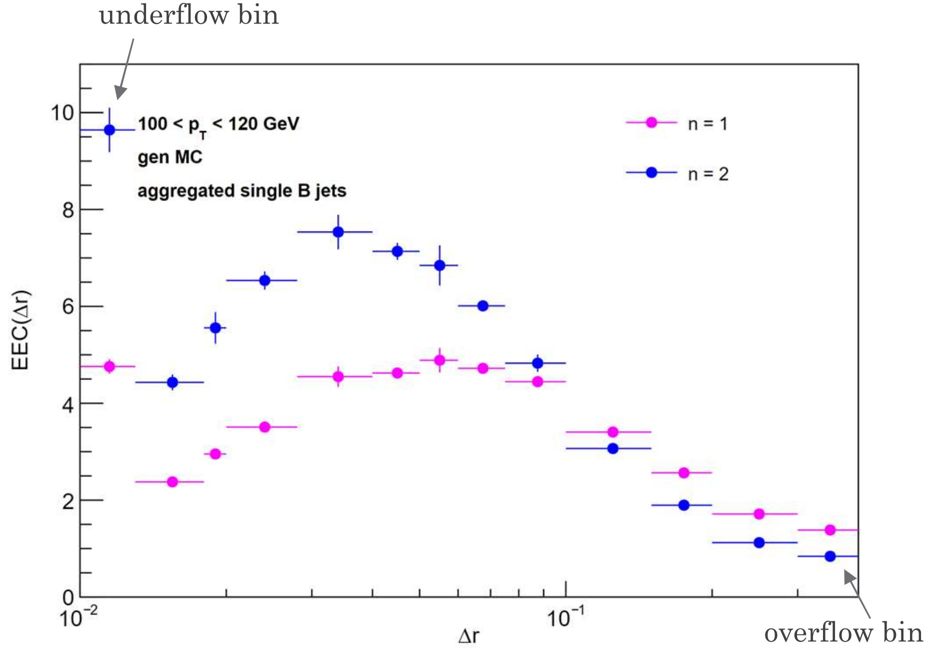
Implementation of EECs

- Following the latest PbPb CMS result : 2-point correlators

$$EEC(\Delta r) = \frac{1}{W_{pairs}} \frac{1}{\delta r} \sum_{jets \in [p_{T,1}, p_{T,2}]} \sum_{pairs \in [\Delta r_a, \Delta r_b]} (p_{T,i} p_{T,j})^n \qquad [13]$$

- How to construct the distribution:
  - Calculate $\Delta r = \sqrt{\Delta\phi^2 + \Delta\eta^2}$ for each pair
  - Fill a weighted histogram with weight $(p_{T,i} p_{T,j})^n$
  - Normalize

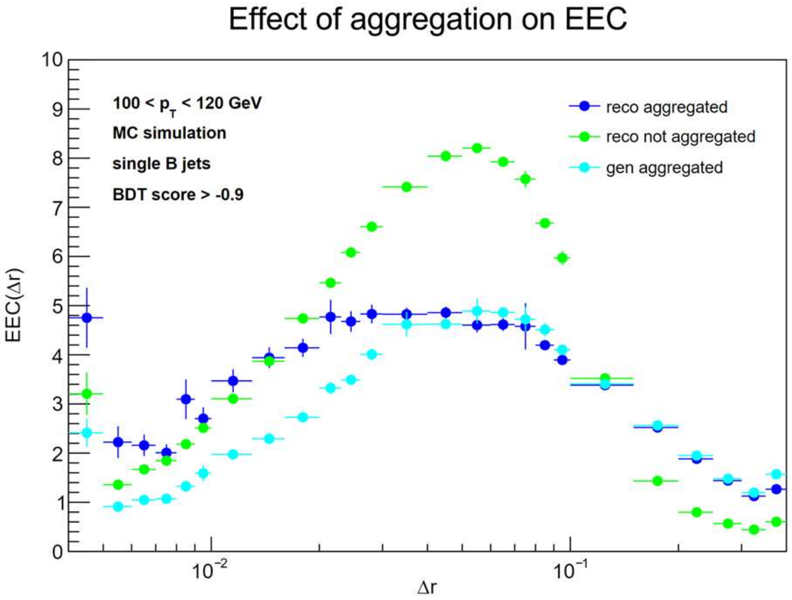
In our analysis:
  - n can be 1 or 2
  - Particles i, j are paired if they are different, no double counting

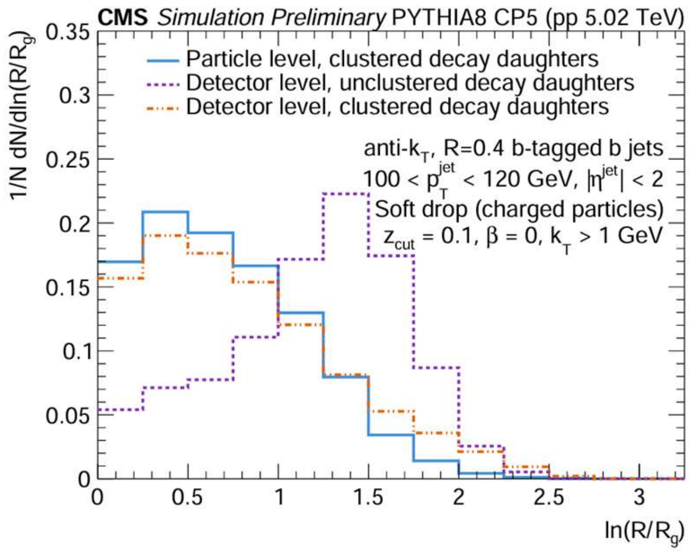


BDT working point

- Jet substructure analysis used a different BDT working point
- Aggregating with the same working point in EEC gives worse results

→Use a looser working point





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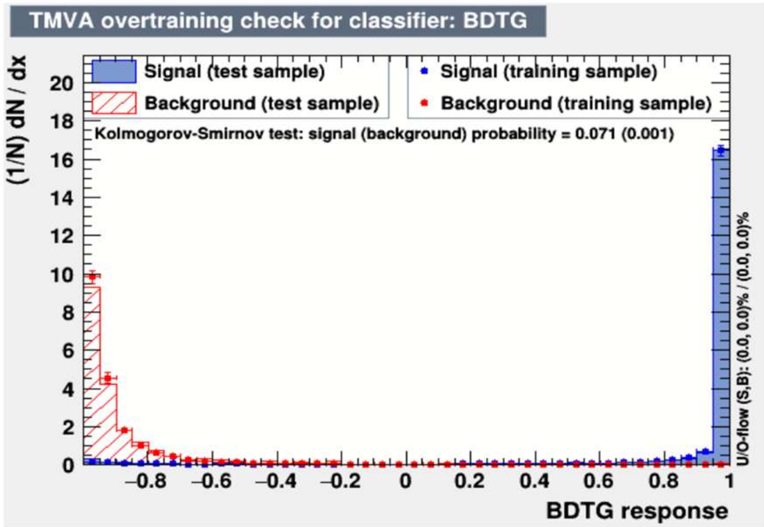


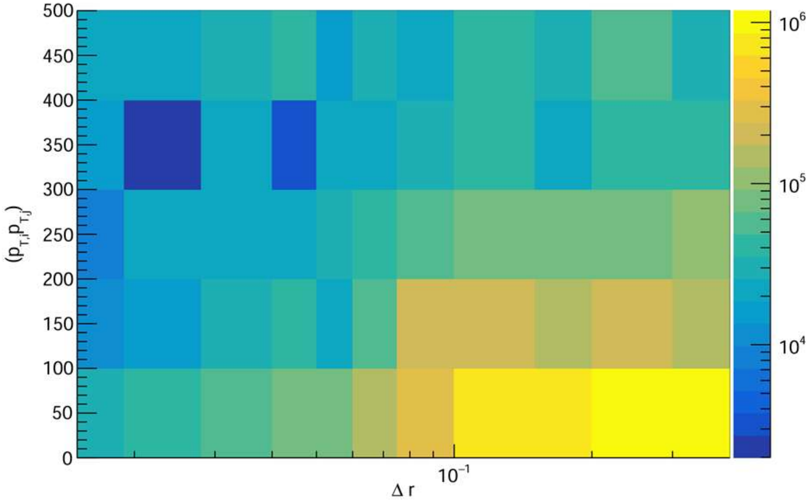
Recovering the EEC(Δr) distribution

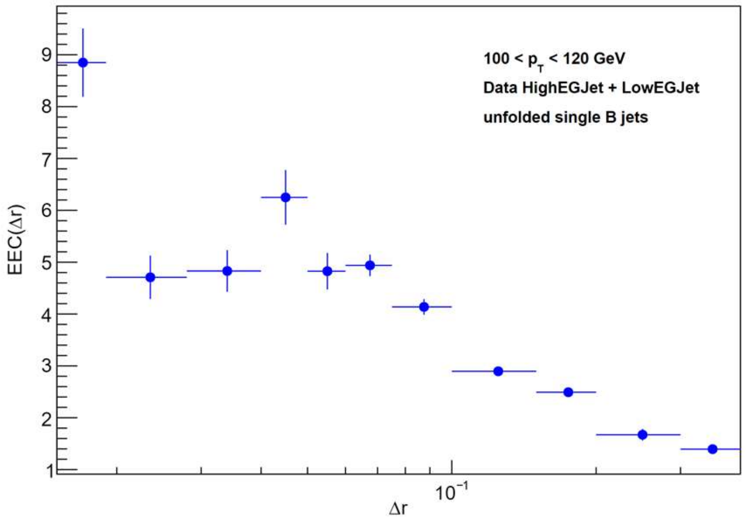
- What we want at the end:

$$EEC(\Delta r) = \frac{1}{W_{pairs}} \frac{1}{\delta r} \sum_{jets\,\in[p_{T,1}, p_{T,2}]} \sum_{pairs\,\in[\Delta r_a, \Delta r_b]} (p_{T,i} p_{T,j})$$

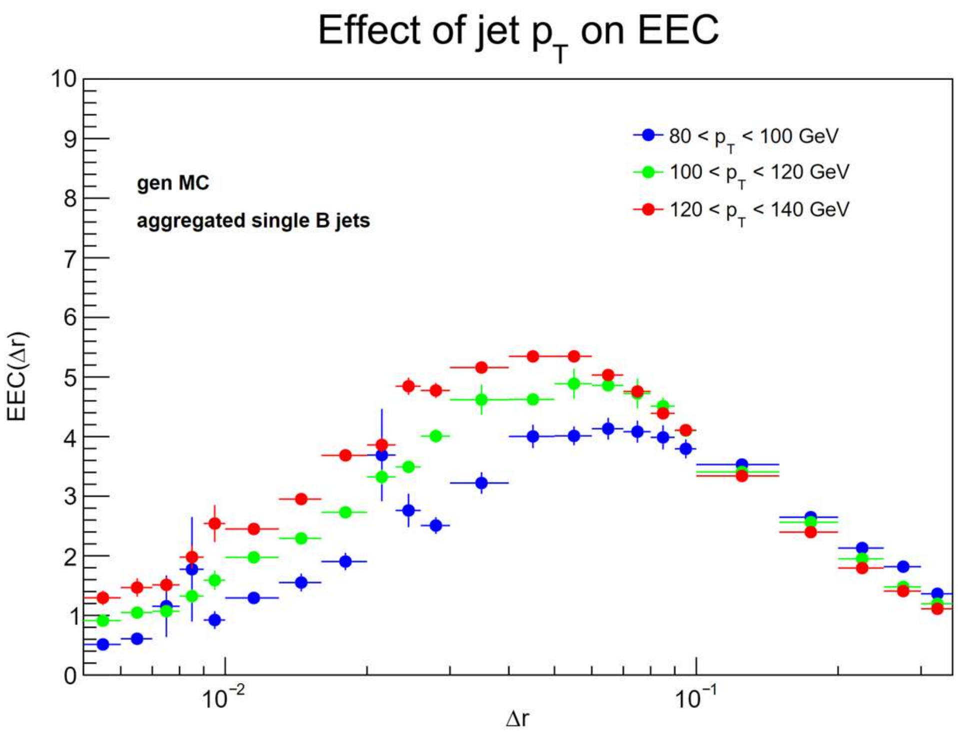
- What we have: Δr and $(p_{T,i} p_{T,j})$ in separate axes

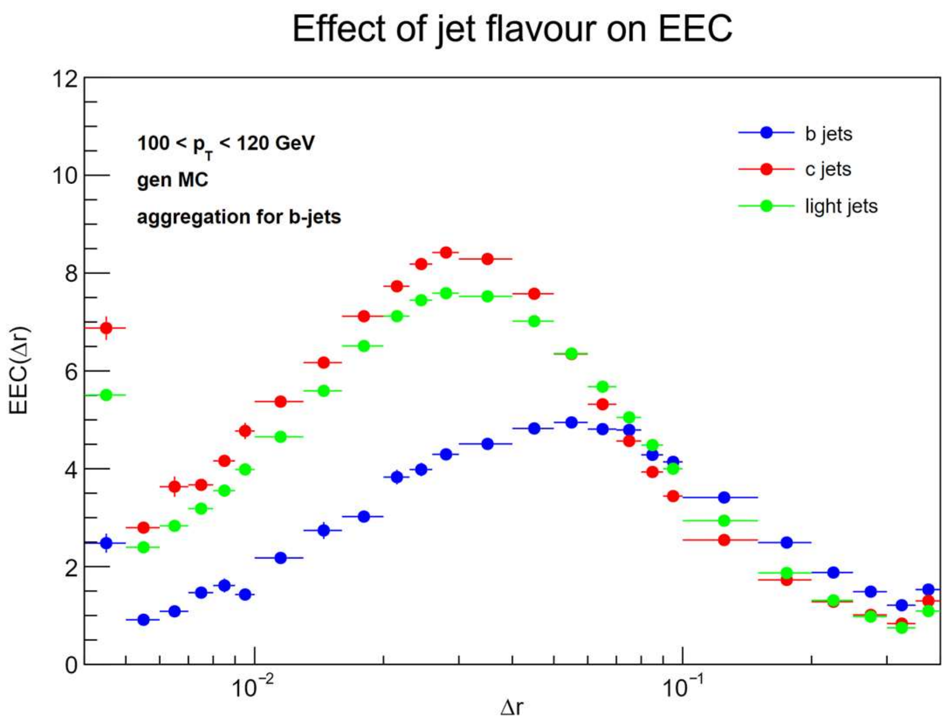
→ For every Δr integrate over $(p_{T,i} p_{T,j})$ and weight by the bin centre





Effect of jet energy and flavour





Extraction of α_S

- In single B hadron aggregated b-jets, reco MC sample