HP2023
Heavy-Flavour Panel Discussion

J. Brewer, S. Cao, L. Cunqueiro, A. Dainese, P.B. Gossiaux, A. Kalweit;
R. Rapp, M. Verweij and U. Wiedemann

Hard Probes 2023 / HF panel discussion

Introduction: Broader Context

(Q1) What are the transport properties of QCD matter and how do they emerge from the underlying interactions of quarks and gluons?

(Q2) What are the spectral functions of QCD matter and what can they tell us about the degrees of freedom at different temperatures?

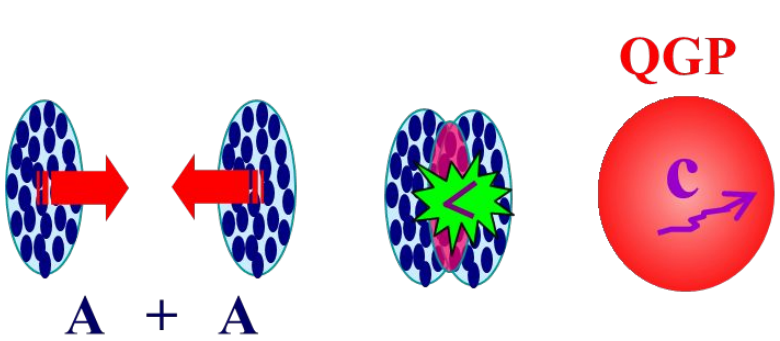
(Q3) How does the quantum many-body physics of the sQGP limit its transport coefficients?

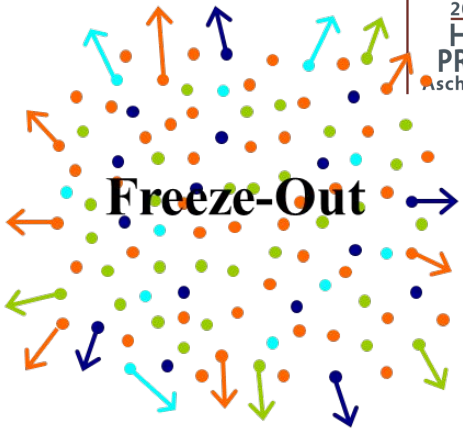
(Q4) What are the mechanisms of converting quarks and gluons into hadrons?

(Q5) How do elastic interactions in QCD matter at low p (diffusive regime) transition into inelastic reactions at high p (radiative regime)?

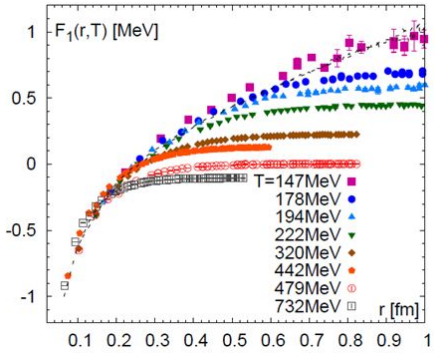
(Q6) How do jets evolve in QCD matter?

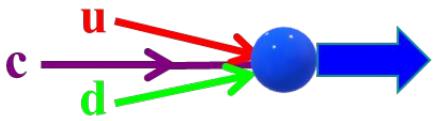
Why Heavy-Flavor Probes?





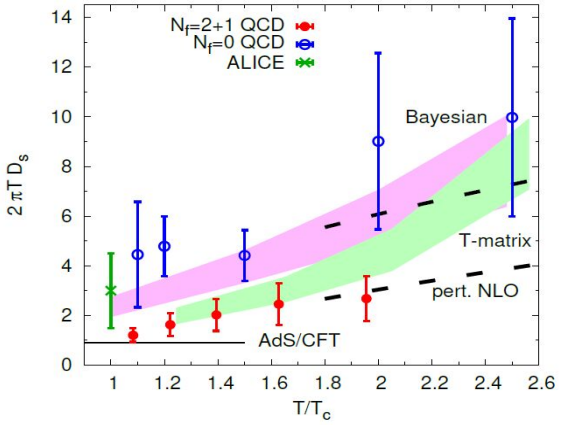
- **Large mass**: $m_Q >> \Lambda_{QCD}, T, T_c$
- Produced early, **diffuse** through QCD medium
- Delayed thermalization: gauge of **interaction strength**
- Ample connections to thermal **lattice QCD**
- **Hadronization:** reco. vs fragm. : **c** → **D**, D_s, Λ_c, **J/ψ**, …
- Discernible **transition** from diffusion to radiation
- Mass/dead cone effects in **radiation,** jet substructure





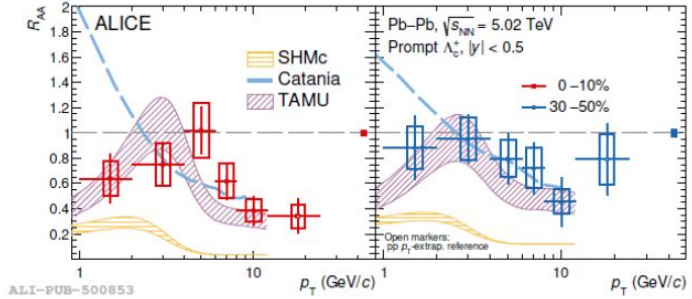
Recent Progress

- **Low-Momentum Brownian Motion**
  - v_2 + R_{AA} data: $1.5 < 2\pi T\, \mathcal{D}_s < 4.5$,
    supported by reaction task forces, lattice QCD,…
  - ➜ scattering rates $\Gamma_c \geq 0.5$ GeV ➜ **quantum liquid**
  - long-range non-perturbative forces essential



[Kaczmarek et al.]

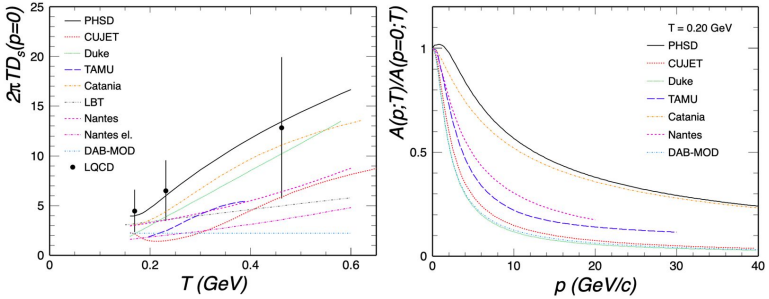
- **Hadro-Chemistry**
  - HQ coupling to collective light partons, SMCs
  - ➜ distinct patterns of charm-hadron production



- **High-Momentum Energy Loss**
  - Theoretical and experimental access to heavy flavor splittings

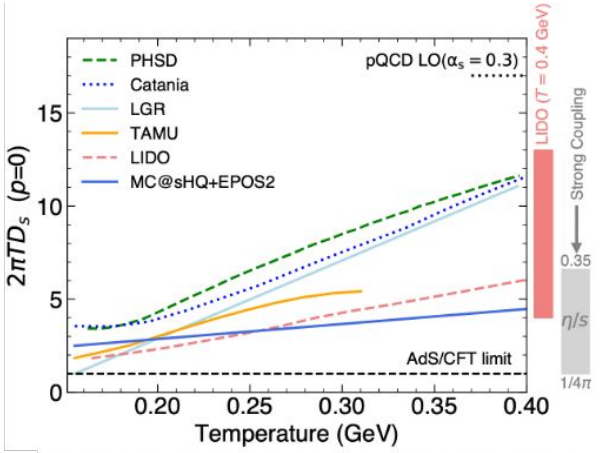
Low Momentum: Diffusion + Flow

- 3-momentum dependence of transport coeffs.
- Non-perturbative HQ-QGP interactions at low p_T
  - ➜ constraints on heavy-light interactions
  - ➜ implications for in-medium color potential and sQGP structure
  - ➜ charm vs. bottom



Trento HF WS '21

- Transport coefficients: community effort to move from "poor man's envelopes" to rigorous Bayesian inference?
  - ➜ include both meson and baryon data



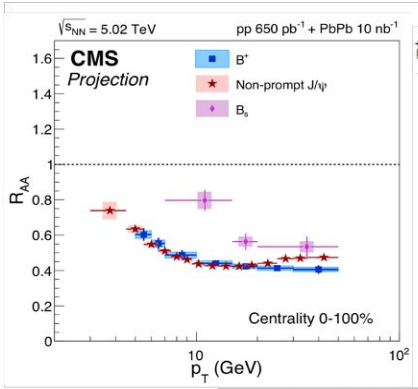
ALICE, A journey through QCD, arXiv:2211.04384

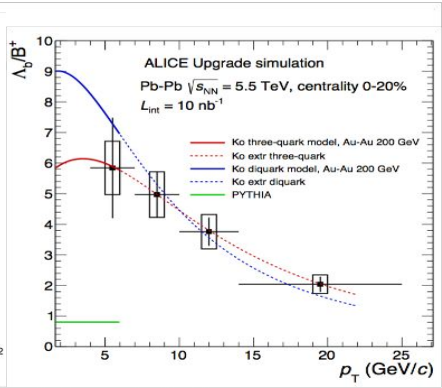
Low Momentum: Diffusion + Flow

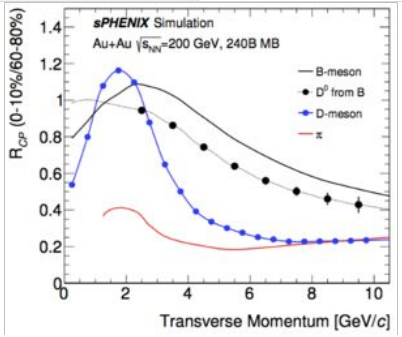
- Spatial diffusion coefficient D_S ~ independent of heavy quark mass (to be verified with more precise lattice calculations)
- Thermalization time ~ linear with mass:

$$\tau_Q = (m_Q/T)D_s$$

- D_S estimates lead to $\tau_{charm} = 3\text{–}9\ \mathrm{fm}/c$
- Is charm fully thermalised? How to assess that?
  - ➔ Correlations of charm and bulk flow?
- b quarks have thermalization time x3-4 larger than c
- B mesons down to p_T=0 (sPHENIX, future LHC runs)
- What additional information do we get from b quarks?

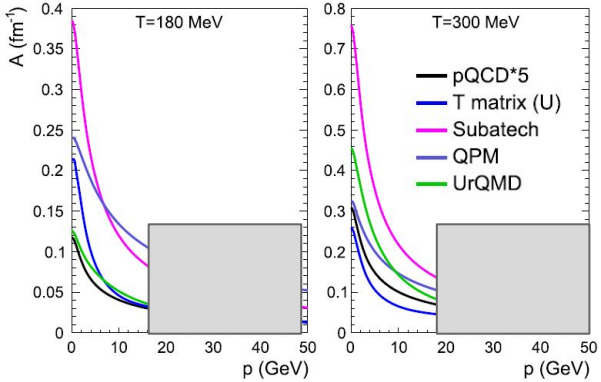




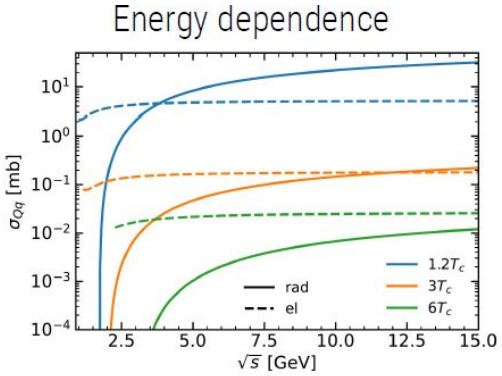


Intermediate Momenta: Kinetics + Hadronization

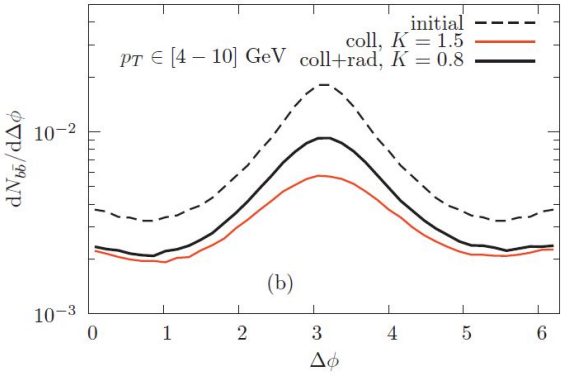
- Transition from: - nonperturbative to perturbative interactions
  - diffusion to radiation
- Single relaxation coefficient at low p vs. 3 transport / FP coefficients at intermediate p
- How to measure/constrain transport coefficients? Important role of correlations:
  - D-Dbar angular momentum correlations, ultimate measurement, longer term;
  - start D-h as proxy in upcoming LHC/RHIC runs
- Pros and cons of Fokker-Planck vs Boltzmann transport



EMMI RRTF report 2018



Ilia Grishmanovskii (DQPM approach, this conference)

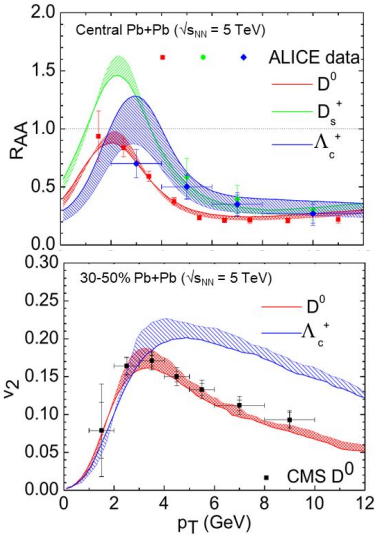


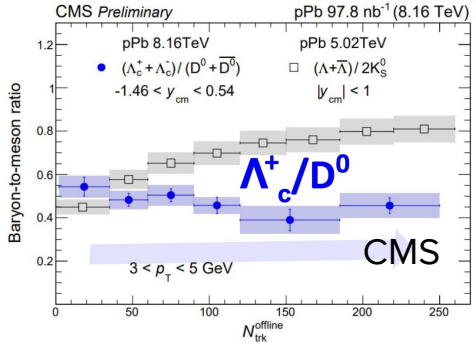
Nahrgang et al PRC90

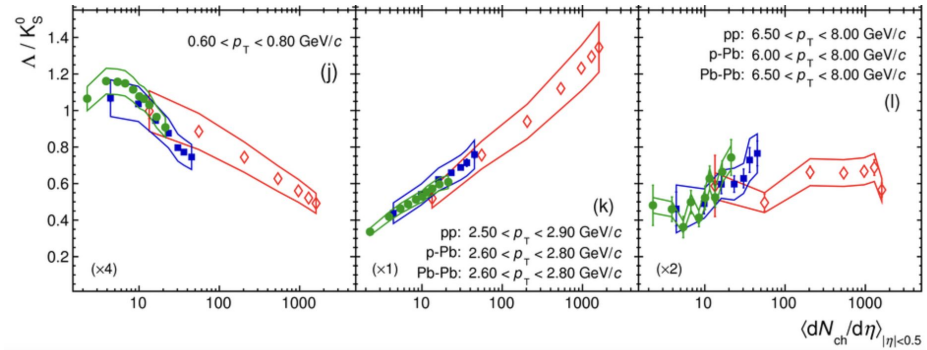
Hard Probes 2023 / HF panel discussion

Intermediate Momenta: Kinetics + Hadronization

- Approach to kinetic and chemical equilibrium:
  How can we compare to light flavour? Importance of hadron masses
- Chemistry + flow of excited baryon production
- Measurement of charm resonances? First measurements of Ds* appearing in our field, look for baryonic charm resonances?







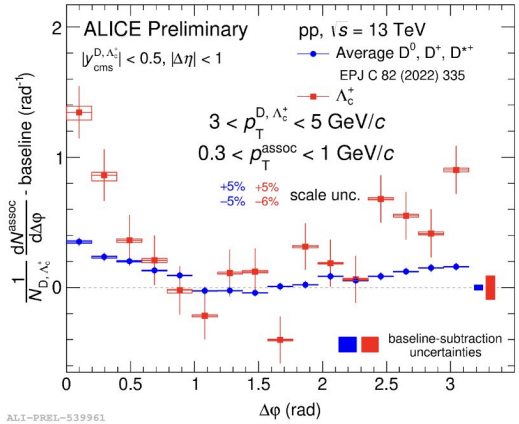
[ALICE, Phys. Rev. C 99, 024906]

Intermediate Momenta: Piecing the puzzle together

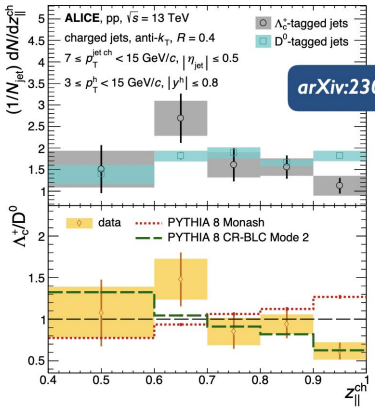
- Jet measurements and correlation measurements

Λ_c^+, D^0-hadron correlations

New preliminary



Λ_c^+ vs. D^0 fragmentation $z_{||}^{ch} = \frac{\boldsymbol{p}_{jet} \cdot \boldsymbol{p}_{\Lambda_c^+}}{\boldsymbol{p}_{jet} \cdot \boldsymbol{p}_{jet}}$



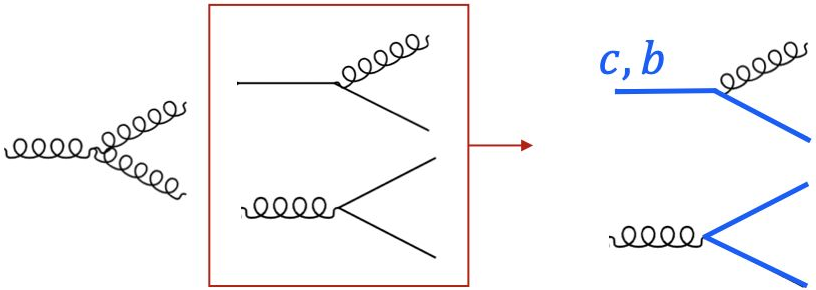
arXiv:2301.13798

Softer fragmentation of Λ_c^+

Motivation for heavy flavor in jets

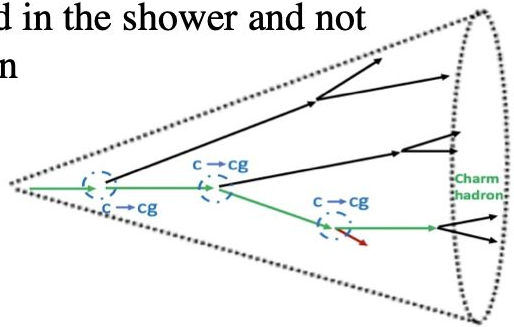
Flavor-dependence of splittings

At high splitter energies, access light flavor splittings



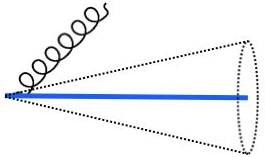
- Heavy flavor is preserved in the shower and not produced at hadronization

Used in ALICE [2106.05713]



Mass-dependence of splittings

At low splitter energies, mass effects are important



$\theta \sim m_Q/E$

- suppressed vacuum radiation around massive quark

ALICE [2106.05713]

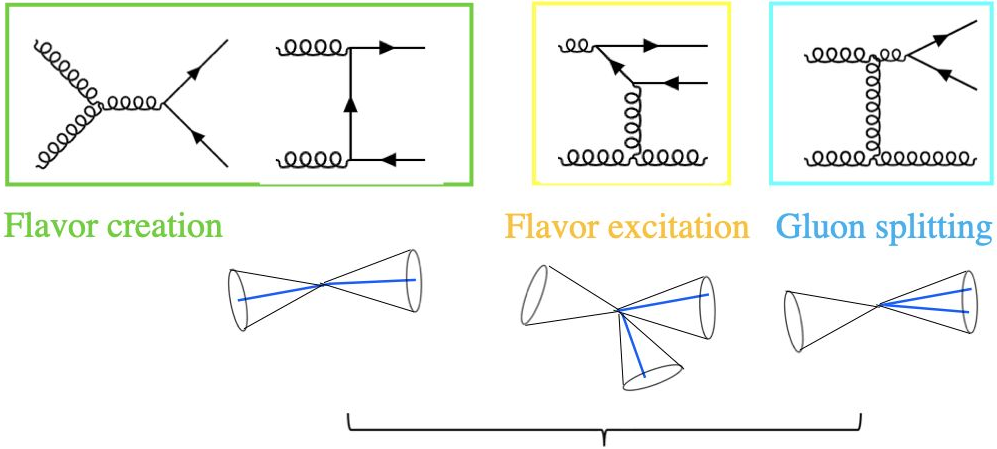
- In heavy-ions: isolate medium-induced emissions inside the deadcone?

Armesto, Salgado, Wiedemann [0312106]
Cunqueiro, Napoletano, Soto-Ontoso [2211.11789]

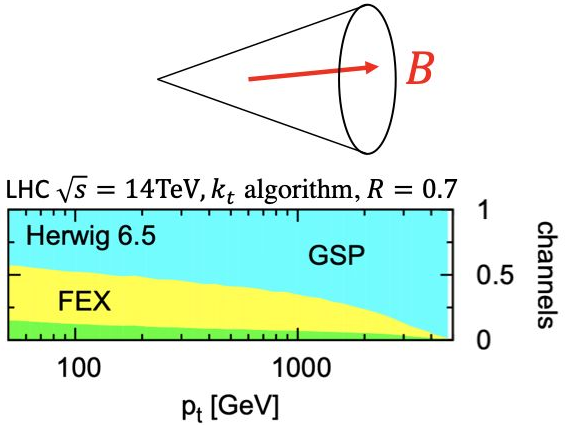
See also Li, Vitev [1801.00008], Attems et al. [2203.11241, 2209.13600]

All require having good control over flavor of splittings

Leading processes for heavy quark production



Single-HF jets include a lot of gluon splitting



Banfi, Salam, Zanderighi [0704.2999]

Distinguish with event structure, jet substructure, decay topology?

Reconstructed heavy hadron

- Hadron kinematics → reconstruct splittings
- Lower statistics (from rare decays)

Displaced vertex

- Tag that there was a heavy hadron without explicit kinematics

Identifying quark-initiated jets

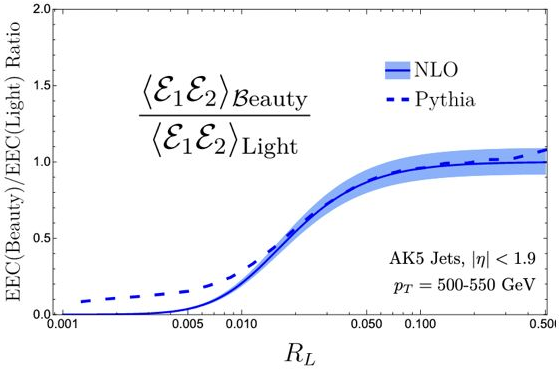
- How effectively do back-to-back HF jets isolate quark-initiated jets?
- Or, can gluon splitting contributions be removed without identifying both hadrons (e.g., using substructure with 0 or 1 hadrons)?

Method using muon correlations in ATLAS [Sebastian Tapia, Wed]

What if (one or both) HF hadrons are not reconstructed?

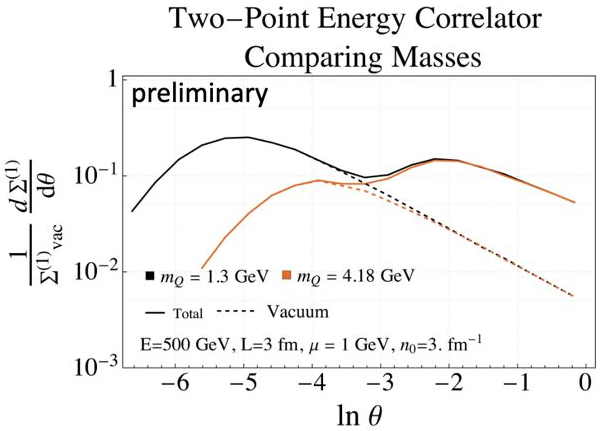
- How well can energy flow in HF-tagged jet constrain the kinematics of the HF hadron?
- Do unreconstructed hadron decay products distort jet substructure?

Jet tree versus correlators: complementary, theoretical/experimental advantages?



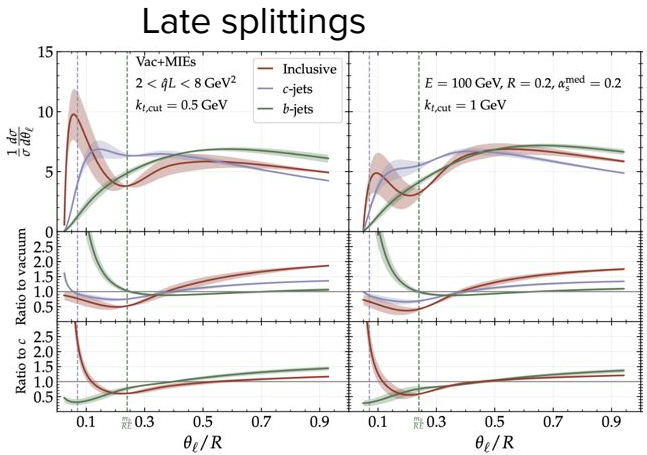
Craft, Lee, Mecca, Moult, 2210.09311

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



Holguin et al, this conference

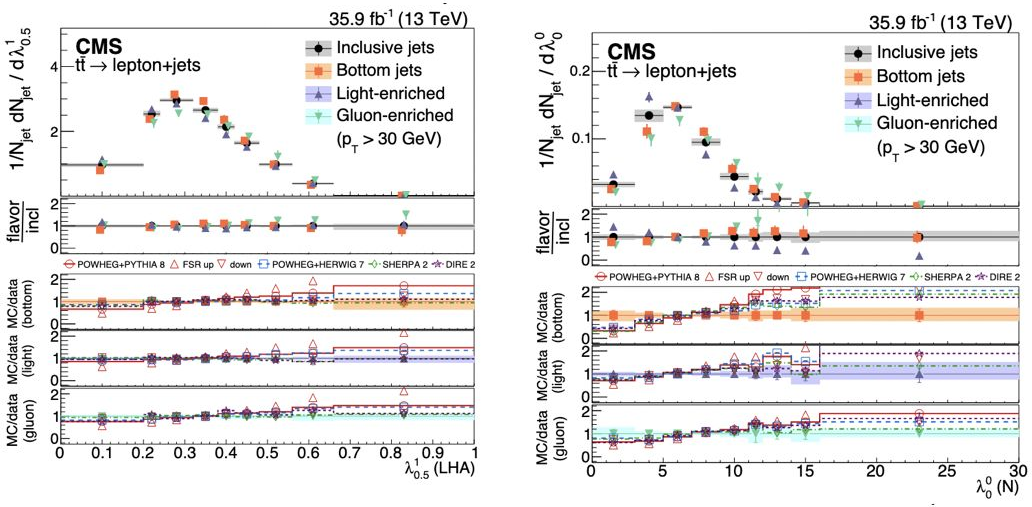
Strong sensitivity to dead cone in EEC



Ontoso et al, this conference

Exposing the filling of the dead cone with the jet tree

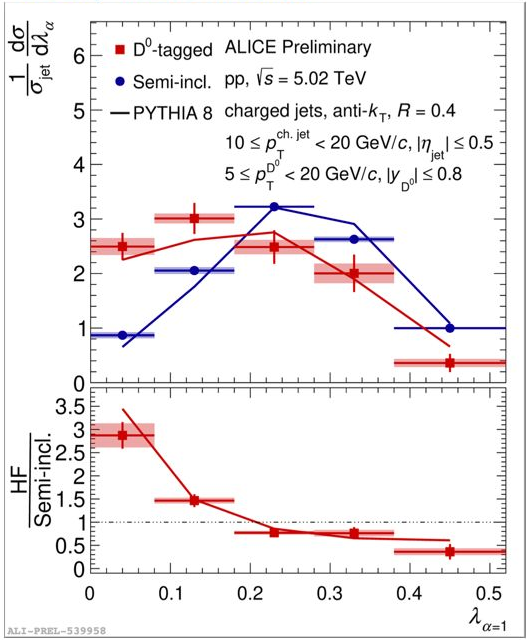
b/c-tagging vs full hadron reco and substructure



Bottom jet multiplicity and angularity very similar to inclusive's
Light-enriched jets have smaller multiplicities than b-jets
Probably due to the impact of the heavy flavour hadron decay daughters

CMS, Phys.Rev.D.98 09 (2014)

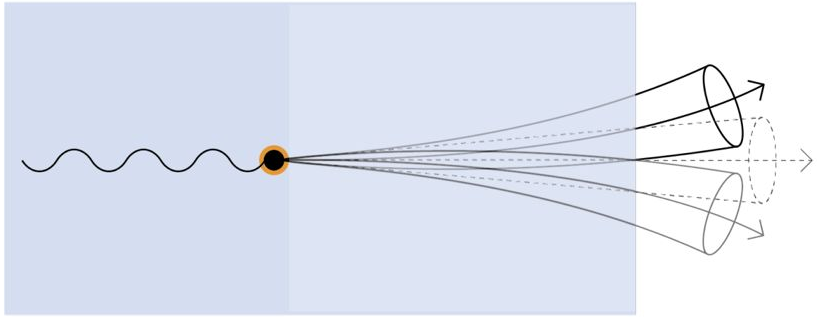
ALICE, this conference



Strong separation, D-jets are narrower

Other interesting mass effects

Mayo et al, this conference



$$\hat{q}_{ij} = \frac{1}{2}\hat{q}\left[1+\frac{m^2}{E^2}\right]\left[\left(1-\frac{m^2\mathbf{u}^2}{2E^2}\right)\delta_{ij} - u_i u_j \frac{m^2}{E^2}\right]$$

depends on mass

anisotropic quenching for massive quarks