Observation of the dead cone effect in charm and bottom quark jets and its QCD explanation

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The dead cone effect in QCD

\[ d \sigma_{Q \rightarrow Qg} = C_F \frac{\alpha_s(k_t)}{\pi} \frac{y^2 dy^2}{(y^2 + \theta_m^2)^2} \frac{dz}{z} \; ; \; y = 2 \sin(\theta/2) \]

\[ y \approx \theta \Rightarrow d \sigma_{Q \rightarrow Qg} \approx C_F \frac{\alpha_s(k_t)}{\pi} \frac{\theta^2 d \theta^2}{(\theta^2 + \theta_m^2)^2} \frac{dz}{z} \]


Dead cone in b- and c-jets

Soft gluons $\sim 1/z$
only for $\theta \gg \theta_m$

Suppression of soft
and hard $(k_t \ll k)$
gluons at $\theta \ll \theta_m$
QCD MLLA dead cone spectra

\[ e^+e^- \rightarrow b\bar{b} + X \]

\[ D_q(\xi, W) \]

QCD MLLA prediction for momentum spectra \( D_Q(\xi) \) of accompanying particles in heavy quark jets

\[ D_Q(\xi, W) = D_q(\xi, W) - D_q(\xi - \bar{\xi}_Q, m_Q\sqrt{e}) \]

\[ \bar{\xi}_Q = \ln(1/\bar{x}_Q), \bar{x}_Q: \text{average } x_Q \]

LPHD: hadronisation correction via scaling factor \( K^{ch} \approx 1.28 \) at \( \sqrt{s} = m_Z \)

Momentum space analysis: no direct dependence on jet axes

Dead cone in b- and c-jets

LEP data “raw” (OPAL)

Tag B or C hadron decay in one Thrust-hemisphere, measure tracks in opposite

Correct for track efficiency and event selection biases to “hadron level“ ($\tau < 3 \times 10^{-10} \text{ s}$)

Accompanying particles and B or C hadron decay products

(Could separate B or C hadron decay products with track IP)

Decay and prompt particles

Separate B or C hadron decay products and prompt particles using MC (Pythia 8.3)

Apply to data with corrections (scaling) and systematics for B decay multiplicity in MC

LEP data “cooked”

Subtract MC simulated $\xi$ spectra of B or C hadron decay products

Scale MC to $n_b^{\text{dec}} = 11.10 \pm 0.18$; MC consistent w/ $n_c^{\text{dec}} = 5.2 \pm 0.3$

Dead cone in b- and c-jets
Dead cone effect

Dead cone confirmed at $> 5\,\sigma$, ratios $Q/uds$ up to factor 10

Dead cone in $b$- and $c$-jets
Dead cone effect in MLLA

QCD MLLA dead cone subtraction consistent with data

Prediction: \( D_Q(\xi, W) = D_q(\xi, W) - D_q(\xi - \xi_Q, m_Q \sqrt{e}) \)
Excess at large $\xi_p$

MLLA prediction at large $\xi_p$ above data

Corresponds to result of multiplicity analysis: $\delta_{bl}^{\text{MLLA}} - \delta_{bl}^{\text{exp}} = 1.26 \pm 0.42$

Dead cone in $b$- and $c$-jets

Sensitivity to b quark mass

Fit central region $1.6 < \xi_p < 2.6$ with free energy scale $W_0$

$W_0^{\text{exp}} = (7.2 \pm 0.5) \text{ GeV (DELPHI, OPAL)}$

$W_0^{\text{MLLA}} = m_b \sqrt{e} = (8.0 \pm 0.2) \text{ GeV} \quad (m_b(m_b) = (4.85 \pm 0.15) \text{ GeV})$

Sensitivity to $m_b(m_b)$ at few % level, but not competitive with other analyses

MLLA LPHD in good agreement with data where approximations valid

Dead cone in b- and c-jets
Relevant today?

- Yes

- Heavy flavour jet tagging at LHC
  - Dist’n of $x = p/p_{jet}$ of acc. part. sensitive to $m_Q$
  - Inclusive (DNN) flavour tagging should profit

- MC heavy flavour modelling
  - Compare acc. part. and Q decay $\xi$ spectra

- Top quark fragmentation
  - Measure acc. part. spectra in top decays?
Conclusion

• Dead cone effect confirmed with LEP data
  - Momentum space analysis for b and c-quark jets
  - $E_{\text{jet}} \approx 45 \text{ GeV}$ (ALICE $E_{\text{Radiator}} < 10 \text{ GeV}$)
  - Model independent (except B, C decay subtraction)
  - No direct jet axis dependence $\Rightarrow$ effect larger w.r.t. ALICE

• Consequences for top quark dead cone studies at LHC?
Outtakes and backup

Dead cone in b- and c-jets
ALICE in dead cone land

Charm tagged jets (anti-$k_t$ R=0.4) (D$^0$ tag), de-cluster with C/A

(Sub)jet axis = c quark direction?

\[
\text{Angle( c-subjet, subjet ) } \overset{\text{def}}{=} \theta
\]

Energy of split (sub)jet \( \overset{\text{def}}{=} E_{\text{Radiator}} \)

\[
R(\theta) = \frac{1/N_c \, dn_c / d\ln(1/\theta)}{1/N_{\text{incl}} \, dn_{\text{incl}} / d\ln(1/\theta)}
\]

in bins of \( E_{\text{Radiator}} \)

[ALICE coll., Nature 605 (2022) 440]
ALICE in dead cone land

\[ R(\theta) = \frac{1/N_c}{1/N_{incl}} \frac{dn_c/d\ln(1/\theta)}{dn_{incl}/d\ln(1/\theta)} \]

Suppression of up to factor \( \sim 2^{\ln(1/\theta)} \)

Dead cone in b- and c-jets

[ALICE coll., Nature 605 (2022) 440]
Introduction

Chudakov effect ... for quarks and gluons

Consider transverse separation of $\gamma$ (gluon) from $e^+e^-$ (parton) pair with $\Delta t \Delta E > \frac{\hbar}{2} \Rightarrow$ angular ordering $\theta_{e^+e^-} > \theta_{e^-\gamma}$ ($\theta_{\text{partons}} > \theta_{\text{parton,g}}$)

Soft gluon interference

Charged particle momentum spectra $\xi_p = \log(1/x_p), \ x_p = 2p/\sqrt{s}$

Soft gluon coherence in $4 < \xi_p < 6$

Quantitative pQCD in MLLA + LPHD
Parton spectra $\approx$ hadron spectra up to normalisation

Chudakov at work