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

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Finally, Scientists Prove the 'Dead Cone Effect,' Shaking Up Particle Physics

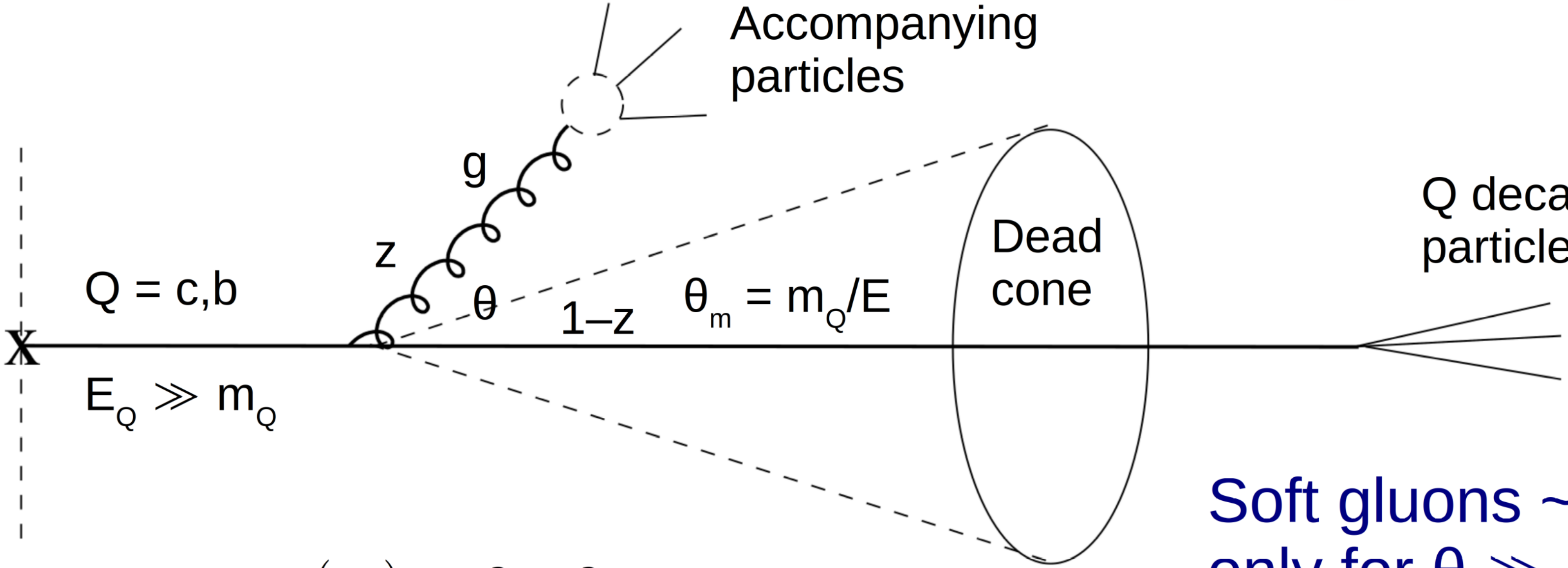
Operators of the ALICE detector have observed the first direct evidence of the "dead cone effect," allowing them to assess the mass of the elusive charm quark.

BY ROBERT LEA PUBLISHED: JUN 27, 2022

SAVE ARTICLE

CERN

The dead cone effect in QCD



$$d\sigma_{Q\to Qg} = C_F \frac{\alpha_S(k_t)}{\pi} \frac{y^2\, dy^2}{(y^2+\theta_m^2)^2} \frac{dz}{z} \quad ; \quad y = 2\sin(\theta/2)$$

$$y \approx \theta \;\Rightarrow\; d\sigma_{Q\to Qg} \approx C_F \frac{\alpha_S(k_t)}{\pi} \frac{\theta^2\, d\theta^2}{(\theta^2+\theta_m^2)^2} \frac{dz}{z}$$

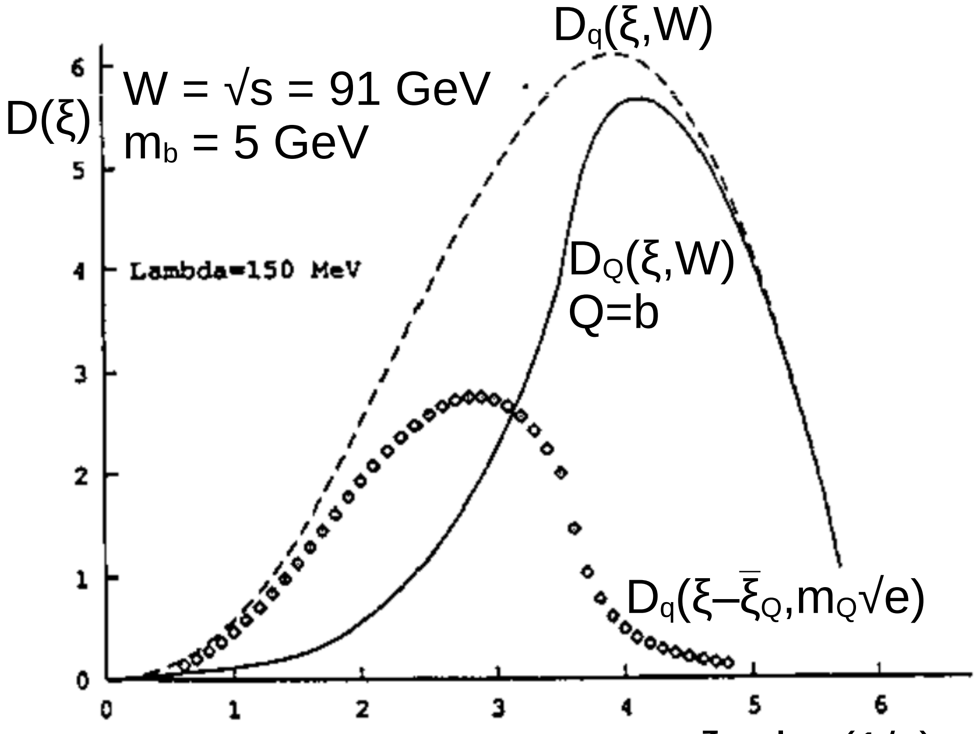
[Dokshitzer, Khoze, Troyan,
J. Phys. G17 (1991) 1481, 1602]

Soft gluons ~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

$e^+e^- \rightarrow b\bar{b} + X$



[Dokshitzer, Khoze, Troyan, J. Phys. G17 (1991) 1481, 1602]

$\xi = \log(1/x)$
$x = 2p/\sqrt{s}$

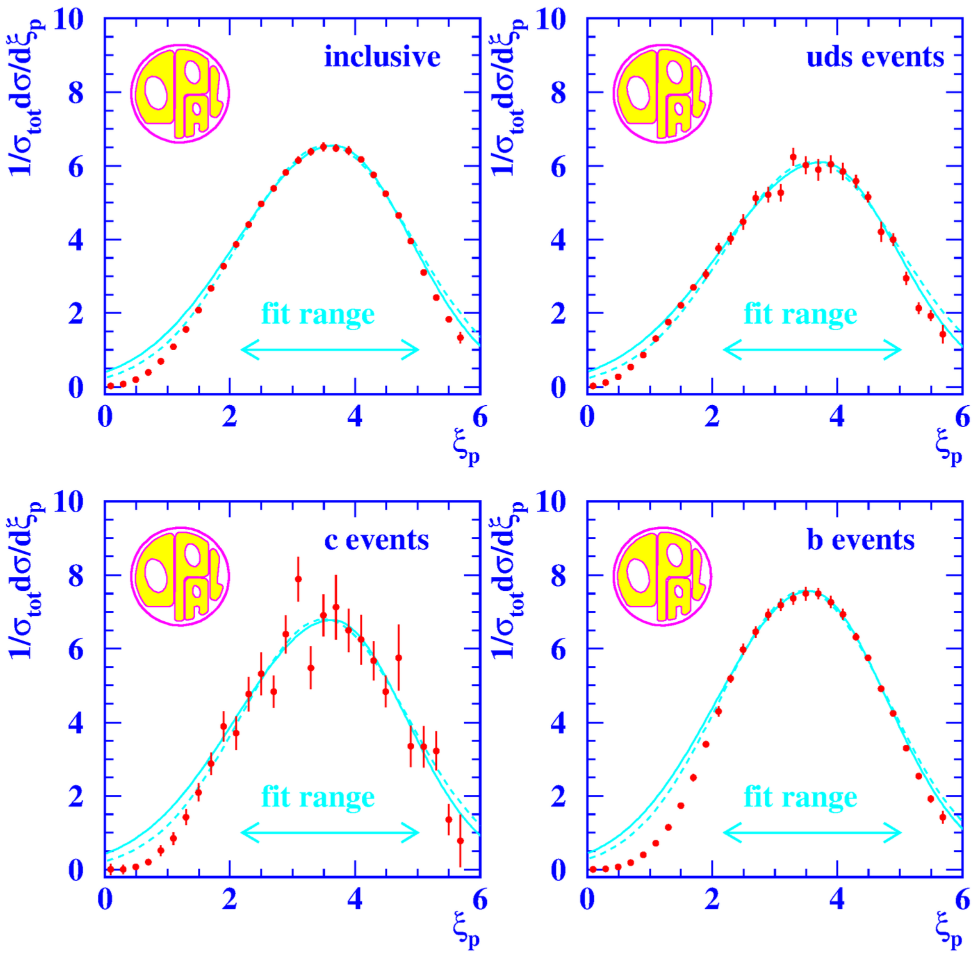
QCD MLLA prediction for momentum spectra $D_Q(\xi)$ of *accompanying particles* in heavy quark jets

$D_Q(\xi,W) = D_q(\xi,W) - D_q(\xi-\bar{\xi}_Q, m_Q\sqrt{e})$
$\bar{\xi}_Q = \ln(1/\bar{x}_Q)$, $\bar{x}_Q$: 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

LEP data “raw” (OPAL)



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

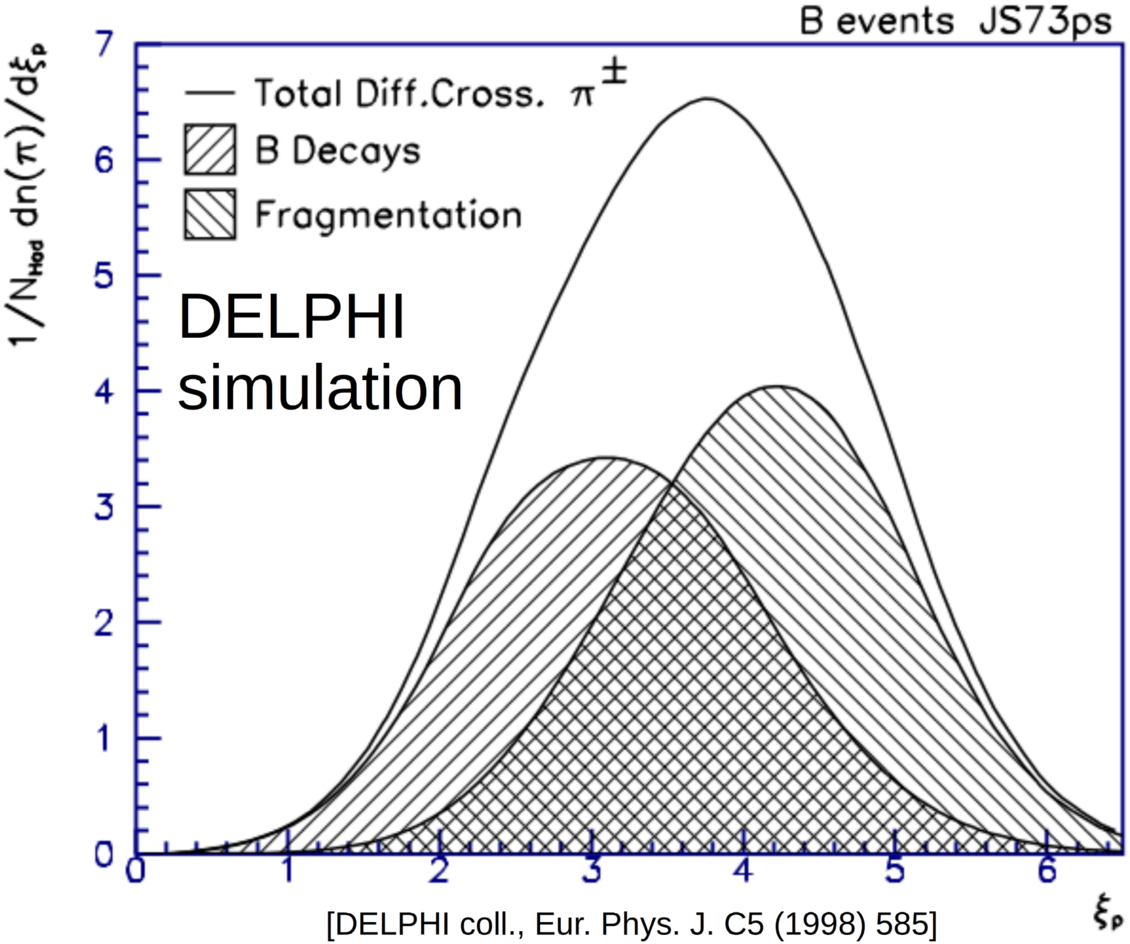
Correct for track efficiency and event selection biases to “hadron level“ ($\tau < 3\times10^{-10}$ s)

Accompanying particles *and* B or C hadron decay products

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

[OPAL coll., Eur. Phys. J. C7 (1999) 369]

Decay and prompt particles



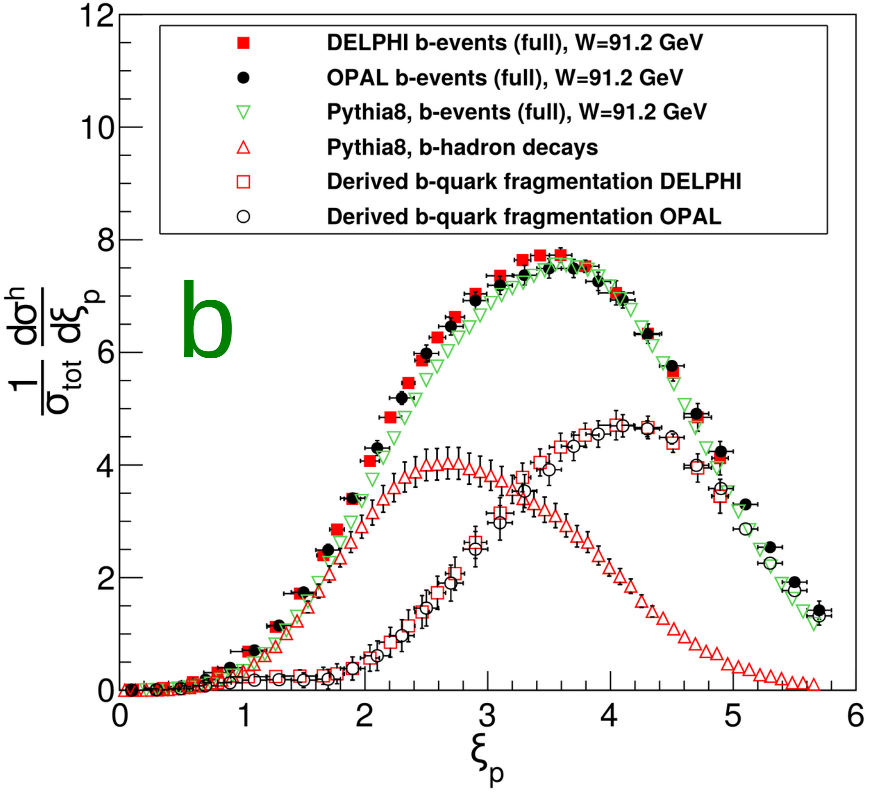
[DELPHI coll., Eur. Phys. J. C5 (1998) 585]

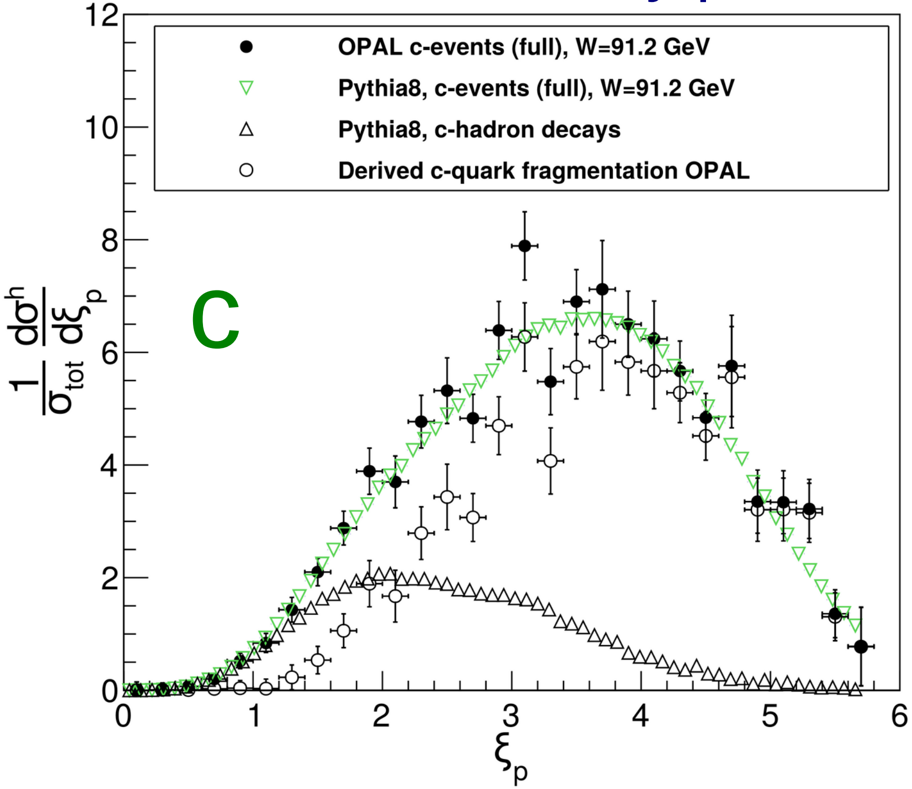
Separate B or C hadron decay products and prompt particles using MC (Pythia 8.3)

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

LEP data “cooked”

Subtract MC simulated ξ spectra of B or C hadron decay products

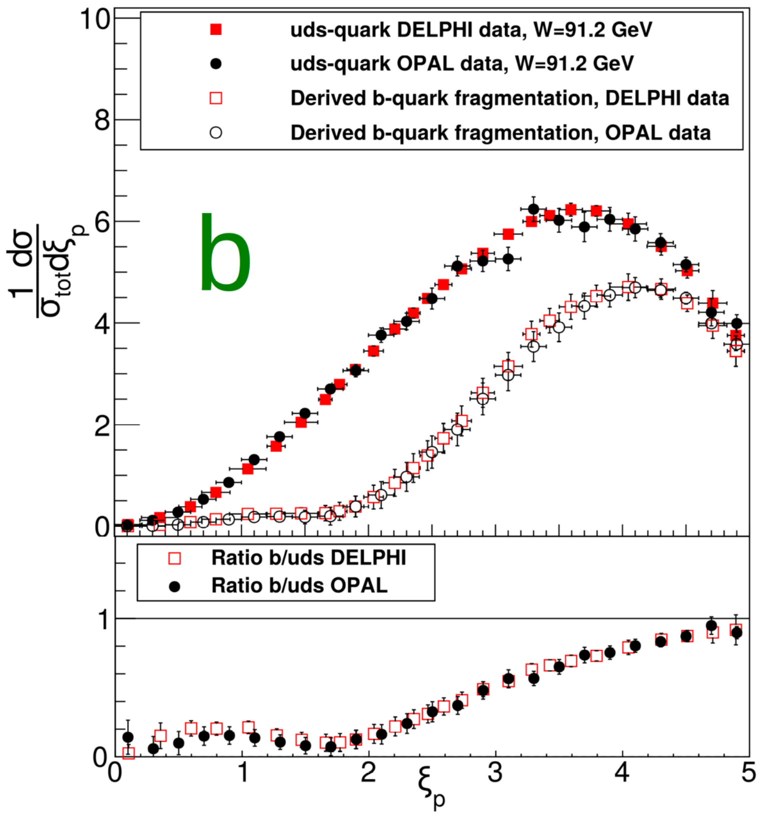


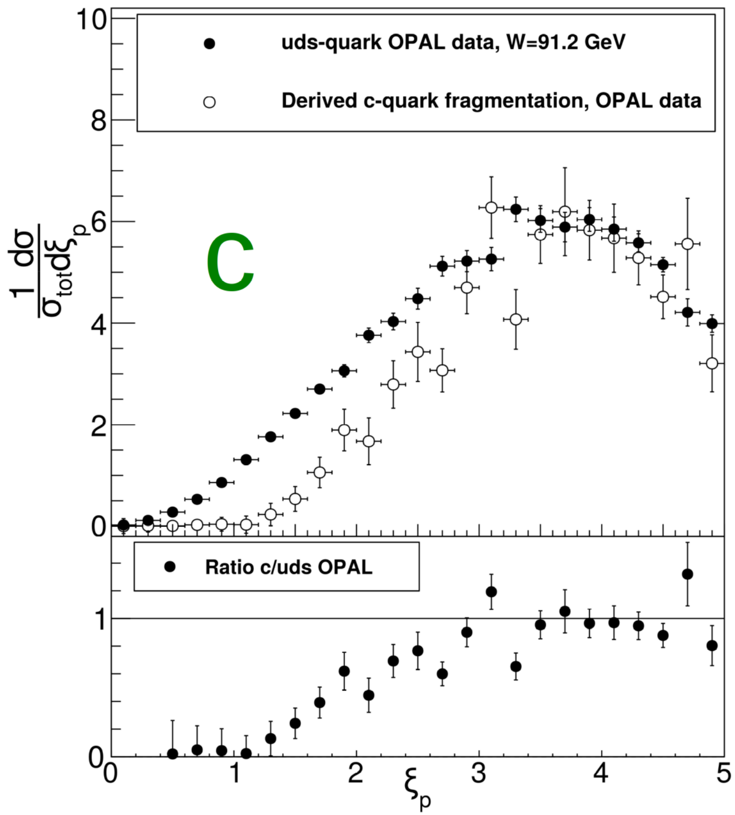


Scale MC to $n_b^{dec} = 11.10 \pm 0.18$; MC consistent w/ $n_c^{dec} = 5.2 \pm 0.3$

Dead cone effect

Dead cone confirmed at > 5 σ, ratios Q/uds up to factor 10

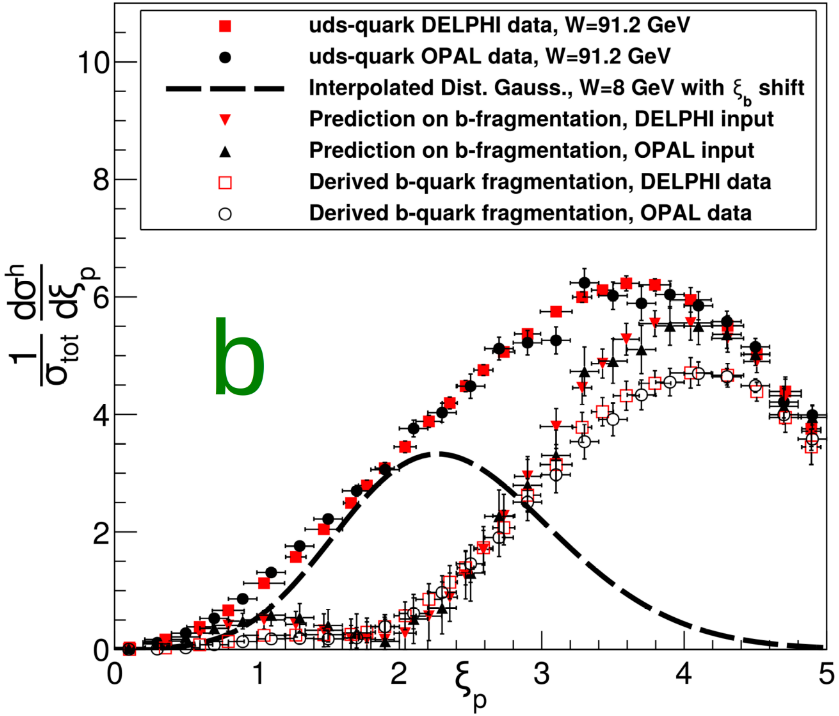


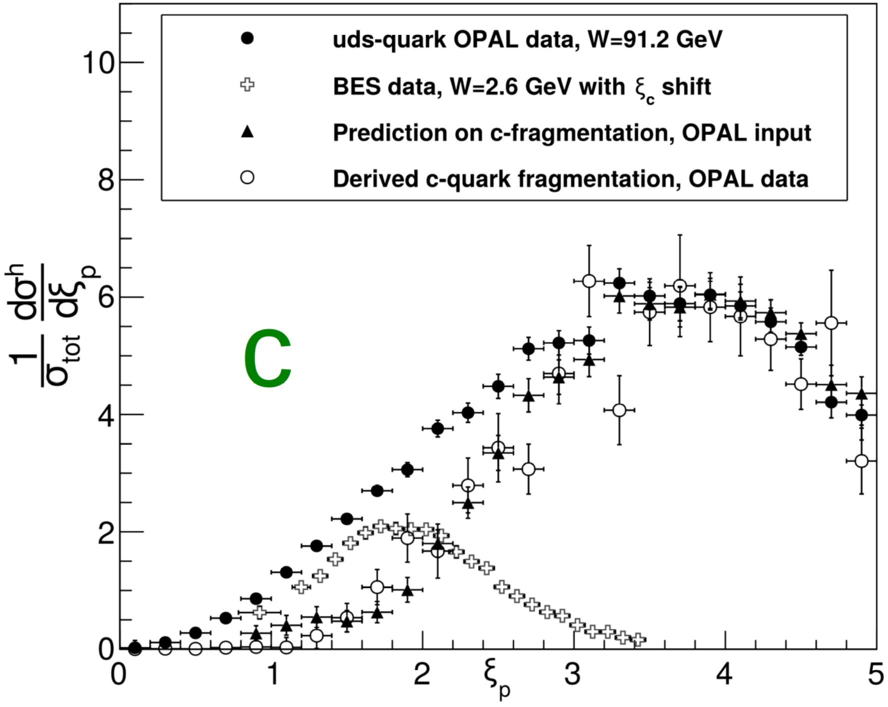


Dead cone effect in MLLA

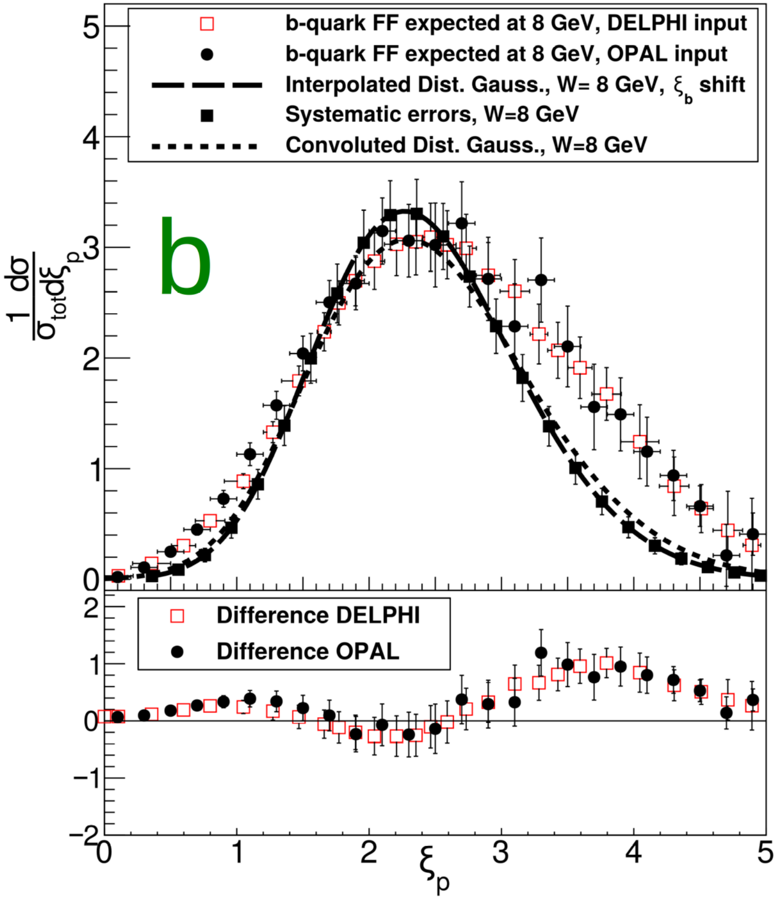
QCD MLLA dead cone subtraction consistent with data

Prediction: $D_Q(\xi,W) = D_q(\xi,W) - D_q(\xi-\bar{\xi}_Q, m_Q\sqrt{e})$



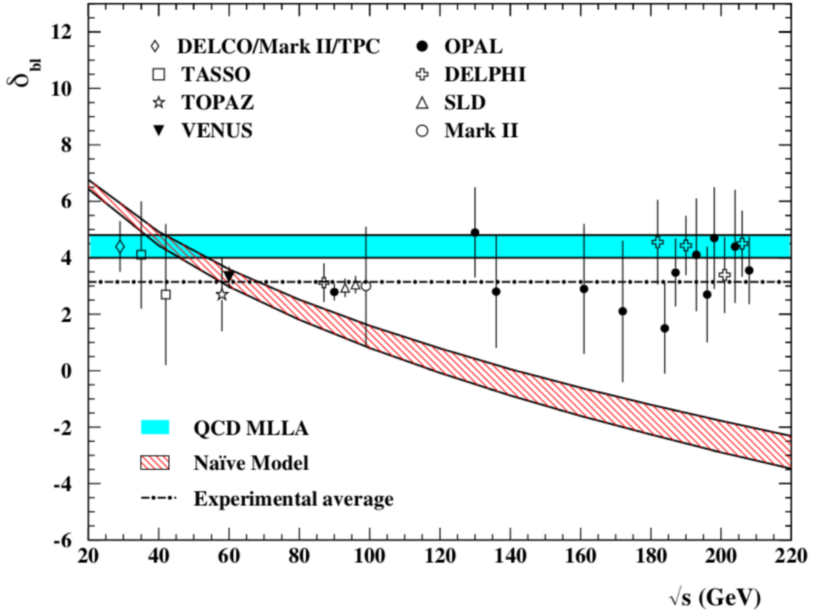


Excess at large ξ_p



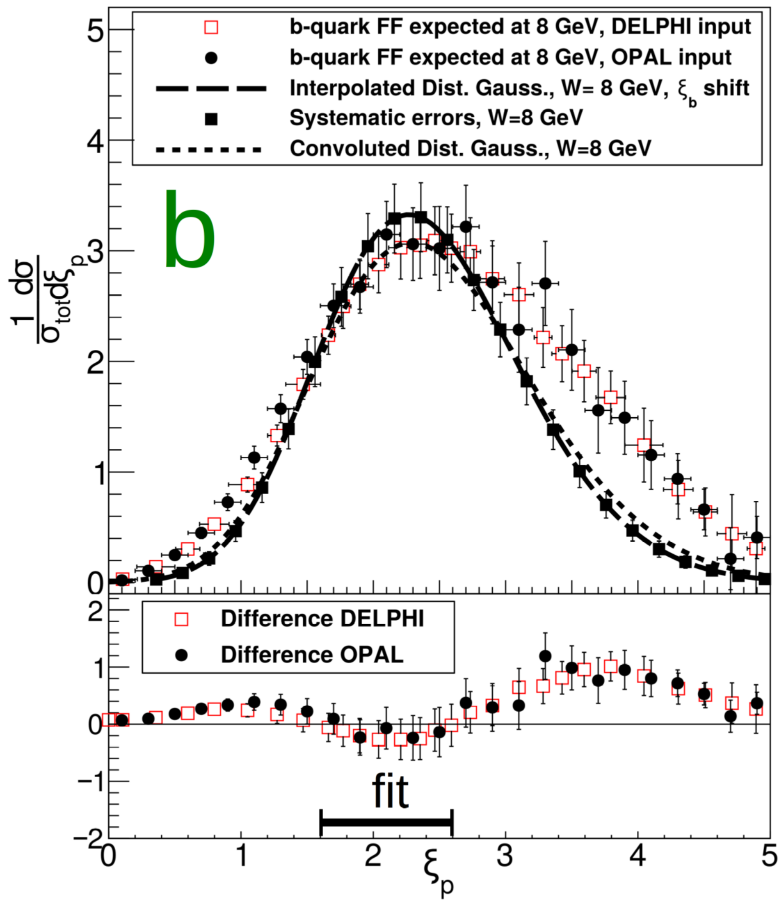
MLLA prediction at large ξ_p above data

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



[Dokshitzer, Fabbri, Khoze, Ochs, Eur. Phys. J. C45 (2006) 387]

Sensitivity to b quark mass



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

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

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

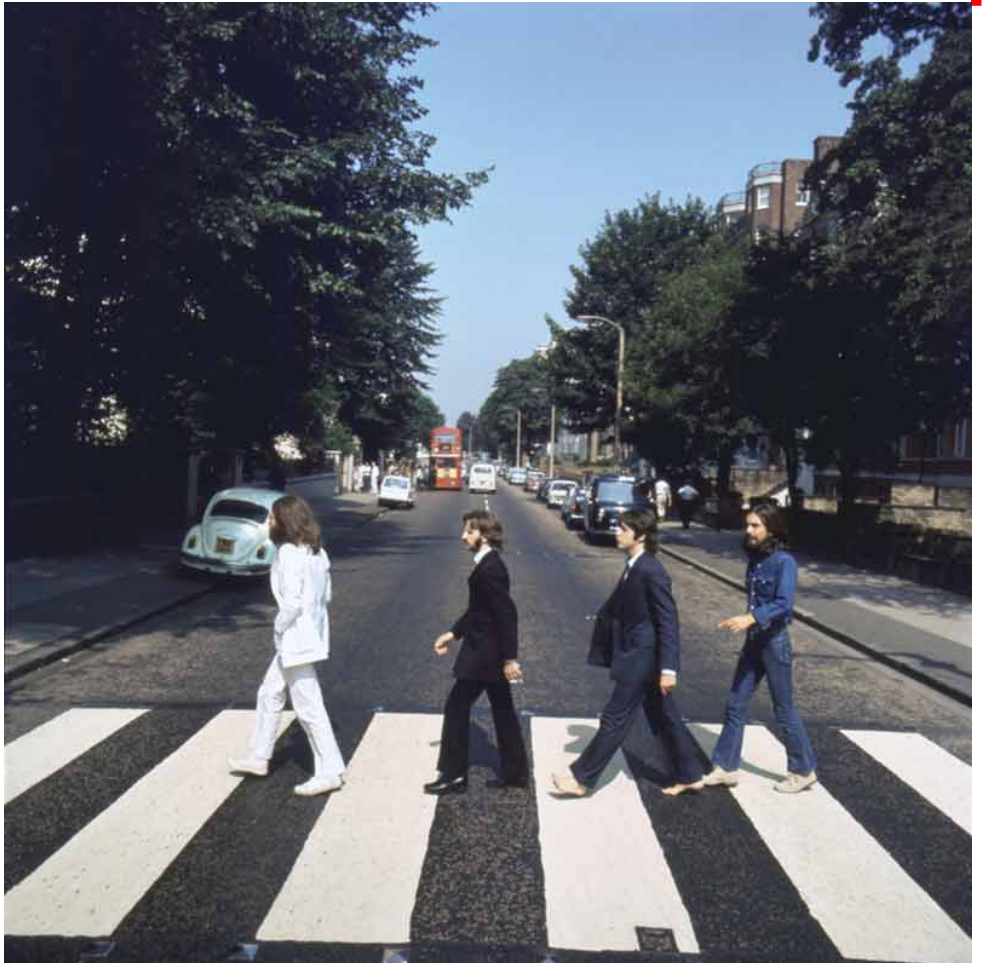
Relevant today?

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

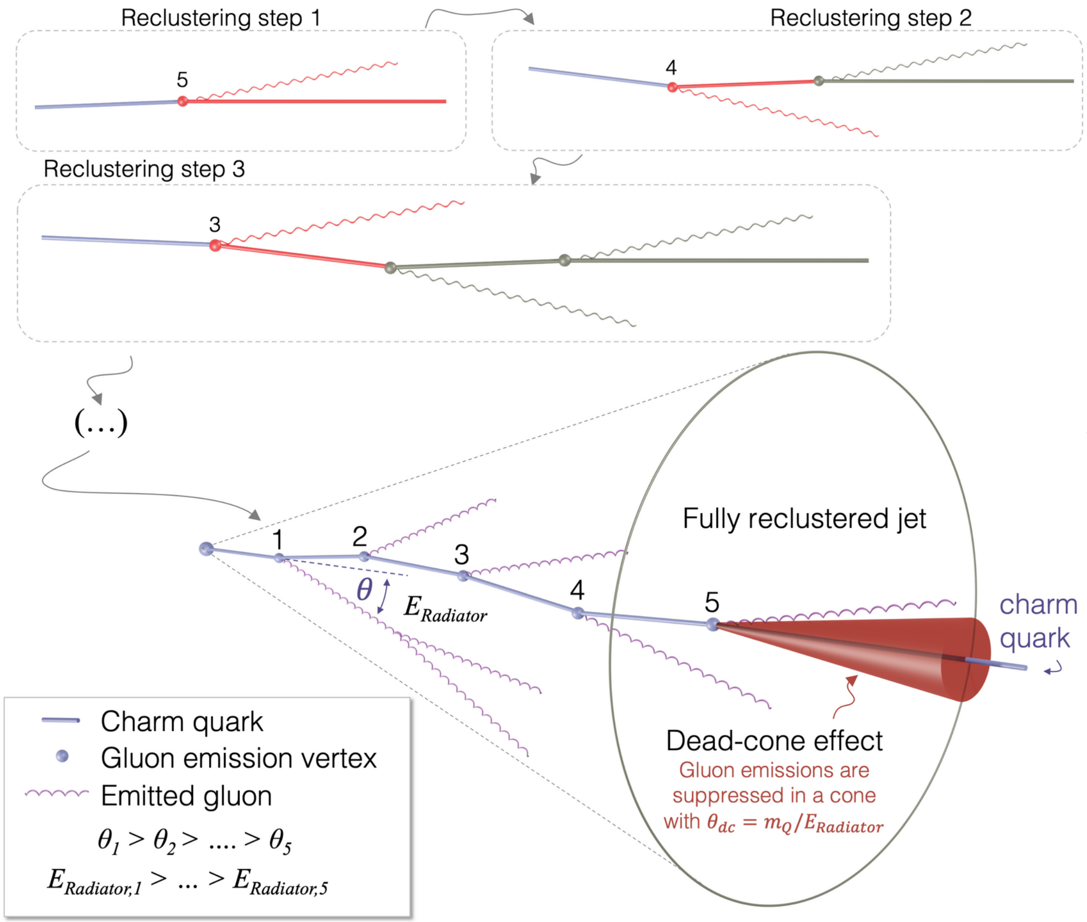
Conclusion

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

Outtakes and backup



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?

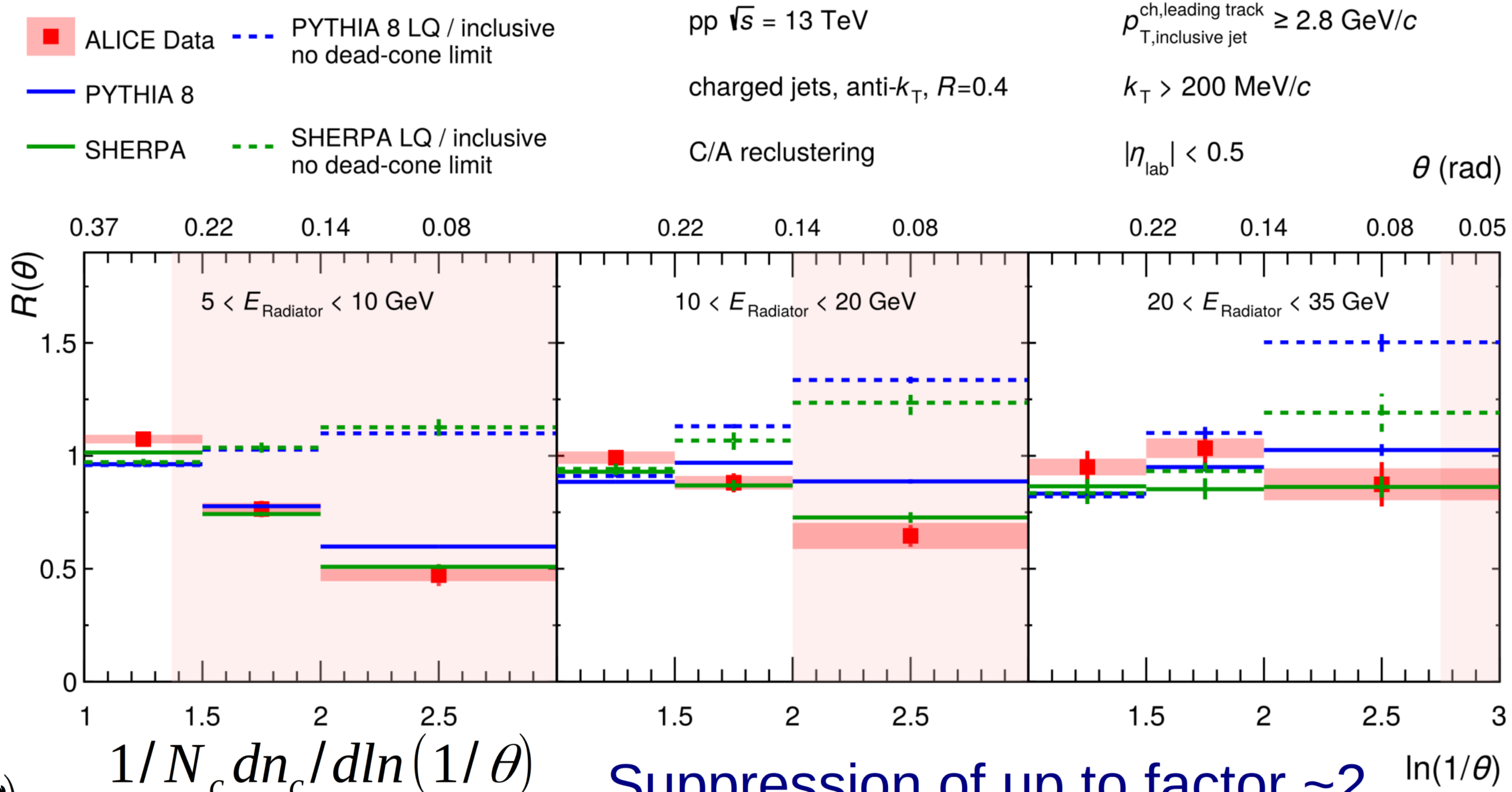
Angle(c-subjet, subjet) $\stackrel{def}{=}$ θ
Energy of split (sub)jet $\stackrel{def}{=}$ $E_{Radiator}$

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

in bins of $E_{Radiator}$

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

ALICE in dead cone land



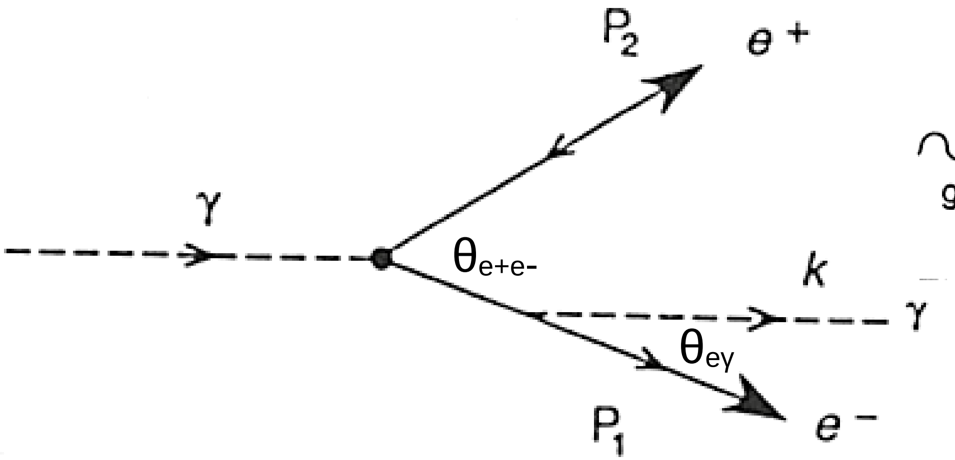
$$R(\theta)=\frac{1/N_c\, dn_c/d\ln(1/\theta)}{1/N_{incl}\, dn_{incl}/d\ln(1/\theta)}$$

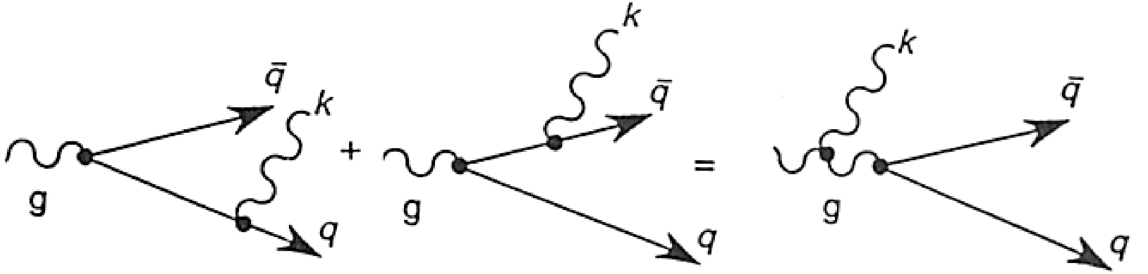
Suppression of up to factor ~2

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

Introduction

Chudakov effect … for quarks and gluons



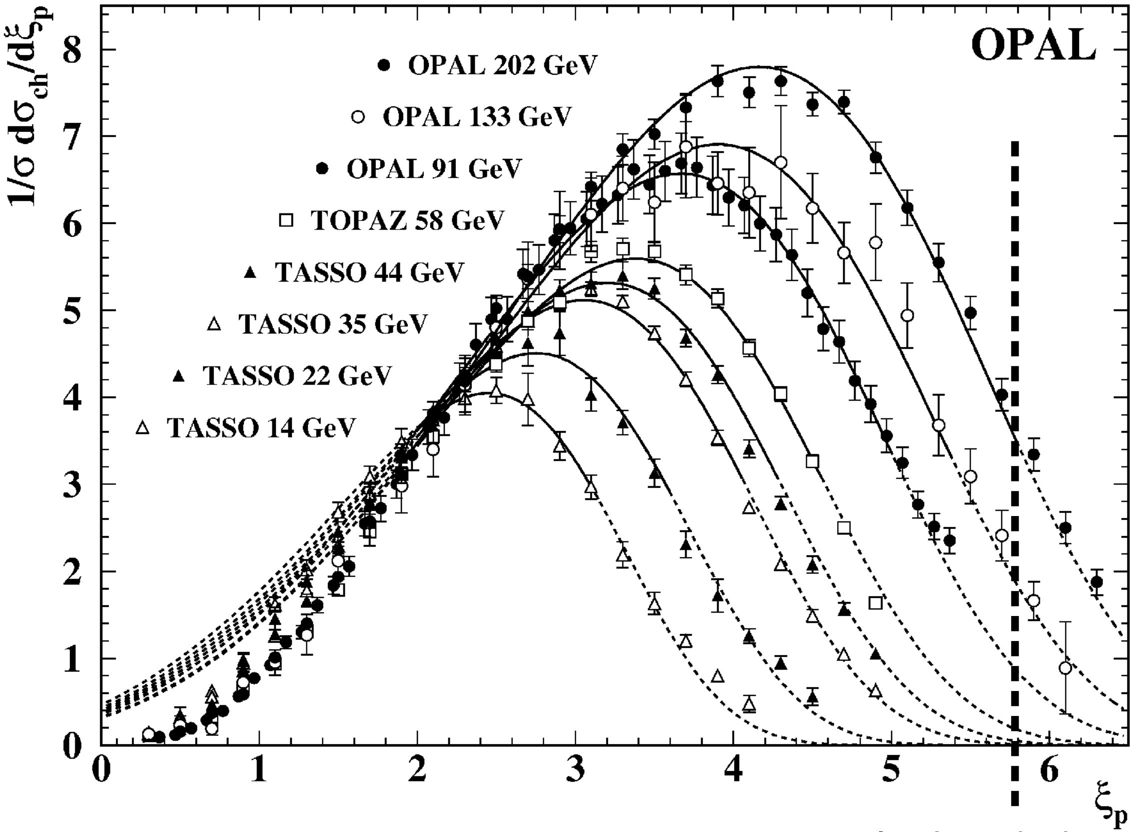


Consider transverse separation of γ (gluon) from e^+e^- (parton) pair with $\Delta t \Delta E > \hbar/2 \Rightarrow$ angular ordering $\theta_{e+e-} > \theta_{e\gamma}$ ($\theta_{partons} > \theta_{parton,g}$)

[Dokshitzer, Khoze, Mueller, Troyan, Basics of perturbative QCD, www.lpthe.jussieu.fr/~yuri/BPQCD/BPQCD.pdf]

Soft gluon interference

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



5.8 = log(0.14/45)

Dead cone in b- and c-jets

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

Quantitative pQCD in MLLA + LPHD

Parton spectra ≈ hadron spectra up to normalisation

Chudakov at work