Study of b quark fragmentation using charged-particle decays of charmed daughter mesons

CMS Collaboration

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Fragmentation

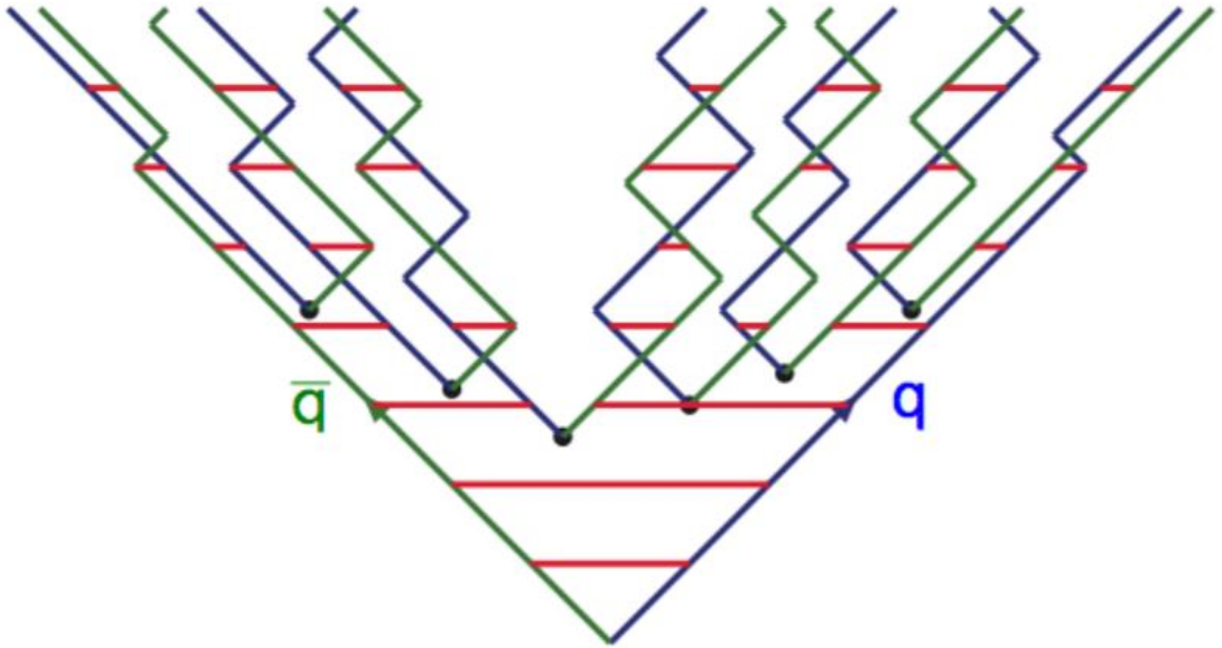
Fragmentation (or hadronization) is the process of partons converting into final state particles

A fraction of the momentum (p_T) of the fragmenting particle (X) is carried away by the new particle produced (Y)

$$z = Y\ p_T\ /\ X\ p_T$$

Fragmentation is not exactly calculable

The Lund symmetric function treats QCD interactions at large r as color strings (breaking of string → fragmentation)



Modeling b quark fragmentation

Lund–Bowler fragmentation function accounts for bottom and charm quark finite mass

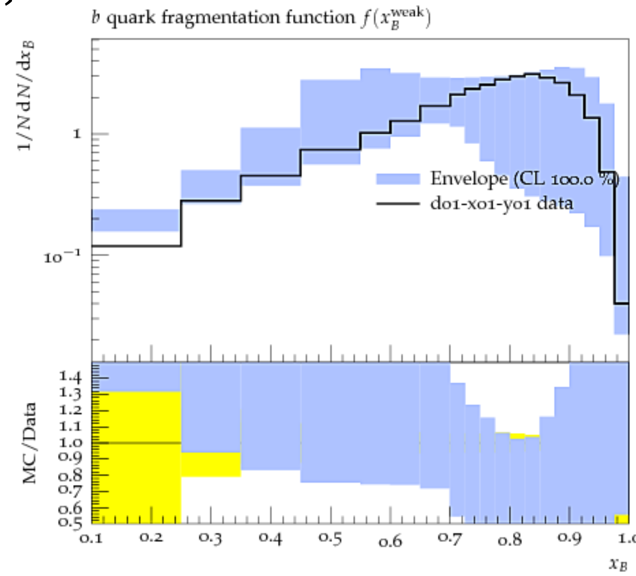
$$f(z) = \frac{1}{z^{1+r_b * b * m_b^2}} (1-z)^a \, e^{\left(\frac{-b\, m_T^2}{z}\right)}$$

Shape is governed by the b quark shape parameter r_b

Previous measurements

Z pole $\left(e^+e^- \to Z^0 \to b\bar{b}\right)$ data from LEP and SLC

$r_b = 0.894^{+0.184}_{-0.197}$

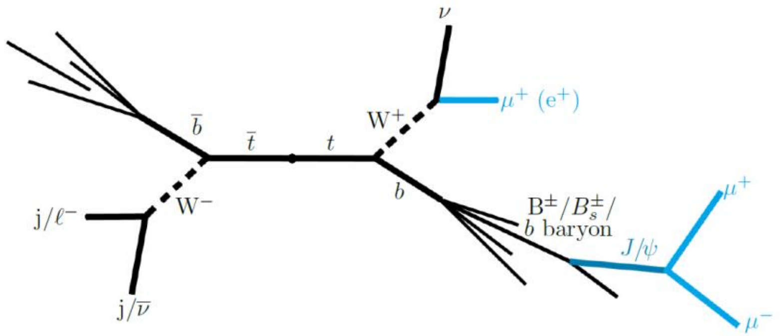


Example from the ALEPH detector M. Seidel 2015

LHC is a color-rich environment

Is the same model applicable?

The analysis



Using charm mesons inside b-jets from $t\bar{t}$ events as a proxy for B meson fragmentation

$$x_{\mathrm{b}} = \frac{\text{B meson } p_{\mathrm{T}}}{\text{b jet } p_{\mathrm{T}}} \sim \frac{\text{charm meson } p_{\mathrm{T}}}{\sum p_{\mathrm{T}}^{\mathrm{ch}}}$$

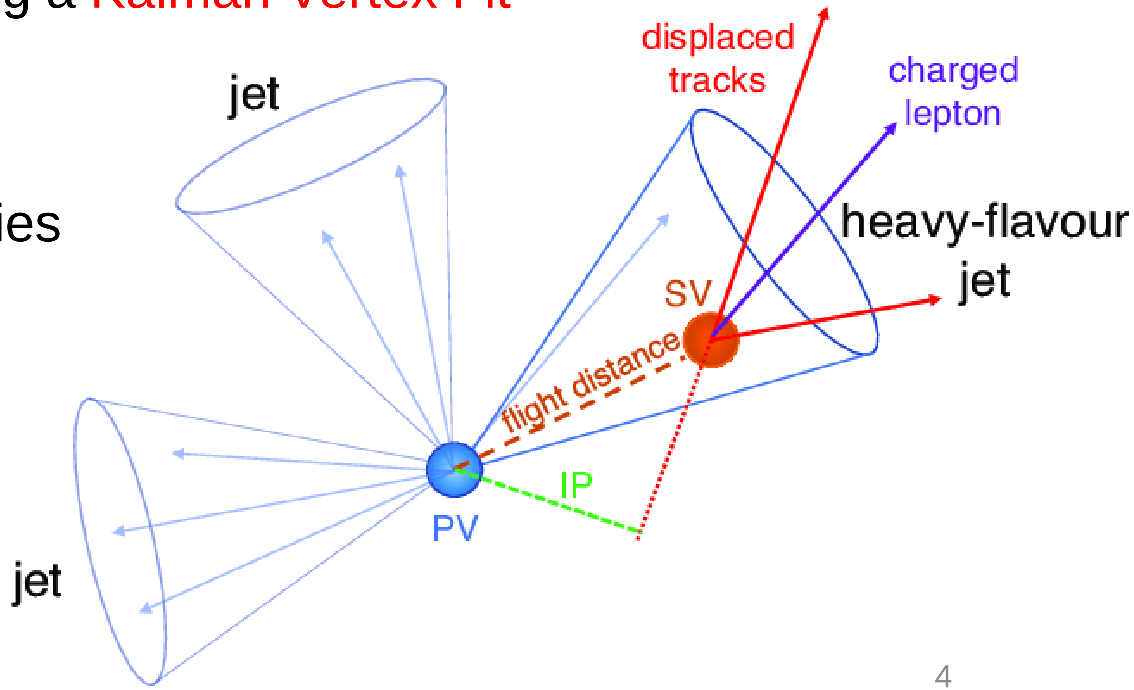
$\mathrm{D}^0 \rightarrow \mathrm{K}^{\pm}\pi^{\mp}$, $\mathrm{D}^0 \rightarrow \mathrm{K}^{\pm}\pi^{\mp} + \mu^{\pm}$, and $\mathrm{J}/\Psi \rightarrow \mu^+\mu^-$ using a Kalman Vertex Fit

Orthogonal channels

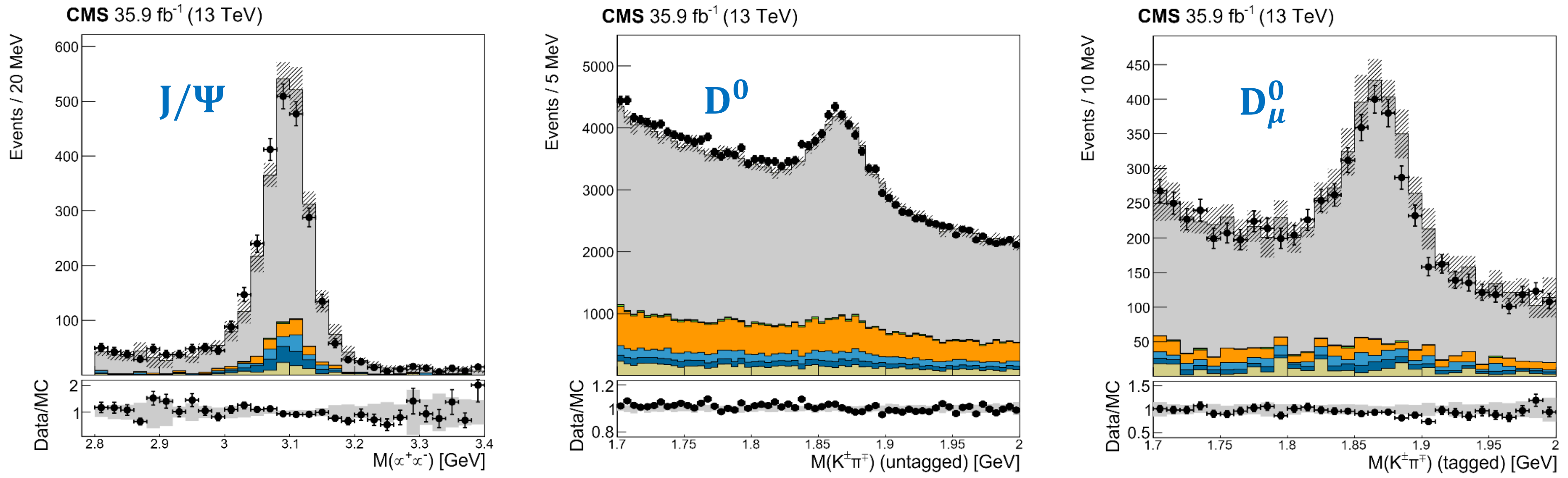
Charged particles only → avoid JES/JER uncertainties

Performed in single lepton (e + jets, μ + jets) and dilepton ($ee, e\mu,$ and $\mu\mu$) channels

$$\int \mathcal{L} = 36\ \mathrm{fb}^{-1} \text{ at } \sqrt{s} = 13\ \mathrm{TeV}$$



Invariant Mass Distributions

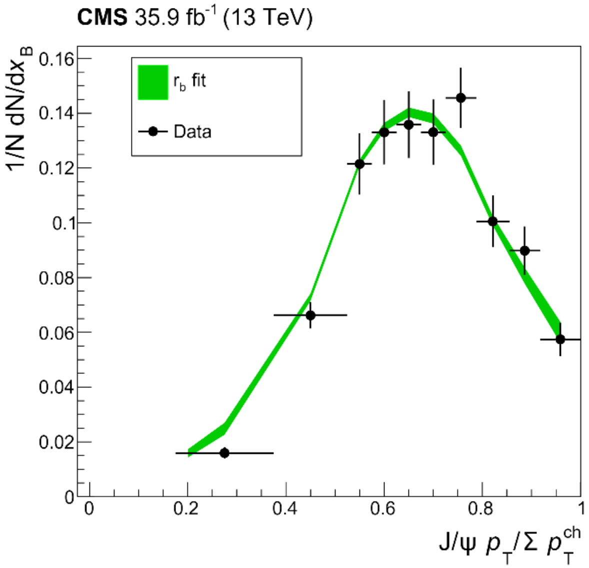


Perform background subtraction (data fit+ MC simulations)

Calculate x_b for data and simulations as a function of r_b

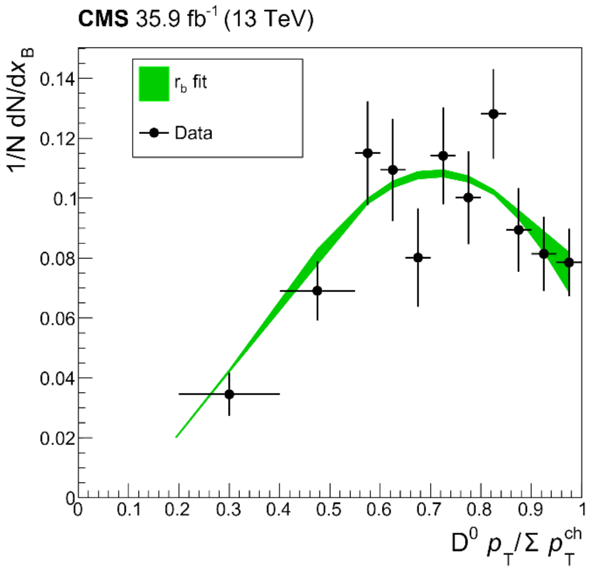
Fit for best value of r_b

Results



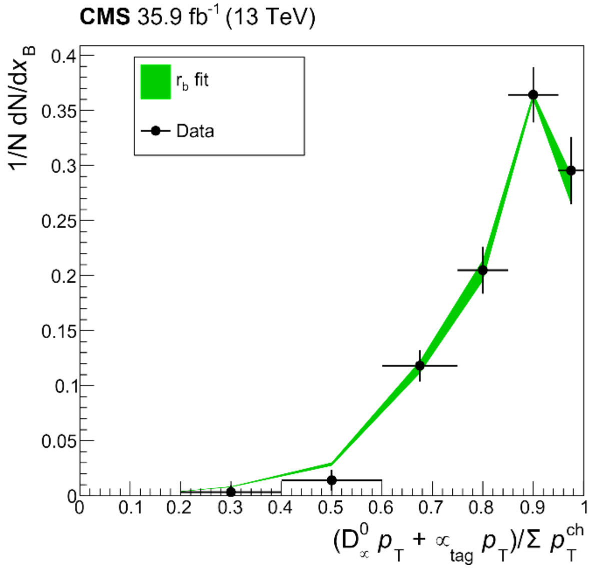
J/Ψ

$r_b = 0.864 \pm 0.053\ (\text{stat}) \pm 0.040 (\text{syst})$



D^0

$r_b = 0.836 \pm 0.070\ (\text{stat}) \pm 0.056\ (\text{syst})$



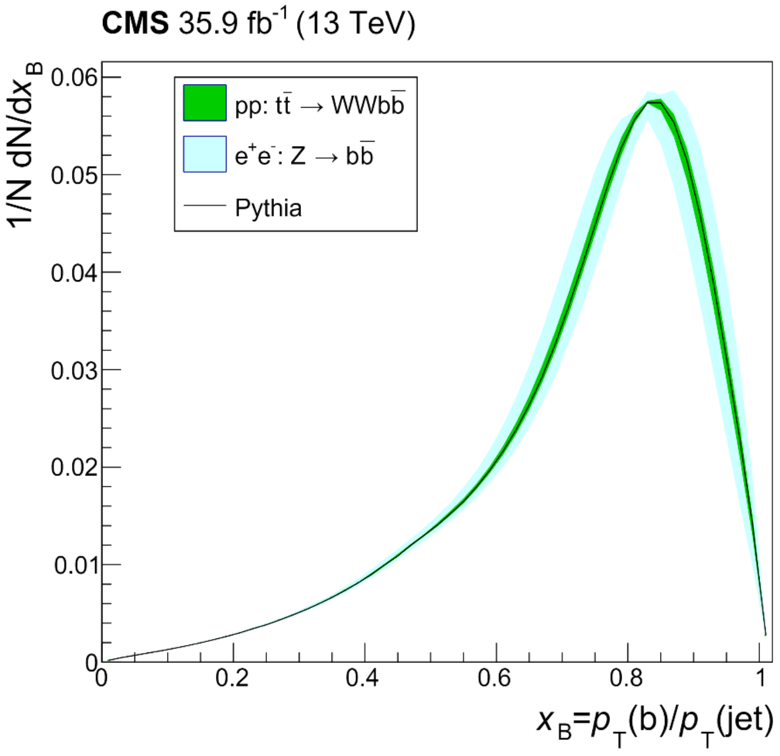
D^0_μ

$r_b = 0.858 \pm 0.072\ (\text{stat}) \pm 0.081\ (\text{syst})$

Green bands are the total fit error

Combined fit $r_b = 0.855 \pm 0.037\ (\text{stat}) \pm 0.031\ (\text{syst})$

Comparison with previous measurements



PYTHIA Monash Tune: $r_b = 0.855$

$Z^0 \to b\bar{b}$: $r_b = 0.894^{+0.184}_{-0.197}$

This analysis: $r_b = 0.855 \pm 0.048$

Conclusion

$J/\Psi, D^0$, and D_μ^0 produced inside of b jets from $t\bar{t}$ decay were used to measure the shape of the b quark fragmentation function

$$r_b = 0.855 \pm 0.037\ (\text{stat}) \pm 0.031\ (\text{syst})$$

More precise than the results from the Z pole in e^+e^-

The fit results are consistent → we observe no evidence for an environmental dependence of the b quark fragmentation

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Backup

Using a Kalman filter to find the meson candidates

A Kalman Vertex Fit (KVF) is performed on all candidate tracks

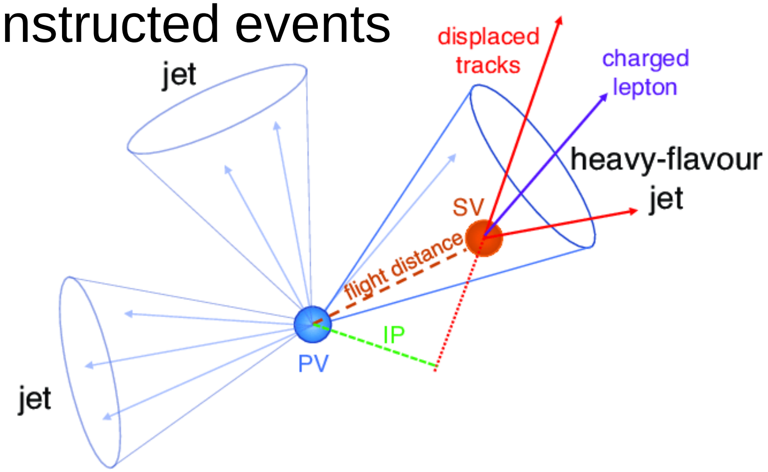
AK4 jets with $p_{\mathrm{T}} > 30\ \mathrm{GeV}$ and $|\eta| < 2.4$

KVF applied to track pairs matching the criteria for the charmed mesons

- μ from J/Ψ: Global Muons, $p_{\mathrm{T}} > 3$ GeV
- π from D^0: $p_{\mathrm{T}} > 5\ \mathrm{GeV}$
- K from D^0: $p_{\mathrm{T}} > 1\ \mathrm{GeV}$

All good Kalman vertices must have:

- $\chi^2 < 5$ to remove combinatorial background
- $c\tau/\sigma_{c\tau} > 10$ to remove prompt mesons
- $\sigma_{c\tau} > 2 * 10^{-4}$ to remove residual prompt background and mis-reconstructed events



Event selection

$\mu(e)$+jets channels:

Lepton cuts

- $p_T > 26(35)$ GeV passing tight ID
- $|\eta| < 2.4$
- RelIso< 0.15
- $\Delta R > 0.4$ to closet jet

Event cuts

- At least 1 jet with $p_T > 30$ GeV
- And at least 1 jet flagged by the Kalman filter

Veto on additional isolated leptons:

- $p_T > 15$ GeV passing loose ID
- $|\eta| < 2.4$
- RelIso< 0.24

$e^+e^-, \mu^+\mu^-, e\mu$ channels:

Lepton cuts

- $p_T > 20$ GeV
- $|\eta| < 2.4$
- RelIso< 0.15
- $\Delta R > 0.4$ to closet jet

Event cuts

- At least 1 jet flagged by the Kalman filter

Mass cuts

- Same flavor final state

  $|91\text{GeV} - M_{ll}| > 15$ GeV; MET > 40 GeV
- $M_{ll} > 20$ GeV

Corrections applied

Muon Trigger, ID, and isolation

- Scale factors
- Split by epochs BCDEF and GH

Electron Trigger and ID

- Scale factors

Pile-up reweighting

Top p_{T} reweighting

- Scale factors

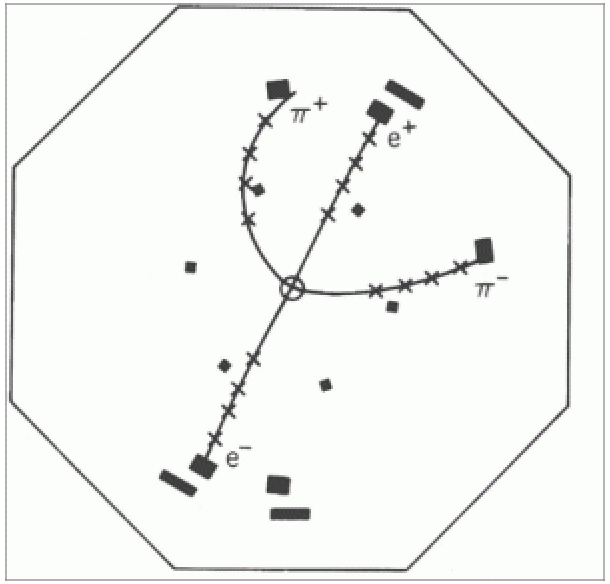
Custom tracker scale factors

- Probability of dropping MC tracks
- Split by epochs BCDEF and GH

J/Ψ candidate selection

For the Kalman flagged jets containing a J/Ψ we require:

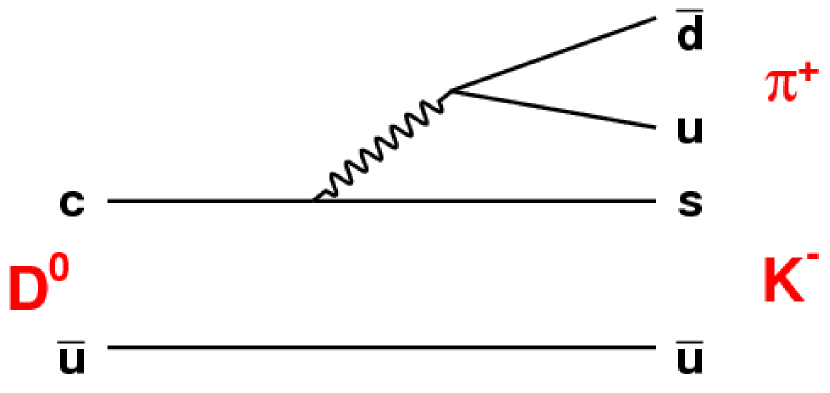
- $\mu\ p_{\mathrm{T}} > 3\ \mathrm{GeV}$
- $\mu\ |\eta| < 2.4$
- $H_{\mathrm{T}} > 80\ \mathrm{GeV}$
- Opposite signed PF muons
- Global muons only
- $2.8 < \left|\mathrm{M}_{\mu^+\mu^-}\right| < 3.4\ \mathrm{GeV}$ – J/Ψ mass peak and side-bands
- $\left|\mathrm{M}_{\mu^+\mu^-} - \mathrm{M}_{\mathrm{PDG}}\right| < 110\ \mathrm{MeV}$ – J/Ψ mass peak



D^0 candidate selection

For the Kalman flagged jets containing a D^0 we require:

- $\pi\ p_T > 5$ GeV and $\mathrm{K}\ p_T > 1$ GeV
- π and $\mathrm{K}\ |\eta| < 1.5$
- $H_T > 180$ GeV
- Opposite signed PF candidates assigned as $\mathrm{K}^{\pm}/\pi^{\mp}$
- $1.7 < |\mathrm{M}_{\pi\mathrm{K}}| < 2.0$ GeV – D^0 mass peak and side-band
- $|\mathrm{M}_{\pi\mathrm{K}} - \mathrm{M}_{\mathrm{PDG}}| < 40$ MeV – D^0 mass peak



The D^0 candidates can also be flavor tagged (denoted as D^0_μ) by requiring an additional soft muon from when the W from $\mathrm{B} \rightarrow \mathrm{D}^0$ decays muonically
(final state $\mathrm{K} + \pi + \mu + \nu_\mu +$ soft tracks)

- $|\mathrm{M}_{\pi\mathrm{K}} - \mathrm{M}_{\mathrm{PDG}}| < 45$ MeV – D^0 mass peak
- The system $\left(\mathrm{D}^0_\mu + \mu\right)$ gives the closet kinematics to the parent B meson

Flavor tagging

$B^{\pm}$	$\rightarrow$	$\overline{D}^{0}/D^{0}$	$\rightarrow$	$K^{\pm}$		$K^{\pm}\pi^{\mp} + \mu^{\pm}$
$u/\bar{u}$	$\rightarrow$	$u/\bar{u}$	$\rightarrow$	$u/\bar{u}$		$u/\bar{u}$
$\bar{b}/b$	$\rightarrow$	$\bar{c}/c$	$\rightarrow$	$\bar{s}/s$		$\bar{s}/s$
	$\downarrow$		$W^{\mp}$	$\rightarrow$	$\pi^{\mp}$	$\pi^{\mp}$
	$W^{\pm}$	$\rightarrow$	$\mu^{\pm} + \nu_{\mu}$			$\mu^{\pm} + \nu_{\mu}$

Data to Data relative corrections

Scale factors were derived based on the B–F / GH ratios as a function of η and p_{T} using Data from the D^0 side-bands ($m < 1.824$ and $m > 1.904$)

Results are used as a probability to drop MC tracks for epochs B–F for:

$p_{\mathrm{T}}(\pi)$

$\eta(\pi)$

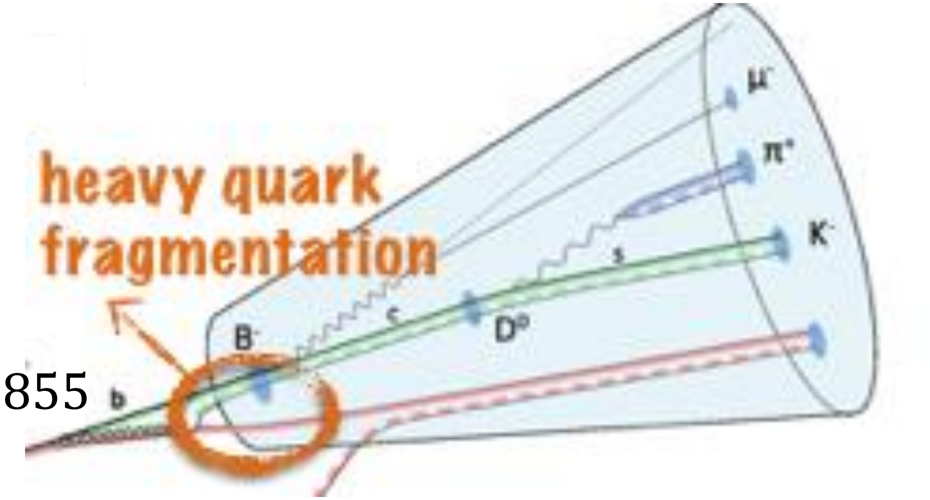
$p_{\mathrm{T}}(\mathrm{K})$

$\eta(\mathrm{K})$

Tuning the fragmentation function

Lund–Bowler function

$$\frac{1}{z^{1+r_{\mathrm{b}}*b*m_{\mathrm{b}}^2}} (1-z)^a \, e^{\left(\frac{-b\, m_{\mathrm{T}}^2}{z}\right)}$$



CMS reference MC PYTHIA 8 CUETP8M2T4 tune with $r_{\mathrm{b}} = 0.855$

MC samples are made at GEN level using different values for r_b

Ratio of new GEN z over default GEN z is used as shape weight at RECO level to generate templates

r_b fit procedure

χ^2 goodness-of-fit is performed w.r.t. the data for each template

χ^2 scan is parameterized

minimum → best fit value

Statistical uncertainty is extracted from $\Delta\chi^2_{\mathrm{min}} \pm 1$

Systematic uncertainties

Source	J/ψ	D^0	$D^0{}_\mu$	Combined
Fit procedure	0.022	0.025	0.025	0.017
Simulated event statistics	0.030	0.042	0.030	0.019
Signal and background functions	0.007	0.021	0.002	0.006
Background subtractions	—	0.010	0.010	0.004
Shape uncertainties	0.013	0.013	0.071	0.016
Total	0.040	0.056	0.081	0.031

All other uncertainties are negligible:

- JSF and JER
- Trigger
- m_{t}
- Etc.