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*Inclusive b-jet production in pp collisions at  $\sqrt{s} = 7$  Tev*

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# Inclusive b-jet production in pp collisions at $\sqrt{s} = 7 \text{ TeV}$

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## The CMS collaboration

**ABSTRACT:** The inclusive b-jet production cross section in pp collisions at a center-of-mass energy of 7 TeV is measured using data collected by the CMS experiment at the LHC. The cross section is presented as a function of the jet transverse momentum in the range  $18 < p_T < 200 \text{ GeV}$  for several rapidity intervals. The results are also given as the ratio of the b-jet production cross section to the inclusive jet production cross section. The measurement is performed with two different analyses, which differ in their trigger selection and b-jet identification: a jet analysis that selects events with a b jet using a sample corresponding to an integrated luminosity of  $34 \text{ pb}^{-1}$ , and a muon analysis requiring a b jet with a muon based on an integrated luminosity of  $3 \text{ pb}^{-1}$ . In both approaches the b jets are identified by requiring a secondary vertex. The results from the two methods are in agreement with each other and with next-to-leading order calculations, as well as with predictions based on the PYTHIA event generator.

**KEYWORDS:** Hadron-Hadron Scattering

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**1 Introduction**

The experimental measurement of the b-quark production cross section has been pursued with interest at hadron colliders because of discrepancies between theoretical predictions and experimental results, e.g., at the Tevatron [1–4] and at HERA [5–8]. Substantial progress has been made in understanding the b-quark production and fragmentation processes, and the measurements are now in reasonable agreement with the predictions in most regions of the phase space [9–12]. Theoretical uncertainties are, however, sizable, and there is great interest in verifying the results at the higher center-of-mass energies provided by the LHC. Identification of b-quark jets by methods relying on the long b lifetime is almost independent of the details of the fragmentation of a b quark into a b hadron. Therefore, measuring the rate of b jets is a direct measurement of the b-quark production rate, with a negligible systematic uncertainty originating from fragmentation [13]. In addition, large logarithmic corrections due to hard collinear gluons are avoided when inclusive b jets are considered, leading to more sensitive comparisons between experimental results and theoretical calculations.

First results on  $b\bar{b}$  production in pp collisions at  $\sqrt{s} = 7$  TeV have been reported by the LHCb Collaboration using semi-inclusive decays in the forward rapidity region [14], and by the Compact Muon Solenoid (CMS) Collaboration [15] using inclusive  $b \rightarrow \mu X$  decays [16] in the central rapidity region and measuring the b-hadron production cross section as a function of the muon transverse momentum and pseudorapidity. CMS has also measured the production cross sections of fully reconstructed  $B^+$  [17],  $B^0$  [18], and  $B_s$  [19] mesons, as well as the angular correlations between b and  $\bar{b}$  hadrons, based on secondary vertex reconstruction [20]. The ATLAS Collaboration has measured the inclusive and dijet cross sections of b jets [21].

This paper presents CMS measurements of b-jet cross sections in several bins of jet rapidity  $y$  and transverse momentum  $p_T$ . The b-jet cross section presented in this paper is defined as the sum of the b and  $\bar{b}$  jet contributions. Two independent analyses are presented: a jet analysis, selecting events with a b jet, and a muon analysis, requiring in addition a muon in the b jet. Despite the difference in the corresponding integrated luminosity ( $34 \text{ pb}^{-1}$  and  $3 \text{ pb}^{-1}$ , respectively), the precisions of the two measurements are similar and dominated by systematic uncertainties, which differ because of the use of different triggers and b-jet identification criteria. Most of the analysis procedures are common in the two analyses, and the differences are explained in the sections concerned.

The inclusive b-jet production cross section is also presented as the ratio to the inclusive jet-production cross section measured by CMS in the same rapidity intervals [22]. The results are compared to theoretical predictions from next-to-leading order (NLO) perturbative quantum chromodynamics (QCD) calculations and to predictions from the PYTHIA event generator [23].

## 2 CMS detector

The central feature of the CMS apparatus is a superconducting solenoid, 13 m in length and 6 m in diameter, which provides an axial magnetic field of 3.8 T. The bore of the solenoid is instrumented with various particle detectors. Charged particle trajectories are measured with the silicon pixel and strip trackers, covering  $0 < \phi < 2\pi$  in azimuth and  $|\eta| < 2.5$  in pseudorapidity, where  $\eta = -\ln[\tan \theta/2]$ , with  $\theta$  being the polar angle of the track with respect to the counterclockwise beam direction. The resolution is typically about  $15 \mu\text{m}$  on the impact parameter and about 1% on the transverse momentum for charged particles with  $p_T < 40$  GeV. A crystal electromagnetic calorimeter (ECAL) and a brass/scintillator hadron calorimeter (HCAL) surround the tracking volume. The forward region is covered by an iron/quartz-fiber hadron calorimeter (HF). The ECAL provides coverage in  $|\eta| < 1.5$  in a cylindrical barrel region and  $1.5 < |\eta| < 3.0$  in two endcaps. The ECAL has an energy resolution of better than 0.5% for unconverted photons with transverse energies above 100 GeV. The hadron calorimeters cover  $|\eta| < 5.0$  with a jet energy resolution of about  $100\%/\sqrt{E}$ , with the jet energy  $E$  in GeV. Muons are measured in gas-ionization detectors embedded in the steel return yoke, covering  $|\eta| < 2.4$ . A two-tier trigger system selects the most interesting pp collision events for use in physics analyses. A more detailed description of the CMS detector can be found elsewhere [15].

### 3 Monte Carlo simulation

A detailed Monte Carlo (MC) simulation was performed for comparisons with the data and to evaluate the selection efficiencies. Simulated events were generated with PYTHIA 6.422 [23] using tune Z2 [24] for the underlying event, a b-quark mass of 4.8 GeV, and the CTEQ6L1 [25] proton parton distribution functions (PDF). The generated events were processed through the full GEANT4 [26] detector simulation, trigger emulation, and event reconstruction chain.

The inclusive jet NLO theoretical prediction was calculated with NLOJET++ [27] using the CTEQ6.6M PDF set [25] and FASTNLO [28] implementation. The factorization and renormalization scales were set to  $\mu_F = \mu_R = p_T$ . The inclusive b-jet cross section prediction was calculated with MC@NLO [29, 30] using the CTEQ6M PDF set and the nominal b-quark mass of 4.75 GeV. The parton shower and hadronization were modeled using HERWIG 6.510 [31].

The uncertainty on the predicted cross section was calculated independently by varying the renormalization and factorization scales by factors of two, the b-quark mass by  $\pm 0.25$  GeV, and by using the CTEQ6.6M instead of the CTEQ6M parton distribution functions [25].

### 4 Event selection

The data used for this measurement were collected in 2010 and were required to pass the standard event quality criteria [16, 22], which reject data with anomalous or faulty behavior of the silicon tracker, calorimeters, or muon chambers. The total integrated luminosity amounts to  $34 \text{ pb}^{-1}$  for the jet analysis and to  $3 \text{ pb}^{-1}$  for the muon analysis.

The inclusive jet data were collected using a combination of minimum bias and single-jet triggers [15], where each trigger covers a separate continuous  $p_T$  range (18-37, 37-56, 56-84, 84-114, 114-153, and 153-196 GeV, for trigger thresholds of 0, 6, 15, 30, 50, and 70 GeV in uncorrected  $p_T$ , respectively). For each  $p_T$  bin, the trigger with the highest integrated luminosity is selected from those with  $>98\%$  efficiency at all rapidities. For the muon analysis, the events are required to pass a trigger selection [15] that accepts events with muons having  $p_T^\mu > 9 \text{ GeV}$  and  $|\eta^\mu| < 2.4$ .

Jets are reconstructed using a particle-flow algorithm [22], which uses the information from all CMS sub-detectors to reconstruct different types of particles produced in the event. The basic objects of the particle-flow reconstruction are the tracks of charged particles reconstructed in the central tracker, and energy deposits reconstructed in the calorimetry. These objects are clustered with the anti- $k_T$  algorithm [32, 33] using the jet clustering distance parameter  $R = 0.5$ . Tight jet identification criteria [34] are applied to protect against poorly modeled sources of calorimeter noise. The jet energies are corrected using estimates based on simulated events for the  $p_T$  dependence, while corrections measured from data [34] are applied for the absolute scale and the rapidity dependence.

The b jets are identified by finding the secondary decay vertex of the b hadrons [35]. The secondary vertices from b- and c-hadron decays can be distinguished by a selection on the relative distance from the primary vertex, using the three-dimensional decay-length

significance, which is typically larger for b jets than for c, light-quark, and gluon jets. In the jet analysis, a selection based on secondary vertices with at least three tracks containing signals from the silicon pixel detector provide a clean signal against light-quark and gluon-jet backgrounds. In the muon analysis, the minimum number of tracks to identify the secondary vertex is two, in order to keep the b-tagging efficiency high for semileptonic decays of b hadrons.

In the muon analysis, the offline selection requires at least one muon candidate in the  $p_T$  and  $\eta$  ranges of the trigger selection that fulfills a tight muon selection identical to that used in [16]. The reconstructed muon is associated with the highest- $p_T$  b-tagged jet within a  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$  cone, where  $\Delta\eta$  and  $\Delta\phi$  refer to the angular separation between the b-tagged jet and the muon. If several muons are associated with the b-tagged jet, the muon with the highest  $p_T$  is considered. According to the simulation, the average efficiency of associating the muon with the b-tagged jet is  $(76 \pm 2)\%$ . The probability of a random muon association with a jet is estimated to be less than 0.5%.

The two b-jet cross-section measurement samples are collected with different triggers and are essentially statistically independent. The effective trigger efficiency of the muon trigger is significantly higher, thereby compensating for an order of magnitude smaller integrated luminosity. A total of 43 046 jets pass the event and jet selection for the jet analysis while in the muon analysis a total of 113 561 events pass the event and jet selections, making the two analyses comparable in terms of statistical power.

## 5 Cross section measurement

The production cross section for b jets is calculated as a double differential,

$$\frac{d^2\sigma}{dp_T dy} = \frac{N_{\text{tagged}} f_b C_{\text{unfold}}}{\epsilon \Delta p_T \Delta y \mathcal{L}} \quad , \quad (5.1)$$

where  $N_{\text{tagged}}$  is the measured number of tagged jets per bin from the jet analysis and the number of jets tagged with muons from the muon analysis,  $\Delta p_T$  and  $\Delta y$  are the bin widths in  $p_T$  and  $y$ ,  $f_b$  is the b-tagged sample purity,  $C_{\text{unfold}}$  is the unfolding correction, and  $\mathcal{L}$  is the integrated luminosity. No distinction is made between b-quark jets and  $\bar{b}$ -quark jets, so the cross section is the sum of b and  $\bar{b}$  production.

The  $p_T$  spectra are normalized by the respective integrated luminosities of the individual jet triggers [22], and then combined into a continuous jet  $p_T$  spectrum. Only one trigger is used for each  $p_T$  bin to simplify the analysis. In the jet analysis, the reconstructed  $p_T$  spectra are unfolded using the ansatz method [36, 37], with the jet  $p_T$  resolution obtained with data-based methods from dijet data [34]. In the muon analysis, an unfolding (jet migration) correction derived from simulated events is applied to the selection efficiency as the bin-by-bin ratio of the number of generated b jets in a given  $p_T$  or rapidity bin to the number of reconstructed b candidates in that bin. In the simulation, the generated jets are constructed by clustering the stable particles produced during the hadronization process including neutrinos in the muon analysis, but not in the jet analysis. The two unfolding methods produce consistent results within the uncertainties of the jet  $p_T$  spectrum and the jet  $p_T$ -resolution modeling, which are negligible compared to the total systematic uncertainty.

The efficiency  $\epsilon$  includes the trigger efficiency, event selection efficiency, jet reconstruction and identification efficiency, and the efficiency of tagging b jets. For the muon analysis, the muon reconstruction efficiency is also included.

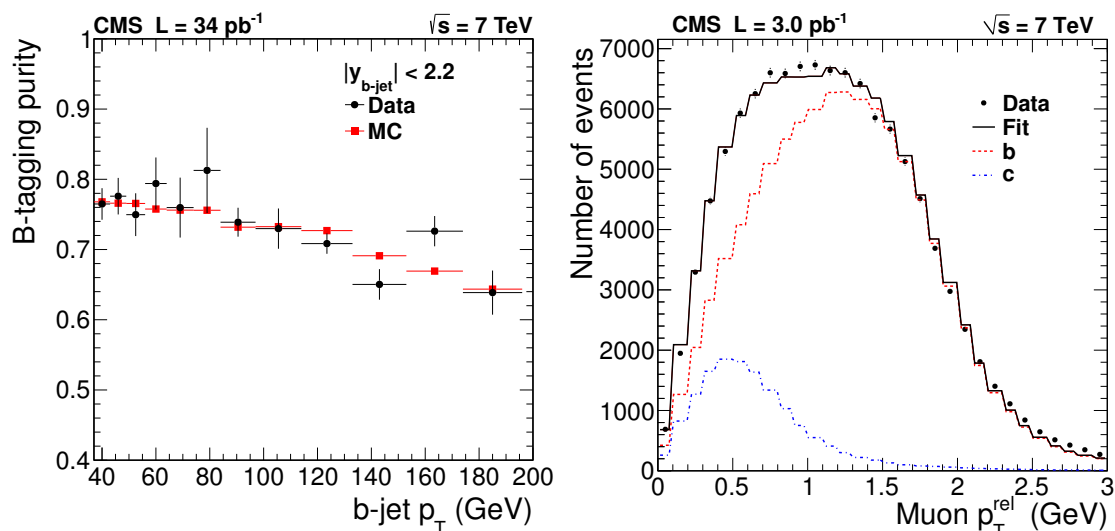
In the jet analysis, the efficiency is about 0.1% to mistag light-quark and gluon jets as b jets, and the b-tagging efficiency is between 5% at  $p_T \approx 18$  GeV and 56% at  $p_T \approx 100$  GeV. The efficiency rises at higher  $p_T$  as the average b-hadron decay length increases. To moderate the statistical fluctuations in the simulation, the b-tagging efficiency in each rapidity bin is fitted to a functional parameterization versus  $p_T$  accounting for various effects such as the b-hadron proper time and the boost of secondary vertex decay products. The fit result is used in the analysis. In the muon analysis, the average b-tagging efficiency is about 60% in the barrel region ( $|y| < 0.9$ ) and about 55% for the endcap region ( $1.2 < |y| < 2.4$ ). It increases from 50% to 75% for b-jet transverse momenta from 30 to 100 GeV. The data/simulation scale factor for the b-tagging efficiency applied in the analysis is 0.95, with an uncertainty of 10% [35].

In the jet analysis, the distribution of the invariant mass of the tracks originating from the secondary vertex is fitted with probability density functions corresponding to vertex mass distributions for light-, charm-, and b-flavor jets taken from simulated events. The relative normalizations for the combined light- and charm-flavor distribution and the b-flavor distribution are free parameters in the fit. The resulting estimates of  $f_b$  from data and simulated events are shown in figure 1 (left). The overall relative data/simulation scale factor is consistent with unity within uncertainties. Given the good agreement between data and simulation for  $p_T > 37$  GeV, the latter is used to predict the  $p_T$  and  $y$  dependence of the purity, with no additional corrections, and to extrapolate it to  $p_T < 37$  GeV.

In the muon analysis, the b-tagged sample purity is obtained from a fit to the distribution of the relative muon momentum  $p_T^{\text{rel}}$  with respect to the b-jet axis, which effectively discriminates between b events and background. Figure 1 (right) shows the result of the  $p_T^{\text{rel}}$  fit, using the expected shapes from the simulated events for the muons from b-hadron decays and background from charm quark and light-flavor jets. The normalizations of the three contributions are free parameters in the fit. A b fraction of  $(86 \pm 5)\%$  is observed. The shapes obtained from the simulated events provide a reasonable description of the data. The  $p_T^{\text{rel}}$  fit to the data gives a light-quark and gluon contribution to the b-tagged jet sample of less than 3% for all bins in  $p_T$  and  $|y|$ . This is confirmed in the simulated events where the light-quark and gluon fraction of the b-tagged jets is estimated to be less than 2%.

## 6 Systematic uncertainties

The inclusive b-jet differential cross section can be affected by uncertainties on the yield in each of the  $p_T$  bins and on the measurement of the b-jet  $p_T$  itself, which determines the amount of smearing between the neighboring bins and is corrected by unfolding. The leading uncertainties affecting the yields are due to the b-tagging efficiency, the sample purity, and the integrated luminosity. The smearing of the  $p_T$  bin assignment is dominated by the jet energy scale. In the following, the systematic uncertainties common to the two analyses are discussed first, and those specific to each analysis are then described separately. All systematic uncertainties are summarized in table 1.



**Figure 1.** The b-tagged sample purity obtained using fits to the secondary vertex mass from data and simulated events as a function of the b-jet  $p_T$  (left). The distribution of the muon transverse momentum  $p_T^{\text{rel}}$  with respect to the closest b-tagged jet in data for  $p_T > 30$  GeV and  $|y| < 2.4$ , together with the maximum-likelihood fit (solid line) and its components (dashed lines) (right). The light-flavor (udsg) distribution is not visible in the figure since its contribution from the fit is consistent with zero.

The uncertainty of the jet energy correction (JEC) is estimated using photon+jet events with the jet in the barrel region, and dijet events where one jet is measured in the barrel region and the other in one of the endcaps [34]. These uncertainty estimates are further confirmed by indirect observations using comparisons of jet substructure between data and MC simulations, the reconstruction of the  $\pi^0$  mass peak for the ECAL energy scale, and the measurement of the single-particle response in the calorimeters using isolated charged hadrons. The uncertainty of the jet  $p_T$  resolution is estimated using a comparison of dijet  $p_T$  balance between data and simulated events [34].

The cross-section measurement uses the b-tagging efficiency obtained from simulated events and corrected by a scale factor measured in data. Several methods based on muon-tagged jets [35] or  $t\bar{t}$  events [38, 39] are used to measure the b-tagging efficiency in data. The ratio between the efficiencies measured from data and estimated from simulated events determines the scale factor of  $0.95 \pm 0.10$ .

The difference between the inclusive-jet and the b-jet energy corrections is estimated from MC fragmentation studies with PYTHIA and HERWIG to be 0.5-1.5%, while studies based on data find the inclusive jet scale uncertainty to be about 1.5-3.5% for  $p_T > 30$  GeV and  $|y| < 2.2$ . Because of the lack of direct constraints from data on the relative b-jet energy scale, the b-jet and the relative b-jet to inclusive JEC uncertainties are both taken to be the same as the inclusive JEC uncertainty [34]. Each 1% uncertainty in the JEC translates into a 2-5% uncertainty on the measured cross section because of the steeply falling  $p_T$  spectrum.

Signals from the HF calorimeters are used to determine the instantaneous luminosity with a systematic uncertainty of 4% [40].



Source	Jet analysis	Muon analysis
Jet energy correction (JEC)	6-8	4-6
b-tagging efficiency	10-22	10
b sample purity	4-20	3-13
Luminosity	4	4
Trigger efficiency	< 1	3
Muon reconstruction efficiency	—	3
Selection	< 1	2-6
Muon-jet association	—	2
b fragmentation	—	4
b $\rightarrow$ $\mu$ branching fraction	—	2.5
Total	13-24	13-20

**Table 1.** Summary of the systematic uncertainties on the b-jet cross-section measurement, given in percent for the two analyses. The systematic uncertainties can vary depending on the b-tagged jet transverse momentum and rapidity, as indicated by the range in the table.

### 6.1 Systematic uncertainties specific to the jet analysis

The b-tagged sample purity from the fit of the secondary vertex mass distribution and the estimate from the simulated events are in agreement within 3-4%. The purity uncertainty is dominated by the uncertainty of the charm mistag rate across most of the kinematic range, leading to a small uncertainty variation versus  $p_T$  and  $y$ . The light-flavor mistag rate is generally negligible except at high  $p_T$  in the forward region, where the yields are too low to perform a reliable fit. This additional purity uncertainty is estimated by varying the light-quark and gluon mistag rate by  $\pm 30\%$ .

The dominant source of uncertainty is the b-tagging efficiency. In the ratio between the b-jet and the inclusive jet cross sections, the contribution from the luminosity uncertainty cancels, and the impact of the jet energy resolution is negligible. The contribution from the JEC in the ratio is not significantly reduced, however, because the relative b-jet JEC is assumed to be uncorrelated with the inclusive JEC. The JEC contributes 6-8% to the total uncertainty. The remaining systematic uncertainties from charm, light-quark, and gluon mistag rates contribute 3-4% to the b-tagged sample purity, except at high  $p_T$  and  $y$ , where a 30% variation in the light-quark and gluon mistag rate contributes up to 20%.

The consistency of the simulation-based corrections for the b-tagging efficiency, the b-tagged sample purity, the b-jet energy, and the inclusive jet energy scale, among others, is tested by running the full analysis chain on reconstructed simulated events and comparing the results to the particle-level  $p_T$  spectra. This closure test produces good agreement between the generated and reconstructed  $p_T$  spectra to within 5%. This level of agreement is consistent with the statistical uncertainty of the simulation and the systematic uncertainties of the parameterizations of the b-tagging efficiency and b-purity.

## 6.2 Systematic uncertainties specific to the muon analysis

The muon trigger efficiency is determined from data using independent jet triggers. A systematic uncertainty of 3% is assigned, which corresponds to the range of differences between trigger efficiencies derived from data for muons from  $Z$  decays, muons in b-tagged events, and muons with tight quality requirements.

The differences between the muon reconstruction efficiencies derived from data and simulated events is less than 2% in the barrel region and less than 3% in the endcap regions. A systematic uncertainty of 3% is assigned for the muon reconstruction efficiency.

The efficiency for associating a muon with a b-tagged jet agrees between data and simulation to within 2%.

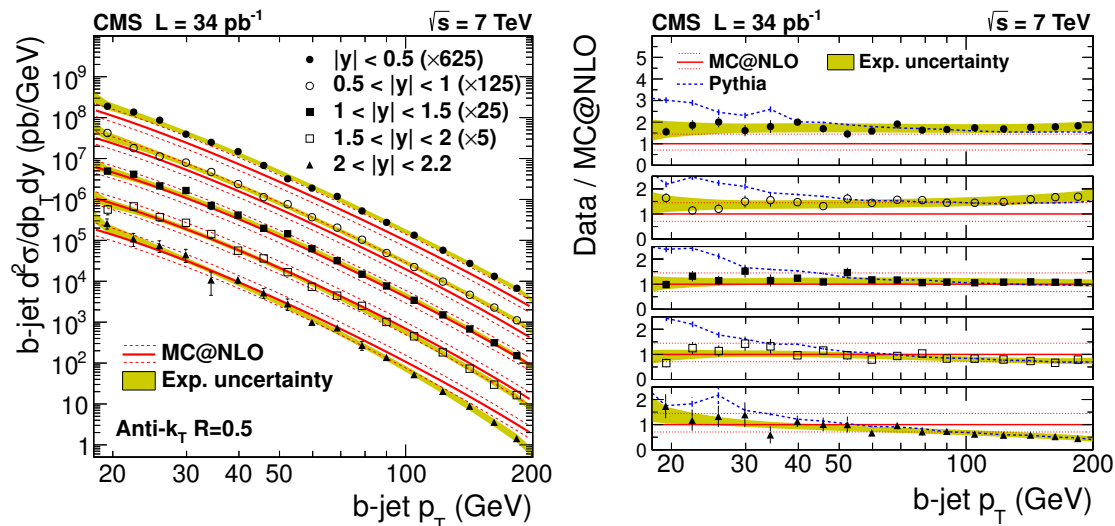
The uncertainties due to variations in the  $p_T^{\text{rel}}$  distributions between data and simulated events range from 3% to 13%. This systematic uncertainty is estimated by varying the binning, including or not including the muon in the definition of the jet direction, using different Monte Carlo simulation tunes, and considering the overall difference between the data and fit results. The largest contribution (up to 12% for high- $p_T$  b jets) is from the difference between the signal fraction obtained by the  $p_T^{\text{rel}}$  fit and by a fit to the secondary vertex mass distribution.

The uncertainty from the event selection is estimated from the variation of the muon selection cuts and the jet reconstruction, and ranges from 2% to 6%. The uncertainty of the b-quark fragmentation is determined by comparing the extrapolation factors to the total muon transverse momentum range between PYTHIA and HERWIG [41]. It leads to a 4% difference. The branching fraction of b semileptonic decays into muons is known [42] to a precision of 2.5%. The signal fraction is also determined with an event selection based on calorimetric jets [34]. The measured cross sections are consistent within the systematic uncertainty. The b fragmentation and  $b \rightarrow \mu$  branching fraction uncertainties are taken into account only for the b-jet cross section measurement extrapolated to cover the full  $p_T$  and  $y$  range of the muons. The total systematic uncertainty is 13% at low jet  $p_T$  and increases to 20% for high- $p_T$  b jets.

## 7 Results

### 7.1 Jet analysis

The measured b-jet cross section from the jet analysis is shown as a function of the jet  $p_T$  for different rapidity bins in figure 2 (left). The values have been multiplied by the arbitrary factors given in the figure for easier viewing. The cross section decreases by four orders of magnitude over the  $p_T$  range 18-200 GeV. This behavior is well described by the theoretical predictions from MC@NLO, shown by the solid lines in the figure. Figure 2 (right) shows the ratio between the measured cross section and the theoretical predictions. The MC@NLO values tend to be below the data in the central region ( $|y| < 1.0$ ) for low  $p_T$  and above the data in the forward region ( $|y| > 2.0$ ) at large  $p_T$ . The predictions from the PYTHIA generator, in contrast, agree with the data at high  $p_T$ , but overestimate the cross section significantly in the  $p_T$  region below 50 GeV, with the difference extending to higher  $p_T$  in the more forward region.

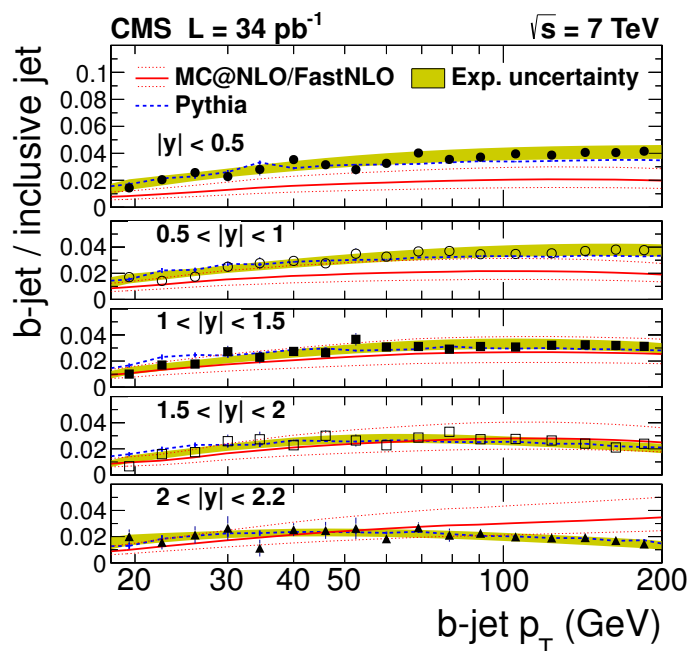


**Figure 2.** Measured b-jet cross section from the jet analysis, multiplied by the arbitrary factors shown in the figure for easier viewing, compared to the MC@NLO calculation (left) and as a ratio to the MC@NLO calculation (right). The experimental systematic uncertainties are shown as a shaded band and the statistical uncertainties as error bars. The MC@NLO uncertainty is shown as dotted lines. The PYTHIA prediction is also shown in the right panel.

The ratio of the b-jet and the inclusive jet cross sections [22] is shown in figure 3 as a function of  $p_T$ . The ratio increases as a function of  $p_T$  by up to a factor of 2, particularly in the central region. The measurements are compared to the MC@NLO prediction divided by the FASTNLO prediction of the inclusive jet cross section [22]. The non-perturbative corrections for the inclusive jet cross section prediction are the average of HERWIG6 [31] and PYTHIA (tune D6T [43]). The data and NLO predictions agree within experimental and theoretical uncertainties. Some difference between the NLO prediction and the data is observed in the central region, where the NLO values are lower than the data, and at  $p_T > 100 \text{ GeV}$  and  $|y| > 2$ , where the NLO prediction is higher than the data. The PYTHIA prediction for the ratio between the inclusive b-jet and inclusive-jet cross sections is in agreement with the data across the full kinematic range of the measurement.

The total b-jet cross section is found by integrating the measured double-differential distributions over  $|y| < 2.2$  and two different  $p_T$  ranges:  $18 < p_T < 200 \text{ GeV}$  and  $32 < p_T < 200 \text{ GeV}$ . The values and the corresponding MC@NLO and PYTHIA predictions are summarized in table 2.

The MC@NLO calculation predicts a total  $pp \rightarrow b\bar{b}X$  cross section of  $238 \mu\text{b}$ . The systematic uncertainty of this prediction comes from varying the renormalization scale by factors of 0.5 and 2.0 (+40%, -25%), from variations in the parameters of the CTEQ PDF (+10%, -6%), and from the changing the b-quark mass from 4.5 to 5.0 GeV (+17%, -14%). The total uncertainty on the theoretical calculation is shown by the shaded bands in figures 2 and 3.



**Figure 3.** Ratio of the measured b-jet cross section from the jet analysis to the inclusive jet cross section [22], as a function of the b-jet  $p_T$  (the jet  $p_T$  in the inclusive case). The predictions from NLO calculations (MC@NLO/FASTNLO) and from PYTHIA are also shown.

## 7.2 Muon analysis

The measured differential cross sections for inclusive b-jet production of b hadrons decaying into a muon with  $p_T^\mu > 9$  GeV and  $|\eta^\mu| < 2.4$  are shown in figure 4 as a function of the b-jet  $p_T$  (left) and  $|y|$  (right). They are compared with the MC@NLO and PYTHIA predictions. The dashed red lines illustrate the MC@NLO theoretical uncertainty from variations in the QCD scale, the b-quark mass, and the parton distribution functions. A difference between the PYTHIA prediction and the data is observed for b-jet  $p_T < 70$  GeV, where the PYTHIA values are higher than the data. The data are in agreement with the PYTHIA prediction for the rapidity dependence of the cross section. However, a significant difference in shape is observed between the data and the MC@NLO predictions for the rapidity dependence of the b-jet cross section. A similar behavior had been observed in an inclusive b measurement with muons [16]. The absolute normalization of the measured cross section is compatible with the NLO QCD predictions within the theoretical and experimental uncertainties.

The measured cross section for b jets with  $p_T > 30$  GeV,  $|y| < 2.4$ , and the b hadrons decaying into muons in the kinematic range  $p_T^\mu > 9$  GeV and  $|\eta^\mu| < 2.4$ , is shown in table 2. The value is obtained by summing over all  $p_T$  bins.

The measurements in the restricted muon kinematic range are extrapolated to cover the full muon  $p_T$  and  $y$  ranges using the PYTHIA simulation, in order to obtain the b-jet cross section limited only by the b-jet  $p_T$  and  $y$ . The extrapolation also corrects for the branching fraction of b semileptonic decays into muons and for the muon acceptance. The extrapolation factor changes from 5% at low b-jet  $p_T$  to 20% at high  $p_T$ . The MC@NLO

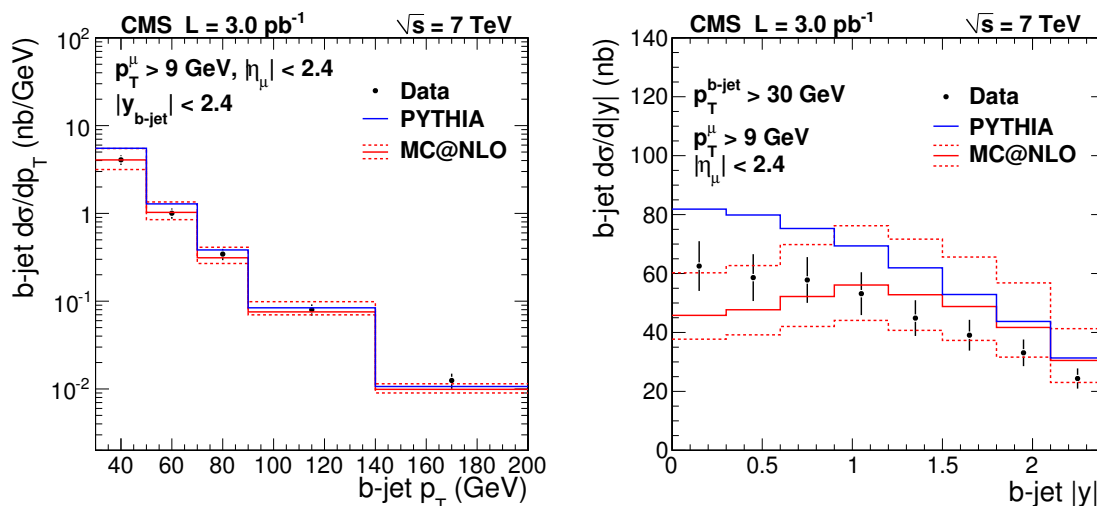
		Data ( $\mu\text{b}$ )	MC@NLO ( $\mu\text{b}$ )	PYTHIA ( $\mu\text{b}$ )
Jet	$p_{\text{T}} > 18 \text{ GeV}$	$9.75 \pm 0.32 \pm 1.67 \pm 0.39$	$7.3^{+2.9}_{-1.8} \pm 1.2 \pm 0.7$	15.3
	$p_{\text{T}} > 32 \text{ GeV}$	$1.73 \pm 0.07 \pm 0.20 \pm 0.07$	$1.3^{+0.5}_{-0.3} \pm 0.2 \pm 0.1$	2.1
Muon	$p_{\text{T}} > 30 \text{ GeV}$ $p_{\text{T}}^{\mu} > 9 \text{ GeV}$ $ \eta^{\mu}  < 2.4$	$0.113 \pm 0.001 \pm 0.014 \pm 0.005$	$0.113^{+0.04}_{-0.023} \pm 0.003 \pm 0.005$	0.158
	$p_{\text{T}} > 30 \text{ GeV}$	$2.25 \pm 0.01 \pm 0.31 \pm 0.09$	$1.83^{+0.64}_{-0.42} \pm 0.05 \pm 0.08$	3.27

**Table 2.** The b-jet cross sections (in  $\mu\text{b}$ ) measured from the jet and muon analyses. The b-jet rapidity range is  $|y| < 2.2$  and  $|y| < 2.4$  for the jet and muon analyses, respectively. The value for  $p_{\text{T}} > 30 \text{ GeV}$  from the muon analysis is an extrapolated result. For the data, the first uncertainty is statistical, the second is systematic, and the third is associated with the estimation of the integrated luminosity. For the MC@NLO prediction, the first uncertainty is from the variations in the QCD scale, the second from the b-quark mass, and the third from the parton distribution functions.

extrapolation factors are similar to those of PYTHIA at high b-jet  $p_{\text{T}}$ , while they are about 20% larger at low  $p_{\text{T}}$ . The cross section measured in data and the corresponding MC@NLO and PYTHIA predictions are summarized in table 2.

### 7.3 Comparison of results

The measurements from the two analyses are compared in figure 5 by adjusting the b-jet cross section from the muon analysis to have the same visible phase space definition as the inclusive b-jet analysis, using PYTHIA for the extrapolation. The overall extrapolation factor is between 0.85 at  $p_{\text{T}} = 30 \text{ GeV}$  and 0.82 at  $p_{\text{T}} = 200 \text{ GeV}$ , and accounts for the reduction in rapidity range from  $|y| < 2.4$  to  $|y| < 2.2$ , exclusion of neutrinos from the particle jet definition, and for counting all b-jets in the event. No additional uncertainty is assigned to the displayed cross sections beyond the experimental uncertainties quoted in table 1 and discussed in section 6. The closed circles in figure 5 correspond to the measured inclusive b-jet  $p_{\text{T}}$  spectrum, and the closed squares show the b-jet  $p_{\text{T}}$  spectrum from the muon analysis, with the yellow band representing the total experimental uncertainty. Two sets of b-jet cross-section measurements from the ATLAS Collaboration [21], also found using a jet analysis and a muon analysis, are shown in the figure for comparison. The CMS results are in good agreement with each other and with the ATLAS measurements to within



**Figure 4.** The differential b-jet cross section from the muon analysis as a function of the b-jet  $p_T$  (left) and  $|y|$  (right), with  $p_T^\mu > 9$  GeV and  $|\eta^\mu| < 2.4$ , and the predictions from PYTHIA and MC@NLO. The error bars on the points correspond to the experimental statistical and systematic uncertainties added in quadrature. The dashed lines represent the MC@NLO uncertainty.

their respective uncertainties. The theoretical prediction from the NLO calculation [29, 30] is displayed as the solid line in the figure, with the dotted lines showing the systematic uncertainties. The CMS results are consistent with the NLO predictions.

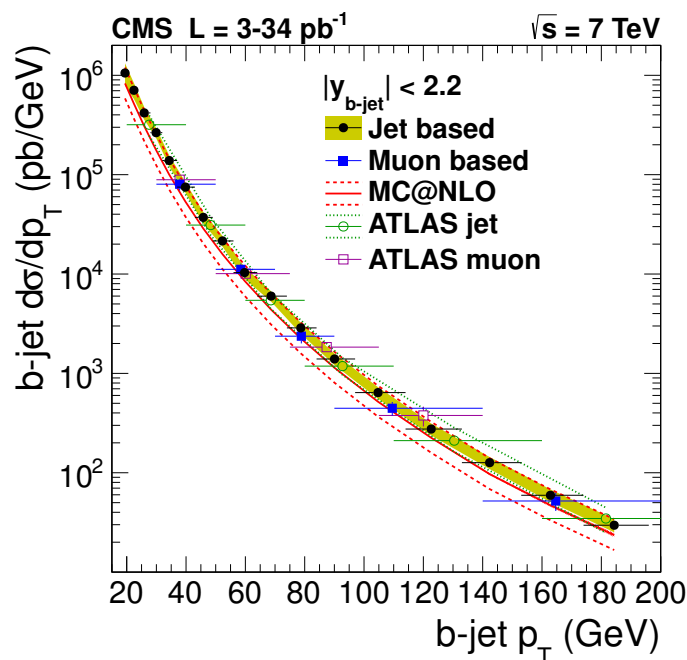
## 8 Summary

The b-jet production cross section has been measured in pp collisions at  $\sqrt{s} = 7$  TeV. The results were presented in several rapidity intervals as a function of the jet transverse momentum. The results were also given as the ratio of the b-jet production cross section and the inclusive jet production cross section. The results of two independent but compatible analyses were reported: a jet analysis selecting events with a b jet or a  $\bar{b}$  jet, and a muon analysis requiring in addition the presence of a muon, based on integrated luminosities of  $34 \text{ pb}^{-1}$  and  $3 \text{ pb}^{-1}$ , respectively.

The measured values of the cross section were found to lie between the MC@NLO and the PYTHIA predictions. The previous CMS measurements of  $B^+$  [17],  $B^0$  [18], and  $B_s$  [19] production cross sections, and an inclusive b-jet measurement with muons [16], also gave values between these two predictions. The measurement of the b-jet production cross section presented here will provide valuable input for testing various theoretical models of b production and for further constraining their parameters.

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**Figure 5.** Measured b-jet cross sections in the jet and muon analyses as a function of the b-jet  $p_T$ , compared to the MC@NLO calculation and to measurements from ATLAS [21].

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**The CMS collaboration****Yerevan Physics Institute, Yerevan, Armenia**

S. Chatrchyan, V. Khachatryan, A.M. Sirunyan, A. Tumasyan

**Institut für Hochenergiephysik der OeAW, Wien, Austria**

W. Adam, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan, M. Friedl, R. Frühwirth, V.M. Ghete, J. Hammer<sup>1</sup>, M. Hoch, N. Hörmann, J. Hrubec, M. Jeitler, W. Kiesenhofer, M. Krammer, D. Liko, I. Mikulec, M. Pernicka<sup>†</sup>, B. Rahbaran, C. Rohringer, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, F. Teischinger, P. Wagner, W. Waltenberger, G. Walzel, E. Widl, C.-E. Wulz

**National Centre for Particle and High Energy Physics, Minsk, Belarus**

V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

**Universiteit Antwerpen, Antwerpen, Belgium**

S. Bansal, L. Benucci, T. Cornelis, E.A. De Wolf, X. Janssen, S. Luyckx, T. Maes, L. Mucibello, S. Ochesanu, B. Roland, R. Rougny, M. Selvaggi, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

**Vrije Universiteit Brussel, Brussel, Belgium**

F. Blekman, S. Blyweert, J. D'Hondt, R. Gonzalez Suarez, A. Kalogeropoulos, M. Maes, A. Olbrechts, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Villella

**Université Libre de Bruxelles, Bruxelles, Belgium**

O. Charaf, B. Clerbaux, G. De Lentdecker, V. Dero, A.P.R. Gay, G.H. Hammad, T. Hreus, A. Léonard, P.E. Marage, L. Thomas, C. Vander Velde, P. Vanlaer, J. Wickens

**Ghent University, Ghent, Belgium**

V. Adler, K. Beernaert, A. Cimmino, S. Costantini, G. Garcia, M. Grunewald, B. Klein, J. Lellouch, A. Marinov, J. Mccartin, A.A. Ocampo Rios, D. Ryckbosch, N. Strobbe, F. Thyssen, M. Tytgat, L. Vanelderen, P. Verwilligen, S. Walsh, E. Yazgan, N. Zaganidis

**Université Catholique de Louvain, Louvain-la-Neuve, Belgium**

S. Basegmez, G. Bruno, L. Ceard, J. De Favereau De Jeneret, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco<sup>2</sup>, G. Grégoire, J. Hollar, V. Lemaitre, J. Liao, O. Militaru, C. Nuttens, D. Pagano, A. Pin, K. Piotrkowski, N. Schul

**Université de Mons, Mons, Belgium**

N. Belyi, T. Caebergs, E. Daubie

**Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil**

G.A. Alves, M. Correa Martins Junior, D. De Jesus Damiao, T. Martins, M.E. Pol, M.H.G. Souza

**Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil**

W.L. Aldá Júnior, W. Carvalho, A. Custódio, E.M. Da Costa, C. De Oliveira Martins, S. Fonseca De Souza, D. Matos Figueiredo, L. Mundim, H. Nogima, V. Oguri, W.L. Prado Da Silva, A. Santoro, S.M. Silva Do Amaral, L. Soares Jorge, A. Sznajder

**Instituto de Fisica Teorica, Universidade Estadual Paulista, Sao Paulo, Brazil**

T.S. Anjos<sup>3</sup>, C.A. Bernardes<sup>3</sup>, F.A. Dias<sup>4</sup>, T.R. Fernandez Perez Tomei, E. M. Gregores<sup>3</sup>, C. Lagana, F. Marinho, P.G. Mercadante<sup>3</sup>, S.F. Novaes, Sandra S. Padula

**Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria**

V. Genchev<sup>1</sup>, P. Iaydjiev<sup>1</sup>, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov, M. Vutova

**University of Sofia, Sofia, Bulgaria**

A. Dimitrov, R. Hadjiiska, A. Karadzhinova, V. Kozhuharov, L. Litov, B. Pavlov, P. Petkov

**Institute of High Energy Physics, Beijing, China**

J.G. Bian, G.M. Chen, H.S. Chen, C.H. Jiang, D. Liang, S. Liang, X. Meng, J. Tao, J. Wang, J. Wang, X. Wang, Z. Wang, H. Xiao, M. Xu, J. Zang, Z. Zhang

**State Key Lab. of Nucl. Phys. and Tech., Peking University, Beijing, China**

C. Asawatrangkuldee, Y. Ban, S. Guo, Y. Guo, W. Li, S. Liu, Y. Mao, S.J. Qian, H. Teng, S. Wang, B. Zhu, W. Zou

**Universidad de Los Andes, Bogota, Colombia**

A. Cabrera, B. Gomez Moreno, A.F. Osorio Oliveros, J.C. Sanabria

**Technical University of Split, Split, Croatia**

N. Godinovic, D. Lelas, R. Plestina<sup>5</sup>, D. Polic, I. Puljak<sup>1</sup>

**University of Split, Split, Croatia**

Z. Antunovic, M. Dzelalija, M. Kovac

**Institute Rudjer Boskovic, Zagreb, Croatia**

V. Brigljevic, S. Duric, K. Kadija, J. Luetic, S. Morovic

**University of Cyprus, Nicosia, Cyprus**

A. Attikis, M. Galanti, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis

**Charles University, Prague, Czech Republic**

M. Finger, M. Finger Jr.

**Academy of Scientific Research and Technology of the Arab Republic of Egypt,  
Egyptian Network of High Energy Physics, Cairo, Egypt**

Y. Assran<sup>6</sup>, A. Ellithi Kamel<sup>7</sup>, S. Khalil<sup>8</sup>, M.A. Mahmoud<sup>9</sup>, A. Radi<sup>8,10</sup>

**National Institute of Chemical Physics and Biophysics, Tallinn, Estonia**

A. Hektor, M. Kadastik, M. Müntel, M. Raidal, L. Rebane, A. Tiko

**Department of Physics, University of Helsinki, Helsinki, Finland**

V. Azzolini, P. Eerola, G. Fedi, M. Voutilainen

**Helsinki Institute of Physics, Helsinki, Finland**

S. Czellar, J. Härkönen, A. Heikkinen, V. Karimäki, R. Kinnunen, M.J. Kortelainen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, T. Peltola, E. Tuominen, J. Tuominiemi, E. Tuovinen, D. Ungaro, L. Wendland

**Lappeenranta University of Technology, Lappeenranta, Finland**

K. Banzuzi, A. Korpela, T. Tuuva

**Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS,  
Annecy-le-Vieux, France**

D. Sillou

**DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France**

M. Besancon, S. Choudhury, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, L. Millischer, J. Rander, A. Rosowsky, I. Shreyber, M. Titov

**Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau,  
France**

S. Baffioni, F. Beaudette, L. Benhabib, L. Bianchini, M. Bluj<sup>11</sup>, C. Broutin, P. Busson, C. Charlot, N. Daci, T. Dahms, L. Dobrzynski, S. Elgammal, R. Granier de Cassagnac, M. Haguenaer, P. Miné, C. Mironov, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Thiebaux, C. Veelken, A. Zabi

**Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Univer-  
sité de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France**

J.-L. Agram<sup>12</sup>, J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte<sup>12</sup>, F. Drouhin<sup>12</sup>, C. Ferro, J.-C. Fontaine<sup>12</sup>, D. Gelé, U. Goerlach, P. Juillot, M. Karim<sup>12</sup>, A.-C. Le Bihan, P. Van Hove

**Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules (IN2P3), Villeurbanne, France**

F. Fassi, D. Mercier

**Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France**

C. Baty, S. Beauceron, N. Beaupere, M. Bedjidian, O. Bondu, G. Boudoul, D. Boumediene, H. Brun, J. Chasserat, R. Chierici<sup>1</sup>, D. Contardo, P. Depasse, H. El Mamouni, A. Falkiewicz, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, T. Le Grand, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, S. Tosi, Y. Tschudi, P. Verdier, S. Viret

**Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia**

D. Lomidze

**RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany**

G. Anagnostou, S. Beranek, M. Edelhoff, L. Feld, N. Heracleous, O. Hindrichs, R. Jussen, K. Klein, J. Merz, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, B. Wittmer, V. Zhukov<sup>13</sup>

**RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany**

M. Ata, J. Caudron, E. Dietz-Laursonn, M. Erdmann, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, T. Klimkovich, D. Klingebiel, P. Kreuzer, D. Lanske<sup>†</sup>, J. Lingemann, C. Magass, M. Merschmeyer, A. Meyer, M. Olschewski, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teyssier, M. Weber

**RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany**

M. Bontenackels, V. Cherepanov, M. Davids, G. Flügge, H. Geenen, M. Geisler, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, A. Linn, A. Nowack, L. Perchalla, O. Pooth, J. Rennefeld, P. Sauerland, A. Stahl, M.H. Zoeller

**Deutsches Elektronen-Synchrotron, Hamburg, Germany**

M. Aldaya Martin, W. Behrenhoff, U. Behrens, M. Bergholz<sup>14</sup>, A. Bethani, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, E. Castro, D. Dammann, G. Eckerlin, D. Eckstein, A. Flossdorf, G. Flucke, A. Geiser, J. Hauk, H. Jung<sup>1</sup>, M. Kasemann, P. Katsas, C. Kleinwort, H. Kluge, A. Knutsson, M. Krämer, D. Krücker, E. Kuznetsova, W. Lange, W. Lohmann<sup>14</sup>, B. Lutz, R. Mankel, I. Marfin, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, S. Naumann-Emme, J. Olzem, A. Petrukhin, D. Pitzl, A. Raspereza, P.M. Ribeiro Cipriano, M. Rosin, J. Salfeld-Nebgen, R. Schmidt<sup>14</sup>, T. Schoerner-Sadenius, N. Sen, A. Spiridonov, M. Stein, J. Tomaszewska, R. Walsh, C. Wissing

**University of Hamburg, Hamburg, Germany**

C. Autermann, V. Blobel, S. Bobrovskiy, J. Draeger, H. Enderle, J. Erfle, U. Gebbert, M. Görner, T. Hermanns, R.S. Höing, K. Kaschube, G. Kaussen, H. Kirschenmann, R. Klanner, J. Lange, B. Mura, F. Nowak, N. Pietsch, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Schröder, T. Schum, H. Stadie, G. Steinbrück, J. Thomsen

**Institut für Experimentelle Kernphysik, Karlsruhe, Germany**

C. Barth, J. Berger, T. Chwalek, W. De Boer, A. Dierlamm, G. Dirkes, M. Feindt, J. Gruschke, M. Guthoff<sup>1</sup>, C. Hackstein, F. Hartmann, M. Heinrich, H. Held, K.H. Hoffmann, S. Honc, I. Katkov<sup>13</sup>, J.R. Komaragiri, T. Kuhr, D. Martschei, S. Mueller, Th. Müller, M. Niegel, A. Nürnberg, O. Oberst, A. Oehler, J. Ott, T. Peiffer, G. Quast, K. Rabbertz, F. Ratnikov, N. Ratnikova, M. Renz, S. Röcker, C. Saout, A. Scheurer, P. Schieferdecker, F.-P. Schilling, M. Schmanau, G. Schott, H.J. Simonis, F.M. Stober, D. Troendle, J. Wagner-Kuhr, T. Weiler, M. Zeise, E.B. Ziebarth

**Institute of Nuclear Physics "Demokritos", Aghia Paraskevi, Greece**

G. Daskalakis, T. Geralis, S. Kesisoglou, A. Kyriakis, D. Loukas, I. Manolakos, A. Markou, C. Markou, C. Mavrommatis, E. Ntomari

**University of Athens, Athens, Greece**

L. Gouskos, T.J. Mertzimekis, A. Panagiotou, N. Saoulidou, E. Stiliaris

**University of Ioánnina, Ioánnina, Greece**

I. Evangelou, C. Foudas<sup>1</sup>, P. Kokkas, N. Manthos, I. Papadopoulos, V. Patras, F.A. Triantis

**KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary**

A. Aranyi, G. Bencze, L. Boldizsar, C. Hajdu<sup>1</sup>, P. Hidas, D. Horvath<sup>15</sup>, A. Kapusi, K. Krajczar<sup>16</sup>, F. Sikler<sup>1</sup>, V. Veszpremi, G. Vesztergombi<sup>16</sup>

**Institute of Nuclear Research ATOMKI, Debrecen, Hungary**

N. Beni, J. Molnar, J. Palinkas, Z. Szillasi

**University of Debrecen, Debrecen, Hungary**

J. Karancsi, P. Raics, Z.L. Trocsanyi, B. Ujvari

**Panjab University, Chandigarh, India**

S.B. Beri, V. Bhatnagar, N. Dhingra, R. Gupta, M. Jindal, M. Kaur, J.M. Kohli, M.Z. Mehta, N. Nishu, L.K. Saini, A. Sharma, A.P. Singh, J. Singh, S.P. Singh

**University of Delhi, Delhi, India**

S. Ahuja, B.C. Choudhary, A. Kumar, A. Kumar, S. Malhotra, M. Naimuddin, K. Ranjan, V. Sharma, R.K. Shivpuri

**Saha Institute of Nuclear Physics, Kolkata, India**

S. Banerjee, S. Bhattacharya, S. Dutta, B. Gomber, S. Jain, S. Jain, R. Khurana, S. Sarkar

**Bhabha Atomic Research Centre, Mumbai, India**

R.K. Choudhury, D. Dutta, S. Kailas, V. Kumar, A.K. Mohanty<sup>1</sup>, L.M. Pant, P. Shukla

**Tata Institute of Fundamental Research - EHEP, Mumbai, India**

T. Aziz, S. Ganguly, M. Guchait<sup>17</sup>, A. Gurtu<sup>18</sup>, M. Maity<sup>19</sup>, G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, A. Saha, K. Sudhakar, N. Wickramage

**Tata Institute of Fundamental Research - HECR, Mumbai, India**

S. Banerjee, S. Dugad, N.K. Mondal

**Institute for Research in Fundamental Sciences (IPM), Tehran, Iran**

H. Arfaei, H. Bakhshiansohi<sup>20</sup>, S.M. Etesami<sup>21</sup>, A. Fahim<sup>20</sup>, M. Hashemi, H. Hesari, A. Jafari<sup>20</sup>, M. Khakzad, A. Mohammadi<sup>22</sup>, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh<sup>23</sup>, M. Zeinali<sup>21</sup>

**INFN Sezione di Bari<sup>a</sup>, Università di Bari<sup>b</sup>, Politecnico di Bari<sup>c</sup>, Bari, Italy**

M. Abbrescia<sup>a,b</sup>, L. Barbone<sup>a,b</sup>, C. Calabria<sup>a,b</sup>, S.S. Chhibra<sup>a,b</sup>, A. Colaleo<sup>a</sup>, D. Creanza<sup>a,c</sup>, N. De Filippis<sup>a,c,1</sup>, M. De Palma<sup>a,b</sup>, L. Fiore<sup>a</sup>, G. Iaselli<sup>a,c</sup>, L. Lusito<sup>a,b</sup>, G. Maggi<sup>a,c</sup>, M. Maggi<sup>a</sup>, N. Manna<sup>a,b</sup>, B. Marangelli<sup>a,b</sup>, S. My<sup>a,c</sup>, S. Nuzzo<sup>a,b</sup>, N. Pacifico<sup>a,b</sup>, A. Pompili<sup>a,b</sup>, G. Pugliese<sup>a,c</sup>, F. Romano<sup>a,c</sup>, G. Selvaggi<sup>a,b</sup>, L. Silvestris<sup>a</sup>, G. Singh<sup>a,b</sup>, S. Tupputi<sup>a,b</sup>, G. Zito<sup>a</sup>

**INFN Sezione di Bologna<sup>a</sup>, Università di Bologna<sup>b</sup>, Bologna, Italy**

G. Abbiendi<sup>a</sup>, A.C. Benvenuti<sup>a</sup>, D. Bonacorsi<sup>a</sup>, S. Braibant-Giacomelli<sup>a,b</sup>, L. Brigliadori<sup>a</sup>, P. Capiluppi<sup>a,b</sup>, A. Castro<sup>a,b</sup>, F.R. Cavallo<sup>a</sup>, M. Cuffiani<sup>a,b</sup>, G.M. Dallavalle<sup>a</sup>, F. Fabbri<sup>a</sup>, A. Fanfani<sup>a,b</sup>, D. Fasanella<sup>a,1</sup>, P. Giacomelli<sup>a</sup>, C. Grandi<sup>a</sup>, S. Marcellini<sup>a</sup>, G. Masetti<sup>a</sup>, M. Meneghelli<sup>a,b</sup>, A. Montanari<sup>a</sup>, F.L. Navarria<sup>a,b</sup>, F. Odorici<sup>a</sup>, A. Perrotta<sup>a</sup>, F. Primavera<sup>a</sup>, A.M. Rossi<sup>a,b</sup>, T. Rovelli<sup>a,b</sup>, G. Siroli<sup>a,b</sup>, R. Travaglini<sup>a,b</sup>

**INFN Sezione di Catania<sup>a</sup>, Università di Catania<sup>b</sup>, Catania, Italy**

S. Albergo<sup>a,b</sup>, G. Cappello<sup>a,b</sup>, M. Chiorboli<sup>a,b</sup>, S. Costa<sup>a,b</sup>, R. Potenza<sup>a,b</sup>, A. Tricomi<sup>a,b</sup>, C. Tuve<sup>a,b</sup>

**INFN Sezione di Firenze<sup>a</sup>, Università di Firenze<sup>b</sup>, Firenze, Italy**

G. Barbagli<sup>a</sup>, V. Ciulli<sup>a,b</sup>, C. Civinini<sup>a</sup>, R. D'Alessandro<sup>a,b</sup>, E. Focardi<sup>a,b</sup>, S. Frosali<sup>a,b</sup>, E. Gallo<sup>a</sup>, S. Gonzi<sup>a,b</sup>, M. Meschini<sup>a</sup>, S. Paoletti<sup>a</sup>, G. Sguazzoni<sup>a</sup>, A. Tropiano<sup>a,1</sup>

**INFN Laboratori Nazionali di Frascati, Frascati, Italy**

L. Benussi, S. Bianco, S. Colafranceschi<sup>24</sup>, F. Fabbri, D. Piccolo



**INFN Sezione di Genova, Genova, Italy**

P. Fabbriatore, R. Musenich

**INFN Sezione di Milano-Bicocca<sup>a</sup>, Università di Milano-Bicocca<sup>b</sup>, Milano, Italy**

A. Benaglia<sup>a,b,1</sup>, F. De Guio<sup>a,b</sup>, L. Di Matteo<sup>a,b</sup>, S. Fiorendi<sup>a,b</sup>, S. Gennai<sup>a,1</sup>, A. Ghezzi<sup>a,b</sup>, S. Malvezzi<sup>a</sup>, R.A. Manzoni<sup>a,b</sup>, A. Martelli<sup>a,b</sup>, A. Massironi<sup>a,b,1</sup>, D. Menasce<sup>a</sup>, L. Moroni<sup>a</sup>, M. Paganoni<sup>a,b</sup>, D. Pedrini<sup>a</sup>, S. Ragazzi<sup>a,b</sup>, N. Redaelli<sup>a</sup>, S. Sala<sup>a</sup>, T. Tabarelli de Fatis<sup>a,b</sup>

**INFN Sezione di Napoli<sup>a</sup>, Università di Napoli "Federico II"<sup>b</sup>, Napoli, Italy**

S. Buontempo<sup>a</sup>, C.A. Carrillo Montoya<sup>a,1</sup>, N. Cavallo<sup>a,25</sup>, A. De Cosa<sup>a,b</sup>, O. Dogangun<sup>a,b</sup>, F. Fabozzi<sup>a,25</sup>, A.O.M. Iorio<sup>a,1</sup>, L. Lista<sup>a</sup>, M. Merola<sup>a,b</sup>, P. Paolucci<sup>a</sup>

**INFN Sezione di Padova<sup>a</sup>, Università di Padova<sup>b</sup>, Università di Trento (Trento)<sup>c</sup>, Padova, Italy**

P. Azzi<sup>a</sup>, N. Bacchetta<sup>a,1</sup>, P. Bellan<sup>a,b</sup>, M. Biasotto<sup>a,26</sup>, D. Bisello<sup>a,b</sup>, A. Branca<sup>a</sup>, R. Carlin<sup>a,b</sup>, P. Checchia<sup>a</sup>, T. Dorigo<sup>a</sup>, U. Dosselli<sup>a</sup>, F. Gasparini<sup>a,b</sup>, F. Gonella<sup>a</sup>, A. Gozzelino<sup>a</sup>, M. Gulmini<sup>a,26</sup>, K. Kanishchev, S. Lacaprara<sup>a,26</sup>, I. Lazzizzera<sup>a,c</sup>, M. Margoni<sup>a,b</sup>, A.T. Meneguzzo<sup>a,b</sup>, M. Nespolo<sup>a,1</sup>, M. Pegoraro<sup>a</sup>, L. Perrozzi<sup>a</sup>, N. Pozzobon<sup>a,b</sup>, P. Ronchese<sup>a,b</sup>, F. Simonetto<sup>a,b</sup>, E. Torassa<sup>a</sup>, M. Tosi<sup>a,b,1</sup>, S. Vanini<sup>a,b</sup>, P. Zotto<sup>a,b</sup>

**INFN Sezione di Pavia<sup>a</sup>, Università di Pavia<sup>b</sup>, Pavia, Italy**

P. Baesso<sup>a,b</sup>, U. Berzano<sup>a</sup>, M. Gabusi<sup>a,b</sup>, S.P. Ratti<sup>a,b</sup>, C. Riccardi<sup>a,b</sup>, P. Torre<sup>a,b</sup>, P. Vitulo<sup>a,b</sup>, C. Viviani<sup>a,b</sup>

**INFN Sezione di Perugia<sup>a</sup>, Università di Perugia<sup>b</sup>, Perugia, Italy**

M. Biasini<sup>a,b</sup>, G.M. Bilei<sup>a</sup>, B. Caponeri<sup>a,b</sup>, L. Fanò<sup>a,b</sup>, P. Lariccia<sup>a,b</sup>, A. Lucaroni<sup>a,b,1</sup>, G. Mantovani<sup>a,b</sup>, M. Menichelli<sup>a</sup>, A. Nappi<sup>a,b</sup>, F. Romeo<sup>a,b</sup>, A. Santocchia<sup>a,b</sup>, S. Taroni<sup>a,b,1</sup>, M. Valdata<sup>a,b</sup>

**INFN Sezione di Pisa<sup>a</sup>, Università di Pisa<sup>b</sup>, Scuola Normale Superiore di Pisa<sup>c</sup>, Pisa, Italy**

P. Azzurri<sup>a,c</sup>, G. Bagliesi<sup>a</sup>, T. Boccali<sup>a</sup>, G. Broccolo<sup>a,c</sup>, R. Castaldi<sup>a</sup>, R.T. D'Agnolo<sup>a,c</sup>, R. Dell'Orso<sup>a</sup>, F. Fiori<sup>a,b</sup>, L. Foà<sup>a,c</sup>, A. Giassi<sup>a</sup>, A. Kraan<sup>a</sup>, F. Ligabue<sup>a,c</sup>, T. Lomtadze<sup>a</sup>, L. Martini<sup>a,27</sup>, A. Messineo<sup>a,b</sup>, F. Palla<sup>a</sup>, F. Palmonari<sup>a</sup>, A. Rizzi, A.T. Serban<sup>a</sup>, P. Spagnolo<sup>a</sup>, R. Tenchini<sup>a</sup>, G. Tonelli<sup>a,b,1</sup>, A. Venturi<sup>a,1</sup>, P.G. Verdini<sup>a</sup>

**INFN Sezione di Roma<sup>a</sup>, Università di Roma "La Sapienza"<sup>b</sup>, Roma, Italy**

L. Barone<sup>a,b</sup>, F. Cavallari<sup>a</sup>, D. Del Re<sup>a,b,1</sup>, M. Diemoz<sup>a</sup>, C. Fanelli, D. Franci<sup>a,b</sup>, M. Grassi<sup>a,1</sup>, E. Longo<sup>a,b</sup>, P. Meridiani<sup>a</sup>, F. Micheli, S. Nourbakhsh<sup>a</sup>, G. Organtini<sup>a,b</sup>, F. Pandolfi<sup>a,b</sup>, R. Paramatti<sup>a</sup>, S. Rahatlou<sup>a,b</sup>, M. Sigamani<sup>a</sup>, L. Soffi

**INFN Sezione di Torino<sup>a</sup>, Università di Torino<sup>b</sup>, Università del Piemonte Orientale (Novara)<sup>c</sup>, Torino, Italy**

N. Amapane<sup>a,b</sup>, R. Arcidiacono<sup>a,c</sup>, S. Argiro<sup>a,b</sup>, M. Arneodo<sup>a,c</sup>, C. Biino<sup>a</sup>, C. Botta<sup>a,b</sup>, N. Cartiglia<sup>a</sup>, R. Castello<sup>a,b</sup>, M. Costa<sup>a,b</sup>, N. Demaria<sup>a</sup>, A. Graziano<sup>a,b</sup>, C. Mariotti<sup>a,1</sup>, S. Maselli<sup>a</sup>, E. Migliore<sup>a,b</sup>, V. Monaco<sup>a,b</sup>, M. Musich<sup>a</sup>, M.M. Obertino<sup>a,c</sup>, N. Pastrone<sup>a</sup>, M. Pelliccioni<sup>a</sup>, A. Potenza<sup>a,b</sup>, A. Romero<sup>a,b</sup>, M. Ruspa<sup>a,c</sup>, R. Sacchi<sup>a,b</sup>, A. Solano<sup>a,b</sup>, A. Staiano<sup>a</sup>, P.P. Trapani<sup>a,b</sup>, A. Vilela Pereira<sup>a</sup>

**INFN Sezione di Trieste<sup>a</sup>, Università di Trieste<sup>b</sup>, Trieste, Italy**

S. Belforte<sup>a</sup>, F. Cossutti<sup>a</sup>, G. Della Ricca<sup>a,b</sup>, B. Gobbo<sup>a</sup>, M. Marone<sup>a,b</sup>, D. Montanino<sup>a,b,1</sup>, A. Penzo<sup>a</sup>

**Kangwon National University, Chunchon, Korea**

S.G. Heo, S.K. Nam

**Kyungpook National University, Daegu, Korea**

S. Chang, J. Chung, D.H. Kim, G.N. Kim, J.E. Kim, D.J. Kong, H. Park, S.R. Ro, D.C. Son

**Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea**

J.Y. Kim, Zero J. Kim, S. Song

**Konkuk University, Seoul, Korea**

H.Y. Jo

**Korea University, Seoul, Korea**

S. Choi, D. Gyun, B. Hong, M. Jo, H. Kim, T.J. Kim, K.S. Lee, D.H. Moon, S.K. Park, E. Seo, K.S. Sim

**University of Seoul, Seoul, Korea**

M. Choi, S. Kang, H. Kim, J.H. Kim, C. Park, I.C. Park, S. Park, G. Ryu

**Sungkyunkwan University, Suwon, Korea**

Y. Cho, Y. Choi, Y.K. Choi, J. Goh, M.S. Kim, B. Lee, J. Lee, S. Lee, H. Seo, I. Yu

**Vilnius University, Vilnius, Lithuania**

M.J. Bilinskas, I. Grigelionis, M. Janulis

**Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico**

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz, R. Lopez-Fernandez, R. Magaña Villalba, J. Martínez-Ortega, A. Sánchez-Hernández, L.M. Villasenor-Cendejas

**Universidad Iberoamericana, Mexico City, Mexico**

S. Carrillo Moreno, F. Vazquez Valencia

**Benemerita Universidad Autonoma de Puebla, Puebla, Mexico**

H.A. Salazar Ibarguen

**Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico**

E. Casimiro Linares, A. Morelos Pineda, M.A. Reyes-Santos

**University of Auckland, Auckland, New Zealand**

D. Krofcheck

**University of Canterbury, Christchurch, New Zealand**

A.J. Bell, P.H. Butler, R. Doesburg, S. Reucroft, H. Silverwood

**National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan**

M. Ahmad, M.I. Asghar, H.R. Hoorani, S. Khalid, W.A. Khan, T. Khurshid, S. Qazi, M.A. Shah, M. Shoaib

**Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland**

G. Brona, M. Cwiok, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski

**Soltan Institute for Nuclear Studies, Warsaw, Poland**

H. Bialkowska, B. Boimska, T. Frueboes, R. Gokieli, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, G. Wrochna, P. Zalewski

**Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal**

N. Almeida, P. Bargassa, A. David, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, P. Musella, A. Nayak, J. Pela<sup>1</sup>, P.Q. Ribeiro, J. Seixas, J. Varela, P. Vischia

**Joint Institute for Nuclear Research, Dubna, Russia**

S. Afanasiev, I. Belotelov, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, G. Kozlov, A. Lanev, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, V. Smirnov, A. Volodko, A. Zarubin

**Petersburg Nuclear Physics Institute, Gatchina (St Petersburg), Russia**

S. Evstyukhin, V. Golovtsov, Y. Ivanov, V. Kim, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, An. Vorobyev

**Institute for Nuclear Research, Moscow, Russia**

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, M. Kirsanov, N. Krasnikov, V. Matveev, A. Pashenkov, A. Toropin, S. Troitsky

**Institute for Theoretical and Experimental Physics, Moscow, Russia**

V. Epshteyn, M. Erofeeva, V. Gavrilov, M. Kossov<sup>1</sup>, A. Krokhotin, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, V. Stolin, E. Vlasov, A. Zhokin

**Moscow State University, Moscow, Russia**

A. Belyaev, E. Boos, M. Dubinin<sup>4</sup>, L. Dudko, A. Ershov, A. Gribushin, O. Kodolova, I. Lokhtin, A. Markina, S. Obraztsov, M. Perfilov, S. Petrushanko, L. Sarycheva<sup>†</sup>, V. Savrin, A. Snigirev

**P.N. Lebedev Physical Institute, Moscow, Russia**

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Leonidov, G. Mesyats, S.V. Rusakov, A. Vinogradov

**State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia**

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Grishin<sup>1</sup>, V. Kachanov, D. Konstantinov, A. Korablev, V. Krychkin, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

**University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia**

P. Adzic<sup>28</sup>, M. Djordjevic, M. Ekmedzic, D. Krpic<sup>28</sup>, J. Milosevic

**Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain**

M. Aguilar-Benitez, J. Alcaraz Maestre, P. Arce, C. Battilana, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, C. Diez Pardos, D. Domínguez Vázquez, C. Fernandez Bedoya, J.P. Fernández Ramos, A. Ferrando, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, G. Merino, J. Puerta Pelayo, I. Redondo, L. Romero, J. Santaolalla, M.S. Soares, C. Willmott

**Universidad Autónoma de Madrid, Madrid, Spain**

C. Albajar, G. Codispoti, J.F. de Trocóniz

**Universidad de Oviedo, Oviedo, Spain**

J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, L. Lloret Iglesias, J. Piedra Gomez<sup>29</sup>, J.M. Vizán Garcia

**Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria,  
Santander, Spain**

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, S.H. Chuang, J. Duarte Campderros, M. Felcini<sup>30</sup>, M. Fernandez, G. Gomez, J. Gonzalez Sanchez, C. Jorda, P. Lobelle Pardo, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, M. Sobron Sanudo, I. Vila, R. Vilar Cortabitarte

**CERN, European Organization for Nuclear Research, Geneva, Switzerland**

D. Abbaneo, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, C. Bernet<sup>5</sup>, W. Bialas, G. Bianchi, P. Bloch, A. Bocci, H. Breuker, K. Bunkowski, T. Camporesi, G. Cerminara, T. Christiansen, J.A. Coarasa Perez, B. Curé, D. D'Enterria, A. De Roeck, S. Di Guida, M. Dobson, N. Dupont-Sagorin, A. Elliott-Peisert, B. Frisch, W. Funk, A. Gaddi, G. Georgiou, H. Gerwig, M. Giffels, D. Gigi, K. Gill, D. Giordano, M. Giunta, F. Glege, R. Gomez-Reino Garrido, P. Govoni, S. Gowdy, R. Guida, L. Guiducci, M. Hansen, P. Harris, C. Hartl, J. Harvey, B. Hegner, A. Hinzmann, H.F. Hoffmann, V. Innocente, P. Janot, K. Kaadze, E. Karavakis, K. Kousouris, P. Lecoq, P. Lenzi, C. Lourenço, T. Mäki, M. Malberti, L. Malgeri, M. Mannelli, L. Masetti, G. Mavromanolakis, F. Meijers, S. Mersi, E. Meschi, R. Moser, M.U. Mozer, M. Mulders, E. Nesvold, M. Nguyen, T. Orimoto, L. Orsini, E. Palencia Cortezon, E. Perez, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimiä, D. Piparo, G. Polese, L. Quertenmont, A. Racz, W. Reece, J. Rodrigues Antunes, G. Rolandi<sup>31</sup>, T. Rommelskirchen, C. Rovelli<sup>32</sup>, M. Rovere, H. Sakulin, F. Santanastasio, C. Schäfer, C. Schwick, I. Segoni, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas<sup>33</sup>, D. Spiga, M. Spiropulu<sup>4</sup>, M. Stoye, A. Tsirou, G.I. Veres<sup>16</sup>, P. Vichoudis, H.K. Wöhri, S.D. Worm<sup>34</sup>, W.D. Zeuner

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**Institute for Particle Physics, ETH Zurich, Zurich, Switzerland**

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A. Adiguzel, M.N. Bakirci<sup>38</sup>, S. Cerci<sup>39</sup>, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, I. Hos, E.E. Kangal, G. Karapinar, A. Kayis Topaksu, G. Onengut, K. Ozdemir, S. Ozturk<sup>40</sup>, A. Polatoz, K. Sogut<sup>41</sup>, D. Sunar Cerci<sup>39</sup>, B. Tali<sup>39</sup>, H. Topakli<sup>38</sup>, D. Uzun, L.N. Vergili, M. Vergili

**Middle East Technical University, Physics Department, Ankara, Turkey**

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M. Deliomeroglu, E. Gülmez, B. Isildak, M. Kaya<sup>42</sup>, O. Kaya<sup>42</sup>, S. Ozkorucuklu<sup>43</sup>, N. Sonmez<sup>44</sup>

**National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine**

L. Levchuk

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F. Bostock, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, R. Frazier, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, L. Kreczko, S. Metson, D.M. Newbold<sup>34</sup>, K. Nirunpong, A. Poll, S. Senkin, V.J. Smith, T. Williams

**Rutherford Appleton Laboratory, Didcot, United Kingdom**

L. Basso<sup>45</sup>, K.W. Bell, A. Belyaev<sup>45</sup>, C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Jackson, B.W. Kennedy, E. Olaiya, D. Petyt, B.C. Radburn-Smith, C.H. Shepherd-Themistocleous, I.R. Tomalin, W.J. Womersley

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C. Henderson

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**The University of Iowa, Iowa City, U.S.A.**

U. Akgun, E.A. Albayrak, B. Bilki<sup>51</sup>, W. Clarida, F. Duru, S. Griffiths, C.K. Lae, E. McCliment, J.-P. Merlo, H. Mermerkaya<sup>52</sup>, A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, J. Olson, Y. Onel, F. Ozok, S. Sen, E. Tiras, J. Wetzel, T. Yetkin, K. Yi

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**Purdue University Calumet, Hammond, U.S.A.**

S. Guragain, N. Parashar

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A. Adair, C. Boulahouache, V. Cuplov, K.M. Ecklund, F.J.M. Geurts, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

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G. Cerizza, M. Hollingsworth, S. Spanier, Z.C. Yang, A. York

**Texas A&M University, College Station, U.S.A.**

R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon<sup>53</sup>, V. Khotilovich, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Safonov, T. Sakuma, S. Sengupta, I. Suarez, A. Tatarinov, D. Toback

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- †: Deceased
- 1: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
  - 2: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
  - 3: Also at Universidade Federal do ABC, Santo Andre, Brazil
  - 4: Also at California Institute of Technology, Pasadena, U.S.A.
  - 5: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
  - 6: Also at Suez Canal University, Suez, Egypt
  - 7: Also at Cairo University, Cairo, Egypt
  - 8: Also at British University, Cairo, Egypt
  - 9: Also at Fayoum University, El-Fayoum, Egypt
  - 10: Now at Ain Shams University, Cairo, Egypt
  - 11: Also at Soltan Institute for Nuclear Studies, Warsaw, Poland
  - 12: Also at Université de Haute-Alsace, Mulhouse, France
  - 13: Also at Moscow State University, Moscow, Russia
  - 14: Also at Brandenburg University of Technology, Cottbus, Germany
  - 15: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
  - 16: Also at Eötvös Loránd University, Budapest, Hungary
  - 17: Also at Tata Institute of Fundamental Research - HECR, Mumbai, India
  - 18: Now at King Abdulaziz University, Jeddah, Saudi Arabia
  - 19: Also at University of Visva-Bharati, Santiniketan, India
  - 20: Also at Sharif University of Technology, Tehran, Iran
  - 21: Also at Isfahan University of Technology, Isfahan, Iran
  - 22: Also at Shiraz University, Shiraz, Iran
  - 23: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Teheran, Iran
  - 24: Also at Facoltà Ingegneria Università di Roma, Roma, Italy
  - 25: Also at Università della Basilicata, Potenza, Italy
  - 26: Also at Laboratori Nazionali di Legnaro dell' INFN, Legnaro, Italy
  - 27: Also at Università degli studi di Siena, Siena, Italy
  - 28: Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia
  - 29: Also at University of Florida, Gainesville, U.S.A.
  - 30: Also at University of California, Los Angeles, Los Angeles, U.S.A.
  - 31: Also at Scuola Normale e Sezione dell' INFN, Pisa, Italy
  - 32: Also at INFN Sezione di Roma; Università di Roma "La Sapienza", Roma, Italy
  - 33: Also at University of Athens, Athens, Greece
  - 34: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
  - 35: Also at The University of Kansas, Lawrence, U.S.A.
  - 36: Also at Paul Scherrer Institut, Villigen, Switzerland
  - 37: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
  - 38: Also at Gaziosmanpasa University, Tokat, Turkey
  - 39: Also at Adiyaman University, Adiyaman, Turkey
  - 40: Also at The University of Iowa, Iowa City, U.S.A.
  - 41: Also at Mersin University, Mersin, Turkey
  - 42: Also at Kafkas University, Kars, Turkey
  - 43: Also at Suleyman Demirel University, Isparta, Turkey
  - 44: Also at Ege University, Izmir, Turkey
  - 45: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
  - 46: Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy
  - 47: Also at Utah Valley University, Orem, U.S.A.
  - 48: Also at Institute for Nuclear Research, Moscow, Russia
  - 49: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
  - 50: Also at Los Alamos National Laboratory, Los Alamos, U.S.A.
  - 51: Also at Argonne National Laboratory, Argonne, U.S.A.
  - 52: Also at Erzincan University, Erzincan, Turkey
  - 53: Also at Kyungpook National University, Daegu, Korea