$B_s^0 \to \phi\mu^+\mu^-$ at LHCb

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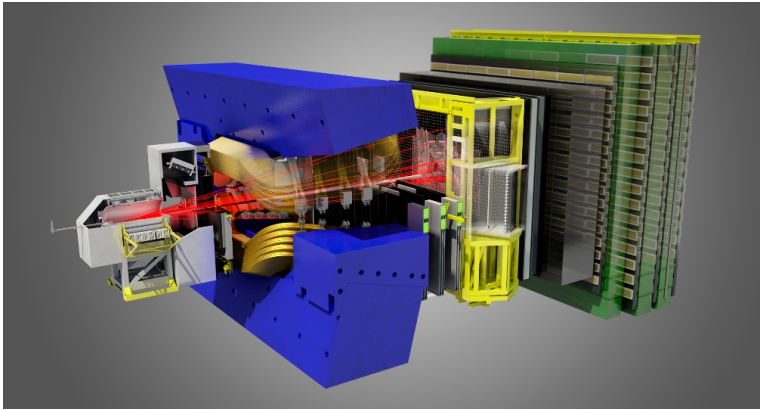
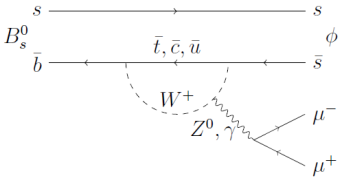
Outline

The LHCb experiment

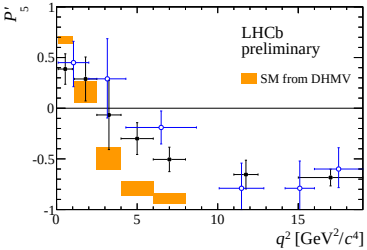


- Single-arm forward spectrometer
- High performance in the forward region
- Large heavy flavour program
  - $\sim 10^{12} b\bar{b}$ pairs/year
  - $\sim 10^{13} c\bar{c}$ pairs/year
- Excellent momentum resolution of $0.4 - 0.6\%$ allows for very precise analyses
- Strong boost leads to exceptional decay time resolution

Electroweak penguin decays

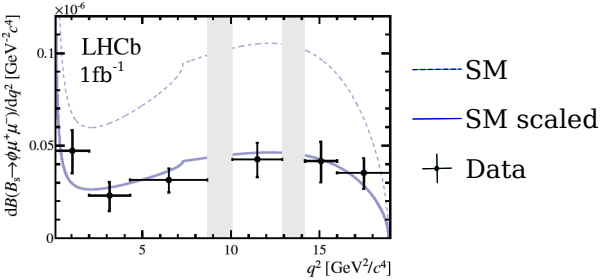


[LHCb-CONF-2015-002]



- Flavour changing neutral currents forbidden in SM at tree-level
- However, allowed in loop processes: penguin decays
- Sensitive to New Physics entering in loop, very small branching fraction prediction allows observation
- Analyses done depending on dimuon invariant mass squared q^2
- Significant deviation from SM predictions observed in $B^0 \to K^{*0}\mu^+\mu^-$

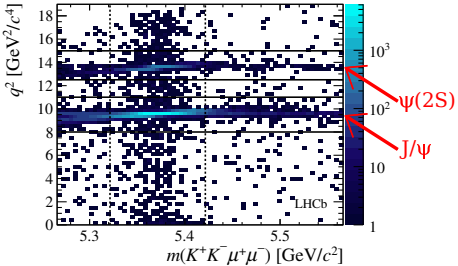
$B_s^0 \to \phi\mu^+\mu^-$



- Second highest statistics penguin decay at LHCb
- Tree-level decay $B_s^0 \to J/\psi(\to \mu^+\mu^-)\,\phi(\to K^+K^-)$ used as control and normalisation mode
- Previous analysis of $1\,\mathrm{fb}^{-1}$ published in 2013 [LHCb-PAPER-2013-017]
- Discrepancy to SM in differential branching fraction
- This talk: analysis of $3\,\mathrm{fb}^{-1}$ including full angular analysis [LHCb-PAPER-2015-023]

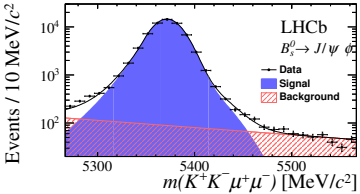
Selection

- Cut based selection:
  - Loose cut on B_s^0 mass, tight ($\pm 12\,\mathrm{MeV}/c^2$) on ϕ mass
  - Particle identification
  - Reconstruction quality criteria
  - Explicit misidentification vetoes
- Multivariate analysis to reduce combinatorial background, trained data-driven using control mode

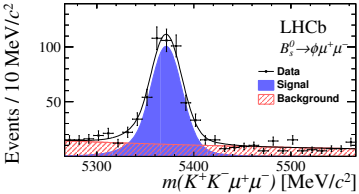


Selection

Control channel yield: 62033 ± 260



Signal yield: 432 ± 24



- Most background sources negligible
- Non-negligible peaking backgrounds:
  - $B^0 \to K^{*0}\mu^+\mu^-$: 1.7 ± 0.4 events expected
  - $\Lambda_b^0 \to \Lambda(1520)\mu^+\mu^-$: 2.0 ± 0.8 events expected
- q^2 binning removes tree-level charmonium decays

q^2 bin	range [GeV^2/c^4]
1	0.1 – 2.0
2	2.0 – 5.0
3	5.0 – 8.0
4	11.0 – 12.5
5	15.0 – 17.0
6	17.0 – 19.0
W1	1.0 – 6.0
W2	15.0 – 19.0

Branching fraction

- Branching fraction ratio calculated via

$$\frac{1}{\mathcal{B}(B_s^0 \to J/\psi\,\phi)} \cdot \frac{\mathrm{d}\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)}{\mathrm{d}q^2} = \frac{\mathcal{B}(J/\psi \to \mu^+\mu^-)}{q^2_{max} - q^2_{min}} \cdot \frac{\mathrm{N}_{\phi\mu^+\mu^-}}{\mathrm{N}_{J/\psi\phi}} \cdot \frac{\varepsilon_{\mathrm{tot}}{}^{J/\psi\phi}}{\varepsilon_{\mathrm{tot}}{}^{\phi\mu^+\mu^-}}$$

- $\mathcal{B}(J/\psi \to \mu^+\,\mu^-)$ from PDG
- Yields determined from unbinned extended maximum likelihood fits to invariant B_s^0 mass
  - Sum of two Crystal Ball shapes used as signal model (fixed for signal from control channel fit)
  - Exponential function as background model
- Relative efficiencies $\varepsilon_{\mathrm{tot}}{}^{J/\psi\phi}/\varepsilon_{\mathrm{tot}}{}^{\phi\mu^+\mu^-}$ determined from simulation

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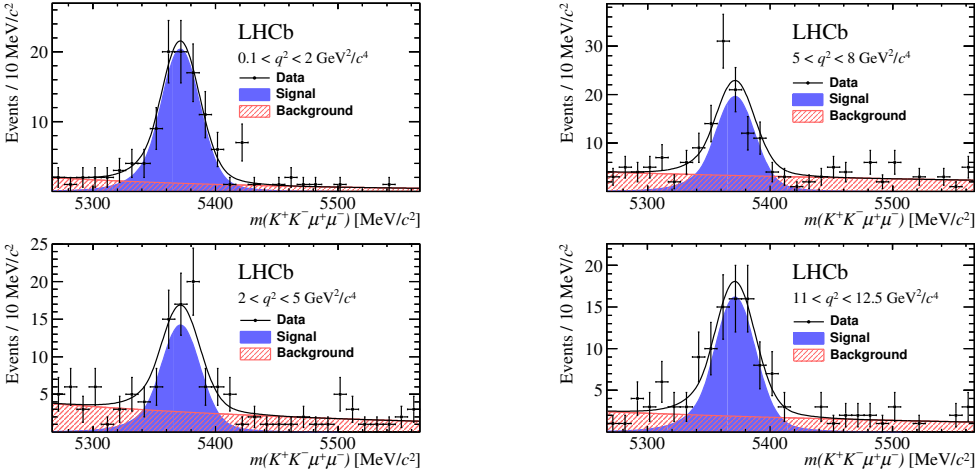
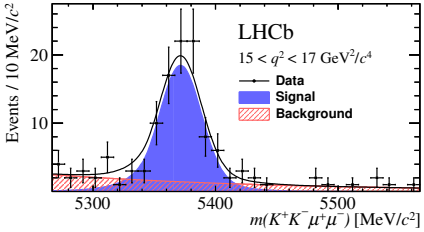
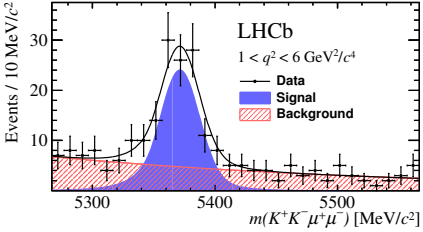
Mass fit in q^2 bins

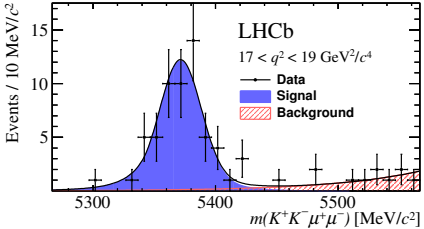


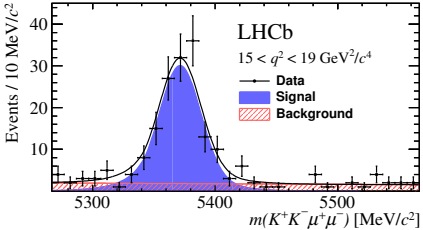
Mass fit in q^2 bins

Wide bins









Relative efficiencies

- Determined from corrected $B_s^0 \to J/\psi\,\phi$ and $B_s^0 \to \phi\mu^+\mu^-$ simulations
- Corrected data-driven to account for data-simulation differences
- Total efficiency for both modes are composed as:

$$\varepsilon_{\rm tot} = \varepsilon_{\rm det} \cdot \varepsilon_{\rm rec/det} \cdot \varepsilon_{\rm sel/rec} \cdot \varepsilon_{\rm trg/sel}$$

- Efficiency dependent on the q^2 bin for the signal mode
- Determined separately for 2011 and 2012, to account for different conditions
- Combined according to data composition

Systematics: Branching fraction ratio

Systematic uncertainties [$10^{-5}\,\mathrm{GeV}^{-2}c^4$] on the branching fraction ratio $\mathrm{d}\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)/\mathcal{B}(B_s^0 \to J/\psi\,\phi)\mathrm{d}q^2$ per bin of q^2 [GeV^2/c^4].

Source	[0.1, 2]	[2, 5]	[5, 8]	[11, 12.5]	[15, 17]	[17, 19]	[1, 6]	[15, 19]
Simulation corr.	0.01	0.01	0.01	0.01	0.05	0.04	0.00	0.04
Angular model	0.04	0.00	0.01	0.00	0.01	0.06	0.00	0.01
Efficiency ratio	0.06	0.03	0.03	0.06	0.06	**0.07**	0.02	0.04
Signal mass model	0.02	0.01	0.03	0.03	0.03	0.00	**0.05**	0.05
Bkg. mass model	0.02	0.02	0.02	0.02	0.03	0.05	0.01	0.06
Time acceptance	**0.09**	**0.04**	**0.05**	**0.07**	**0.07**	0.06	0.04	**0.06**
$\mathcal{B}(J/\psi \to \mu^+\mu^-)$	0.03	0.01	0.02	0.02	0.02	0.02	0.01	0.02
Peaking bkg.	0.03	0.02	0.02	0.10	0.02	0.01	0.02	0.01
Quadratic sum	0.13	0.06	0.07	0.14	0.11	0.13	0.07	0.12
Stat. uncertainty	$^{+0.68}_{-0.64}$	$^{+0.39}_{-0.37}$	$^{+0.41}_{-0.39}$	$^{+0.64}_{-0.61}$	$^{+0.53}_{-0.50}$	$^{+0.53}_{-0.50}$	$^{+0.30}_{-0.29}$	$^{+0.37}_{-0.35}$

- Systematics dominated by efficiency ratio uncertainty and decay time acceptance effects
- This is both tied to the simulation sample used
- However, all systematics small compared to statistical uncertainties

Results: branching fraction

q^2 bin $[\mathrm{GeV}^2c^{-4}]$	$\frac{\mathrm{d}\mathcal{B}(B_s^0\to\phi\mu\mu)}{\mathcal{B}(B_s^0\to J/\psi\,\phi)\mathrm{d}q^2}$ $[10^{-5}\,\mathrm{GeV}^{-2}c^4]$	$\frac{\mathrm{d}\mathcal{B}(B_s^0\to\phi\mu^+\mu^-)}{\mathrm{d}q^2}$ $[10^{-8}\,\mathrm{GeV}^{-2}c^4]$
$0.1 < q^2 < 2.0$	$5.44^{+0.68}_{-0.64} \pm 0.13$	$5.85^{+0.73}_{-0.69} \pm 0.14 \pm 0.44$
$2.0 < q^2 < 5.0$	$2.38^{+0.39}_{-0.37} \pm 0.06$	$2.56^{+0.42}_{-0.39} \pm 0.06 \pm 0.19$
$5.0 < q^2 < 8.0$	$2.98^{+0.41}_{-0.39} \pm 0.07$	$3.21^{+0.44}_{-0.42} \pm 0.08 \pm 0.24$
$11.0 < q^2 < 12.5$	$4.37^{+0.64}_{-0.61} \pm 0.14$	$4.71^{+0.69}_{-0.65} \pm 0.15 \pm 0.36$
$15.0 < q^2 < 17.0$	$4.20^{+0.53}_{-0.50} \pm 0.11$	$4.51^{+0.57}_{-0.54} \pm 0.12 \pm 0.34$
$17.0 < q^2 < 19.0$	$3.68^{+0.53}_{-0.50} \pm 0.13$	$3.96^{+0.57}_{-0.54} \pm 0.14 \pm 0.30$
$1.0 < q^2 < 6.0$	$2.40^{+0.30}_{-0.29} \pm 0.07$	$2.58^{+0.33}_{-0.31} \pm 0.08 \pm 0.19$
$15.0 < q^2 < 19.0$	$3.75^{+0.37}_{-0.35} \pm 0.12$	$4.04^{+0.39}_{-0.38} \pm 0.13 \pm 0.30$

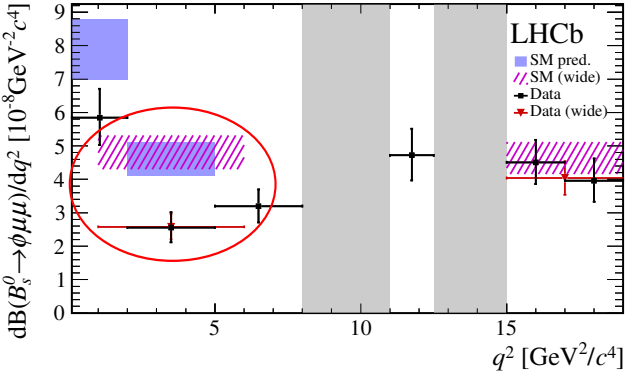
- Extrapolation to full q^2 range yields:

$$\frac{\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)}{\mathcal{B}(B_s^0 \to J/\psi\,\phi)} = (7.40^{+0.42}_{-0.40\ \mathrm{stat.}} \pm 0.16_{\mathrm{sys.}} \pm 0.21_{\mathrm{extrapol.}}) \cdot 10^{-4}$$

$$\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-) = (7.97^{+0.45}_{-0.43\ \mathrm{stat.}} \pm 0.18_{\mathrm{sys.}} \pm 0.23_{\mathrm{extrapol.}} \pm 0.60_{J/\psi\,\phi}) \cdot 10^{-7}$$

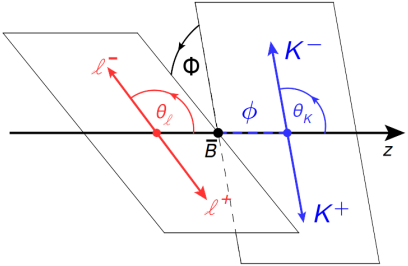
Branching fraction: Comparison to SM

[LHCb-PAPER-2015-023]



- SM predictions from Altmannshofer/Straub [arXiv:1411.3161]
- Confirmed $\mathcal{B}$ to be significantly smaller than SM expectations in low q^2 region
- Deviation of 3.5σ in $1.0 - 6.0\,\mathrm{GeV}^2/c^4$ bin

Angular analysis

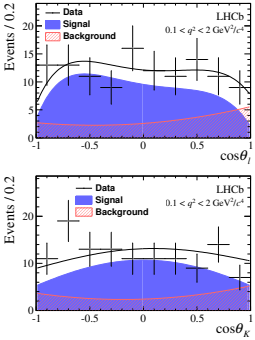


- Fit performed three-dimensional in $\cos\theta_l$, $\cos\theta_K$ and Φ
- Access to eight observables:
  - CP-averages F_L, $S_{3,4,7}$
  - CP-asymmetries $A_{5,6,8,9}$
- Angular acceptances derived from simulation, parametrised by Legendre-polynomials

Angular analysis

- Angular distributions modelled three-dimensional:

$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^3\Gamma}{\mathrm{d}\cos\theta_l\,\mathrm{d}\cos\theta_K\,\mathrm{d}\Phi} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \tfrac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_l - F_\mathrm{L}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\Phi + S_4\sin 2\theta_K\sin 2\theta_l\cos\Phi + A_5\sin 2\theta_K\sin\theta_l\cos\Phi + A_6^s\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\Phi + A_8\sin 2\theta_K\sin 2\theta_l\sin\Phi + A_9\sin^2\theta_K\sin^2\theta_l\sin 2\Phi\Big]$$



- Background description from B_s^0 mass sidebands, using second order polynomials

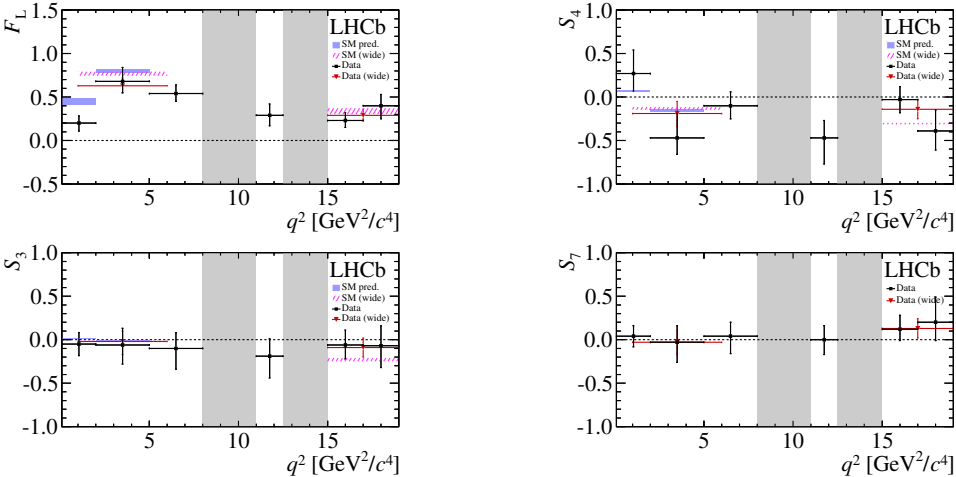
Systematics: Angular analysis

$$1.0 < q^2 < 6.0\,\mathrm{GeV}^2/c^4$$

	F_L	S_3	S_4	A_5	A_6	S_7	A_8	A_9
MC statistics	0.002	0.002	0.001	0.001	0.001	0.001	0.001	0.001
MC corrections	0.002	0.001	0.001	0.000	0.001	0.000	0.001	0.000
data-MC diff.	0.003	0.000	0.001	0.000	0.000	0.000	0.000	0.000
acc. q^2 dependence	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Bkg parameterization	**0.024**	0.003	0.002	0.000	0.002	0.000	0.000	0.000
Bkg statistics	0.007	**0.004**	**0.004**	**0.003**	**0.010**	**0.002**	**0.003**	**0.004**
S-wave	0.008	0.000	0.002	0.002	0.001	0.001	0.001	0.001
Peaking bkg	0.001	0.001	0.000	0.002	0.001	**0.002**	0.001	0.002
Quadratic sum	0.027	0.006	0.005	0.004	0.010	0.003	0.004	0.005
Stat. uncertainty	$^{+0.09}_{-0.08}$	$^{+0.12}_{-0.15}$	$^{+0.14}_{-0.15}$	$^{+0.14}_{-0.14}$	$^{+0.14}_{-0.13}$	$^{+0.12}_{-0.11}$	$^{+0.15}_{-0.17}$	$^{+0.13}_{-0.13}$

- Most systematics related to angular acceptance
- F_L dominated by background parametrisation
- Background statistics dominant uncertainty for most other observables
- All systematics small compared to statistical uncertainties

Angular analysis: Comparison to SM



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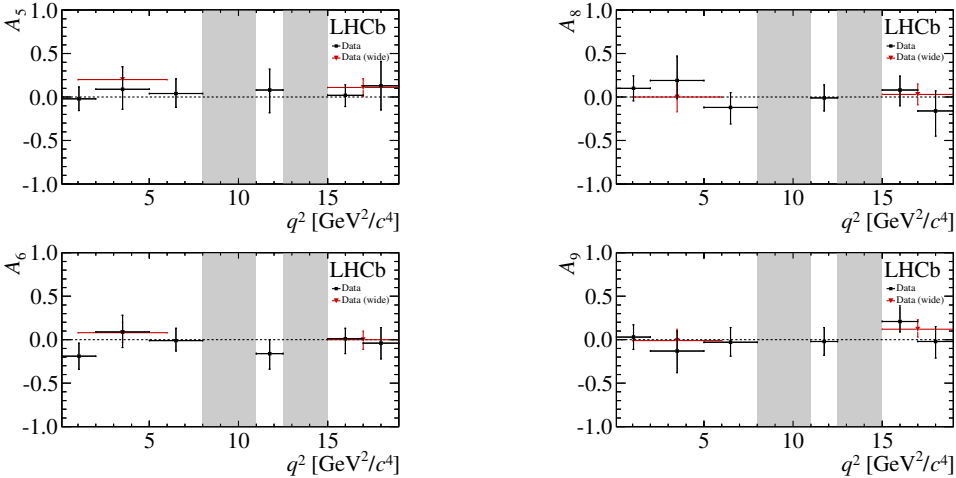


Conclusion

- Deviation in branching fraction for low q^2 confirmed
- This fits well into deviations observed in $B^0 \to K^{*0}\mu^+\mu^-$
- Reasons for these deviations are being discussed in the theory community (underestimated charmonium loops $\leftrightarrow$ New Physics in Wilson coefficients)
- Most precise branching fraction measurement for this channel so far:

$$\boxed{\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-) = (7.97^{+0.45}_{-0.43\ \mathrm{stat.}} \pm 0.18_{\mathrm{sys.}} \pm 0.23_{\mathrm{extrapol.}} \pm 0.60_{J/\psi\,\phi}) \cdot 10^{-7}}$$

- Angular observables show good agreement with SM expectations within their uncertainties

Backup slides

Relative efficiencies

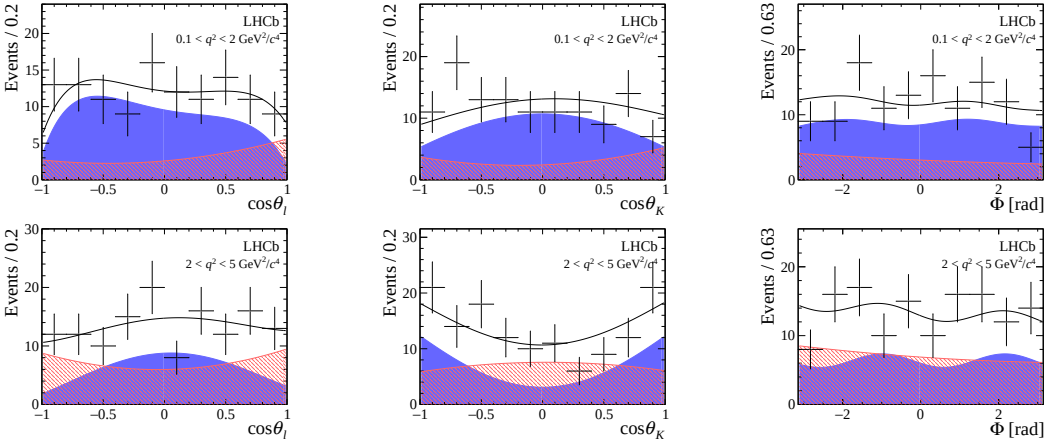
q^2	$\varepsilon_{\rm tot}^{J/\psi\phi}/\varepsilon_{\rm tot}^{\phi\mu^+\mu^-}$ 2011	$\varepsilon_{\rm tot}^{J/\psi\phi}/\varepsilon_{\rm tot}^{\phi\mu^+\mu^-}$ 2012	$\varepsilon_{\rm tot}^{J/\psi\phi}/\varepsilon_{\rm tot}^{\phi\mu^+\mu^-}$ combined
$0.1-2.0$	1.260 ± 0.015	1.264 ± 0.018	1.263 ± 0.015
$2.0-5.0$	1.204 ± 0.015	1.268 ± 0.019	1.247 ± 0.015
$5.0-8.0$	1.084 ± 0.013	1.145 ± 0.015	1.125 ± 0.013
$11.0-12.5$	0.963 ± 0.014	0.974 ± 0.016	0.970 ± 0.013
$15.0-17.0$	1.064 ± 0.015	1.045 ± 0.017	1.051 ± 0.014
$17.0-19.0$	1.449 ± 0.031	1.398 ± 0.035	1.414 ± 0.027
$1.0-6.0$	1.194 ± 0.012	1.257 ± 0.015	1.236 ± 0.013
$15.0-19.0$	1.171 ± 0.014	1.145 ± 0.016	1.153 ± 0.014

Results: angular analysis

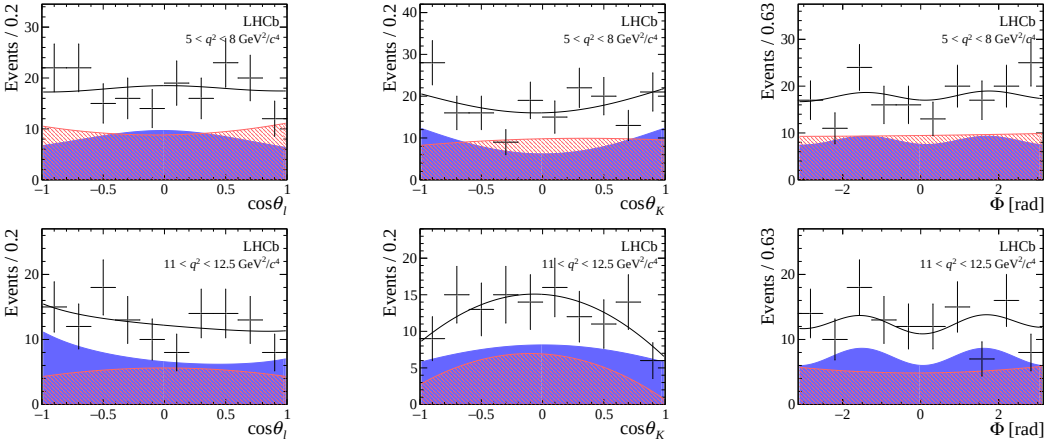
q^2 bin $[\mathrm{GeV}^2c^{-4}]$	F_L	S_3	S_4	S_7
$0.1 < q^2 < 2.0$	$0.20^{+0.09}_{-0.08} \pm 0.02$	$-0.05^{+0.13}_{-0.13} \pm 0.01$	$0.27^{+0.27}_{-0.20} \pm 0.01$	$0.04^{+0.12}_{-0.12} \pm 0.00$
$2.0 < q^2 < 5.0$	$0.68^{+0.16}_{-0.13} \pm 0.03$	$-0.06^{+0.19}_{-0.22} \pm 0.01$	$-0.47^{+0.28}_{-0.19} \pm 0.01$	$-0.03^{+0.19}_{-0.23} \pm 0.01$
$5.0 < q^2 < 8.0$	$0.54^{+0.10}_{-0.09} \pm 0.02$	$-0.10^{+0.18}_{-0.24} \pm 0.01$	$-0.10^{+0.16}_{-0.15} \pm 0.01$	$0.04^{+0.16}_{-0.20} \pm 0.01$
$11.0 < q^2 < 12.5$	$0.29^{+0.13}_{-0.12} \pm 0.04$	$-0.19^{+0.20}_{-0.25} \pm 0.01$	$-0.47^{+0.20}_{-0.30} \pm 0.01$	$0.00^{+0.16}_{-0.17} \pm 0.01$
$15.0 < q^2 < 17.0$	$0.23^{+0.09}_{-0.08} \pm 0.02$	$-0.06^{+0.17}_{-0.16} \pm 0.01$	$-0.03^{+0.15}_{-0.15} \pm 0.01$	$0.12^{+0.16}_{-0.13} \pm 0.01$
$17.0 < q^2 < 19.0$	$0.40^{+0.13}_{-0.15} \pm 0.02$	$-0.07^{+0.23}_{-0.25} \pm 0.02$	$-0.39^{+0.24}_{-0.22} \pm 0.02$	$0.20^{+0.29}_{-0.21} \pm 0.01$
$1.0 < q^2 < 6.0$	$0.63^{+0.09}_{-0.08} \pm 0.03$	$-0.02^{+0.12}_{-0.15} \pm 0.01$	$-0.19^{+0.14}_{-0.15} \pm 0.01$	$-0.03^{+0.14}_{-0.14} \pm 0.00$
$15.0 < q^2 < 19.0$	$0.29^{+0.07}_{-0.06} \pm 0.02$	$-0.09^{+0.11}_{-0.11} \pm 0.01$	$-0.14^{+0.11}_{-0.11} \pm 0.01$	$0.13^{+0.11}_{-0.11} \pm 0.01$

q^2 bin $[\mathrm{GeV}^2c^{-4}]$	A_5	A_6	A_8	A_9
$0.1 < q^2 < 2.0$	$-0.02^{+0.13}_{-0.13} \pm 0.00$	$-0.19^{+0.15}_{-0.15} \pm 0.01$	$0.10^{+0.14}_{-0.14} \pm 0.00$	$0.03^{+0.14}_{-0.14} \pm 0.01$
$2.0 < q^2 < 5.0$	$0.09^{+0.26}_{-0.23} \pm 0.01$	$0.09^{+0.19}_{-0.18} \pm 0.02$	$-0.19^{+0.28}_{-0.21} \pm 0.01$	$-0.13^{+0.23}_{-0.25} \pm 0.01$
$5.0 < q^2 < 8.0$	$0.04^{+0.17}_{-0.16} \pm 0.01$	$-0.01^{+0.14}_{-0.12} \pm 0.01$	$-0.12^{+0.17}_{-0.19} \pm 0.01$	$-0.03^{+0.17}_{-0.16} \pm 0.01$
$11.0 < q^2 < 12.5$	$0.08^{+0.24}_{-0.26} \pm 0.01$	$-0.16^{+0.16}_{-0.18} \pm 0.01$	$0.01^{+0.15}_{-0.15} \pm 0.01$	$-0.02^{+0.16}_{-0.16} \pm 0.01$
$15.0 < q^2 < 17.0$	$0.02^{+0.12}_{-0.13} \pm 0.01$	$0.01^{+0.12}_{-0.17} \pm 0.01$	$0.08^{+0.16}_{-0.18} \pm 0.01$	$0.21^{+0.18}_{-0.12} \pm 0.01$
$17.0 < q^2 < 19.0$	$0.13^{+0.28}_{-0.28} \pm 0.01$	$-0.04^{+0.18}_{-0.18} \pm 0.01$	$-0.16^{+0.23}_{-0.29} \pm 0.01$	$-0.02^{+0.17}_{-0.19} \pm 0.01$
$1.0 < q^2 < 6.0$	$0.20^{+0.14}_{-0.13} \pm 0.00$	$0.08^{+0.12}_{-0.11} \pm 0.01$	$-0.00^{+0.15}_{-0.17} \pm 0.00$	$-0.01^{+0.13}_{-0.13} \pm 0.01$
$15.0 < q^2 < 19.0$	$0.11^{+0.10}_{-0.10} \pm 0.00$	$0.00^{+0.10}_{-0.11} \pm 0.01$	$0.03^{+0.12}_{-0.12} \pm 0.00$	$0.12^{+0.11}_{-0.09} \pm 0.00$

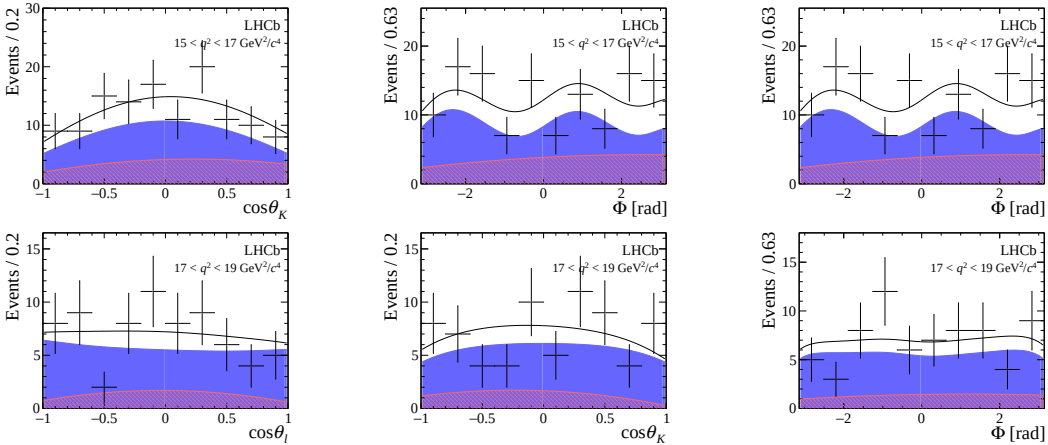
Angular fit projections



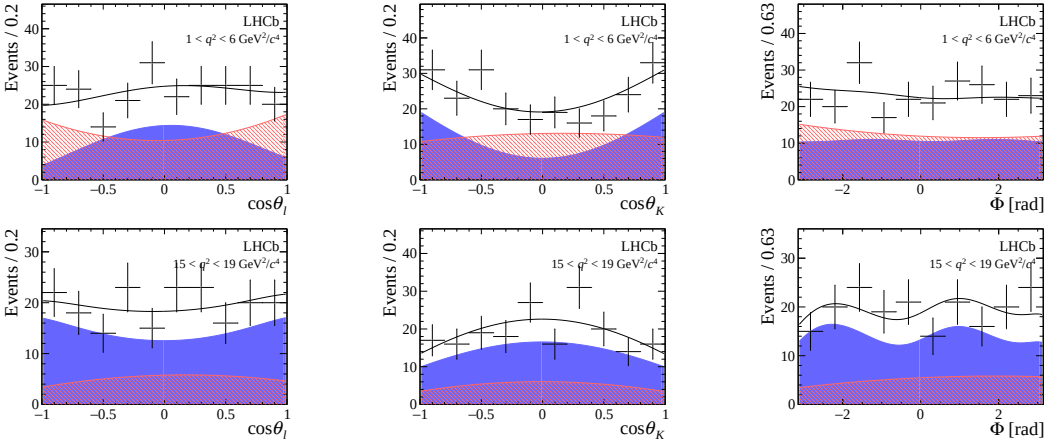
Angular fit projections



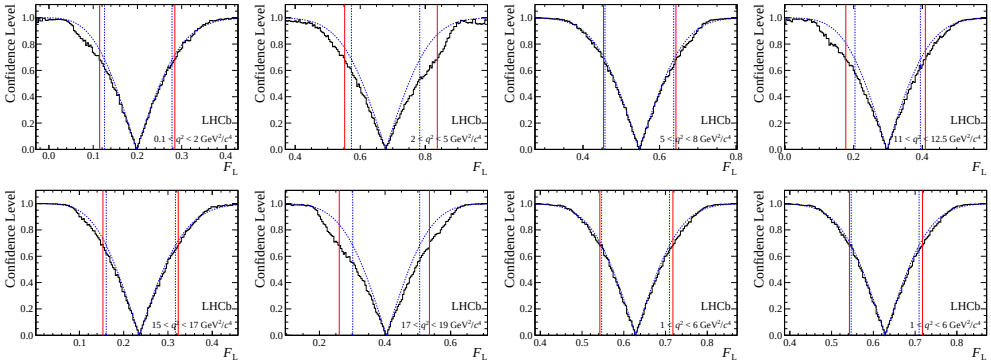
Angular fit projections



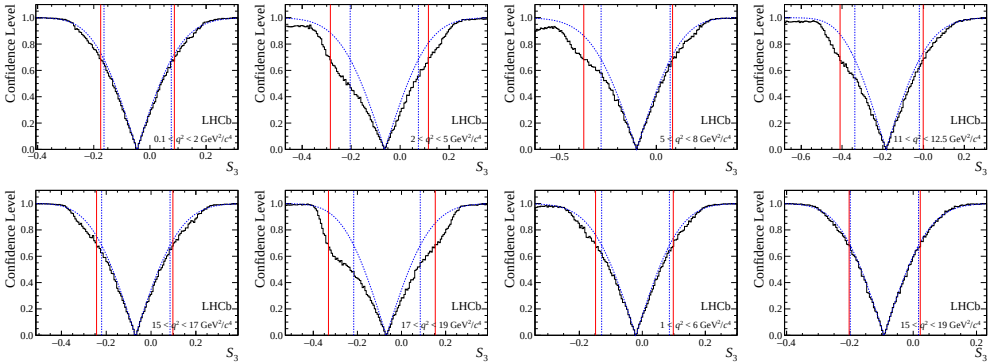
Angular fit projections



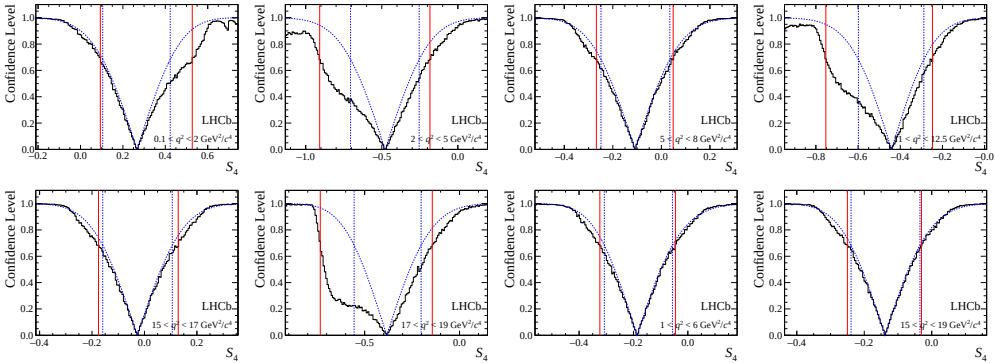
FC scans: F_L


Confidence Level
LHCb
0.1 < q² < 2 GeV²/c⁴
2 < q² < 5 GeV²/c⁴
5 < q² < 8 GeV²/c⁴
11 < q² < 12.5 GeV²/c⁴
15 < q² < 17 GeV²/c⁴
17 < q² < 19 GeV²/c⁴
1 < q² < 6 GeV²/c⁴
1 < q² < 6 GeV²/c⁴
F_L

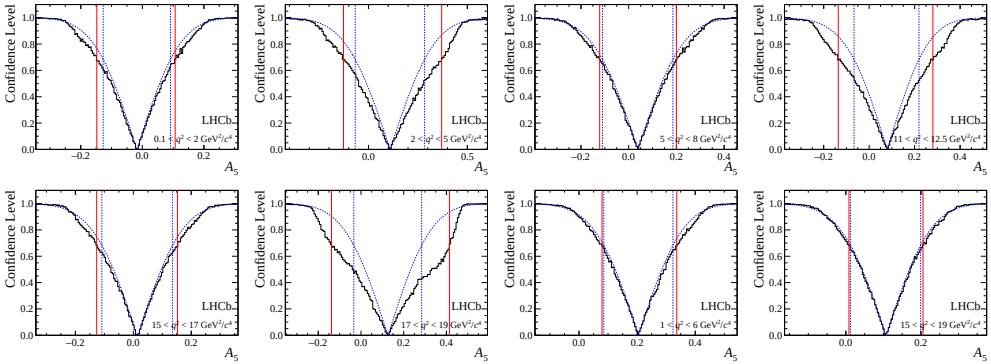
FC scans: S_3


Confidence Level
LHCb
0.1 < q² < 2 GeV²/c⁴
2 < q² < 5 GeV²/c⁴
5 < q² < 8 GeV²/c⁴
11 < q² < 12.5 GeV²/c⁴
15 < q² < 17 GeV²/c⁴
17 < q² < 19 GeV²/c⁴
1 < q² < 6 GeV²/c⁴
15 < q² < 19 GeV²/c⁴
S₃

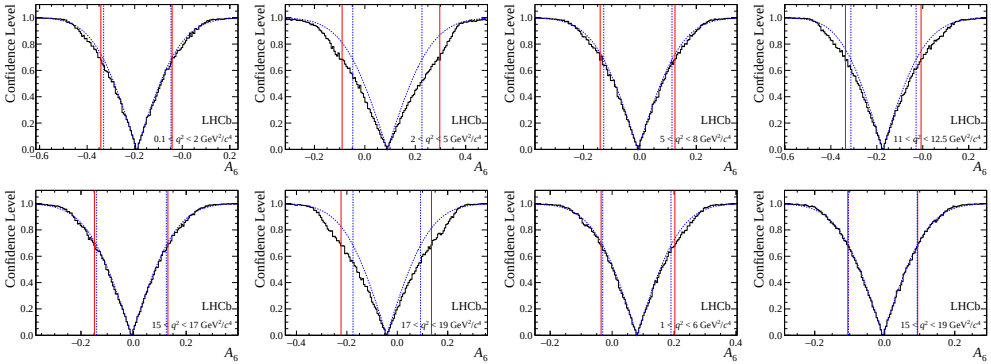
FC scans: S_4


Confidence Level
S_4
LHCb
$0.1 < q^2 < 2$ GeV$^2/c^4$
$2 < q^2 < 5$ GeV$^2/c^4$
$5 < q^2 < 8$ GeV$^2/c^4$
$11 < q^2 < 12.5$ GeV$^2/c^4$
$15 < q^2 < 17$ GeV$^2/c^4$
$17 < q^2 < 19$ GeV$^2/c^4$
$1 < q^2 < 6$ GeV$^2/c^4$
$15 < q^2 < 19$ GeV$^2/c^4$

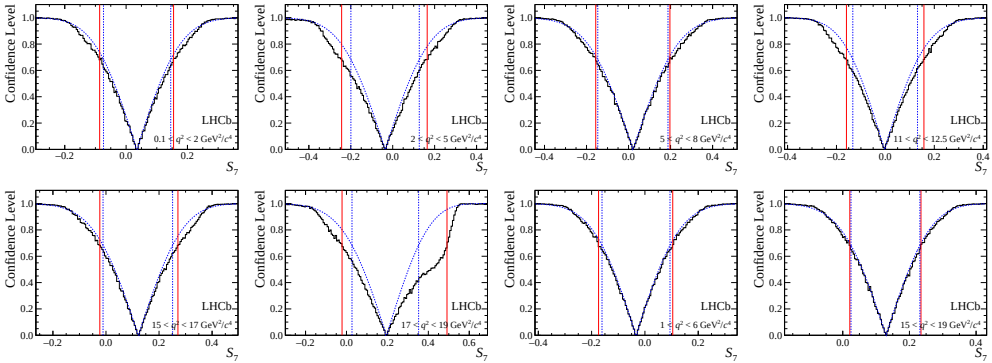
FC scans: A_5


Confidence Level
LHCb
0.1 < q² < 2 GeV²/c⁴
2 < q² < 5 GeV²/c⁴
5 < q² < 8 GeV²/c⁴
11 < q² < 12.5 GeV²/c⁴
15 < q² < 17 GeV²/c⁴
17 < q² < 19 GeV²/c⁴
1 < q² < 6 GeV²/c⁴
15 < q² < 19 GeV²/c⁴
A5

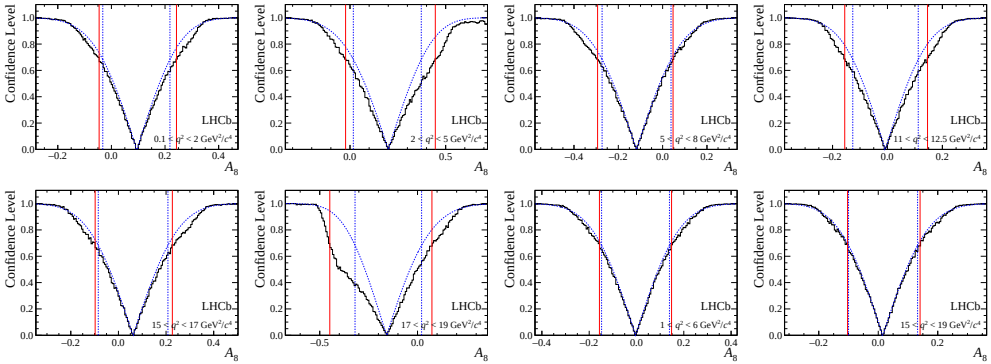
FC scans: A_6


Confidence Level
LHCb
0.1 < q² < 2 GeV²/c⁴
2 < q² < 5 GeV²/c⁴
5 < q² < 8 GeV²/c⁴
11 < q² < 12.5 GeV²/c⁴
15 < q² < 17 GeV²/c⁴
17 < q² < 19 GeV²/c⁴
1 < q² < 6 GeV²/c⁴
15 < q² < 19 GeV²/c⁴
A₆

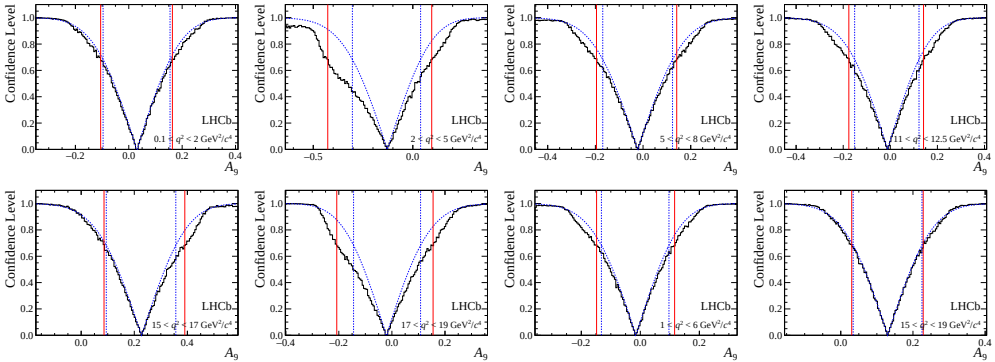
FC scans: S_7


Confidence Level
S_7
LHCb
$0.1 < q^2 < 2$ GeV$^2/c^4$
$2 < q^2 < 5$ GeV$^2/c^4$
$5 < q^2 < 8$ GeV$^2/c^4$
$11 < q^2 < 12.5$ GeV$^2/c^4$
$15 < q^2 < 17$ GeV$^2/c^4$
$17 < q^2 < 19$ GeV$^2/c^4$
$1 < q^2 < 6$ GeV$^2/c^4$
$15 < q^2 < 19$ GeV$^2/c^4$

FC scans: A_8


Confidence Level
LHCb
0.1 < q² < 2 GeV²/c⁴
2 < q² < 5 GeV²/c⁴
5 < q² < 8 GeV²/c⁴
11 < q² < 12.5 GeV²/c⁴
15 < q² < 17 GeV²/c⁴
17 < q² < 19 GeV²/c⁴
1 < q² < 6 GeV²/c⁴
15 < q² < 19 GeV²/c⁴
A8

FC scans: A_9


Confidence Level
LHCb
0.1 < q² < 2 GeV²/c⁴
2 < q² < 5 GeV²/c⁴
5 < q² < 8 GeV²/c⁴
11 < q² < 12.5 GeV²/c⁴
15 < q² < 17 GeV²/c⁴
17 < q² < 19 GeV²/c⁴
1 < q² < 6 GeV²/c⁴
15 < q² < 19 GeV²/c⁴
A9