$\Lambda_b \to \Lambda\mu\mu$ status

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Beautiful and charming baryons,
Durham, 9-11. Sep. 2024

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Why $\Lambda_b \rightarrow \Lambda\mu\mu$

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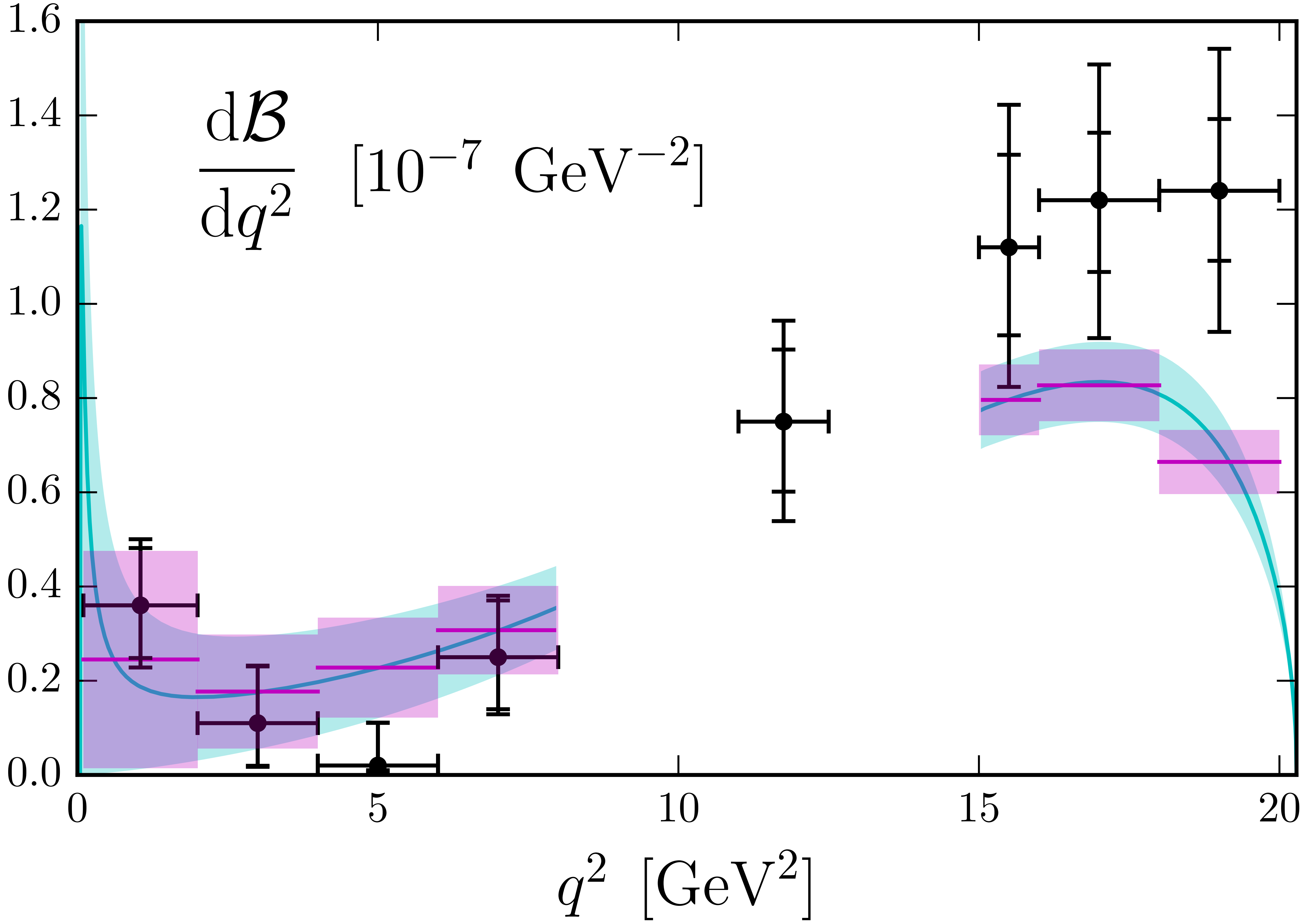
- ➡ Provides rich angular structure thanks to non-zero spin of initial state
- ➡ Λ baryon is very long lived and can be easily treated as stable particle in calculations
- ➡ Both experimentally and theoretically very clean from any interference and backgrounds
- ➡ If produced polarised, it offers access to information not available with mesons
- ➡ Con: Long Λ lifetime decreases detection efficiency, so statistics is usually smaller than similar meson decays

Differential branching fraction

- ➡ Measured at LHCb with Run 1 data
- ➡ Theory prediction is currently more precise than experiment
- ➡ Experimentally measured relative to $\Lambda_b \rightarrow J/\psi \Lambda$ for which we do not have good BF
- ➡ No significant signal below J/ψ yet

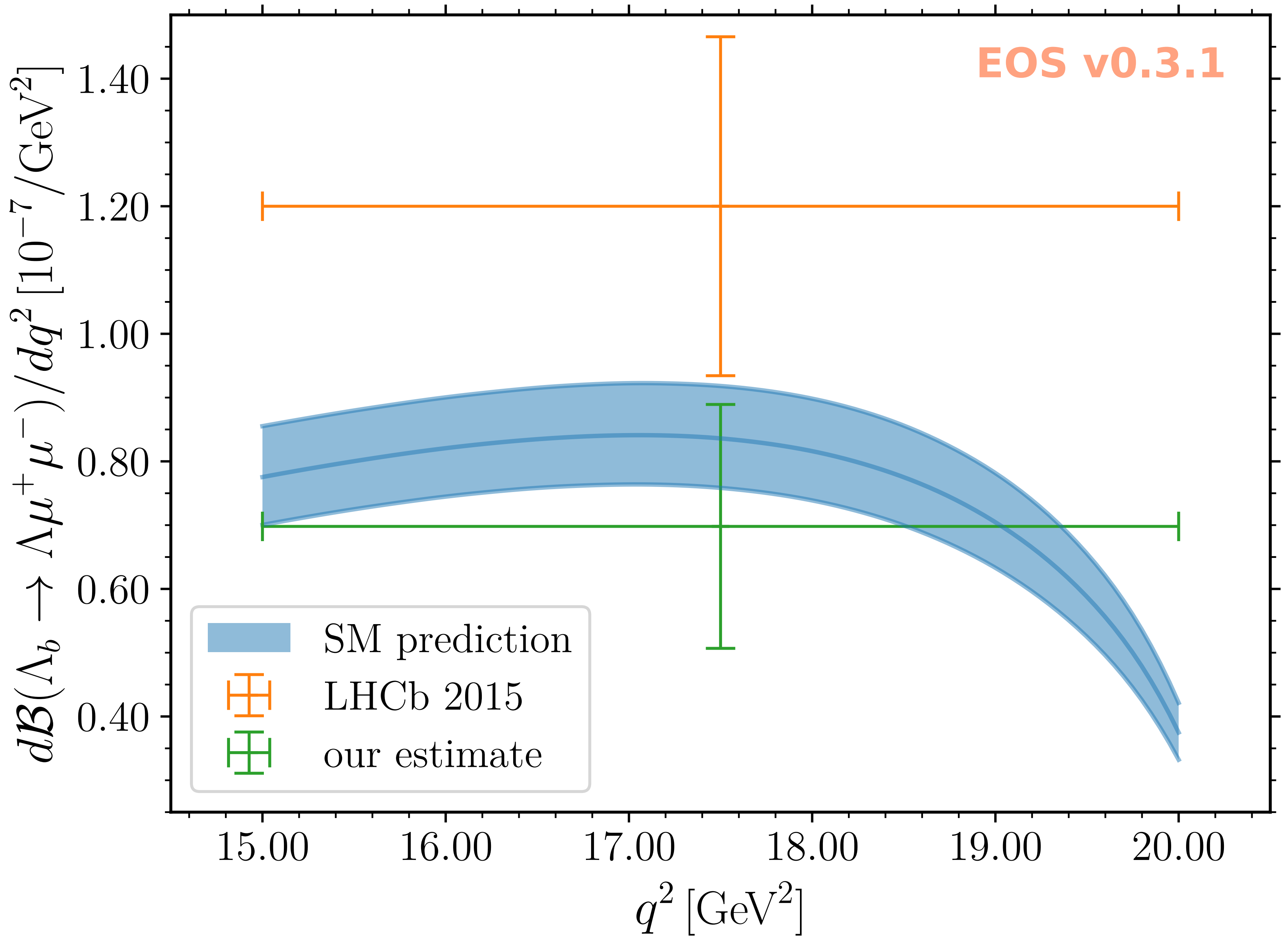
arXiv:1602.01399v2



Experimental normalisation

- Measurements for $\Lambda_b \to J/\psi\Lambda$ come from Tevatron which measured $\frac{f_\Lambda}{f_d}\frac{B(\Lambda_b \to J/\psi\Lambda)}{B(B^0 \to J/\psi K_S)}$
- Best number comes from D0
- One needs also fragmentation fraction, in past one would average LEP and Tevatron
- But there is pT dependence, which means that averaging LEP and Tevatron is not good
- Needs measurement of both ingredients from same experiment ⇒ ongoing at LHCb

arXiv:1912.05811v1

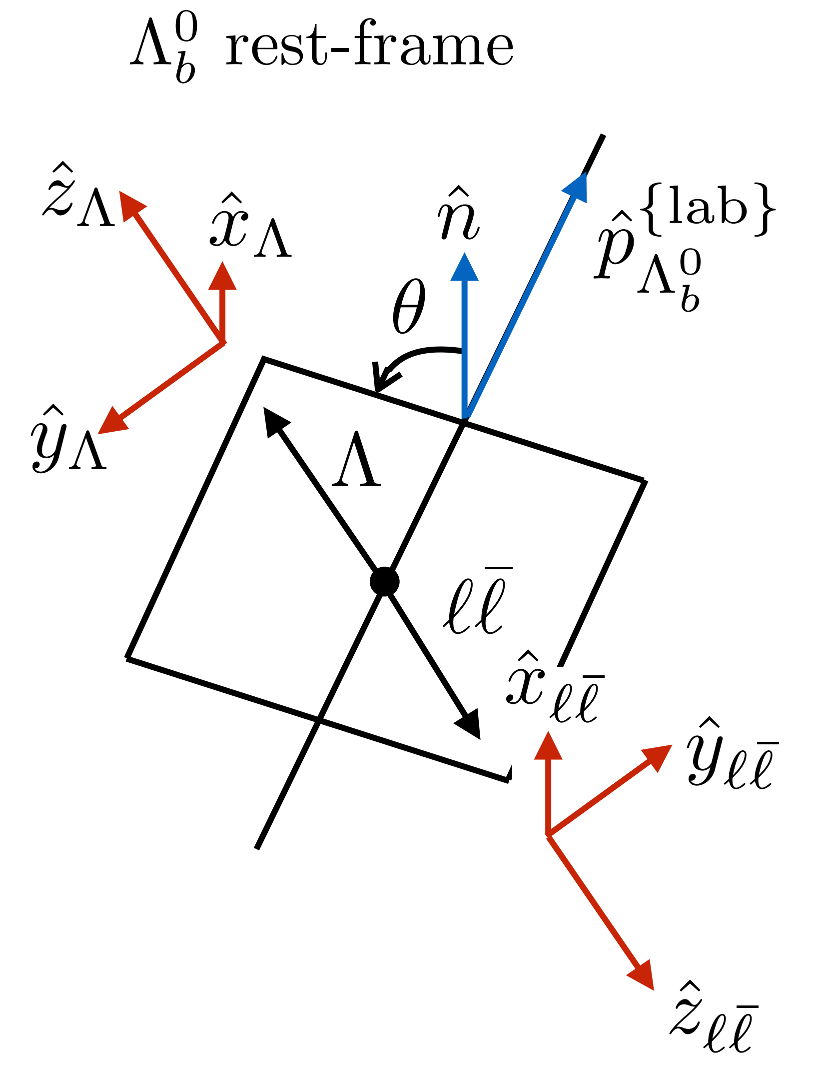


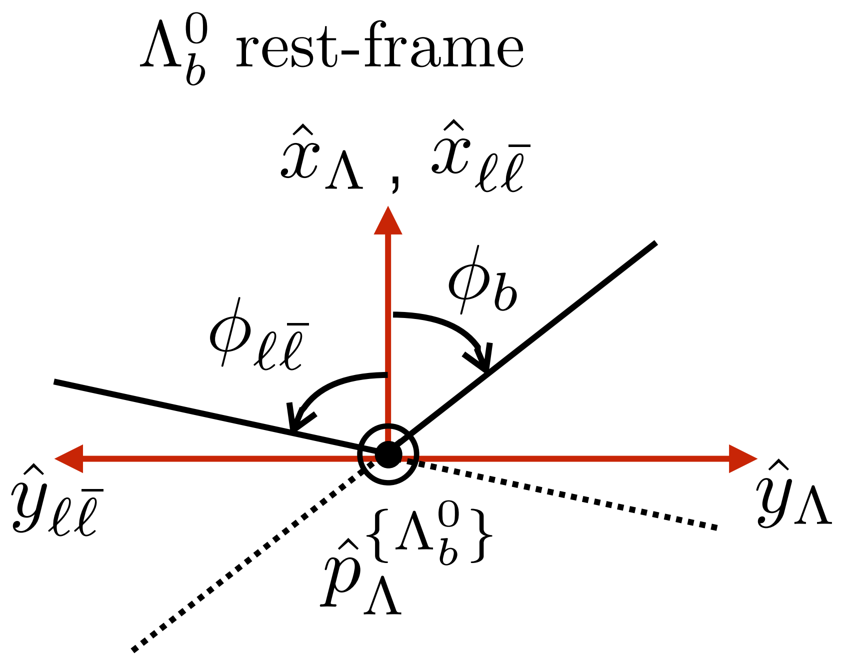
Angular distributions

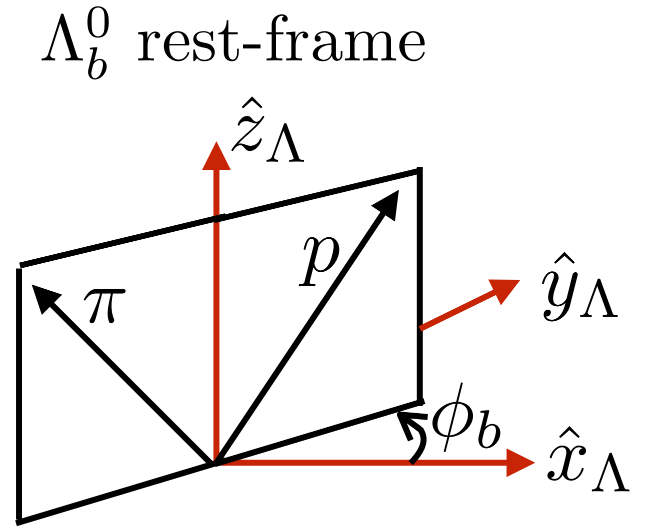
- ➡ With polarised production, 5 angles to describe kinematics
- ➡ Without polarisation, one is sensitive only to $\phi_l + \phi_b$
- ➡ Angle θ should correspond to production polarisation axis
  - ❖ Figure shows case for *pp* collisions with transverse polarisation

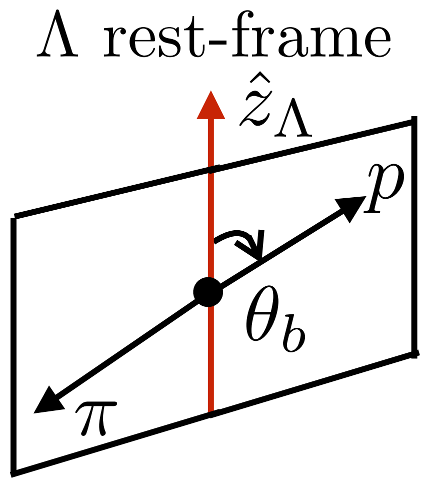
$\hat{z}_\Lambda = \hat{p}_\Lambda^{\{\Lambda_b^0\}}$
$\hat{y}_\Lambda = \hat{n} \times \hat{p}_\Lambda^{\Lambda_b^0}$

$\hat{z}_{\ell\bar{\ell}} = \hat{p}_{\ell\bar{\ell}}^{\{\Lambda_b^0\}}$
$\hat{y}_{\ell\bar{\ell}} = \hat{n} \times \hat{p}_{\ell\bar{\ell}}^{\{\Lambda_b^0\}}$









$\hat{z}_\Lambda^{\{\Lambda\}} = -\hat{p}_{\ell\bar{\ell}}^{\{\Lambda\}}$

Angular distributions

- Up to some constants, angular distribution in unpolarised case is

$$\begin{aligned}K(q^2, \cos\theta_\ell, \cos\theta_\Lambda, \phi) = {} & \left(K_{1ss}\sin^2\theta_\ell + K_{1cc}\cos^2\theta_\ell + K_{1c}\cos\theta_\ell\right) \\ & + \left(K_{2ss}\sin^2\theta_\ell + K_{2cc}\cos^2\theta_\ell + K_{2c}\cos\theta_\ell\right)\cos\theta_\Lambda \\ & + \left(K_{3sc}\sin\theta_\ell\cos\theta_\ell + K_{3s}\sin\theta_\ell\right)\sin\theta_\Lambda\sin\phi \\ & + \left(K_{4sc}\sin\theta_\ell\cos\theta_\ell + K_{4s}\sin\theta_\ell\right)\sin\theta_\Lambda\cos\phi\,.\end{aligned}$$

arXiv:1410.2115v3

- Specific features :
  - We can still define fraction of longitudinally polarised dilepton system
  - There is non-zero hadron side forward-backward asymmetry thanks to weak decay of Λ with significant differences between two amplitudes α_Λ=…
  - One can also construct combined forward-backward asymmetry

Angular distributions

- One can take ratios of observables to construct quantities which in first order are sensitive only to:
  - Form factors

$$\frac{2\,K_{2ss}}{K_{2cc}} = 1 + \frac{m_{\Lambda_b}^2 - m_\Lambda^2}{q^2}\,\frac{f_0^V\,f_0^A}{f_\perp^V\,f_\perp^A}\,,$$

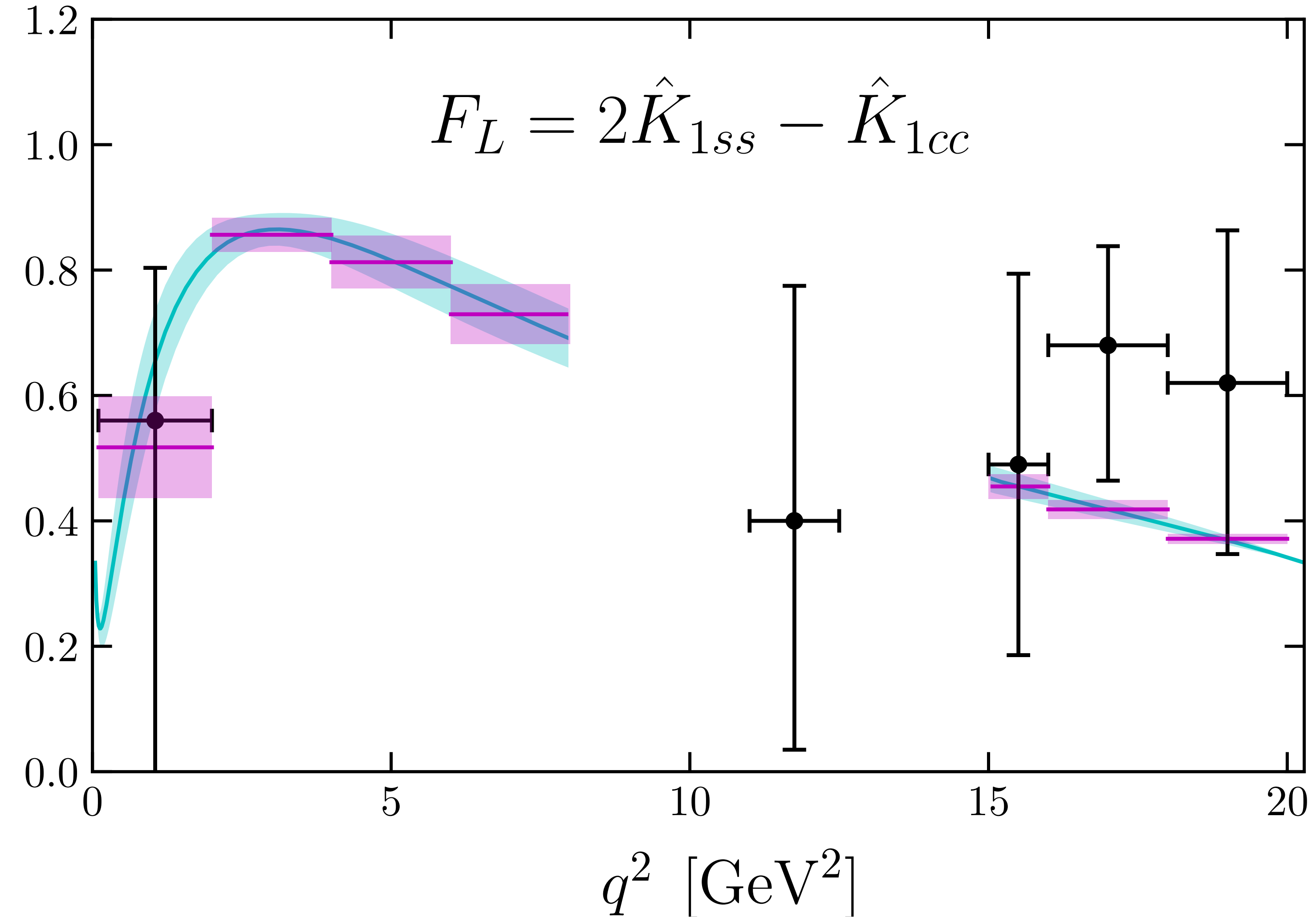
$$\frac{2\,K_{4sc}}{K_{2cc}} = \frac{m_{\Lambda_b} + m_\Lambda}{\sqrt{q^2}}\,\frac{f_0^V}{f_\perp^V} - \frac{m_{\Lambda_b} - m_\Lambda}{\sqrt{q^2}}\,\frac{f_0^A}{f_\perp^A}\,.$$

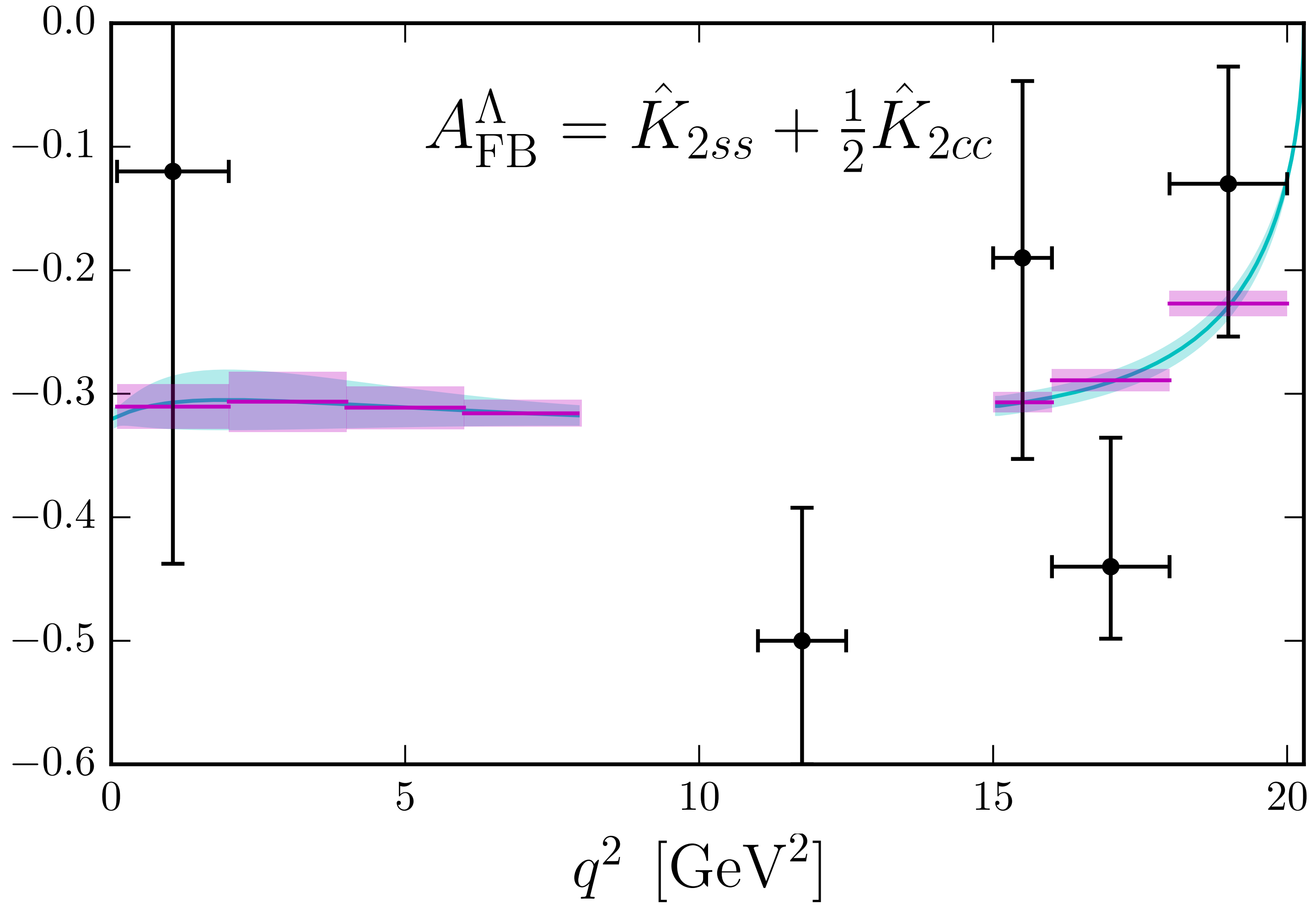
  - Short-scale physics

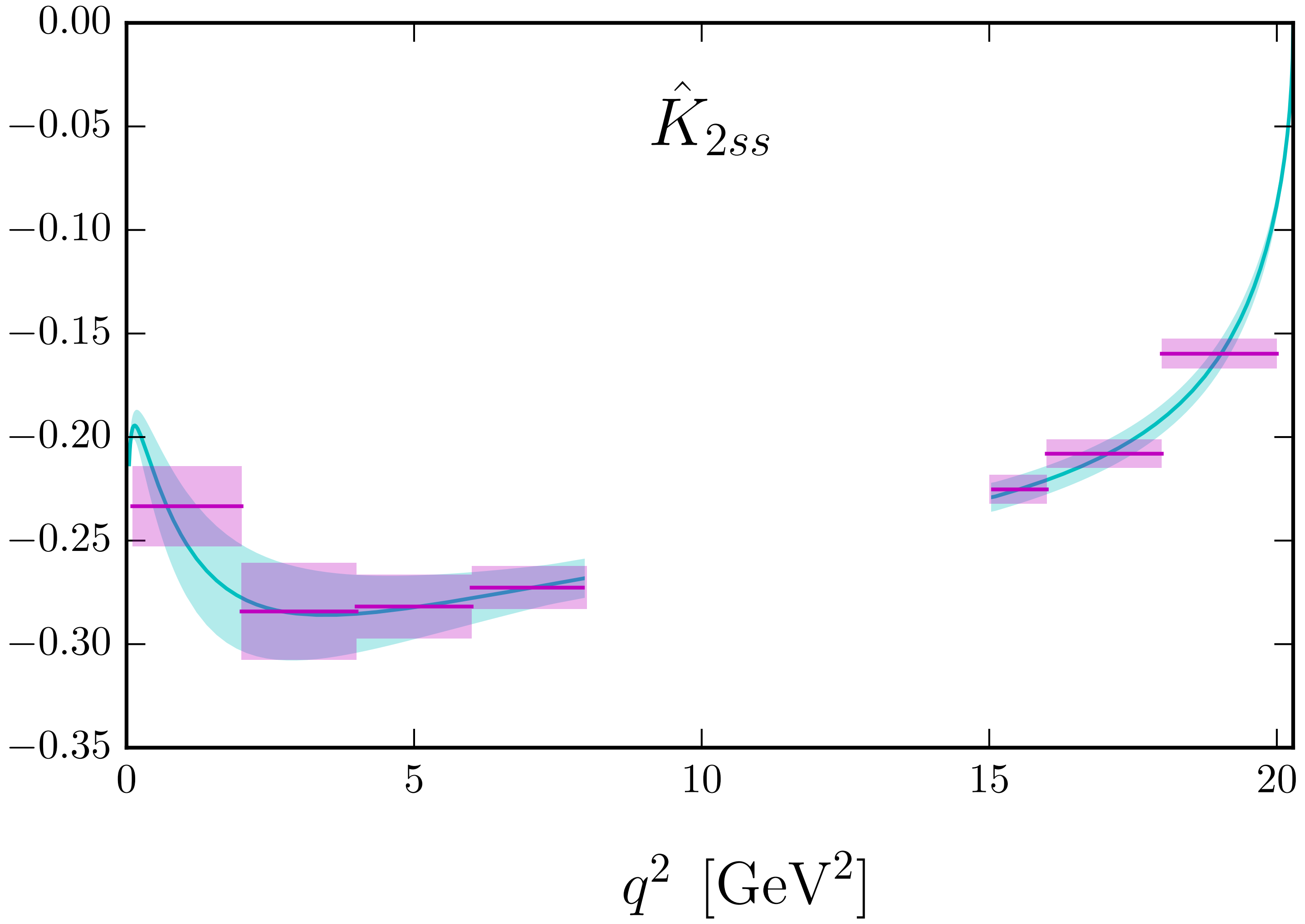
$$X_1 \equiv \frac{K_{1c}}{K_{2cc}} = -\frac{\mathrm{Re}\,\{\rho_2\}}{\alpha\,\mathrm{Re}\,\{\rho_4\}}\,,$$

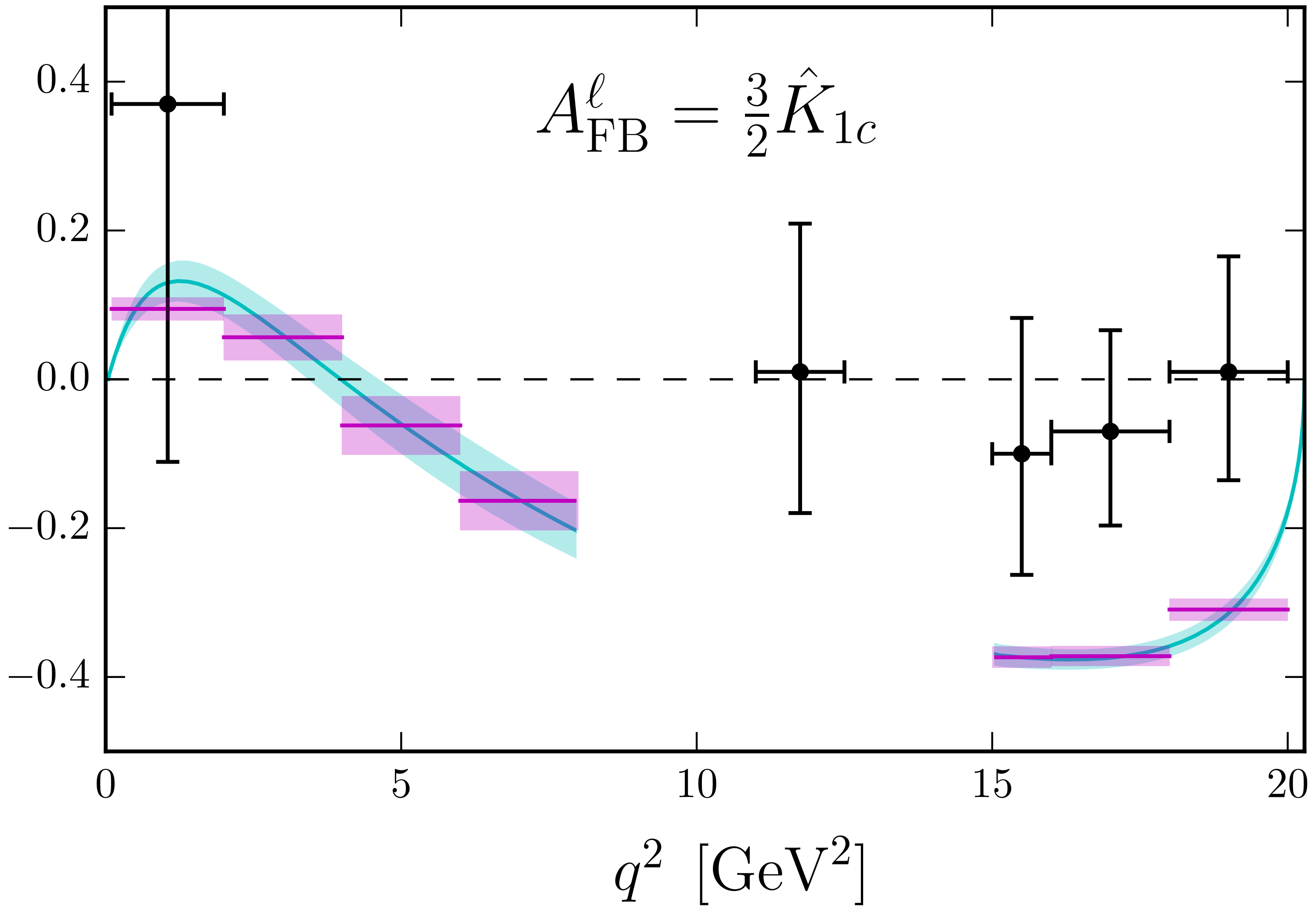
Predictions

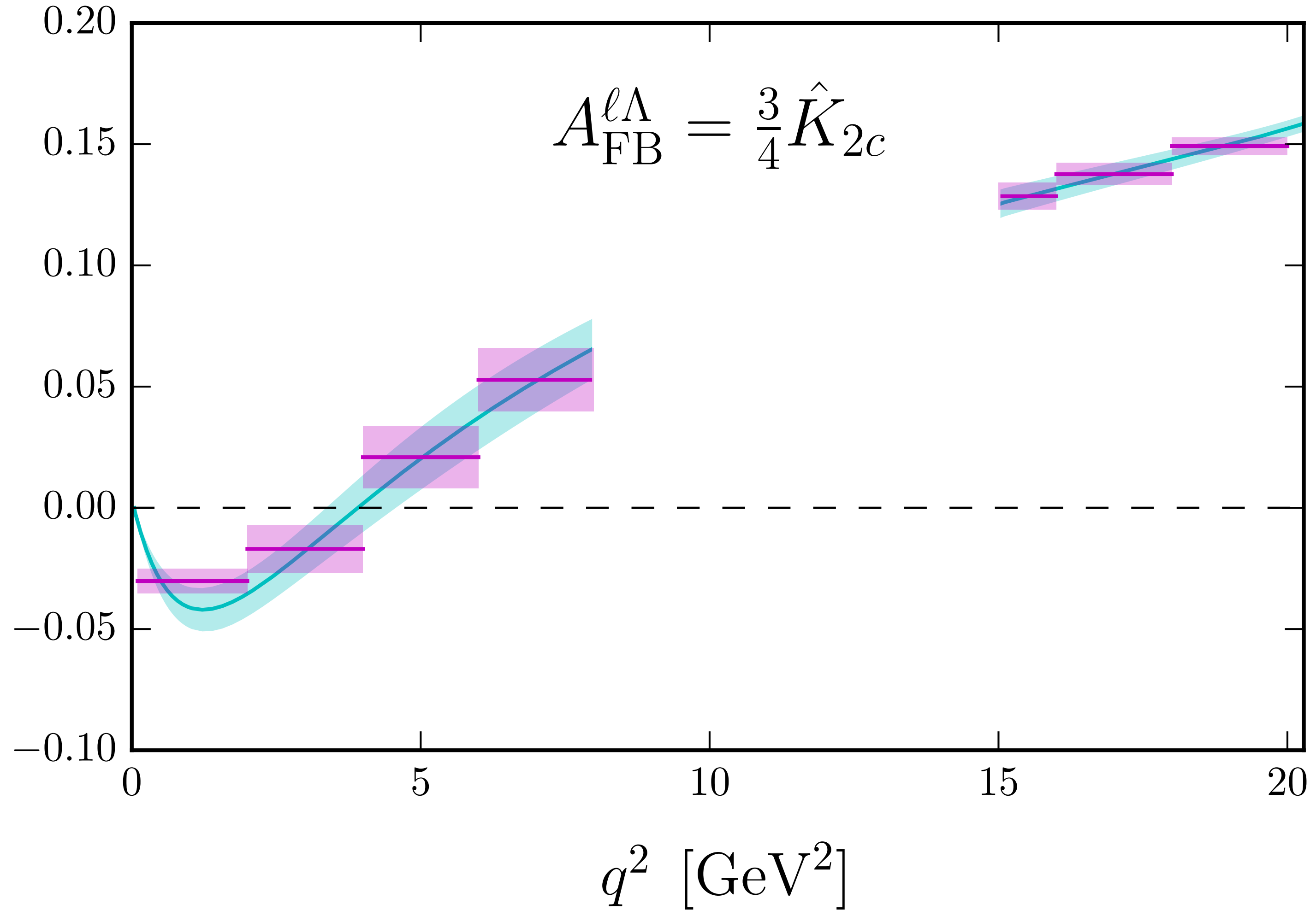
arXiv:1602.01399v2

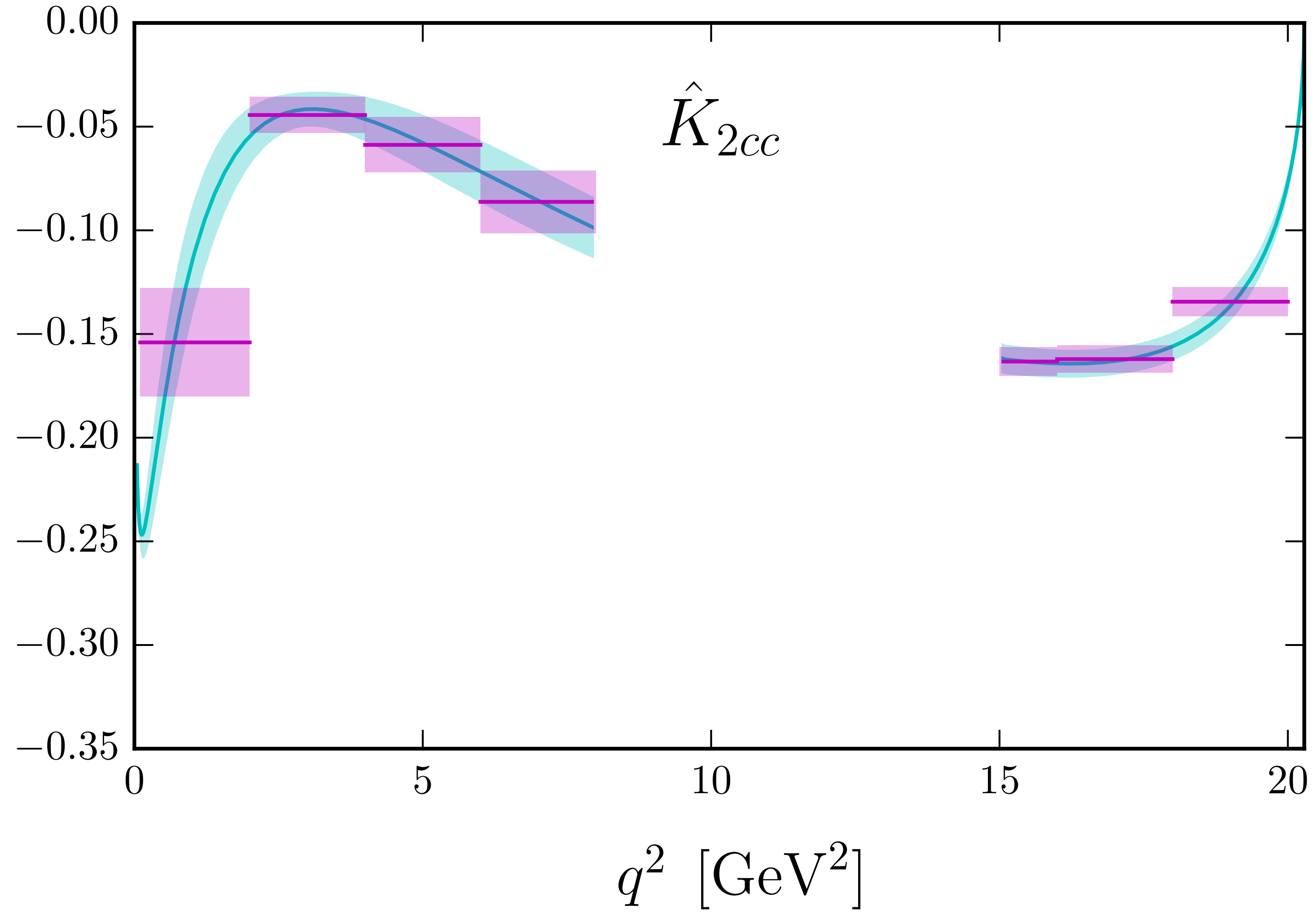






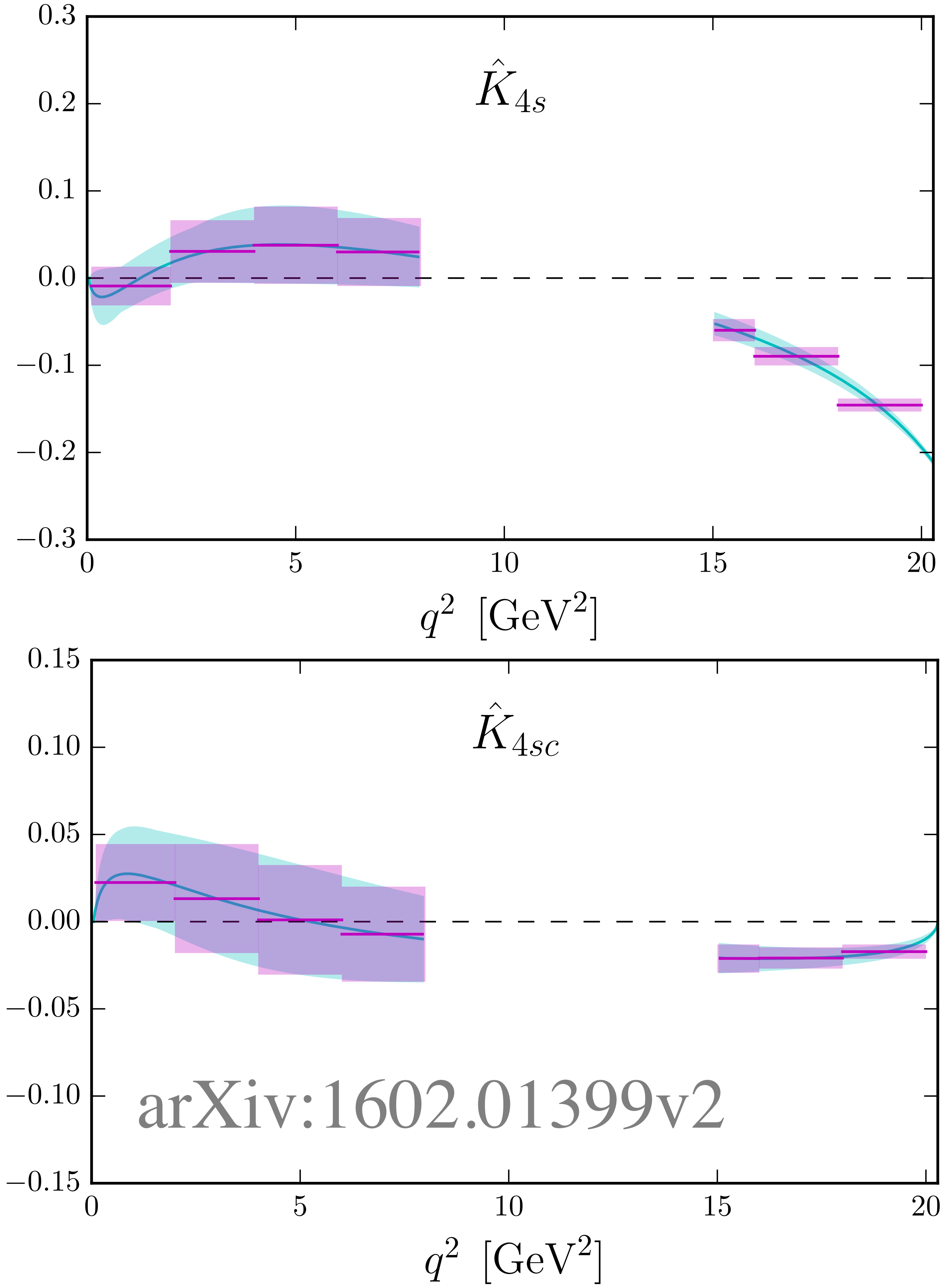






Predictions

- ➡ Predictions are generally reasonably precise
- ➡ Measurements on these plots come from very early analysis when we were figuring out what we should be actually doing
- ➡ With Tom Blake we extended work to polarised case, which adds another 24 observables
  - ❖ 10 have same structure as unpolarised case, just being multiplied by production polarisation
  - ❖ 14 are proportional to production polarisation and give access to more information



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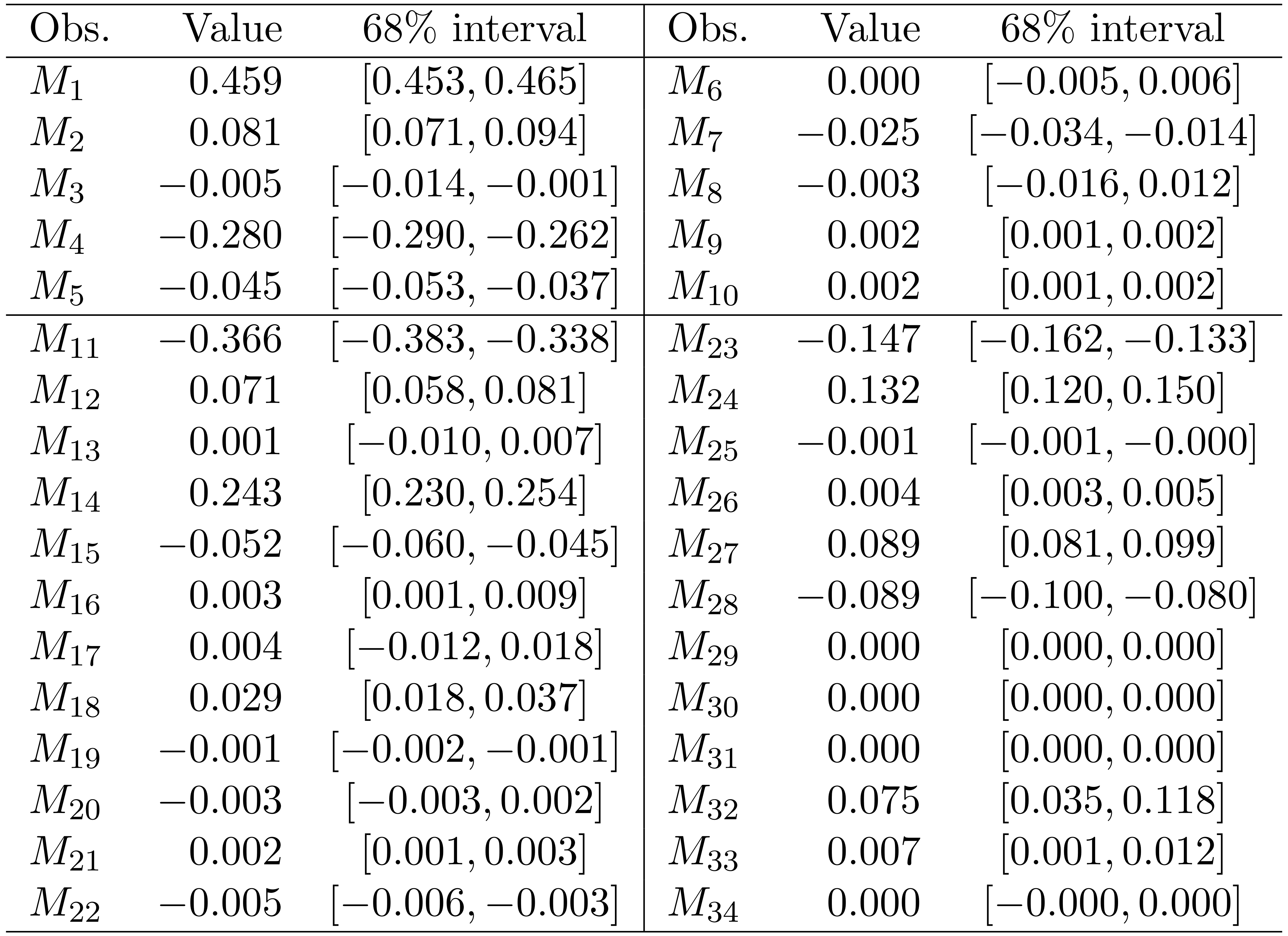
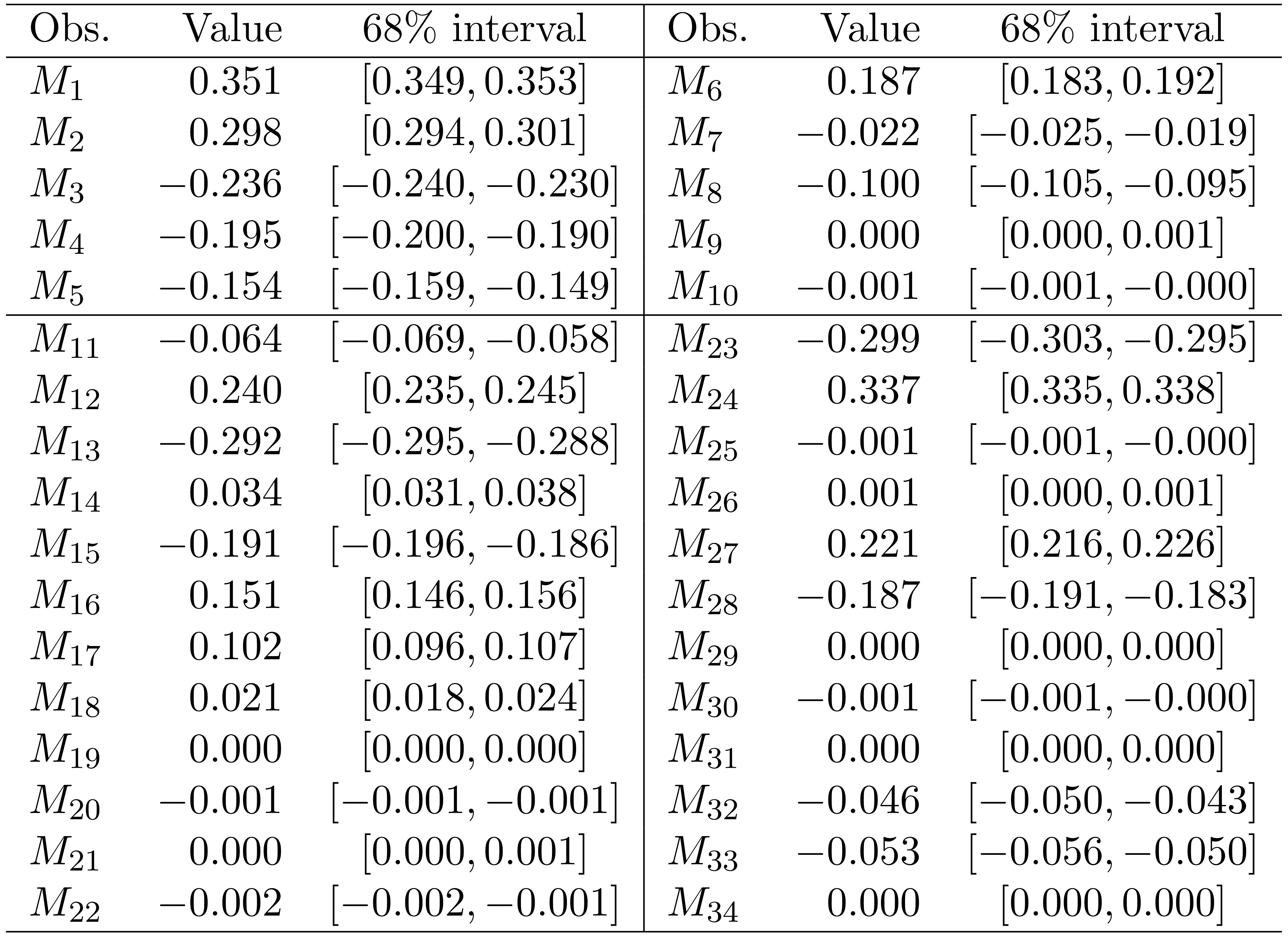
Prediction for polarised case



Obs.	Value	68% interval	Obs.	Value	68% interval
M_1	0.459	$[0.453, 0.465]$	M_6	0.000	$[-0.005, 0.006]$
M_2	0.081	$[0.071, 0.094]$	M_7	-0.025	$[-0.034, -0.014]$
M_3	-0.005	$[-0.014, -0.001]$	M_8	-0.003	$[-0.016, 0.012]$
M_4	-0.280	$[-0.290, -0.262]$	M_9	0.002	$[0.001, 0.002]$
M_5	-0.045	$[-0.053, -0.037]$	M_{10}	0.002	$[0.001, 0.002]$
M_{11}	-0.366	$[-0.383, -0.338]$	M_{23}	-0.147	$[-0.162, -0.133]$
M_{12}	0.071	$[0.058, 0.081]$	M_{24}	0.132	$[0.120, 0.150]$
M_{13}	0.001	$[-0.010, 0.007]$	M_{25}	-0.001	$[-0.001, -0.000]$
M_{14}	0.243	$[0.230, 0.254]$	M_{26}	0.004	$[0.003, 0.005]$
M_{15}	-0.052	$[-0.060, -0.045]$	M_{27}	0.089	$[0.081, 0.099]$
M_{16}	0.003	$[0.001, 0.009]$	M_{28}	-0.089	$[-0.100, -0.080]$
M_{17}	0.004	$[-0.012, 0.018]$	M_{29}	0.000	$[0.000, 0.000]$
M_{18}	0.029	$[0.018, 0.037]$	M_{30}	0.000	$[0.000, 0.000]$
M_{19}	-0.001	$[-0.002, -0.001]$	M_{31}	0.000	$[0.000, 0.000]$
M_{20}	-0.003	$[-0.003, 0.002]$	M_{32}	0.075	$[0.035, 0.118]$
M_{21}	0.002	$[0.001, 0.003]$	M_{33}	0.007	$[0.001, 0.012]$
M_{22}	-0.005	$[-0.006, -0.003]$	M_{34}	0.000	$[-0.000, 0.000]$

$1 < q^2 < 6$ GeV^2

$P_\Lambda = 1$



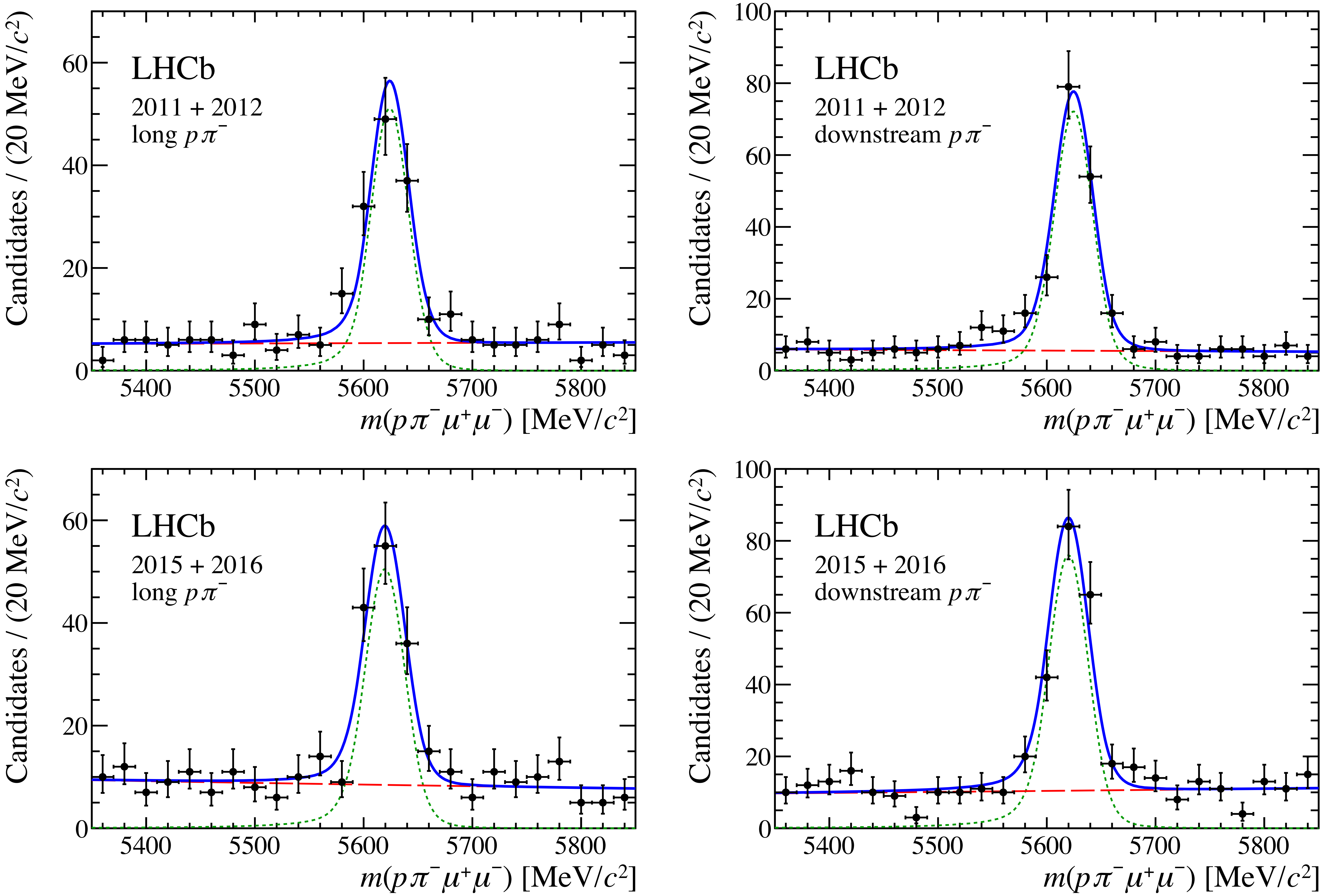
Obs.	Value	68% interval	Obs.	Value	68% interval
M_1	0.351	$[0.349, 0.353]$	M_6	0.187	$[0.183, 0.192]$
M_2	0.298	$[0.294, 0.301]$	M_7	-0.022	$[-0.025, -0.019]$
M_3	-0.236	$[-0.240, -0.230]$	M_8	-0.100	$[-0.105, -0.095]$
M_4	-0.195	$[-0.200, -0.190]$	M_9	0.000	$[0.000, 0.001]$
M_5	-0.154	$[-0.159, -0.149]$	M_{10}	-0.001	$[-0.001, -0.000]$
M_{11}	-0.064	$[-0.069, -0.058]$	M_{23}	-0.299	$[-0.303, -0.295]$
M_{12}	0.240	$[0.235, 0.245]$	M_{24}	0.337	$[0.335, 0.338]$
M_{13}	-0.292	$[-0.295, -0.288]$	M_{25}	-0.001	$[-0.001, -0.000]$
M_{14}	0.034	$[0.031, 0.038]$	M_{26}	0.001	$[0.000, 0.001]$
M_{15}	-0.191	$[-0.196, -0.186]$	M_{27}	0.221	$[0.216, 0.226]$
M_{16}	0.151	$[0.146, 0.156]$	M_{28}	-0.187	$[-0.191, -0.183]$
M_{17}	0.102	$[0.096, 0.107]$	M_{29}	0.000	$[0.000, 0.000]$
M_{18}	0.021	$[0.018, 0.024]$	M_{30}	-0.001	$[-0.001, -0.000]$
M_{19}	0.000	$[0.000, 0.000]$	M_{31}	0.000	$[0.000, 0.000]$
M_{20}	-0.001	$[-0.001, -0.001]$	M_{32}	-0.046	$[-0.050, -0.043]$
M_{21}	0.000	$[0.000, 0.001]$	M_{33}	-0.053	$[-0.056, -0.050]$
M_{22}	-0.002	$[-0.002, -0.001]$	M_{34}	0.000	$[0.000, 0.000]$

$15 < q^2 < 20$ GeV^2

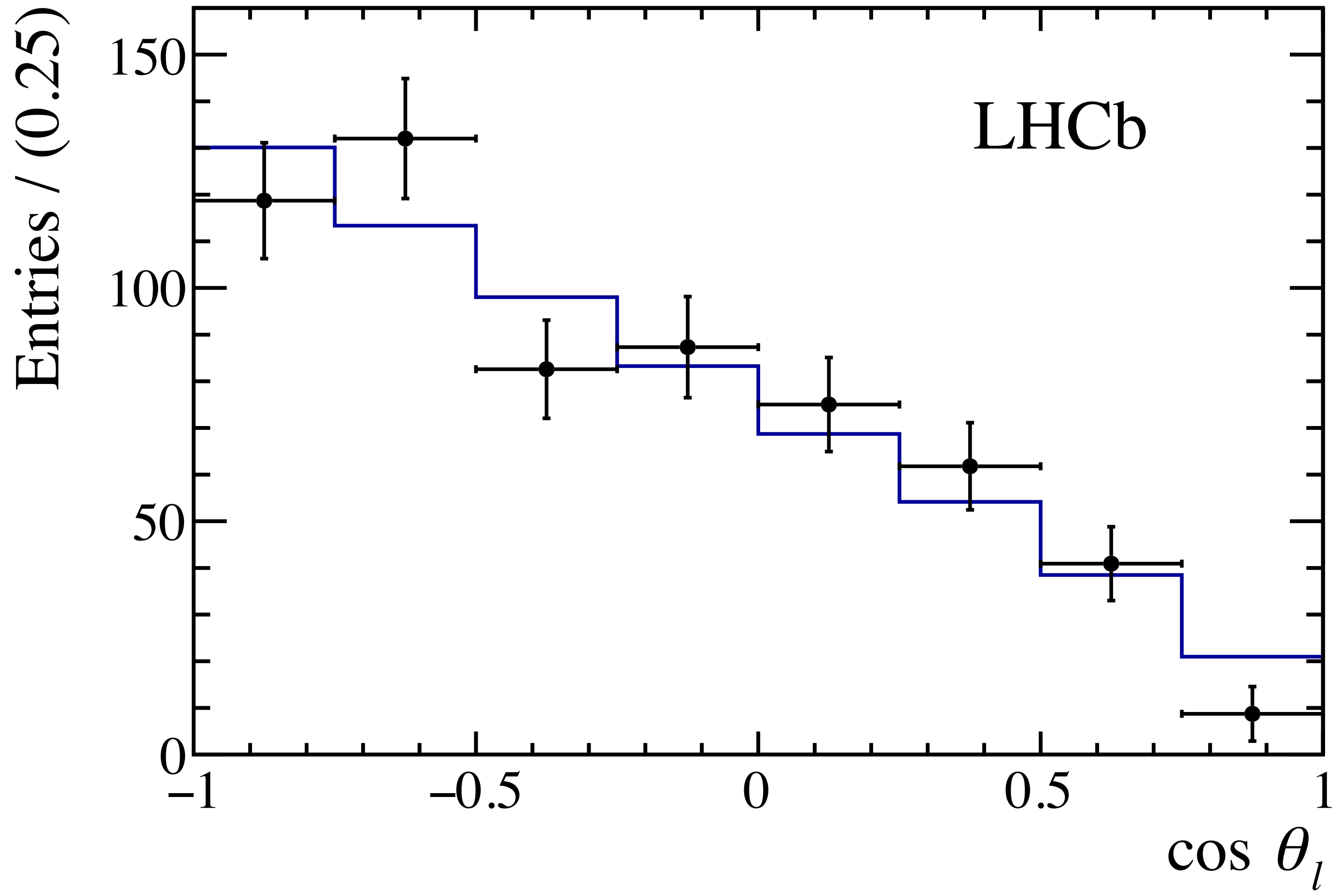
$P_\Lambda = 1$

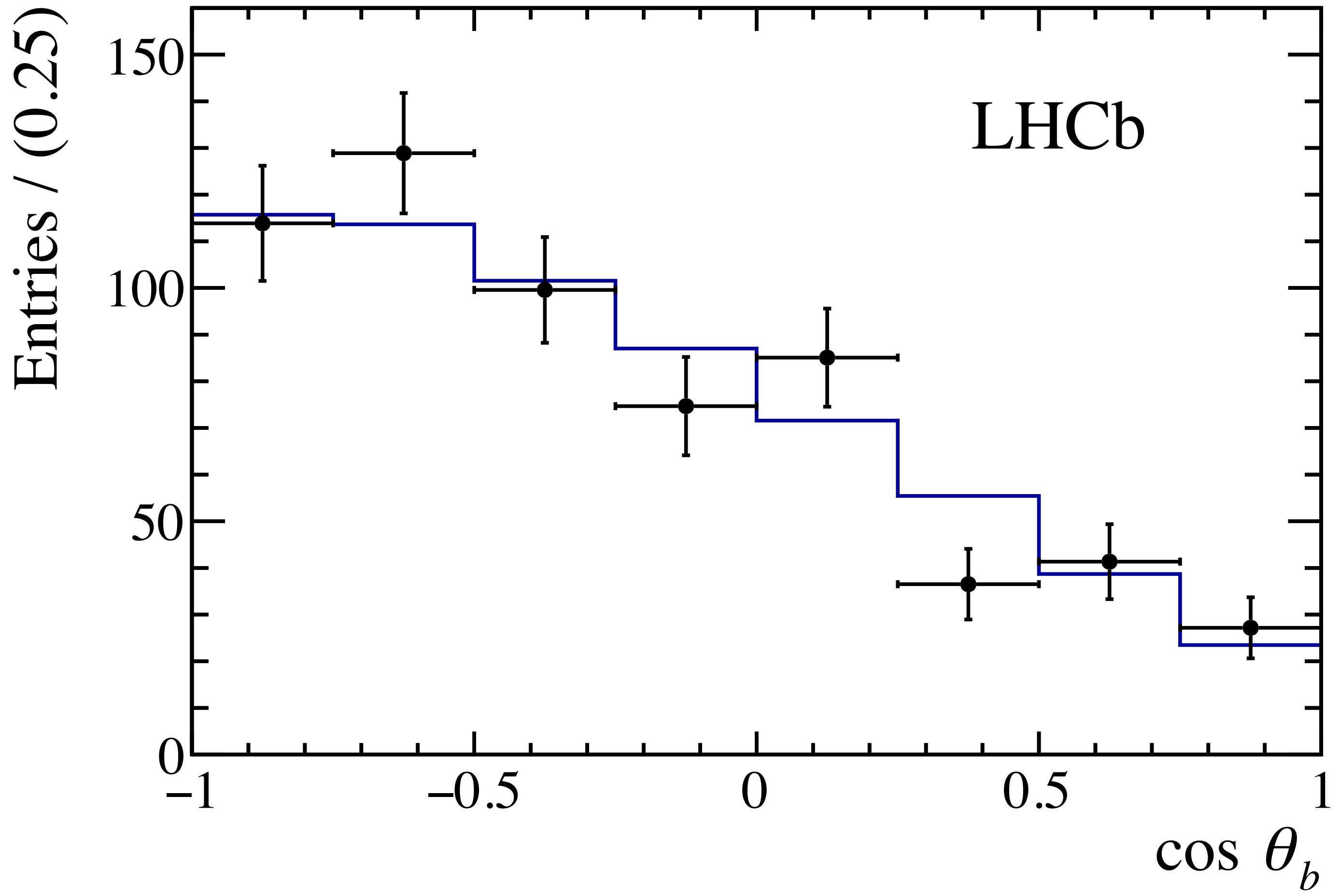
Latest measurement

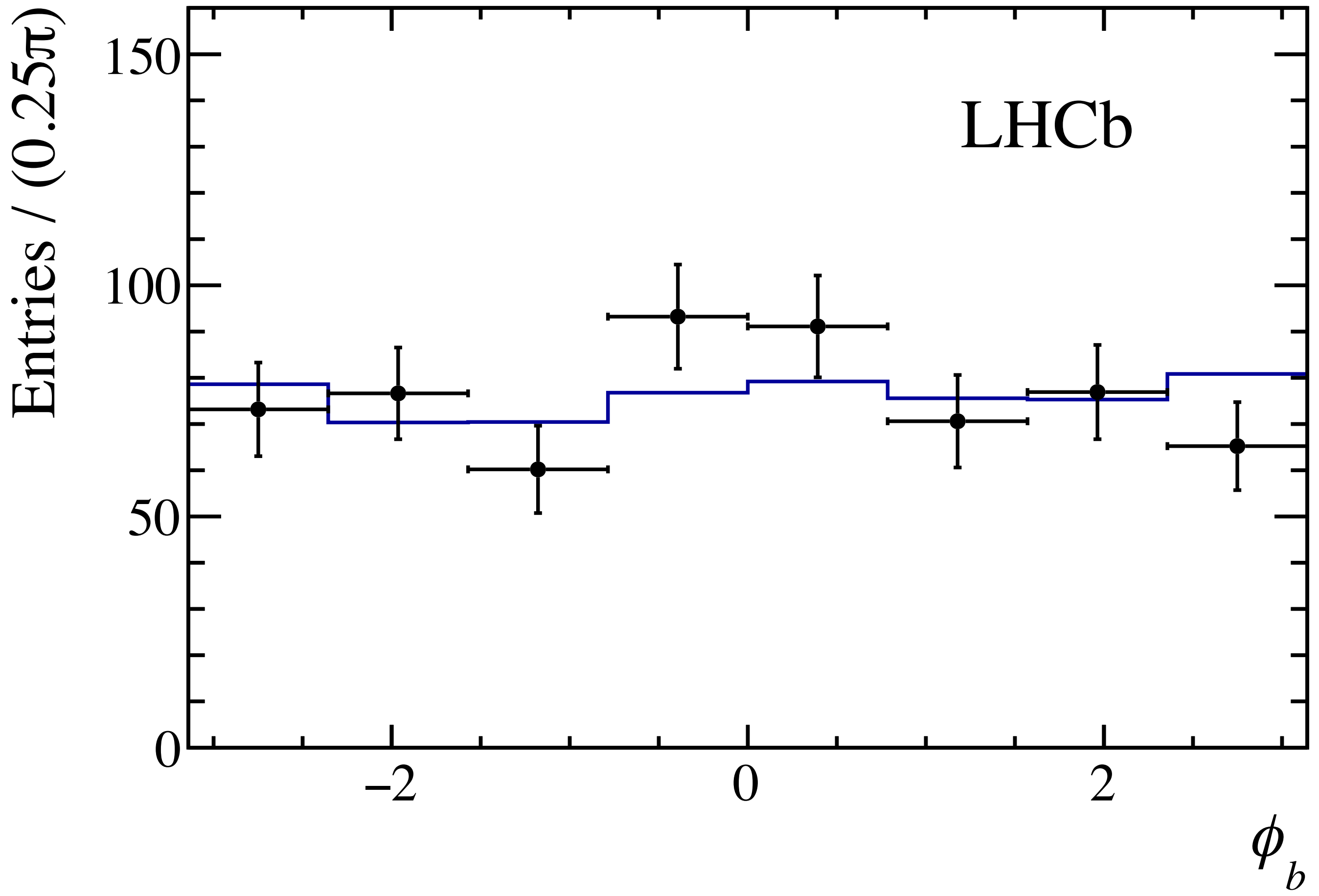
- Uses Run 1 and part of Run 2 data from LHCb
- Measured only $15 < q^2 < 20$ GeV^2 bin as this is the only one having significant yield
- About 610 signal decays
- Used method of moments
  - Luckily, otherwise would run to troubles with value of α_Λ

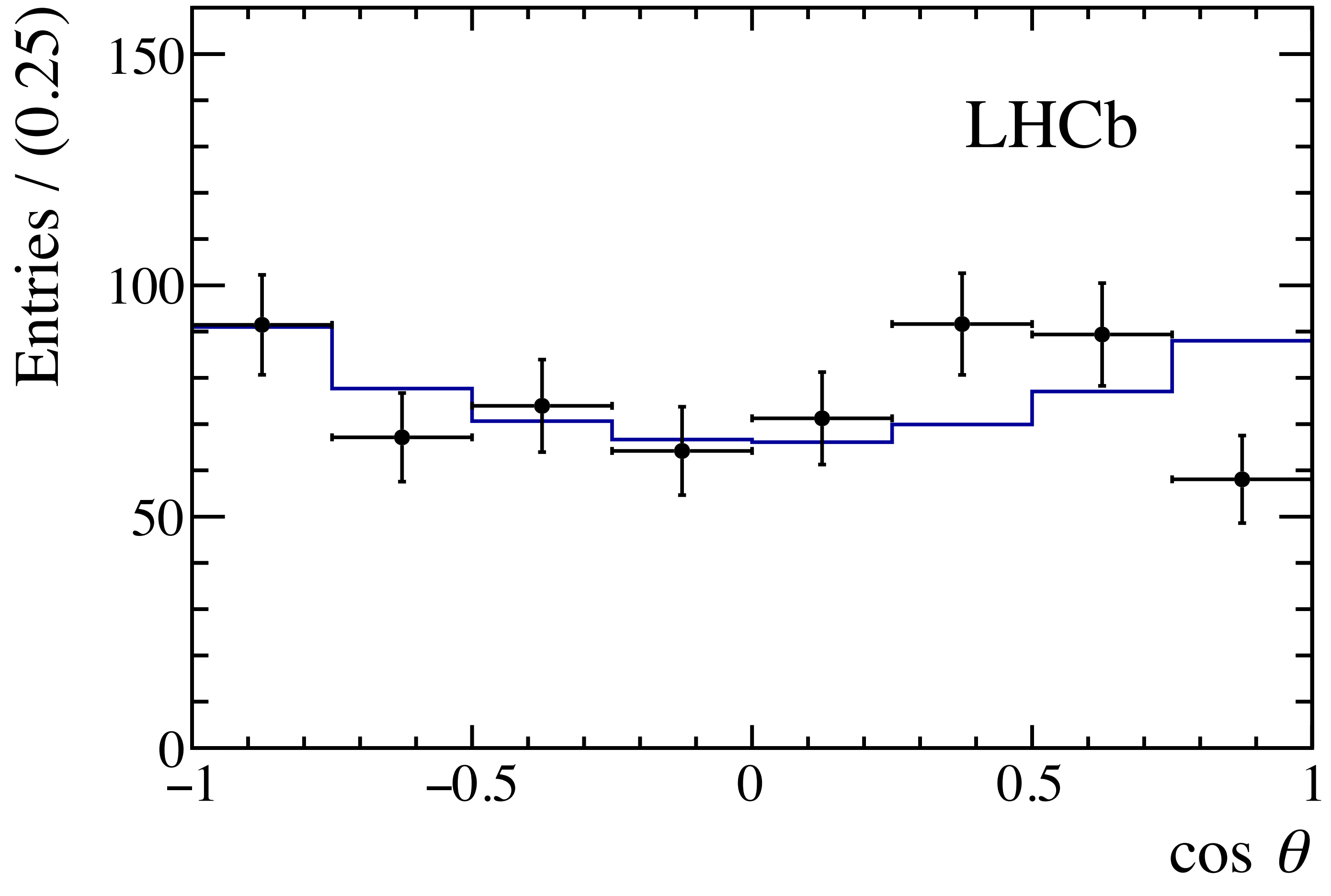


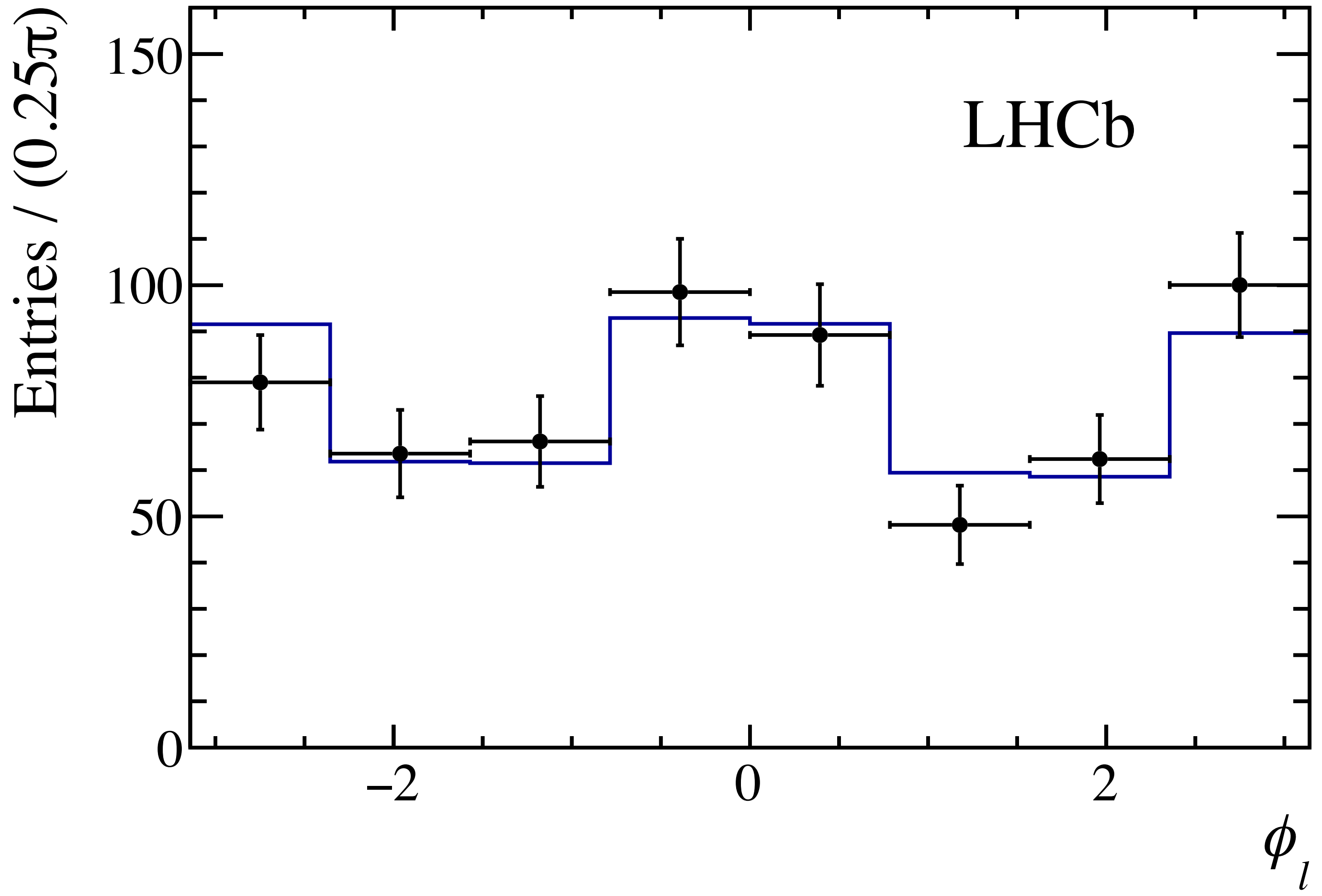
Latest measurement





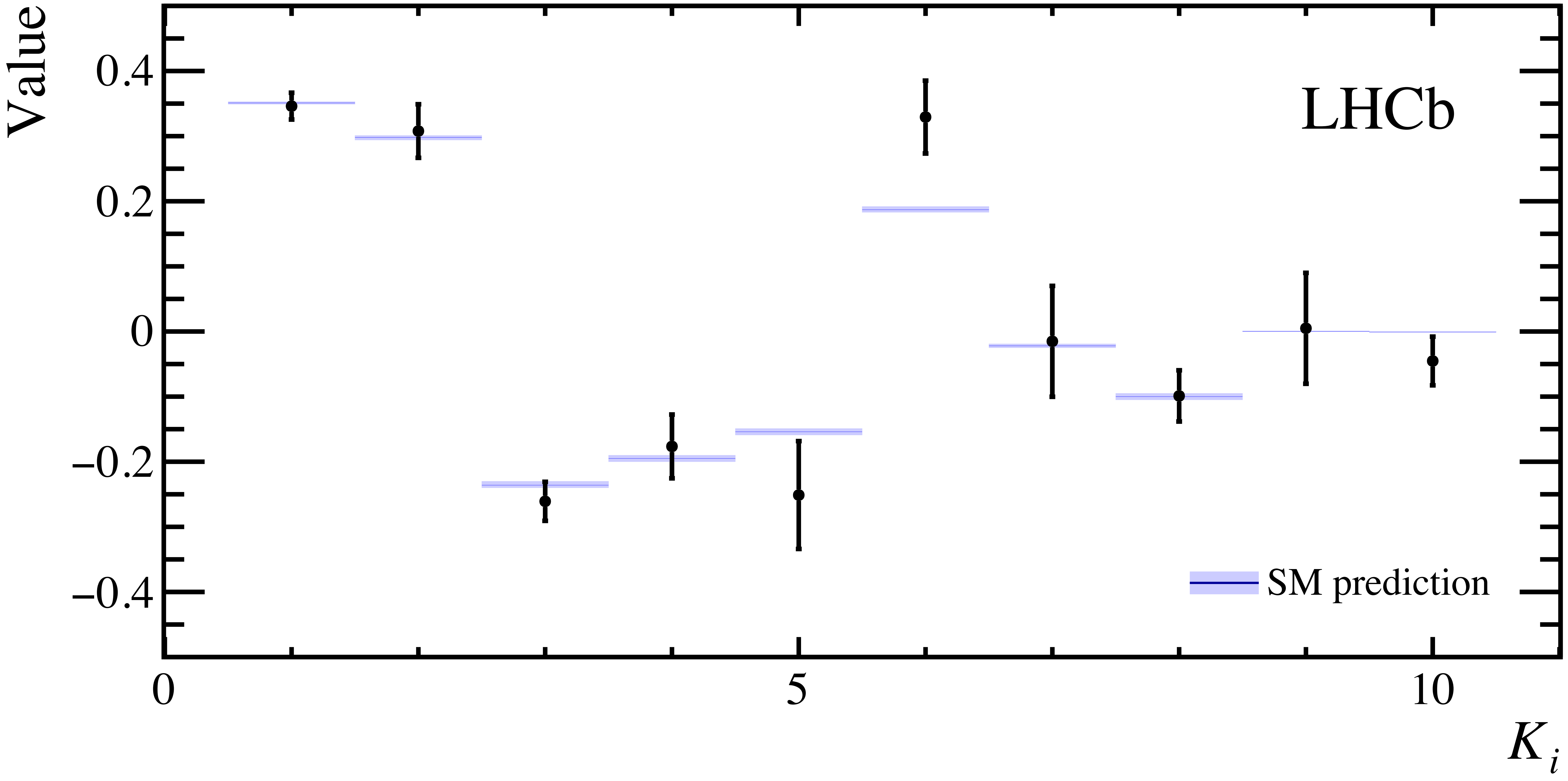






Source	Uncertainty $[10^{-3}]$	
	Range among K_i	Mean
Simulated sample size	3–22	9
Efficiency parameterisation	1–13	4
Data-simulation differences	2–16	6
Angular resolution	1–11	4
Beam crossing angle	1–8	4
Signal mass model	1–4	2

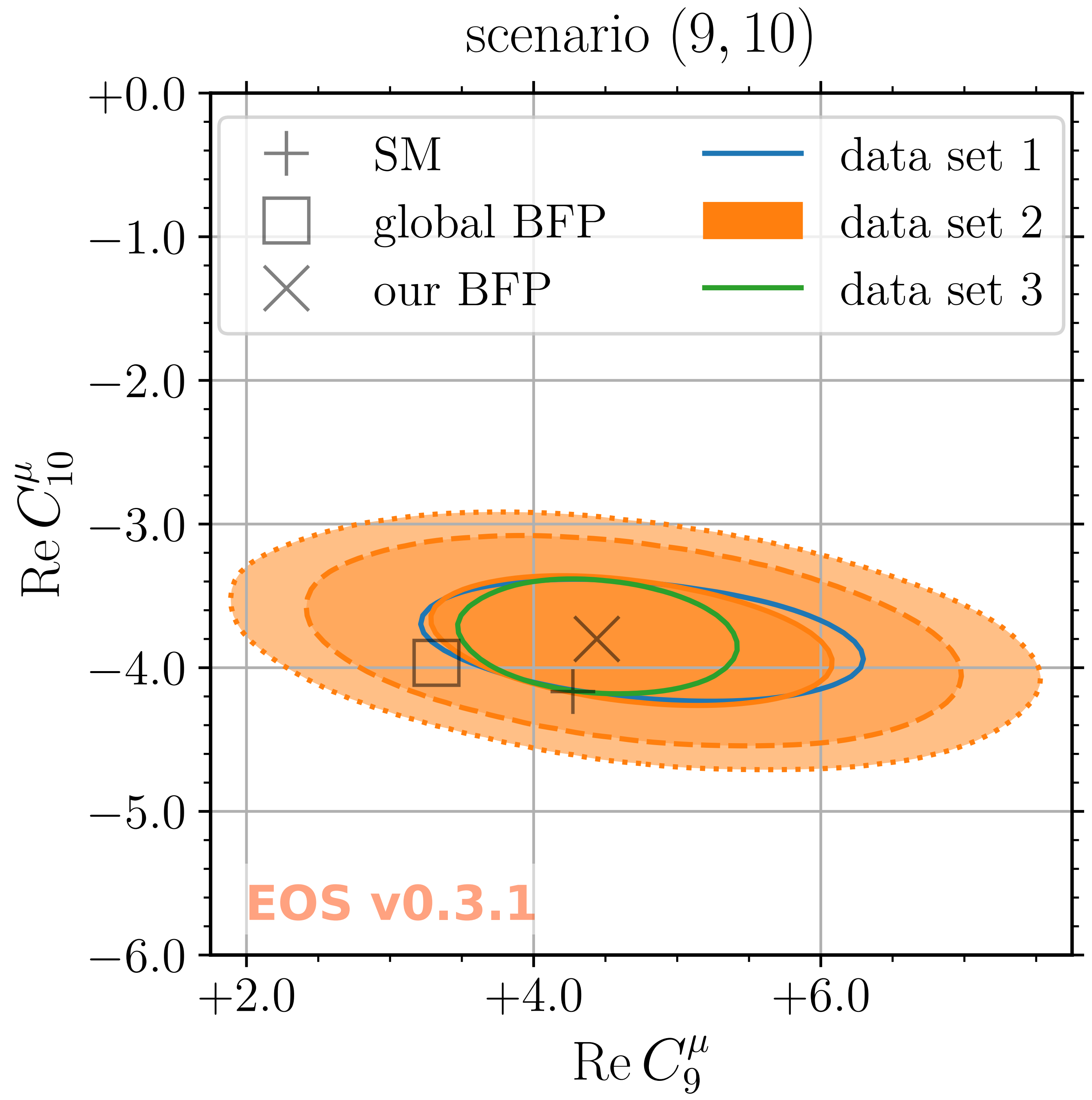
Latest measurement

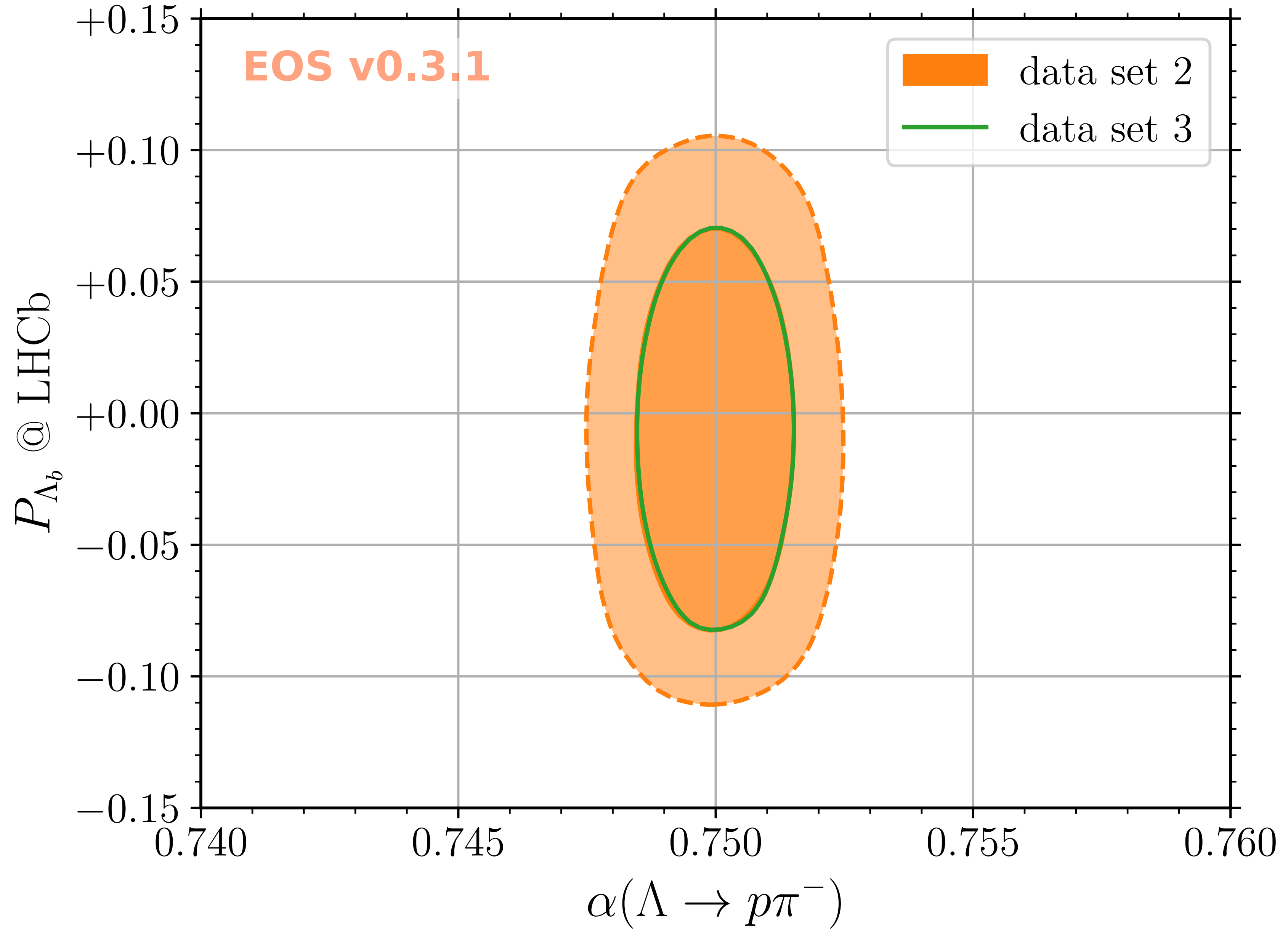


- ➡ Well compatible with the SM
- ➡ Remaining observables compatible with zero

Global fit

- Uses just $\Lambda_b \to \Lambda\mu\mu$ observables and $B_s \to \mu\mu$ branching fraction
- Interestingly it constrains production polarisation and Λ decay asymmetry as well as dedicated measurement with $\Lambda_b \to J/\psi\Lambda$

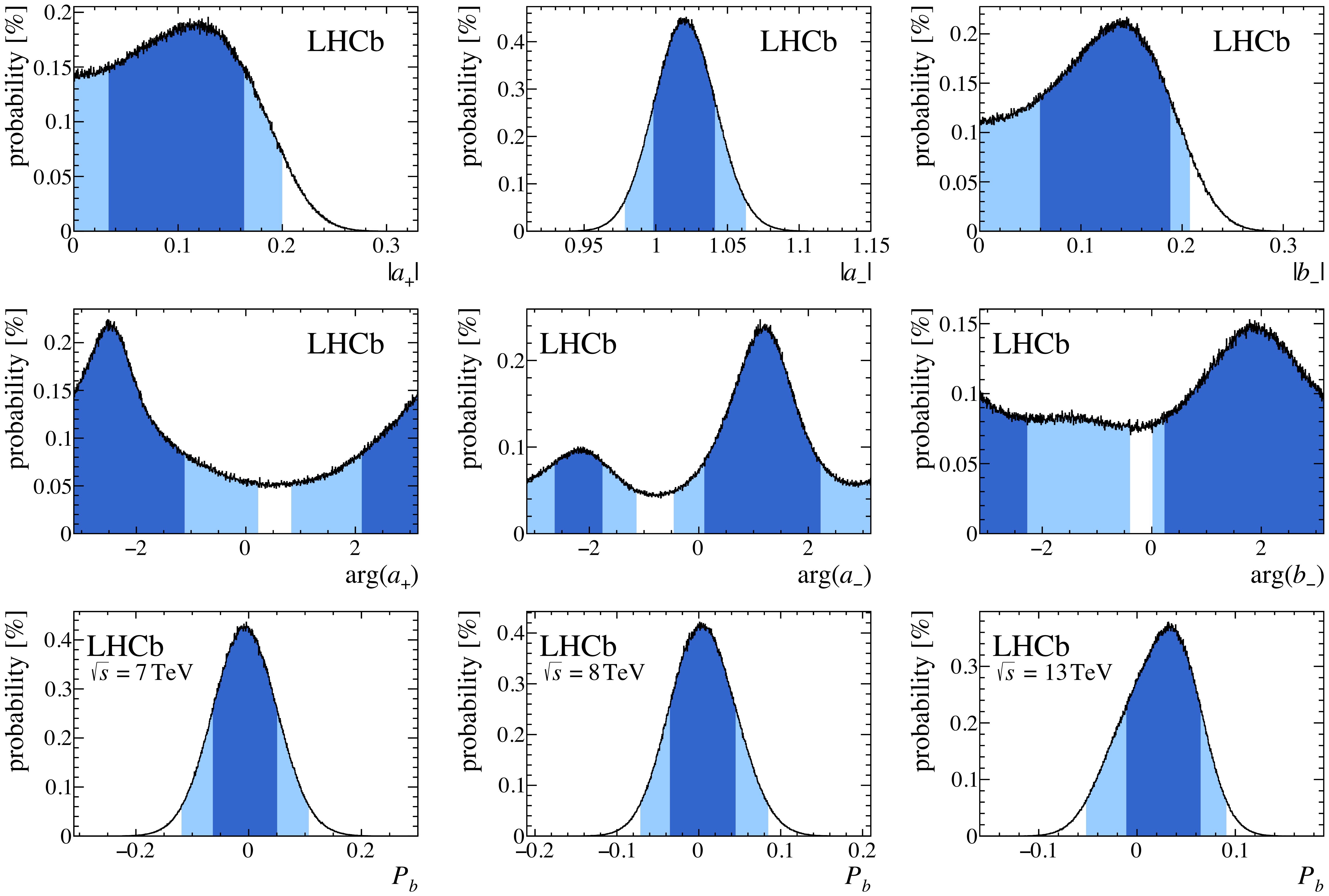




arXiv:1912.05811v1

Production polarisation

- ➡ Measure angular moments in $\Lambda_b \rightarrow J/\psi\Lambda$ and then perform Bayesian analysis
- ➡ Uses same dataset as rare decays
- ➡ Polarisation consistent with zero without visible energy dependence



How to get polarised sample

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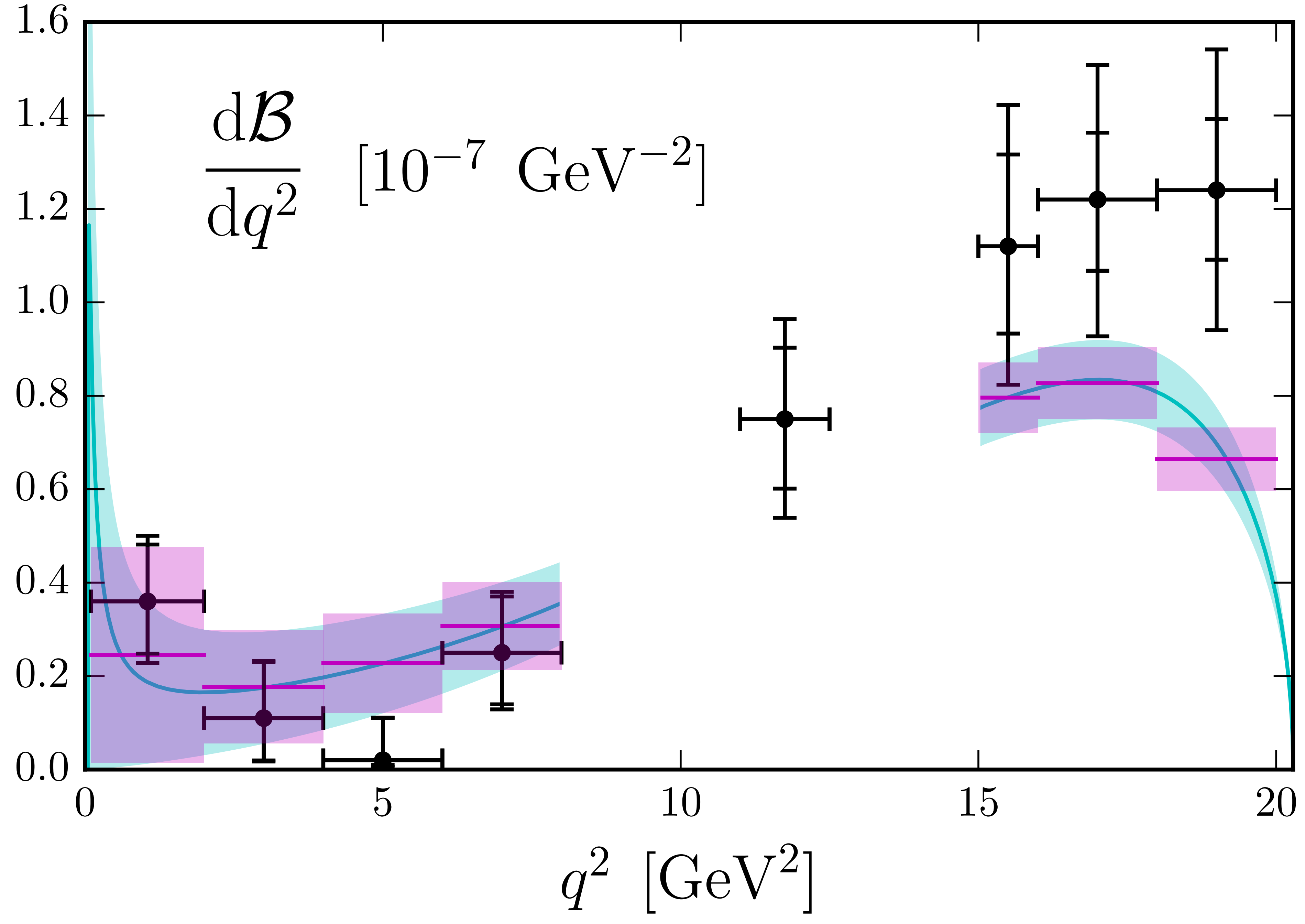
- If there is enough interest in observables accessible only with polarisation, we can try to play some tricks
  - We measured polarisation only integrated over large η-p_T region, but it does not have to be constant
  - One can look for Λ_b coming from decays which itself could introduce polarisation
    - Obvious choice for LHCb would be $\Sigma_b{}^*$ but my intuition is that it will not help
    - Top quark decays might be interesting, W in such case is polarised and so would be b-quark, this would be more suitable for ATLAS and CMS
- Each idea would need dedicated study whether it would work
- Each idea would mean lower statistics, on the other hand, one does not need to do all observables

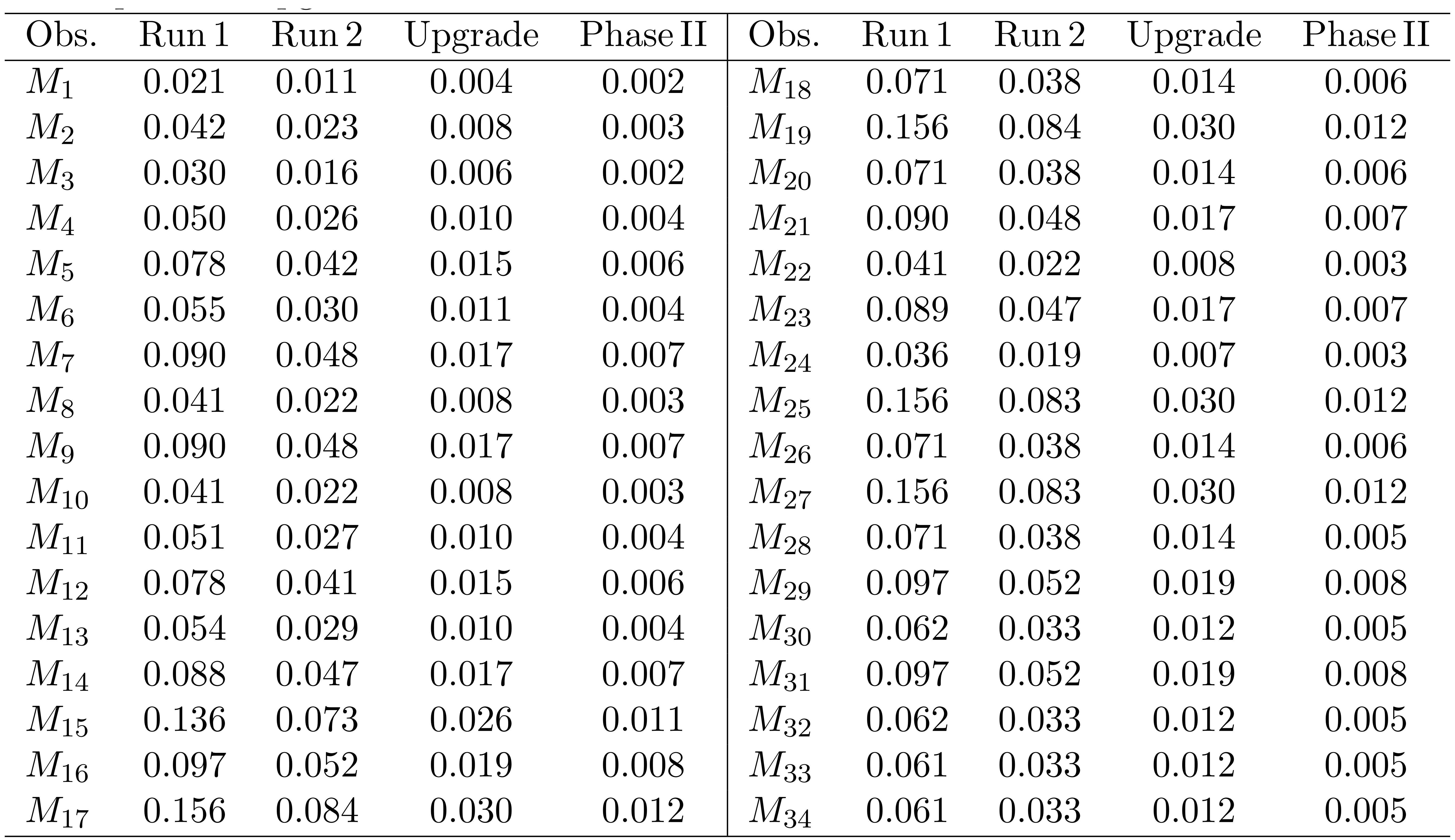
What to expect

- ➡ LHCb is working on update of $\Lambda_b \to \Lambda\mu\mu$ branching fraction with Run 1+2 data
- ➡ Good chance to see signal in more q^2 bins, we have about 4 times more data in Run 2
- ➡ Not yet clear what we can do with angular observables below J/ψ
- ➡ Want to look back to polarisation measurement to see whether there is at least some indication of non-zero polarisation somewhere



Future

- ➡ When we did work on full distribution, we made crude estimate of precision at LHCb
- ➡ $15 < q^2 < 20$ GeV^2
- ➡ Pure signal toys without any background
- ➡ Just scale yields from published numbers



Obs.	Run 1	Run 2	Upgrade	Phase II	Obs.	Run 1	Run 2	Upgrade	Phase II
M_1	0.021	0.011	0.004	0.002	M_{18}	0.071	0.038	0.014	0.006
M_2	0.042	0.023	0.008	0.003	M_{19}	0.156	0.084	0.030	0.012
M_3	0.030	0.016	0.006	0.002	M_{20}	0.071	0.038	0.014	0.006
M_4	0.050	0.026	0.010	0.004	M_{21}	0.090	0.048	0.017	0.007
M_5	0.078	0.042	0.015	0.006	M_{22}	0.041	0.022	0.008	0.003
M_6	0.055	0.030	0.011	0.004	M_{23}	0.089	0.047	0.017	0.007
M_7	0.090	0.048	0.017	0.007	M_{24}	0.036	0.019	0.007	0.003
M_8	0.041	0.022	0.008	0.003	M_{25}	0.156	0.083	0.030	0.012
M_9	0.090	0.048	0.017	0.007	M_{26}	0.071	0.038	0.014	0.006
M_{10}	0.041	0.022	0.008	0.003	M_{27}	0.156	0.083	0.030	0.012
M_{11}	0.051	0.027	0.010	0.004	M_{28}	0.071	0.038	0.014	0.005
M_{12}	0.078	0.041	0.015	0.006	M_{29}	0.097	0.052	0.019	0.008
M_{13}	0.054	0.029	0.010	0.004	M_{30}	0.062	0.033	0.012	0.005
M_{14}	0.088	0.047	0.017	0.007	M_{31}	0.097	0.052	0.019	0.008
M_{15}	0.136	0.073	0.026	0.011	M_{32}	0.062	0.033	0.012	0.005
M_{16}	0.097	0.052	0.019	0.008	M_{33}	0.061	0.033	0.012	0.005
M_{17}	0.156	0.084	0.030	0.012	M_{34}	0.061	0.033	0.012	0.005