**Imperial College**
**London**

# Experimental aspects of $B^0 \rightarrow K^* \mu^+ \mu^-$

**Ulrik Egede**

**Rare b-Decays @ Low Recoil (bsll2011)**
**DESY, 14-16 June 2011**

# Outline

Experimental status of $B^0 \to K^{(*)}l^+l^-$ decays

Observables and how to get hold of them

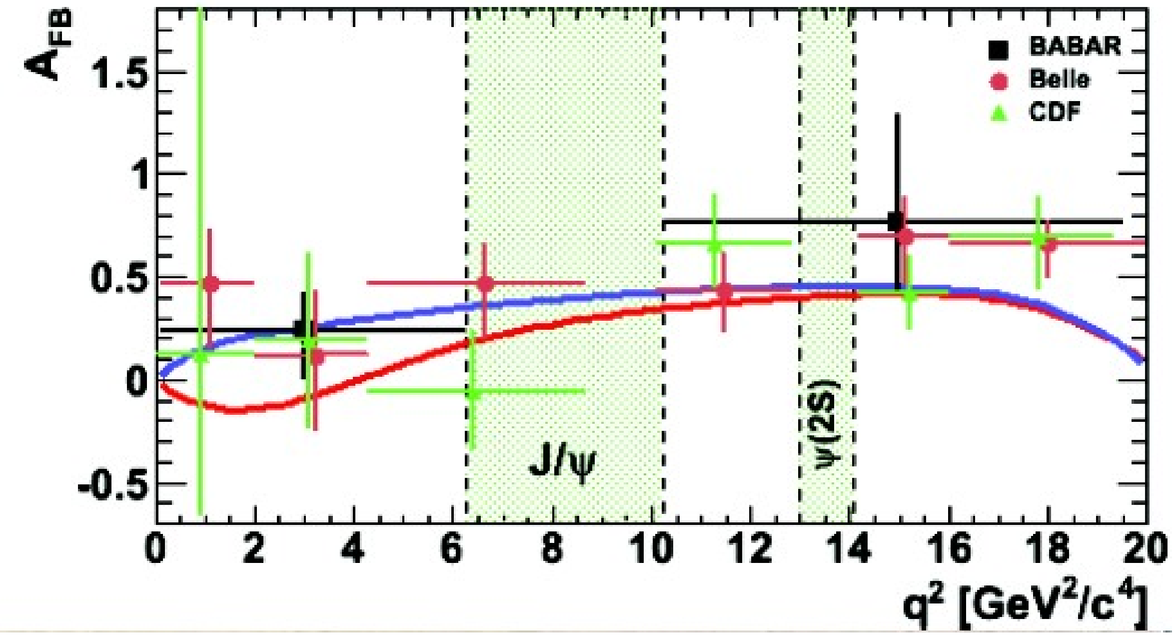
The low recoil region

Binning

Fitting

# The past

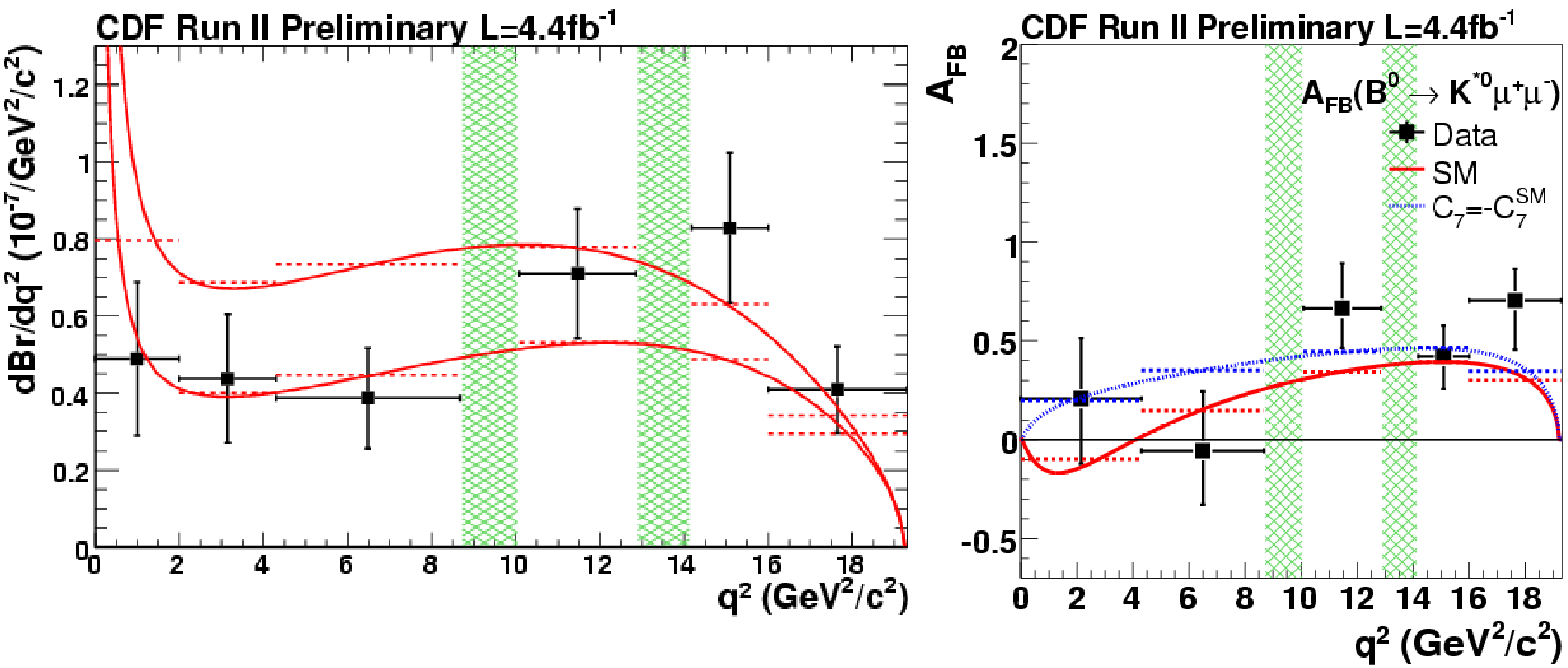
- Belle and BaBar collected data at the Υ(4S) resonance
  - 711 $fb^{-1}$, and 433 $fb^{-1}$ collected respectively
- Looked at $B \rightarrow K^{(*)} l^+ l^-$ in 10 exclusive final states
  - BaBar has around 100 events and Belle around 250
  - Both experiments can make modest improvements with current data



# The present

CDF presented results in 2010 based on 4.4 fb-1

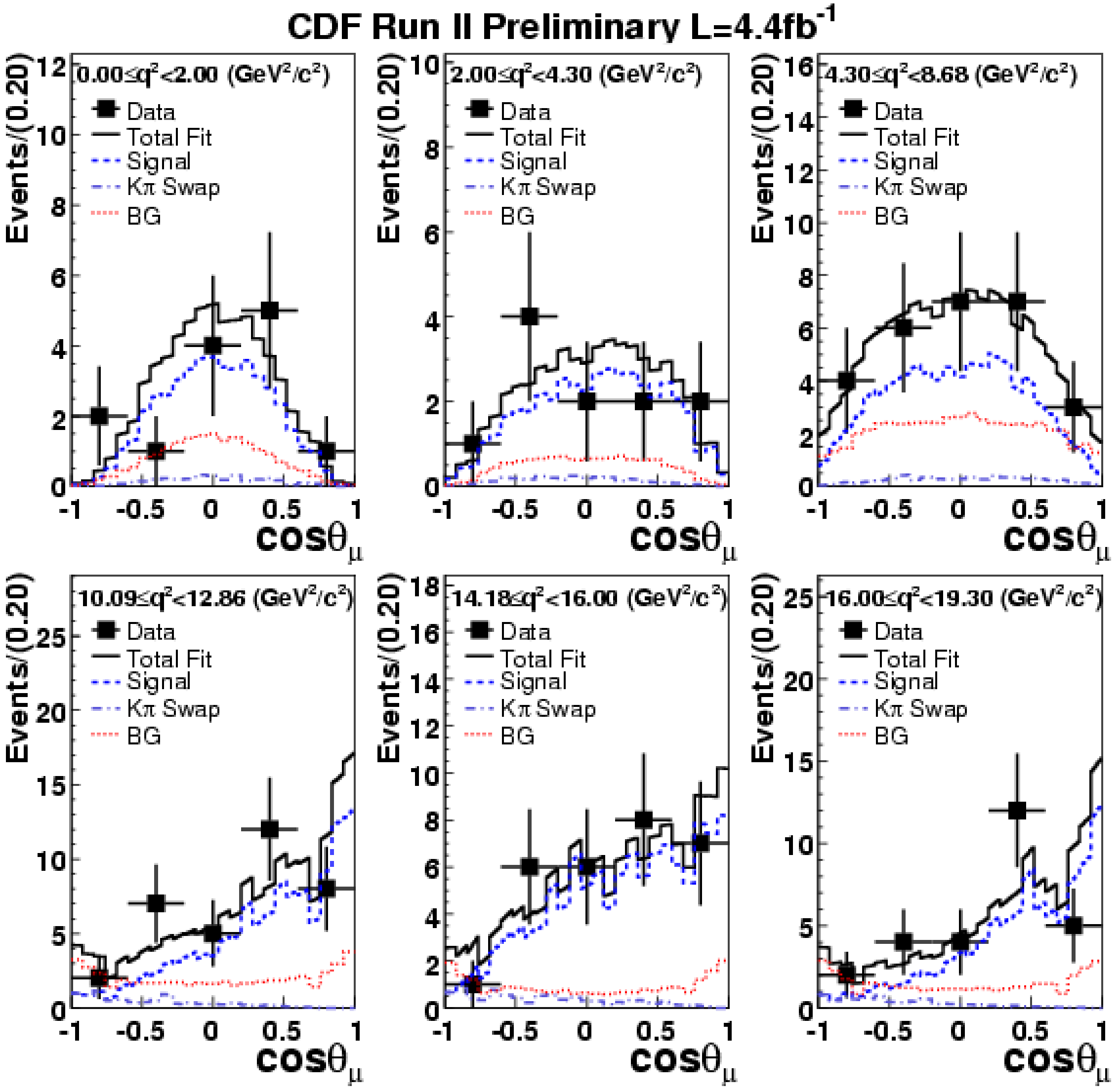
This gives about 100 events in total



# The present

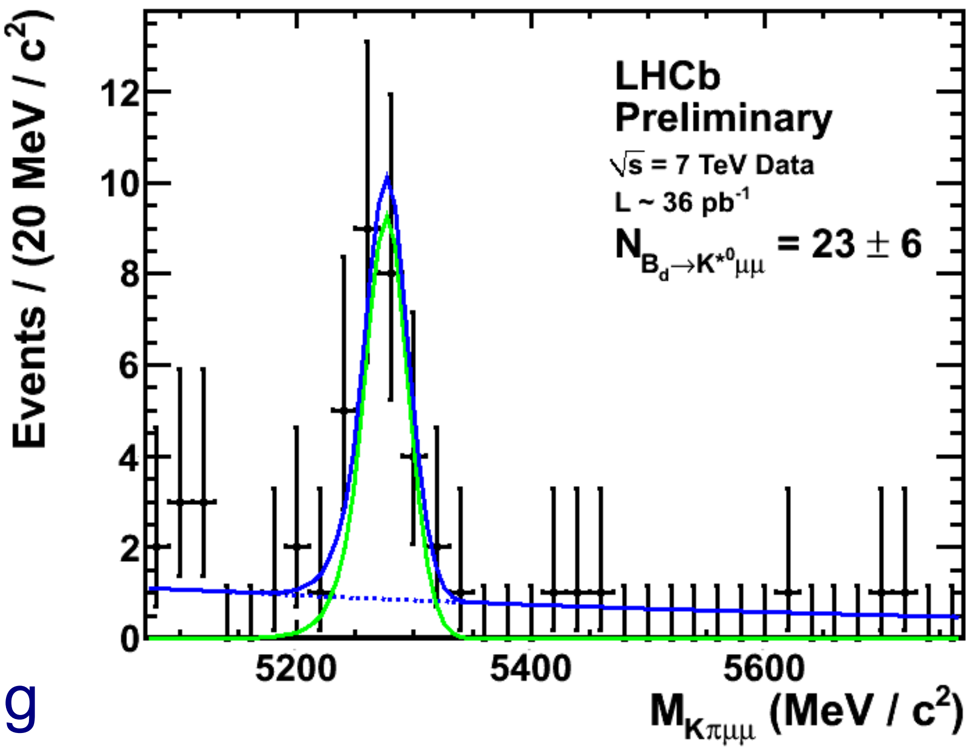
Example of fits to $\theta_l$ distributions

A factor 2 more to come from data on tape



# The present

From 36 $pb^{-1}$ of data taken in 2010, LHCb, demonstrated they can see decay




Despite a very rare decay, almost no background

Sensitivity illustrated by latest result on Lepton Flavour Violating decays from 2010 data

$BF(B^+ \to K^- \mu^+ \mu^+) < 4.3\ 10^{-8}$ @ 90% CL

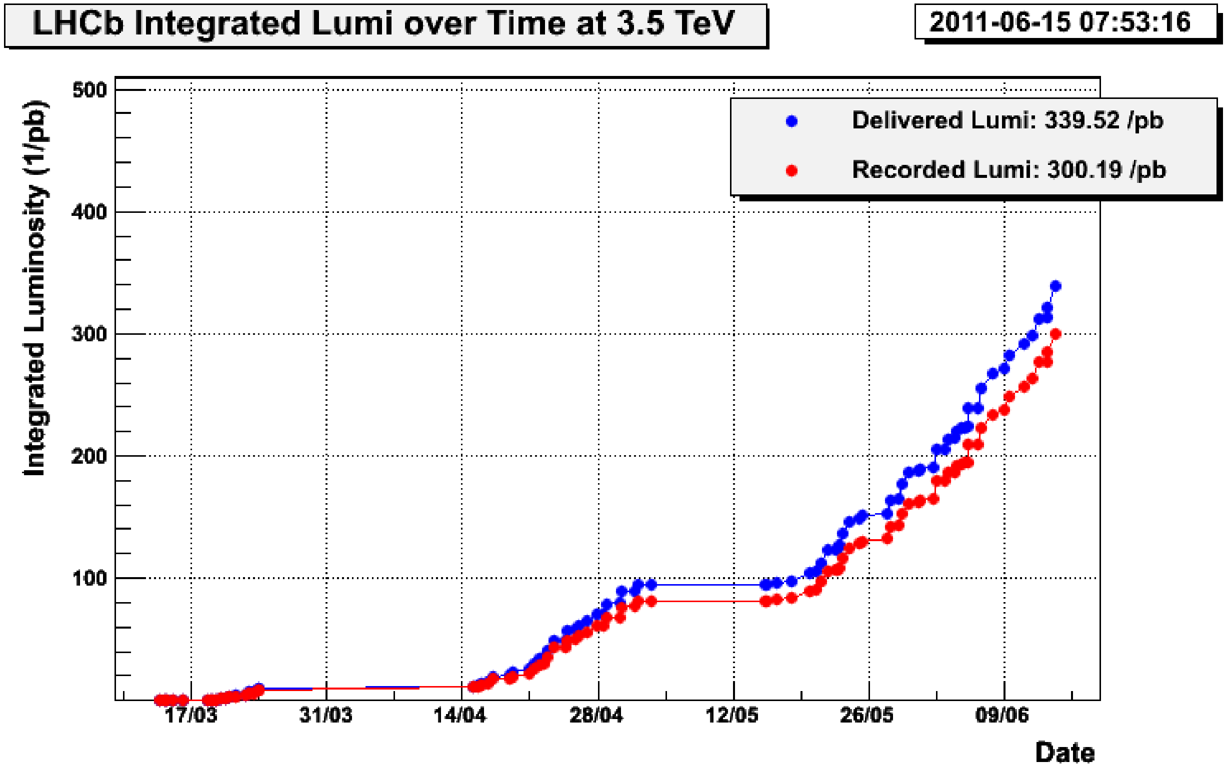
$BF(B^+ \to \pi^- \mu^+ \mu^+) < 4.5\ 10^{-8}$ @ 90% CL

# The near future

During summer LHCb should have results based on hundreds of $pb^{-1}$

Full year should give 1 $fb^{-1}$

Extrapolations dangerous (when soon to be confronted) but O(600) events within reach from 2011




Will dominate results

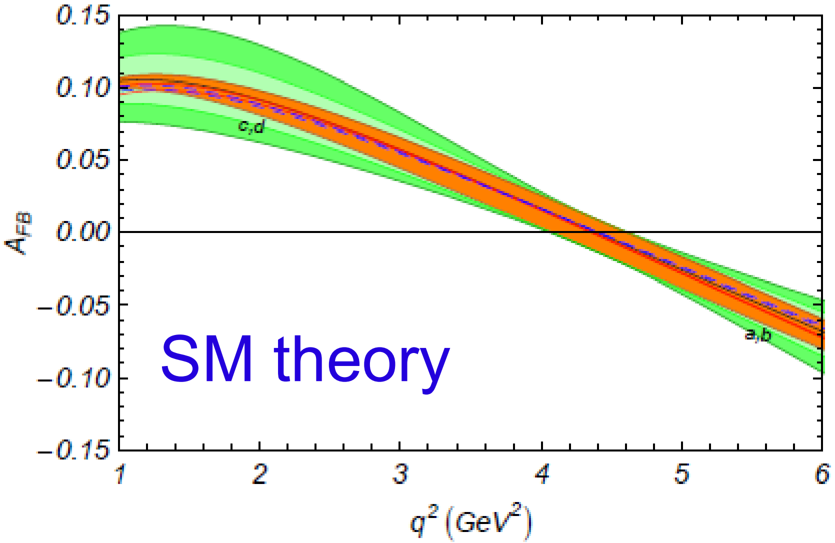
2011 data taken so far

# The future

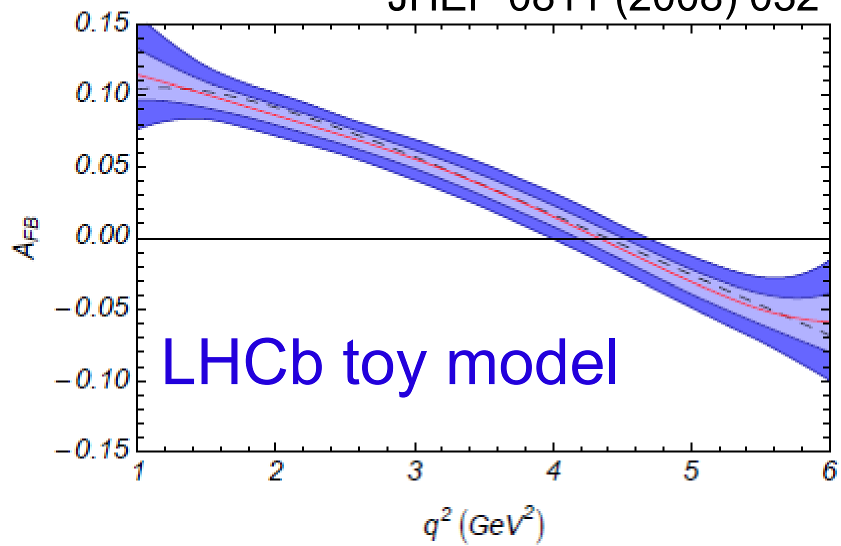
With LHC going to full energy the B-cross section will double.

Several years of running will make LHCb reach towards 10 $fb^{-1}$

Precise measurement of $A_{FB}$ zero point possible




JHEP 0811 (2008) 032



# The far future

## LHCb upgrade

- With 50 – 100 fb-1 and yield taken from arXiv 0912.4179 we can expect O(500k) events.

## Super B-factories

- O(20k) events expected (G. Eigen, Elba, May 2011) with 75 $ab^{-1}$
- Also prospect for (semi)-inclusive analysis of $B \to X l^+ l^-$

# What is the problem

- We are dealing with an exclusive decay
- Multiple problems coming from QCD
  - Form factor calculation
  - This leaves us with $\Lambda_{QCD}/m_b$ corrections
  - Mass of charm quark introduce uncertainties
  - Charm loops

# From theory to measurements

We start out with a shiny New Physics model

Physics model

# From theory to measurements

Then calculate the Wilson coefficients

Physics model

Wilson coefficients

# From theory to measurements

To get to the transversity amplitudes involves form factors and unknown $\Lambda/m_b$ corrections

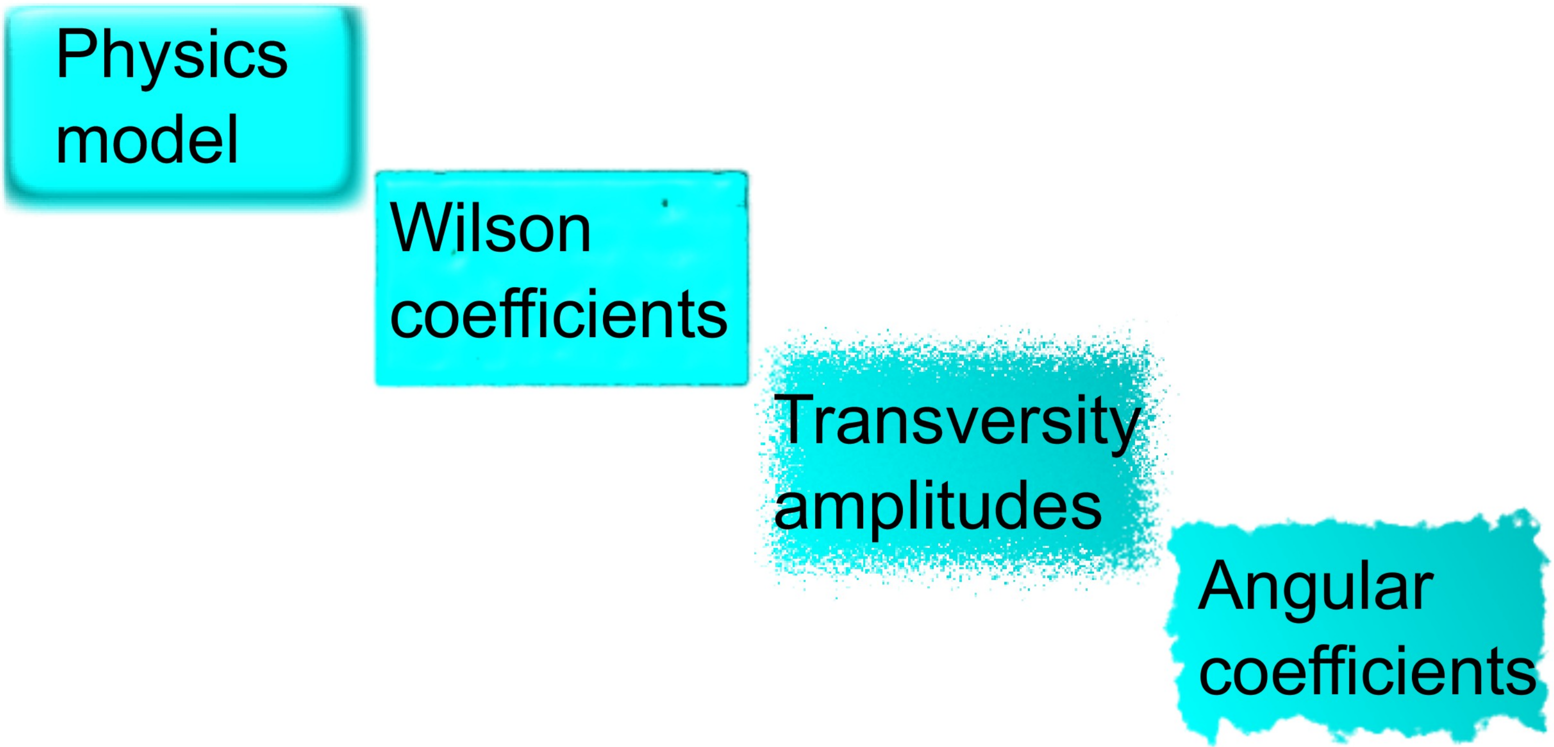
Physics model

Wilson coefficients

Transversity amplitudes

# From theory to measurements

Finally getting to the angular coefficients involves a loss of information



# From measurement to theory

Now from the experimental side we start with an all shiny set of angular coefficients

Angular coefficients

## From measurement to theory

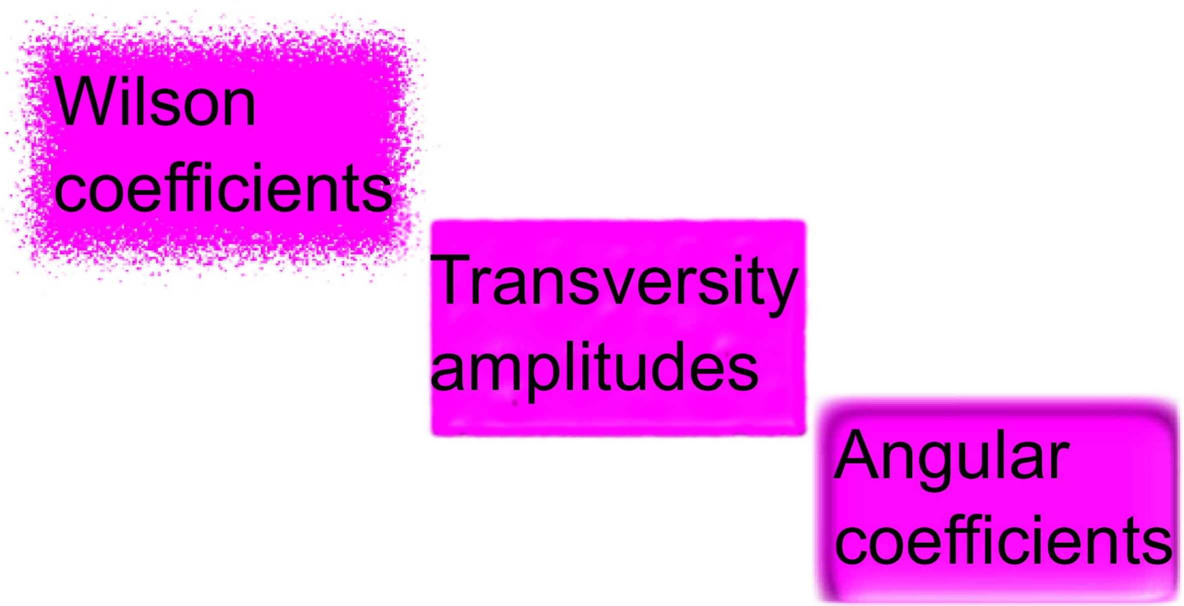
Getting to the transversity amplitudes is not a well defined operation due to symmetries

Transversity amplitudes

Angular coefficients

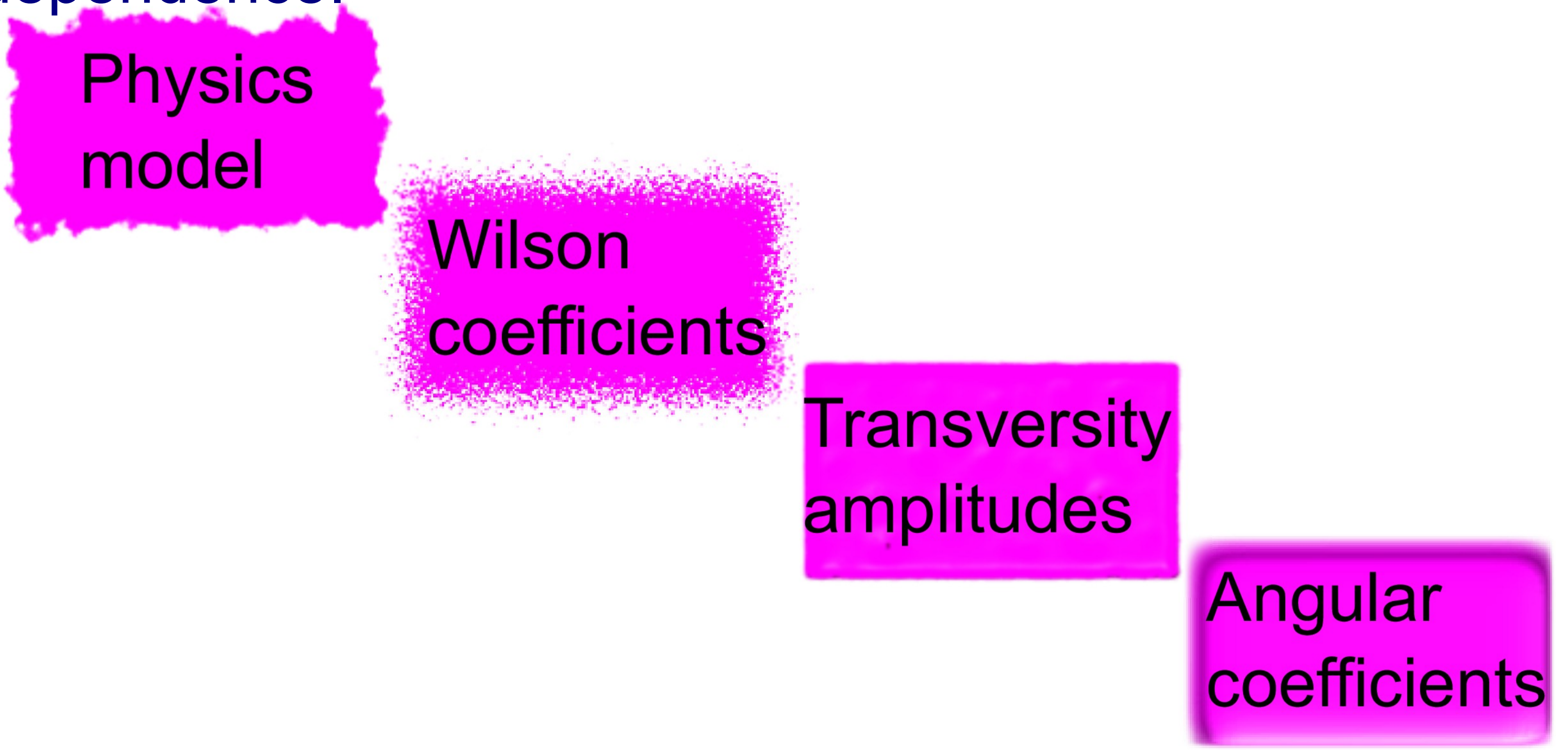
## From measurement to theory

Getting to the Wilson coefficients introduce the form factor uncertainties

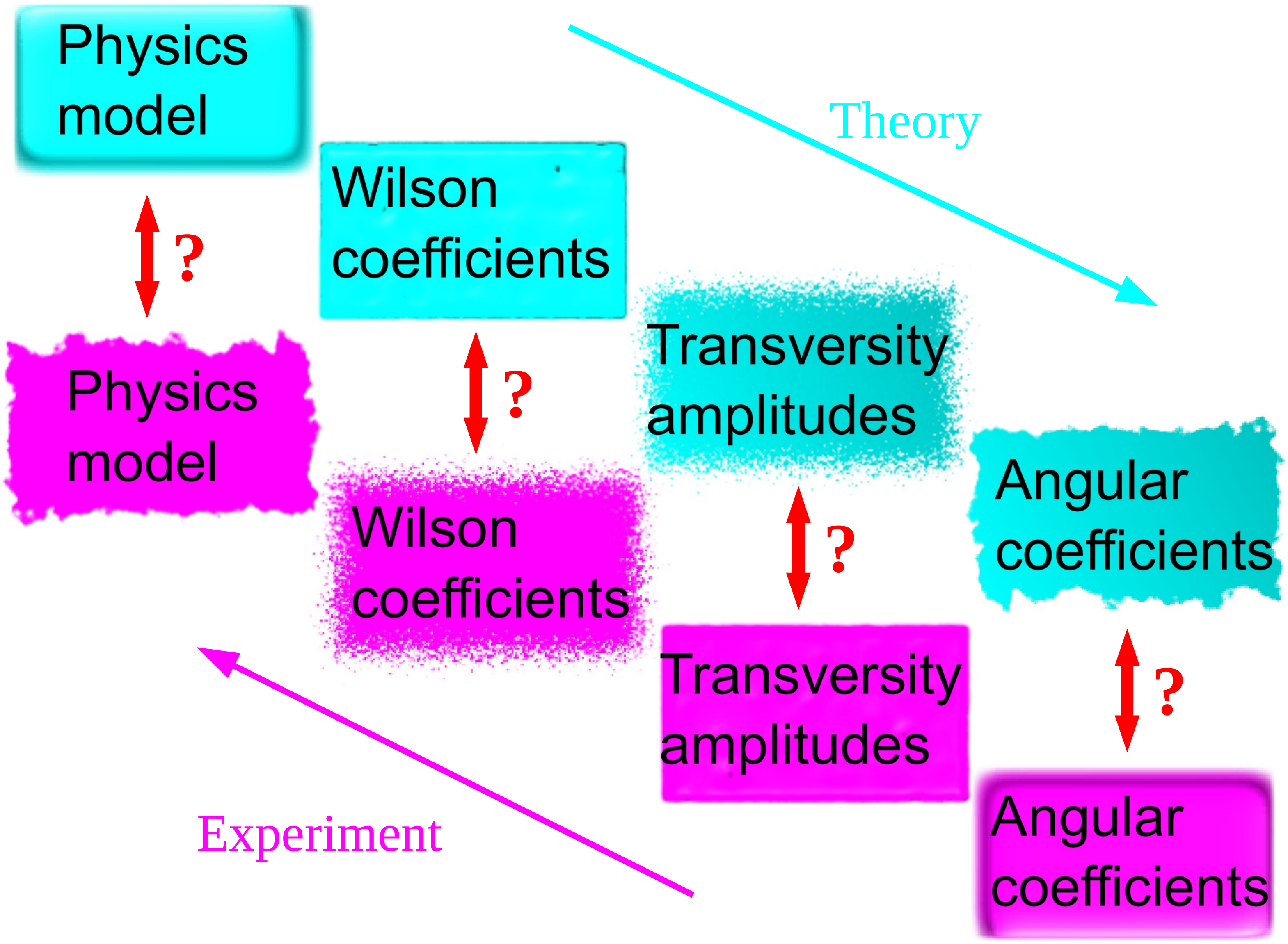


# From measurement to theory

Finally extracting a specific physics model loses model independence.

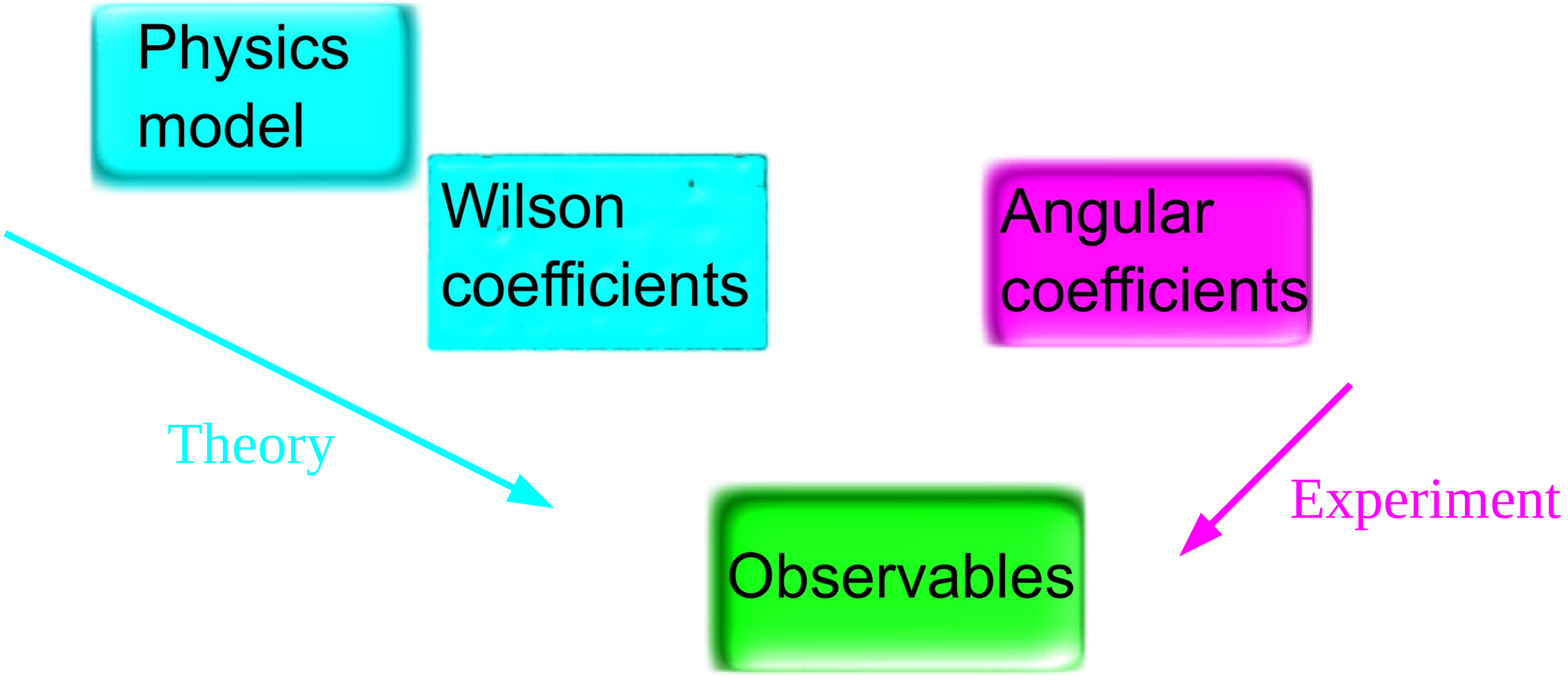


# How to compare?



# New observables

Create observables which are made with both theory and experiment in mind



# Constructing observables

New observables are constructed to satisfy multiple criteria

- Sensitivity to a given set of New Physics scenarios
- Form factors should cancel at leading order
- $\Lambda/m_b$ corrections under control
- Respect symmetries of decay
- Have good experimental statistical sensitivity
- Minimise systematics in experimental measurement

# Angular distribution

The full angular distribution is given as

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_l\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi} J(q^2, \theta_l, \theta_K, \phi)\,, \tag{2.1}$$

The dependence on the three angles can be made more explicit:

$$\begin{aligned} J(q^2, \theta_l, \theta_K, \phi) = \\ = J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K + (J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_l + J_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi \\ + J_4\sin 2\theta_K\sin 2\theta_l\cos\phi + J_5\sin 2\theta_K\sin\theta_l\cos\phi + (J_{6s}\sin^2\theta_K + J_{6c}\cos^2\theta_K)\cos\theta_l \\ + J_7\sin 2\theta_K\sin\theta_l\sin\phi + J_8\sin 2\theta_K\sin 2\theta_l\sin\phi + J_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\,. \end{aligned} \tag{2.2}$$

With 8 (out of the 12) $J_i$ independent in the limit of massless leptons.

# How to measure the observables

Table shows which projections are required for measuring each observable

$\Theta_K * \theta_l$ means simultaneous fit of two 1D projections

$\Theta_K\ \theta_l$ means fit to 2D projection

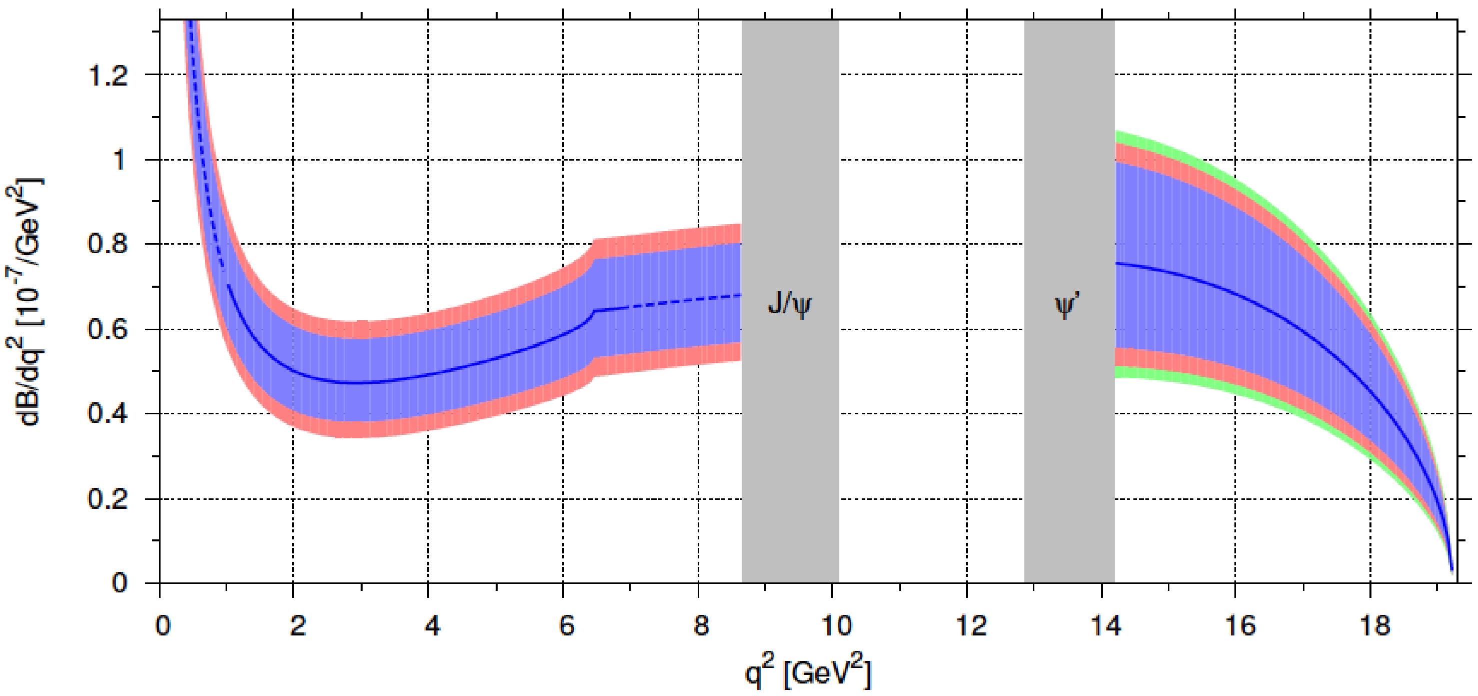
| | Easy | | | Hard | | | V. Hard | Easy | | | Hard | | | Hard |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $\theta_L$ | $\theta_K$ | $\varphi$ | $\theta_L\ \theta_K$ | $\theta_L\ \varphi$ | $\theta_K\ \varphi$ | $\theta_L\ \theta_K\ \varphi$ | $\theta_L *\theta_K$ | $\theta_L * \varphi$ | $\theta_K * \varphi$ | $\theta_L *\theta_K\ \varphi$ | $\theta_K *\theta_L\ \varphi$ | $\varphi*\theta_L\ \theta_K$ | $\varphi*\theta_L*\ \theta_K$ |
| $A_{FB}$ | green | red | red | green | green | red | green | green | green | red | green | green | green | green |
| $F_L$ | green | green | red | green | green | green | green | green | green | green | green | green | green | green |
| $A_{T1}$ | red | red | red | red | red | red | red | red | red | red | red | red | red | red |
| $A_{T2}$ | red | red | red | red | green | green | green | red | green | green | green | green | green | green |
| $A_{T3}$ | red | red | red | red | red | red | green | red | red | red | red | red | red | red |
| $A_{T4}$ | red | red | red | red | red | red | green | red | red | red | red | red | red | red |
| $A_{T5}$ | red | red | red | red | red | red | red | red | red | red | red | red | red | red |
| $H_{T1}$ | red | red | red | red | red | red | green | red | red | red | red | red | red | red |
| $H_{T2}$ | red | red | red | red | red | green | green | red | red | red | green | red | red | red |
| $H_{T3}$ | red | red | red | red | green | red | green | red | green | red | green | green | green | green |
| $J_1$ | green | green | red | green | green | green | green | green | green | green | green | green | green | green |
| $J_2$ | green | green | red | green | green | green | green | green | green | green | green | green | green | green |
| $J_3$ | red | red | green | red | green | green | green | red | green | green | green | green | green | green |
| $J_4$ | red | red | red | red | red | red | green | red | red | red | red | red | red | red |
| $J_5$ | red | red | red | red | red | green | green | red | red | red | green | red | red | red |
| $J_6$ | green | red | red | green | green | red | green | green | green | red | green | green | green | green |
| $J_7$ | red | red | red | red | red | green | green | red | red | red | green | red | red | red |
| $J_8$ | red | red | red | red | red | red | green | red | red | red | red | red | red | red |
| $J_9$ | red | red | green | red | green | green | green | red | green | green | green | green | green | green |

# The low recoil region

The statistics in the low recoil region are limited for two reasons

- The phase-space becomes small

JHEP 1007:098,2010

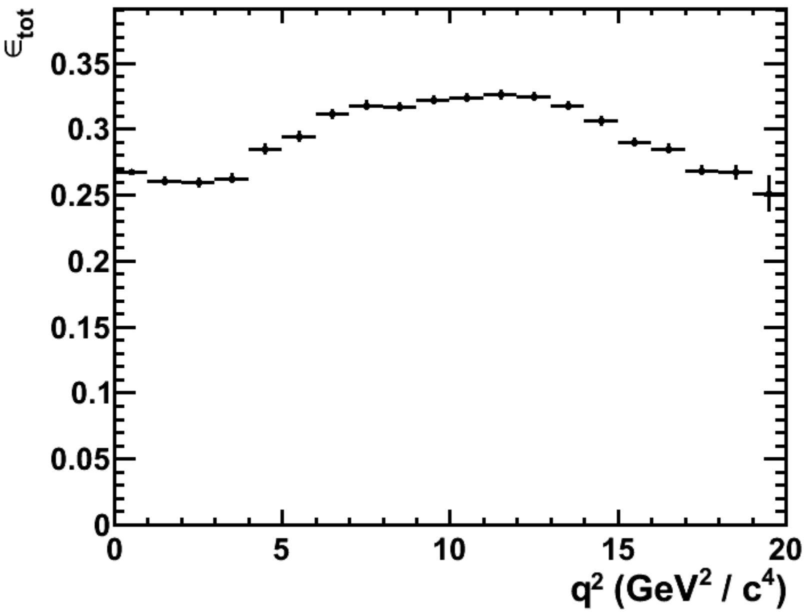


# The low recoil region

The statistics in the low recoil region are limited for two reasons

- The phase-space becomes small
- The efficiency starts to go down as endpoint is reached

LHCb modelled efficiency (%)



# The low recoil region

The "usual" observables will be measured in the low recoil region

- The differential branching fraction as function of q
- $A_{FB}$ and $F_L$ from $\theta_K$ and $\theta_l$ projections

High $q^2$ observables from JHEP 1007:098,2010

$$H_T^{(1)} = \frac{\sqrt{2} I_4}{\sqrt{-I_2^c \left(2 I_2^s - I_3\right)}} = 1$$

$$H_T^{(2)} = \frac{I_5}{\sqrt{-2 I_2^c \left(2 I_2^s + I_3\right)}} = 2\,\frac{\rho_2}{\rho_1}, \qquad H_T^{(3)} = \frac{I_6}{2\sqrt{(2 I_2^s)^2 - I_3^2}} = 2\,\frac{\rho_2}{\rho_1}$$

# The low recoil region

The "usual" observables will be measured in the low recoil region

- The differential branching fraction as function of q
- $A_{FB}$ and $F_L$ from $\theta_K$ and $\theta_l$ projections

Will Reece have made some preliminary estimates of precision in $q^2$>14 $GeV^2$ region

| Observable | $2\,fb^{-1}$ | $1\,fb^{-1}$ | $0.5\,fb^{-1}$ | LHC*b* $2\,fb^{-1}$ | Ref. |
|---|---|---|---|---|---|
| My (unofficial) high-$q^2$ estimates: | | | | Offical low-$q^2$ | |
| $A_{FB}$: | ±0.01 | | | ±0.02 | |
| $F_L$: | ±0.01 | | | ±0.016 | |
| $A_T^{(2)}$: | ±0.2 | | | ±0.42 | |
| $H_T^{(3)}$: | ±0.1 | | | | |
| Based on CERN-LHCB-2007-057 | | | | | |

# Binning

The default choice of LHCb is to use the same $q^2$ binning at Belle

- <2.00, 2.00-4.30, 4.30-8.68, 10.09-12.86, 14.18-16.00, >16.00

and in addition the overlapping bin

- 1.00 – 6.00 $GeV^2$

Is this a reasonable choice?

- Some places seems to have the low-recoil limit at 15 $GeV^2$

# Fitting

When moving to a fit in all kinematic variables, some choices have to be made.

Fit for 8 independent spin amplitudes

- Concept proven, see JHEP 0811 (2008) 032, JHEP 1010 (2010) 056
- Bins in $q^2$ doesn't work, require a parametrised dependence of amplitudes with $q^2$
- Result is always physical as all values of amplitudes allowed

Fit for 8 independent angular $J_i$ coefficients

- Allows for binned or parametrised $q^2$ fit
- Approach failed when tried a few years ago!
  - Tricky to make sure probability density function stays positive during fit

# Fitting

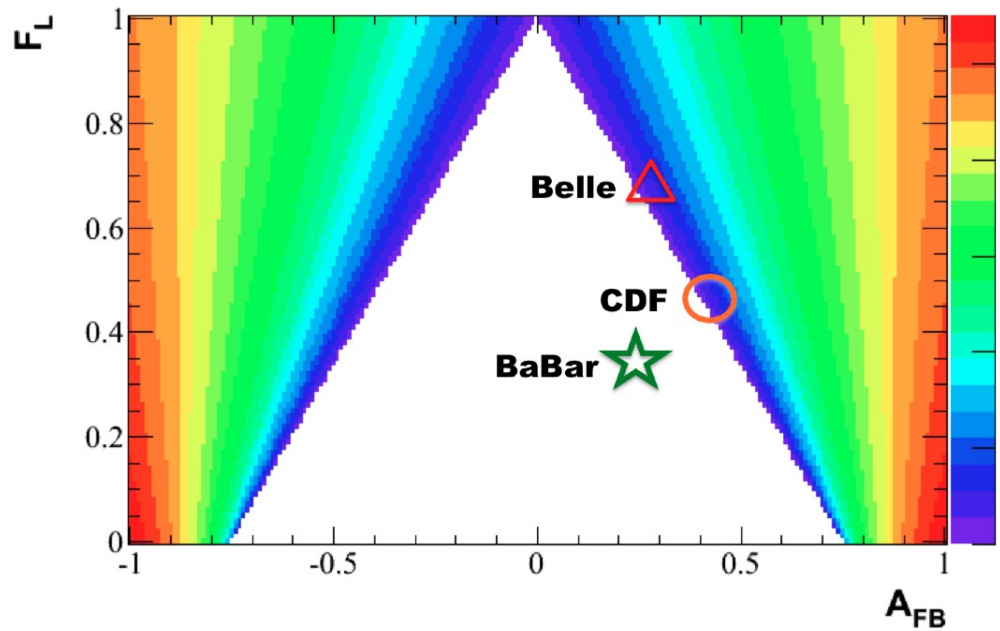
T. Blake

Obtaining un-physical results in fit for $A_{FB}$ and $F_L$

$$\frac{1}{\Gamma}\frac{d^3\Gamma}{d\cos\theta_\ell \, d\cos\theta_K \, dq^2} = \frac{9}{16}\Bigg[\frac{3}{4}(1-F_L)(1-\cos^2\theta_K) + F_L\cos^2\theta_K$$
$$(2\cos^2\theta_\ell - 1)\left(\frac{1}{4}(1-F_L)(1-\cos^2\theta_K) - F_L\cos^2\theta_K\right)$$
$$\frac{4}{3}A_{FB}(1-\cos^2\theta_K)\cos\theta_\ell\Bigg]$$

Coloured region is where value results in negative PDF.

Central value for CDF and BELLE are not possible!



# Fitting

Both fit for amplitudes and fit for coefficients contain in principle the same amount of information

- Observables are in both cases highly non-linear functions of fit variables.
- Simply giving central values and (linear) correlation matrix could give misleading results.

# Conclusion

The $B^0 \to K^{*0}\mu^+\mu^-$ decay is on the brink of moving into precision physics

Over the next few years increasingly complex analyses will be performed

I did not (explicitly) discuss isopin asymmetries, higher K resonances, $B \to \pi/\rho\ \mu\mu$, $B_s$ or $\Lambda_b$ decays which all have prospects for updated and new results

Interpretation of results will require careful collaboration between experimentalists and theorists