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Rare decays at LHCb

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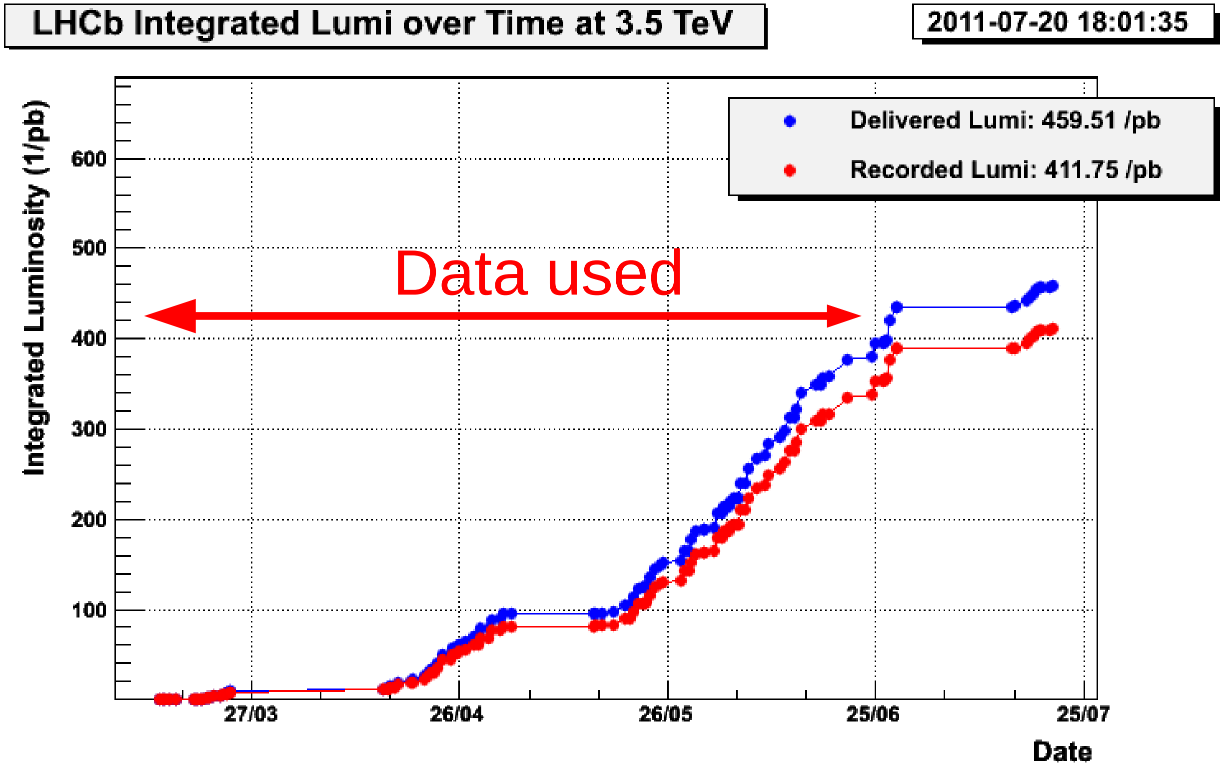
Angular analysis of $B^0 \rightarrow K^{*0}\mu^+\mu^-$
Search for $B \rightarrow \mu^+\mu^-$
Search for lepton number violation in $B^+ \rightarrow h^-\mu^+\mu^+$

PANIC, July 2011, MIT

LHCb as a probe for Rare Decays

Results presented here are for data collected in about 300 pb^{-1} of integrated luminosity

- Collected in just 3 months of 2011
- Already the best results in the world



What do we mean by Rare Decays?

- Flavour Changing Neutral Current decays that are only allowed in the SM at loop level
  - SM and New Physics on equal footing opening up possibility for large NP effects

- Exclusive decays are a good probe for New Physics
  - High sensitivity, i.e. large changes to observables may occur
  - Few constraints from other measurements, so probes new “regions” of physics
  - Theoretical uncertainties are small
  - Systematics are not an issue for a long time.

An effective theory for New Physics

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{gauge}}(A_i, \Psi_j; \mathbf{Y}, \mathbf{C}) + \mathscr{L}_{\text{Higgs}}(A_i, \Psi_j, \phi; \langle\phi\rangle) +$$

$$\sum_{d>4} \frac{c^n}{\Lambda^{d-4}} O_n^d$$

O_d^n: All possible operators with heavy d.o.f

c^n: Parameters arising from New Physics

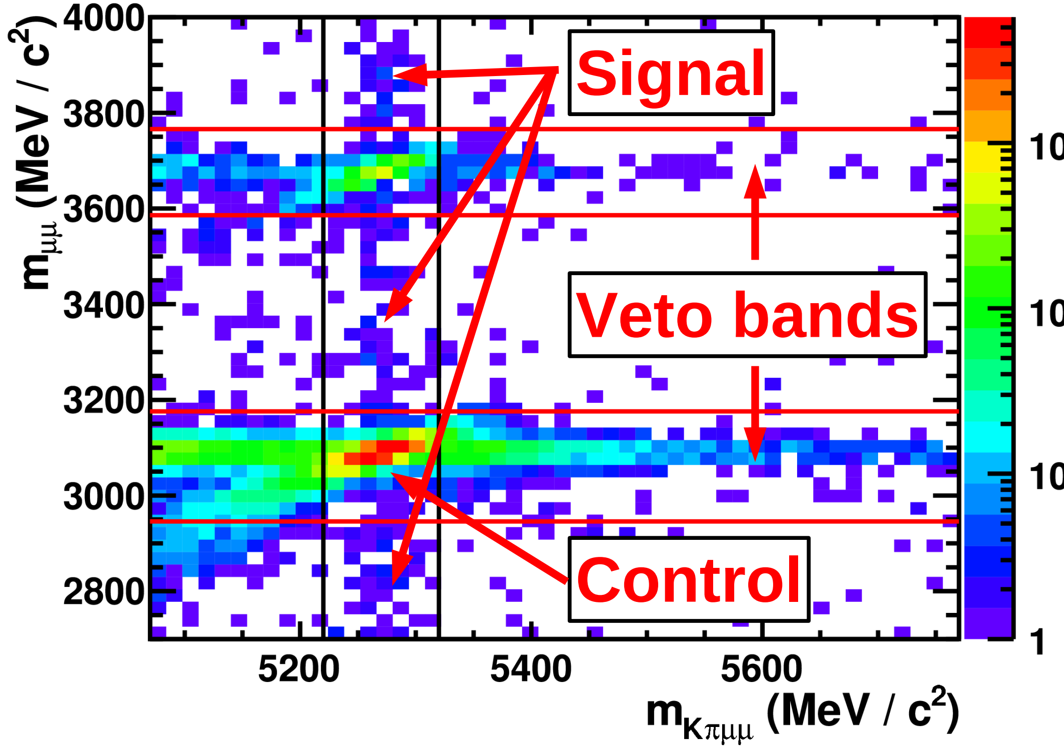
Λ: Energy scale of New Physics

$B^0 \to K^{*0}\mu^+\mu^-$ sensitive to C^7, C^9 and C^{10} and in particular the right handed counterparts

$B \to \mu^+\mu^-$ sensitive to scalar operators, e.g SUSY Higgs sector

Analysis strategy for $B^0 \to K^{*0}\mu^+\mu^-$

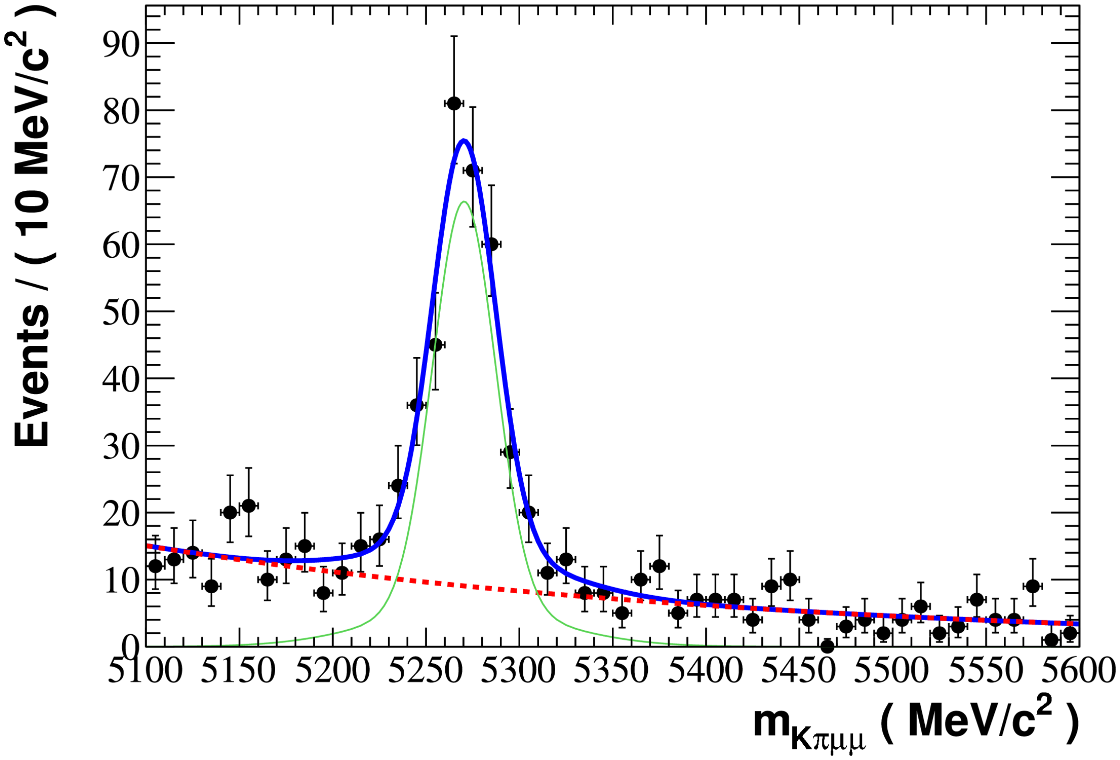
- Select events with boosted decision tree
  - Trained on $B^0 \to J/\psi K^{*0}$ control channel and signal side-band from 2010 data
- Correct for efficiency
  - Use event-by-event correction
- Verify analysis
  - Use known $B^0 \to J/\psi K^{*0}$ angular distribution
- Fit for observables
  - Perform simultaneous fit to mass and angular distribution



The signal from 309 pb^{-1}

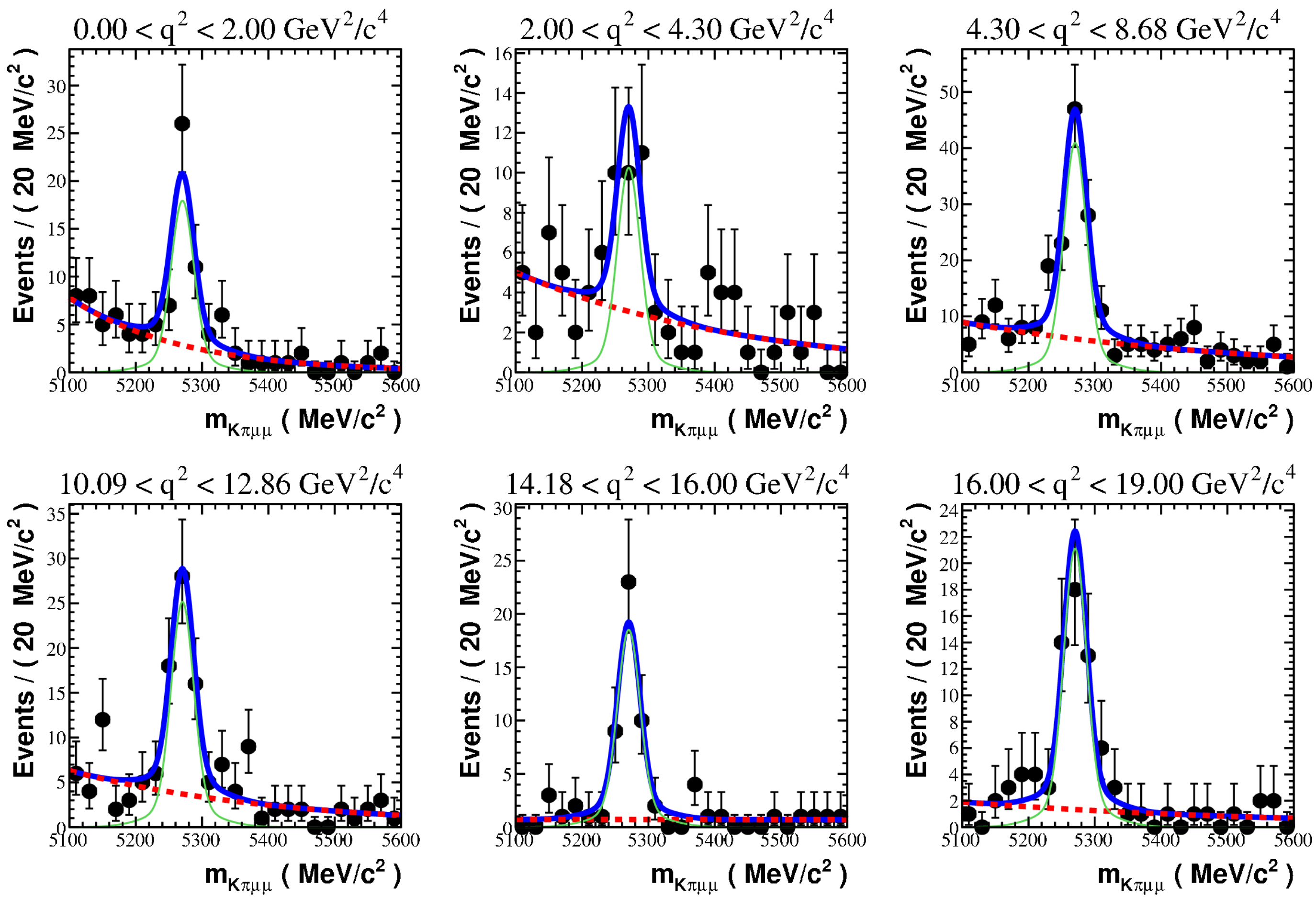
After J/ψ and ψ(2S) vetoes, we see 302±20 signal events

$B^0 \to K^{*0}\mu^+\mu^-$ signal is very clean!



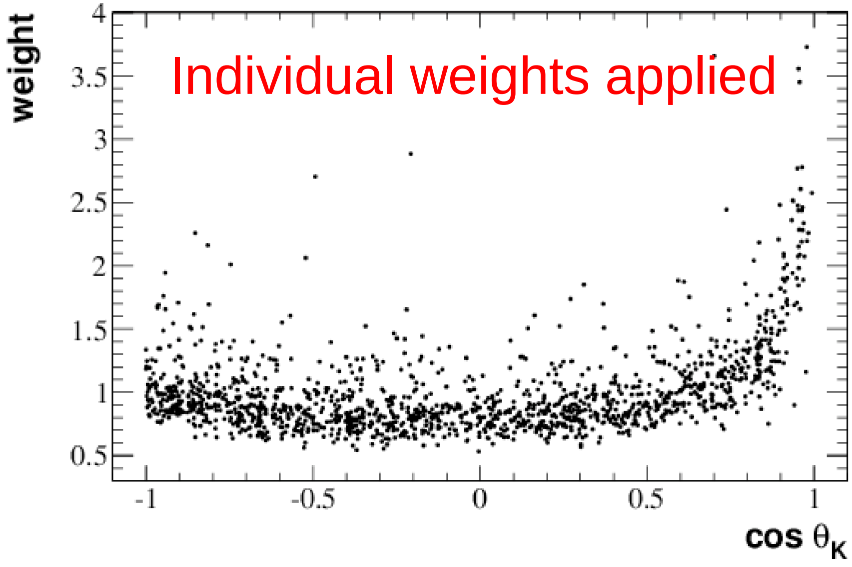
Regions of squared di-muon mass, q^2

In each of the bins we have signal significance of 5 or higher



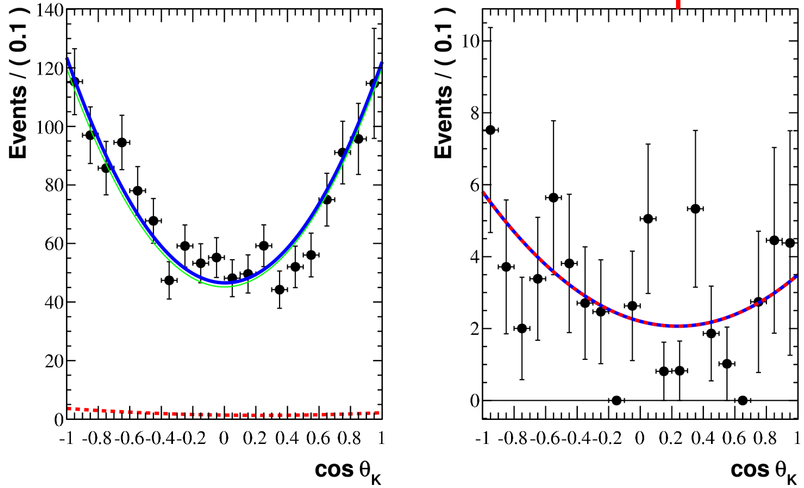
Efficiency correction

- Events are individually efficiency corrected based on their kinematics in the B rest frame
  - Simulation calibrated with data driven input on PID and detector resolution



- Method cross checked by fitting $B^0 \to J/\psi K^{*0}$
  - When including S-wave, result is in very good agreement with BaBar analysis

Cross check on B0→J/ψK*0



Fit for observables

An unbinned likelihood fit with event-by-event weights is performed for each q^2 bin

Simultaneous fit to mass, θ_K and θ_l projections

Signal

- Crystal Ball in mass

$$\frac{1}{\Gamma}\frac{\mathrm{d}^2\Gamma}{\mathrm{d}\cos\theta_K\,\mathrm{d}q^2} = \frac{3}{2}F_L\cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K)$$

$$\frac{1}{\Gamma}\frac{\mathrm{d}^2\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}q^2} = \frac{3}{4}F_L(1-\cos^2\theta_\ell) + \frac{3}{8}(1-F_L)(1+\cos^2\theta_\ell) + A_{FB}\cos\theta_\ell$$

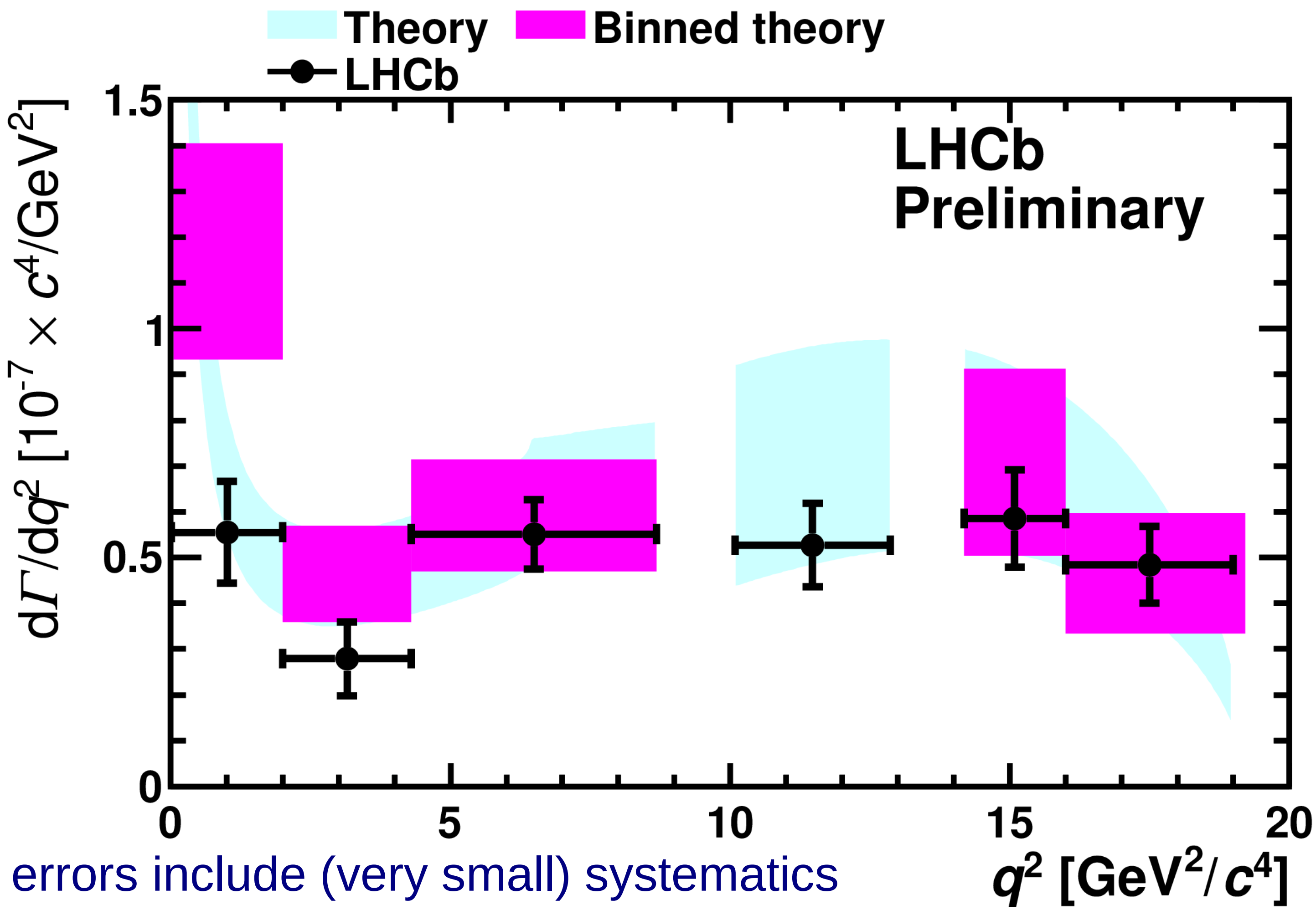
Background

- Exponential in mass
- Polynomial in angles

Systematic evaluations

- Issues related to efficiency correction
  - Variation in PID and detector resolution corrections
  - Trigger modelling
  - Uncertainty in B momentum spectra
  - Track reconstruction efficiency
- Fitting
  - Signal shape uncertainty
  - Background shape uncertainty
- The largest systematics are all dominated by statistics of data or simulation
  - Same analysis strategy can be used for much larger sample
  - Total error is never more than 10% larger than statistics only error

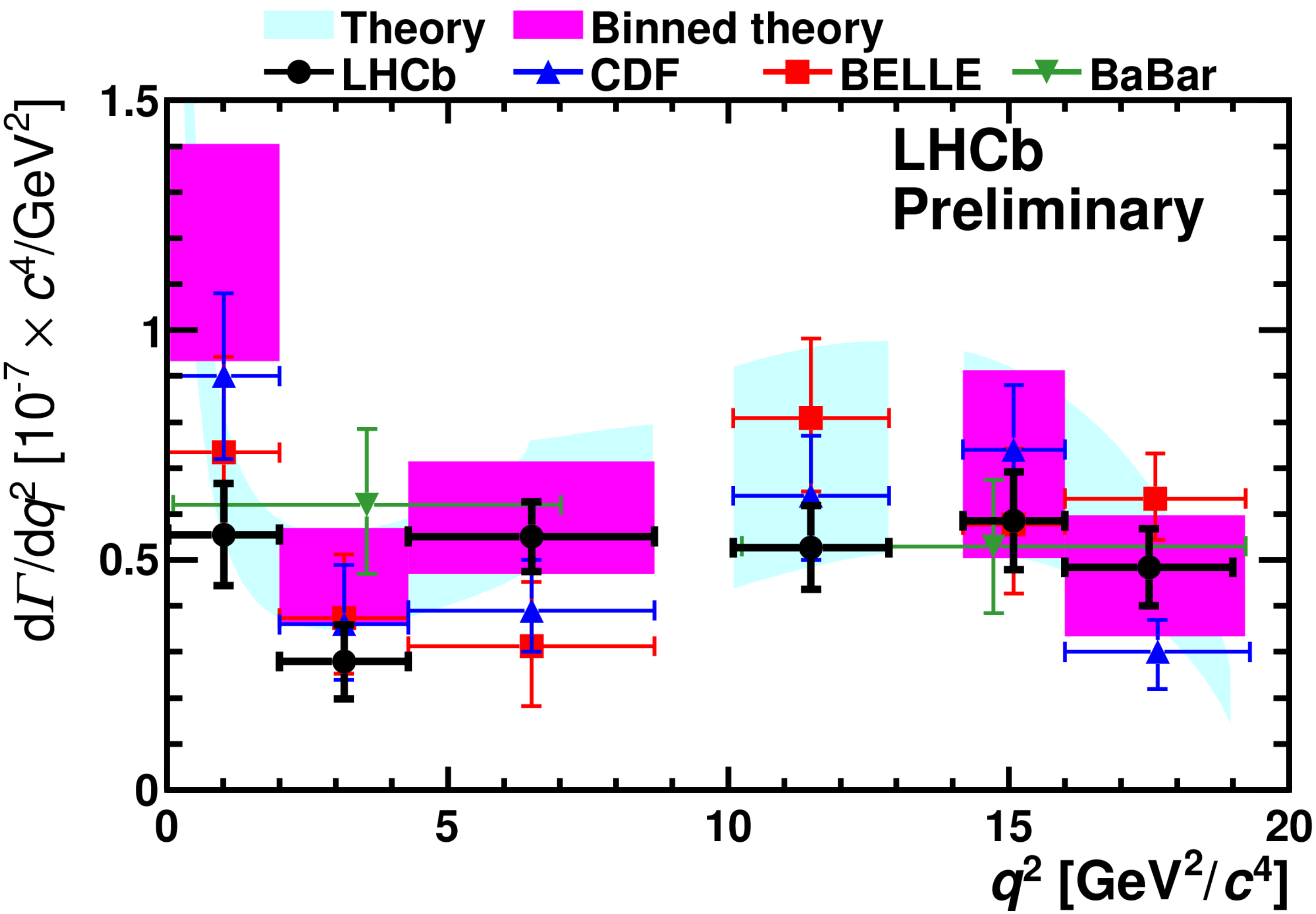
Differential decay rate



LHCb errors include (very small) systematics

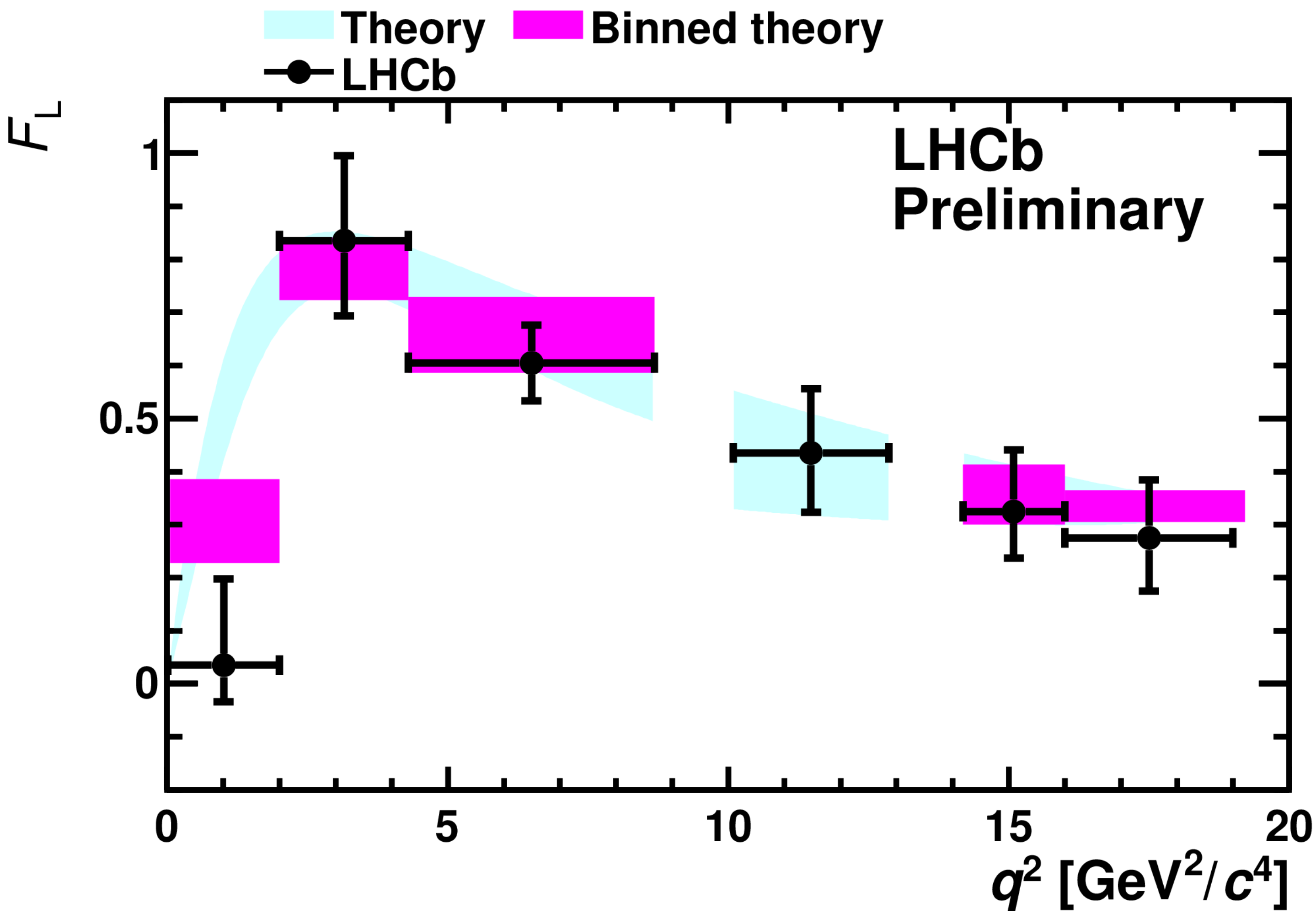
SM theory from Bobeth, Hiller, van Dyk. JHEP 1007, 098 (2010) and arXiv:1105.0376

Differential decay rate



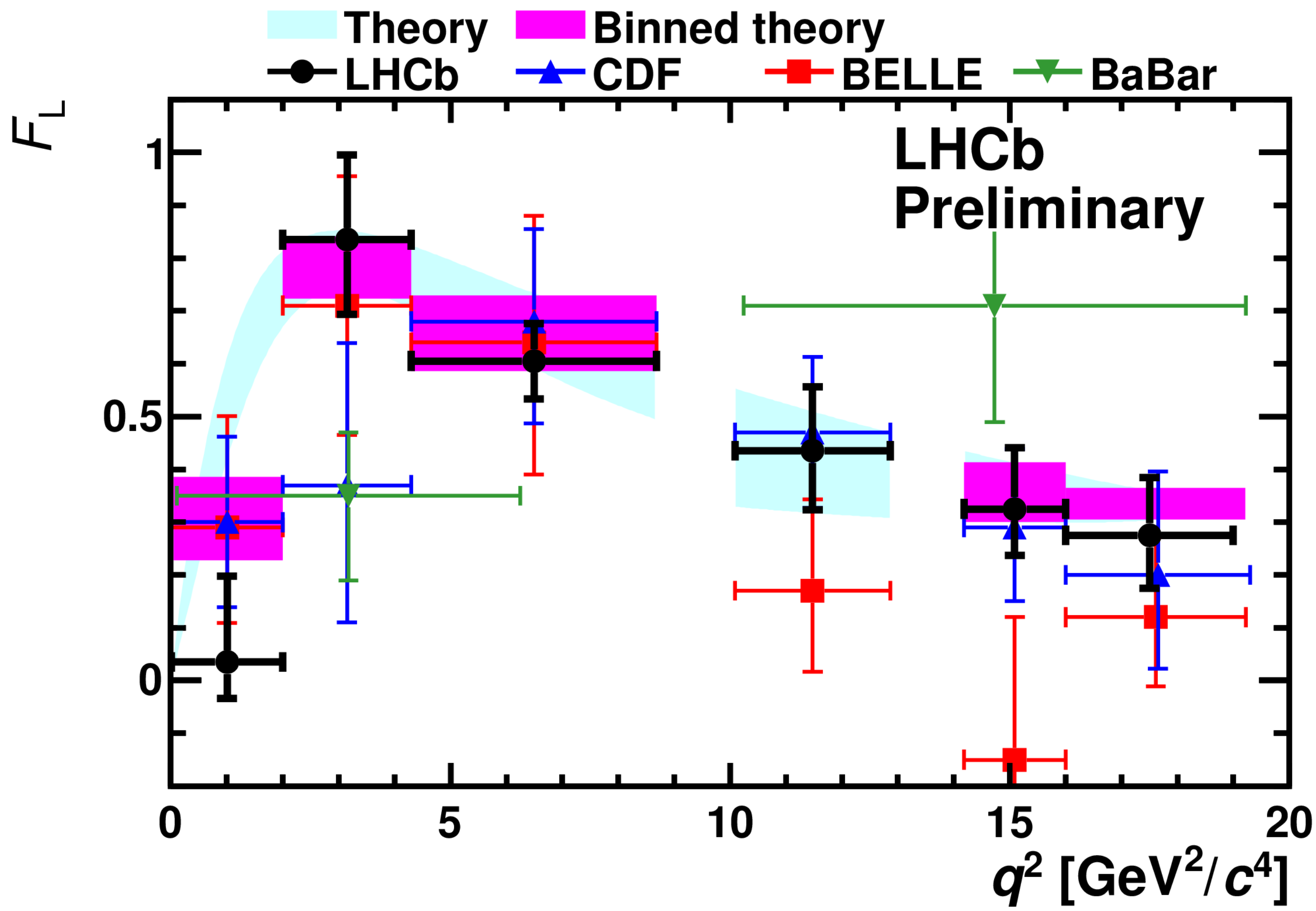
CDF: Result presented at EPS
BELLE: PRL103:171801,2009
BaBar: PRD73:092001,2006

K^{*0} longitudinal polarisation, F_L

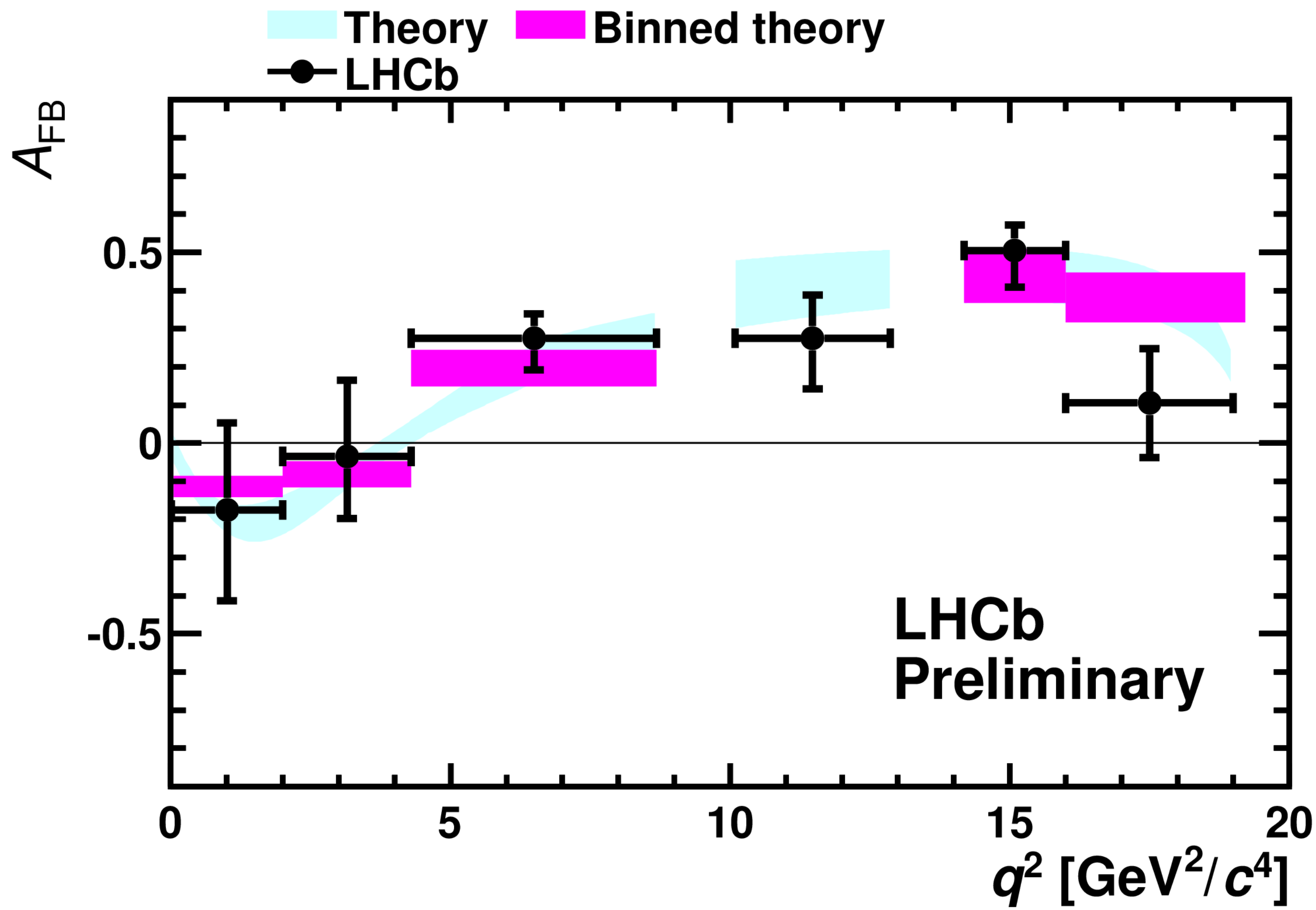


Errors from Bayesian approach with flat prior for physical region of F_L,A_{FB} plane. Systematics included.

K^{*0} longitudinal polarisation, F_L

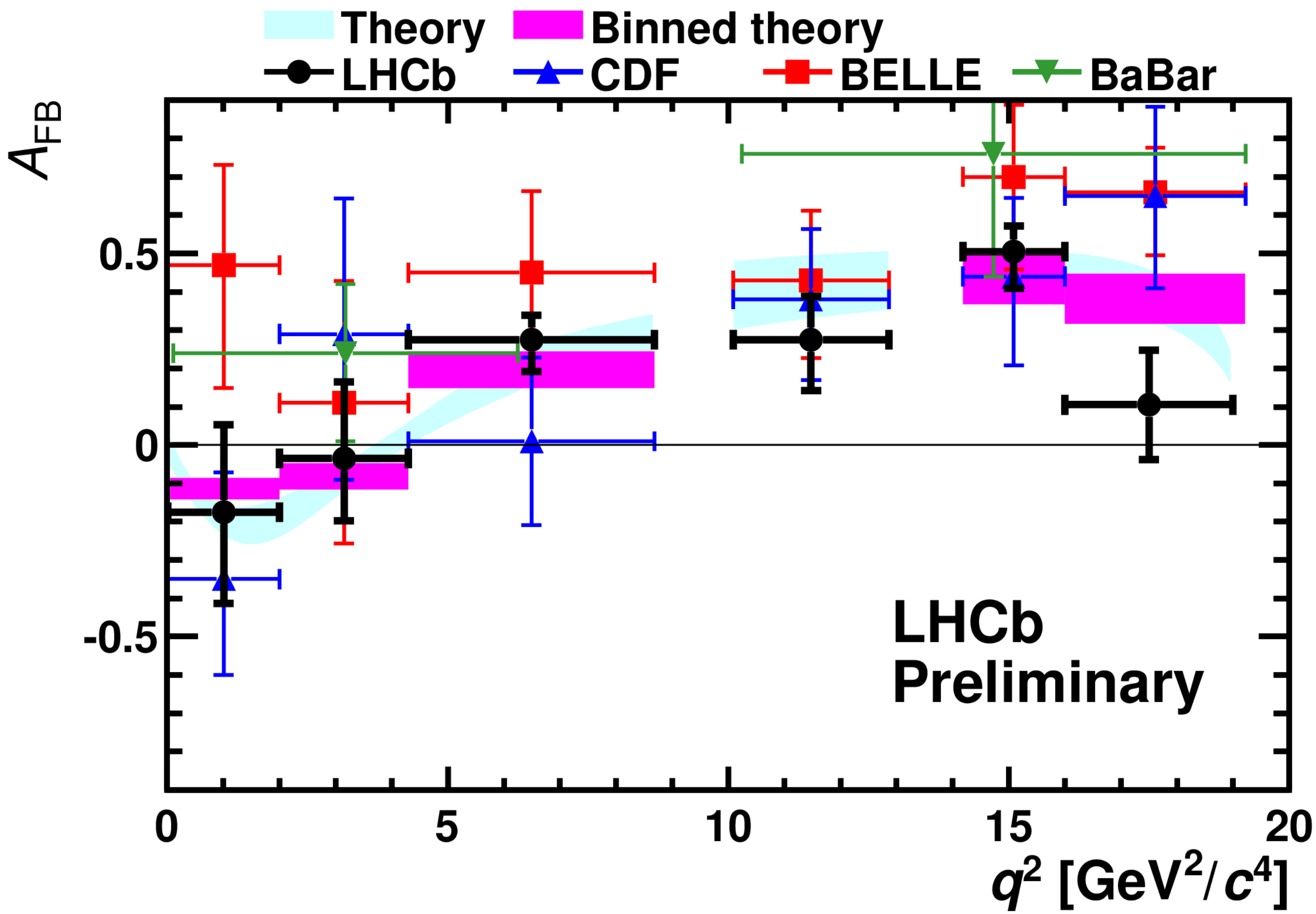


Forward-backward asymmetry A_{FB}



Tabulated results, including $1<q^2<6$ GeV^2/c^4 results available in backup slides

Forward-backward asymmetry A_{FB}



Analysis strategy for $B \to \mu^+\mu^-$ search

Use highly efficient muon trigger

Perform loose selection based on di-muon secondary vertex

Train boosted decision tree to separate signal from background with real muons

Calibrate BDT from control channels

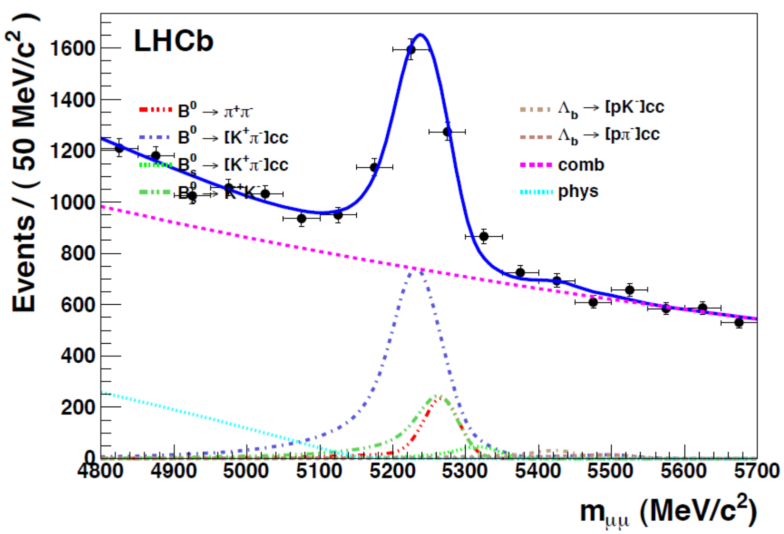
Normalise event yield from control channels

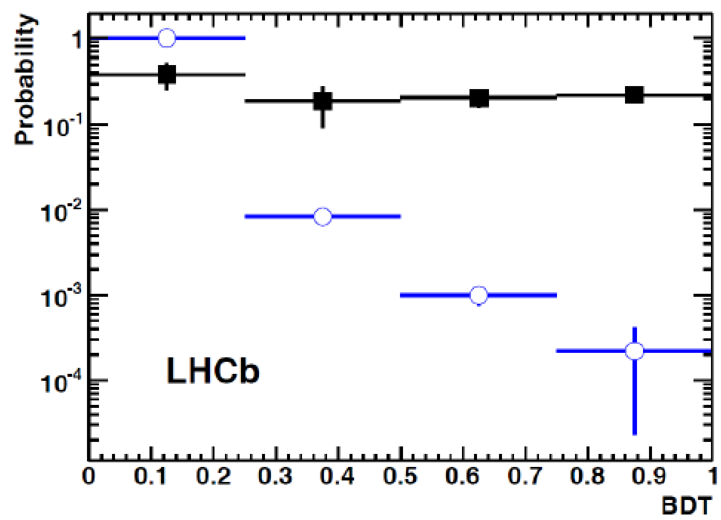
Count events in BDT and invariant mass bins and extract limit

Calibration

BDT calibrated from sidebands (background) and $B \to h^+h^-$ (signal)

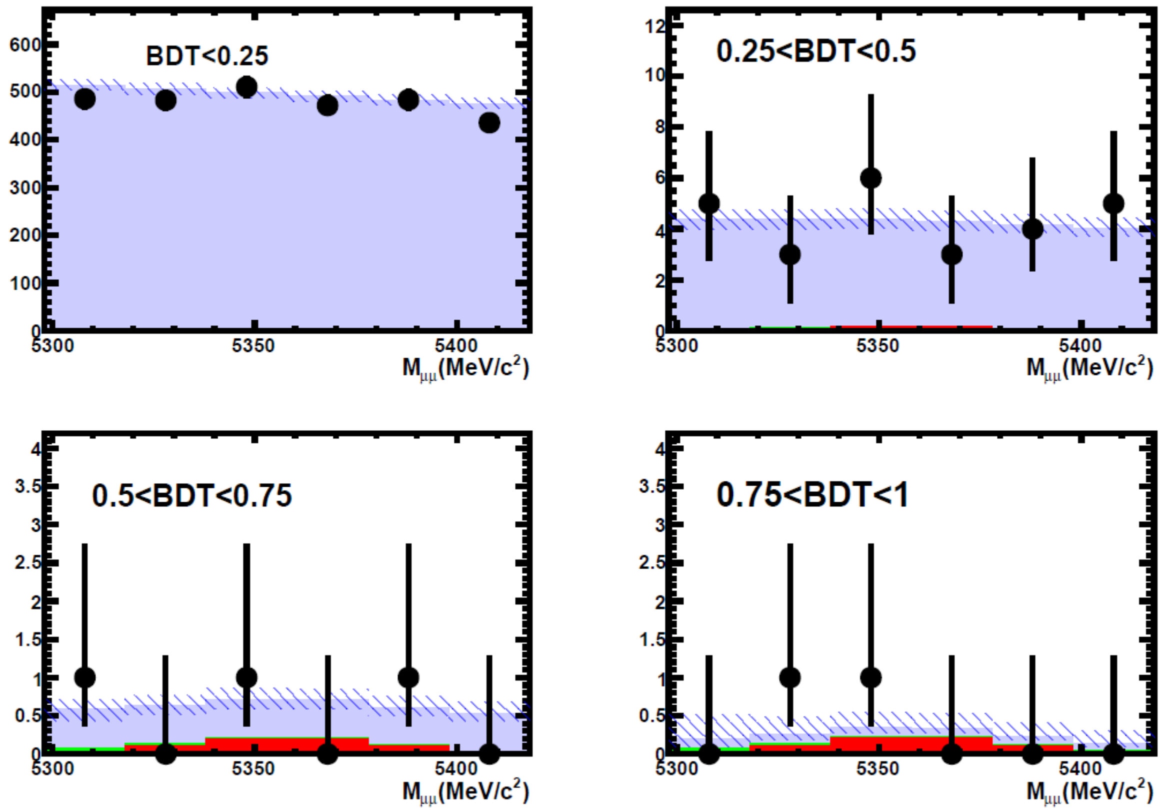
- Use $B \to h^+h^-$ candidates that did not contribute to trigger decision to avoid trigger bias





Invariant mass resolution calibrated from interpolation between ψ and Υ resonances

Signal region in bins of BDT response



Combinatorial bkg

Misid bkg

Signal SM

Data

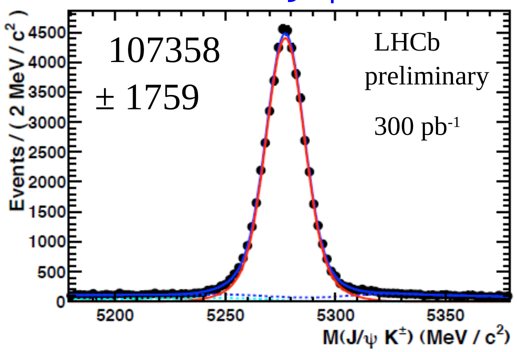
No signal is observed !

	BDT<0.25	0.25<BDT<0.5	0.5<BDT<0.75	0.75<BDT
Exp.combinatorial	2968 ± 69	25 ± 2.5	2.99 ± 0.89	0.66 ± 0.40
Exp. SM signal	1.26 ± 0.13	0.61 ± 0.06	0.67 ± 0.07	0.72 ± 0.07
observed	2872	26	3	2

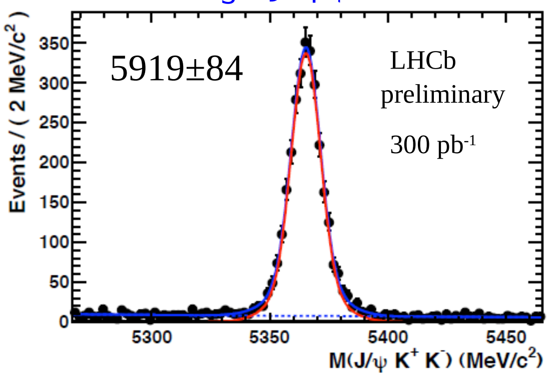
Normalisation

The event rate is normalised to 3 channels

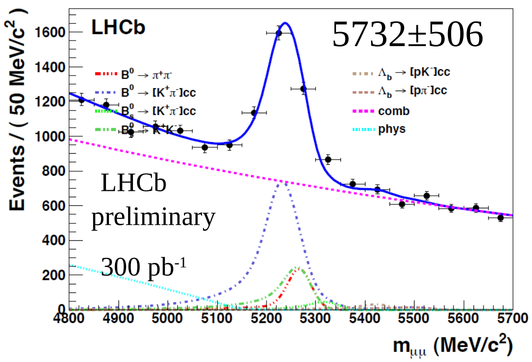
$B^+ \to J/\psi K^+$



$B_s \to J/\psi\phi$



$B^0 \to \pi^- K^+$

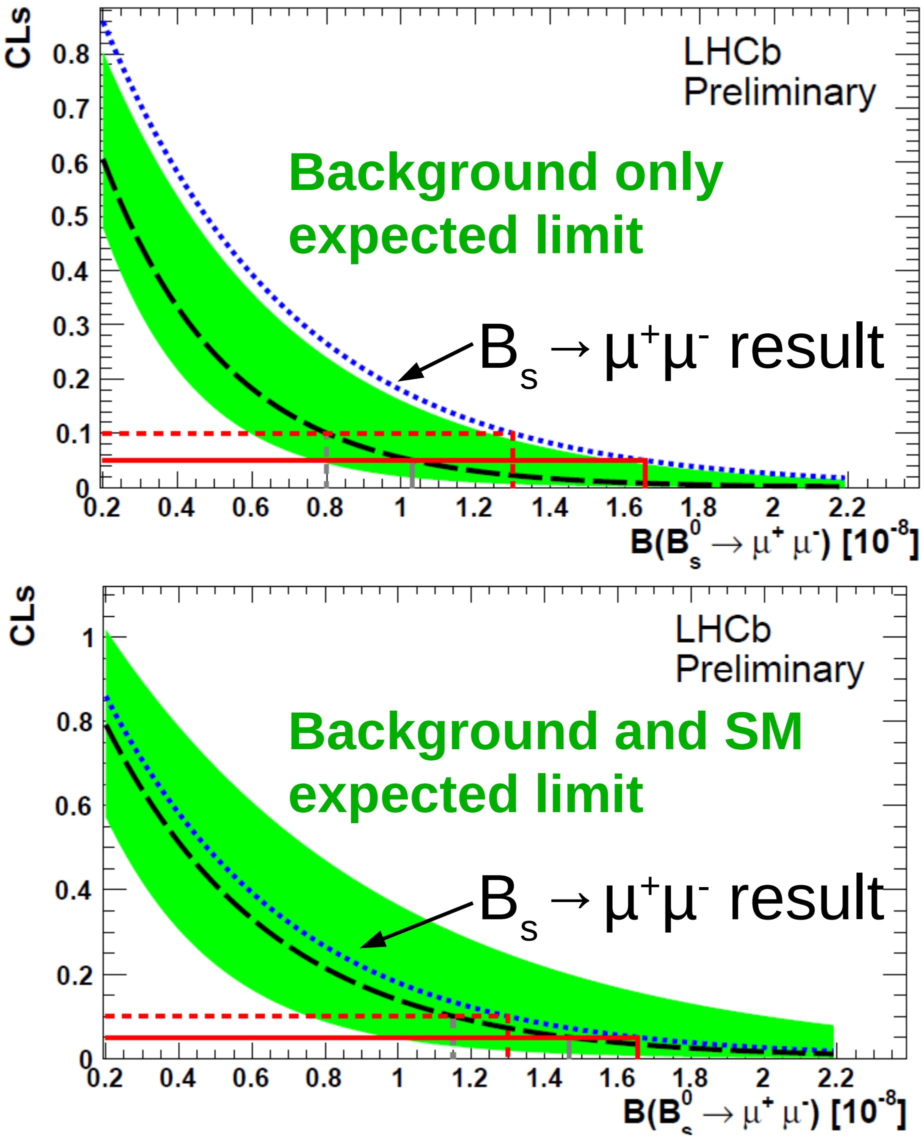


For all need to correct for difference in selection and trigger efficiency

For $B^+ \to J/\psi K^+$ and $B^0 \to \pi^- K^+$ need to correct for production fractions

Use new LHCb average for this: $f_s / f_d = 0.267^{+0.021}_{-0.020}$

Extracted limit for $B \to \mu^+\mu^-$



The limit is extracted using a modified frequentist approach (CL_s method)

Systematics folded into limit using toy MC approach

Limits @ 90% CL in full agreement with expectation

$BF(B^0_s \to \mu^+\mu^-) < 1.30\ 10^{-8}$

$BF(B^0 \to \mu^+\mu^-) < 0.43\ 10^{-8}$

SM prediction

$BF(B^0_s \to \mu^+\mu^-) = 3.2 \pm 0.2\ 10^{-9}$

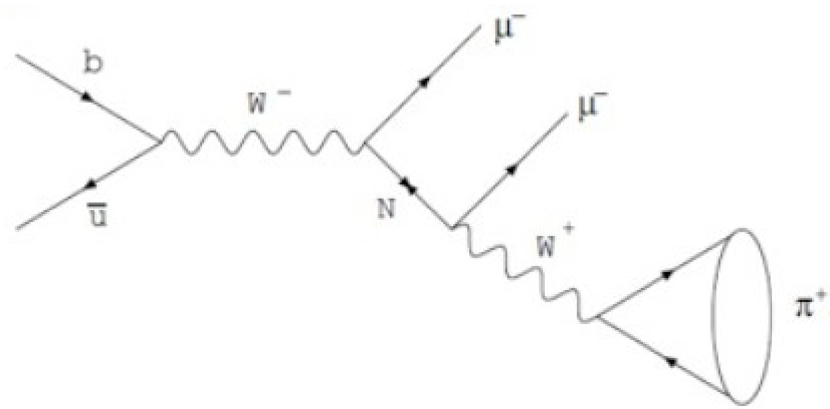
$BF(B^0 \to \mu^+\mu^-) = 1.1 \pm 0.1\ 10^{-10}$

A.J.Buras: arXiv:1012.1447

Lepton number violation

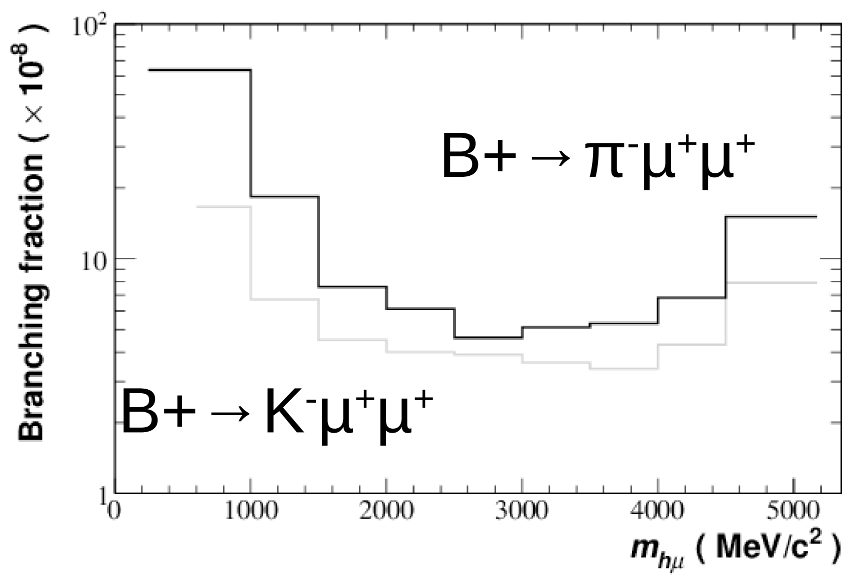
A search has been conducted for the lepton number violating decays $B^+ \to K^- \mu^+ \mu^+$ and $B^+ \to \pi^- \mu^+ \mu^+$

These decays possible if there is a GeV range Majorana neutrino



Search conducted in 2010 data (36 pb^{-1})

- Nothing found and limits set at 90% CL
- $BF(B^+ \to K^- \mu^+ \mu^+) < 4.1\ 10^{-8}$
- $BF(B^+ \to \pi^- \mu^+ \mu^+) < 4.4\ 10^{-8}$



Conclusion

Results presented for Rare FCNC decays

- Just 3 months of data makes LHCb world competitive

$B^0 \to K^{*0}\mu^+\mu^-$

- Angular analysis performed to measure width, F_L and A_{FB} in q^2 bins
- First hint of (SM predicted) zero crossing in A_{FB} seen

$B \to \mu^+\mu^-$

- No excess observed for neither $B^0_s \to \mu^+\mu^-$ nor $B^0 \to \mu^+\mu^-$
  - $BF(B^0_s \to \mu^+\mu^-) < 1.30\ 10^{-8}$ @ 90% CL
  - $BF(B^0 \to \mu^+\mu^-) < 0.43\ 10^{-8}$ @ 90% CL

$B^+ \to h^-\mu^+\mu^+$ with just 2010 data (36 pb^{-1})

- Set limit at $BF(B^+ \to K^-(\pi^-)\mu^+\mu^+) < 4.1\ (4.4)\ 10^{-8}$

Tabulated $B^0 \to K^{*0}\mu^+\mu^-$ results

Yield and signal significance in q^2 bins

Significance obtained from difference in log likelihood between a signal+background and a background only hypothesis. Position of peak and width fixed from $B^0 \to J/\psi K^{*0}$

q^2 (GeV^2)	n_{sig}	n_{bkg}	significance (σ)
$0 < q^2 < 2$	40.9 ± 7.5	14.4 ± 8.5	7.7
$2 < q^2 < 4.3$	23.3 ± 6.2	15.3 ± 8.6	4.9
$4.3 < q^2 < 8.68$	93.3 ± 11.3	30.0 ± 12.5	11.7
$10.09 < q^2 < 12.9$	57.3 ± 8.8	18.6 ± 9.7	9.3
$14.18 < q^2 < 16$	42.2 ± 6.8	3.6 ± 4.7	10.1
$16 < q^2 < 19$	48.1 ± 7.8	6.7 ± 6.4	9.2
$1 < q^2 < 6\,\mathrm{GeV}^2$	70.0 ± 10.2	$32. \pm 3.2$	9.4
Full	302.3 ± 20.1	91.0 ± 5.4	–

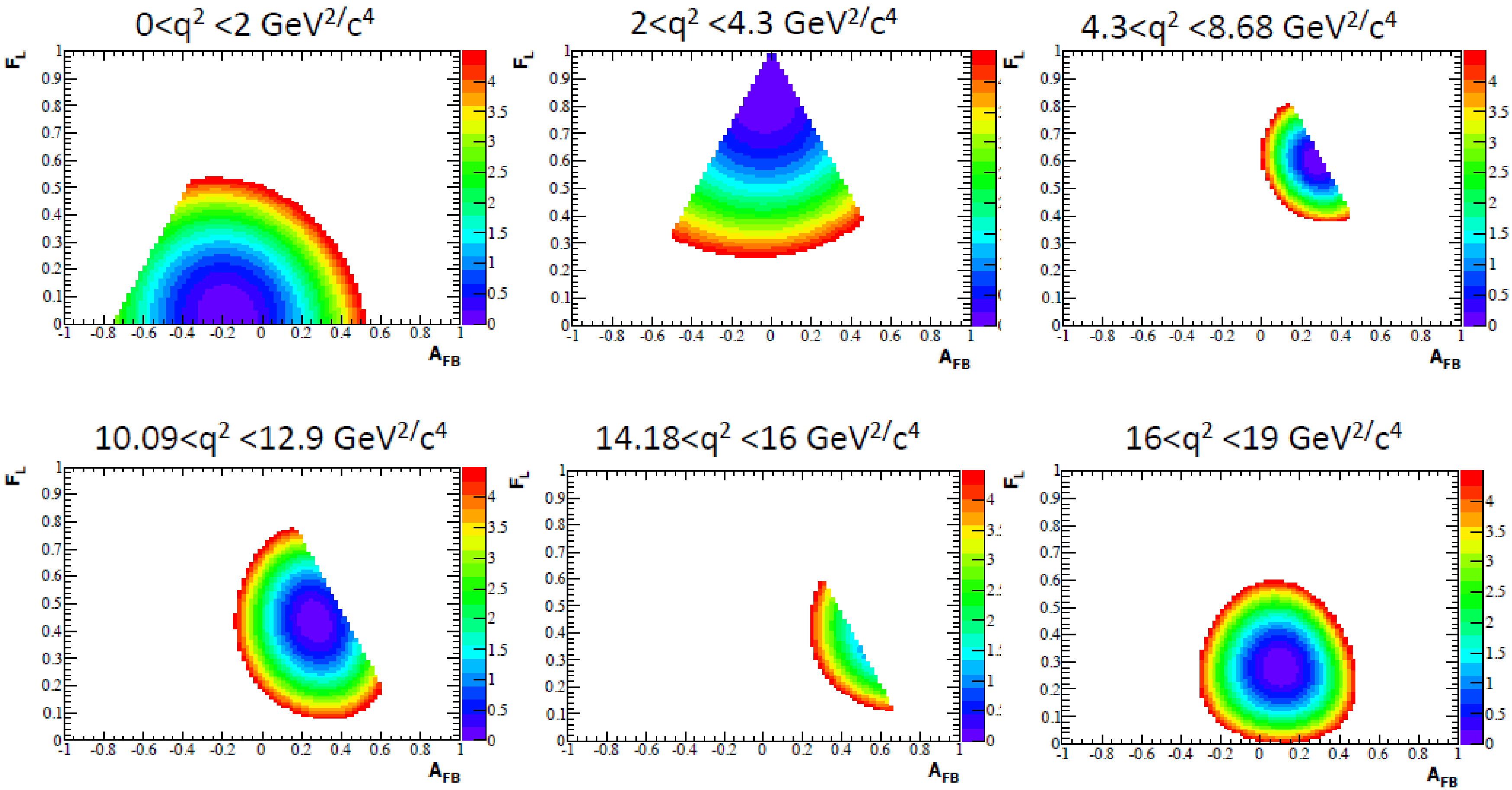
Tabulated $B^0 \rightarrow K^{*0}\mu^+\mu^-$ results

Results for A_{FB}, F_L and differential width in q^2 bins

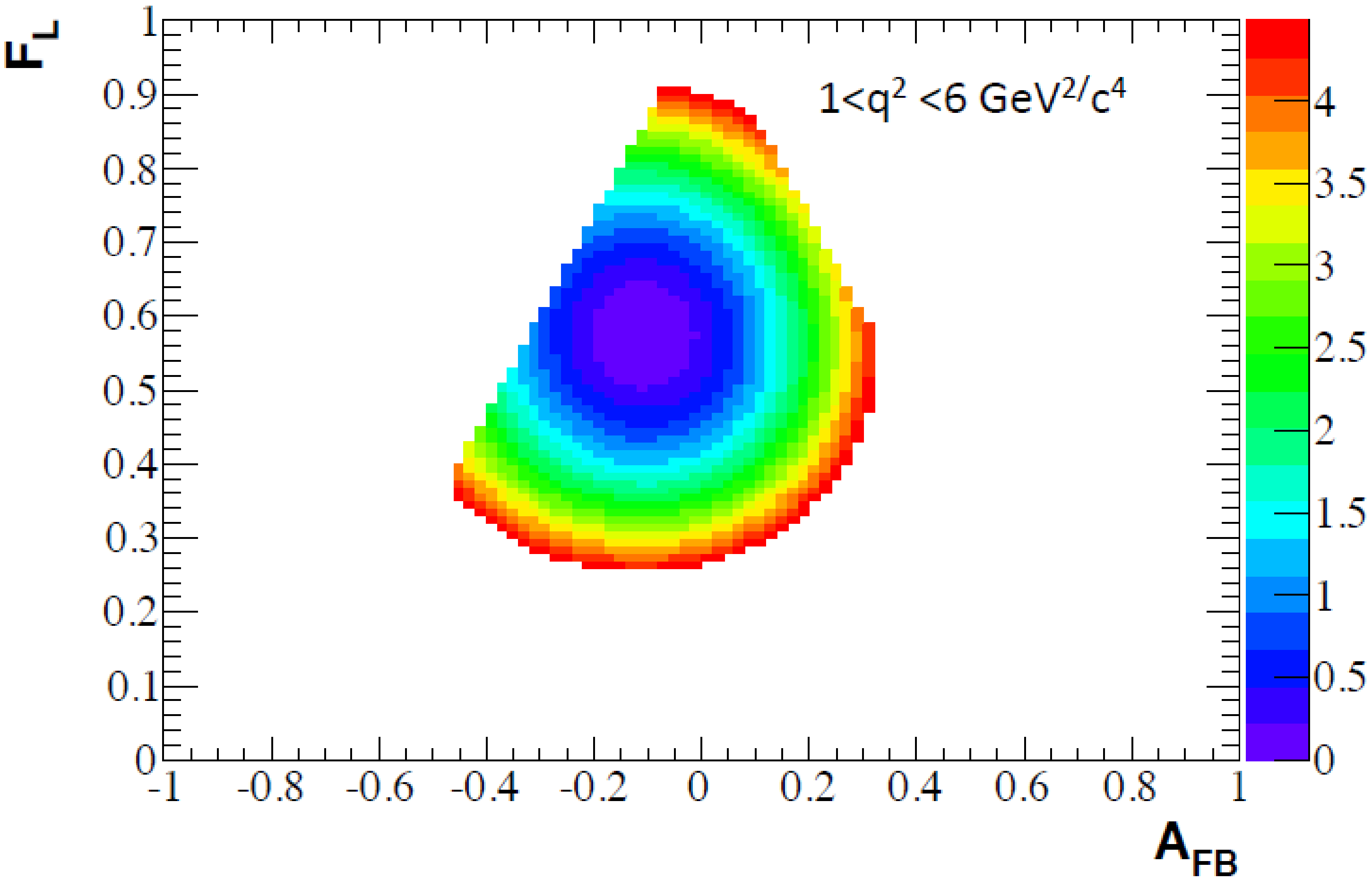
The width is the average width in the bin in units of 10^{-7} GeV/c^4

$q^2(\mathrm{GeV}^2)$	A_{FB}	F_L	$\mathrm{d}\Gamma/\mathrm{d}q^2$
$0 < q^2 < 2$	$-0.17^{+0.22}_{-0.23} \pm 0.06$	$0.03^{+0.15}_{-0.03} \pm 0.06$	$0.56 \pm 0.11 \pm 0.03$
$2 < q^2 < 4.3$	$-0.04^{+0.19}_{-0.15} \pm 0.06$	$0.84^{+0.15}_{-0.13} \pm 0.06$	$0.28 \pm 0.08 \pm 0.02$
$4.3 < q^2 < 8.68$	$0.28^{+0.06}_{-0.08} \pm 0.02$	$0.60^{+0.07}_{-0.07} \pm 0.01$	$0.55 \pm 0.07 \pm 0.03$
$10.09 < q^2 < 12.9$	$0.27^{+0.11}_{-0.13} \pm 0.03$	$0.44^{+0.12}_{-0.11} \pm 0.02$	$0.53 \pm 0.09 \pm 0.03$
$14.18 < q^2 < 16$	$0.50^{+0.06}_{-0.09} \pm 0.03$	$0.33^{+0.11}_{-0.08} \pm 0.04$	$0.59 \pm 0.10 \pm 0.03$
$16 < q^2 < 19$	$0.10^{-0.13}_{-0.13} \pm 0.06$	$0.28^{+0.10}_{-0.09} \pm 0.04$	$0.48 \pm 0.08 \pm 0.03$
$1 < q^2 < 6$	$-0.10^{+0.14}_{-0.14} \pm 0.05$	$0.57^{+0.11}_{-0.10} \pm 0.03$	$0.39 \pm 0.06 \pm 0.02$

Likelihoods in A_{FB},F_L plane



Likelihoods in A_{FB},F_L plane



Tabulated $B^0_s \to \mu^+\mu^-$ results

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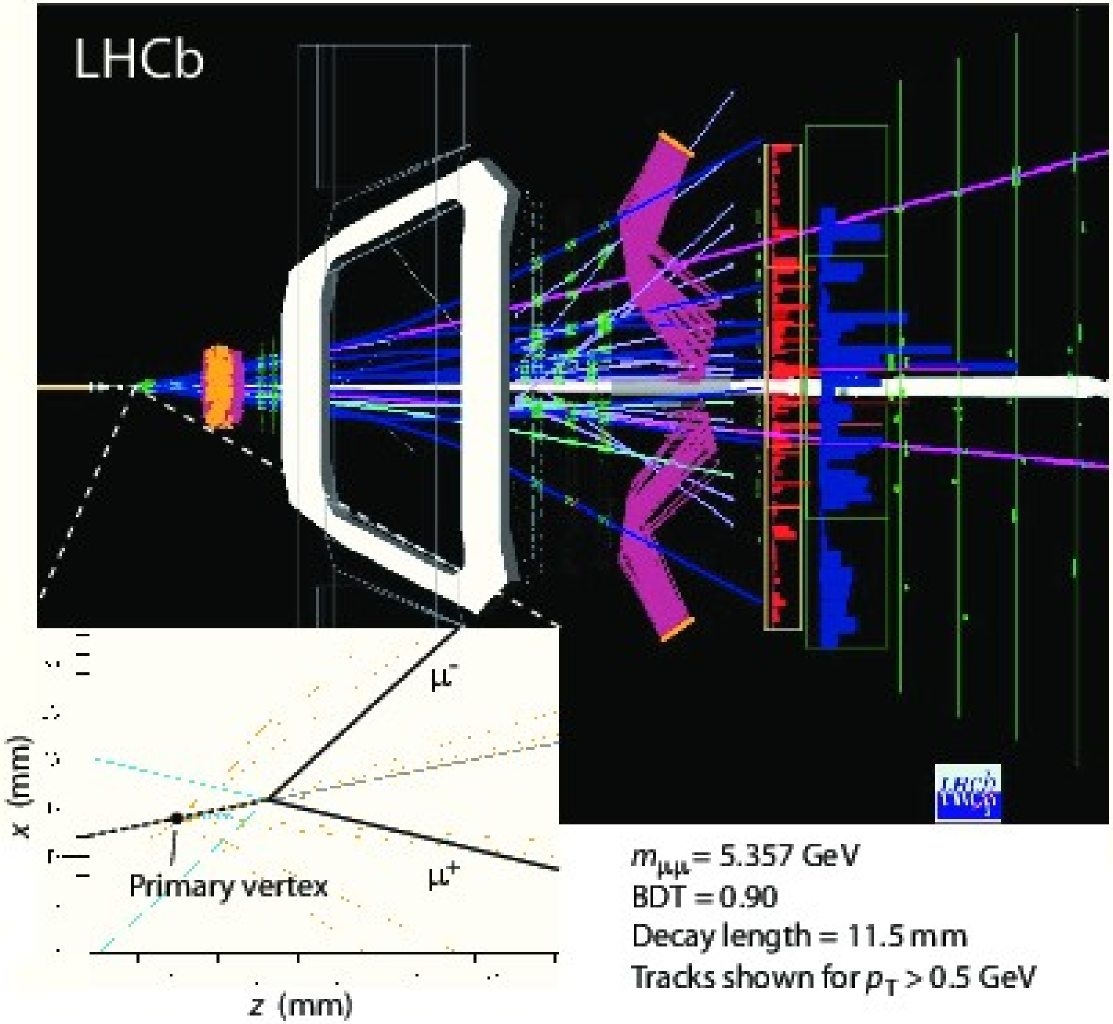
Exp.combinatorial	2968 ± 69	25 ± 2.5	2.99 ± 0.89	0.66 ± 0.40
Exp. SM signal	1.26 ± 0.13	0.61 ± 0.06	0.67 ± 0.07	0.72 ± 0.07
observed	2872	26	3	2

$B^0_s \to \mu^+\mu^-$	at 90% CL	at 95% CL	CL_b
expected limit (bkg only hypothesis)	0.8×10^{-8}	1.0×10^{-8}	
expected limit (bkg+SM hypothesis)	1.2×10^{-8}	1.5×10^{-8}	
observed limit	1.3×10^{-8}	1.6×10^{-8}	0.86

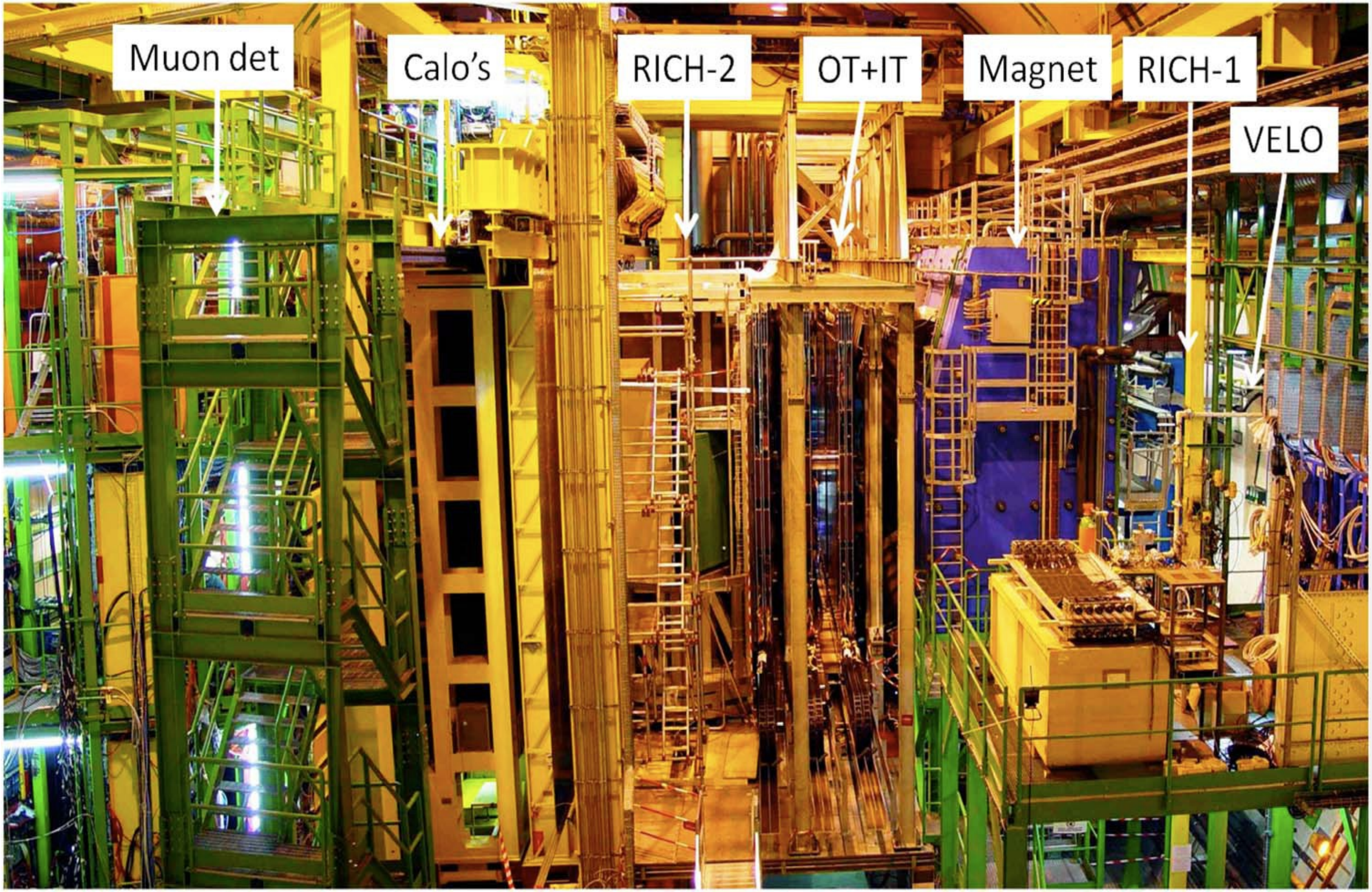
Tabulated $B^0 \to \mu^+\mu^-$ results

$B^0 \to \mu^+\mu^-$	at 90% CL	at 95% CL	CL_b
expected limit (bkg only hypothesis)	2.4×10^{-9}	3.1×10^{-9}	
observed limit	4.2×10^{-9}	5.2×10^{-9}	0.90

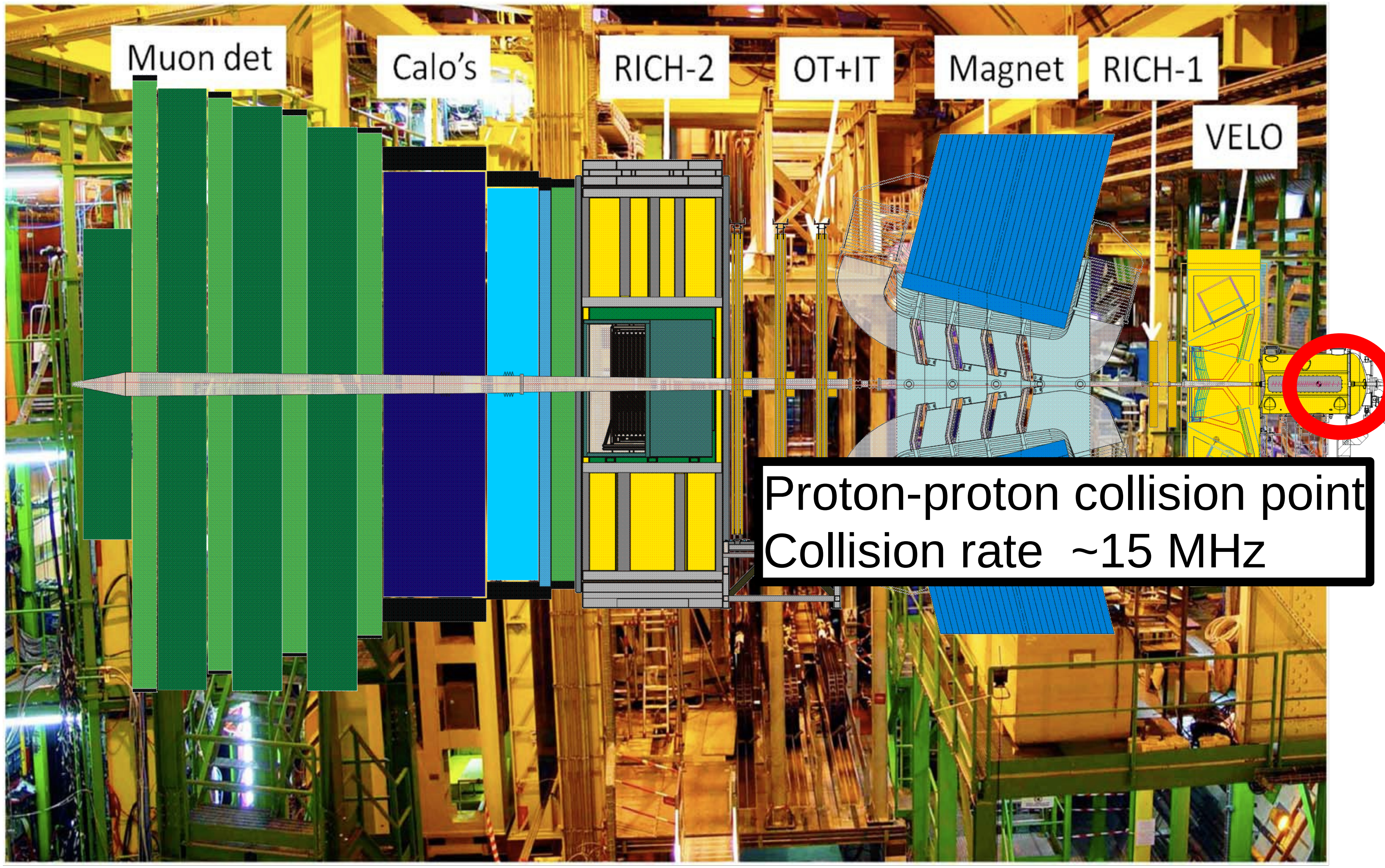
Most signal like $B^0_s \to \mu^+\mu^-$ candidate



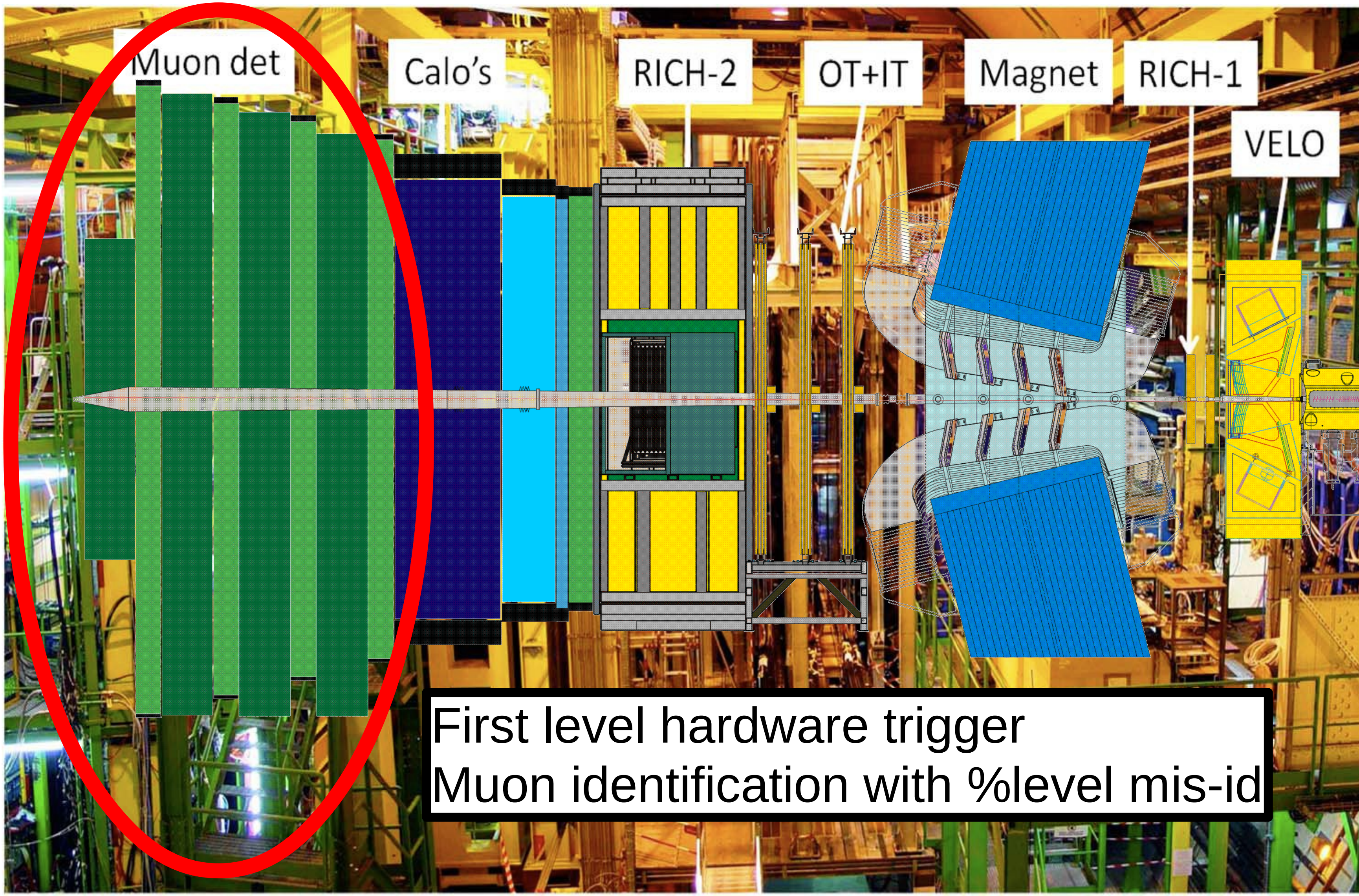
LHCb layout



LHCb layout

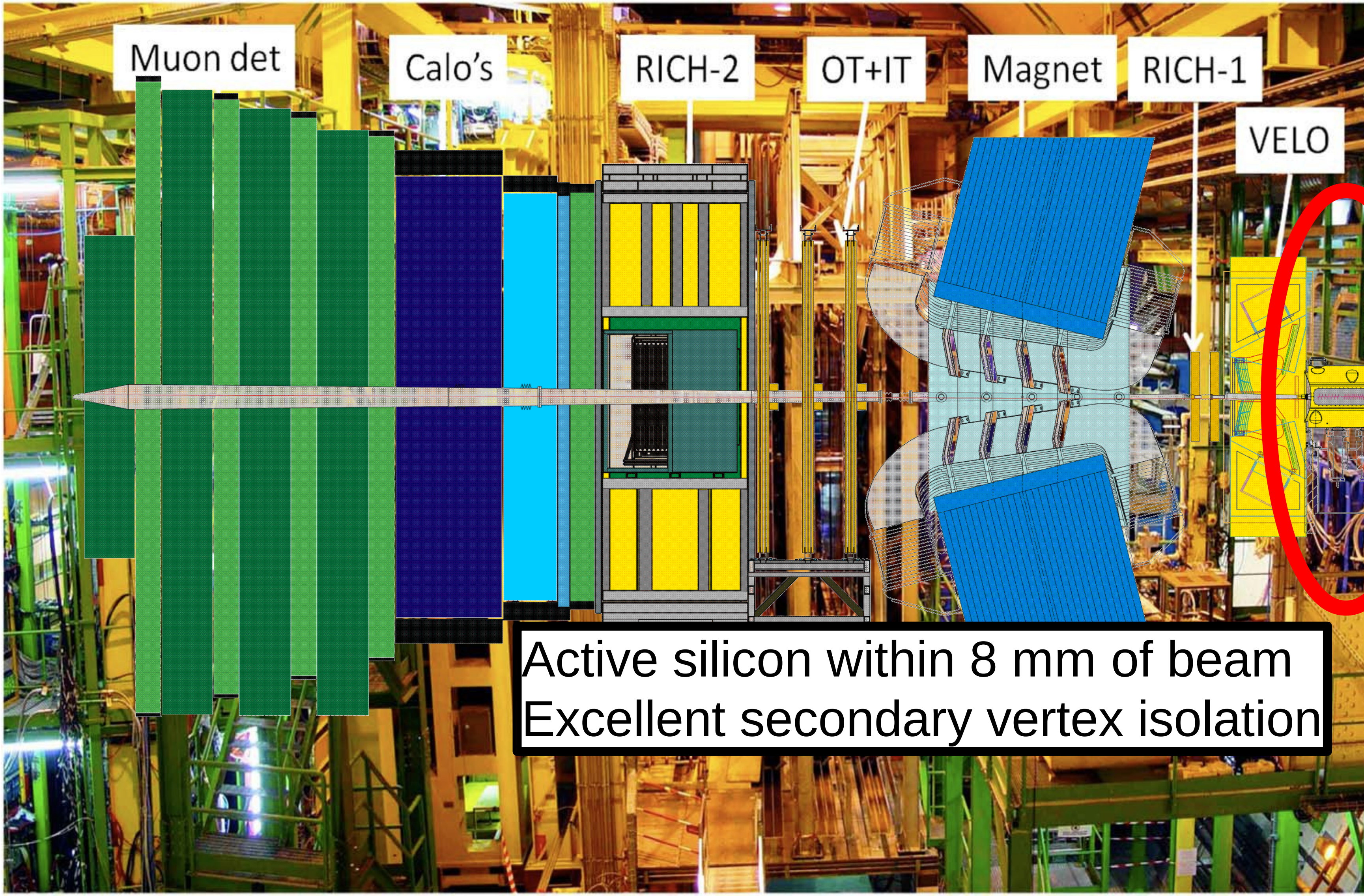

Muon det
Calo's
RICH-2
OT+IT
Magnet
RICH-1
VELO
Proton-proton collision point
Collision rate ~15 MHz

LHCb layout



Muon det
Calo's
RICH-2
OT+IT
Magnet
RICH-1
VELO
First level hardware trigger
Muon identification with %level mis-id

LHCb layout


Muon det
Calo's
RICH-2
OT+IT
Magnet
RICH-1
VELO
Active silicon within 8 mm of beam
Excellent secondary vertex isolation