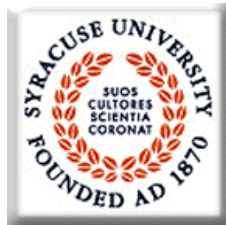
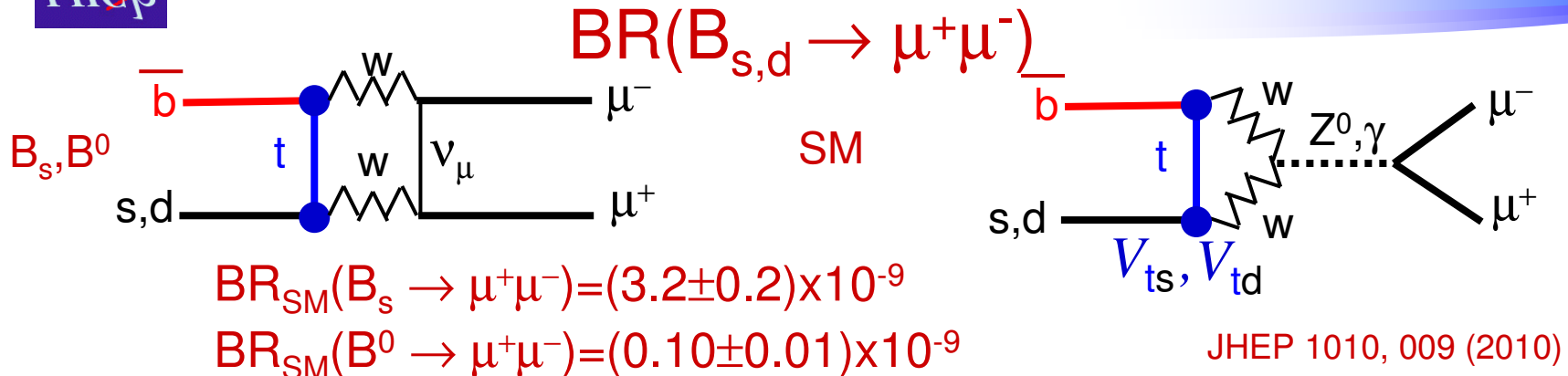


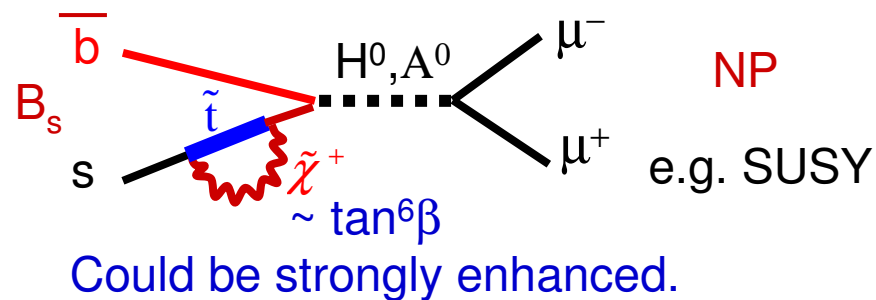
# Studies of rare B decays at LHCb

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Syracuse University





- **Very rare decays in SM:**
  - PDG: the smallest measured BR in any B decay  $\sim 10^{-6}$
  - PDG: the tightest UL on any B decay BR  $< \sim 10^{-7}$
- Small theoretical uncertainty
- Excellent place to look for contributions from BSM:



In some models negative interference with the SM.

CDF 7 fb<sup>-1</sup> 7/12/11

PRL 107, 191801 (2011)

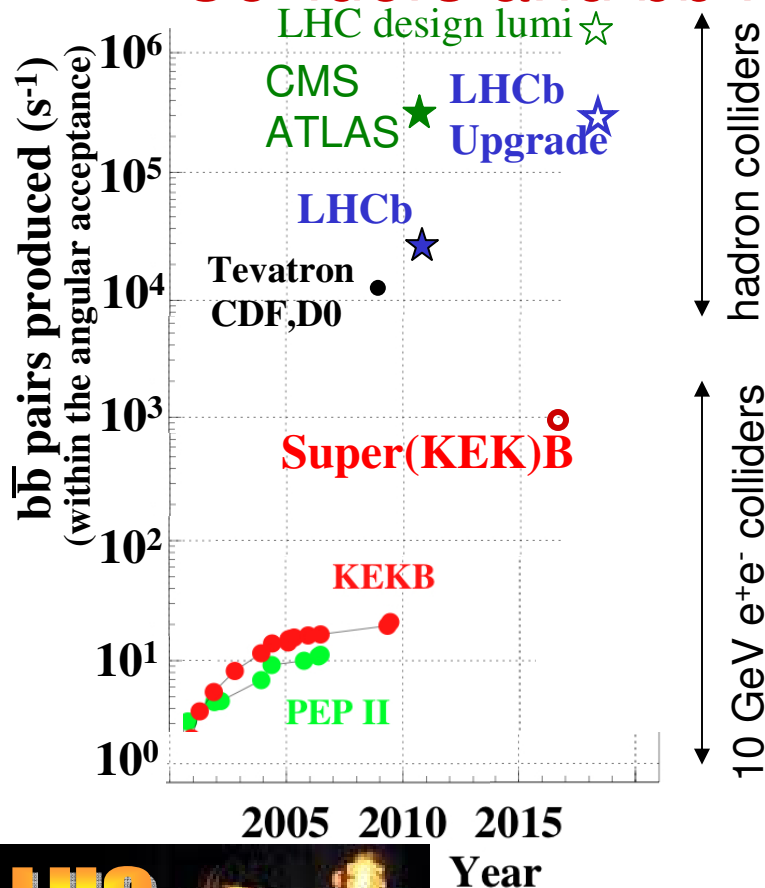
CDF 9.6 fb<sup>-1</sup> 3/5/12

$(1.8_{-0.9}^{+1.1}) \times 10^{-8} < 4.0 \times 10^{-8}$  (95% CL)

$(1.3_{-0.7}^{+0.9}) \times 10^{-8} < 3.1 \times 10^{-8}$

2.1σ evidence for NP

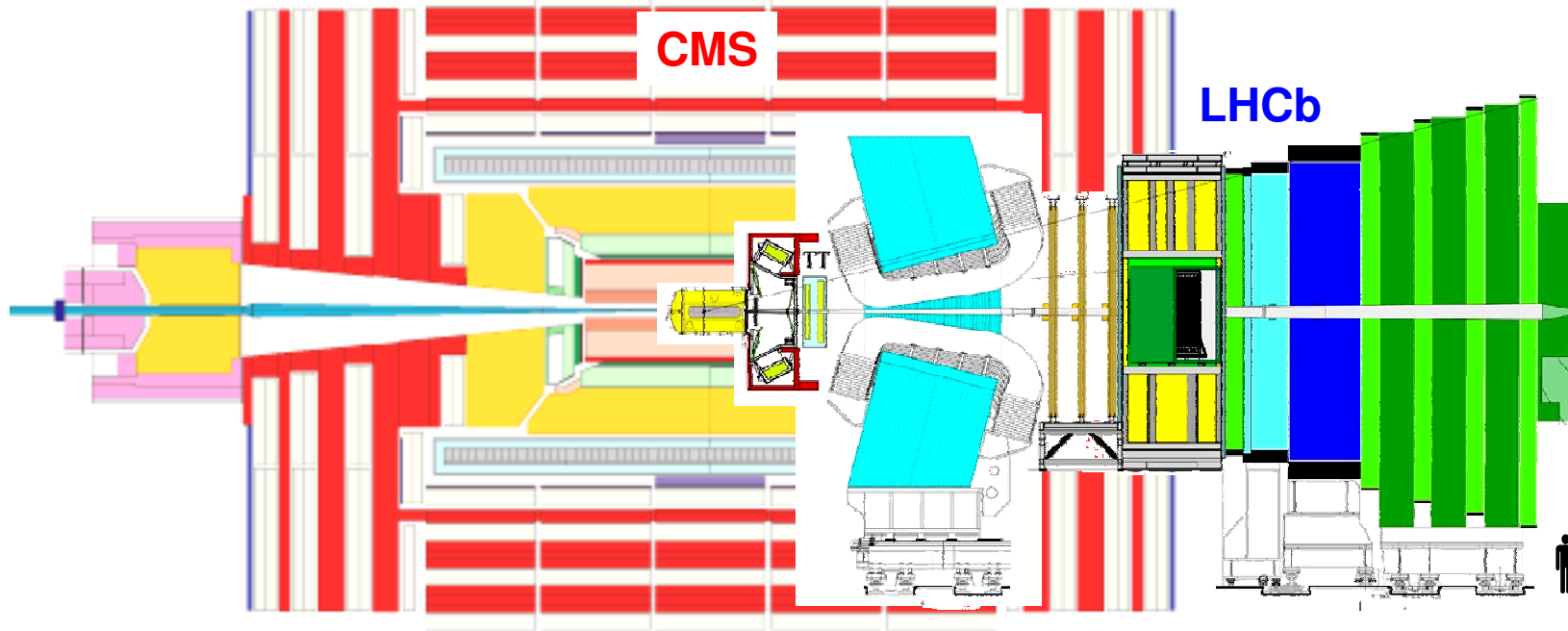
# Colliders and $b\bar{b}$ rates



- Tremendous rate potential at hadron colliders
  - physics reach determined by the detector capabilities not by the machine
- Collect all b-hadron species at the same time:
  - additional gain by a factor of ~10-100 in integrated  $B_s$  rates at hadronic colliders
- Charm rates factor of 10 higher than beauty rates:
  - nuisance and great physics opportunity at the same time



## LHCb vs central detectors



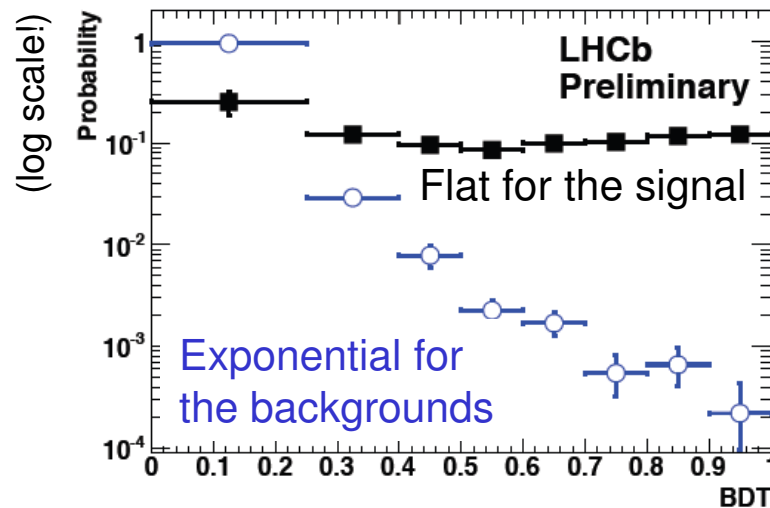
- Some advantages of LHCb (forward spectrometer):
  - comparable  $bb$  cross-section in much smaller solid angle; smaller number of electronic channels; smaller event size; **much larger trigger bandwidth to tape** ( $\sim 3.5$  kHz)
  - Dedicated heavy flavor experiment: **b and c physics dominate the trigger bandwidth** (e.g. CMS b-trigger rate in 2011  $\sim 25$  Hz; 2 orders of magnitude less than LHCb)
  - large  $p$  for small  $p_T$  (in central region  $p \sim p_T$ ); **can identify muons to lower  $p_T$  values**
- Limitation of LHCb:
  - luminosity limited by the detector readout capabilities

$$\text{BR}(\text{B}_{s,d} \rightarrow \mu^+ \mu^-)$$

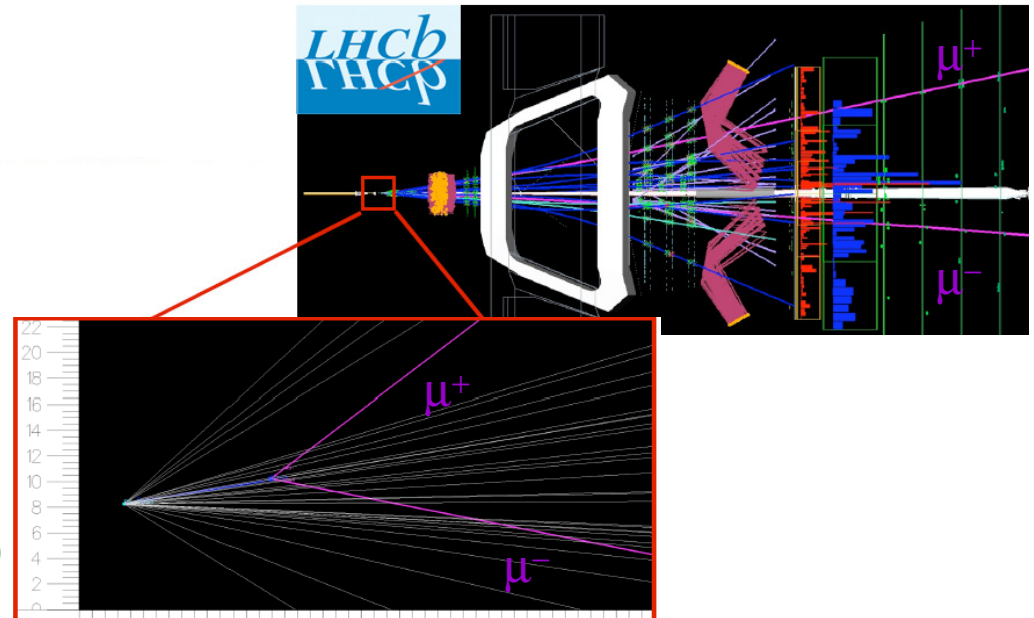
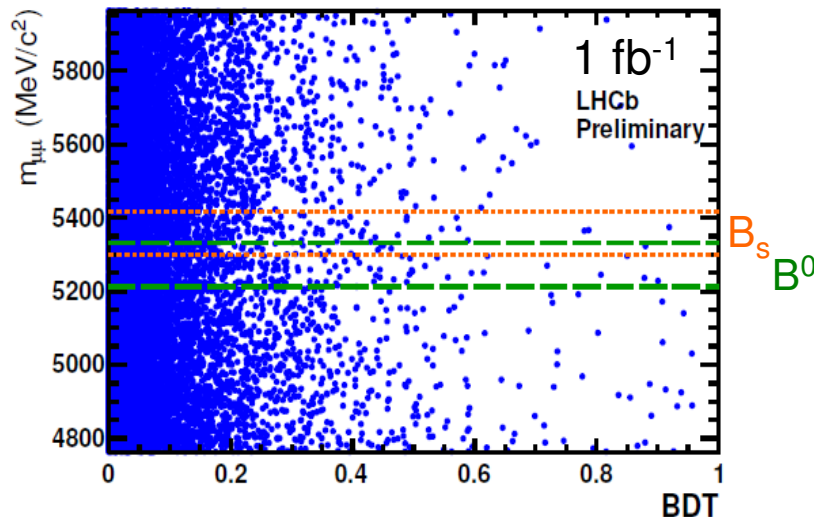
LHCb-PAPER-20120007 arXiv:1203.4493  
1 fb<sup>-1</sup> (full 2011 statistics)

## Analysis approach

**Boosted Decision Tree** discriminator combining info from  $p_T$ , polarization angle, vertex displacement, isolation etc. Independent of the charged track ID. Uncorrelated with  $m_{\mu\mu}$ .



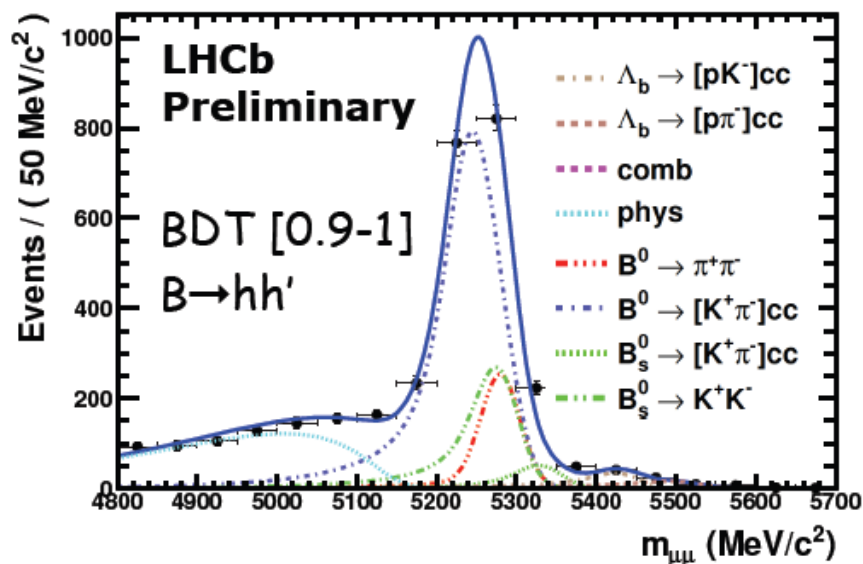
Trained on signal and background MC but then signal and background distributions determined from the real data:  $\text{B}^0 \rightarrow \text{h}^+ \text{h}^-$  for signal,  $m_{\mu\mu}$  sidebands for the background



Estimate  $m_{\mu\mu}$  resolution by interpolating from the observed resolution for  $\text{J}/\psi, \psi', \text{Y}, \text{Y}', \text{Y}'' \rightarrow \mu^+ \mu^-$  and  $\text{B}^0 \rightarrow \text{h}^+ \text{h}^-$

# BR( $B_{s,d} \rightarrow \mu^+\mu^-$ ) normalization

- Normalization of BR determined from 3 different control channels:



BR / N <sub>signal</sub>	Bd	Bs
	$\alpha_{B_d \rightarrow \mu^+\mu^-}^{cal}$ ( $\times 10^{-11}$ )	$\alpha_{B_s \rightarrow \mu^+\mu^-}^{cal}$ ( $\times 10^{-10}$ )
$B^+ \rightarrow J/\psi K^+$	$8.464 \pm 0.433$	$3.170 \pm 0.297$
$B_s^0 \rightarrow J/\psi \phi$	$11.13 \pm 3.124$	$4.169 \pm 1.123$
$B^0 \rightarrow K^+\pi^-$	$7.709 \pm 0.957$	$2.887 \pm 0.424$

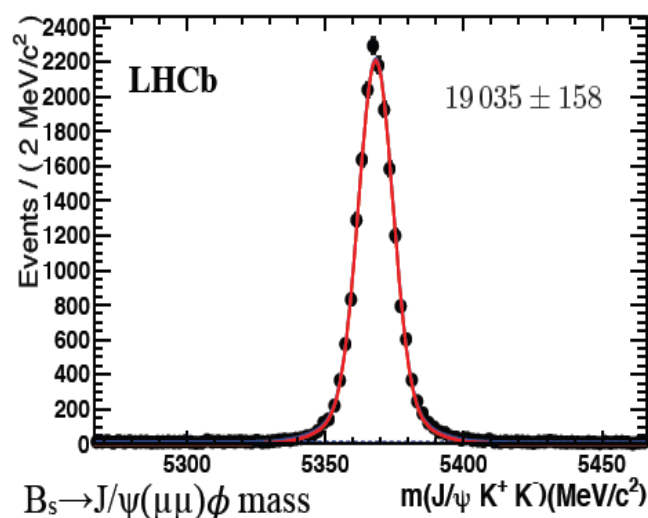
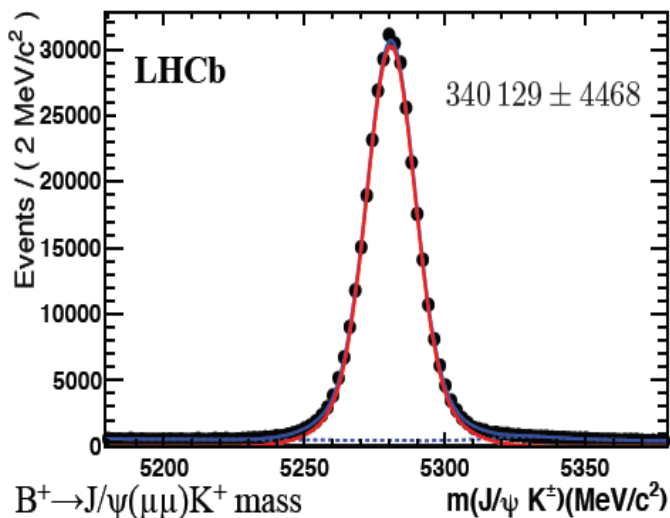
$(8.4 \pm 0.4) \times 10^{-11}$      $(3.2 \pm 0.3) \times 10^{-10}$

According to SM BRs expect:

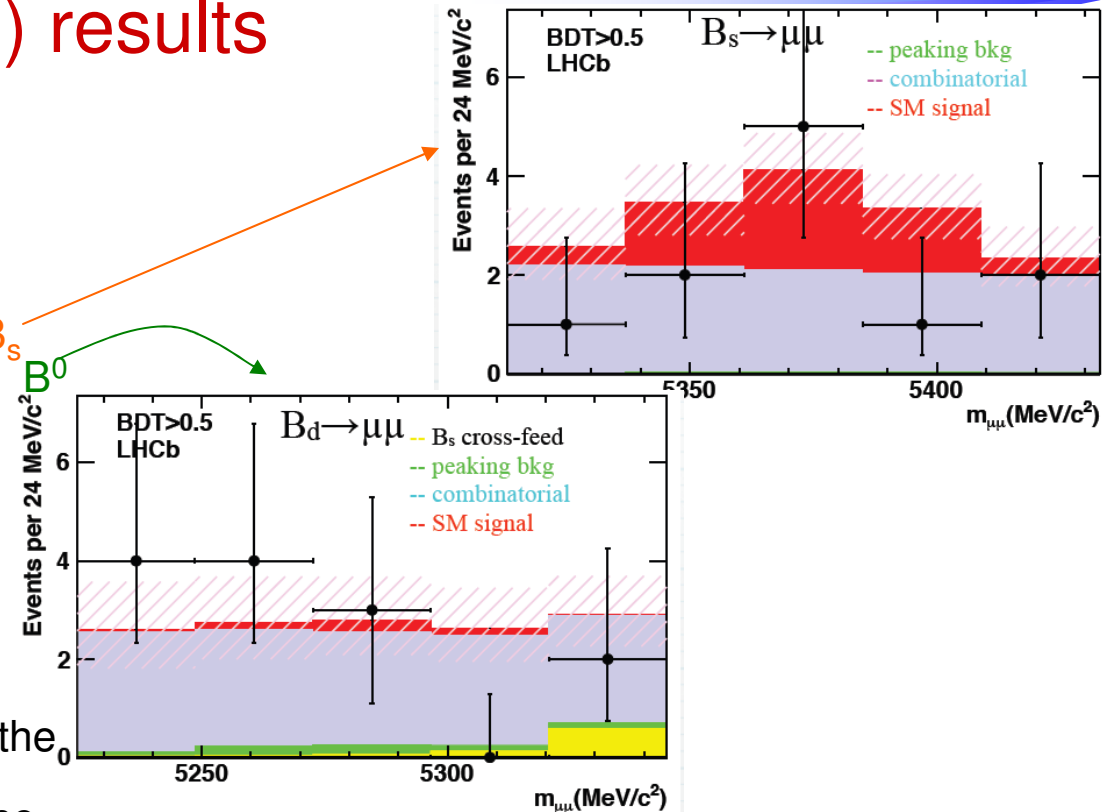
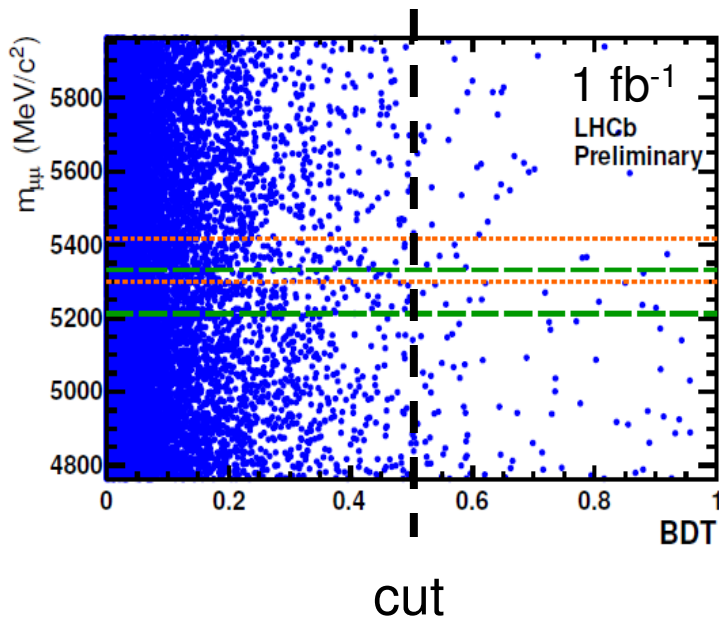
$\sim 10 B_s \rightarrow \mu^+\mu^-$

$\sim 1 B^0 \rightarrow \mu^+\mu^-$

events



# $BR(B_{s,d} \rightarrow \mu^+\mu^-)$ results

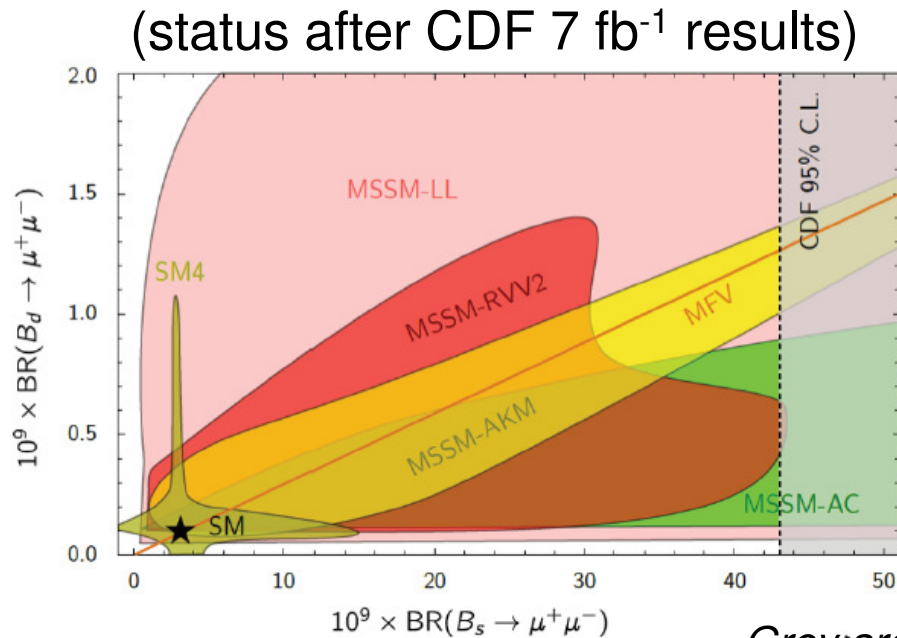


- Actual upper limits determined from the 2D information without the BDT cut (97% of the sensitivity comes from the  $BDT > 0.5$  data)

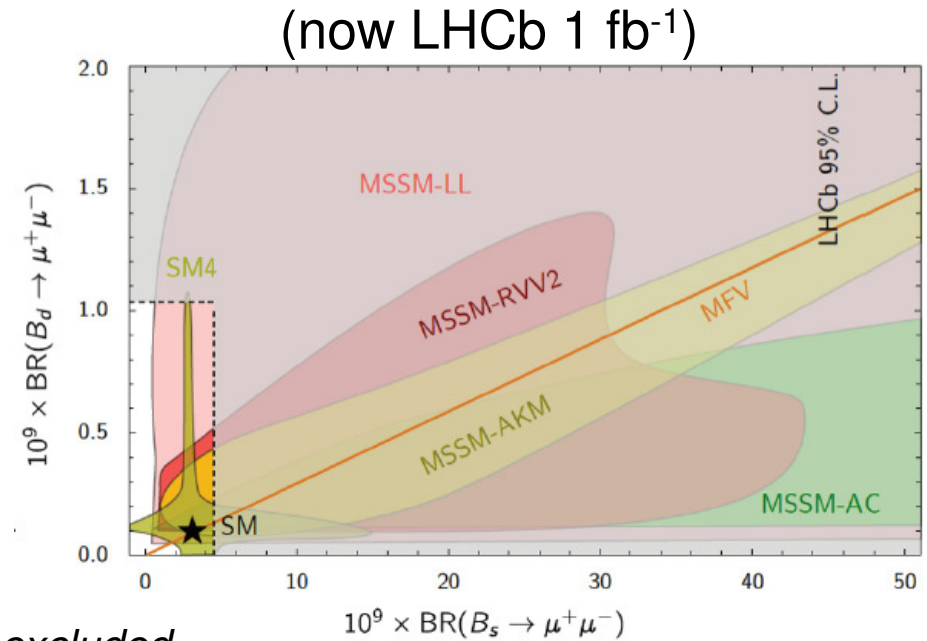
$BR(B_s \rightarrow \mu^+\mu^-)$	SM	$(3.2 \pm 0.2) \times 10^{-9}$	
	CDF $9.6 \text{ fb}^{-1}$	$(13_{-7}^{+9}) \times 10^{-9}$	$< 31 \times 10^{-9} \text{ (95\%CL)}$
$BR(B^0 \rightarrow \mu^+\mu^-)$	LHCb $1 \text{ fb}^{-1}$	$(0.8_{-1.2}^{+1.8}) \times 10^{-9}$	$< 4.5 \times 10^{-9} \text{ (95\%CL)}$
		(1.3 $\sigma$ below SM)	
$BR(B^0 \rightarrow \mu^+\mu^-)$	SM	$(0.10 \pm 0.01) \times 10^{-9}$	
	LHCb $1 \text{ fb}^{-1}$	$< 1.0 \times 10^{-9} \text{ (95\%CL)}$	

# BR( $B_{s,d} \rightarrow \mu^+\mu^-$ ) implications

From D. Straub  
@ Moriond E.W.



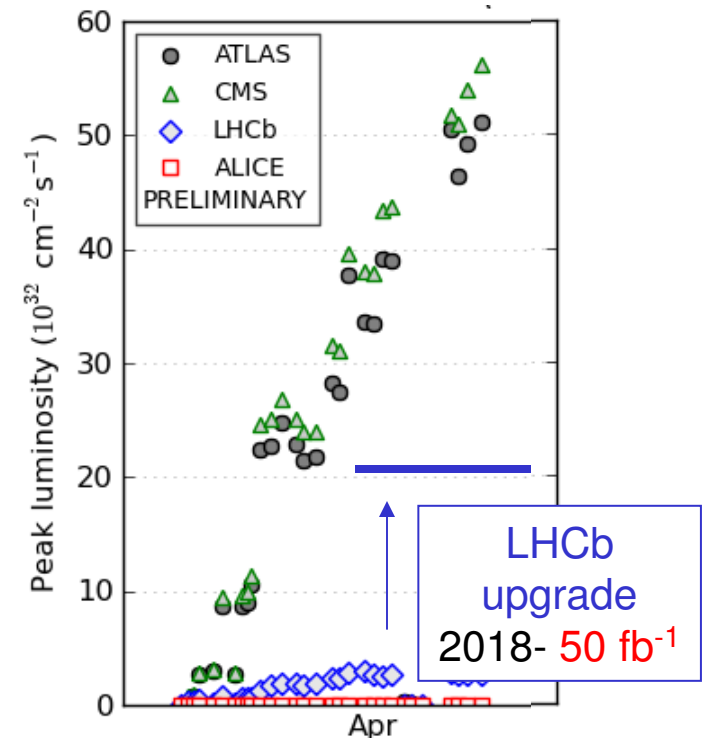
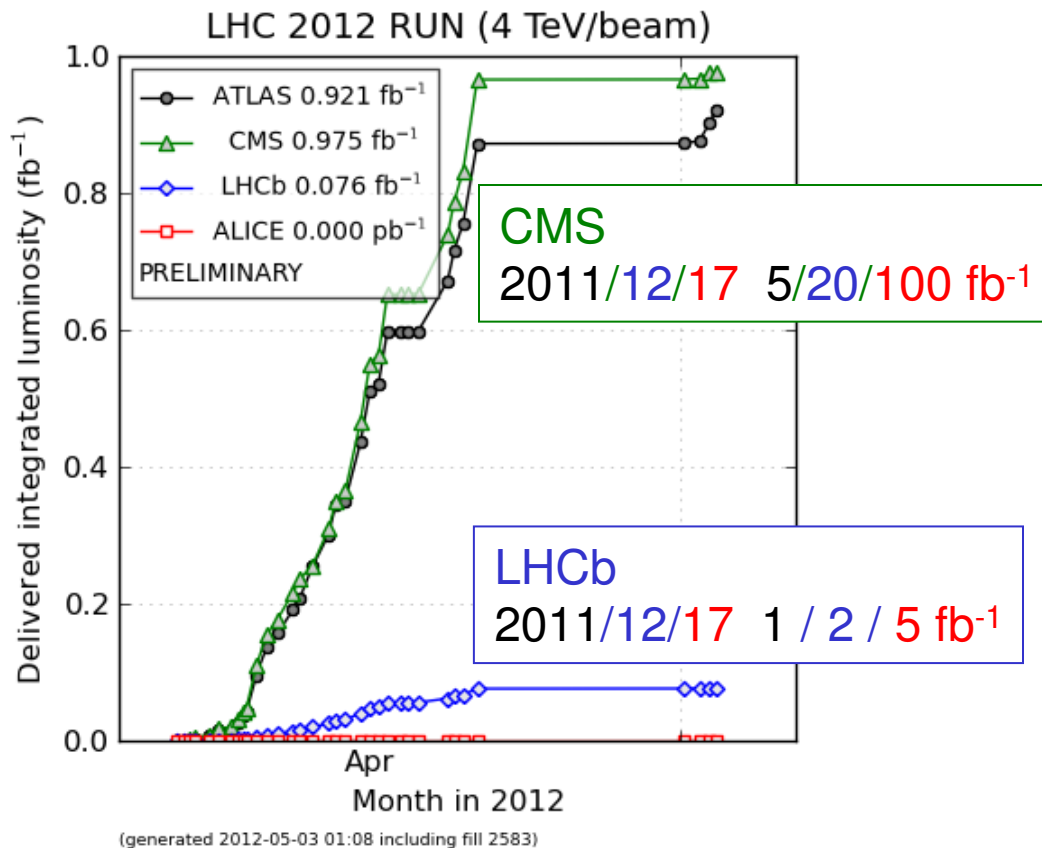
Grey area excluded



- SM has survived an order of magnitude improvement in the experimental sensitivity
- Lots of room still left for NP before the experimental errors reach the theoretical uncertainty in the SM predictions

# BR( $B_{s,d} \rightarrow \mu^+\mu^-$ ) future

- $B_{s,d} \rightarrow \mu^+\mu^-$  are the easiest B decays to probe
- CMS** (ATLAS) have meaningful results (see Joel's talk) and can become more sensitive in the next few years (until LHCb upgrade) thanks to larger integrated luminosities
- LHCb upgrade** needed to probe BR( $B_s \rightarrow \mu^+\mu^-$ ) with a sensitivity comparable to the theoretical uncertainty on the SM predictions

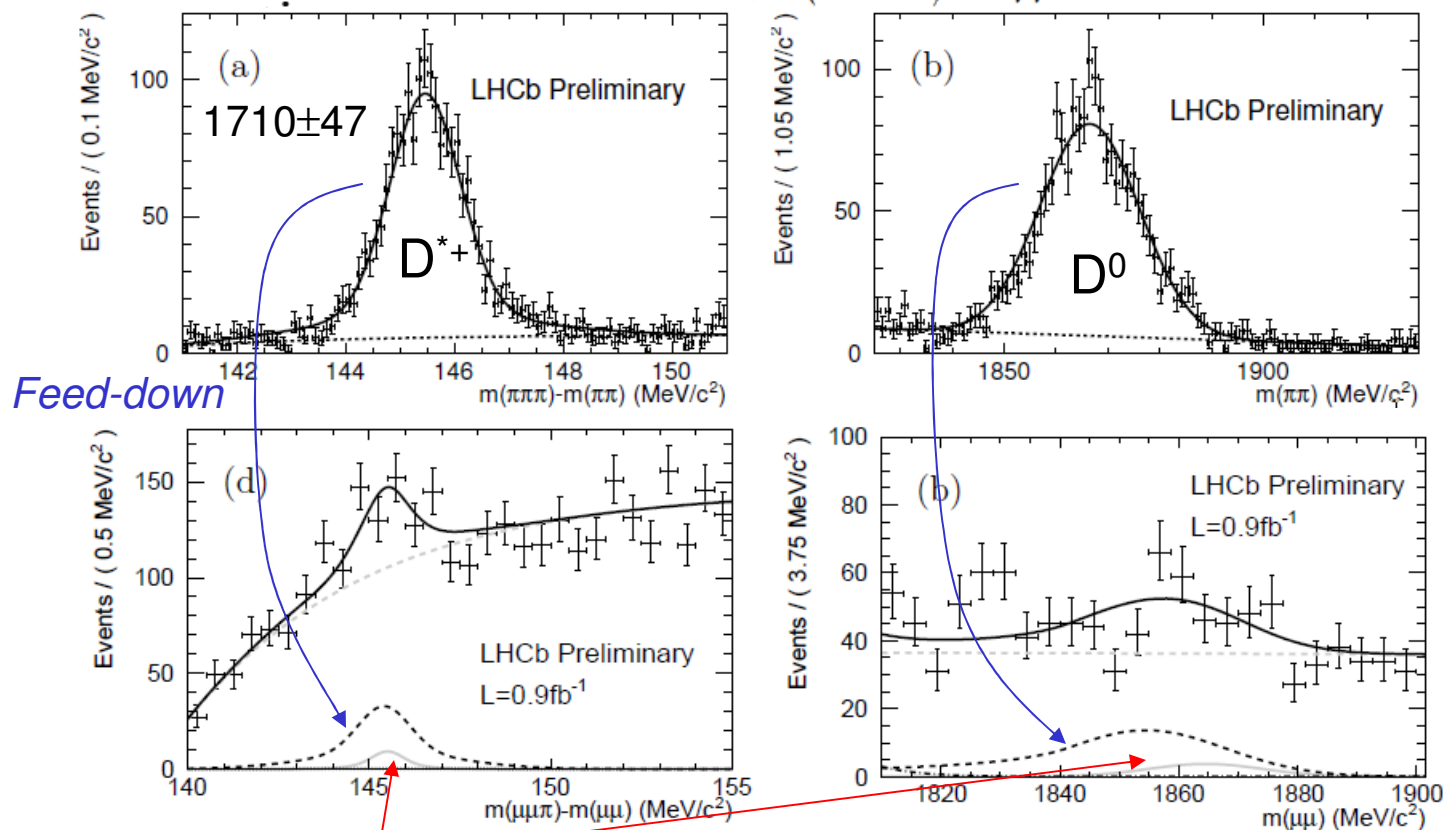


# Search for $D^0 \rightarrow \mu^+ \mu^-$

LHCb-CONF-2012-005 0.9 fb<sup>-1</sup>

- Extremely small is SM:  $BR_{SM}(D^0 \rightarrow \mu^+ \mu^-) < 6 \times 10^{-11}$
- Best limit from Belle PRD 81,091102 (2010)  $< 1.4 \times 10^{-7}$  (90% CL)

$$\mathcal{B}(D^0 \rightarrow \mu^+ \mu^-) = \frac{N_{D^{*+} \rightarrow D^0(\rightarrow \mu^+ \mu^-) \pi^+} \varepsilon_{\pi\pi}}{N_{D^{*+} \rightarrow D^0(\rightarrow \pi^+ \pi^-) \pi^+} \varepsilon_{\mu\mu}} \cdot \mathcal{B}(D^0 \rightarrow \pi^+ \pi^-)$$



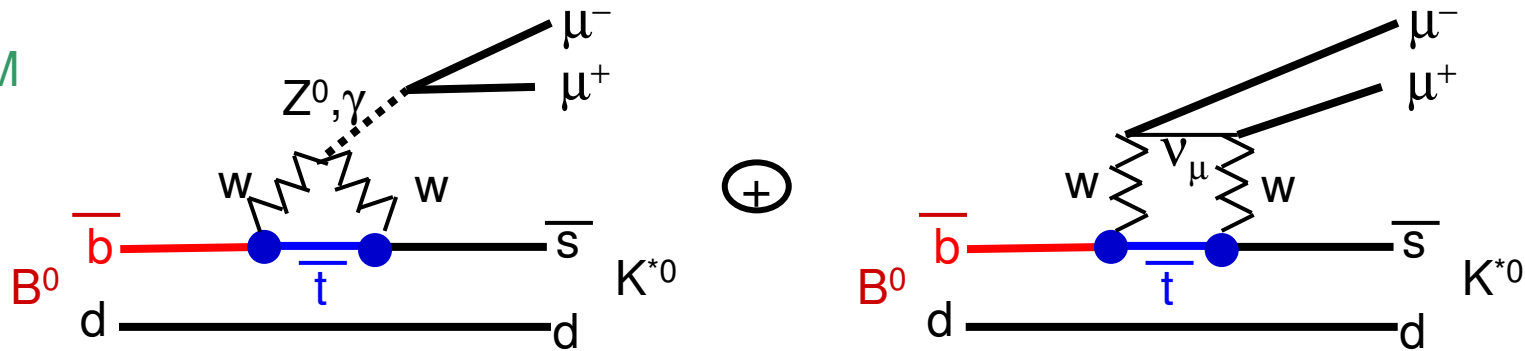
Fitted signal yield  
(1.2σ from zero)

LHCb preliminary

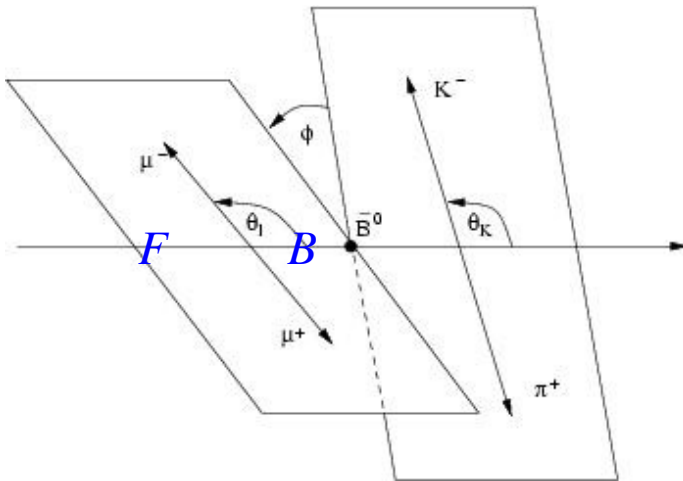
$< 1.1 \times 10^{-8}$

# EW penguin: $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

SM



- Look for interference of these SM diagrams. NP diagrams can contribute.
- Need to eliminate effect of form-factors – various observables related to angular correlations. Most famous  $A_{FB}$



$$A_{FB}(q^2) = \frac{N_F - N_B}{N_F + N_B}$$

# EW penguin: $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

BaBar: PRD 79, 031102 (2009)

Belle: PRL103, 171801 (2009)

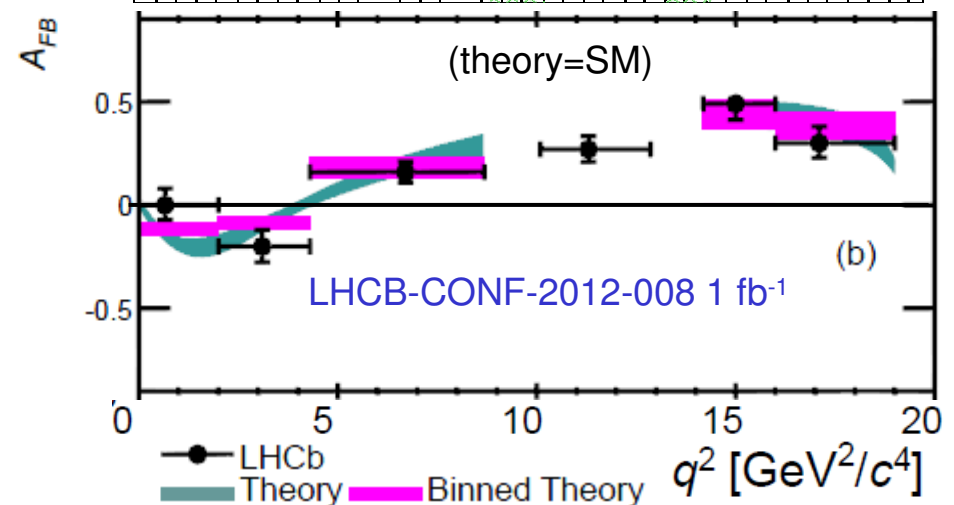
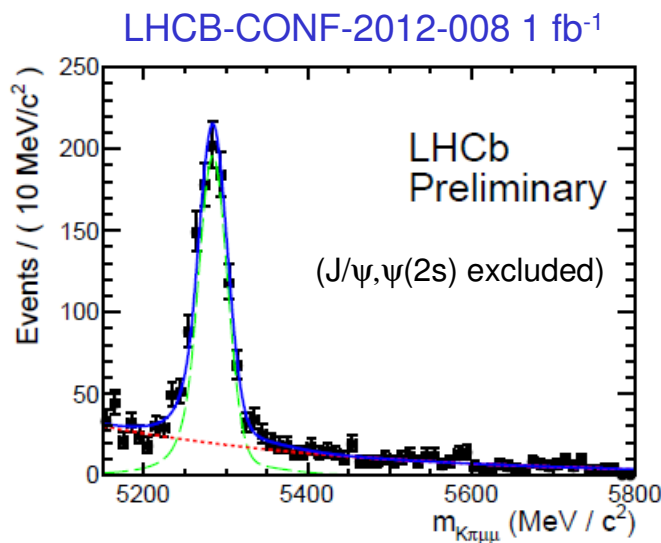
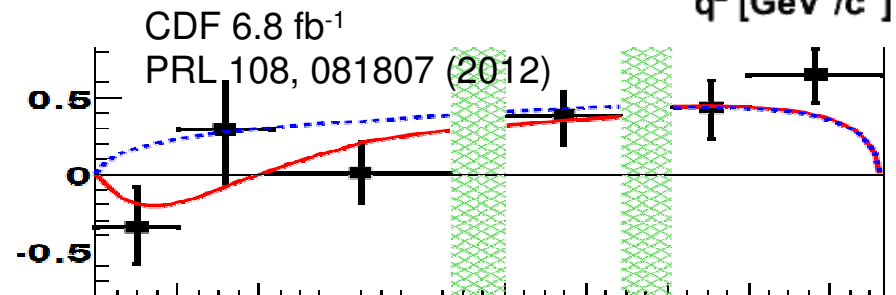
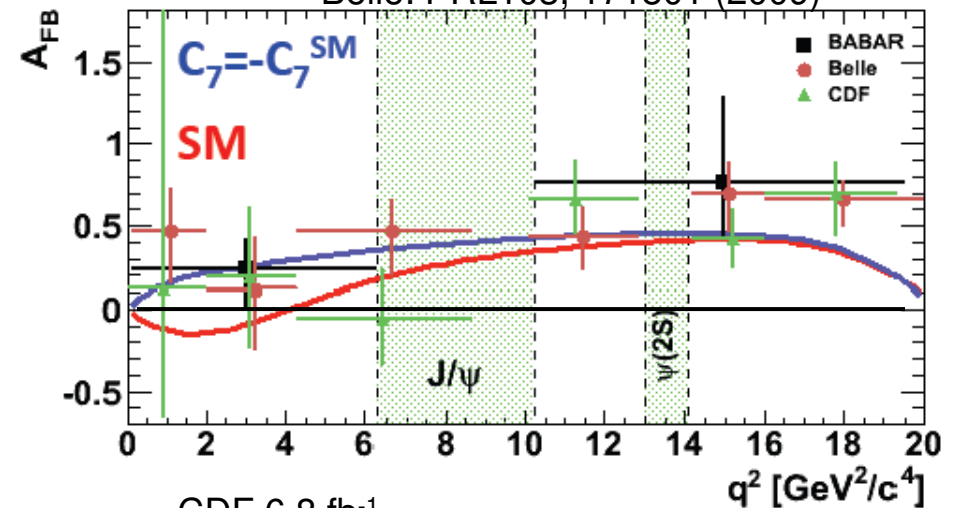
Before summer 2011:

Babar, Belle and CDF

- Babar 60 events with  $B/S=0.3$
- Belle 247 0.25
- CDF 100 (4.4 fb<sup>-1</sup>) 0.4

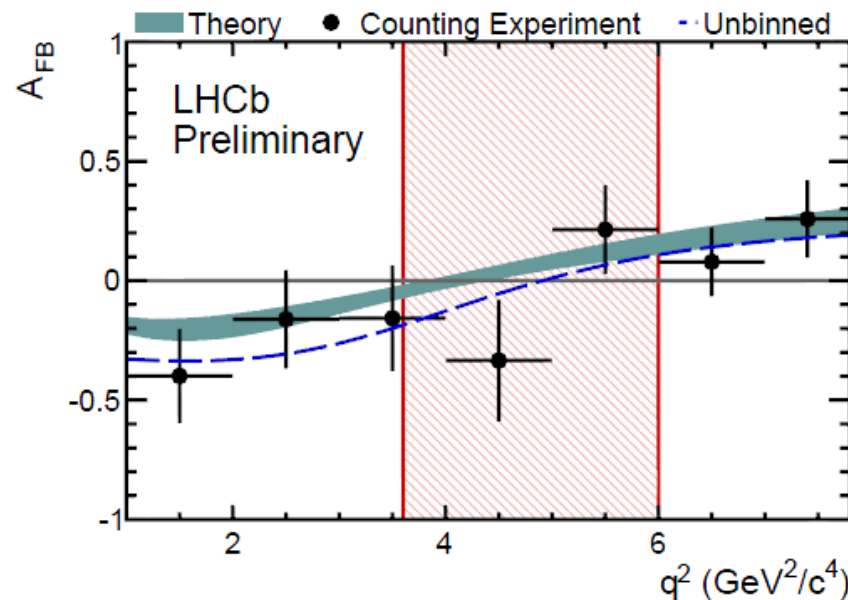
New results:

- CDF 164 (6.8 fb<sup>-1</sup>) 0.4
- LHCb 900 (1.0 fb<sup>-1</sup>) 0.25



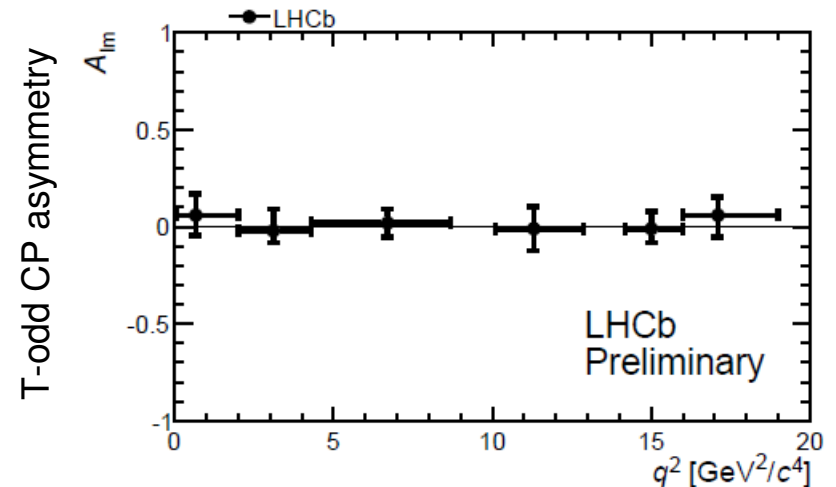
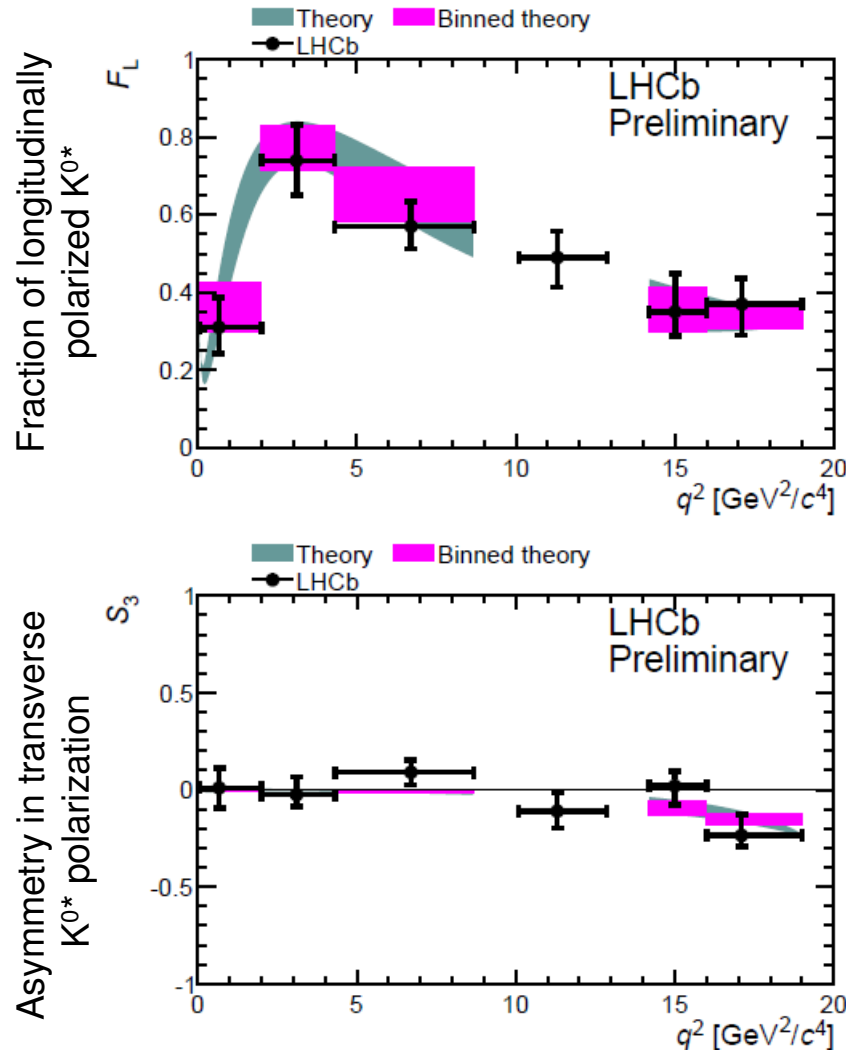
# First measurement of $A_{FB}$ zero-crossing point

- The SM predicts  $A_{FB}$  to change sign at a well defined point in  $q^2$
- This zero-crossing point  $q_0^2$  is largely free from form-factor uncertainties
- Extracted through a 2D fit to the forward- and backward-going  $m_{B^0}$  and  $q^2$  distributions



- The **worlds first measurement** of  $q_0^2$ , at  $q_0^2 = 4.9_{-1.3}^{+1.1} \text{ GeV}^2/c^4$  [preliminary]
- This is consistent with SM predictions which range from  $4 - 4.3 \text{ GeV}^2/c^4$

# $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ more observables



- So far no challenge to SM
- Experimental errors statistics dominated and larger than theoretical uncertainty
- LHCb already has the most sensitive measurements:
  - 5 times more data by 2018
  - 50 times more data with upgrade
- LHCb upgrade will have better sensitivity than super  $e^+e^-$  factories in this exclusive channel ( $e^+e^-$  can also do inclusive measurement)

We have also measured:

$$\text{BR}(B_s \rightarrow \phi \mu^+ \mu^-) = (0.78 \pm 0.01 \pm 0.06 \pm 0.28) \times 10^{-6}$$

$$B^+ \rightarrow \pi^+ \mu^+ \mu^-$$

- $b \rightarrow d$  transition, suppressed relatively to  $B^+ \rightarrow K^+ \mu^+ \mu^-$  by  $|V_{td}|^2 / |V_{ts}|^2 \sim 0.05$

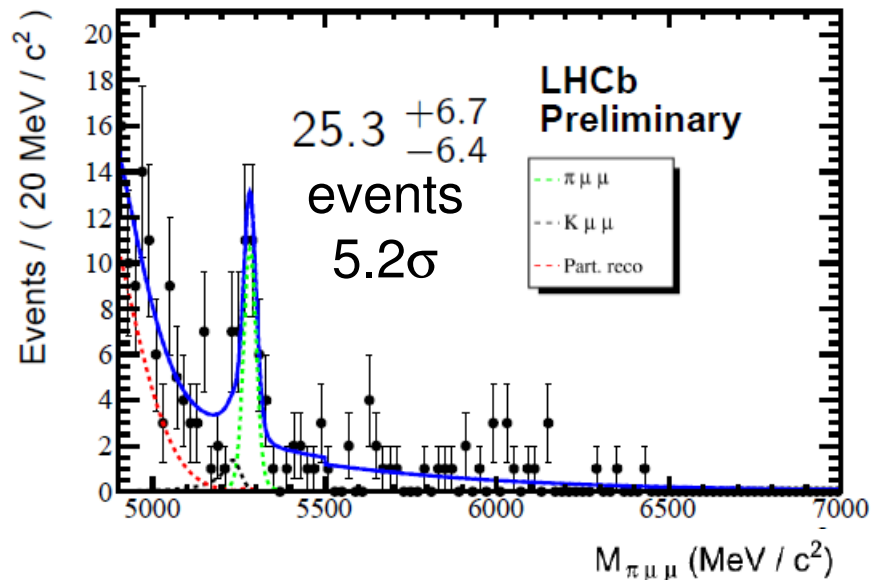
$$BR_{SM}(B^+ \rightarrow \pi^+ \mu^+ \mu^-) = (2.0 \pm 0.2) \times 10^{-8}$$

- Could be larger in non-SM

$$\text{Belle PRD 78, 011101 (2008)} < 7.0 \times 10^{-8}$$

LHCb

$$(2.4 \pm 0.6 \pm 0.2) \times 10^{-8}$$



LHCb-CONF-2012-006

Rarest B decay ever detected!

## Other new rare decay results

- Search for  $B^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-$  (first limits) LHCb-CONF-2012-010
- Search for majorana neutrino in  $B^- \rightarrow X^+ \mu^- \mu^-$  (tightest limits) LHCb-PAPER-2011-038 arXiv:1201.5600
- Measurement of direct CP asymmetry in  $B^0 \rightarrow K^{*0} \gamma$  (consistent with zero, best measurement) LHCb-CONF-2012-004
- Most precise measurement of direct CP asymmetry in  $B^0 \rightarrow K^+ \pi^-$  ( $6\sigma$  away from zero), first observation of CP violation in  $B_s \rightarrow K^+ \pi^-$  ( $3.3\sigma$  away from zero) LHCb-PAPER-2011-029
- Time dependent measurement of CPV in  $B_{d,s} \rightarrow hh$  (direct CP asymmetry term in  $B^0 \rightarrow \pi^+ \pi^-$  favors BaBar results) LHCb-CONF-2012-007

## Conclusions

- LHC is a beauty and charm factory for foreseeable future:
  - Unique reach in  $B_s$  physics. Best sensitivity in many  $B_{d,u}, D$  measurements.
- LHCb is the first hadron collider experiment dedicated to heavy flavor physics
  - The recent results have proven that a broad beauty and charm physics program at a hadronic collider is possible with quality of results matching the  $e^+e^-$  factories.
  - Reaching new levels of sensitivity (i.e. higher energy scales) in many key measurements:
    - No indication of NP in beauty decays yet. Plenty of room for NP before theoretical limitations are reached.
    - NP seen in  $D^0$  decays  $[A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)]$  ?
    - More data to be collected in next few years
  - Channels with many neutrals and neutrino(s) will remain exclusive domain of the  $e^+e^-$  factories.
- Physics reach limited by the detector capabilities not the collider:
  - LHCb upgrade in 2018.