1st International Conference on New Frontiers in Physics
Kolymbari, Crete, Greece – 10th-16th June 2012

Rare **B** decays as probe for new physics

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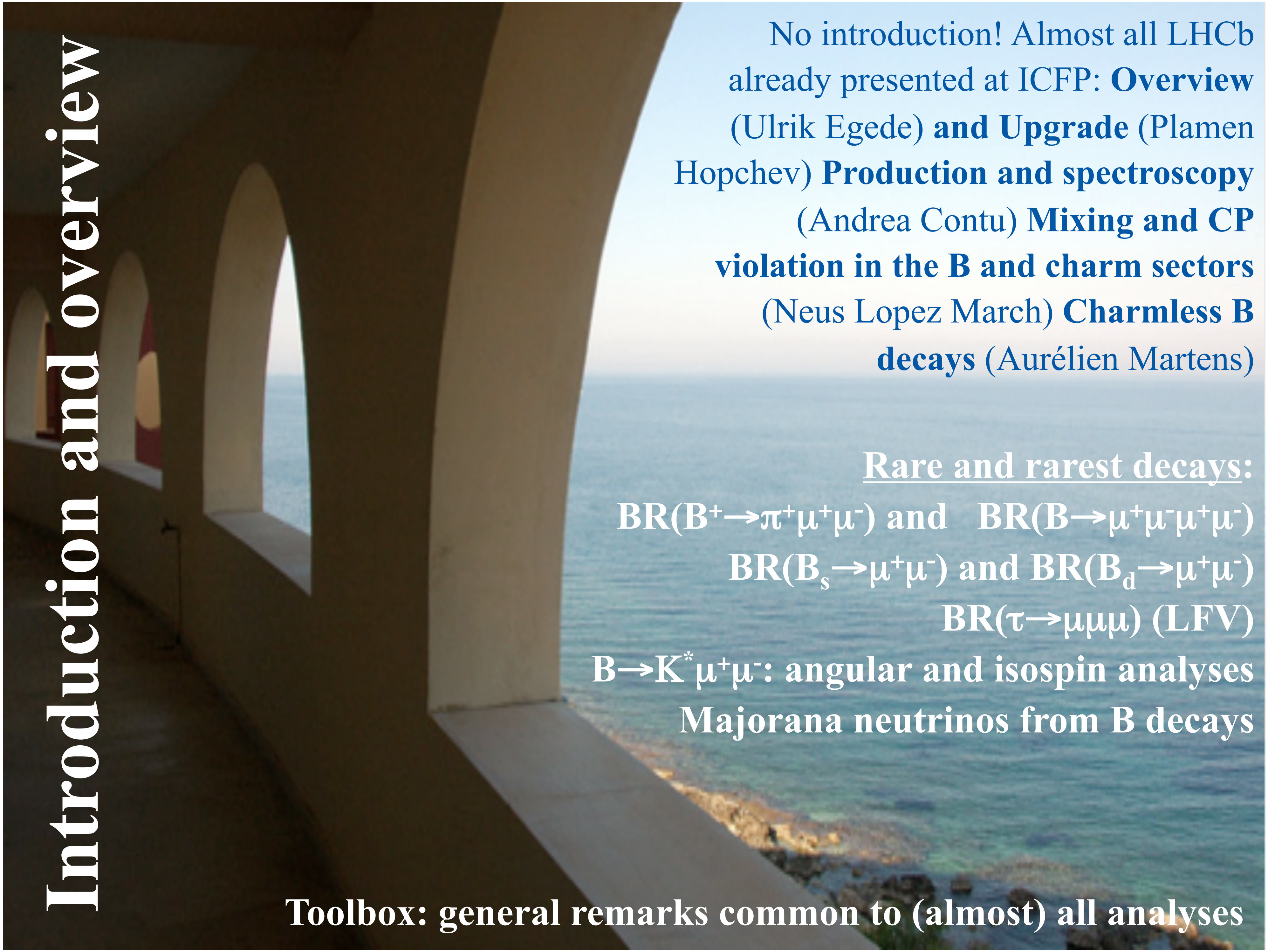
on behalf of the LHCb Collaboration


Introduction and overview
No introduction! Almost all LHCb already presented at ICFP: Overview (Ulrik Egede) and Upgrade (Plamen Hopchev) Production and spectroscopy (Andrea Contu) Mixing and CP violation in the B and charm sectors (Neus Lopez March) Charmless B decays (Aurélien Martens)
Rare and rarest decays:
BR($B^+ \to \pi^+\mu^+\mu^-$) and BR($B \to \mu^+\mu^-\mu^+\mu^-$)
BR($B_s \to \mu^+\mu^-$) and BR($B_d \to \mu^+\mu^-$)
BR($\tau \to \mu\mu\mu$) (LFV)
$B \to K^*\mu^+\mu^-$: angular and isospin analyses
Majorana neutrinos from B decays
Toolbox: general remarks common to (almost) all analyses

Toolbox

In SM b→s transitions are loop-induced and thus suppressed; NP diagrams could compete. **Compare experimental results with (accurate) SM predictions to find NP hints**.

- the use of normalization channels to convert observed number of events in BR **reduces systematic errors, in particular from little known production rates**;

- use of control channels/samples [with geometry/trigger/selection/… as similar as possible to the signal] to **avoid/reduce dependence on simulation**;

- very good PID for muons and hadrons; **performance and misID from data**;

- MVA operators, based on Boosted Decision Tree (**BDT**): combine kinematical and/or geometrical and/or quality information (B vertex position, p_T, $\chi 2$ track fit, PID,…) to **classify events as signal or background**;

- blind analyses: signal region not looked at until the analyses are frozen.

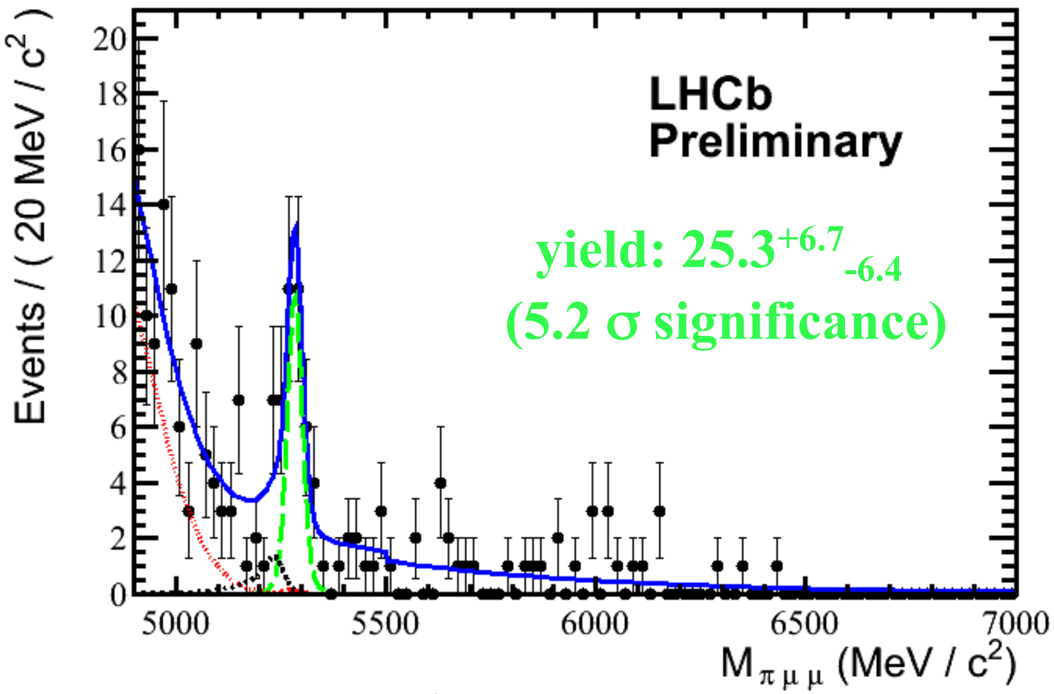
$BR(B^+ \to \pi^+ \mu^+ \mu^-)$

LHCb-CONF-2012-006

In the SM **b→dl⁺l⁻** transitions suppressed by $|V_{td}/V_{ts}|$ wrt the $b \to s l^+ l^-$:
$BR_{SM} = (1.96 \pm 0.21) \times 10^{-8}$. [H.Z.Song et alComm. in Th. Phys. 50 (2008) 696]

- Not [necessarily] needed BSM: even with strong experimental constraints from $b \to l^+ l^-$, $BR(B^+ \to \pi^+ \mu^+ \mu^-)$ can be enhanced by NP models.

- Never observed before; expect 21±3 SM events in **1 fb⁻¹**.
- Veto J/ψ and ψ'(2S) in $m_{\mu\mu}$.
- **BDT** signal/bkg rejection.
- Yield from fit to $M_{\pi\mu\mu}$ distribution, bkg **mass shapes from data control channels**: $B^+ \to J/\psi K^+$ and $B^+ \to J/\psi \pi^+$.
- Normalize to $B^+ \to J/\psi K^+$.



$BR(B^+ \to \pi^+ \mu^+ \mu^-) = (2.4 \pm 0.6_{STAT} \pm 0.2_{SYST}) \times 10^{-8}$ [preliminary]

$BR(B_s \to \mu^+\mu^-\mu^+\mu^-)$ and $BR(B_d \to \mu^+\mu^-\mu^+\mu^-)$

- Strongly suppressed in SM; contributions from: $B \to J/\psi(\mu^+\mu^-)\phi(\mu^+\mu^-)$ = **2.3(9)×10⁻⁸**

$B \to \mu^+\mu^- \gamma^*(\mu^+\mu^-)$ ~**10^{-10}-10^{-11}**

[Phys. Rev. D 70(2004)114028]

- possible enhancement in BSM, with new particles decaying in $\mu^+\mu^-$.

[S.Demidov, D.Gorbunov arXiv:1112.5230]

- cut based analysis to maximize S/B, tuned on $B \to J/\psi(\mu^+\mu^-)\phi(\mu^+\mu^-)$ decays.

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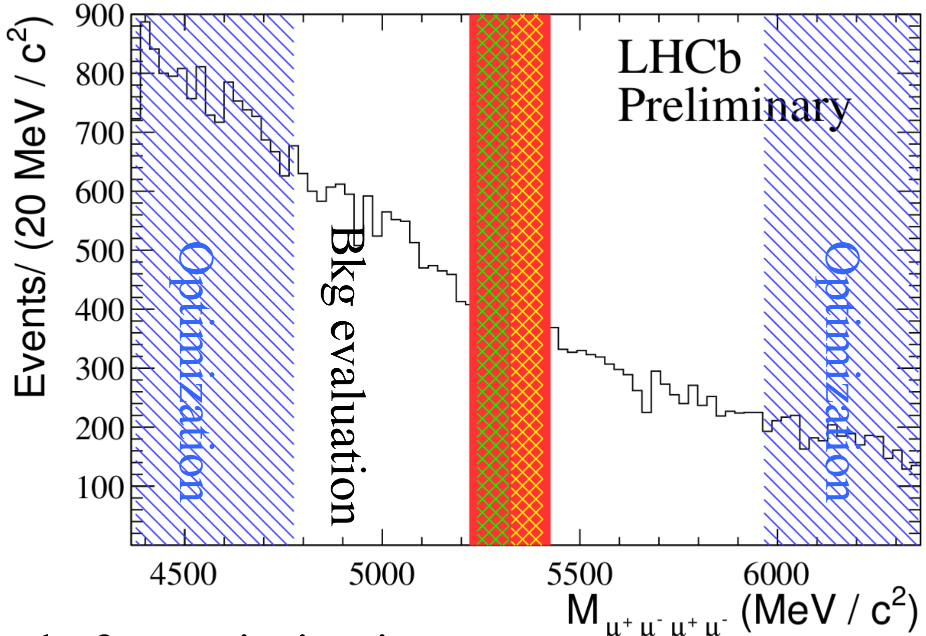
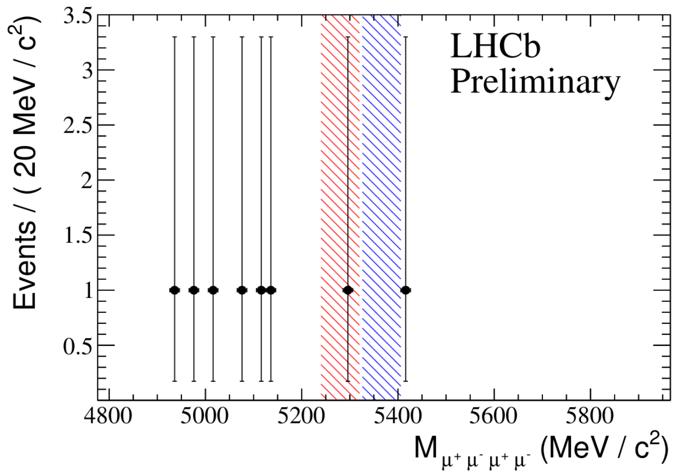




- Side bands for optimizations and background evaluation.
- Check on resonant bkg: SM compatible.
- Unblind **non resonant** region $M_{4\mu}$ for **1 fb^{-1}**:

1 B_d and **0 B_s** events in signal window.

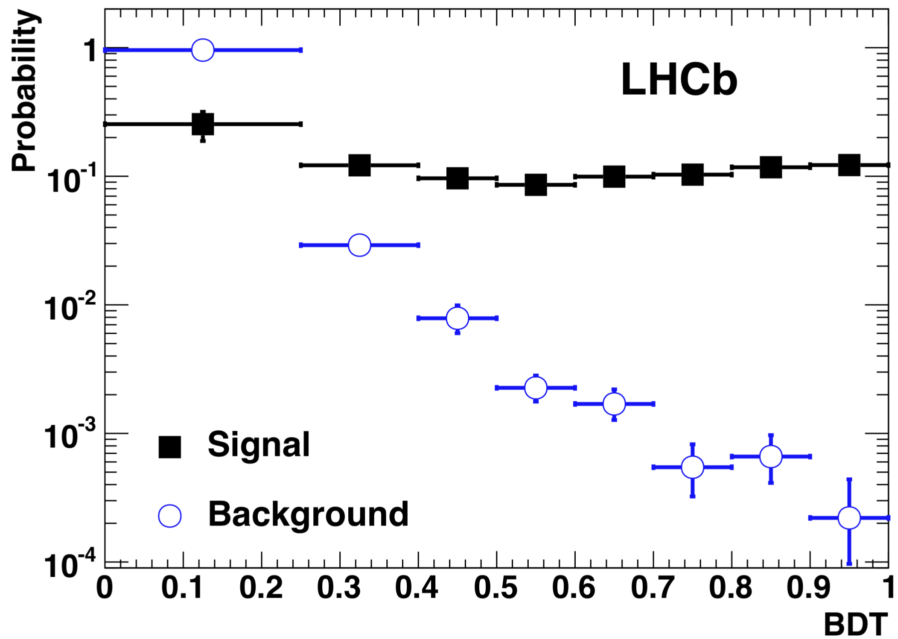
Normalize to $B \to J/\psi(\mu^+\mu^-)K^{*0}(K^+\pi^-)$

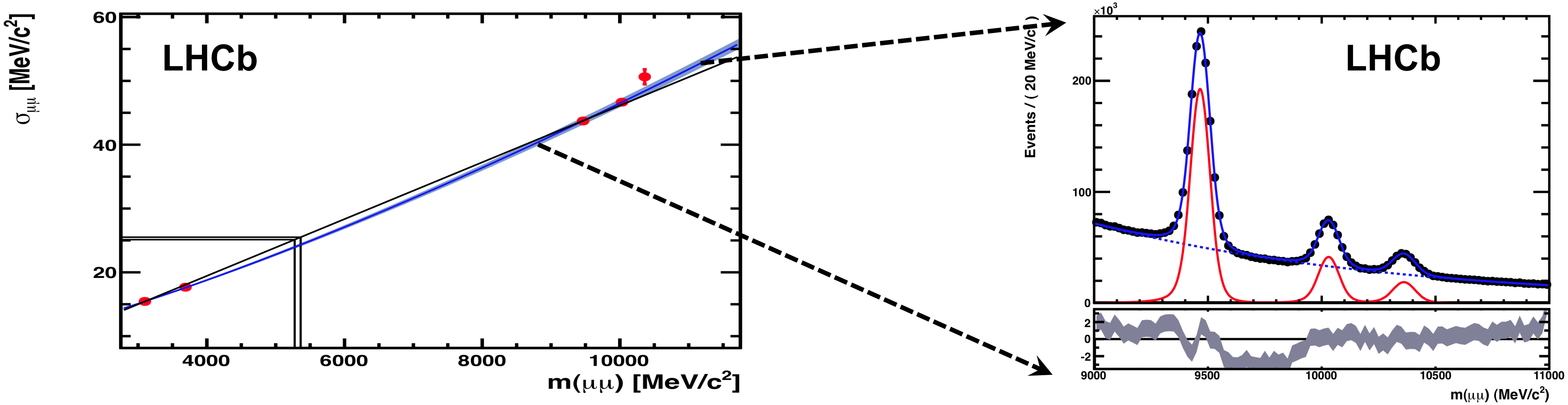
$BR(B_s \to \mu^+\mu^-\mu^+\mu^-) < 1.3\times10^{-8}$ and $BR(B_d \to \mu^+\mu^-\mu^+\mu^-) < 5.4\times10^{-9}$ [preliminary]

BR($B_s \to \mu\mu$) and BR($B_d \to \mu\mu$)

PRL 108,231801(2012)

- Loose μμ preselection
- Classify each event using BDT and invariant m(μμ) mass
- **BDT** optimized on MC but calibrated with data: **signal from B→hh** and **background from sidebands**.
- Mass parameters from B→hh and dimuon resonances.

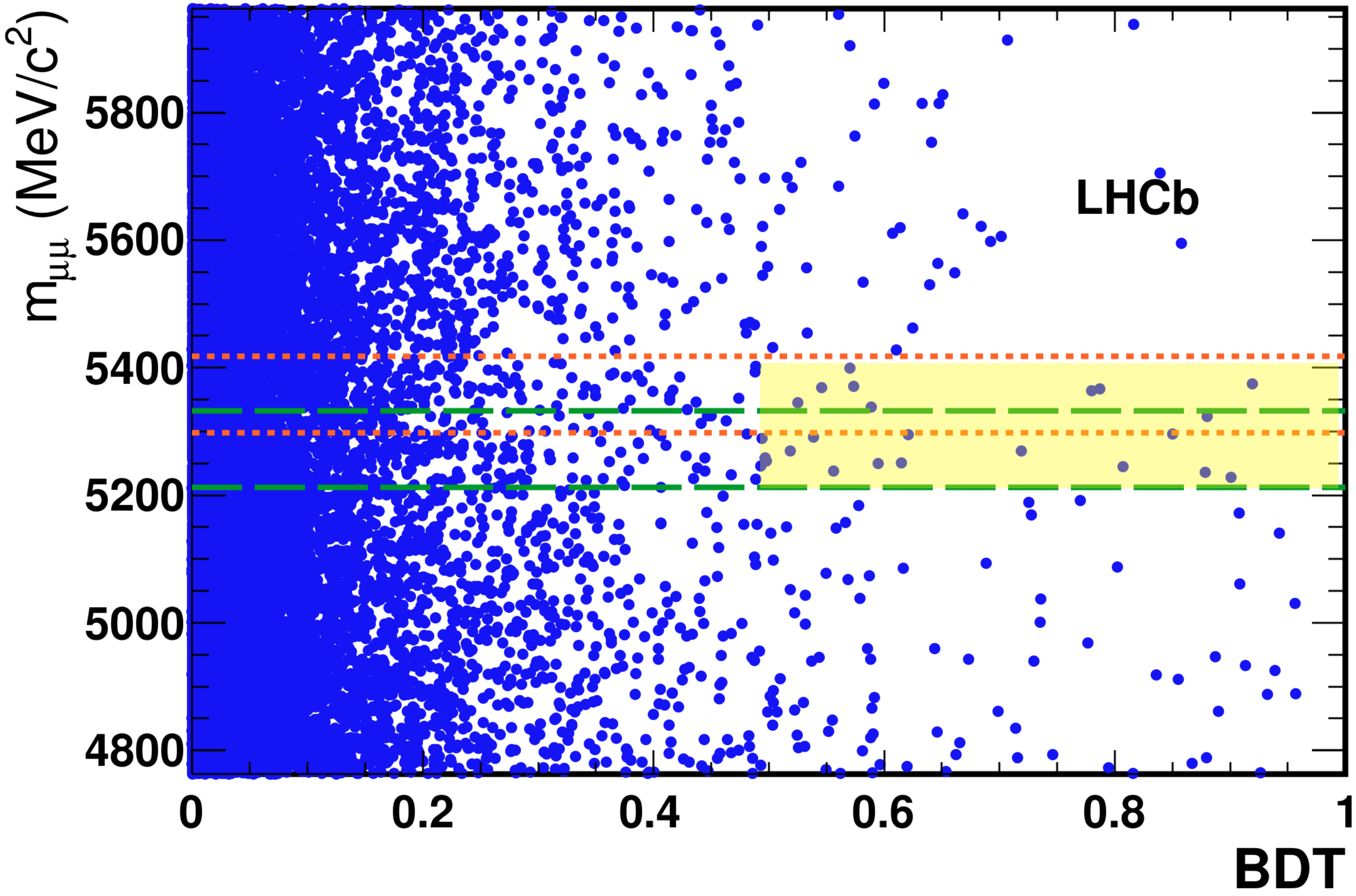




$BR(B_s \to \mu\mu)$ and $BR(B_d \to \mu\mu)$

PRL 108,231801(2012)

1 fb^{-1} data distribution on the **BDT×mass plane**.



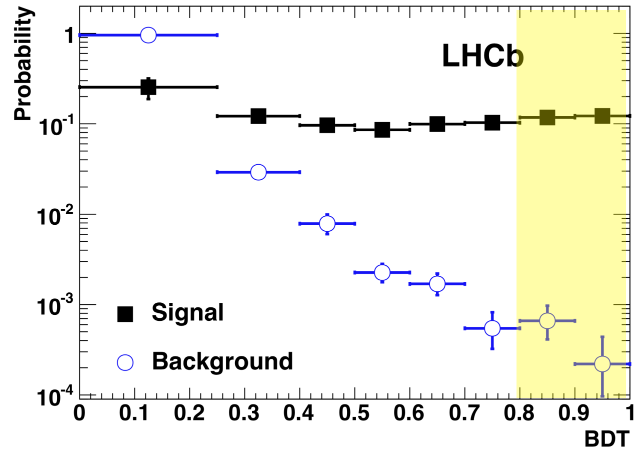
Fit in 8×9 bins on the plane [maximize S/B separation] for each search window, B_s and B_d, separately.

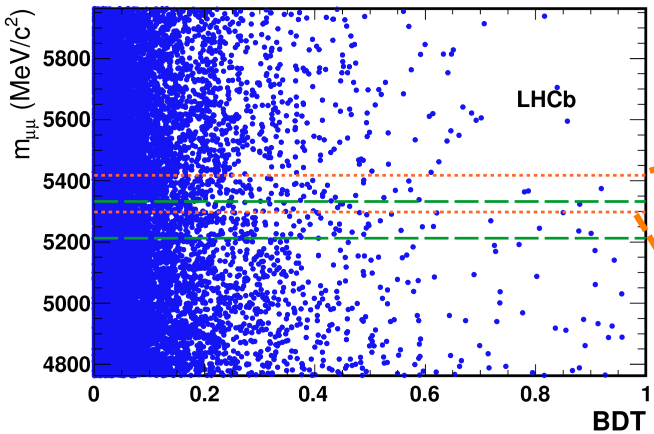
The whole BDT range is used to measure the two limits.

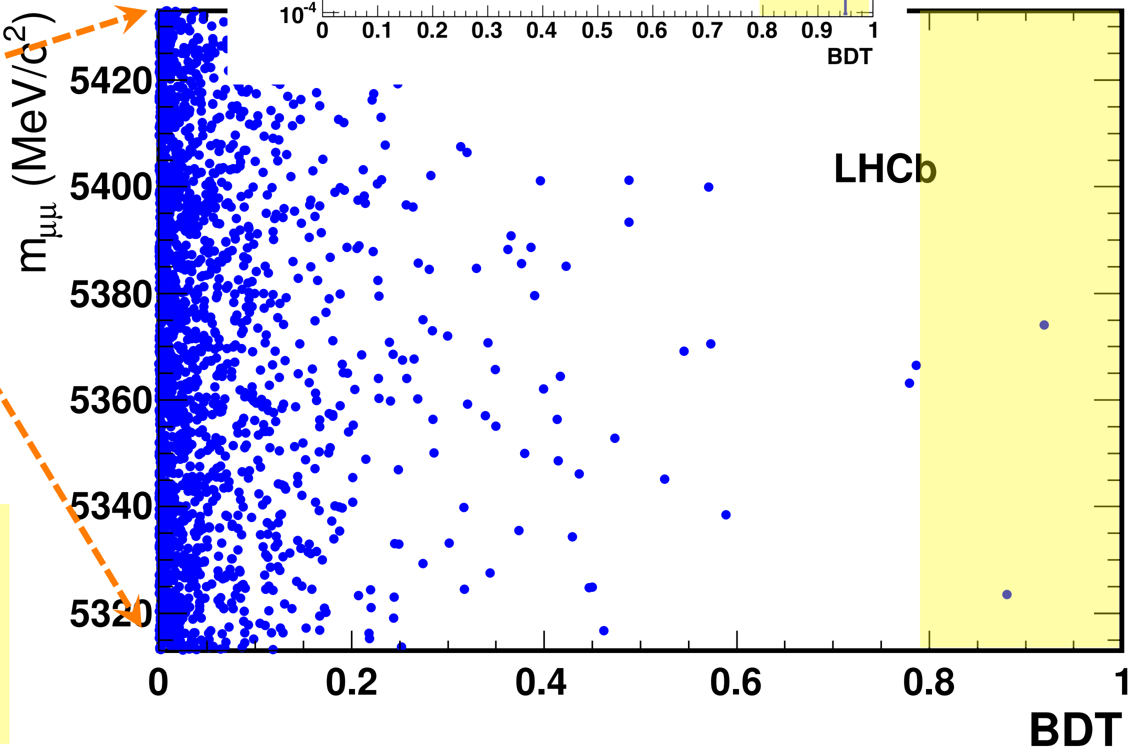
$BR(B_s \to \mu\mu)$ and $BR(B_d \to \mu\mu)$

PRL 108,231801(2012)

1 fb^{-1} data distribution: **zoom the B_s search window**.



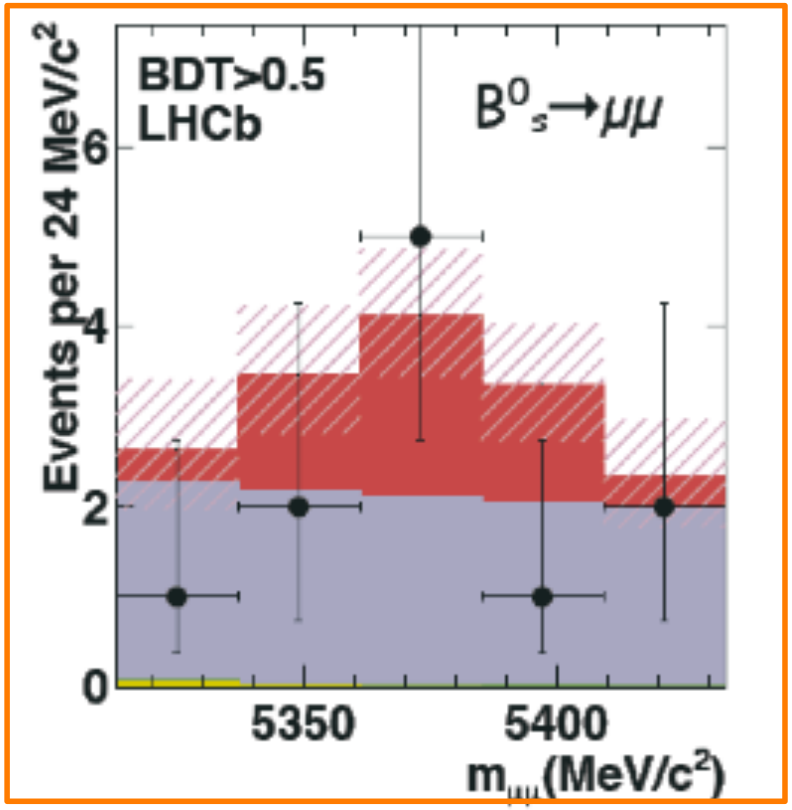


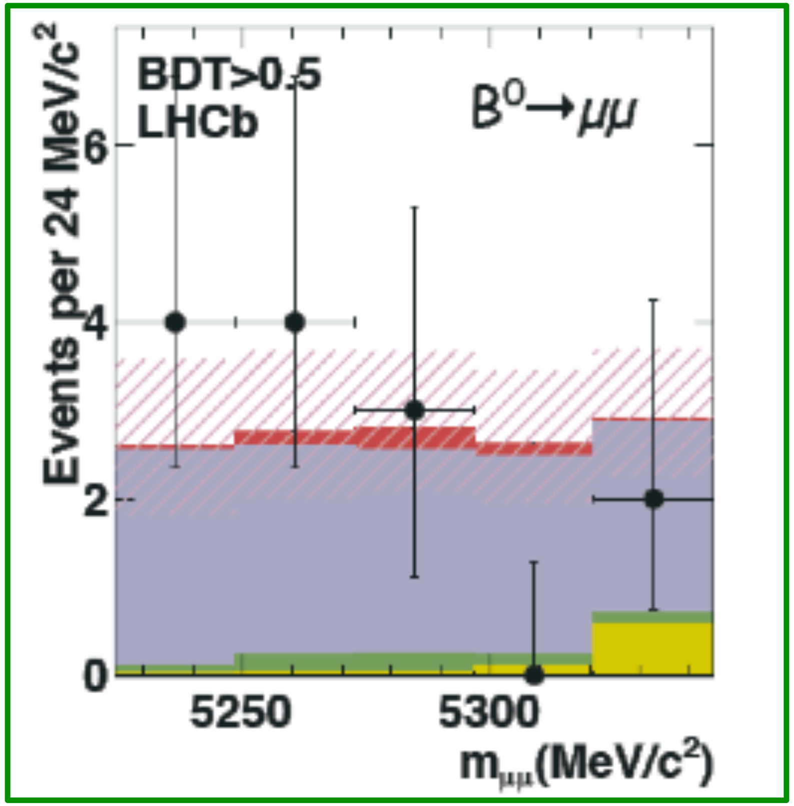


No background in the high BDT region (>0.8) where LHCb is most sensitive to signal.

$BR(B_s \to \mu\mu)$ and $BR(B_d \to \mu\mu)$

PRL 108,231801(2012)





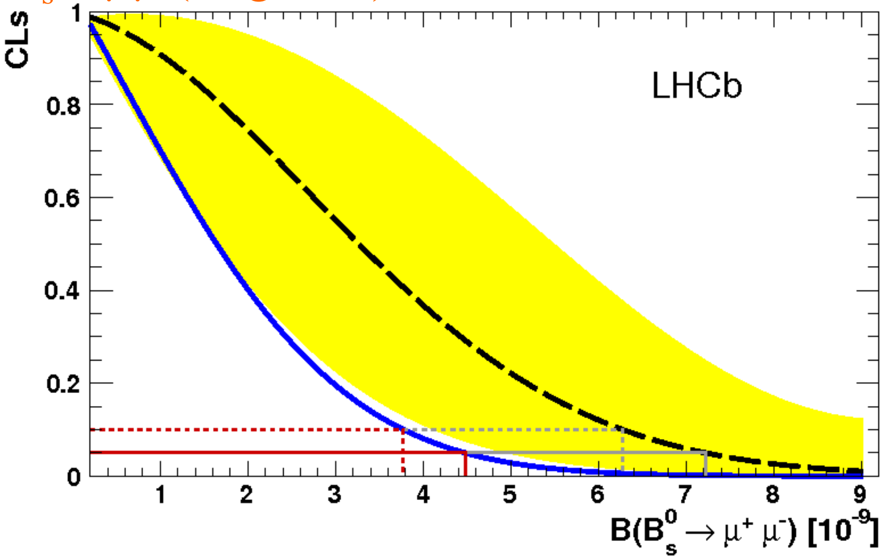
Pictorial synthesis of the events in the all mass bins with BDT>0.5:
expected SM signal, comb. bkg, B→hh bkg, cross-feed between channels.

Number of events translate into BR, normalizing to $\mathbf{B_s \to J/\psi\phi}$, $\mathbf{B_d \to J/\psi K^*}$, $\mathbf{B_d \to K\pi}$.

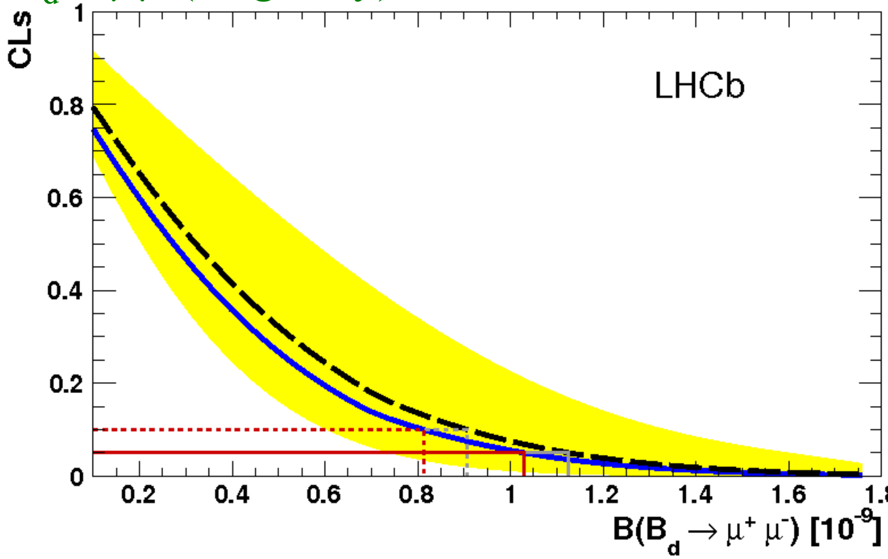
$BR(B_s \to \mu\mu)$ and $BR(B_d \to \mu\mu)$

PRL 108,231801(2012)

$B_s \to \mu\mu$ (Bkg+SM)



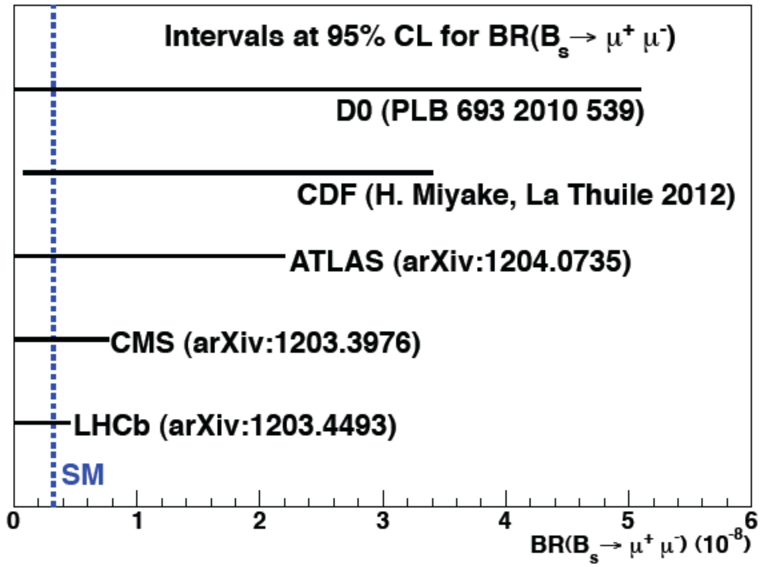
$B_d \to \mu\mu$ (Bkg only)



at 95%CL

$B_s \to \mu\mu$	**Exp. bkg + SM**	**7.2×10^{-9}**
	Exp. bkg	3.4×10^{-9}
	Observed	**4.5×10^{-9}**

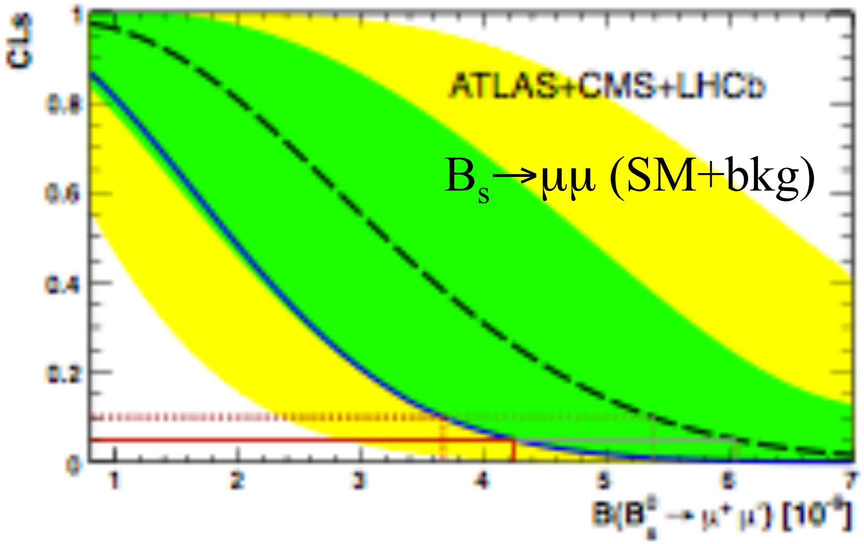
$B_d \to \mu\mu$	**Exp. bkg**	**1.1×10^{-9}**
	Observed	**1.0×10^{-9}**

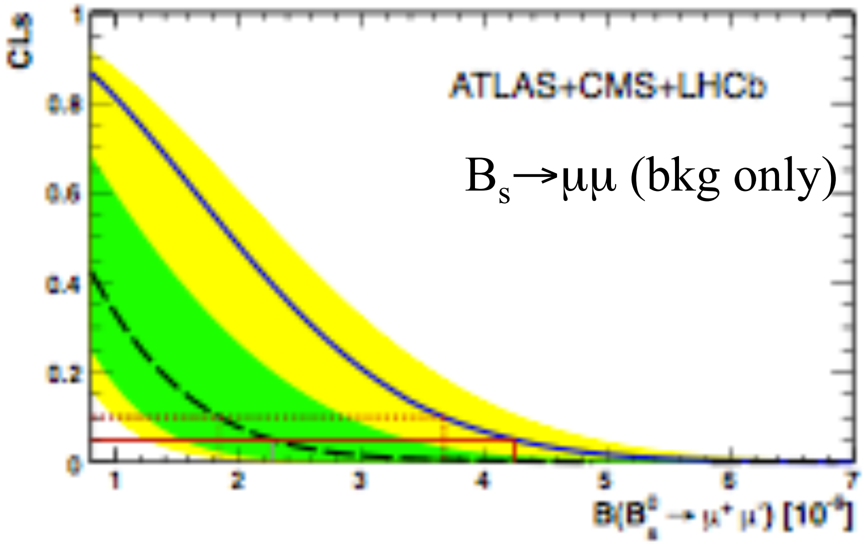


$B_s\mu\mu$ combination and perspectives

arXiv:1204.0735, JHEP 1204(2012) 033, PRL 108,231801(2012), LHCb-CONF-2012-017

New ATLAS, CMS, and LHCb results have been combined [preliminary].

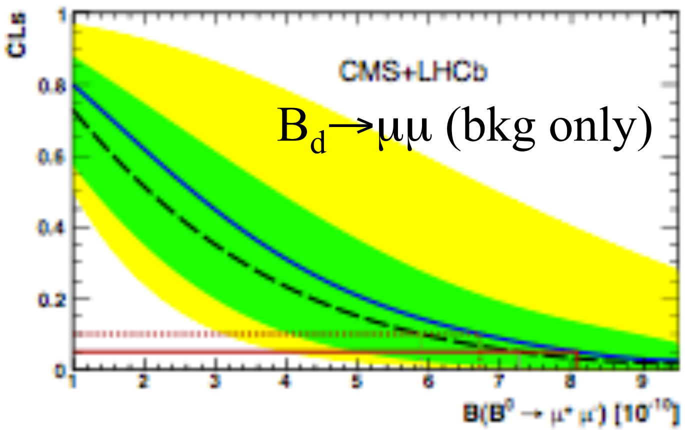




BR($B_s \to \mu\mu$)<**4.2×10^{-9}** at 95% CL

excess over bkg at 2σ; compatible with SM at 1σ.

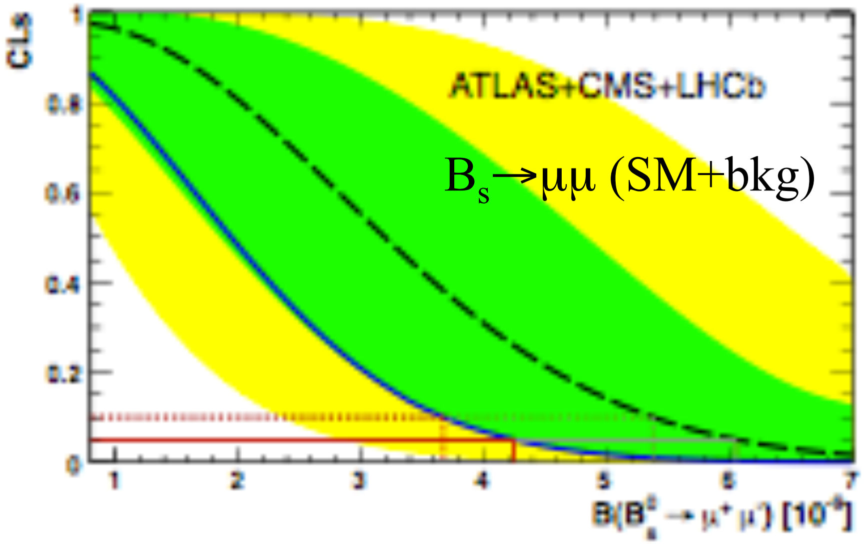
BBR($B_d \to \mu\mu$) <**0.81×10^{-9}** at 95%)CL

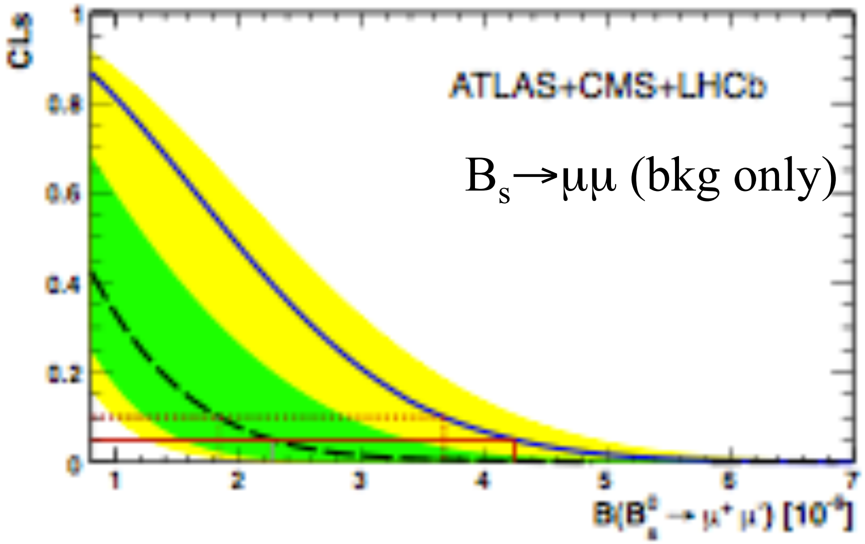


$B_s\mu\mu$ combination and perspectives

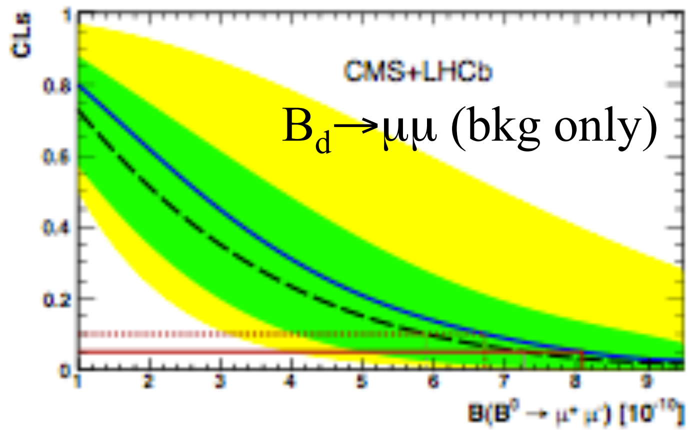
LHCb-CONF-2012-017

SM prediction $(3.2\pm0.2)\times10^{-9}$ [Buras, Acta Phys. Pol. vol 41 (2010)]





- No significant BR($B_s\to\mu\mu$) enhancement.
- $B_s\to\mu\mu$: eating in SM prediction
- Precision measurement of $B_s\to\mu\mu$.
- Observation of $B_d\to\mu\mu$ SM
- Measure the ratio $B_s\to\mu\mu/B_d\to\mu\mu$: test MFV models



$BR(\tau \to \mu\mu\mu)$

LHCb-CONF-2012-015

Neutrino oscillations implies LFV at some level.

SM+ $\nu_\mu - \nu_\tau$ oscillations predict $BR(\tau \to \mu\mu\mu) \sim O(10^{-54})$.

In many BSM theories, LFV amplified in τ wrt μ; can predict $BR(\tau \to \mu\mu\mu)$ experimentally achievable 10^{-8}-10^{-10}.

[e.g. W.Marciano et al Ann.Rev.Nucl.Part.Sci 58 (2008)315]

Best limit $BR(\tau \to \mu\mu\mu) < 2.1 \times 10^{-8}$ at 90% CL [Belle, PLB687(2010)139].

Large inclusive σ_τ (from B, D_s^- and D^0 mesons).

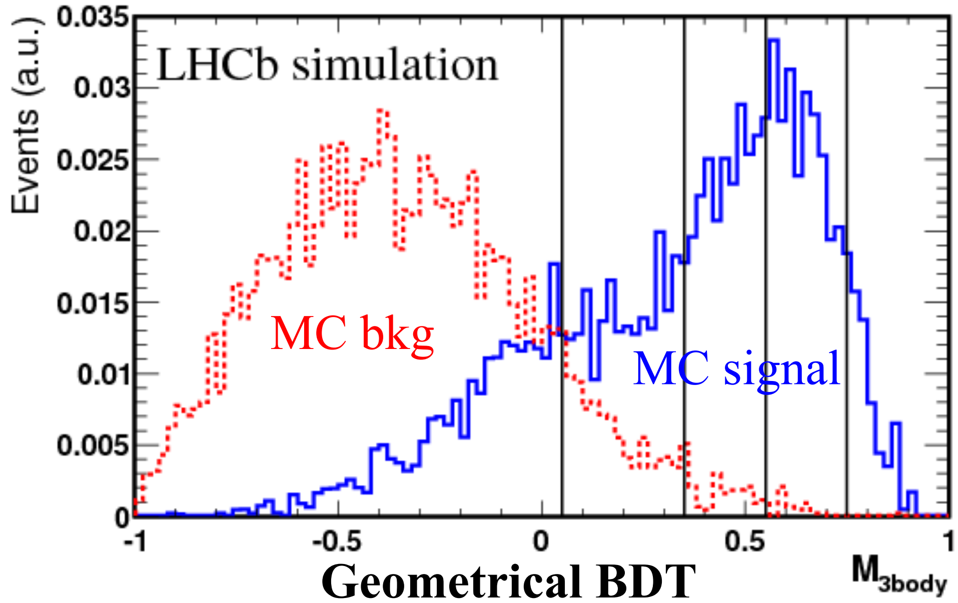
PID and bkg rejection: 3μ easier than $\mu^-\gamma$ or 3e.

Analysis strategy similar to $B_s\mu\mu$.

Signal/bkg discrimination via 3 classifiers:

- geometrical BDT (combinatorial bkg)
- PID BDT (μ hypothesis)
- 3 muons invariant mass, $m_{3\mu}$.

Developed using sig and bkg MC.



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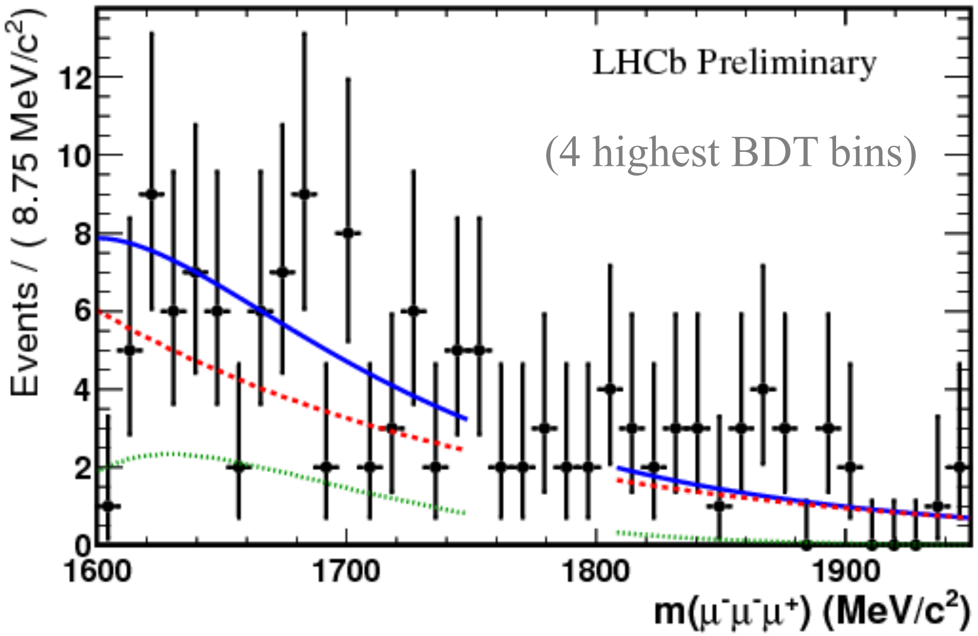
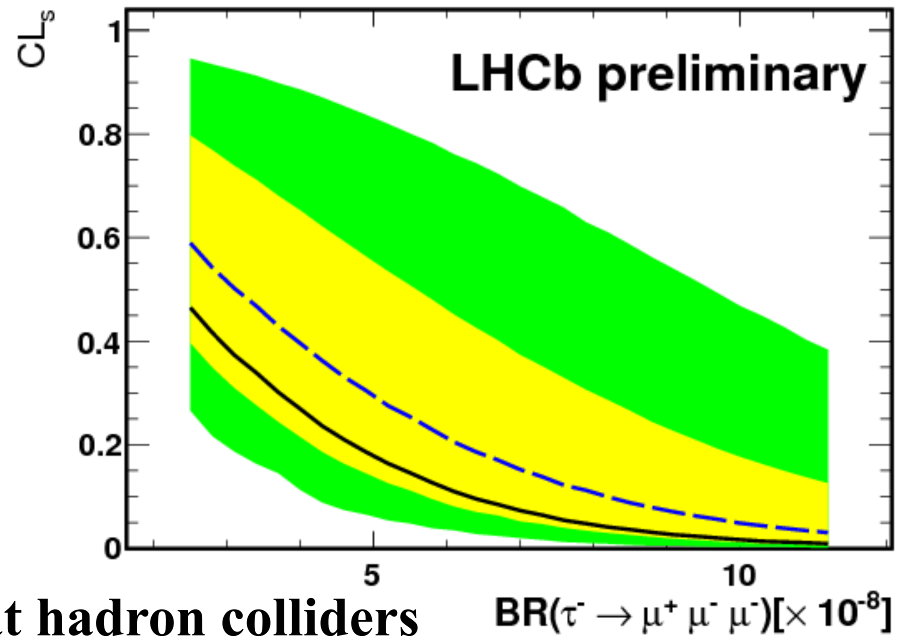


Final signal/bkg classifier **calibrated on $D_s^- \to \phi(\mu\mu)\pi^-$ data**: 5×5 bins with PID and geometrical information.

In each bin, fit $m(\mu^-\mu^-\mu^+)$ distribution.

Blind region: $m_\tau \pm 30$ MeV

Normalize to $D_s^- \to \phi(\mu\mu)\pi^-$, in **1 fb^{-1}** data



BR($\tau \to \mu\mu\mu$) [preliminary]

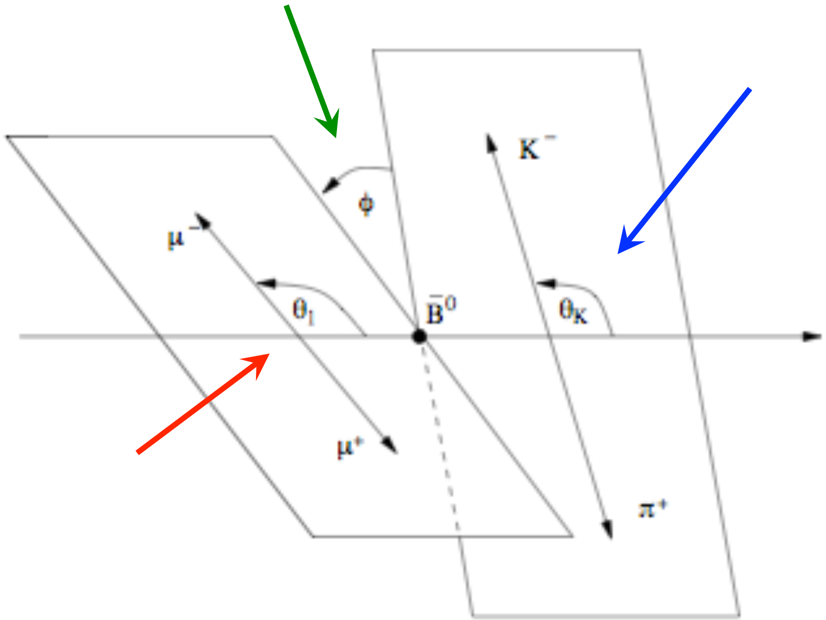
Expected $< 9.7 \times 10^{-8}$ at 95% CL

Observed $< 7.8 \times 10^{-8}$ at 95% CL

Proof of principle: can be made at hadron colliders

$B \to K^* \mu^+ \mu^-$: angular analysis

LHCb-CONF-2012-008



- The decay is described by three angles (θ_l, θ_K, ϕ) and the μμ invariant mass $\mathbf{q^2}$.

- Can define angular observables, where the hadronic uncertainties are under control and sensitive to NP.
- Full angular PDF:

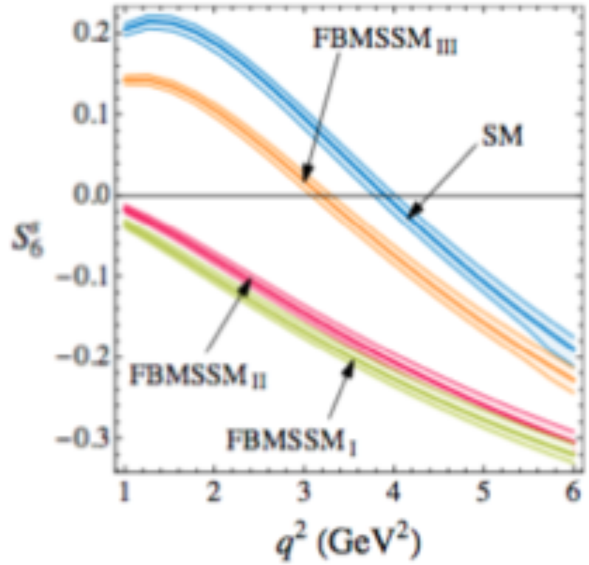
$$\frac{d^4\Gamma}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi\, dq^2} \propto \left[I_1^s \sin^2\theta_K + I_1^c \cos^2\theta_K + (I_2^s \sin^2\theta_K + I_2^c \cos^2\theta_K)\cos 2\theta_\ell + I_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + I_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi + I_5 \sin 2\theta_K \sin\theta_\ell \cos\phi + (I_6^s \sin^2\theta_K + I_6^c \cos^2\theta_K)\cos\theta_\ell + I_7 \sin 2\theta_K \sin\theta_\ell \sin\phi + I_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi + I_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi \right],$$

None of the experiments has enough statistics to attempt a full angular fit: projection of angles (BaBar, Belle, CDF) or **3D fit, folding $\phi \to \phi+\pi$, if $\phi<0$ (LHCb)**.

$B \to K^* \mu^+ \mu^-$: angular analysis

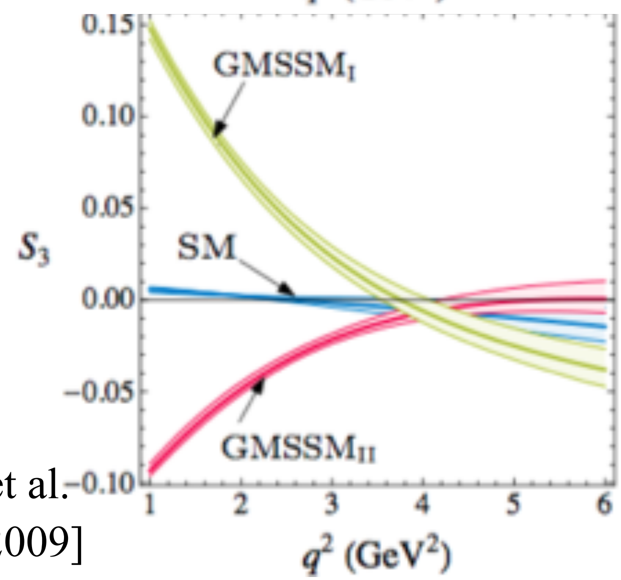
LHCb-CONF-2012-008

$$\frac{1}{\Gamma}\frac{d^4\Gamma}{d\cos\theta_\ell \, d\cos\theta_K \, d\hat{\phi} \, dq^2} = \frac{9}{16\pi}\Big[F_L \cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K) + F_L\cos^2\theta_K(2\cos^2\theta_\ell - 1) + \frac{1}{4}(1-F_L)(1-\cos^2\theta_K)(2\cos^2\theta_\ell - 1) + S_3(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\cos 2\hat{\phi} + \frac{4}{3}A_{FB}(1-\cos^2\theta_K)\cos\theta_\ell + A_{Im}(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\sin 2\hat{\phi} \Big]$$



The 3D fit in q^2 bins, allows to measure:

- F_L, K^* longitudinal polarization;
- S_6=4/3A_{FB}, the forward-backward asymmetry;
- S_3=(1-F_L)A_T^2, the transverse asymmetry;
- A_{Im}, the T-odd asymmetry.

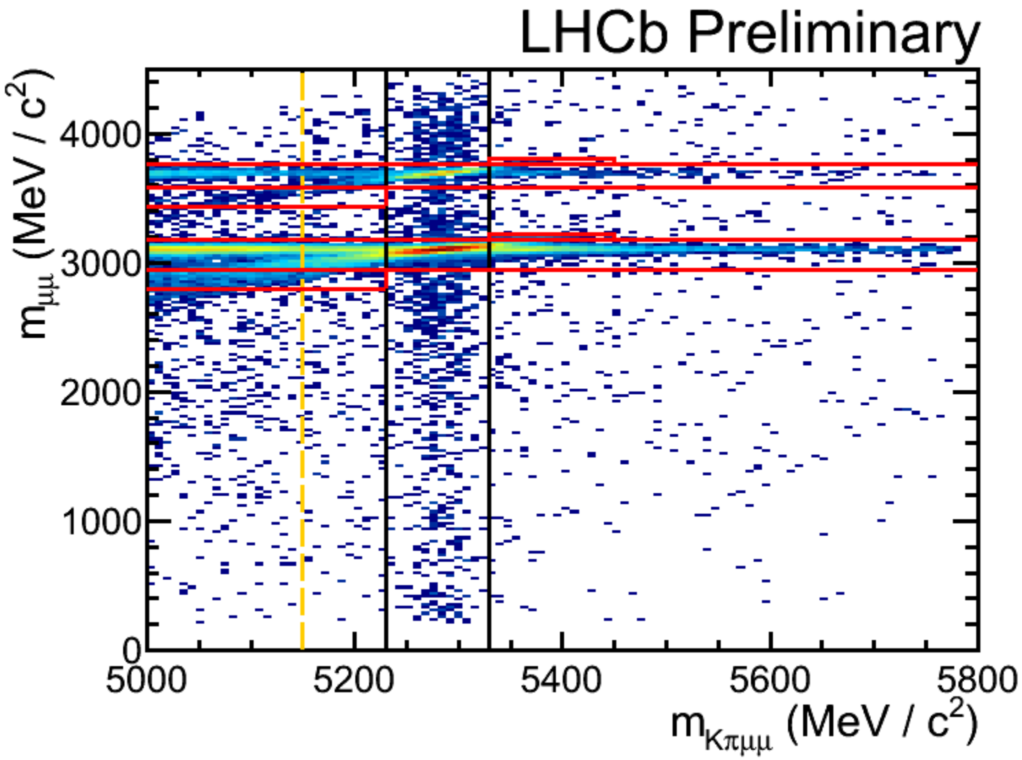


Better sensitivity and easier (natural) correlations treatment.

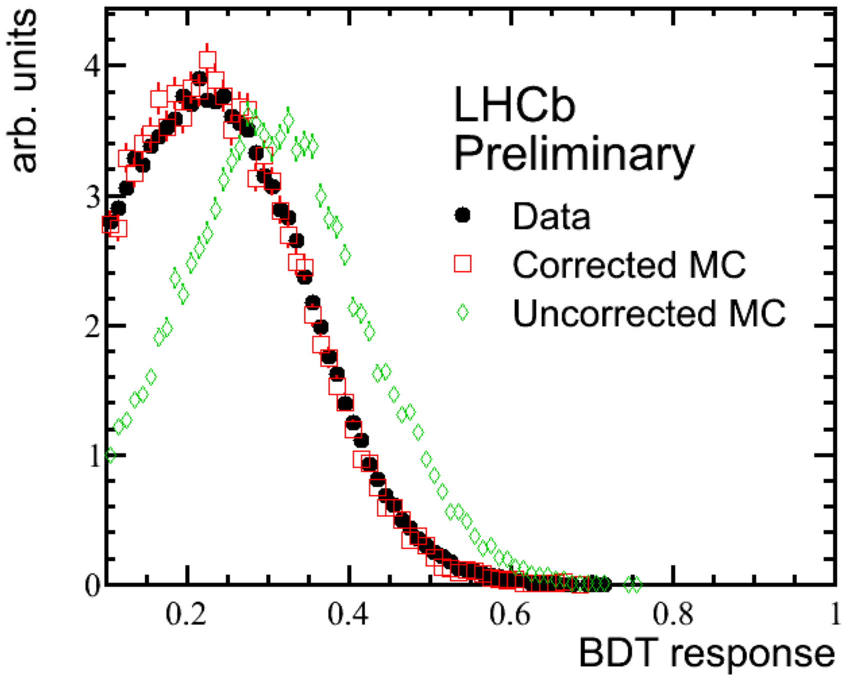
[Altmannshofer et al. JHEP 0901:019,2009]

$B \to K^* \mu^+ \mu^-$: angular analysis

LHCb-CONF-2012-008

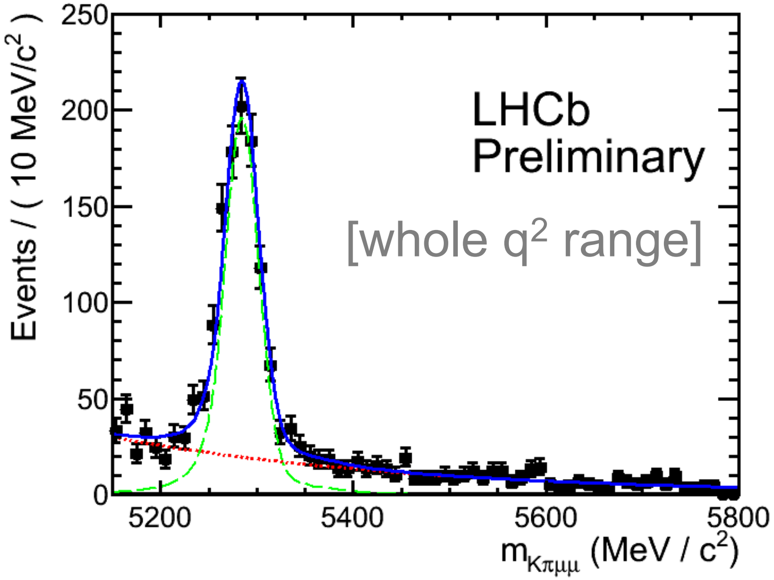


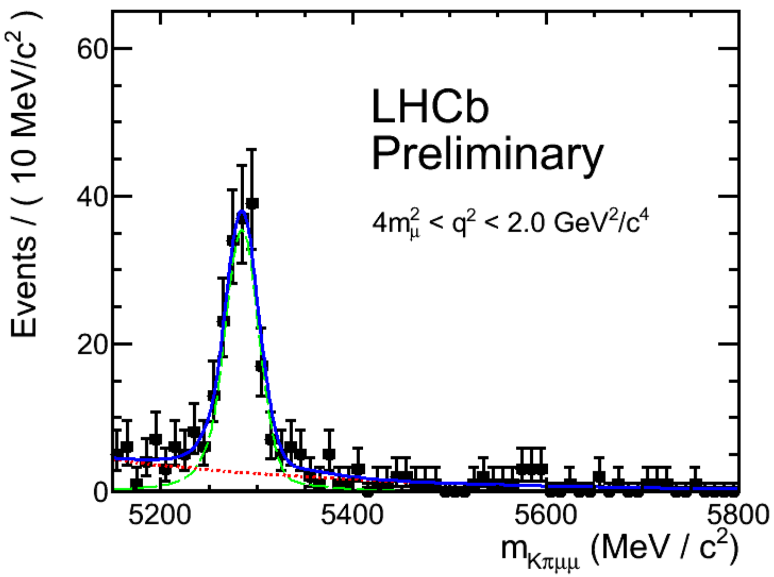
- Use a **BDT** to select $B \to K^* \mu^+ \mu^-$ events.
- Remove J/ψ and $\psi(2S)$ dimuon resonances.



Detector acceptance effects:

- tuning of MC using data driven techniques.
- check MC quality with $B_d \to K^* J/\psi$ data control sample.
- **each event is weighted using corrected MC efficiency $\varepsilon(\theta_l, \theta_K, \phi, q^2)$**.

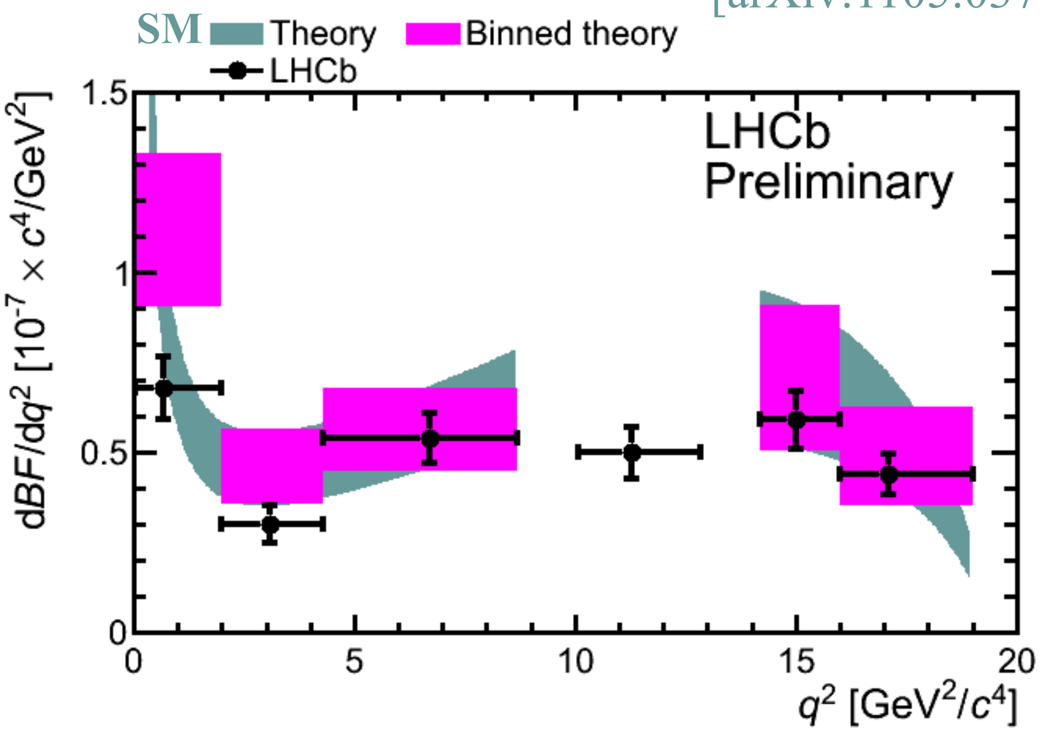




LHCb-CONF-2012-008

- In total, observe 900±34 events in **$1\ fb^{-1}$** data.
- Fitting m(Kπμμ) in q^2 bins measure differential BR (normalize to $B \to K^{0*} J/\psi$).
- Compare with **SM predictions**.

[arXiv:1105.0376]



$B \to K^* \mu^+ \mu^-$: angular analysis

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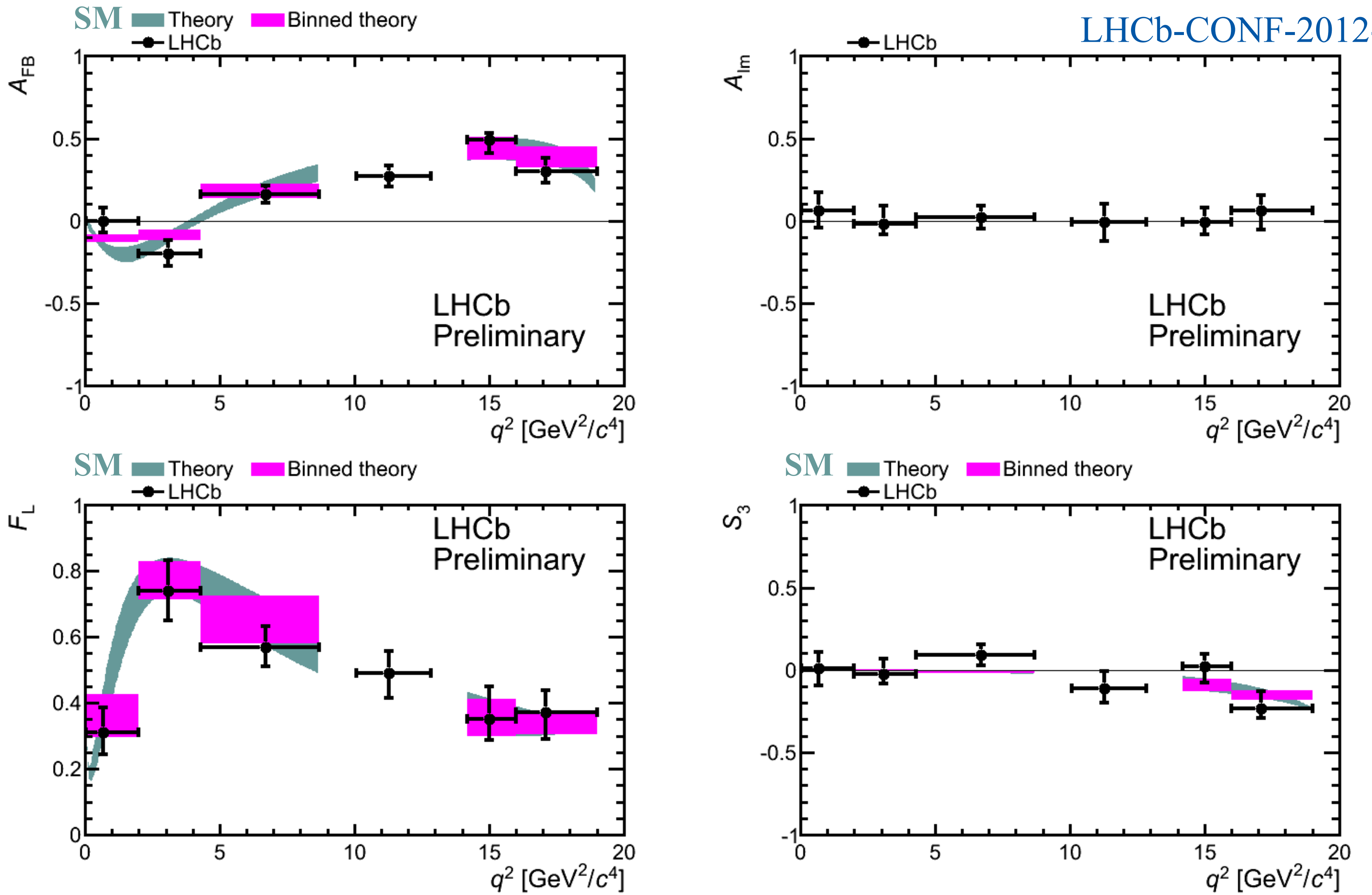
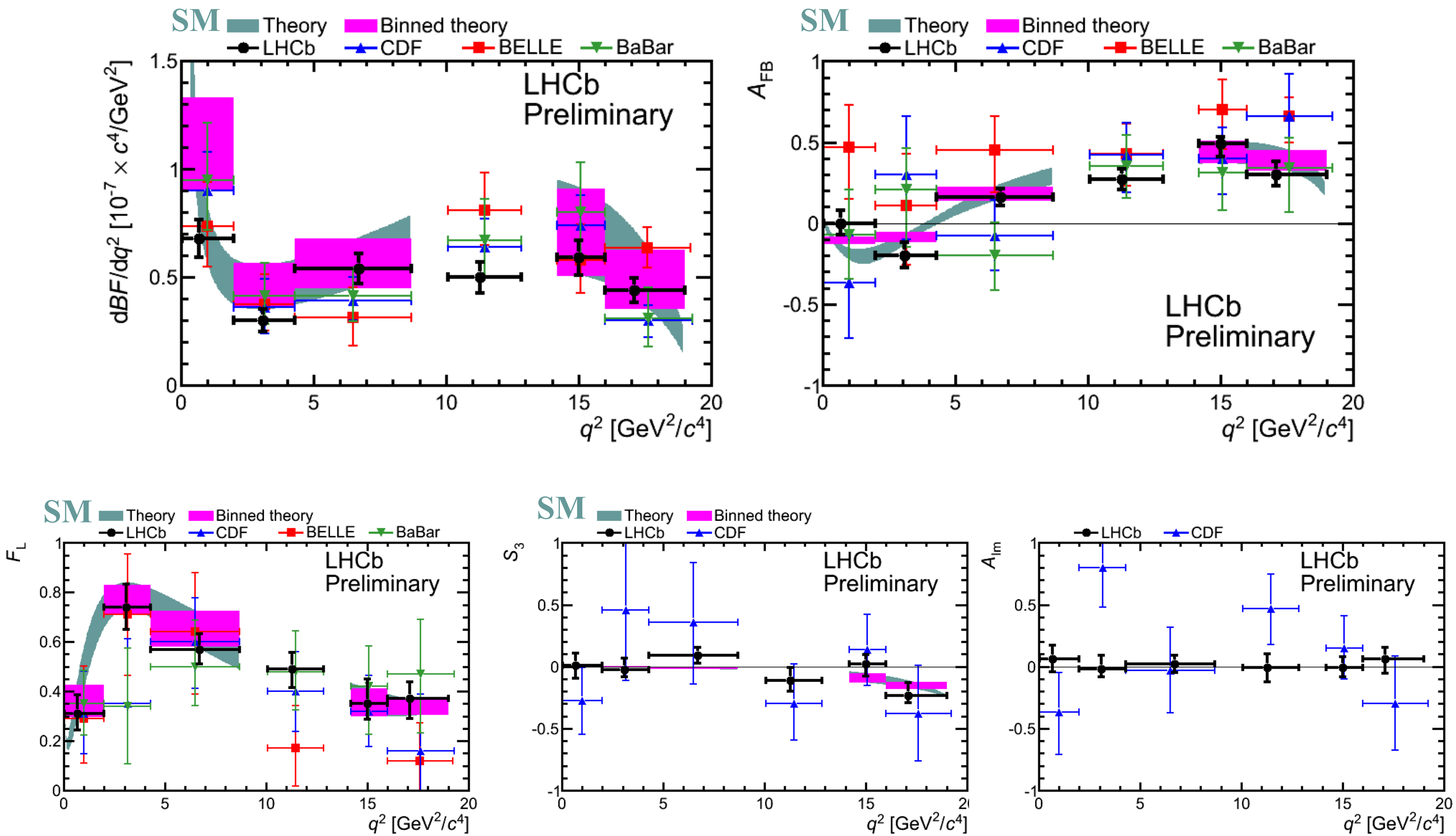


$B \to K^* \mu^+ \mu^-$: angular analysis

LHCb-CONF-2012-008



$B \to K^{*} \mu^{+} \mu^{-}$: angular analysis

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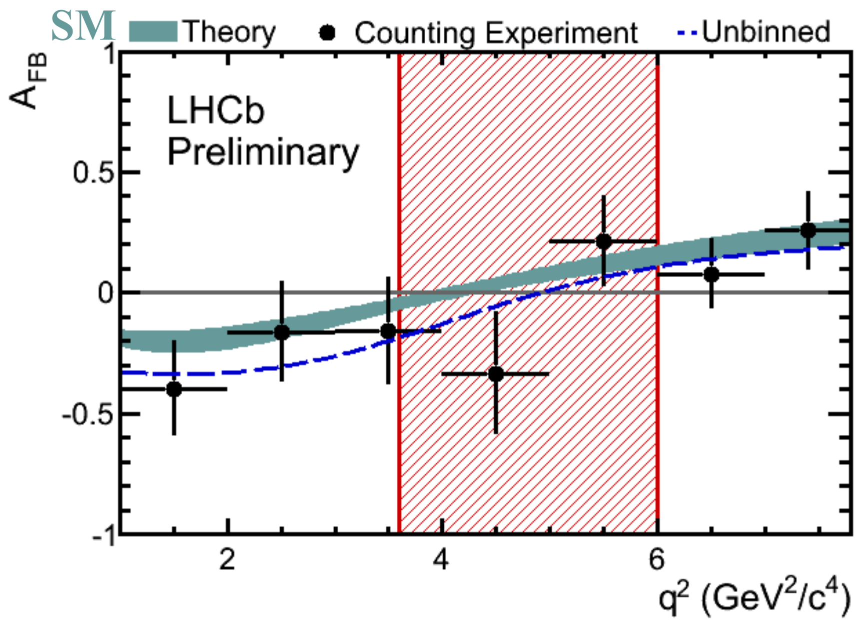
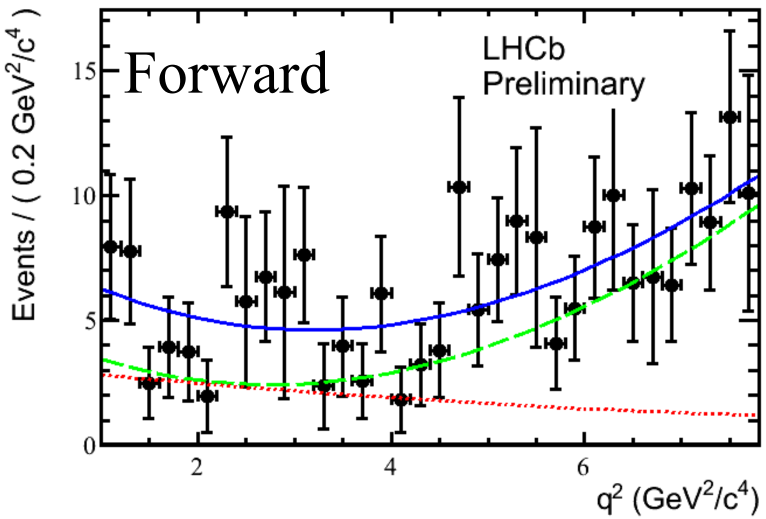
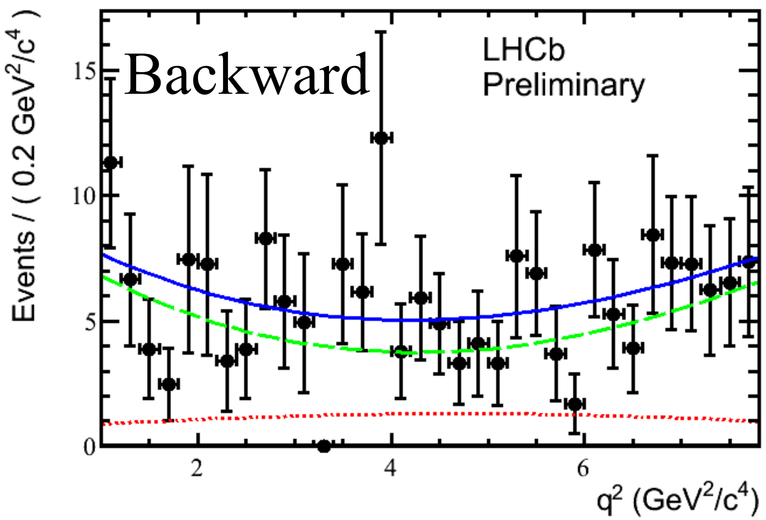






- In SM A_{FB} changes sign at a well defined q^2 point, predicted with no hadronic uncertainties e.g.: $q_0^2(K^*)=4.36^{+0.33}_{-0.31}$ GeV^2.

[Eur. Phys. J. C 41 (2005) 173-188]

- Extract q_0^2 from a 2D fit to q^2 distribution and the invariant mass M(Kπμμ) of forward and backward events separately: **$4.9^{+1.1}_{-1.3}$ GeV^2** [preliminary]

$B \to K\mu^+\mu^-$: isospin asymmetry

LHCb-PAPER-2012-011, arXiv:1205.3422

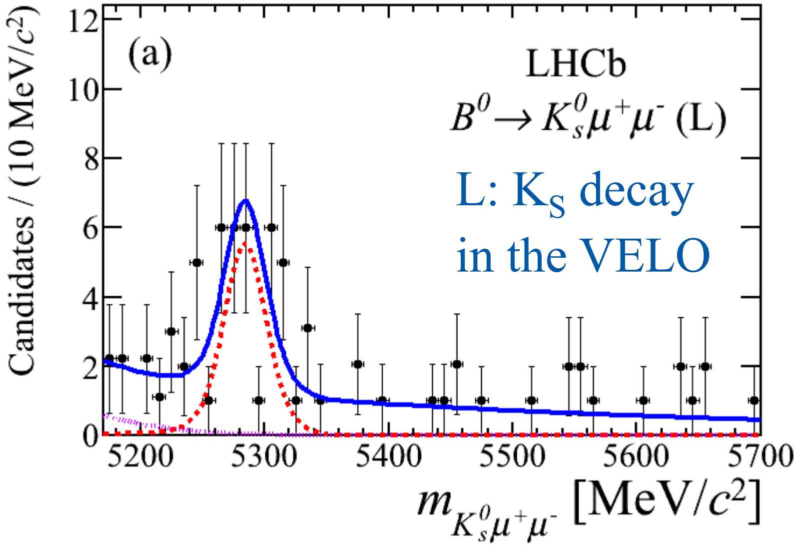
Measure differential BR of four decay modes:

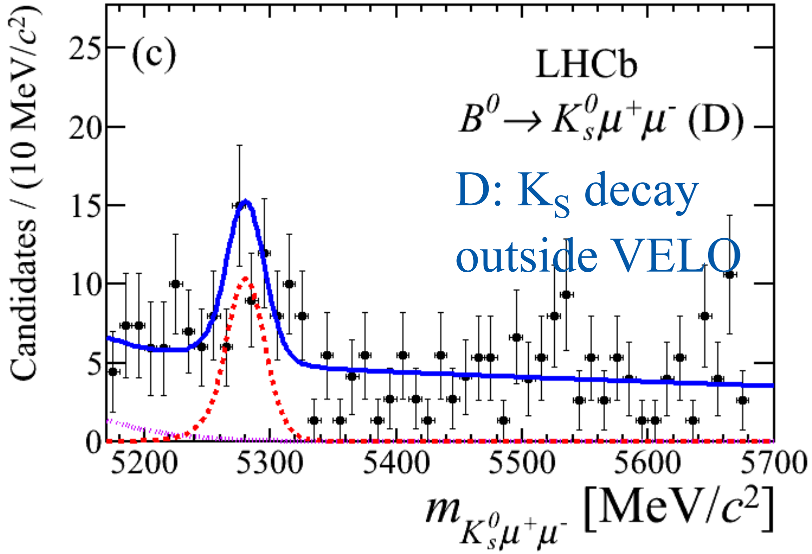
$B^0 \to K_S\mu^+\mu^-$ $B^0 \to (K^{*0} \to K^+\pi^-)\mu^+\mu^-$ $B^+ \to K^+\mu^+\mu^-$ $B^+ \to (K^{*+} \to K_S\pi^+)\mu^+\mu^-$

Predictions for BRs suffer from large hadronic uncertainties; in the asymmetries these contributions cancel at leading order. Define A_I comparing with relevant charged mode:

$$A_I = \frac{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) - \frac{\tau_0}{\tau_+}\mathcal{B}(B^\pm \to K^{(*)\pm}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) + \frac{\tau_0}{\tau_+}\mathcal{B}(B^\pm \to K^{(*)\pm}\mu^+\mu^-)}$$

Veto dimuon chamonium resonances; "K_S signal" channel split into L and D categories.





$B \to K\mu^+\mu^-$: isospin asymmetry

LHCb-PAPER-2012-011, arXiv:1205.3422

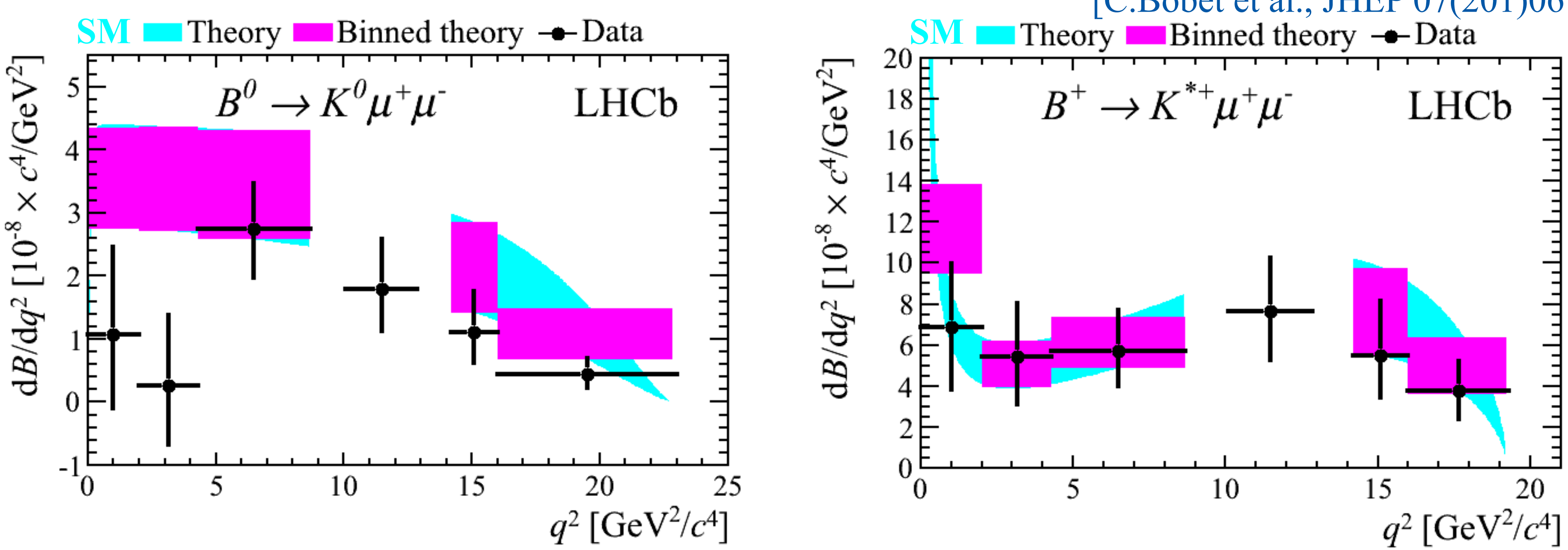
Normalize to $B^0 \to K^{(*)}(J/\psi \to \mu^+\mu^-)$ to get BR (stat+syst errors):

$BR(B^0 \to K_S\mu^+\mu^-) = (0.31^{+0.07}_{-0.06}) \times 10^{-6}$, **first observation (5.7σ)**.

$BR(B^+ \to K^{*+}\mu^+\mu^-) = (1.16 \pm 0.19) \times 10^{-6}$.

Extract differential BR for $B^0 \to K_S\mu^+\mu^-$ and $B^+ \to K^+\mu^+\mu^-$:

[C.Bobet et al., JHEP 07(201)067]

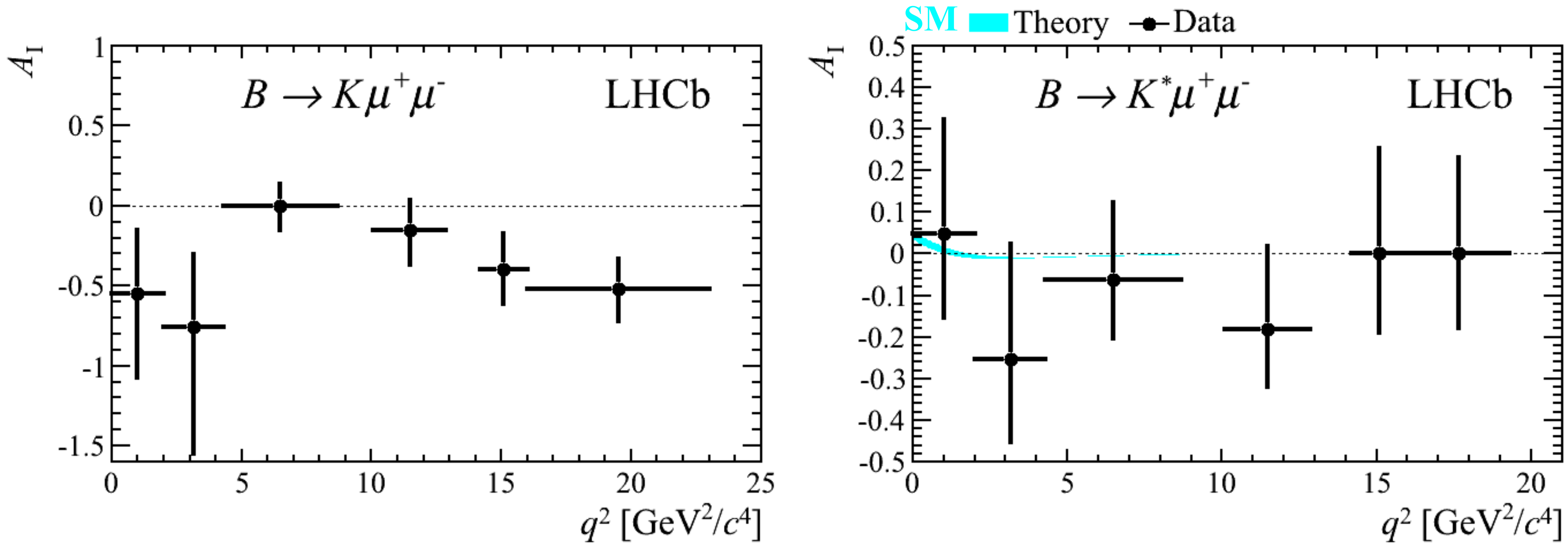


$B \to K\mu^+\mu^-$: isospin asymmetry

LHCb-PAPER-2012-011, arXiv:1205.3422

SM predicts A_I~0; sizable (10%) deviation from 0 only in the low q^2(<1) spectrum.

[T.Feldmann and J.Matias, JHEP 01(2002)074]



Integrated across q^2:

- $A_I(B^+ \to K^{*+}\mu^+\mu^-)$: consistent with zero, as predicted by SM.
- **$A_I(B^0 \to K^0\mu^+\mu^-)$: 4.4σ deviations from zero**;

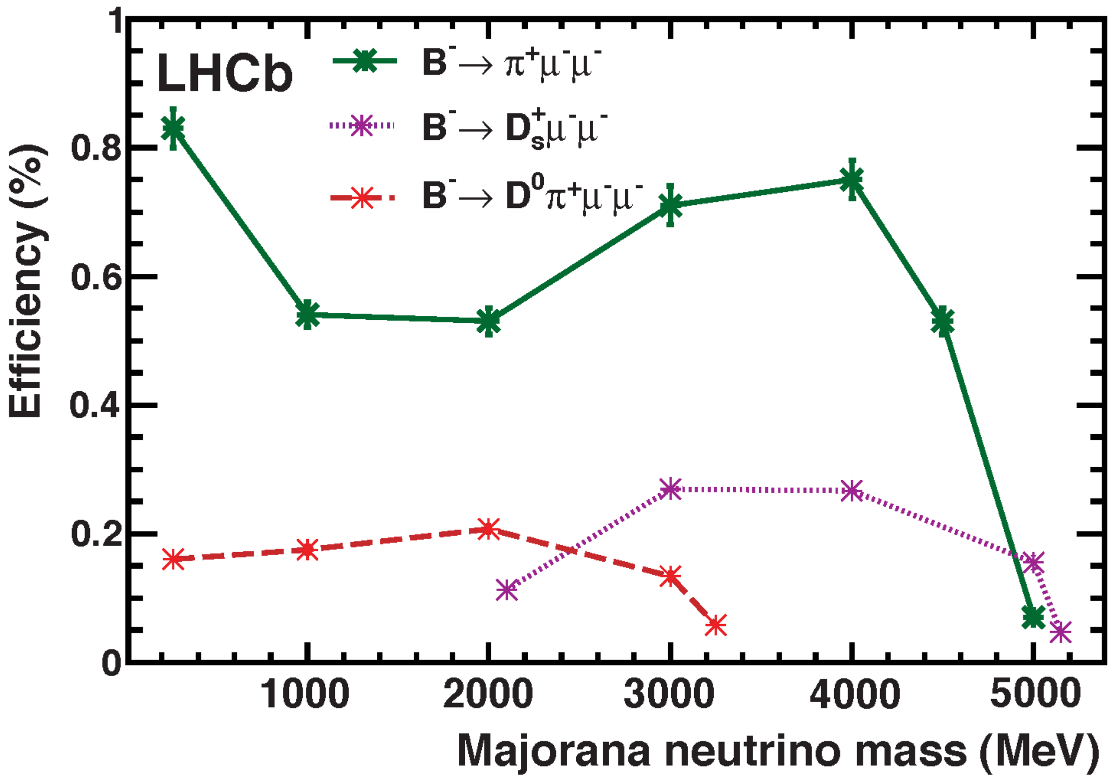
no explanations in or beyond SM.

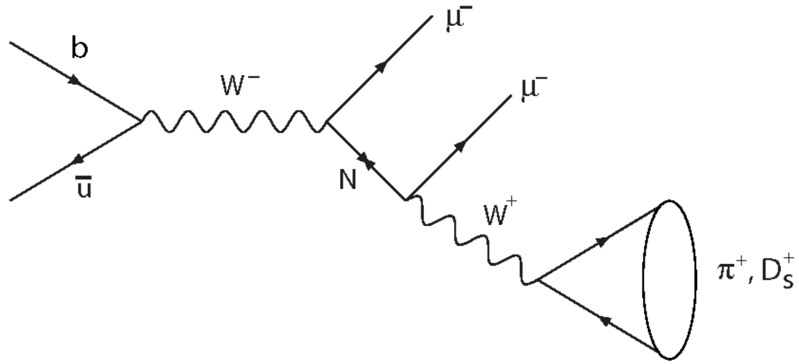
Majorana neutrino from B decays

Phys. Rev. Lett. 108 (2012) 101601, Phys. Rev. D 85, 112004 (2012)

Searches for Majorana neutrinos in $\mathbf{B^+ \to h^- \mu^+ \mu^+}$ or $\mathbf{B^- \to \mu^- \mu^- + hadrons}$:
- $D^{(*)+}\mu^-\mu^-$ final states: mediated by ν_M of any mass;
- final states with π^+, D_s^+ or $D^0\pi^+$: mediated by on-shell ν_M.

Each channel allows to explore different ν_M mass ranges.

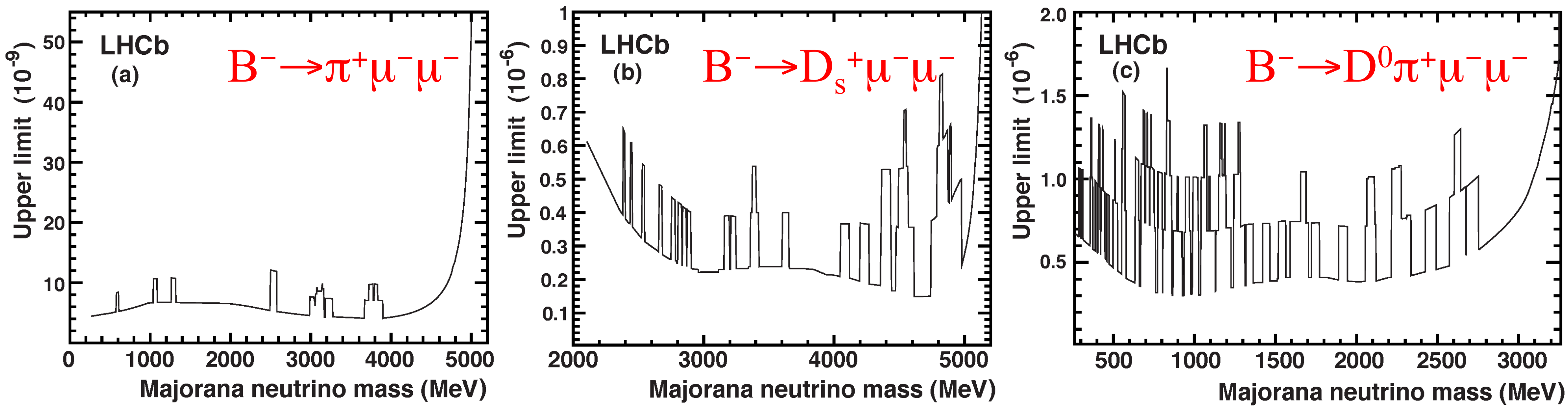




Normalization: channels with same number of muons in the final state and equal track multiplicity

Majorana neutrino from B decays

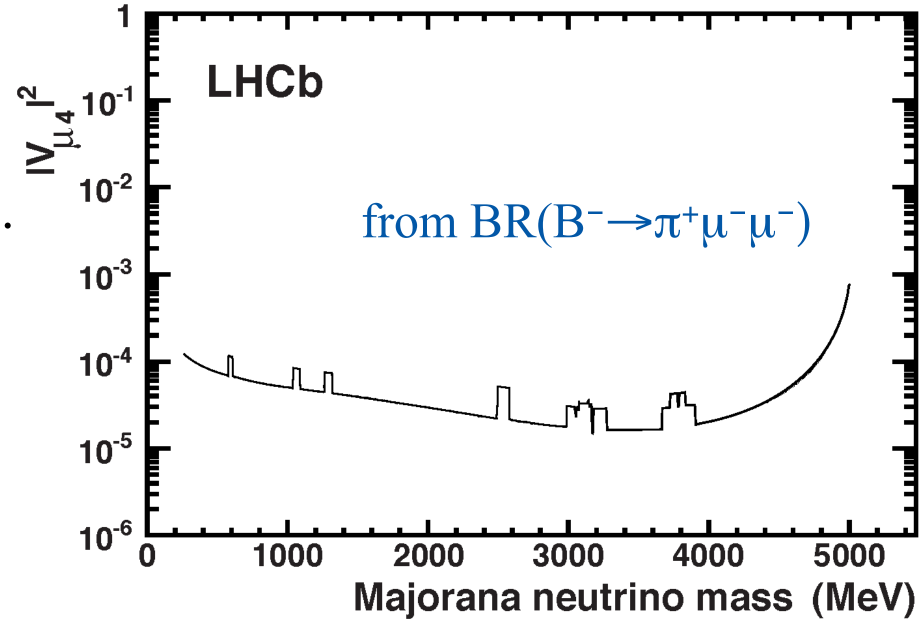
Phys. Rev. Lett. 108 (2012) 101601, Phys. Rev. D 85, 112004 (2012)



No events found in **0.41 fb^{-1}**.

BR limits at 95% CL: most restrictive to date.

The limit on $B^- \to \pi^+\mu^-\mu^-$ can be used to establish the limits for the coupling $|V_{\mu 4}|$ **complementary to 0vββ searches** which probe (V_{e4}, m_4) plane.



Conclusions and perspectives

LHCb beautifully demonstrated the power of LHC in the flavour physics.

$B_{(s)}\to\mu\mu$: strong constraints on BR rule out a large part of NP parameters; eating into SM predictions.

$B\to K^*\mu^+\mu^-$ <u>angular analysis</u>: results constrain NP scenarios, still room for NP; not all the independent terms of the angular distribution have been measured yet; still limited statistical accuracy with respect to the accurate SM predictions.

$B\to K\mu^+\mu^-$ <u>isospin analysis</u>:
- $B\to K^*\mu^+\mu^-$ mode: agrees with SM prediction;
- $B\to K\mu^+\mu^-$ mode significantly deviates from zero, difficult to interpret.

No evidence for $B\to h\mu\mu$ (Majorana neutrino) or $\tau\to\mu\mu\mu$ (LFV).

SM still describes observations well: be prepared to observe tiny NP effects.
LHCb: ideally suited for this!

$BR(B\to\mu\mu)$: entering the precision realm

experiments	LHCb 1.0 fb^{-1}		CMS 4.9 fb^{-1}	
upper limit (95% CL)	expected	observed	expected	observed
$BR(B_s \to \mu^+\mu^-)$	7.2×10^{-9}	4.5×10^{-9}	8.4×10^{-9}	7.7×10^{-9}

With ×5 luminosity , CMS has comparable (15% lower) sensitivity to LHCb

theory (SM)

$BR(B_s\to\mu^+\mu^-) = (3.2 \pm 0.2)\times10^{-9}$ used so far Buras, Acta Phys. Pol. vol. 41 (2010)

careful comparison btw experiment and theory!

$$\mathrm{BF}\left(B_s \to f\right)_{\mathrm{theo}} = \left[\frac{1-y_s^2}{1+\mathcal{A}^f_{\Delta\Gamma}\, y_s}\right] \mathrm{BF}\left(B_s \to f\right)_{\mathrm{exp}}$$

De Bruyin et al., arXiv:1204.1735

0.911 ± 0.014

for $B_s \to \mu^+\mu^-$

P. Koppenburg, Analysis Week 24/4

using y_s from LHCb-CONF-2012-002

=> BR_{theo} < $4.5*0.91=4.1\times10^{-9}$ at 95%CL

$BR(B\to\mu\mu)$: entering the precision realm

1) $\mathcal{B}(B_q \to \mu^+\mu^-) = 4.36 \cdot 10^{-10} \frac{\tau_{B_q}}{\hat{B}_q} \frac{Y^2(v)}{S(v)} \Delta M_q$ — Buras, Physics Letters B 566 (2003)

used so far — $BR(B_s\to\mu^+\mu^-) = (3.2 \pm 0.2)\times10^{-9}$ (6.3%) — Buras, Acta Phys. Pol. vol. 41 (2010)

which makes use of Bs=1.33 ± 0.06 (4.5%) — Gamiz et al. (HPQCD), arXiv:0902.1815

2)

$$BR(B_s \to \mu^+\mu^-) = \frac{G_F^2\alpha^2}{64\pi^2} f_{B_s}^2 m_{B_s}^3 |V_{tb}V_{ts}^*|^2 \tau_{B_s} \sqrt{1-\frac{4m_\mu^2}{m_{B_s}^2}} \times \left\{ \left(1-\frac{4m_\mu^2}{m_{B_s}^2}\right) |C_{Q_1}-C'_{Q_1}|^2 + \left|(C_{Q_2}-C'_{Q_2}) + 2(C_{10}-C'_{10})\frac{m_\mu}{m_{B_s}}\right|^2 \right\} . \quad (2.4)$$

main uncertainty from fBs, but impressive lattice results -> all authors agree this is best option for the future

$BR(B_s\to\mu^+\mu^-) = (3.1 \pm 0.2)\times10^{-9}$ — Buras, arXiv:1204.5064 — use f_{Bs}= (227.7 ± 6.2) MeV

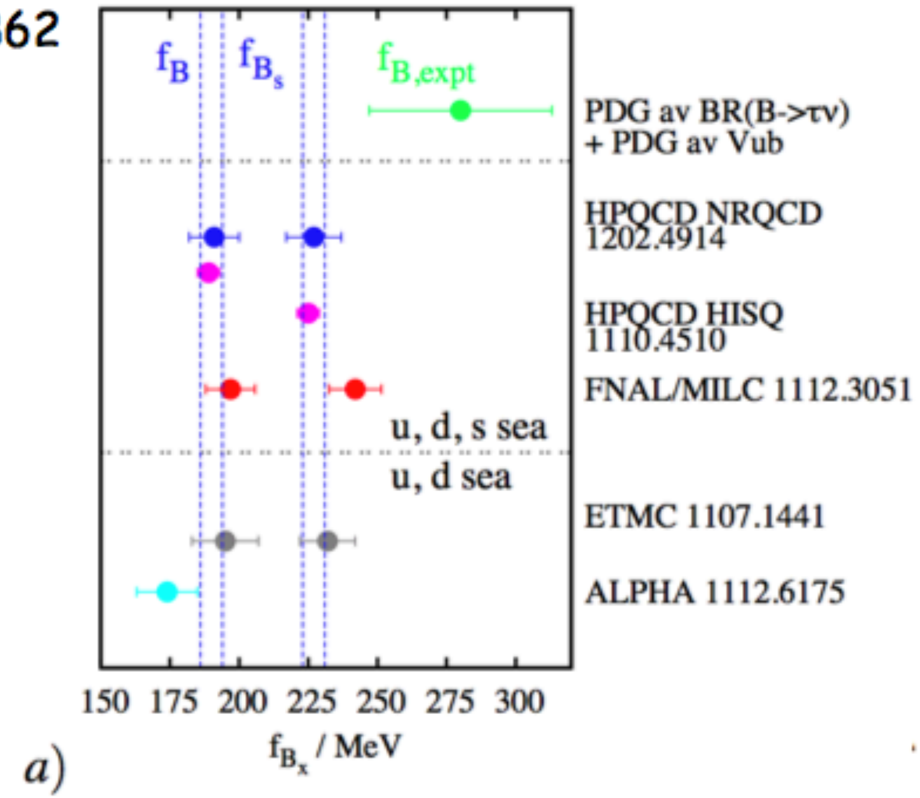
$= (3.64\,^{+0.17}_{-0.31})\times10^{-9}$ — CKM fitter, arXiv:,1106.4041 — use f_{Bs} = (231 ± 15) MeV

$= (3.53 \pm 0.38)\times10^{-9}$ — Mahmoudi, arXiv:,1205.1845 — use f_{Bs} = (234 ± 10) MeV

BR(B→μμ): entering the precision realm

plot from C. Davies review

arXiv:1203.3862



make your choice!

arXiv:1205.1845 (Mahmoudi et al.)

HPQCD-NRQCD + FNAL/MILC + ETMC

f_{Bs} = (234 ± 10) MeV

=> BR =(3.53 ± 0.38)×10^{-9}

arXiv:1203.3862 (Davies)

HPQCD-NRQCD + HPQCD-HISQ + FNAL/MILC

f_{Bs} = (227 ± 4) MeV

=> BR = (3.32 ± 0.25)×10^{-9}

all other inputs from Mahmoudi

new results will come, and a more clear strategy for getting an average, too: FLAG-2, 1st review end of 2012 (FPCP 2012, El-Khadra)