Rare decays at LHCb

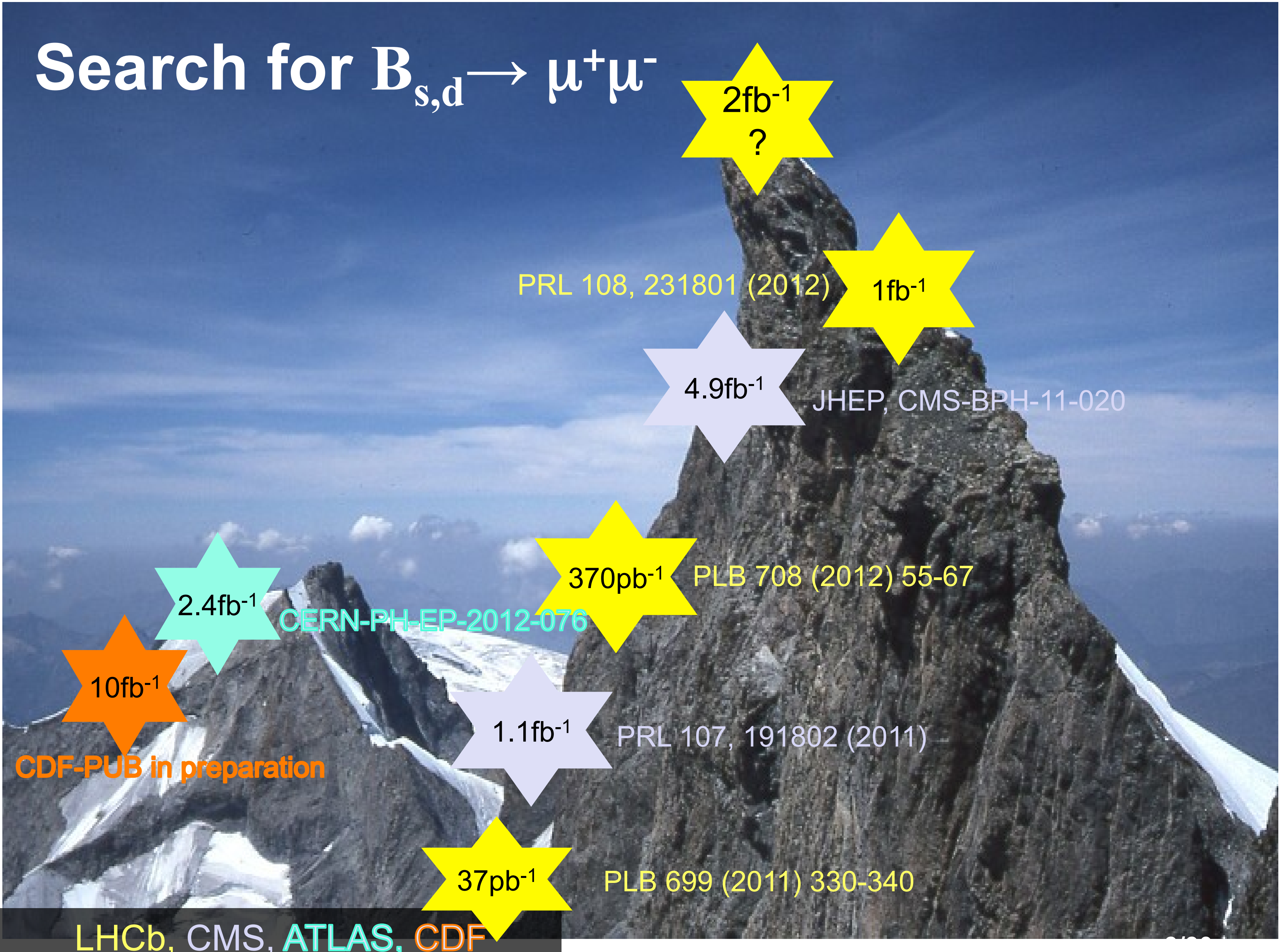
Johannes Albrecht (CERN)
on behalf of the LHCb Collaboration

June 11-13 2012, Capri
Fourth Workshop on Theory, Phenomenology and Experiments in Flavour Physics

Outline

- CPV measurements shown by M. Pepe Altarelli yesterday
- Use rare heavy flavor decays to search for
  - an extended Higgs sector
    → BR($B_{s,d} \to \mu^+\mu^-$)
  - new vector or axial couplings
    → Angular analysis of $B_d \to K^* \mu^+\mu^-$ decays
    → Isospin asymmetry in $B \to K^{(*)} \mu^+\mu^-$
  - new Majorana neutrinos → $B^+ \to h^- \mu^+\mu^+$
  - lepton flavor violation ($\tau^- \to \mu^+\mu^-\mu^-$)
- Outlook for LHCb: The detector upgrade

Search for $B_{s,d} \rightarrow \mu^+\mu^-$



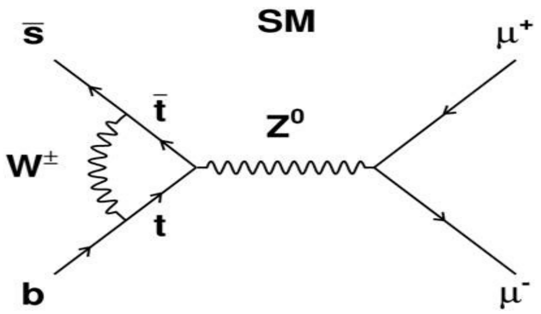
$B_{s,d} \rightarrow \mu^+\mu^-$ in the Standard Model

Double suppressed decay: **FCNC process** and **helicity suppressed**:

➔ **very small in the Standard Model but well predicted:**

Mode	SM
$B_s \rightarrow \mu^+\mu^-$	$3.1 \pm 0.2\ 10^{-9}$
$B^0 \rightarrow \mu^+\mu^-$	$0.10 \pm 0.01\ 10^{-9}$

A.J.Buras: arXiv:1204.5064 and ref therein
E. Gamiz et al: Phys.Rev.D 80 (2009) 014503

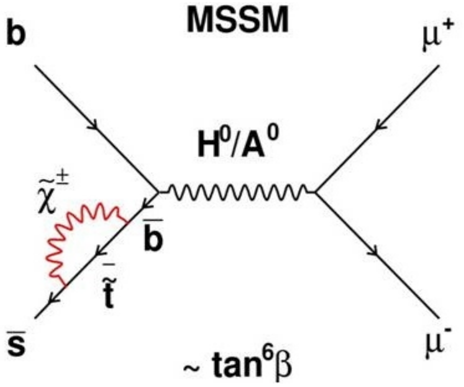


→ sensitive to contributions in the **scalar/pseudo-scalar sector**
→ highly interesting to probe **extended Higgs** models

$B_{s,d} \rightarrow \mu^+\mu^-$ in NP models: e.g. MSSM

Proportional to $\tan^6\beta$

➔ **limit or measurement of $B_{s,d} \rightarrow \mu^+\mu^-$ will strongly constrain parameter space**



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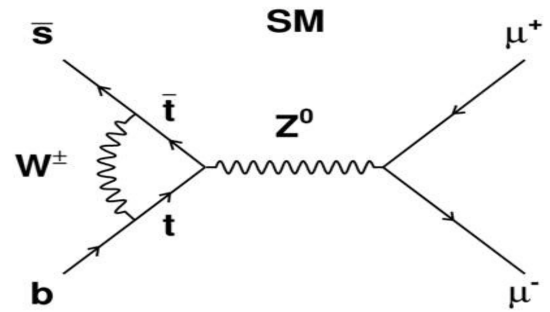

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Compare TH with experiment

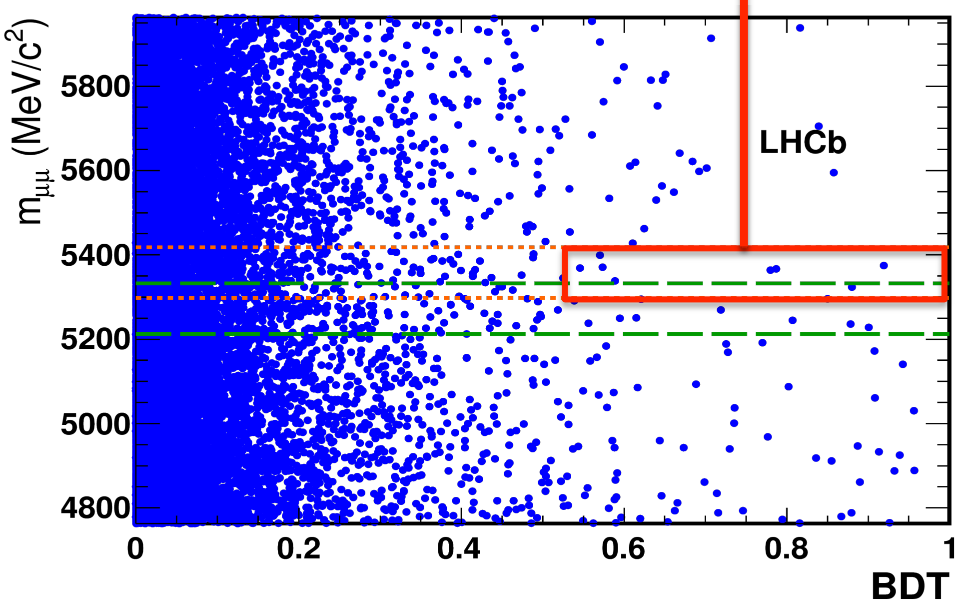
- Recently, LHCb measured $\Delta\Gamma_s = 0.116 \pm 0.019 ps^{-1}$ **[LHCb-CONF-2012-002]**
  → CP averaged and time averaged BR are different
  (as nicely explained by R. Fleischer some minutes ago)
- Adjust TH calculation:

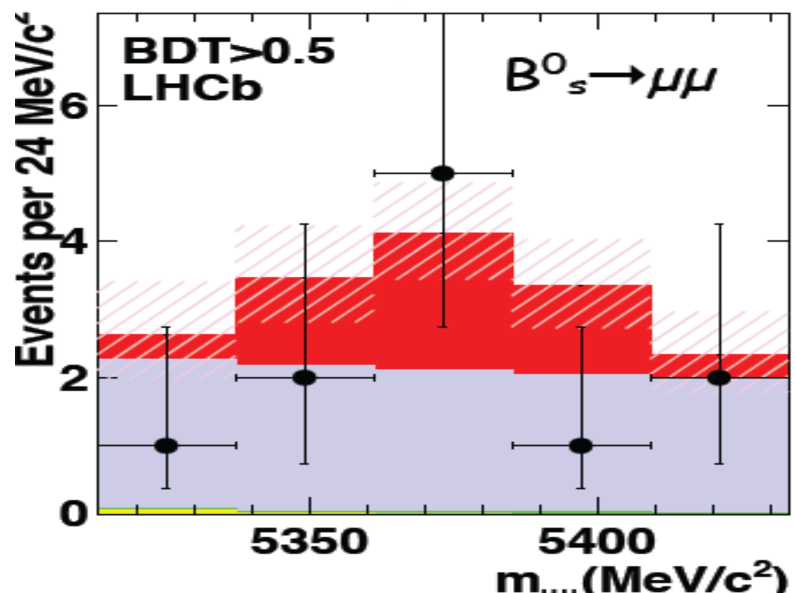
$$BR(B_s \to \mu^+\mu^-)^{EXP} = 1.088 \cdot BR(B_s \to \mu^+\mu^-)^{TH} = 3.4 \cdot 10^{-9}$$

De Bruin, R. Fleischer et al, [1204.1737]

$B_{s,d} \to \mu^+\mu^-$ measurement at LHCb @ 1fb^{-1}

- Relative BR measurement using $B^+ \to J/\psi K^+$, $B_s \to J/\psi\phi$ and $B_d \to K^+\pi^-$ as control channels
- Perform analysis is 2D
  - 8 bins of BDT and 9 bins of mass
- Estimate compatibility with signal and background hypothesis using CLs

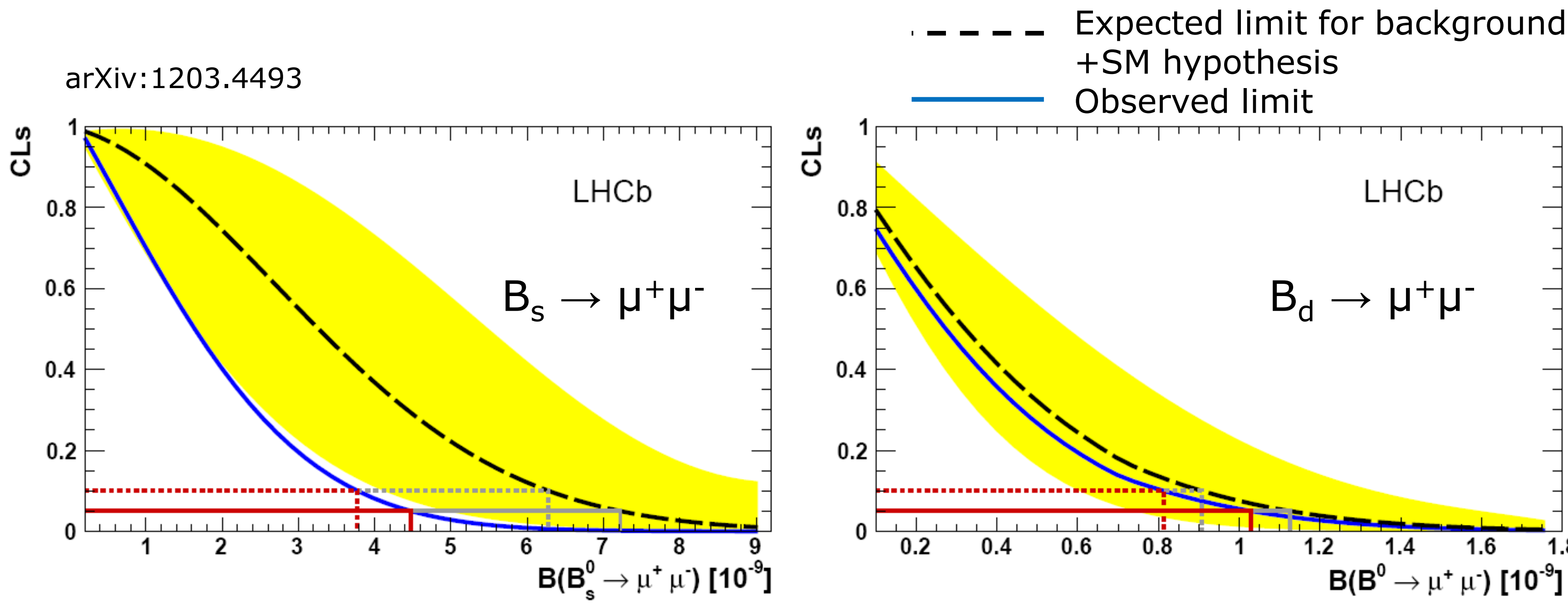




PRL 108, 231801 (2012) [1203.4493]

A hint of the $B_{s,d} \to \mu^+\mu^-$ signal is emerging!

$B_{s,d} \to \mu^+\mu^-$ result from LHCb @ 1fb^{-1}



- Worlds best limits with 1 fb^{-1} @ 95% CL
  - **BR($B_s \to \mu^+\mu^-$) < 4.5 10^{-9}**
  - **BR(BR($B_s \to \mu^+\mu^-$) estimate: (0.8 $^{+1.8}_{-1.3}$) 10^{-9}**
  - BR($B_d \to \mu^+\mu^-$) < 1.0 10^{-9}

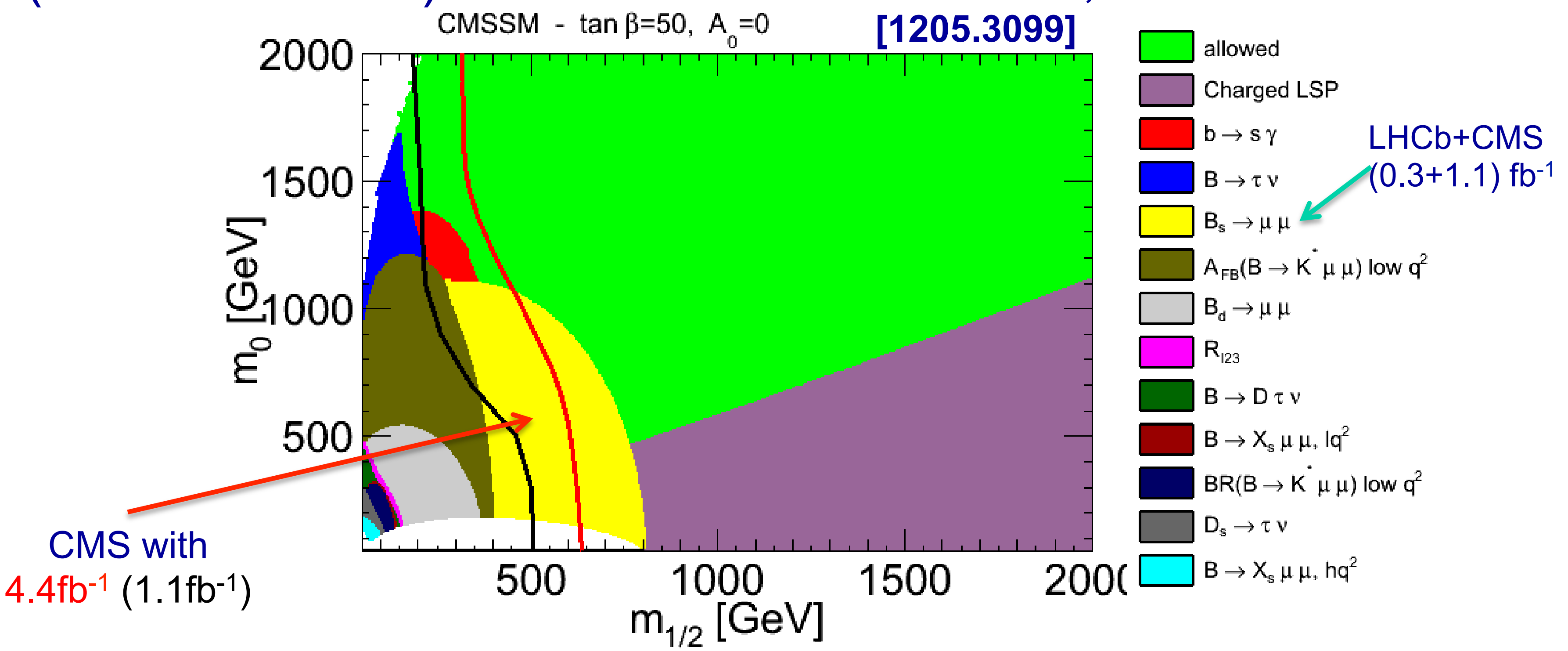
PRL 108, 231801 (2012) [1203.4493]

- Uploaded 21st of March 2012, ~0.5 citations per day since

Impact of $B_s \to \mu^+\mu^-$ on SUSY

- Global fit to flavour and high PT observables
  - Includes Higgs and SUSY direct searches, XENON100, EW and flavour measurements
- Done for constrained SUSY models, here CMSSM (NUHM1 similar)

F. Mahmoudi, [1205.3099]



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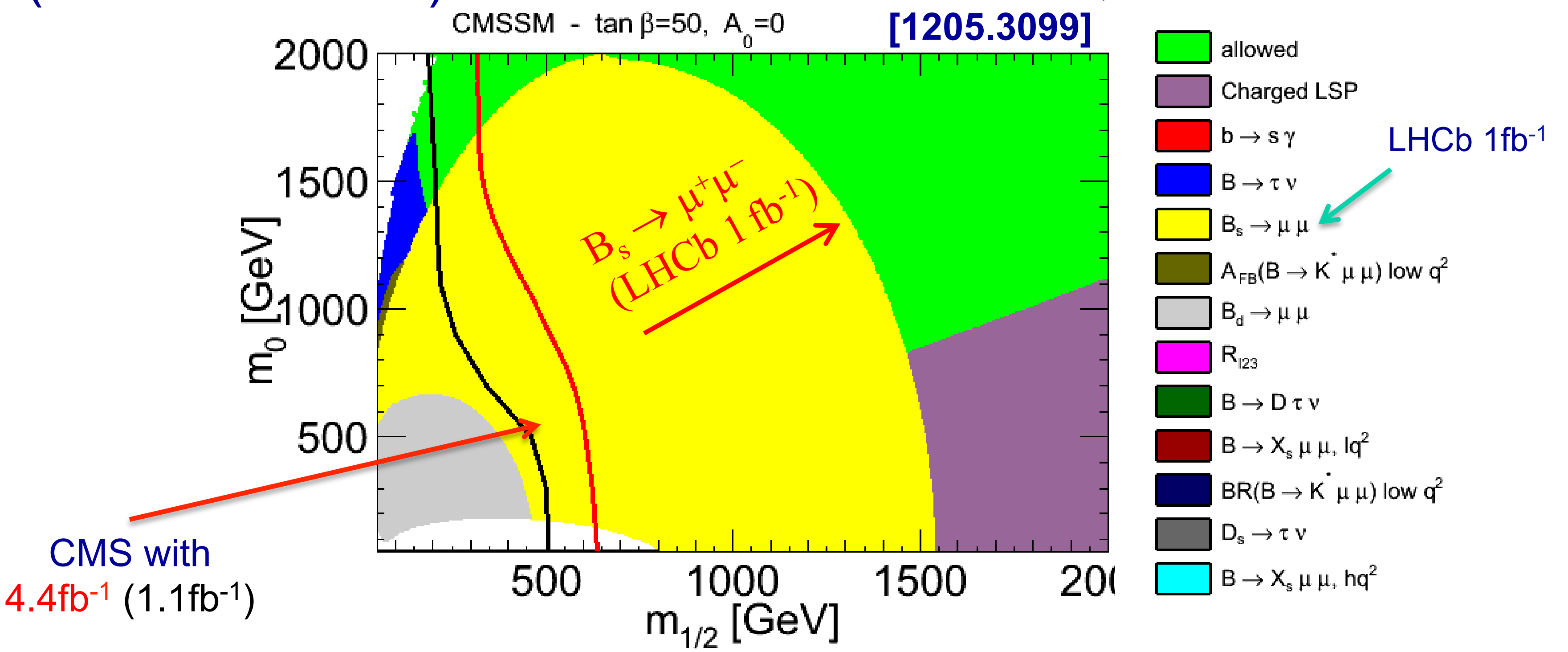
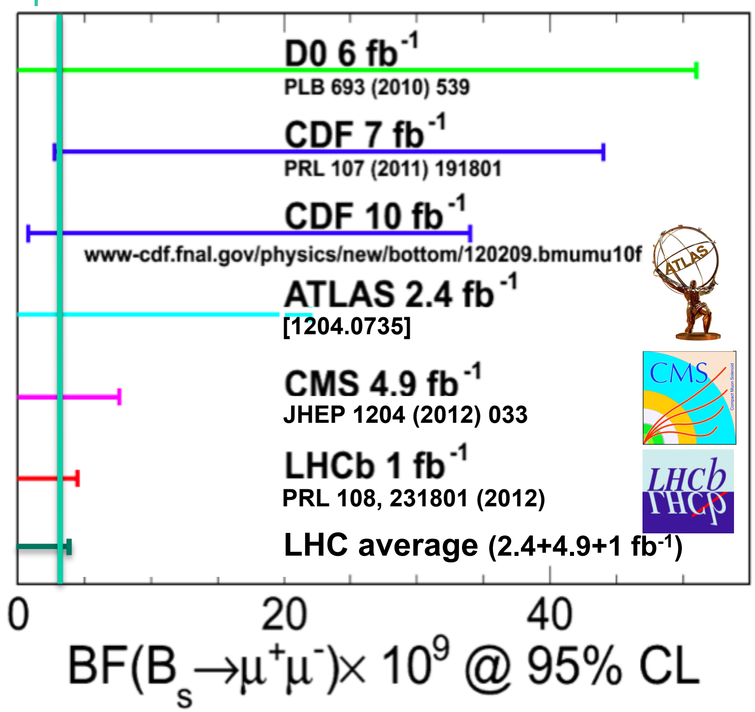


Limits on $B_s \rightarrow \mu^+\mu^-$ disfavour constrained SUSY at high tanβ

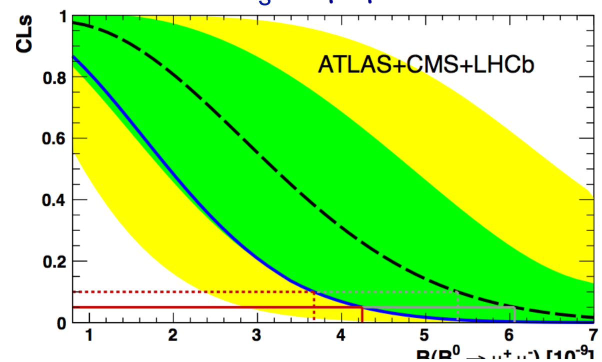
Summary of experimental status

SM prediction



NEW LHC combination…

$B_s^0 \to \mu^+\mu^-$



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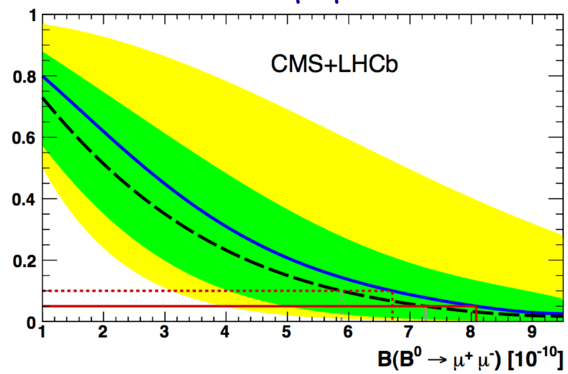

ATLAS, CMS and LHCb measurements combined:

$B(B_s^0 \to \mu\mu) < (3.7\ (4.2)) \times 10^{-9}$ at 90(95) % C.L.

- Excess over background at ~2σ level (1-CL_b (p-value)=5%)
- Compatible with SM at 1σ (1-CL_{s+b}=84%)

$B(B^0 \to \mu\mu) < (0.67\ (0.81)) \times 10^{-9}$ at 90(95) % C.L.

c.f. SM value:
p5: $3.4\ 10^{-9}$

LHCb-CONF-2012-017, also as CMS-PAS-BPH, ATLAS-CONF

Search for New Physics in (axial-) vector couplings in EW penguins`

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

- Flavour changing neutral current → loop
- Allows to test Lorentz-structure:

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \Big[\underbrace{C_i(\mu) O_i(\mu)}_{\text{left-handed part}} + \underbrace{C_i'(\mu) O_i'(\mu)}_{\substack{\text{right-handed part} \\ \text{suppressed in SM}}} \Big]$$

$i = 1,2$	Tree
$i = 3-6,8$	Gluon penguin
$i = 7$	Photon penguin
$i = 9,10$	Electroweak penguin
$i = S$	Higgs (scalar) penguin
$i = P$	Pseudoscalar penguin

- Angular analysis of $B^0 \to K^* \mu^+\mu^-$
  - $K^* \to K\pi$ self tagging → allows to probe helicity structure
  - Highly sensitive to $C_7^{(')}$, $C_9^{(')}$, $C_{10}^{(')}$
- Can measure a variety of angular observables which have small hadronic uncertainties
  - A_{FB}, the forward-backward asymmetry and its zero crossing point
  - F_L, the fraction of K^{*0} longitudinal polarization
  - $S_3 \sim A^2_T(1-F_L)$, the asymmetry in K^{*0} transverse polarization

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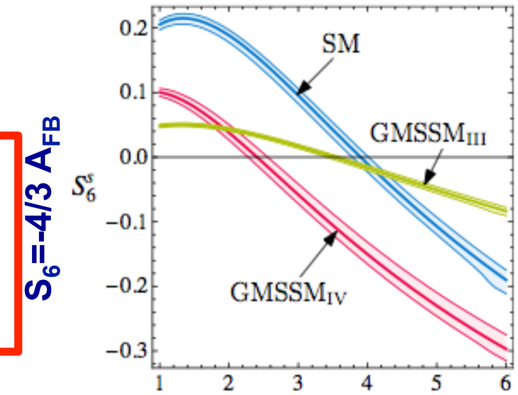
[arXiv:0801.1214]



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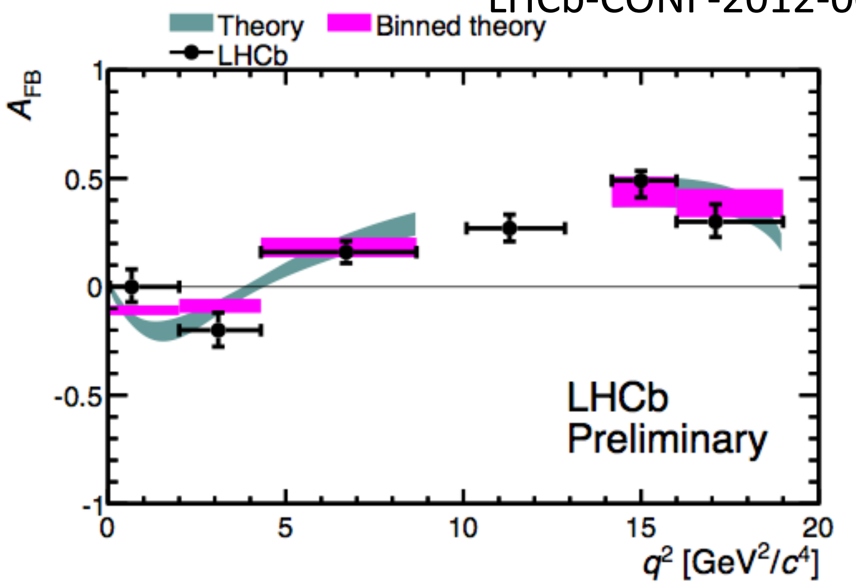
Angular Analysis: A_{FB}

- (Pre-LHC) measurements of ang. asymm. A_{FB} but errors are such that there is no real discrimination between models

LHCb-CONF-2012-008



- LHCb measurements are the most precise to-date – completely consistent with the SM prediction

Theory prediction from C. Bobeth et al. [arXiv:1105.0376] (and ref. therein)

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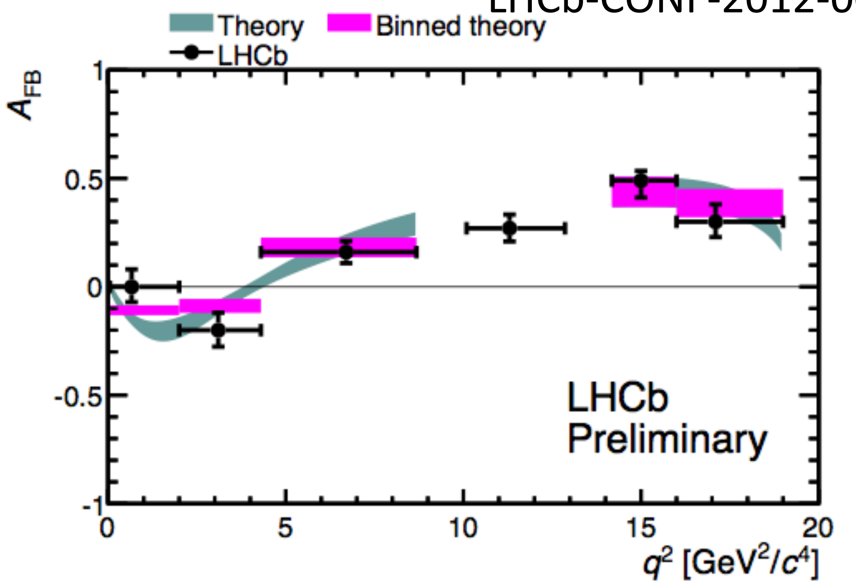
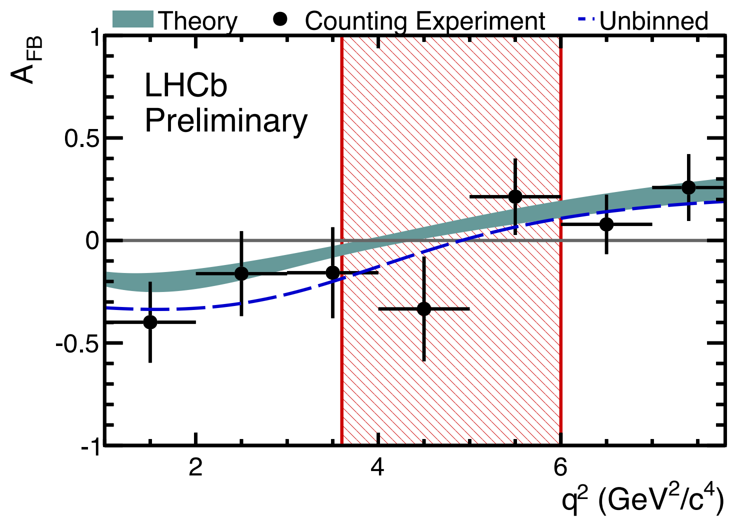




- LHCb measurements are the most precise to-date – completely consistent with the SM prediction

LHCb has performed the world's first measurement of the zero-crossing point:

$$q_0^2 = 4.9\,^{+1.1}_{-1.3}\ \mathrm{GeV}^2$$

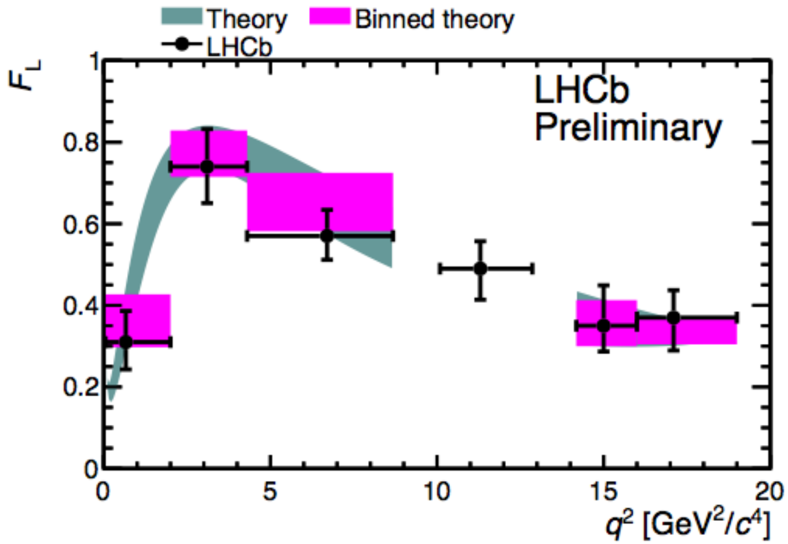
consistent with SM prediction: 4-4.3 GeV^2 [Eur. Phys. J C 41 (2005) 173-188]

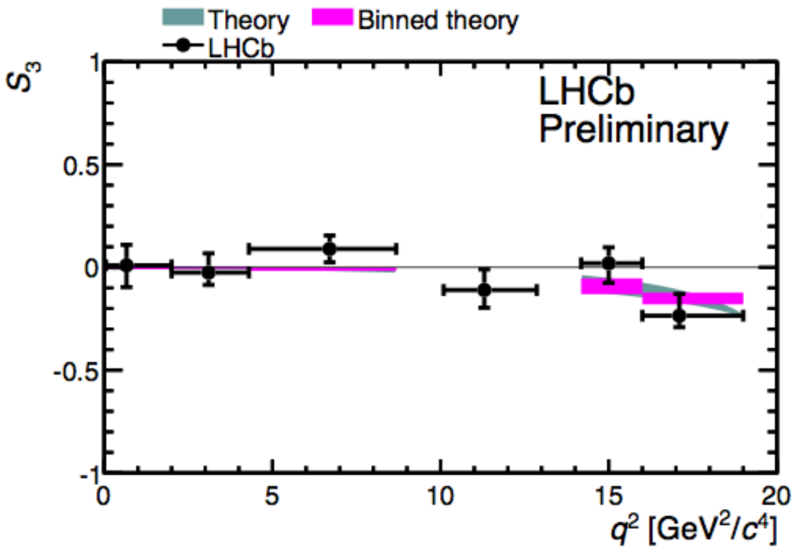
Theory prediction from C. Bobeth et al. [arXiv:1105.0376] (and ref. therein)

Angular Analysis: S_3, F_L

- Other observables show similarly spectacular agreement with SM predictions, again most precise measurements to-date

LHCb-CONF-2012-008



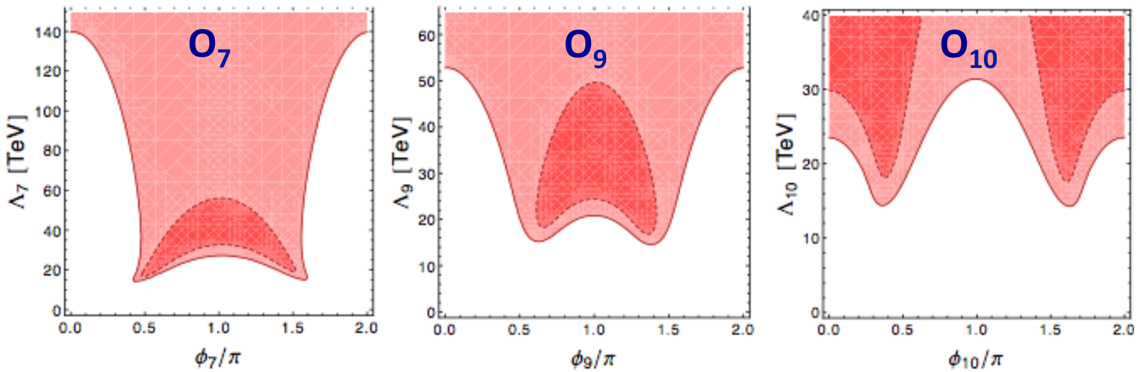


- F_L, the fraction of K^{*0} longitudinal polarisation
- $S_3 \propto A^2_T(1-F_L)$, the asymmetry in K^{*0} transverse polarisation

Tree level flavour violation:

$$\mathscr{L} = \mathscr{L}_{SM} + \sum_{j=7,9,10} \frac{e^{i\phi_j}}{\Lambda_j^2} \mathcal{O}_j$$

~tree level generic flavour violation

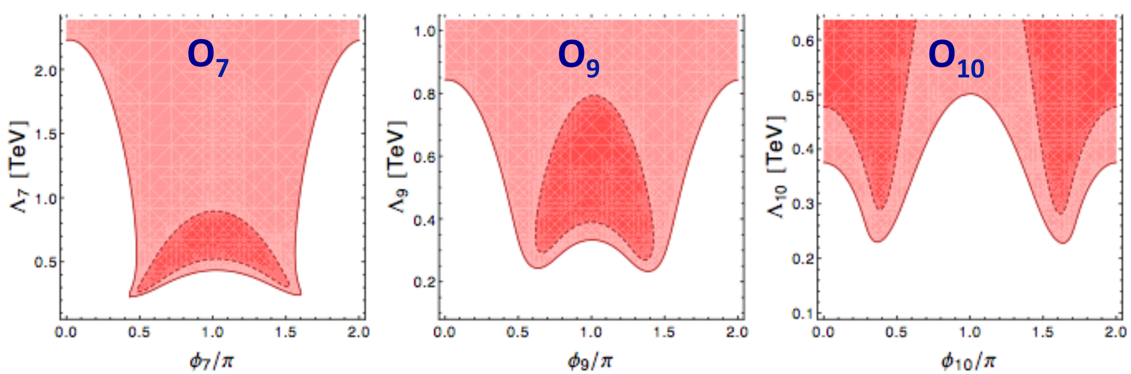


Couplings O(1)
→ NP at mass scales 15-140TeV

Loop level flavour violation (CKM like):

$$\mathscr{L} = \mathscr{L}_{SM} - \sum_{j=7,9,10} \frac{V_{tb}V_{ts}^*}{16\pi^2} \frac{e^{i\phi_j}}{\Lambda_j^2} \mathcal{O}_j$$

~loop level CKM-like flavour violation



Couplings O(loop)
→ NP at mass scales 0.3-2TeV

Straub, Altmannshofer, Paradisi [1111.1257, JHEP1202:106]

Isospin Asymmetries in $B \to K^{(*)} \mu^+\mu^-$

- Isospin asymmetry expected to be close to zero in SM

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

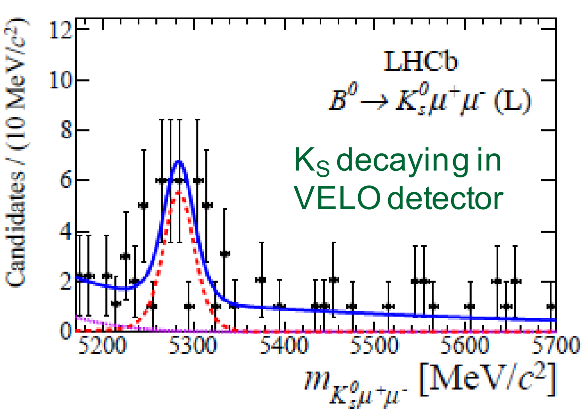
- Hints of non standard A_I from CDF, B-factories

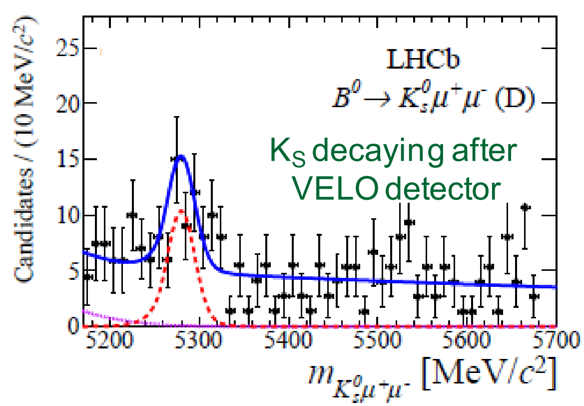
- Very recently measured by LHCb in two modes:
  - $B^0 \to K^0 \mu^+\mu^-$ vs $B^+ \to K^+ \mu^+\mu^-$
  - $B^0 \to K^{0*} (K^+\pi^-)\ \mu^+\mu^-$ vs $B^+ \to K^{*+} (K^0\pi^+)\ \mu^+\mu^-$

(K^0 reconstructed as $K_s^0 \to \pi^+\pi^-$)

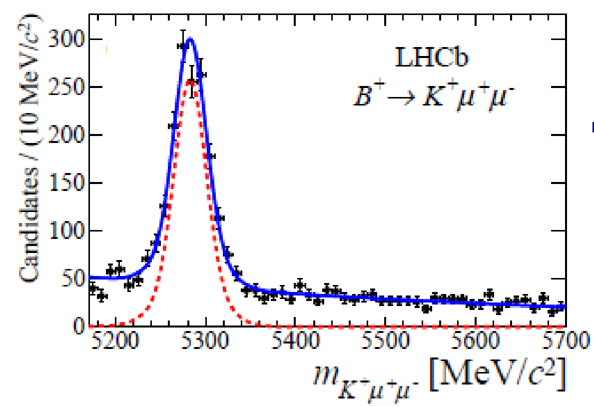
[1205.3422]

$B^0 \to K_S \mu\mu$



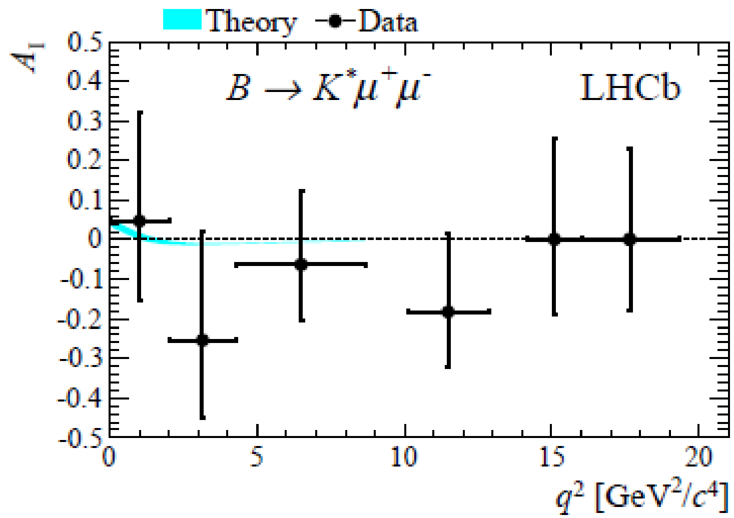


$B^+ \to K^+ \mu\mu$



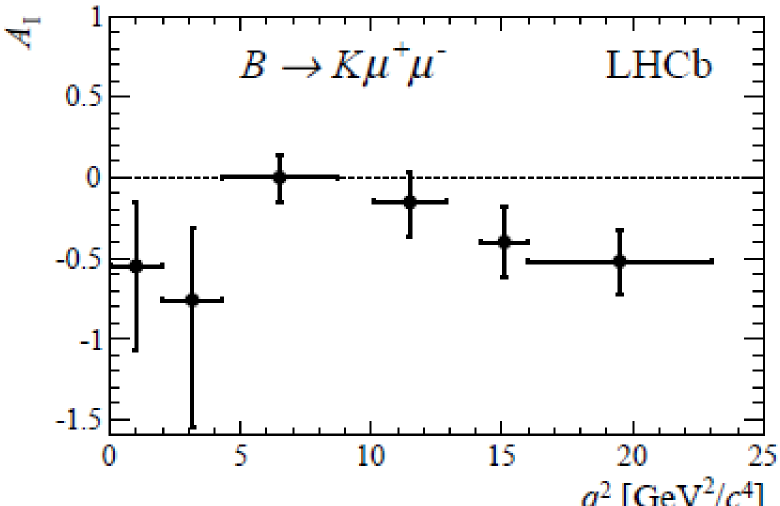
Isospin Asymmetries in B→ K$^{(*)}$ $\mu^+\mu^-$

Results for B→K*μμ vs q2 of di-muons consistent with 0, as expected

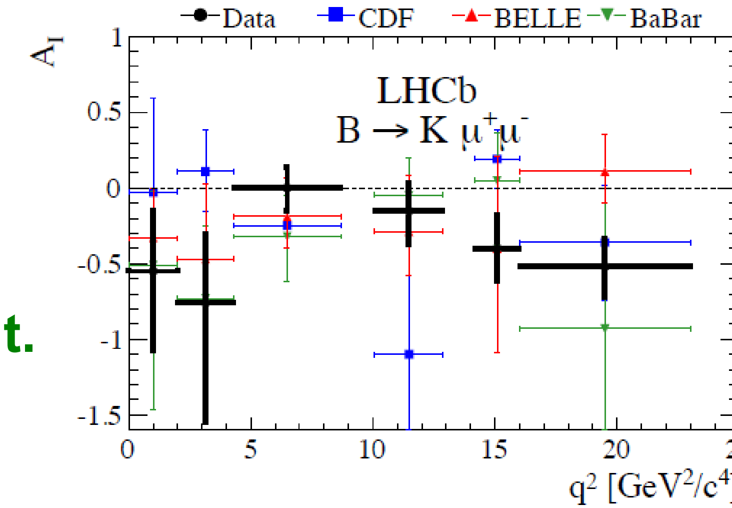


[1205.3422], TH from C. Bobeth, G. Hiller and D. van Dyk

But that for B→Kμμ is systematically low !
Naive average over q^2 gives 4.4σ effect,...



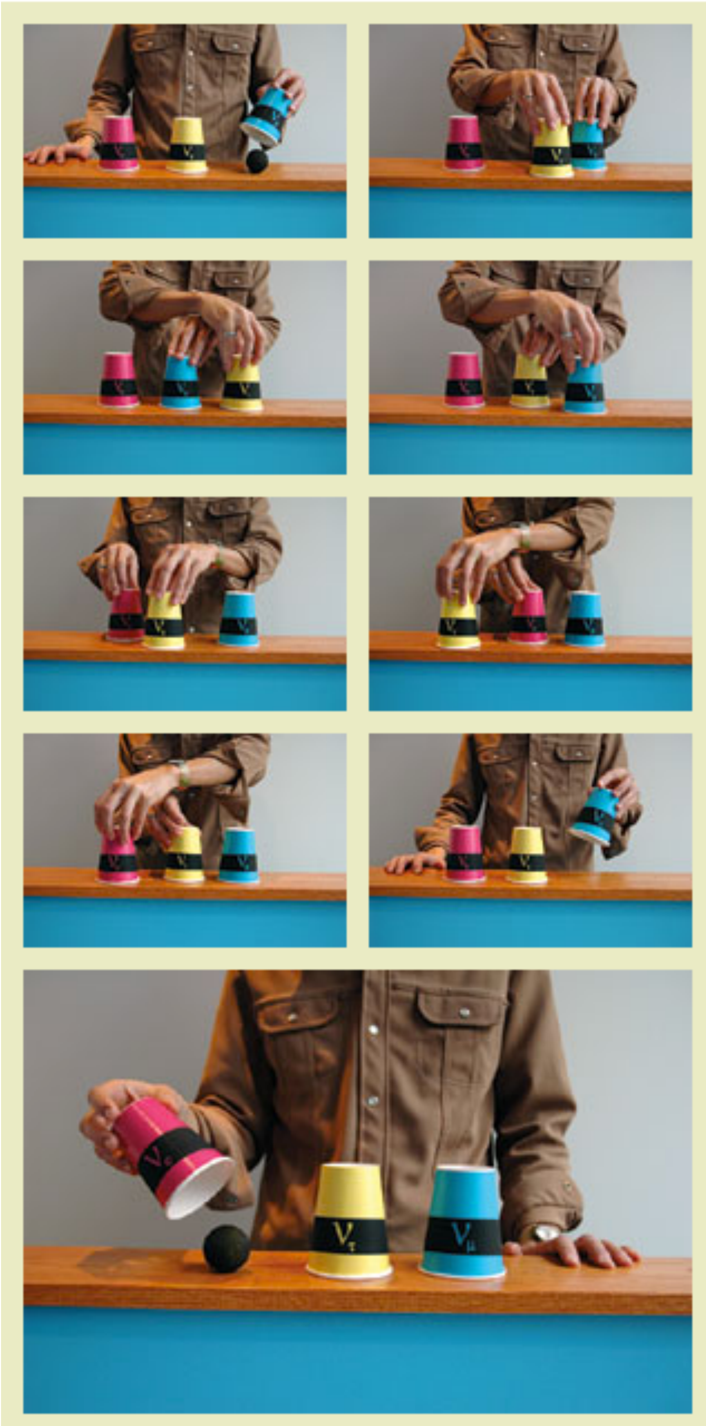
Consistent with existing hints from CDF, Belle, BaBar



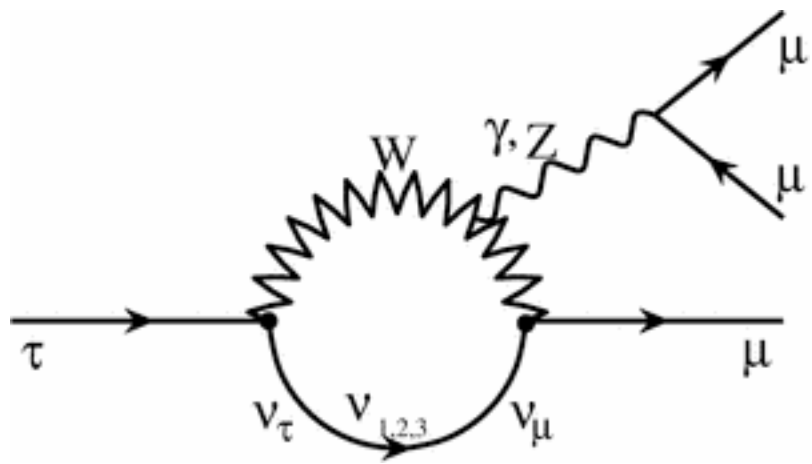
Unexpected effect, but quite significant.

Need more statistics.

Interpretation in SM or NP???

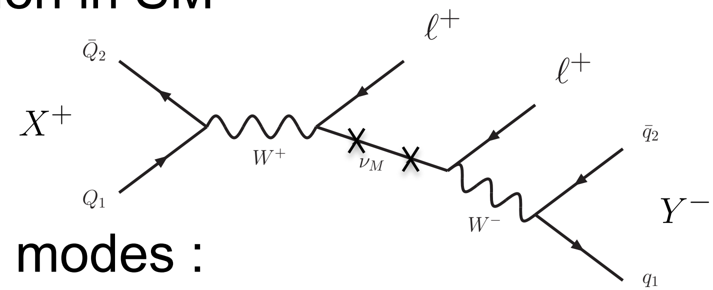


Lepton Number and Flavor Violation



Search for Majorana neutrinos

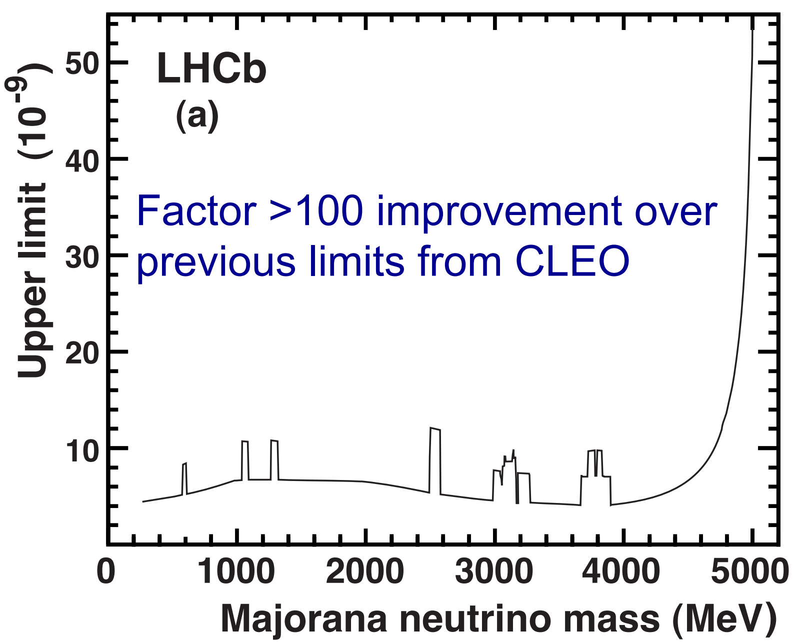
- Decays $B^+ \to h^- \mu^+ \mu^+$ are ($\Delta L=2$) strictly forbidden in SM
  - Sterile Majorana ν of mass O(1GeV/c^2) could enhance branching fraction

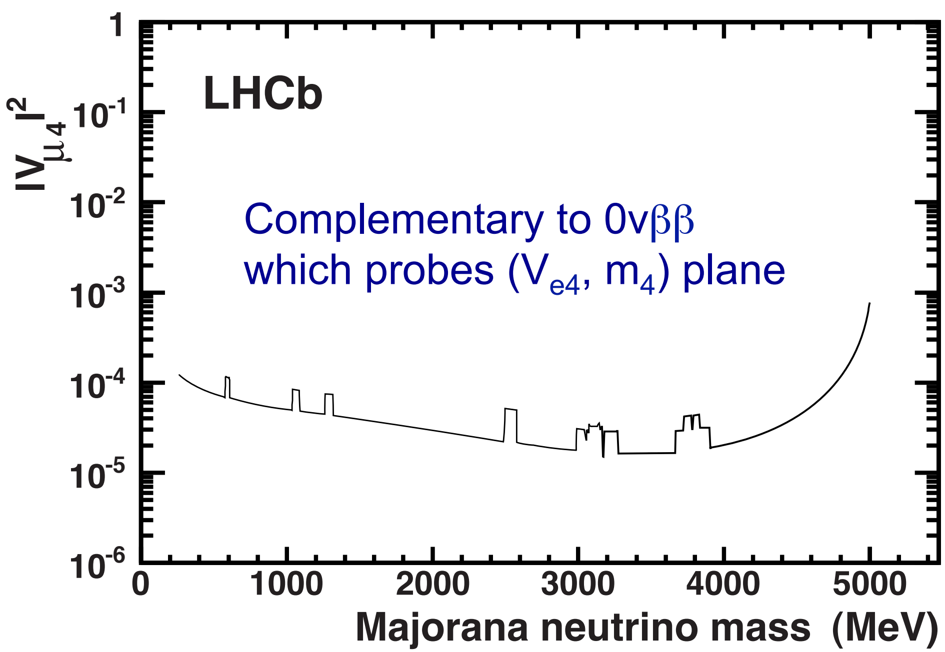


- LHCb search for a wide range of such decay modes :
  $D^- \mu^+ \mu^+$, $D^{*-} \mu^+ \mu^+$, $\pi^- \mu^+ \mu^+$, $D_s^- \mu^+ \mu^+$, $D^0 \pi^- \mu^+ \mu^+$

[Phys. Rev. Lett. 108 (2012) 101601 arXiv:1201.5600]

- No signal found - results for $B^+ \to \pi^- \mu^+ \mu^+$:

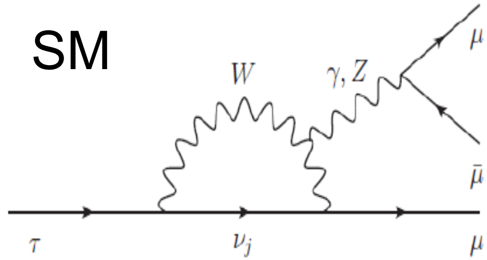




Search for $\tau^- \to \mu^-\mu^+\mu^-$

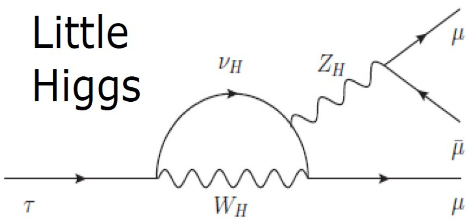
- Observation of n-oscillation implies (small) charged LFV

SM



- Lepton flavour violating decay $\tau^- \to \mu^-\mu^+\mu^-$ is predicted to have BR~10^{-54} in SM
  - Many BSM predictions, e.g.
  - Variants of SUSY ~10^{-10}
    non universal Z' ~10^{-8}

Little Higgs



- Currently τ^- LFV dominated by B-factories
  - BaBar, 468pb^{-1}: BR($\tau^- \to \mu^-\mu^+\mu^-$) < 3.3 10^{-8} @90% CL
  - Belle, 782pb^{-1}: BR($\tau^- \to \mu^-\mu^+\mu^-$) < 2.1 10^{-8} @90% CL

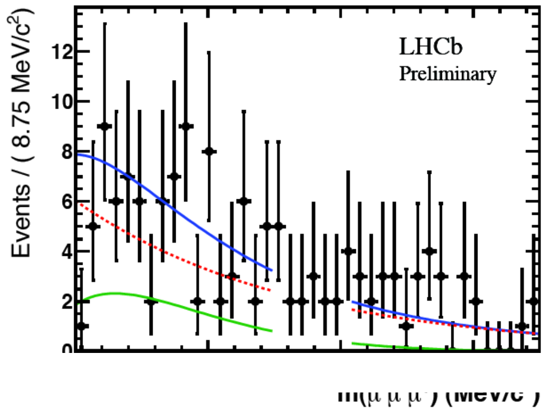
  [PDG, J Phys G37 (2010) 075021]

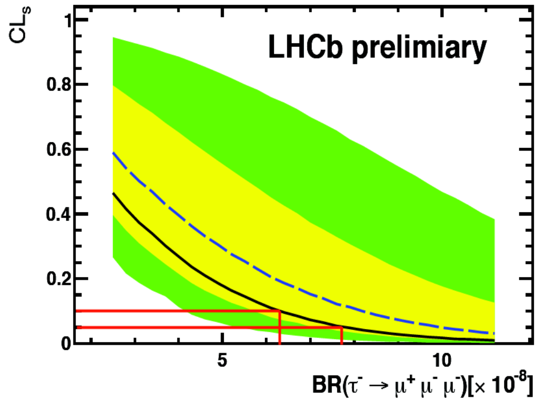
- Large τ-production rate at the LHC
  - $\sigma(\tau)$ = 21.6 ± 3.3 μb within LHCb acceptance
    → ~10^{11} τ^- in LHCb per year (dominantly from D^+_s decays)

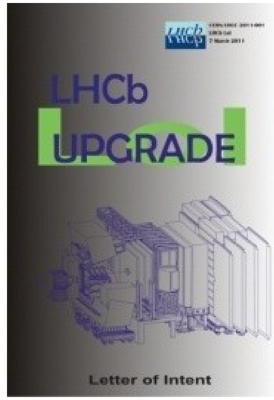
Search for $\tau^- \rightarrow \mu^-\mu^+\mu^-$ in LHCb

- Event classification in bins of
  - BDT with geometric & kinematic info (5 bins)
  - BDT with muon PID info (5 bins)
  - τ^- invariant mass (6 bins)
- High Likelihood background composed of combinatorial and physical (dominant: $D_s^+ \rightarrow \eta(\mu^+\mu^-\gamma)\ \mu^+\nu_\mu$)
- **Observed Limit:**
  $BR(\tau^- \rightarrow \mu^-\mu^+\mu^-) < 6.3(7.8)\ 10^{-8}$ @ 90(95)%
- Proof of principle – measurement can be made at hadron collider
- With $1 fb^{-1}$ LHCb is close to B-factory sensitivity
  → excellent prospects for next years and LHCb upgrade!

Mass of 4 highest LL bins

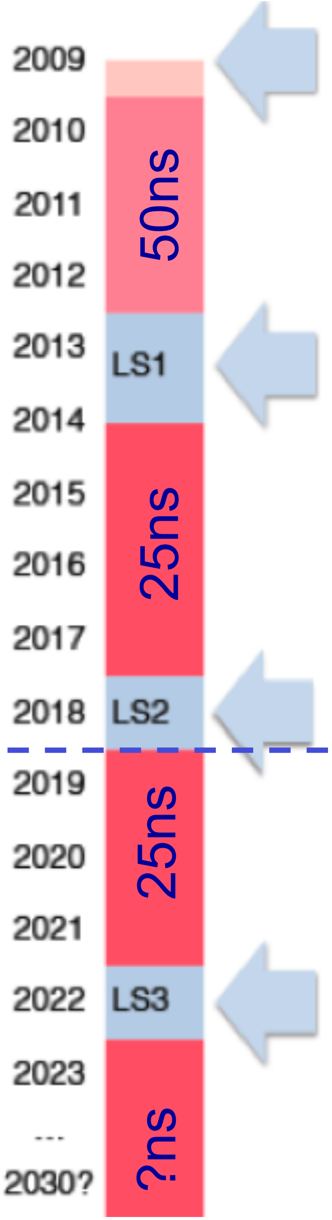






Upgrade of the LHCb detector

LHC(b) long term plan



$\int L\,dt$

✧ LHC startup, $\sqrt{s}$ = 900 GeV

$\sqrt{s}$=7/8TeV; L_{LHCb}= 3-4x10^{32} cm^{-2}s^{-1}
→ ~1.5fb^{-1}/year

2.5/fb

Go to design energy, nominal luminosity

$\sqrt{s}$=13/14TeV; L_{LHCb}= 4x10^{32} cm^{-2}s^{-1}
→ 1.5-2fb^{-1}/year

5-7/fb

Injector and LHC Phase-1 upgrade to full design luminosity

$\sqrt{s}$=14TeV; L_{LHCb}= 1-2x10^{33} cm^{-2}s^{-1}
→ >5fb^{-1}/year

50/fb

HL-LHC Phase-2 upgrade, IR, crab cavities?

$\sqrt{s}$=14TeV; L_{LHCb}= ~2x10^{33} cm^{-2}s^{-1}

LHCb Physics with $50 fb^{-1}$

Essential features:

- Full software trigger: will readout into DAQ all subdetectors at 40 MHz (c.f. 1 MHz at present). This will improve efficiency compared with current hardware trigger, giving factor of two improvement for hadronic final states
- Increase operational luminosity to 10^{33} $cm^{-2}s^{-1}$ (and a possibility to raise still further to 2 x 10^{33} $cm^{-2}s^{-1}$)

Annual yields in muonic final states will increase 10x w.r.t. 2011, and 20x for hadronic decays. Aim to collect 50 fb^{-1}.

Type	Observvble	Current precision	LHCb 2018	LHCb $50fb^{-1}$
(pseudo)- scalar	$BR(B_s \to \mu^+\mu^-)$	$1.5\ 10^{-9}$	$0.5\ 10^{-9}$	$0.15\ 10^{-9}$
MFV	$BR(B_s \to \mu^+\mu^-)/BR(B_d \to \mu^+\mu^-)$	-	100%	35%
B_s mixing	$2\beta_s$	0.1	0.025	0.008
EW penguins	$s_0\ A_{FB}$	25%	6%	2%
	A_L	0.25	0.08	0.025
UT triangle	γ	~12°	~4°	<1°

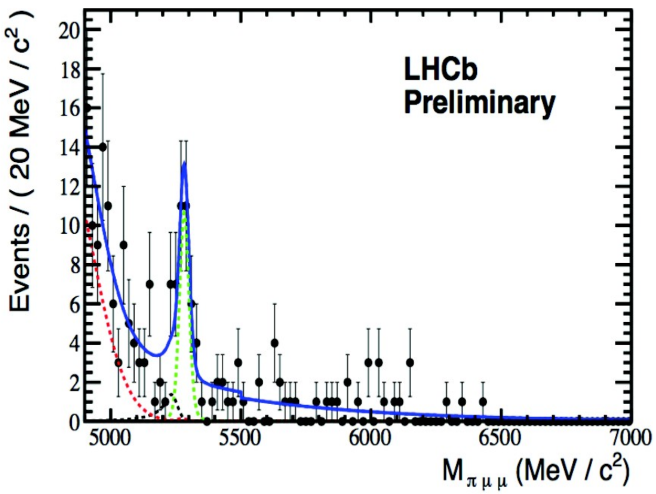
Conclusions

- Search for $B_s \rightarrow \mu^+\mu^-$:
  - **LHCb provides worlds best limit: BR($B_s \rightarrow \mu^+\mu^-$) < 4.5 10^{-9}** @ 95% CL
    Dominates new LHC average: BR($B_s \rightarrow \mu^+\mu^-$) < 4.2 10^{-9} @ 95% CL
  - ~2σ excess over background seen (LHC average)
  - Existing results strongly constrain SUSY models, competitive with direct searches
- Angular analysis of the decay $B^0 \rightarrow K^* \mu^+\mu^-$:
  - With couplings O(1) → NP at mass scales >> O(10TeV)
  - With couplings O(loop suppressed) → NP at mass scales O(0.3-2TeV)
- Isospin analysis in $B \rightarrow K^{(*)} \mu^+\mu^-$:
  - $B \rightarrow K \mu^+\mu^-$: Isospin asymmetry >4$\sigma$ away from SM
- No evidence for Majorana neutrinos or LFV in $\tau^- \rightarrow \mu^-\mu^+\mu^-$
- Upgrade of LHCb detector gives excellent prospects for 2018++

Many interesting measurements not shown…

- $D^0 \to \mu^+\mu^-$: BR < 1.3 10^{-8} @ 95% CL (worlds best by factor 10)

- BR($B^+ \to \pi^+\mu^+\mu^-$) = 2.4±0.6±0.2 10^{-8}
agrees with SM, rarest B decay observed



- BR($B_s \to \mu^+\mu^-\mu^+\mu^-$) < 1.3 10^{-8} @ 95% CL
BR($B_d \to \mu^+\mu^-\mu^+\mu^-$) < 0.5 10^{-8} @ 95% CL
worlds first limits, constrains light scalars

- Differential decay rate of $B_s \to \phi\mu^+\mu^-$

- Worlds most precise measurement of $A_{CP}(B^0 \to K^*\gamma)$, BR($B_s \to \phi\,\gamma$)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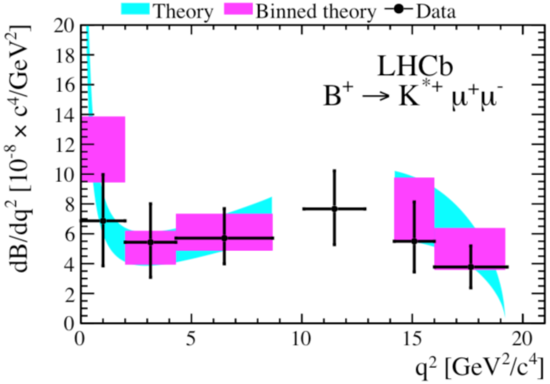
Isospin Asymmetry B→K*μμ

$dBF/q^2(B^+ \to K^{*+}\mu^+\mu^-)$

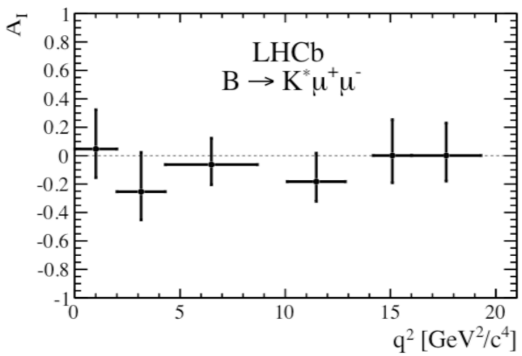
- Measurements are consistent with the SM :

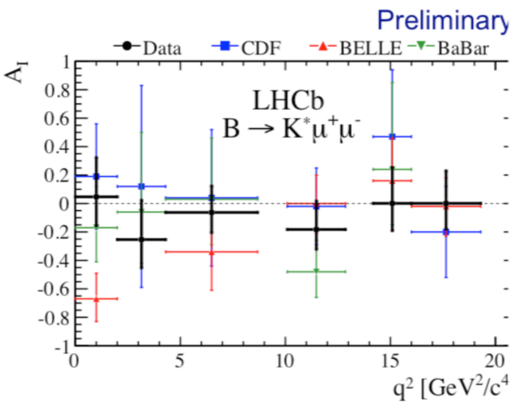


Theory prediction from [C. Bobeth, G. Hiller, and D. van Dyk, JHEP (2011) 067, arXiv:1105.0376]

A_I for $B \to K^*\mu^+\mu^-$

- A_I for $B \to K^*\mu^+\mu^-$ is consistent with zero, as predicted by the SM
- LHCb results in agreement with previous measurements



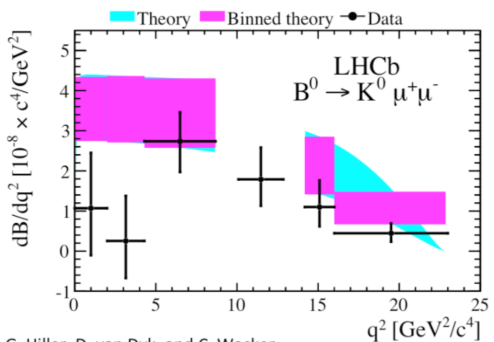


Isospin Asymmetry B→Kμμ

dBF/q^2($B^0 \to K^0\mu^+\mu^-$)

- There is a deficit of $B^0 \to K^0\mu^+\mu^-$ signal in the q^2 regions which are n adjacent to the charmonium resonances

Prelim

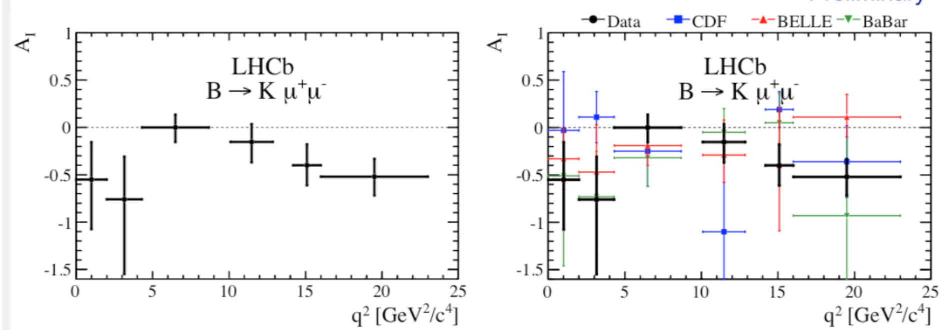


C. Bobeth, G. Hiller, D. van Dyk, and C. Wacker,

A_I for $B \to K\mu^+\mu^-$

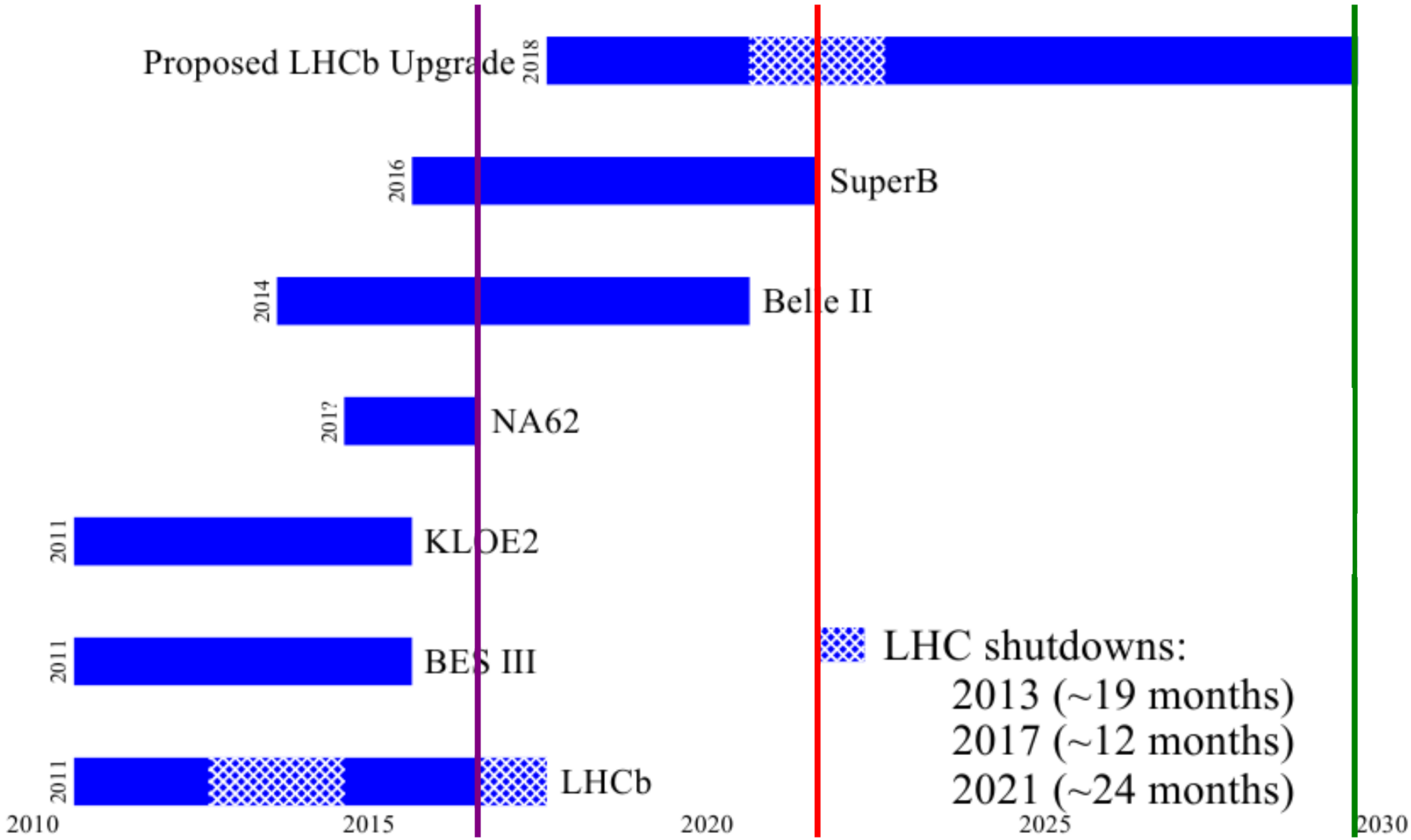
- As a result, A_I for $B \to K\mu^+\mu^-$ tends to sit below the SM prediction
- Results agree with previous measurements but nearly all measurements of A_I are negative
- Ignoring the small correlation of (syst) errors between each q^2 bin, the significance of the deviation from zero integrated across q^2 is 4.4σ (from LHCb alone)

Preliminary



LHCb upgrade physics reach

Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\mathrm{fb}^{-1}$)	Theory uncertainty
B^0_s mixing	$2\beta_s\ (B^0_s \to J/\psi\ \phi)$	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s\ (B^0_s \to J/\psi\ f_0(980))$	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\mathrm{fs}}(B^0_s)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta^{\mathrm{eff}}_s(B^0_s \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta^{\mathrm{eff}}_s(B^0_s \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K^0_S)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta^{\mathrm{eff}}_s(B^0_s \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\mathrm{eff}}(B^0_s \to \phi\gamma)/\tau_{B^0_s}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\ A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.25 [15]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	2.5 %	~ 10 %
Higgs penguin	$\mathcal{B}(B^0_s \to \mu^+\mu^-)$	1.5×10^{-9} [2]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	~ 10–12° [19, 20]	4°	0.9°	negligible
	$\gamma\ (B^0_s \to D_sK)$	–	11°	2.0°	negligible
	$\beta\ (B^0 \to J/\psi\ K^0_S)$	0.8° [18]	0.6°	0.2°	negligible
Charm CP violation	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–


Proposed LHCb Upgrade
2018
2016
SuperB
2014
Belle II
2012
NA62
2011
KLOE2
2011
BES III
2011
LHCb
LHC shutdowns:
2013 (~19 months)
2017 (~12 months)
2021 (~24 months)
2010
2015
2020
2025
2030

[Ciuchini]