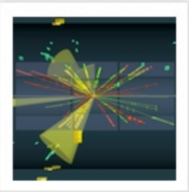
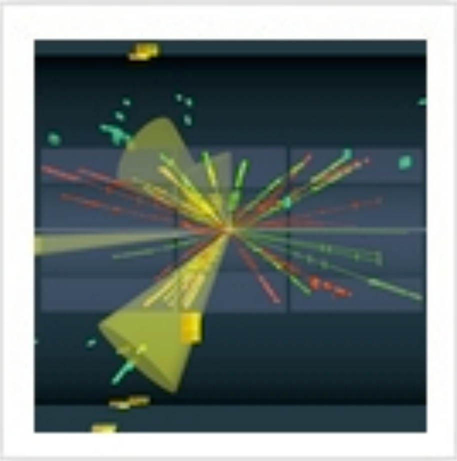


FLAVOUR PHYSICS
Experimental Results

CENTRO DE CIENCIAS
DE BENASQUE
PEDRO PASCUAL

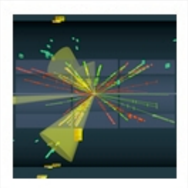


UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Bernardo Adeva
University of Santiago de Compostela

Outline of Course:

- Flavour physics, the core of the Standard Model
- Mixing and CPV in b-quark
- Mixing and CPV in charm
- $B_s \rightarrow \mu\mu$, $b \rightarrow s\mu\mu$ and rare decays



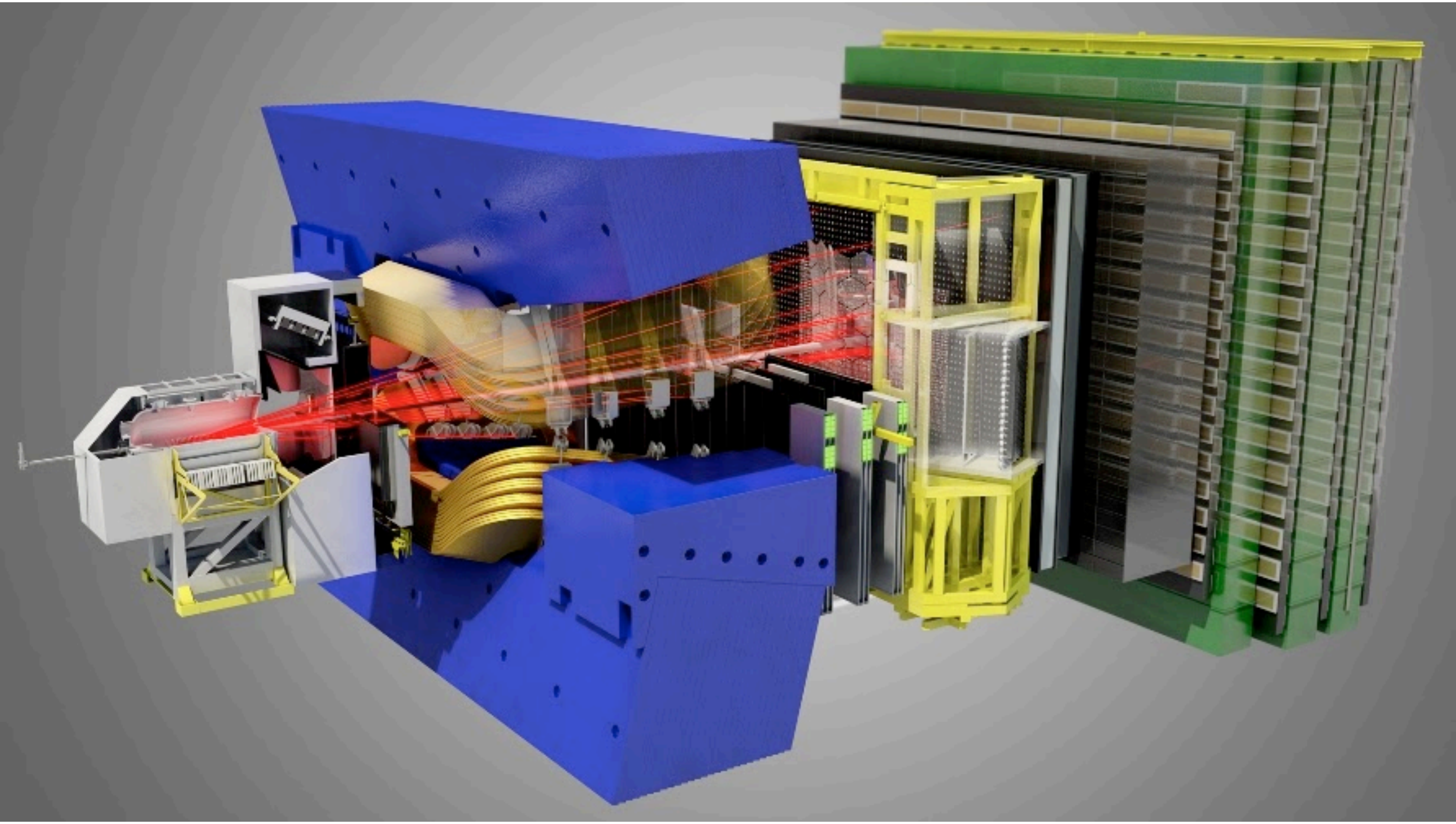
FLAVOUR PHYSICS
Experimental Results

Bernardo Adeva
University of Santiago de Compostela

Flavour Physics (part II) :

- Mixing and CPV in charm
- Rare decays

CPV in charm



Charm Mixing

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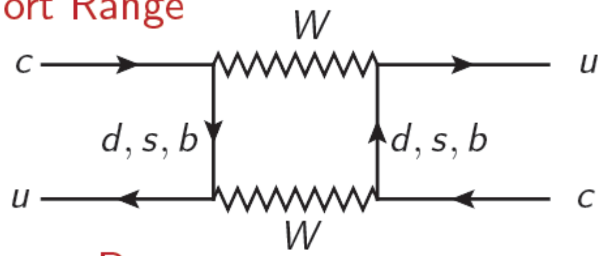
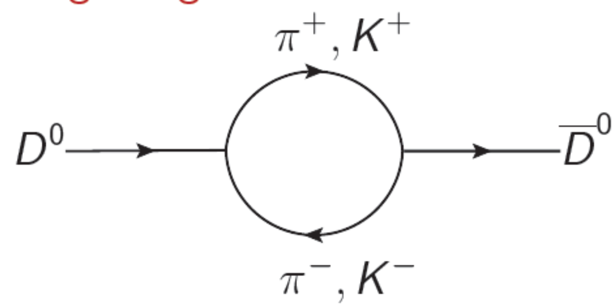
Charm Mixing in the SM

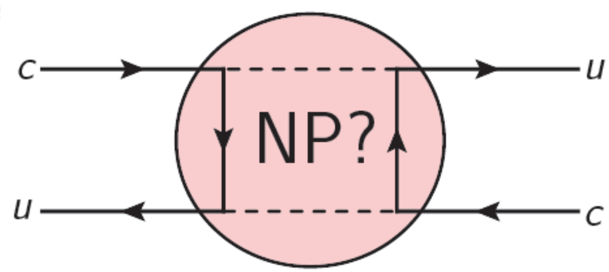
- Only up-type quark system with mixing/CPV
- Mixing enters at 1 loop level in SM, GIM and CKM suppressed
- Non-perturbative long-range effects may dominate short-range interactions, difficult to calculate
- x, y expected to be small in short and long range limits, CPV expected to be $\mathcal{O}(10^{-3})$ in SM
- If enhancement of CPV is seen, could be caused by New Physics (NP)

Short Range



Long Range

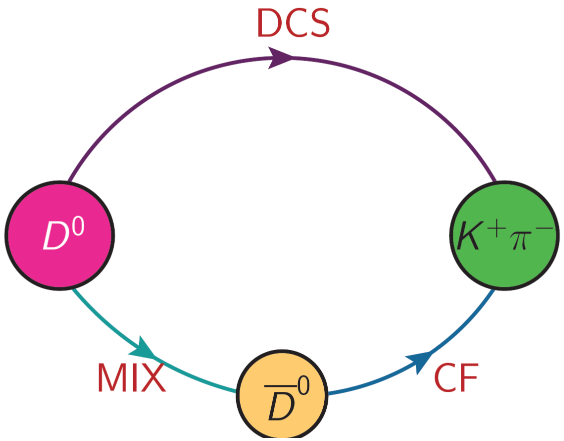




Mixing Hamiltonian : $H = \mathbf{M} - i/2\mathbf{\Gamma}$ (2×2 matrices) induces mass eigenstates:

$|D_{1,2}> = p|D^0> + q|\bar{D}^0>$ $x = (m_2 - m_1)/\Gamma = \Delta m/\Gamma$ $y = (\Gamma_2 - \Gamma_1)/2\Gamma = \Delta\Gamma/2\Gamma$ $\Gamma = (\Gamma_2 + \Gamma_1)/2$

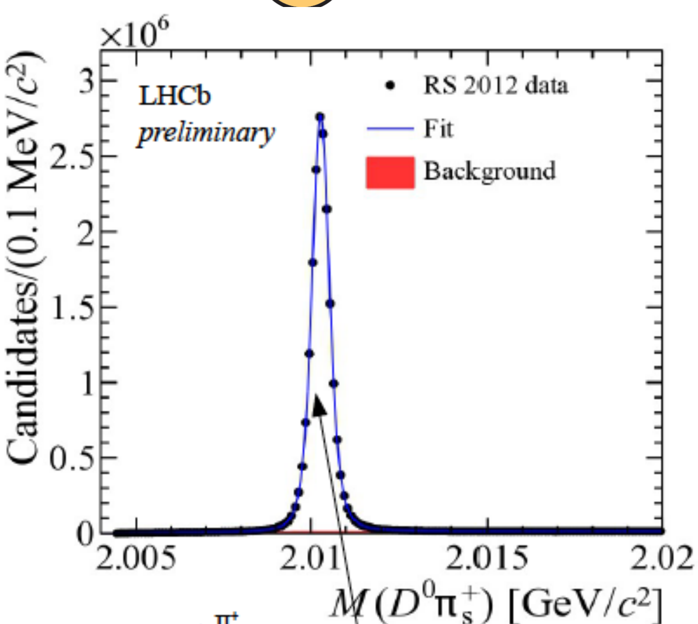
D^0 mixing from prompt $D^{*+} \rightarrow D^0 \pi^+_s$

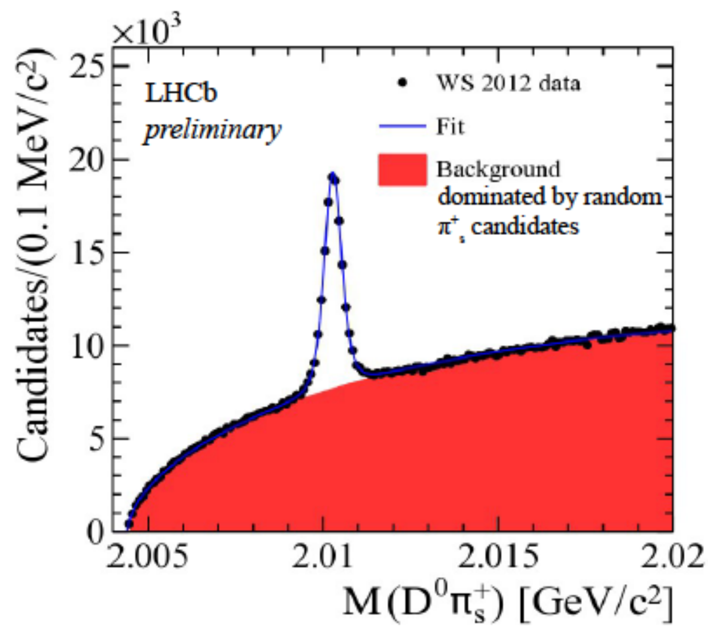


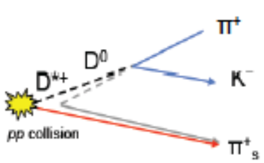
$D^{*+} \rightarrow D^0 (K^- \pi^+) \pi^+_s$, $D^{*+} \rightarrow D^0 (K^+ \pi^-) \pi^+_s$
where pion charge tags D^0 flavour

LHCb 1 fb^{-1} : Phys. Rev. Lett. 110 (2013) 101802

LHCb-PAPER-2013-053 in preparation







Mass resolution at ~ 0.3 MeV/c^2 due to D^* vertex being well constrained to measured PV position

Example fits with part of full data. In total ~54 M RS candidates and ~0.23 M WS candidates are collected.

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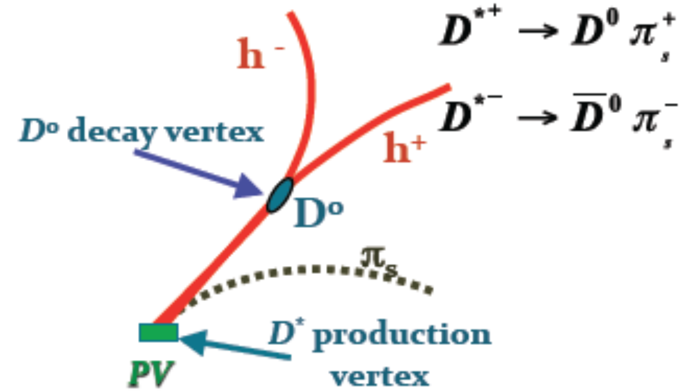
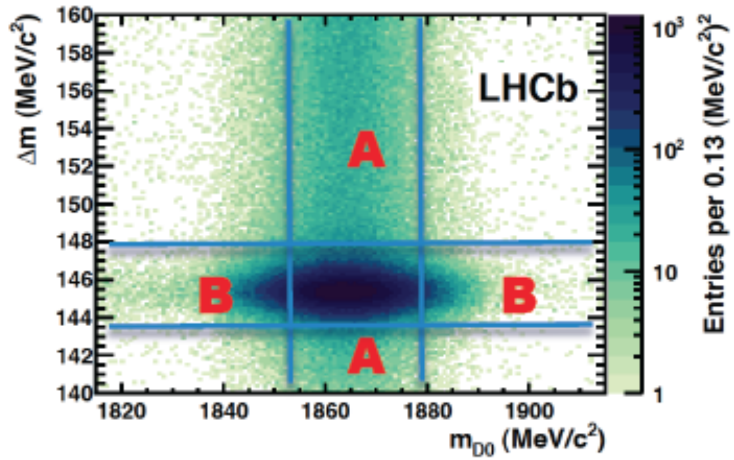
$D^{*0} \rightarrow D^0(f)\pi^+_s$ flavour tagging

Background characterization

- The D^0 flavour is determined by the sign of the slow pion in the decays $D^{*+} \rightarrow D^0(f)\pi_s^+$
- Signal and background discrimination by the D^0 invariant mass and delta mass ($\Delta m = m_{D^*} - m_{D^0}$)
- Partially reconstructed charm background modelled using simulation





A random slow pion bkg
B combinatorial bkg + specific bkg

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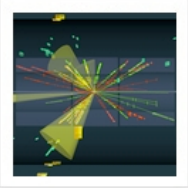
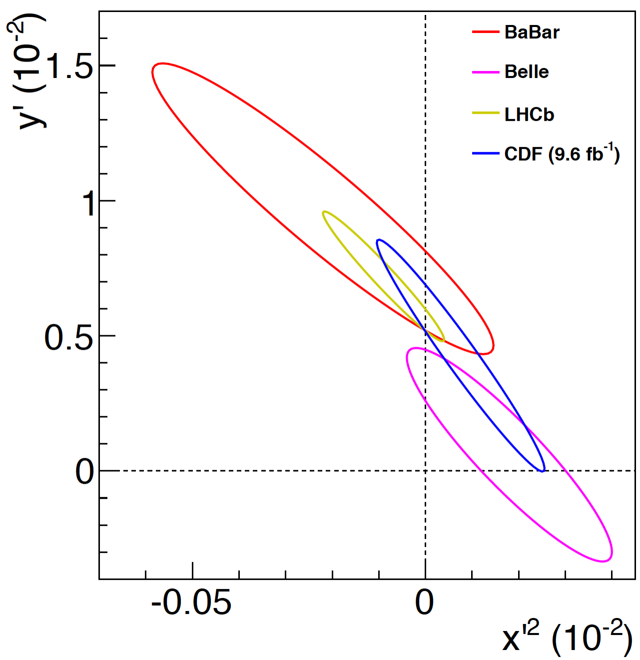


Charm Mixing

Ratio of wrong-sign to right-sign decay rates:

$$R(t) \approx R_D + \sqrt{R_D}\, y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4}\left(\frac{t}{\tau}\right)^2$$

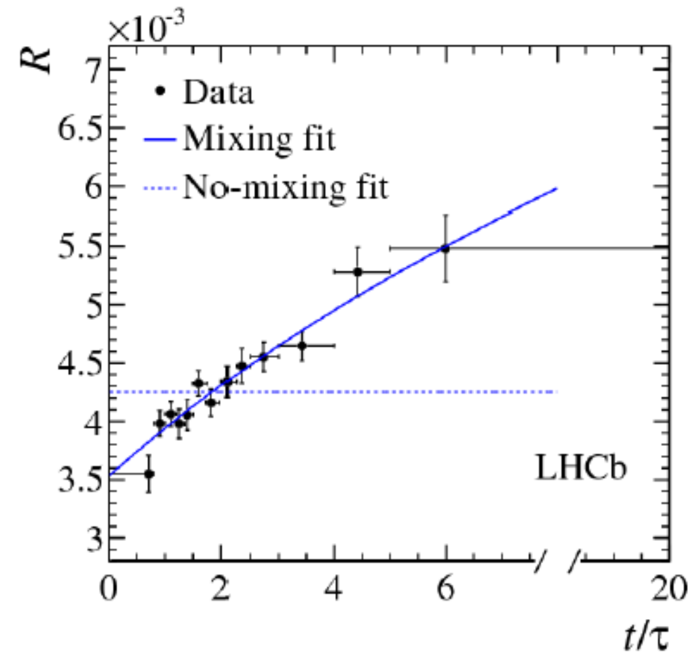
decay interference mixing



δ strong phase difference between CF and DCS :

$x' = x\cos(\delta) + y\sin(\delta)$ $y' = y\cos(\delta) - x\sin(\delta)$

LHCb 1 fb^{-1} datasample



CDF: 6.1 σ; CDF Public Note 10990,

LHCb: 9.1 σ; Phys. Rev. Lett 110 (2013) 101802

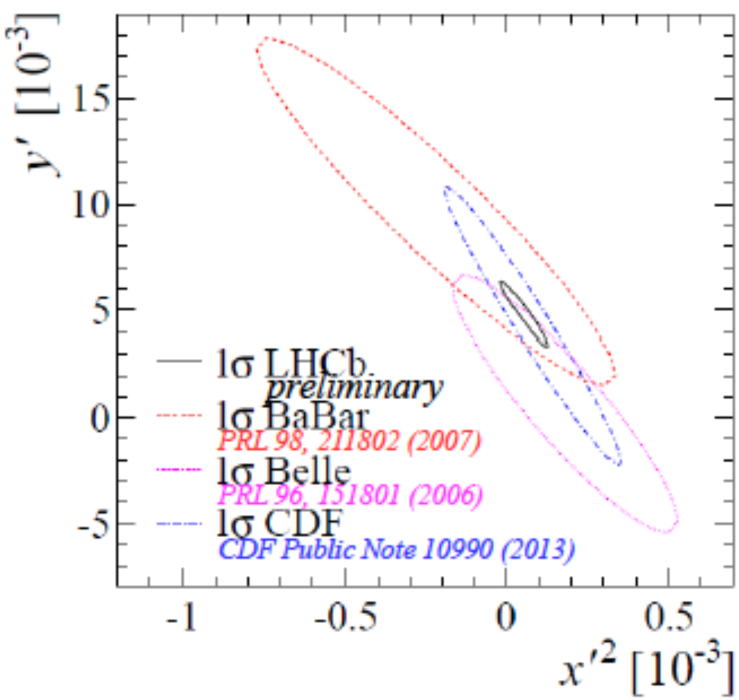
Babar: 3.9 σ; Phys. Rev. Let 98 (2007) 211802

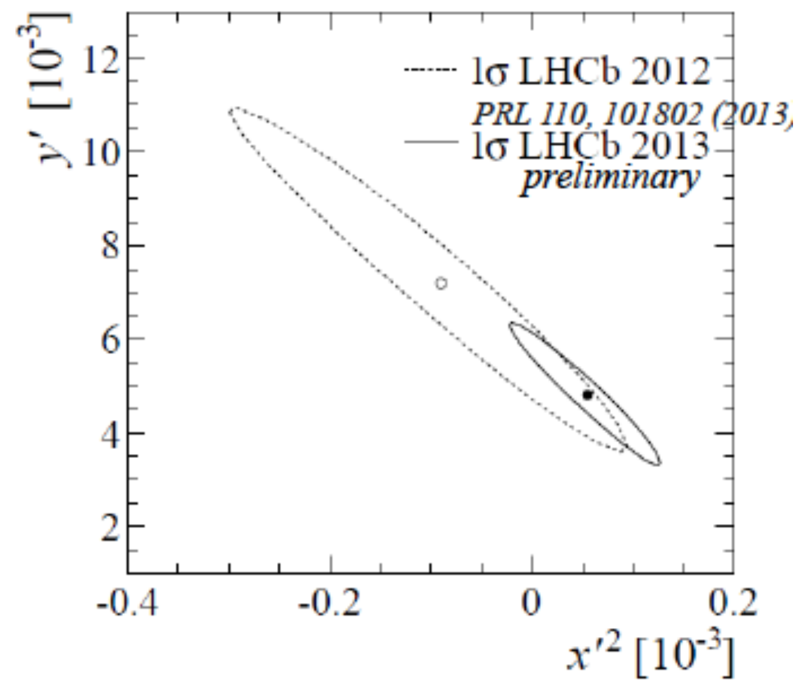
Belle: 2.0 σ; Phys. Rev. Lett 96 (2006) 151801

Latest LHCb results on charm mixing

LHCb-PAPER-2013-053 in preparation [3 fb^{-1}]

- The current LHCb results are consistent with other results, and provide an update to the previous ones





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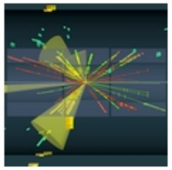

CPV in charm mixing

- Allowing for CPV, the WS/RS ratios are expressed separately for D^0 and $\overline{D}^0$:
  - $$R^+(t) = R_D^+ + \sqrt{R_D^+}\, y'^+ t + \frac{(x'^+)^2 + (y'^+)^2}{4}\, t^2,$$
    $$R^-(t) = R_D^- + \sqrt{R_D^-}\, y'^- t + \frac{(x'^-)^2 + (y'^-)^2}{4}\, t^2.$$

Mixing measurements on $R_D^{\pm}$, $x'^{2\pm}$, and $y'^{\pm}$ in $D^{*\pm}$, and look for the differences

$$x'^{\pm} = \left(\frac{1 \pm A_M}{1 \mp A_M}\right)^{1/4} (x' \cos\phi \pm y' \sin\phi)$$
$$y'^{\pm} = \left(\frac{1 \pm A_M}{1 \mp A_M}\right)^{1/4} (y' \cos\phi \mp x' \sin\phi)$$

$$A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-}$$

CPV in WS decay amplitude (**Direct CPV**)

$$A_M = \frac{|q/p|^2 - |p/q|^2}{|q/p|^2 + |p/q|^2}, \qquad \phi = \arg\left(\frac{q}{p}\right);$$

CPV in mixing / interference between mixing and decay

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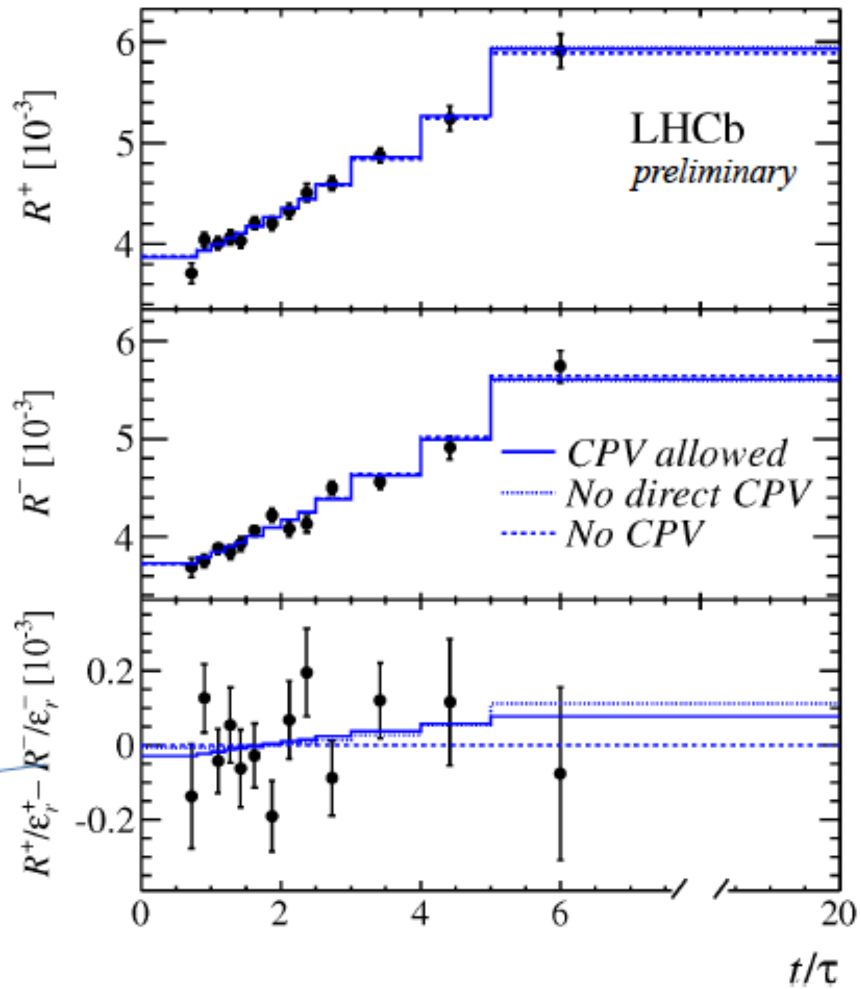
LHCb results on charm mixing

LHCb-PAPER-2013-053 in preparation

- Fits to the 3fb^{-1} data for 3 different hypotheses on the CP symmetry



Efficiency corrected differences between the WS/RS ratios of D $^{*\pm}$

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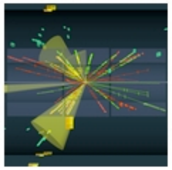

LHCb results on charm mixing CPV

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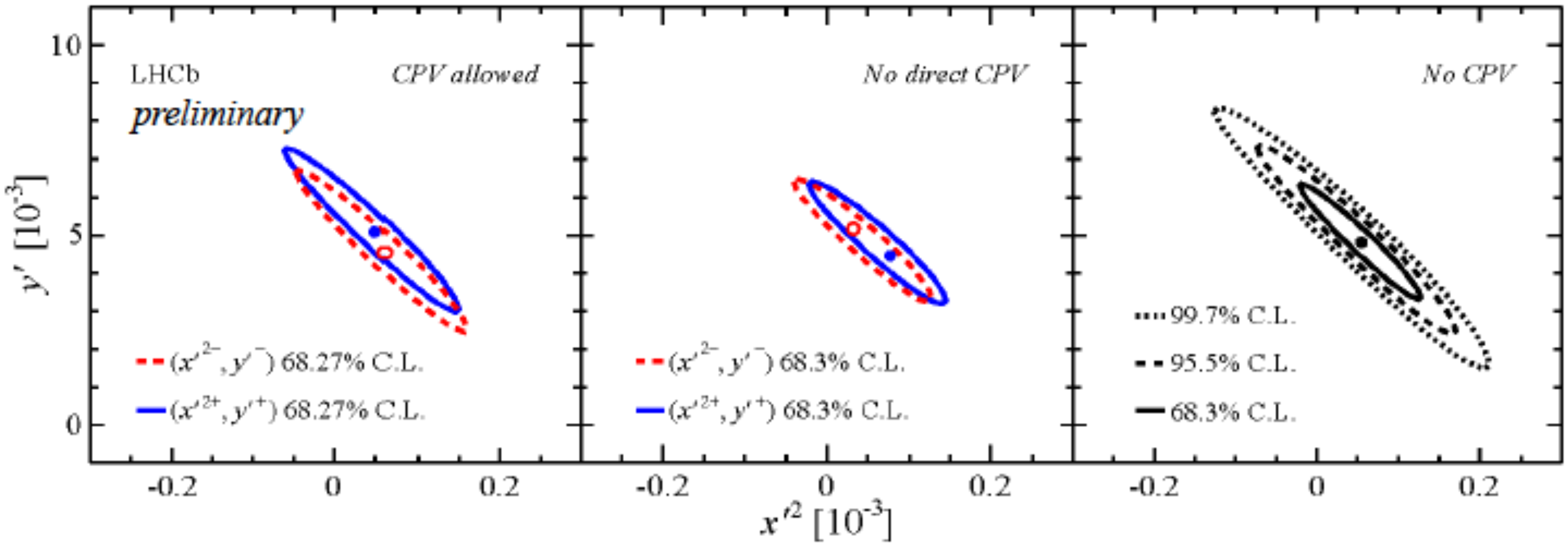
LHCb-PAPER-2013-053 in preparation



LHCb *preliminary* — *Uncertainties are statistical and systematic combined*

Direct and indirect CP violation			no direct CP violation			no CP violation		
R_D	$[10^{-3}]$	3.568 ± 0.066	R_D	$[10^{-3}]$	3.568 ± 0.066	R_D	$[10^{-3}]$	3.568 ± 0.066
A_D	$[10^{-2}]$	-0.7 ± 1.9	y'^+	$[10^{-3}]$	4.78 ± 1.07	y'	$[10^{-3}]$	4.81 ± 1.00
y'^+	$[10^{-3}]$	5.1 ± 1.4	x'^{2+}	$[10^{-5}]$	6.4 ± 5.5	x'^2	$[10^{-5}]$	5.5 ± 4.9
x'^{2+}	$[10^{-5}]$	4.9 ± 7.0	y'^-	$[10^{-3}]$	4.83 ± 1.07	χ^2/ndf		$86.41/101$
y'^-	$[10^{-3}]$	4.5 ± 1.4	x'^{2-}	$[10^{-5}]$	4.6 ± 5.5			
x'^{2-}	$[10^{-5}]$	6.0 ± 6.8	χ^2/ndf		$85.99/99$			
χ^2/ndf		$85.87/98$						

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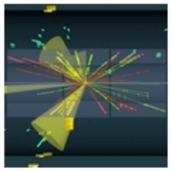
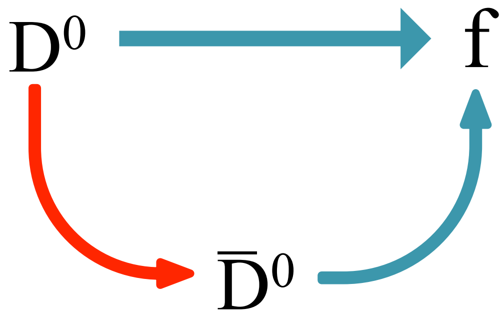


Charm decays into CP-eigenstates f=K⁺K⁻,π⁺π⁻,...

$A_f(D^0 \to f)$

$\bar{A}_f(\bar{D}^0 \to f)$



$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f} = -\eta_{CP}|\frac{q}{p}||\frac{\bar{A}_f}{A_f}|e^{i\phi}$$

ϕ : phase difference between decay and mixing

$\eta_{CP} = \pm 1$

CP violation in MIXING $\quad |\frac{q}{p}|^2 \approx 1 + A_m \qquad |\frac{\bar{A}_f}{A_f}|^2 \approx 1 + A_d \quad$ DIRECT CP violation

- since x = Δm/Γ, y=ΔΓ/2Γ are very small, perturbations to single exponential are tiny
- they can be measured in precision experiments

$$\Gamma(D^0(t) \to f) = \frac{1}{2}e^{-\Gamma t}|A_f|^2\Big\{(1+|\lambda_f|^2)cosh(\Delta\Gamma t) + (1-|\lambda_f|^2)cos(\Delta\Gamma t)$$

$$+2Re(\lambda_f)sinh(\Delta\Gamma t) - 2\Im(\lambda_f)sin(\Delta m t)\Big\}$$

$\Gamma(\bar{D}^0(t) \to f) \qquad \lambda_f \to 1/\lambda_f \qquad \Im\lambda_f \to -\Im\lambda_f$

Charm indirect CPV observables

$$a_{CP}^{dir} = -\frac{1}{2}A_d \qquad a_{CP}^{ind} = -\frac{1}{2}A_m y cos\phi + x sin\phi$$

INDIRECT : particular theoretical interest

Effective lifetime: $1/\Gamma_{eff}$ → fit to a single exponential parameter: $e^{-\Gamma_{eff}\, t}$

D^0 and $\bar{D}^0$ can be tagged at t=0 (both at e^+e^- and hadron colliders)

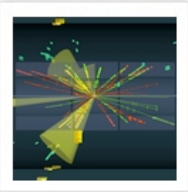
$$y_{CP} = \frac{\Gamma_{eff} + \bar{\Gamma}_{eff}}{2\Gamma} - 1 \approx \eta_{CP}\left[(1 - \frac{1}{8}A_m^2) y cos\phi - \frac{1}{2}A_m x sin\phi\right]$$

→ least affected by direct CPV

$$A_\Gamma = \frac{\Gamma_{eff} - \bar{\Gamma}_{eff}}{\Gamma_{eff} + \bar{\Gamma}_{eff}} \approx \eta_{CP}\left(-a_{CP}^{dir} y cos\phi - a_{CP}^{ind}\right)$$

→ a contribution from direct CPV still exists, at the level 10^{-4}

see M. Gersabeck et al. arXiv:1111:6515 (2012), A. L. Kagan and M. D. Sokoloff PR D80: 076008 (2009)



Charm direct CPV

Asymmetry in decay rate (time integrated):

$$A_{CP} = \frac{\Gamma(D^0) - \Gamma(\overline{D^0})}{\Gamma(D^0) - \Gamma(\overline{D^0})} \approx a_{CP}^{dir} - A_\Gamma \frac{\langle t \rangle}{\tau_D}$$

$< t >$: average decay time of the observed candidates

$$\frac{\langle t \rangle}{\tau_D}$$

- 1 for B-factory experiments
- 2.083 ± 0.001 for LHCb
- 2.53 ± 0.02 for CDF

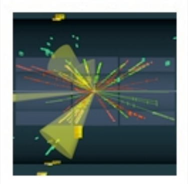
$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$

reduce experimental systematic uncertainties

$$\Delta A_{CP} = \Delta a_{CP}^{dir}\left(1 + y cos\phi \frac{\overline{\langle t \rangle}}{\tau_D}\right) + \left(a_{CP}^{ind} + \overline{a_{CP}^{dir}} y cos\phi\right)\frac{\Delta\langle t \rangle}{\tau_D}$$

small negligible

→ ΔA_{CP} : largely a measure of DIRECT CPV (while some contribution from indirect)



ΔA_{CP} from $D^0 \to h^+h^-$ decays

Time dependent asymmetry for D^0 decays to a CP eigenstate :

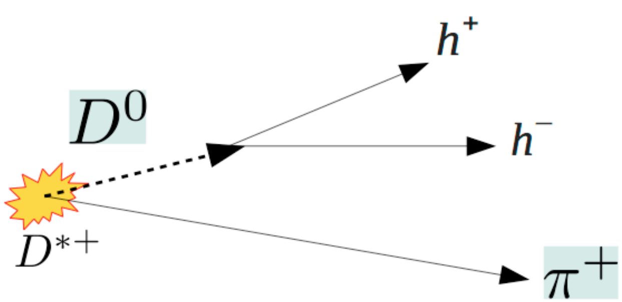
$$A_{CP}(f;t) = \frac{\Gamma(D^0(t) \to f) - \Gamma(\bar{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\bar{D}^0(t) \to f)} = a_{CP}^{dir}(f) + \frac{<t>}{\tau} a_{CP}^{ind}$$

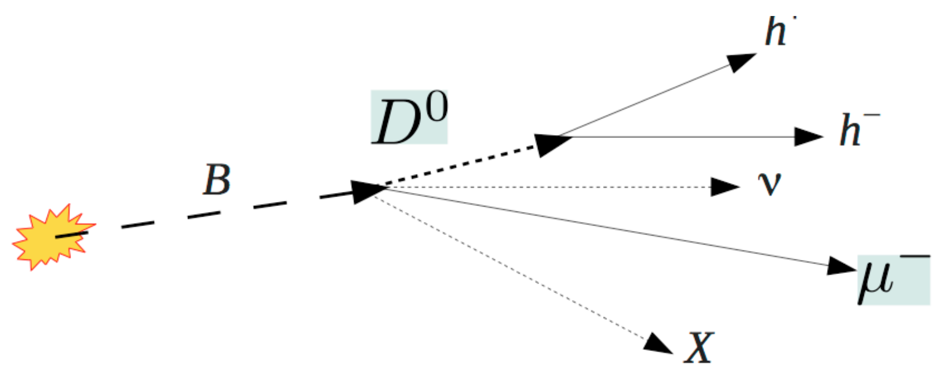
- Measure ΔA_{CP} between $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays
- Assume equal decay time acceptance for K^+K^- and $\pi^+\pi^-$
- Two datasets:
  - Prompt : $D^{*+} \to (D^0 \to h^+h^-)\, \pi^+_{soft}$ **Update**
  - Secondary : $B \to (D^0 \to h^+h^-)\, \mu X$ **New result**

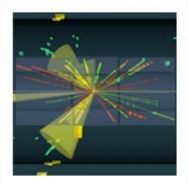
  Little overlap between them (statistics and systematics)
- In both cases assume:

$$\Delta A_{CP} = A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) = \left[a_{CP}^{dir}(K^-K^+) - a_{CP}^{dir}(\pi^-\pi^+)\right] + \frac{\Delta\langle t\rangle}{\tau_D} a_{CP}^{ind} \approx A_{raw}(K^-K^+) - A_{raw}(\pi^-\pi^+)$$

- Insensitive to indirect CP violation $\to$ universal to both final states

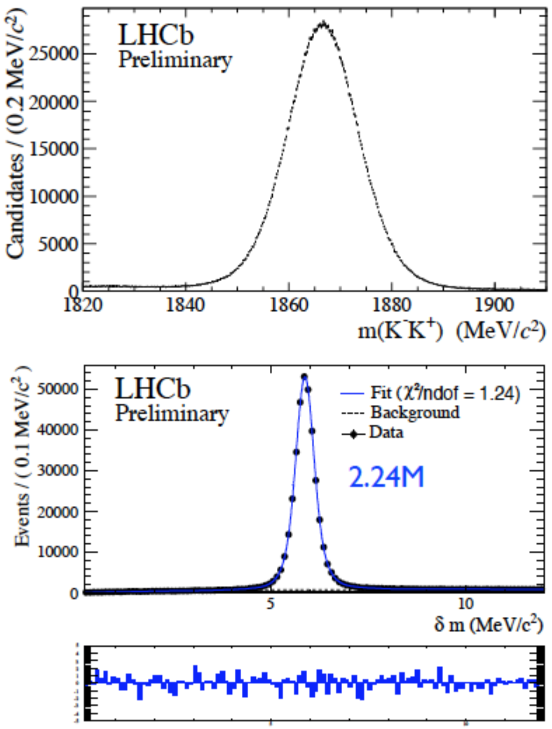




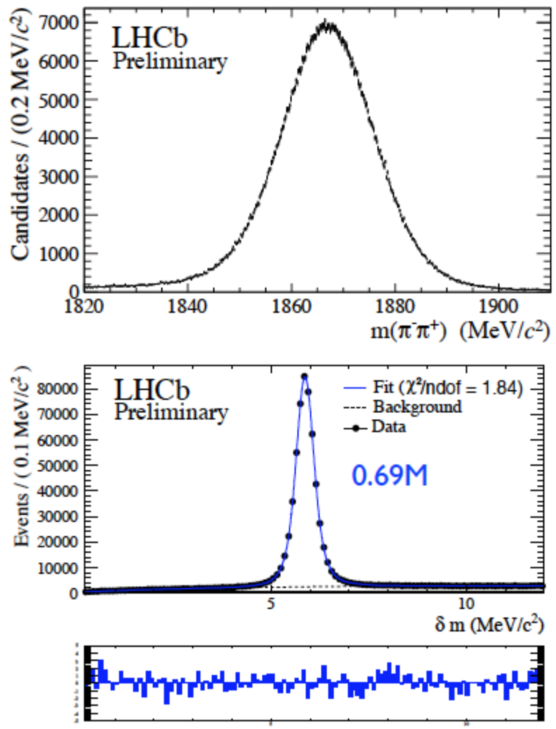


ΔA_{CP} from prompt $D^{*+} \rightarrow D^0 \pi^+_s$

$$\Delta A_{CP} = \left[a^{dir}_{CP}(K^-K^+) - a^{dir}_{CP}(\pi^-\pi^+)\right] + \frac{\Delta\langle t\rangle}{\tau_D}$$



$K^+ K^-$



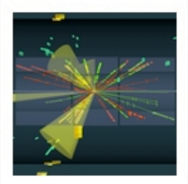
$\pi^+ \pi^-$

Raw asymmetry given by:

- $A_{raw}(t) =$ $A_{CP}(t) + A_D(t) + A_D(\pi_s^+) + A_P(D^{*+})$
- To first order $A_D(f)=0$ with f=self-conjugate
- $A_D(\pi_s^+)$, and $A_P(D^{*+})$ depend on D^{*+} kinematics
- Soft pion constrained to primary vertex

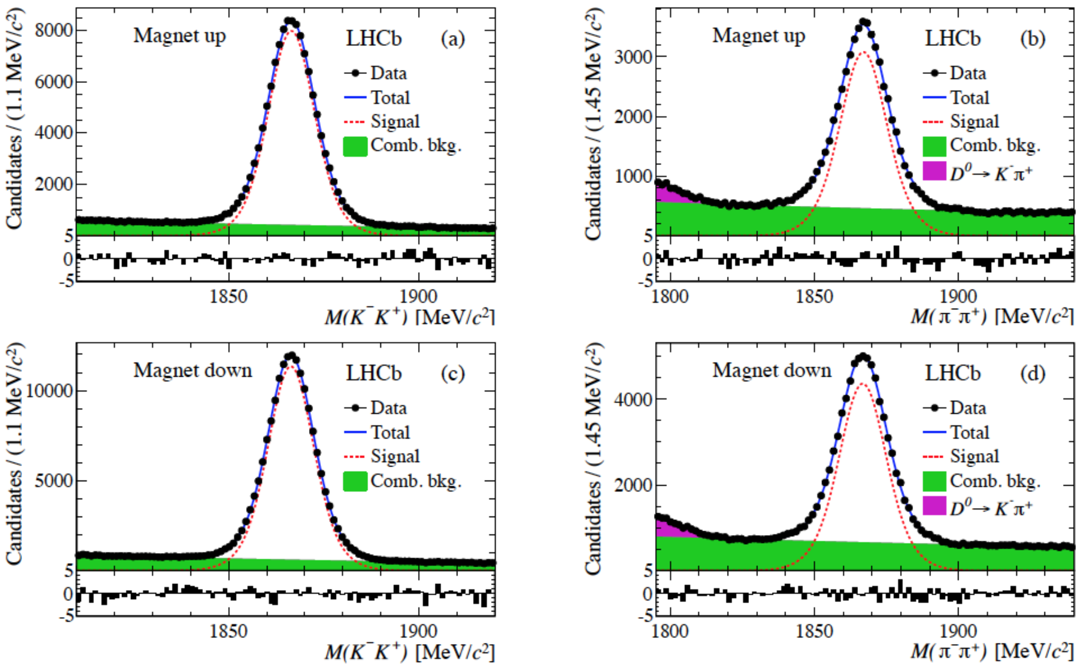
LHCb-CONF-2013-003 , Phys. Lett. B723 (2013) 33.

ΔA_{CP} = -0.34 ± 0.15 (stat) ± 0.10 (syst) %



ΔA_{CP} in $D \rightarrow h^+h^-$ from $B \rightarrow D^0 \mu X$

D^0 flavour tagged from the muon charge



$K^+ K^-$ (559k)

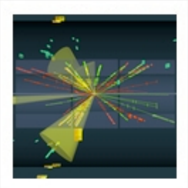
$\pi^+ \pi^-$ (222k)

LHCb-PAPER-2013-003
Phys. Lett. B723 (2013) 33.

LHCb [1.0 fb^{-1} (2011)] ΔA_{CP} = (+0.49 ± 0.30 (stat) ± 0.14 (syst))%

It does not confirm the direct CPV observed in other analyses

- Raw asymmetry can be approximated to $A_{raw} = A_{CP} + A^{\mu}_{D} + A^{B}_{P}$
- A^{B}_{P} is the $b/\bar{b}$ production asymmetry, independent of the final state particles
- Re-weight D^0 (p_T, η) distributions to account for differences in A^{μ}_{D} between the ππ and KK final states



Combined ΔA_{CP} from 1fb^{-1} LHCb

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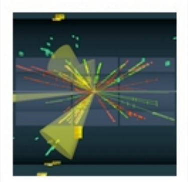
- Naive LHCb combination (assuming negligible indirect CPV):

D^{*+}-tagged	$-0.34 \pm 0.15 \pm 0.10\%$	(preliminary)
Muon-tagged	$+0.49 \pm 0.30 \pm 0.14\%$	
Combination	$-0.15 \pm 0.16\%$	(preliminary)

- The results are 2.2σ apart (compatible at 3% level)

- More on tape -- total of 3 fb^{-1} recorded before LS1
- Work in progress to isolate $A_{CP}(\pi^+\pi^-)$ and $A_{CP}(K^+K^-)$

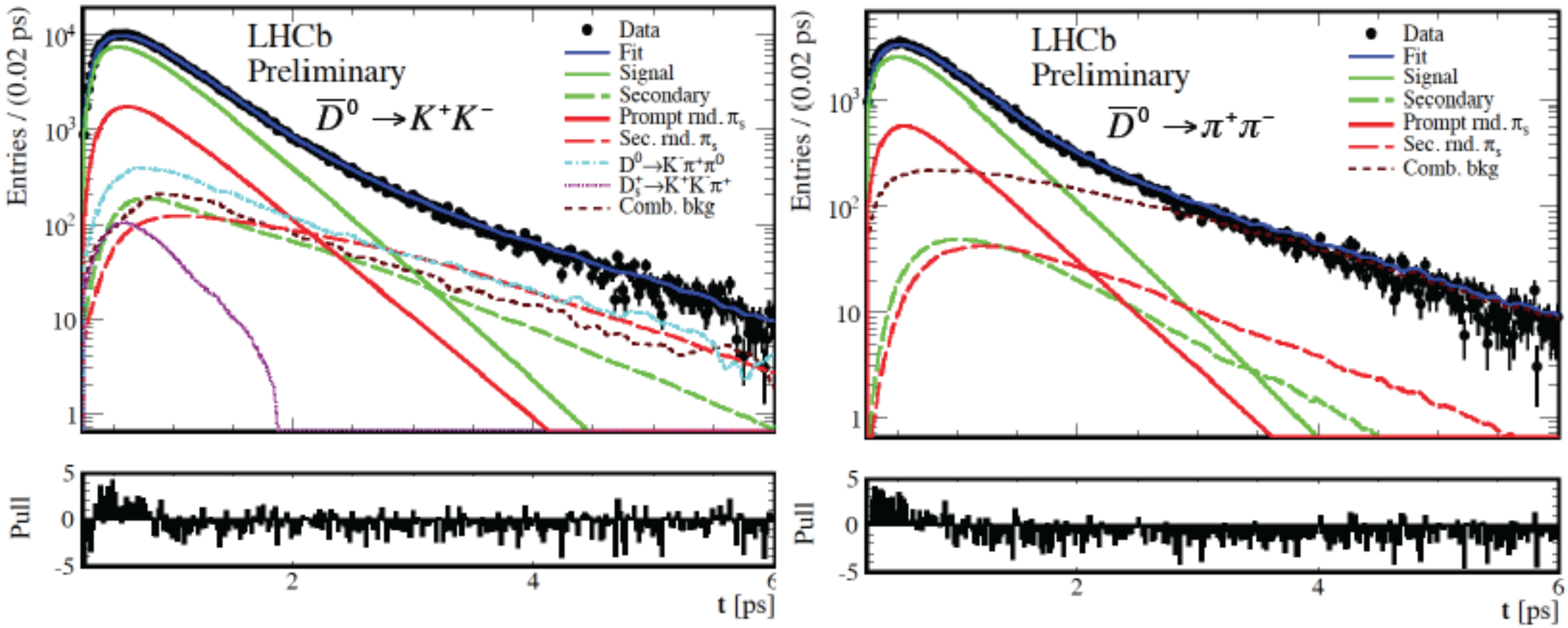
M. Charles at CHARM 2013 Manchester



A_Γ results : D^0 lifetime fit

LHCb-PAPER-2013-054 in preparation

- Measurement of the lifetime for each final state and each D^0 flavour



$A_\Gamma(KK) = (-0.35 \pm 0.62_{stat} \pm 0.12_{syst})\ 10^{-3}$

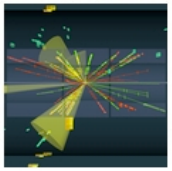
$A_\Gamma(\pi\pi) = (\ 0.33 \pm 1.06_{stat} \pm 0.14_{syst})\ 10^{-3}$

LHCb preliminary

No evidence for CP violation

No difference between the two final states

S. Borghi at CHARM 2013 Manchester

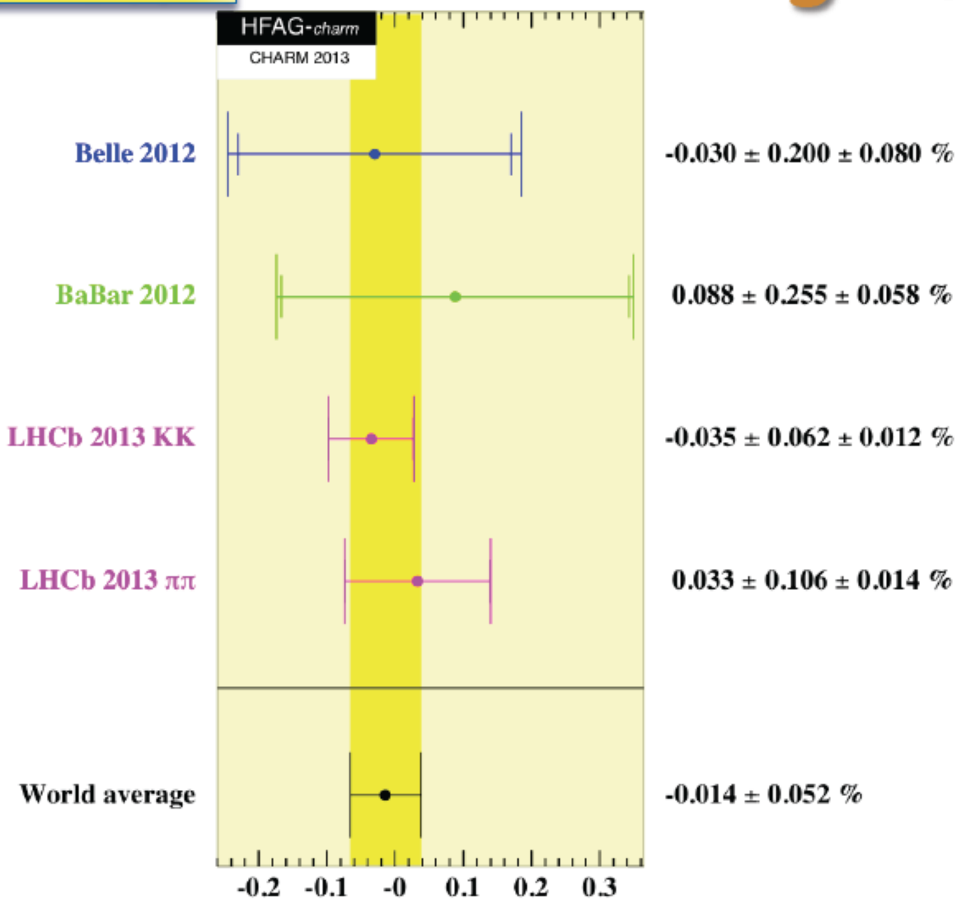


HFAG average for A_Γ

HFAG-*charm*
CHARM 2013

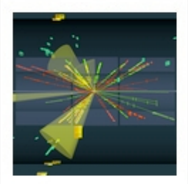
MANCHESTER 1824

New HFAG Average for A_Γ

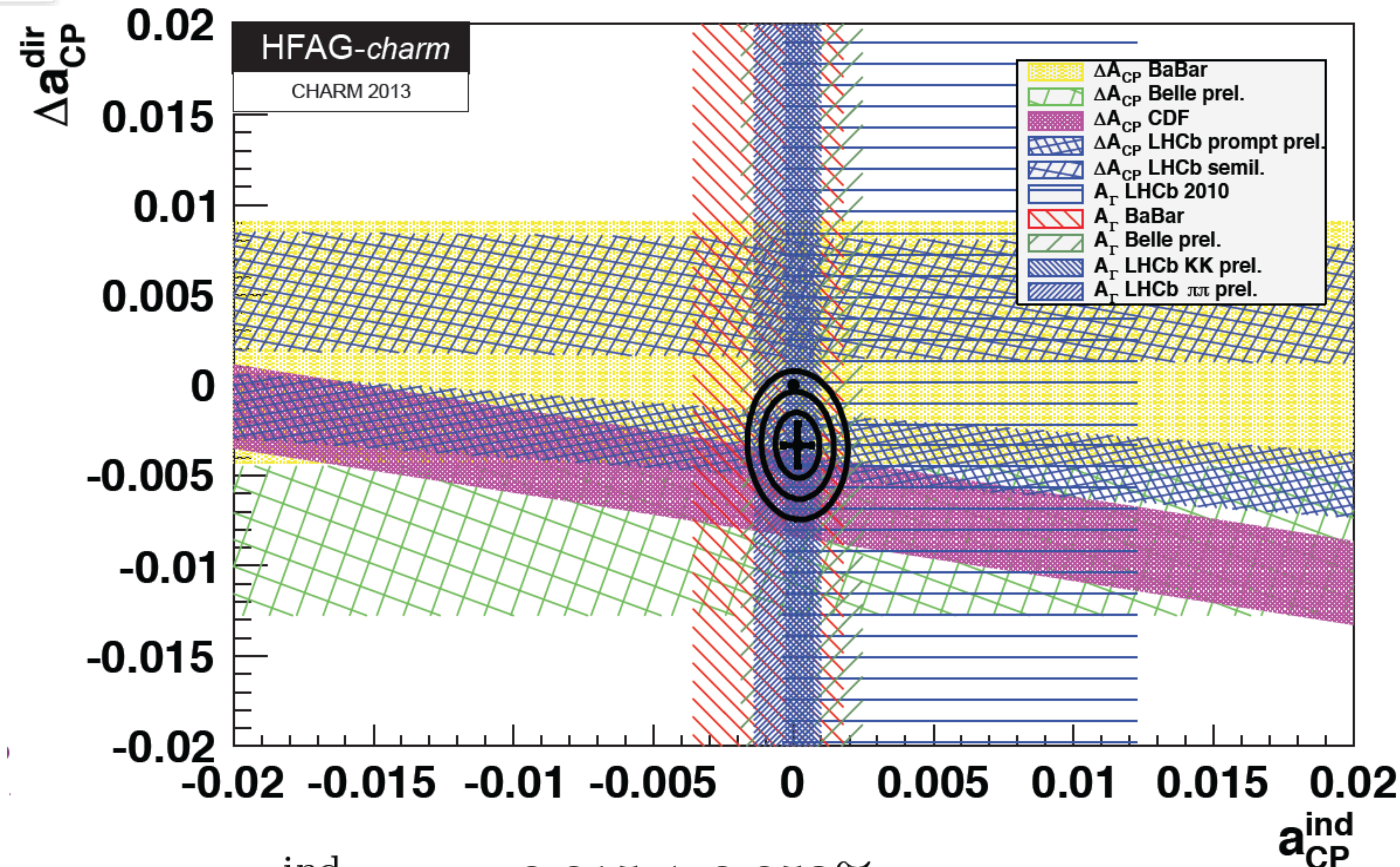


If $A_\Gamma \neq 0$
$\Rightarrow$ CP violation

S. Borghi at CHARM 2013



a_{CP}^{dir} versus a_{CP}^{ind} in D^0 meson



$$a_{CP}^{\rm ind} = +0.015 \pm 0.052\%$$
$$a_{CP}^{\rm dir} = -0.333 \pm 0.120\%$$

Compatible with no CPV at 2.0% CL

M. Charles at CHARM 2013 Manchester

Direct CPV in $D^+ \rightarrow \Phi\pi^+$ / $K^0_s\pi^+$

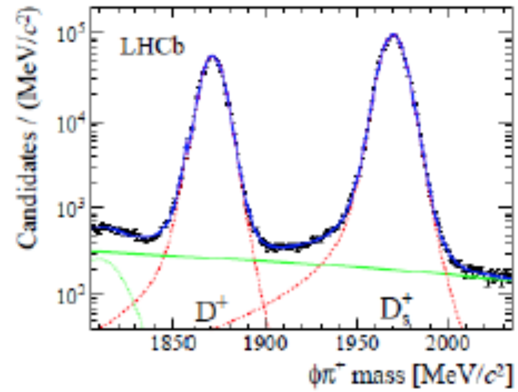
CENTRO DE CIENCIAS DE BENASQUE PEDRO PASCUAL

Searches for CPV in $D^+ \to \Phi\pi^+$

$(-0.04 \pm 0.14 \pm 0.14)\%$ LHCb [JHEP 06 (2013) 112]

$(+0.51 \pm 0.28 \pm 0.05)\%$ Belle [PRL 108 (2012) 071801]

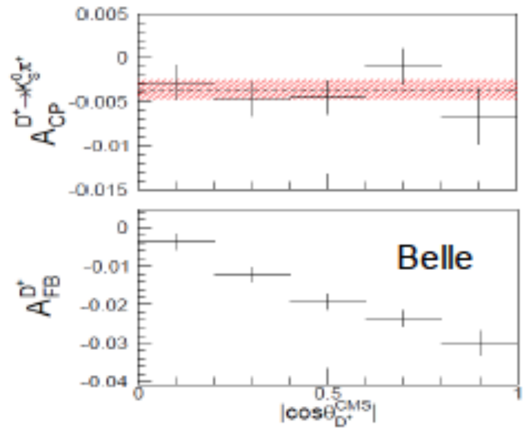
$(-0.3 \pm 0.3 \pm 0.5)\%$ BaBar [PRD 87 (2012) 052010]



Searches for CPV in $D^+ \to K^0_S\pi^+$

$(-0.363 \pm 0.094 \pm 0.067)\%$ Belle [PRL 109 (2012) 021601]

$(-0.44 \pm 0.13 \pm 0.10)\%$ BaBar [PRD 83 (2011) 071103]



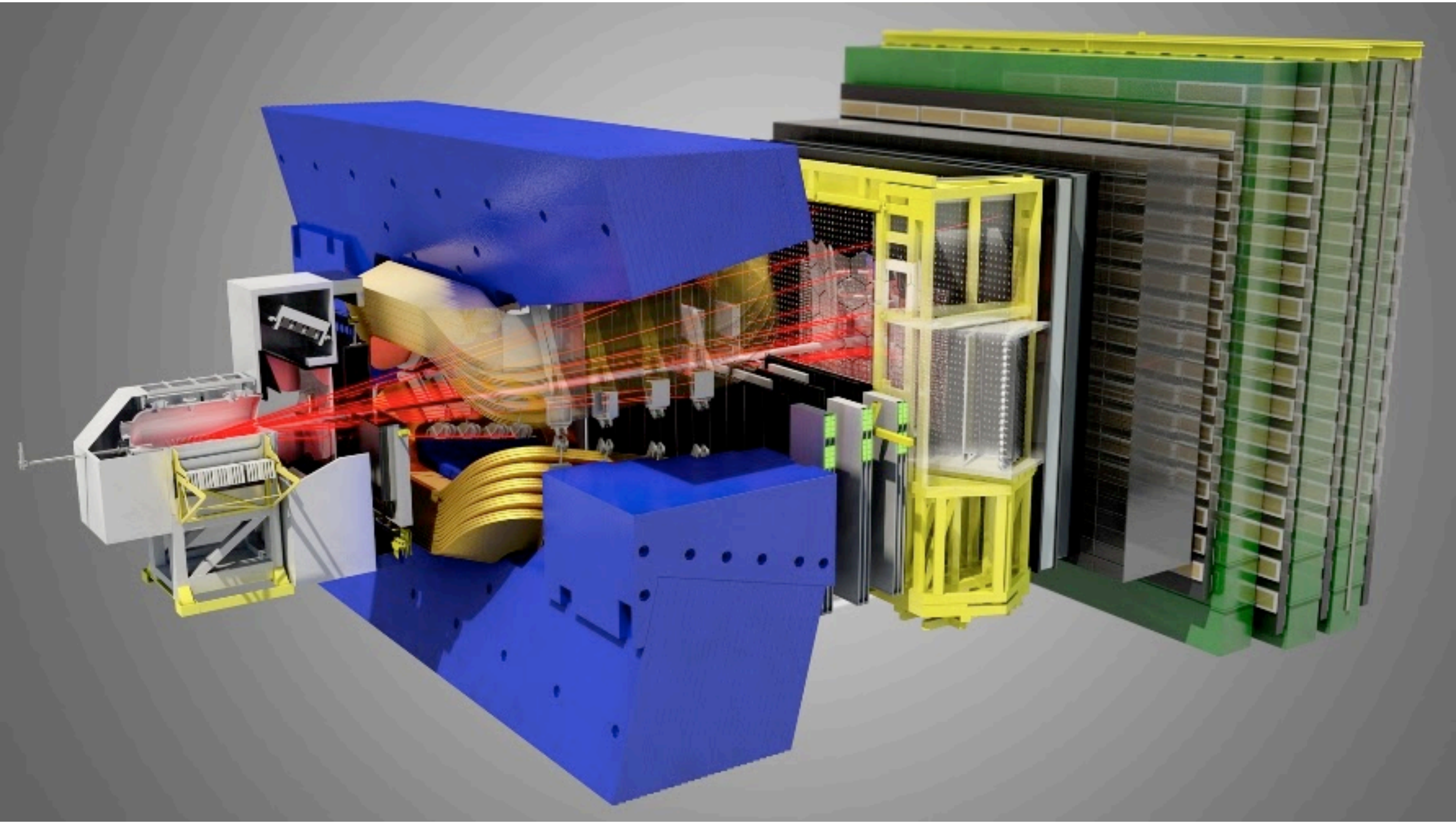
This *is* significant! *But* it is driven by K^0 CPV, and value is entirely consistent with this single source

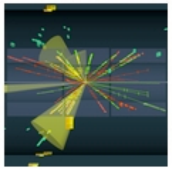
(Also see JHEP 02 (2013) 098 for $K^0_S K^+$ result)

Even in SCS modes searches now at per-mille precision. Prospects of direct CPV revealing clear sign of NP receding. But still of *great* interest to find a non-0 signal.

A. Schwartz G. Wilkinson at CHARM 2013 Manchester

Rare decays





Rare decays

CENTRO DE CIENCIAS DE BENASQUE PEDRO PASCUAL

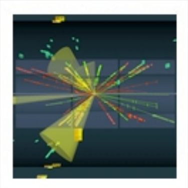
Rare decays probe fundamental principles of the SM

- $B_{(s)} \rightarrow \mu^+\mu^-$
- $b \rightarrow s\mu^+\mu^-$ transitions

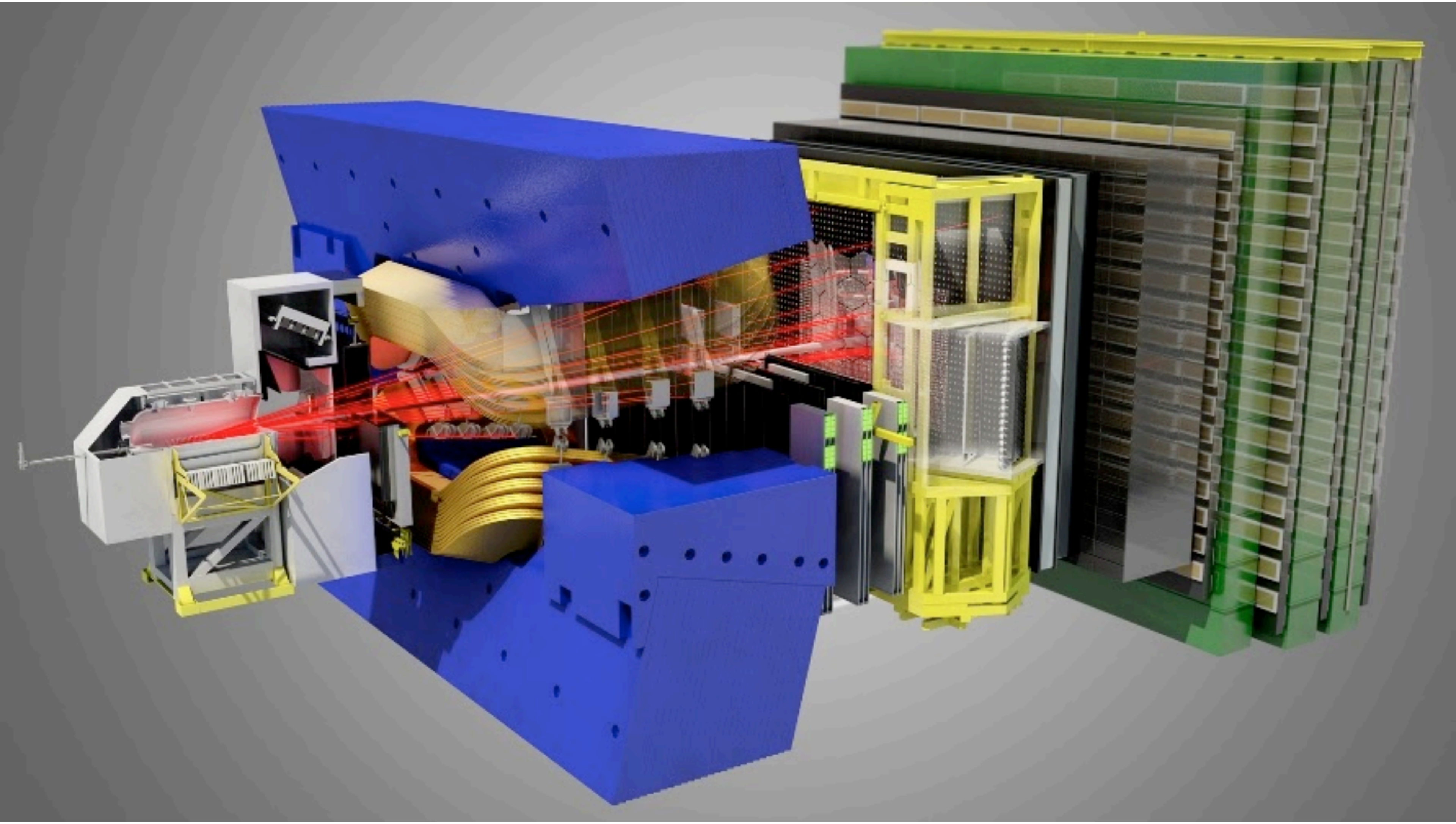
  $B^0 \rightarrow K^*l^+l^-$, $B^+ \rightarrow K^+l^+l^-$, $B_s \rightarrow \phi l^+l^-$, $\Lambda_b \rightarrow \Lambda\mu^+\mu^-$, $B^0 \rightarrow X_s l^+l^-$
- $B \rightarrow K\pi\pi\gamma$
- $B_{(s)} \rightarrow e^+\mu^-$

- $D^0 \rightarrow \mu^+\mu^-$
- $D^+_{(s)} \rightarrow \pi^+\mu^+\mu^-$
- $D^+_{(s)} \rightarrow \pi^-\mu^+\mu^+$

- $\tau^- \rightarrow \mu^-\mu^+\mu^-$
- $\tau^- \rightarrow p\mu^-\mu^-$, $\tau^- \rightarrow p\mu^+\mu^-$



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



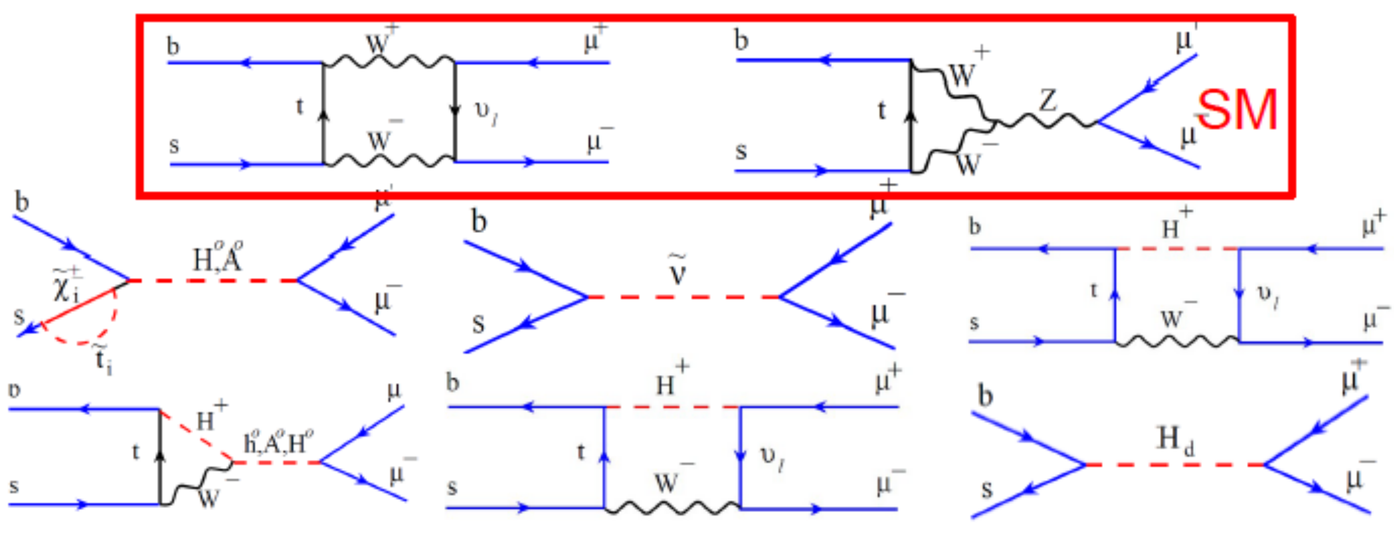
$B \rightarrow \mu^+\mu^-$

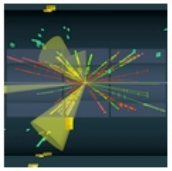
The two very rare decays $B^0_s \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$ have drawn much interest !

Easy to predict SM branching fraction with great precision

$BF\ (B^0_s \rightarrow \mu^+\mu^-)_{SM} = 3.56 \pm 0.30 \times 10^{-9}$ (time averaged)
$BF\ (B^0_s \rightarrow \mu^+\mu^-)_{SM} = 0.10 \pm 0.01 \times 10^{-9}$

Sensitive to the scalar sector of flavour couplings





Quest for $B^0_s \rightarrow \mu^+\mu^-$

LHCb: Phys Rev Lett 110 (2013) 021801 (2.1 fb^{-1})

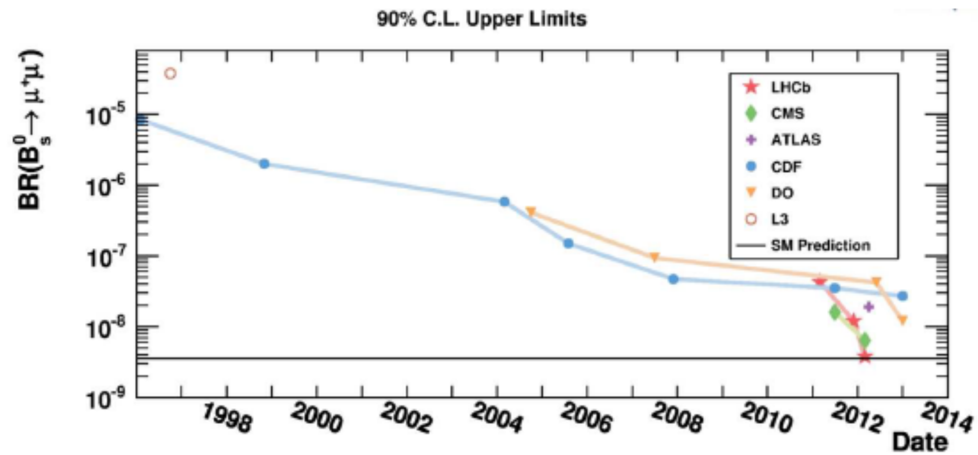
CMS: J. High Energy Phys 04 (2012) 033 (5.0 fb^{-1})

ATLAS: ATLAS-CONF-2013-076 (5.0 fb^{-1})

CDF: Phys. Rev. D 87, 072003 (2013) (9.7 fb^{-1})

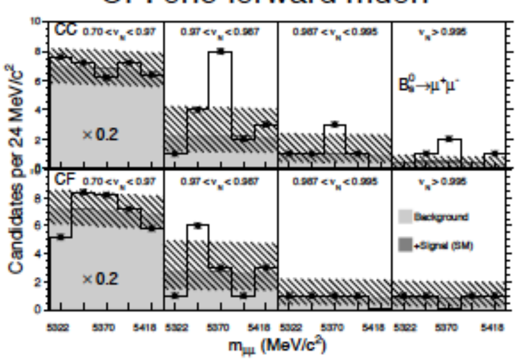
D0: Phys. Rev. D87 07.2006 (2013) (10.4 fb^{-1})

S. Hansemann-Menzemer at EPS2013



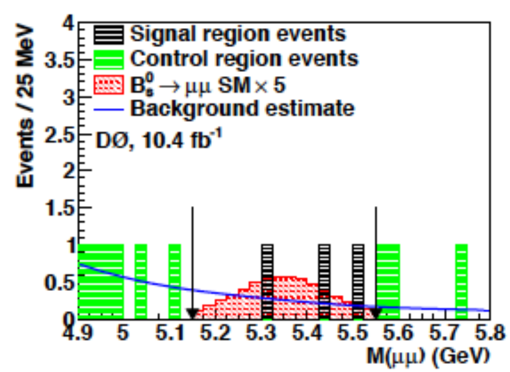
CC: two central muons

CF: one forward muon



95% CL:

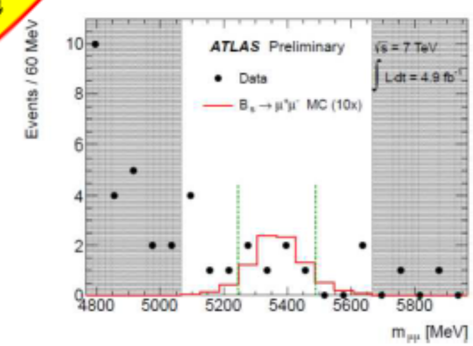
$BR(B_s \rightarrow \mu^+\mu^-) < 3.1 \times 10^{-8}$



95% CL:

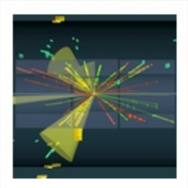
$BR(B_s \rightarrow \mu^+\mu^-) < 1.5 \times 10^{-8}$

new @ EPS2013



95% CL:

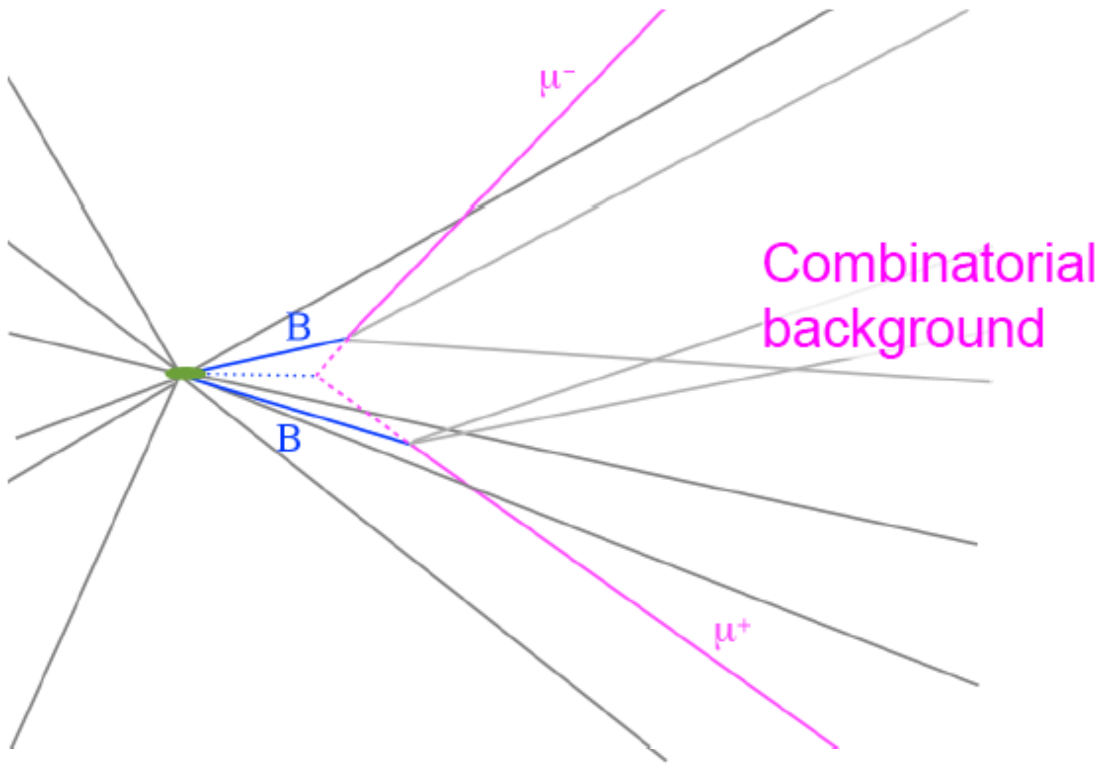
$BR(B_s \rightarrow \mu^+\mu^-) < 1.5 \times 10^{-8}$



B → $\mu^+\mu^-$

Decay topology is simple

Challenge is to keep trigger and selection efficiency high, while rejecting combinatorial background



Combined result $B^0_{(s)} \rightarrow \mu^+\mu^-$

Isolation for the dimuon vertex is very important

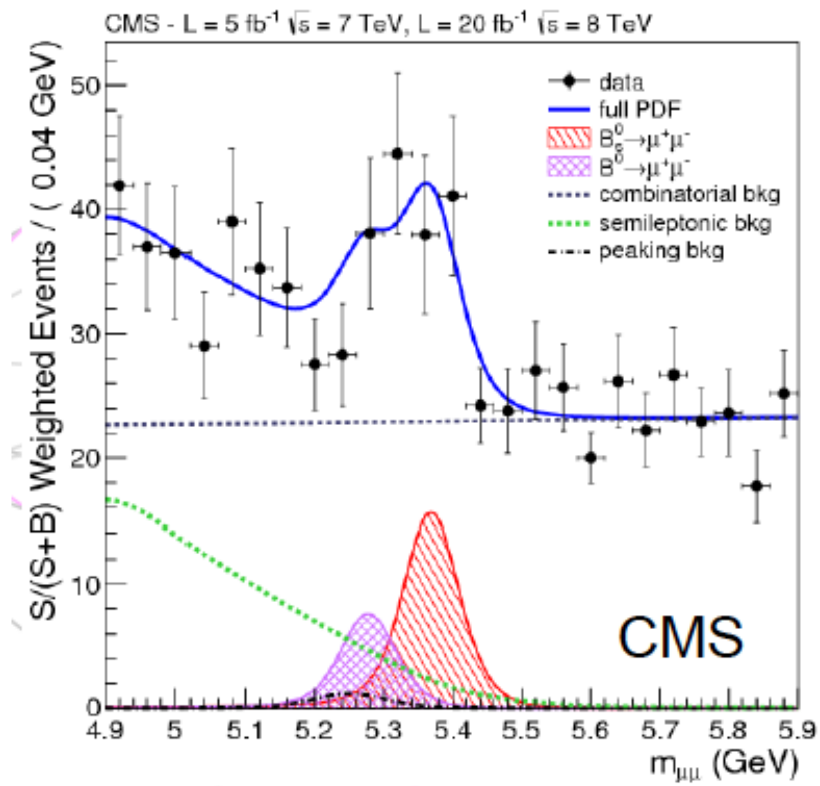
For ATLAS and CMS the higher integrated luminosity compensates for lower trigger efficiency

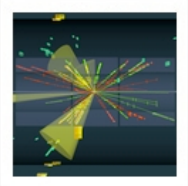
Both CMS and LHCb see $B^0_s \rightarrow \mu^+\mu^-$ at the 4σ level

CMS 25 fb^{-1}

LHCb 3 fb^{-1}

Combination is above 3σ





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

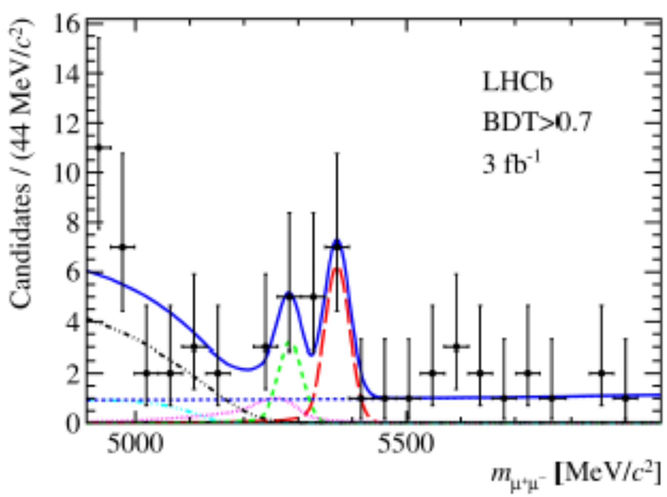
Challenge now is to look for $B^0 \rightarrow \mu^+\mu^-$

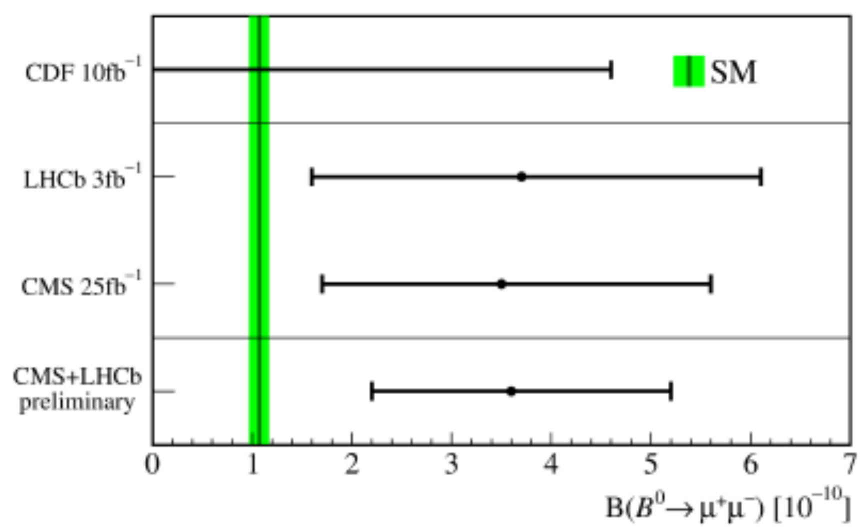
In the SM suppressed by $|V_{ts}|^2 / |V_{td}|^2 \sim 25$

New physics not following this pattern may manifest itself as a higher $B^0 \rightarrow \mu^+\mu^-$ rate

Lower rate and peaking backgrounds now a real issue

CMS: $< 1.1\ 10^{-9}$ at 95% CL LHCb: $< 0.7\ 10^{-9}$ at 95% CL





Combined result $B^0_{(s)} \rightarrow \mu^+\mu^-$

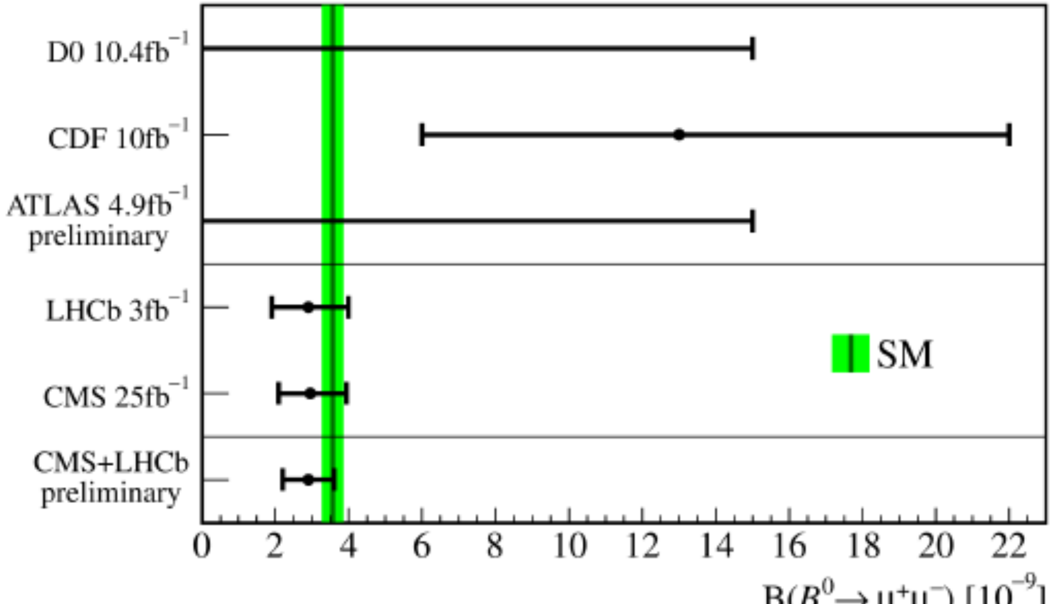
Combined CMS and LHCb result

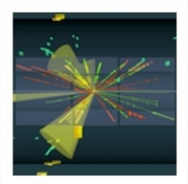
BF (B^0_s) = (2.9 ± 0.7) × 10^{-9}

ATLAS limit on 5 fb^{-1}

BF (B^0_s) < 15 × 10^{-9} at 95% CL

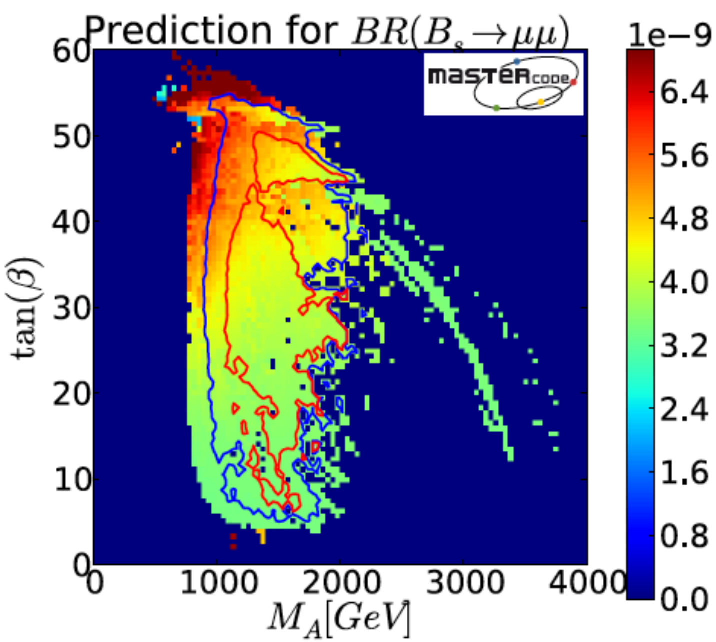
LHCb : Phys. Rev. Lett. 111, 101805 (2013)
CMS : arXiv: 1307.5025
Comb : LHCb-CONF-2013-076
ATLAS : ATLAS-CONF-2013-076

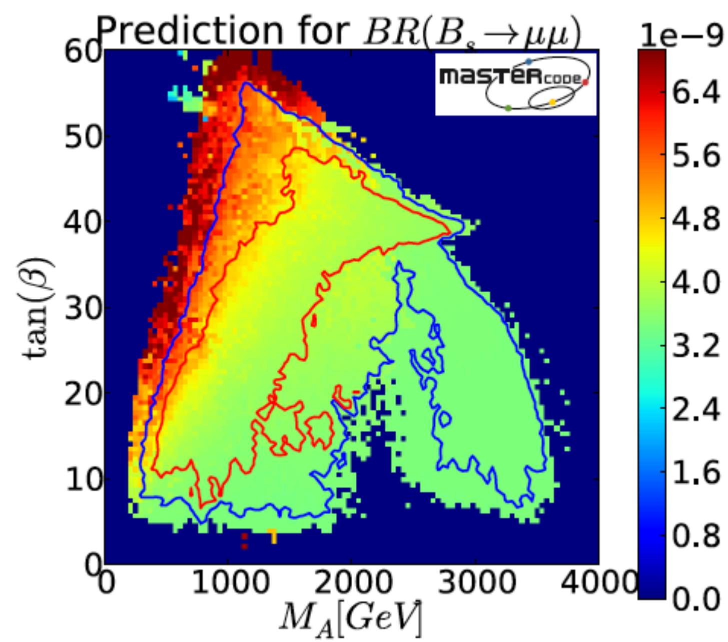




$B \rightarrow \mu^+\mu^-$ constraining Supersymmetry

$BR(B_s \rightarrow \mu^+\mu^-)$ sets strong bounds on tanβ, at least in CMSSM, and reduces the phase space of Supersymmetry, complementary to direct searches. Higgs mass of 125 GeV included, as well as other electroweak and XENON100 data. Some scenarios of new Physics are removed. SUSY now confronted.

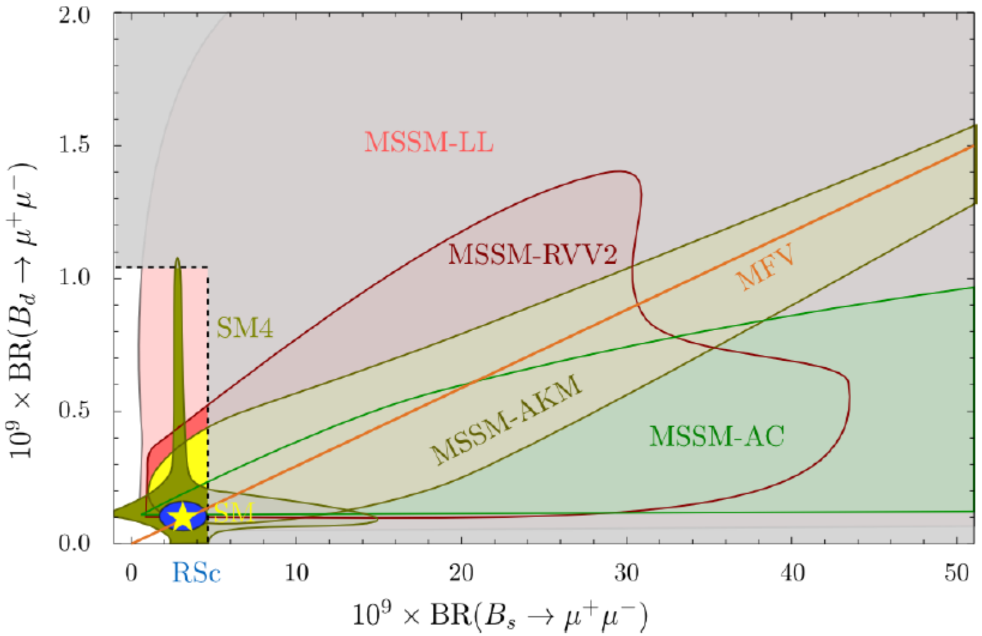


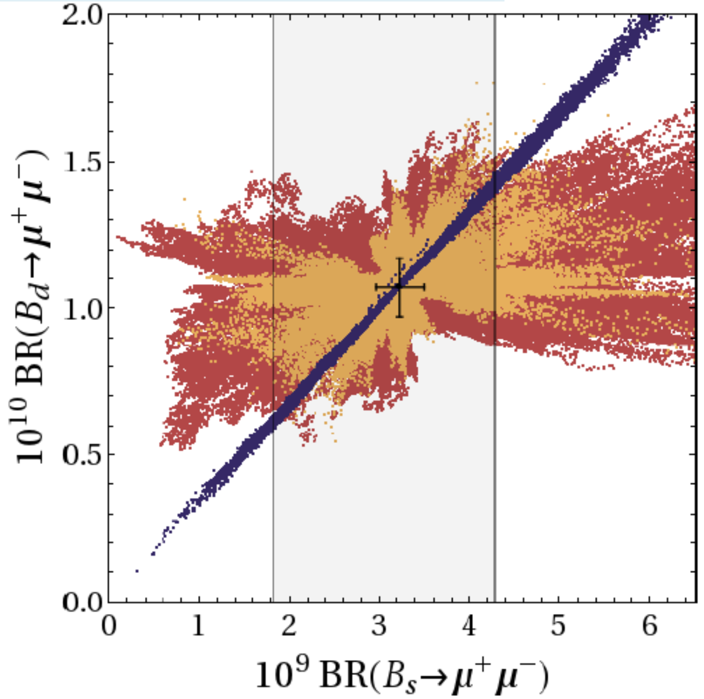


BR predictions in the CMSSM and in the CMSSM with non-universal Higgs masses NUHM1 (right). Allowed region regions of parameter space at 68% and 98% CL

O. Buchmueller et al., Eur. Phys. J. C 72 (2012) 2243 [arXiv:1207.7315]

$B \rightarrow \mu^+\mu^-$ constraining SUSY and compositeness





Large tanβ with **light pseudoscalar Higgs** in CMSSM is strongly **disfavored.**
Now in the regime where more "natural" O(50%) NP effects can be probed

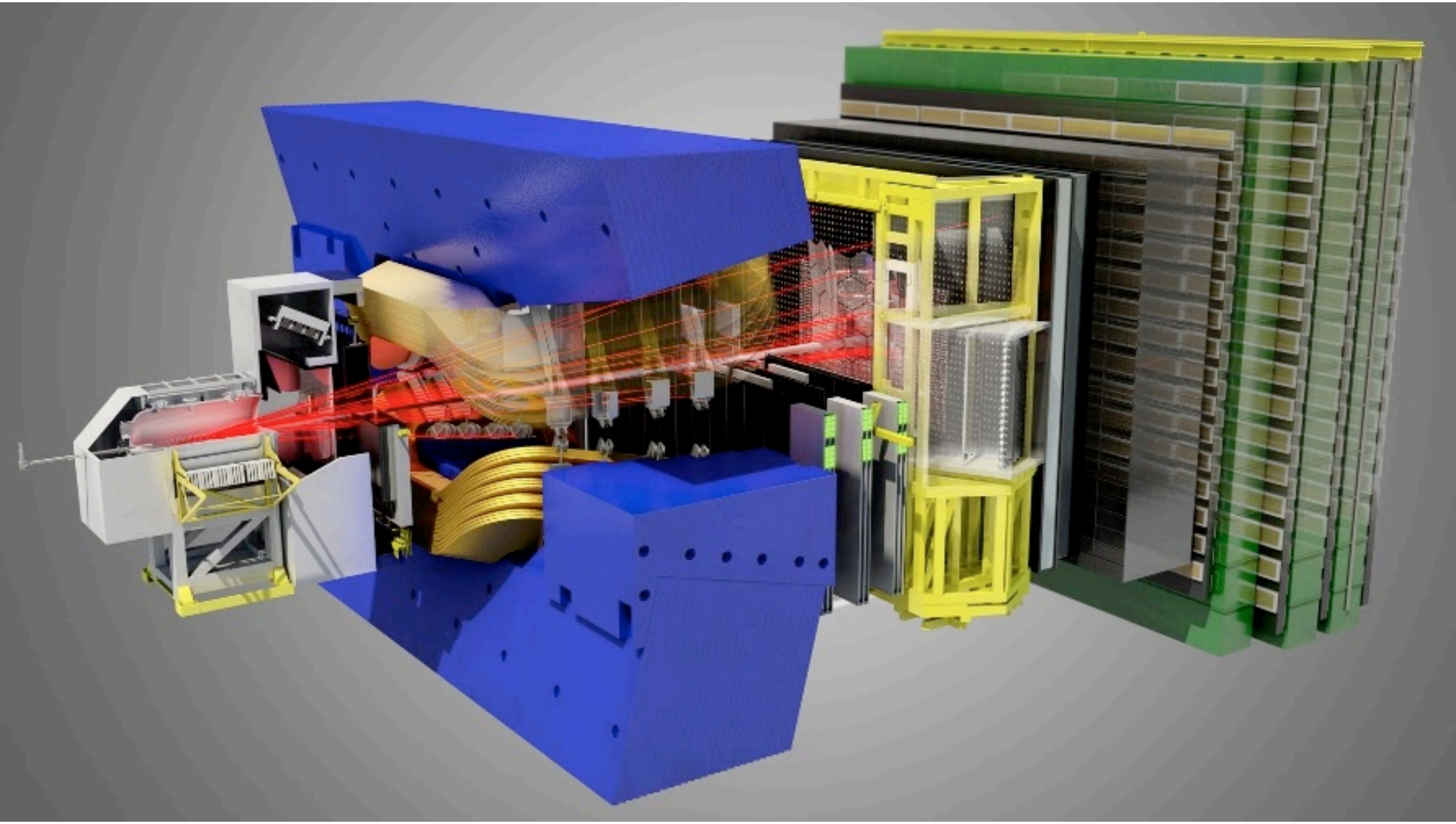
Straub arXiv:1302.4651
Analysis of several models with partial compositeness

Now vital to measure:

- **$BR(B_s \rightarrow \mu^+\mu^-)$ down to theory uncertainty (a few x 10^{-10})**
- $BR(B_d \rightarrow \mu^+\mu^-)$ to test "golden" relation between SM and MFV, distinguish between NP models

$$\frac{BR(B_s \to \mu^+\mu^-)}{BR(B_d \to \mu^+\mu^-)} \approx \frac{f_{B_s}^2}{f_{B_d}^2} \frac{\tau_{B_s}}{\tau_{B_d}} \frac{|V_{ts}|^2}{|V_{td}|^2} \approx 32$$

$b \rightarrow s\mu^+\mu^-$



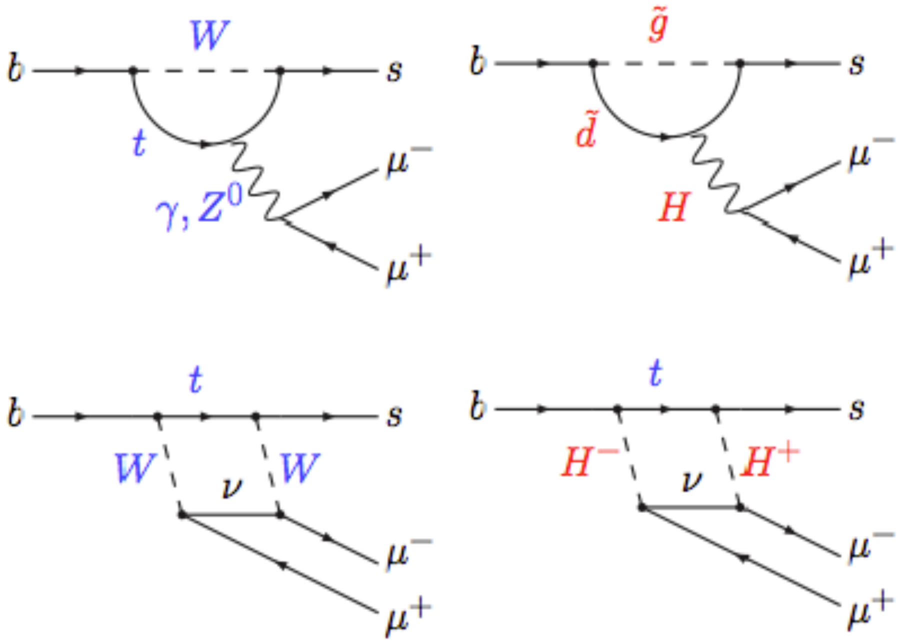
b → $s\mu^+\mu^-$

$$H = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum (C_i^{SM} + C_i^{NP}) O_i^{SM} + \sum \frac{c}{\Lambda_{NP}} \ O_{NP}$$

b → $s\mu^+\mu^-$ rare processes where new physics can enter to modify SM amplitudes

$B^0 \to K^* \ell^+ \ell^-$ is the most prominent (large statistic and flavour specific) candidate

Studies in statistical limited $B_s \to \phi\mu^+\mu^-$, $\Lambda_b \to \Lambda\mu^+\mu^-$ started

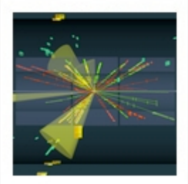


In the SM contribution from :

$$\mathcal{O}_7 \sim m_b(\bar{s}_L \sigma_{\mu\nu} b_R) F_{\mu\nu}$$

$$\mathcal{O}_9 \sim (\bar{s}b)_{V-A}(\bar{\ell}\ell)_V$$

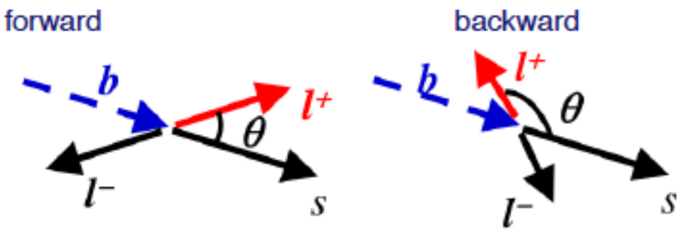
$$\mathcal{O}_{10} \sim (\bar{s}b)_{V-A}(\bar{\ell}\ell)_A$$



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

One very famous variable:

$$A_{FB} \propto -Re[(2C_7^{eff} + \frac{q^2}{m_b^2}C_9^{eff})C_{10}]$$



Introduce 3 relative angles to describe angular distribution of final state particles.

Folding $\phi \to \phi + \pi$ if $\phi < 0$ increase sensitivity for some coefficients.

e.g. $A_{FB} = \frac{3}{4}(1 - F_L)A_T^{Re}$

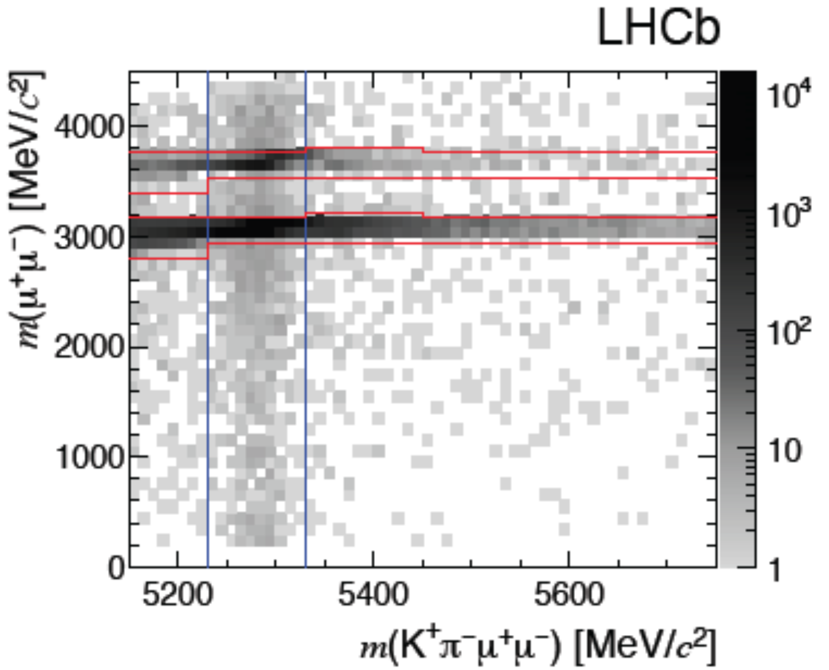
$$\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + \frac{1}{2}(1-F_L)A_T^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi +$$
$$\sqrt{F_L(1-F_L)}P'_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + \sqrt{F_L(1-F_L)}P'_5\sin 2\theta_K\sin\theta_\ell\cos\phi +$$
$$\frac{1}{2}(1-F_L)A_{Re}^T\sin^2\theta_K\cos\theta_\ell + \sqrt{F_L(1-F_L)}P'_6\sin 2\theta_K\sin\theta_\ell\sin\phi +$$
$$\sqrt{F_L(1-F_L)}P'_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + (S/A)_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

New: alternative folding give access to form factor independent parameters

(arXiv:1106.3283, arXiv:1106.3283, arXiv:hep-ph/050206, arXiv:0807.2589, arXiv:1105.0376)

Candidate selection $B^0 \to K^*\mu^+\mu$

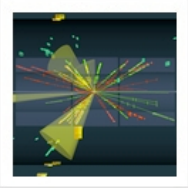
arXiv:1304.6325 ($1fb^{-1}$)



- Candidates selected using a BDT
- (Tree-level) Charmonium resonances vetoed
- Exclusive and partially reconstructed background investigated and reduced to negligible level

883 ± 34 evts

Control modes $B^0 \to J/\psi\, K^{*0}$ and $D^* \to D(K\pi)\pi_s$

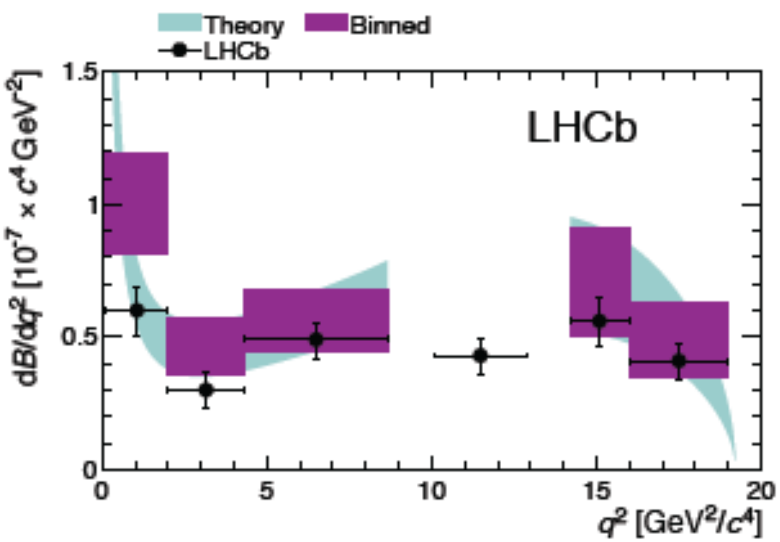


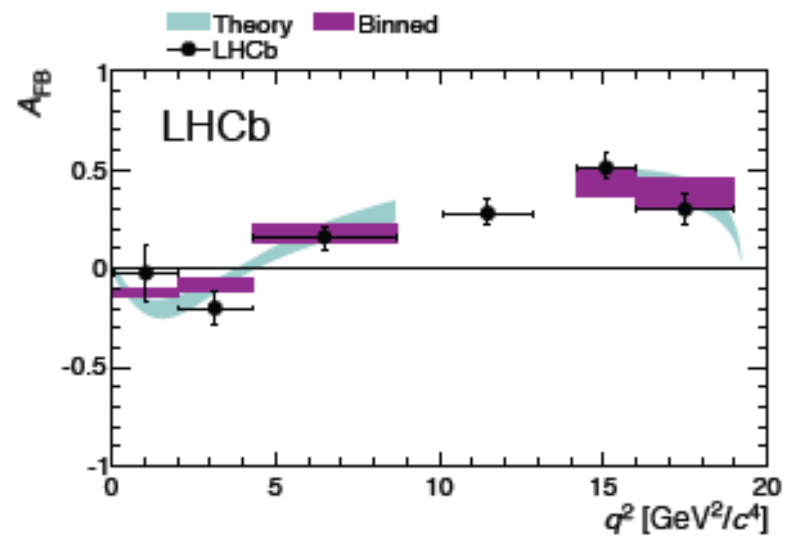
$B^0 \rightarrow K^{*0}\mu^+\mu^-$

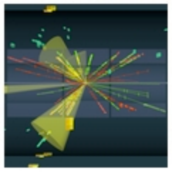
arXiv:1304.6325 ($1fb^{-1}$)

- Results accord with the SM predictions (Bobeth et al., JHEP 01 (2012) 107)
- First measurement of the zero-crossing point of A_{FB} (error is stat+sys) (SM predictions in range 3.9-4.4 GeV^2/c^4)

$$q_0^2 = 4.9 \pm 0.9\,\mathrm{GeV}^2/c^4$$

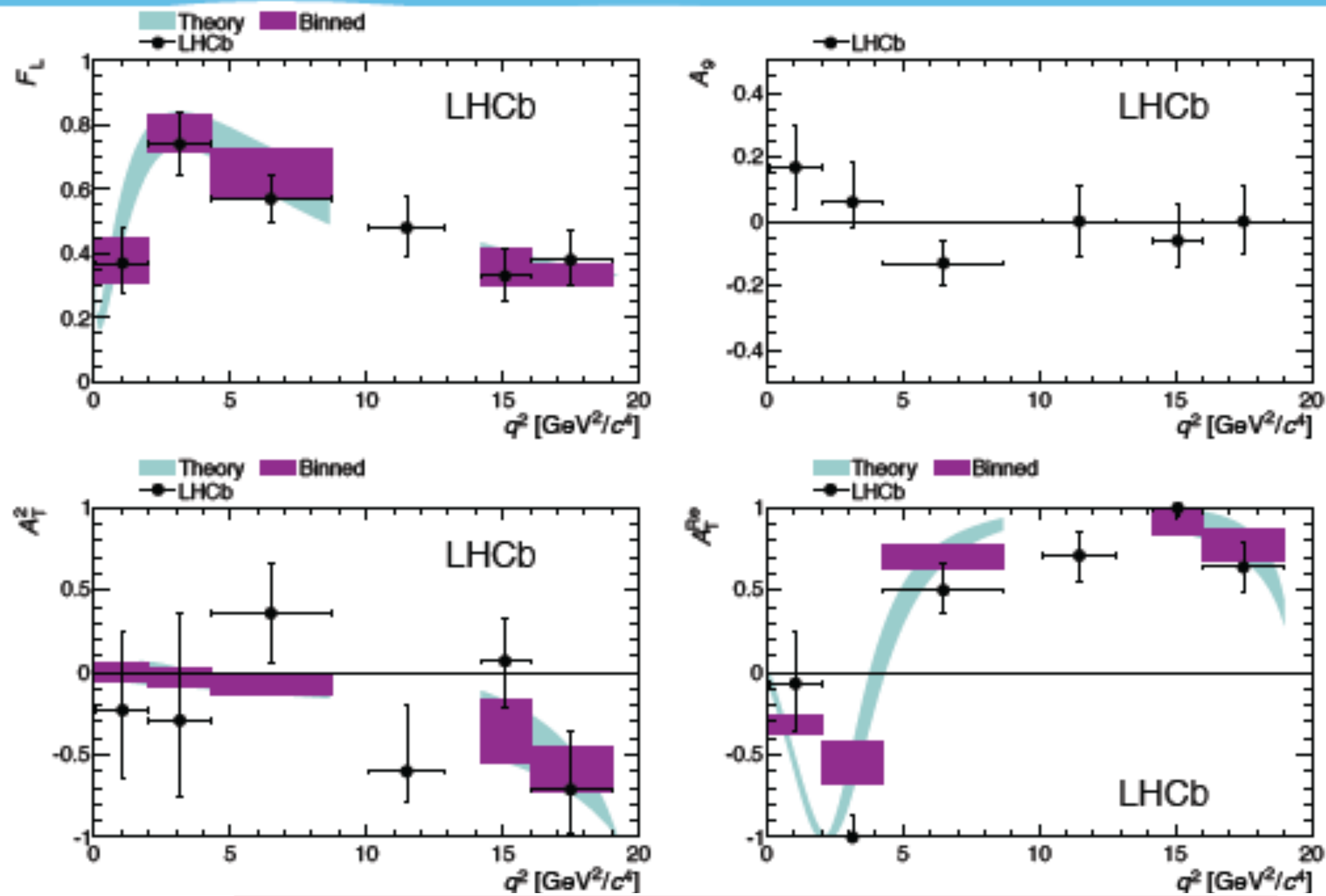




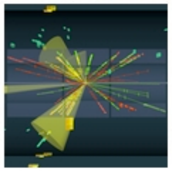


$B^0 \rightarrow K^{*0}\mu^+\mu^-$

arXiv:1304.6325 ($1fb^{-1}$)



Good agreement with SM predictions
Bobeth-Hiller-Van Dyk (2011): form-factor from Ball-Zwiky (2005):
Consistent with Matias et al.(2013)

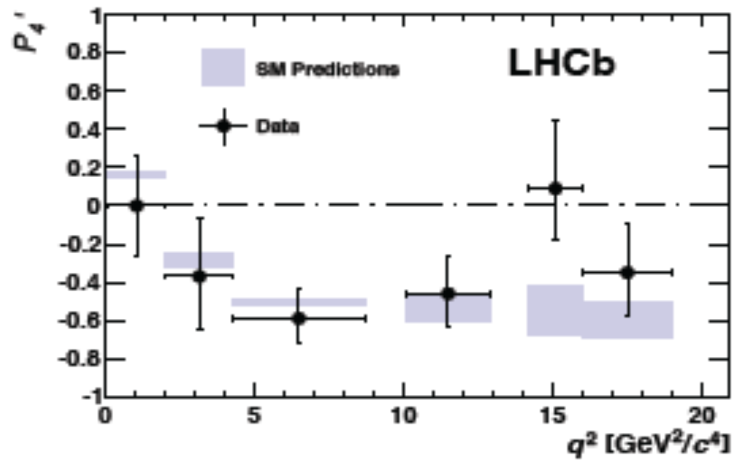


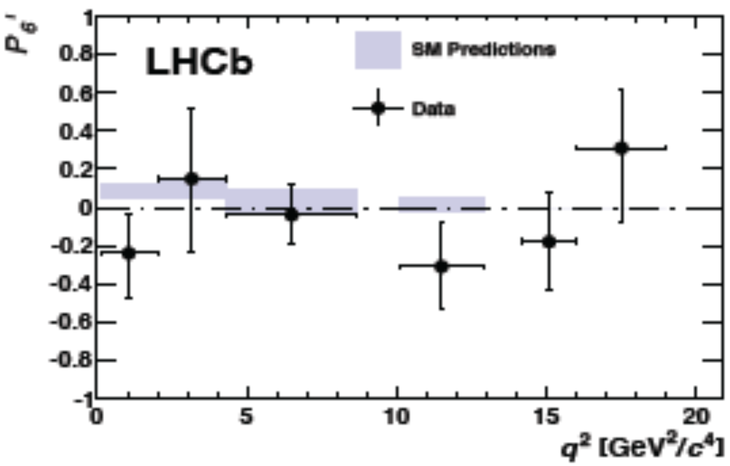
$B^0 \rightarrow K^{*0}\mu^+\mu^-$

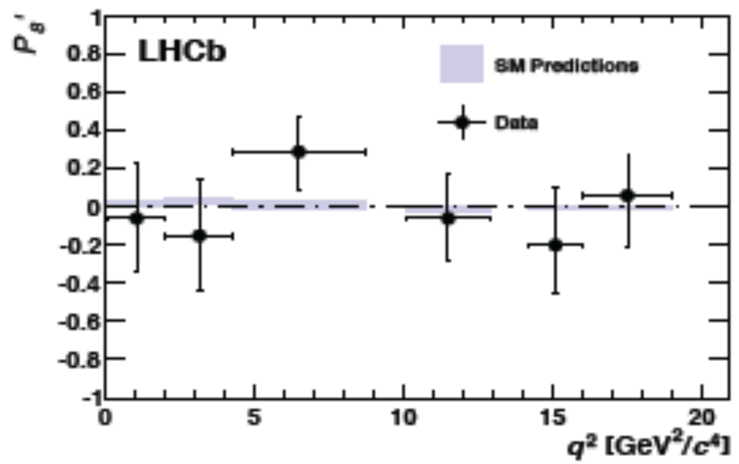
LHCb-PAPER-2013-037 arXiv:1308.1707 ($1fb^{-1}$)

First measurement of new observables

- Results accord with SM predictions
  J. Matías at al., JHEP 05 (2013) 137
  arXiv: 1303.5794







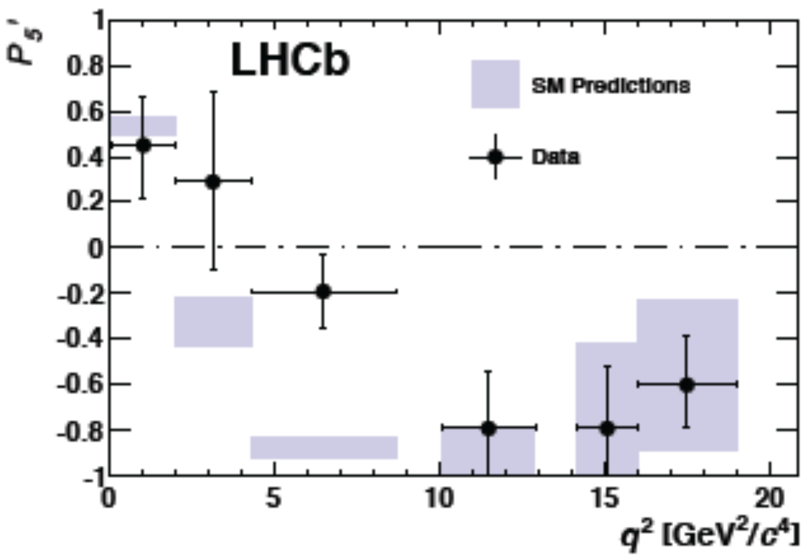
$B^0 \rightarrow K^{*0}\mu^+\mu^-$

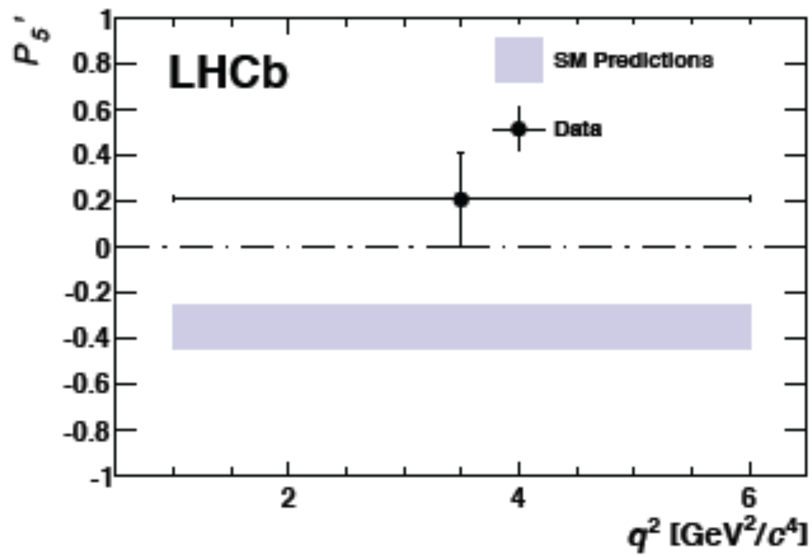
LHCb-PAPER-2013-037 arXiv:1308.1707 ($1fb^{-1}$)

First measurement of new observables

- Local discrepancy of 3.7σ in 3rd bin of P_5' (wrt J. Matías at al., arXiv:1303.5794)
- 2.5σ discrepancy in theoretically clean $1<q^2<6$ GeV^2/c^4 bin

- 0.5% probability to observe 3.7σ deviation in 24 independent measurements



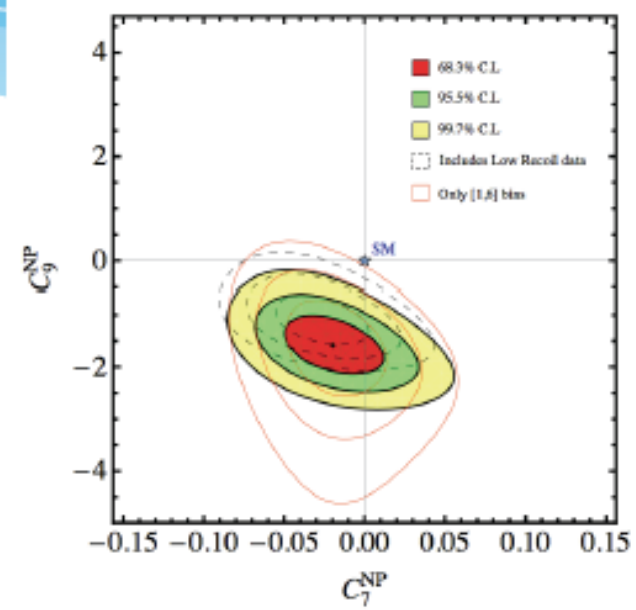


N. Serra EPS-2013

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

LHCb-PAPER-2013-037 arXiv:1308.1707 ($1fb^{-1}$)

- Descotes-Genon et al. (arXiv:1307.5683) explain the discrepancy in P_5' and other smaller deviations through a large New Physics contribution to the Wilson coefficient of the semileptonic operator O_9



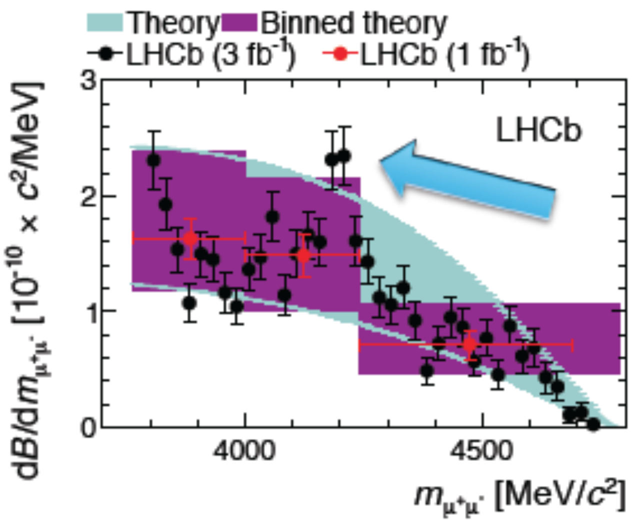
- Predictions for the first two bins and $1<q^2<6$ GeV^2/c^4 are also given by Jäger et al. (JHEP 05 (2013) 043)
- Leads to a larger theoretical uncertainty wrt J. Mathias et al.

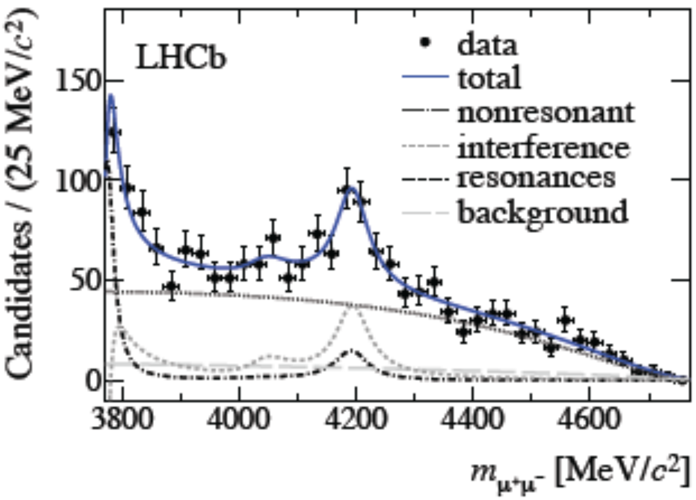
- Measurements with higher statistics and further theoretical studies are necessary to draw more definitive conclusions

Espen Eie Bowen at DPF-2013

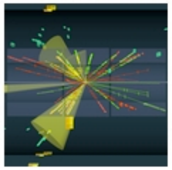
New resonant structure in $B^+ \to K^+\mu^+\mu^-$ at high q^2

- Resonance compatible with the ψ(4160) meson
- Larger than theoretical estimates
- First observation of both $B^+ \to \psi(4160)K^+$ and $\psi(4160) \to \mu^+\mu^-$
- Could complicate further $b \to s\mu^+\mu^-$ measurements at high q^2



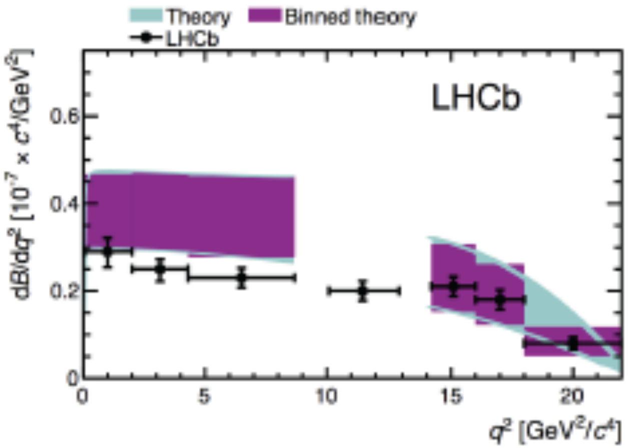


LHCb-PAPER-2013-039 arXiv:1307.7595 (1fb^{-1})



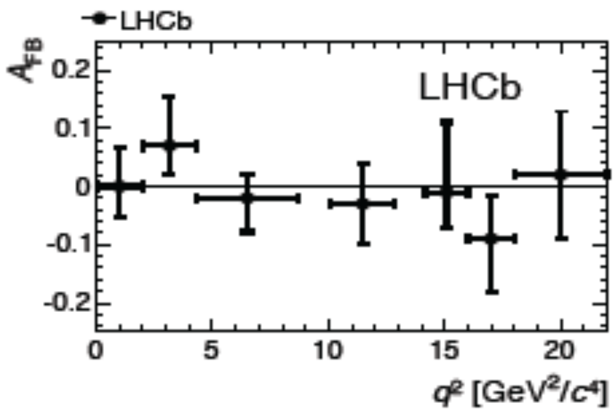
$B^+ \rightarrow K^+\mu^+\mu^-$

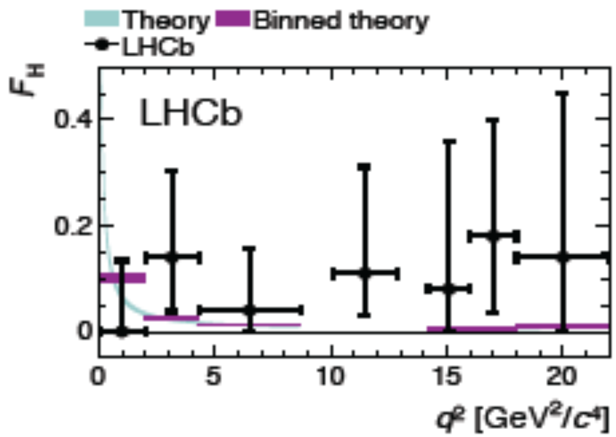
JHEP 02 (2013) 105 ($1fb^{-1}$)



- Differential angular distribution described by single angle θ_l
- A_{FB} and F_H consistent with SM prediction of zero

$$\frac{1}{\Gamma}\frac{d\Gamma[B^+ \rightarrow K^+\mu^+\mu^-]}{d\cos\theta_l} = \frac{3}{4}(1-F_H)(1-\cos^2\theta_l) + \frac{1}{2}F_H + A_{FB}\cos\theta_l$$





sensitive to O_P and O_S

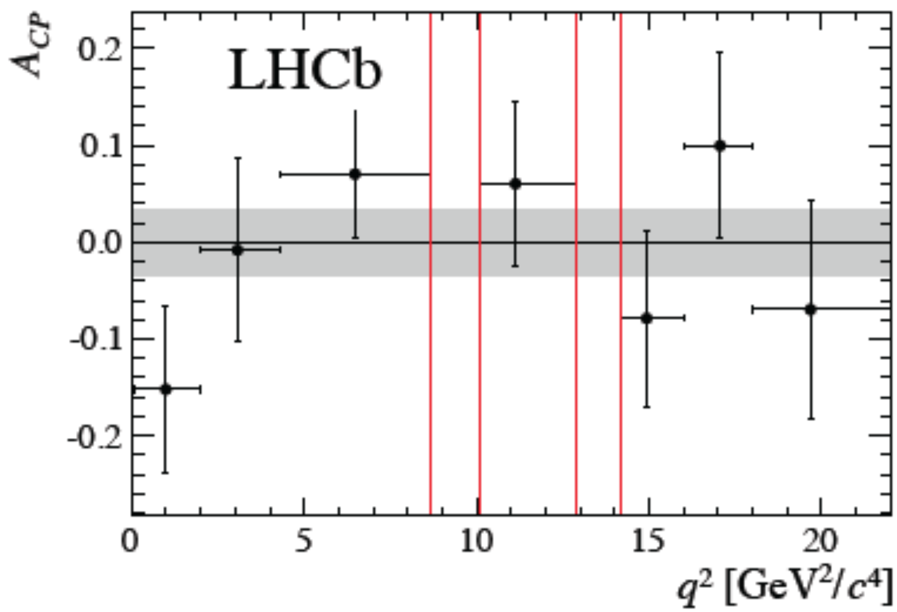
$B^+ \rightarrow K^+\mu^+\mu^-$

LHCb-PAPER-2013-043 arXiv:1308.1340 ($1fb^{-1}$)

A_{CP} in $B^+ \rightarrow K^+\mu^+\mu^-$

$$A_{CP} = \frac{\Gamma(B^- \to K^-\mu^+\mu^-) - \Gamma(B^+ \to K^+\mu^+\mu^-)}{\Gamma(B^- \to K^-\mu^+\mu^-) + \Gamma(B^+ \to K^+\mu^+\mu^-)} = -0.0004 \pm 0.033 \pm 0.005 \pm 0.007$$

- Control channel $B^+ \to J/\psi K^+$ used to account for production and detection asymmetries
- Left-Right asymmetry accounted for by averaging magnet polarity
- Result consistent with SM prediction



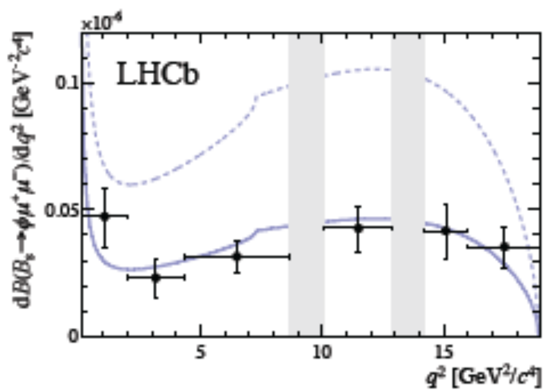
Espen Eie Bowen at DPF-2013

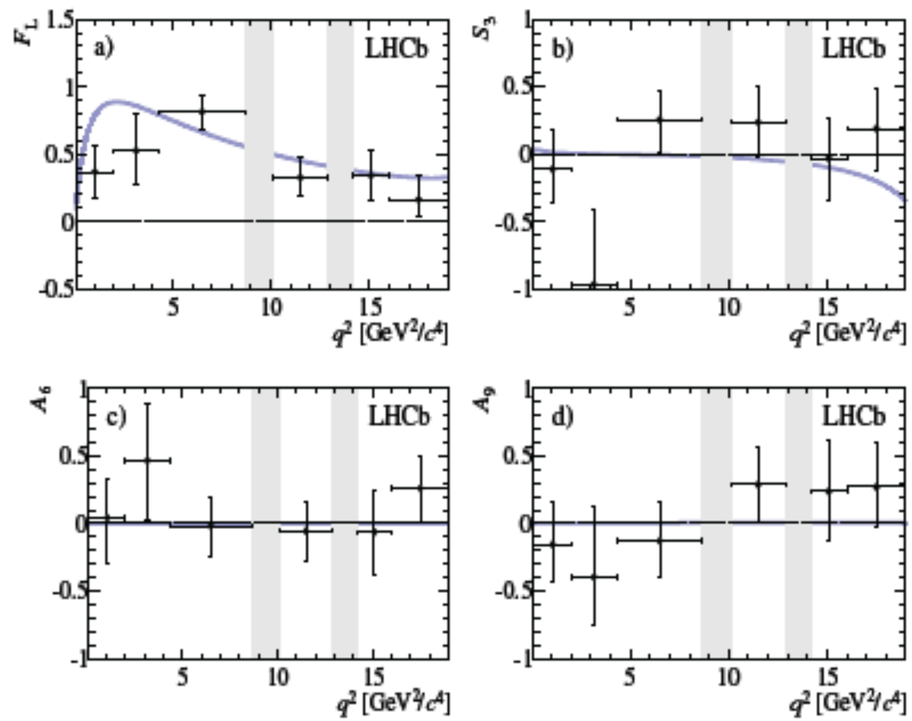
$B_s \rightarrow \phi\mu^+\mu^-$

CENTRO DE CIENCIAS DE BENASQUE PEDRO PASCUAL

arXiv:1305.2168 ($1fb^{-1}$) $B^0_s \rightarrow \Phi(\rightarrow K^+K^-)\mu^+\mu^-$

- Branching fraction lower than SM theory predictions (blue dotted line)
- First angular analysis of $B_s^o \rightarrow \phi\mu^+\mu^-$
- All observables are consistent with SM expectation

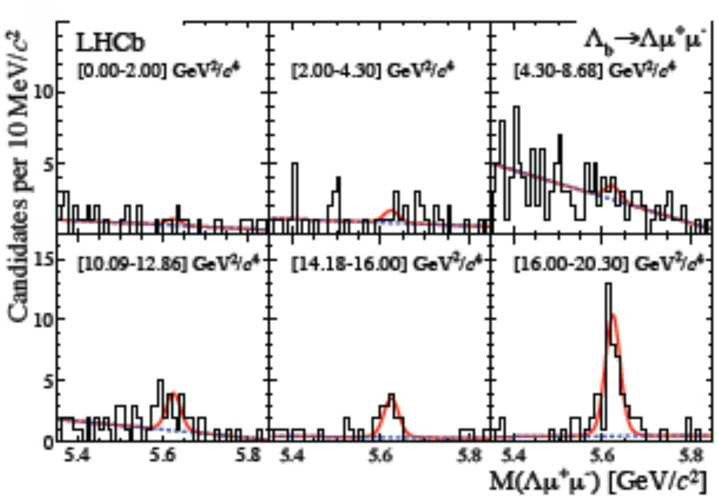


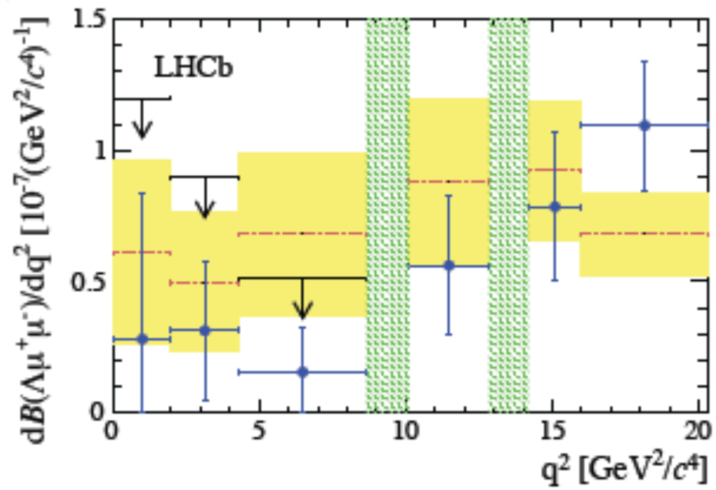


$\Lambda_b \rightarrow \Lambda\mu^+\mu^-$

arXiv:1306.2577 ($1fb^{-1}$) $\Lambda_b \rightarrow \Lambda(p\pi^-)\mu^+\mu^-$

- Baryon decays more theoretically complex
- Yield of 78±12 $\Lambda_b \rightarrow \Lambda\mu^+\mu^-$ decays observed, mostly in q^2 regions above J/ψ mass
- $\Lambda_b \rightarrow J/\psi\Lambda$ normalization mode





- Limits set at low q^2
- Good agreement with SM expectation

(Detmold et al., Phys.Rev. D87 (2013) 074502)

$$BR(\Lambda_b \rightarrow \Lambda\mu\mu) = (0.96 \pm 0.16(stat) \pm 0.13(syst) \pm 0.21(norm)) \times 10^{-6}$$

$B \to X_s l^+ l^-$

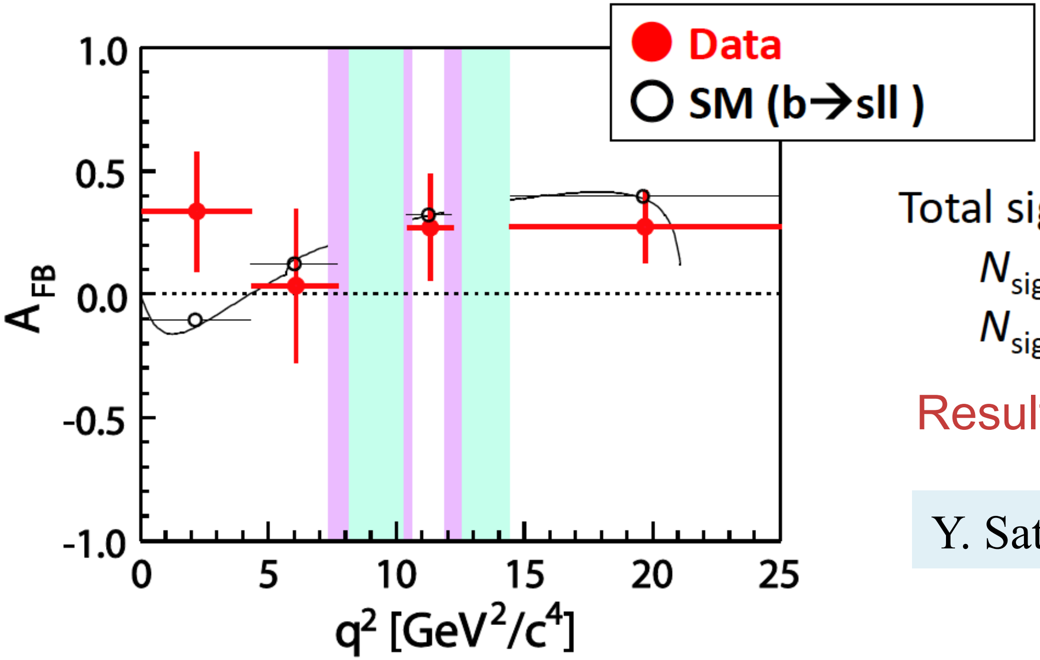
Less theoretical uncertainties for inclusive $B \to X_s\, ll$ analysis

Semi-inclusive analysis from adding many exclusive channels
$X_s = K^{\pm}/K^0_s + n\pi$ with n=1,2,3,4 (at most one π^0) $l = e^-$ or μ^-

36 (18 × 2) modes studied

20 (10 × 2) modes used for final result

≡ 50% of all X_s



Total signal yields

$N_{sig}^{ee} = 139.9 \pm 18.6$ (stat)

$N_{sig}^{\mu\mu} = 160.8 \pm 20.0$ (stat)

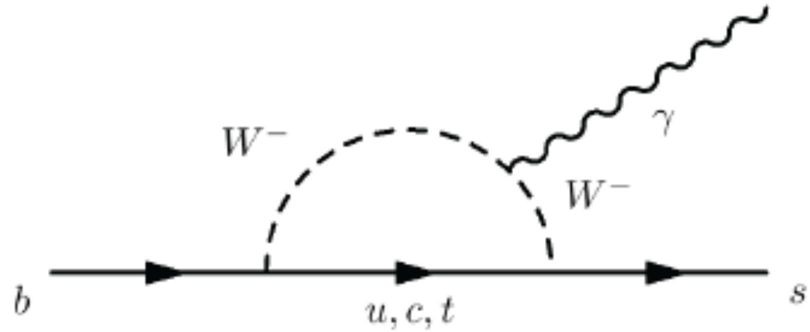
Results consistent with the SM

Y. Sato at EPS 2013

Results $B^+ \rightarrow K^+\pi^+\pi^-\gamma$

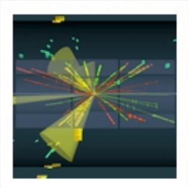
Radiative B decays

- $b \to s\gamma$ is a FCNC process
- In SM emitted photons in such decays are predicted to be predominately left handed since the recoil s quark that couples to the W boson if left handed



The photon polarization is defined as:

$$\lambda_\gamma \equiv \frac{|c_R|^2 - |c_L|^2}{|c_R|^2 + |c_L|^2}$$

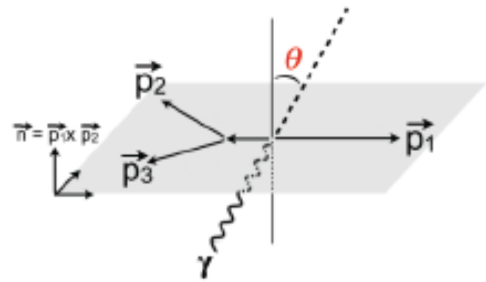


Results $B^+ \to K^+\pi^+\pi^-\gamma$

$B \to K_{res}\gamma \to K\pi\pi\gamma$

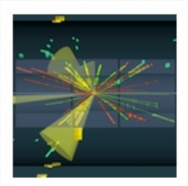
LHCb-CONF-2013-017 (2 fb^{-1})

- For decays of the type $B \to K_{res}\gamma \to K\pi\pi\gamma$, the photon polarization can be studied through the angular correlations of the daughters of the K_{res}
- For a single resonance, A_{ud} is proportional to λ_γ
- If the helicity amplitude J is known, λ_γ can be determined from a measurement of A_{ud}



$$\mathcal{A}_{\rm ud} \equiv \frac{\int_0^1 \mathrm{d}\cos\tilde\theta \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\tilde\theta} - \int_{-1}^0 \mathrm{d}\cos\tilde\theta \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\tilde\theta}}{\int_{-1}^1 \mathrm{d}\cos\tilde\theta \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\tilde\theta}} = \frac{3}{4}\lambda_\gamma \frac{\int \mathrm{d}s\,\mathrm{d}s_{13}\,\mathrm{d}s_{23}\,\mathrm{Im}\left[\vec{n}\cdot(\vec{\mathcal{J}}\times\vec{\mathcal{J}}^*)\right]}{\int \mathrm{d}s\,\mathrm{d}s_{13}\,\mathrm{d}s_{23}|\mathcal{J}|^2}$$

Theory input needed!



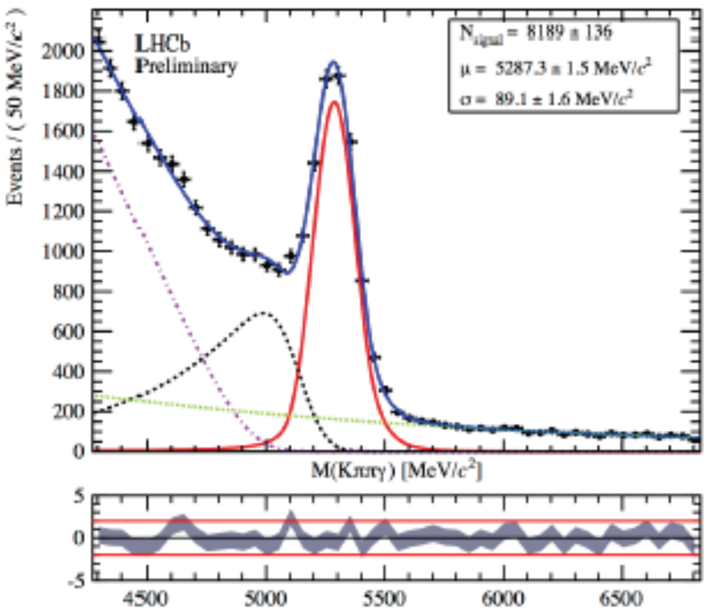
Results $B^+ \rightarrow K^+\pi^+\pi^-\gamma$

$B \rightarrow K\pi\pi\gamma$

LHCb-CONF-2013-017 (2 fb^{-1})

- Inclusive CP asymmetry measured for first time
- A_{CP} compatible with zero

- A_{ud} measured for the first time
- Result 4.5σ from zero
- Evidence of photon polarization in b->sγ decays
- If theoretical predictions existed, first measurement of λ_γ possible



$$\mathcal{A}_{CP} = -0.007 \pm 0.015\,(\text{stat})^{+0.012}_{-0.011}\,(\text{syst}) \quad \mathcal{A}_{\text{ud}} = -0.085 \pm 0.019\,(\text{stat}) \pm 0.004\,(\text{syst})$$

Albert Puig EPS-2013

Espen Eie Bowen DPF-2013

Combined leptonic and semileptonic

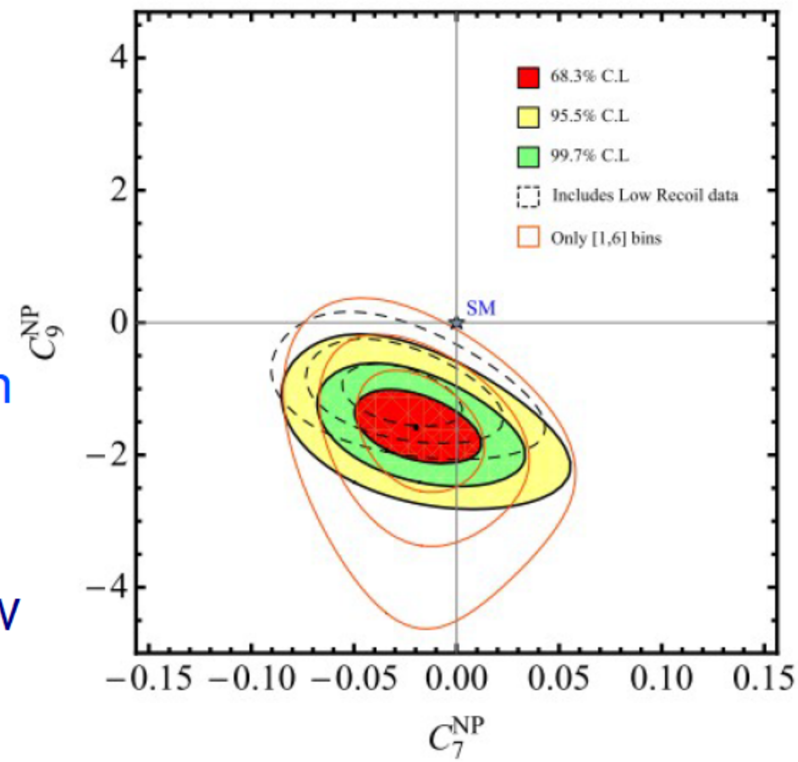
Constraints on new physics

Genon, Matias, Virto: arXiv:1307.5683
Altmannshofer, Straub: arXiv:1307.5683
Gauld, Goertz, Haisch: arXiv:1308.1959

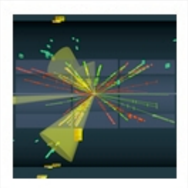
Results from B→K*μμ, B→μμ, B→X_sγ and B→K*γ combined to put constraints on New Physics

- Treated as effective interactions from NP at mass scale above m_W
- Indicates a significant deviation in C_9 (dileptonic vector operator)

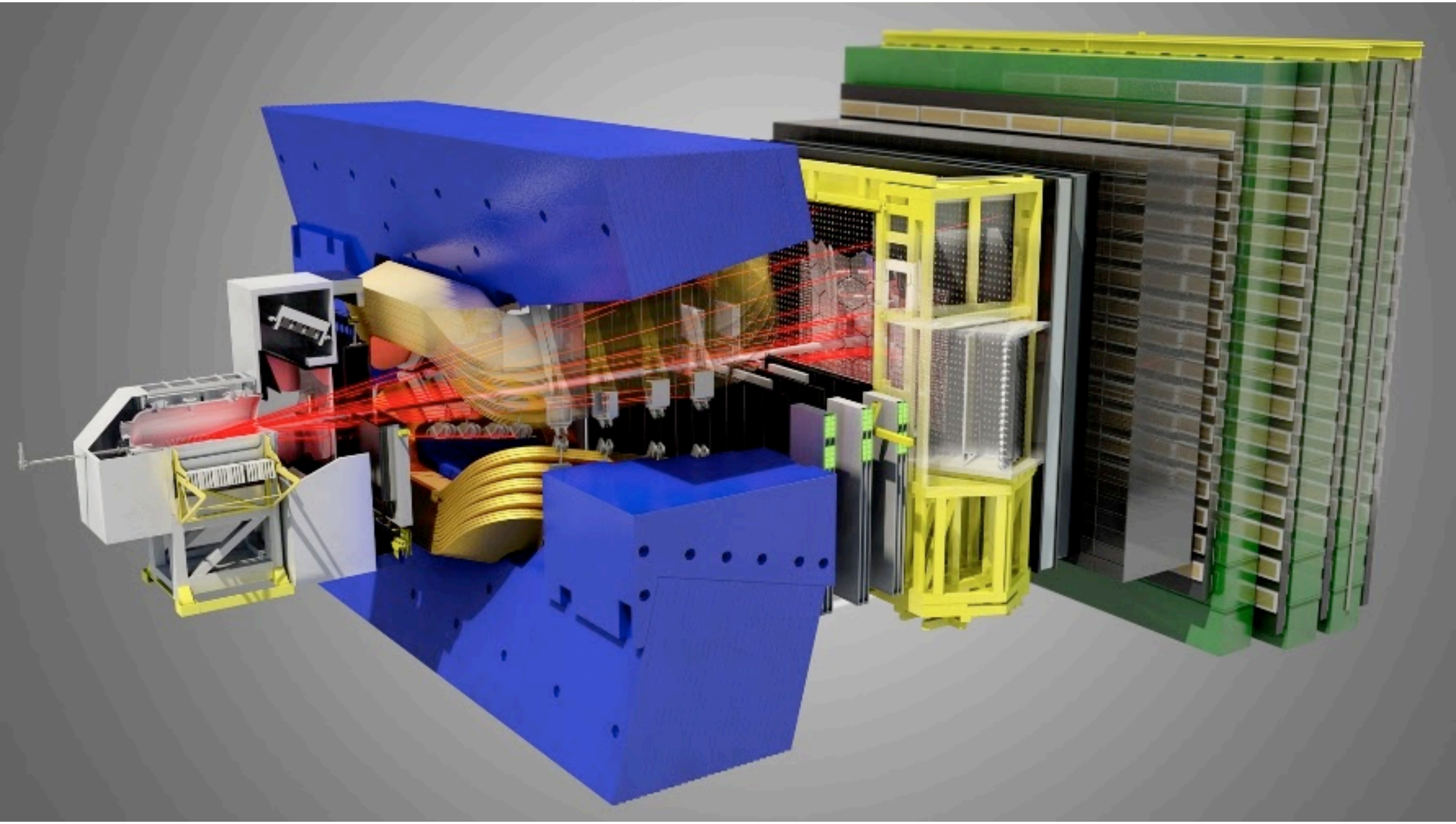
Will be very interesting to follow more experimental data and other phenomenological interpretations

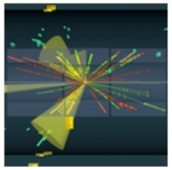


U. Egede at Mass 2013, Aug. 2013, Odense, DK



$B_{(s)} \rightarrow e^+\mu^-$

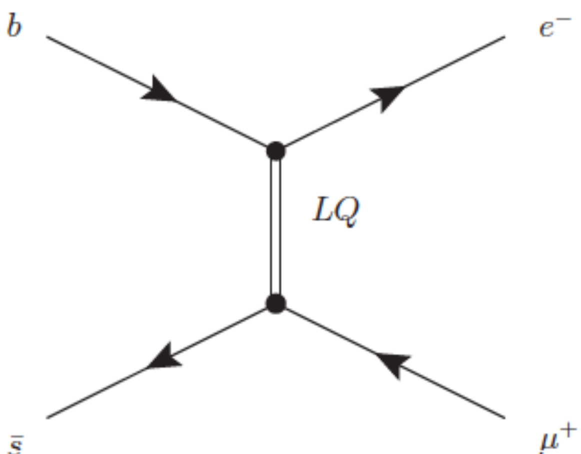




$B^0_{(s)} \to e^+\mu^-$

LHCb-PAPER-2013-030 arXiv:1307.4889

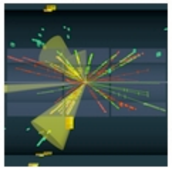
- Charged LFV process are forbidden in the SM (~10^{-54})
- Decays like $B^0_{(s)} \to e\mu$ are allowed in model with a local gauge symmetry between leptons and quarks like the Pati-Salam model [Phys. Rev. D 10 (1974) 275.]
  - new interaction between lepton and quarks mediated by a spin-1 gauge boson (LQ)



- limits from CDF [Phys. Rev. Lett. 102 (2009) 201901]:

$$\mathcal{B}(B_s \to e^\pm\mu^\mp) < 2.0(2.6) \cdot 10^{-7} \text{ @ } 90(95)\% \text{ CL}$$

$$\mathcal{B}(B^0 \to e^\pm\mu^\mp) < 6.4(7.9) \cdot 10^{-8} \text{ @ } 90(95)\% \text{ CL}$$

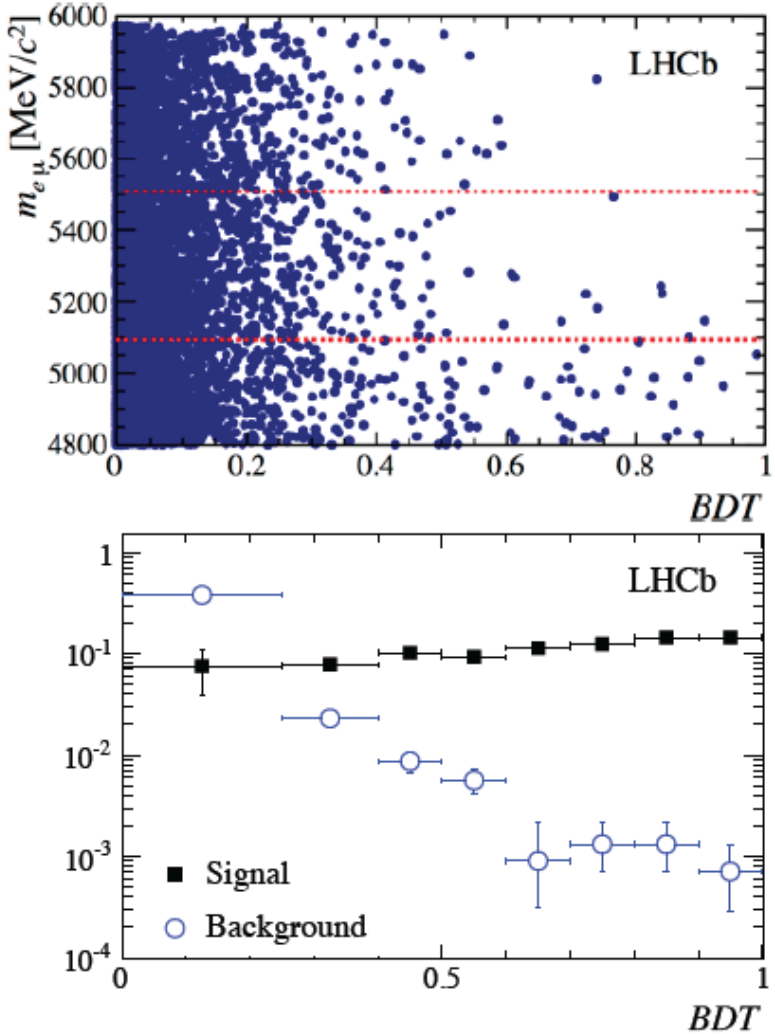


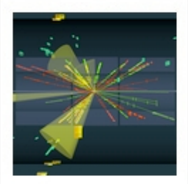
Search for $B^0_s \rightarrow e^+\mu^-$

LHCb-PAPER-2013-030 arXiv:1307.4889

Analysis strategy

- Blind analysis based on $1 fb^{-1}$ of data recorded in 2011 ($\sqrt{s} = 7 TeV$)
- Analysis inherited from $B^0_{(s)} \rightarrow \mu^+\mu^-$
- Events studied in $m_{e\mu}$ vs BDT plane
- Normalized to $B_d \rightarrow K\pi$ yield in data
- Upper limit on BF evaluated using the CLs method



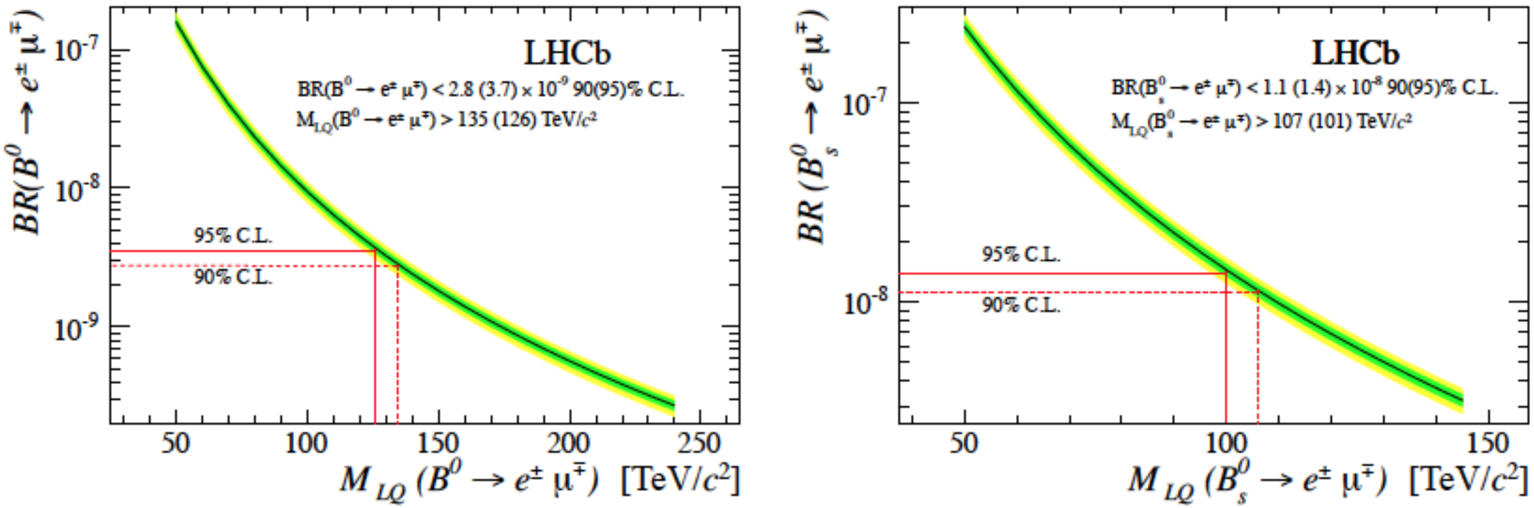


Search for $B^0_s \rightarrow e^+\mu^-$

Pati-Salam Lepto-quark mass bounds

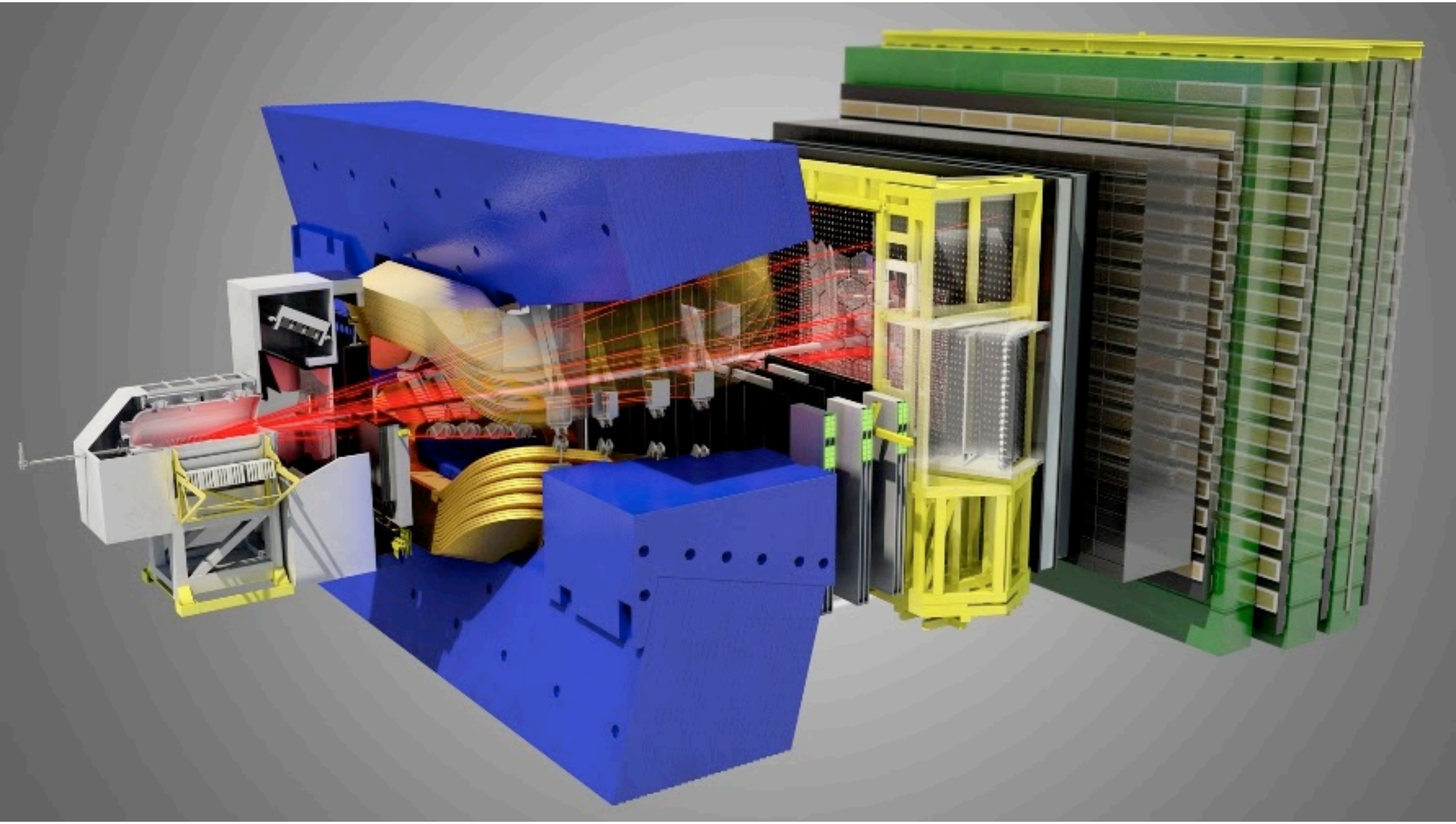
LHCb-PAPER-2013-030 arXiv:1307.4889 theo. formula : Phys. Rev. D 50 (1994) 6843)

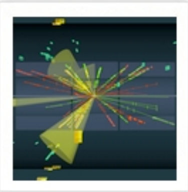
ATLAS/CMS : same generation leptoquarks < 0.5 – 1.0 TeV/c^2 (direct searches)



- CDF measurements:
  $m_{LQ}(B_s \to e^+\mu^-) > 47.8(44.9)\ TeV/c^2$ @ 90(95)%CL,
  $m_{LQ}(B_d \to e^+\mu^-) > 59.3(56.3)\ TeV/c^2$ @ 90(95)%CL
- LHCb new constraints:
  $m_{LQ}(B_s \to e^+\mu^-) > 107(101)\ TeV/c^2$ @ 90(95)%CL,
  $m_{LQ}(B_d \to e^+\mu^-) > 135(126)\ TeV/c^2$ @ 90(95)%CL

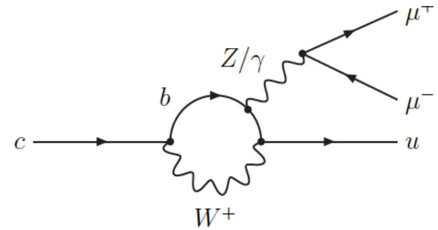
Charm rare decays

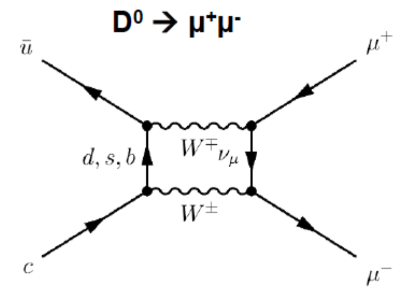




Charm rare decays - Motivations

c → u μ⁺μ⁻





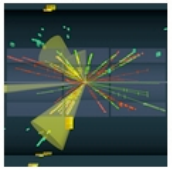
- Suppresion from GIM mechanism (down-type quarks in the loop)
  Absence of very high-mass down-type quarks
- Predictions harder because of non-negligible long distance contributions
  (Burdman et al.) Phys. Rev. Lett. D 66, 014009 (2002)
  $B\,(D^0 \to \mu\mu) \approx 3 \times 10^{-13}$ 90% CL
- Current best limit is from Belle Phys. Rev. D 81, 091102 (2010)
  $B\,(D^0 \to \mu\mu) < 1.4 \times 10^{-7}$ 90% CL

Decay is sensitive to:

– Supersymmetry with R-parity violation
– New spin 1 boson, V, Golowich et al. Phys. Rev. D79 (2009) 114030.

$$\mathcal{B}^V(D^0 \to \mu^+\mu^-) = \frac{f_D^2 m_\mu^2 M_D}{32\pi M_V^4}\sqrt{1-\frac{4m_\mu^2}{M_D^2}}(g_{V1}-g_{V2})^2(g'_{V1}-g'_{V2})^2$$

g_{V1} (g_{V2}) and g'_{V1} (g'_{V2}) coupling to left (right) handed quarks and leptons
– New spin 0 scalar, also proportional to $1 / M_s^4$



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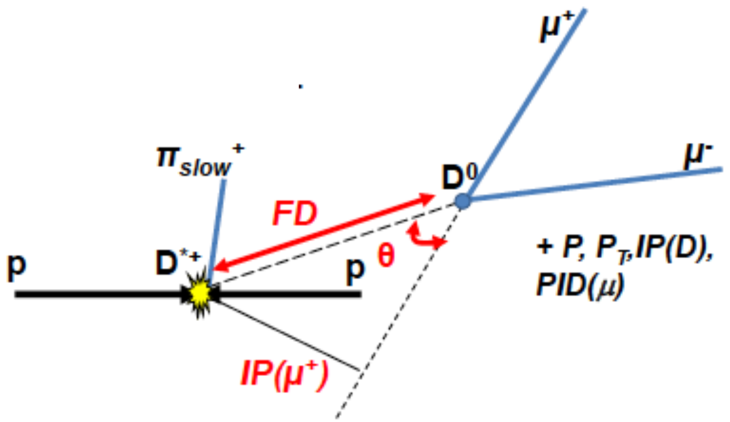
General strategy at LHCb



- Use D^*-tagged sample : $D^{*+} \rightarrow D^0 \pi_{slow}$
- Very rare means very high relative combinatorial background
  → Use Multivariate Analysis
- Another difficulty with charm decays: very high peaking backgrounds (Ex: $D \rightarrow \pi\pi > 10^6 \times D \rightarrow \mu\mu$)
  → Use particle identification to fight against $\pi \rightarrow \mu$ misID
- Normalized Measurements to help controlling the systematics

$$BF_{(signal)} = BF_{(norm)} \frac{\varepsilon_{(norm)}}{\varepsilon_{(signal)}} \frac{N_{(signal)}}{N_{(norm)}}$$

Ex. : $D^+ \rightarrow \pi^+\mu^+\mu^-$ and $D^+ \rightarrow \pi^+ \varphi(\mu^+\mu^-)$

- Efficiencies : simulations + extensive data-driven corrections & systematics
  $J/\psi \rightarrow \mu\mu$, $D \rightarrow K\pi$, $\Lambda \rightarrow p\,\pi$, $K_s \rightarrow \pi\pi$: reconstruction, PID, trigger efficiencies …
- $\pi \leftrightarrow \mu$ misID rate: simulations and control from data: $D \rightarrow K\pi$, with π swapped with μ
- Blind analyses, Upper limits from the CLs method *[A. Read, J. Phys. G28 (2002)]*

$D^0 \rightarrow \mu^+\mu^-$ at LHCb

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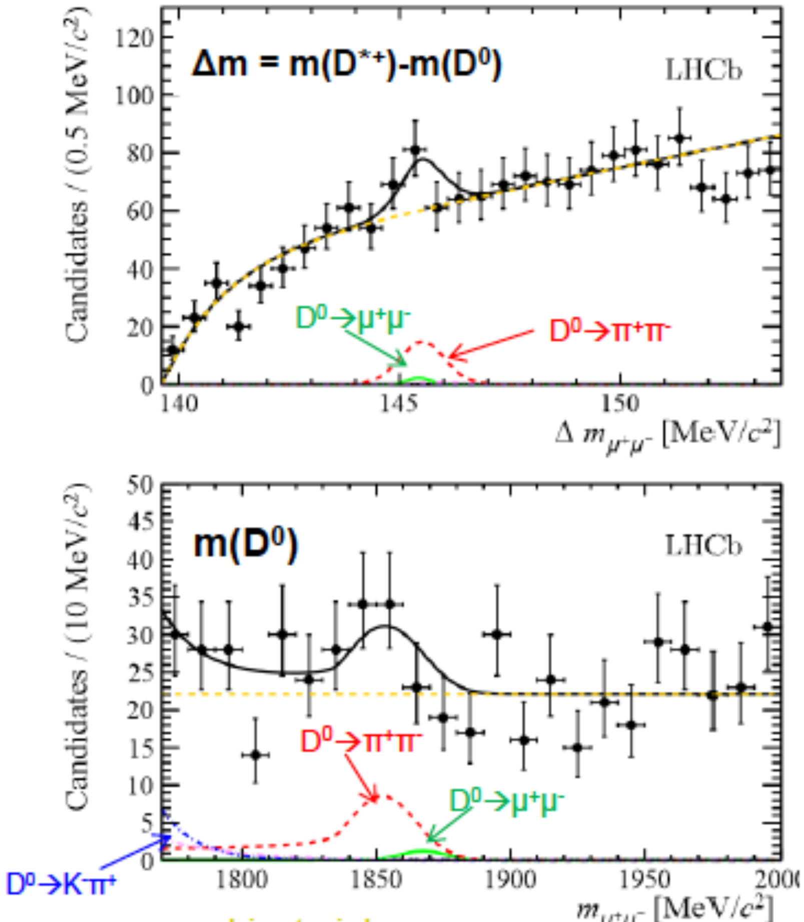
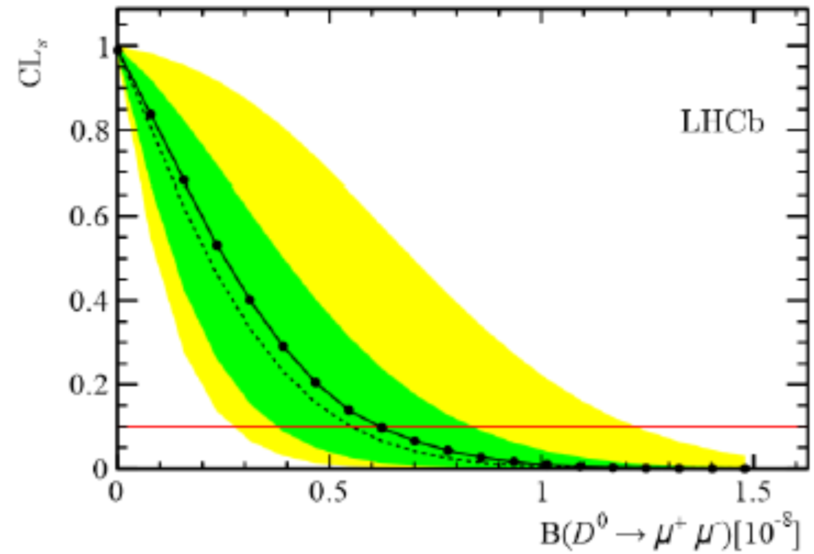


-- combinatorial

-- peaking $D^0 \rightarrow \pi^+\pi^-$, with $2 \times (\pi \leftrightarrow \mu)$

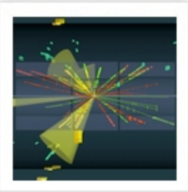
-- $D^0 \rightarrow K^-\pi^+$, with $(\pi \leftrightarrow \mu)$ and $(K \leftrightarrow \mu)$

– signal $D^0 \rightarrow \mu^+\mu^-$



BF($D^0 \rightarrow \mu\mu$) < 6.2 (7.6)·10^{-9} @ 90% (95%) CL

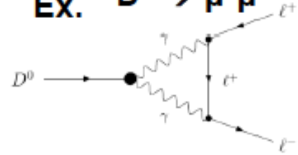
- ✓ **20 times better than previous limit**
- ✓ **Still 2 orders of magnitude above the SM prediction**



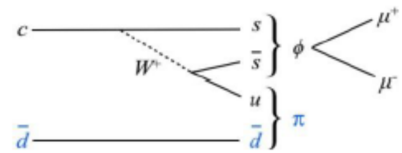
Rare charm – General considerations

- Branching ratios dominated by long distance (**LD**) effects, via intermediate states

Ex. $D^0 \to \mu^+\mu^-$

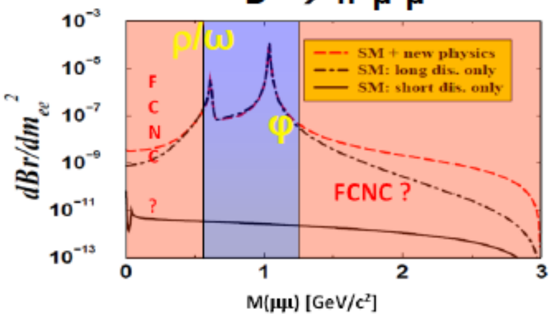


$D^+ \to \pi^+\mu^+\mu^-$



- The solution adopted by present searches is to measure BF's far from the resonances

$D^+ \to \pi^+\mu^+\mu^-$



- Recent literature suggests to use **asymmetries** (CP, T-odd, FB,…): **SD** *amplitudes* are more likely to compete with **LD** in an interference than in a BF. In that case, even the resonant regions are useful.

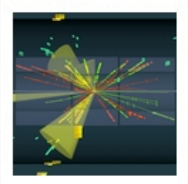
Mode	T-odd asym	FB asym
$K^-\pi^+\mu^+\mu^-$ (CF)	~ 7%	~ 0.06%
$K^+\pi^-\mu^+\mu^-$ (DCS)	~ 7%	~ 3%
$K^+K^-\mu^+\mu^-$	~ 6%	~ 0.5%
$\pi^-\pi^+\mu^+\mu^-$	~ 8%	~ 0.5%

Ex:arXiv:1209.4235v2

We measure the total BF's with present data to predict our future sensitivity (e.g. upgrade).

L.Cappiello et al. arXiv:1209.4235 (2013)
S.Fajfer et al. PRD87, 054026 (2013)
I.Bigi et al. JHEP03, 021 (2012) 5

O.Kochebina at EPS2013



Experimental status up to 2011

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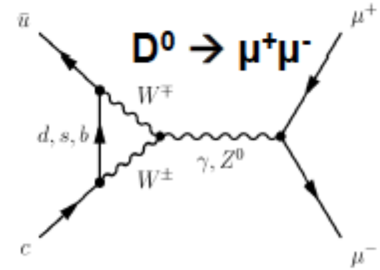
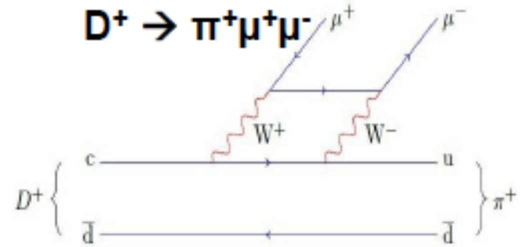
- Upper limits of BF, @90% CL

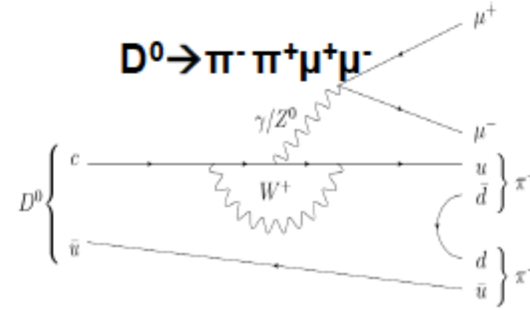
$D^0 \rightarrow \mu^+\mu^-$	1.4×10^{-7} [1]
$D^+ \rightarrow \pi^+ \mu^+\mu^-$	3.9×10^{-6} [2]
$D_s^+ \rightarrow \pi^+ \mu^+\mu^-$	2.6×10^{-5} [3]
$D^+ \rightarrow \pi^- \mu^+\mu^+$	2.0×10^{-6} [4]
$D_s^+ \rightarrow \pi^- \mu^+\mu^+$	1.4×10^{-5} [4]
$D^0 \rightarrow K^- \pi^+ \mu^+\mu^-$	3.6×10^{-4} [5]
$D^0 \rightarrow K^- K^+ \mu^+\mu^-$	3.3×10^{-5} [5]
$D^0 \rightarrow \pi^- \pi^+ \mu^+\mu^-$	3.0×10^{-5} [5]

$\sim 10^{-5} - 10^{-6}$ (rows 2–5)

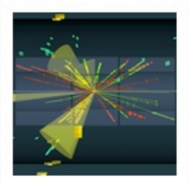
$\sim 10^{-4} - 10^{-5}$ (rows 6–8)



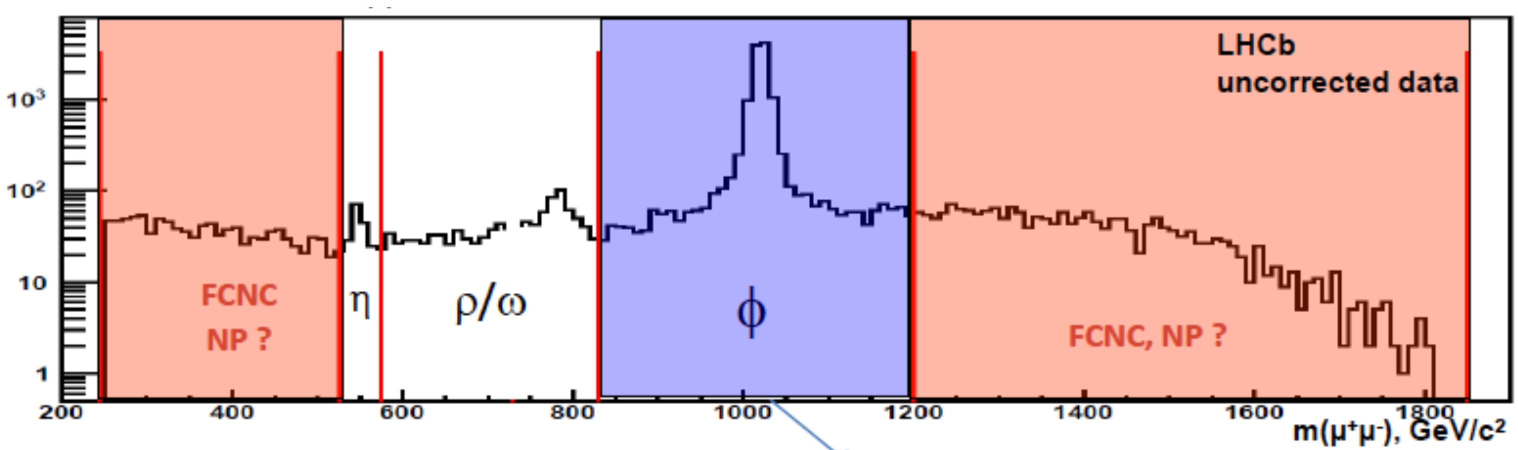




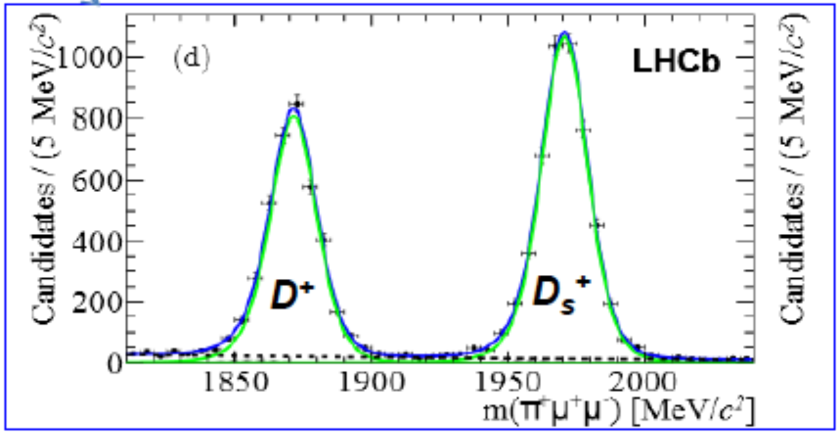
[1] Belle, PRD81,091102 (2010)
[2] D0, PRL 100,101801 (2008)
[3] FOCUS, PLB 572, 21 (2003)
[4] BaBar, PRD 84, 072006 (2011)
[5] E791, PRL 86, 3969 (2001)

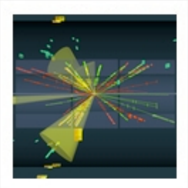


$D^+_{(s)} \rightarrow \pi^+\mu^+\mu^-$ at LHCb

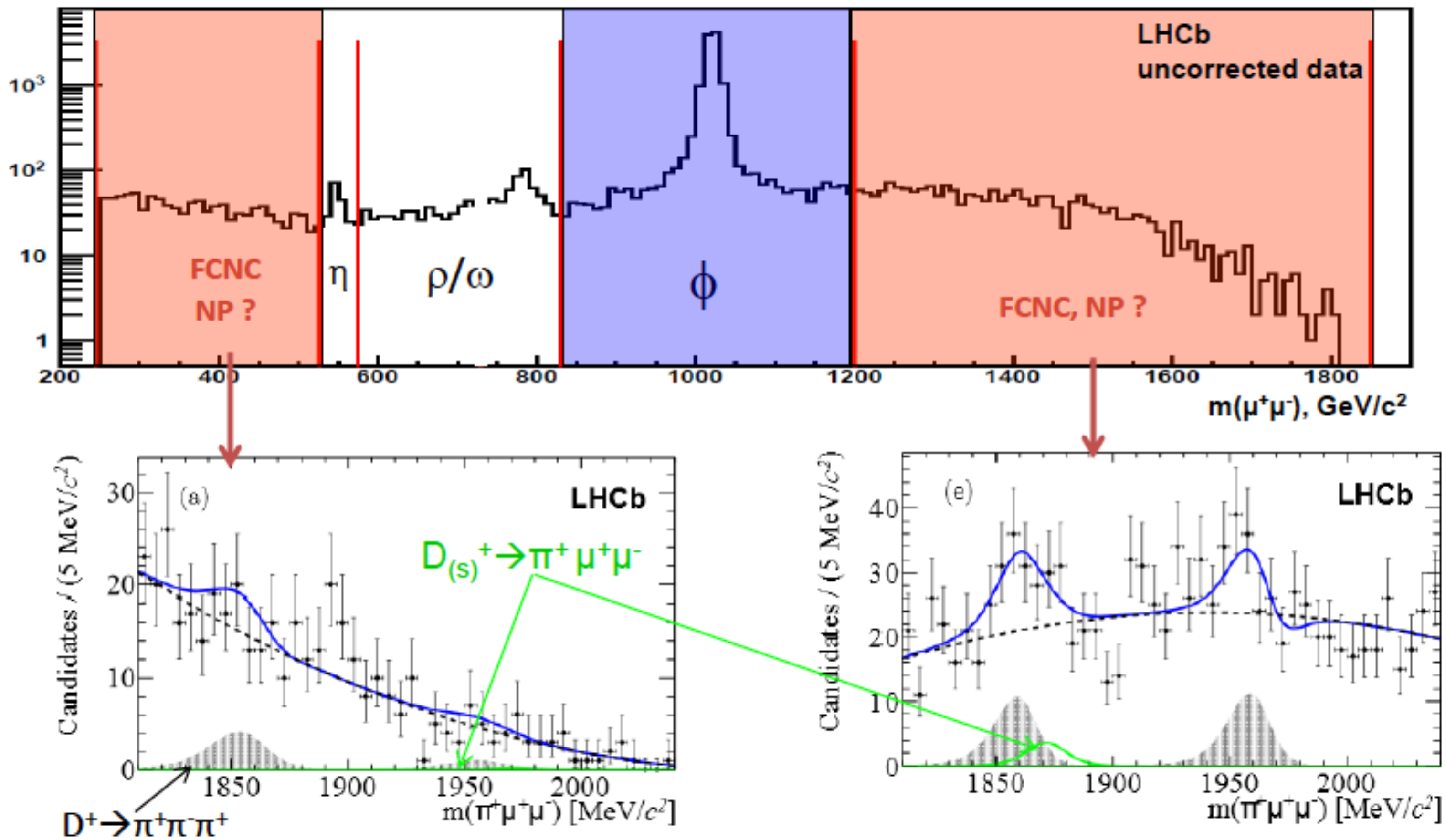


- $D^+ \rightarrow \pi^+ \phi\ (\mu^-\mu^+)$ mode:
  - Normalization
  - "Standard candle": provides a signal proxy to optimize the selection, constrain the PDF's shape, study and correct data/MC…



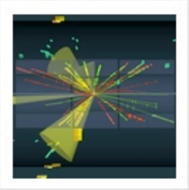


$D^{+}_{(s)} \rightarrow \pi^{+}\mu^{+}\mu^{-}$ at LHCb

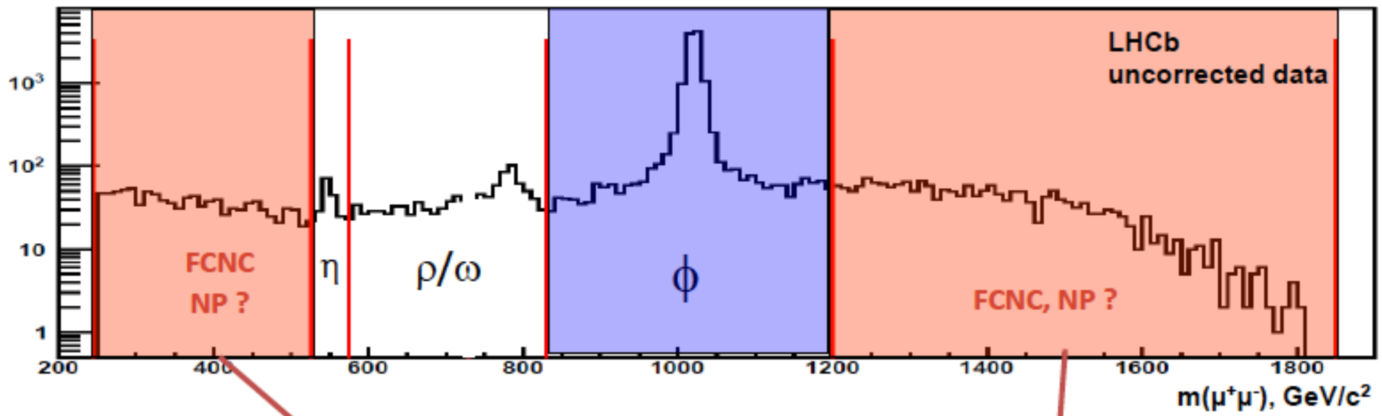


- Peaking background : $D^{+} \rightarrow \pi^{+}\pi^{-}\pi^{+}$ with double misID $\pi \leftrightarrow \mu$
  - *Shapes determined from data sample (loosened muon ID)*
  - *The fit is able to determine the yields*

14



$D^+_{(s)} \rightarrow \pi^+\mu^+\mu^-$ at LHCb



Upper limits, ×10⁻⁸ @ 90% (95%) CL

***BF*($D^+ \rightarrow \pi^+\mu^+\mu^-$)**	***2.0 (2.5)***	***2.6 (2.9)***
***BF*($D_s^+ \rightarrow \pi^+\mu^+\mu^-$)**	***6.9 (7.7)***	***16.0 (18.6)***

Total:

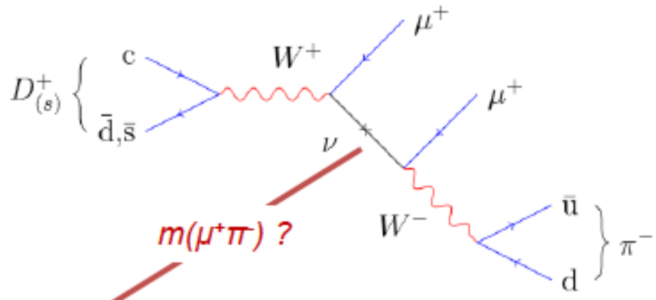
***BF*($D^+ \rightarrow \pi^+\mu^+\mu^-$) < 7.3 (8.3)·$10^{-8}$ @ 90% (95%) CL**

***BF*($D_s^+ \rightarrow \pi^+\mu^+\mu^-$) < 4.1 (4.8)·$10^{-7}$ @ 90 % (95%) CL**

- ✓ **~ 50 times better than previous limit**
- ✓ **Still orders of magnitude above the SM prediction**

O.Kochebina at EPS2013

Majorana neutrino with $D^+_{(s)} \to \pi^- \mu^+ \mu^+$



- Searches in regions of ***m(μ⁺π⁻)*** which is the mass of a potential majorana neutrino

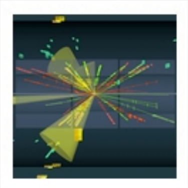
$m(\mu^+\pi^-)$?

Region [MeV/c²]	250<M(μπ) <1140	1140<M(μπ)<1340	1340<M(μπ)<1540	1540<M(μπ)
BF($D^+ \to \pi^+\mu^+\mu^-$)	1.4 (1.7)	1.1 (1.3)	1.3 (1.5)	1.3 (1.5)
BF($D_s^+ \to \pi^+\mu^+\mu^-$)	6.2 (7.6)	4.4 (5.3)	6.0 (7.3)	7.5 (8.7)

Total:

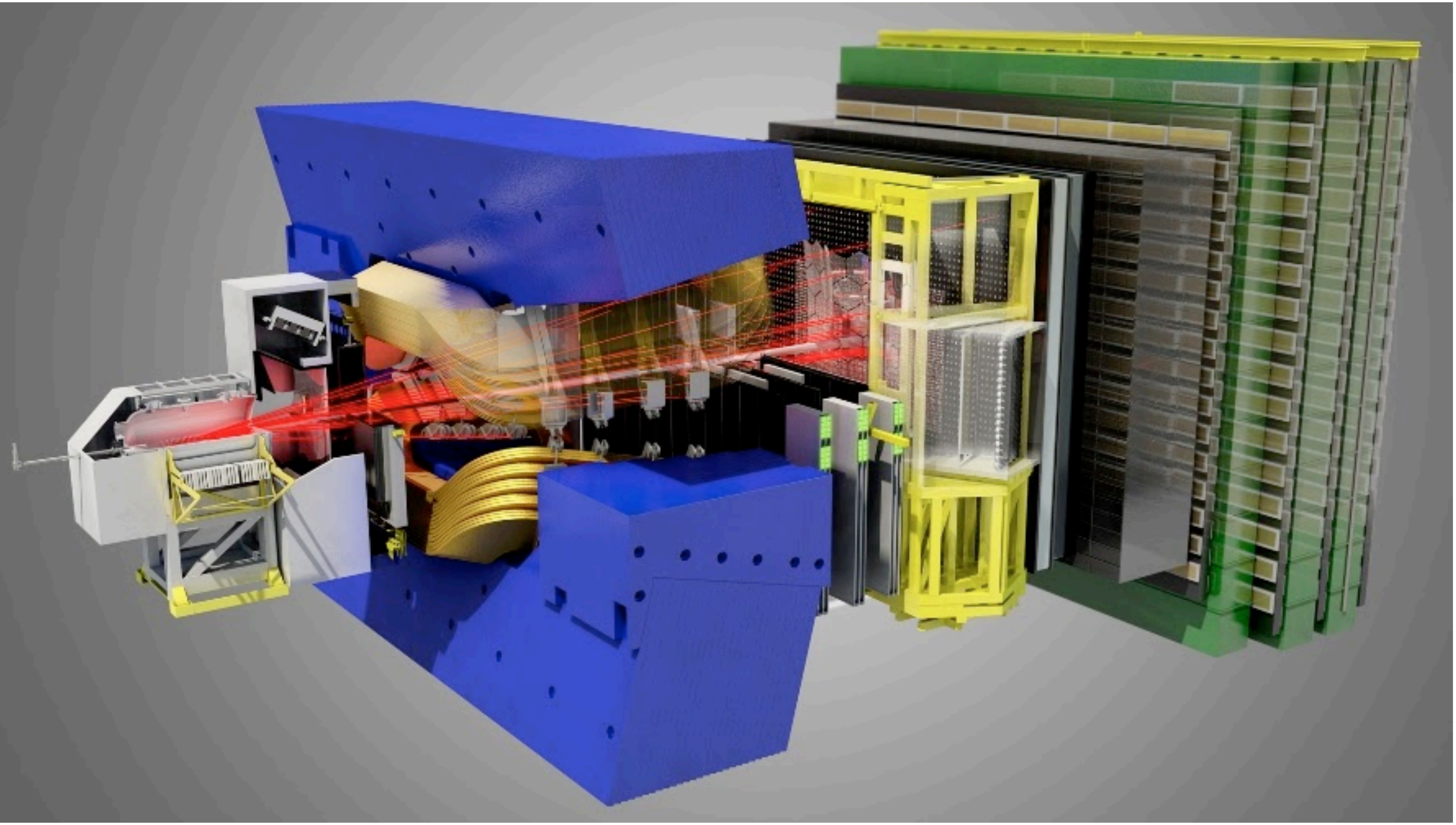
BF($D^+ \to \pi^-\mu^+\mu^+$) < 2.2 (2.5)·10^{-8} @ 90% (95%) CL
BF($D_s^+ \to \pi^-\mu^+\mu^+$) < 1.2 (1.4)·$10^{-7}$ @ 90% (95%) CL

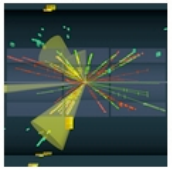
✓ **~ 50 times better than previous limit**



BACKUP

Rare τ decays

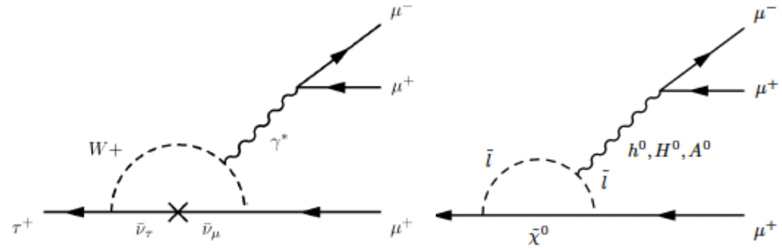




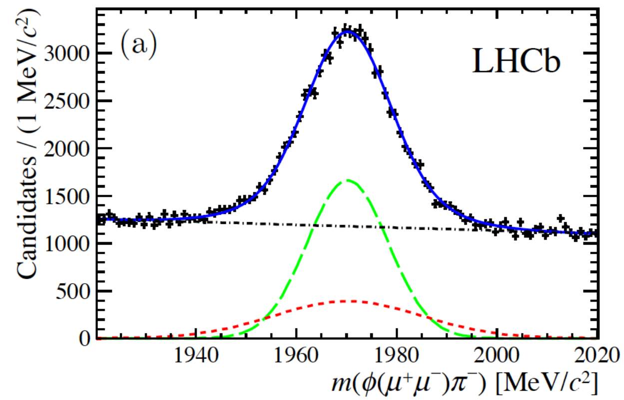
Lepton Flavour Violation in $\tau^{\pm} \rightarrow \mu^{+}\mu^{-}\mu^{\pm}$

LHCb-PAPER-2013-014

LFV decay $\tau \rightarrow \mu\mu\mu$
In SM only allowed via neutrino oscillations with **BR ~ 10^{-54}** . Some New Physics models predict significant enhancement :
BR ~ 10^{-10} – 10^{-8}

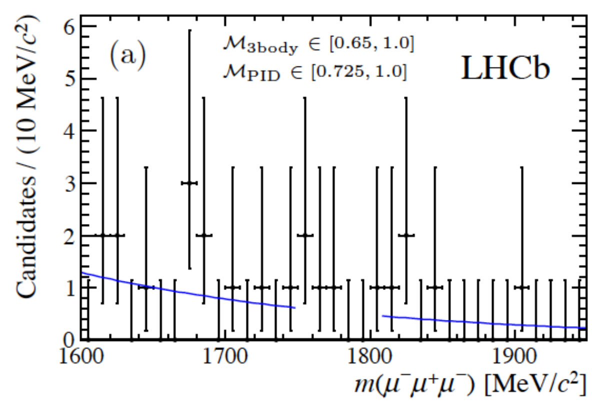


So far only measurements at e^+e^- colliders:
BR ($\tau^{\pm} \rightarrow \mu^{+}\mu^{-}\mu^{\pm}$) < 2.1 x 10^{-8} (90% CL)
is current best limit from Belle (782 fb^{-1})
[Phys. Lett. B 687 (2010) 3]



At LHC large τ production cross section :
~ 80 μb (25% in LHCb acceptance)

~ 10^{11} τ decays/y in LHCb (from $D_s \rightarrow \tau\nu_\mu$)
Normalisation to $D_s \rightarrow \phi(\mu\mu)\pi$



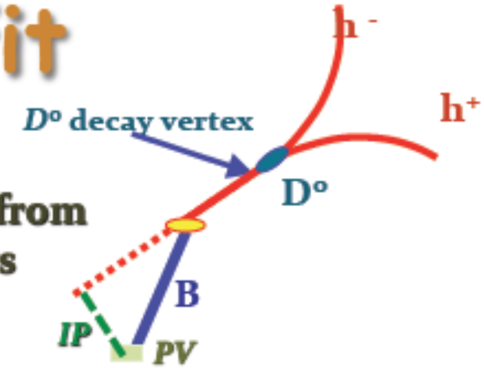
BR < 8.0 x 10^{-8} (90% CL)
LHCb: 1.0 fb^{-1}

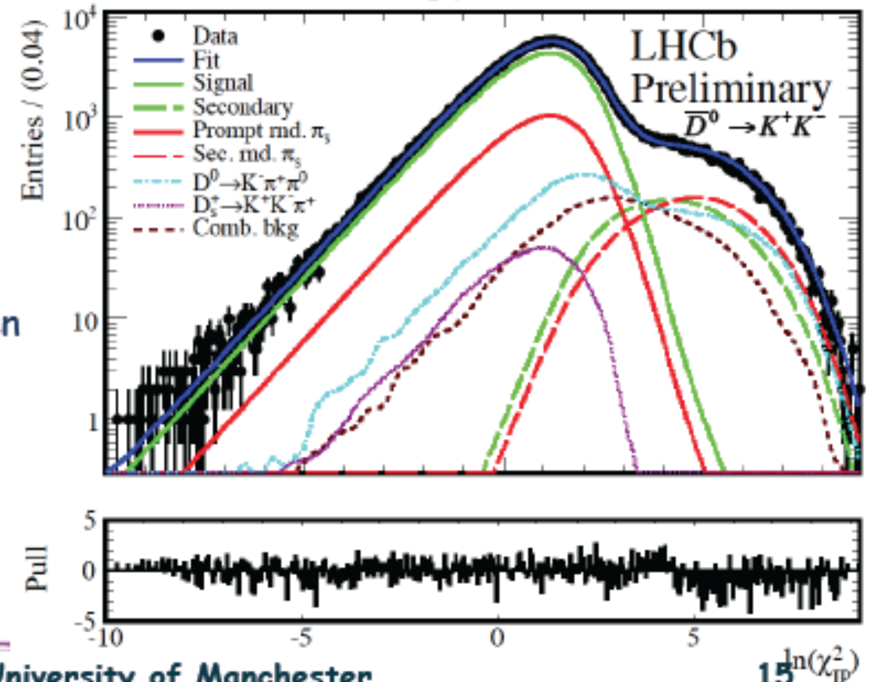
Proof of principle for a hadron collider:
Good prospects for future

HFAG average for A_Γ

2^{nd} step Lifetime fit

- Main background due to secondary D^0
  - Dangerous background → bias the lifetime measurement
  - Not distinguishable by the invariant mass distribution
  - Need statistical separation by $\ln(\chi^2_{IP})$
- Simultaneous fit of proper time and $\ln(\chi^2_{IP})$ to distinguish between prompt and secondary





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

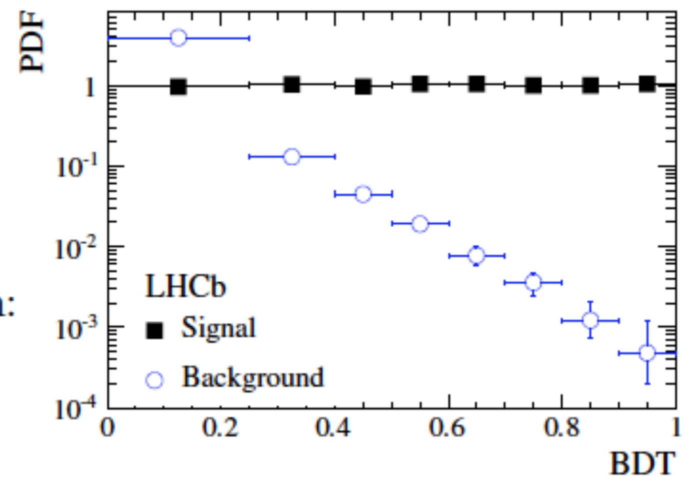
Calibrations

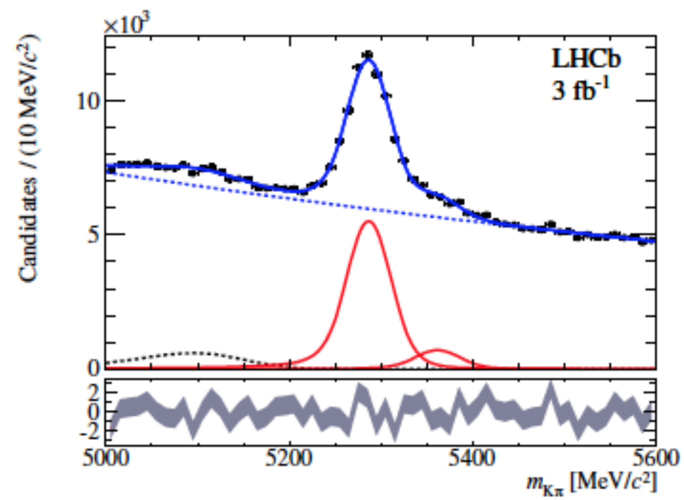
[arXiv:1307.5024]

- BDT classifier PDFs are calibrated using:
  - B→hh' events for signal
  - mass sidebands B→μμ candidates for bkg

- Invariant mass:
  - signal described by a Crystal Ball function:
    - mean value calibrated with exclusive B→hh' decays
    - resolution from di-μ resonance and exclusive B→hh'
  - background PDFs from data sidebands

$$\sigma_{B^0} = 22.8 \pm 0.4\,\mathrm{MeV}/c^2$$
$$\sigma_{B^0_s} = 23.2 \pm 0.4\,\mathrm{MeV}/c^2$$





5

Updated results $B^0_s \rightarrow \mu^+\mu^-$

Normalization

[arXiv:1307.5024]

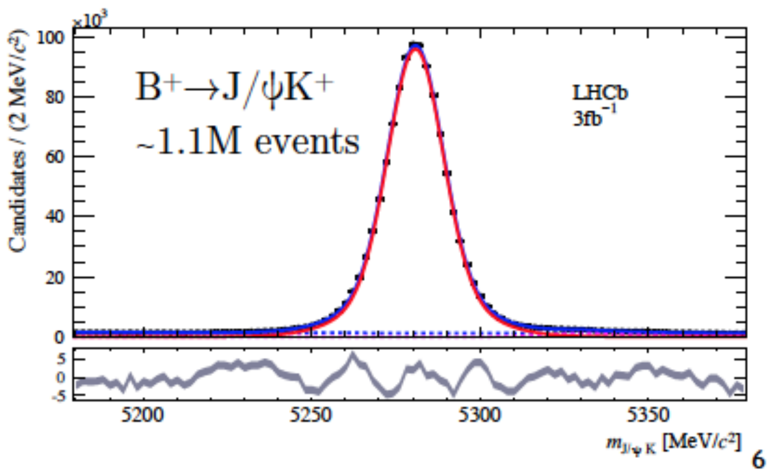
- Two control channels used for the normalization: $B^+ \rightarrow J/\psi K^+$ and $B^0 \rightarrow K^+\pi^-$

$$BR = BR_{cal} \times \frac{\epsilon^{REC}_{cal}\epsilon^{SEL}_{cal}}{\epsilon^{REC}_{sig}\epsilon^{SEL}_{sig}} \times \frac{\epsilon^{TRIG}_{cal}}{\epsilon^{TRIG}_{sig}} \times \frac{f_{cal}}{f_{d(s)}} \times \frac{N_{B^0_{(s)}\rightarrow\mu^+\mu^-}}{N_{cal}} = \alpha_{(s)} \times N_{B^0_{(s)}\rightarrow\mu^+\mu^-}$$

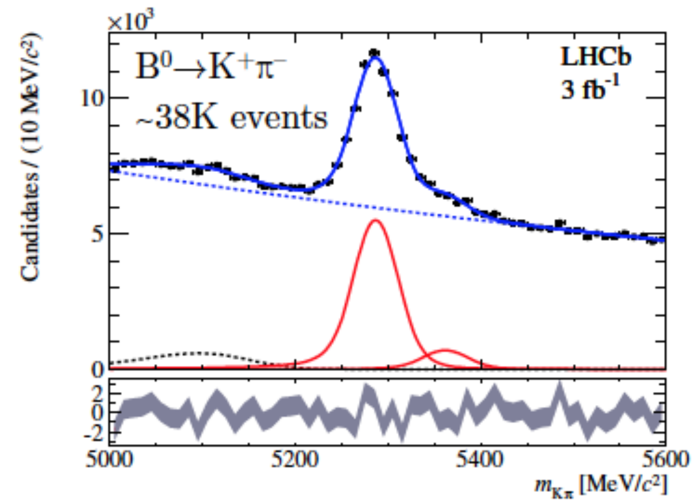
- From MC and x-checked on data
- Trigger efficiency from $J/\psi \rightarrow \mu\mu$ data
- fs/fd from LHCb measurement (next slide)

$$\alpha_s = (9.41 \pm 0.65) \cdot 10^{-11}$$
$$\alpha = (2.40 \pm 0.09) \cdot 10^{-11}$$

- Using the SM signal we expect 39.5 ± 4.3 $B_s \rightarrow \mu^+\mu^-$ and 4.5 ± 0.4 $B^0 \rightarrow \mu^+\mu^-$



6



Updated results $B^0_s \rightarrow \mu^+\mu^-$

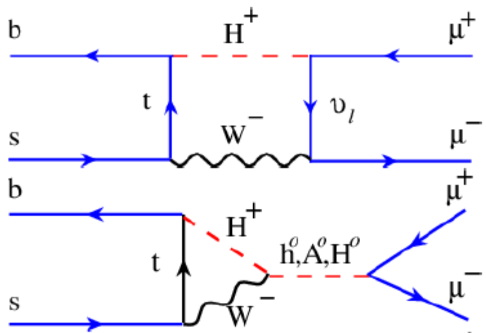
Doubly suppressed decay: **FCNC process** and **helicity suppressed.**

$$B(B_s^0 \to \mu^+\mu^-) \propto \left(1 - \frac{4m_\mu^2}{m_{B_s}{}^2}\right)|C_S - C_S'|^2 + \left|(C_P - C_P') + 2\frac{m_\mu}{m_{B_s}}(C_{10} - C_{10}')\right|^2$$

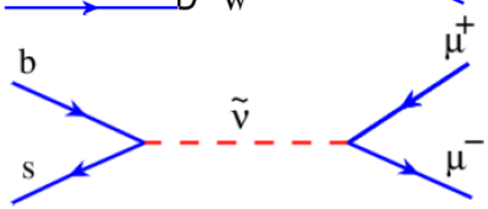
In MSSM:

$$c_{S,P}^{MSSM\,2} \propto \frac{m_b^2 m_\mu^2 \tan^6\beta}{M_A^4}$$

2HDM:

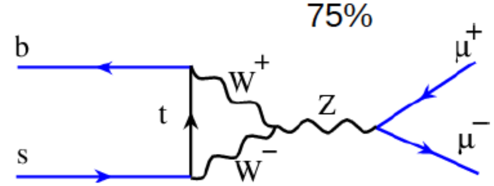


RPV:

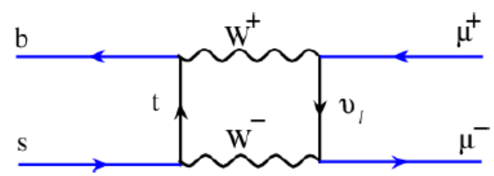


SM contributions:

75%



24%



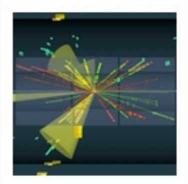
Mode	SM
$B_s \rightarrow \mu^+\mu^-$	$3.28 \pm 0.17 \times 10^{-9}$
$B^0 \rightarrow \mu^+\mu^-$	$1.07 \pm 0.10 \times 10^{-10}$

A.J.Buras et al: arXiv:1303.3820+PDG2013

sensitive to contributions in the **scalar/pseudo-scalar sector**

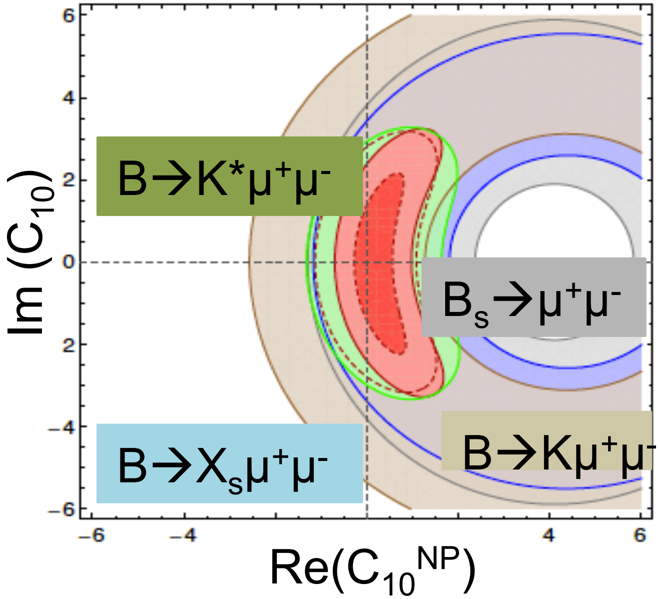
highly interesting to probe **extended Higgs** models and **high tanβ**

limit or measurement of $B_{s,d} \rightarrow \mu\mu$ strongly constrain **tanβ vs M_A plane**



Combined leptonic and semileptonic B decays

arXiv:1206.0273



Constraints on new physics

Measurements of B→μμ, B→K*μμ, B→$X_s$ll , b→ sγ set limits on the mass scale of non-SM contributions

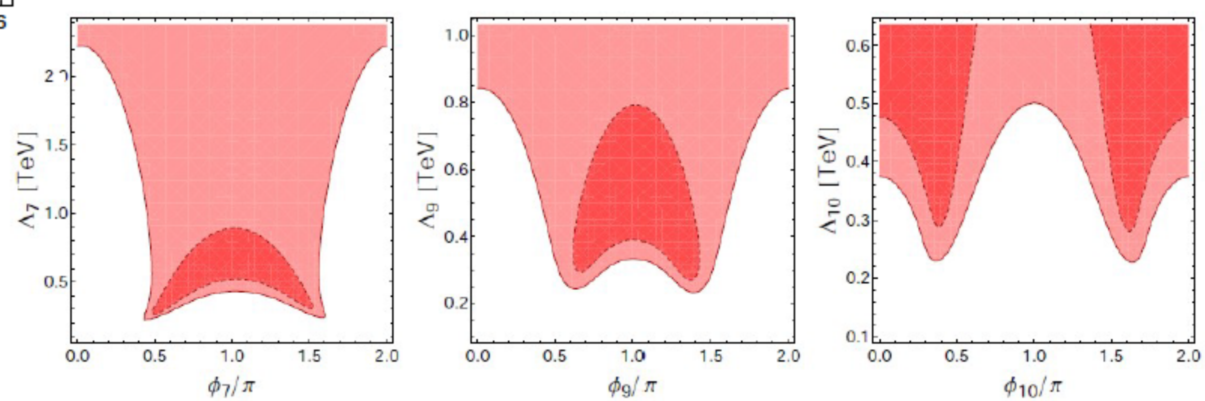
$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum (C_i O_i + C'_i O'_i) + h.c.$$

Effective Hamiltonian relevant for b→sγ and b→ sl^+l^-

~ loop level CKM-like flavour violation

$$L = L_{SM} - \sum_{j=7,9,10} \frac{V_{tb} V_{ts}^*}{16\pi^2} \frac{e^{i\phi_i}}{\Lambda_j^2} O_j$$

Almannshofer, Paradisi, Straub
JHEP 04 (2012) 008 + updates



$$O_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu \gamma_5 l) \quad O_9 = (\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu l) \qquad O_7 = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu} P_R b)(F^{\mu\nu})$$

Nothing with SM type flavour couplings below O(400 GeV)