Heavy flavour and search for new physics at LHCb

Justine Serrano

Centre de Physique des Particules de Marseille

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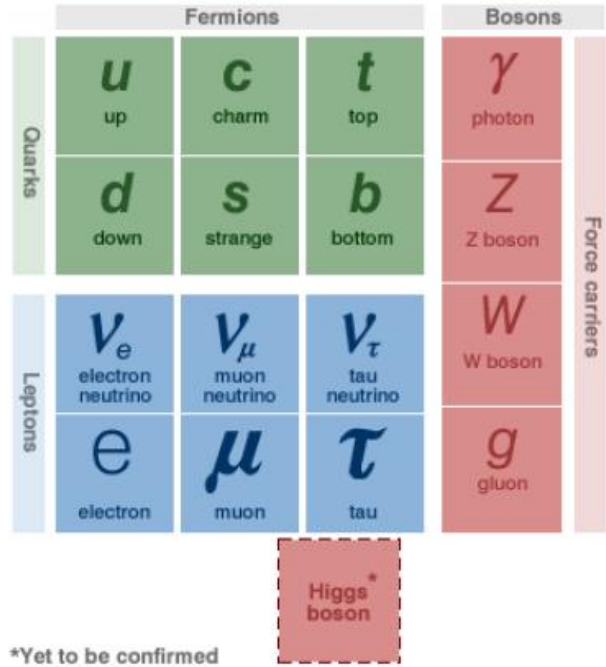
Flavour in the SM

- Transitions between quarks of different families are allowed through charged weak interaction



$$\mathcal{L}_{cc} = -\frac{g}{\sqrt{2}}\left(J^{\mu}W_{\mu}^{\dagger} + J^{\mu\dagger}W_{\mu}\right)$$

with $$J_{\mu} = \sum_{i,j} \bar{u}_i \gamma_{\mu} \frac{1}{2}(1-\gamma_5) V_{ij} d_j$$

Flavour eigenstates

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

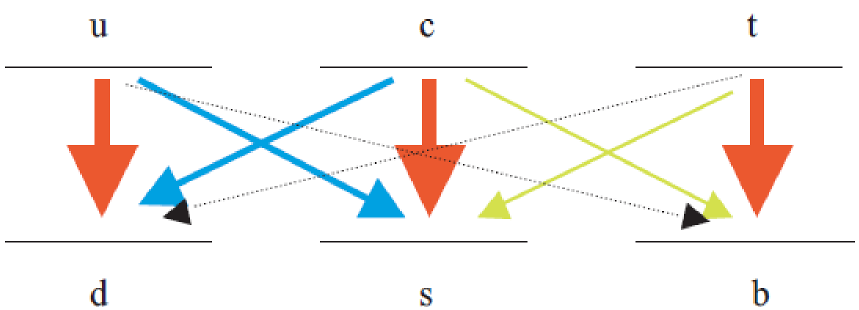
Mass eigenstate

CKM matrix

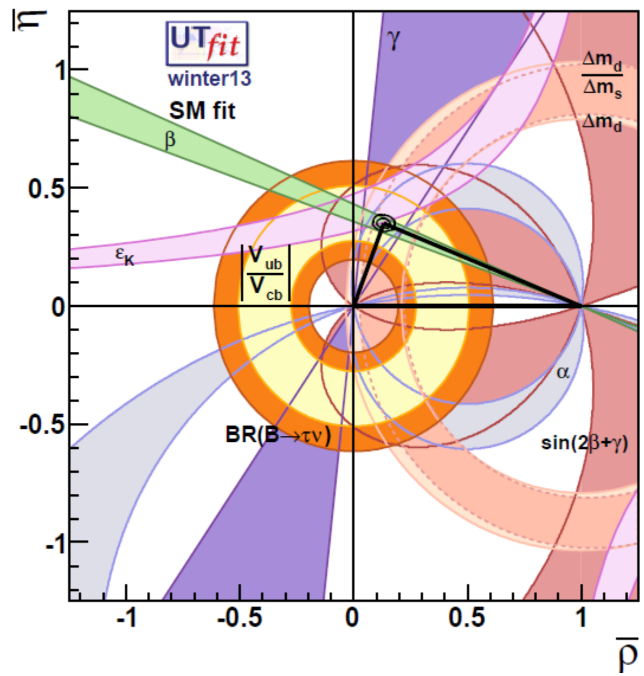
V_{CKM} is described by 4 parameters (but their values are unknown in SM)

Flavour in the SM

- The quark mixing angles have a special hierarchy



  - We don't know why
  - But the consistency of the CKM picture has been tested experimentaly with a great precision



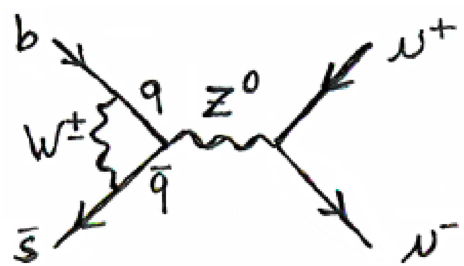
- There is no flavour changing neutral current at the tree level in the SM
  - FCNC are only possible through penguins/boxes diagrams so there are highly suppressed.

- CP violation is explained by the phase of the CKM matrix
  - It could be connected to the matter-antimatter asymetry of the Universe

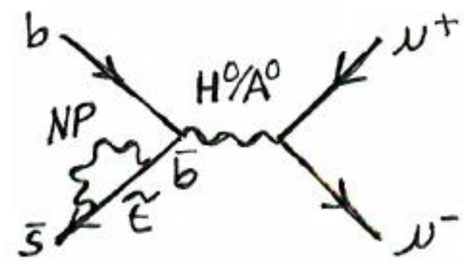
The indirect search for new physics

- NP particles can virtually enter in the loop processes and modify the prediction of the SM for physics observables. Ex: BR($B_s \rightarrow \mu^+\mu^-$)

SM



NP



- « indirect » because the NP particle are not explicitely created and observed in the experiment
- The goal is to look for deviation from SM prediction. The rules of the game are
  - great precision of experimental measurement (statistics)
  - great precision of theoretical prediction
- These searches have been largely successful in the past:
  - Ex: heavyness of top quark (observed in 1995 at the Tevatron) through the B^0 oscillations (1987 by ARGUS)

The new physics scale

- NP contribution can be expressed as a perturbation to the SM lagrangian

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{c_{NP}}{\Lambda^2}$$

NP coupling

NP scale

- If NP particles are discovered at the LHC, we are able to study the flavour structure of the NP
- Flavour physics can probe very high energy scale (even beyond the LHC reach)

- Considering the present experimental constraints in flavour physics:
  - if C=1, $\Lambda \sim O(100\text{TeV})$
  - If $\Lambda \sim 1\text{TeV}$ (quantum stabilization of electroweak scale), C ~ $O(10^{-7})$. Where is this suppression coming from ?

$\Rightarrow$ This is the NP flavour problem. The flavour strucure of NP should be highly non trivial.

Where to look ?

- Different observables give different constraints on different NP models

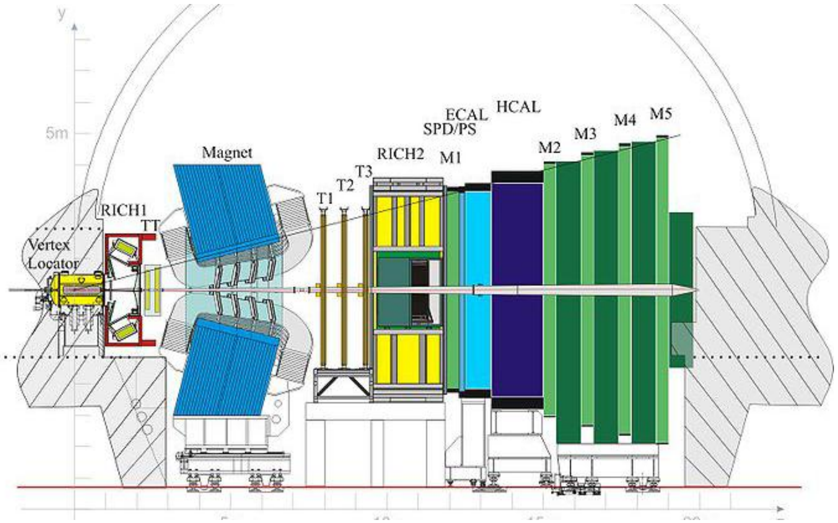
LHCb Physics program:

- B decay to charmonium
  - B_s mixing, CPV
- B decay to open charm
  - γ, B decay to double charm, rare hadronic B decay
- Rare decays
  - leptonic, electroweak, radiative, LFV
- Charm physics
  - Mixing and CPV, charm production and spectroscopy
- Charmless B decay
  - $B \to hh'$, $B \to VV$
- Semileptonic B decays
  - Search for CPV in mixing, form factors, rare decay
- B hadron and quarkonia
  - Production and spectroscopy
- QCD, electroweak and exotica
  - EW boson production, new long lived particles

I will focus on : $BR(B_{s/d} \to \mu^+\mu^-)$, CP violation in B_s mixing, CKM angle γ

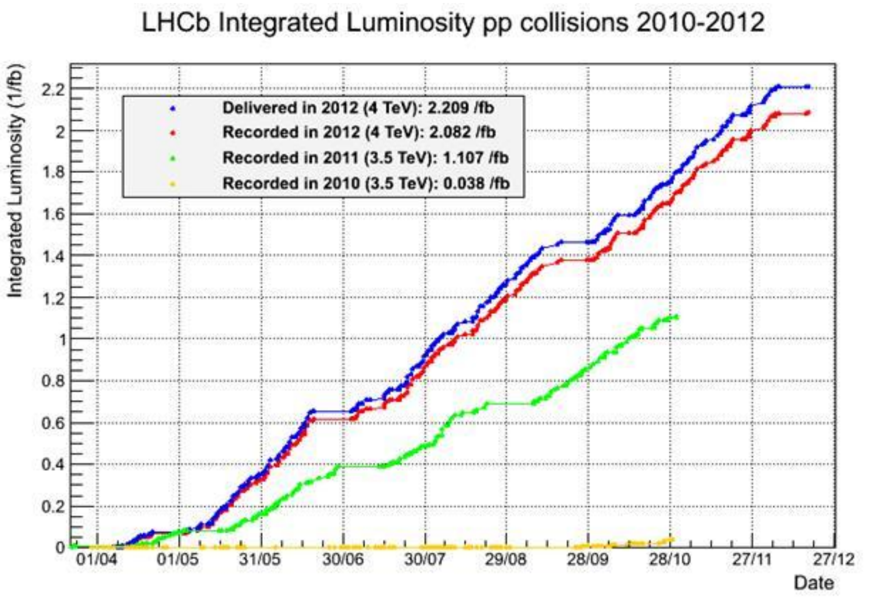
LHCb

- Forward spectrometer optimised for heavy flavour physics at the LHC
  - Large acceptance 2<η<5
  - Low trigger thresholds
  - Precise vertexing
  - Efficient particle identification
  - Large boost (B mesons flight ~1cm)

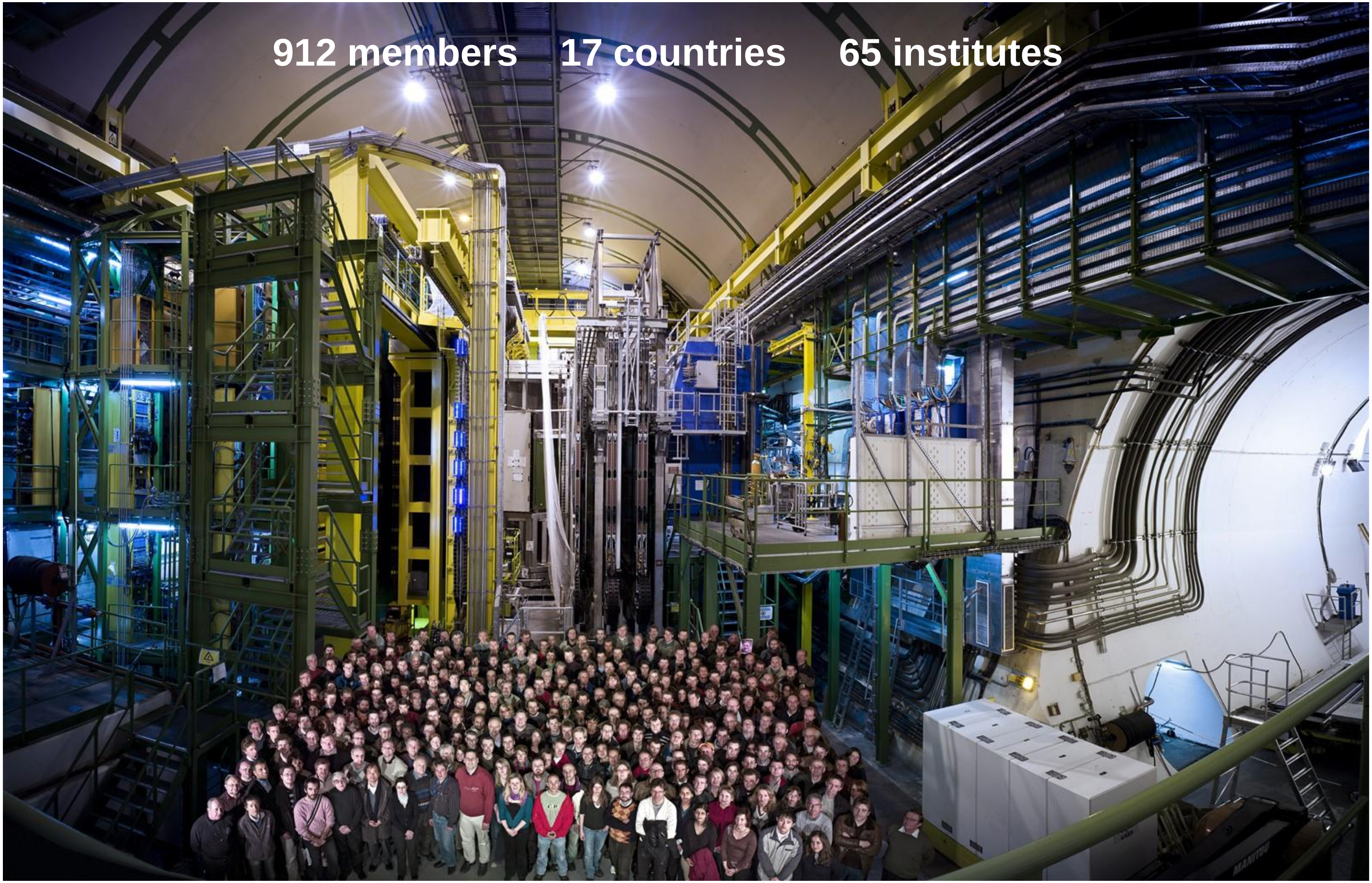


- Running at a constant luminosity of 4.10^{32} cm^{-2} s^{-1} thanks to the luminosity leveling (design 2.10^{32})

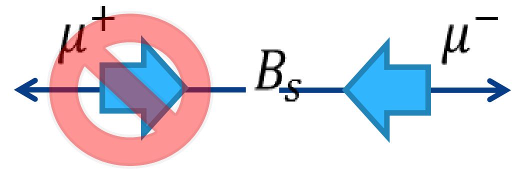
- Precision physics easier in a low pile-up environment: interactions per bunch crossing ~1.5



The LHCb Collaboration



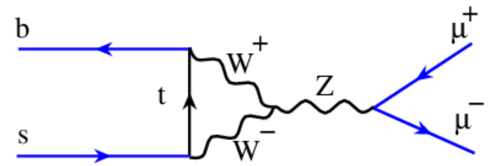
- FCNC and helicity suppressed decays



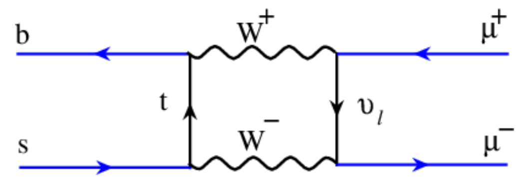
- Precise SM prediction:
  - $BR(B_s \to \mu^+\mu^-) = (3.23 \pm 0.27) \times 10^{-9}$
  - $BR(B_d \to \mu^+\mu^-) = (1.07 \pm 0.10) \times 10^{-10}$

    A.J.Buras: arXiv:1208.0934

  - Taking Bs oscillation into account, measured BR should be compare to:
    $B(B_s^0 \to \mu^+\mu^-)^{SM}_{exp} = (3.54 \pm 0.30) \times 10^{-9}$



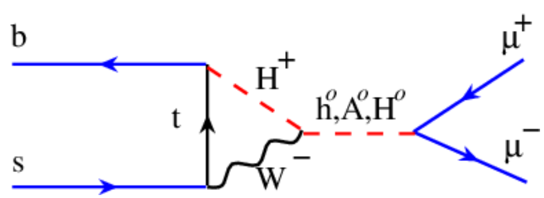
75%



24%

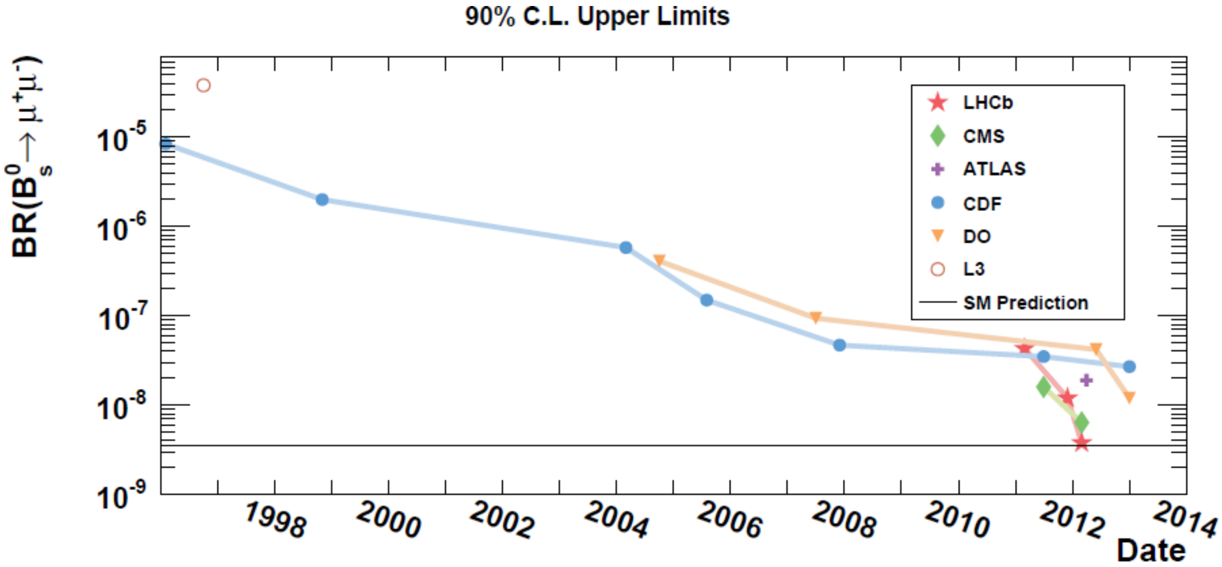
- Possible new particles in the loops

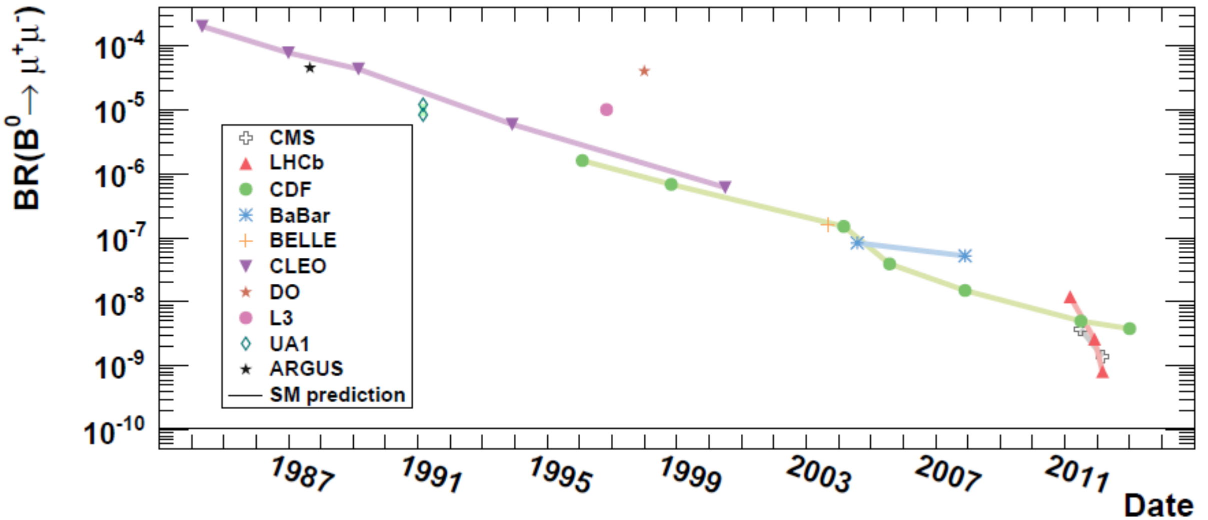
Ex:2HDM



⇨ Very good pace to look for physics beyond SM

Experimental picture

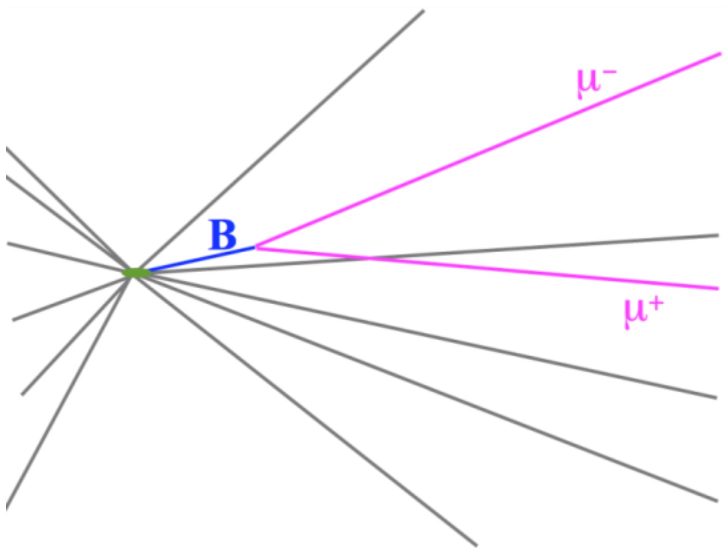


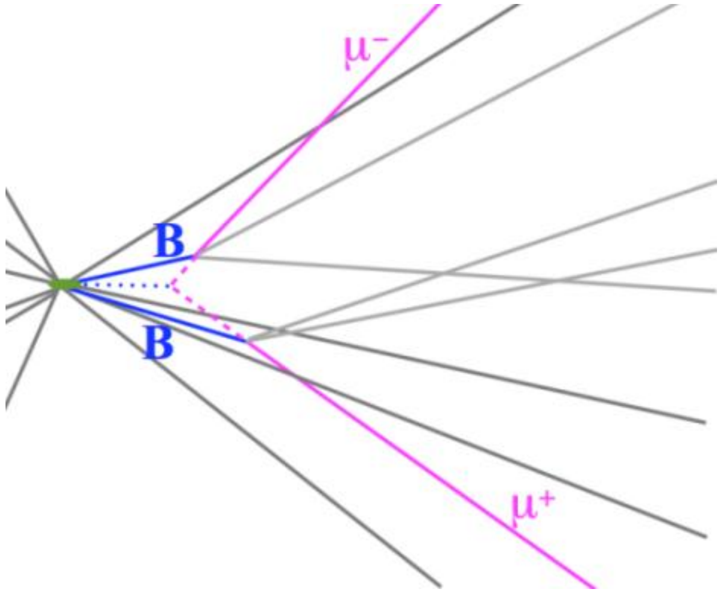


Significant enhancements ruled out for $BR(B_s \to \mu^+\mu^-)$

Analysis strategy

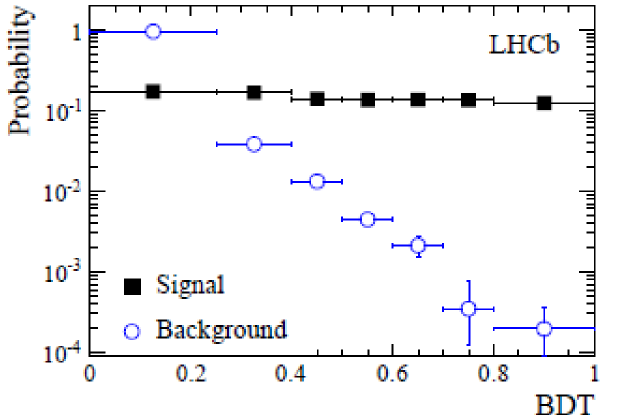
Spot the differences





- Geometrical variables: Impact Parameters, Distance of Closest Approach, isolation
- Kinematic variables: Transverse momentum

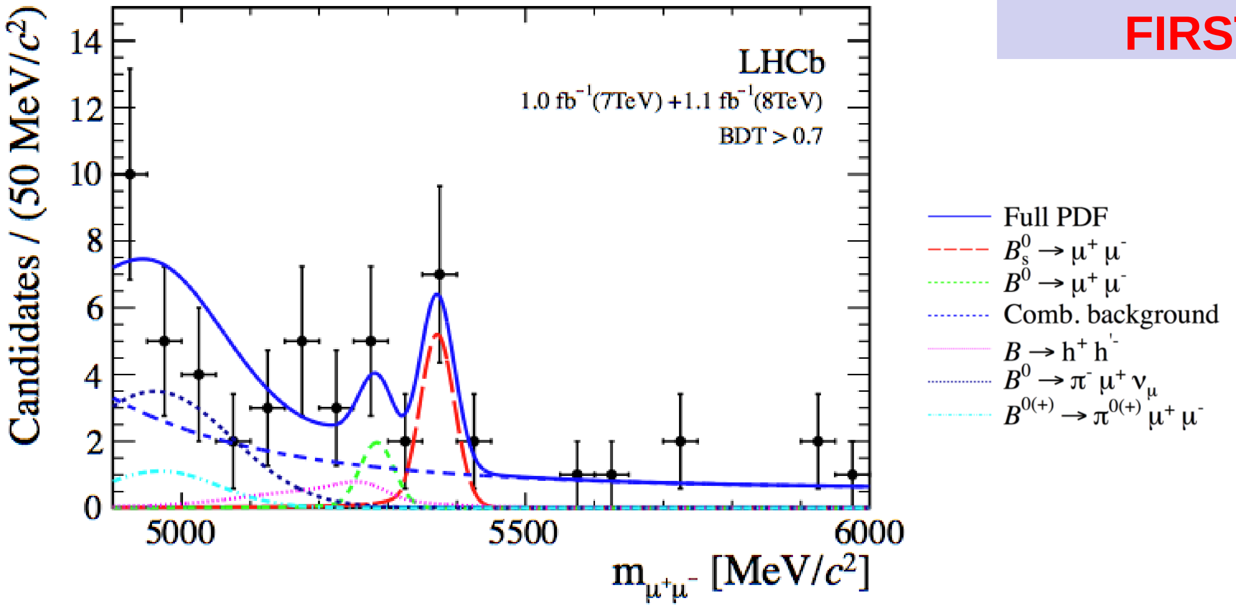
Boosted decision tree



Results

$$B(B_s^0 \to \mu^+\mu^-) = \left(3.2^{+1.5}_{-1.2}\right) \times 10^{-9}$$

Bkg only p-value:
$5.3x10^{-4}$
3.5 σ excess
FIRST EVIDENCE

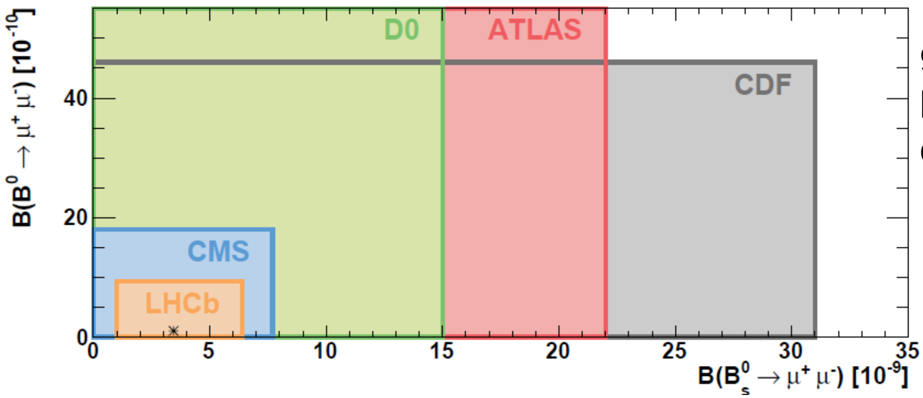


$B(B^0 \to \mu^+\mu^-) < 9.4 \times 10^{-10}$ at 95% CL ($7.1\ 10^{-10}$expected)

Results published in Phys. Rev. Lett. 110, 021801 (2013)

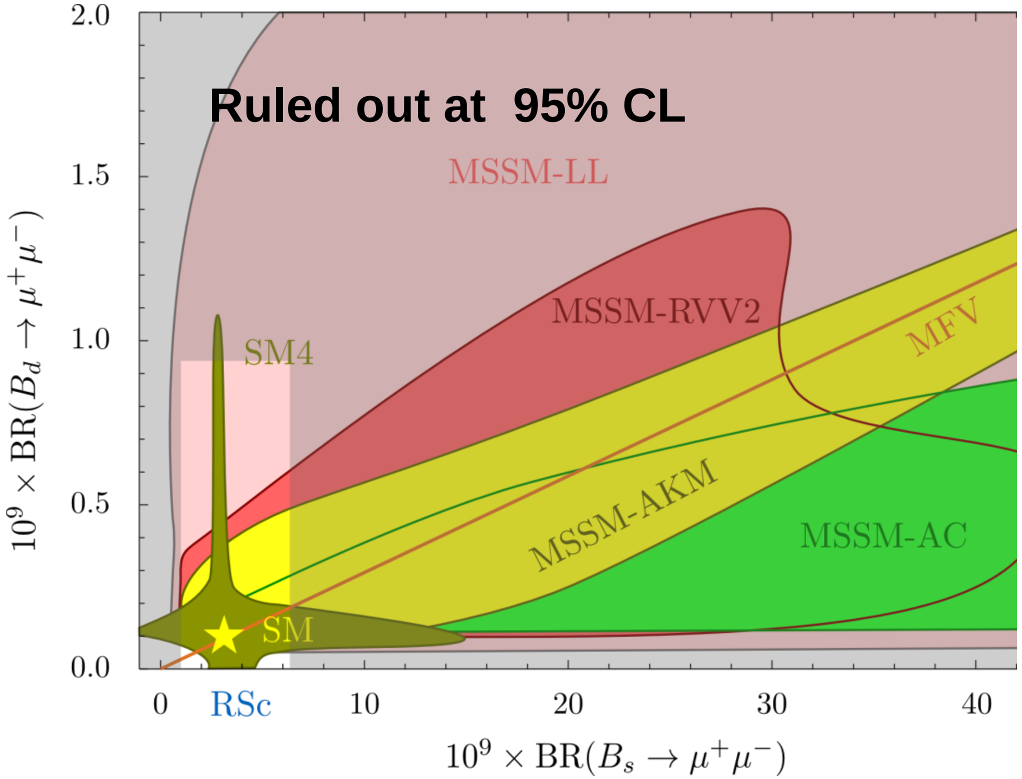
We still have another 1 fb^{-1} of data to be analysed

Experimental picture:
(should change in the coming weeks!)



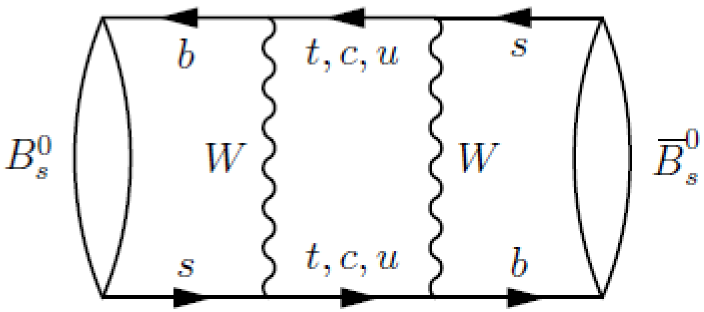
95% contours by hadronic machine experiments

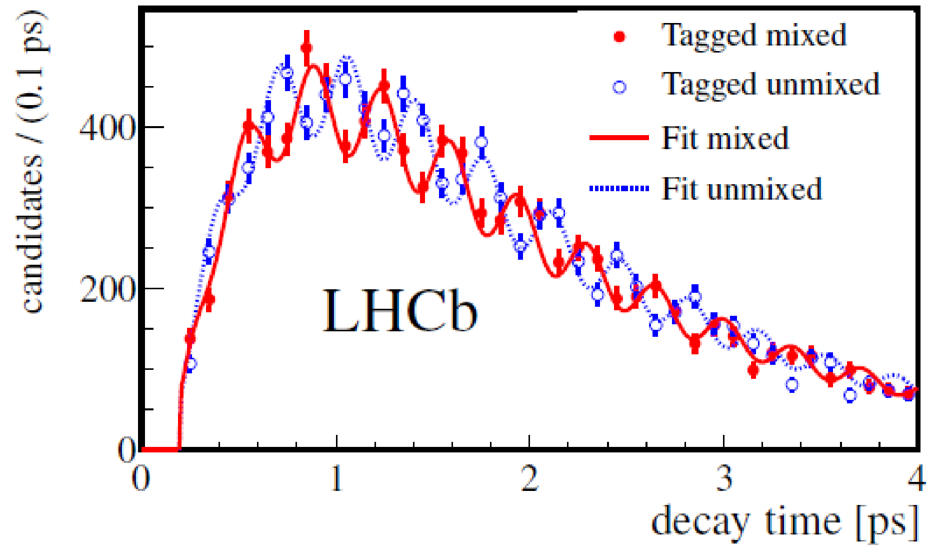
NP picture:



arXiv 1205.6094

- B$_s$ oscillation studied at high precision at LHCb (arXiv:1304.4741)



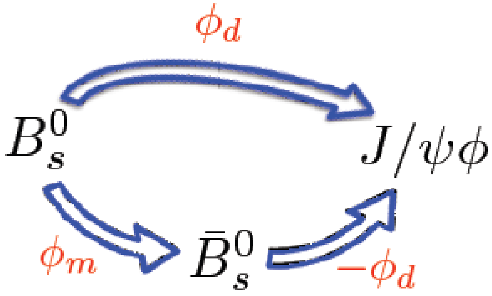


$$\Delta m_s = 17.768 \pm 0.023\ (\mathrm{stat}) \pm 0.006\ (\mathrm{syst})\ \mathrm{ps}^{-1}$$

- NP can enter into the mixing amplitude, accessible via interference

ϕ_s in $B_s \to J/\psi\phi$

- Interference between mixing and decay gives rise to a CP violating phase ϕ_s

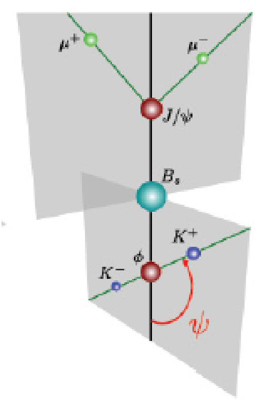


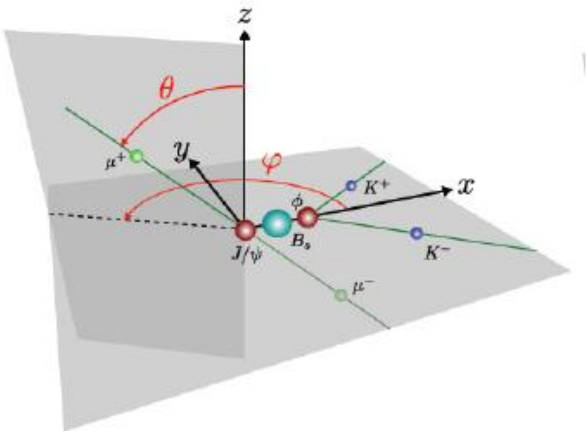
- Very precisely predicted in SM

$$\phi_s^{SM} \approx -2\arg\left(\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cs}^*}\right) = 0.036 \pm 0.002\ \ rad$$

Charles et al, PRD84 (2011) 033005

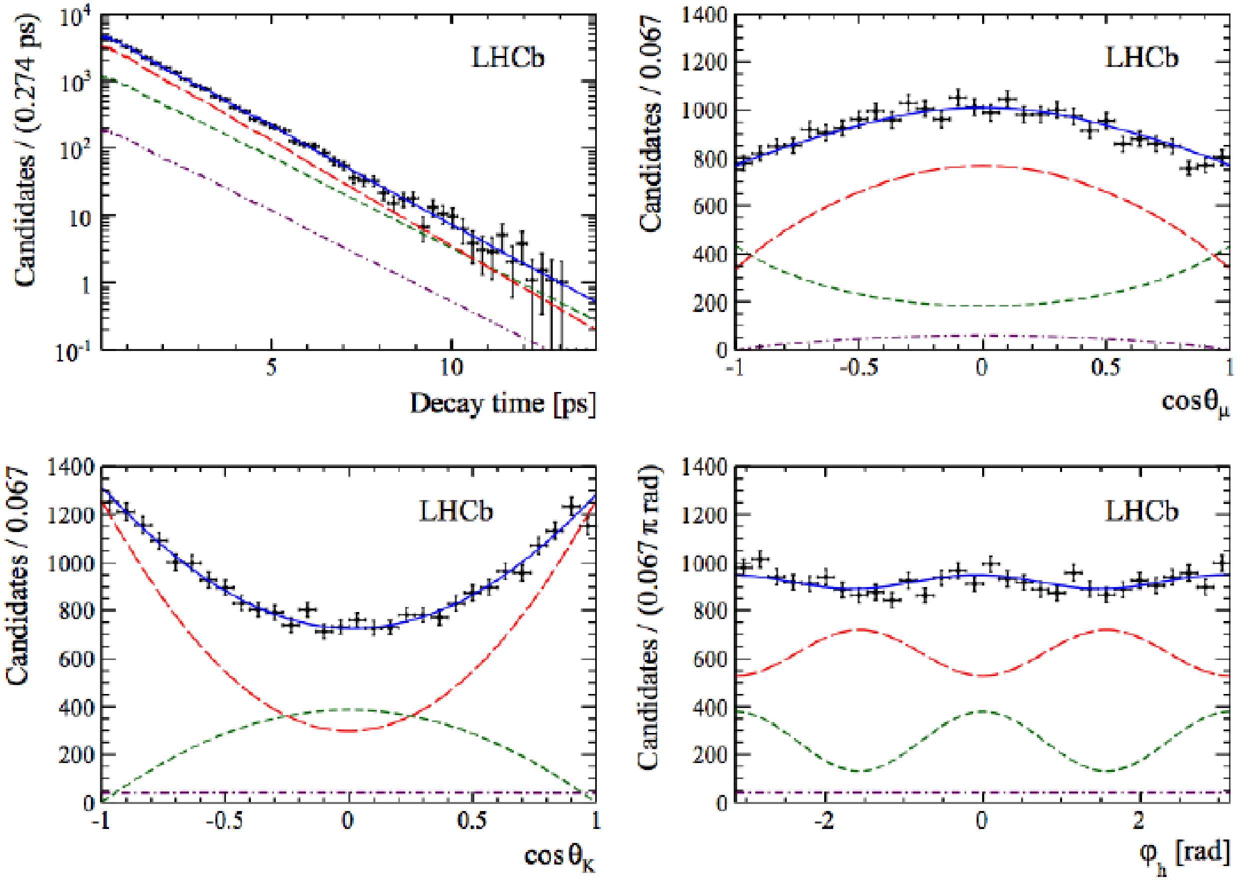
- $B_s \to J/\psi\phi$ is a mixing of CP odd and even final state. Need an analysis
  - Time dependent
  - Tagged
  - Full angular
  - Should measure also $\Delta\Gamma_s$





ϕ_s in $B_s \to J/\psi\phi$

Phys. Rev. D 87, 112010 (2013)

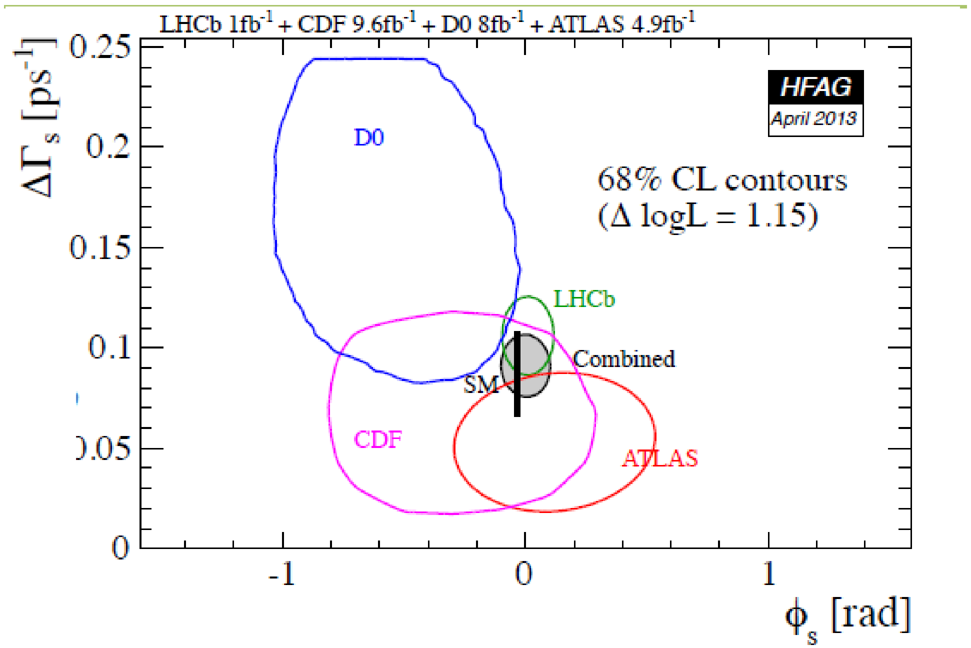


CP-even

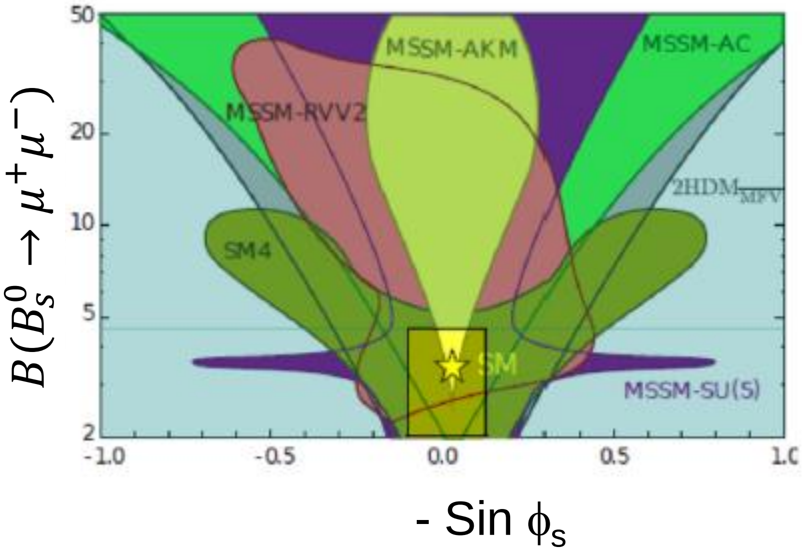
CP-odd

background

ϕ_s in $B_s \to J/\psi\phi$



Based on arXiv:1107.0266



- Combined result with $B_s \to J/\psi\,\pi\pi$: *arXiv:1304.2600*

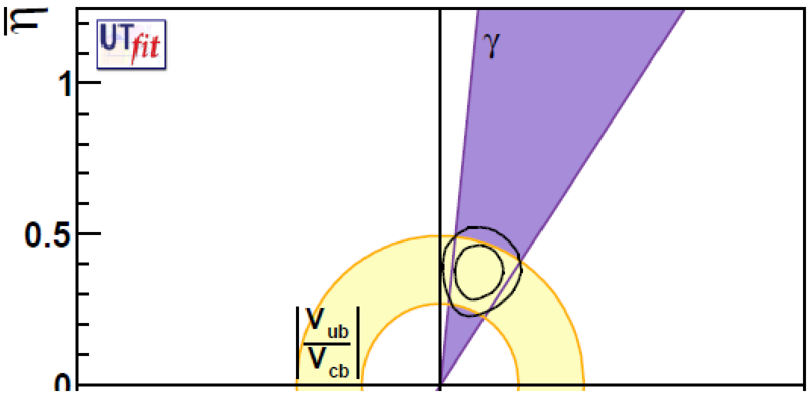
  $\phi_s = 0.01 \pm 0.07 \pm 0.01$ rad

- Good agreement with the SM prediction

The CKM angle γ

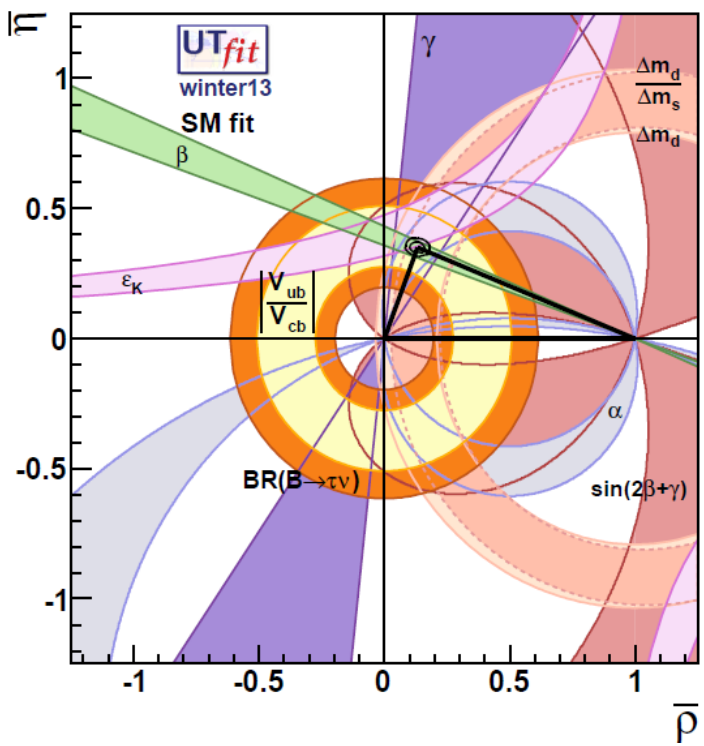
- If NP enters only at loop level, it is interesting to compare tree dominated measurements with loop dominated measurements

Trees



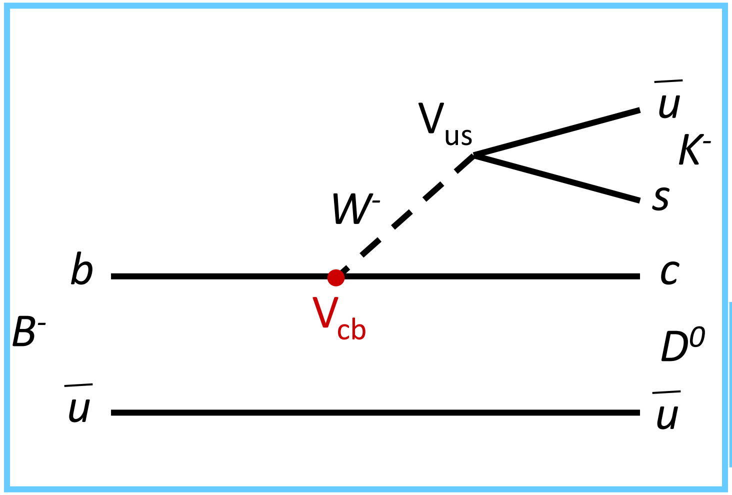
$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^{\star}}{V_{cd}V_{cb}^{\star}}\right)$$

Trees + loops

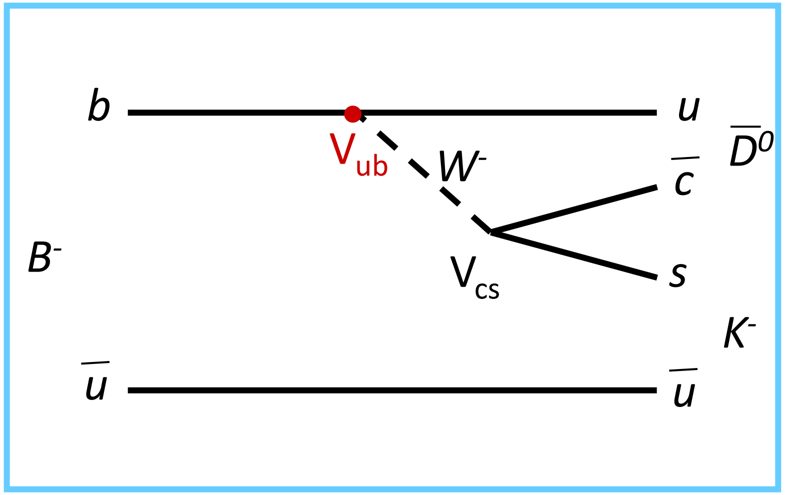


- Important to improve γ from tree: $B \to DK$

γ from B → DK

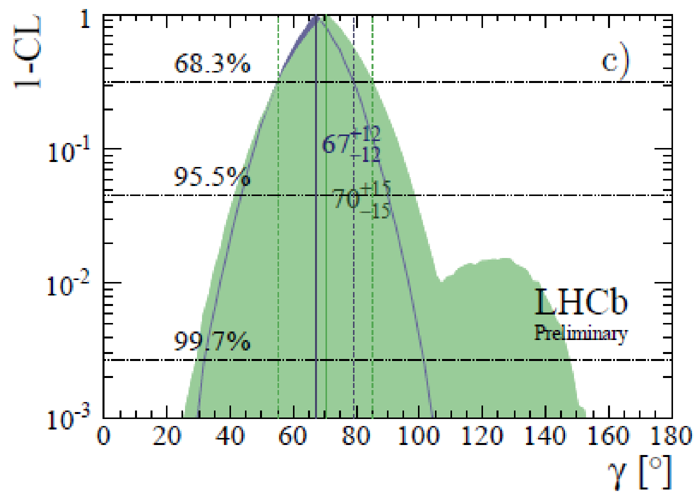


Relative magnitude
r_B
relative phase δ_B-γ



- Many analysis using different methods
- LHCb Combination: $\gamma = (67 \pm 12)^o$
- Compare to:
  - Belle: $(69^{+17}_{-16})^o$
  - Babar: $(68^{+15}_{-14})^o$
  - Prediction from fit: $(68.6 \pm 3.6)^o$ UTFIT
  - Prediction from fit: $(68.0^{+4.1}_{-4.6})^o$ CKMFitter

LHCb-CONF-2013-006



Future: LHCb upgrade

- New physics has not shown itself clearly at the LHC
- Essential to improve measurements of precisely predicted quantities
  - $\Rightarrow$Need more statistics: LHCb upgrade
- Installation during LS2: 2018

- Main limitation that prevents expoiting higher luminosity is the hardware trigger limiting the output rate at 1 MHz

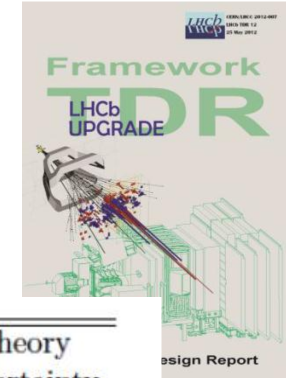
- Propose to remove the hardware trigger and read out LHCb at 40MHz crossing rate

  $\Rightarrow$ increase yields by 10-20 at 1-2 $10^{33}cm^{2}s^{-1}$

  $\Rightarrow$ aim to collect 50 fb^{-1}

- LOI submitted to LHCC in March 2011, Framework TDR submitted in may 2012, all detector TDRs by end 2013

What we can expect



- LHCb upgrade: Expect 5 fb^{-1} per year after 2018

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

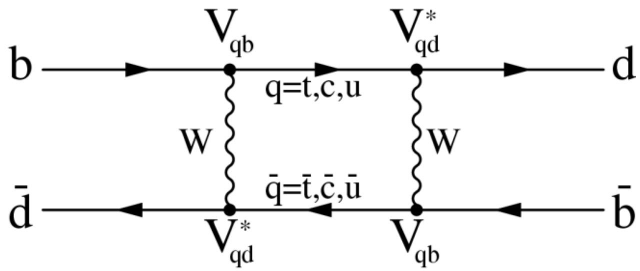
Conclusion

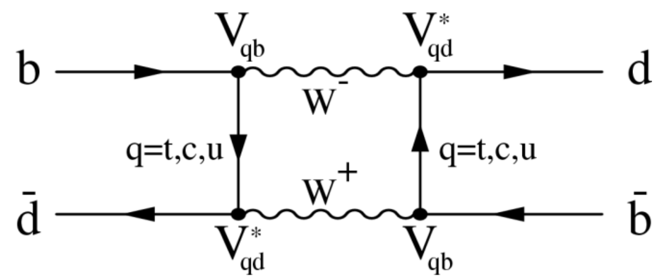
- Direct and indirect searches for new physics are both needed and complementary
- LHCb is probing beyond stantard model physics in different ways
- For the moment, the agreement with the SM is very good… but the search has just started!
  - Most of analysis published with <2 fb^{-1} , still more data to analysed
  - LHCb is preparing upgrade for 2019

backup

Success of the indirect method

- Several predictions made in the past ~40 year. As exemple, the charm quark from K decays or top quark through the B^0 oscillations:





Dominated by the top quark

$$t-\bar{t} :\propto m_t^2 \left|V_{tb}V_{td}^*\right|^2 \propto m^2\lambda^6$$

B^0B^0 mixing: ARGUS, 1987

Phys.Lett.B192:245,1987

$$\Delta m_B \approx 0.00002 \cdot \left(\frac{m_t}{\mathrm{GeV}/c^2}\right)^2 \mathrm{ps}^{-1}$$

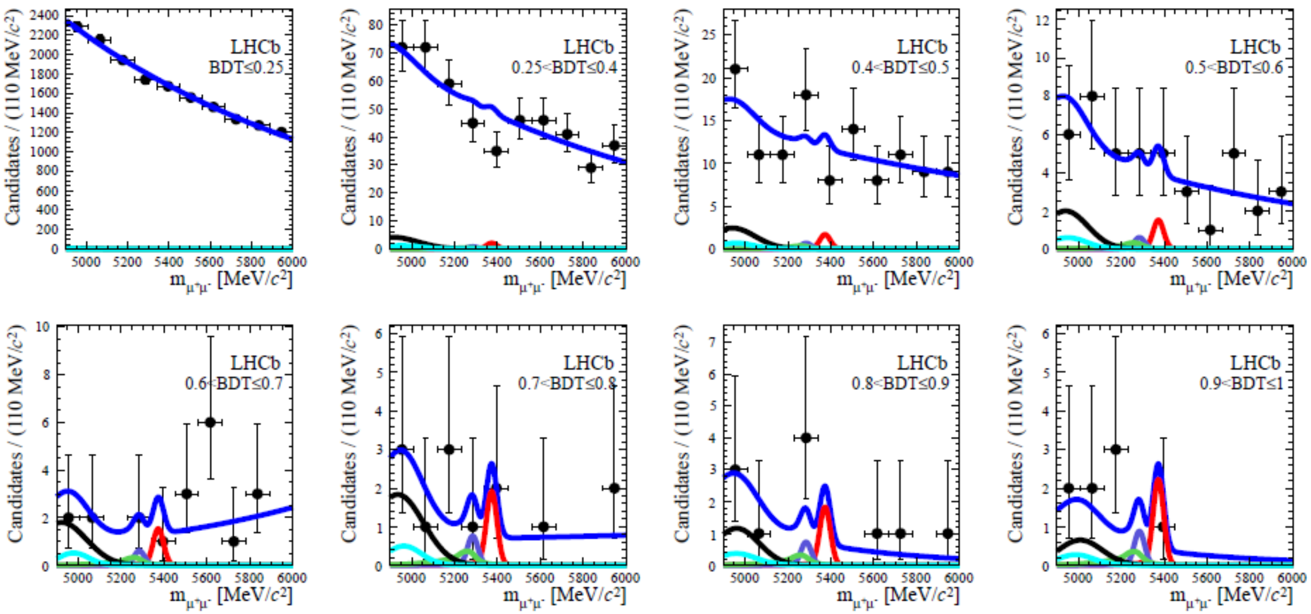
$$\approx 0.5\mathrm{ps}^{-1}$$

→ First hint of a *really large* m_{top}!

directly observed in 1995

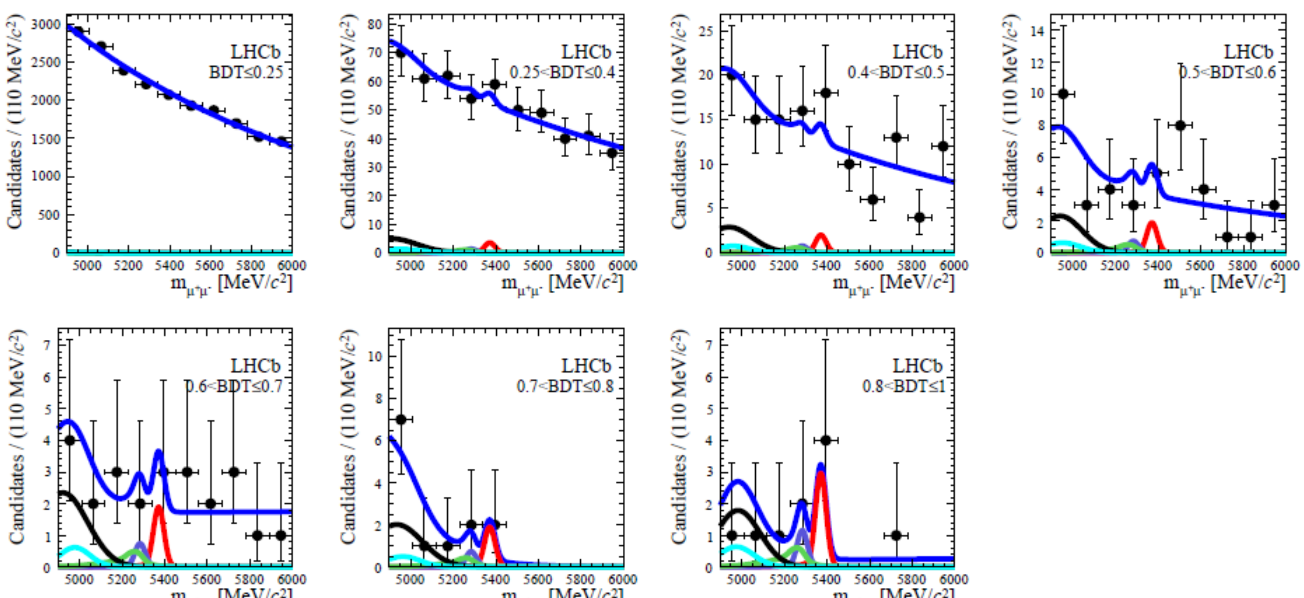
Fit projections

2011
7 TeV data, 1.0 fb^{-1}
8 BDT bins

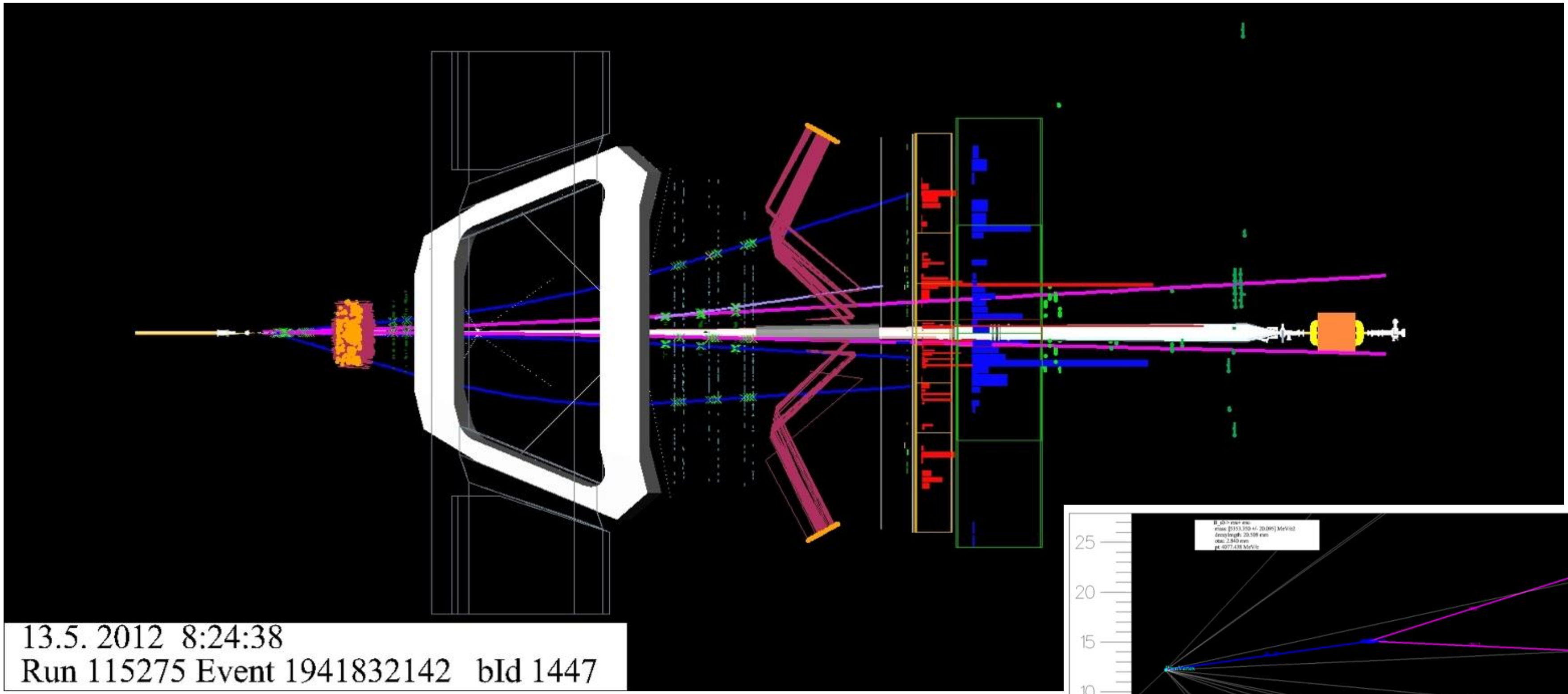


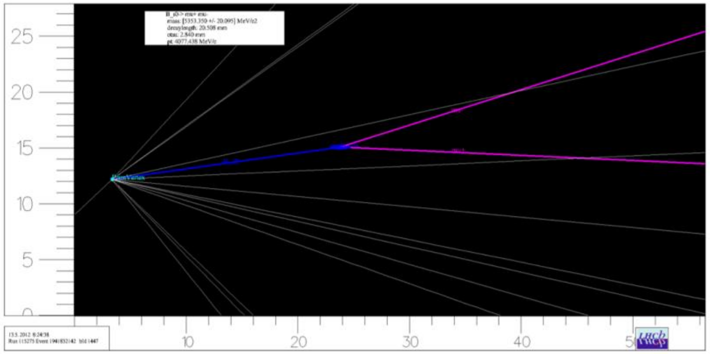
$B^0_s \to \mu^+\mu^-$
$B^0 \to \mu^+\mu^-$
$B^0_{(s)} \to h^+h'^-$
$B^0 \to \pi^-\mu^+\nu_\mu$
$B^{\pm,0} \to \pi^{\pm,0}\mu^+\mu^-$
total

2012
8 TeV data, 1.1 fb^{-1}
7 BDT bins



A nice signal candidate!





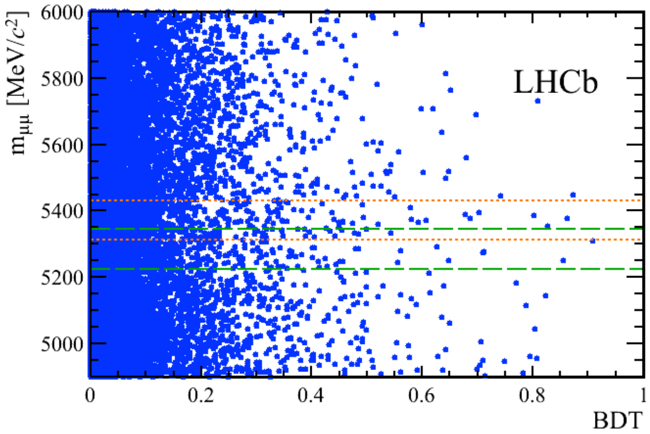
B candidate: $m_{\mu\mu}$ = 5353.4 MeV/c^2 BDT = 0.826

p_T = 4077.4 MeV/c τ = 2.84 ps

muons: $p_{T\mu+}$ = 2329.5 MeV/c $p_{T\mu-}$ = 4179.4 MeV/c

Analysis strategy

- Selection
  - muon-based trigger
  - Soft selection to reduce size of dataset
  - Similar to control channels ($B_{d/s} \to h^+h^-$, $B^+ \to J/\psi K^+$)
  - Blind signal region (M_{Bd}-60MeV, M_{Bs}+60MeV)



- Signal and background discrimination:
  - boosted decision tree combining kinematic and geometrical properties
  - Invariant mass

- Data driven calibration through control channels to get signal and background expectations

- Translate number of observed events into branching fraction measurement by normalizing with channels of known BR

- Limit measurement using the modified frequentist CLs method in bins of mass and BDT

- BR measurement using a maximum likelihood fit

Experimental observable

- Neutral B_s^0 mesons undergo mixing:

$$\langle \Gamma(B_s^0(t) \to f) \rangle \equiv R_H^f e^{-\Gamma_H^s t} + R_L^f e^{-\Gamma_L^s t}$$

- Experimental observable is the time integrated $\mathcal{B}$:

$$\mathcal{B}(B_s^0 \to f)_{\text{exp}} \equiv \frac{1}{2} \int_0^\infty \langle \Gamma(B_s^0(t) \to f) \rangle dt$$

- Theoretical definition for the prediction:

$$\mathcal{B}(B_s^0 \to f)_{\text{theo}} \equiv \frac{\tau_{B_s^0}}{2} \langle \Gamma(B_s^0(t) \to f) \rangle \Big|_{t=0}$$

- Time integrated prediction:

De Bruyn et al., PRL 109, 041801 (2012), uses $\Delta\Gamma_s$ from LHCb-CONF-2012-002

CPV in charm decay

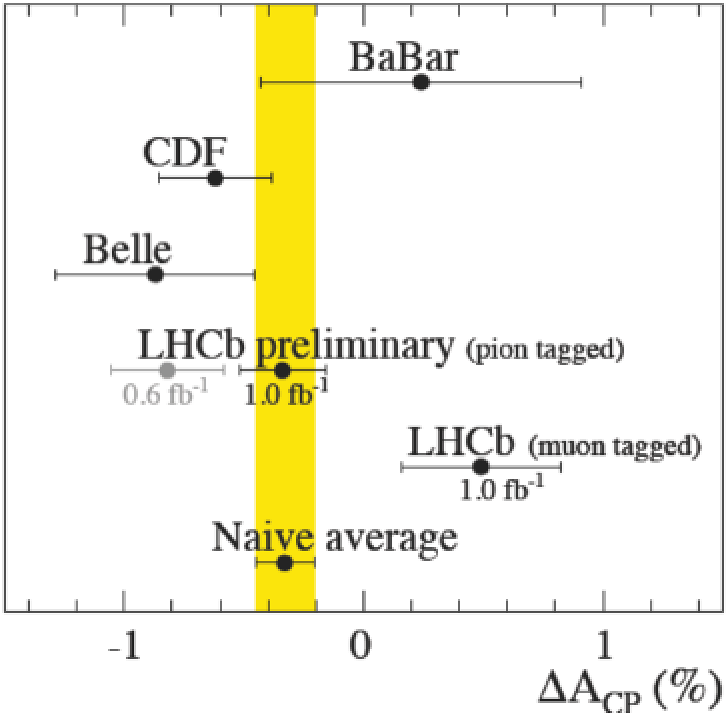
$$\Delta(\mathcal{A}^{CP}) = \mathcal{A}^{CP}(D^0 \to K^+K^-) - \mathcal{A}^{CP}(D^0 \to \pi^+\pi^-)$$

Results with 2011 data, [LHCb-CONF-2013-003], [arXiv:1303.2614]:

$$\Delta(\mathcal{A}^{CP})_{\text{prompt}} = [-0.34 \pm 0.15(stat) \pm 0.10(syst)]\%$$

$$\Delta(\mathcal{A}^{CP})_{\text{semilep}} = [0.49 \pm 0.30(stat) \pm 0.14(syst)]\%$$

- Previous evidence not confirmed with update.
- More precise/complementary measurements coming soon.



40 MHz Detector Upgrade