Introduction to B physics

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Outline

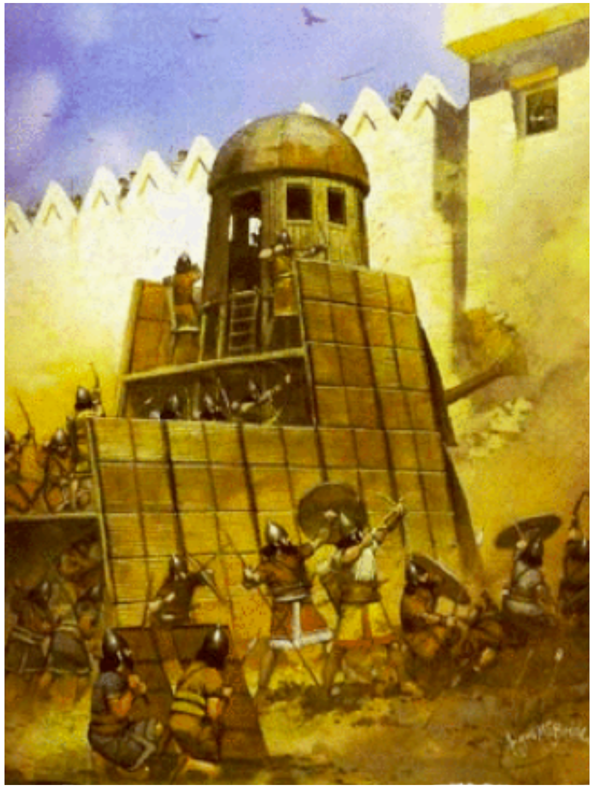
- Why study B physics?
- Introduction to the LHCb experiment
- Status of LHCb measurements
  - CKM measurements
  - Rare decays measurements
- Flavour Problem
- Light at the end of the tunnel?

Physics beyond the SM

- SM has explained essential all experimental observations for decades
- BUT: whole host of open questions:
  - What is origin of dark matter?
    - One or more weakly interacting massive particles (WIMPs)?
  - Why are there so many types of matter particles?
    - Mixing of different flavours of quarks and leptons
    - Observed matter-antimatter difference
  - Are fundamental forces unified?
    - Do all the forces unify at some higher energy scale?
  - What is quantum theory of gravity?
    - String theory?
  - …

Breaching the walls of the SM

Full frontal assault



The direct search approach
i.e. on-shell production of
e.g. SUSY particles

Something more cunning…

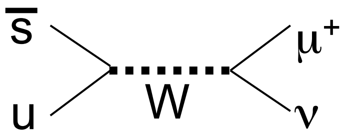
The indirect approach: **flavour physics**
e.g. virtual SUSY in rare heavy flavour-transitions

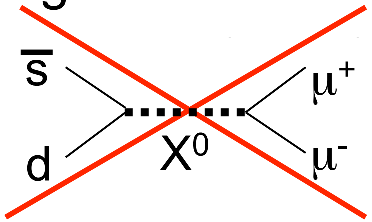
Why study B physics?

- B-mesons offer measurements that we can compare to precise theoretical predictions to try and find physics beyond the SM
  - Consistency of the CKM picture
  - Observables in rare decays
- Tools to exploit this laboratory are somewhat different between **e^+e^-** environment of (super-) B factories and **pp** environment at LHC
  - Will focus on LHCb
  - Adrian will discuss (super-) B-factories next
- Lots of reasons to advocate this approach : complementary to direct searches, ability to play a central role
- Neither of these is the reason I work in B physics…

Kaons and the GIM Mechanism

- Decay $K^+ \to \mu\nu$ observed with large BR



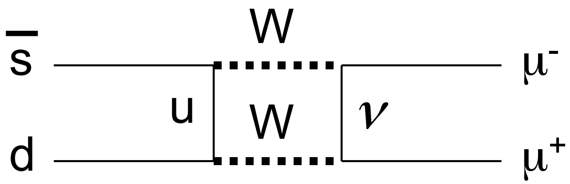


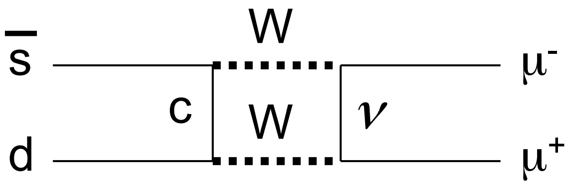
- Decay $K^0 \to \mu\mu$ observed but with tiny BR:

$$\frac{BR(K^0 \to \mu^+\mu^-)}{BR(K^+ \to \mu^+\nu_\mu)} = \frac{7\times10^{-9}}{0.64} \approx 10^{-8}$$

→ No neutral flavour changing currents

– Contribution from box diagram much too large to account for this:





– Led Glashow, Illiopolous, Maiani to postulate existence of the charm quark (GIM mechanism – 1970) before it was discovered (1974)

  - (nearly(*)) cancels the box diagram involving the u-quark

(*) not entirely: $m_u \neq m_c$

– Study $K_L \to \gamma\gamma$ and K_S-K_L mass difference even allowed Gaillard and Lee to predict the c-quark mass was ~1.5GeV before it was discovered

Other Examples

- Neutrino scattering → First observation of neutral currents (Z^0)
  - Gargamelle bubble chamber sees evidence for

    $$\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$$

    in 1973
  - Z^0 observed directly by UA1,2 in 1983

- Observation of CPV → three generations of quarks
  - Cronin, Fitch and Turlay observe CPV in 1964
  - Requires 3 generations of quarks – at the time didn't even know there were two!

- B-$\bar{B}$ oscillations → Indication that top heavy
  - Argus experiment observes large mixing rate 1987
    → heavy top quark
  - Top quark observed directly by CDF/D0 experiments 1995
- ...

Historically, there have been hints that direct observation of NP was on the cards (even if we didn't understand them entirely ...)

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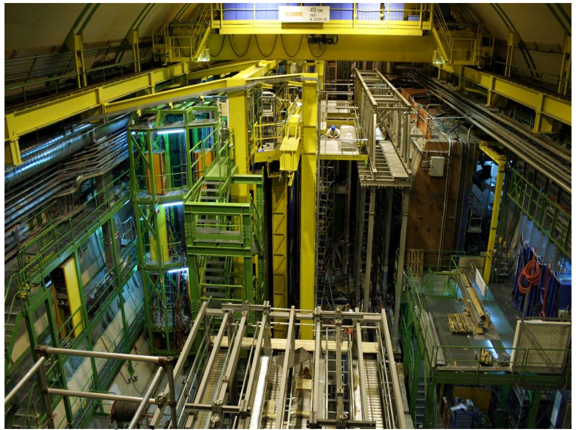
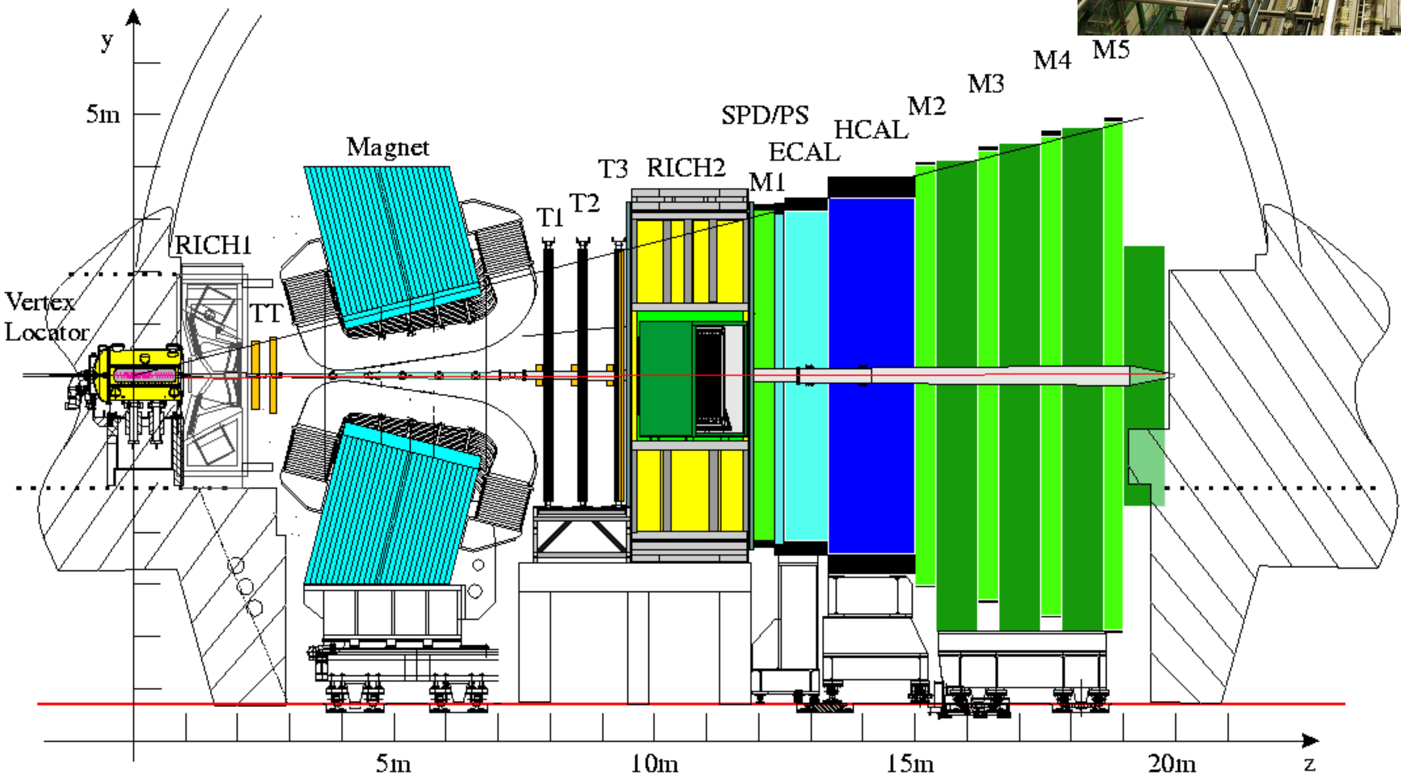
The LHCb Experiment

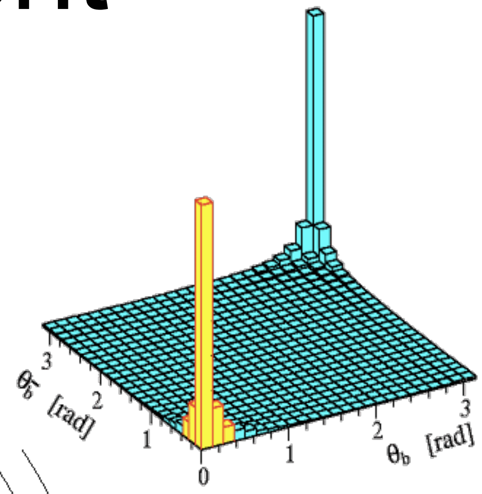
- The LHCb experiment looks very different to the other LHC detectors:

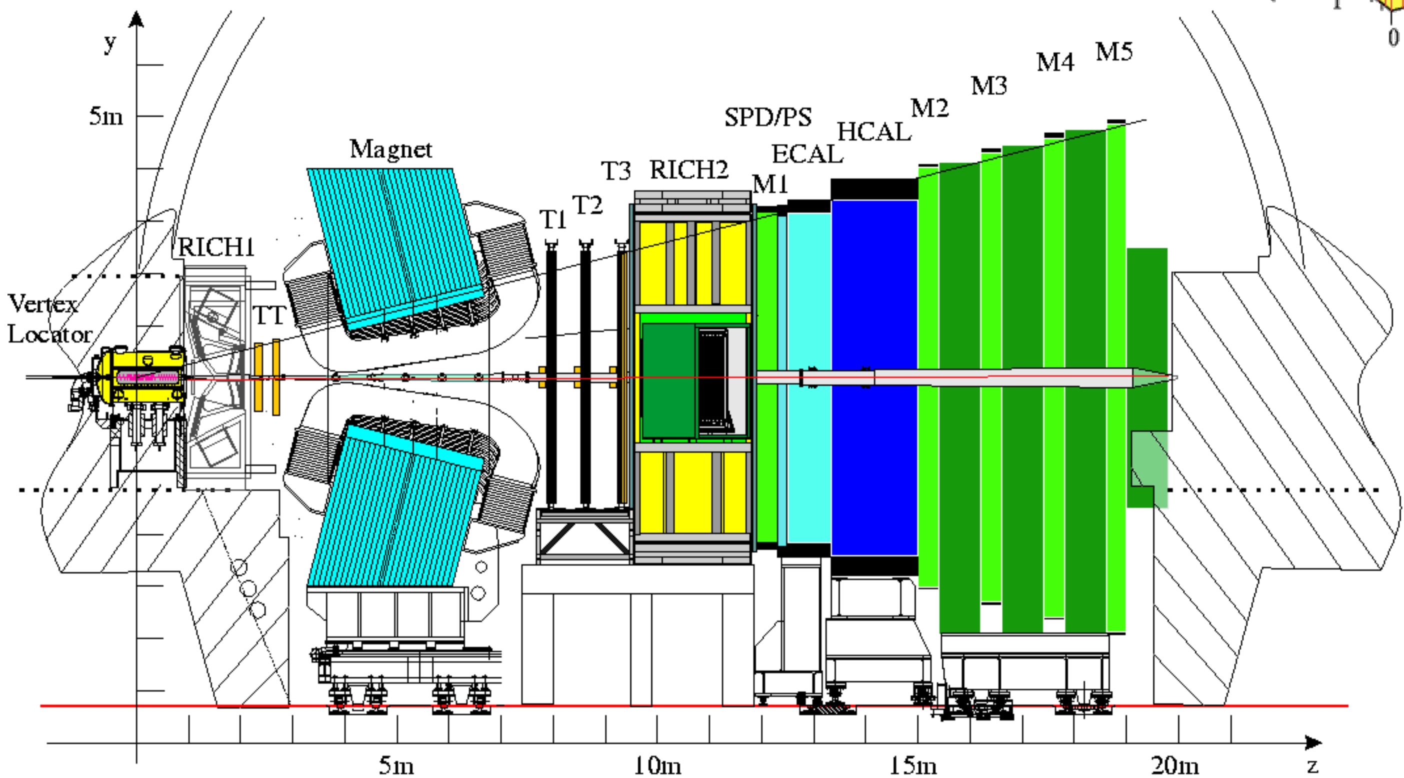




The LHCb Experiment

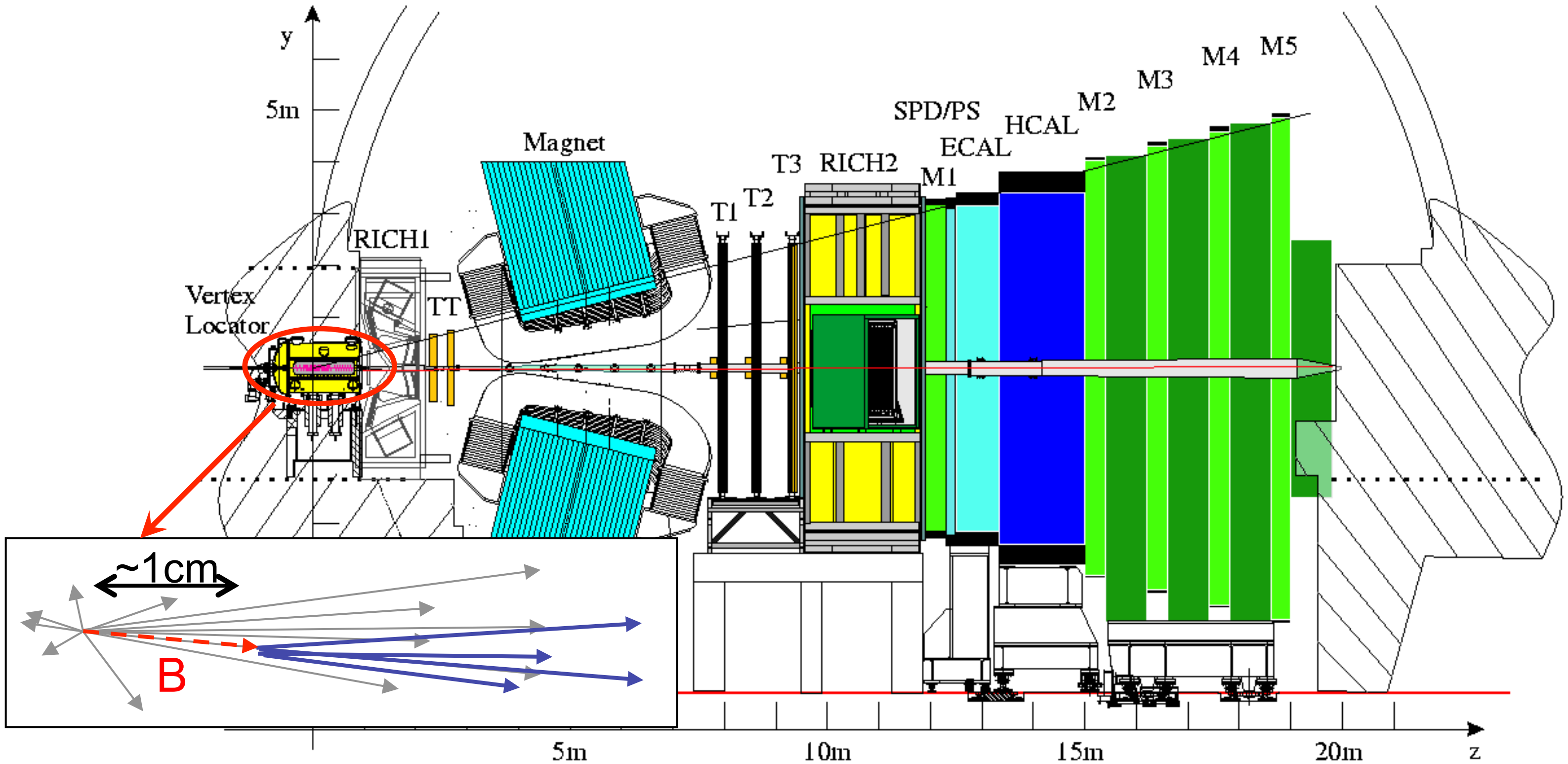
- b production predominately at small polar angles
  → forward spectrometer





The LHCb Experiment

- B lifetime → displaced secondary vertex
  - Vertex detector capable of picking out the displaced vertex
  - Need ~1 interaction/event → operate at luminosity 10–50 times lower that central detectors



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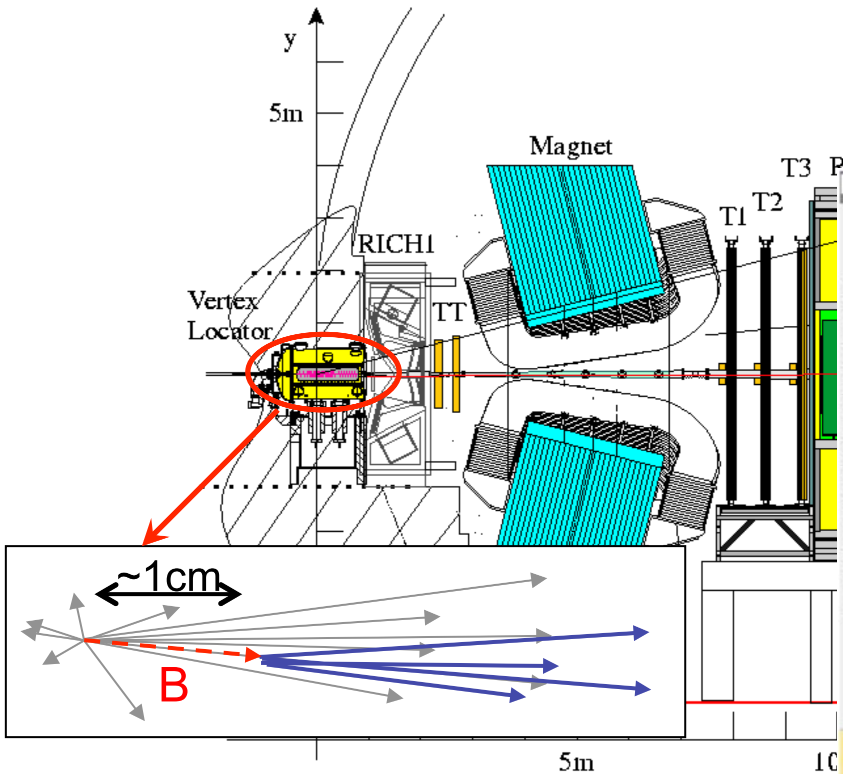
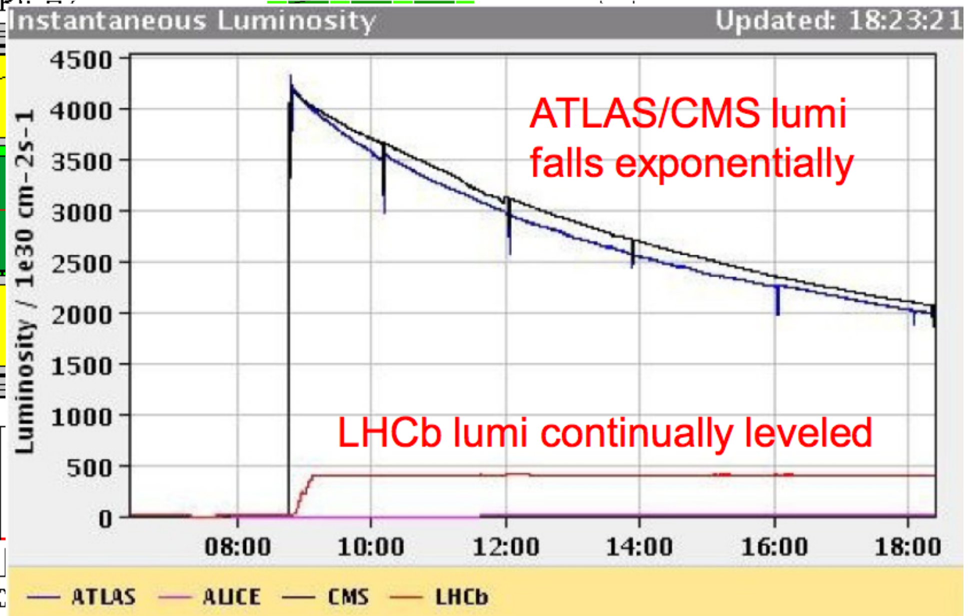


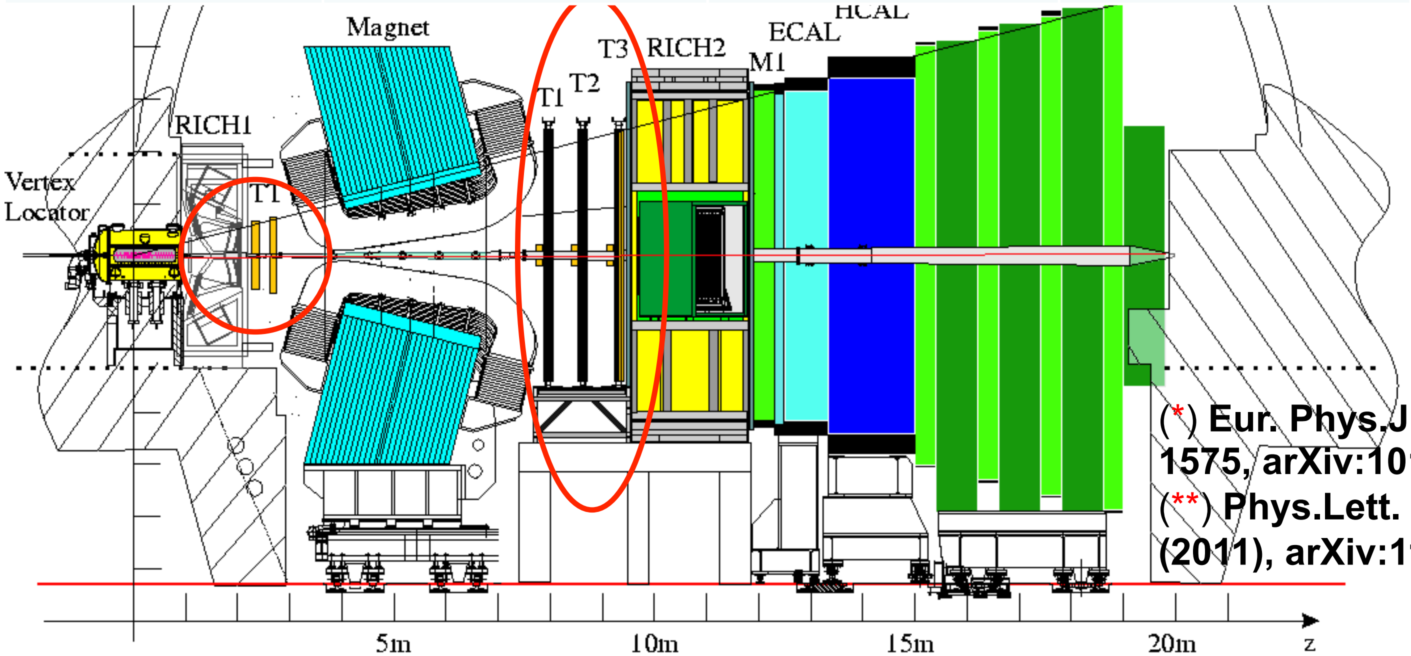
LHCb operation proceeds in harmony with higher luminosity operation of ATLAS/CMS thanks to luminosity leveling



The LHCb Experiment

- Precision momentum resolution → mass resolution

	LHCb	CMS	ATLAS
Momentum Resolution	$\delta p/p$=0.4-0.6%	$\delta p_T/p_T$=1-3%	$\delta p_T/p_T$=5-6%
Mass resoln $J/\psi \rightarrow \mu\mu$	13 MeV/c^2	28 MeV/c^2 (*)	46 MeV/c^2 (**)

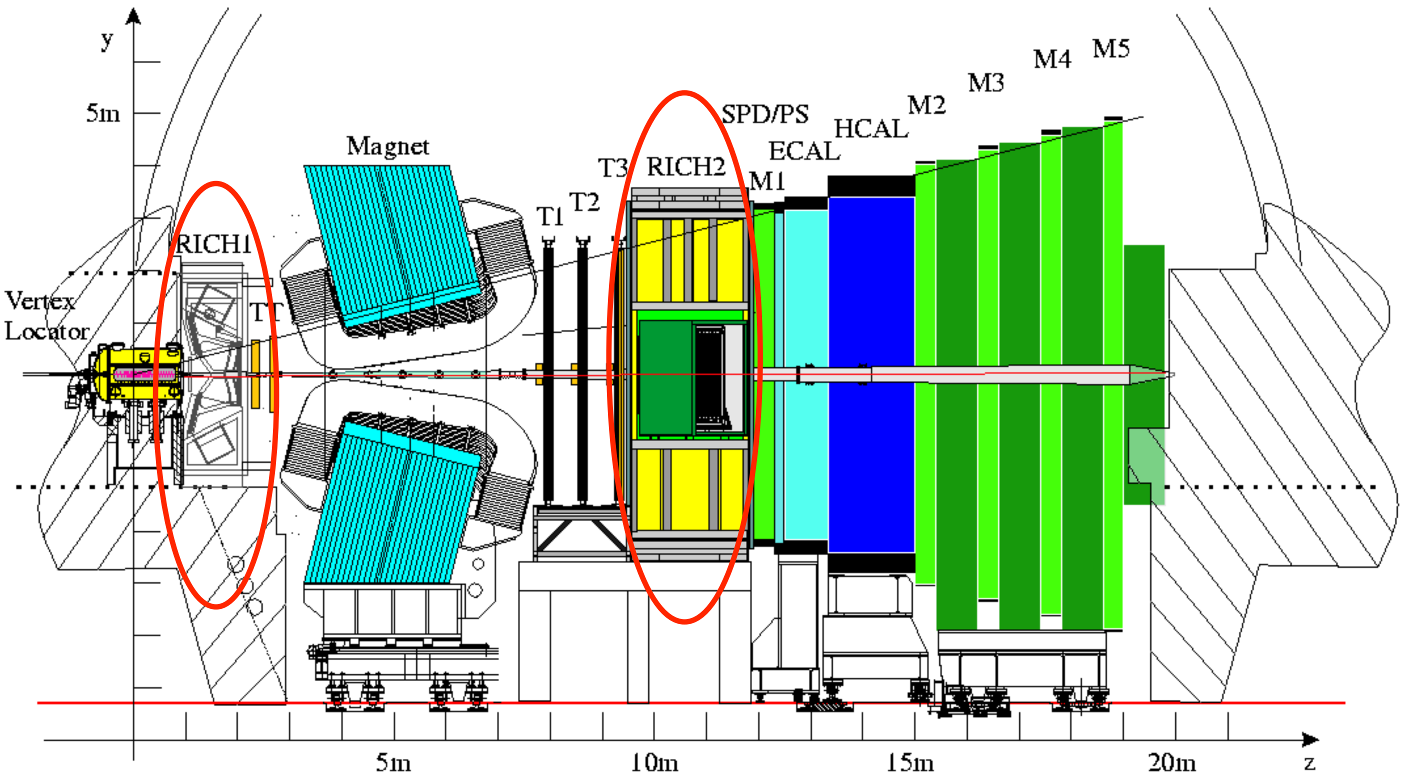


(*) Eur. Phys.J. C71 (2011) 1575, arXiv:1011.4193
(**) Phys.Lett. B697 (2011), arXiv:1104.3038v2

The LHCb Experiment

- Many of final states of interest contain kaons, in general decays dominated by pions

  → particle identification critical



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Reminder: Origin of CKM

- Can't add dirac mass terms (couple left- and right-handed components of the fields) to SM Lagrangian – are not gauge invariant e.g. for a particle X

$$\mathcal{L}_{\text{Dirac}} = -m_X \bar{X} X = -m_X \left(\bar{X}_L X_R + \bar{X}_R X_L \right)$$

- Can add Yukawa interactions e.g. for an electron,

$$\mathcal{L}_{\text{Y}}^e = -g_e \left(\bar{e}_L \phi e_R + \bar{e}_R \phi^\dagger e_L \right)$$

- where g_e is the Yukawa coupling strength for the electron, $e_{L,R}$ are the left- and right- handed components of the electron field and ϕ is the Higgs doublet

- In unitary gauge,

$$\mathcal{L}_{\text{Y}}^e = -\frac{1}{\sqrt{2}} g_e \nu (\bar{e}_L e_R + \bar{e}_R e_L),$$

$$= -\frac{1}{\sqrt{2}} g_e \nu \bar{e} e.$$

- i.e. like Dirac mass term for the electron with a mass of $m_e = \frac{1}{\sqrt{2}} g_e \nu$

Reminder: Origin of CKM

- The Yukawa terms for the quarks are

$$\mathcal{L}_{\mathrm{Y}}^{q} = (a_{ij}\bar{q}_{Li}\phi_C u_{Rj} + b_{ij}\bar{q}_{Li}\phi d_{Rj} + \text{h.c.})$$

- where the indices i and j run over the three quark generations. The matrices a_{ij} and b_{ij} are the Yukawa coupling strengths for each generation and,

$$q_{Li} = \begin{pmatrix} u_{Li} \\ d_{Li} \end{pmatrix}, \qquad u_{Ri} = \begin{pmatrix} u_{Ri} \\ 0 \end{pmatrix}, \qquad d_{Ri} = \begin{pmatrix} 0 \\ d_{Ri} \end{pmatrix}$$

- Can again write this in unitary gauge to give mass terms :

$$\mathcal{L}_{\mathrm{Y}}^{q} = -\left(1 + \frac{H}{\nu}\right)\left(\bar{u}_{Li} m_{ij}^{u} u_{Rj} + \bar{d}_{Li} m_{ij}^{d} d_{Rj} + \text{h.c.}\right)$$

- Where,

$$m_{ij}^{u} = -\frac{1}{\sqrt{2}}\nu a_{ij}, \qquad m_{ij}^{d} = -\frac{1}{\sqrt{2}}\nu b_{ij}.$$

Reminder: Origin of CKM

- The matrices $m_{i,j}^{u,d}$ are not in general diagonal. Four separate rotations are required to diagonalise these matrices

$$u_{L\alpha} = (U_L^u)_{\alpha i} u_{Li}, \qquad u_{R\alpha} = (U_R^u)_{\alpha i} u_{Ri},$$

$$d_{L\alpha} = (U_L^d)_{\alpha i} d_{Li}, \qquad d_{R\alpha} = (U_R^d)_{\alpha i} d_{Ri},$$

- where each rotation matrix U is unitary and α runs over the mass eigenstates of the quarks

$$u_\alpha = \{u, c, t\},$$

$$d_\alpha = \{d, s, b\}.$$

- The diagonalised version can then be written

$$m_\alpha^u = (U_L^{u\dagger})_{i\alpha} m_{ij}^u (U_R^u)_{\alpha j},$$

$$m_\alpha^d = (U_L^{d\dagger})_{i\alpha} m_{ij}^d (U_R^d)_{\alpha j},$$

Reminder: Origin of CKM

- Can then write the Lagrangian as,

$$\mathcal{L}_{\mathrm{Y}}^{q} = -\left[\bar{u}_{L\alpha}(U_L^{u\dagger})_{i\alpha} m_{ij}^{u} (U_R^{u})_{\alpha j} u_{R\alpha} + \bar{d}_{L\alpha}(U_L^{d\dagger})_{i\alpha} m_{ij}^{d} (U_R^{d})_{\alpha j} d_{R\alpha} + \mathrm{h.c.}\right]$$

$$= -\left[m_\alpha^u \bar{u}_{L\alpha} u_{R\alpha} + m_\alpha^d \bar{d}_{L\alpha} d_{R\alpha} + \mathrm{h.c.}\right]$$

$$= -\left[m_\alpha^u \bar{u}_{L\alpha} u_{R\alpha} + m_\alpha^u \bar{u}_{R\alpha} u_{L\alpha} + m_\alpha^d \bar{d}_{L\alpha} d_{R\alpha} + m_\alpha^d \bar{d}_{R\alpha} d_{L\alpha}\right]$$

$$= -\left[m_\alpha^u \bar{u}_\alpha u_\alpha + m_\alpha^d \bar{d}_\alpha d_\alpha\right],$$

- where,

$$m_\alpha^u = \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t \end{pmatrix}, \qquad m_\alpha^d = \begin{pmatrix} m_d & 0 & 0 \\ 0 & m_s & 0 \\ 0 & 0 & m_b \end{pmatrix}$$

- To get spectrum of quark masses we observe require,

$$\begin{aligned} a_u &= 2\times 10^{-5}, & b_d &= 4\times 10^{-5}, \\ a_c &= 9\times 10^{-3}, & b_s &= 8\times 10^{-4}, \\ a_t &= 1, & b_b &= 3\times 10^{-2}. \end{aligned}$$

No explanation for wide range of Yukawa coupling strengths in the SM

Reminder: Origin of CKM

- The rotation matrices U also appear in the weak interactions of quarks. The interaction Lagrangian for charged-current quark interactions in the generation basis is

$$\mathcal{L}_{\mathrm{CC}} = \frac{ig_2}{\sqrt{2}} \left[W^+_\mu \bar{u}_{Lj} \gamma^\mu d_{Lj} + W^-_\mu \bar{d}_{Lj} \gamma^\mu u_{Lj}\right]$$

Weak eigenstates — Strong eigenstates

$$\begin{pmatrix} d_{L1} \\ d_{L2} \\ d_{L3} \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d_{L\alpha=d} \\ d_{L\alpha=s} \\ d_{L\alpha=b} \end{pmatrix}$$

- In the mass basis this is

$$\mathcal{L}_{\mathrm{CC}} = \frac{ig_2}{\sqrt{2}} \left[W^+_\mu \bar{u}_{L\alpha} \left[(U^u_L)_{\alpha j} (U^{d\dagger}_L)_{j\beta}\right] \gamma^\mu d_{L\beta} + W^-_\mu \bar{d}_{L\alpha} \left[(U^d_L)_{\alpha j} (U^{u\dagger}_L)_{j\beta}\right] \gamma^\mu u_{L\beta}\right],$$

- where,

$$V_{\alpha\beta} \equiv \left[U^u_L U^{d\dagger}_L\right]_{\alpha\beta},$$

- is the CKM matrix → difference between the rotations required to diagonalise the up and down quark mass matrices, or equivalently the mis-alignment of the up- and down-quark mass bases

Origin of CKM: Summary

- Fermion masses arise from the Yukawa couplings of the quarks and charged leptons to the Higgs field

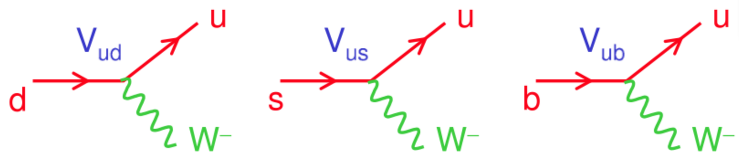
- The CKM matrix arises from the relative misalignment of the Yukawa matrices for the up- and down-type quarks

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

weak eigenstates — CKM matrix — strong eigenstates

(Cabibbo, Kobayashi, Maskawa)

i.e. the weak $W^{\pm}$ vertices contain factors,



  - 3x3 complex unitary matrix, described by 9 parameters
    - 5 can be absorbed as phase differences between the quark fields
    - 3 can be expressed as (Euler) mixing angles
    - 1 remaining parameter makes the CKM matrix complex (i.e. gives it a phase)

→ weak interaction couplings differ for quarks and antiquarks

→ CP violation

Origin of CKM: Summary

- It follows that only flavour-changing interactions are the charged current weak interactions
  - no flavour-changing neutral currents
  - flavour-changing processes provide sensitive tests of consistency and structure of SM

- Note
  - The V_{ij} are complex constants, not predicted by SM
  - In SM, this is all there is – matrix is unitary – may not be the case in new physics theories
  - Observation of CPV in 1964 implied there existed at least three generations at time we didn't know there were two!

CKM parameterisations

- **PDG parameterisation** : 3 mixing angles and 1 phase, δ

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

  – apparent hierarchy: $s_{12} \sim 0.2$, $s_{23} \sim 0.04$, $s_{13} \sim 0.004$

- **Wolfenstein parameterisation** : expansion parameter $\boldsymbol{\lambda \sim \sin\theta_c}$

$$= \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

  – the phase of $(\rho+i\eta)$ is what gives CPV in SM
  – parameters are now quite well measured:
    - $\lambda = 0.2254 \pm 0.0007$ $\quad\rho = 0.130 \pm 0.024$
    - $A = 0.822 \pm 0.012$ $\quad\eta = 0.362 \pm 0.014$

CKM Hierarchy

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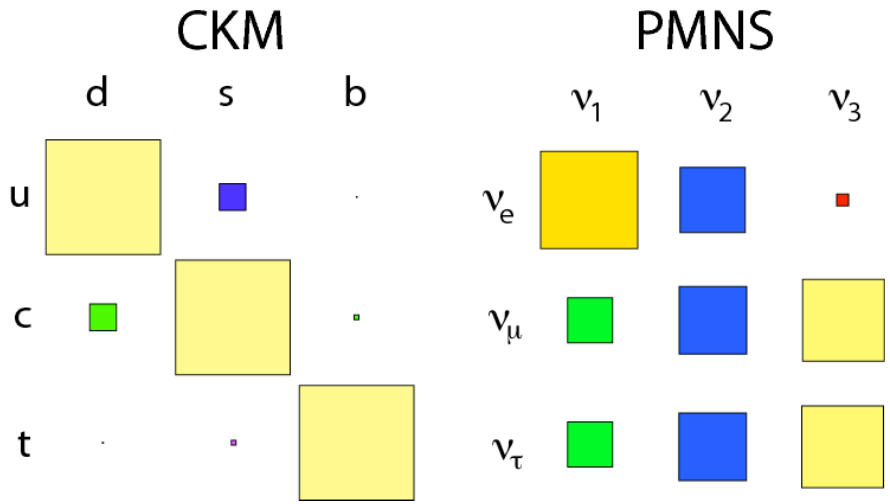
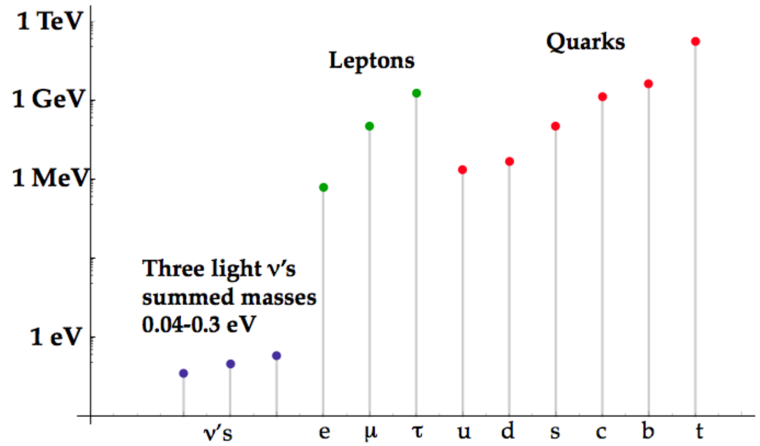
  – Hierarchy in the quark mixing has a suggestive pattern … but no known reason for this

(CKM vs PMNS) and masses

- CKM and PMNS are both cornerstones of our understanding of particle physics…





- … but we do not understand the relative sizes of the values, or the relationship between quarks and neutrinos

- Pattern of masses is similarly mysterious, spanning 12 orders of magnitude

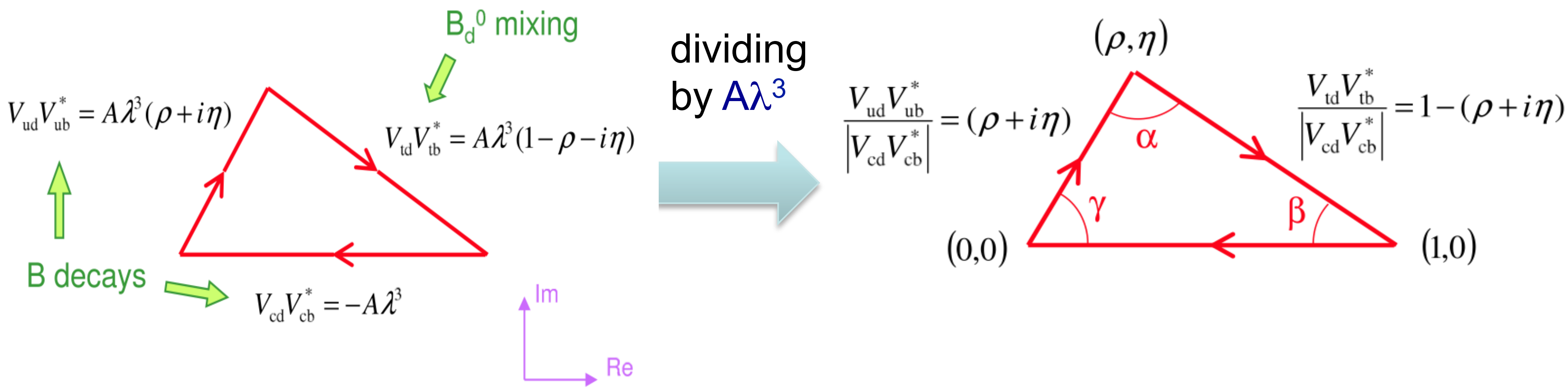
The Unitarity Triangle

- Unitarity of CKM matrix gives

$$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$

(plus five other similar relationships)

- Can represent this in the complex plane as the unitarity triangle (UT)



Experimental Constraints on UT

- B_d^0 mixing:

  $$\Delta m_d \propto |V_{td} V_{tb}^*|^2$$

  $$|V_{td} V_{tb}^*| / A\lambda^3 = \sqrt{(1-\rho)^2 + \eta^2}$$

  $\rightarrow$ A measurement of Δm_d fixes the radius of a circle centred on (1,0)

- B_s^0 mixing:

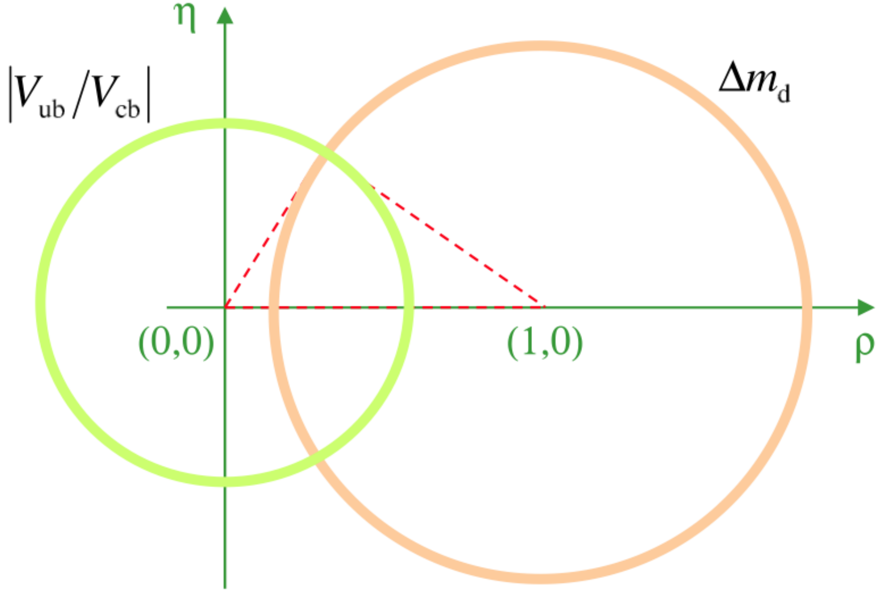
  $$\Delta m_s \propto |V_{td} V_{ts}^*|^2$$

- $\rightarrow$ A measurement of Δm_s gives similar constraint

- $b \rightarrow u$ decays:

  $$|V_{ub}| / |V_{cb}| = \lambda\sqrt{\rho^2 + \eta^2}$$

  $\rightarrow$ A measurement of BR($b \rightarrow u$) fixes the radius of a circle centred on (0,0)



Experimental Constraints on UT

- K^0-$\overline{K}^0$ mixing

  $$|\varepsilon| \propto \eta(1-\rho+const.)$$

  → A measurement of $|\varepsilon|$ determines a hyperbola in the (ρ,η) plane

- B_d^0-$\overline{B}_d^0$ mixing

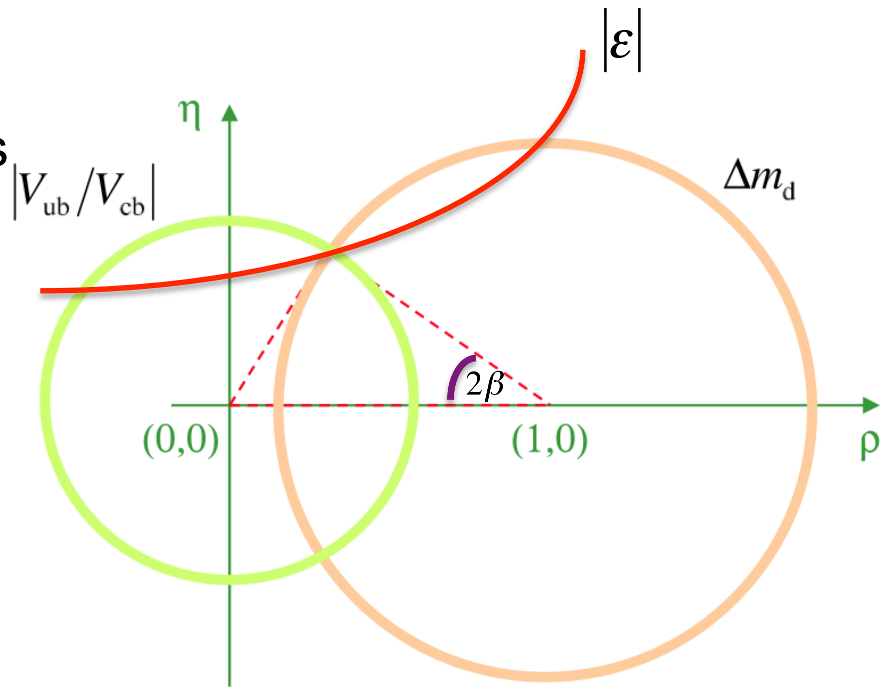
  $$A_{\psi K_{S,L}} \equiv \frac{\Gamma(\overline{B}^0_{t=0} \to \psi K_{S,L}) - \Gamma(B^0_{t=0} \to \psi K_{S,L})}{\Gamma(\overline{B}^0_{t=0} \to \psi K_{S,L}) + \Gamma(B^0_{t=0} \to \psi K_{S,L})}$$

  $$= +\sin 2\beta \sin \Delta m_d t \quad (K_S) \quad CP(\psi K_S) = -1$$

  $$= -\sin 2\beta \sin \Delta m_d t \quad (K_L) \quad CP(\psi K_L) = +1$$

  → A measurement of $A_{\psi K_{S,L}}$ determines the angle 2β

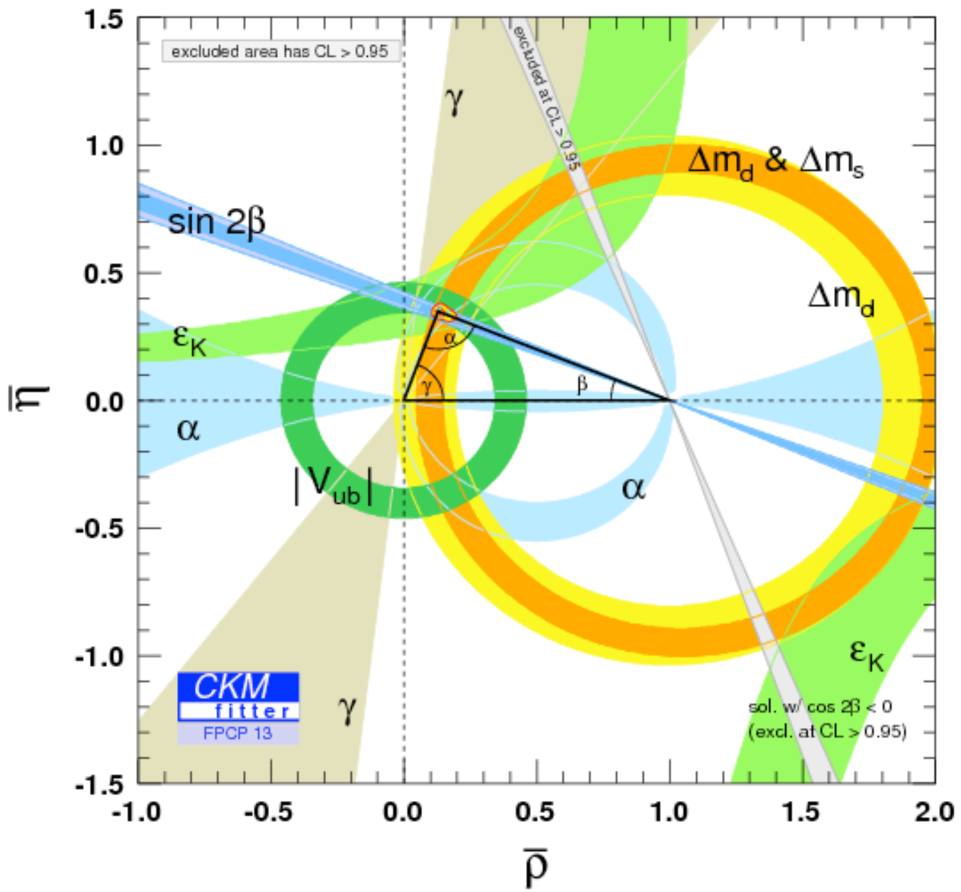
  – CPV observed for first time outside of K^0 system using B^0 ($\overline{B}^0$)→$J/\psi K_{S,L}$ decays



Status of the UT

- CKM is certainly the dominant mechanism at work

  → 2008 Nobel Prize for Kobayashi and Maskawa (but not Cabibbo!)



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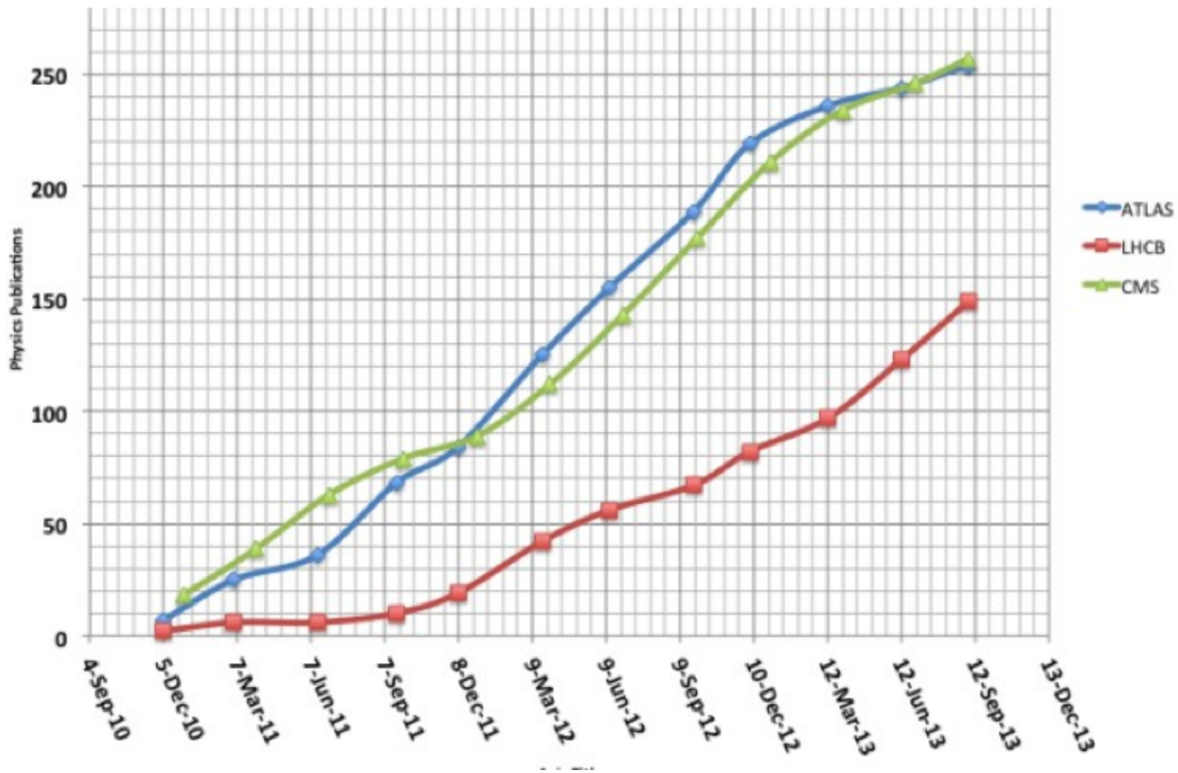
LHCb Results

- Majority of results from $1fb^{-1}$ data taken in 2011, have further $2fb^{-1}$ in-hand from 2012 data-taking



Time-integrated CPV in $B \rightarrow K^+\pi^-$

[PRL110(2013)221601]

- Measure time-integrated CPV in $B \rightarrow K^+\pi^-$ decays (both tree and penguin contributions) :

  $A_{CP}(B_d^0 \rightarrow K^+\pi^-) = -0.080 \pm 0.007 \pm 0.003$ [world's best]

  $A_{CP}(B_s^0 \rightarrow K^-\pi^+) = +0.27 \pm 0.04 \pm 0.01$ [world's first 5σ observation of CPV in B_s^0 system]

  - Det. asymm — $D^* \rightarrow D(K\pi/KK)\,\pi$
  - Prod. asymm — time-dep study

- Exploit approx. flavour symmetry to cancel unknown theory parameters and hadronic uncert.

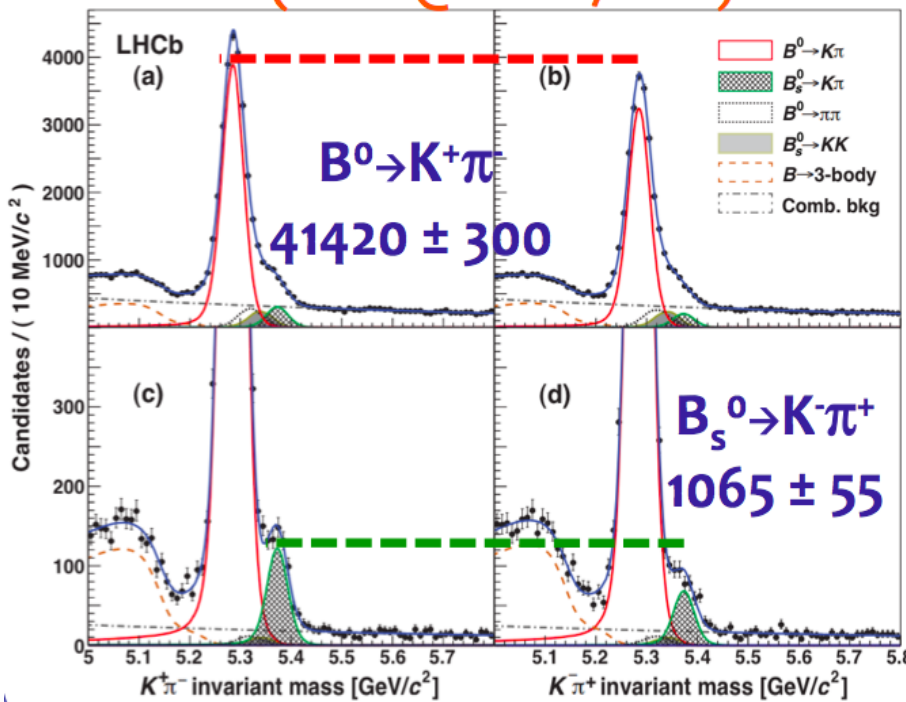
- SM predicts

$$\Delta = \frac{A_{CP}(B^0 \rightarrow K^+\pi^-)}{A_{CP}(B_s \rightarrow K^-\pi^+)} + \frac{BR(B_s \rightarrow K^-\pi^+)}{BR(B^0 \rightarrow K^+\pi^-)}\frac{\tau_d}{\tau_s} = 0$$

- LHCb measurement :

  $\Delta = -0.02 \pm 0.05 \pm 0.04$

$\mathcal{L}$ =(1 fb^{-1} @ $\sqrt{s}$ = 7 TeV)



Time-dependent CPV in $B_d^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$

- Measure asymmetry,

$$\mathcal{A}(t) = \frac{-C_f \cos(\Delta m_{d(s)} t) + S_f \sin(\Delta m_{d(s)} t)}{\cosh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right) - A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right)}$$

C_f → direct CP violation

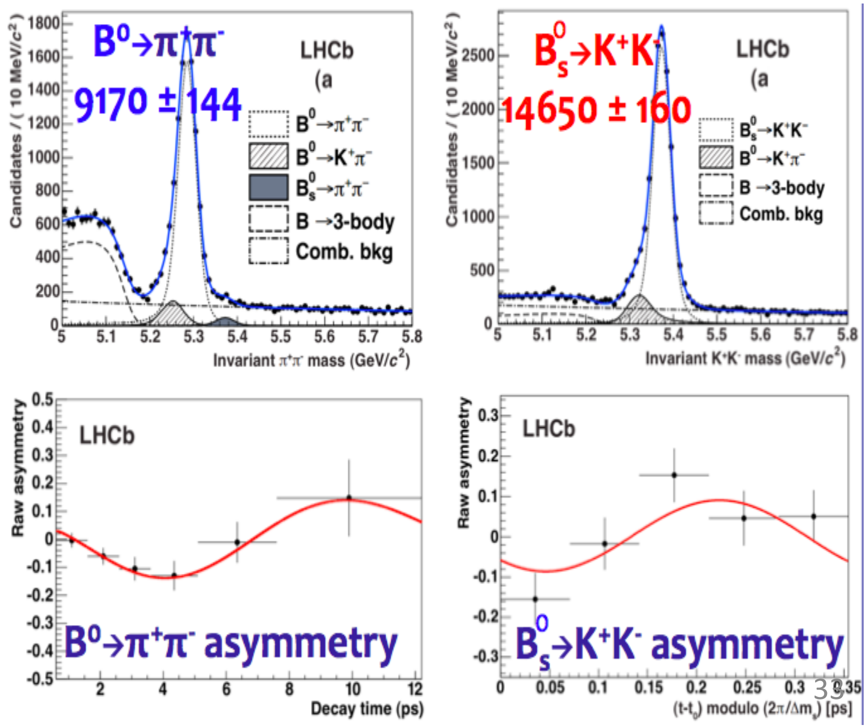
S_f → mixing-induced CP violation

[JHEP 10 (2013) 183]

- For B_d^0 decays
  – $C_{\pi+\pi-}$ = -0.38 ± 0.15 ± 0.02
  – $S_{\pi+\pi-}$ = -0.71 ± 0.13 ± 0.02
- [compatible with prev. B-factory results]

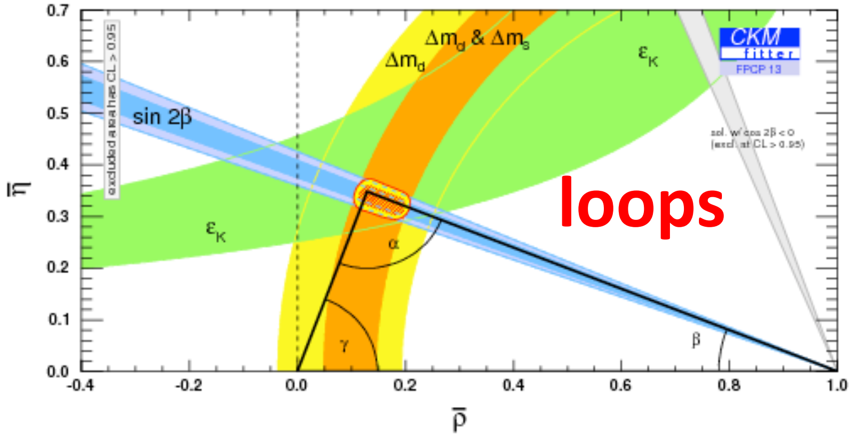
- For B_s^0 decays
  – C_{K+K-} = 0.14 ± 0.11 ± 0.03
  – S_{K+K-} = 0.30 ± 0.12 ± 0.04

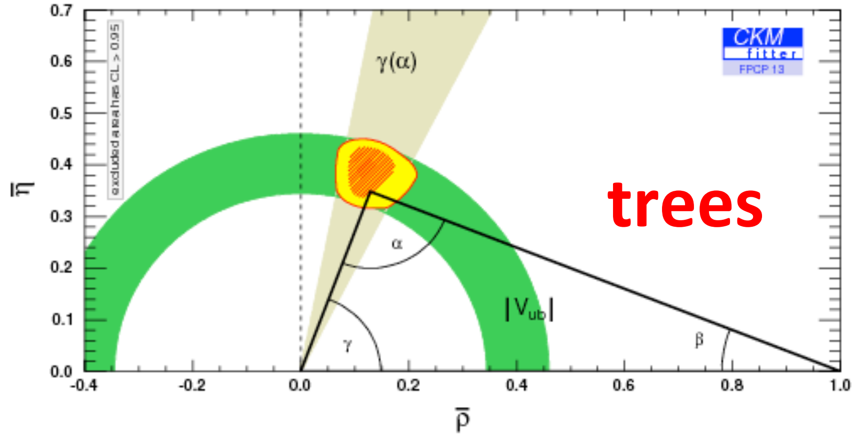
[world's first, 2.7σ from 0,0]



CKM angle γ

- Progress in comparison of tree and loop level constraints needs improved knowledge of angle γ
  - Before LHCb data-taking direct knowledge at 12^o level
  - Indirectly (i.e. NP sensitive) determination at the ~3^o level



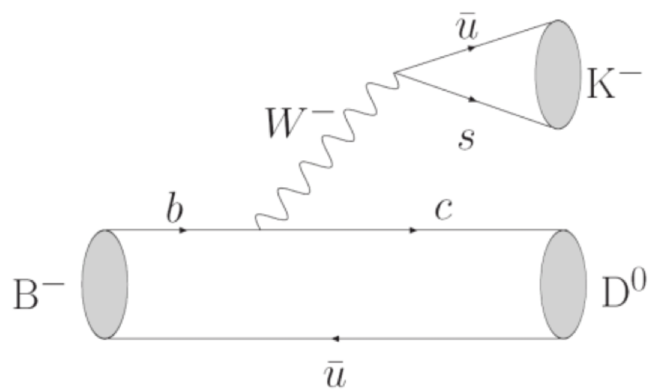


- LHCb results from a wide range of modes :
  - $B \to Dh$, $D \to \pi K$ [ADS] [PLB 712 (2012) 203, 1fb^{-1}]
  - $B \to Dh$, $D \to KK$, $D \to \pi\pi$ [GLW] [PLB 712 (2012) 203, 1fb^{-1}]
  - $B \to Dh$, $D \to K3\pi$ [K3π] [PLB 723 (2013) 44, 1fb^{-1}]
  - $B \to DK$, $D \to K_S^0\pi\pi$ [GGSZ] [LHCb-CONF-2013-004, 2fb^{-1}]

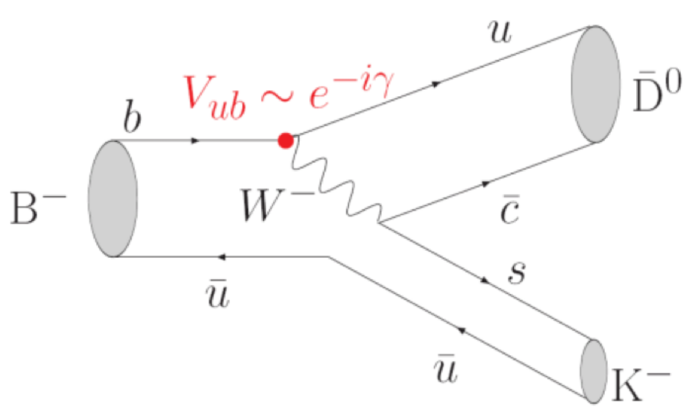
γ measurements

- γ measured in $B^{\pm}\rightarrow DK^{\pm}$ decays using common mode for D^0 and $\bar{D}^0$
  → γ sensitive interference
  → different rates for B^+ & B^- (CPV!)

Favoured



Suppressed

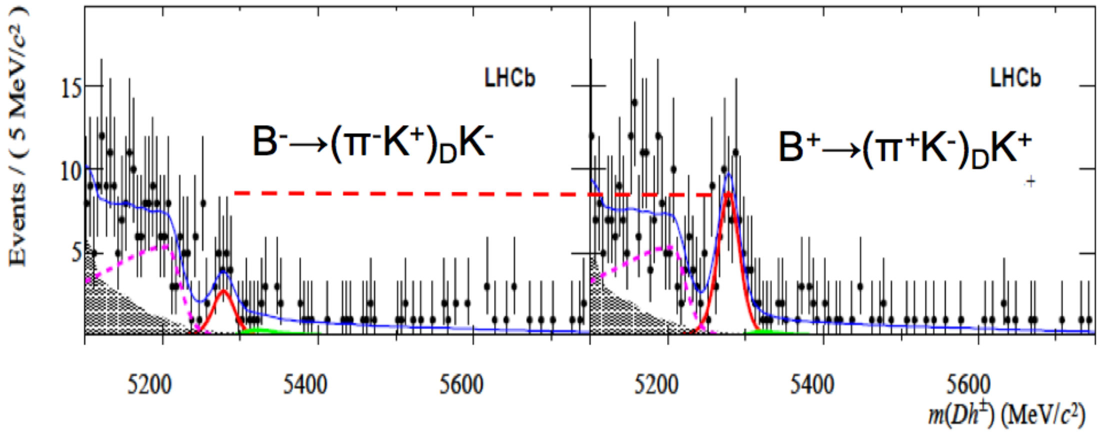


- Wide range of possible decay modes: Kπ, Kππ etc.
- Tree-level decays: strategy clean and insensitive to NP
- Provides SM benchmark against which other loop-driven NP sensitive observables can be compared (e.g. $\Delta m_d/\Delta m_s$, sin2β, γ measured in $B\rightarrow hh$)

γ in tree decays – ADS

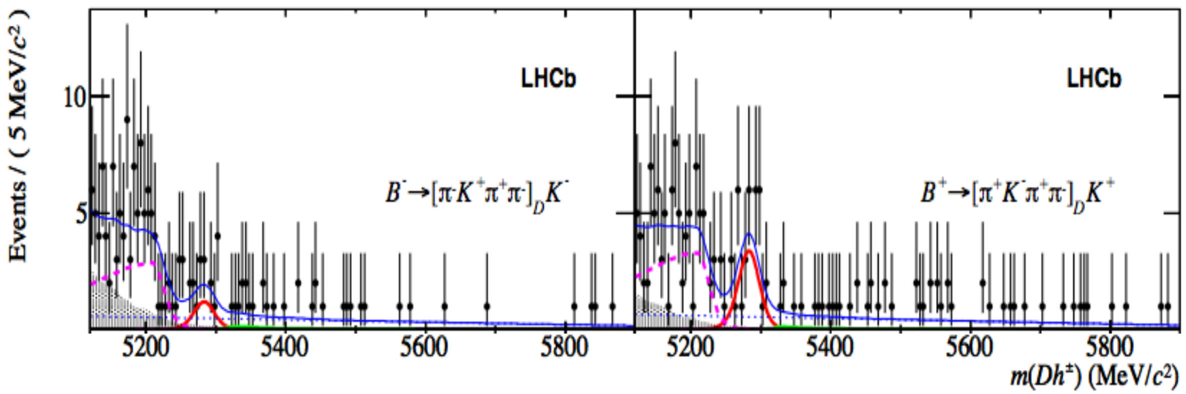
- Discovery of 'suppressed ADS' mode
  - Visible BF ~10^{-7} , large CP asymmetry gives *clean* information on γ

[PLB 712 (2012) 203]



  - Analogous method used to isolate $B^{\pm}\rightarrow(K\pi\pi\pi)_D K^{\pm}$, provides orthogonal information rather than just statistics

[PLB 723 (2013) 44]



γ in tree decays – GGSZ

[LHCb-CONF-2013-004]

- Model independent Dalitz plot analysis of $B^{\pm} \rightarrow DK^{\pm}$ with $D \rightarrow K_S^0 h^+ h^-$ ($h = \pi, K$)
  - Strong phase of D^0 decay varies across Dalitz plot – take from CLEO measurements of DD *pairs from* $\Psi(3770)$ [PRD 82 (2010) 112006]
  - Measure,

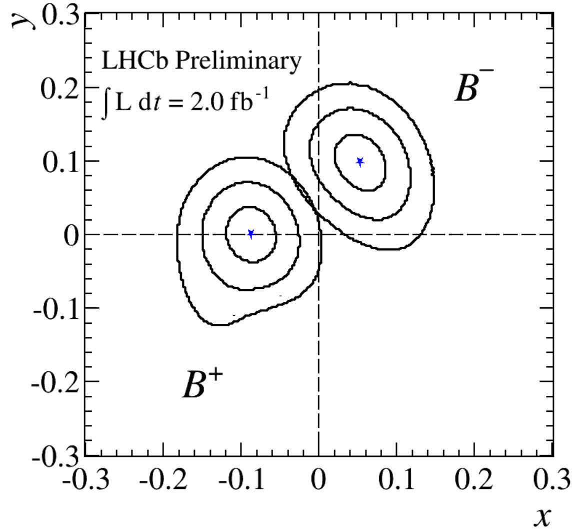
    $x_{\pm} = r_B \cos(\delta_B \pm \gamma)$

    $y_{\pm} = r_B \sin(\delta_B \pm \gamma)$
  - **3fb^{-1}** results:

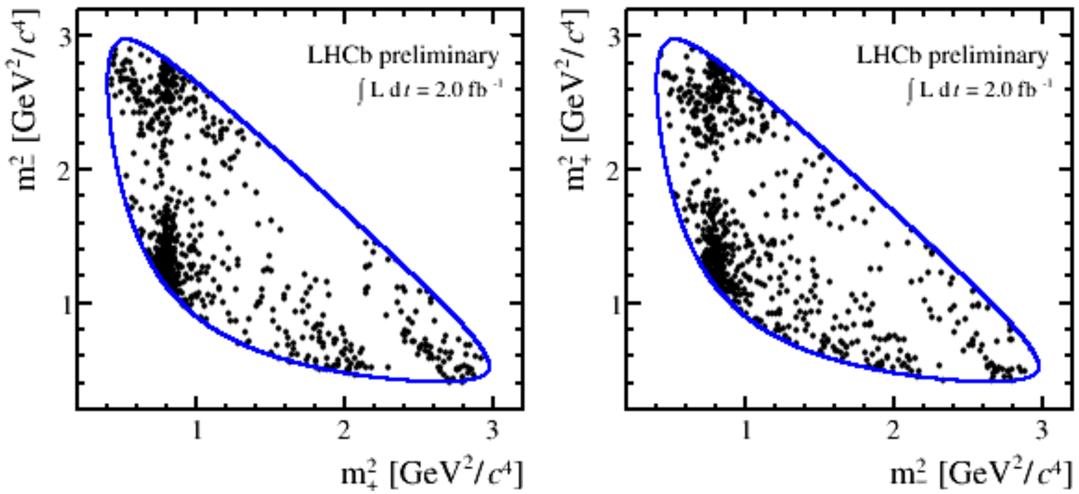
    $\gamma = (57 \pm 16)°$

    $r_B = (8.8^{+2.3}_{-2.4}) \times 10^{-2}$

    $\delta_B = (124^{+15}_{-17})°$



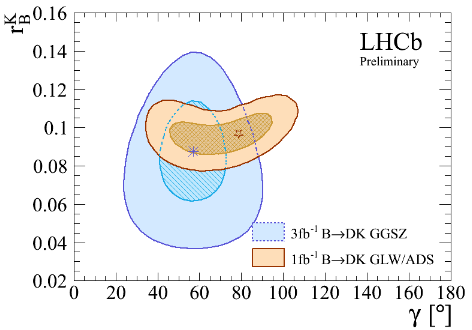
$B^{\pm} \rightarrow DK^{\pm}$ with $D \rightarrow K_S^0 \pi^+ \pi^-$

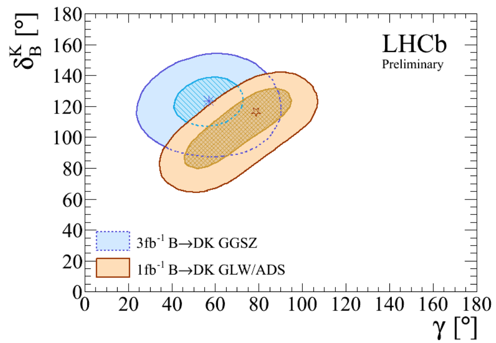


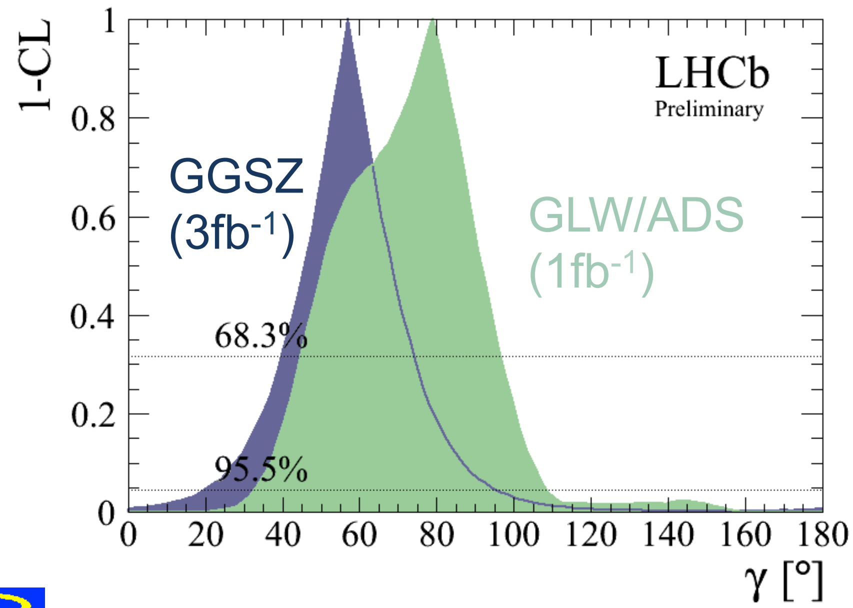
γ in tree decays – combination

[LHCb-CONF-2013-006]

- Channels combined to give overall LHCb result for γ







$\gamma = (67 \pm 12)^\circ$

$r_B = (9.2 \pm 0.8) \times 10^{-2}$

$\delta_B = (114^{+12}_{-13})^\circ$

cf. $(68^{+15}_{-14})^\circ$ [arXiv:1301.2033]

$(69^{+17}_{-16})^\circ$ [PRD 87 (2013) 052015]

predictions: $(70.3 \pm 3.5)^\circ$ [UTFit]

$(69.7^{+1.3}_{-2.8})^\circ$ [CKMFitter]

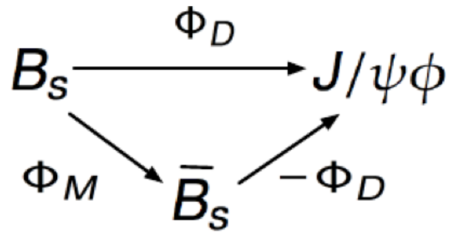
→ Very good agreement between direct measurements and fit

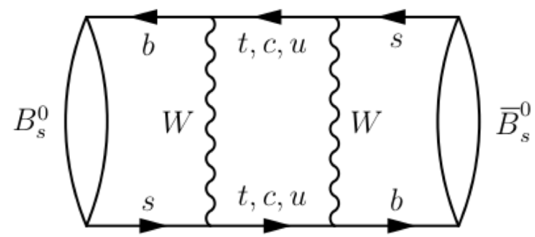
- $3fb^{-1}$ updates to ADS/GLW methods will improve precision further

Mixing induced CPV in B_s^0 system

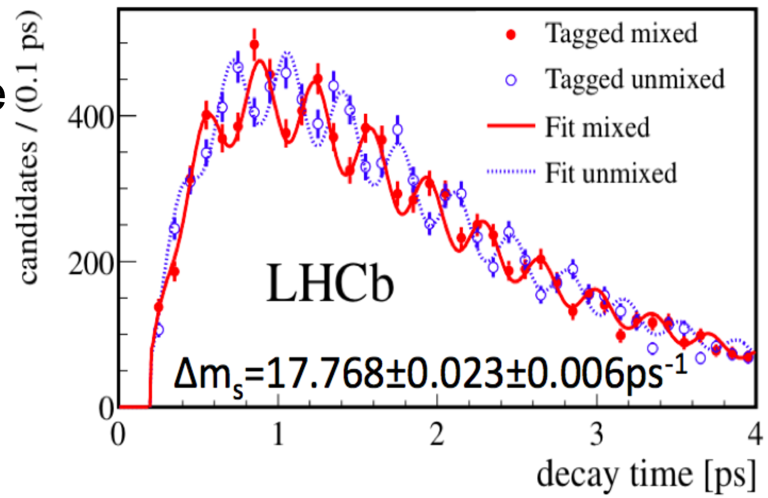
- Interference between *decay* or *mixing and then decay* results in CP-violating phase:
  - $\phi_S = \phi_M - 2\phi_D$

  can be precisely predicted in SM, new physics could change phase
- Mass eigenstates ≠ weak eigenstates: system described by: m, Γ, $\Delta\Gamma_s$, Δm_s, ϕ_S
  - CPV modulated by high Δm_s
- $J/\psi\phi(K^+K^-)$ decays – high BF, mixture CP-even/odd → angular analysis to disentangle
- $J/\psi f_0(\pi^+\pi^-)$ decays – smaller yield but pure CP-odd
- $m(K^+K^-)$ dependence allows to resolve two-fold ambiguity [PRL 108 (2012) 241801]
- S-wave contribution : 4±2%

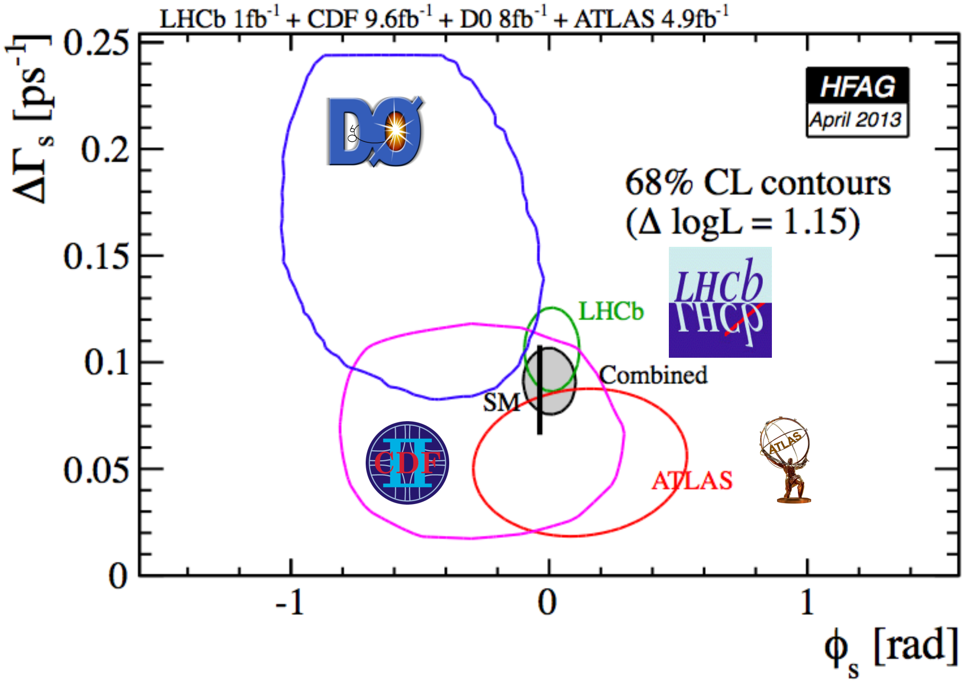




[New J Phys 15 (2013) 053021]



Mixing induced CPV in B_s^0 system



	CDF	D0	LHCb	ATLAS	CMS*)
$\int \mathcal{L}$ [fb^{-1}]	9.6	8.0	1.0	4.9	5.0
# $B_s \to J/\psi KK(f_0)$	11k	5.6k	27.6k (7.4k)	22.7k	14.5k
ϵD^2 OS [%]	1.39 ± 0.05	2.48 ± 0.22	2.29±0.22	1.45±0.05	-
ϵD^2 SS [%]	3.5±1.4	-	0.89±0.18	-	-
σ_t [fs]	100	100	48	100	-
Reference	PRL 109(2012) 171802	PRD85(2012) 032006	PRD87(2013) 112010	ATLAS-CONF-2013.029	CMS-PAS BPH-11-006

* CMS: $\Delta\Gamma$ only: 0.048±0.024±0.003 ps^{-1}

Time dependent analysis of $B_s^0 \to \phi\phi$

[PRL 110 (2013) 241802]

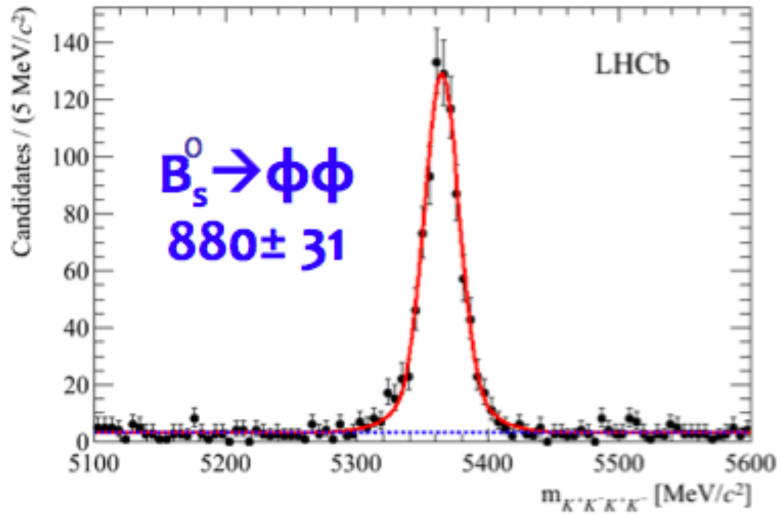
- $B_s^0 \to \phi\phi$ only proceeds via a (gluonic) penguin process

- SM predicts small CP-violating phase **<0.02 rad**

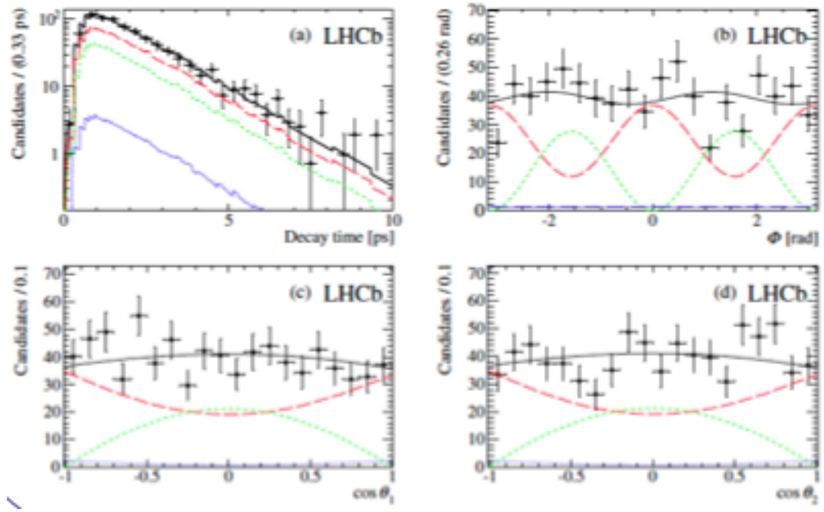
- LHCb analysis gives,

  $-2.46 < \phi_s^{\phi\phi} < -0.76$ rad at 68% C.L.

- Systematics at 0.22 rad level with largest contribution from s-wave contribution



$\mathcal{L}$ = (1 fb^{-1} @ $\sqrt{s}$ = 7 TeV)



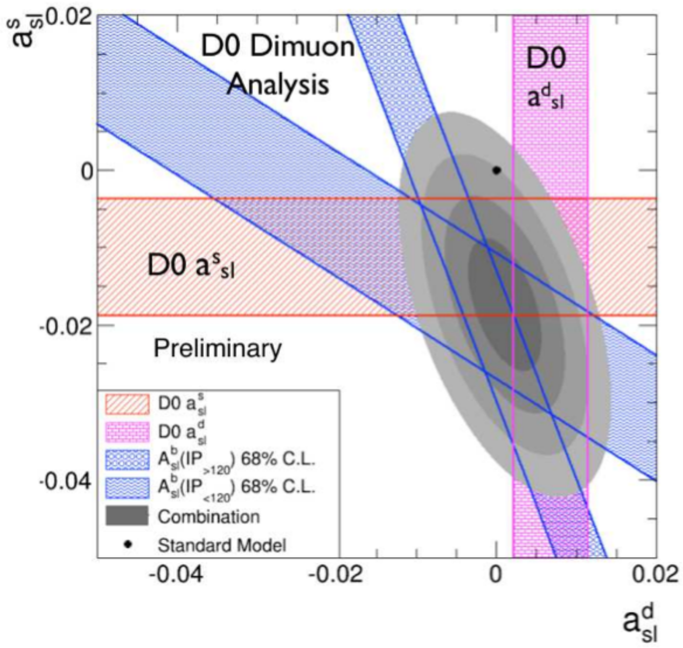
Semileptonic asymmetries

- Another way of probing mixing - semileptonic asymmetries :

$$a^s_{sl} \propto \frac{N(\mu^+ D_s^{(*)-}) - N(\mu^- D_s^{(*)+})}{N(\mu^+ D_s^{(*)-}) + N(\mu^- D_s^{(*)+})}$$

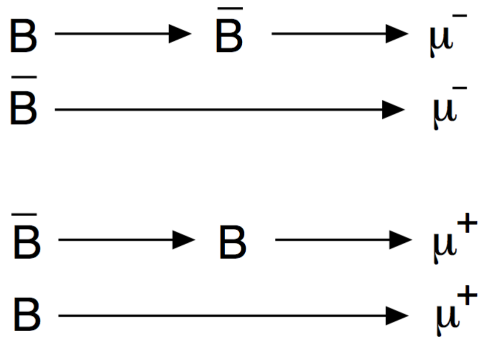
$$a^d_{sl} \propto \frac{N(\mu^+ D^{(*)-}) - N(\mu^- D^{(*)+})}{N(\mu^+ D^{(*)-}) + N(\mu^- D^{(*)+})}$$

sensitive probes of NP as expected to be small in SM ($\sim 10^{-5}$ (10^{-4}) for B^0_s (B^0))



- D0 experiment measured dimuon asymmetry :

$$A = \frac{N(\mu^+\mu^+) - N(\mu^-\mu^-)}{N(\mu^+\mu^+) + N(\mu^-\mu^-)}$$



A_{CP} = (-0.276 ± 0.067 ± 0.063)% (9.0 fb^{-1})

3.9σ ≡ 0.33% compatible with SM

Semileptonic asymmetries

- At LHC, collide pp → production asymmetry
  - Measurements sensitive to production and detection asymmetries

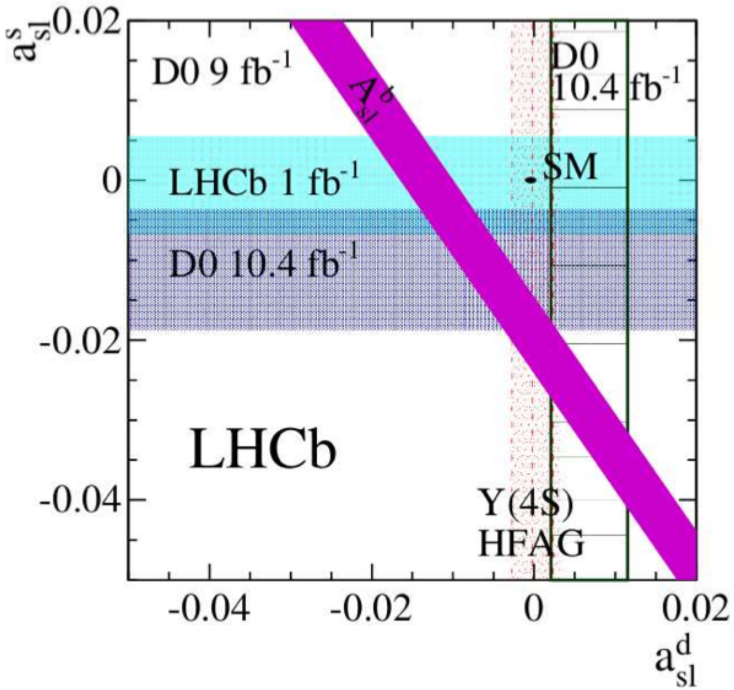
$$A_{meas} = \frac{N(D_q^- \mu^+) - N(D_q^+ \mu^-)}{N(D_q^- \mu^+) + N(D_q^+ \mu^-)} = \frac{a_{sl}^q}{2} + \left[a_{prod} - \frac{a_{sl}^q}{2}\right]\kappa_q$$

  - fast B_s^0 oscillations → time integrated a_{sl}^s measurement possible (κ_s=0.2%)
  - slow B_d^0 oscillations → time dependent analysis required to get a_{sl}^d (κ_d=30%)

- LHCb measurement of a_{sl}^s with 1fb^{-1}
  - a_{sl}^s = (-0.06 ± 0.50 ± 0.36)%

    [arXiv:1308.1048]
  - This result and B-factory average for a_{sl}^d in good agreement with SM

- LHCb has demonstrated ability to reconstruct semileptonic states



Outline

- Why study B physics?
- Introduction to the LHCb experiment
- Status of LHCb measurements
  - CKM measurements
  - **Rare decays measurements**
- Flavour Problem
- Light at the end of the tunnel?

Why should we study rare decays?

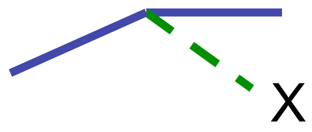
- Main thing of interest for probing NP: loops/trees
  - NP unlikely to affect decays at tree level
  - Loop decays involve second order (→ suppressed, *potentially* “rare”) diagrams in which new, *virtual* particles can contribute

- Most interesting processes those where there is no tree contribution (and/or the SM process is suppressed) → any anomaly is from NP
  - e.g. Flavour Changing Neutral Currents – forbidden at tree level in SM

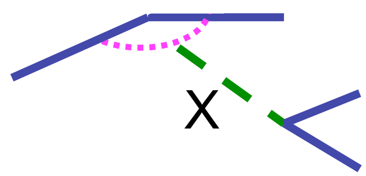
    → FCNC processes necessarily involve loops
  - Loops can involve (virtual) NP particles!

    → Can probe masses > CM energy of accelerator

Tree-level decay

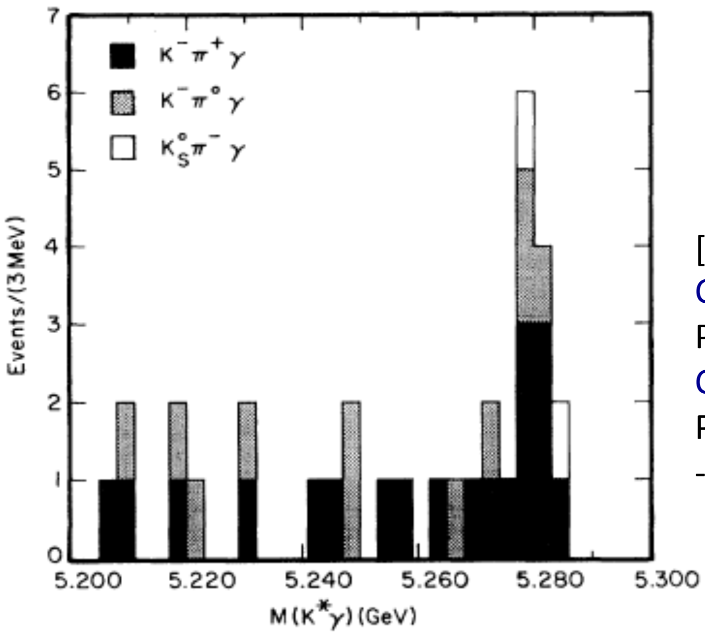


Loop decay

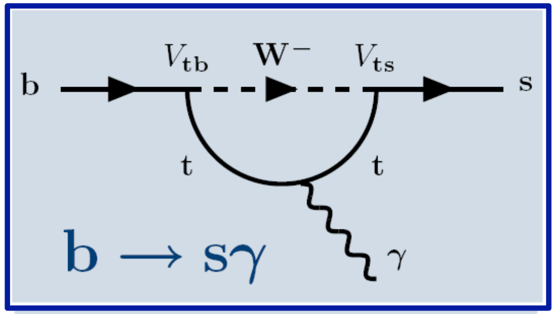


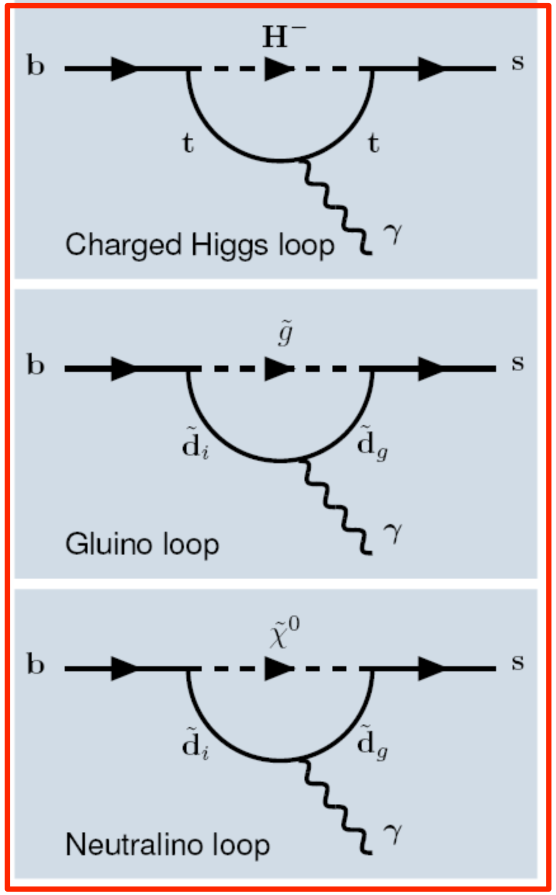
A historical example – $B_d^0 \rightarrow K^{*0}\gamma$

- In SM: occurs through a dominating W-t loop
- Possible NP diagrams:
- Observed by CLEO in 1993, two years before the direct observation of the top quark
  - BR was expected to be $(2\text{-}4)\times10^{-4}$
  - $\rightarrow$ measured BR = $(4.5\pm1.7)\times10^{-4}$



[Phys.Rev.Lett. 71 (1993) 674 - Cited by 605 records
Phys.Rev.Lett. 74 (1995) 2885 - Cited by 836 records
Phys.Rev.Lett. 87 (2001) 251807 - Cited by 565 records]





Theoretical Framework

The Operator Product Expansion

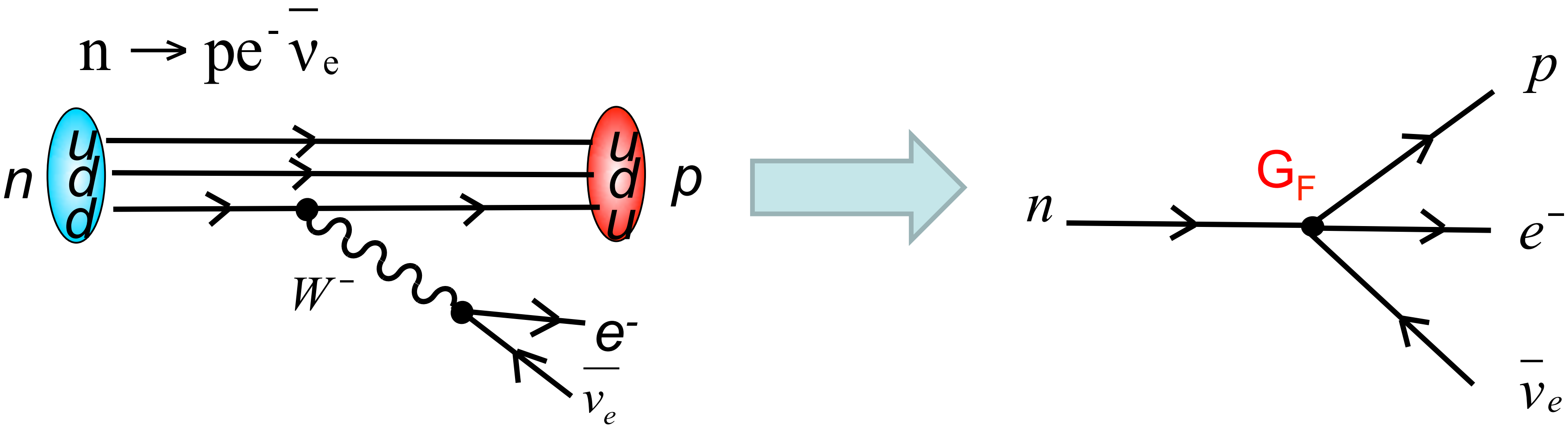
- Make an *effective theory* which gives us *model independent things to measure*
  - Rewrite (part of) SM Lagrangian as:

$$\mathcal{L} = \sum_i C_i O_i$$

  - "Wilson Coefficients" C_i
    - Describe the short distance part, can compute perturbatively in given theory
    - Integrate out the heavy degrees of freedom that can't resolve at some energy scale $\mu \rightarrow$ Wilson coefficient just a (complex) number
    - All degrees of freedom with mass>μ are taken into account by the Wilson Coefficients, while those with mass<μ go into the operators ...
  - "Operators" O_i
    - Describe the long distance, non-perturbative part involving particles below the scale μ
    - Form a complete basis – can put in all operators from NP/SM
    - Account for effects of strong interactions and are *difficult to calculate reliably*

The Operator Product Expansion

- Most familiar example of this Fermi's theory of beta decays
  - Z and W are very massive – the weak interactions take place at very short distance scales $O(1/M_W^2)$
  - Construct effective theory where integrated out → four-particle coupling



- For $q^2 \ll m_W^2$ can replace W propagator: $\frac{1}{q^2 - M_W^2} \rightarrow \frac{1}{-M_W^2}$
- Effectively absorbs the contribution from the W into the factor G_F, in the limit when W is too heavy to be resolved

The Operator Product Expansion

- Key point:
  - In *certain* rare decays can measure observables (BFs, angular distributions, oscillation frequencies, phases …), typically involving ratio of quantities, where the uncertainties on the operators cancel out – then (to some greater or lesser extent…) we are free from theoretical problems and measuring the Wilson Coefficients tells us about the heavy degrees of freedom – *independent of model*

- Why bother with all this?
  - If some NP particle contributes to the loop it can change the Wilson coefficient. If we can measure the Wilson coefficient we have a very powerful way of identifying deviation from SM
  - Again, because loop process, NP particle can be *virtual* – not limited by E_{CM} of accelerator

Wilson Coefficients

- Can be computed perturbatively in SM and in many NP models

- If we were able to calculate the full perturbative series then the dependence of our Hamiltonian on μ would fall out... this is never the case in practice and the residual scale dependence introduces some theoretical error

- For β decays $\mu \sim m_W$

- For K decays $\mu \sim 1$ GeV (below the c-quark mass)
  - info. about diagrams with a c-quark or some NP particle that is heavier than 1 GeV is in the Wilson Coefficient

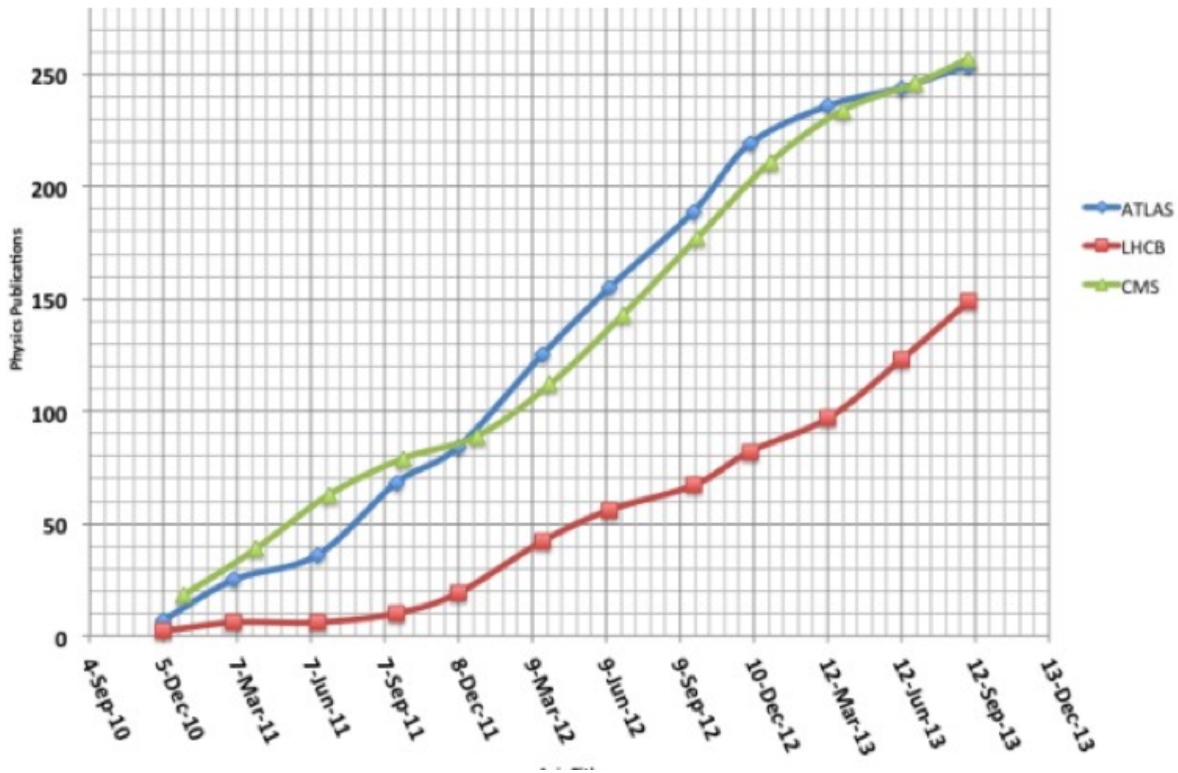
- For B decays $\mu \sim m_b$ (above the c-quark mass)
  - info. about diagrams with a top quark or some NP particle that is heavier than b-quark is in the Wilson Coefficient

How do we get information from rare decays?

- We use the Operator Product Expansion:
  - New particles at masses above scale μ only contribute to the Wilson Coefficients
  - If we measure those Wilson Coefficients we can see if there's other (virtual) non-SM contribution in the loop processes [or if the SM particles couple in some non-SM way]
  - In a whole range of NP models the Wilson Coefficient could be computed perturbatively, hence you could check experiment against prediction of a given theory
  - Complication: the non-perturbative bit involving the operator e.g. $\langle F|Q_i|K\rangle$ has to be computed and this can have a large theory uncertainty
  - Therefore focus on processes where, for one reason or another, the theory uncertainty on this part is small or cancels... hence observables often involve ratios

LHCb Results

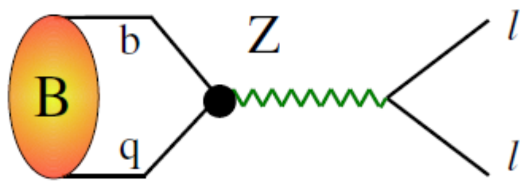
- Majority of results from $1fb^{-1}$ data taken in 2011, have further $2fb^{-1}$ in-hand from 2012 data-taking

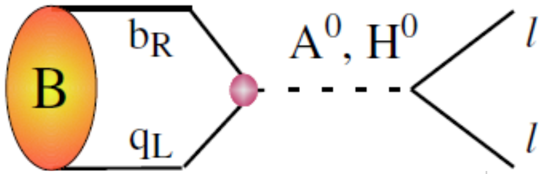


$B_s^0 \to \mu^+\mu^-$ – Physics Interest

- Both helicity suppressed and GIM suppressed
  - In the SM,
    - dominant contribution from Z-penguin diagram (box-diagram suppressed by a factor $(M_W/m_t)^2$)
    - $B(B_s^0 \to \mu\mu) = (3.2 \pm 0.2) \times 10^{-9}$ [precision!]
    - $B(B_d^0 \to \mu\mu) = (1.0 \pm 0.1) \times 10^{-10}$

[*Buras et al., arXiv:1007.5291*]



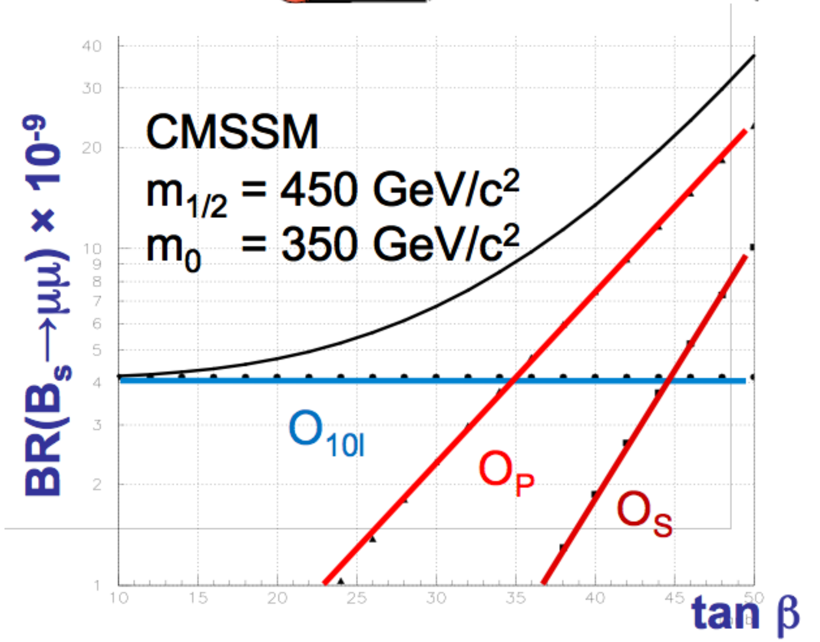


  - In NP models,
    - New scalar (O_S) or pseudoscalar (O_P) interactions can modify BR

    e.g. in MSSM, extended Higgs sector gives BR that scales with $\tan^6 \beta / M_{A^0}^4$

    [β is the ratio of Higgs vacuum expectation values]

→ Extremely sensitive probe of NP!



Experimental Status – 25 yrs ago

DEUTSCHES ELEKTRONEN - SYNCHROTRON **DESY**

DESY 87-111
September 1987

B MESON DECAYS INTO CHARMONIUM STATES

ABSTRACT. Using the ARGUS detector at the e^+e^- storage ring DORIS II, we have studied the colour–suppressed decays $B \to J/\psi\ X$ and $B \to \psi'\ X$. We find the inclusive branching ratios for these two channels to be $(1.07 \pm 0.16 \pm 0.19)\%$ and $(0.46 \pm 0.17 \pm 0.11)\%$ respectively. From a sample of reconstructed exclusive events the masses of the B^0 and B^+ mesons are determined to be $(5279.5 \pm 1.6 \pm 3.0)\ MeV/c^2$ and $(5278.5 \pm 1.8 \pm 3.0)\ MeV/c^2$ respectively. Branching ratios are determined from five events of the type $B^0 \to J/\psi\ K^{*0}$ and three of $B^+ \to J/\psi\ K^+$. In the same data sample a search for $B^0 \to e^+e^-$, $\mu^+\mu^-$ and $\mu^\pm e^\mp$ leads to upper limits for such decays.

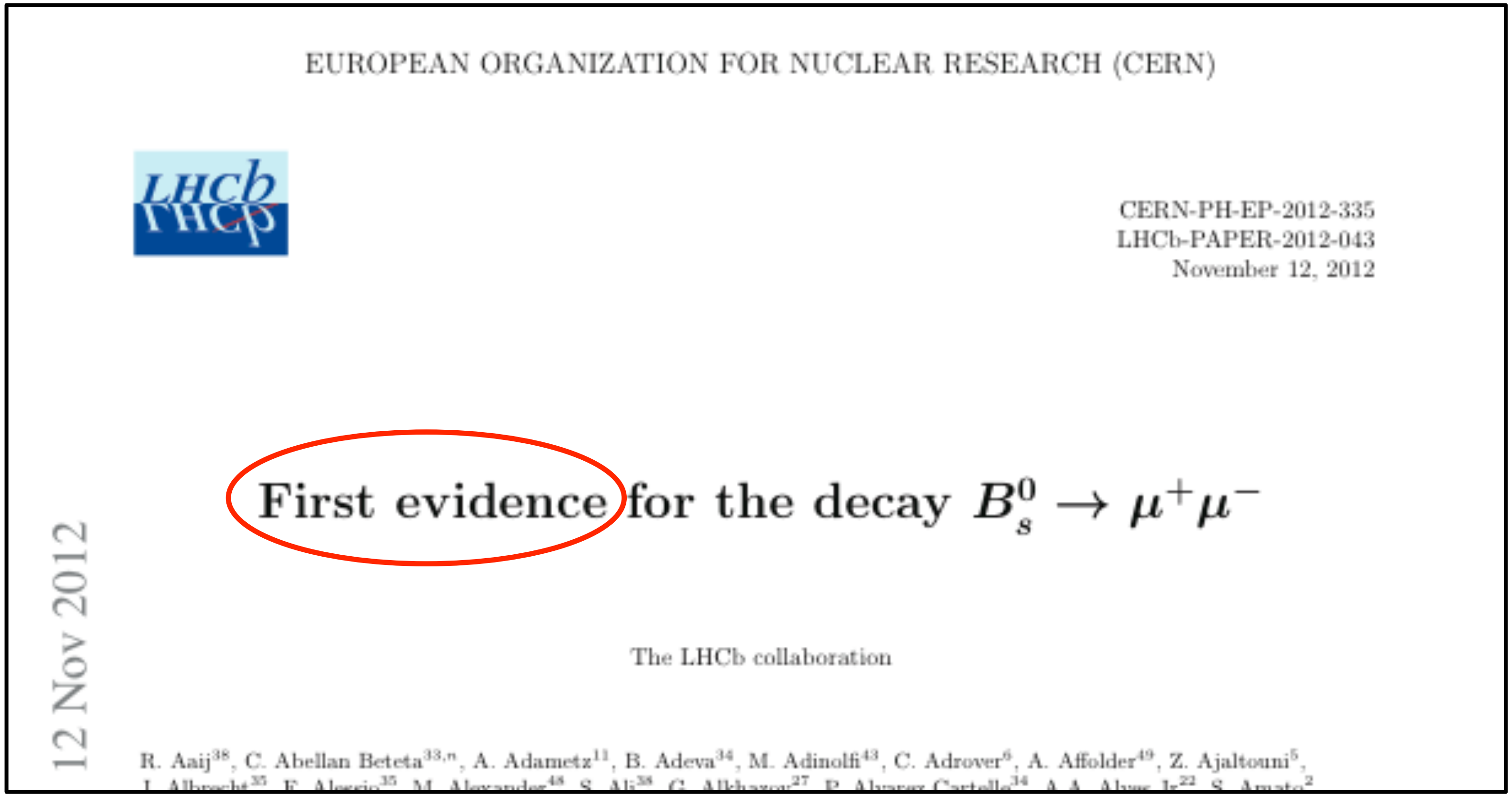
Table 2 Upper limits for exclusive dilepton decays.

decay channel	upper limit with 90% CL
$B^0 \to e^+e^-$	$8.5 \cdot 10^{-5}$
$B^0 \to \mu^+\mu^-$	$5.0 \cdot 10^{-5}$
$B^0 \to e^\pm\mu^\mp$	$5.0 \cdot 10^{-5}$

First evidence for $B_s^0 \to \mu^+\mu^-$

[arXiv:1211.2674]

- LHCb announced first evidence for $\mathbf{B_s^0 \to \mu^+\mu^-}$ at HCP conference 2012



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-PH-EP-2012-335
LHCb-PAPER-2012-043
November 12, 2012

First evidence for the decay $B_s^0 \to \mu^+\mu^-$

The LHCb collaboration

R. Aaij[38], C. Abellan Beteta[33,n], A. Adametz[11], B. Adeva[34], M. Adinolfi[43], C. Adrover[6], A. Affolder[49], Z. Ajaltouni[5],

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- CMS strangely silent …

Results for Fitting $B(B_s^0 \to \mu^+\mu^-)$

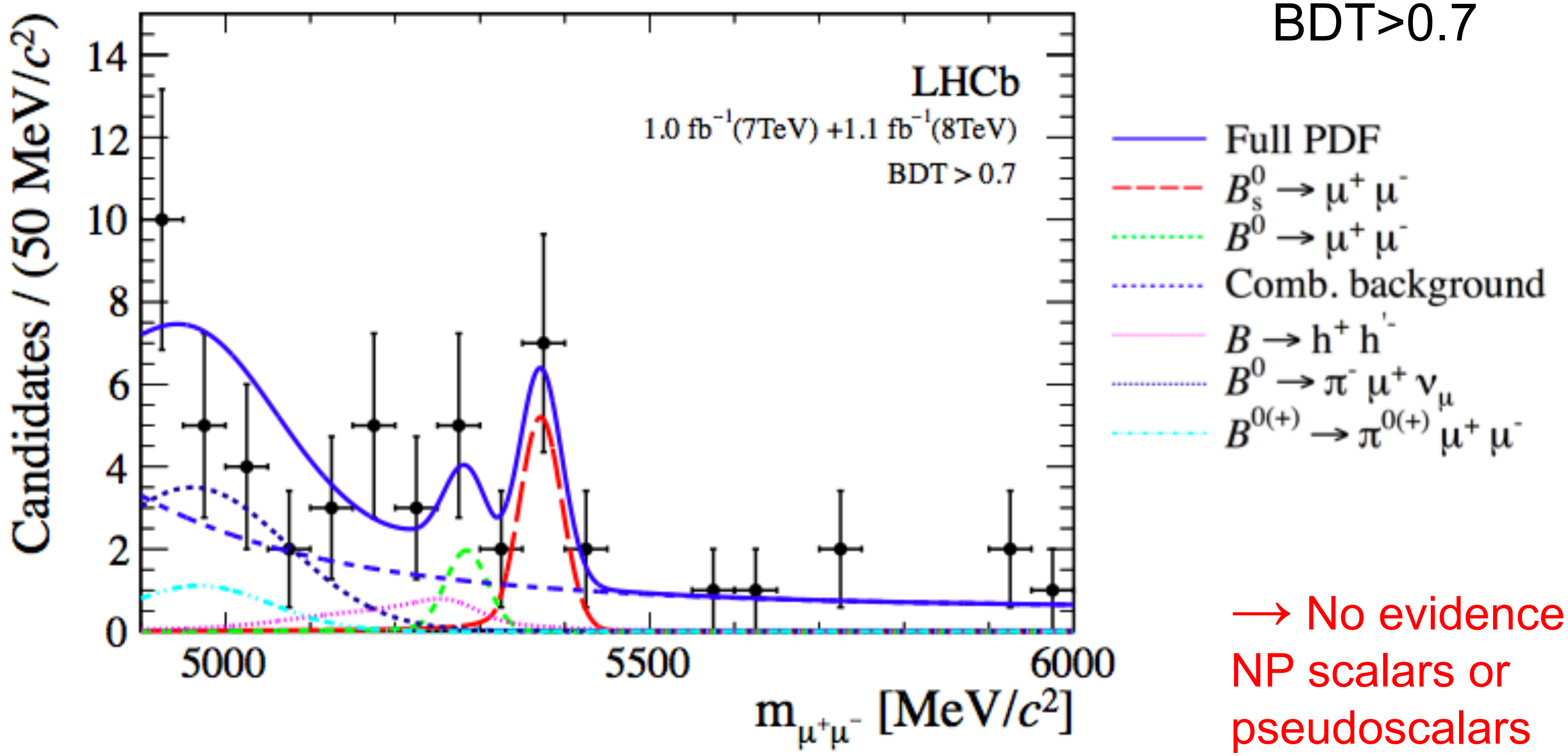
[arXiv:1211.2674]

- Fitted branching fraction

$$B(B_s^0 \to \mu^+\mu^-) = (\ 3.2^{+1.5}_{-1.2}(\text{stat})^{+0.5}_{-0.3}(\text{syst})\ )\times 10^{-9}$$

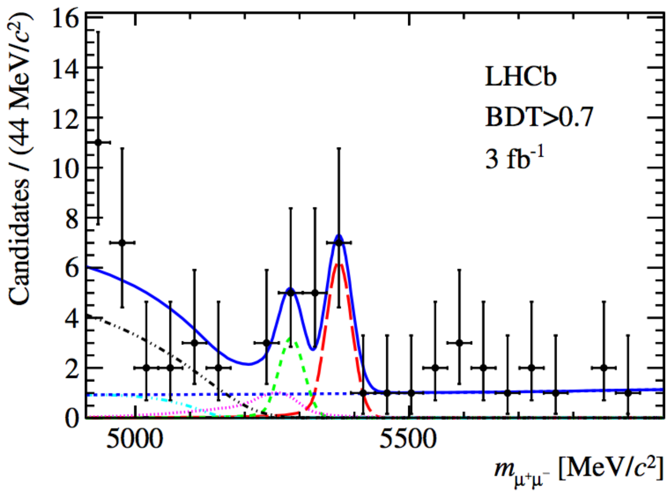
cf. SM expectation: $(3.54\pm0.30)\times10^{-9}$

BDT>0.7



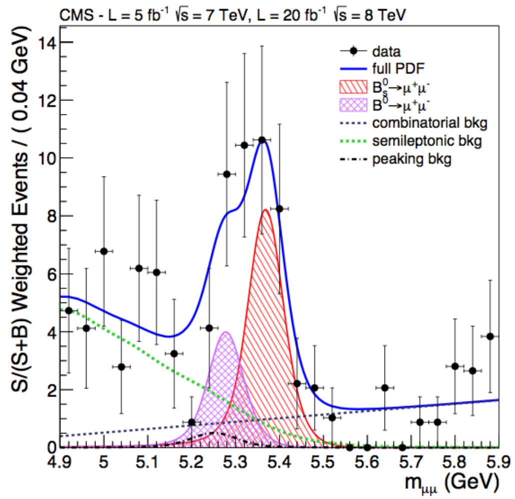
→ No evidence of NP scalars or pseudoscalars [arXiv:1307.5024] [arXiv:1307.5025]

- LHCb update at EPS:
  - $2.1 fb^{-1} \rightarrow 3.0 fb^{-1}$
  - Improved reconstruction
  - Additional variables added to BDT
  - Expected sensitivity: $3.7 \rightarrow 5.0\sigma$



- $\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) =$
  $(2.9^{+1.1}_{-1.0}(stat)^{+0.3}_{-0.1}(syst)) \times 10^{-9}$
  $\rightarrow 4\sigma$
- $\mathcal{B}(B_d^0 \rightarrow \mu^+\mu^-) =$
  $(3.7^{+2.4}_{-2.1}(stat)^{+0.6}_{-0.4}(syst)) \times 10^{-10}$
  $\rightarrow 2.0\sigma$ [$< 7.4 \times 10^{-10}$ at 95% CL]

- CMS update at EPS
  - $5 fb^{-1} \rightarrow 25 fb^{-1}$
  - Cut-based selection → BDT
  - New and improved variables
  - Expected sensitivity: 4.8σ



- $\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) =$
  $(3.0^{+1.0}_{-0.9}) \times 10^{-9}$
  $\rightarrow 4.3\sigma$
- $\mathcal{B}(B_d^0 \rightarrow \mu^+\mu^-) =$
  $(3.5^{+2.1}_{-1.8}) \times 10^{-10}$
  $\rightarrow 2.0\sigma$ [$< 11.0 \times 10^{-10}$ at 95% CL]

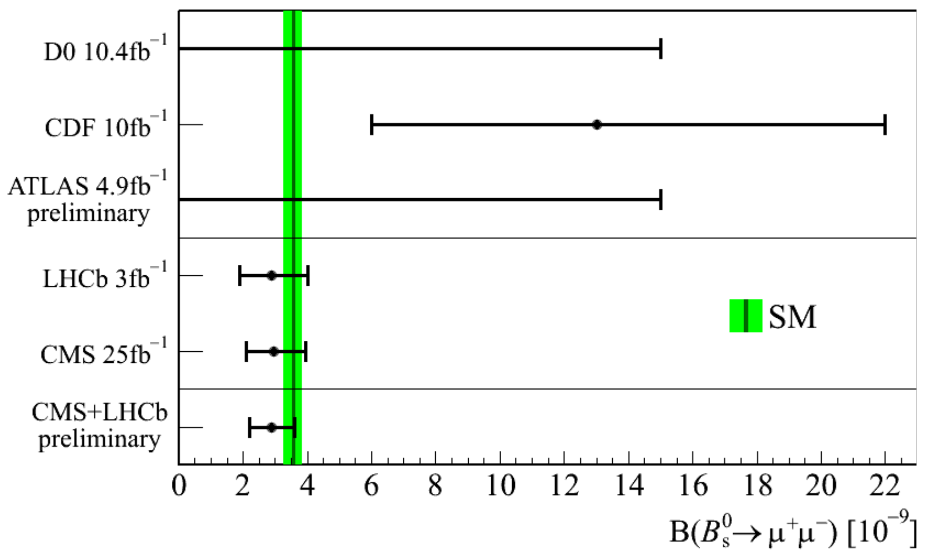
- ATLAS also gave an update at EPS : $\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) < 1.5 \times 10^{-8}$ at 95% CL

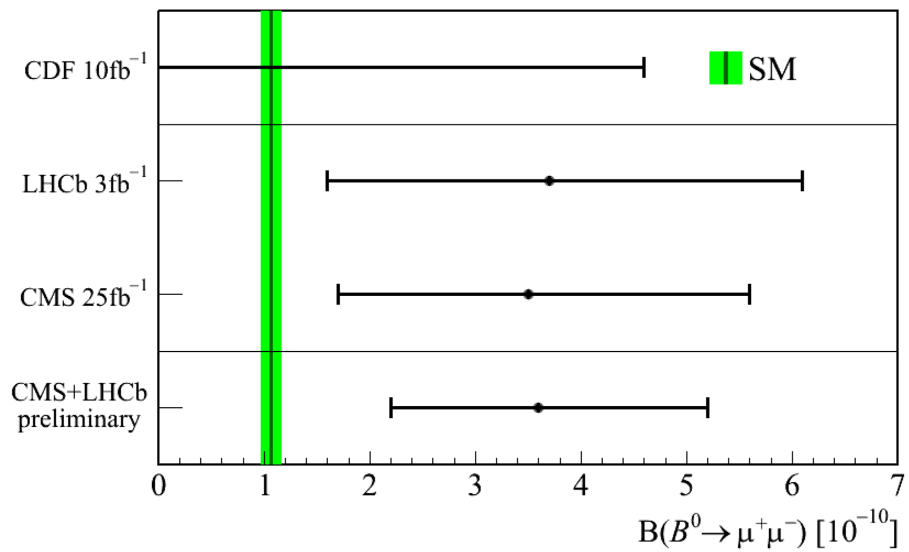
Combined LHCb, CMS result

- The LHCb and CMS results have been combined [LHCb-CONF-2013-012] [CMS-PAS-BPH-13-007]

$B\,(B_s^0 \rightarrow \mu^+\mu^-) \quad = \quad (2.9 \pm 0.7)\times 10^{-9} \qquad$ (First observation)

$B\,(B_d^0 \rightarrow \mu^+\mu^-) \quad = \quad (3.6^{+1.6}_{-1.4})\times 10^{-10}$



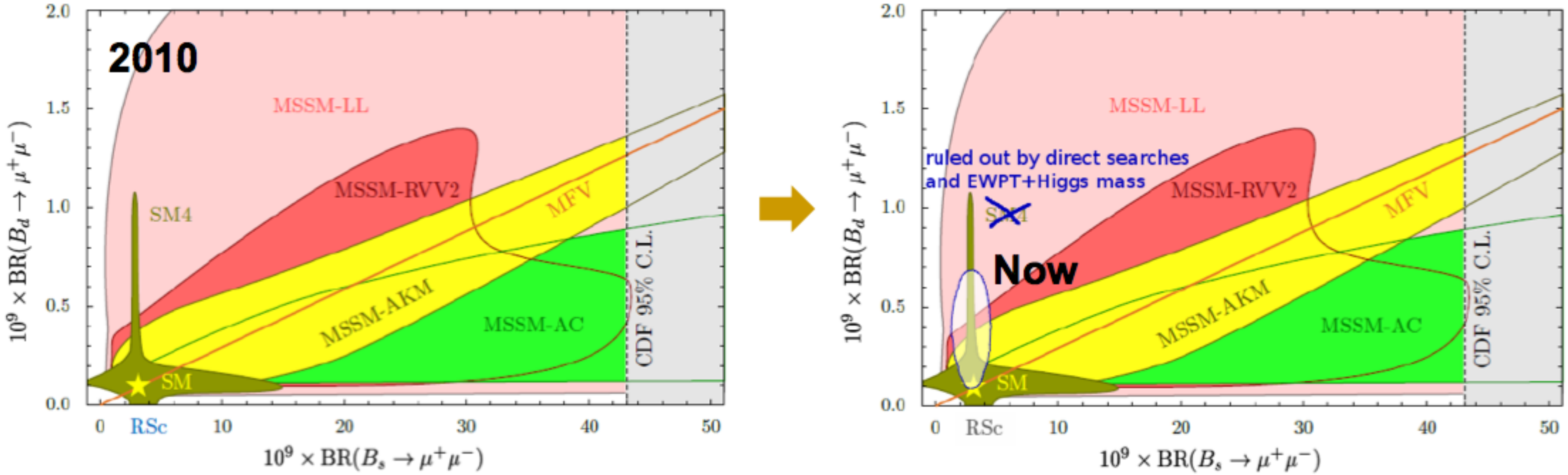


- Good agreement with SM predictions

Impact

- Precise SM prediction → constraints on scalar and pseudoscalar sector of NP e.g. severely constrains high tan β SUSY

[Straub, arXiv:1012.3893]

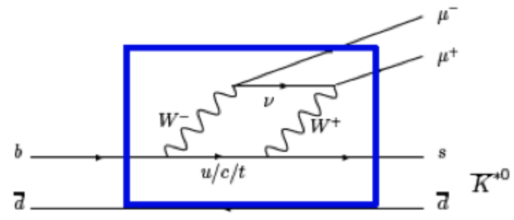


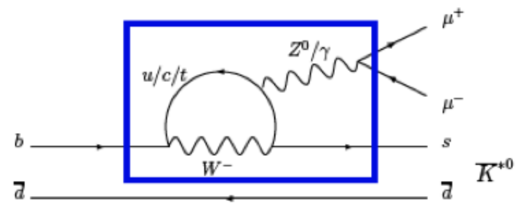
- Still much to do:
  - measure BR precisely – maybe it is lower than SM?
  - measure BR($B_d^0 \to \mu\mu$)/BR($B_s^0 \to \mu\mu$)
  - (eventually) measure lifetime and CP asymmetries

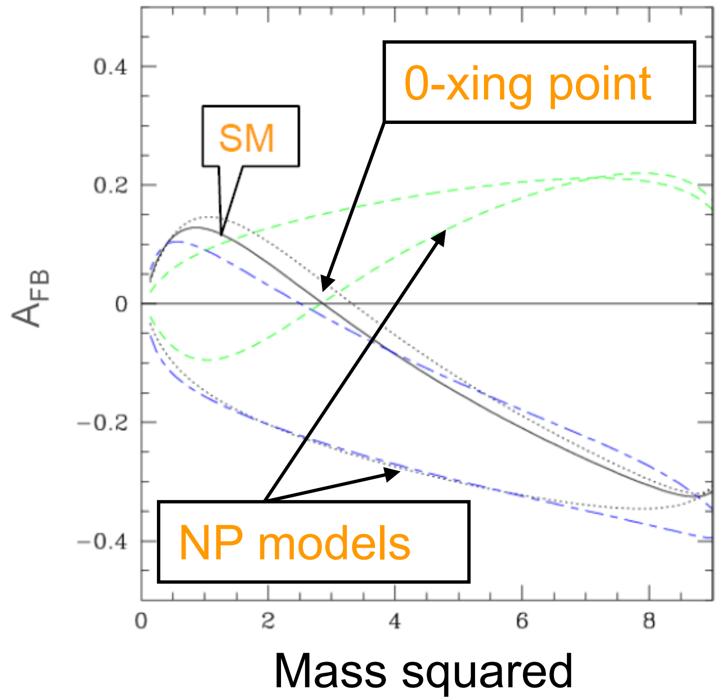
$B_d^0 \rightarrow K^{*0}\mu\mu$

- Flavour changing neutral current → loop process (→ sensitive to NP)
- Decay described by three angles (θ_l, ϕ, θ_K) and di-μ invariant mass
- Try to use observables where theoretical uncertainties cancel

  e.g. Forward-backward asymmetry A_{FB} of θ_l distribution
- Zero-crossing point: ±6% uncertainty
- In SM dominated by C_7, C_9, C_{10} Wilson Coefficients – NP may enhance other contributions

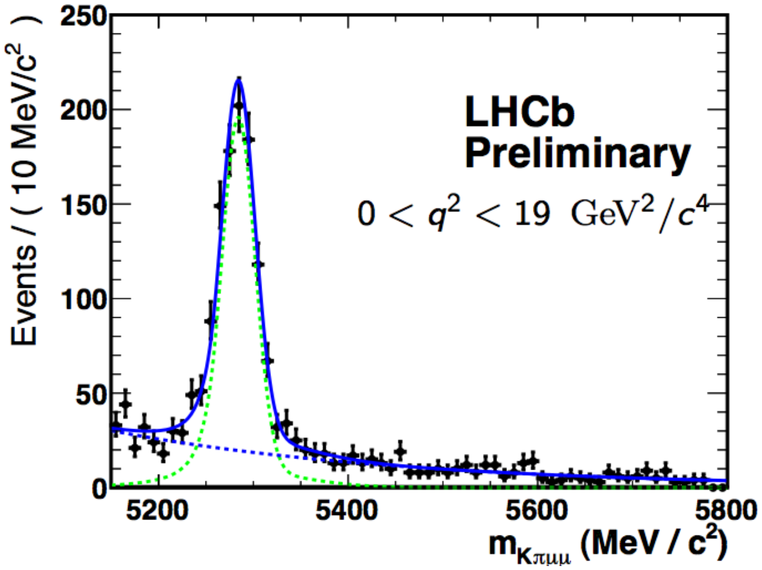


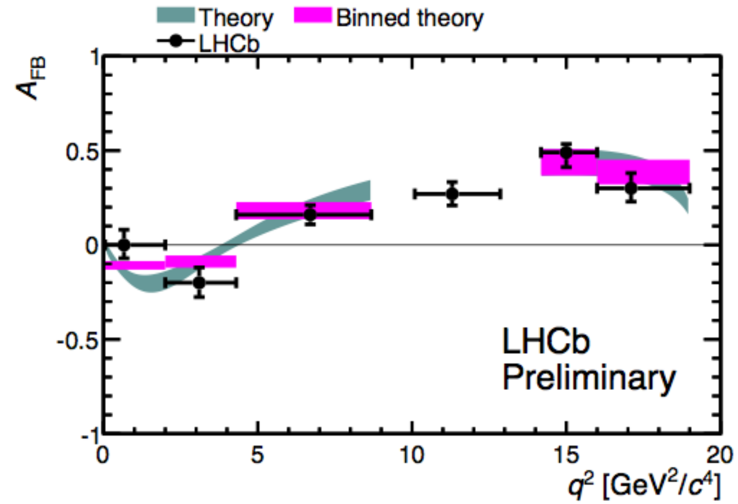




LHCb $B_d^0 \to K^{*0}\mu\mu$ measurements

- With 2011 data find 900±34 signal events (BaBar + Belle + CDF ~ 600)
- B/S≈0.25
- World's most precise measurements of angular observables
- The world's first measurement of 0-crossing point at $4.9^{+1.1}_{-1.3}$ GeV^2/c^4
- Will come back to other observables





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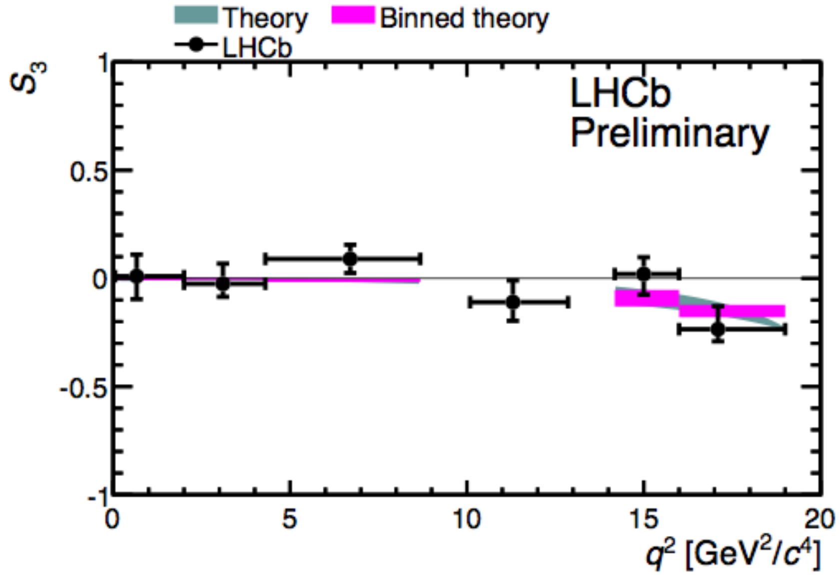
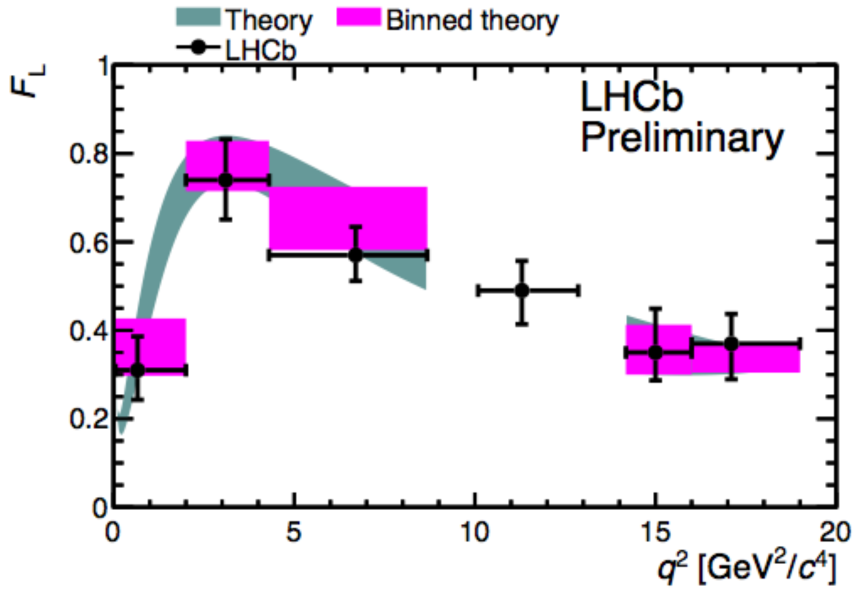
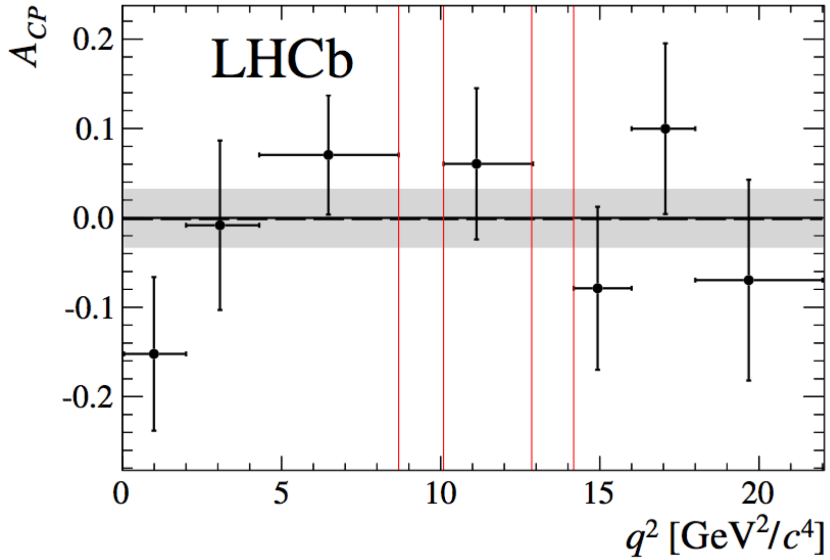




A_{CP} in $B_d^0 \to K^{*0}\mu\mu$

- Have also measured A_{CP} in $B_d^0 \to K^{*0}\mu\mu$
  - Use $B_d^0 \to K^{*0} J/\psi$ control channel, which has same final state, to cancel detector and production asymmetries
  - Use fits to both magnetic field polarities to reduce detector effects



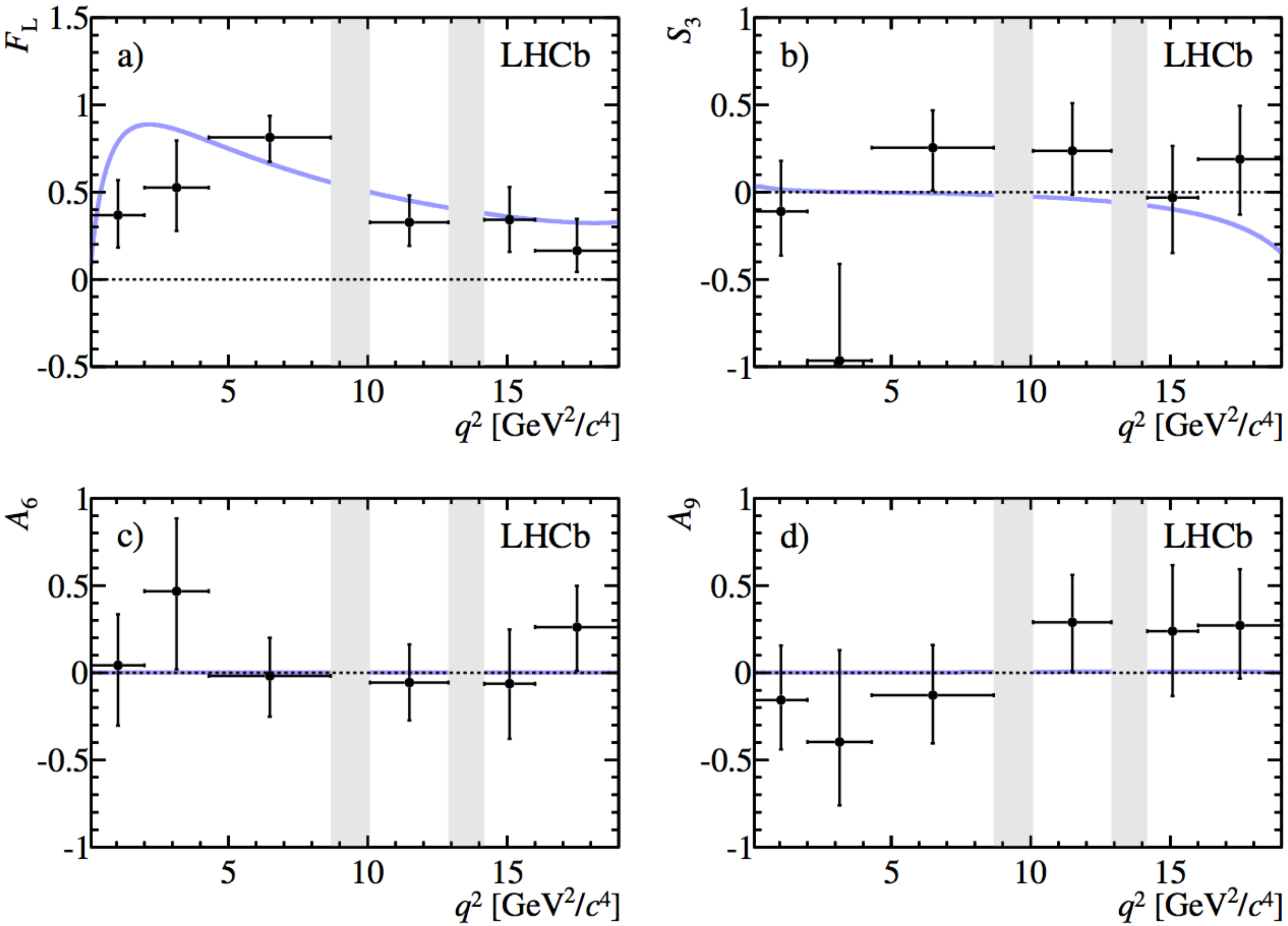
– LHCb $A_{CP}(B_d^0 \to K^{*0}\mu\mu)$ =-0.072±0.040±0.005 [JHEP 1307 (2013) 84]

– BABAR $A_{CP}(B_d^0 \to K^{*0}\mu\mu)$ = 0.03 ± 0.13(stat.) ± 0.01(syst.) [PRD 86 (2012) 032012]

– BELLE $A_{CP}(B_d^0 \to K^{*0}\mu\mu)$ = −0.10 ± 0.10(stat.) ± 0.01(syst.) [PRL103 (2009) 171801]

$B_s^0 \to \phi\mu\mu$ angular analysis

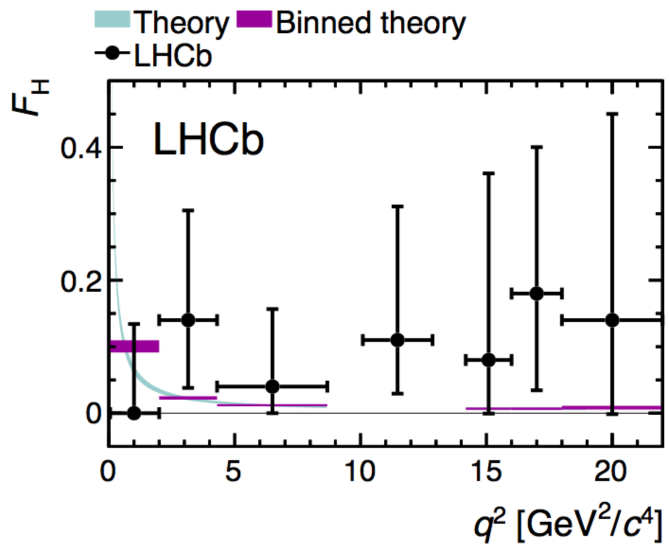
[arXiv:1305.2168]

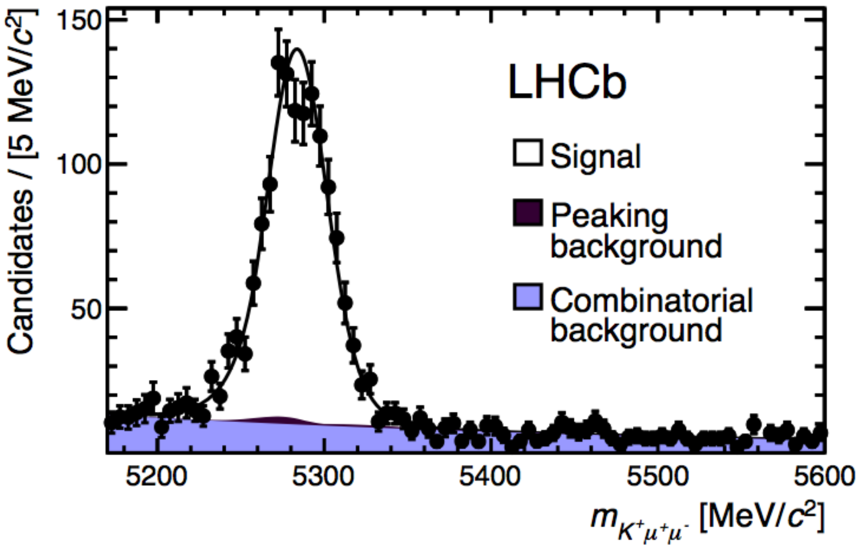


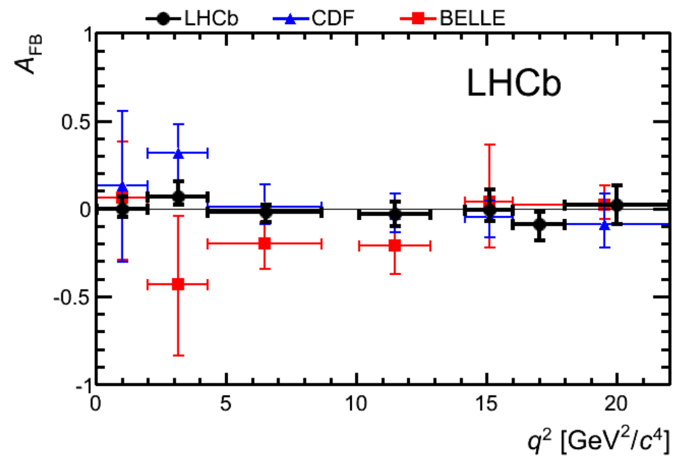
LHCb $B^+ \to K^+\mu\mu$ measurements

[arXiv:1209.4284]

- LHCb has also isolated 1232±40 $B^+ \to K^+\mu\mu$ candidates in 1fb^{-1} 2011 data
- Can again measure angular distributions
  - Very good agreement with SM
  - Measurements constrain C_9, C_{10}
  - BF measurement constrains scalar, tensor







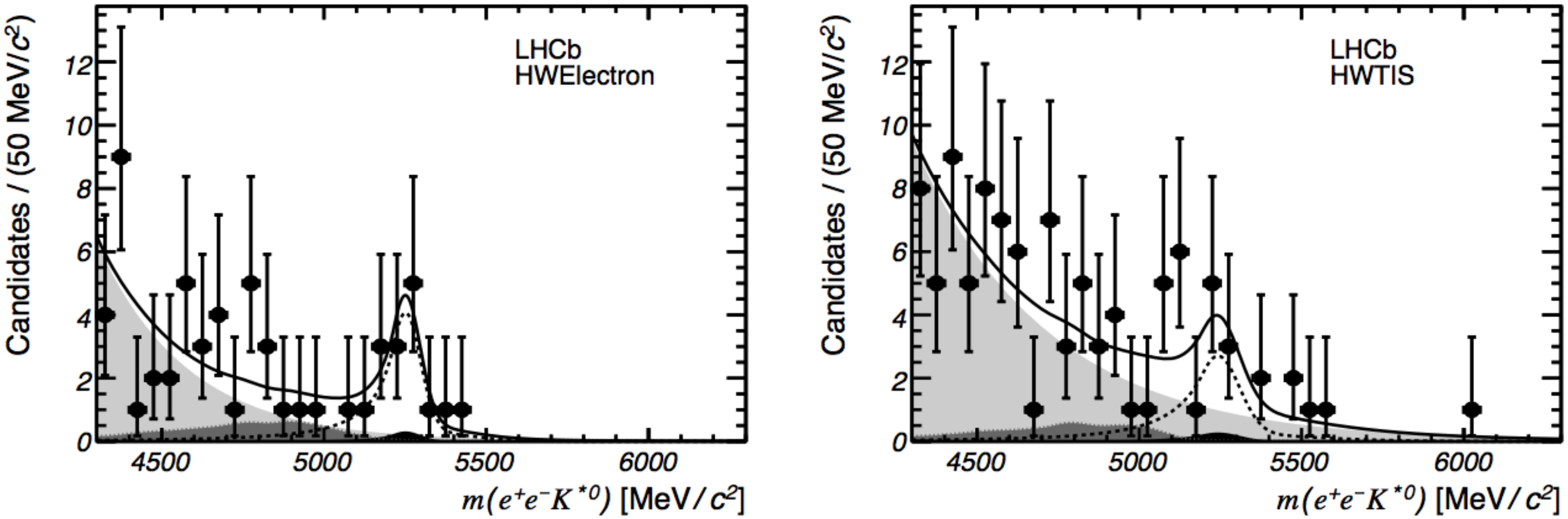
$B_d^0 \to K^{*0} e^+ e^-$

[arXiv:1304.3035]

- Although $B(B_d^0 \to K^{*0}\gamma)$ in agreement with SM prediction there could still NP contributions giving e.g. contribution from right-handed γ
- Can explore this through angular analysis of low q^2 region- electron modes allows to go lower than muon equivalent with no complications from mass terms
- At present have just measured branching fraction:

$$B(B_d^0 \to K^{*0} e^+ e^-)_{30-1000\ \mathrm{MeV}/c^2} = (3.1^{+0.9}_{-0.8}) \times 10^{-7}$$

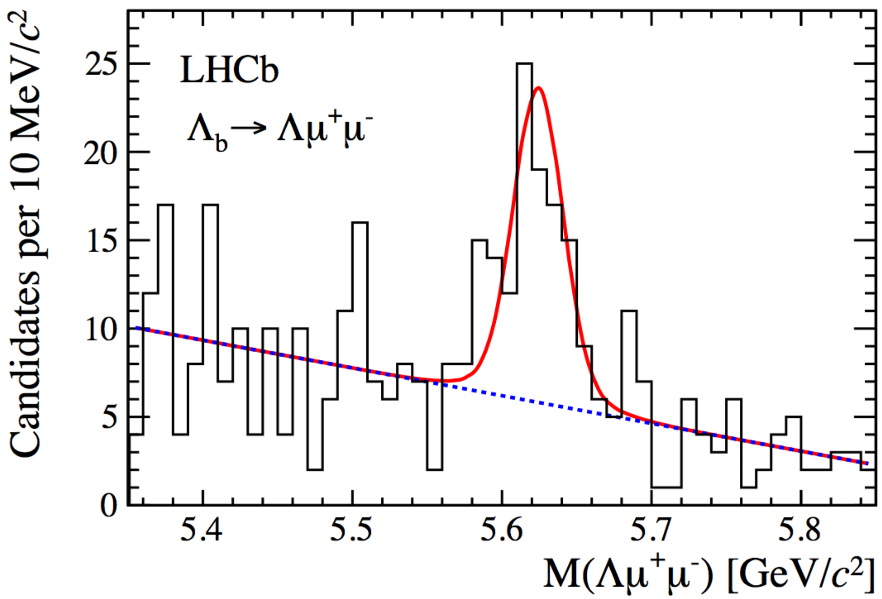
- Longer term will be able to measure the ratio between the electron and muon modes, R_K, sensitive to e.g. Higgs contributions

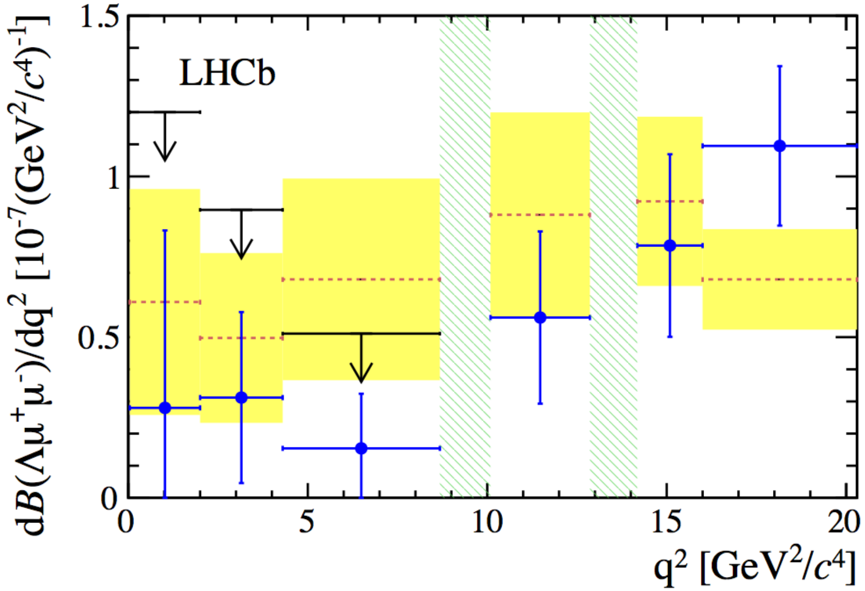


$\Lambda_B^0 \rightarrow \Lambda^0 \mu\mu$

[arXiv:1306.2577]

- Λ_B^0 has non-zero spin → can allow a different probe of the helicity structure of the b→s transition
- Observe 78±12 $\Lambda_B^0 \rightarrow \Lambda^0 \mu\mu$ decays
- Significant signal is found in the q^2 region above the J/ψ resonance → measure branching fraction
- At lower-q^2 values upper limits are set on the differential branching fraction





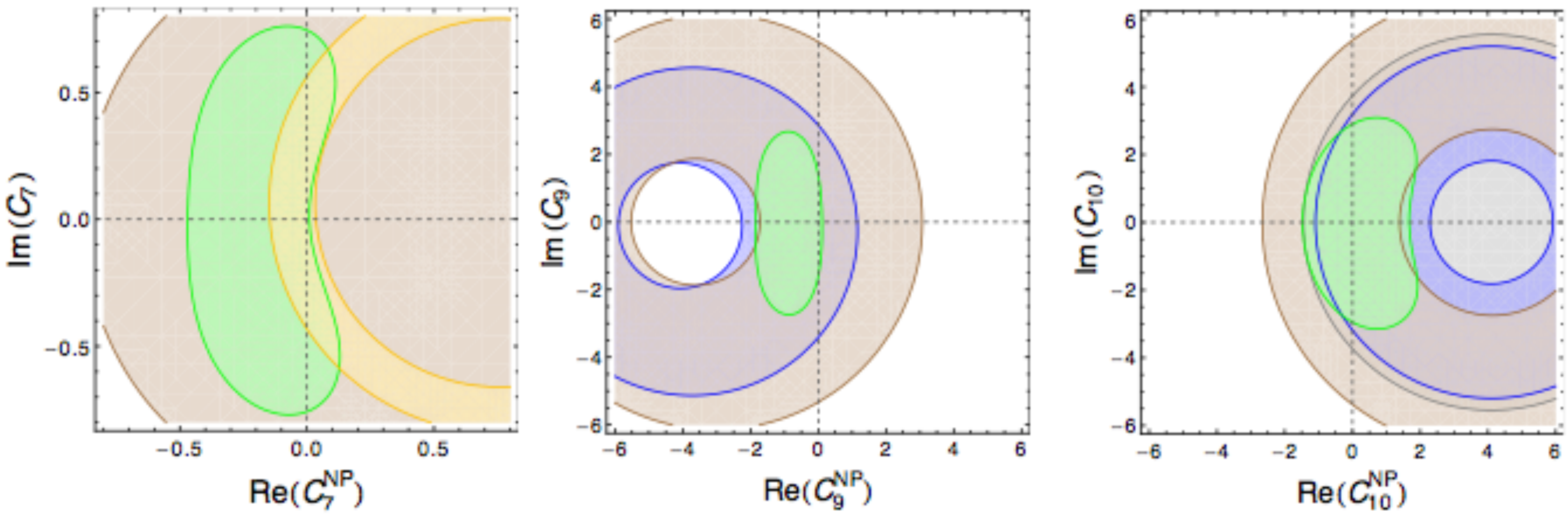
Outline

- Why study B physics?
- Introduction to the LHCb experiment
- Status of LHCb measurements
  - CKM measurements
  - Rare decays measurements
- **Flavour Problem**
- Light at the end of the tunnel?

Constraints on C_7, C_9, C_{10}

D. Straub, arXiv:1111.1257, JHEP 1202:106

Varying 1 Wilson coefficient at a time. $C_i = C_i^{SM} + C_i^{NP}$ *preliminary*



$BR(B \to X_s \ell^+ \ell^-)$ $BR(B \to X_s \gamma)$ $B \to K^* \mu^+ \mu^-$ $BR(B \to K \mu^+ \mu^-)$ $BR(B_s \to \mu^+ \mu^-)$

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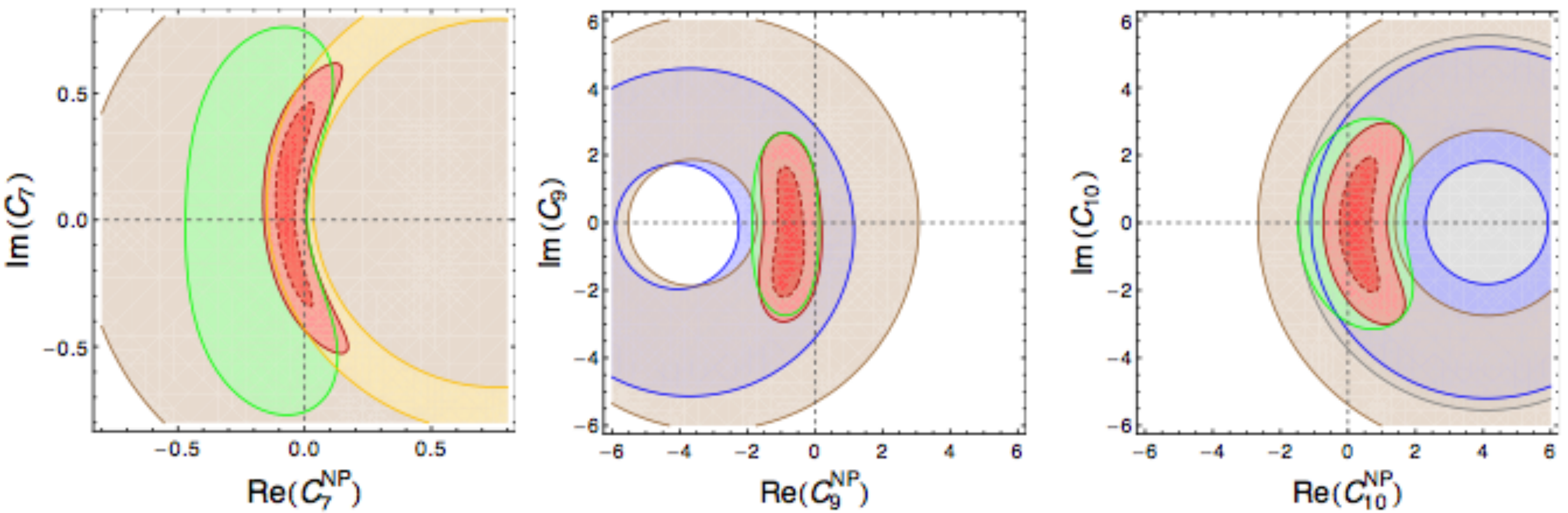


$BR(B \to X_s \ell^+ \ell^-)$ $BR(B \to X_s \gamma)$ $B \to K^* \mu^+ \mu^-$ $BR(B \to K \mu^+ \mu^-)$ $BR(B_s \to \mu^+ \mu^-)$

- Good agreement with SM expectations
- Complementarity between observables crucial to break degeneracies

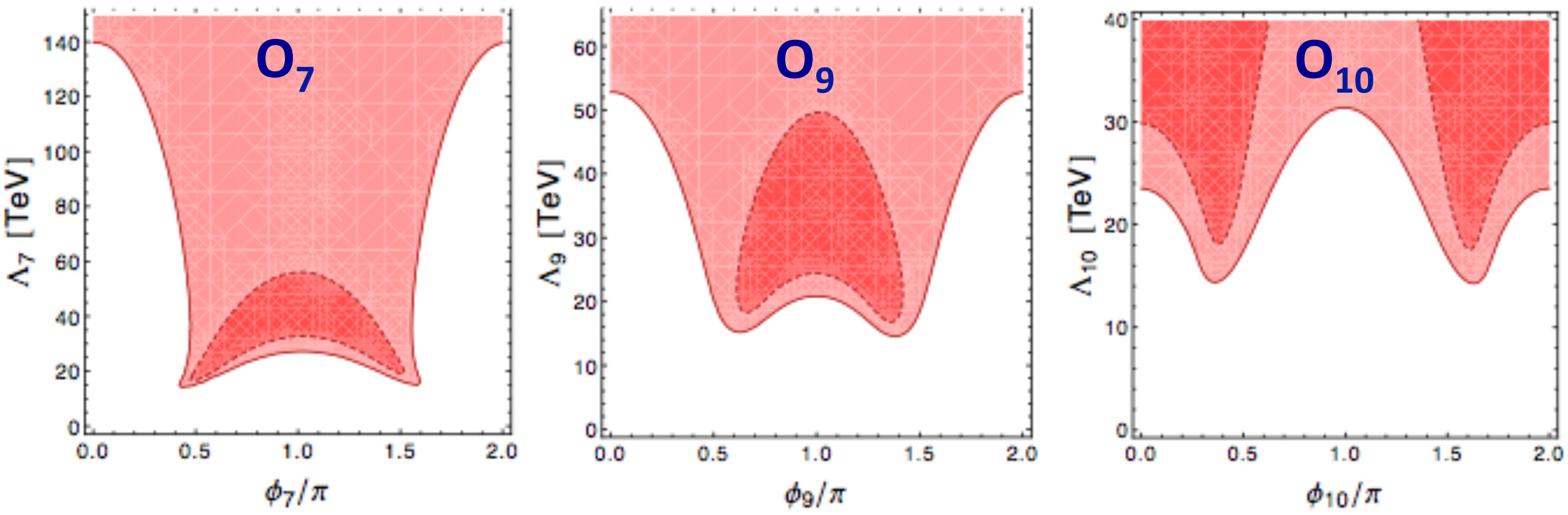
Impact – with tree level FV

D. Straub, arXiv:1111.1257, JHEP 1202:106

Results can be interpreted as bounds on the scale of new physics:

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

~tree level generic flavour violation



Λ_{NP}>14-140TeV !!!

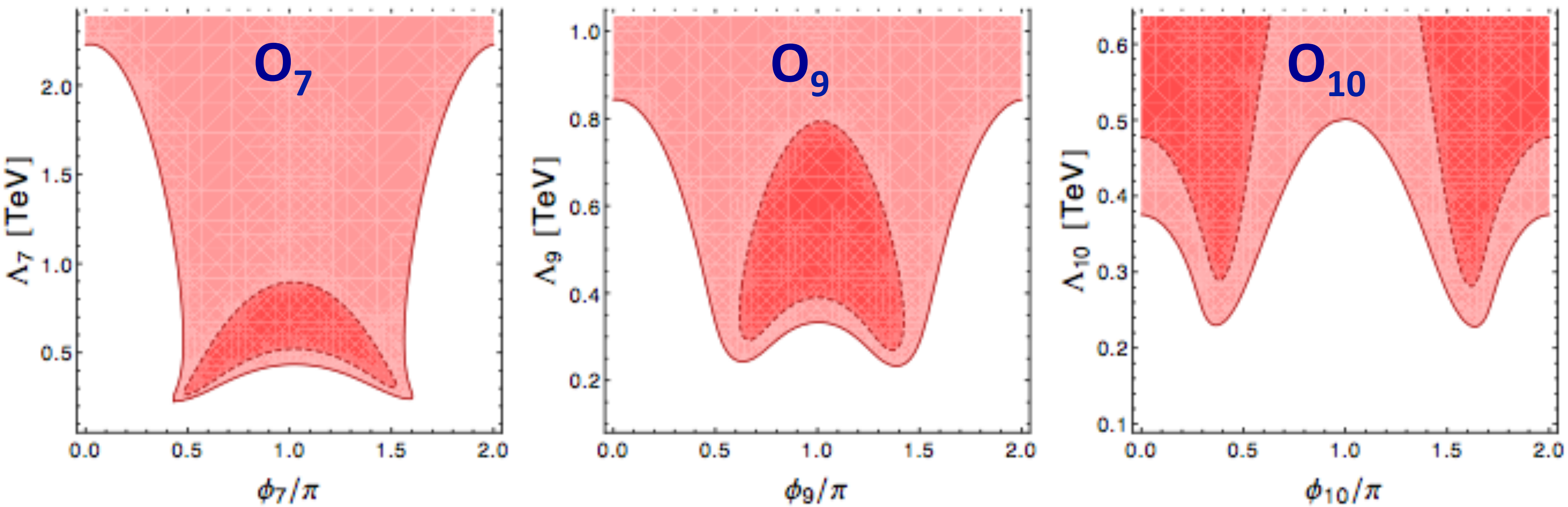
Impact – with loop CKM-like FV

D. Straub, arXiv:1111.1257, JHEP 1202:106

Results can be interpreted as bounds on the scale of new physics:

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

~loop level CKM-like flavour violation

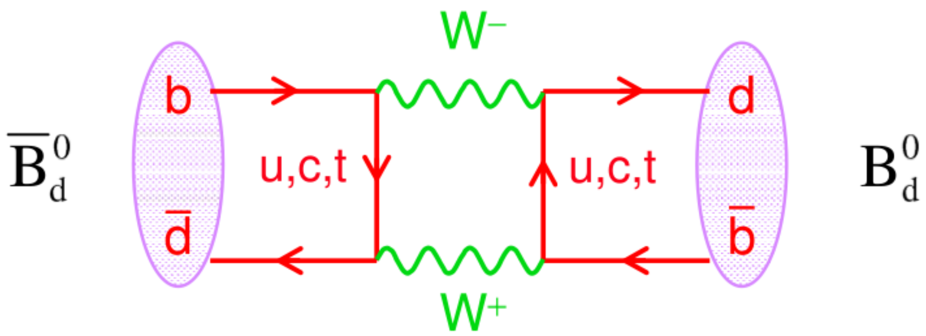


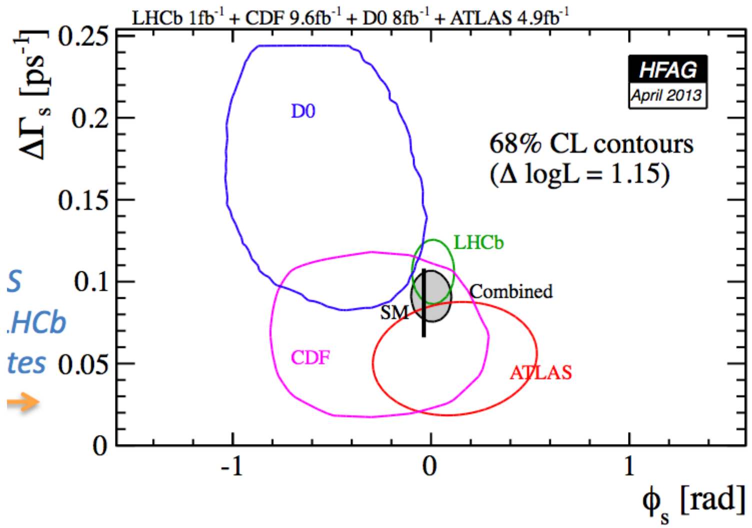
→ No evidence for NP in vectors, axial vectors

(Analysis doesn't yet include $A_{CP}(B_d^0 \to K^{*0}\mu\mu)$ or $B^+ \to K^+\mu\mu$)

B-$\overline{\text{B}}$ mixing and MFV

- b→s transitions change flavour by one unit **ΔF=1**
- Problems are in fact much worse from **ΔF=2** processes – mixing





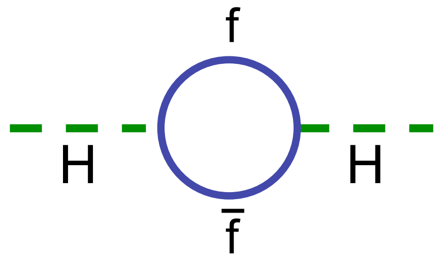
$$M(B_d\text{–}\overline{B}_d) \sim \frac{(y_t^2 V_{tb}^* V_{td})^2}{16\pi^2 m_t^2} + c_{NP}\frac{1}{\Lambda^2}$$

c_{NP}:

- ~ 1 —tree/strong + generic flavor→ $\Lambda \gtrsim 2\times10^4$ TeV [K]
- $\sim 1/(16\pi^2)$ —loop + generic flavor→ $\Lambda \gtrsim 2\times10^3$ TeV [K]
- $\sim (y_t V_{ti}^* V_{tj})^2$ —tree/strong + "alignment"→ $\Lambda \gtrsim 5$ TeV [K & B]
- $\sim (y_t V_{ti}^* V_{tj})^2/(16\pi^2)$ —loop + "alignment"→ $\Lambda \gtrsim 0.5$ TeV [K & B]

New Physics on the TeV scale?

- Hierarchy "problem" associated with observation of Higgs
  - Try to calculate m_H → contributions (correction) from loop diagrams



  - Should make m_H → scale of new physics, unless there is an *incredible* fine-tuning cancellation between these radiative corrections and the bare mass – **idea is that NP should make things "natural"**

- Range of theories proposed to cancel these loops – all predict new particles, dynamics and/or symmetries at a higher energy scale
  - Supersymmetry (SUSY)
  - Littlest Higgs Theories (LHT)
  - Universal Extra-Dimensions (UED)

We expect New Physics!

- Even if SUSY discovered tomorrow, fine tuning will be **1 part in 10^3** – but now the floodgates are open … if 1 in 10^3 ok, why not 1 part in 10^4 ?

"The Flavour Problem"

- The fact we don't see a significant deviation from SM in flavour processes suggests NP is at a *very* high energy scale

- This can be softened by saying that NP diagrams have the same flavour violation as the SM

  → the Minimal Flavour Violation (MFV) hypothesis

  i.e. the CKM matrix is the only source of flavour changing currents, even in NP processes

- This doesn't mean flavour observables no longer useful … look at e.g. $B \to \mu\mu$, $B_d^0 \to K^{*0}\mu\mu$ etc. – loop processes may be the only way to get information!

- Must continue testing MFV : $b \to d$ transitions important! CKM observables still important!

“The Flavour Problem”

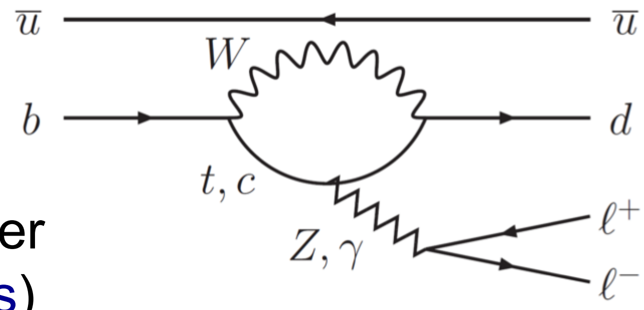
- Every theorist building some NP model from SUSY to UED has to make sure their model doesn’t produce too large deviations in the flavour sector – cuts out great swathes of models

- Personally, I don’t find MFV entirely satisfactory : in a bid to keep the mass-scale of new physics low, so that we can avoid fine-tuning contributions to the Higgs mass (and at least maintain “un-natural naturalness”), we are tuning the flavour sector

- Still, it could be true… only way we will find out is by making higher precision flavour measurements

- Are still many rare decays out there to measure which can give high quality information about NP!

The search for $B^+ \to \pi^+ \mu^+ \mu^-$



- The $B^+ \to \pi^+ \mu^+ \mu^-$ decay is a $b \to d$ transition

- In the SM the branching fraction is ~25x smaller $(V_{ts}/V_{td})^2$ than the well known $B^+ \to K^+ \mu^+ \mu^-$ ($b \to s$) transition but can be enhanced in non-MFV NP models

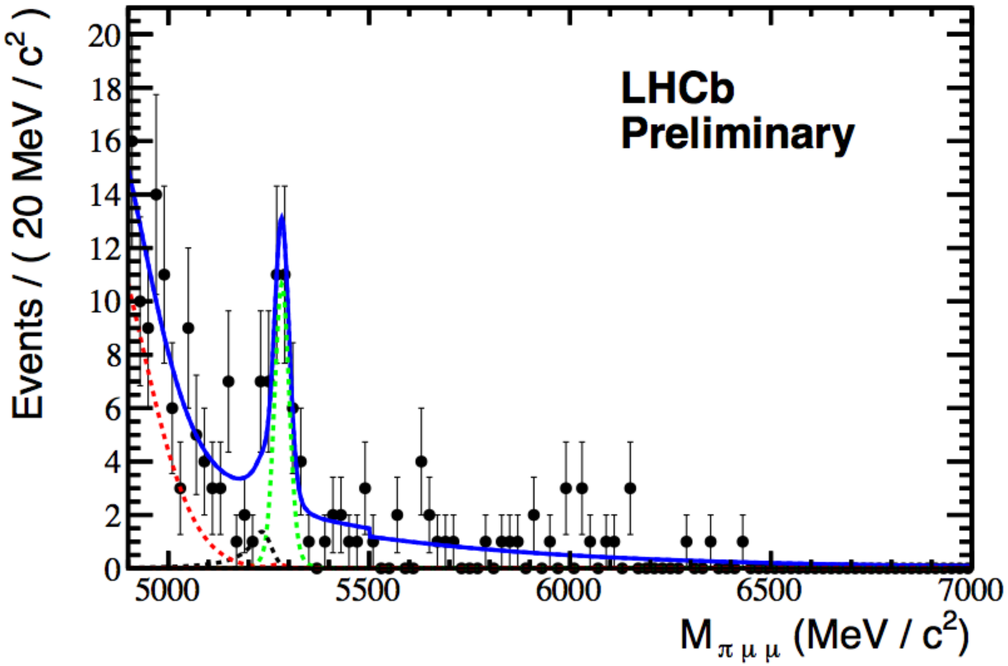
- SM prediction: $\mathcal{B}(B^+ \to \pi^+ \mu^+ \mu^-) = (1.96 \pm 0.21) \times 10^{-8}$ (*)

- While ratio CKM elements V_{ts}/V_{td} known from oscillation measurements, this decay probes V_{ts}/V_{td} in above penguin decays

(*) Hai-Zhen et al., Comm in Theo Ph 50 (2008) 696

First observation of $B^+ \to \pi^+\mu^+\mu^-$

- With 1.0 fb^{-1} LHCb finds $25.3^{+6.7}_{-6.4}$ $B^+ \to \pi^+\mu^+\mu^-$ signal events
  - 5.2σ excess above background



[LHCb-CONF-2012-006]

- $B(B^+ \to \pi^+\mu^+\mu^-) = (2.4 \pm 0.6(stat) \pm 0.2(syst)) \times 10^{-8}$, within 1σ of SM pred.
- Until we found $B^0_s \to \mu^+\mu^-$, rarest B decay ever observed

Summary

- Decays like:
  - $B_s^0 \to \mu^+\mu^-$ → no new scalars/pseudoscalars / no high tan β SUSY
    $B_d^0 \to K^{*0}\mu\mu$ → no new vectors/axial vectors / NP > 100 (0.5) TeV
  - B_d^0-B_d^0 mixing → NP > 10^4 (0.5) TeV
  - Wide range of non-B decays: K_s, D, τ …

  Have had a big impact on our understanding of new physics – have created the "**flavour problem**" – if new physics is out there, why aren't we seeing the effect of it in loop processes?

- [IMHO] sobering given historical track record of "indirect probes"

- Minimal Flavour Violation hypothesis a response to this:
  - NP diagrams have the same flavour violation as the SM i.e. CKM matrix is the only source of flavour changing currents, even in NP processes
  - Tune flavour sector to keep O(TeV) scale NP theories (e.g. SUSY) alive

- LHCb continues to actively test the MFV hypothesis :
  - All CKM observables
  - b→d transitions like $B^+ \to \pi^+\mu^+\mu^-$
  - New and improved loop processes to constrain NP further

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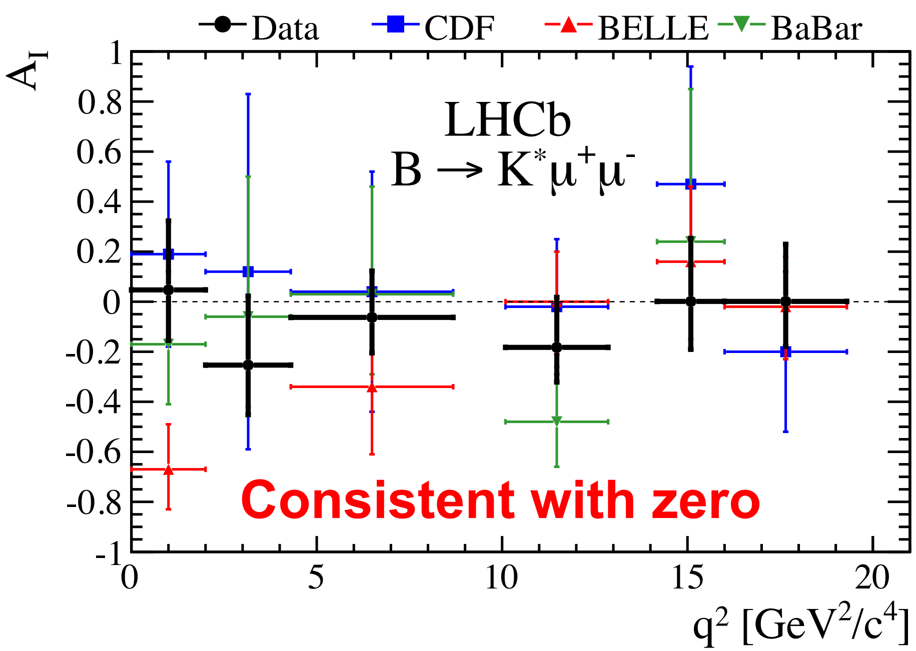
Isospin Asymmetry in $B \rightarrow K^{(*)}\mu^+\mu^-$

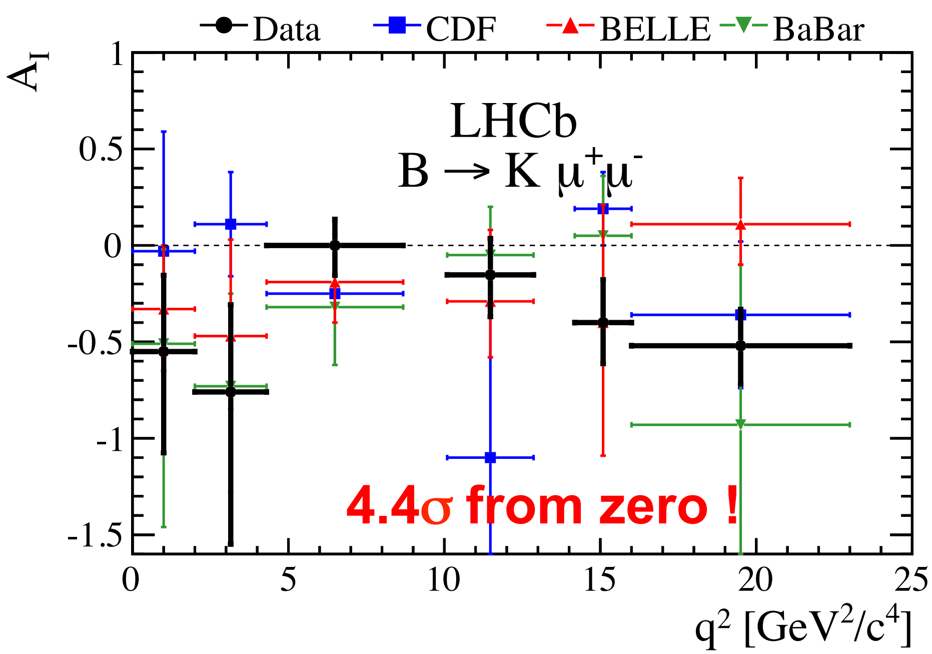
- The isospin asymmetry of $B \rightarrow K^{(*)}\mu^+\mu^-$, A_I is defined as:

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

can be more precisely predicted than the branching fractions, =0 in SM

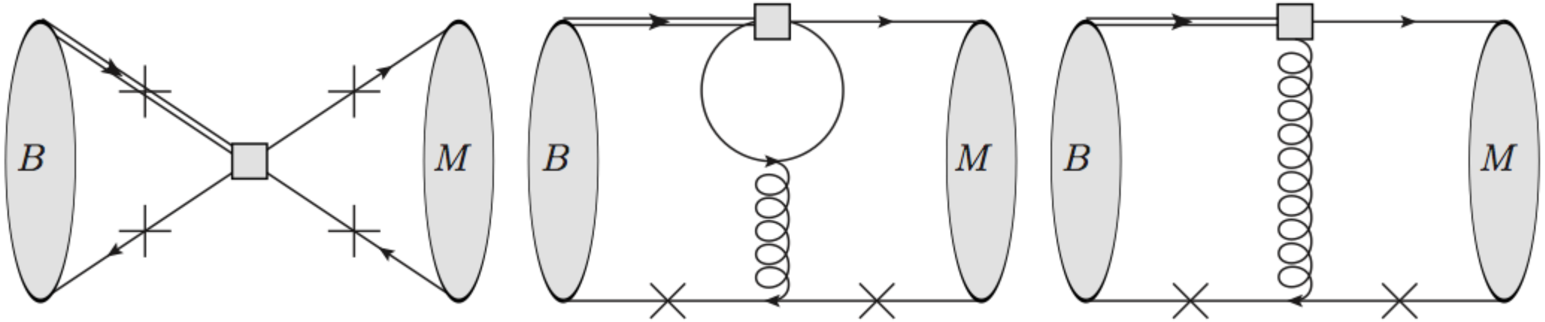
- $1fb^{-1} \rightarrow 3fb^{-1}$ update is imminent



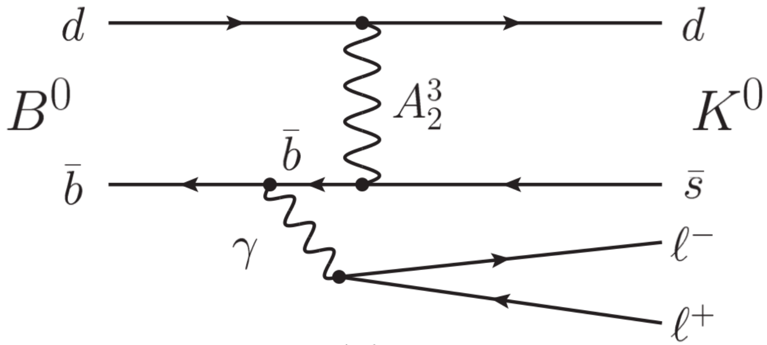


Physics of A_I

- Isospin asymmetries can arise where the spectator radiates a photon
- Contributions depend on C_{1-6} and C_8



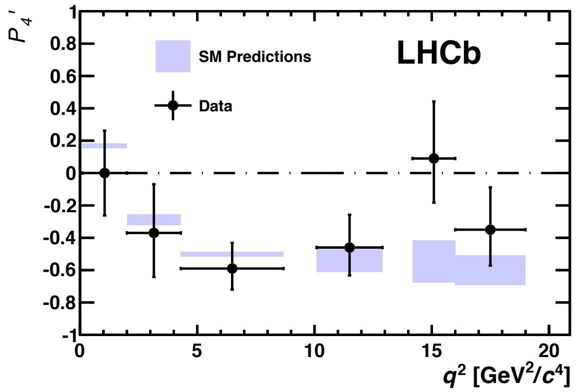
- Example of diagram from exotic "family gauge boson" model shows a possible NP contribution …
- … but expect to contribute mostly at low q^2

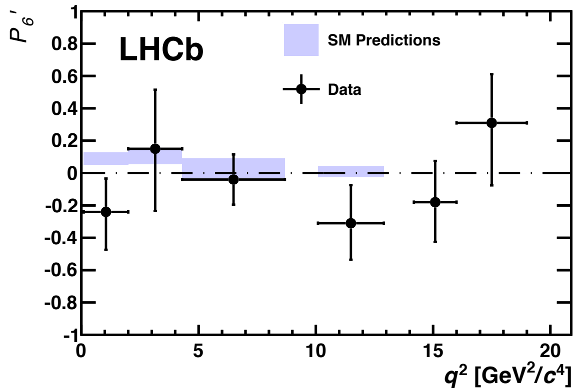


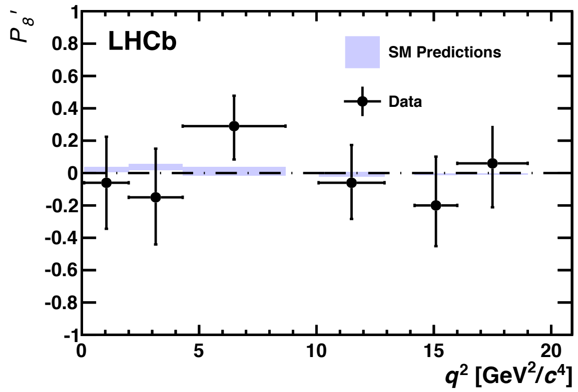
$B_d^0 \to K^{*0}\mu\mu$ – new observables

[arXiv:1308.1707]

- Good agreement with predictions for P_4', P_6', P_8' observables

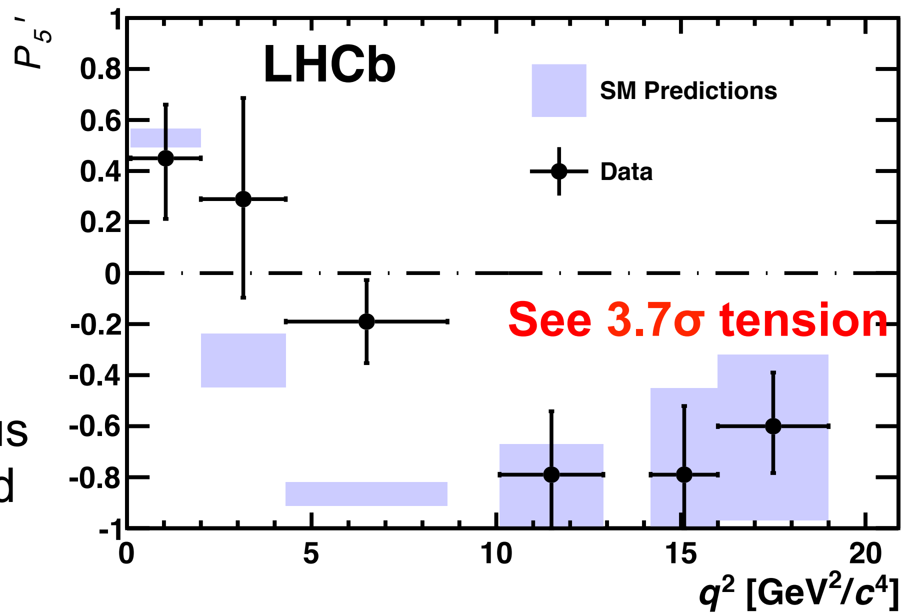






- 0.5% probability to see such a deviation with 24 independent measurements

- Finding a consistent NP explanation is highly non-trivial: prev. $B_d^0 \to K^{*0}\mu\mu$ observables plus $B_S^0 \to \mu\mu$, $B \to K\mu\mu$, $B \to X_s\gamma$ depend on same short-distance physics



See 3.7σ tension in P_5'

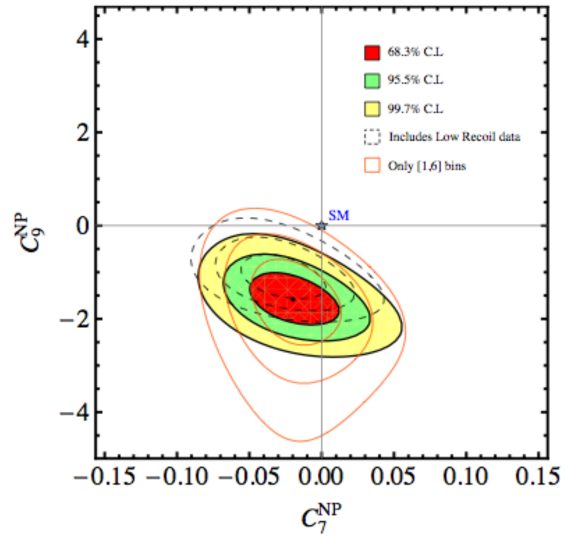
$B_d^0 \to K^{*0}\mu\mu$ – interpretation

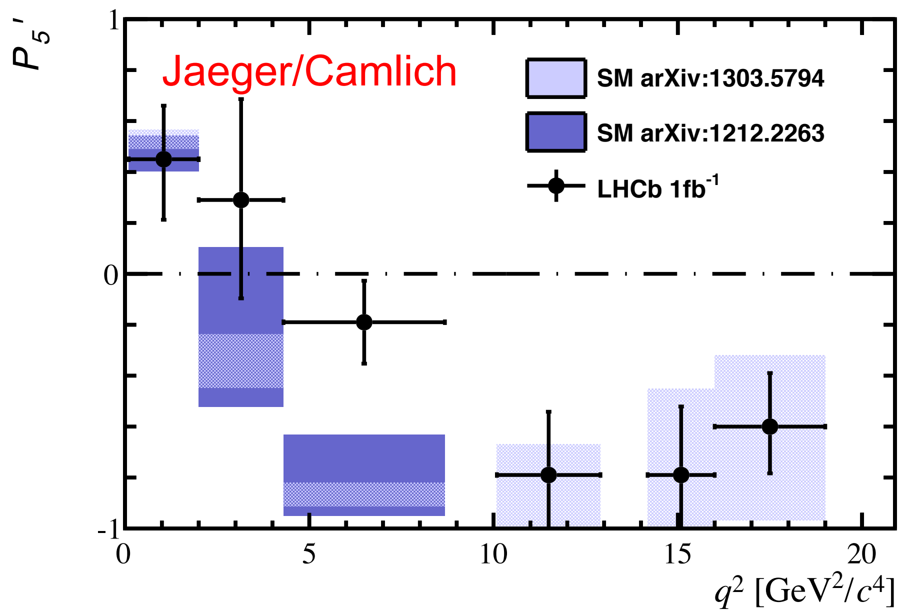
- Observables can be related to underlying Wilson coefficients

- Some theorists claim correlated behaviour from (smaller) discrepancies in other observables.

- Others believe tension is overstated

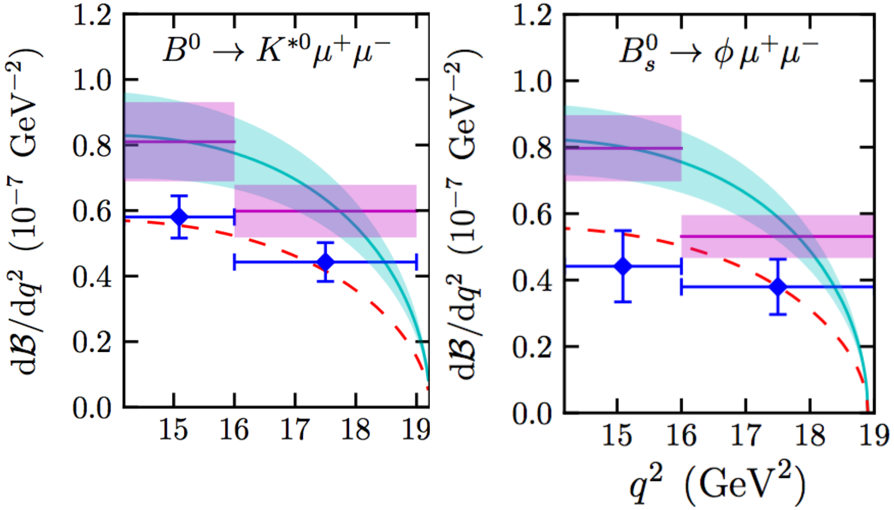
[arXiv:1307.5683]





Wingate *et al.*

[arXiv:1310.3887]

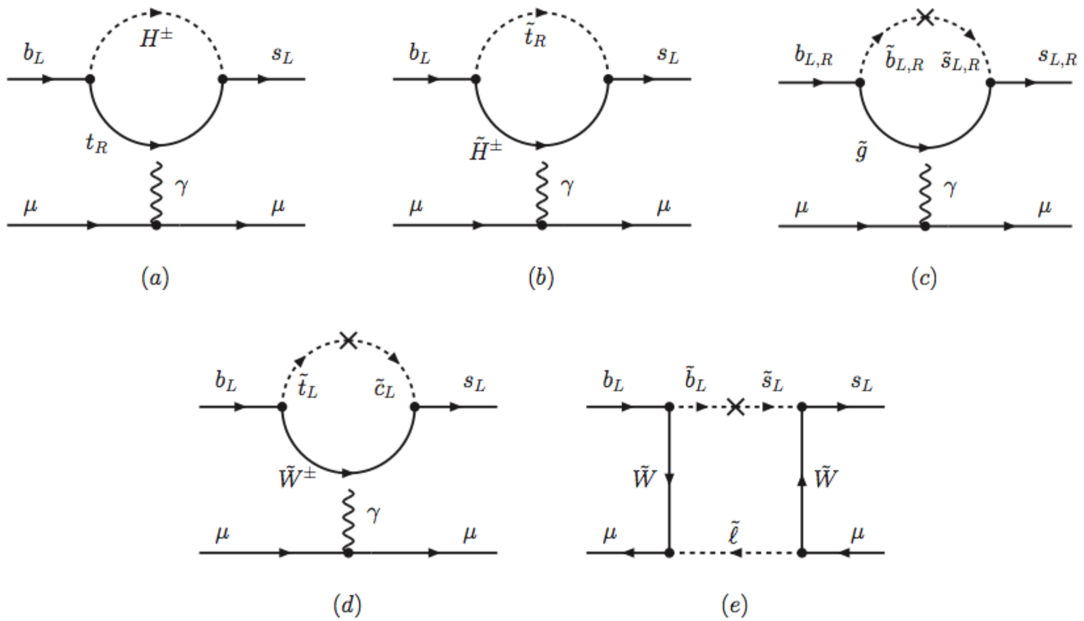


$B_d^0 \to K^{*0}\mu\mu$ – theoretical view

- Very difficult to generate in SUSY models [arXiv:1308.1501] :

  “[C_9 remains] *SM-like throughout the viable MSSM parameter space, even if we allow for completely generic flavour mixing in the squark section*”

Straub/Altmannshofer



- Models with composite Higgs/extra dimensions have same problem

- **Could generate deviation with a Z’ (given constraints from mixing need >7TeV)**

Dreaming about ultra-high statistics

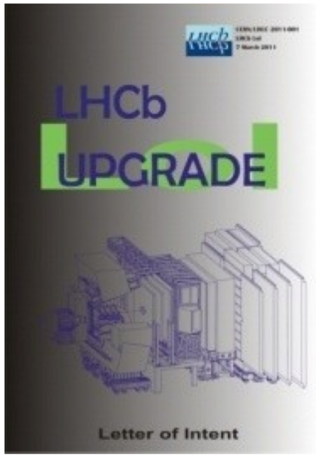
- Expect LHCb to take a further **$\sim 8fb^{-1}$** (cf. $3fb^{-1}$ in-hand) before long-shutdown of LHC accelerator 2018-19, also expect ~doubling in cross-section from increased **E_{CM}**, improved analysis methods

- Can dream of what could be achieved with a very large increase in sample sizes *e.g.*
  - CKM metrology
    - Determine γ with sub-degree precision to match anticipated improvements in indirect precision coming from lattice QCD. Improve β down to $\sim 0.02^o$
  - CPV in B_s^0 mixing
    - Measurement of ϕ_s with precision much better than SM central value, to probe for sub-leading contributions from NP
  - $B_{(d,s)}^0 \to \mu\mu$
    - Precision measurement of branching fraction down to theory uncertainty and first measurement of ultra-suppressed $B_d^0 \to \mu\mu$ branching fraction
  - $B_d^0 \to K^{*0}\mu\mu$
    - Precision studies of all observables of interest through full angular analysis

Dreaming about ultra-high statistics

- LHCb collaboration plans an upgrade, to be installed in 2018-19
- Essential features:
  - Full software trigger: will readout 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 1-2×10^{33} cm^{-2}s^{-1}
- Annual yields in muonic final states will increase 10× w.r.t. most published analyses, and 20× for hadronic decays. Aim to collect ~50 fb^{-1} in total

- LoI (March 2011) and 'Framework TDR' (May 2012) approved by LHCC
- First detector TDRs also produced



Conclusions

- B-mesons offer measurements that we can compare to precise theoretical predictions to try and find physics beyond the SM
  - Consistency of the CKM picture
  - Observables in rare decays

- LHCb actively pursuing both approaches and has bright prospects for future measurements in both areas

- Have a few interesting deviations from SM predictions – $3fb^{-1}$ analysis will yield higher precision measurements that may help clarify situation

- Collaboration planning a 2018-19 upgrade to access next generation precision