Heavy Flavour at the LHC

Valerie Gibson

Nobel Symposium, 14th May 2013

"In the lands of the North, where the Black Rocks stand guard against the cold sea, in the dark night that is very long, the People of the Northlands sit by their great log fires and they tell a tale……"

Heavy Flavour at the LHC

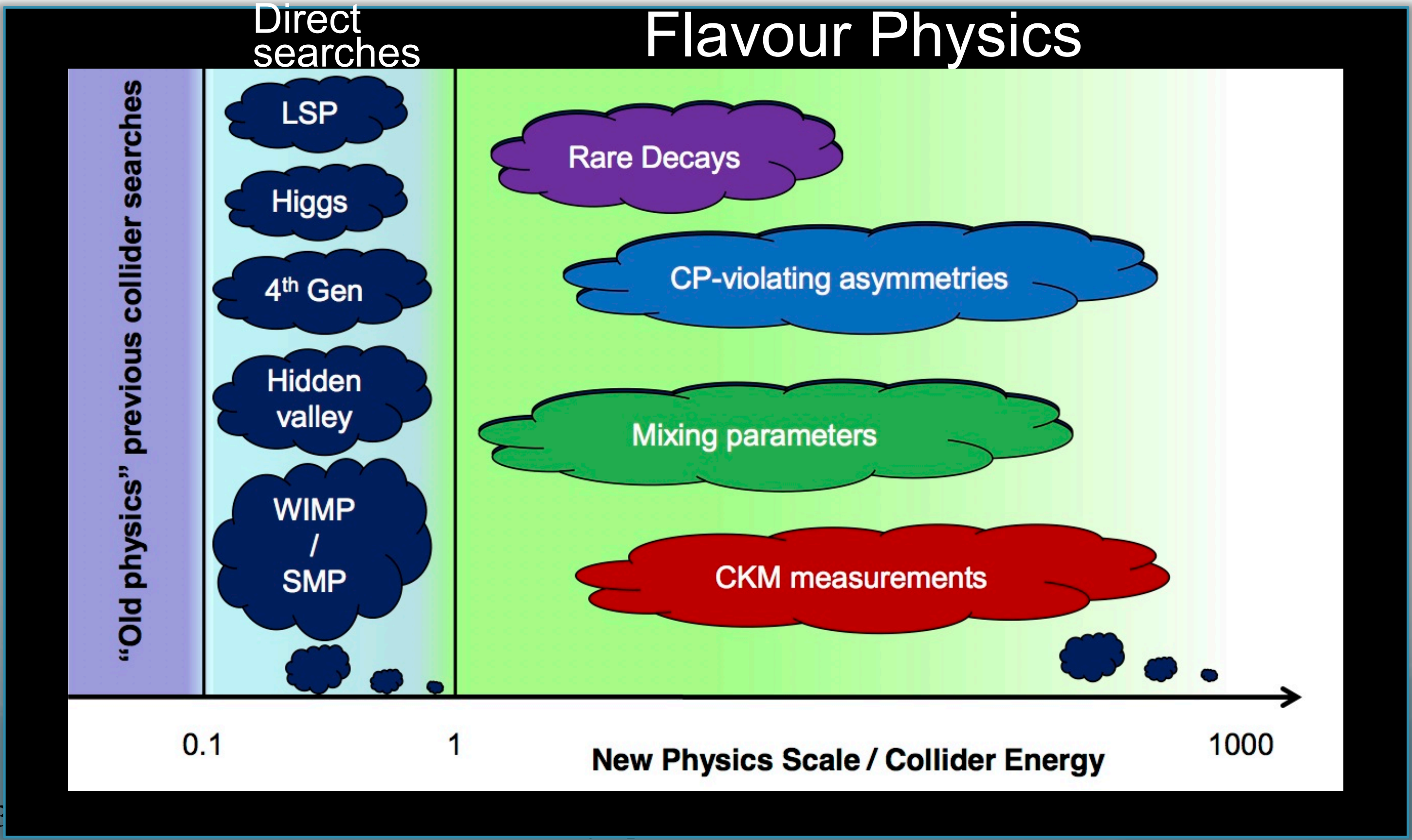
- Why study heavy flavour physics ?
- Selected highlights from recent results
  - Production & spectroscopy
  - Mixing & CP Violation
  - Rare Decays
- Future prospects
- Questions…

LHC Flavour Physicist

Noggin the Nog

Why heavy flavour physics ?

Heavy flavour physics probes beyond the LHC energy frontier and is complementary to direct searches for New Physics, providing information on the masses, couplings, spins and CP phases.



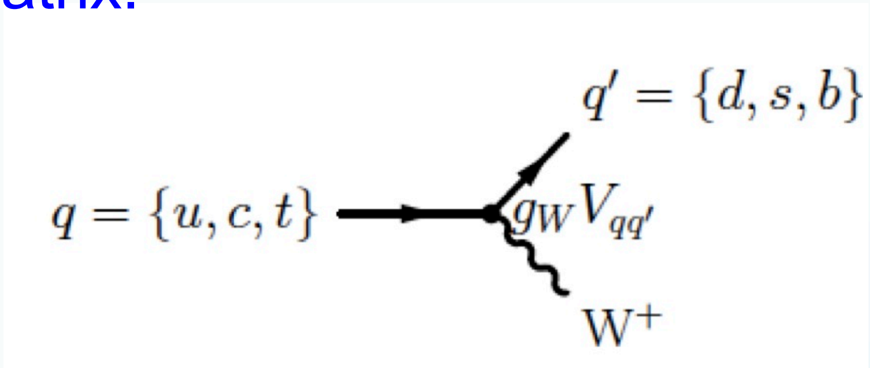
CKM picture

SM interactions are governed by Yukawa couplings to the Higgs field and the weak force.

Electroweak symmetry breaking & diagonalization of Yukawa (mass matrix) gives rise to CKM matrix.

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

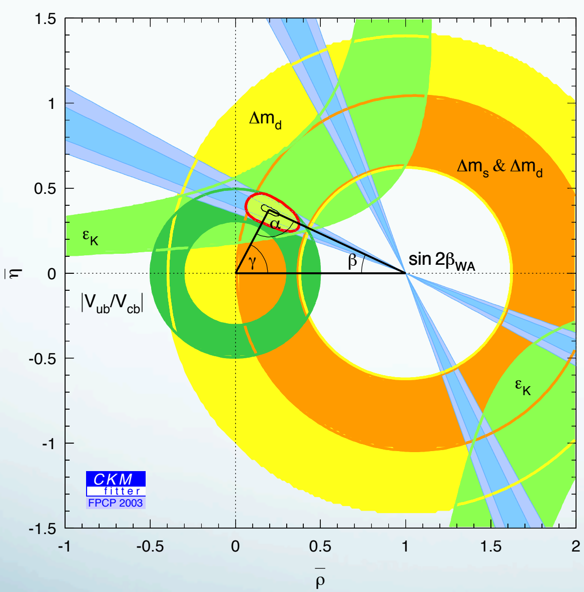
L.Wolfenstein PRL 51 (1983) 1945



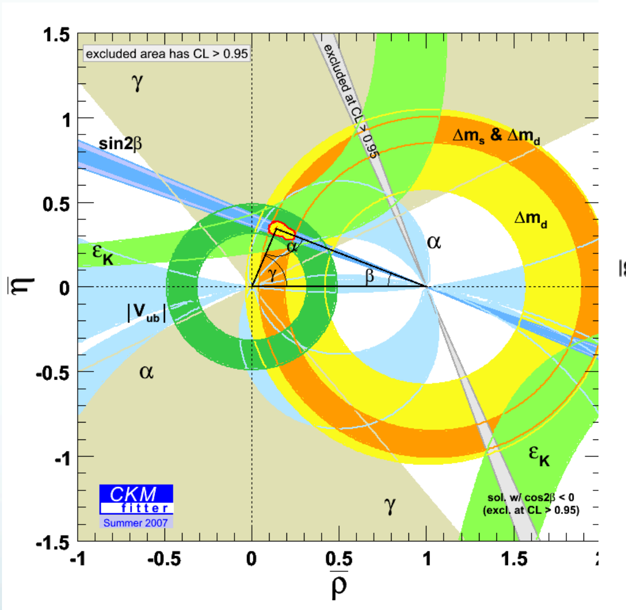
- CKM theory is highly predictive (a huge range of phenomena with only 4 parameters)
- CKM matrix is hierarchical (quark masses)
- CP violation accommodated by a single complex phase

CKM picture

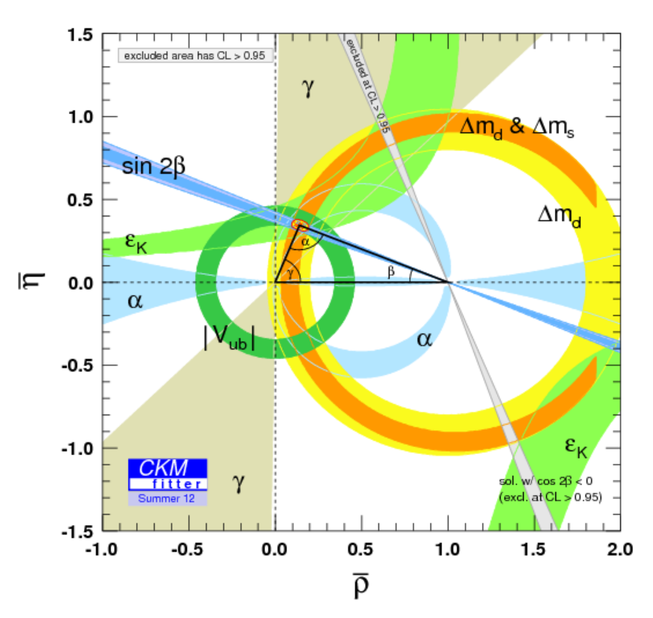
Very impressive achievements from all heavy flavour experiments (e^+e^-, $p\bar{p}$, pp) and lattice theory over the last 10 years….



2003



2007

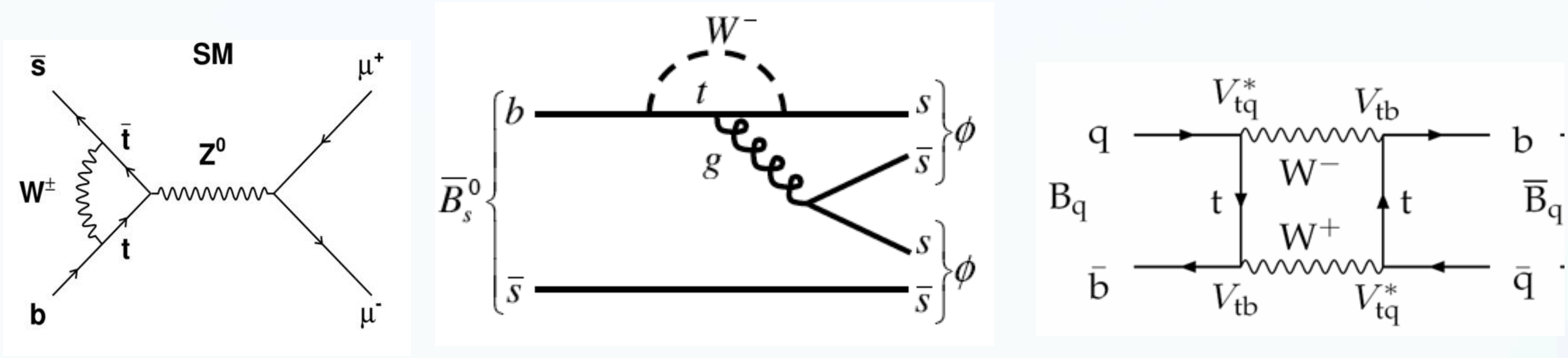


2013

http://ckmfitter.in2p3.fr

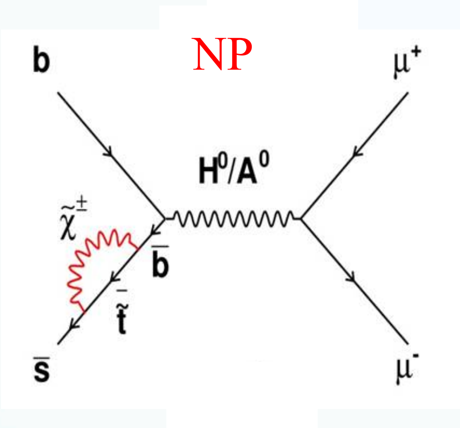
CKM picture

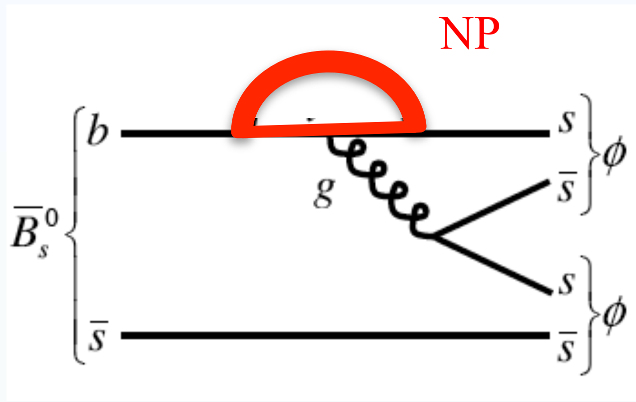
Quantum effects in loops sensitive to combination of mass and couplings

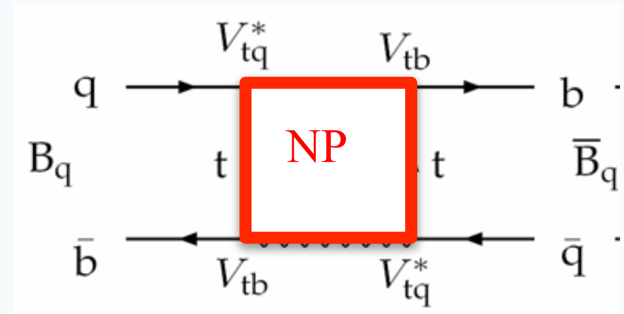


NP picture

Quantum effects in loops sensitive to combination of mass and couplings

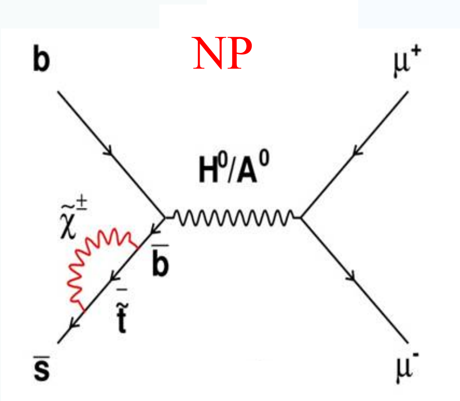


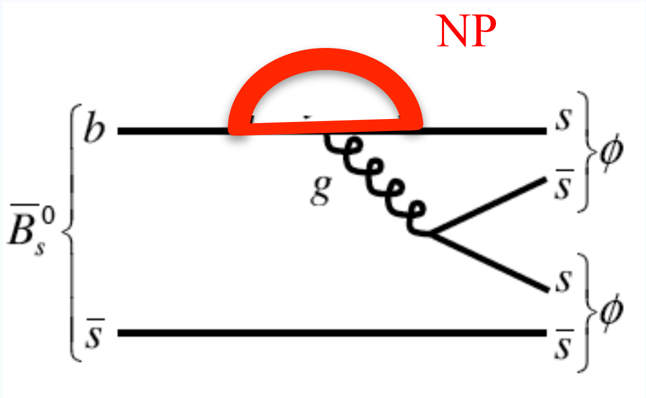


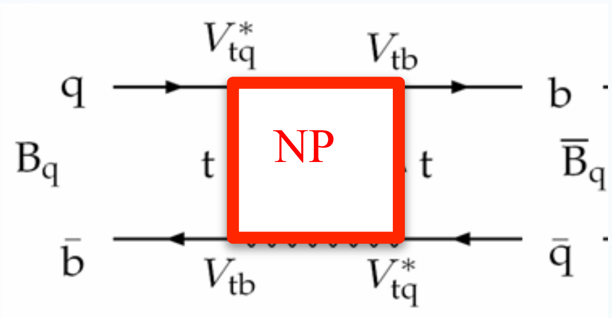


NP picture

Quantum effects in loops sensitive to combination of mass and couplings







If NP "hides" behind the SM interactions…

- either the mass scale is VERY LARGE
- or NP couplings mimic Yukawa couplings …Minimal Flavour Violation (MFV)

Flavour Physics will reveal or constrain NP theories !

Two routes to NP

LHC Flavour Physicist

Noggin the Nog

New Physics

Nooka the Nook

Two routes to NP

LHC Flavour Physicist

CP Violation

New Physics

Noggin the Nog

Extra sources must exist

BUT

No guarantee of the scale

No guarantee of more CP violation in the quark sector

Nooka the Nook

Two routes to NP

Rare decays

Strong theoretical arguments

BUT

How high is the scale?

Need to retain FCNC suppression mechanism for rare processes already seen

LHC Flavour Physicist

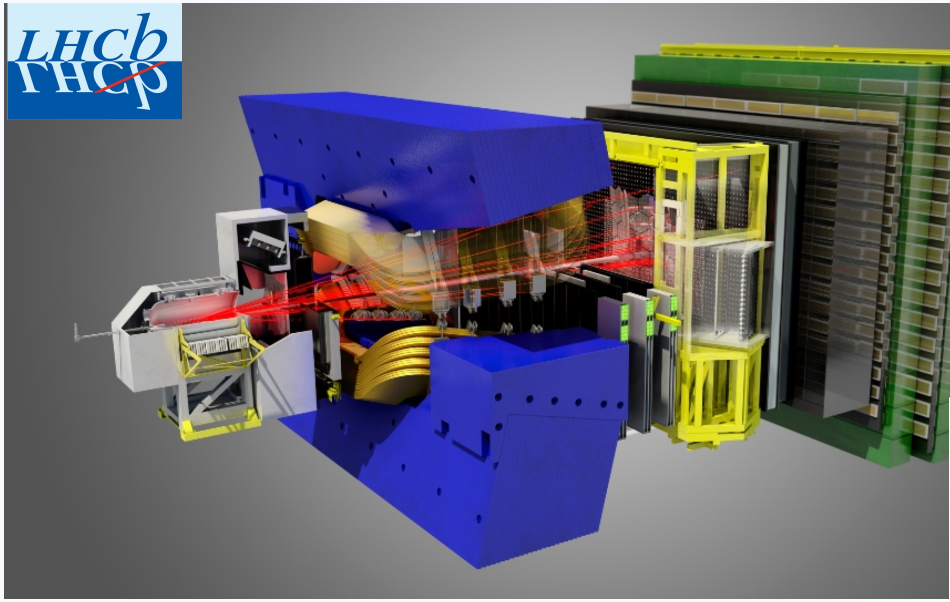
Noggin the Nog

New Physics

Nooka the Nook

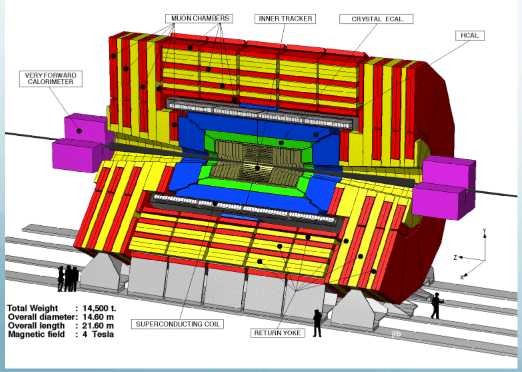
The Experiments

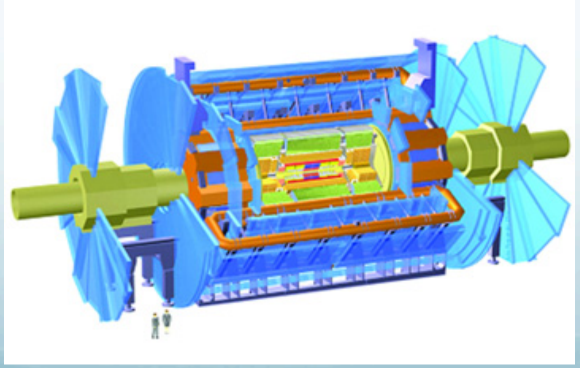
LHC is world's most copious source of heavy quarks

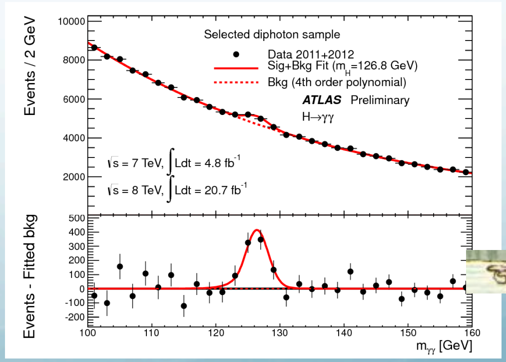


LHCb is dedicated to the study of b & c hadrons (101 papers)

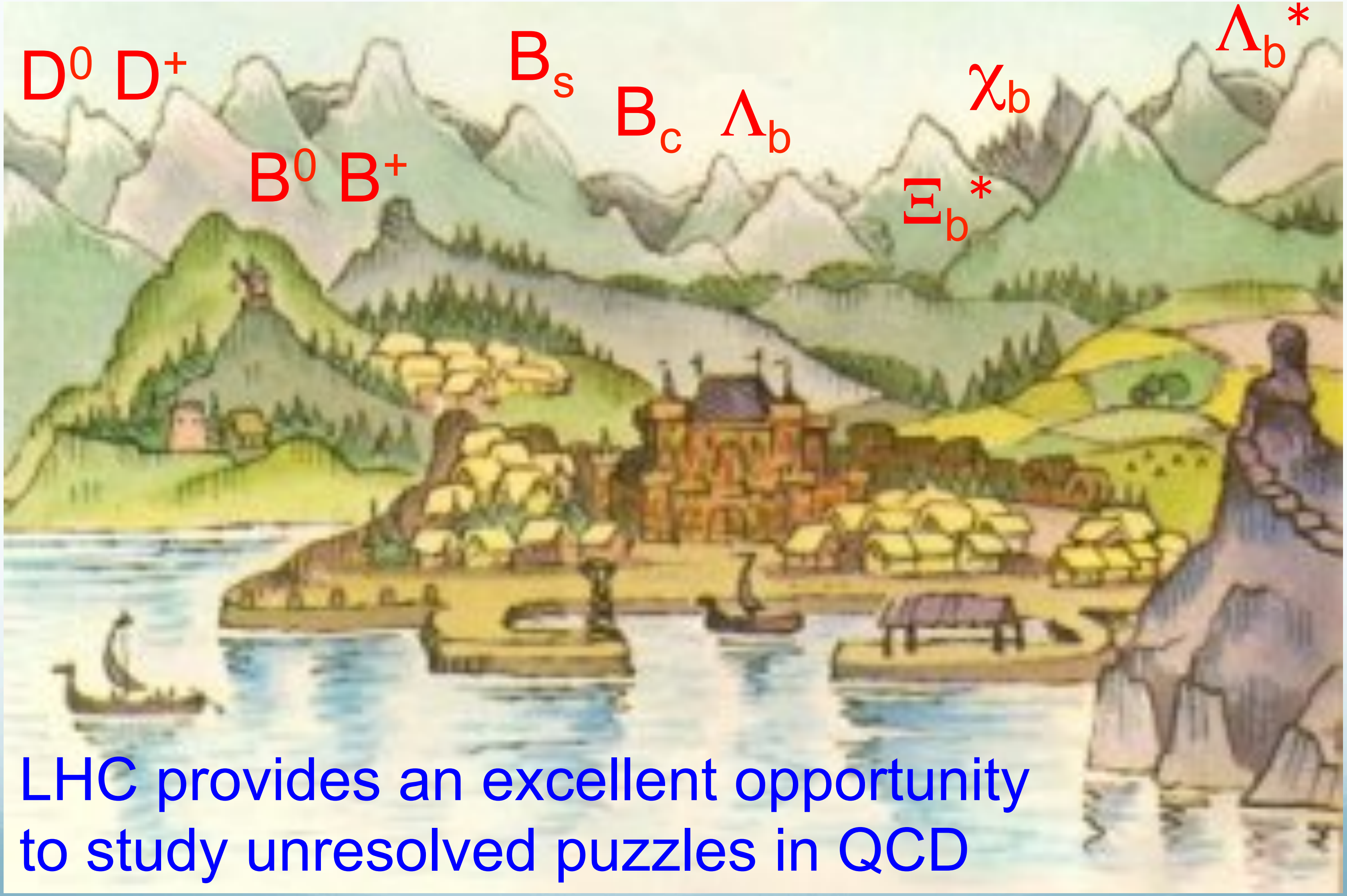
ATLAS/CMS exploit their capabilities in this sector (12/18 papers)





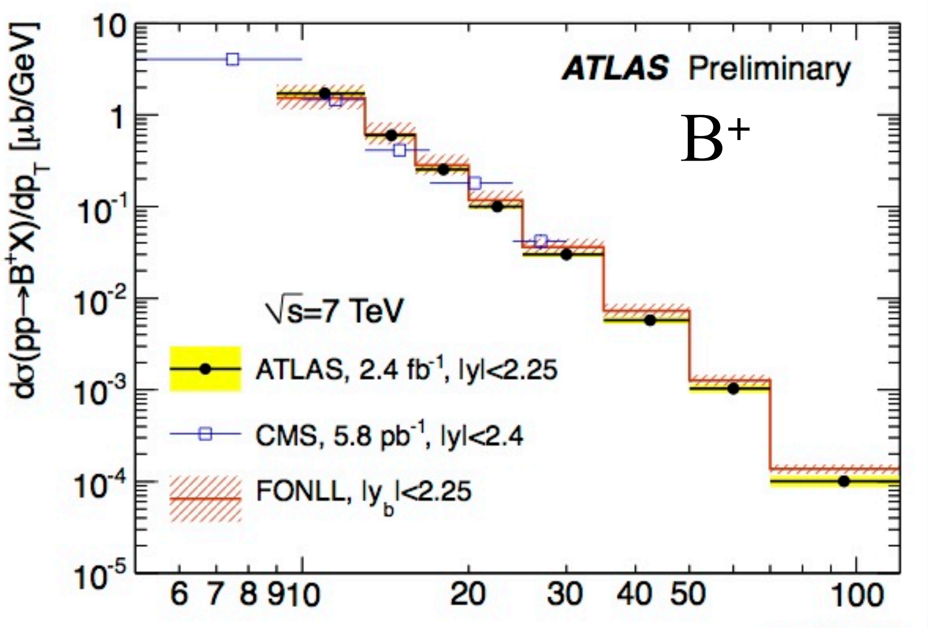


Production and Spectroscopy

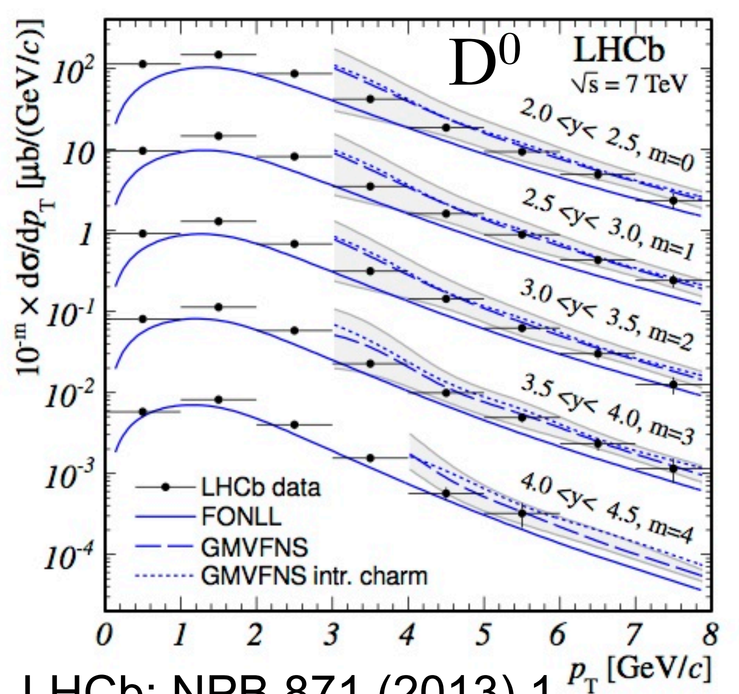


Open B and D Production

Successful description of open heavy flavour production with well developed and reliable tools (FONLL & NLO+PS).



ATLAS-CONF-2013-008



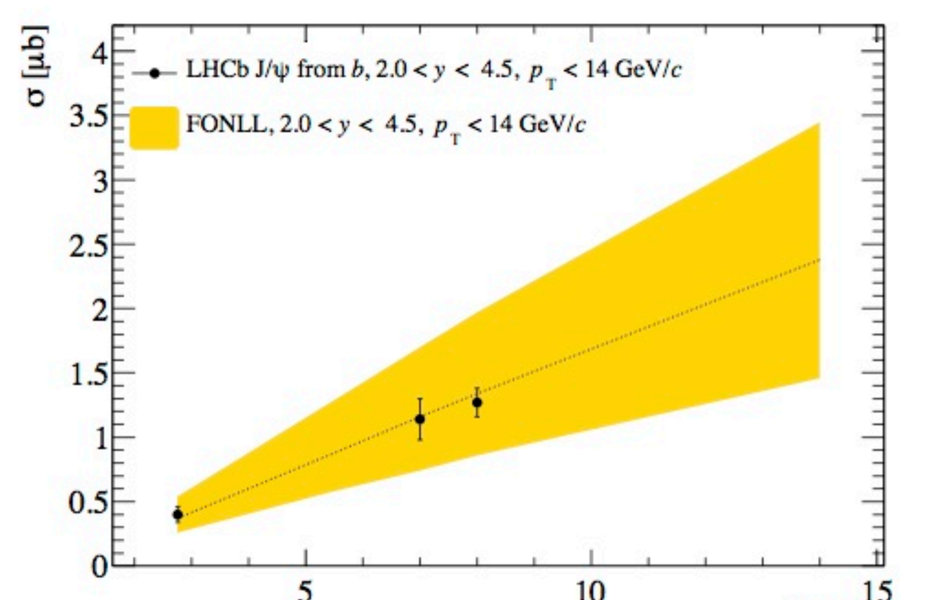
LHCb: NPB 871 (2013) 1

- Can better predictions be made of production asymmetries at LHC ? Measurements of increasing precision now arriving and issues very relevant for studies of CP violation.

Onia Production & Polarization

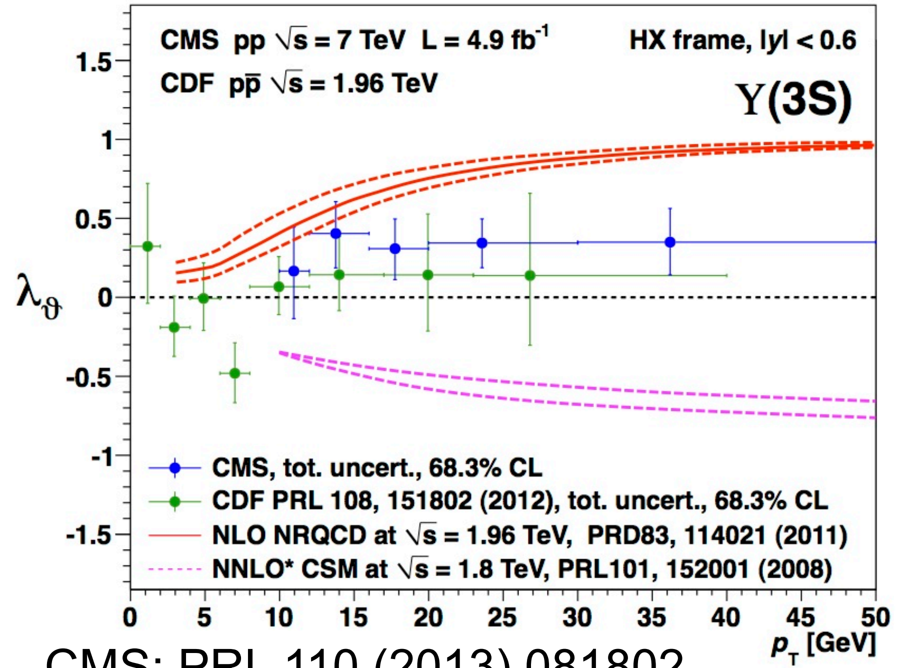
Theory less successful in describing onia production.

J/ψ from B hadrons



LHCb: arXiv:1304.6977

Υ polarization



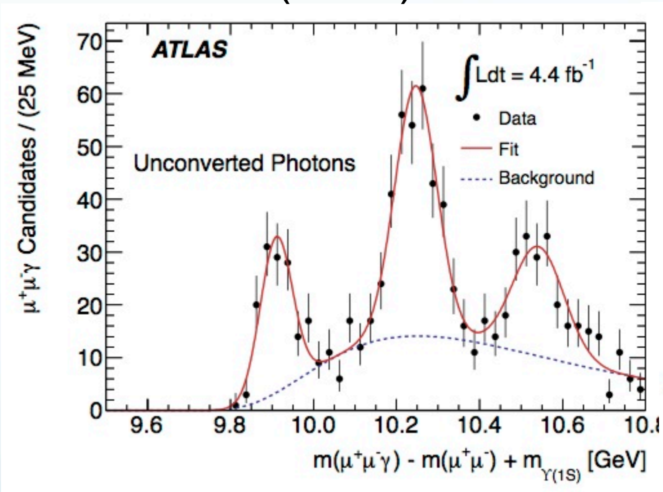
CMS: PRL 110 (2013) 081802

- Can the theory (e.g. FONLL) provide even better precision?
- Polarization measurements stubbornly refuse to match predictions.

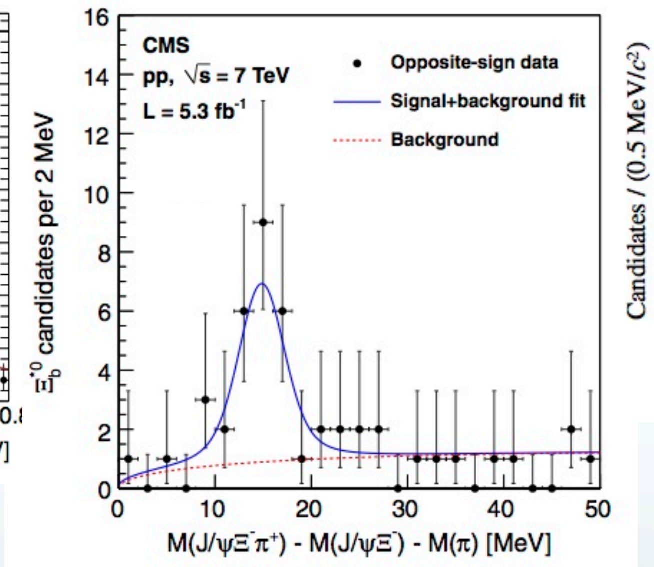
Observation of New States

Many new states have already been discovered…

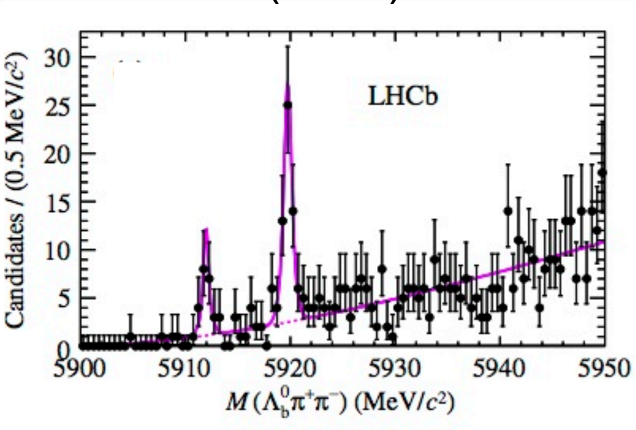
New χ_b State
PRL 108 (2012) 152001



New Ξ_b Baryon
PRL 108 (2012) 252002



Excited Λ^0s
PRL 109 (2012) 172003

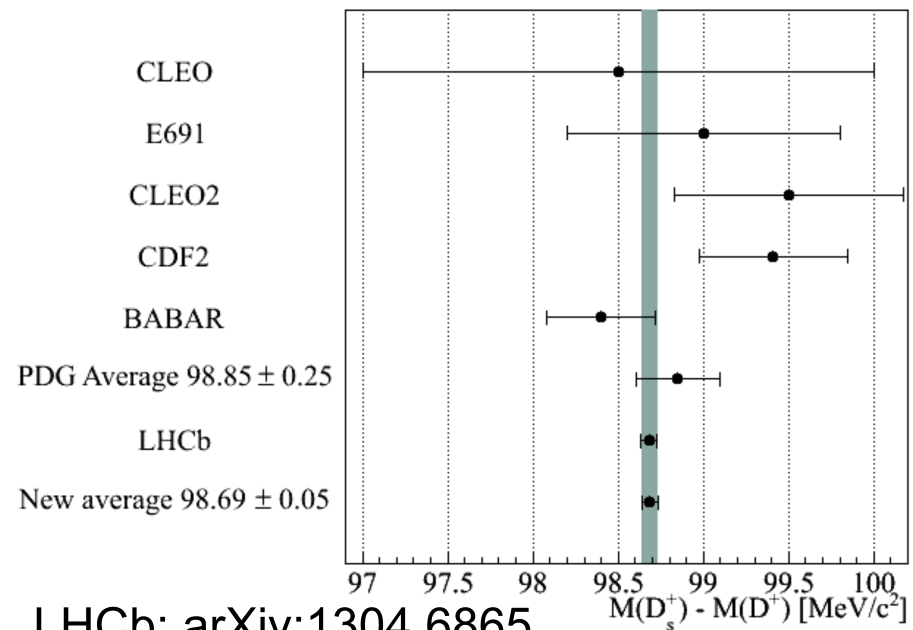


… and many new B_s and B_c decay modes and excited states observed for the first time.

Masses and Lifetimes

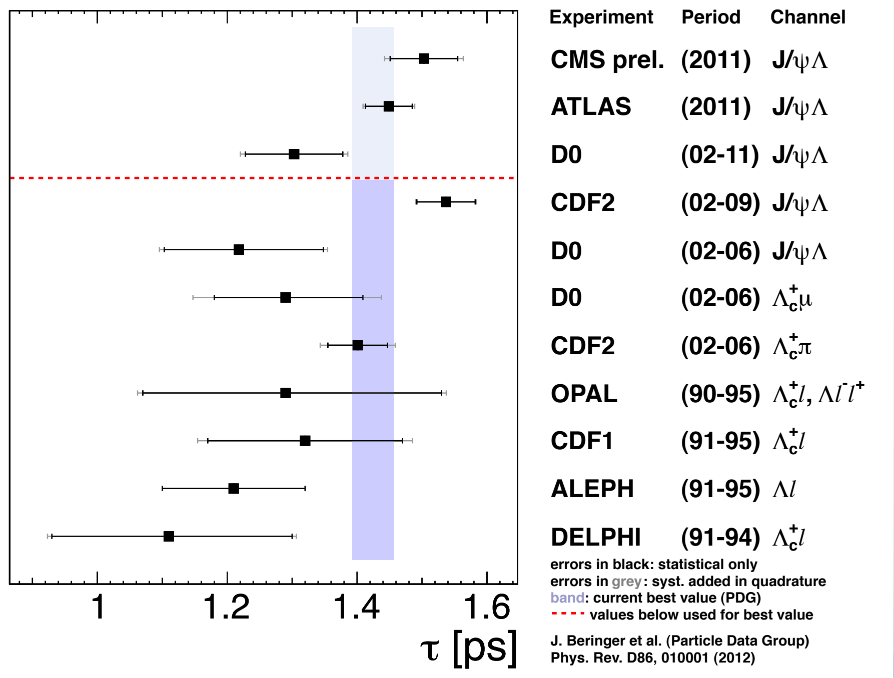
LHC measures mass and lifetimes with unrivalled precision.

$D_S^+ - D^+$ mass difference



LHCb: arXiv:1304.6865

Λ_b lifetime



Tension of Λ_b lifetime with expectation greatly reduced.

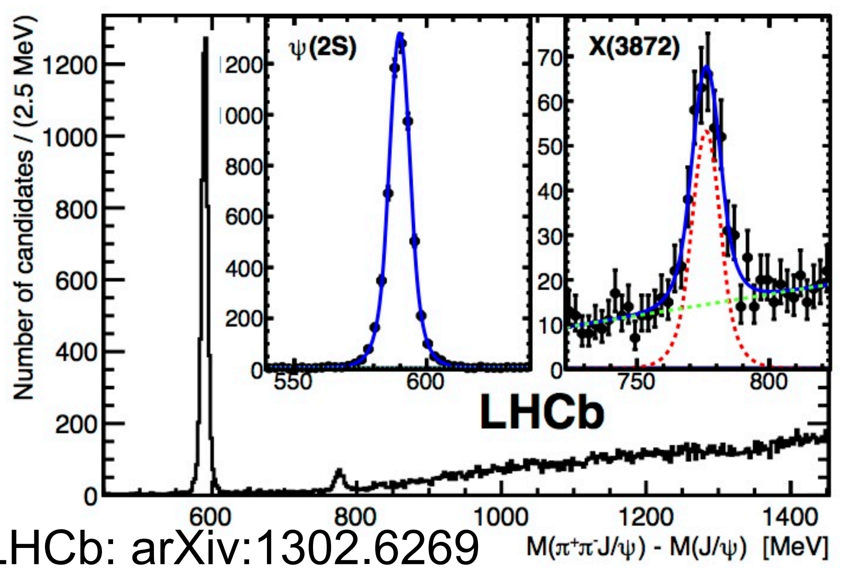
Exotic spectroscopy

X(3872) discovered in 2003 (Belle PRL 91 (2003) 262001) and J^{PC} limited to 1^{++} or 2^{-+} (CDF PRL 98 (2007) 132002).

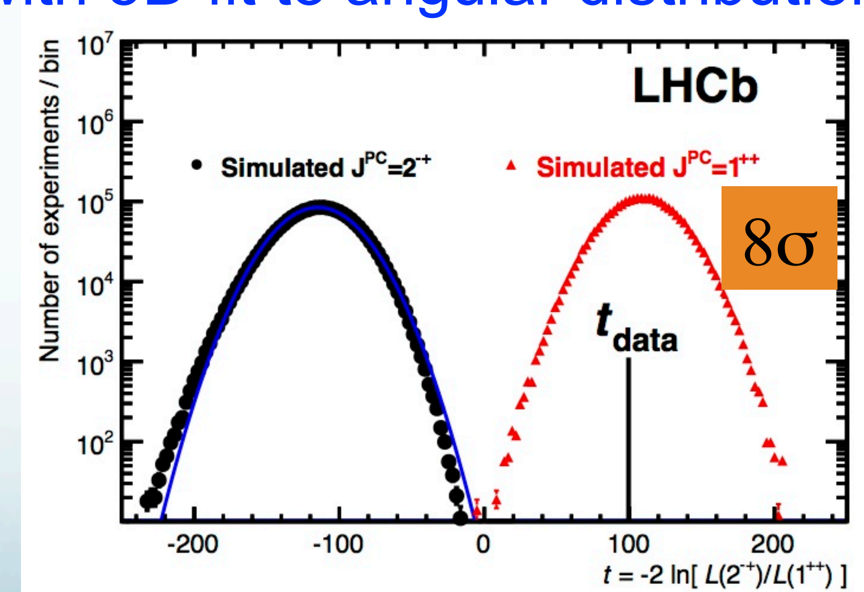
Nature unclear (INSPIRE: 224 papers with X(3872) in title)

- does not fit well with conventional $c\bar{c}$ models (above open charm threshold with narrow width).

LHCb analysis of $B^+ \to X(3872) K^+$ with 5D fit to angular distributions



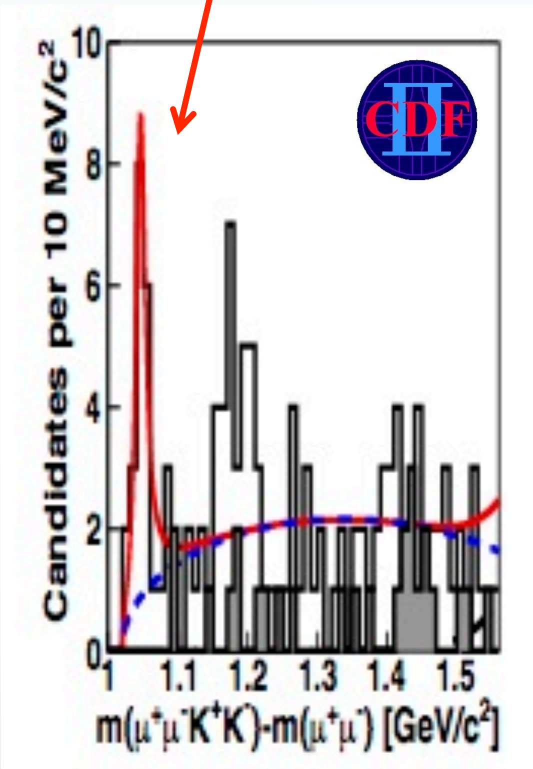
LHCb: arXiv:1302.6269



$J^{PC}=1^{++}$ supports molecular interpretation.

Is there an X(4140) ?

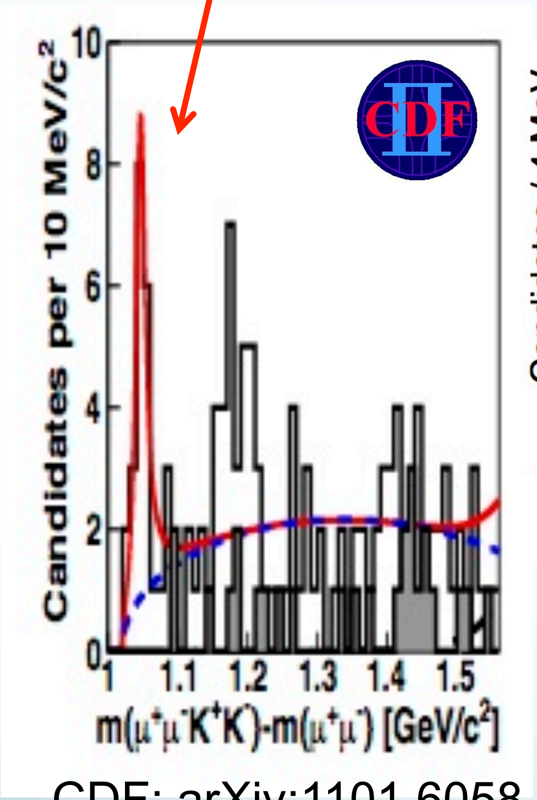
Spotted in $B^+ \to J/\psi \phi K^+$ decays…



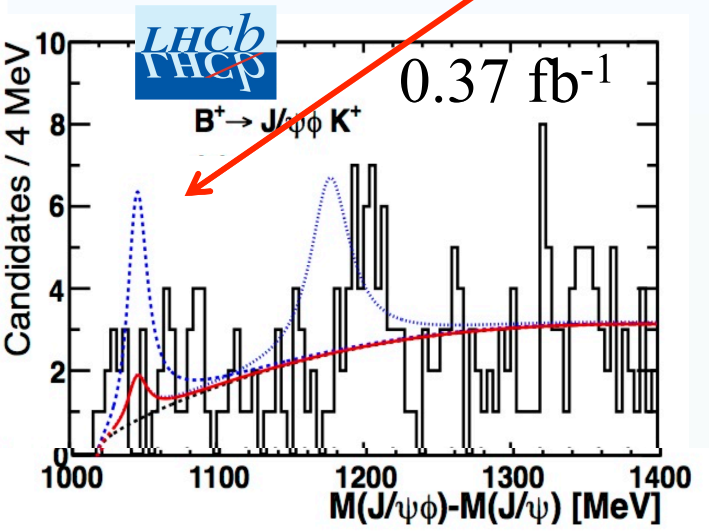
CDF: arXiv:1101.6058

Is there an X(4140) ?

Spotted in $B^+ \to J/\psi\phi K^+$ decays…unspotted…



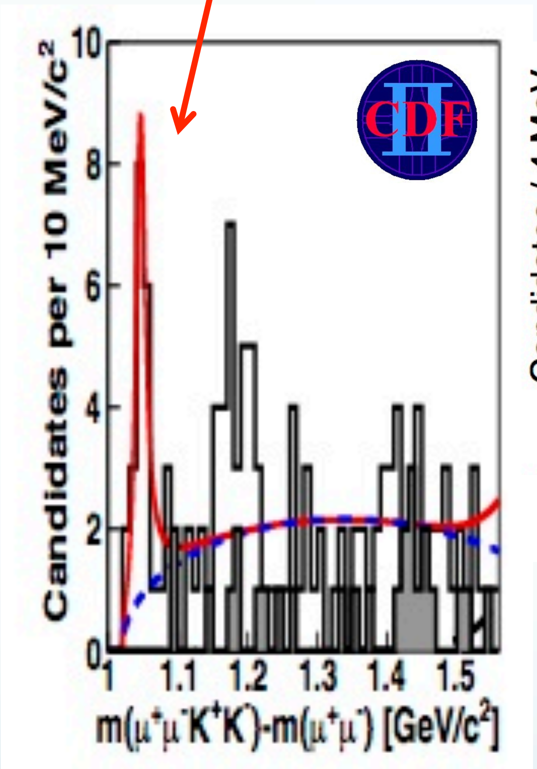
CDF: arXiv:1101.6058



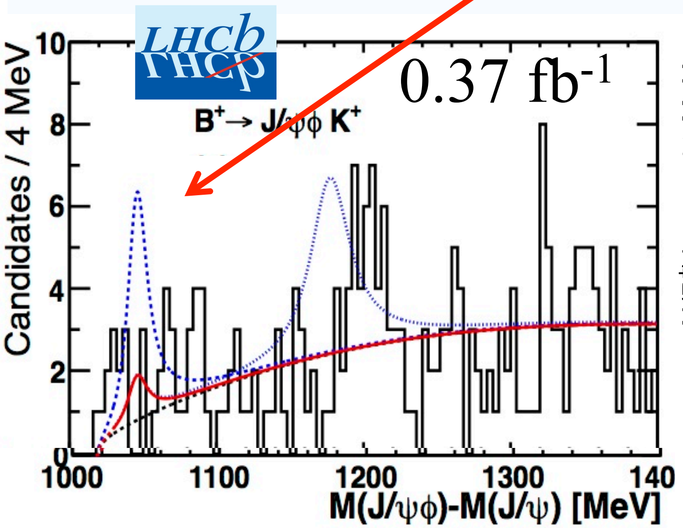
LHCb: PRD 85 (2012) 091103 (R)

Is there an X(4140) ?

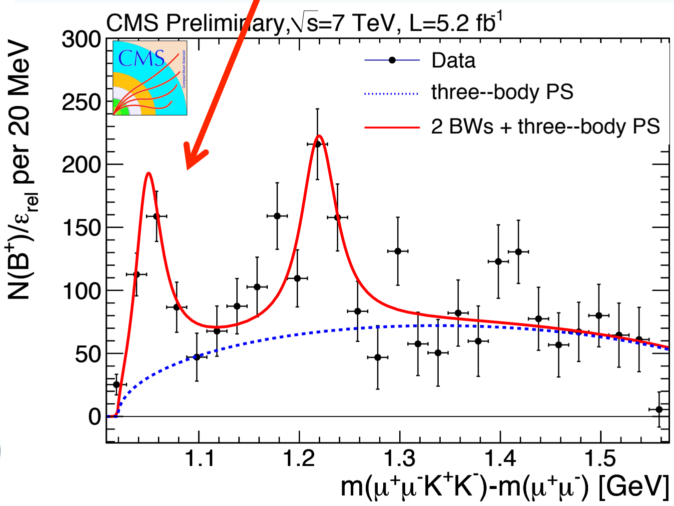
Spotted in $B^+ \to J/\psi\phi K^+$ decays…unspotted…spotted…



CDF: arXiv:1101.6058



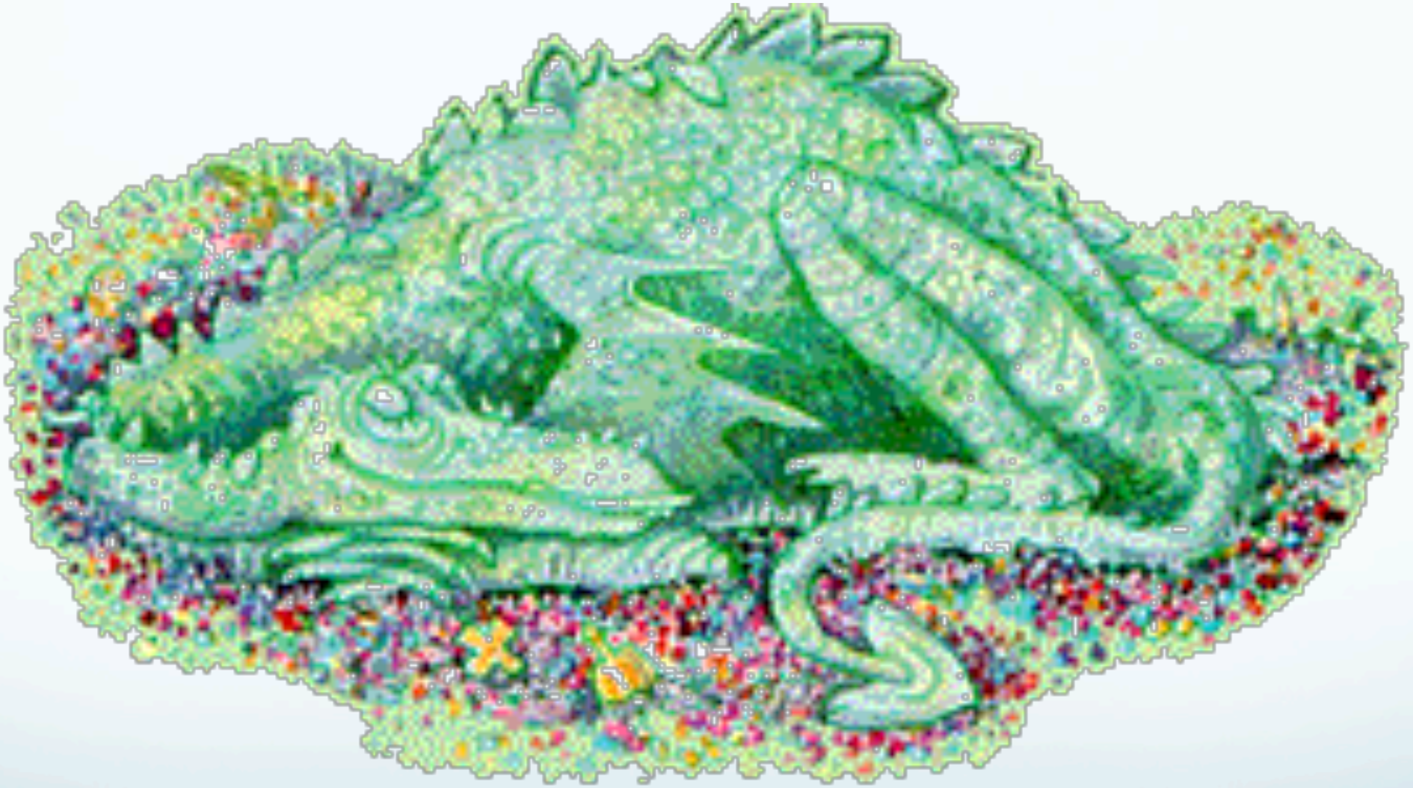
LHCb: PRD 85 (2012) 091103 (R)



CMS: PhysicsResultsBPH11026

Wait for LHCb update and full amplitude analysis of spectrum

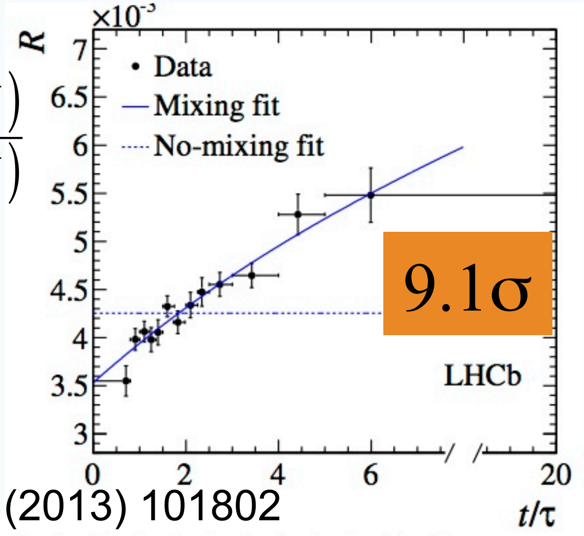
Mixing & CP Violation



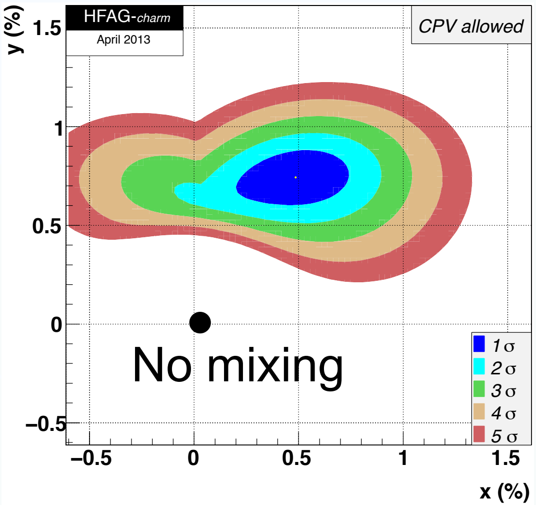
D and B mixing

Mixing well established in D^0, B^0 and B_s systems…

$$R = \frac{\Gamma\left(D^0 \to K^+\pi^-\right)}{\Gamma\left(D^0 \to K^-\pi^+\right)}$$

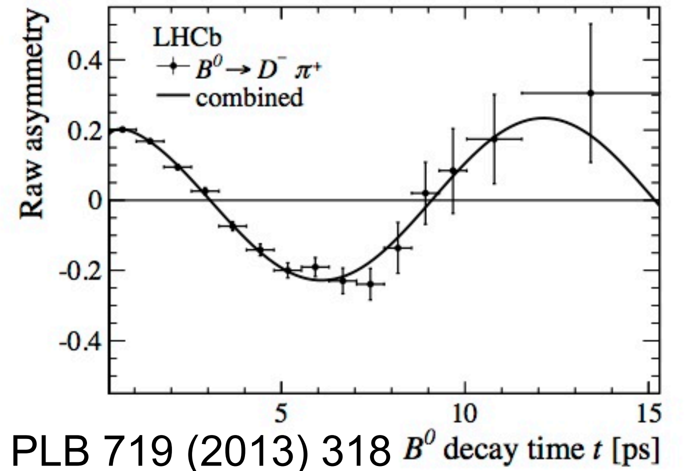


LHCb: PRL 110 (2013) 101802

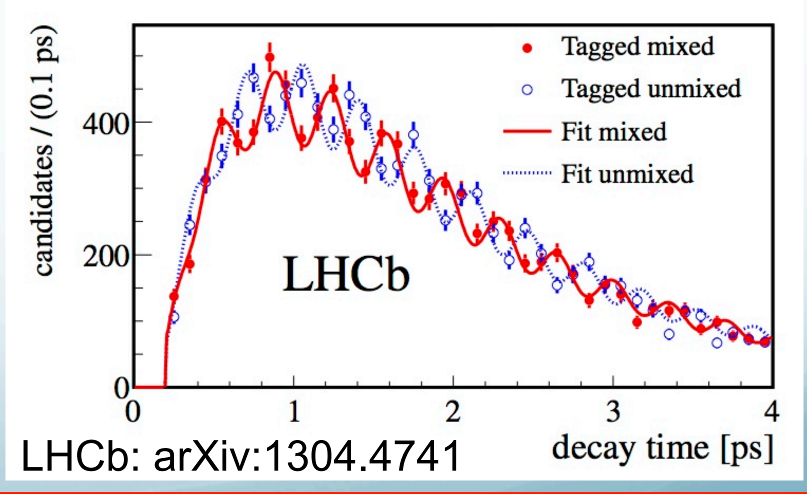


$$x = \frac{(m_2 - m_1)}{\Gamma}$$

$$y = \frac{(\Gamma_2 - \Gamma_1)}{\Gamma}$$



LHCb: PLB 719 (2013) 318



LHCb: arXiv:1304.4741

$\Delta m_d = 0.5156 \pm 0.0051\,(\text{stat.}) \pm 0.0033\,(\text{syst.})\,\text{ps}^{-1}.$

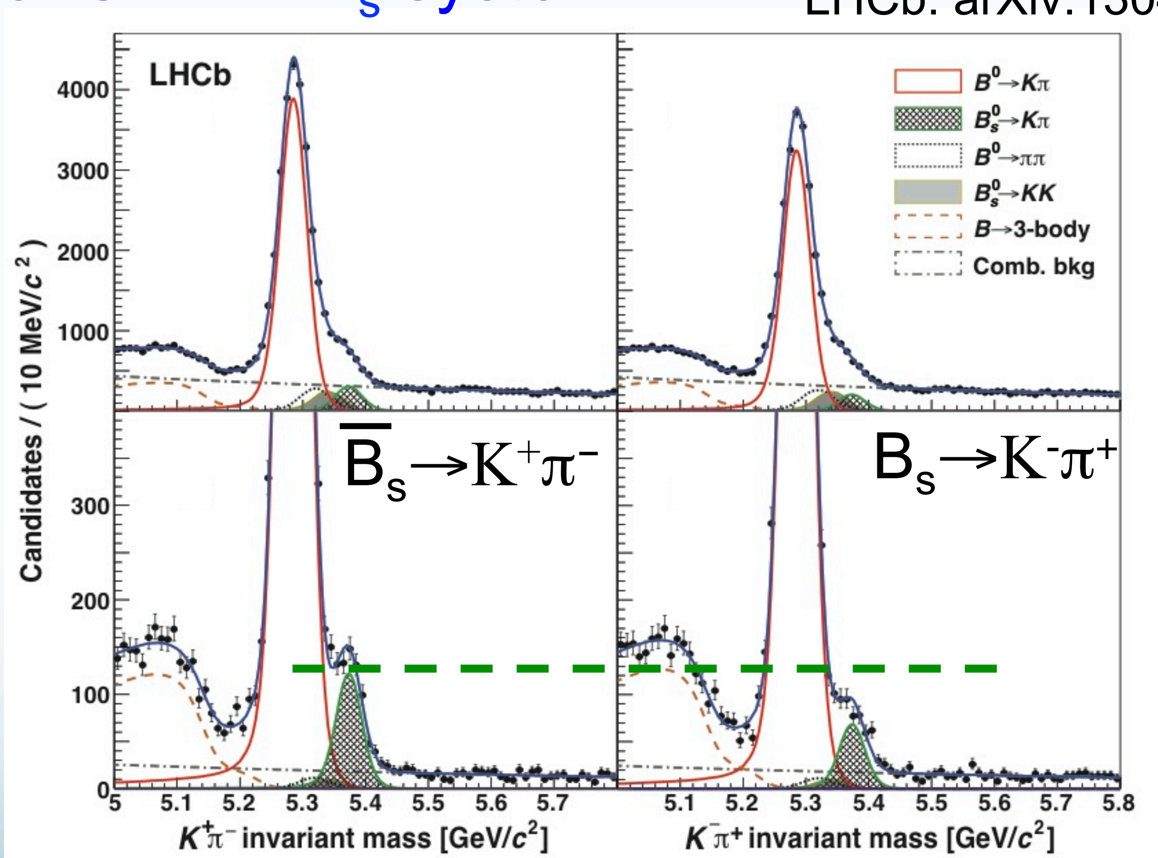
$\Delta m_s = 17.768 \pm 0.023\,(\text{stat}) \pm 0.006\,(\text{syst})\,\text{ps}^{-1}$

Large CPV exists in B system

Observed in $B^0 \to J/\psi K_s$ decays (sin 2β from B factories)

Discovery of CPV in B_s system

LHCb: arXiv:1304.6173



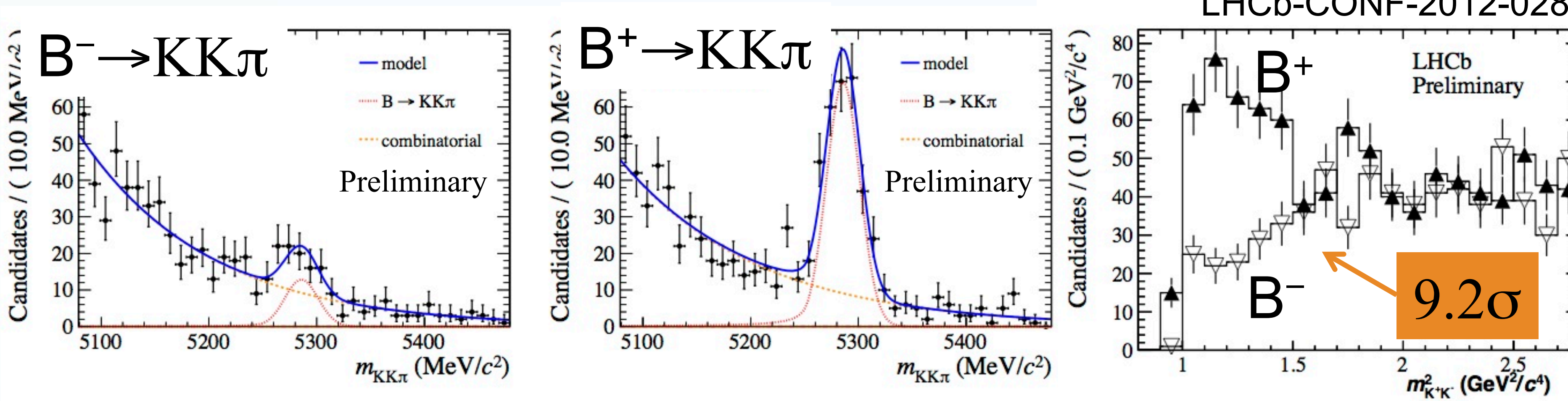
$$A_{CP}(B_s^0 \to K^-\pi^+) = 0.27 \pm 0.04\,(\text{stat}) \pm 0.01\,(\text{syst}).$$

6.5σ

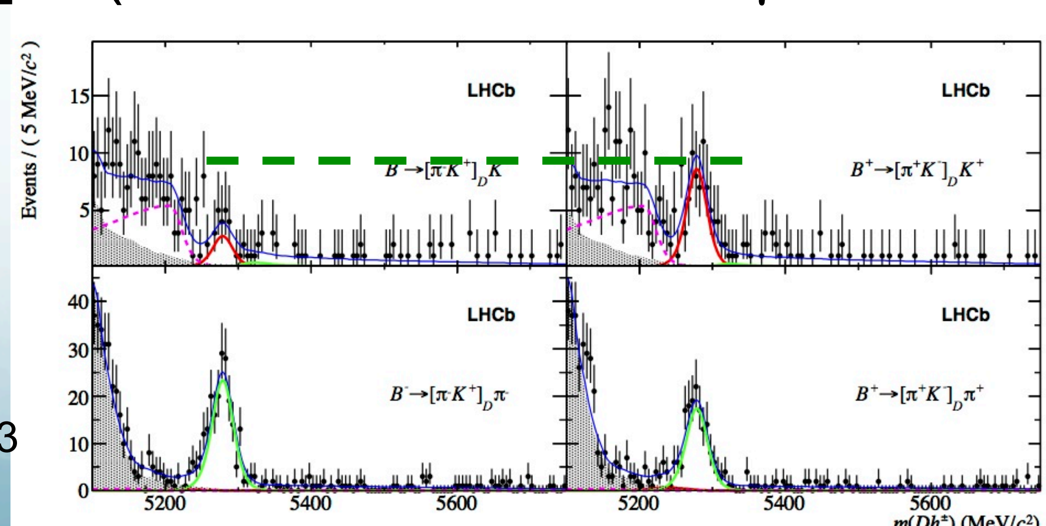
Large Direct CPV

Large direct CPV observed in $B^\pm \to h^\pm h^+ h^-$ Dalitz plot regions

LHCb-CONF-2012-028



and $B^\pm \to D[\to K\pi]K^\pm$ (ADS mode used for γ measurement)



LHCb: PLB 712 (2012) 203

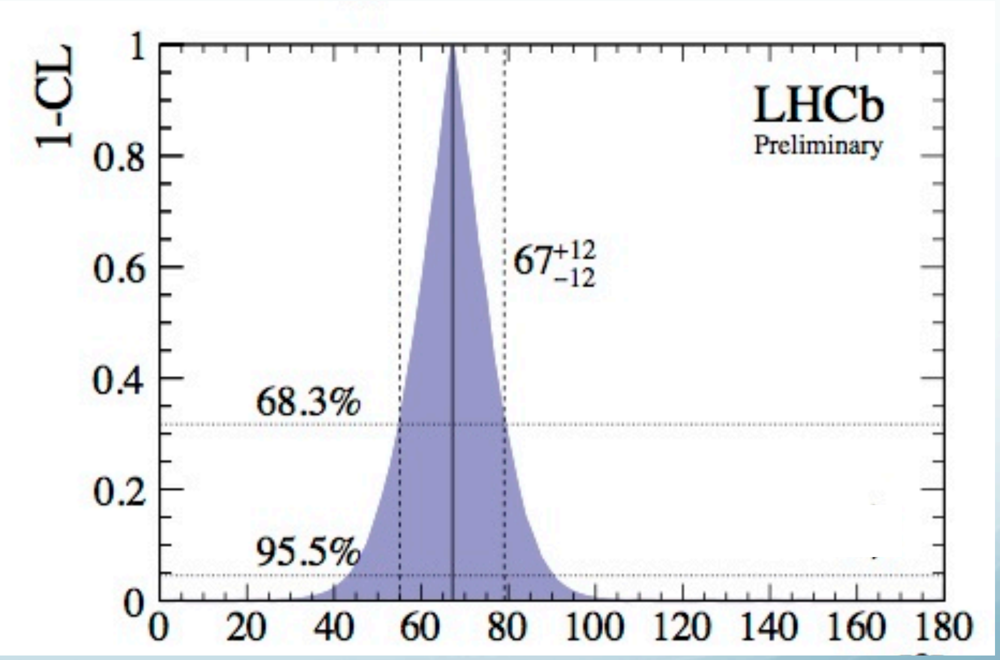
CP angle γ

Direct CP violation caused by the angle γ in the CKM matrix.

Only tree-level processes e.g. $B^{\pm} \rightarrow DK^{\pm}$ enable γ to be determined with negligible SM theoretical uncertainty.

LHCb combination of results using GLW/ADS ($D \rightarrow hh$) & GGSZ ($D \rightarrow KShh$) analyses gives

$\gamma = 67 \pm 12$ deg.



LHCb-CONF-2013-006 γ (degrees)

(BaBar/Belle sensitivity both 16 deg.)

Is there CPV in Mixing ?

Dimuon charge asymmetry using semileptonic b decays

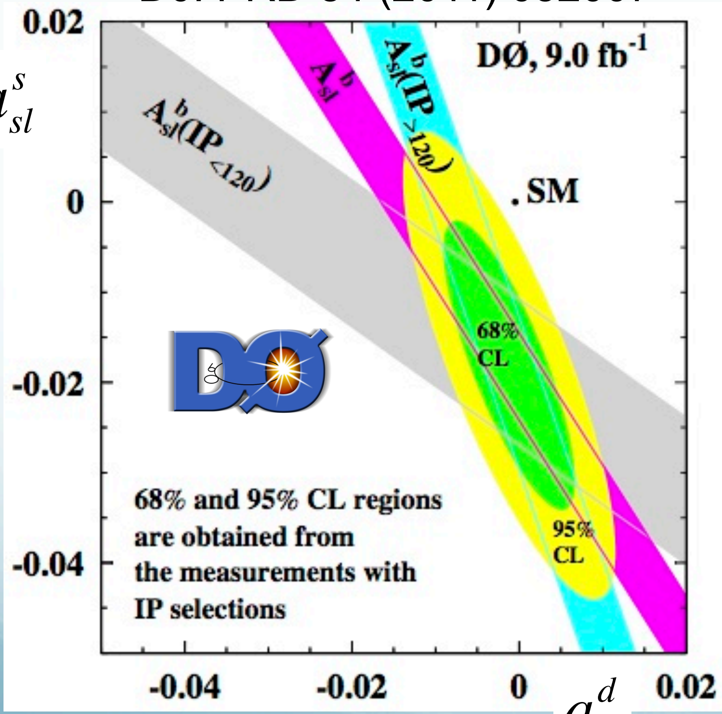
$$A^b_{sl} = C_d\, a^d_{sl} + C_s\, a^s_{sl} \quad \text{with} \quad a^q_{sl} = \frac{\Delta\Gamma_q}{\Delta M_q}\tan\phi_q$$

2011

D0: 3.9σ from SM

D0: PRD 84 (2011) 052007

a^s_{sl}

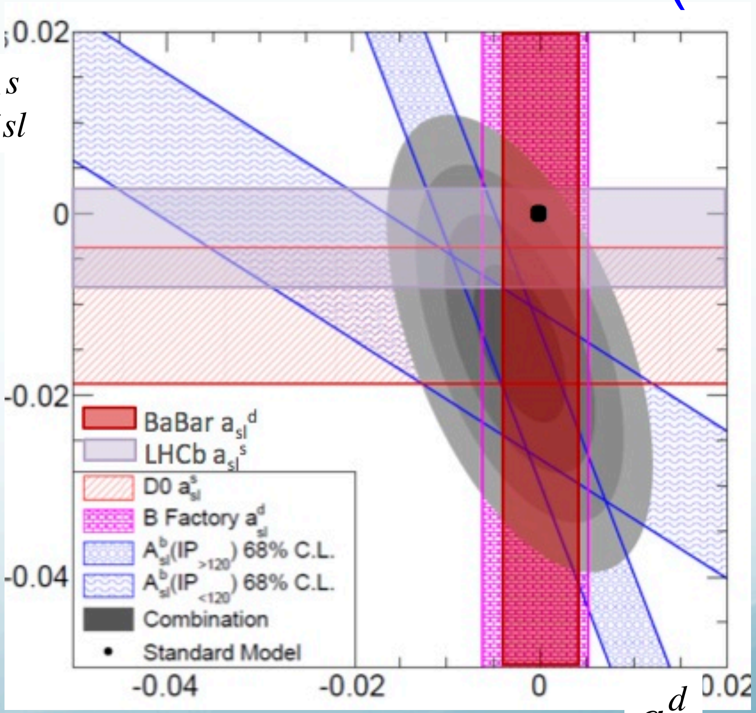


a^d_{sl}

2013

All measurements consistent with D0 and with the SM (2.4σ)

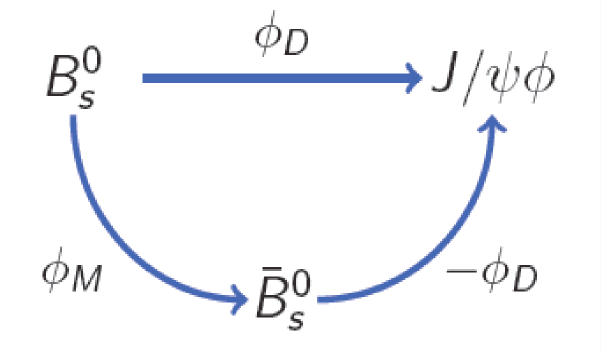
a^s_{sl}



a^d_{sl}

Mixing Induced CPV in B_s system

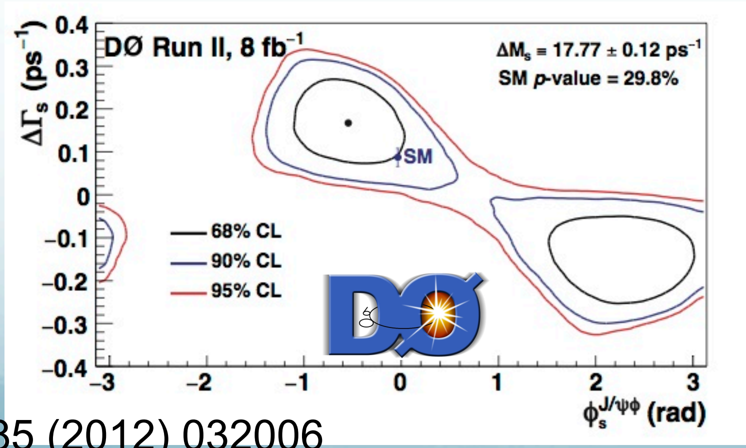
CP violation in interference between mixing and decay
e.g. as measured in $B_s \to J/\psi\phi$



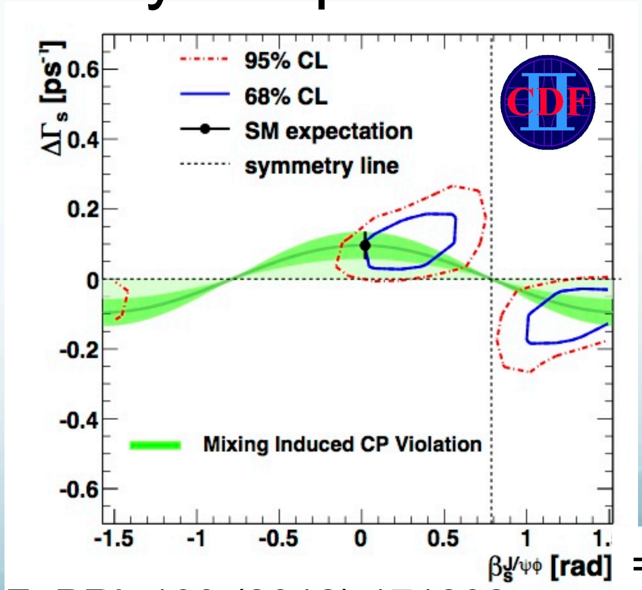
CP violating phase $\phi_s = \phi_M + 2\phi_D$
very small and well determined in SM.

Possible NP in box diagram can modify the phase.

Tevatron final results…..



D0: PRD 85 (2012) 032006



$= -\phi_s/2$

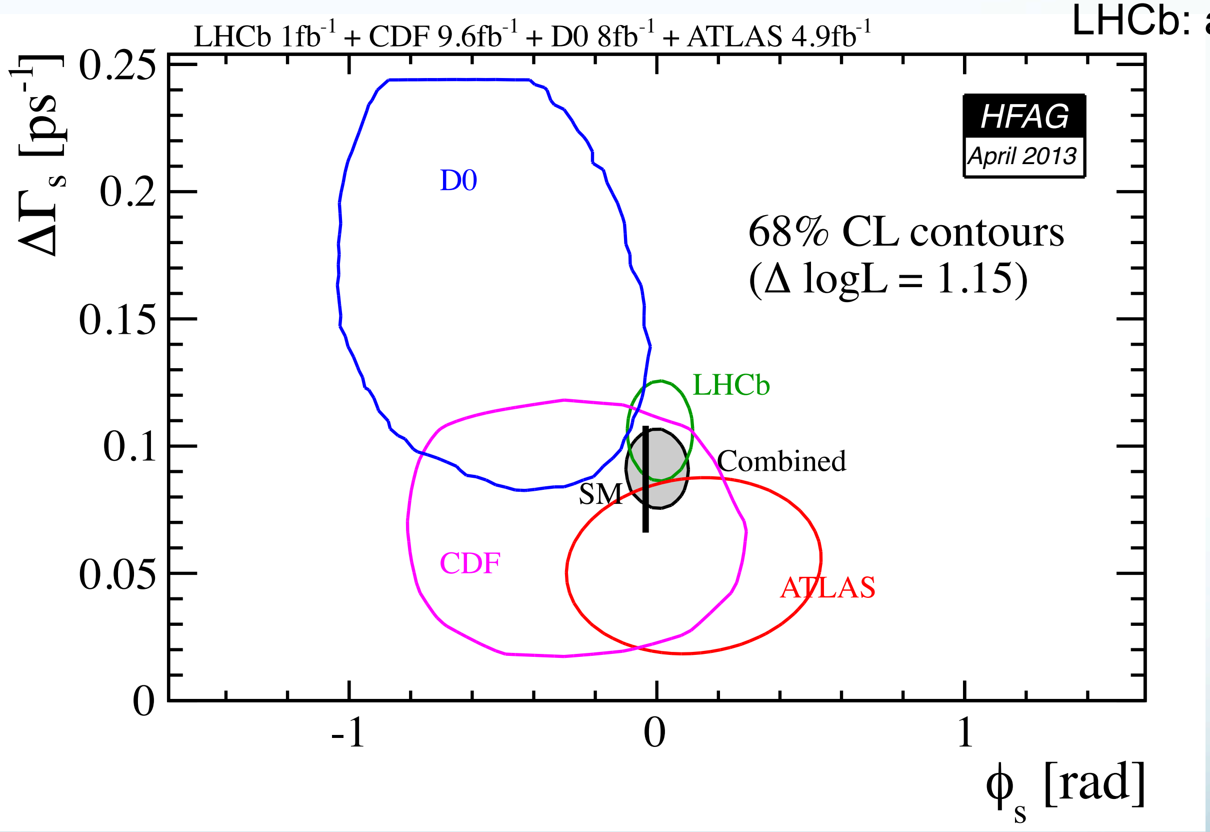
CDF: PRL 109 (2012) 171802

Mixing Induced CPV in B_s system

Picture recently (Beauty 2013) added to by ATLAS (flavour-tagged) & final LHCb 2011 measurements.

ATLAS-CONF-2013-039

LHCb: arXiv:1304.2600

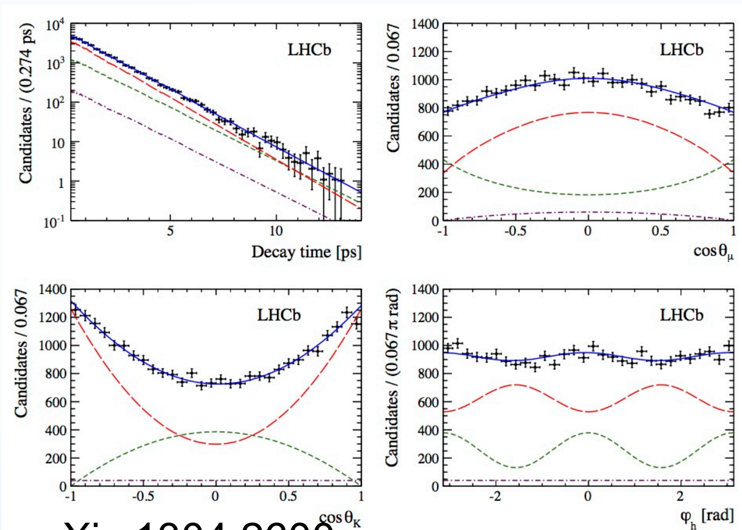


No big NP effect observed, now crucial to improve precision.

Mixing Induced CPV in B_s system

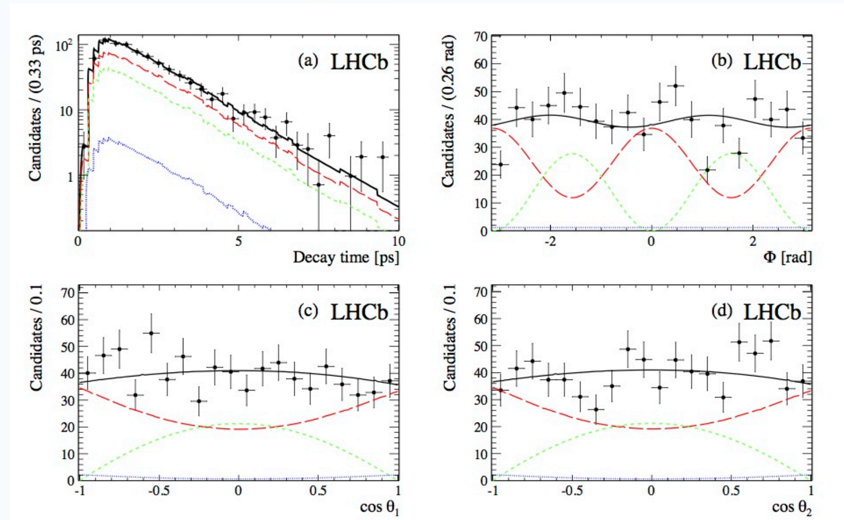
Compare tree-level decays with rare penguin processes.

$B_s \to J/\psi KK$ (& $B_s \to J/\psi\pi\pi$)



LHCb: arXiv:1304.2600

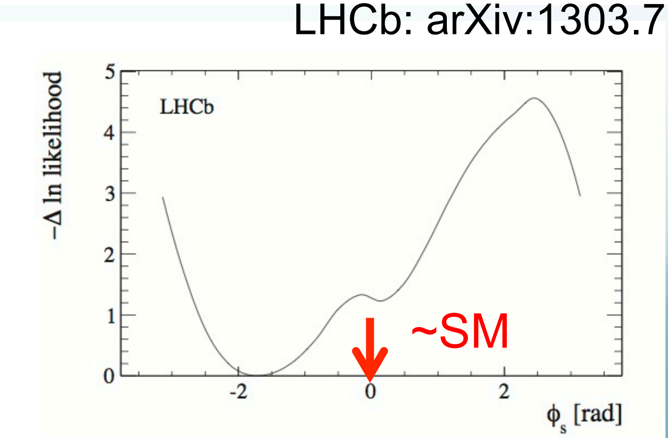
$B_s \to \phi\phi$



LHCb: arXiv:1303.7125

First result of ϕ_s from $B_s \to \phi\phi$ has p-value w.r.t. SM of 16%.

Should help to clarify "$\sin 2\beta^{eff}$" picture.



Is there CPV in charm system?

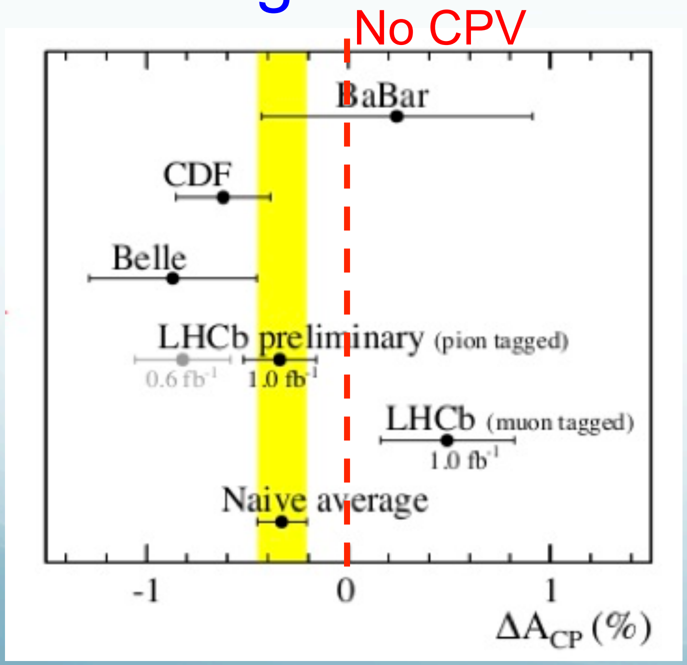
In 2012 measurement of ΔA_{CP} consistent with ~0.5% direct CPV in SCS charm decays (LHCb, CDF, Belle).

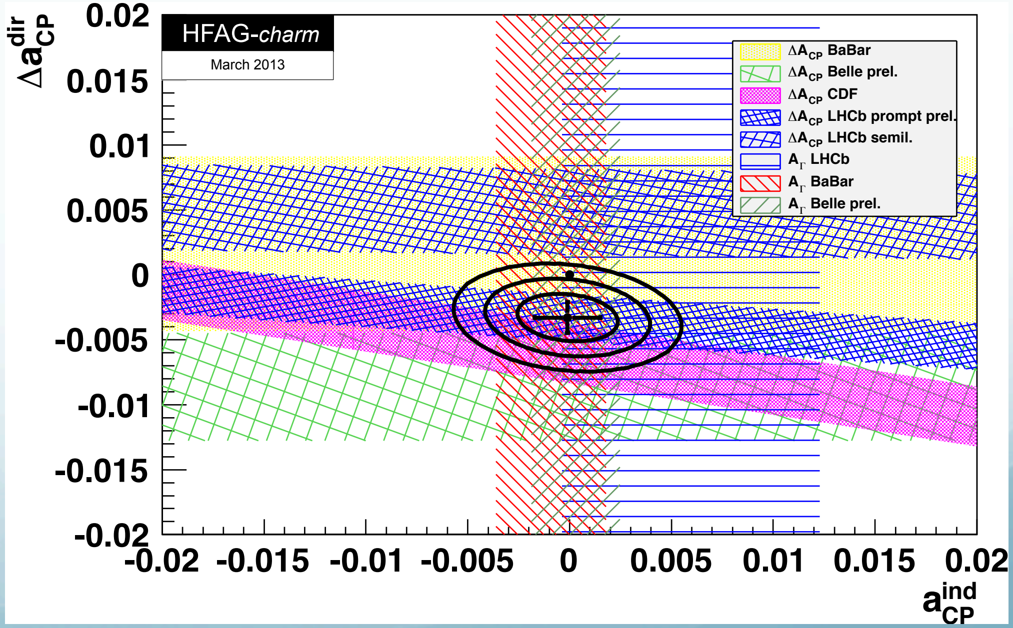
$$\Delta A_{CP} \equiv A_{CP}\left(K^-K^+\right) - A_{CP}\left(\pi^-\pi^+\right) = \left[a_{CP}^{\mathrm{dir}}\left(K^-K^+\right) - a_{CP}^{\mathrm{dir}}\left(\pi^-\pi^+\right)\right] + \frac{\Delta\langle t\rangle}{\tau} a_{CP}^{\mathrm{ind}}$$

Recent LHCb results (prompt update and semileptonic B) reduces significance.

LHCb-CONF-2013-003

LHCb: arXiv:1303.2614

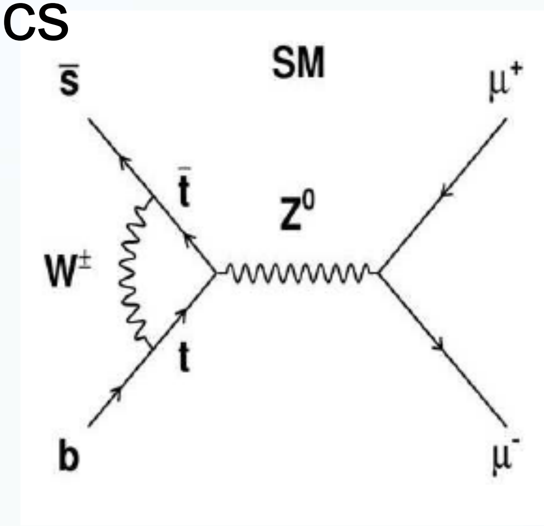




Rare Decays

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

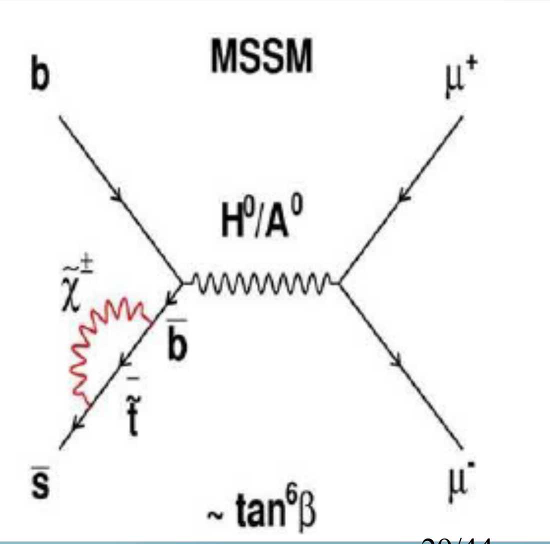
A Nobel (!) place to search for New Physics



Very rare in the Standard Model

- absence of tree-level FCNC
- helicity suppressed
- CKM suppressed

$$B\left(B_s \rightarrow \mu^+\mu^-\right)_{SM} = \left(3.54 \pm 0.30\right) \times 10^{-9}$$

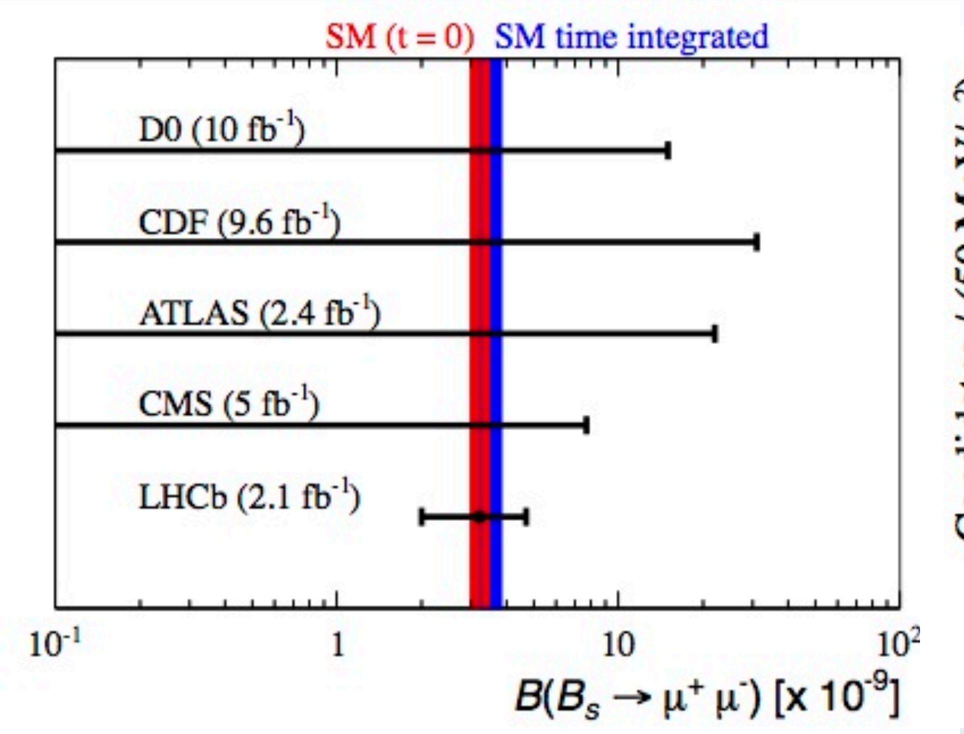


Strong enhancement (or suppression) possible in MSSM

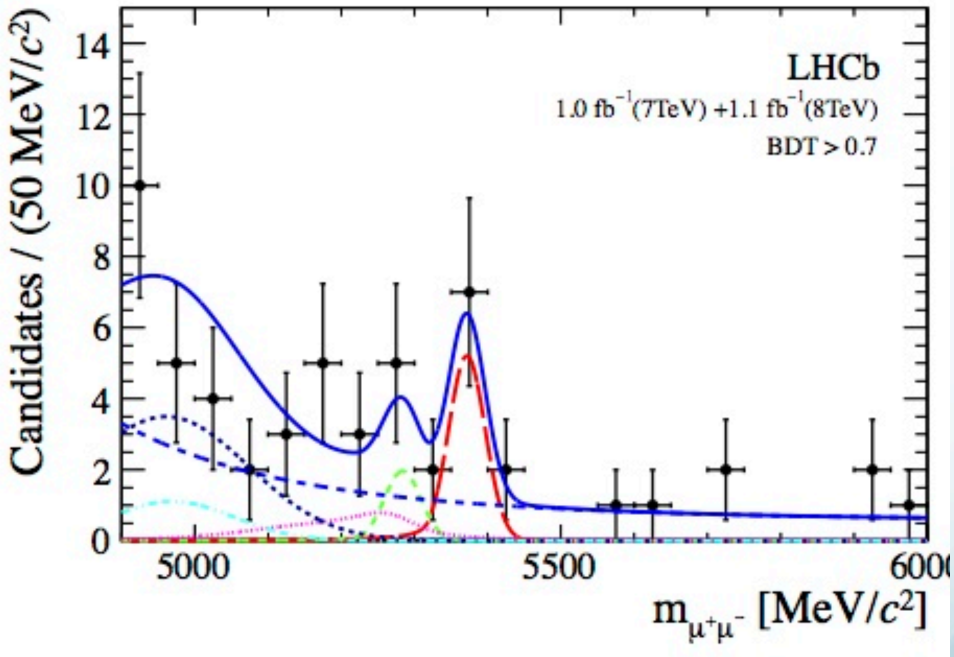
$$B\left(B_s \rightarrow \mu^+\mu^-\right) \propto \frac{\tan^6\beta}{M_A^4}$$

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

Impressive limits set by LHC (& Tevatron) experiments
….and first evidence of decay seen…

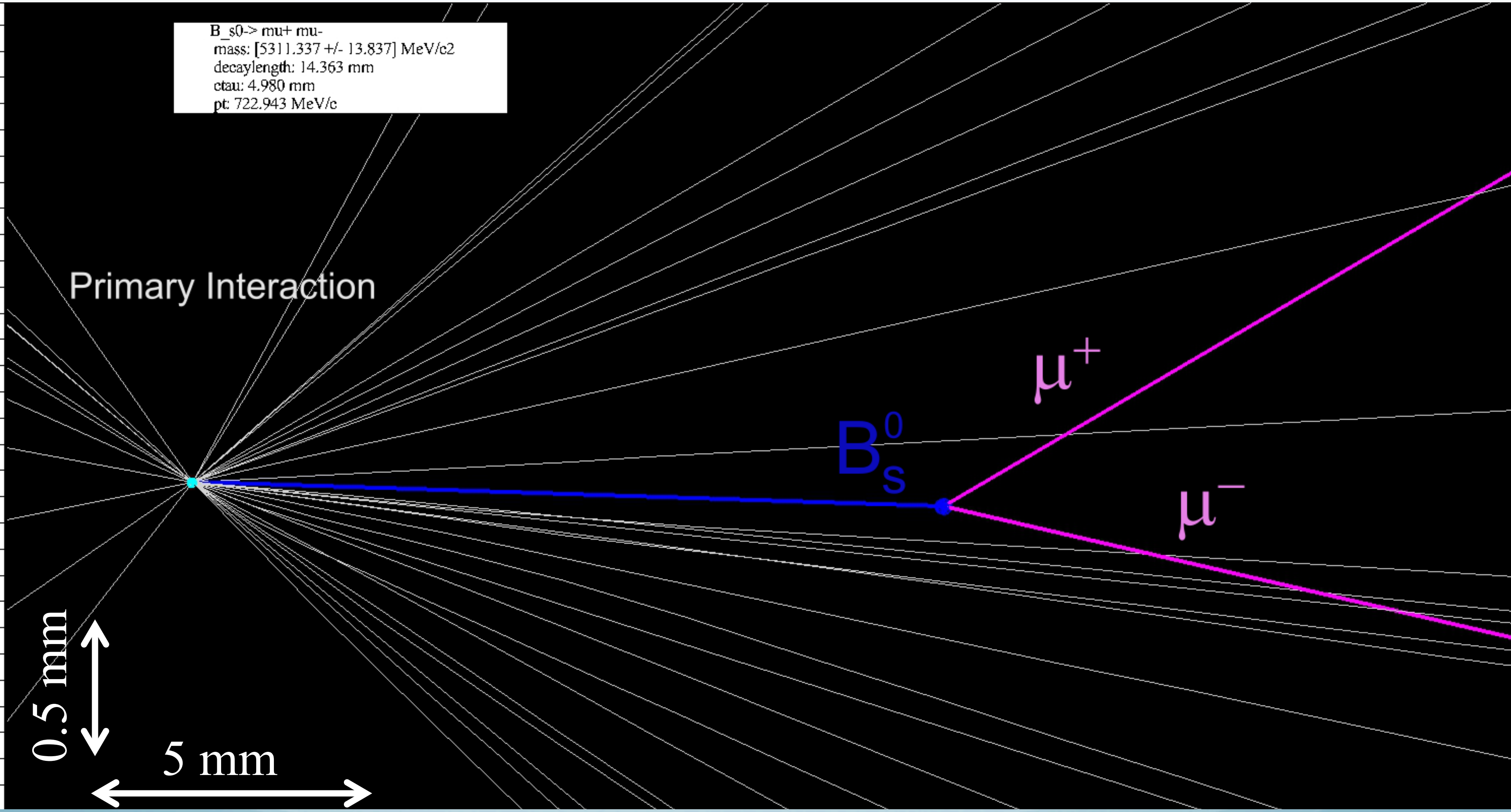


LHCb: PRL 110 (2013) 021801



$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.2\,^{+1.4}_{-1.2}(\text{stat})\,^{+0.5}_{-0.3}(\text{syst})) \times 10^{-9}$$

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



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

$B_s \to \mu^+\mu^-$ measurement rules out MSSM at large tanβ with light pseudoscalar Higgs

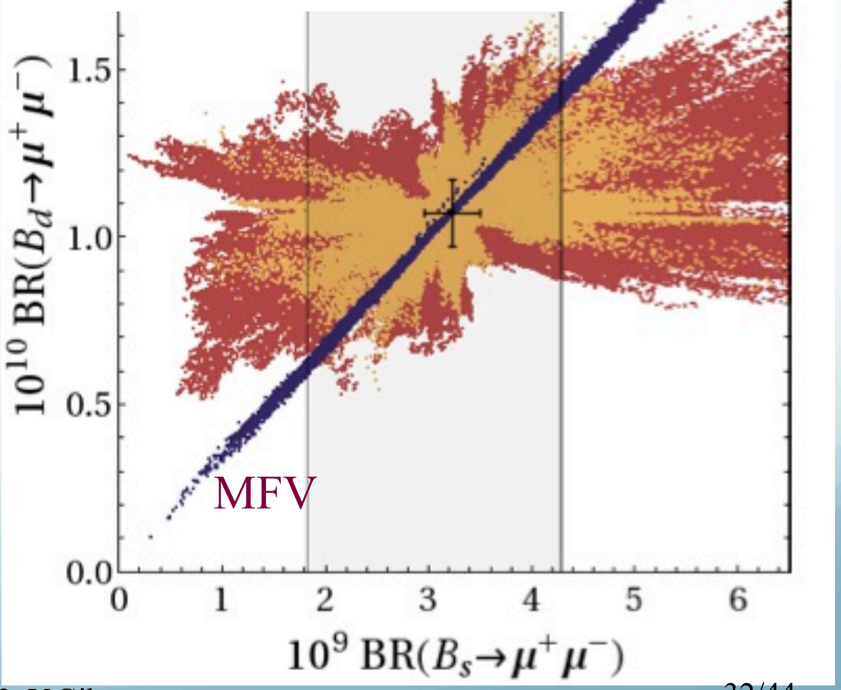
Now in the regime where more "natural" *O*(50%) NP effects can be probed

It is now vital to measure

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

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

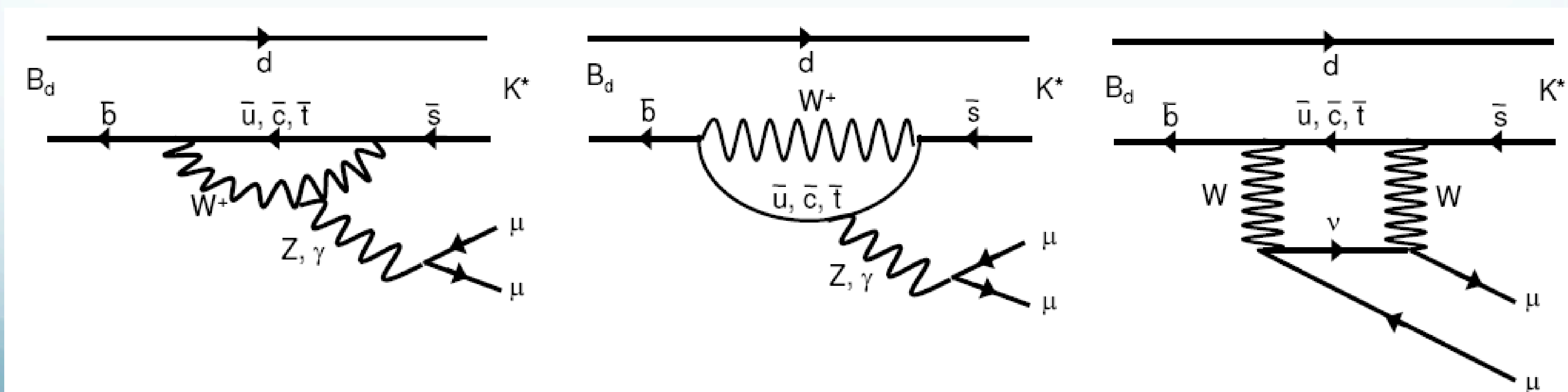
Straub arXiv:1302.4651
Analysis of several models with partial compositeness



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

Powerful approach to study helicity structure of New Physics.

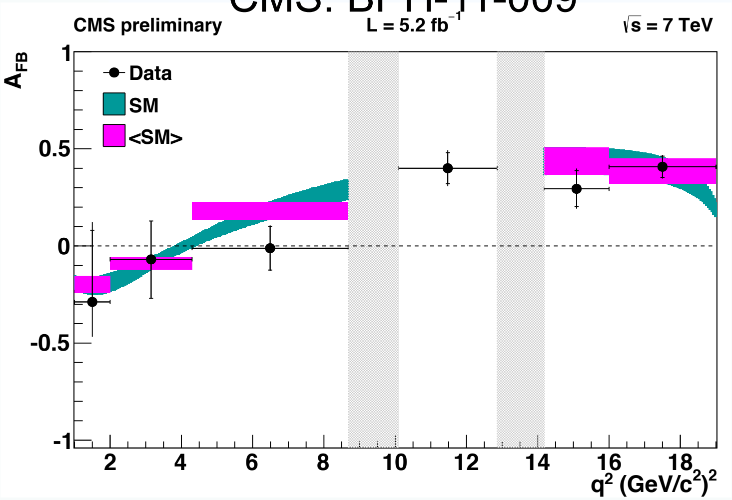
- Many observables (rates, angular distributions, asymmetries)
- Experimentally clean signature
- Clean theoretical predictions (especially at low-q^2)



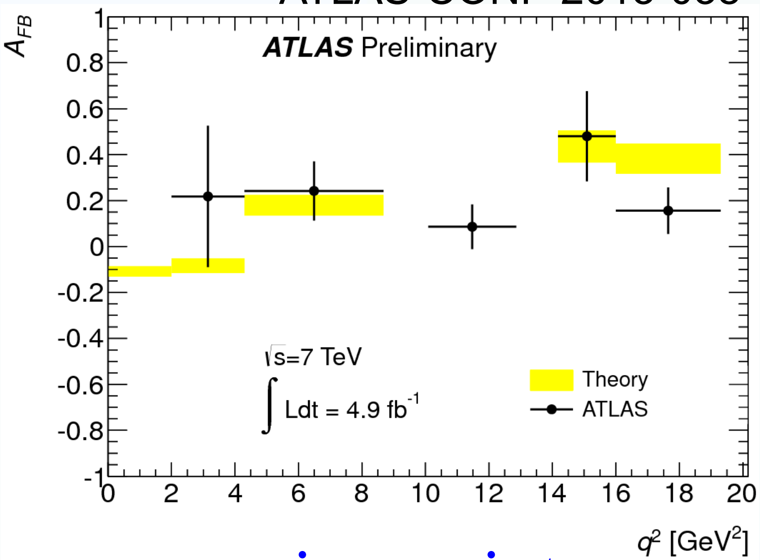
$B^0 \rightarrow K^*\mu^+\mu^-$

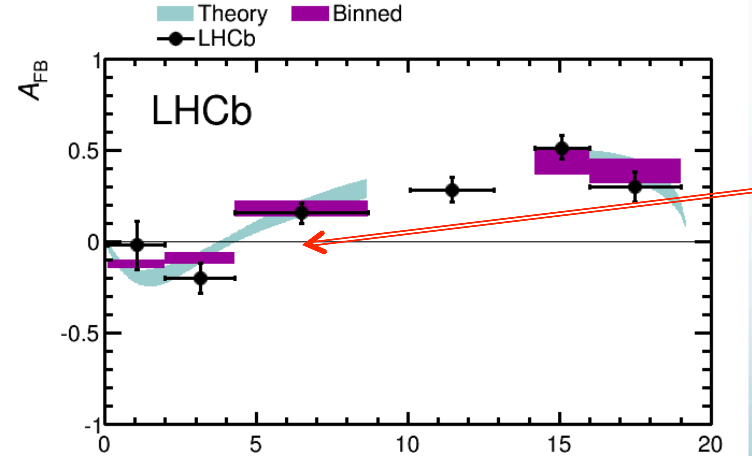
Flagship measurement is A_{FB}

CMS: BPH-11-009



ATLAS-CONF-2013-038





LHCb: arXiv: 1304.6325

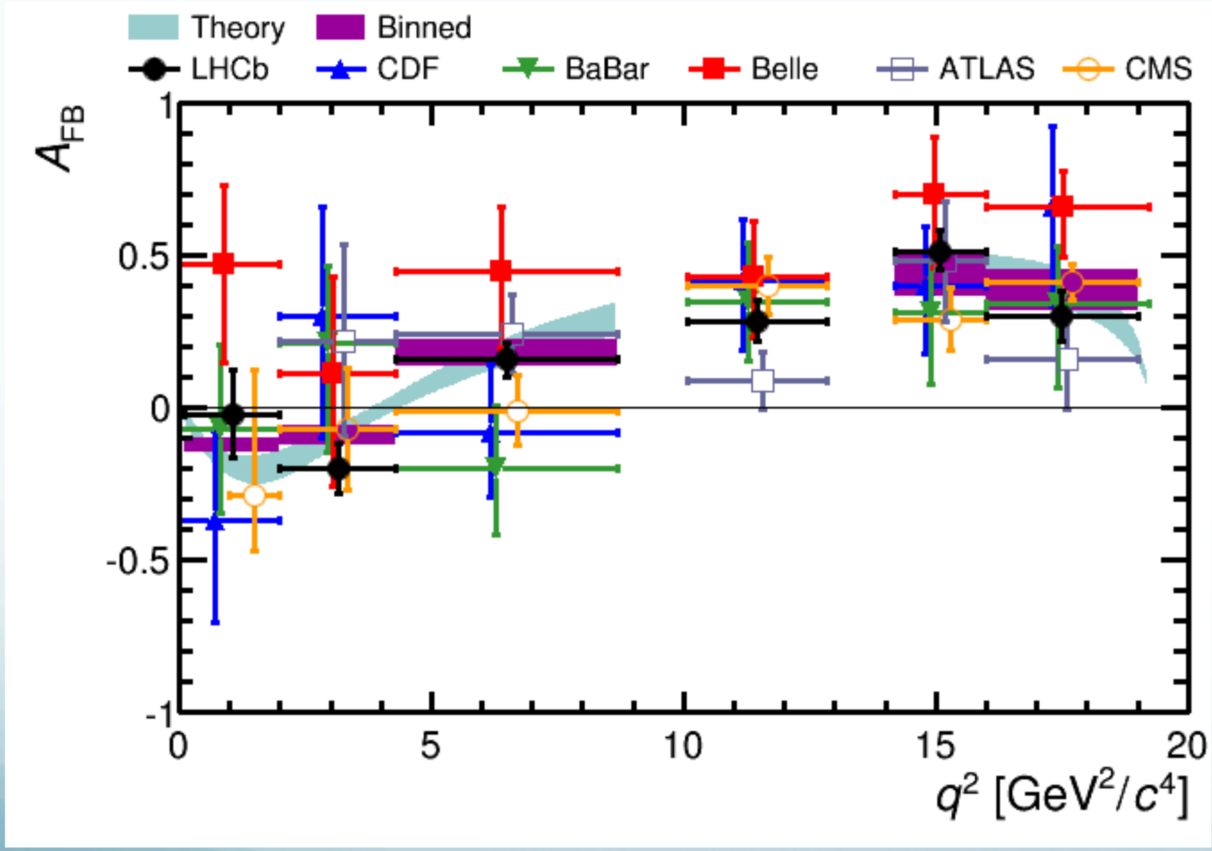
zero-crossing point

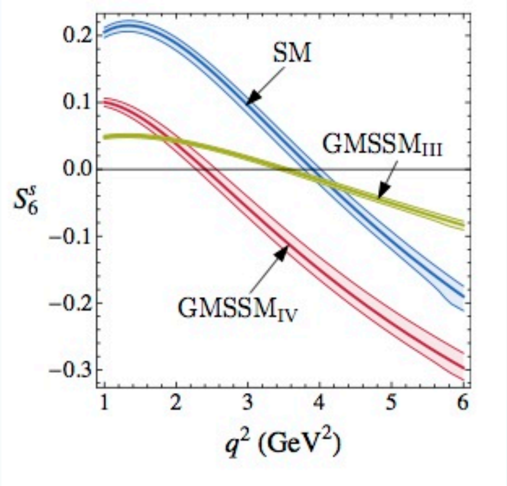
$$q_0^2 = 4.9 \pm 0.9\,\mathrm{GeV}^2/c^4$$

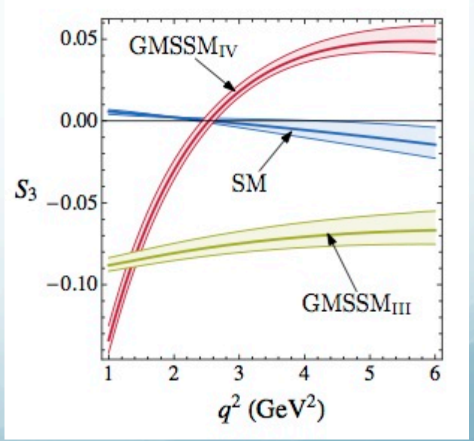
Theory predictions in the range 3.9-4.4 GeV^2/c^4 with ~10% uncertainties

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

Looking forward to HFAG average of A_{FB} and studies of other observables (now starting to appear)







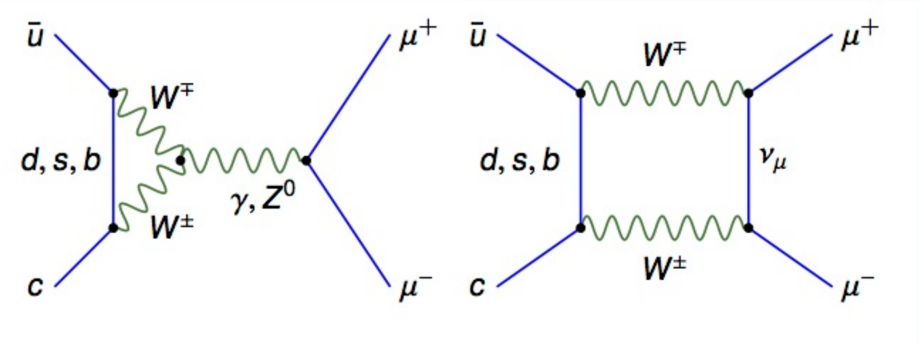
Altmannshofer et al JHEP 01 (2009) 019

Rare D decays

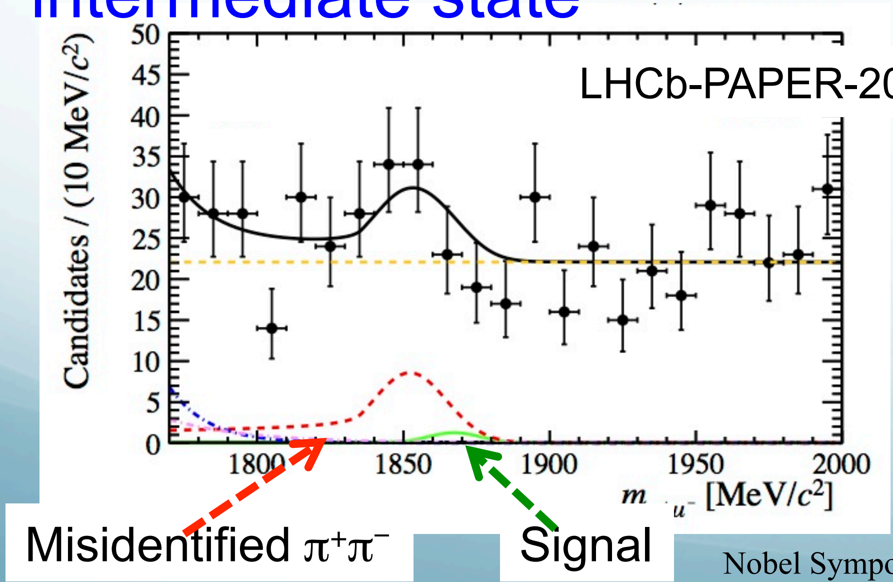
Rare D decays also offer many opportunities to search for New Physics

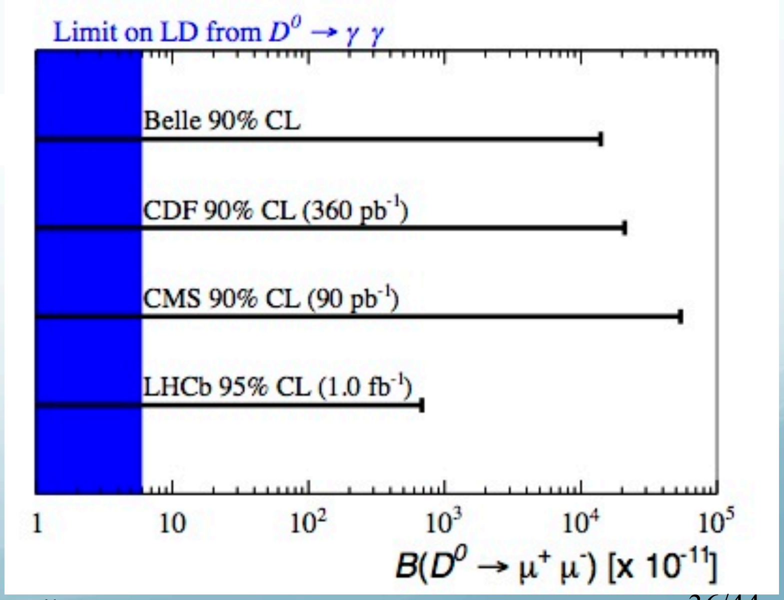
e.g. $D^0 \to \mu^+\mu^-$

Helicity & GIM suppressed



Dominated by long-distance contributions from γγ intermediate state





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

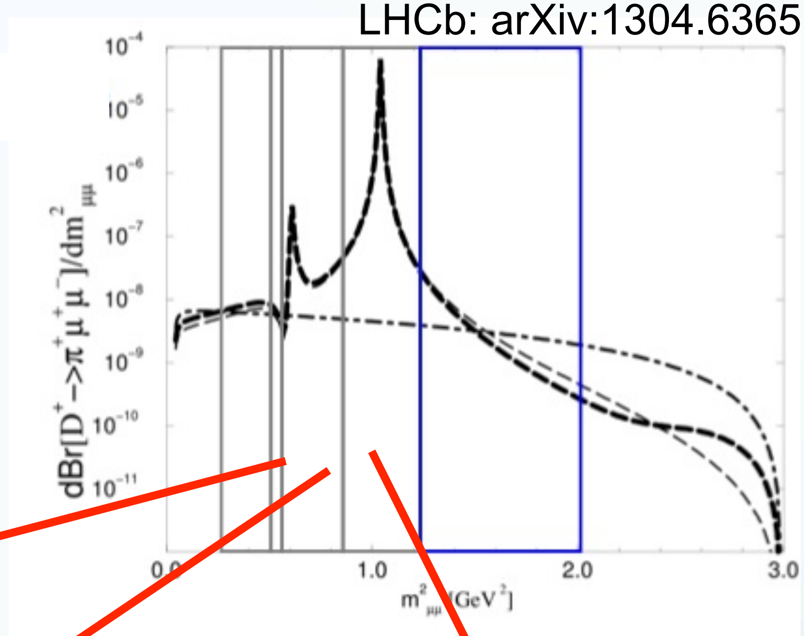
FCNC decay (& search for Majorana neutrinos $D^+_{(s)} \to \pi^-\mu^+\mu^+$)

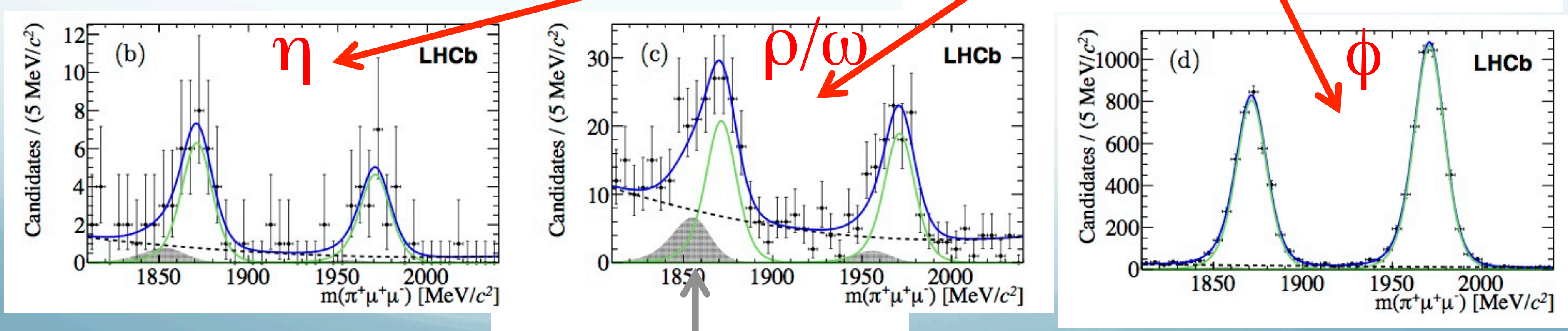
LHCb: arXiv:1304.6365

Observation soon within reach

$$B\left(c \to u\mu^+\mu^-\right)_{SM} = \left(1-3\right)\times 10^{-9}$$

Clear peaks seen in resonance regions





Misidentified $\pi^+\pi^+\pi^-$

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

FCNC decay (& search for Majorana neutrinos $D^{+}_{(s)} \to \pi^{-}\mu^{+}\mu^{+}$)

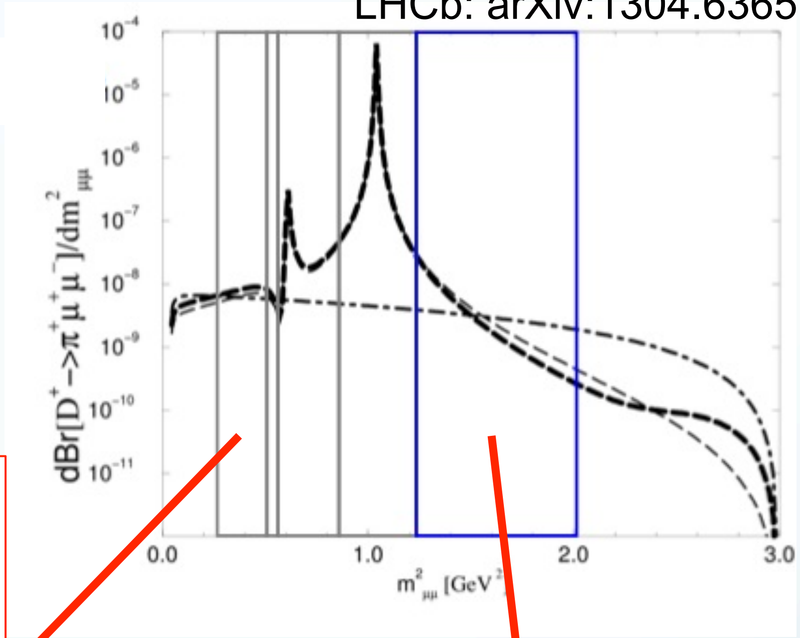
LHCb: arXiv:1304.6365

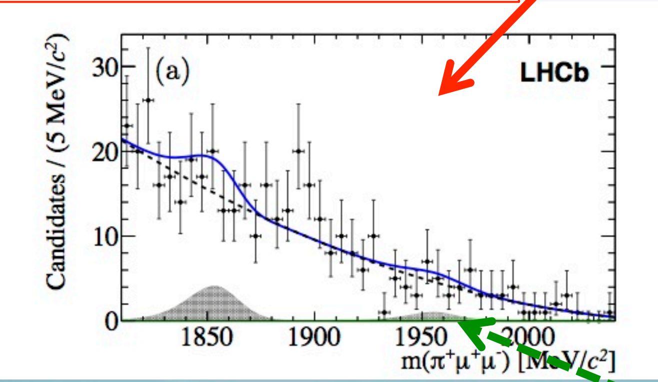
Observation soon within reach

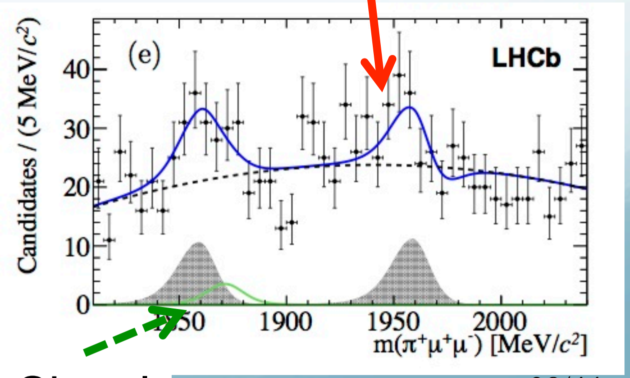
$$B\left(c \to u\mu^{+}\mu^{-}\right)_{SM} = \left(1-3\right)\times 10^{-9}$$

Nothing (yet) in low or high mass non-resonance regions

$$\mathcal{B}(D^{+} \to \pi^{+}\mu^{+}\mu^{-}) < 7.3\,(8.3) \times 10^{-8},$$
$$\mathcal{B}(D_s^{+} \to \pi^{+}\mu^{+}\mu^{-}) < 4.1\,(4.8) \times 10^{-7},$$

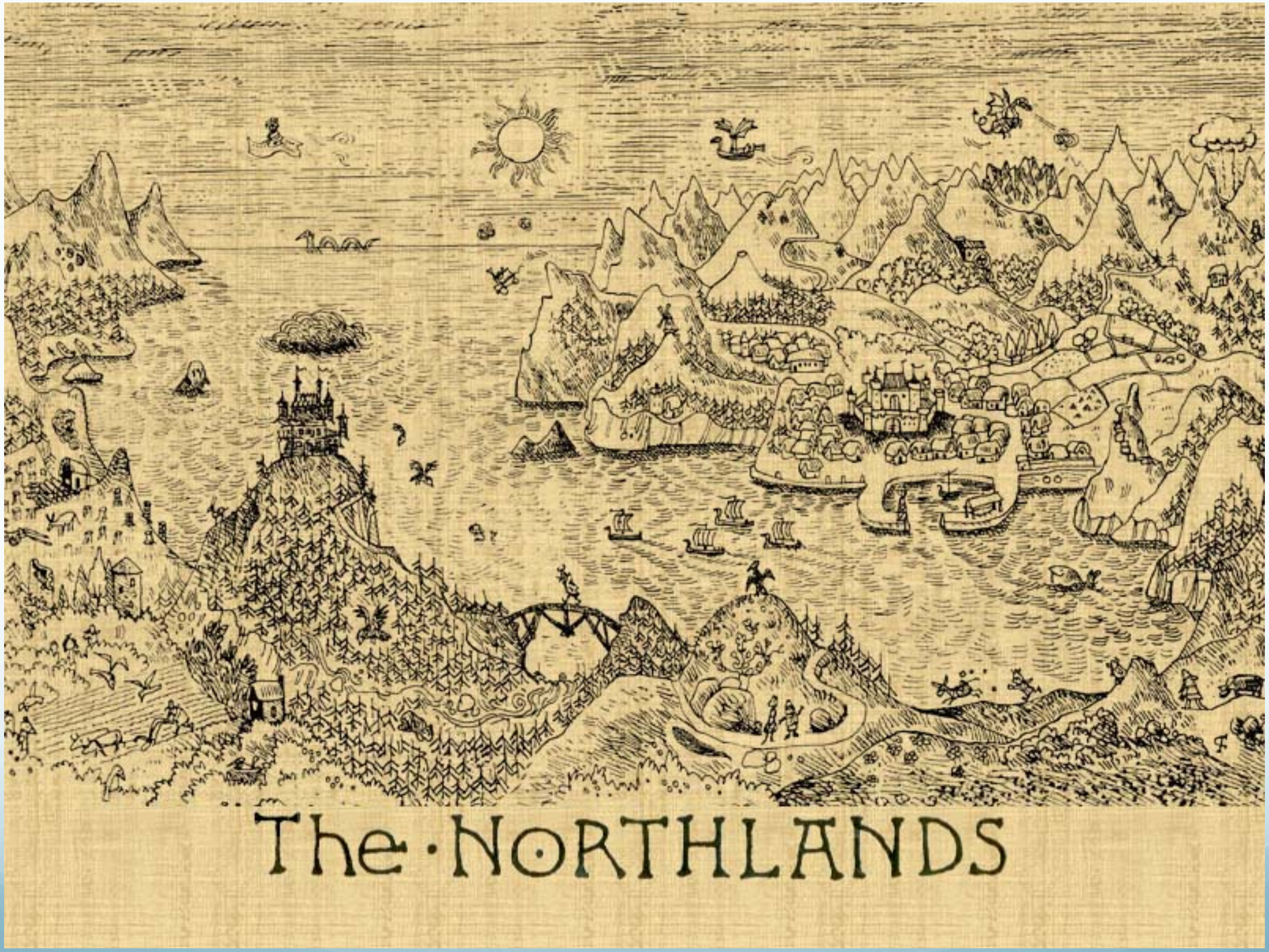




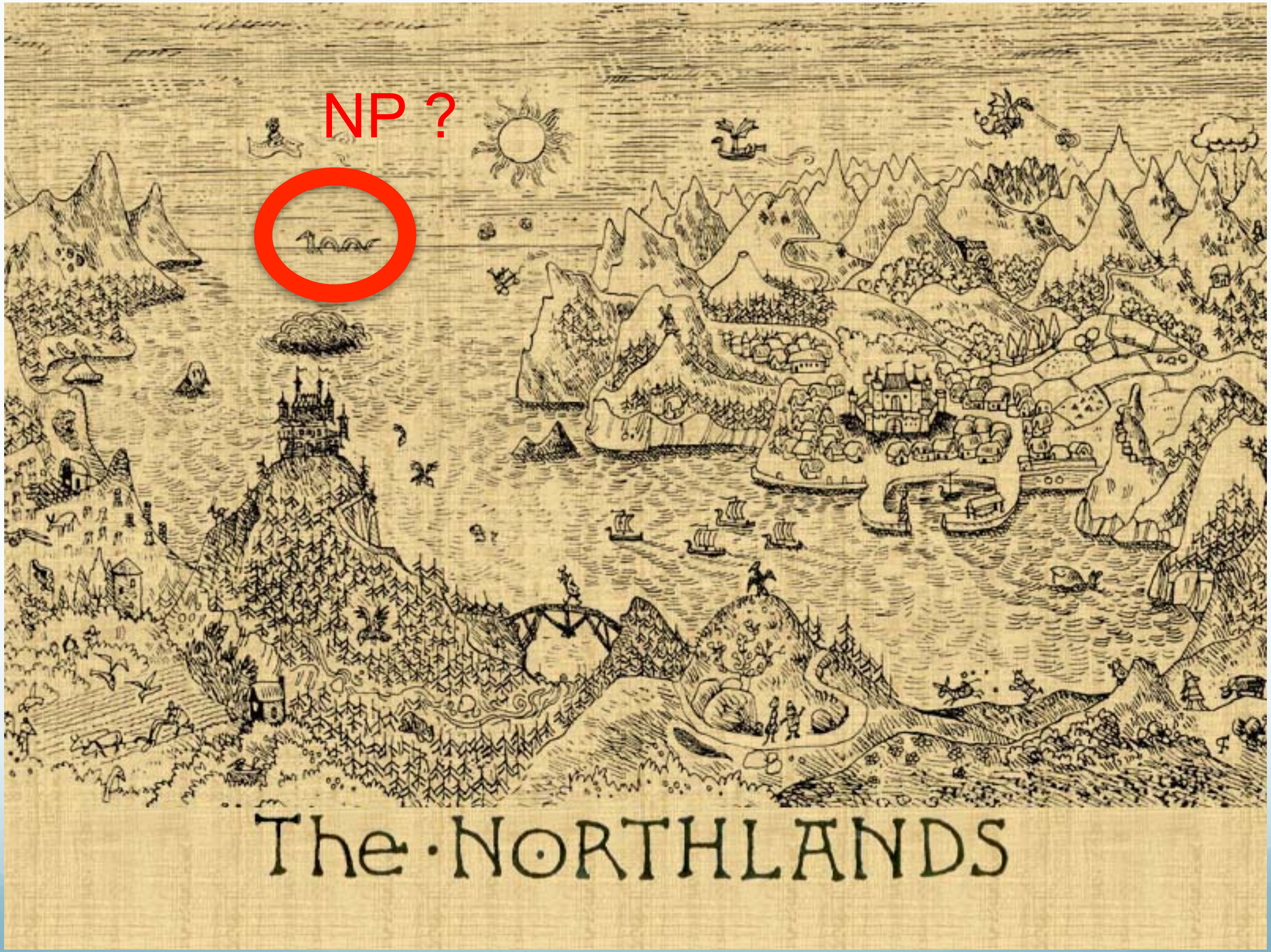


Signal

Future Prospects



Future Prospects



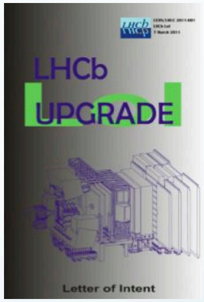
Future Prospects for Heavy Flavour at the LHC

- Short term prospects are excellent… lots of LHCb & ATLAS/CMS data still to come from 2012 run and post-LS1.

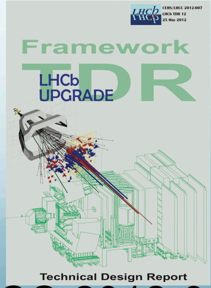
- Second half of decade will see the transition to the next generation of experiments.

- LHCb upgrade will be installed in LS2 (2018)
  - Readout all detector at 40 MHz
  - Trigger fully in software
  - Run at instantaneous luminosity of ~2 x10^{33} cm^{-2}s^{-1}

- LHCb plans to collect > 50 fb^{-1} after upgrade.

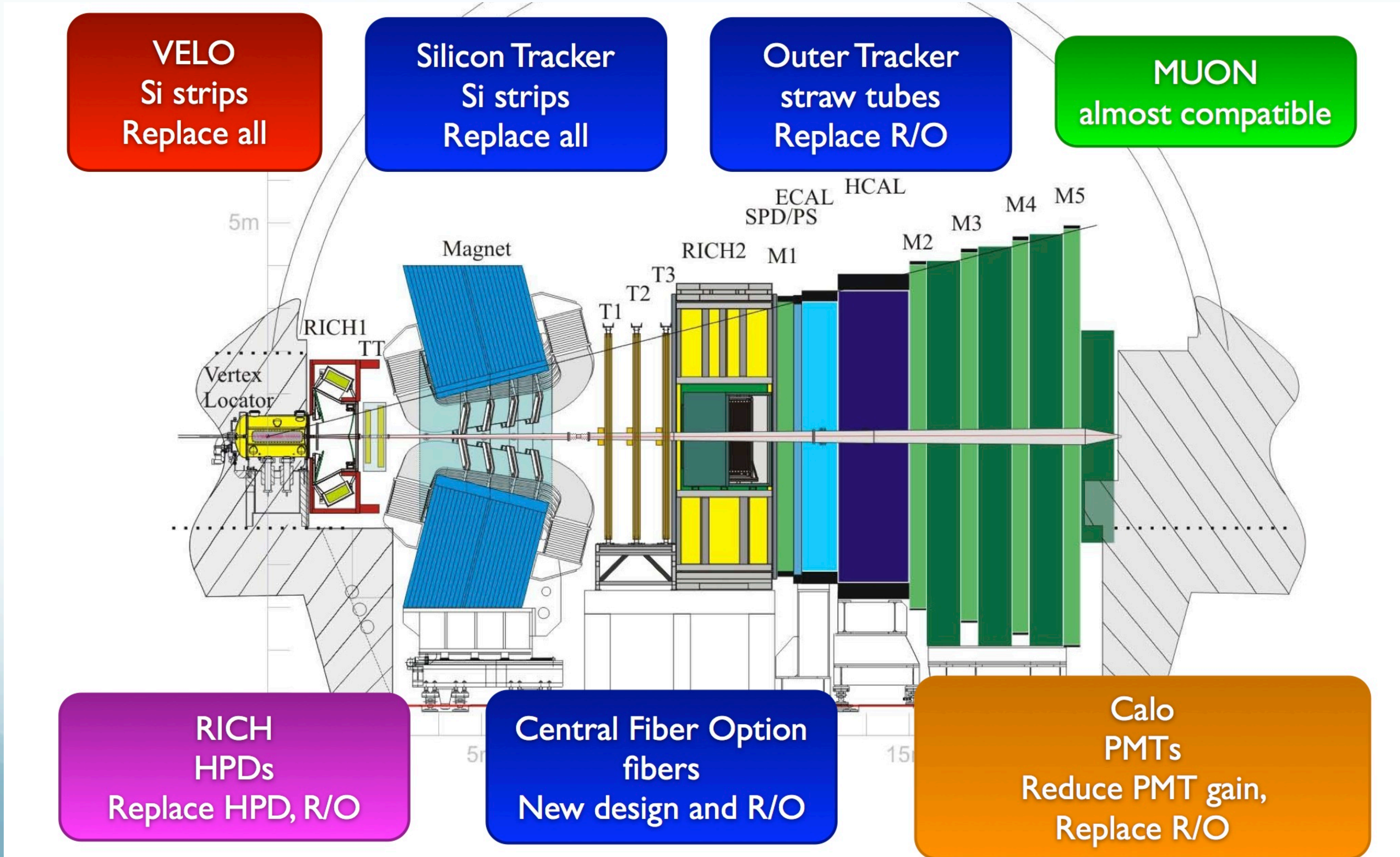


CERN/LHCC-2011-001



CERN/LHCC-2012-007

LHCb Upgrade



Future Prospects for Heavy Flavour at the LHC

Fantastic prospects after LHCb upgrade…

- CP Violation
  - factor >10 reduction in uncertainty on γ
  - precision measurement of ϕ_s
  - sensitivity to direct CPV in charm at SM expectation, and precise probing of indirect CPV in charm
- Rare decays
  - measure $BR(B_s \rightarrow \mu^+\mu^-)$ to better than theory prediction and measure $BR(B_d \rightarrow \mu^+\mu^-)$
  - extensive exploration of electroweak penguins using exclusive $B \rightarrow X_s l^+ l^-$ decays
- And many many other topics….

The tale will continue for many years…

The tale will continue for many years…

LHC Physicist

Noggin the Nog

New Physics

Nooka the Nook

Will Noggin find Nooka ?

The tale will continue for many years…

LHC Physicist

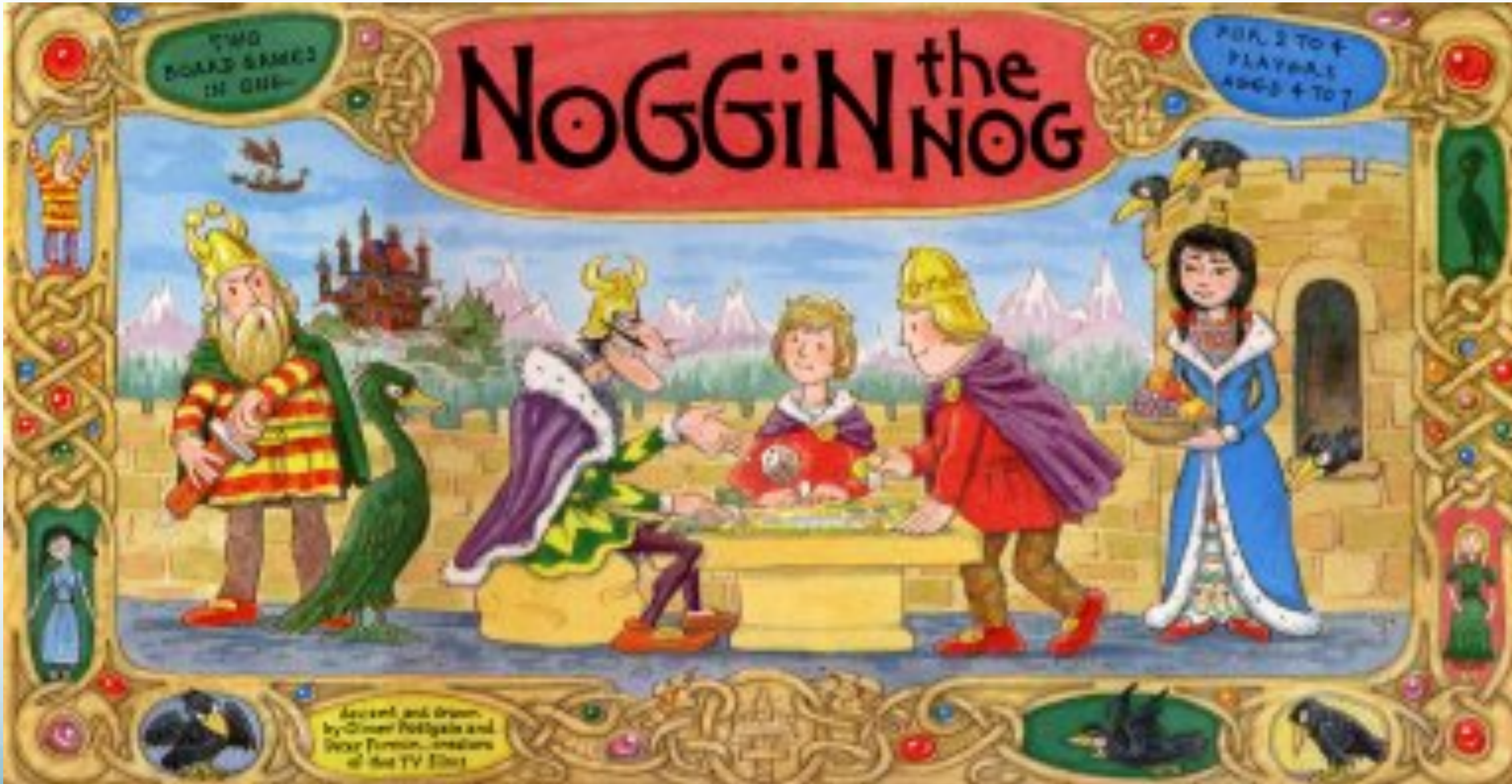
Noggin the Nog

Standard Model

Nogbad the Bad

Or will he just keep finding the Standard Model ?

Let’s hope for a happy ending…..



And now for my questions…

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Question 1

If the LHCb upgrade does not reveal NP by the end of the 2020's, what is the fate of flavour physics (incl. neutrinos, EDM, $\mu \to e\gamma$….) ?

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If the LHCb upgrade does not reveal NP by the end of the 2020's, what is the fate of flavour physics (incl. neutrinos, EDM, $\mu \to e\gamma$….) ?

Question 2

At the moment we have "two roads to discovery", CPV and rare decays. Should we contemplate e.g. a "rare decay only" experiment ?

Question 3

What ultimate precision on CPV and rare decay observables should a quark flavour physics experiment aspire to ? i.e. is there a need to go well beyond SM theory uncertainties ?

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And finally….Question 4

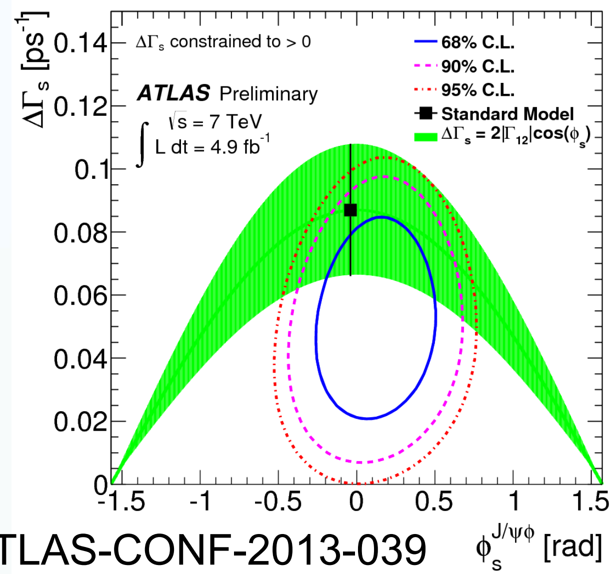
We do not seem to be making much progress towards a "theory of flavour” - i.e. an understanding of the patterns in, and relations (if any) between, the quark and lepton masses and mixing. Are different experimental and/or theoretical approaches needed to address this question?

Backup

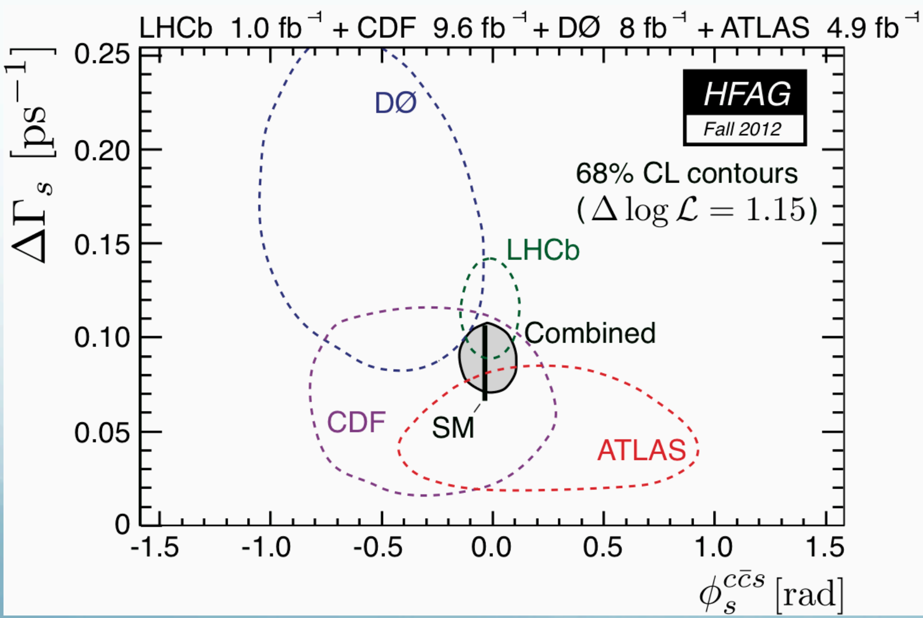
Mixing Induced CPV in B_s system

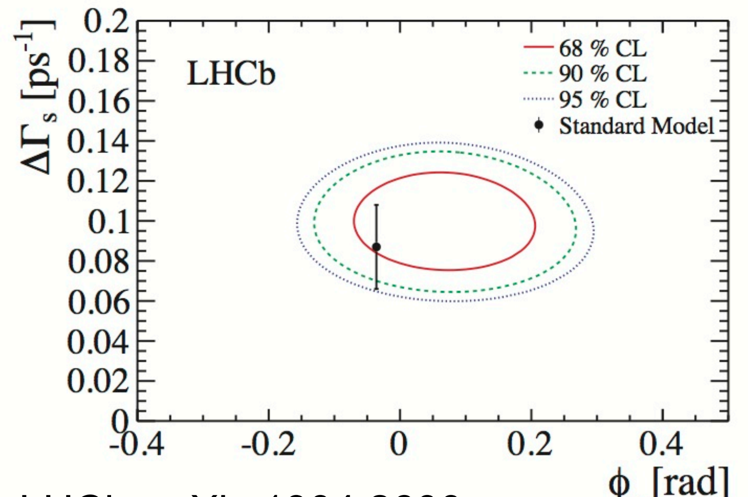
Picture recently (Beauty 2013) added to by ATLAS (flavour-tagged) & final LHCb 2011 measurements.

No big NP effect observed, now crucial to improve precision.



ATLAS-CONF-2013-039

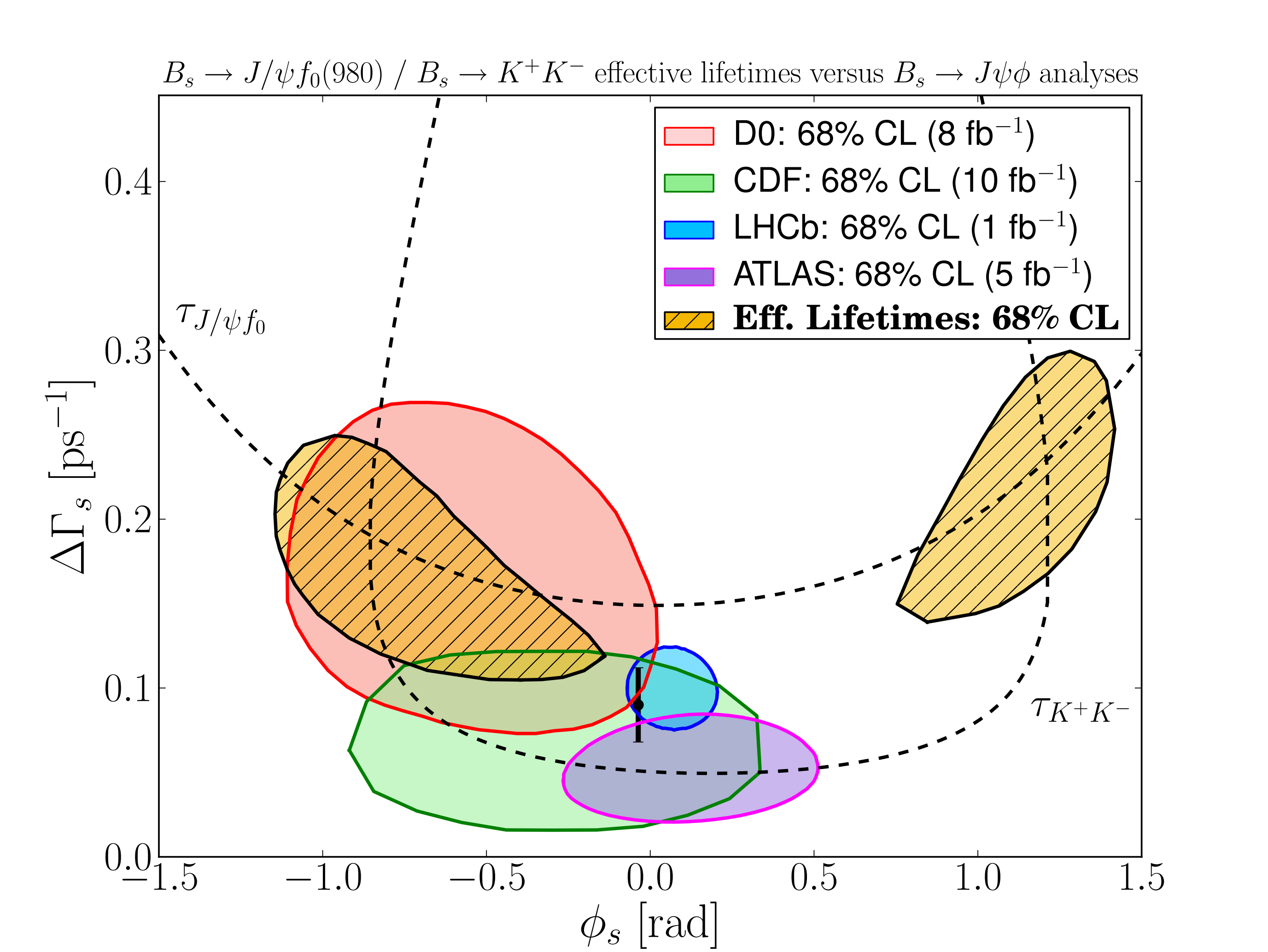




LHCb: arXiv:1304.2600

Mixing Induced CPV in B_s system

Also compare to measurements of B_s effective lifetime



LHCb Upgrade

Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\text{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s\ (B_s^0 \to J/\psi\ \phi)$	0.10 [30]	0.025	0.008	~ 0.003
	$2\beta_s\ (B_s^0 \to J/\psi\ f_0(980))$	0.17 [32]	0.045	0.014	~ 0.01
	a_{sl}^s	6.4×10^{-3} [63]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\text{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\text{eff}}(B^0 \to \phi K_S^0)$	0.17 [63]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\text{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguins	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.08 [64]	0.025	0.008	0.02
	$s_0\, A_{\text{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [64]	6 %	2 %	7 %
	$A_{\text{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.25 [9]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [29]	8 %	2.5 %	$\sim 10\,\%$
Higgs penguins	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [4]	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	$\gamma\ (B \to D^{(*)}K^{(*)})$	~ 10–12° [40, 41]	4°	0.9°	negligible
	$\gamma\ (B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	$\beta\ (B^0 \to J/\psi\ K_S^0)$	0.8° [63]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [63]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [8]	0.65×10^{-3}	0.12×10^{-3}	–

LHCb & theorists: EPJ C 73 (2013) 2373