CP violation and rare decays in the *b*-quark sector at LHCb

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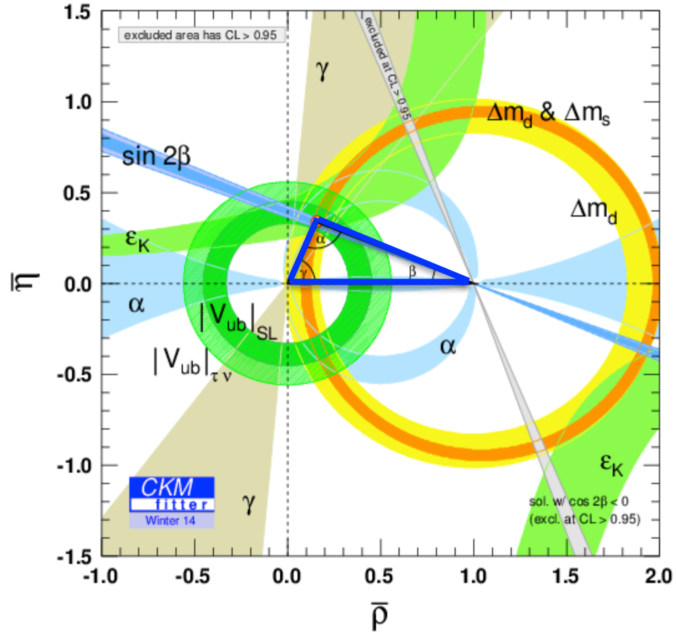
on behalf of the LHCb Collaboration

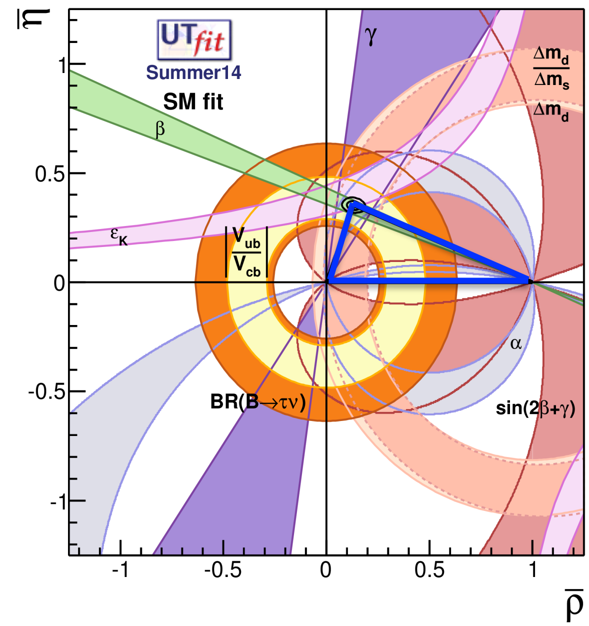
Workshop on flavour and top physics at 100 TeV

IHEP, Beijing 2015

Consistency of global CKM fits

- Tremendous success of the CKM paradigm!
  - All of the measurements agree in a highly profound way



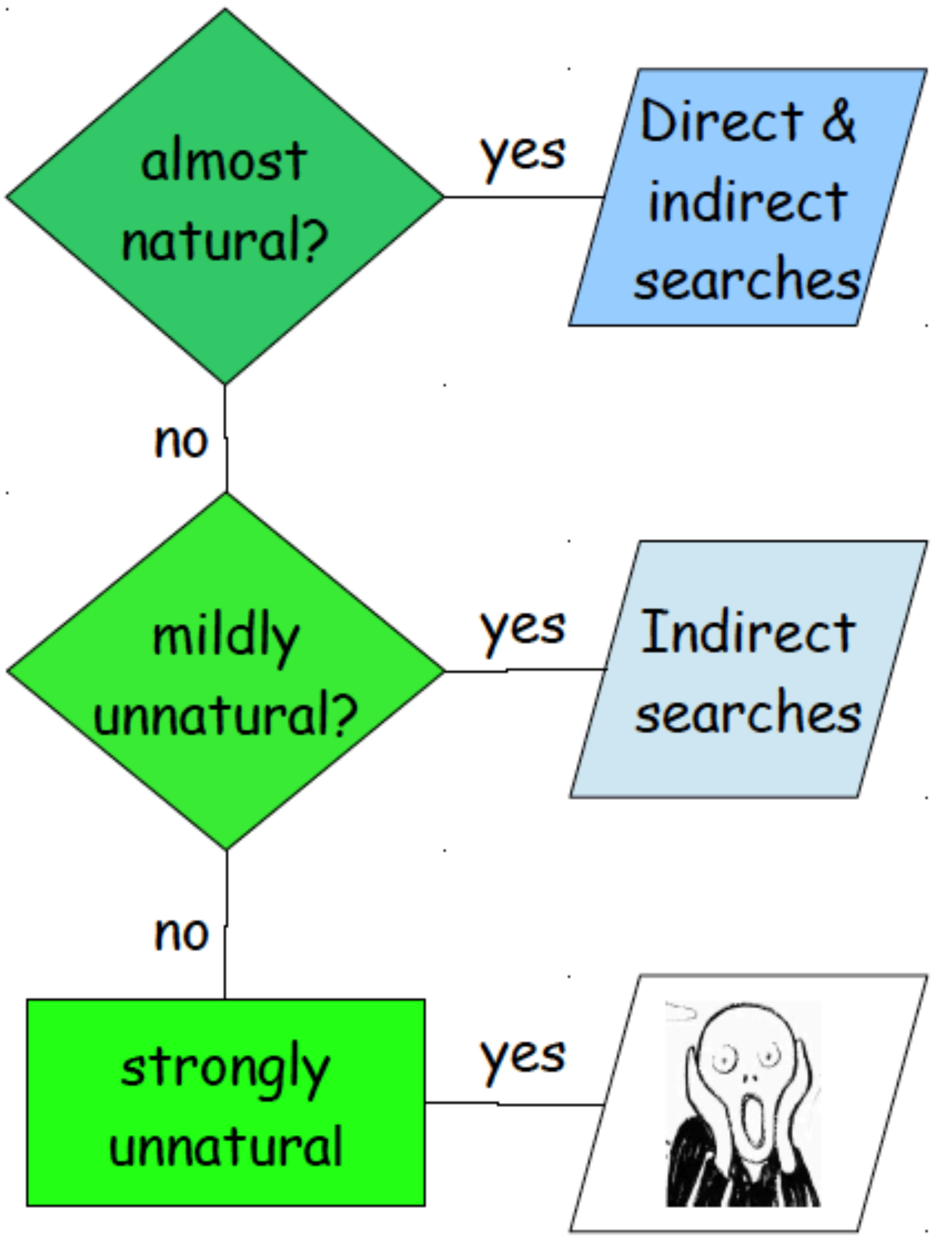


- The quark flavour sector is well described by the CKM mechanism
  - large sources of flavour symmetry breaking are excluded at the TeV scale
  - the flavour structure of NP should be very peculiar

Nevertheless...

- The good reasons why we believed that the SM was incomplete are still there
  - hierarchy problem
  - unification of gauge couplings
  - dark matter
  - baryon asymmetry
  - ...
- By studying *CP*-violating and flavour-changing processes we can accomplish two fundamental tasks
  - Identify new symmetries (and their breaking) beyond the SM
  - Probe mass scales not accessible directly
- Measurable deviations from the SM, although not large as naively hoped, are still possible
  - need to go to high precision measurements to probe theoretically clean observables

How much "natural" is Nature?



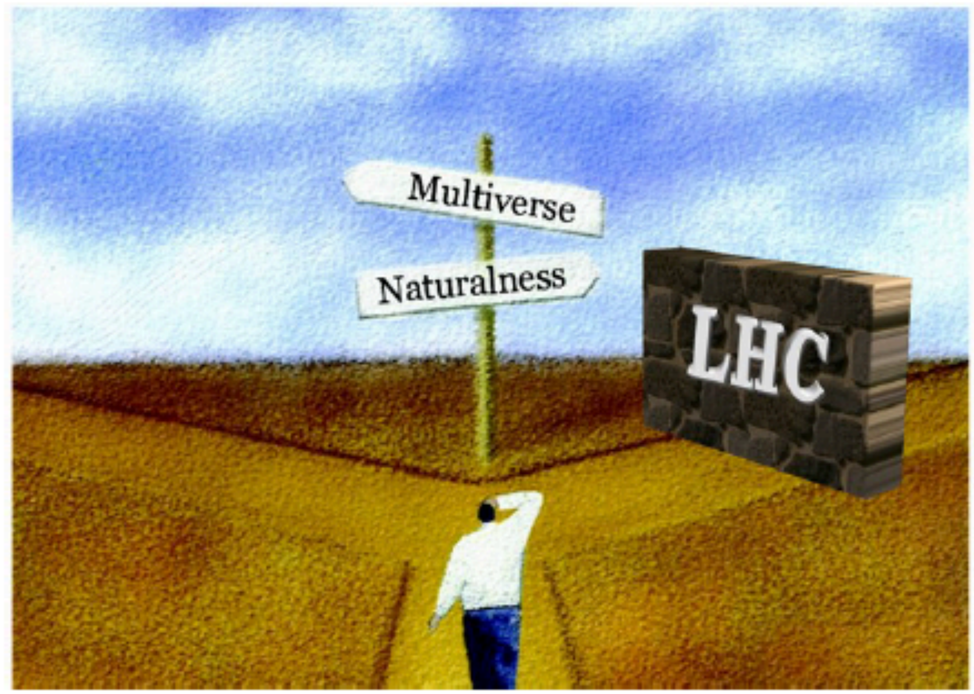


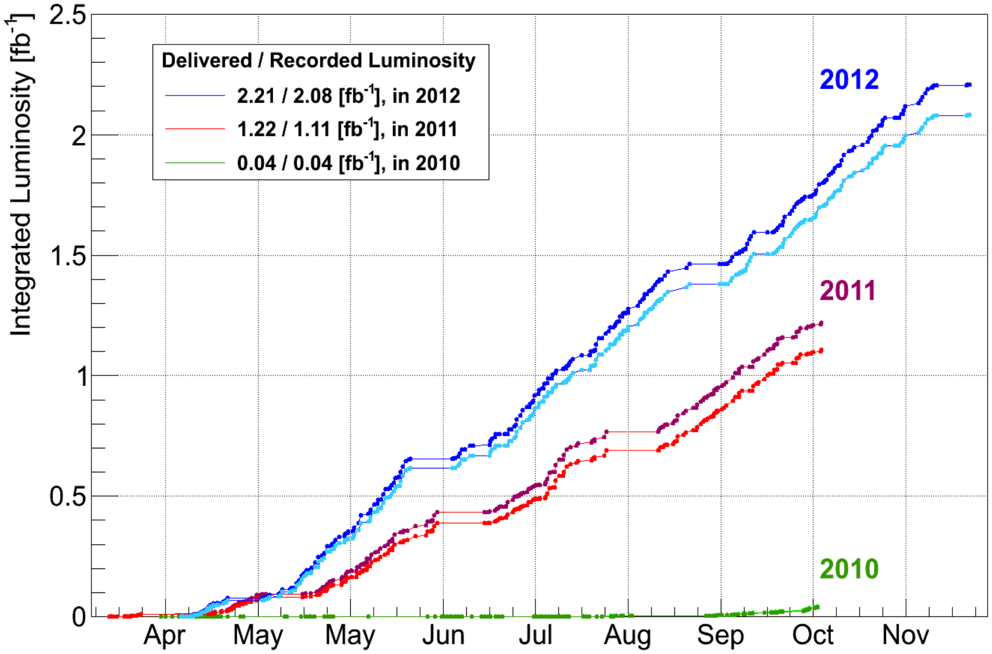
illustration by G. Villadoro

Marco Ciuchini at KEK-FF 2014

Outline

- LHCb luminosity prospects
- *CP* violation in the interference between mixing and decay
  - $b \to c\bar{c}s$ and $b \to s\bar{s}s$ transitions
- Semileptonic asymmetries of B_d and B_s mesons
- Determination of γ
  - from tree-level decays
  - from charmless two-body decays
- Rare decays
  - $B_{d,s} \to \mu\mu$, $B_d \to K^*\mu\mu$ and $B_u \to K^+\ell^+\ell^-$

LHCb luminosity prospects



During Run 1

- 7 and 8 TeV collisions
- luminosity levelled at $4{\cdot}10^{32}$ cm^{-2}s^{-1}
- software trigger running at 1 MHz after hardware trigger and record 3-5 kHz

LHC era			HL-LHC era	
Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2020-22)	Run 4 (2025-28)	Run 5+ (2030+)
3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	100 fb^{-1}

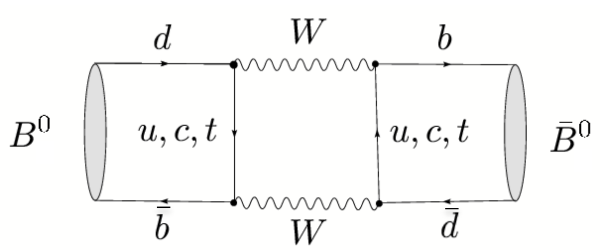
Note that beauty production cross section is roughly doubled passing from 7 TeV to 14 TeV *pp* collisions

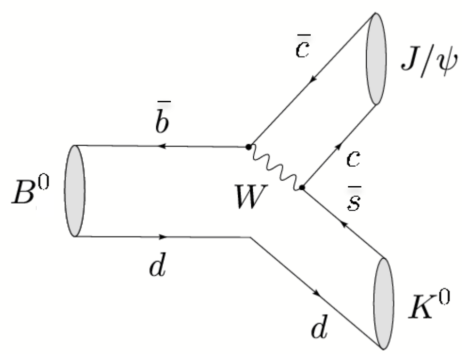
LHCb upgrade

- running at $2{\cdot}10^{33}$ cm^{-2}s^{-1}
- replace R/O, RICH photodetectors and tracking detectors
- full software trigger, running at 40 MHz and record 20 kHz

Measurement of sin(2β) [yesterday]

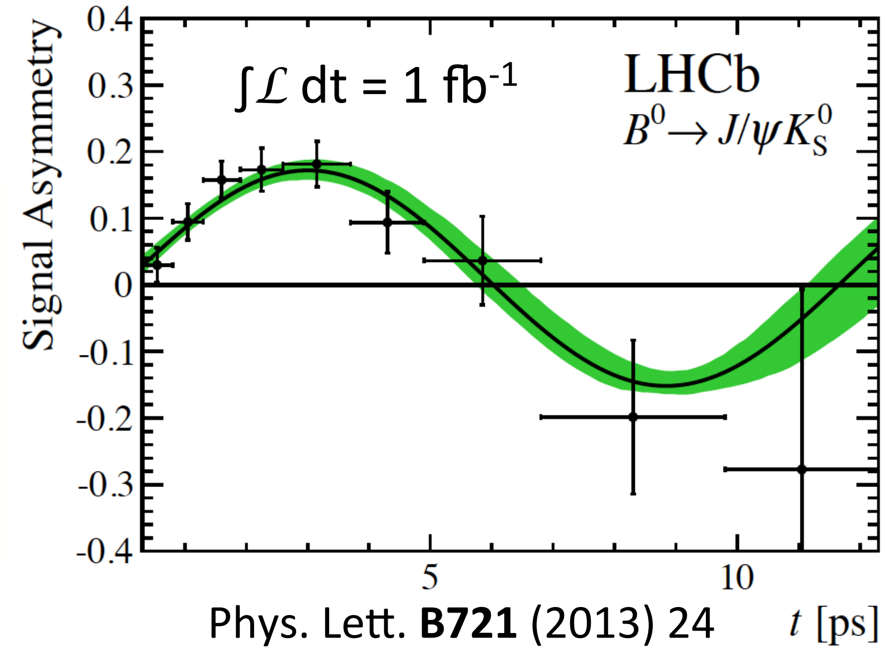
- *CP* violation due to interference between mixing and decay



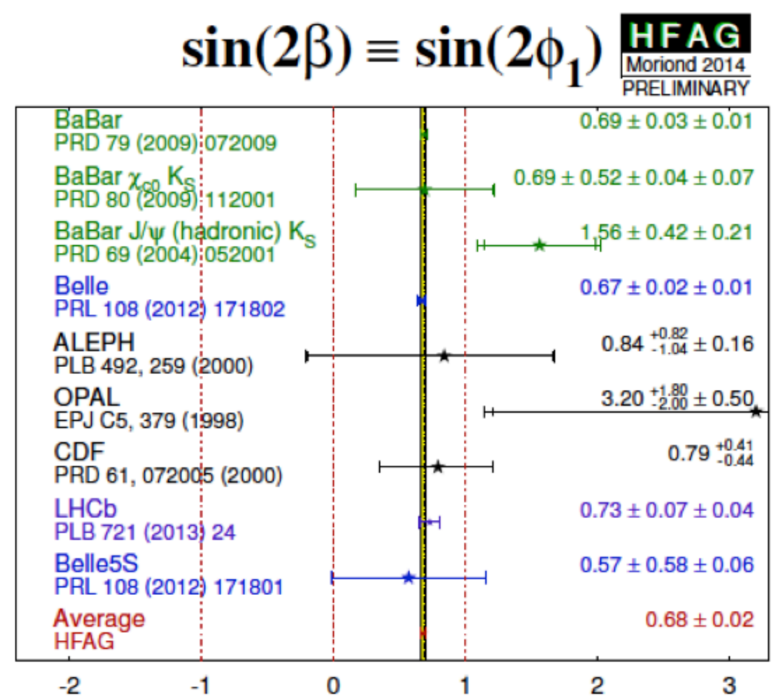


$$\mathcal{A}_{J/\psi K^0_S}(t) \equiv \frac{\Gamma(\overline{B}^0(t) \to J/\psi\, K^0_S) - \Gamma(B^0(t) \to J/\psi\, K^0_S)}{\Gamma(\overline{B}^0(t) \to J/\psi\, K^0_S) + \Gamma(B^0(t) \to J/\psi\, K^0_S)}$$
$$= S_{J/\psi K^0_S} \sin(\Delta m_d t) - C_{J/\psi K^0_S} \cos(\Delta m_d t).$$

$$S_{J/\psi K^0_S} = 0.73 \pm 0.07\,(\mathrm{stat}) \pm 0.04\,(\mathrm{syst})$$
$$C_{J/\psi K^0_S} = 0.03 \pm 0.09\,(\mathrm{stat}) \pm 0.01\,(\mathrm{syst})$$



Phys. Lett. **B721** (2013) 24

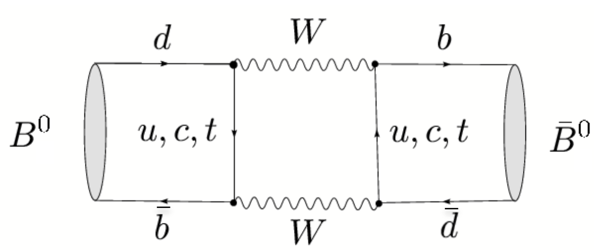


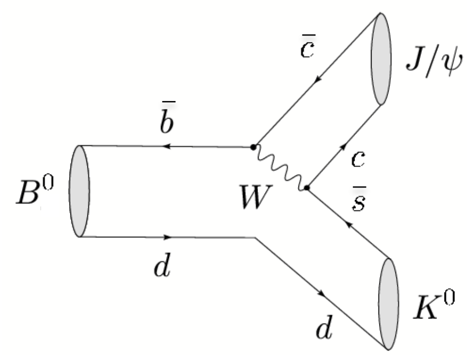
World average: sin(2β)=0.682 ± 0.019

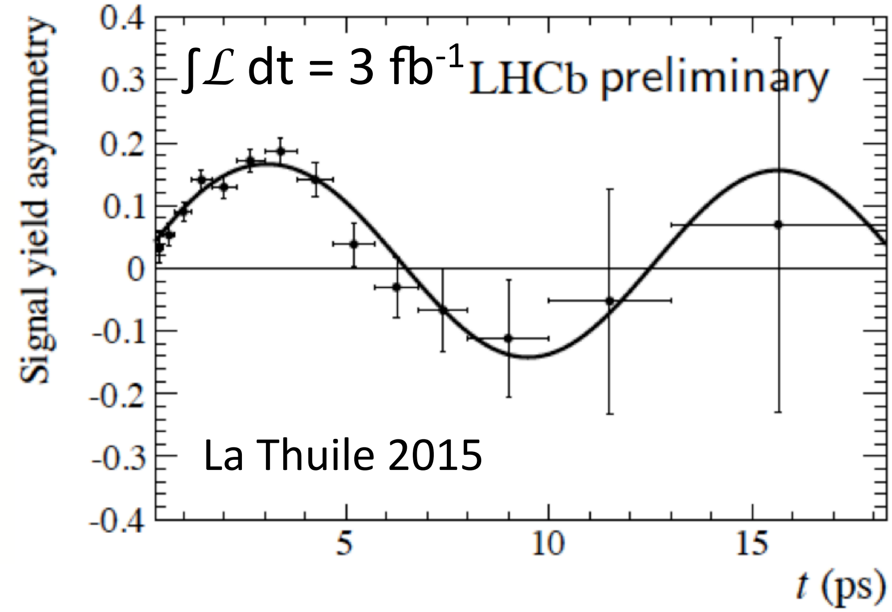
Largely dominated by BaBar and Belle

Measurement of sin(2β) [today]

- *CP* violation due to interference between mixing and decay







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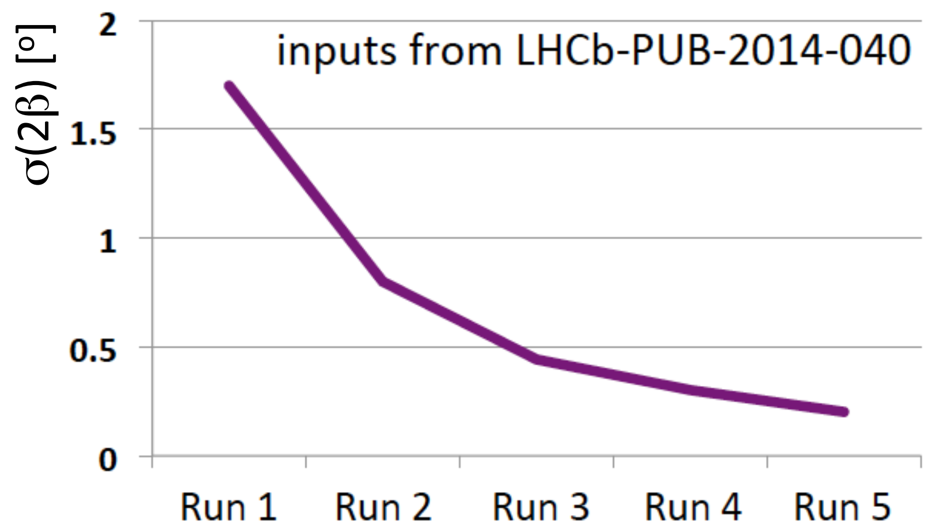
$$= S_{J/\psi K^0_S} \sin(\Delta m_d t) - C_{J/\psi K^0_S} \cos(\Delta m_d t).$$

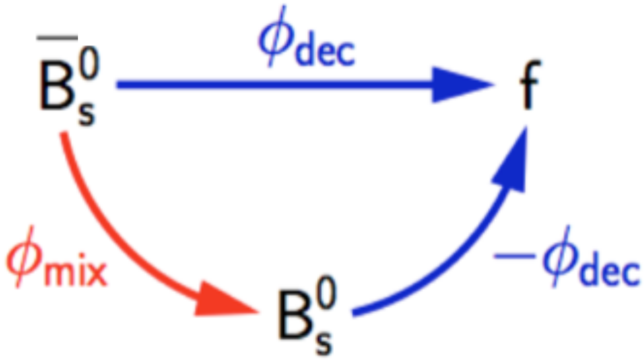
$$C = -0.038 \pm 0.032 \pm 0.005$$

$$S = 0.731 \pm 0.035 \pm 0.020$$

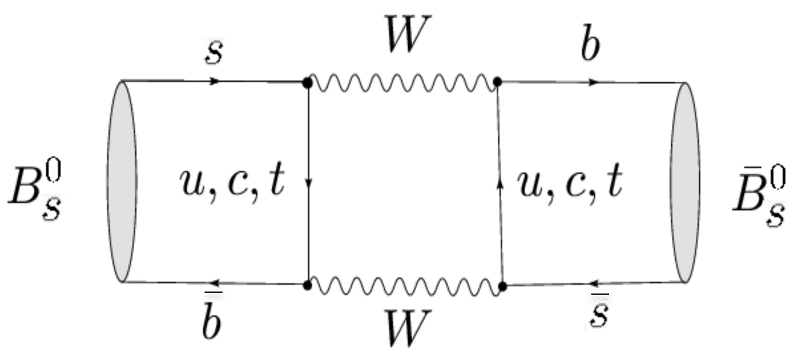


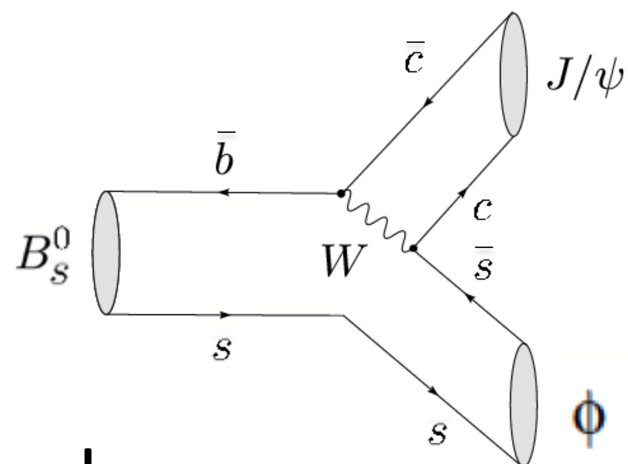
- Increased data set (1 fb^{-1}→3 fb^{-1}) and improved flavour tagging
- Similar precision to *B* factories

CP violation induced by B_s mixing



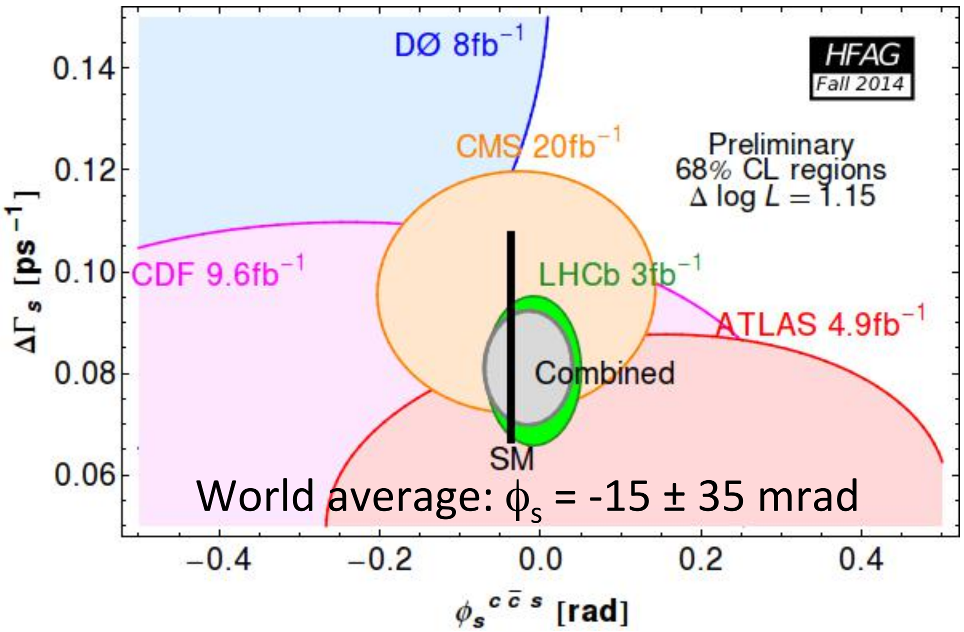
- Golden mode $B_s \rightarrow J/\psi\phi$ also proceeds (mostly) via a $b \rightarrow c\bar{c}s$ tree diagram





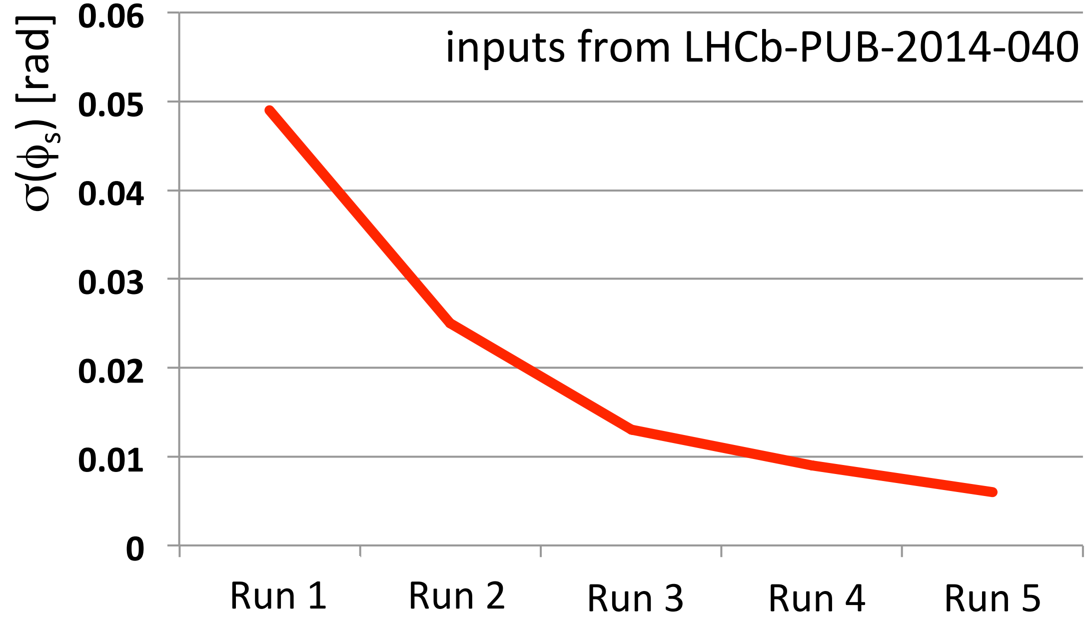
- $B_s \rightarrow \phi\phi$ is $b \rightarrow s\bar{s}s$ penguin-dominated
  - NP can show up in the mixing and/or in the decay
- $P \rightarrow VV$ decays
  - Full angular analysis is needed to disentangle *CP*-even and *CP*-odd amplitude components

ϕ_s from $b \rightarrow c\bar{c}s$

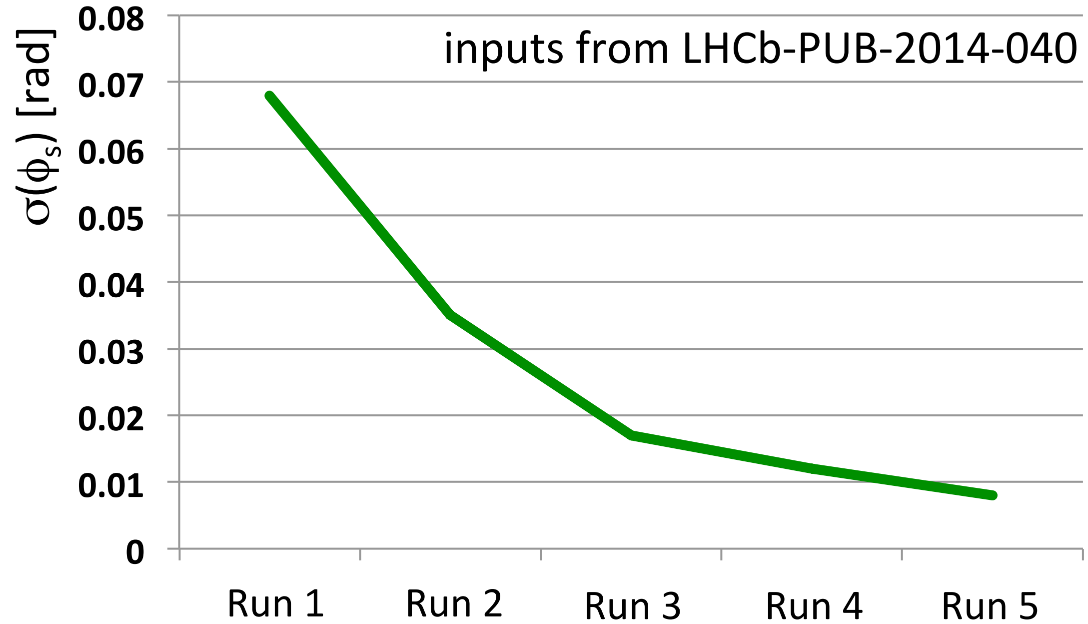


- $B_s \rightarrow J/\psi K^+K^-$ (3 fb^{-1})
  - Phys. Rev. Lett. **114** (2015) 041801
    ϕ_s = -58 ± 49 ± 6 mrad
- $B_s \rightarrow J/\psi \pi^+\pi^-$ (3 fb^{-1})
  - Phys. Lett. **B736** (2014) 186
    ϕ_s = 70 ± 68 ± 8 mrad
- $B_s \rightarrow D_s^+D_s^-$ (3 fb^{-1})
  - Phys. Rev. Lett. **113** (2014) 211801
    ϕ_s = 20 ± 170 ± 20 mrad

ϕ_s from $B_s \rightarrow J/\psi\phi$



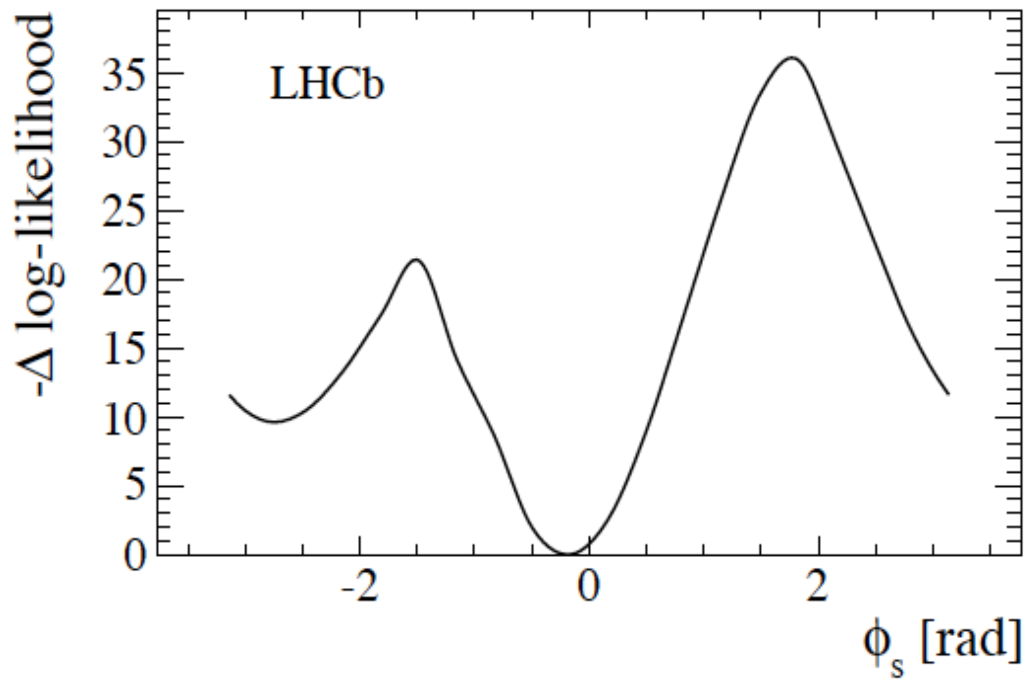
ϕ_s from $B_s \rightarrow J/\psi f_0$



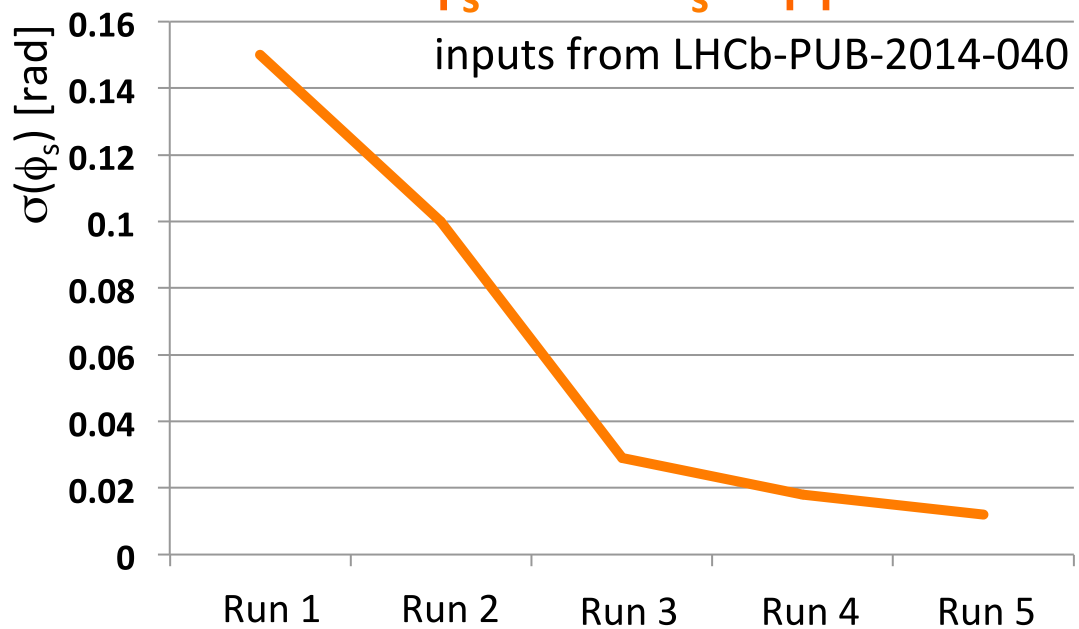
CP violation in $B_s \to \phi\phi$

- Gluonic $b \to s\bar{s}s$ penguin
  - Provides an excellent probe of new heavy particles entering the penguin quantum loops
- Latest LHCb result with full Run 1 data set
  - Phys. Rev. **D90** (2014) 052011

  $\phi_s^{\phi\phi}$ = -170 ± 150 ± 30 mrad
- No sign of discrepancy yet, but overall precision comparable to golden $b \to c\bar{c}s$ modes

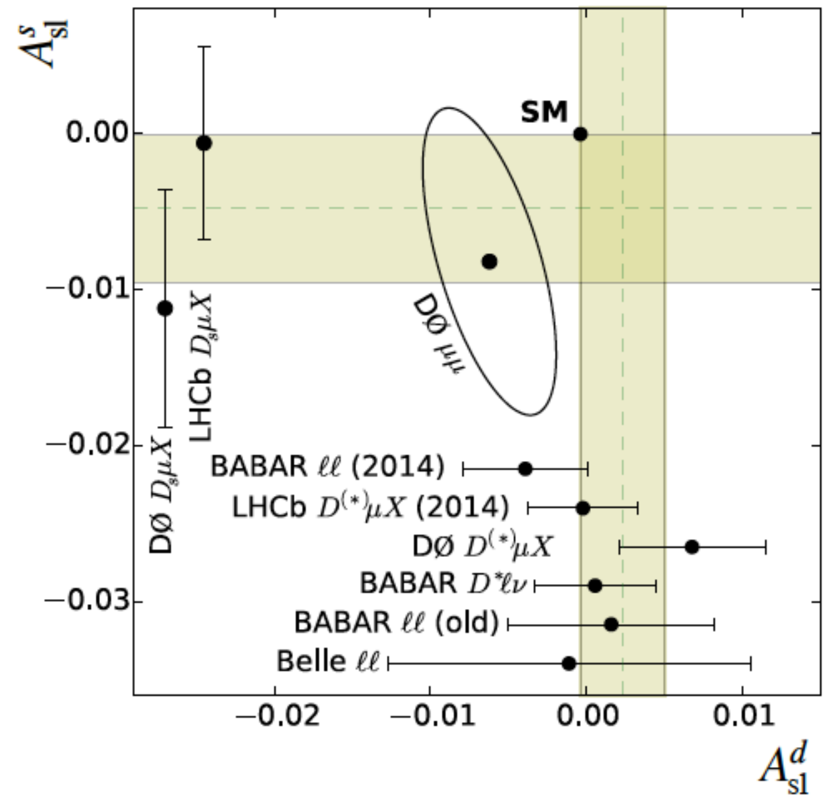


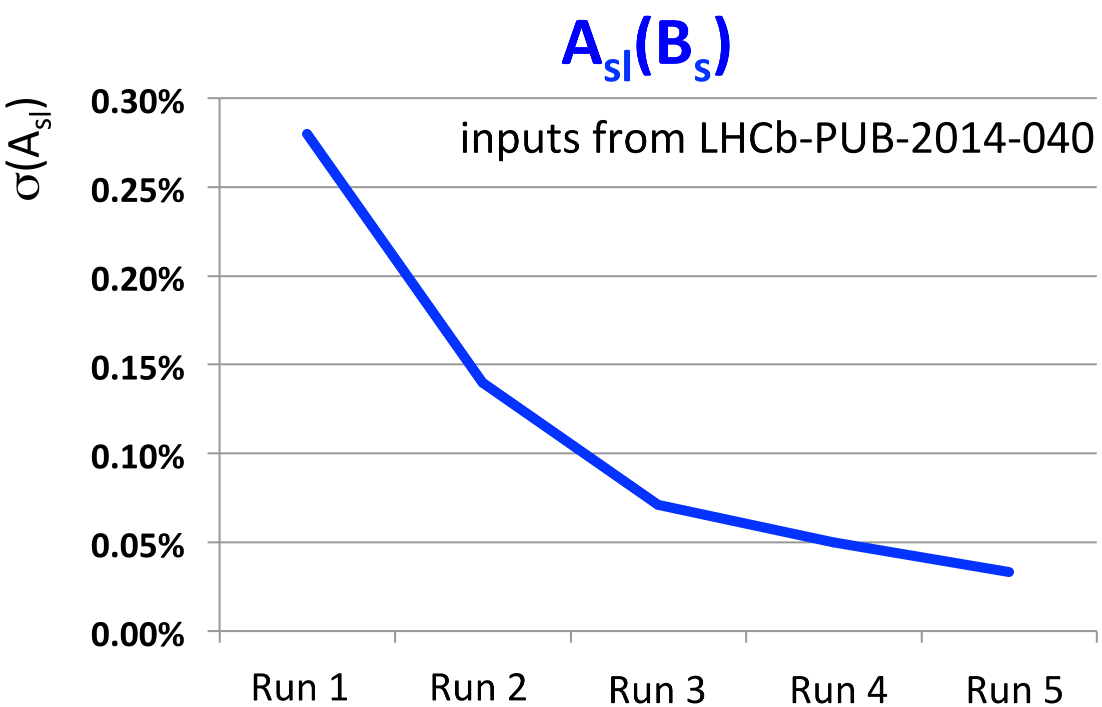
ϕ_s from $B_s \to \phi\phi$



Semileptonic asymmetries

- We have measured $a_{sl}(B^0)$ with 3 fb^{-1}
  - Phys. Rev. Lett. **114** (2015) 041601
- and $a_{sl}(B_s)$ with 1 fb^{-1}
  - Phys. Lett. **B728** (2014) 607
- The measurements agree with the SM, but do not exclude the D0 same-sign dimuon result yet

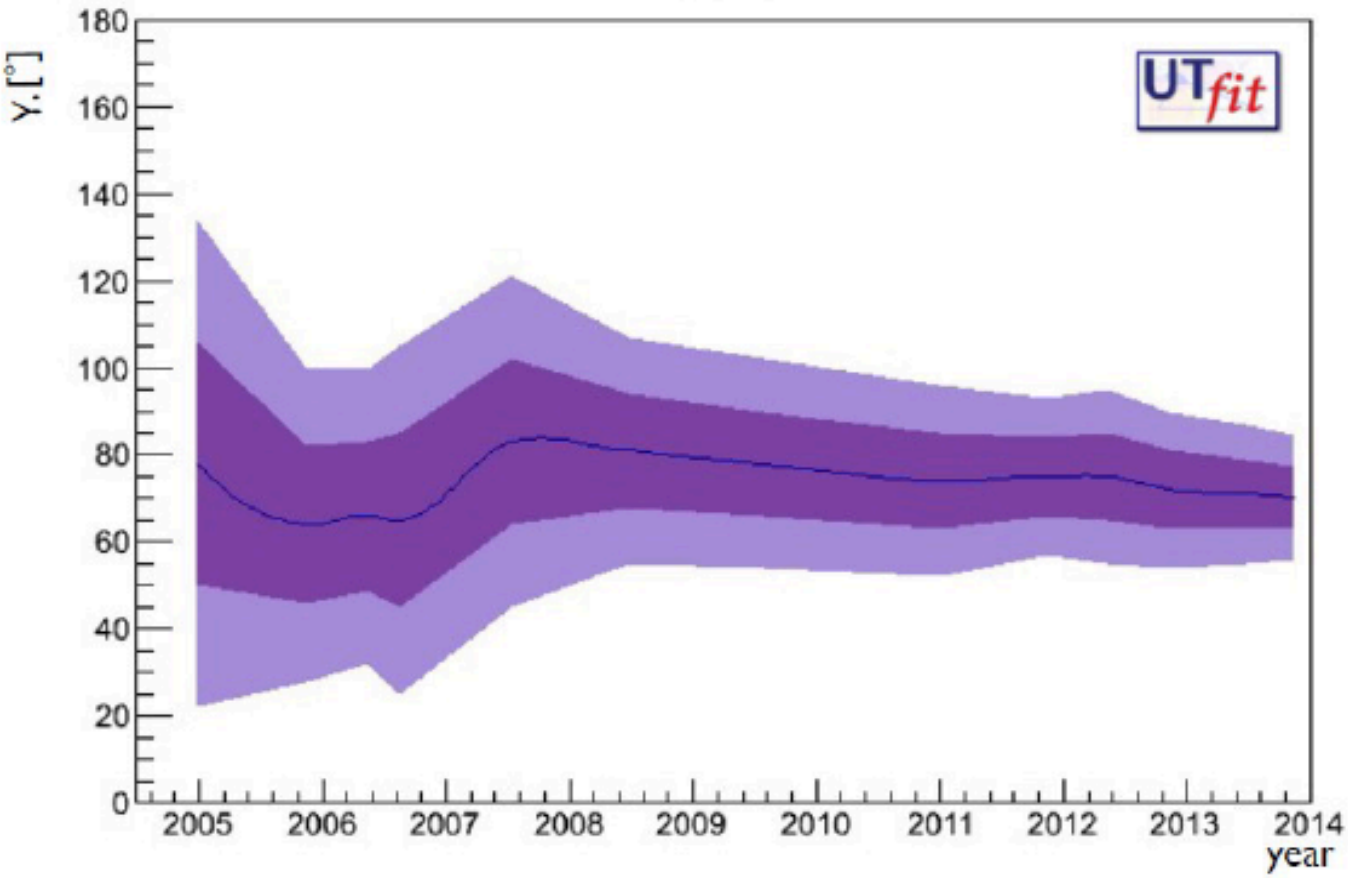




Tree-level determination of γ

- γ is experimentally the least known angle of the UT
- Two main routes
  - Time-independent, $B^{\pm} \rightarrow DK^{\pm}$, $B^{\pm} \rightarrow D\pi^{\pm}$ and $B^0 \rightarrow DK^{*0}$ decays
    - $B^+ \to Dh^+$, $D \to hh$, GLW/ADS Phys. Lett. **B712** (2012) 203
    - $B^+ \to Dh^+$, $D \to K\pi\pi\pi$, ADS Phys. Lett. **B723** (2013) 44
    - $B^+ \to DK^+$, $D \to K^0_S hh$, GGSZ JHEP **10** (2014) 097
    - $B^+ \to DK^+$, $D \to K^0_S K\pi$, GLS Phys. Lett. **B733** (2014) 36
    - $B^0 \to DK^{*0}$, $D \to hh$, GLW/ADS Phys. Rev. **D90** (2014) 112002
  - Time-dependent, $B_s \rightarrow D_s K$ JHEP **11** (2014) 060
- Possible interplay with charmless *B* decays
  - Also sensitive to γ, but including penguin diagrams $\rightarrow$ NP could show up, but much more difficult to control theoretically
- Combining several independent decay modes is the key to achieve the ultimate precision

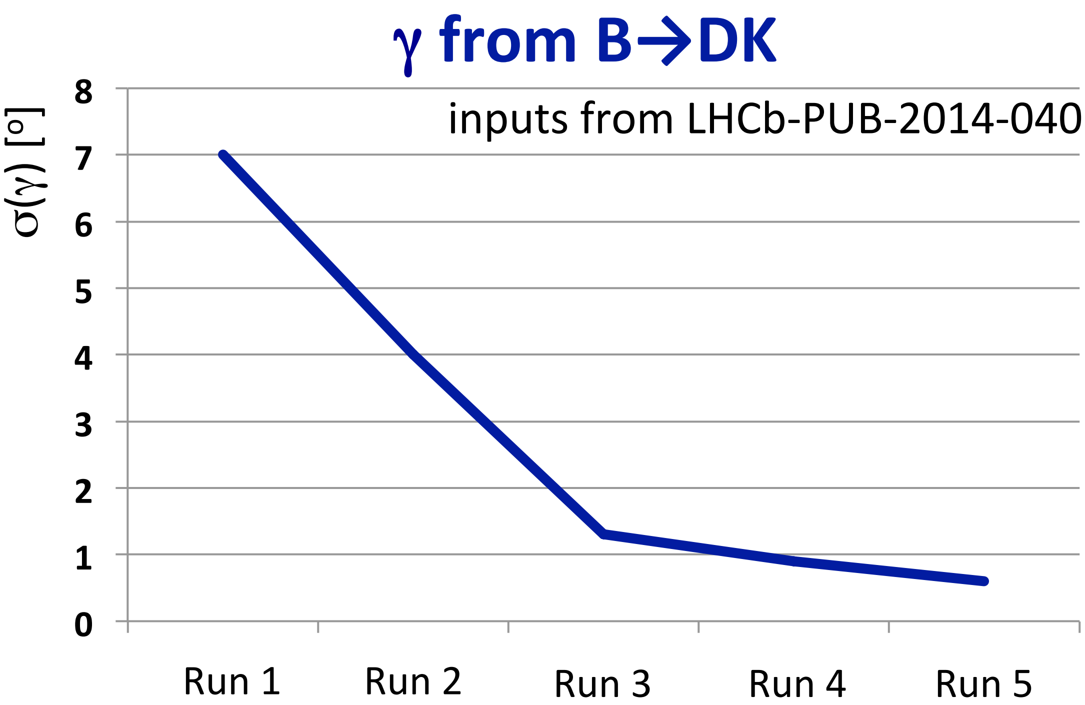
Improvements in γ from tree-level decays over the last decade

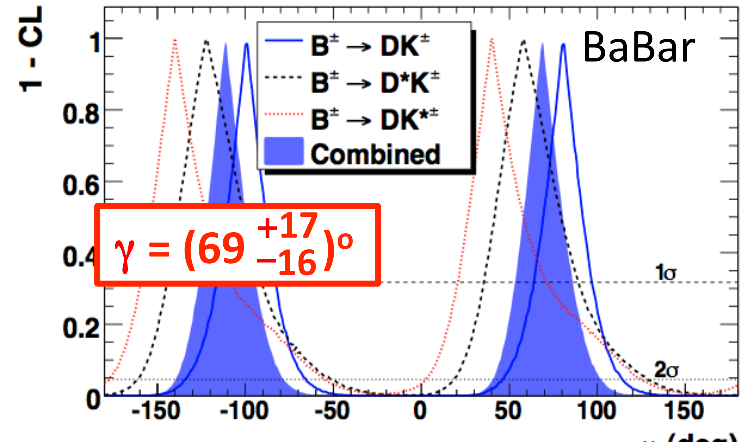


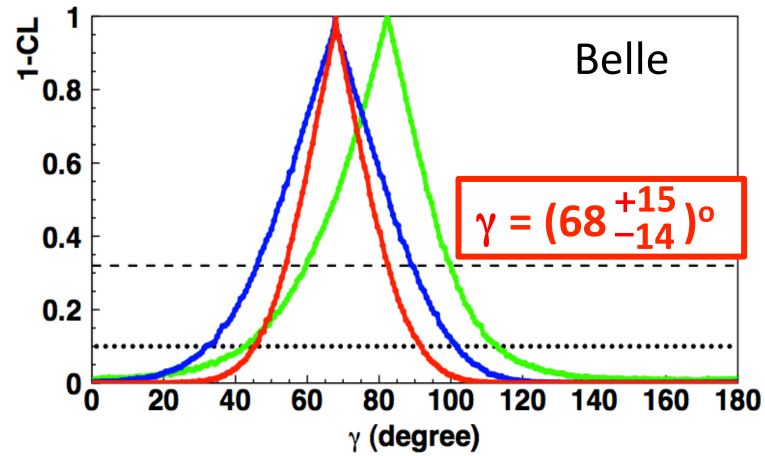
A good factor 3 in 10 years, but not yet matching the precision of the indirect determination from CKM fits (~3°)

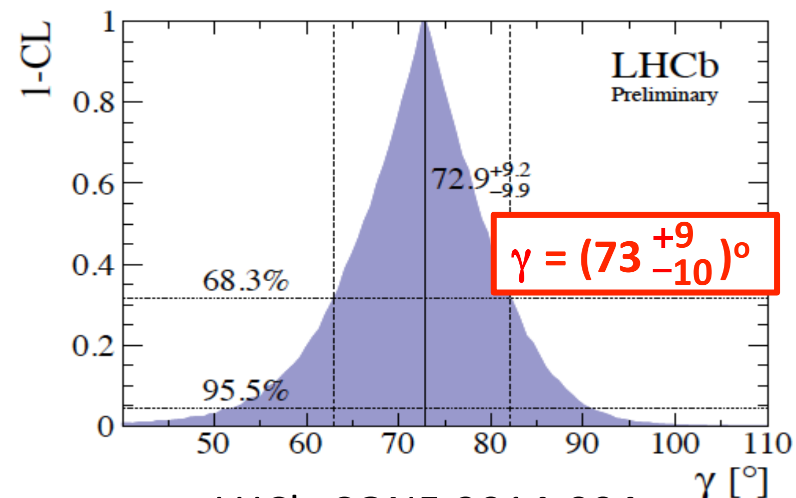
Experimental status for γ

- LHCb is now starting to dominate the world average









LHCb-CONF-2014-004

γ and ϕ_s from charmless two-body decays

- Determination of γ and ϕ_s using $B^0 \rightarrow \pi^+\pi^-$, $B^0 \rightarrow \pi^0\pi^0$, $B^\pm \rightarrow \pi^\pm\pi^0$ and $B_s \rightarrow K^+K^-$
  - approaches described in Phys. Lett. **B459** (1999) 306 and JHEP **10** (2012) 029
  - based on use of isospin and U-spin symmetries
  - impact of non-factorisable U-spin breaking effects taken into account
- Results published in Phys. Lett. **B741** (2015) 1

$$\gamma = \left(63.5^{+7.2}_{-6.7}\right)^\circ$$

$$\phi_s = -0.12^{+0.14}_{-0.16} \text{ rad}$$

Up to 50% non-factorizable U-spin breaking effects included

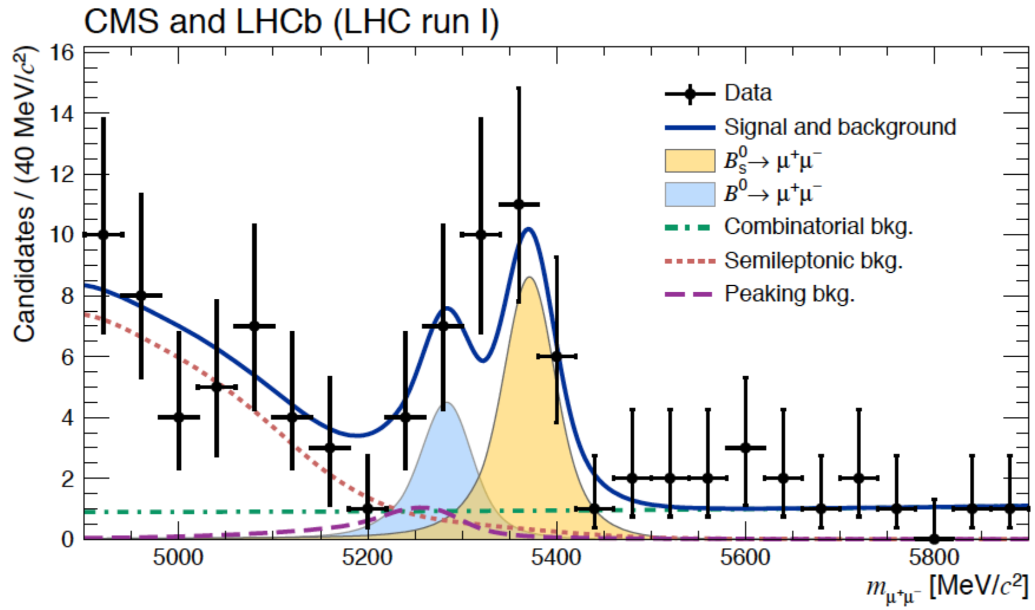
to be updated to 3 fb^{-1}

$B_{d,s} \to \mu^+\mu^-$ from CMS and LHCb

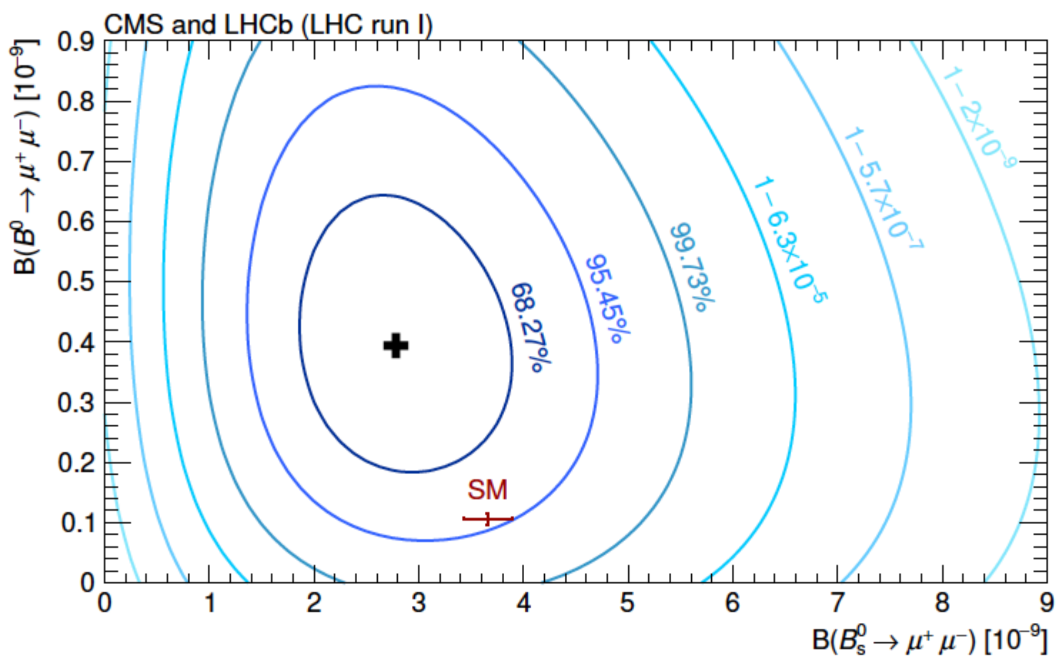
- CMS and LHCb have now performed a combined fit to their full Run 1 data sets

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$$



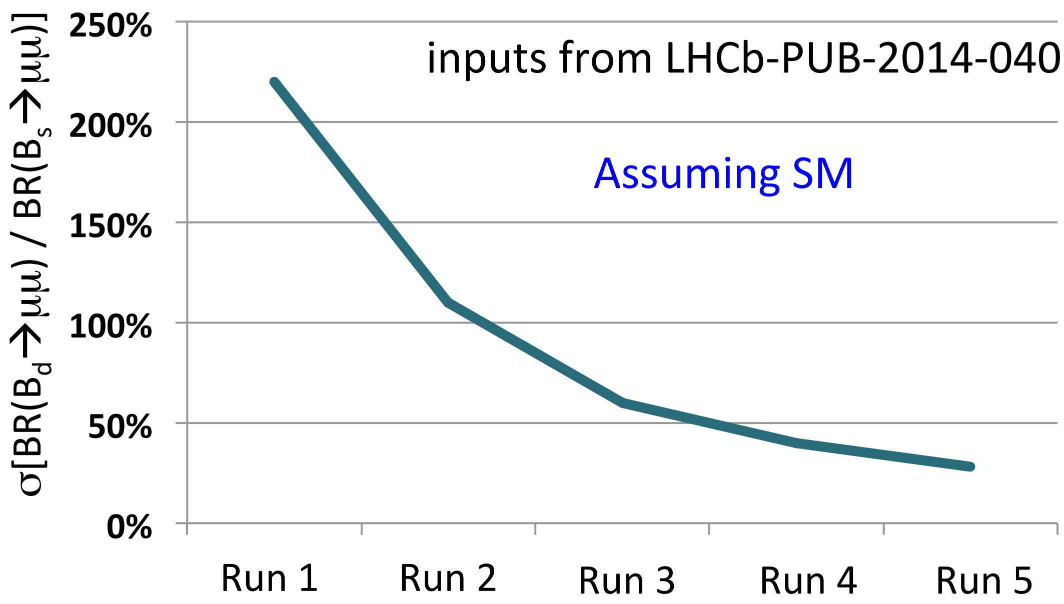
- Significance of $B_s \to \mu\mu$ 6.2σ: **first observation!**
  - Compatibility with the SM at 1.2σ
- Excess of events at the 3σ level observed for the $B^0 \to \mu\mu$ hypothesis with respect to background-only
  - Compatible with SM at 2.2σ



CMS-BPH-13-007, LHCb-PAPER-2014-049: submitted to Nature

Prospects with $B_{d,s} \to \mu^+\mu^-$

- Focus here on the ratio between $BR(B_d \to \mu^+\mu^-)$ and $BR(B_s \to \mu^+\mu^-)$
- Measurement will still be dominated by experimental uncertainty by the end of the present programme

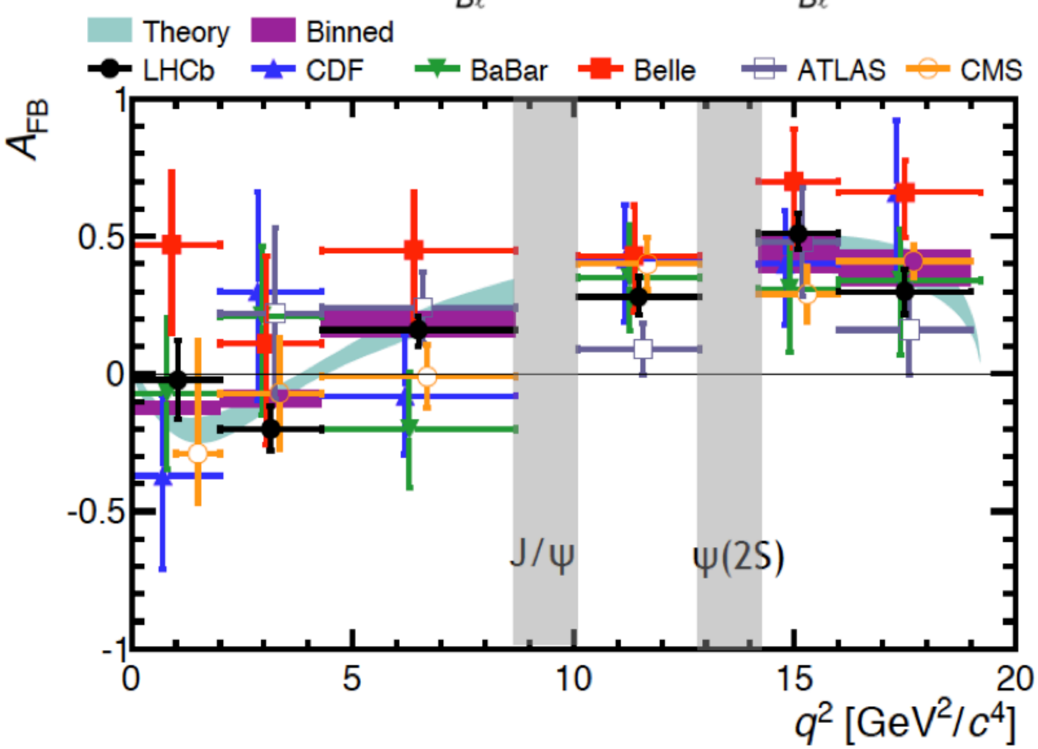


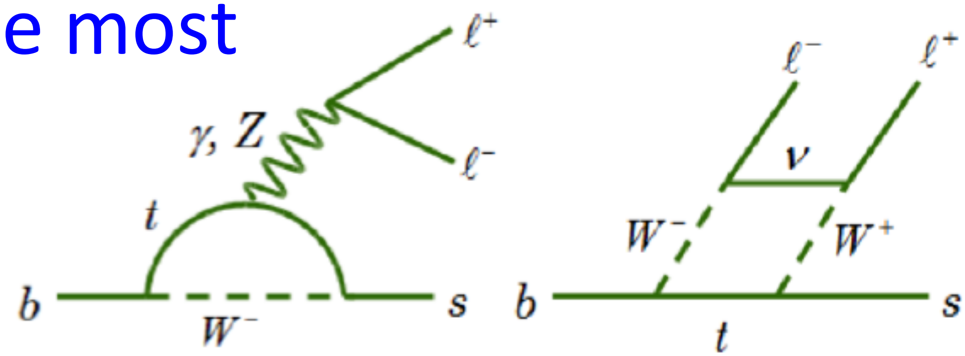
- With increased statistics, the measurement of effective $B_s \to \mu^+\mu^-$ lifetime and possibly time-dependent CP violation will become possible

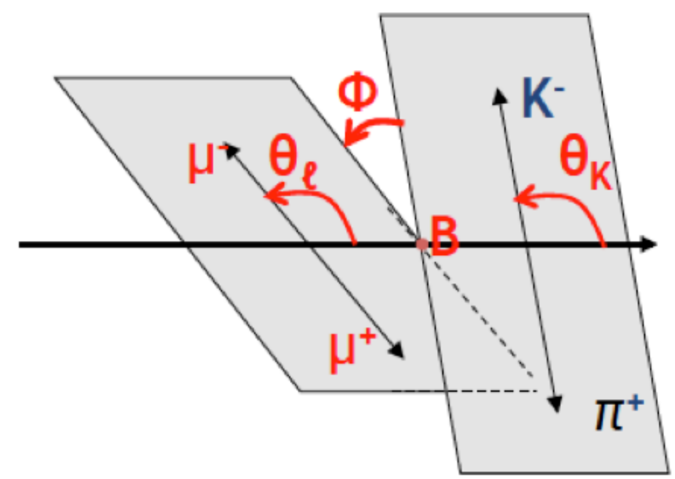
Status of $B_d \rightarrow K^* \mu^+ \mu^-$

- Observables are q^2 (dimuon mass squared) and 3 angles
  - distributions are quite precisely predicted in the SM
- A_{FB}: LHCb presently giving the most precise results

$$A_{FB} = \frac{\Gamma(\cos\theta_{B\ell^+} > 0) - \Gamma(\cos\theta_{B\ell^+} < 0)}{\Gamma(\cos\theta_{B\ell^+} > 0) + \Gamma(\cos\theta_{B\ell^+} < 0)}$$



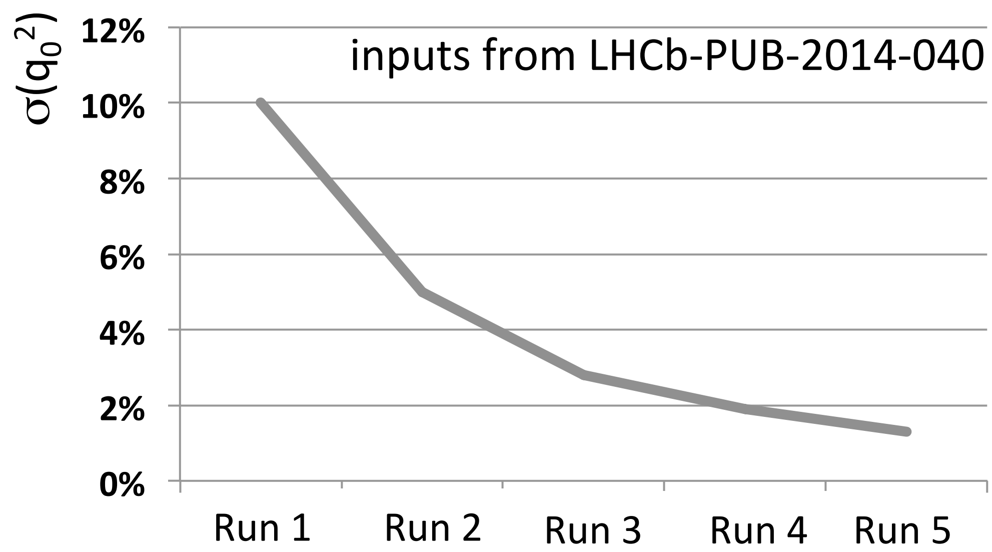




A_{FB} Prospects with $B_d \rightarrow K^*\mu^+\mu^-$

- LHCb expects to reach an accuracy of better than 2% in the zero-crossing of the forward-backward asymmetry

Expected relative sensitivity on the zero-crossing point



- A_{FB} is not necessarily the best variable
- Lot of phenomenological work ongoing to define observables where hadronic uncertainties are partially cancelled

$B_d \to K^{*0}\mu^+\mu^-$: P'_5 anomaly

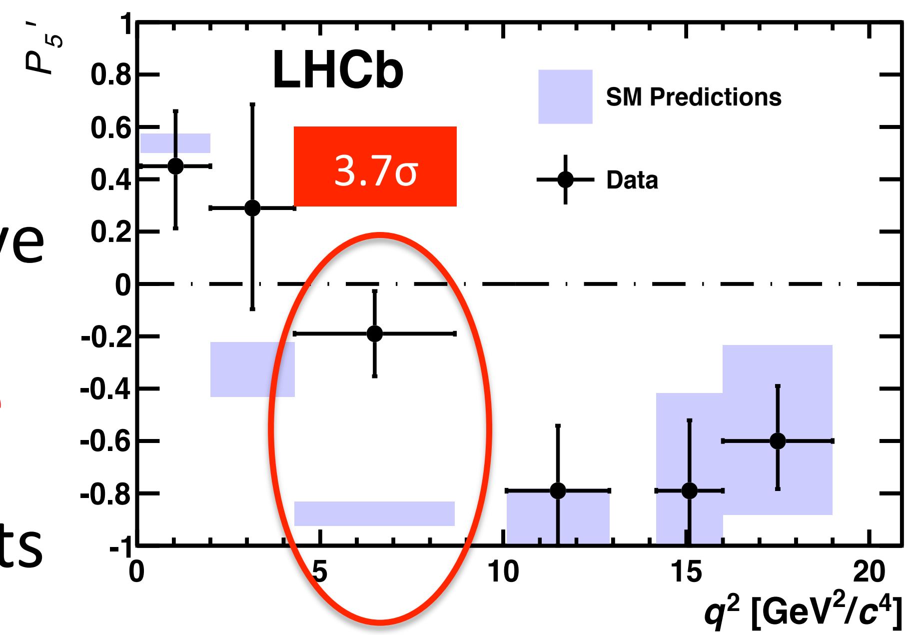
Differential decay rate

$$\frac{1}{\mathrm{d}\Gamma/dq^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \frac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big],$$

$$\boxed{P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_{\mathrm{L}}(1-F_{\mathrm{L}})}}.}$$

- Interesting feature in one of the observables (P'_5)
  - No definitive conclusion yet
  - Additional statistics and theoretical studies are needed
- LHCb has great potential to improve in this sector
- On the long run, progresses on the theory side are needed for a clean interpretation of the measurements

Phys. Rev. Lett. 111 (2013) 191801

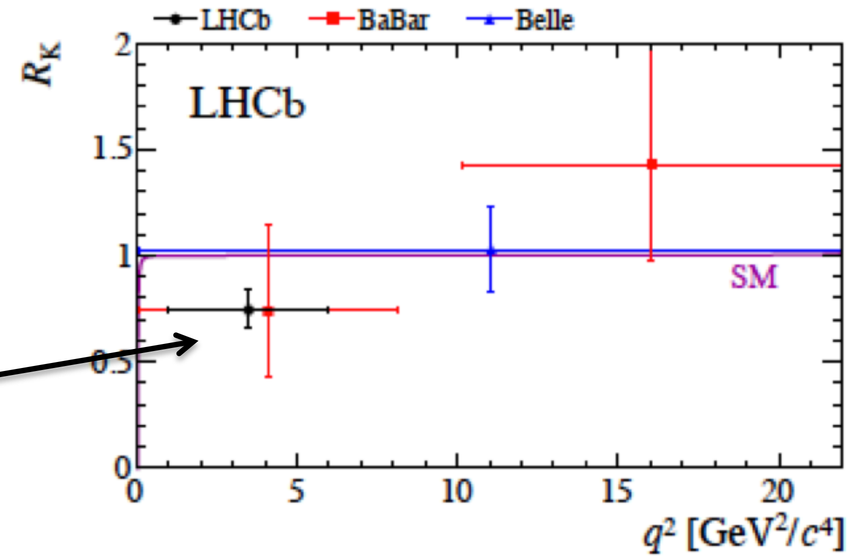


$B^+ \to K^+\ell^+\ell^-$: R_K anomaly

- $R_K = \mathfrak{B}(B^+ \to K^+\mu^+\mu^-) \,/\, \mathfrak{B}(B^+ \to K^+e^+e^-)$
  - expected in the SM to be 1 with great accuracy
  - test of lepton universality
- Hint of a possible discrepancy with SM measured by LHCb with 3 fb^{-1}

$$0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})$$

$$1 < q^2 < 6\ \text{GeV}^2/c^4$$



LHCb, PRL 113 (2014) 151601
Belle, PRL 103 (2009) 171801
Babar, PRD 86 (2012) 032012

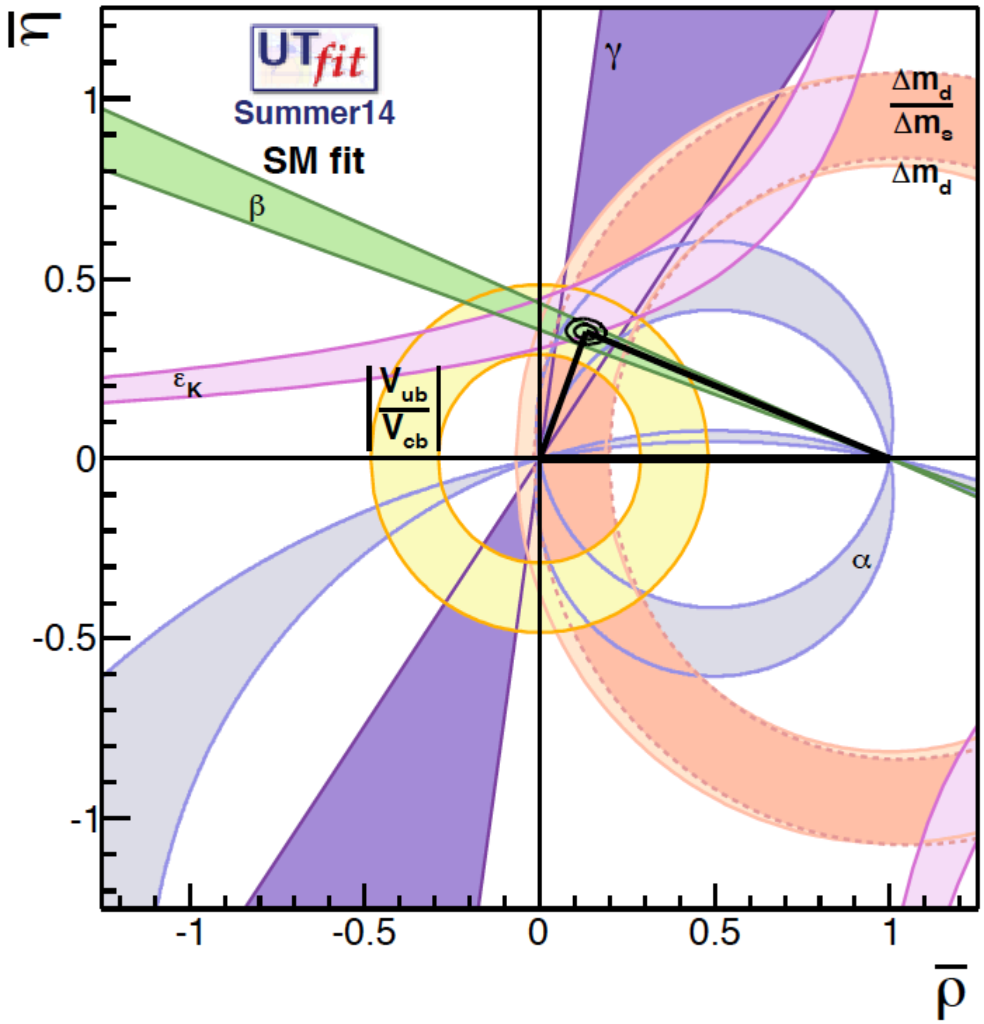
- Compatible with SM at 2.6σ at low di-lepton invariant mass

Conclusions

- LHCb has performed spectacularly well in Run 1 confirming so far the robustness of the Standard Model
  - No striking smoking guns of NP
    - apart from small discrepancies here and there
  - But many new results to come, and full impact of Run 1 data is still to be seen
- Big improvements will come in Run 2, and much more are expected with the LHCb Upgrade
  - The standard detector will take data till 2018 and the upgraded detector will start taking data in 2020
- Experimental prospects are excellent
  - Key measurements are still far from being limited by systematic uncertainties
- *B* physics at LHCb has large room for improvements!

How it could look like...

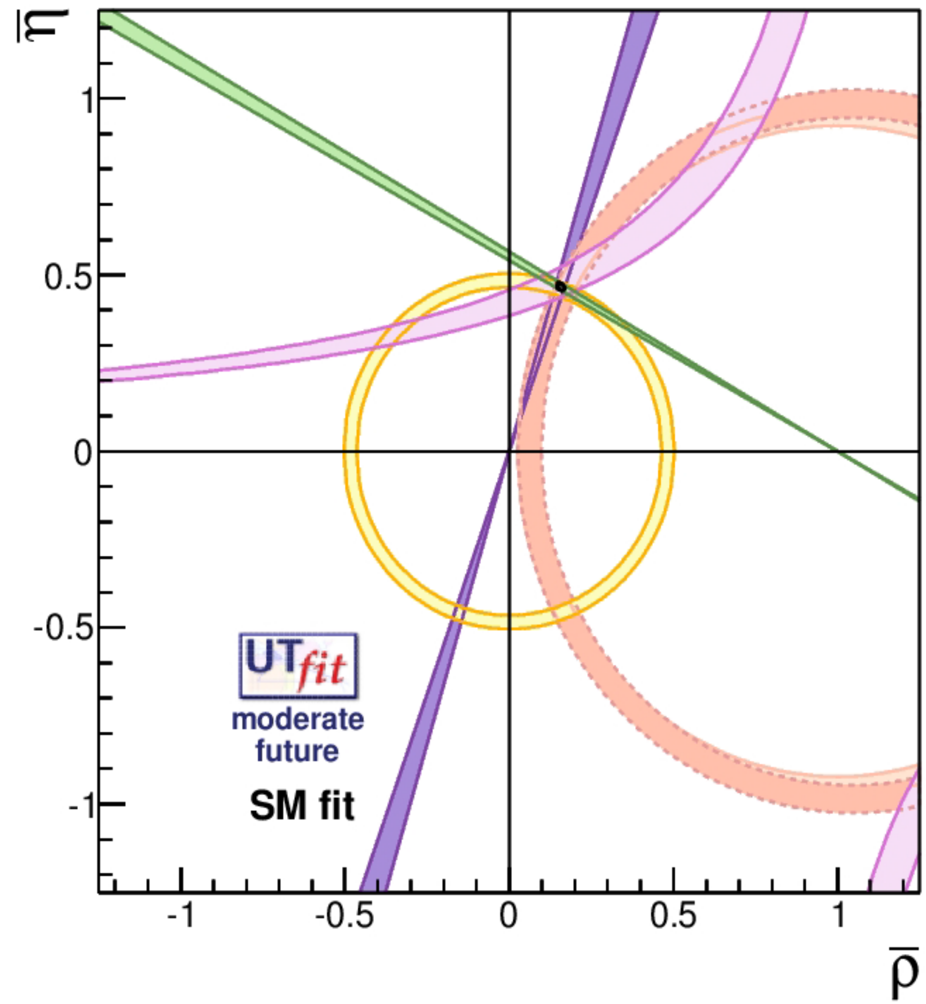
Today



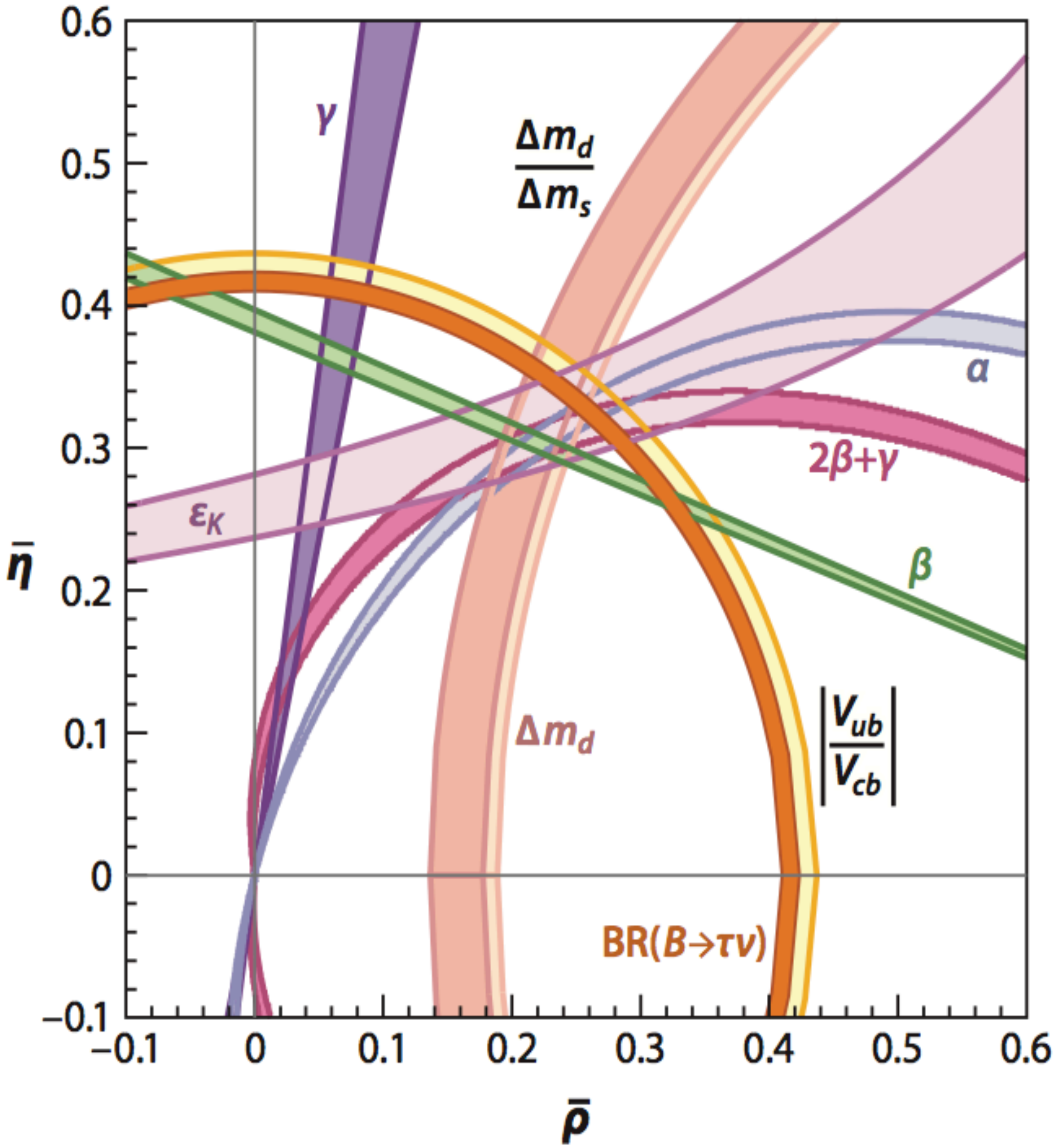
$\sigma(\beta)=0.2^o$ $\sigma(\gamma)=0.9^o$

$\sigma(V_{ub})=2\%$ $\sigma(V_{cb})=1\%$

+ improvements from LQCD



...but maybe this!



Outlook of the Outlook

In the current confusing state of fundamental physics useful/necessary to have a diversified program (LHC, precision, flavour, astro-cosmo-particle, DM)

R. Barbieri at ZPW2015

Latest sensitivity prospects

LHCb-PUB-2014-040

Type	Observable	LHC Run 1	LHCb 2018	LHCb upgrade	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.049	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\, f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 0.01
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.15	0.10	**0.018**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.023**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.036**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$ (rad)	0.20	0.13	**0.025**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.6%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\, A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.09	0.05	**0.017**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\,\%$
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**0.9°**	negligible
	$\gamma(B_s^0 \to D_s^\mp K^\pm)$	17°	11°	**2.0°**	negligible
	$\beta(B^0 \to J/\psi\, K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm CP violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.4**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.1**	–

- Before the upgrade (8 fb^{-1})
- After the upgrade (50 fb^{-1})
- Theory uncertainty (as far as we know today)