Heavy flavour LHC results

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On behalf of the ATLAS, CMS and LHCb collaborations

Florence, April 21-24, 2015

Outline

- Results on rare B decays
- CP violating phases and V_{ub}
- Conclusions and prospects

$B^0_{(s)} \rightarrow \mu^+ \mu^-$: LHCb and CMS

The branching fraction of this very rare fully leptonic decay is precisely predicted within the Standard Moldel:

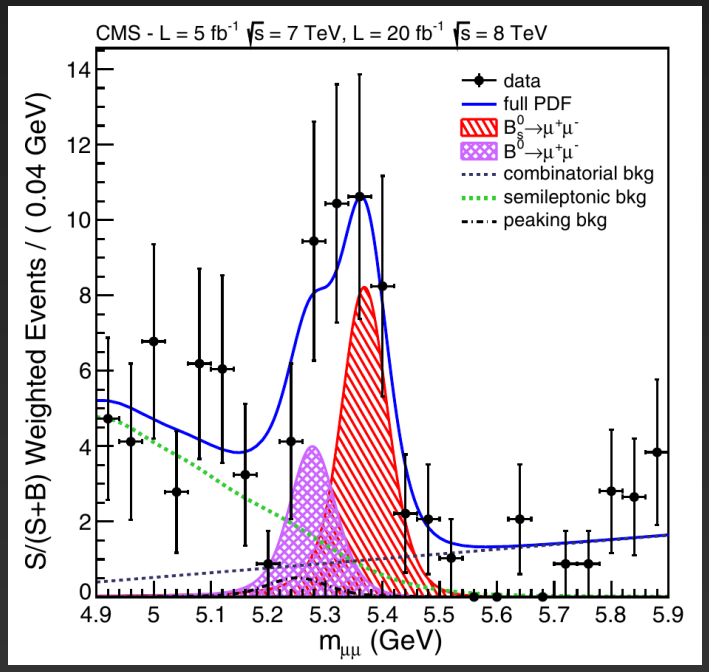
$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$

$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$

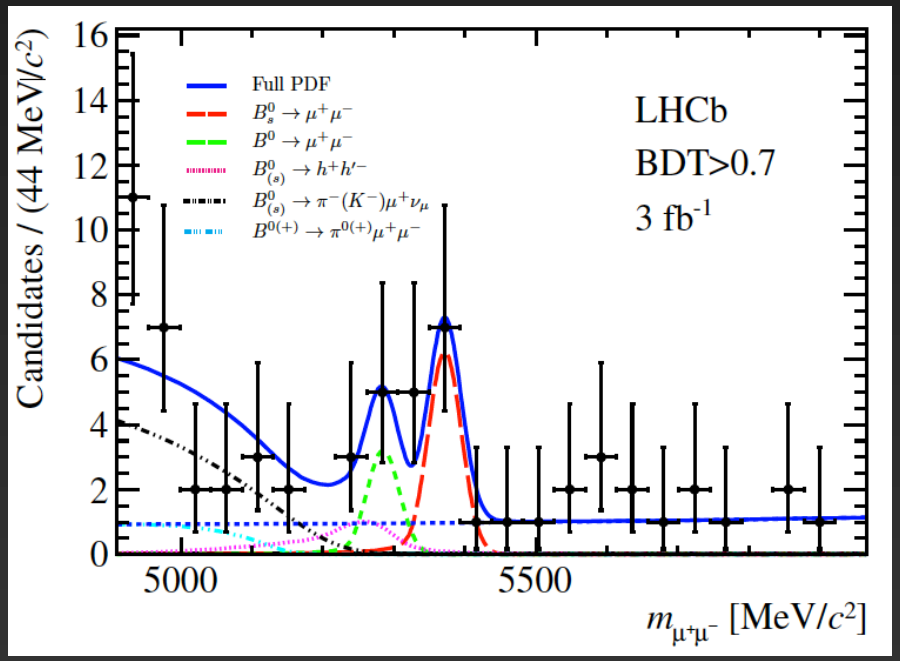
(Bobeth et al, PRL 112 (2014) 101801)

Seen by both LHCb and CMS with LHC Run I data

[CMS - Phys. Rev. Lett. 111, 101804 (2013)]



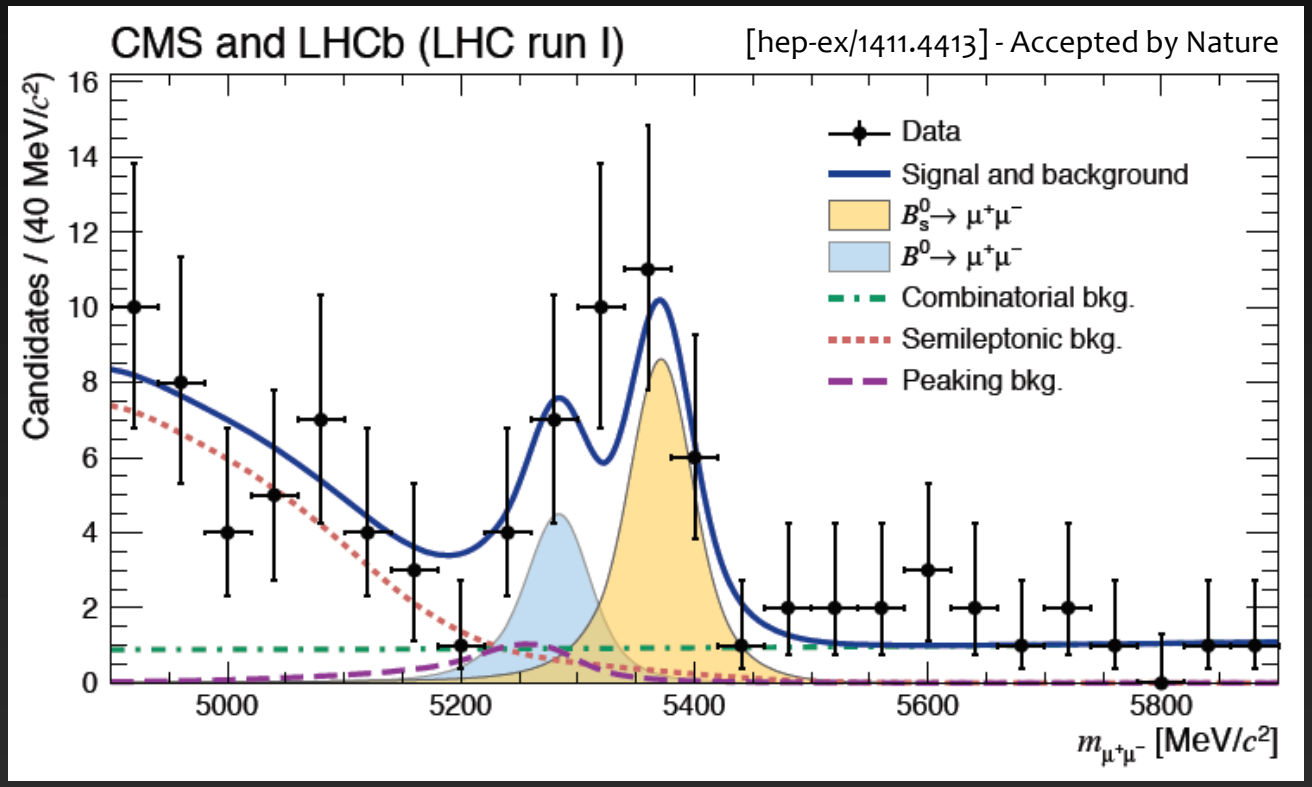
[LHCb - Phys. Rev. Lett. 111, 101805 (2013)]



Full combination of the two experiment analyses

$B^0_{(s)} \rightarrow \mu^+ \mu^-$: LHCb and CMS

Results of combination



6 most sensitive cathegories

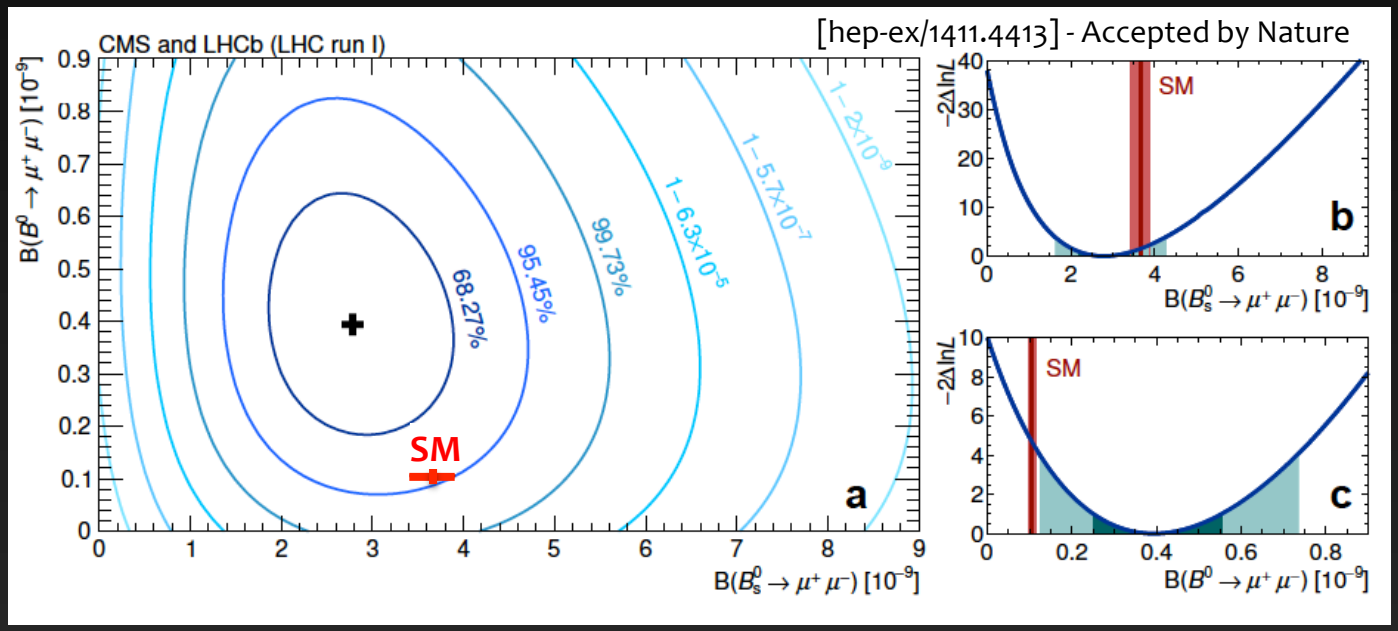
$$\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9} \ (6.2\ \sigma \text{ significance})$$

$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10} \ (3.0\ \sigma \text{ significance}^*)$$

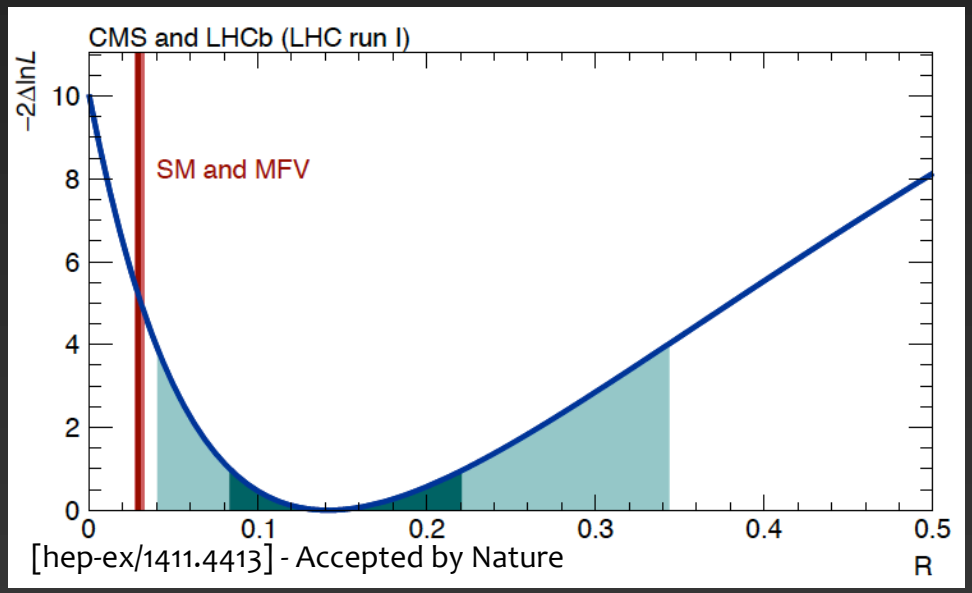
±2 σ Feldman-Cousins confidence interval for $\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)$: $[1.4, 7.4] \times 10^{-10}$

*Feldman Cousins

$B^0_{(s)} \to \mu^+ \mu^-$: LHCb and CMS



Confidence intervals



Measurement of the ratio

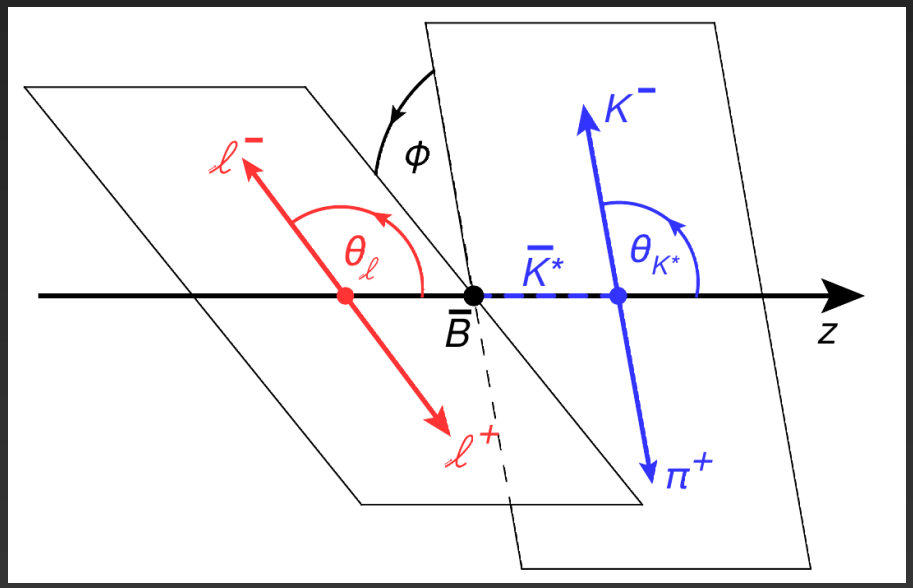
$$\mathrm{R} = \frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B^0_s \to \mu^+\mu^-)} = 0.14^{+0.08}_{-0.06}$$

compatible with the SM prediction

$$\mathrm{R} = 0.0295^{+0.0028}_{-0.0025} \text{ at } 2.3\ \sigma \text{ level}$$

Angular analysis of $B^0_d \to K^* \ell^+ \ell^-$

- $b \to s$ transition with vector in the final state described by $q^2 = m^2_{\ell^+\ell^-}$ and three angles $\Omega = (\vartheta_\ell, \vartheta_K, \phi)$
- Differential amplitudes parametrized in terms of F_L A_{FB}, S_i observables, sensitive to the Wilson coefficients $C^{(\prime)}_7$, $C^{(\prime)}_9$, $C^{(\prime)}_{10}$
- $B^0_d \to K^* \mu^+ \mu^-$: analysis performed by ATLAS, CMS (2011 data) and LHCb (full Run I statistics, new results)



Angular analysis of $B^0_d \to K^* \mu^+ \mu^-$

LHCb: [LHCb-CONF-2015-002]

- Full Run I data update for a total luminosity of 3 fb^{-1}
- **Kπ** S-wave component and P-S interference term included in the fit (parameters F_S and A_S)
- Full angular analysis: simultaneous determination of CP-averaged observables
  ☞ Covariance matrix to be used for global fits
- Simultaneous fit of angular observables and mass in q^2 bins

ATLAS: [ATLAS-CONF-2013-038]

- 2011 data, 4.9 fb^{-1}
- Sequential fit:
  Yields from mass fit
  A_{FB} , F_L from angles fit
  F_S from BaBar

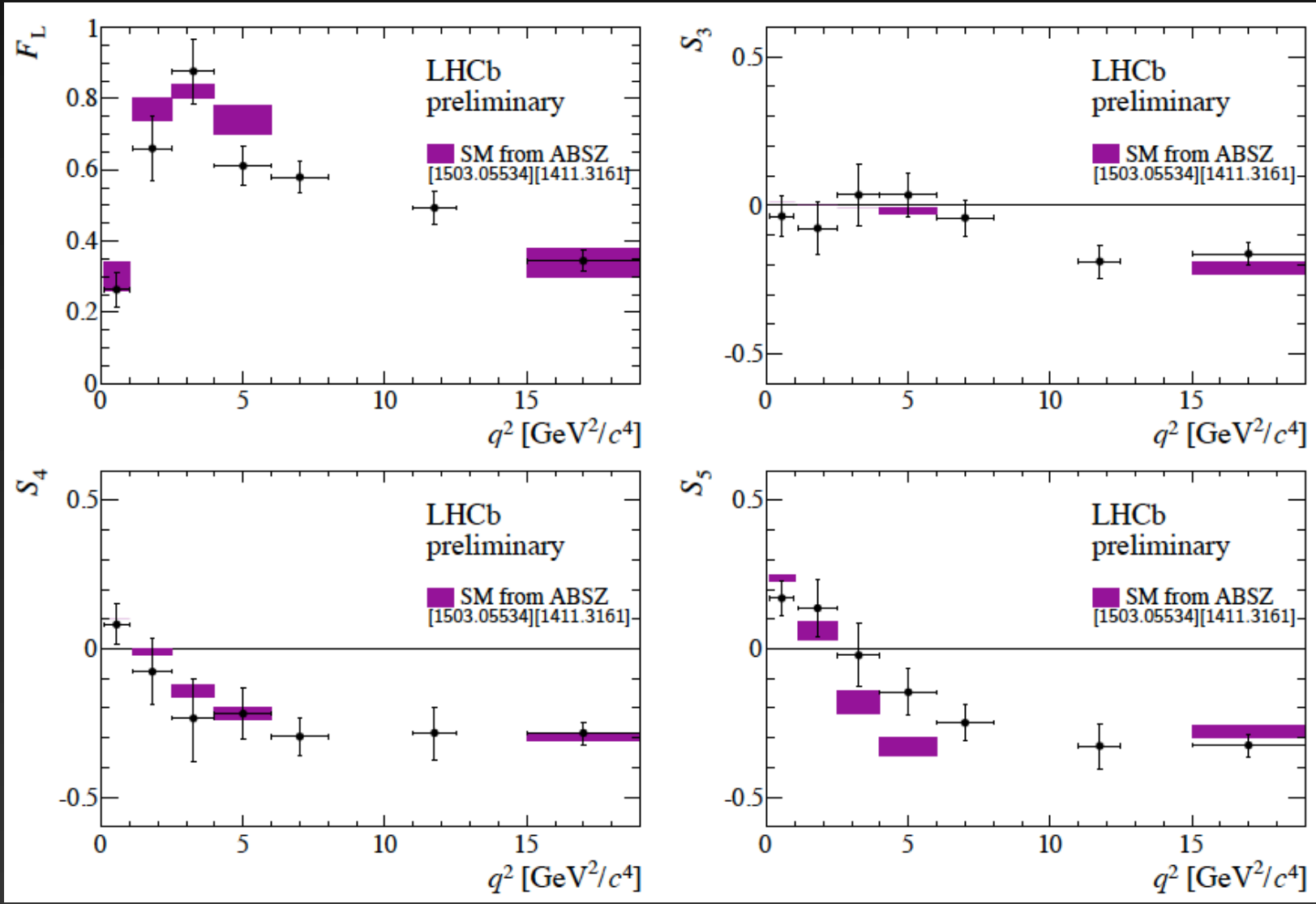
CMS: [PLB 727 (2013) 77]

- 2011 data, 5.2 fb^{-1}
- Simultaneous fit: A_{FB} , F_L, F_S, A_S (S-P interference)
- dB/dq^2 normalized to $B^0_d \to K^* J/\psi$

Angular analysis of $B^0_d \to K^* \mu^+ \mu^-$

Results

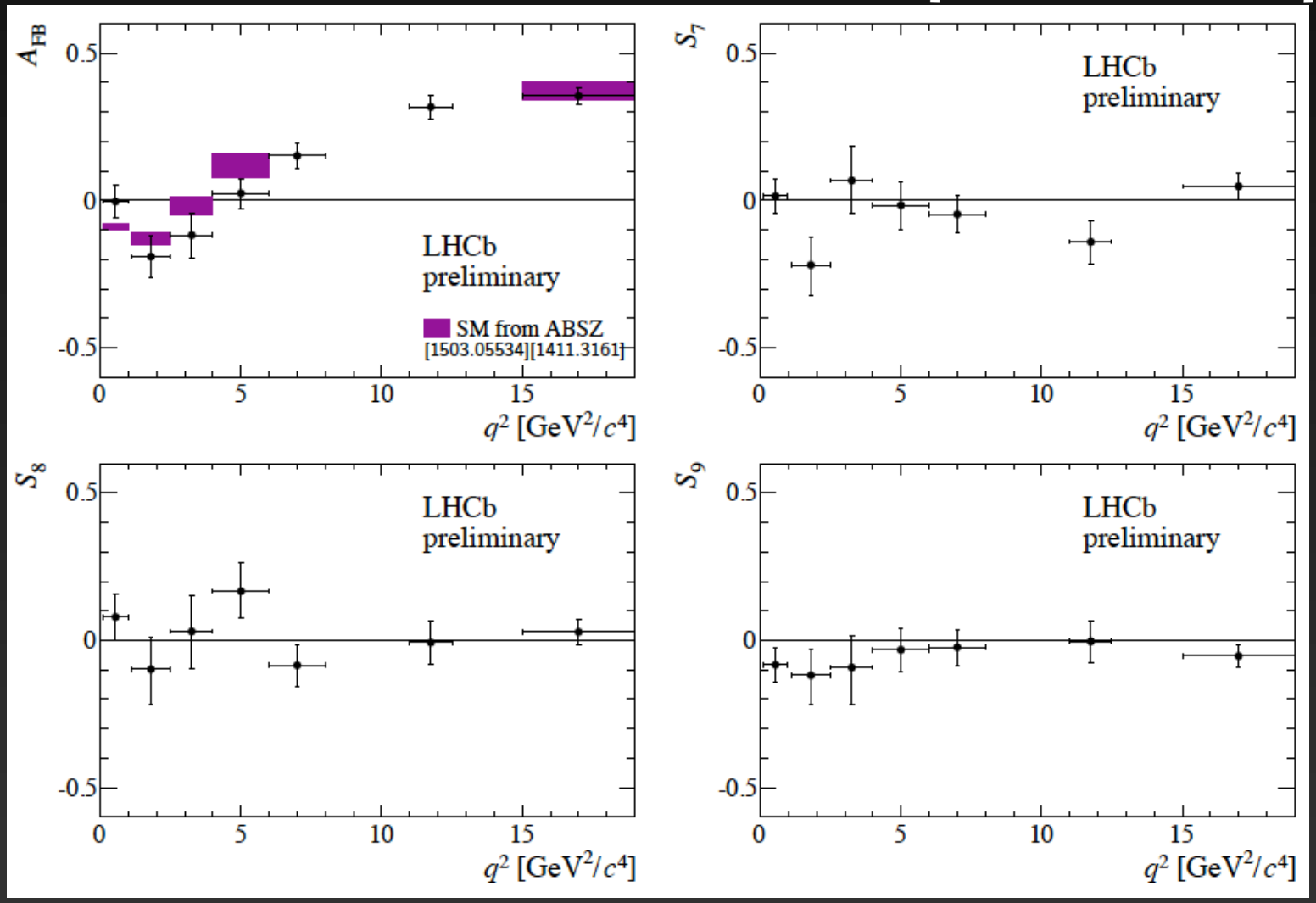
3 fb^{-1} [LHCb-CONF-2015-002]



Angular analysis of $B^0_d \to K^* \mu^+ \mu^-$

Results

3 fb^{-1} [LHCb-CONF-2015-002]



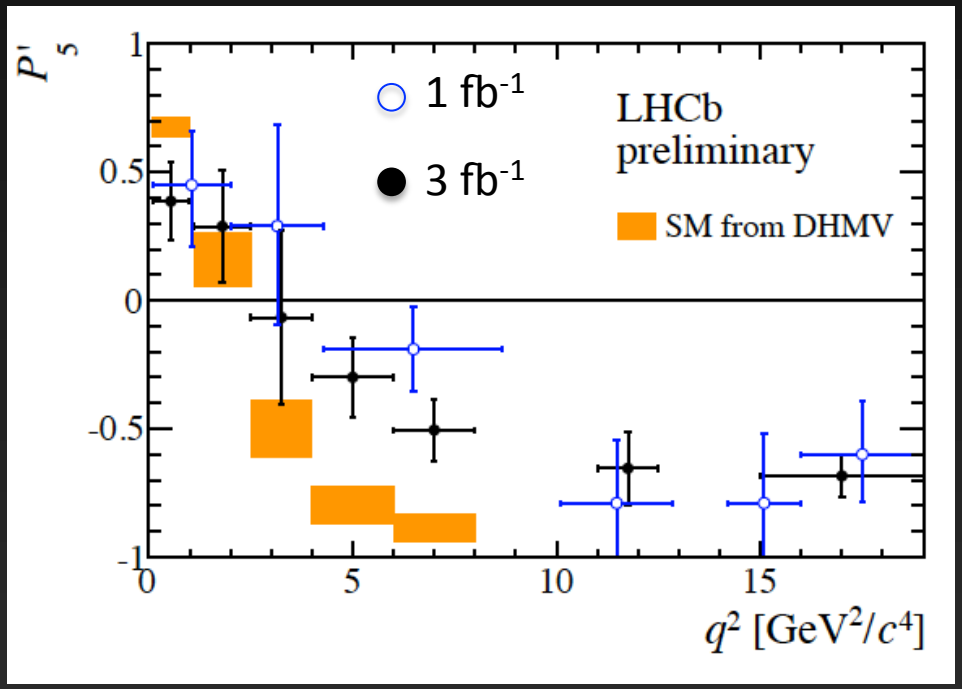
A_{FB} zero-crossing point = $3.7^{+0.8}_{-1.1}$ GeV²

($q^2_{0;SM} = 4.36^{+0.33}_{-0.31}$ GeV² [EPJ C41 (2005) 173-188])

Angular analysis of $B^0_d \to K^* \mu^+ \mu^-$

Results

3 fb^{-1} [LHCb-CONF-2015-002]



Form-factor independent observables:

$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

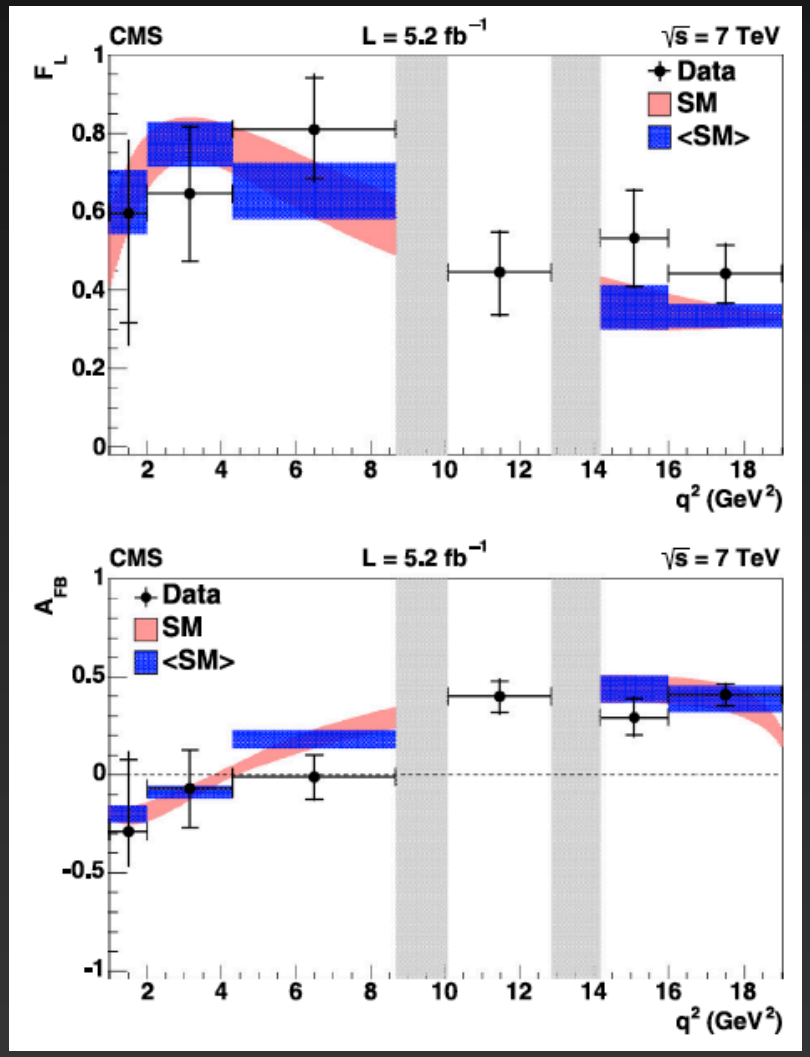
Comparison of 1 fb^{-1} and full Run 1 results

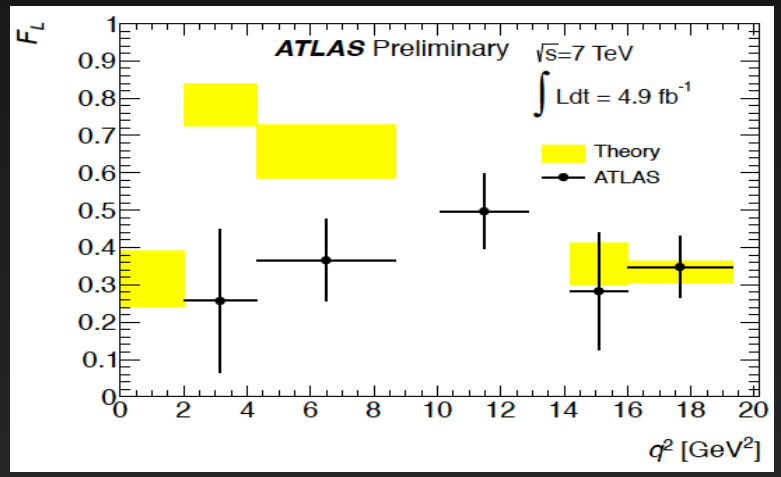
- Tension in P'_5 from previous measurement [1 fb^{-1} PRL 111, 191802 (2013), blue points] confirmed with 3 fb^{-1}
- Local deviations of 2.9 σ and 3.0 σ for $q^2 \in [4.0, 6.0]$ and $[6.0, 8.0]$ GeV^2
- Naive combination of the two gives local signicance of 3.7 σ

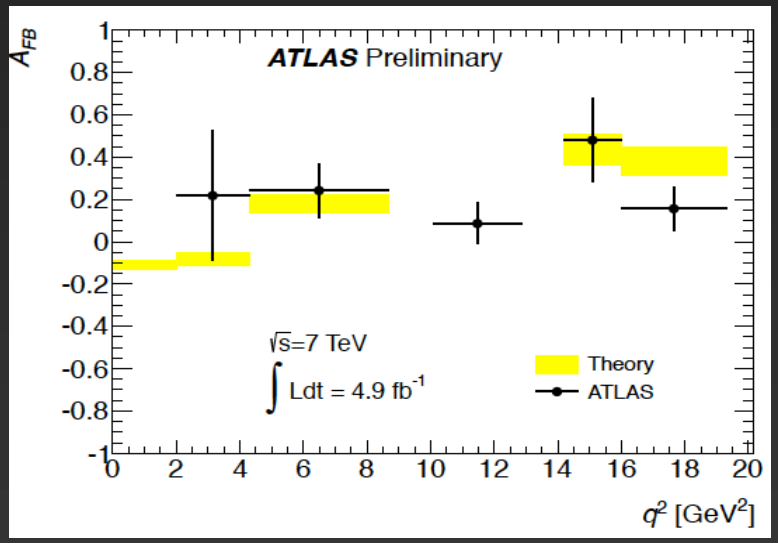
Angular analysis of $B^0_d \to K^* \mu^+ \mu^-$

Results

CMS, 2011 data PLB 727 (2013) 77
ATLAS 2011 data ATLAS-CONF-2013-038



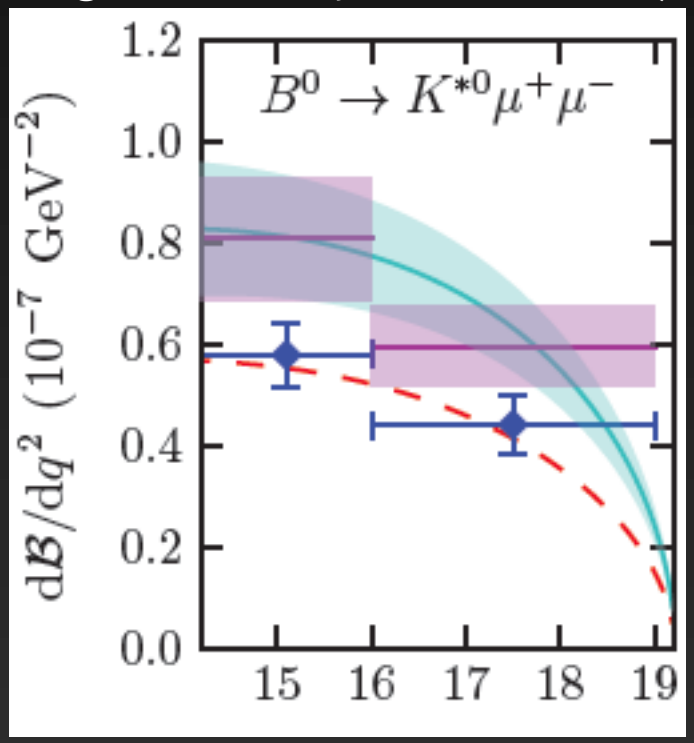


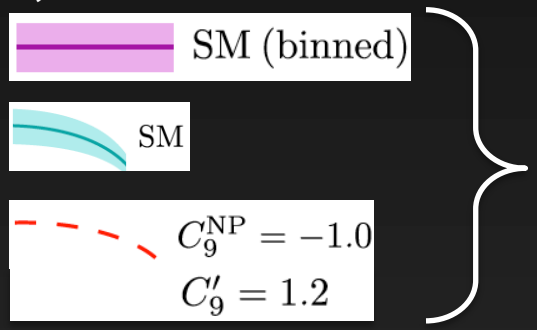


Angular analysis of $B^0_d \to K^* \mu^+ \mu^-$

Differential branching fractions: $B^0_d \to K^* \mu^+ \mu^-$

Horgan et al., Phys.Rev.Lett. 112 (2014) 212003



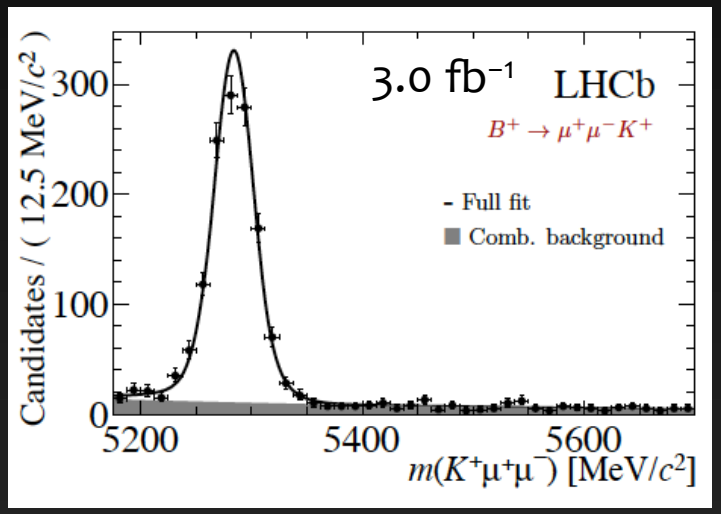


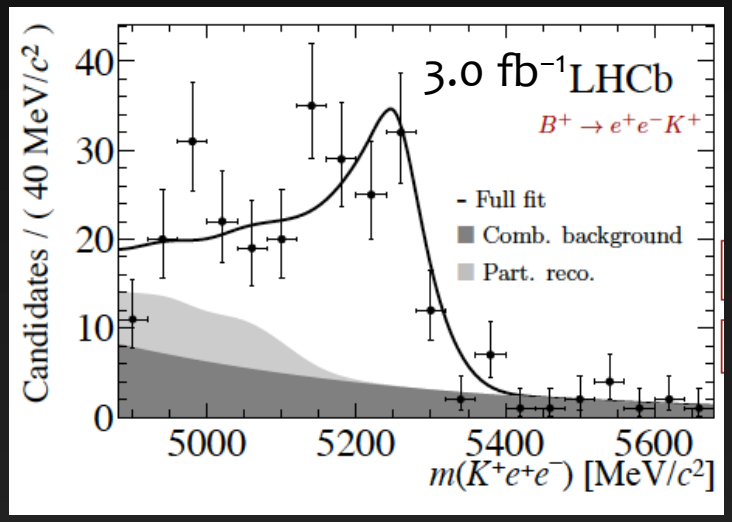
Calculations by Horgan et al.

Interesting enough, all differential branching fractions are systematically lower than SM predictions

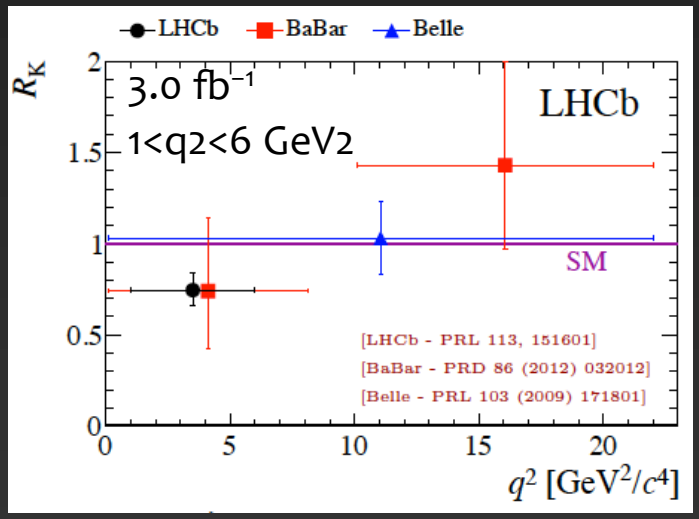
Average of ATLAS, CMS, CDF, LHCb
LHCb: JHEP 06 (2014) 133, JHEP 08 (2013)131, JHEP 07 (2013) 084
CDF: Public note 10894, CMS: PLB 727 (2013) 77, ATLAS: ATLAS-CONF-2013-038

Test of lepton universality using $B^+ \to K^+ \ell^+ \ell^-$ decays





[Phys. Rev. Lett. 113, 151601]



Ratio R_K of branching fractions of $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+e^+e^-$ sensitive to lepton universality

SM prediction: $R_K = 1 \pm \mathcal{O}(10^{-4})$
[Phys. Rev. Lett. 111 (2013) 162002; JHEP 12 (2007) 040]

LHCb measurement:

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

Most precise measurement to date, compatible with SM at 2.6σ level

B_s CP violating phase ϕ_s

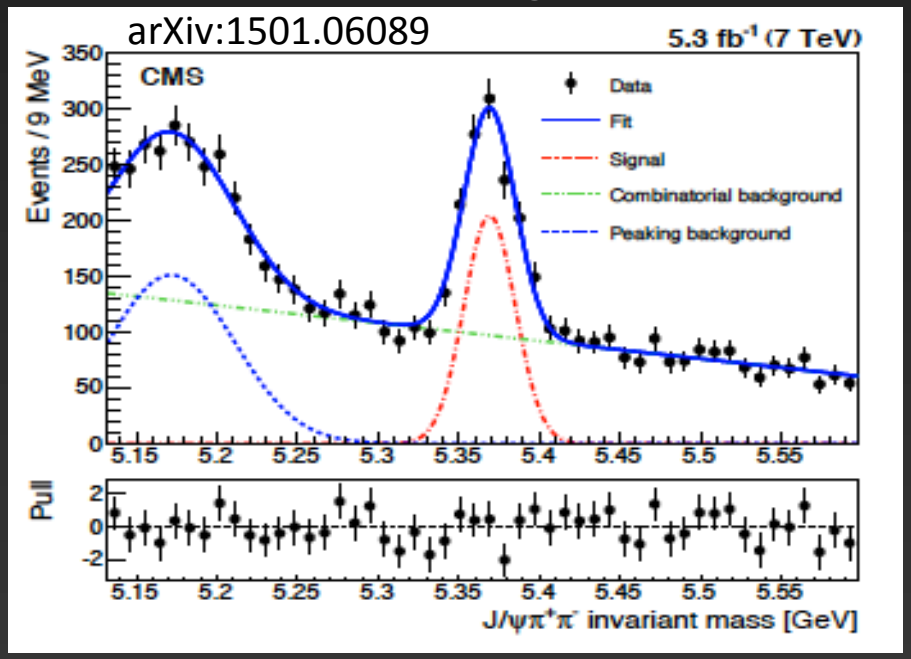
- CPV arises in interference between direct decay and decay after oscillation
- Precise theoretical prediction of CP violating phase φ_S within SM:

$\phi_S(SM) \sim -2\beta_S = -0.036 \pm 0.002$ rad [J. Charles et al. arXiv:1501.05013]

- Measured by ATLAS, CMS and LHCb in the golden channel $B_S \to J/\psi KK$. Need full angular analysis to disentangle CP-even and CP-odd components

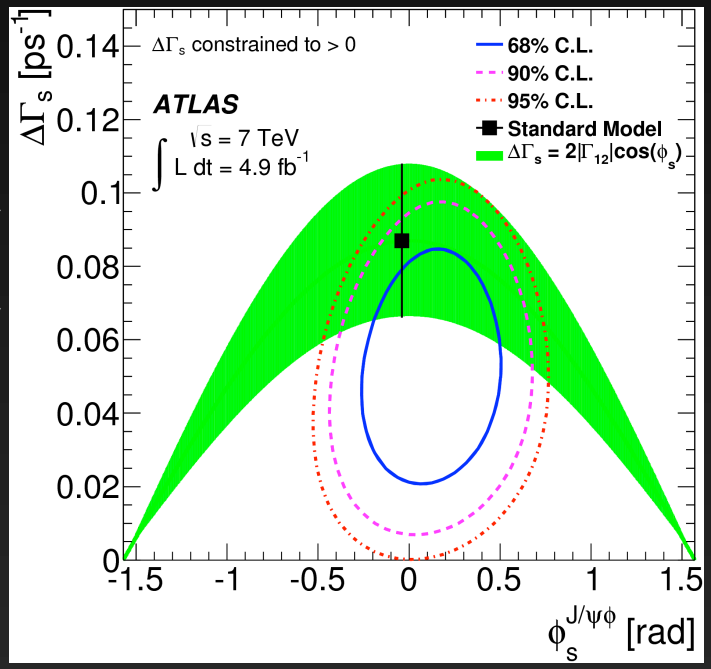
- LHCb uses also $B_S \to J/\psi\pi\pi$. Almost pure CP-odd state No need for angular analysis. [Phys. Rev. D 89, 092006 (2014)]
- CMS has performed a preparatory study of this channel measuring the branching fraction

$$\frac{\mathcal{B}(\mathbf{B_s \to J/\psi f^0})}{\mathcal{B}(\mathbf{B_s \to J/\psi \phi})} = \mathbf{0.140 \pm 0.013 \pm 0.018}$$

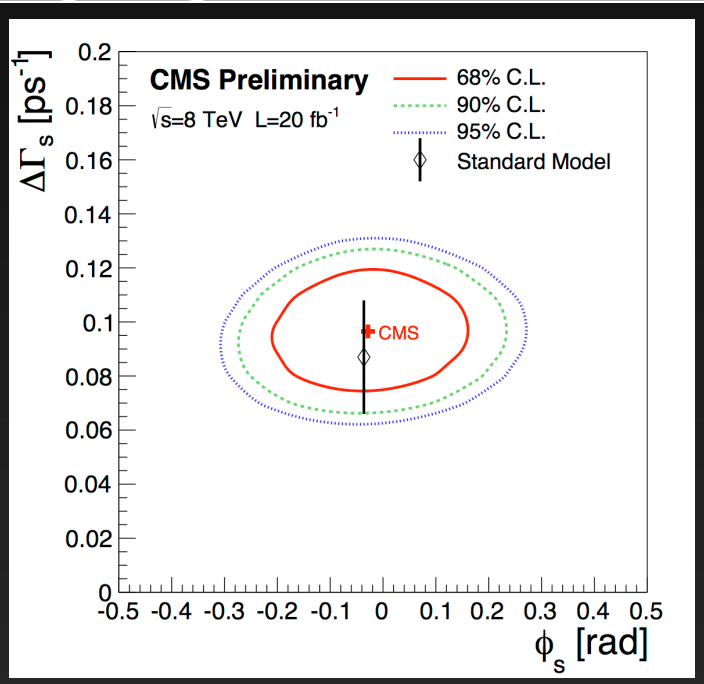


B_s CP violating phase ϕ_s: $B_s \to J/\psi KK$

PRD 90 (2014) 052007

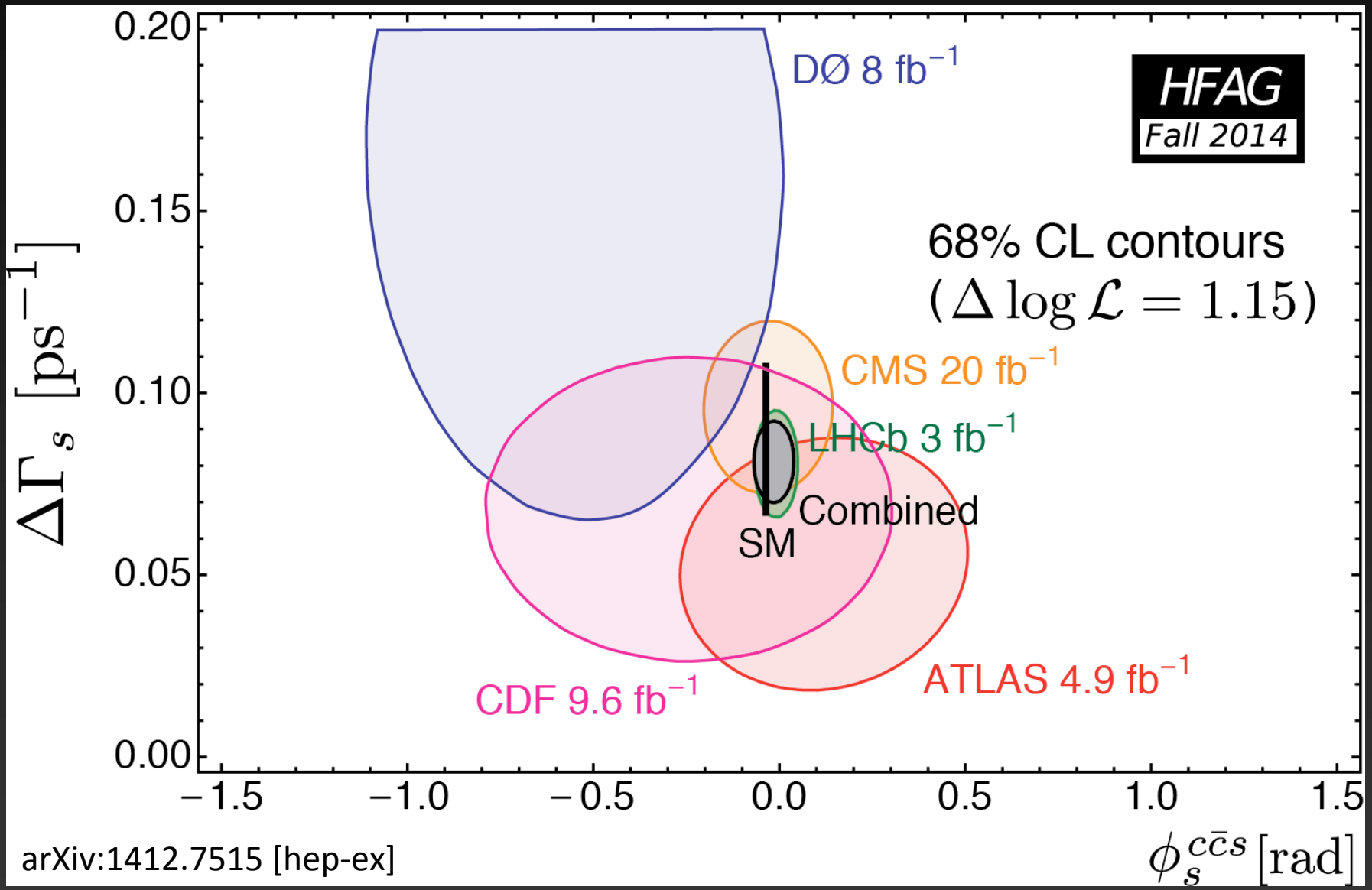


CMS-PAS-BPH-13-012



	$\Delta\Gamma_s$ [ps^{-1}]	ϕ_s [rad]
ATLAS ($\sqrt{s}$ = 7 TeV 4.9 fb^{-1}) PRD 90 (2014) 052007	0.053 ± 0.021 ± 0.010	0.12 ± 0.25 ± 0.05
CMS ($\sqrt{s}$ = 8 TeV 20 fb^{-1}) CMS-PAS-BPH-13-012	0.096 ± 0.014 ± 0.007	-0.03 ± 0.11 ± 0.03
LHCb ($B_s \to J/\psi KK$ 3 fb^{-1}) PRL 114, 041801	0.0805 ± 0.0091 ± 0.0032	-0.058 ± 0.049 ± 0.006
LHCb (comb. $B_s \to J/\psi KK + J/\psi\pi\pi$ 3 fb^{-1}) PRL 114, 041801		-0.010 ± 0.039

B_s CP violating phase φ_s



arXiv:1412.7515 [hep-ex]

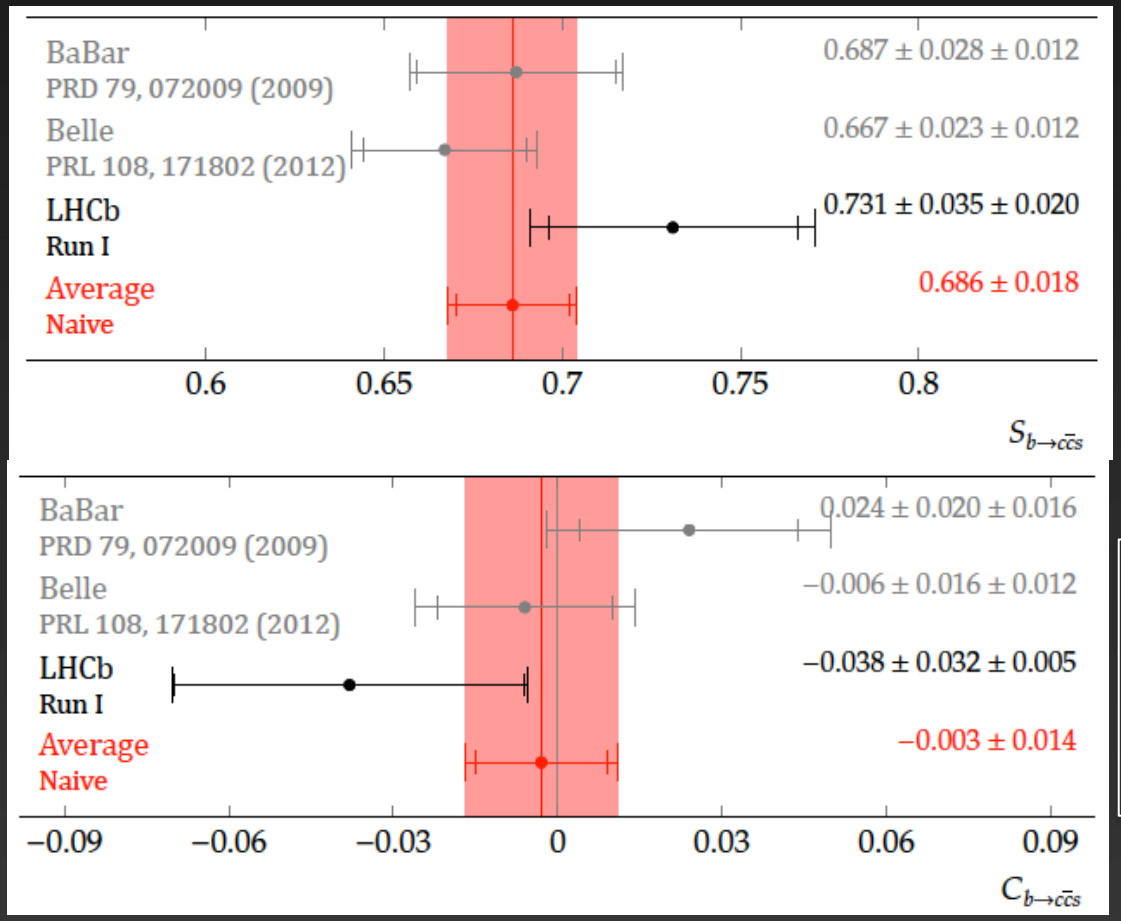
sin2β from $B^0 \to J/\psi\ K_S$

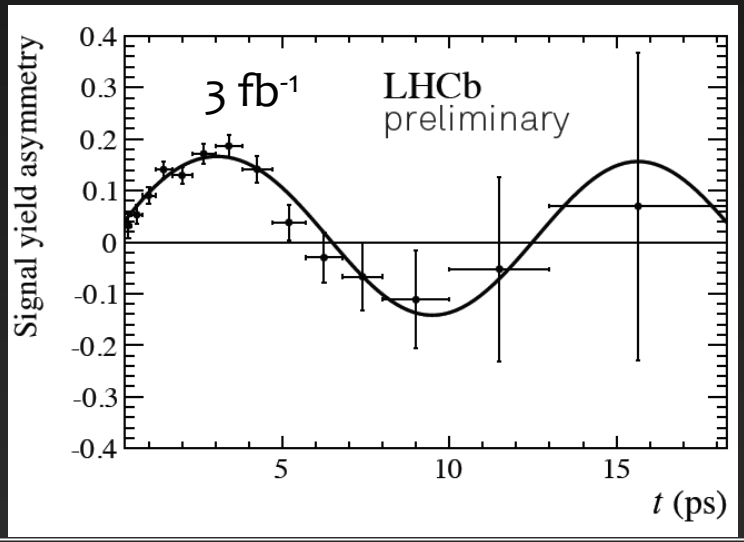
LHCb measurement with full Run I statistics. Preliminary results:

S = 0.731 ± 0.035 (stat) ± 0.020 (syst)

C = 0.038 ± 0.032 (stat) ± 0.005 (syst)

[LHCb-PAPER-2015-004, in preparation]





$$A(t) \equiv \frac{\Gamma(\bar{B}(t)\to J/\psi K^0_S)-\Gamma(B(t)\to J/\psi K^0_S)}{\Gamma(\bar{B}(t)\to J/\psi K^0_S)+\Gamma(B(t)\to J/\psi K^0_S)}$$

$$= \frac{S\ \sin(\Delta m t)-C\ \cos(\Delta m t)}{\cosh(\Delta\Gamma t/2)+A_{\Delta\Gamma}\sinh(\Delta\Gamma t/2)}$$

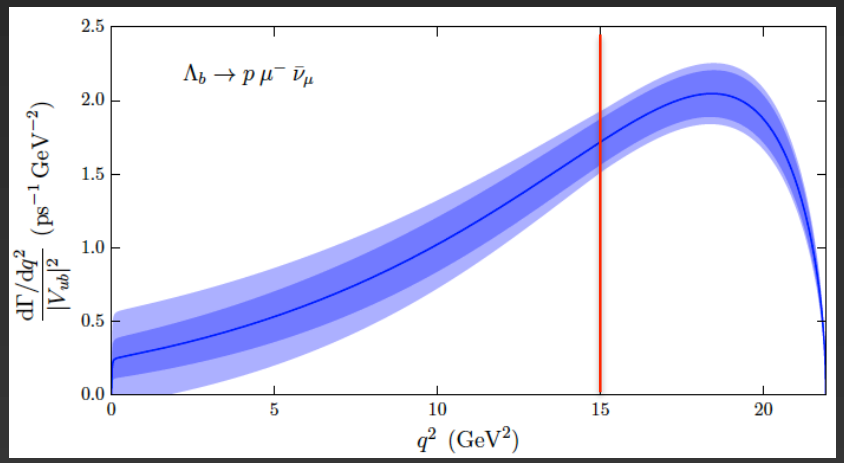
Precise determination of $|V_{ub}|$ from $\Lambda_b \to p\mu\nu$ decays at LHCb

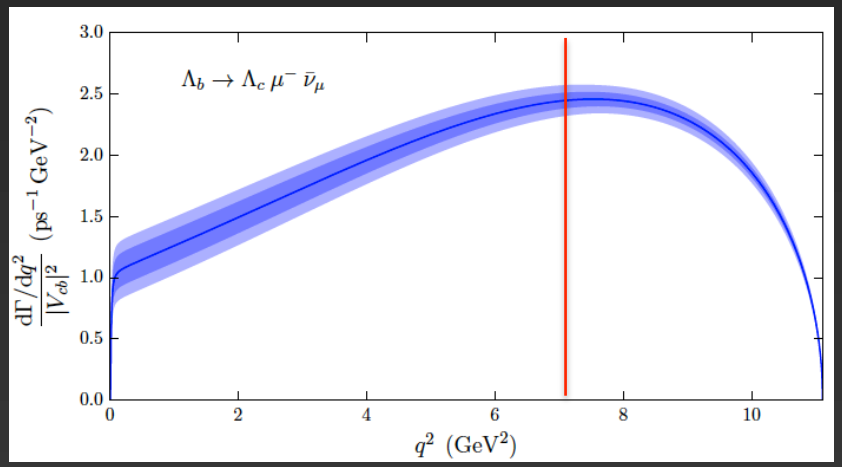
- |Vub| extracted from the following experimental ratio, using exclusive Λ_b decays:
- $$\frac{|\mathbf{V_{ub}}|^2}{|\mathbf{V_{cb}}|^2} = \frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu)}\mathbf{R_{FF}}$$

  Use measured $|V_{cb}|$ and $B(\Lambda_b \to \Lambda_c\mu\nu)$ values.

- R_{FF}: ratio of form factors.
  Calculation with LQCD by W. Detmold, C. Lehner and S. Meinel [arXiv:1503.01421]
- $\mathcal{B}$ are the measured branching fractions
- Smaller uncertainty on form factors at high q^2 ($\mu\nu$ invariant mass squared)
  $q^2 > 15$ GeV^2 for $\Lambda_b \to p\mu\nu$
  $q^2 > 7$ GeV^2 for $\Lambda_b \to \Lambda_c\mu\nu$

In this range $R_{FF} = 0.68 \pm 0.07$

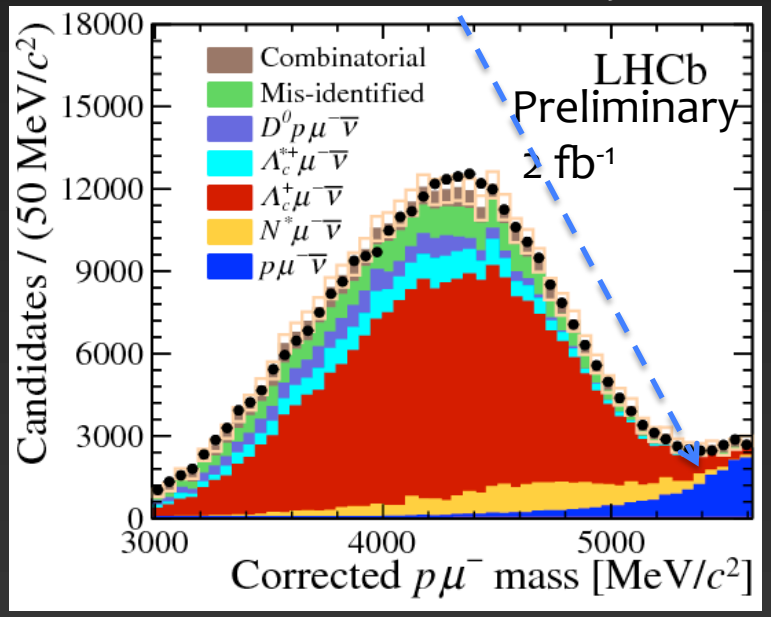


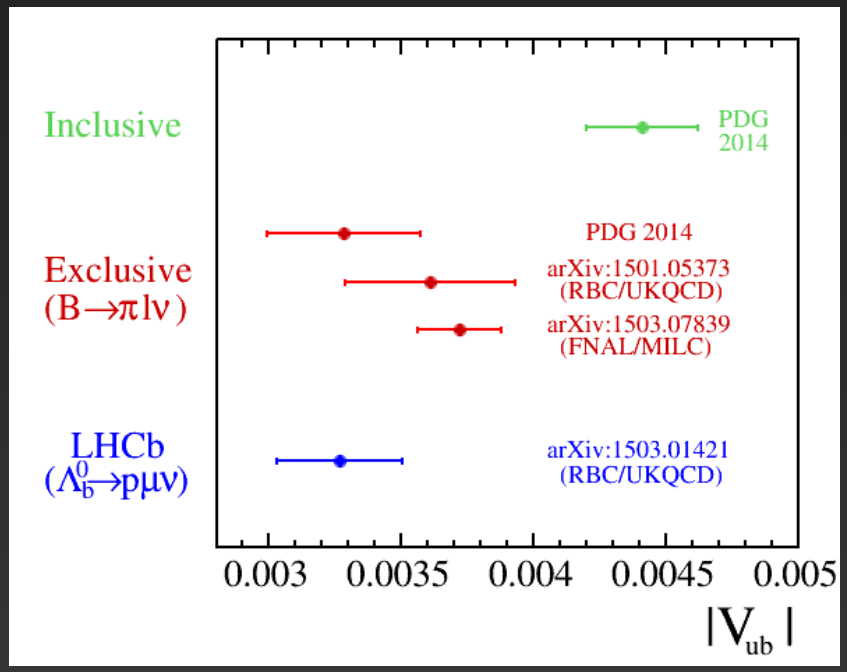


Precise determination of $|V_{ub}|$ from $\Lambda_b \to p\mu\nu$ decays at LHCb

- 2012 data 2 fb^{-1}
- $|V_{ub}| = (3.27 \pm 0.15(exp) \pm 0.17(th) \pm 0.06(|V_{cb}|)) \times 10^{-3}$
- Most precise measurement to date; First measurement at a hadron collider !
- LHCb result alone is 3.5 σ away from inclusive average.
- A naive combination with $B \to \pi \ell \nu$ gives a 3.9σ discrepancy.

17683 ± 733 $\Lambda_b \to p\mu\nu$ events selected:
first observation of this decay





arXiv:1504.01568 submitted to Nature Physics

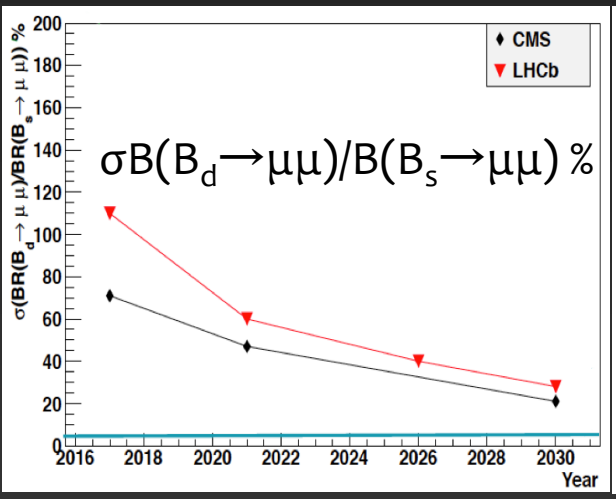
Conclusions and outlook

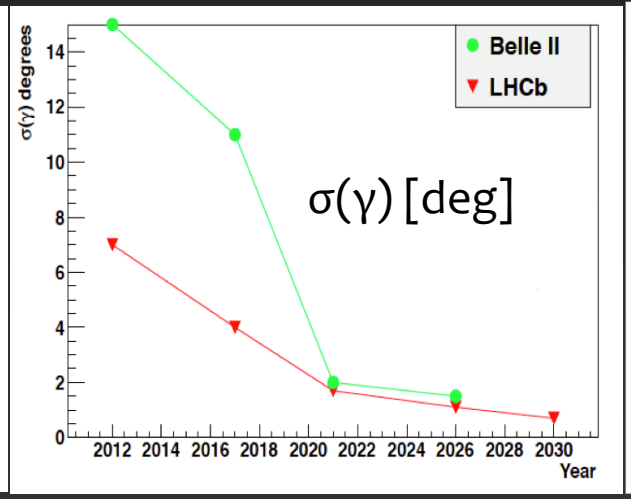
- LHC is providing a wealth of excellent results in the heavy flavour domain
- LHCb is exploring systematically all aspects of flavour physics. Precision measurements of rare decays and CKM parameters are a portal to NP !
- ATLAS and CMS are both providing excellent results, in some cases competitive with LHCb
- Potential of ATLAS and CMS in flavour physics fully demonstrated not only for rare decays and CKM measurements but also for spectroscopy, meson production and properties measurements (many new results, not shown here)

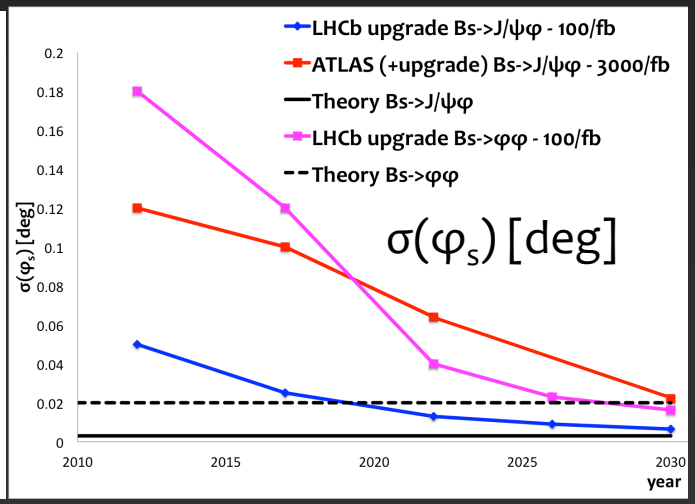
Conclusions and outlook

- LHC Run 2 is expected to provide many more results:
  - ★ LHCb: more statistics, more data on tape, optimised trigger
  - ★ ATLAS, CMS: higher luminosity, upgraded tracking detectors, triggers
- Run 3 and HL-LHC: upgraded experiments

	LHC era			HL-LHC era		
	Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2020-22)	Run 4 (2025-28)	Run 5+ (2030+)	
ATLAS, CMS	25 fb^{-1}	100 fb^{-1}	300 fb^{-1}	→	3000 fb^{-1}	Upgrades phase I & II
LHCb	3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	100 fb^{-1}	Upgraded LHCb







V. Vagnoni 2nd HL-LHC ECFA meeting, ATL-PHYS-PUB-2013-010

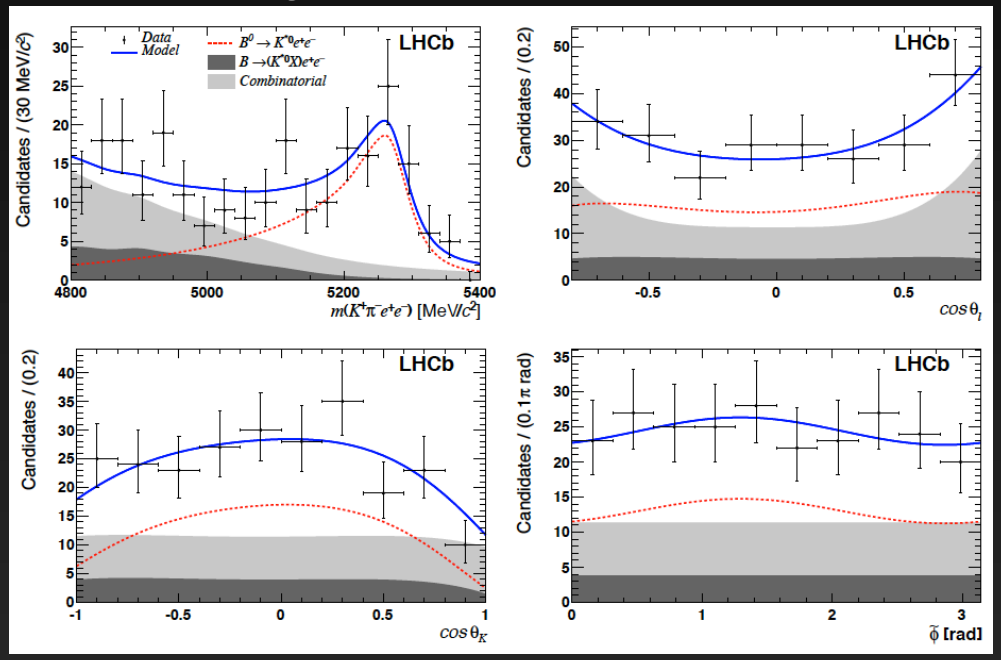
THANK YOU

BACKUP SLIDES

Angular analysis of $B^0_d \to K^* e^+ e^-$

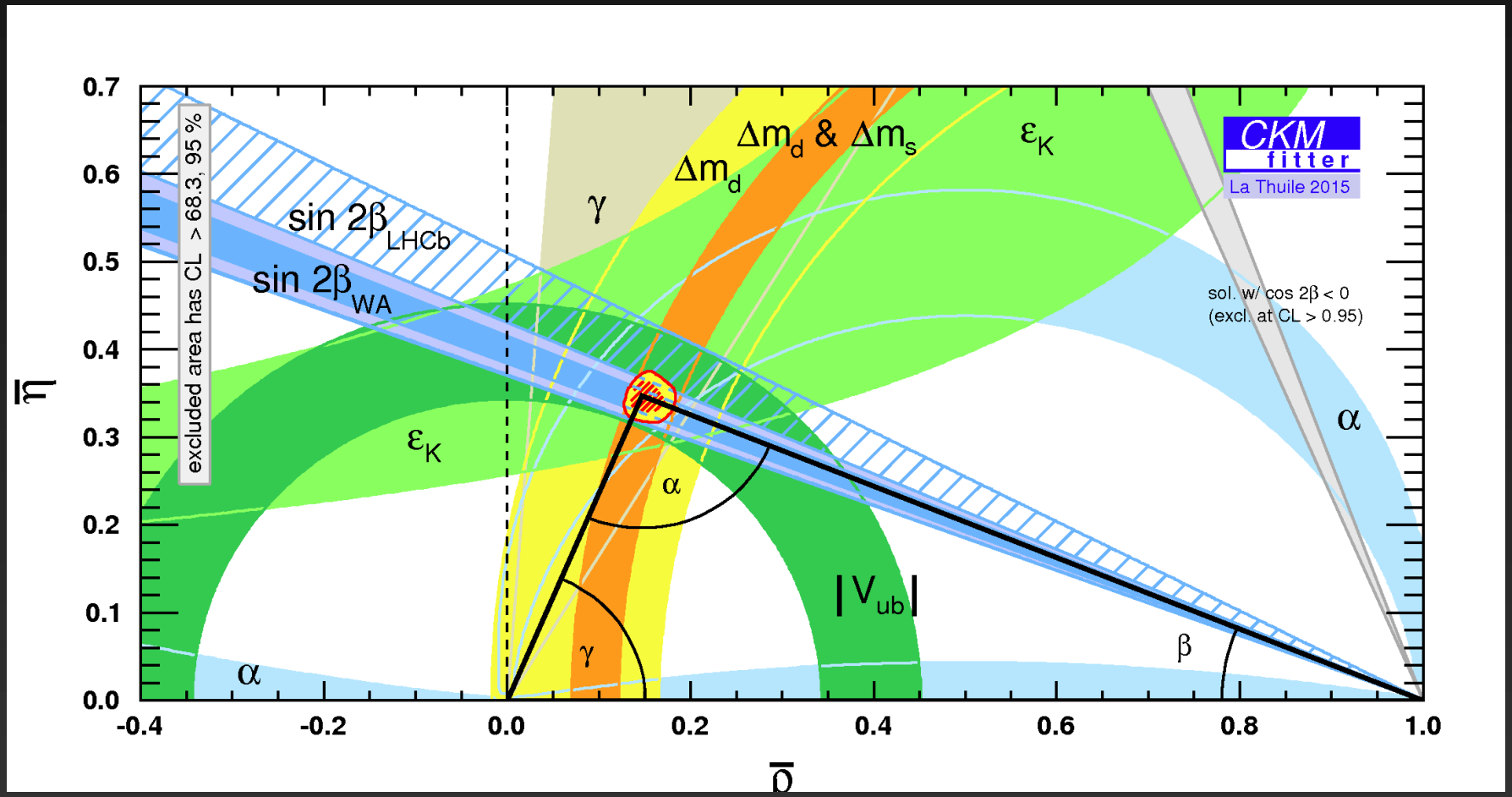
[LHCb-PAPER-2014-066, arXiv:1501.03038 - Submitted to JHEP]

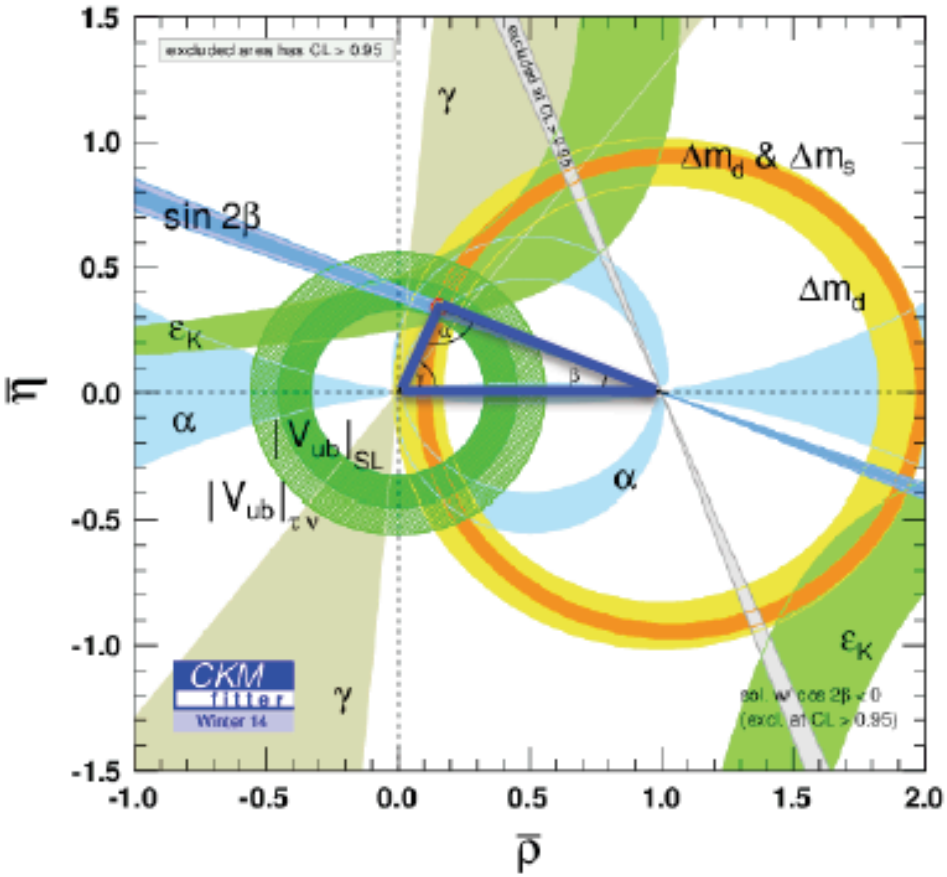
Measurements in agreement with SM

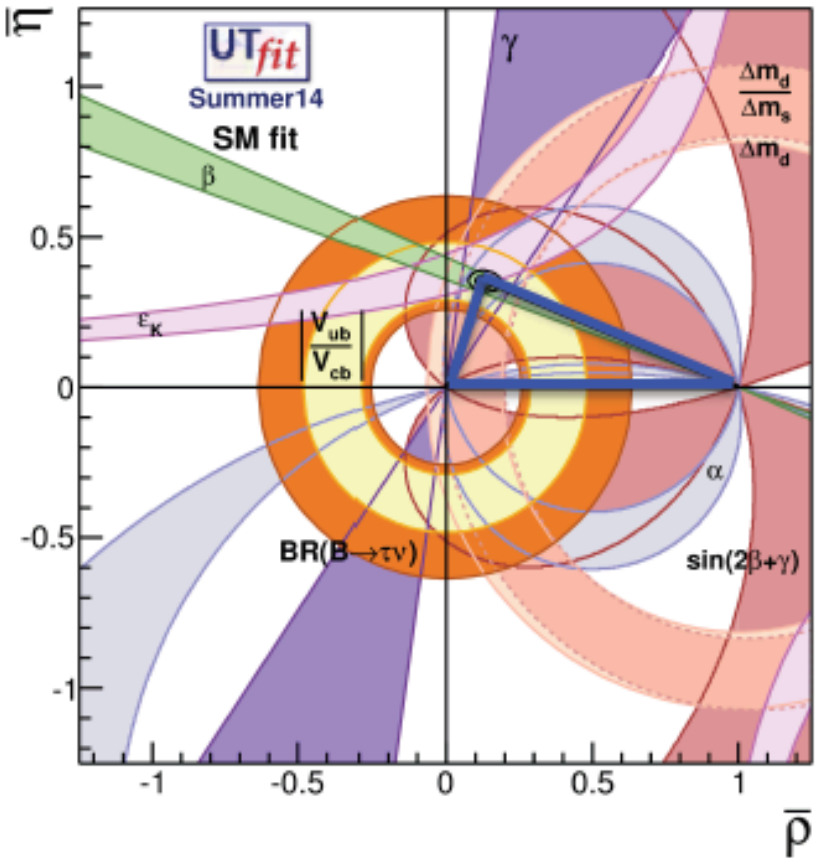


Observable	Measurement	SM prediction†
F_L	$+0.16 \pm 0.06 \pm 0.03$	$+0.10^{+0.11}_{-0.05}$
$A_T^{(2)}$	$-0.23 \pm 0.23 \pm 0.05$	$0.03^{+0.05}_{-0.04}$
A_T^{Re}	$+0.10 \pm 0.18 \pm 0.05$	$-0.15^{+0.04}_{-0.03}$
A_T^{Im}	$+0.14 \pm 0.22 \pm 0.05$	$(-0.2^{+1.2}_{-1.2}) \times 10^{-4}$

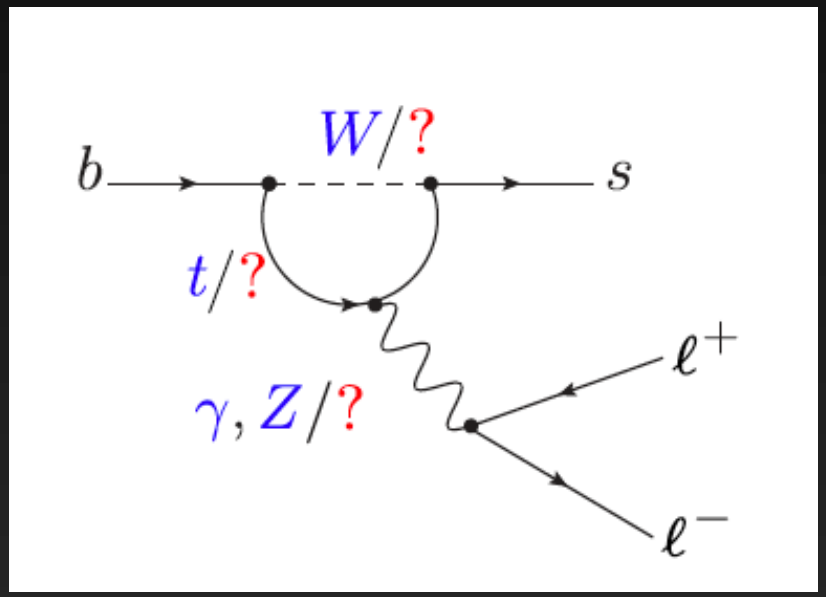
† S. Jager, J. M. Camalich [arXiv/1412.3283]

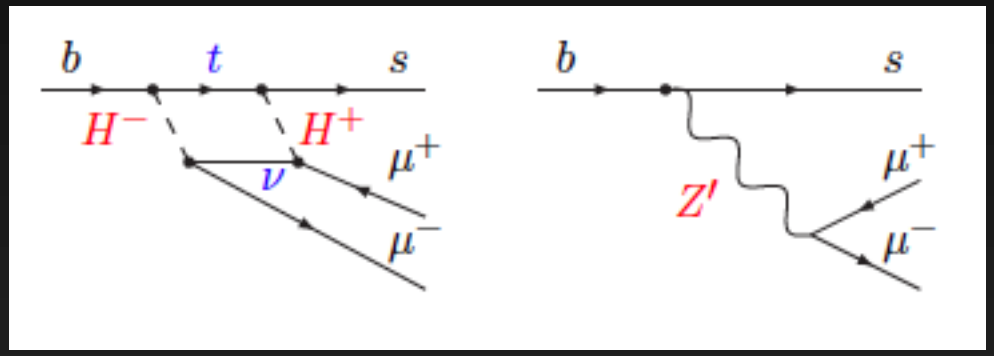

CKM fitter
La Thuile 2015
excluded area has CL > 68.3, 95 %
sin 2β LHCb
sin 2β WA
γ
Δm_d
Δm_d & Δm_s
ε_K
ε_K
α
α
α
|V_ub|
γ
β
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
η̄
ρ̄
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0

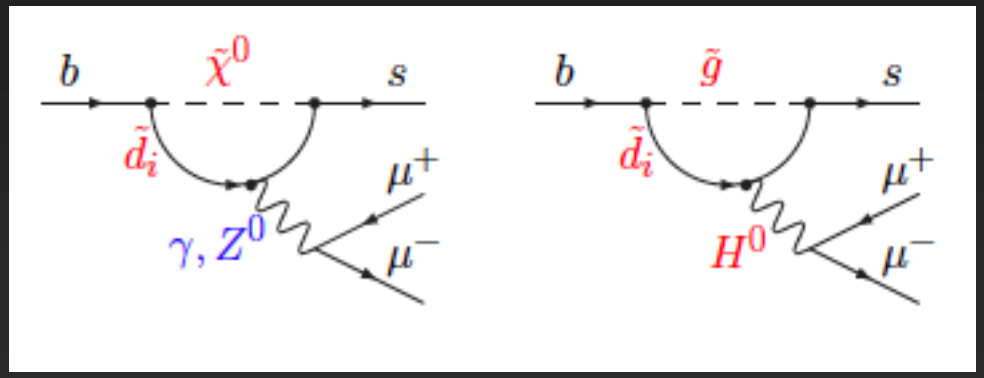

excluded area has CL > 0.95
γ
excluded at CL > 0.95
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
|V_ub|_SL
|V_ub|_τν
α
ε_K
CKM fitter
Winter 14
γ
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
η̄
ρ̄


UTfit
Summer14
SM fit
γ
Δm_d/Δm_s
Δm_d
β
ε_K
|V_ub/V_cb|
α
BR(B→τν)
sin(2β+γ)
η̄
ρ̄

Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.050	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	**0.023**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.029**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.04**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$	0.20	0.13	**0.030**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.8%**	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°	**1.1°**	negligible
	$\gamma(B_s^0 \to D_s^\mp K^\pm)$	17°	11°	**2.4°**	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	**0.5**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.12**	–


b
W/?
s
t/?
γ, Z/?
ℓ+
ℓ−


b
t
s
H−
H+
ν
μ+
μ−
b
s
Z′
μ+
μ−


b
χ̃0
s
d̃i
γ, Z0
μ+
μ−
b
g̃
s
d̃i
H0
μ+
μ−

...