Experimental prospects for studies of *CP* violation in the beauty and charm systems

Science & Technology Facilities Council

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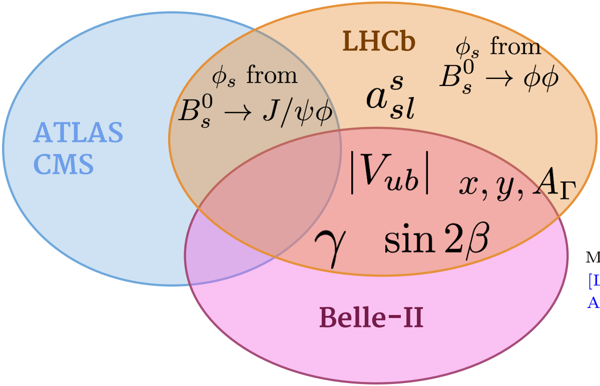
On behalf of ATLAS, CMS, LHCb
May 13th 2015

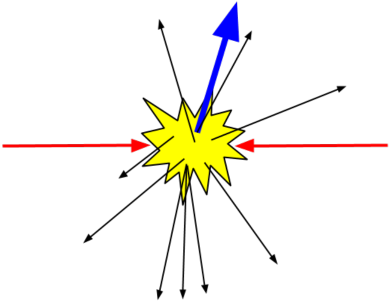
- **Why *CP* violation?**
- **Luminosity prospects**
- ***CP* violation in the beauty system (ϕ_s, γ, $a_{\rm sl}$)**
- ***CP* violation in the charm system ($|q/p|$, A_Γ)**



Most projections from [LHCb-PUB-2014-040 ATL-PHYS-PUB-2013-010]

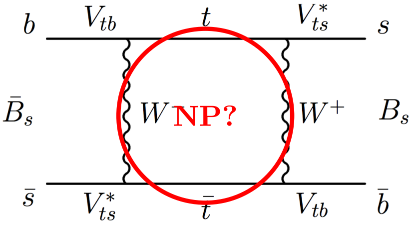
DIRECT

Cannot produce particles with $mc^2 > E$



INDIRECT

Higher energy particles can appear virtually in quantum loops $\rightarrow$ flavour physics

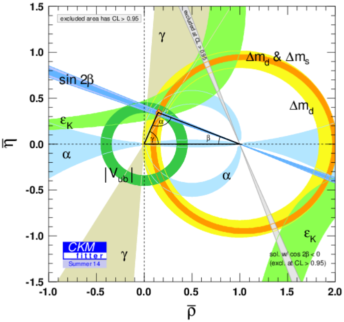


History: top quark mass predicted by quark mixing

CP violation in the Standard Model

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\bar\rho - i\bar\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\bar\rho - i\bar\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

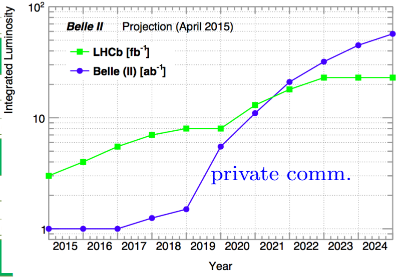
Wolfenstein parameterisation



- 3 generations + **1 phase** → $\bar\eta \neq 0$ is only source of *CP* violation in SM.
- CKM picture confirmed up to ∼ 20%.
- Couplings show strong hierarchy not seen in lepton sector
  ⇒ "*SM flavour puzzle*"

- New Physics should have flavour structure similar to SM…
- …or the NP scale is very very large (∼ 100TeV) ⇒ "*NP flavour puzzle*"
- Need more **precision measurements** to look for small deviations.

Projected luminosity

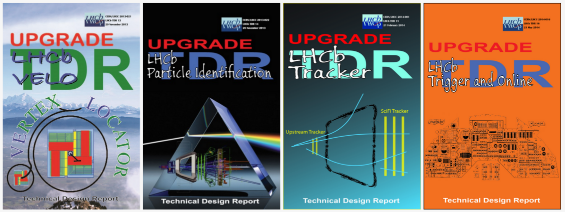


$\int \mathcal{L}\, dt$	LHC era			HL-LHC era	
	2010-12 (Run-1)	2015-18 (Run-2)	2020-22 (Run-3)	2025-28 (Run-4)	2030++ (Run-5)
ATLAS, CMS	25 fb^{-1}	100 fb^{-1}	300 fb^{-1}	$\rightarrow$	3000 fb^{-1}
LHCb	3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	100 fb^{-1}

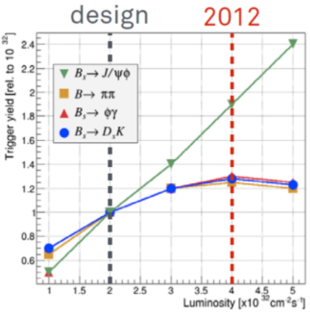
- $\sigma(b\bar{b}) \sim$ doubles from 7 $\rightarrow$ 14 TeV.
- LHCb will be upgraded after Run-2.
- ATLAS, CMS phase-2 upgrades after Run-3.
- Belle-II starts to make an impact $\sim$ 2018-19.
  - Important competition /complementarity with LHC(b).

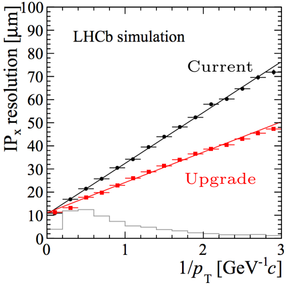
LHCb upgrade (installed after Run-2)

- Aim: significant increase in event statistics.
- Increase $\mathcal{L}$ to $2 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$.
- Improve detector readout from 1MHz $\rightarrow$ 40MHz. Use full software trigger.
- Will have big impact for hadronic decays (e.g., 10$\times$ charm).



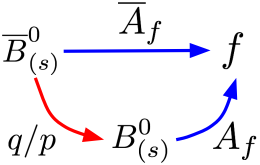
- Framework TDR, CERN-LHCC-2012-007
- Approved upgrade TDRs for VELO, RICH, Tracker, Trigger (computing to come).

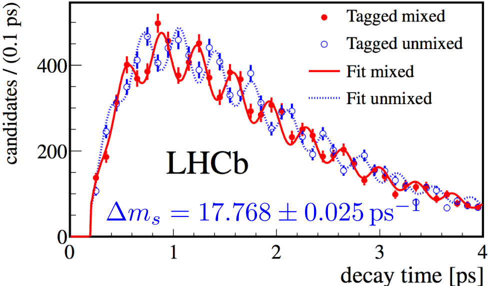




1. Decay: $|\overline{A}_{\overline{f}}/A_f| \neq 1$
2. Mixing: $|q/p| \neq 1$
3. Interference between mixing and decay:
   $\phi \equiv \arg(\lambda_f) \equiv \arg\left(\frac{q}{p}\frac{A_f}{\overline{A}_f}\right) \neq 0$

$$|M_{\rm L,H}\rangle = p|M^0\rangle \pm q|\overline{M}^0\rangle$$



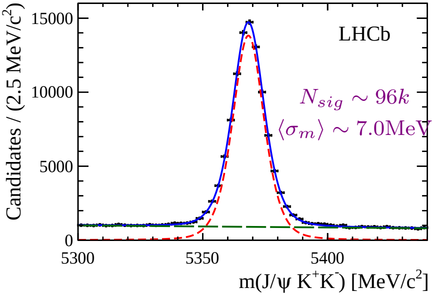


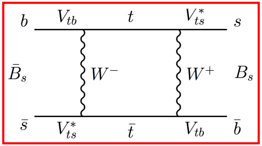
- Mixing observables:

$$\Delta m \equiv (m_H - m_L)$$
$$\Gamma \equiv (\Gamma_L + \Gamma_H)/2$$
$$\Delta\Gamma \equiv \Gamma_L - \Gamma_H$$

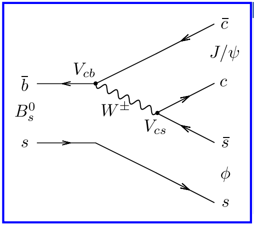
Measuring ϕ_s using $B_s^0 \to J/\psi\,\phi$

- $J/\psi \to \mu^+\mu^-$, $\phi \to K^+K^-$
- Time-dependent tagged analyses.
- $B_s^0 \to J/\psi\,\phi$, $B^0 \to J/\psi\,\pi^+\pi^-$ are $P \to VV$ decays so use angular information to disentangle CP-odd and CP-even components.
- Measure $\phi_s, \Delta m_s, \Gamma_s, \Delta\Gamma_s, |\lambda_f| \ldots$
  [this makes $B_s^0 \to J/\psi\,\phi$ special]





$$\phi_{mix} = 2\arg(\mathrm{V_{tb}V_{ts}^*})$$



$$\phi_{dec} = \arg(\mathrm{V_{cb}V_{cs}^*})$$

$$\phi_s \stackrel{\text{SM}}{=} -2\arg\left(-\frac{V_{cb}V_{cs}^*}{V_{tb}V_{ts}^*}\right) \equiv -2\beta_s$$

$$\phi_s \stackrel{\text{SM}}{=} -0.0365 \pm 0.0012\,\text{rad}$$

[CKMFitter]

(†) Assuming we ignore sub-leading penguin contributions - more later

MEASURING ϕ_s USING $B_s^0 \to J/\psi\,\phi$

- $J/\psi \to \mu^+\mu^-$, $\phi \to K^+K^-$
- Time-dependent tagged analyses.
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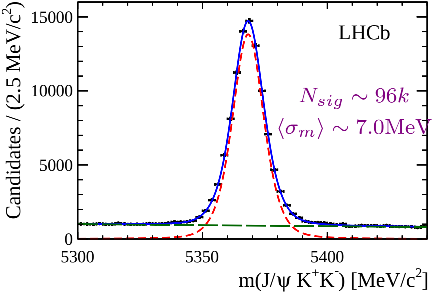
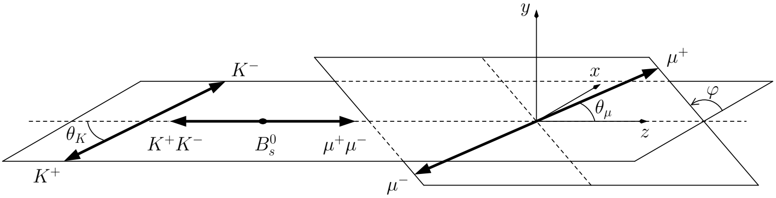
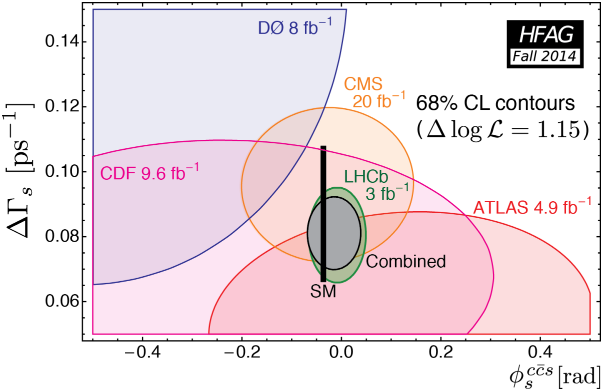




Exp	$N_{\rm sig}$	$\langle\sigma_t\rangle$ [fs]	Tagging power
LHCb ($3\,{\rm fb}^{-1}$)	96k	$\sim 43 \;\Rightarrow \mathcal{D} \sim 73\%$	$\sim 3.0\%$
CMS ($20\,{\rm fb}^{-1}$)	49k	$\sim 70 \;\Rightarrow \mathcal{D} \sim 46\%$	$\sim 1.0\%$
ATLAS ($4.9\,{\rm fb}^{-1}$)	22k	$\sim 100 \Rightarrow \mathcal{D} \sim 21\%$	$\sim 1.5\%$

$\Delta\Gamma_s - \phi_s$ global combination



Combination

$\phi_s = -0.015 \pm 0.035$rad
$\Delta\Gamma_s = 0.081 \pm 0.006\,\mathrm{ps}^{-1}$

- New physics not a large effect

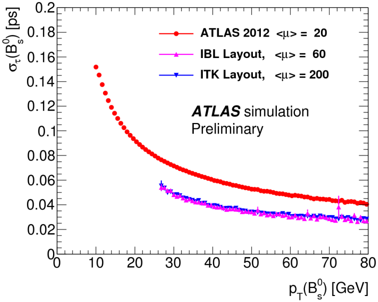
$\Rightarrow$ need to control SM effects (penguins).

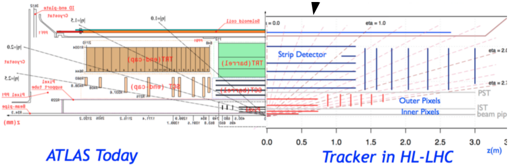
Mode	$\sigma(\phi_s)$[rad]	Ref.	Exp
$B_s^0 \to J/\psi\,\phi$	$-0.058 \pm 0.049 \pm 0.006$	PRL 114 (2015) 041801	LHCb (3 fb^{-1})
$B_s^0 \to J/\psi\,\phi$	$-0.030 \pm 0.110 \pm 0.030$	CMS-PAC-BPH-13-012	CMS (20 fb^{-1})
$B_s^0 \to J/\psi\,\phi$	$+0.120 \pm 0.250 \pm 0.050$	PRD 90 (2014) 052007	ATLAS (4.9 fb^{-1})
$B_s^0 \to J/\psi\,\pi^+\pi^-$	$+0.070 \pm 0.068 \pm 0.008$	PLB 736 (2014)	LHCb (3 fb^{-1})
$B_s^0 \to D_s^+ D_s^-$	$+0.020 \pm 0.170 \pm 0.020$	PRL 113, (2014) 211801	LHCb (3 fb^{-1})

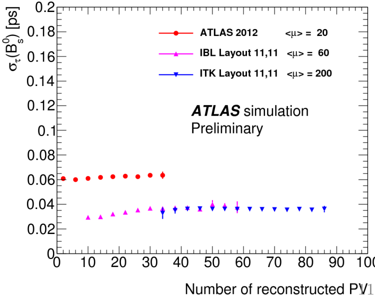
- Expect $\sigma(\phi_s)^{\mathrm{LHCb}} \sim 0.010$ rad after LHCb upgrade [LHCb-PUB-2014-040]

ATLAS prospects for $B_s^0 \to J/\psi\phi$ [ATL-PHYS-PUB-2013-010]

- $\sigma(\phi_s)$ dependent on N_{sig}, σ_t, flavour tagging.
- Upgraded inner detector (IBL in Run-2, ITK for HL-LHC) improves decay time resolution by 30% w.r.t. Run-1.
- Higher p_T improves σ_t and signal purity (but lower lower efficiency).
- Small (14%) increase in σ_t in Run-2 as a function of nPV, but stable > 40.

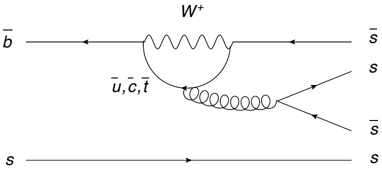


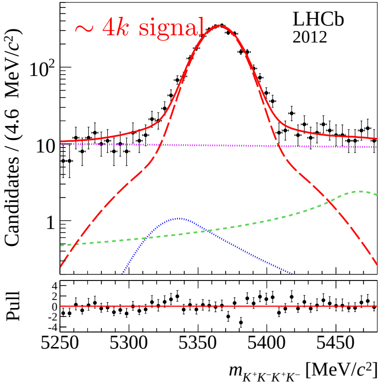


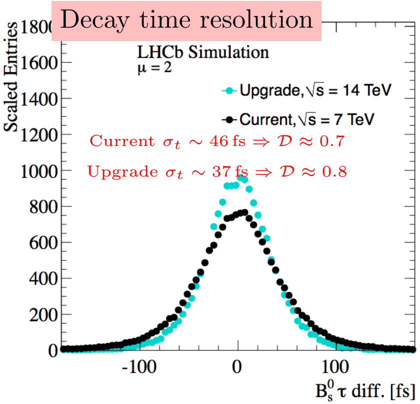


- $B_s^0 \to \phi\phi$: $b \to s$ penguin decays sensitive to NP in the loops.
- $\phi \to KK$: 5 different polarisation amplitudes $\Rightarrow$ angular analysis.
- $\phi_s = -0.17 \pm 0.15 \pm 0.03$ rad.
- $|\lambda| = 1.04 \pm 0.07 \pm 0.03 \Rightarrow$ **no direct CPV**.

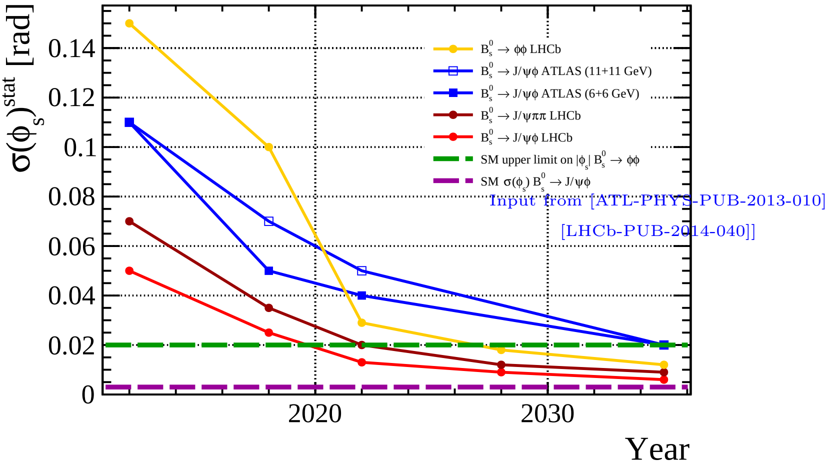
SM: $|\phi_s| < 0.02\,\mathrm{rad}$





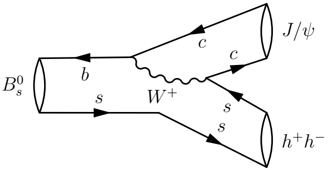


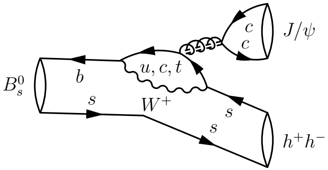
Prospects for ϕ_s at HL-LHC



- ATLAS sensitivities using toy-MC using 2011 analysis with fully simulated signal. Background from 2012 data sidebands.
- Strong dependence on $\sigma(\phi_s)$ on muon p_T thresholds in ATLAS trigger:
  - Run-2/3: 6+6 GeV (nominal, assuming basic L1-topo usage) or 11+11 GeV (pessimistic ⇒ ×7 fewer events)
  - HL-LHC: 11+11 GeV

Controlling penguin pollution in ϕ_q





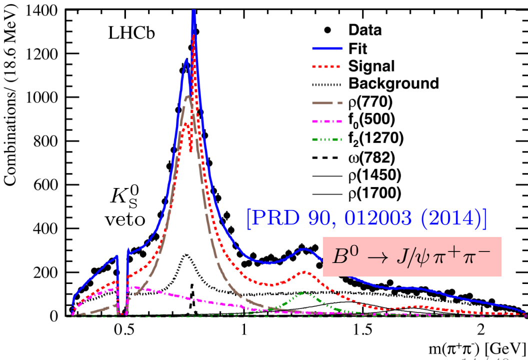
Penguin-to-tree suppression:

$$\epsilon = \frac{|V_{us}|^2}{1-|V_{us}|^2} = 0.05$$

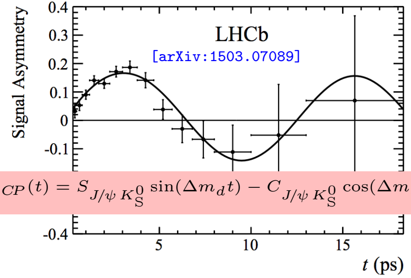
$$\phi_q^{\text{measured}} = \phi_q + \delta_{\text{Penguin}} + \delta_{\text{New Physics}}$$

- Difficult-to-calculate non-perturbative hadronic effects could lead to big enhancement.
- Measure δ_{Penguin} using decays where penguin/tree ratio is enhanced.
  [Faller et al. arXiv:0810.4248, De Bruyn & Fleischer, arXiv:1412.6834]
- Use SU(3) relations to link B_s^0 and B^0 (broken at level of 20-30%).
- $|\delta_{\text{P}}| < 1.8°$

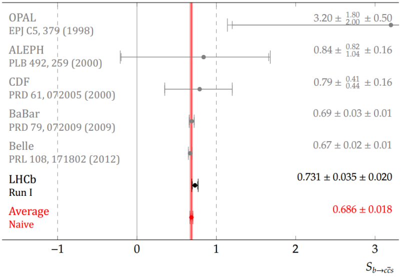
c.f. $\sigma(\phi_s) = \pm 2.0°$, $\sigma(\phi_d) = \pm 1.4°$



CP violation in $B^0 \to J/\psi K^0_S$



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

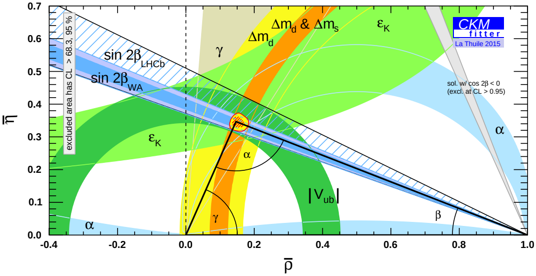


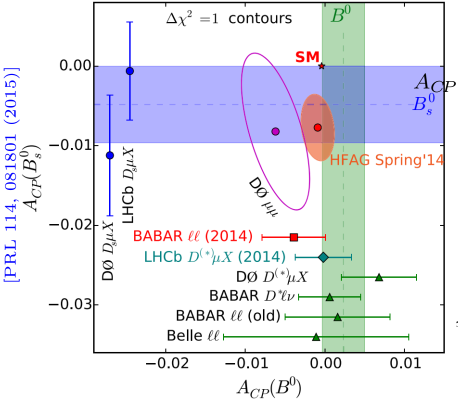
$$S_{J/\psi K^0_S} \approx \sin 2\beta$$

$$S_{J/\psi K^0_S} = +0.731 \pm 0.035 \pm 0.020$$

$$C_{J/\psi K^0_S} = -0.038 \pm 0.032 \pm 0.005$$

- Consistent with world average and similar precision to B-factories.
- **HL-LHC**: expect $\sigma(S_{J/\psi K^0_S}) \sim 0.005$, similar from Belle-II.





$$A_{CP} = a_{\mathrm{sl}} = \frac{\Gamma(\overline{B}\to B\to f) - \Gamma(B\to \overline{B}\to \overline{f})}{\Gamma(\overline{B}\to B\to f) + \Gamma(B\to \overline{B}\to \overline{f})}$$
$$= \frac{1-|q/p|^4}{1+|q/p|^4}$$

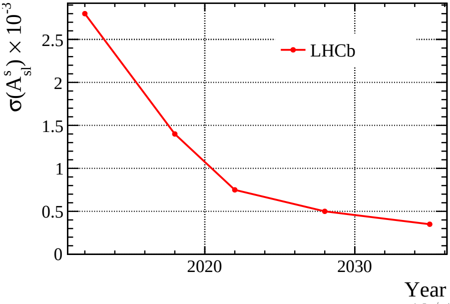
[Lenz arXiv:1205.1444] - tiny in SM

$$a^d_{\mathrm{sl}} = (-4.1 \pm 0.6) \times 10^{-4}$$
$$a^s_{\mathrm{sl}} = (+1.9 \pm 0.3) \times 10^{-5}$$

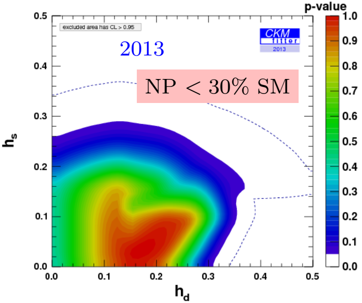
$$a^s_{\mathrm{sl}} = [-0.06 \pm 0.50 \pm 0.36]\% \ (\text{LHCb}, 1\,\text{fb}^{-1})$$
$$a^d_{\mathrm{sl}} = [-0.02 \pm 0.19 \pm 0.30]\% \ (\text{LHCb}, 3\,\text{fb}^{-1})$$

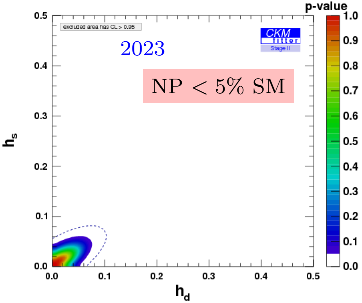
[PLB 728 (2014) 607, PRL 114 (2014) 041601]

- **$\sim 3\sigma$ tension with SM from D0 not confirmed or excluded by LHCb.**



- Assume that NP only enters B^0 and B_s^0 mixing: $M_{12}^{d,s} = (M_{12}^{d,s})_{\rm SM}(1 + h_{d,s}e^{2i\sigma_{d,s}})$.

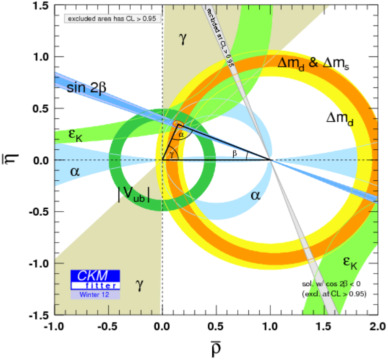


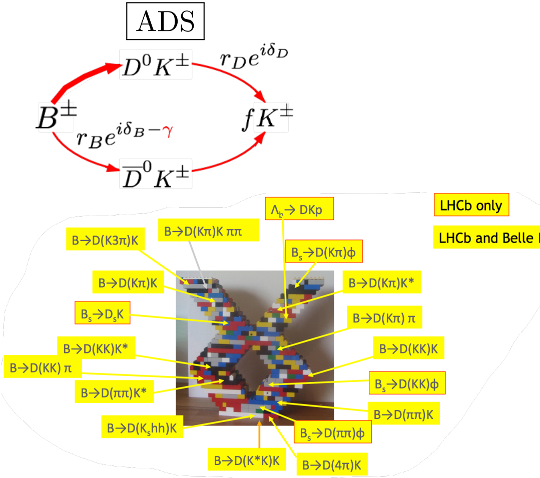


$$h \approx \frac{|C_{ij}|^2}{|V_{ti}^* V_{tj}|^2} \left(\frac{4.5\ \text{TeV}}{\Lambda}\right)^2$$

Couplings	NP loop order	Scales (in TeV) probed by B_d mixing	Scales (in TeV) probed by B_s mixing
$\lvert C_{ij}\rvert = \lvert V_{ti}V_{tj}^*\rvert$ (CKM-like)	tree level	17	19
	one loop	1.4	1.5
$\lvert C_{ij}\rvert = 1$ (no hierarchy)	tree level	2×10^3	5×10^2
	one loop	2×10^2	40

Tree-level measurement of γ

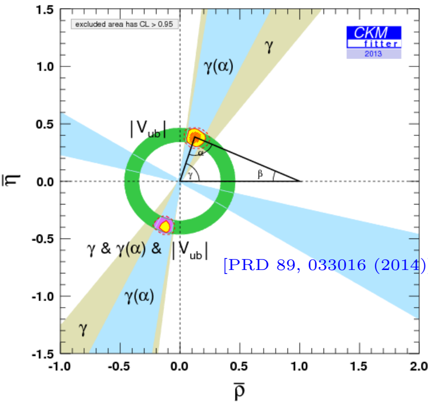


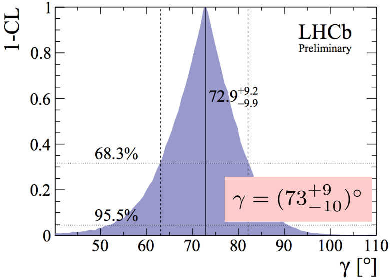


- Least well known of the CKM angles.
- Small theoretical uncertainty on the tree level diagrams – no NP contributions
- Use interference between $B^\pm \to D^0 K^\pm$, $D^0 \to f$ decay amplitudes
- Time-independent $B^\pm \to D^0 K^\pm$ and $B^0 \to D K^*$
- . . . or time-dependent $B_s^0 \to D_s^\mp K$ $(\gamma + \beta)$

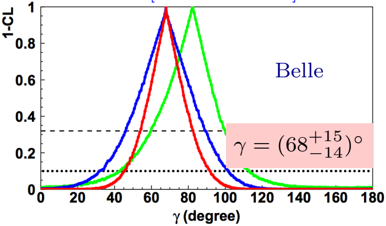
γ COMBINATION

- **Best precision comes from combining many independent decay modes.**
- Run-1 dataset: $\sigma(\gamma) \sim 7°$.
- 2025: $\sigma_{\text{LHCb}}(\gamma) \sim \sigma_{\text{Belle-II}}(\gamma) < 1°$. $\sigma_{\text{syst}} < 1°$.
- Theoretical uncertainties $< 1°$ (D mixing, K mixing, CPV in D decays).





[arXiv:1301.2033]



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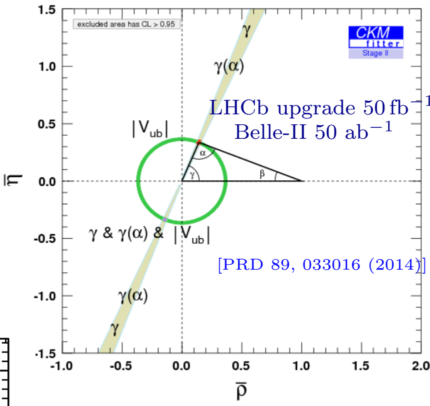
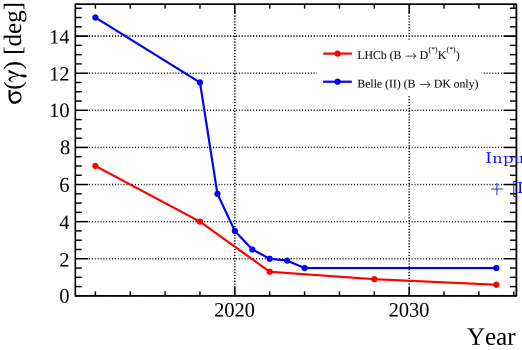
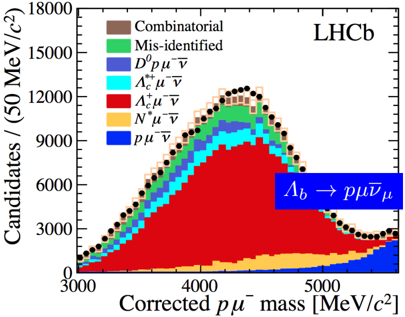


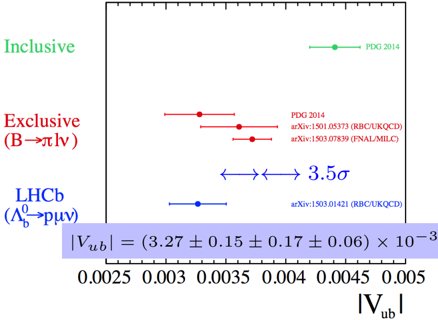


Input from private comm.

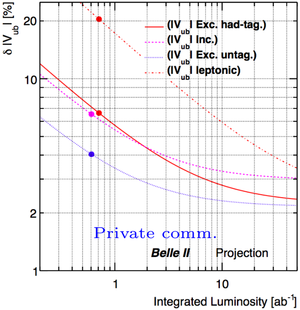
+ [LHCb-PUB-2014-040]

Exclusive $|V_{ub}|$





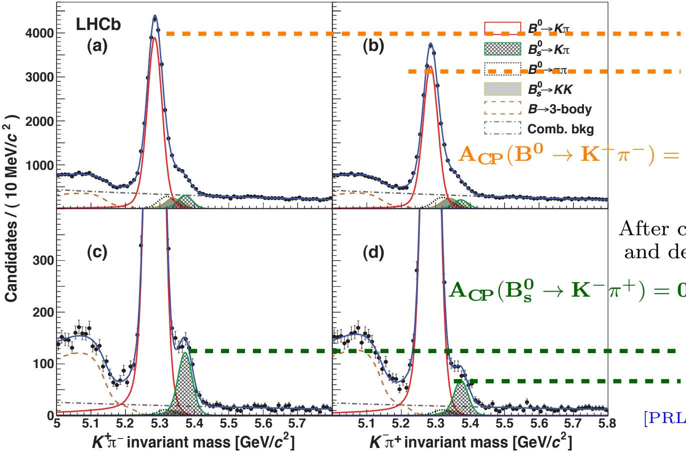
- **Syst. limited** from Lattice QCD calc. of Λ_b form-factor (more precise at high q^2).
- $\Lambda_b \to p\mu\nu$ has different dependence on right-handed currents (ϵ_R), but combination starts to disfavour interpretation of RHC.
- **Future:** measurement using $B_s^0 \to K\mu\nu$ (difficult at Belle-II?)
- $\sigma(|V_{ub}|) \sim 2-3\%$ at Belle-II. Also improve normalisation mode $\mathcal{B}(\Lambda_c \to pK\pi)$.



Direct CP violation in $B^0_{(s)}$ meson decays

- Arises from interfering amplitudes with different weak and strong phases.
- B^0 mode more precise than and compatible with B-factories.
- **B^0_s mode: first observation!**

$$A_{CP} = \frac{\Gamma(\overline{B}^0_{(s)} \to \overline{f}) - \Gamma(B^0_{(s)} \to f)}{\Gamma(\overline{B}^0_{(s)} \to \overline{f}) + \Gamma(B^0_{(s)} \to f)}$$



1 fb^{-1} only

$\mathbf{A_{CP}(B^0 \to K^+\pi^-) = -0.080 \pm 0.007 \pm 0.003}$

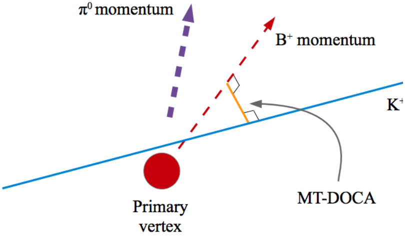
After correcting for production and detection asymmetries

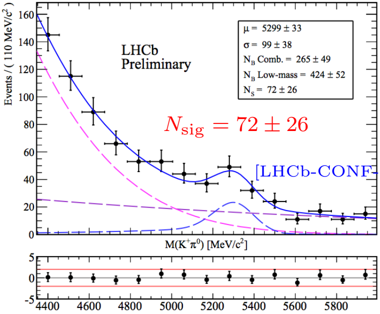
$\mathbf{A_{CP}(B^0_s \to K^-\pi^+) = 0.27 \pm 0.04 \pm 0.01}$

[PRL 110 (2013) 221601]

$$\Delta A_{CP} \equiv A_{CP}(B^+ \to K^+\pi^0) - A_{CP}(B^0 \to K^+\pi^-) = 0.12 \pm 0.02$$

- Naively expect direct *CP* asym. to be the same. NP in electroweak penguin loop?
- Need isospin analysis to understand what is going on.
- $B^+ \to K^+\pi^0$ challenging at LHCb (no secondary vertex + photons in final state).





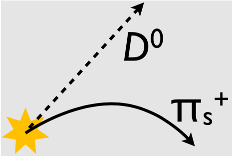
[LHCb-CONF-2015-001]

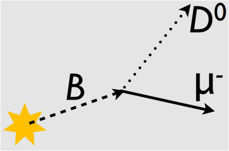
- Improvements and future prospects:
  - Dedicated trigger ($\times 3-5$), increase in $\sigma(b\bar{b})$ ($\times 2$), offline analysis ($\times 5$).
  - $\Rightarrow$ ~ 1000 events per fb^{-1} ($\Rightarrow$ 10% measurements, competitive with current B-factory samples).
  - Expect Belle-II to make significant improvements here (including $B^0 \to K^0\pi^0$).

$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$

$x \equiv \Delta m/\Gamma$ $y \equiv \Delta\Gamma/(2\Gamma)$

- Mixing in charm sector is small ($|x|, |y| < \mathcal{O}(10^{-2})$)
- Direct CP violation when $A_{CP}^{\text{dir}} \equiv \frac{|A_f|^2 - |\overline{A}_f|^2}{|A_f|^2 + |\overline{A}_f|^2} \neq 0$
- Indirect CP violation when $A_{CP}^{\text{mix}} \equiv |q/p|^2 - 1 \neq 0$, $\phi \equiv \arg(\frac{q}{p}\frac{A_f}{\overline{A}_f}) \neq 0, \pi$
- Huge charm samples at the LHC from different sources:
  1. Prompt charm
  2. Semileptonic b-hadron decays

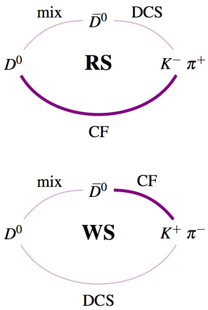


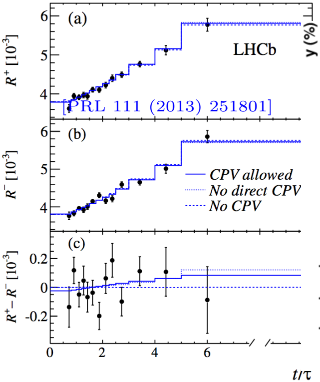


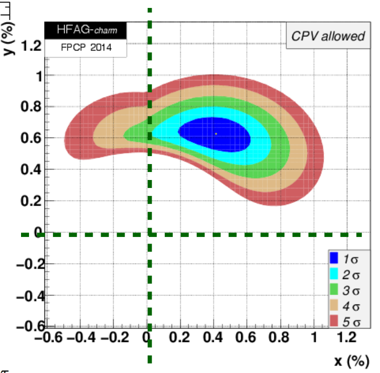
D^0 MIXING AND CP VIOLATION

- Mixing in charm sector dominated by long distance effects ⇒ v. small CPV expected
- First $> 5\sigma$ observation of charm mixing made by LHCb [PRL 110 (2013) 101802].
- right-sign: $D^{*+} \to D^0\pi^+ \to (K^-\pi^+)\pi^+$ (Cabibbo favoured, mixing+DCS - 54M events)
- wrong-sign: $D^{*+} \to D^0\pi^+ \to (K^+\pi^-)\pi^+$ (DCS, mixing+CF - 0.23M events)

$$R(t) \equiv \frac{N_{\rm ws}(t)}{N_{\rm rs}(t)} \approx R_D + \sqrt{R_D}y'\frac{t}{\tau} + \frac{1}{4}(x'^2 + y'^2)(\frac{t}{\tau})^2$$



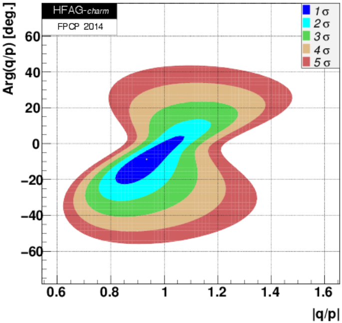


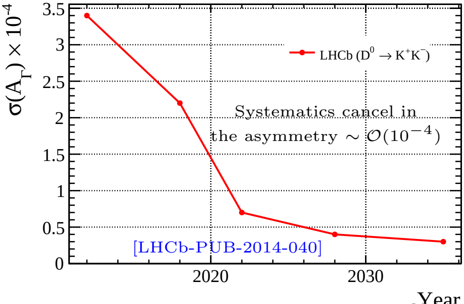


$$A_\Gamma \equiv \frac{\tau(\overline{D}^0 \to h^+h^-) - \tau(D^0 \to h^+h^-)}{\tau(\overline{D}^0 \to h^+h^-) + \tau(D^0 \to h^+h^-)} \approx (A_{CP}^{\text{mix}}/2 - A_{CP}^{\text{dir}})y\cos\phi - x\sin\phi$$

- Distinguish CP violation in charm mixing from that in decay.
  1. $A_\Gamma \neq 0$ $\Rightarrow$ CP violation in mixing ($\mathcal{O}(10^{-4})$ in SM)
  2. $[A_\Gamma(K^+K^-) - A_\Gamma(\pi^+\pi^-)] \neq 0 \Rightarrow$ CP violation in decay

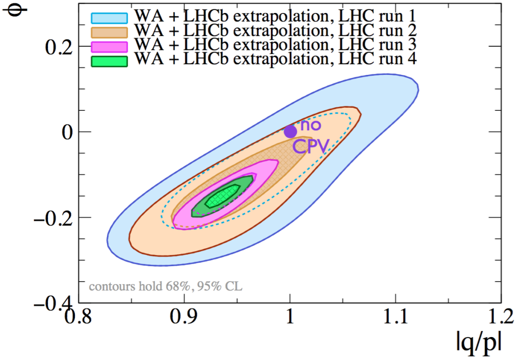
Tagging method	$A_\Gamma(K^+K^-) \times 10^{-3}$	$A_\Gamma(\pi^+\pi^-) \times 10^{-3}$	Ref.
Prompt D^*'s	$-0.35 \pm 0.62 \pm 0.12$	$+0.33 \pm 1.06 \pm 0.14$	$1\,\text{fb}^{-1}$ [PRL 112 (2014) 041801
Semileptonic B's	$-1.34 \pm 0.77 \pm 0.30$	$-0.92 \pm 1.45 \pm 0.29$	$3\,\text{fb}^{-1}$ [JHEP 04 (2015) 043]





FUTURE CHARM SENSITIVITIES

- Scale sensitivities with $\sqrt{N}$.
  - Assumes scaling of systematic uncertainties.
  - Ignores analysis improvements.
- LHCb-upgrade will improve hadronic $\varepsilon_{\text{trig}}$ by factor 2 (removal of E_{T} cuts and improvements in tracking efficiency).
- **Will be able to probe SM-level *CP* violation.**

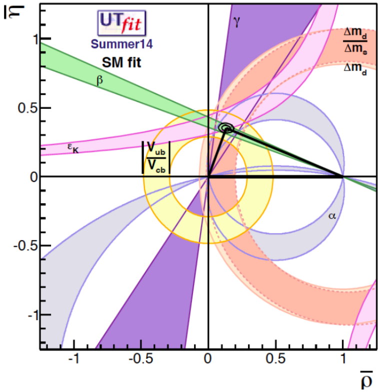


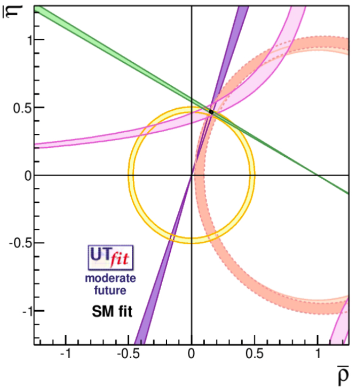
$\int \mathcal{L}\,dt$	LHC era Run-1 (2010-12)	LHC era Run-2 (2015-18)	LHC era Run-3 (2020-22)	HL-LHC era Run-4 (2025-28)	HL-LHC era Run-5 (2030++)
x $[10^{-3}]$	1.22	0.92	0.42	0.25	0.18
y $[10^{-3}]$	0.53	0.37	0.15	0.09	0.06
$\lvert q/p\rvert$ $[10^{-3}]$	59	44	20	12	8
ϕ [mrad]	89	70	33	20	14

Mixing and indirect *CP* violation sensitivities

Summary

- Higher precision *CP* violation measurements probe TeV scales, beyond reach of direct measurements.
- Significant progress has been made, CKM holding strong.
- Detailed *CP* violation programme from LHCb, ATLAS, CMS covering HL-LHC era.
  - Many many more observables not discussed today.
  - Competition/complementarity with Belle-II from $\sim$ 2018.

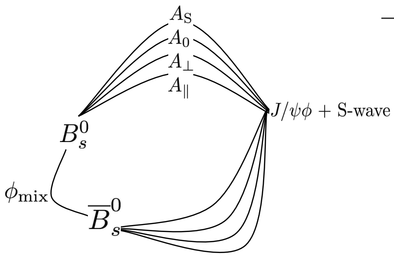




Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.049	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\ f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 0.01
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (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 upgrade.
- After upgrade.
- Current theory uncertainty.

- Relax assumption that $\lambda^f \equiv \eta_f \frac{q}{p} \frac{A_f}{\overline{A}_f}$ is same for all $J/\psi K^+ K^-$ polarisation states.
  - Measure $\lambda^f = |\lambda^f| e^{-i\phi_s^f}, f \in (0, \perp, \|, \mathrm{S})$
- Penguin pollution and/or CPV could be different for each state, f [Bhattacharya, Datta, Int. J. Mod, Phys. A28(2013) 1350063].

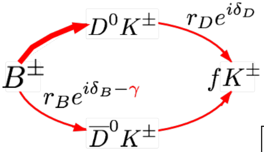


Parameter	Value
$\|\lambda^0\|$	$1.012 \pm 0.058 \pm 0.013$
$\|\lambda^{\|}/\lambda^0\|$	$1.02 \pm 0.12 \pm 0.05$
$\|\lambda^{\perp}/\lambda^0\|$	$0.97 \pm 0.16 \pm 0.01$
$\|\lambda^{\mathrm{S}}/\lambda^0\|$	$0.86 \pm 0.12 \pm 0.04$
ϕ_s^0 [rad]	$-0.045 \pm 0.053 \pm 0.007$
$\phi_s^{\|} - \phi_s^0$ [rad]	$-0.018 \pm 0.043 \pm 0.009$
$\phi_s^{\perp} - \phi_s^0$ [rad]	$-0.014 \pm 0.035 \pm 0.006$
$\phi_s^{\mathrm{S}} - \phi_s^0$ [rad]	$0.015 \pm 0.061 \pm 0.021$

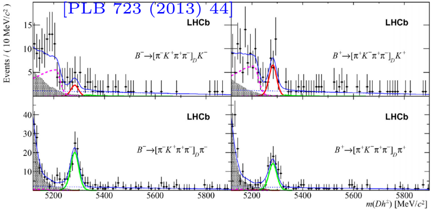
- Everything compatible with no polarisation dependence.

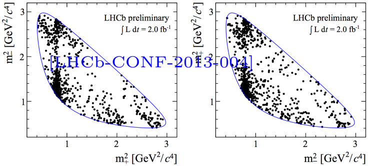
Measurement of γ from $B \to DK$

1. **GLW/ADS:** f is CP eigenstate $(D^0 \to K^+K^-, \pi^+\pi^-)$
   - Large rate, small interference.
   - PLB 712 (2012) 203
2. **ADS:** f is common final state $(D^0 \to K^\pm\pi^\mp, K^\pm\pi^\mp\pi^+\pi^-)$
   - Lower rate, larger interference.
   - PLB 723 (2013) 44
3. **GGSZ:** f is common final state $(D^0 \to K^0_S K^+K^-, K^0_S\pi^+\pi^-)$
   - Requires Dalitz analysis.
   - JHEP 10 (2014) 097
4. **GLS:** $f = K^0_S K\pi$
   - PLB 733 (2014) 36
5. **GLW/ADS:** $B^0 \to DK^*, D \to hh$
   - PRD 90 (2014) 112002



ADS



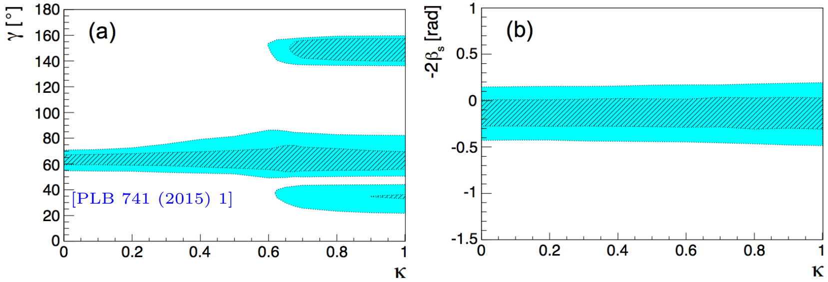


- Modes have different $b \to u$ and $b \to c$ amplitude ratios so different sensitivity to γ.

γ AND ϕ_s FROM CHARMLESS 2-BODY DECAYS

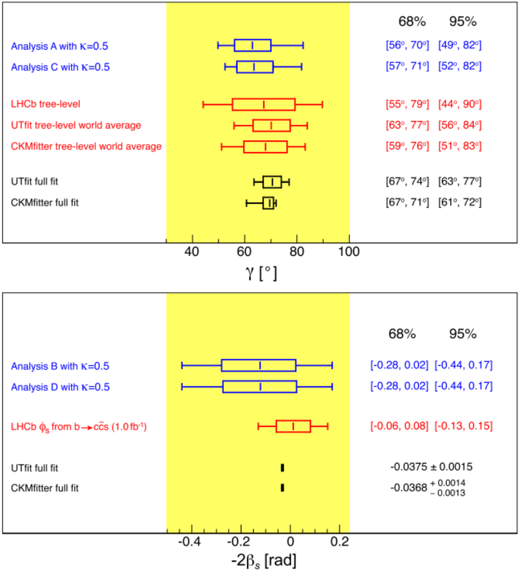
- Determine γ and ϕ_s using $B^0 \to \pi^+\pi^-$, $B^0 \to \pi^0\pi^0$, $B^0 \to \pi^\pm\pi^0$, $B^0 \to K^+K^-$ [PLB 459 (1999) 306, JHEP 10 (2012) 029]
- Use isospin and U-spin symmetries, accounting for non-factorisable U-spin breaking effects (κ).

$$\gamma = (63.5^{+7.2}_{-6.7})^\circ \quad \text{OR} \quad \phi_s = -0.12^{+0.12}_{-0.16}\ \text{rad}$$



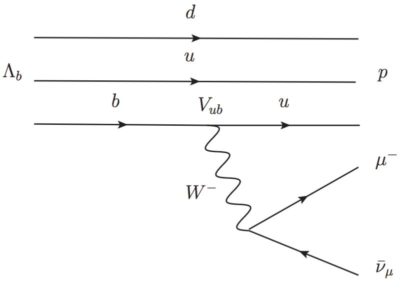
- Consistent with tree-level measurement of γ and (separately) consistent with ϕ_s from $b \to c\bar{c}s$ (potentially competitive measurement).
- Needs to be updated with $3\,\mathrm{fb}^{-1}$.

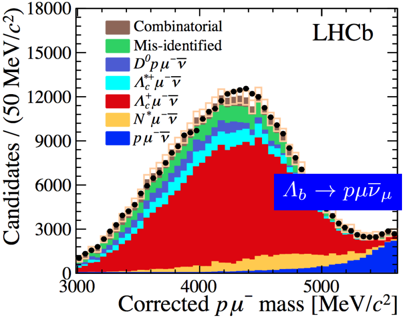
γ and ϕ_s from charmless 2-body decays



EXCLUSIVE $|V_{ub}|$

- Long-standing discrepancy between inclusive and exclusive determinations of $|V_{ub}|$.
- Large production of Λ_b baryons at LHC. Cleaner than $B \to \pi l \nu$ due to protons in final state.



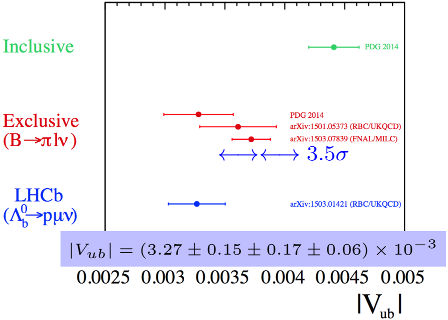


- First observation of $\Lambda_b \to p\mu\bar{\nu}_\mu$!
- Normalise to the V_{cb} decay, $\Lambda_b \to \Lambda_c \mu \nu$ and use world average $|V_{cb}|$ value.

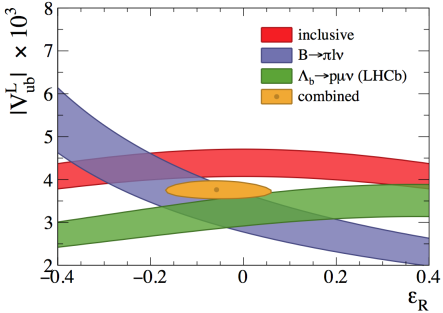
$$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda_b \to p\mu\nu)_{q^2 > 15\text{ GeV}}}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu\nu)_{q^2 > 7\text{ GeV}}} R_{\text{FF}}$$

Exclusive $|V_{ub}|$

- **Syst. limited** from Lattice QCD calc. of Λ_b form-factor (more precise at high q^2).
- $\Lambda_b \to p\mu\nu$ has different dependence on right-handed currents (ϵ_R), but combination starts to disfavour interpretation of RHC.
  - Is effect of RHC accounted for in experimental efficiencies for $B \to \pi l\nu$ and $B \to X_u l\nu$?.

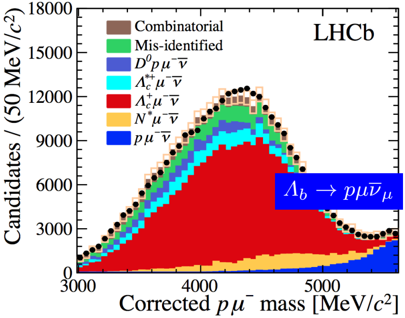


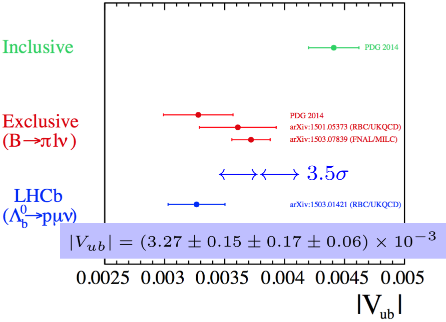
$|V_{ub}| = (3.27 \pm 0.15 \pm 0.17 \pm 0.06) \times 10^{-3}$



- **Future:** can make other measurement using $B_s^0 \to K\mu\nu$ (difficult at Belle-II?)
- $\sigma(|V_{ub}|) \sim 2-3\%$ at Belle-II. Also improve $\mathcal{B}(\Lambda_c \to pK\pi)$ for normalisation mode ($\Lambda_b \to \Lambda_c\mu\nu$).

Exclusive $|V_{ub}|$





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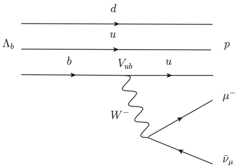

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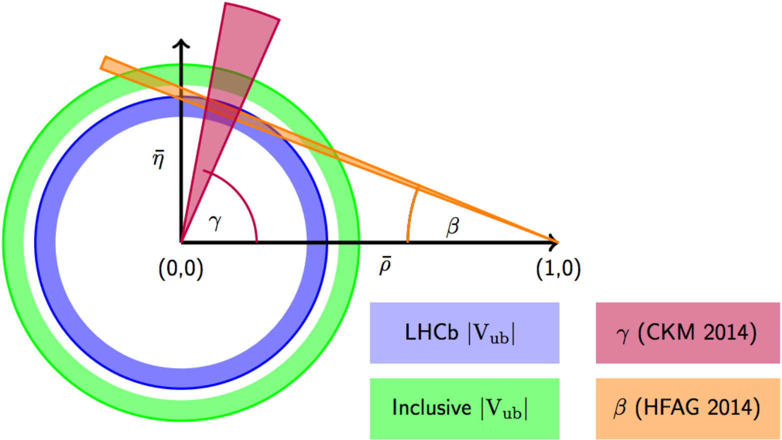
- $\sigma(|V_{ub}|) \sim 2-3\%$ at Belle-II. Also improve $\mathcal{B}(\Lambda_c \to pK\pi)$ for normalisation mode ($\Lambda_b \to \Lambda_c\mu\nu$).

Impact of $|V_{ub}|$ on unitarity triangle



- LHCb $|V_{ub}|$ result consistent with world average value of $\sin 2\beta$.

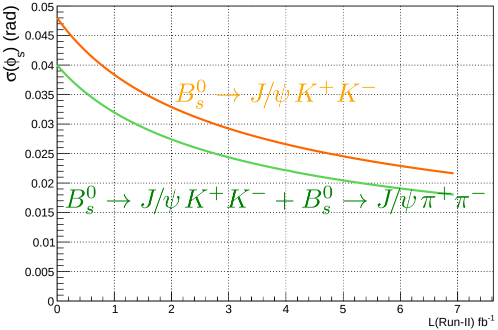
ATLAS prospects for $B_s^0 \to J/\psi\phi$: triggers

- Muon p_T thresholds in trigger:
  - Run-2/3: 6+6 GeV (nominal, assuming basic L1-topo usage) or 11+11 GeV (pessimistic $\Rightarrow \times 7$ fewer events)
  - HL-LHC: 11+11 GeV

	2011	2012	2015-17		2019-21	2023-30+
Detector	current	current	IBL		IBL	ITK
Average interactions per BX $<\mu>$	6-12	21	60		60	200
Luminosity, fb^{-1}	4.9	20	100		250	3 000
Di-μ trigger p_T thresholds, GeV	4 - 4(6)	4 - 6	6 - 6	11 - 11	11 - 11	11 - 11
Signal events per fb^{-1}	4 400	4 320	3 280	460	460	330
Signal events	22 000	86 400	327 900	45 500	114 000	810 000
Total events in analysis	130 000	550 000	1 874 000	284 000	758 000	6 461 000
MC $\sigma(\phi_s)$ (stat.), rad	0.25	0.12	0.054	0.10	0.064	0.022

- Sensitivities using toy-MC using 2011 analysis with fully simulated signal and background from 2012 data sidebands.
- Expected developments should improve sensitivity further:
  - Flavour tagging and multi-dimensional fit from 8 TeV (2012) analysis.
  - L1-topo trigger $\to$ some Run-2 data expected to be collected with triggers using lower p_T thresholds (4-6 GeV).

ϕ_s PROSPECTS



- In future, use other channels:
  - $B_s^0 \to \psi(2S)\phi$
  - $B_s^0 \to J/\psi \eta$
  - $B_s^0 \to J/\psi(ee)\phi$
  - $B_s^0 \to J/\psi K^+K^-$ (high K^+K^- mass)
- Control of penguins essential!
  - $B_s^0 \to J/\psi K_S^0$, $B_s^0 \to J/\psi K^*$, $B^0 \to J/\psi \rho^0$ [NPB 873 (2013) 275-292, PRD 86 (2012) 071102]

ϕ_s error (rad)	Run 1 (2010–12) 3 fb^{-1}	Run 2 (2015–18) 8 fb^{-1}	Upgrade (2019–??) 50 fb^{-1}	Theory
$B_s^0 \to J/\psi K^+K^-$	0.049	0.025	0.009	~ 0.003
$B_s^0 \to J/\psi \pi^+\pi^-$	0.068	0.035	0.012	~ 0.01
$B_s^0 \to \phi\phi$	0.15	0.10	0.018	< 0.02

- Upgraded detector will be read out at 40MHz.
- Factor-10 increase signal yields.
- Existing design will saturate at higher luminosities.

LHCb trigger