Mixing and CPV in the B system

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(University of Edinburgh),

On behalf of the LHCb collaboration,

PLHC, Vancouver, 4-9 June 2012.

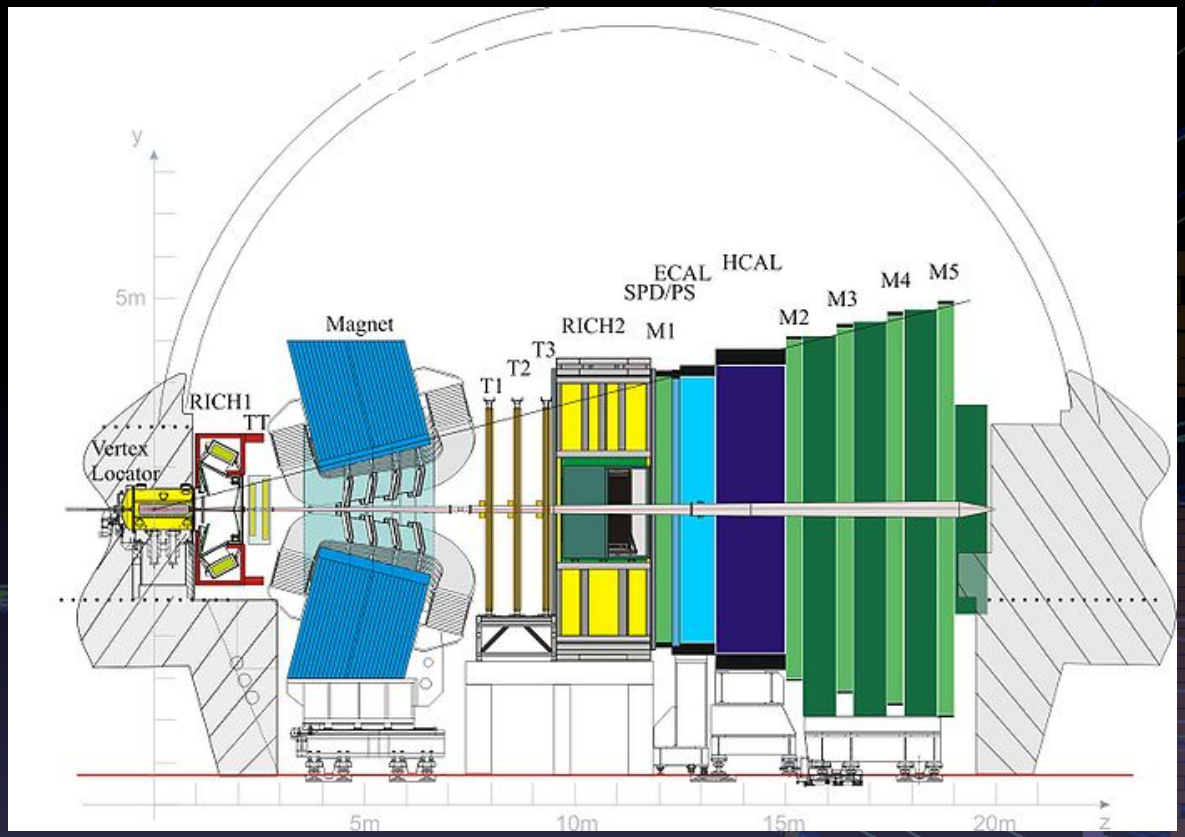
Main results to be presented

Results presented are based on the full 2011 dataset of ~1 fb^{-1} collected with the LHCb detector

- Measurement of Φ_s in B_s -> $J/\psi\pi\pi$ decays (LHCb-PAPER-2012-006, arXiv:1204.5675) – 26/3/2012,
- Time-dependent angular analysis of B_s -> $J/\psi\phi$ decays (LHCb-CONF-2012-002) – 5/3/2012 ,
- Determination of the sign of the decay width difference in the B_s system (LHCb-PAPER-2011-028, arXiv:1202.4717) – 22/2/2012,
- Measurement of the polarization amplitudes and triple product asymmetries in the B_s -> $\phi\phi$ decay (LHCb-PAPER-2012-004, arXiv:1204.2813) – 10/4/2012.

The LHCb detector

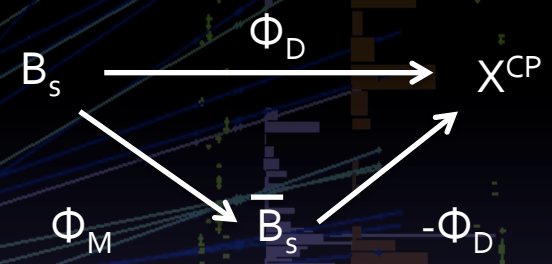
- Smooth running of the detector thanks to the 804 members,
- All possible thanks to high beam quality provided by the LHC.



- LHCb is a forward arm spectrometer (pseudo-rapidity range: $2 < \eta < 5$),
- Accurate decay time resolution through vertex locator (VELO),
- Accurate particle ID provided by RICH detectors,
- High muon reconstruction efficiency from muon stations,
- Accurate momentum resolution from tracking stations ($\delta p/p$ = 0.35%-0.55%).

Φ_s phenomenology

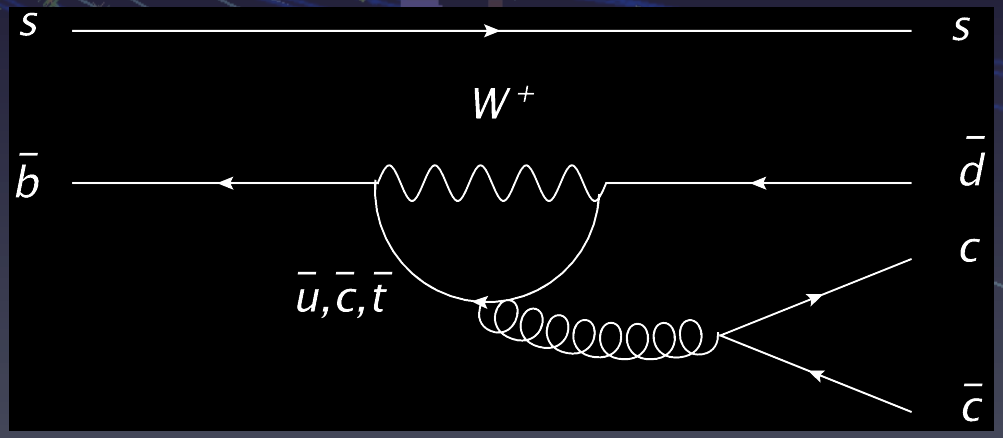
In this presentation, Φ_s is used to denote the CP violation interference between mixing and decay:



I.e. $\Phi_s = \Phi_M - 2\Phi_D$

Mode can still be sensitive to $\not{CP}$ in mixing interference even if no direct $\not{CP}$ in mixing and decay individually.
In SM, Φ_S in b->$c\bar{c}$s transitions is predicted to be -0.04 Charles *et al.* (2011) Phys. Rev **D84** 033005

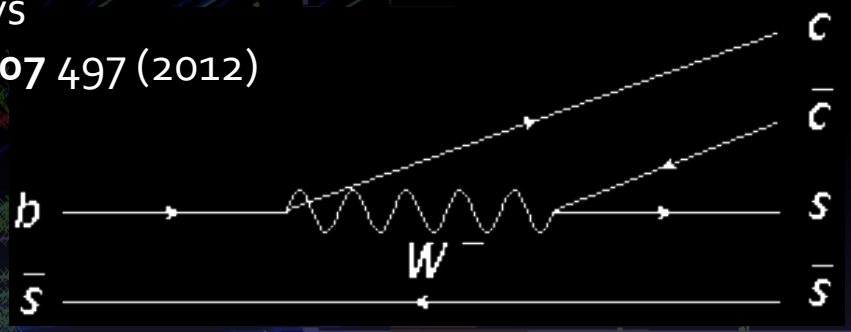
Experimentally, penguin pollution understood with B_s-> $J/\psi K^*$
In progress, decay already seen at LHCb (LHCb-CONF-2011-025)



Φ_s in B_s-> J/ψππ decays

LHCb-PAPER-2012-006, arXiv:1204.5675

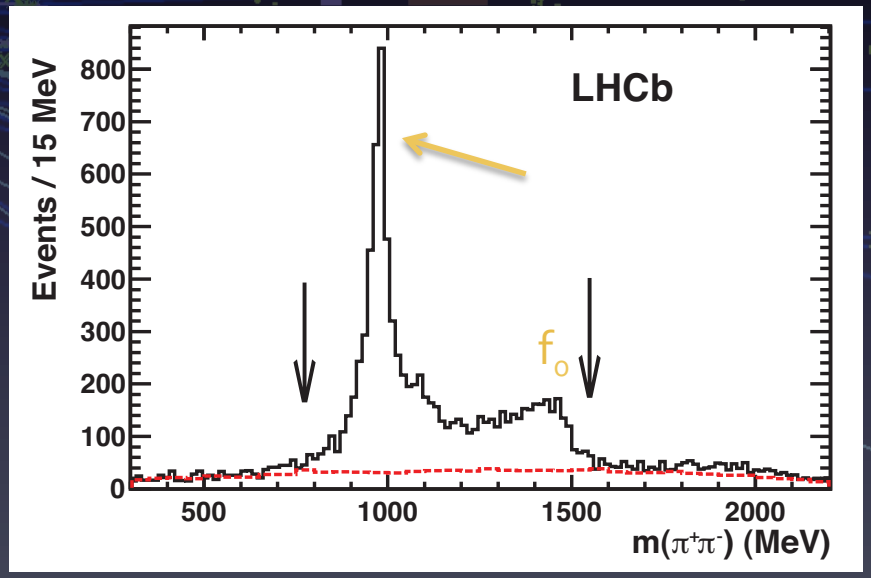
Previous study using B_s-> $J/\psi f_0(980)$ decays with 0.41 fb^{-1} of LHCb data: Phys. Lett. **B707** 497 (2012)



m(ππ) in range 775<m(ππ)<1500 MeV found to be CP-odd
0.975 @ 95% confidence level (LHCb-PAPER-2012-005)

Found from Dalitz analysis of resonance structure (see additional information)

⇒ Allows for greater number of events (7421±105 signal candidates from 1.0 fb^{-1}) to be studied for Φ_s analysis

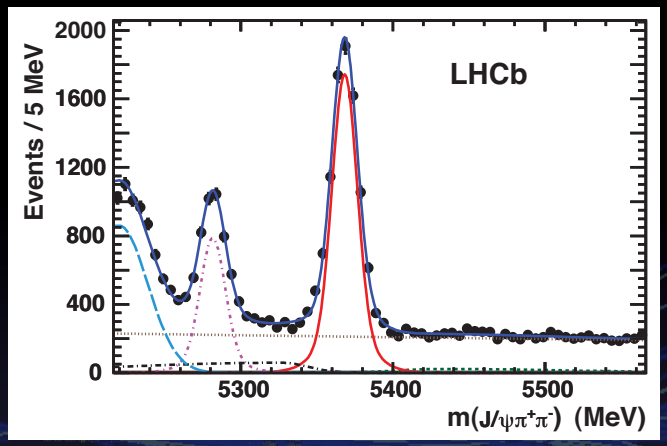


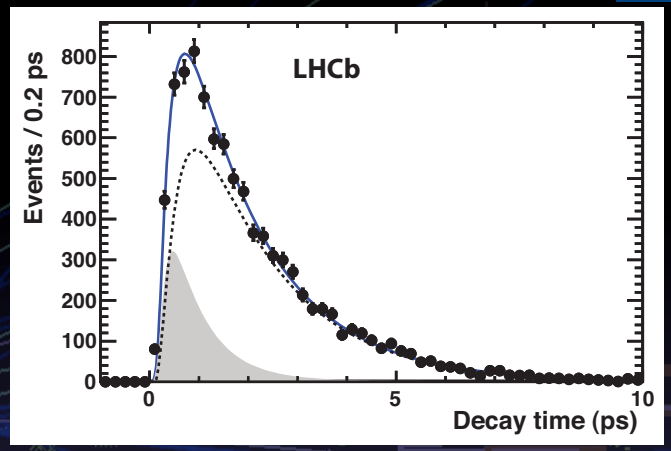
Sample all CP-odd

⇒ Maximum likelihood fit to mass and time only

Major peaking backgrounds: $B^0 \to J/\psi K\pi$ (blue), $B^0 \to J/\psi\pi\pi$ (purple)

Decay time distribution: Signal (dashed), background (shaded)





Tagged decay rate:

$$\Gamma\left(\overset{(-)}{B}{}^0_s \to J/\psi\, f_{\rm odd}\right) = \frac{\mathcal{N}}{2} e^{-\Gamma_s t}\left\{ e^{\Delta\Gamma_s t/2}(1+\cos\phi_s) + e^{-\Delta\Gamma_s t/2}(1-\cos\phi_s) \pm \sin\phi_s \sin(\Delta m_s\, t)\right\},$$

Main Φ_s sensitivity

Untagged decay rate:

$$\Gamma\left(B^0_s \to J/\psi\, f_{\rm odd}\right) + \Gamma\left(\overline{B}^0_s \to J/\psi\, f_{\rm odd}\right) = \mathcal{N} e^{-\Gamma_s t}\left\{ e^{\Delta\Gamma_s t/2}(1+\cos\phi_s) + e^{-\Delta\Gamma_s t/2}(1-\cos\phi_s)\right\}$$

Important to understand time resolution and acceptance

Data driven methods for time resolution and acceptance. Prompt J/Ψ->μμ used to find resolution, acceptance found from B^0-> J/ψK*

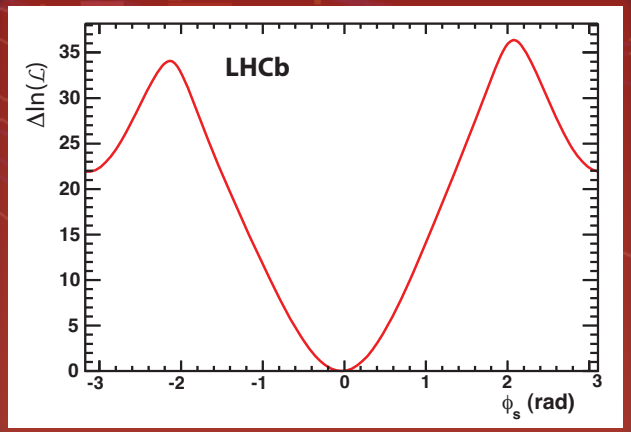
Γ_S & $\Delta\Gamma_S$ (and associated correlation) taken from B_s-> J/ψΦ analysis (LHCb-CONF-2012-002)

Major systematics from signal yield and background lifetime parameters

Result:

$$\phi_s = -0.019^{+0.173+0.004}_{-0.174-0.003}$$

Previous study: ϕ_s=-0.44 ± 0.44 (stat) ± 0.02 (syst)



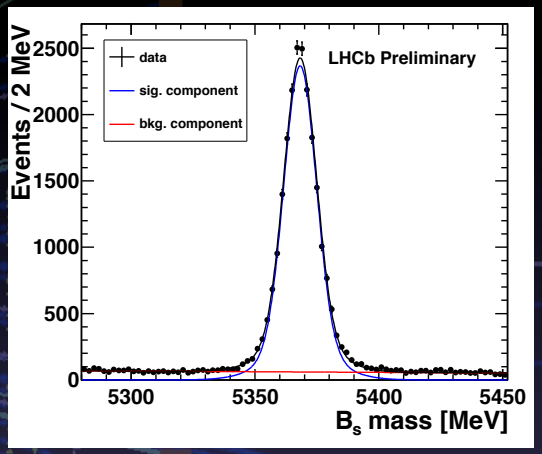
Tagged time-dependent measurement of Φ_s in B_s->J/Ψϕ decays

LHCb-CONF-2012-002

Measurement based on a sample of ~21200 events from 1.0 fb^{-1} at LHCb

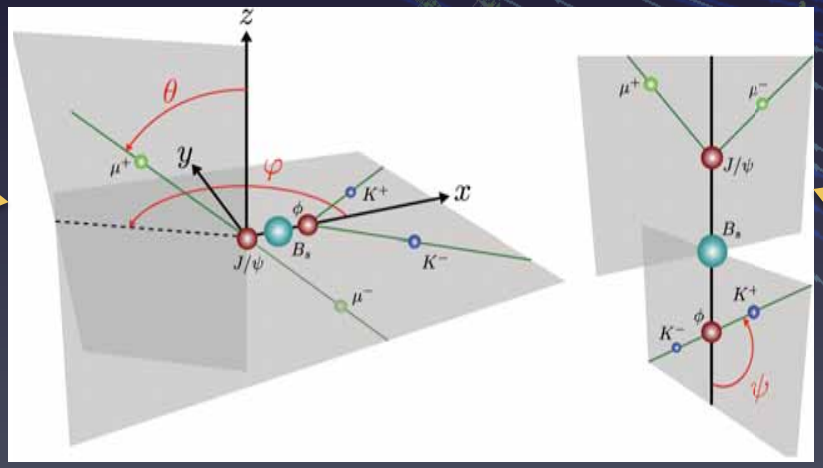
Update of previous analysis based on 370 pb^{-1}

LHCb collaboration (2011) PRL **108**, 101803



Mixture of CP-odd and CP-even components in the final state => full angular analysis in transversity basis is employed

J/Ψ rest frame



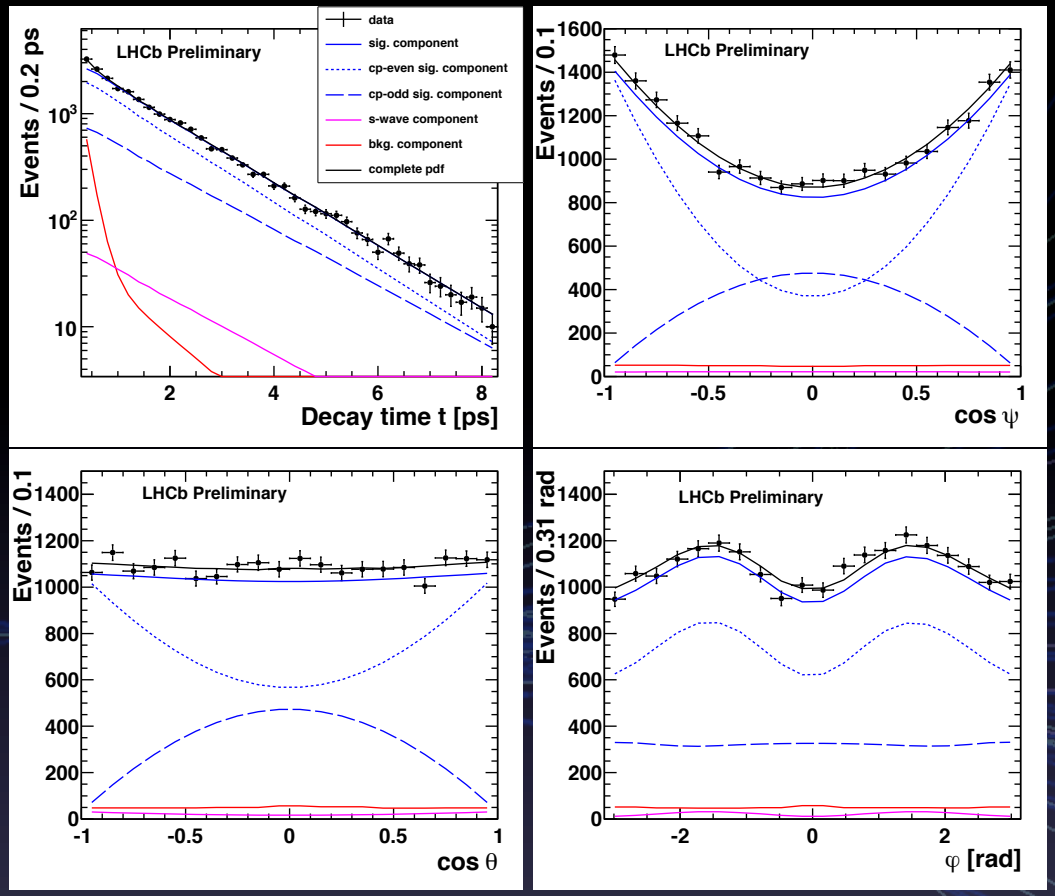
ϕ rest frame

$$
\begin{aligned}
A_1 &= |A_0|^2 e^{-\Gamma_s t}[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)] \\
A_2 &= |A_\parallel|^2 e^{-\Gamma_s t}[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)] \\
A_3 &= |A_\perp|^2 e^{-\Gamma_s t}[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s \sin(\Delta m t)] \\
A_4 &= |A_\parallel||A_\perp| e^{-\Gamma_s t}[-\cos(\delta_\perp - \delta_\parallel)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \cos(\delta_\perp - \delta_\parallel)\cos\phi_s \sin(\Delta m t) \\
&\quad + \sin(\delta_\perp - \delta_\parallel)\cos(\Delta m t)] \\
A_5 &= |A_0||A_\parallel| e^{-\Gamma_s t}\cos(\delta_\parallel - \delta_0)[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)] \\
A_6 &= |A_0||A_\perp| e^{-\Gamma_s t}[-\cos(\delta_\perp - \delta_0)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \cos(\delta_\perp - \delta_0)\cos\phi_s \sin(\Delta m t) \\
&\quad + \sin(\delta_\perp - \delta_0)\cos(\Delta m t)] \\
A_7 &= |A_s|^2 e^{-\Gamma_s t}[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s \sin(\Delta m t] \\
A_8 &= |A_s||A_\parallel| e^{-\Gamma_s t}[-\sin(\delta_\parallel - \delta_S)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin(\delta_\parallel - \delta_S)\cos\phi_s \sin(\Delta m t) \\
&\quad + \cos(\delta_\parallel - \delta_S)\cos(\Delta m t)] \\
A_9 &= |A_s||A_\perp| e^{-\Gamma_s t}\sin(\delta_\perp - \delta_S)[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s \sin(\Delta m t)] \\
A_{10} &= |A_s||A_0| e^{-\Gamma_s t}[-\sin(\delta_0 - \delta_S)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin(\delta_0 - \delta_S)\cos\phi_s \sin(\Delta m t) \\
&\quad + \cos(\delta_0 - \delta_S)\cos(\Delta m t)]
\end{aligned}
$$

For Φ_s measurements mainly sensitive to $\sin\Phi_s \sin\Delta m_s t$ terms

PDF also allows fitting for $\Delta\Gamma_s$ and Δm_s

NOTE: There is an ambiguity $\Phi_s \to \pi - \Phi_s$, $\Delta\Gamma_s \to -\Delta\Gamma_s$ +strong phase changes



Analysis requires good understanding of time and angular acceptances

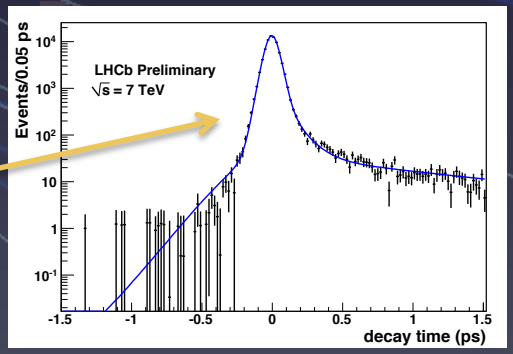
Effective tagging efficiency:
$\varepsilon_{tag}\,\mathcal{D}^2 = (2.29\pm0.27)\%$

where $\mathcal{D} = (1-2\omega_{mistag})$

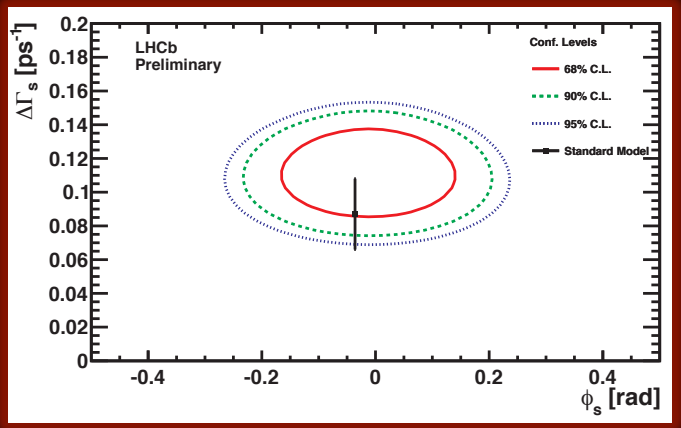
(For more tagging info, see additional slides or talk on Monday)

Time resolution of ~45 fs

Resolution found from fits to prompt J/Ψ->μμ candidates



Results:

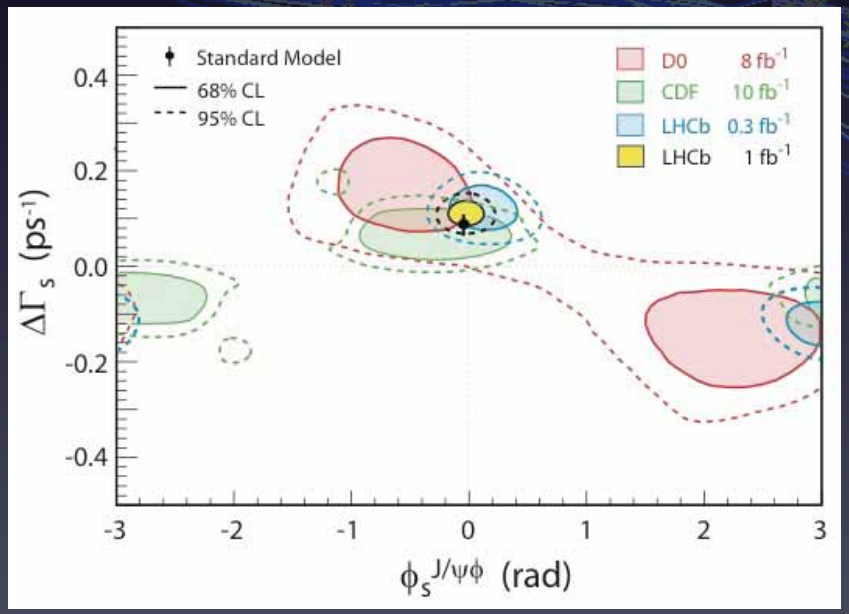


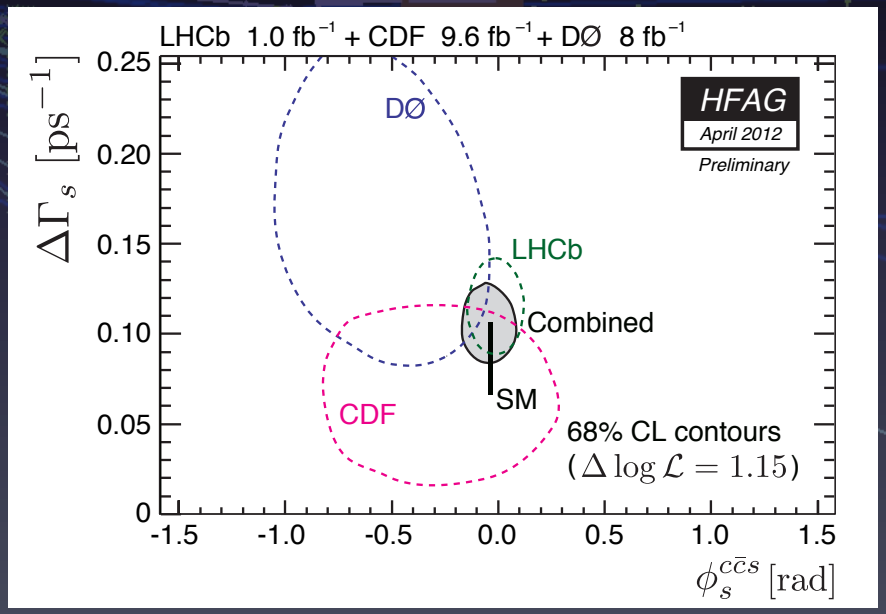
$$\begin{aligned}
\phi_s &= -0.001 \pm 0.101 \ (\text{stat}) \pm 0.027 \ (\text{syst}) \ \text{rad}, \\
\Gamma_s &= 0.6580 \pm 0.0054 \ (\text{stat}) \pm 0.0066 \ (\text{syst}) \ \text{ps}^{-1}, \\
\Delta\Gamma_s &= 0.116 \pm 0.018 \ (\text{stat}) \pm 0.006 \ (\text{syst}) \ \text{ps}^{-1}.
\end{aligned}$$

Combination with LHCb measurement of Φ_s in B_s-> J/ψππ:

ϕ_s=-0.002 ±0.083(stat)±0.027(syst)

Comparison:





Sign of the $\Delta\Gamma_s$ in the B_s system

LHCb-PAPER-2011-028, arXiv:1202.4717

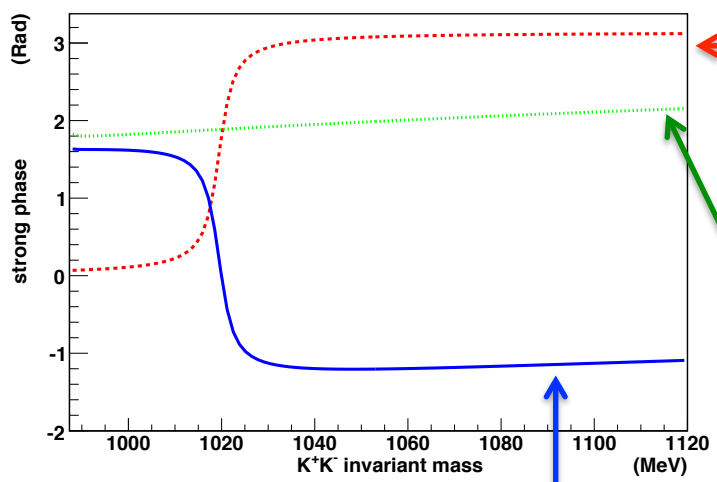
As mentioned earlier, two ambiguous solutions:

$\Phi_s \to \pi - \Phi_s$,

$\Delta\Gamma_s \to -\Delta\Gamma_s$ + strong phase changes

Solved using P-wave <-> S-wave interference

Principle described in Xie *et al.* (2009) JHEP 0909:074



KK P-wave: ϕ meson spin-1

=> Amplitude described by Breit-Wigner

(rapid phase increase across ϕ mass region)

$$BW(m_{KK}) = \frac{F_r F_D}{m_\phi^2 - m_{KK}^2 - i m_\phi \Gamma(m_{KK})}$$

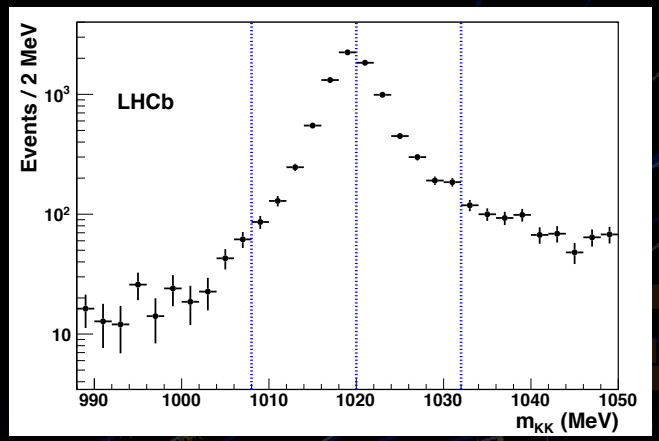
KK S-wave:

Amplitude described by Flatté function

(approx. flat across ϕ mass region)

=> Rapid decrease in difference between S-wave and P-wave

Data split into 4 bins by m_{KK}

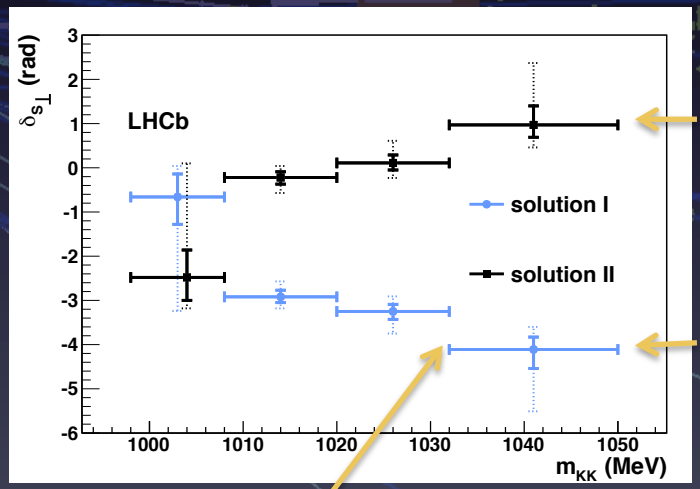


In each bin, measure

$$\delta_{s_\perp} \equiv \delta_s - \delta_\perp$$

along with fraction of S-wave (F_s)

Parameter	Solution I	Solution II
ϕ_s (rad)	0.167 ± 0.175	2.975 ± 0.175
$\Delta\Gamma$ (ps^{-1})	0.120 ± 0.028	-0.120 ± 0.028
$F_{S;1}$	0.283 ± 0.113	0.283 ± 0.113
$F_{S;2}$	0.061 ± 0.022	0.061 ± 0.022
$F_{S;3}$	0.044 ± 0.022	0.044 ± 0.022
$F_{S;4}$	0.269 ± 0.067	0.269 ± 0.067
$\delta_{S\perp;1}$ (rad)	$-0.46\ ^{+0.35}_{-0.42}$	$-2.68\ ^{+0.42}_{-0.35}$
$\delta_{S\perp;2}$ (rad)	$-2.92\ ^{+0.15}_{-0.13}$	$-0.22\ ^{+0.13}_{-0.15}$
$\delta_{S\perp;3}$ (rad)	$-3.25\ ^{+0.16}_{-0.18}$	$0.11\ ^{+0.18}_{-0.16}$
$\delta_{S\perp;4}$ (rad)	$-4.11\ ^{+0.28}_{-0.43}$	$0.97\ ^{+0.43}_{-0.28}$



$\Delta\Gamma_s<0$

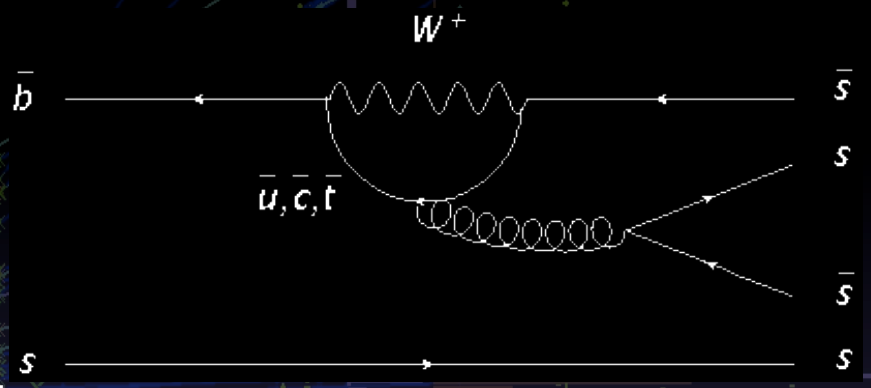
$\Delta\Gamma_s>0$

⇒ Solution I is selected, $\Delta\Gamma_s>0$
⇒ Heavy B_s mass eigenstate lives longer

4.7σ negative trend

Polarization amplitudes and triple product asymmetries in the B_s->ϕϕ decay

LHCb-PAPER-2012-004, arXiv:1204.2813



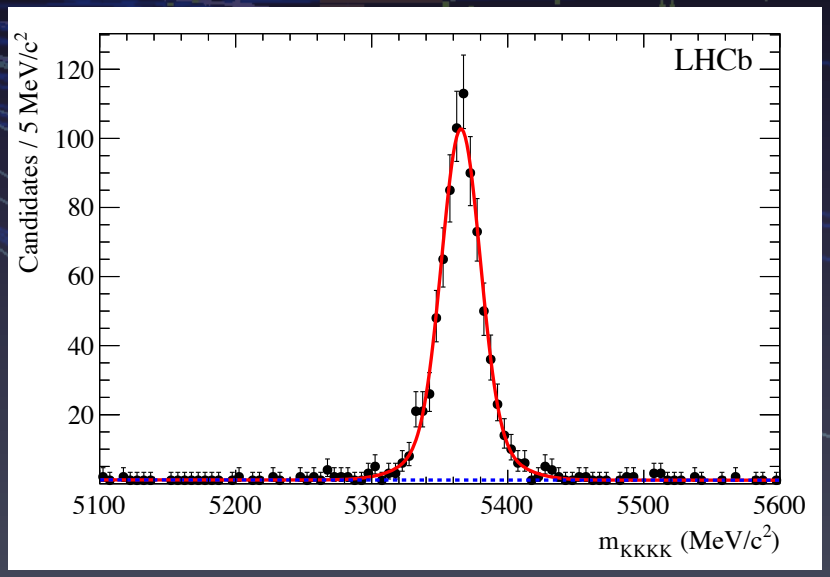
B_s->ϕϕ a pure penguin P->VV decay

Sensitive to new physics in mixing and decay

801±29 events observed in 1.0 fb^{-1} LHCb data

Results presented based on time-integrated angular analysis

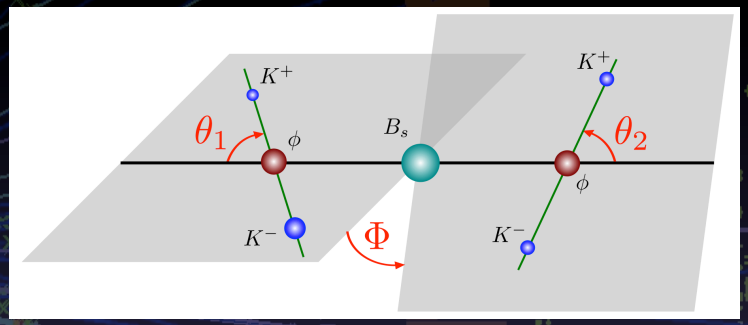
Very clean signal for hadronic mode at a hadronic collider!!!!



Triple product asymmetries

Principle: Through CPT theorem, T violation equivalent to CP violation
⇒ Look at observables in P->VV decays, corresponding to T-odd triple products

Consider B_s->ϕϕ decay:



We look at observables :

$$U = \sin(2\Phi)/2$$

$$V = sign(\cos\theta_1 \cos\theta_2)\sin\Phi$$

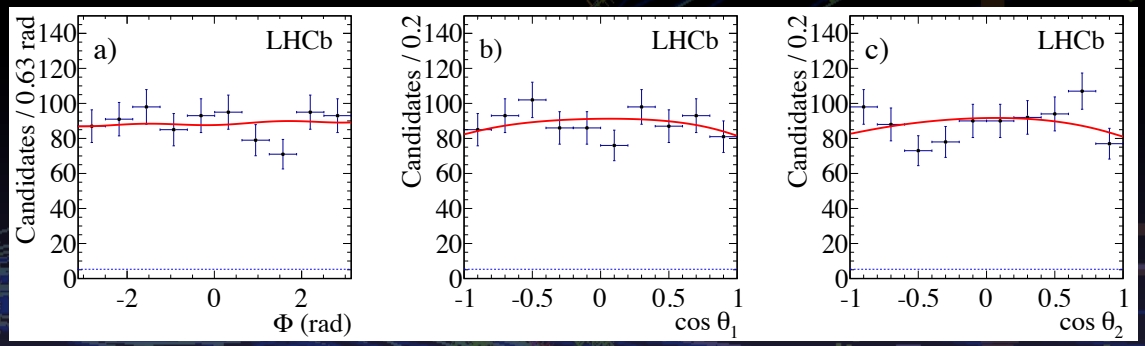
Related to T-odd triple products
Gronau, Rosner (2011) – arXiv:1107.1232

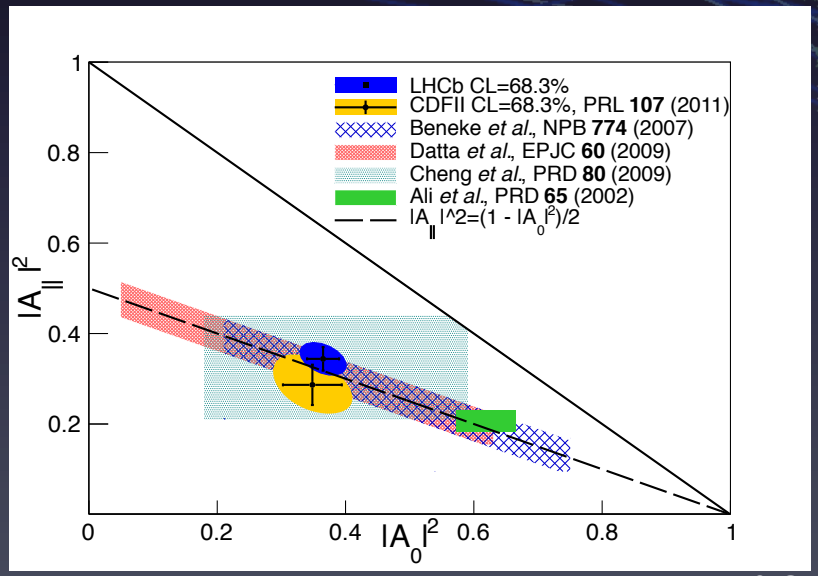
which then pick out CP-even - CP-odd interference terms from decay rate
(see additional information)

Polarization amplitudes and strong phase difference measured from time-integrated PDF

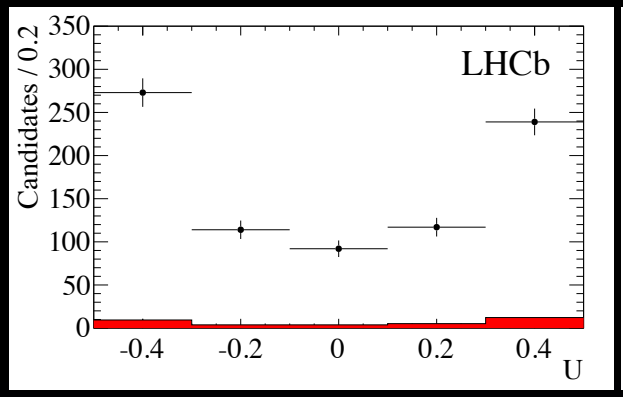
$$\frac{d\Gamma}{d\omega} = 4|A_0|^2\tau_L \cos^2\theta_1 \cos^2\theta_2 + |A_\parallel|^2\tau_L \sin^2\theta_1 \sin^2\theta_2(1+\cos 2\Phi) + |A_\perp|^2\tau_H \sin^2\theta_1 \sin^2\theta_2(1-\cos 2\Phi) + \sqrt{2}|A_0||A_\parallel|\cos(\delta_\parallel)\tau_L \sin 2\theta_1 \sin 2\theta_2 \cos\Phi$$

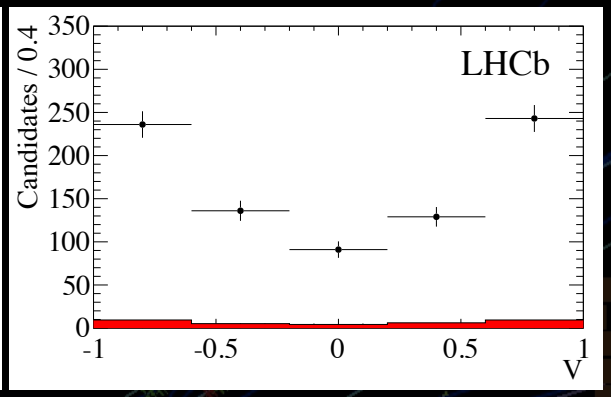
Lifetimes constrained from $B_s \to J/\psi\phi$ measurements of Γ_s & $\Delta\Gamma_s$





$$|A_0|^2 = 0.365 \pm 0.022\,(\text{stat}) \pm 0.012\,(\text{syst})$$
$$|A_\perp|^2 = 0.291 \pm 0.024\,(\text{stat}) \pm 0.010\,(\text{syst})$$
$$\cos(\delta_\parallel) = -0.844 \pm 0.068\,(\text{stat}) \pm 0.029\,(\text{syst})$$





Triple products asymmetries measured from U & V observables to be:

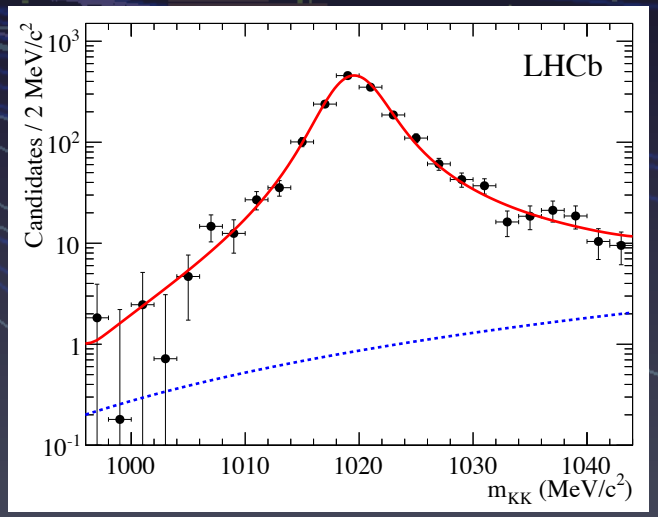
$$A_U = -0.055 \pm 0.036\,(\text{stat}) \pm 0.018\,(\text{syst})$$
$$A_V = 0.010 \pm 0.036\,(\text{stat}) \pm 0.018\,(\text{syst})$$

Result consistent with hypothesis of CP conservation

Main systematics from angular and time acceptances

Assumed no S-wave (2% contribution for systematic in polarization amplitudes), found to be negligible from data

Uniform time acceptance assumed



Summary

LHCb has presented the most accurate measurements of $\not{CP}$ in the B_s system with the 2011 1 fb^{-1} dataset:

- In the B_s->J/ΨΦ decay, we measure:

$$\begin{aligned} \phi_s &= -0.001 \pm 0.101 \text{ (stat)} \pm 0.027 \text{ (syst) rad,} \\ \Gamma_s &= 0.6580 \pm 0.0054 \text{ (stat)} \pm 0.0066 \text{ (syst) ps}^{-1} \\ \Delta\Gamma_s &= 0.116 \pm 0.018 \text{ (stat)} \pm 0.006 \text{ (syst) ps}^{-1} \end{aligned}$$

- In the B_s-> J/ψππ decay, we measure: arXiv:1204.5675

$$\phi_s = -0.019^{+0.173+0.004}_{-0.174-0.003}$$

- The combination of the two results is therefore: ϕ_s=-0.002 ±0.083(stat)±0.027(syst)

- The decay width difference has been resolved to be: arXiv:1202.4717

$\Delta\Gamma_s$>0 4.7σ

- In the B_s->ΦΦ decay, polarization amplitudes and triple product asymmetries have been measured to be: arXiv:1204.2813

$$\begin{aligned} |A_0|^2 &= 0.365 \pm 0.022 \text{ (stat)} \pm 0.012 \text{ (syst)} \\ |A_\perp|^2 &= 0.291 \pm 0.024 \text{ (stat)} \pm 0.010 \text{ (syst)} \\ \cos(\delta_\parallel) &= -0.844 \pm 0.068 \text{ (stat)} \pm 0.029 \text{ (syst)} \\ A_U &= -0.055 \pm 0.036 \text{ (stat)} \pm 0.018 \text{ (syst)} \\ A_V &= 0.010 \pm 0.036 \text{ (stat)} \pm 0.018 \text{ (syst)} \end{aligned}$$