Measurement of CP observables in semileptonic decays at LHCb

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Neutral B meson mixing

- Oscillation and decay description:

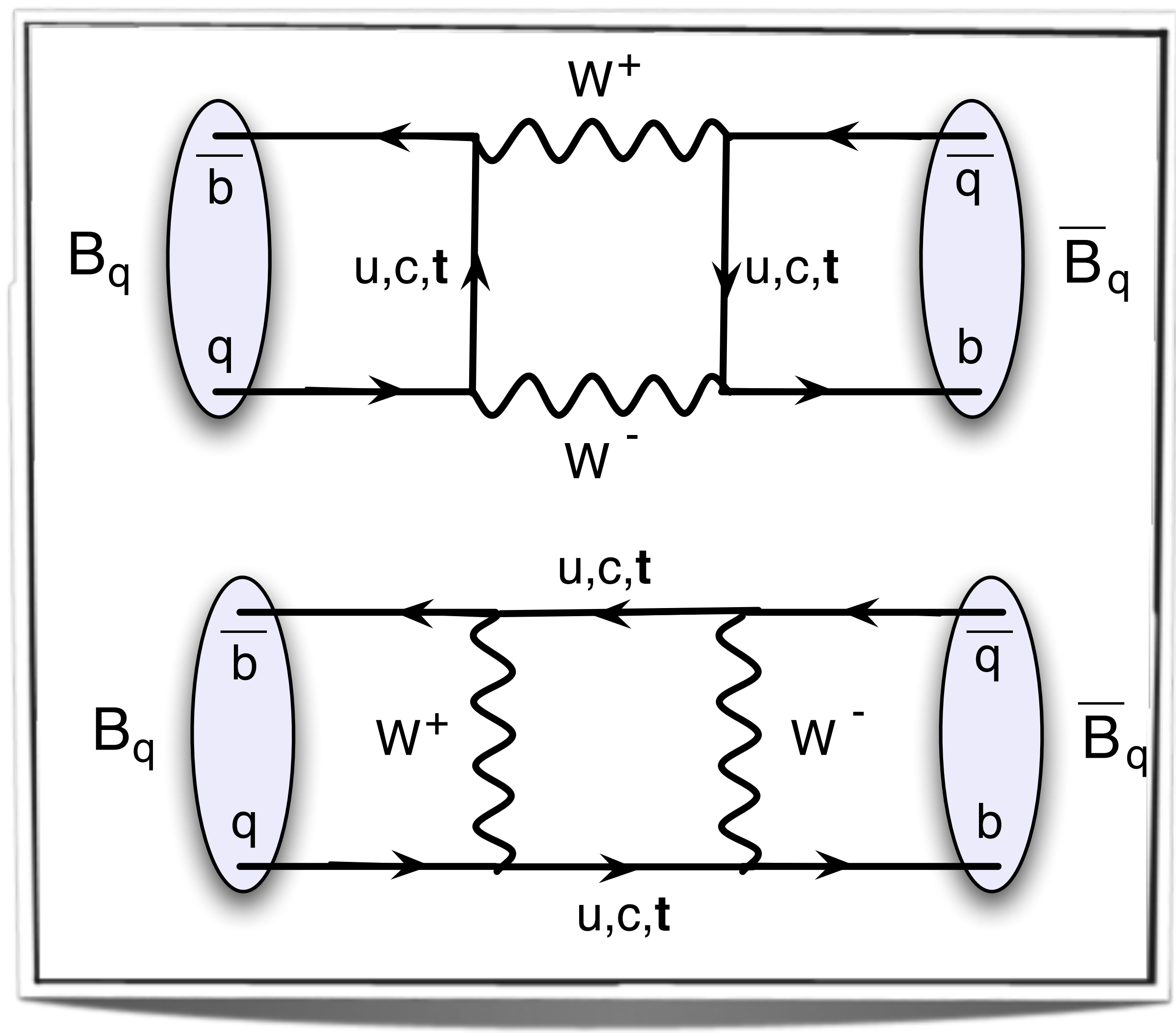
$$i\frac{d}{dt}\begin{pmatrix} |B_q(t)\rangle \\ |\overline{B_q(t)}\rangle \end{pmatrix} = \begin{pmatrix} M_{11} - i\frac{\Gamma_{11}}{2} & M_{12} - i\frac{\Gamma_{12}}{2} \\ M_{12}^* - i\frac{\Gamma_{12}^*}{2} & M_{22} - i\frac{\Gamma_{22}}{2} \end{pmatrix}\begin{pmatrix} |B_q(t)\rangle \\ |\overline{B_q(t)}\rangle \end{pmatrix}$$

- Mass eigenstates are superpositions of flavor eigenstates:

$$|B_L\rangle = p|B_q\rangle + q|\overline{B_q}\rangle$$
$$|B_H\rangle = p|B_q\rangle - q|\overline{B_q}\rangle$$

- Mixing observables

$$\Delta m = m_H - m_L$$
$$\Delta\Gamma = \Gamma_L - \Gamma_H$$



CP violation in B meson mixing

- Oscillation and decay description

$$i\frac{d}{dt}\begin{pmatrix} |B_q(t)\rangle \\ |\overline{B}_q(t)\rangle \end{pmatrix} = \begin{pmatrix} M_{11} - i\frac{\Gamma_{11}}{2} & M_{12} - i\frac{\Gamma_{12}}{2} \\ M_{12}^* - i\frac{\Gamma_{12}^*}{2} & M_{22} - i\frac{\Gamma_{22}}{2} \end{pmatrix} \begin{pmatrix} |B_q(t)\rangle \\ |\overline{B}_q(t)\rangle \end{pmatrix}$$

- Mass eigenstates are superpositions of flavor eigenstates

$$|B_L\rangle = p|B_q\rangle + q|\overline{B_q}\rangle$$
$$|B_H\rangle = p|B_q\rangle - q|\overline{B_q}\rangle$$

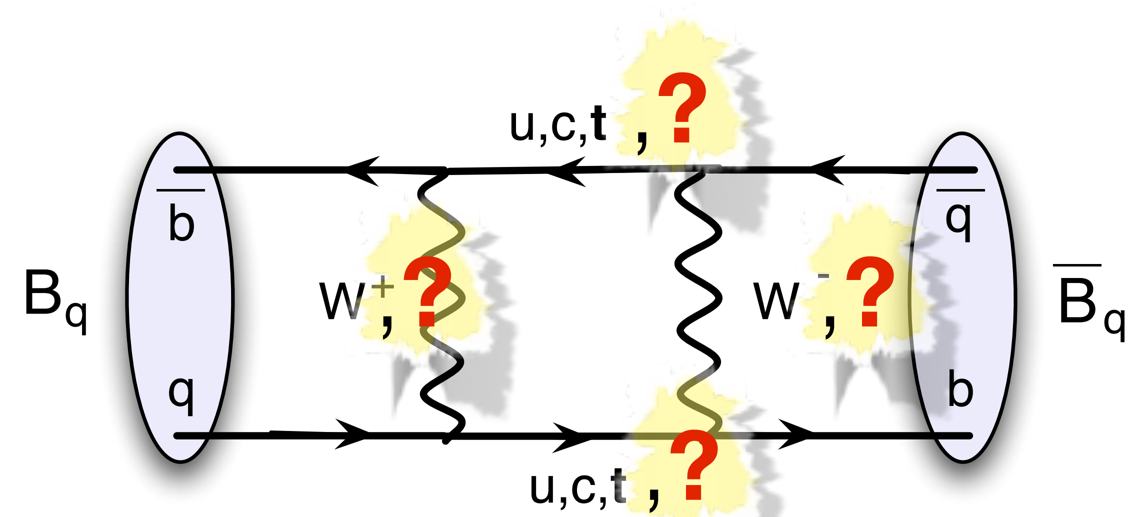
$$a = 1 - \left|\frac{q}{p}\right|$$

Measures
CP violation in mixing

$$\mathcal{P}(\bar{B}\rightarrow B) \neq \mathcal{P}(B\rightarrow \bar{B})$$

- Mixing observables

$$\Delta m = m_H - m_L$$
$$\Delta\Gamma = \Gamma_L - \Gamma_H$$



sensitive probe of New Physics

Semileptonic CP asymmetries

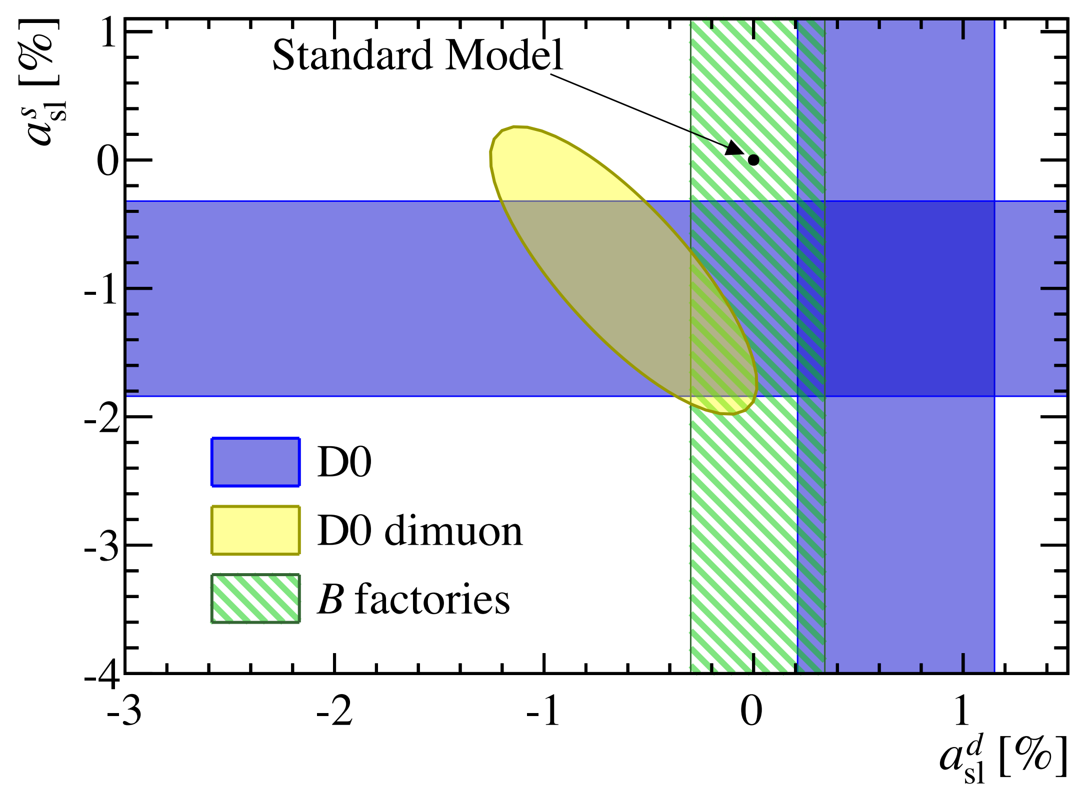
- Using semileptonic flavor specific B decays:

$$a_{\rm sl} = a = \frac{N(\bar{B}\to B \to f) - N(B\to\bar{B} \to \bar{f})}{N(\bar{B}\to B \to f) + N(B\to\bar{B} \to \bar{f})}$$

- SM predictions:

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

TINY!!!



- Experimental status:

...

2013: *"Study of CP-violating charge asymmetries of single muons and like-sign dimuons in $p\bar{p}$ collisions"* , DØ, Phys. Rev. D 89, 012002.

~3σ tension with the SM

SM ? ...or DØ di-muon analysis like?

- **In this talk:**

reminder of $a^s_{\rm sl}$ measurement from LHCb using 1 $\rm fb^{-1}$ of data

NEW preliminary $a^d_{\rm sl}$ measurement from LHCb using 3 $\rm fb^{-1}$ of data

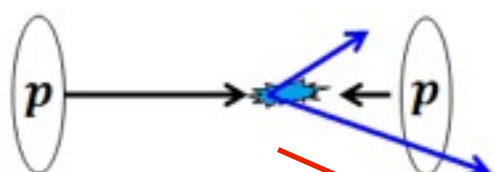
LHCb

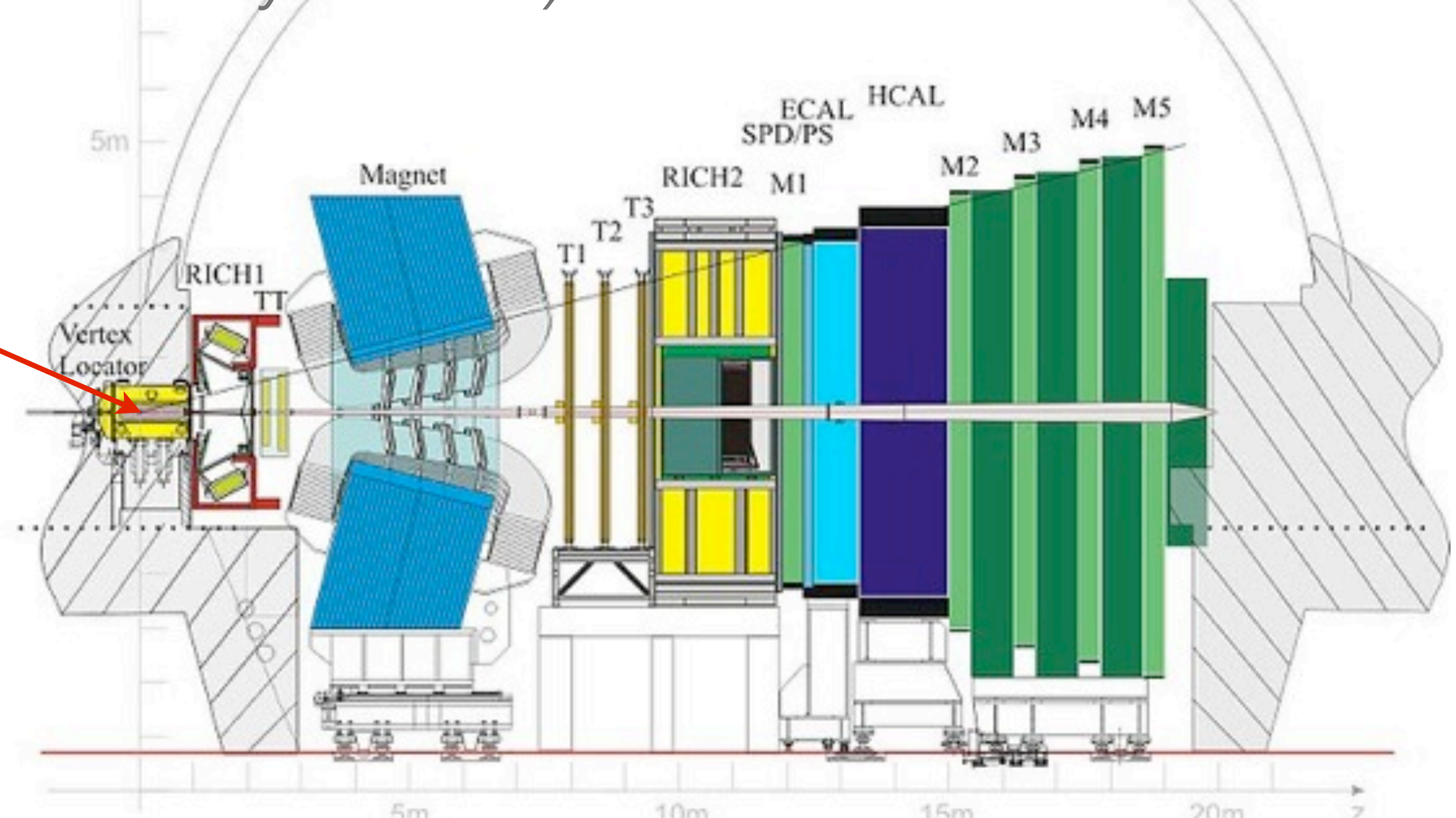
Single-arm forward spectrometer at LHC collider

- ~25 kHz b$\bar{b}$ pairs, ~500 kHz c$\bar{c}$ pairs produced in the forward region

    Large samples of semileptonic B decays

- Analysis based on tracking and muon system+ RICH detectors to identify charged hadrons
- Magnet polarity is reversed frequently *(useful to understand first order left-right detection asymmetries)*





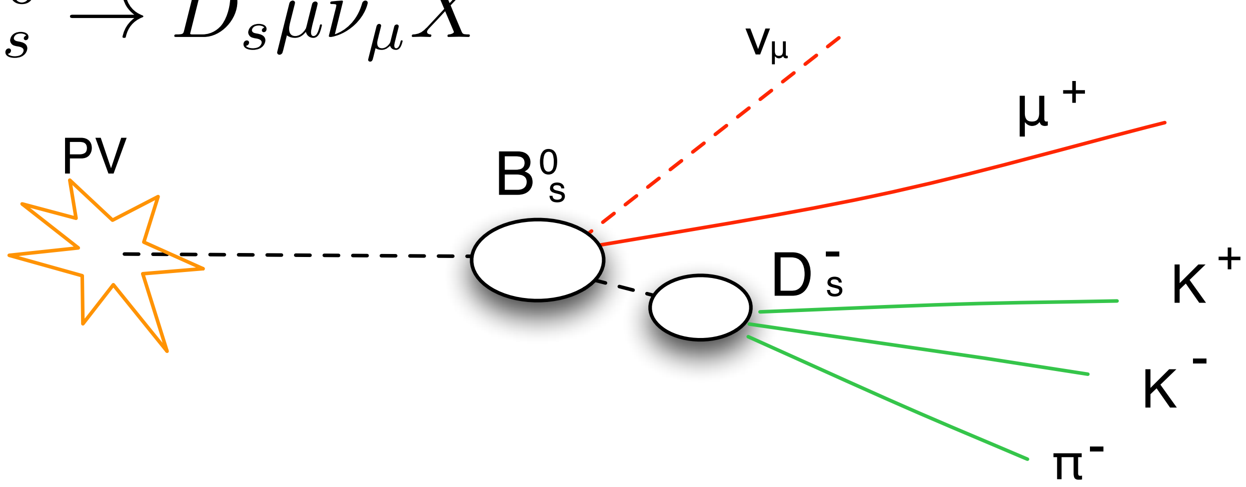
- *pp* collisions: B mesons *production asymmetry*

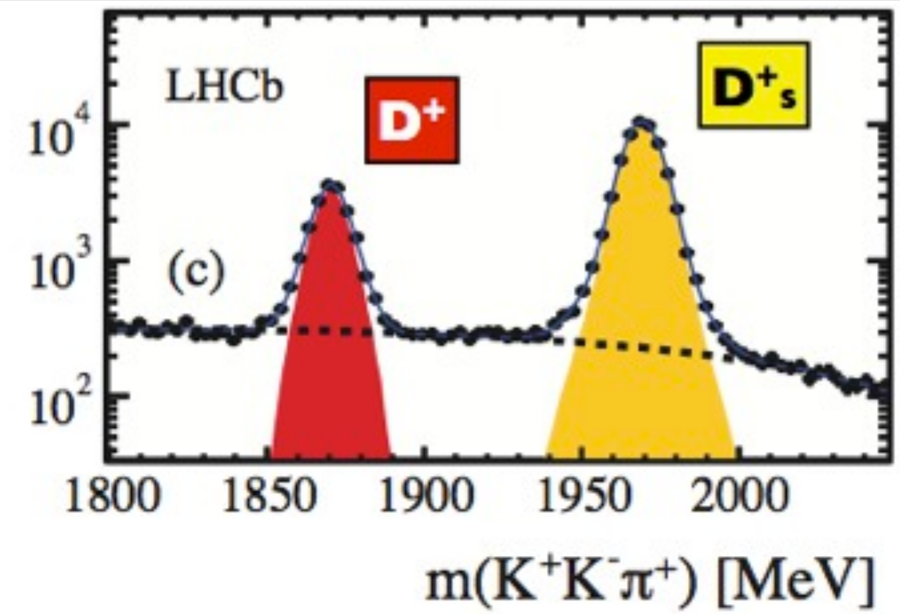
$$A_{\mathrm{P}} = \frac{\sigma(\bar{B}) - \sigma(B)}{\sigma(\bar{B}) + \sigma(B)}$$

a_{sl}^s Measurement

$\mathcal{L} = 1\ \text{fb}^{-1}$

$B_s^0 \to D_s \mu \nu_\mu X$





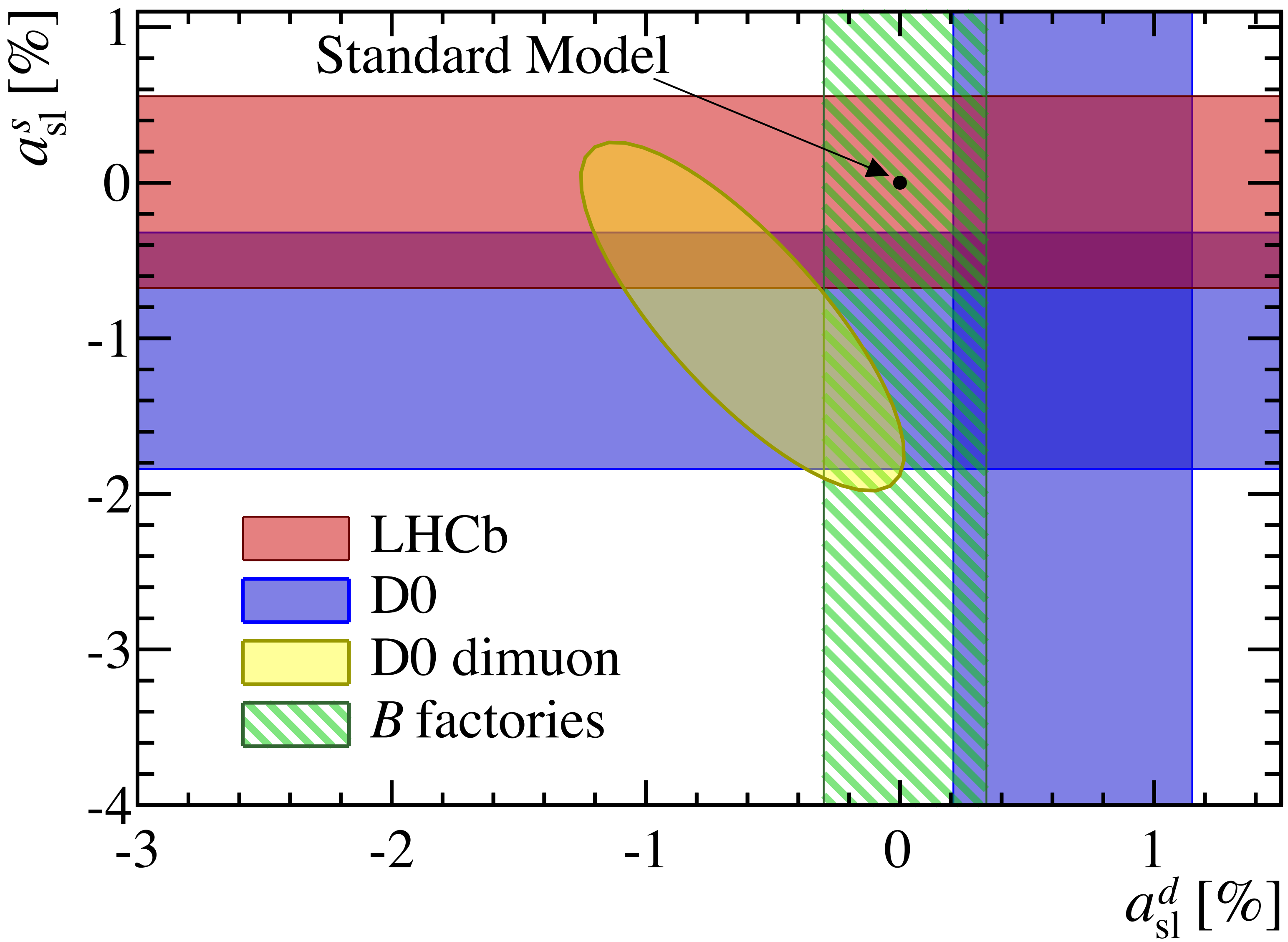
- Untagged, time integrated semileptonic asymmetry:

$$A_{\text{meas}} = \frac{\Gamma(D_s^- \mu^+) - \Gamma(D_s^+ \mu^-)}{\Gamma(D_s^- \mu^+) + \Gamma(D_s^+ \mu^-)} = \frac{a_{sl}^s}{2} + A_D - \underbrace{\left(A_P + \frac{a_{sl}^s}{2}\right) \frac{\int e^{\Gamma_s t} \cos(\Delta m_s t) \epsilon(t) dt}{\int e^{\Gamma_s t} \cosh(\Delta \Gamma_s t/2) \epsilon(t) dt}}_{\sim 10^{-4}}$$

- Fast B_s^0 oscillation dilutes second term below precision of this measurement
- Signal yields for each charge extracted from KKπ invariant mass distributions
- Correct raw asymmetry for detection and background asymmetries
- See Basem Khanji's talk tomorrow

Result

$\mathcal{L} = 1\ \text{fb}^{-1}$



$$a_{\rm sl}^s = (-0.06 \pm 0.50(\text{stat}) \pm 0.36(\text{syst}))\%$$

SM!

[Phys. Lett. B 728 (2014) 607-615]

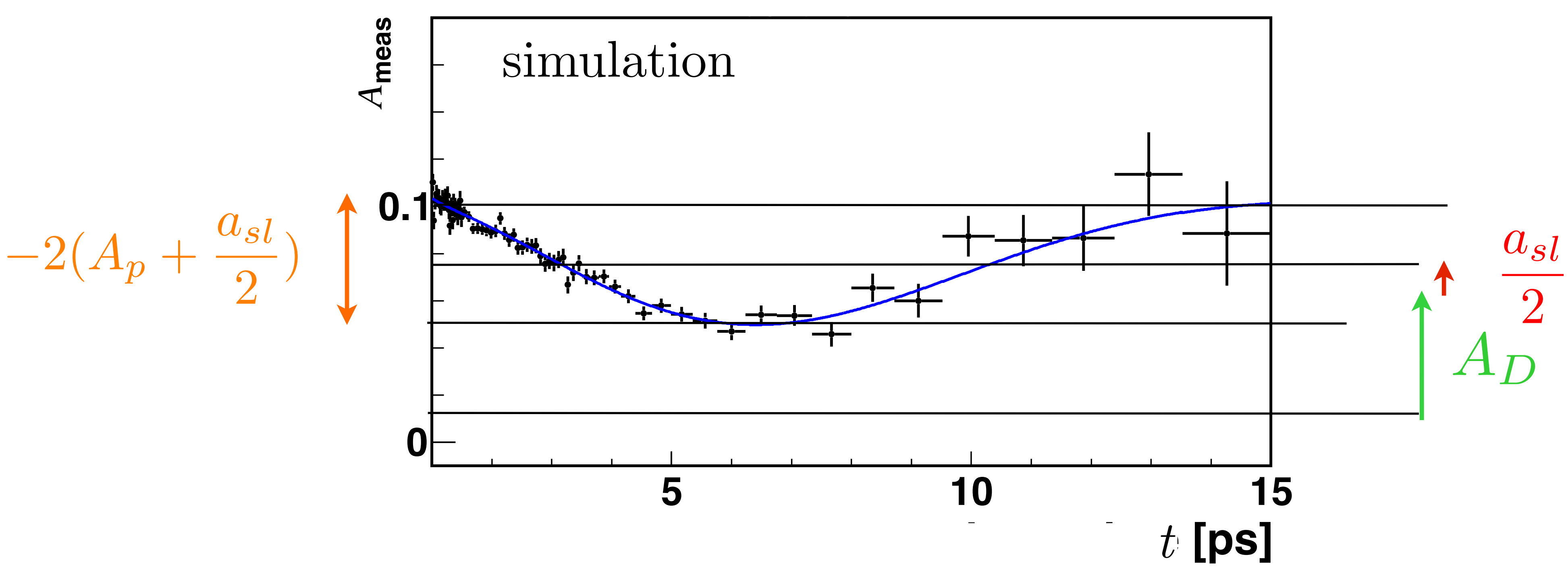
$3\ \text{fb}^{-1}$ MEASUREMENT COMING SOON...

$a_{\rm sl}^d$ Measurement: analysis strategy

- Untagged, time dependent, charge asymmetry of the final state particles:

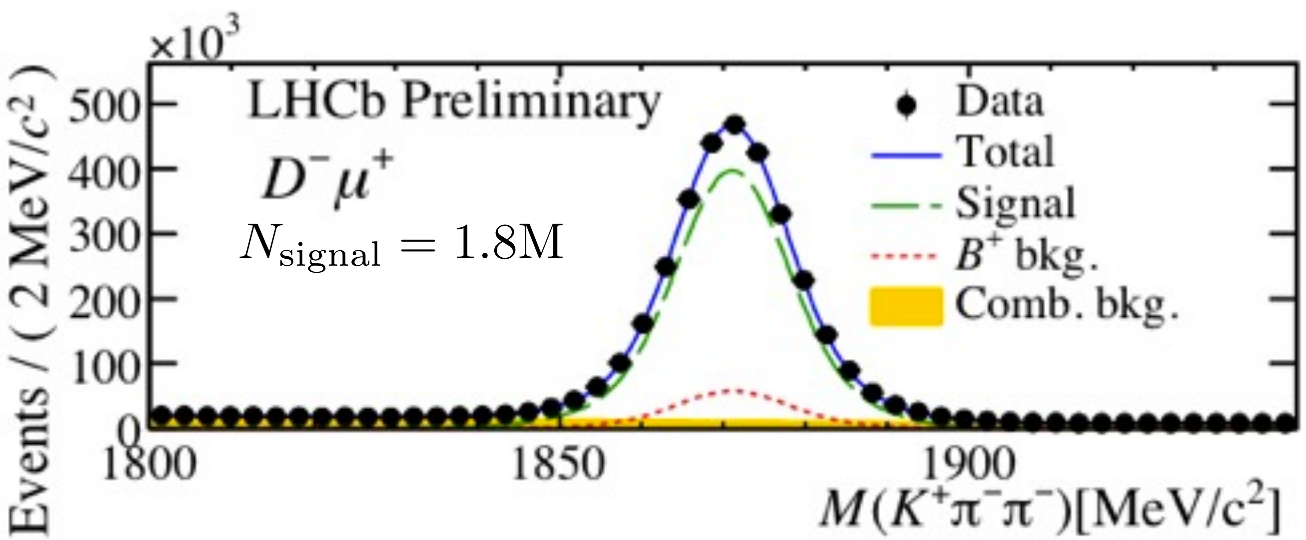
$$A_{\rm meas}(t) = \frac{\Gamma(f,t) - \Gamma(\bar{f},t)}{\Gamma(f,t) + \Gamma(\bar{f},t)} = \frac{a_{\rm sl}^d}{2} + A_{\rm D} - \left(A_{\rm P} + \frac{a_{\rm sl}^d}{2}\right)\frac{\cos(\Delta m_d t)}{\cosh(\Delta\Gamma_d t/2)}$$

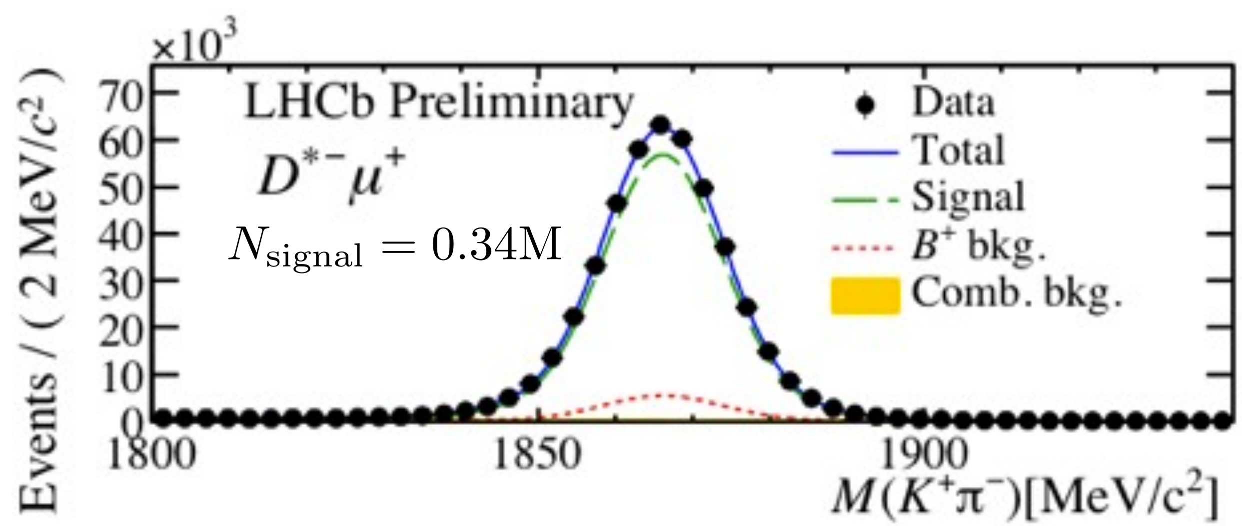
- Time-dependent fit to disentangle the *CP* violating asymmetry from the B^0 production asymmetry
- Independent determination of the detection asymmetries with control samples



Detection asymmetries

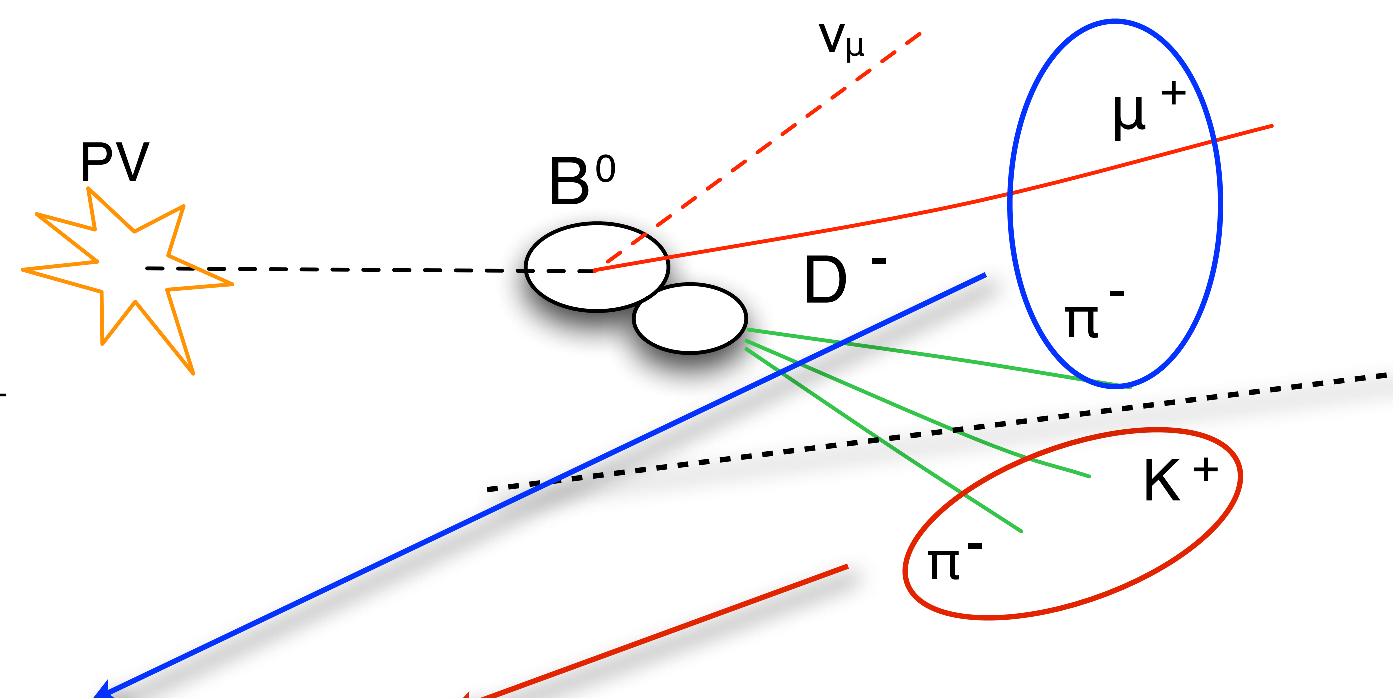
- Data samples: $B^0 \to D^{\pm}\mu^{\mp}\nu_{\mu}$ and $B^0 \to D^{*\pm}\mu^{\mp}\nu_{\mu}$ decays collected in 2011 and 2012





- Detection asymmetry of the final state:

$$A_{\rm D} = \frac{\epsilon(\mu^+K^+\pi^-\pi^-) - \epsilon(\mu^-K^-\pi^+\pi^+)}{\epsilon(\mu^+K^+\pi^-\pi^-) + \epsilon(\mu^-K^-\pi^+\pi^+)}$$



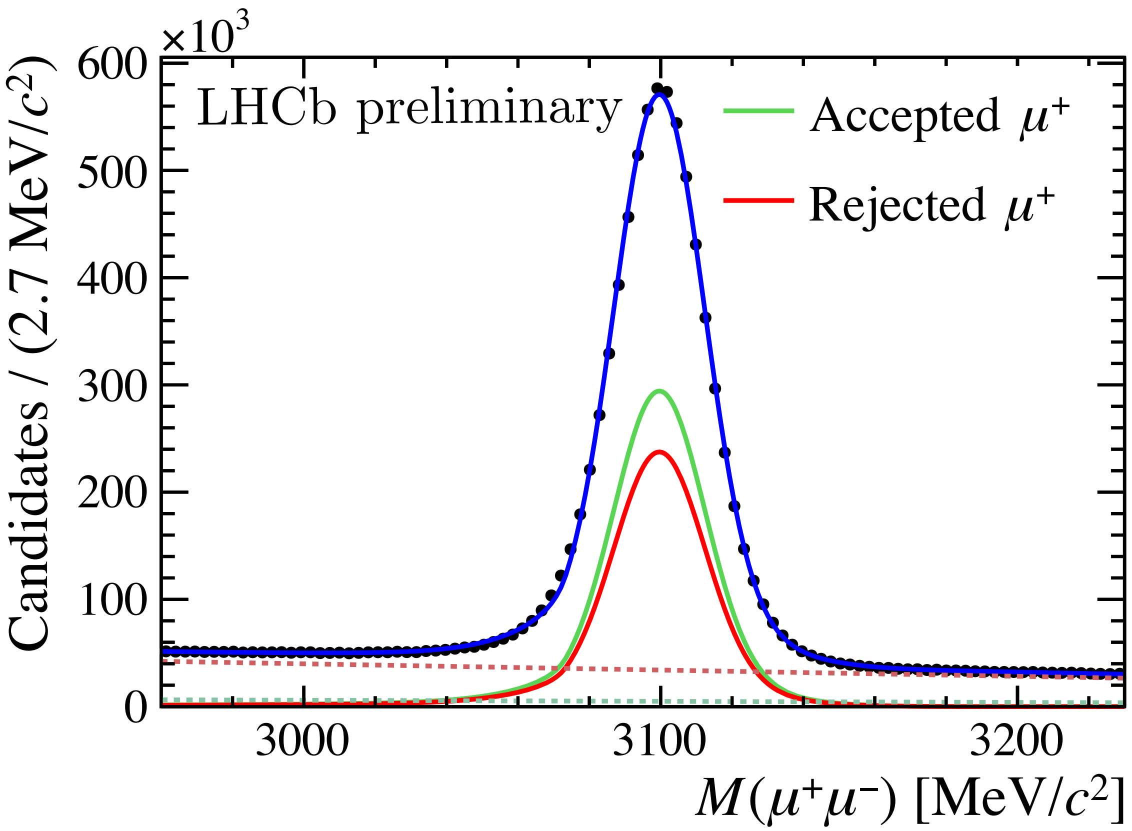
$$A_D = A_{\mu\pi} + A_{K\pi}$$

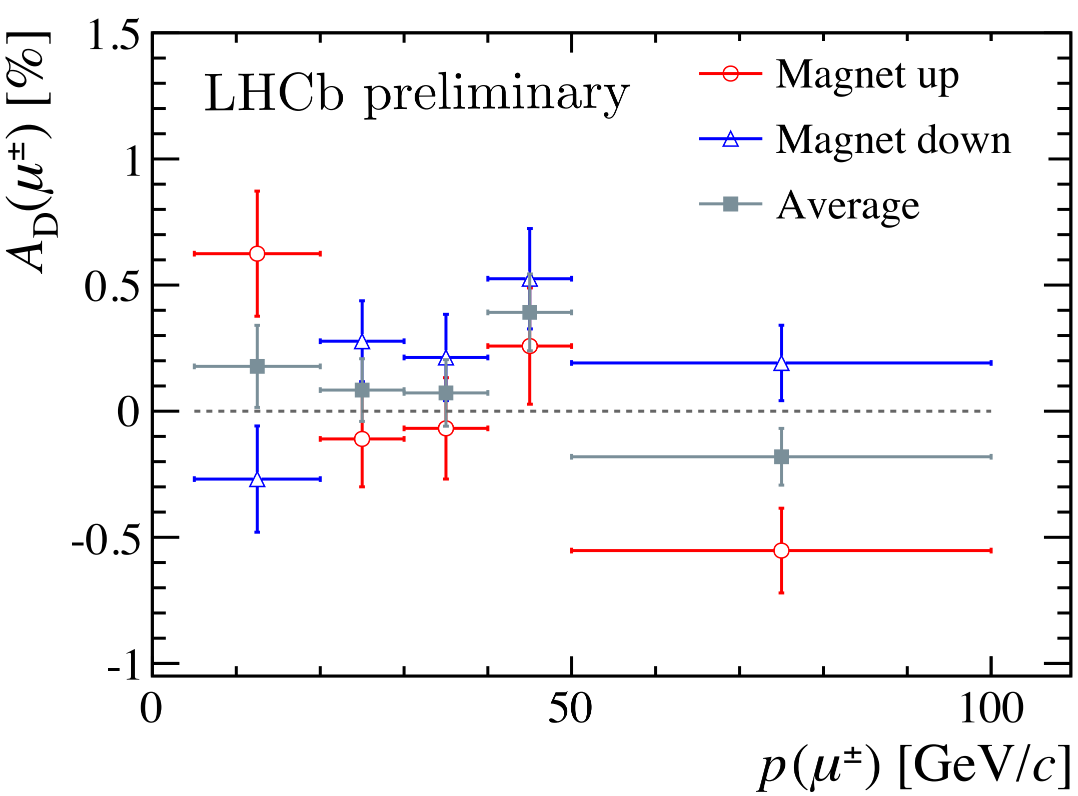
μπ detection asymmetry

- Transverse momentum dependence of the **tracking efficiencies**

re-weight the data sample to obtain a good overlapping kinematic phase space between **μ** and π . Residual asymmetry (0.00 +/- 0.02)%

- **Muon-ID and trigger asymmetries**: A tag-and-probe method is applied to $J/\psi \to \mu\mu$ decays





Few per-mille corrections, depending on run period, magnet polarity. **Overall uncertainty 0.04%**

Kπ detection asymmetry

- Using prompt D+ decays into Kππ and K_S π

$$A_{K\pi} \equiv \frac{\epsilon(K^+\pi^-) - \epsilon(K^-\pi^+)}{\epsilon(K^+\pi^-) + \epsilon(K^-\pi^+)}$$
$$= A(D \to K\pi\pi)$$
$$- A(D \to K_S\pi)$$
$$- A(K_S)$$

- Re-weighting needed to map: the Kπ pair of the control sample to match the signal, the D kinematics to cancel the D production asymmetry, the pion in the two control samples.

- Neutral kaon asymmetry : $A(K_S) = (0.054 \pm 0.011)\%$ JHEP 07 (2014) 041

$$A_{K\pi} = (1.15 \pm 0.08(\text{stat}) \pm 0.07(\text{syst}))\%$$

Reweighted (for the D+ mode)

- Main contribution: nuclear kaon interaction, the method accounts for all possible sources of detection asymmetry

Time dependent fit: B decay time and Resolutions

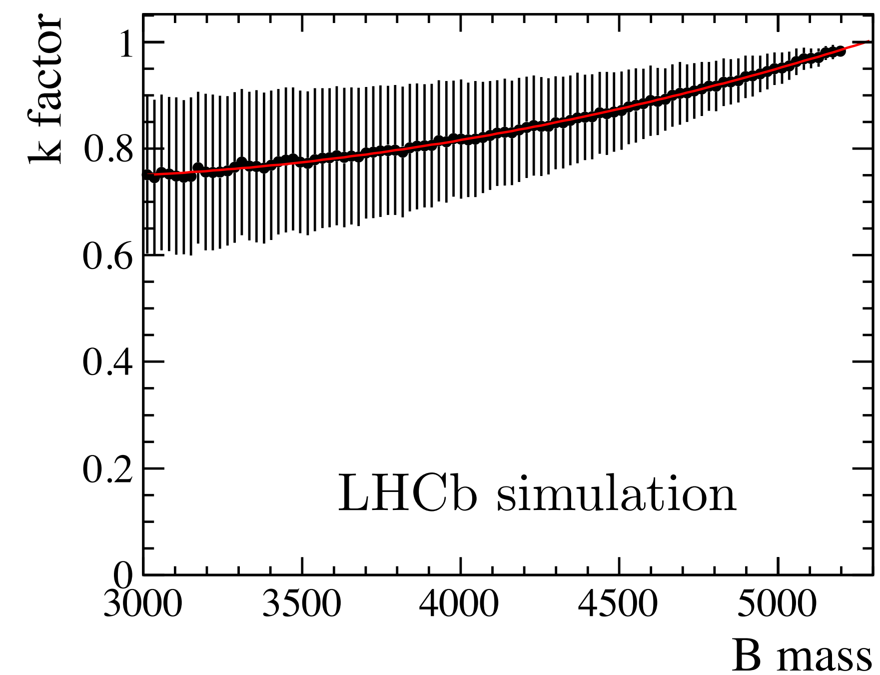
- The momentum of the B meson cannot be measured precisely due to the partial reconstruction of the decay.

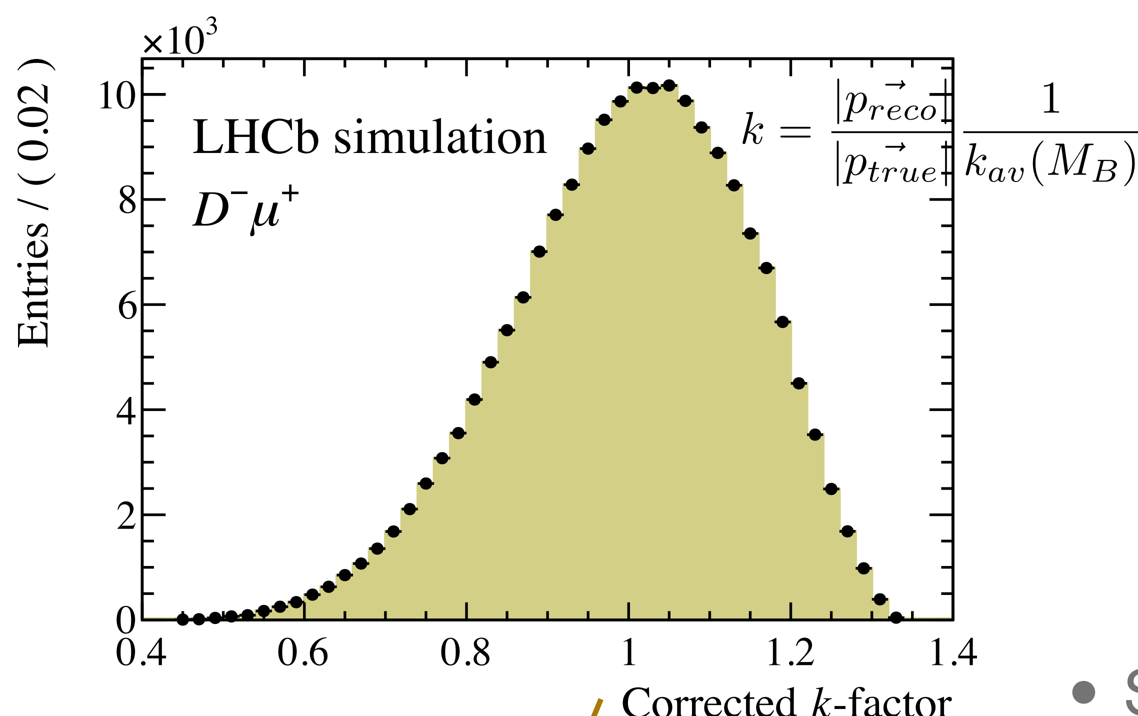
$$t = \frac{L \cdot M_{PDG}}{|\vec{p}|} \cdot k_{av}(M)$$

- The B decay time is corrected using the factor:

$$k = p_{reco}/p_{true}$$

- The k-factors are also used to model the decay time resolution:





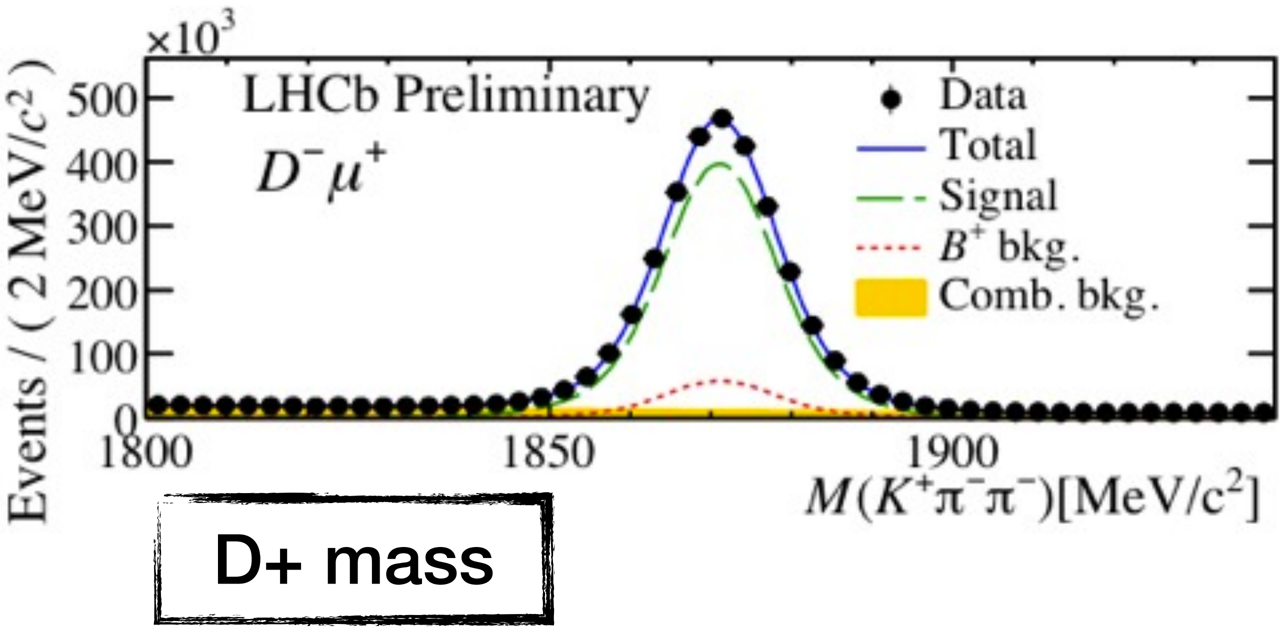
"L resolution"

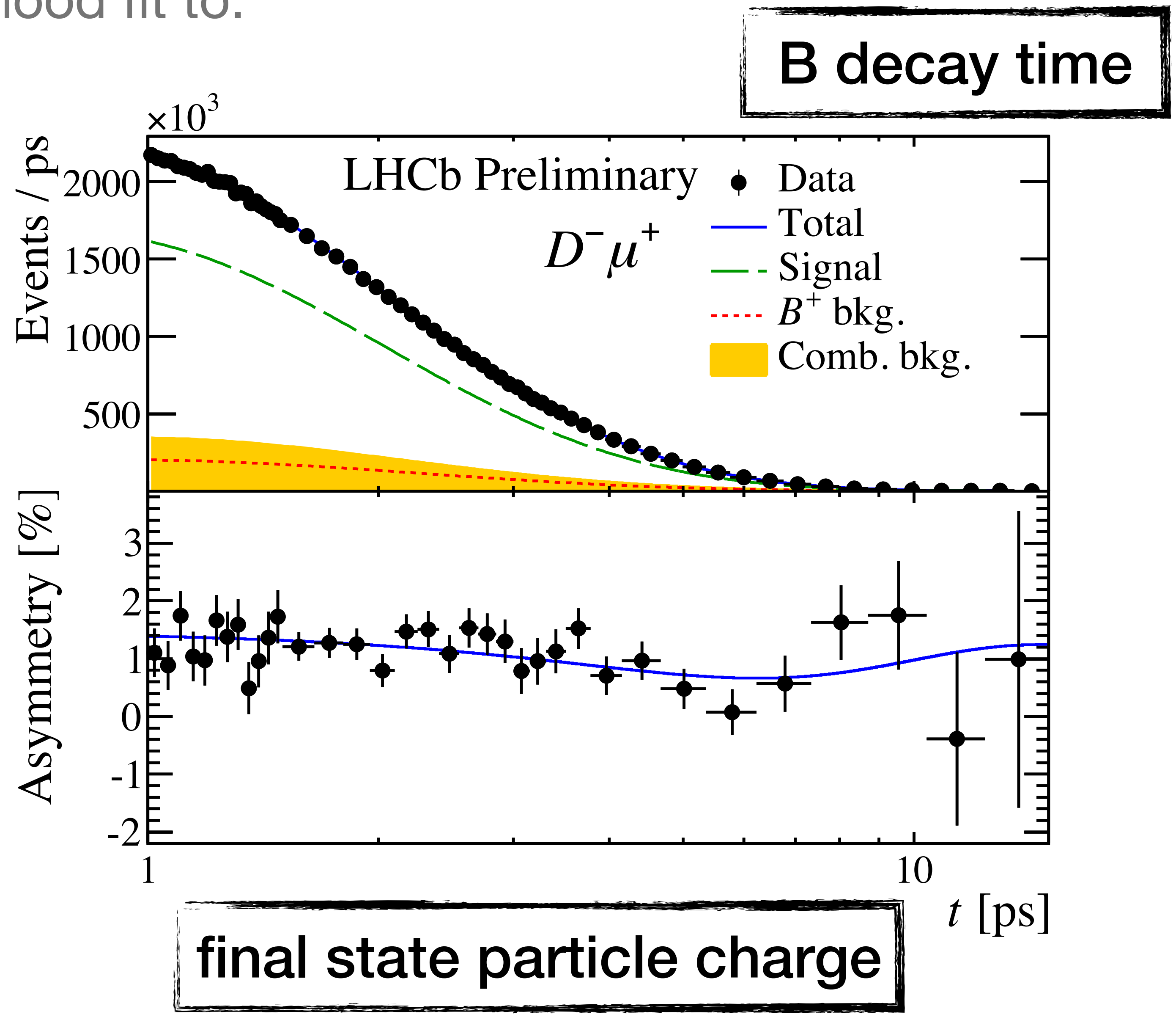
$$\mathcal{P}_{sig} = (T(t) \otimes_t R(t) \otimes_k F(k)) \cdot A(t)$$

- Similar method used for $\Delta m_{d,s}$ measurement using semileptonic B decay [Eur. Phys. J. C (2013) 73:2655]

Time dependent fit: the full picture

- Time-dependent binned maximum likelihood fit to:





example of projections (for D+ mode)

- The analysis is performed independently on magnet polarity and year datasets

- Main background: $B^+ \to D^{(*)-}\mu^+X^+$ external input for the detection asymmetries and the B+ production asymmetry

Backgrounds

- Main background: $B^+ \to D^{(*)-}\mu^+ X^+$

fractions and shapes are taken from simulation and measured Branching Fractions.

$$f_{B+}(D^{*-}\mu^+X^+) = (8.8 \pm 2.2)\% \qquad f_{B+}(D^-\mu^+X^+) = (12.7 \pm 2.2)\%$$

B+ production asymmetry from LHCb measurement using B+→J/ψK+ decays arXiv:1408.0978
corrected by the CP asymmetry (PDG 2014)

$$A_{\mathrm{P}}(B^+) = (-0.6 \pm 0.6)\%$$

- Other backgrounds: $\Lambda_b^0 \to D^{(*)-}\mu^+ X_n$

$$f_{\Lambda_b^0} \sim 2\%$$

from production ratio, Phys. Rev.D85 (2012) 032008
efficiency ratio
branching ratio of $\Lambda_b^0 \to \Lambda_c^+\pi^-$ and $\Lambda_b^0 \to D^0 p\pi^-$
Phys. Rev.D89 (2014) 032001

$$A_{\mathrm{P}}(\Lambda_b^0) \sim (-0.9 \pm 1.5)\%$$

raw asymmetry in $\Lambda_b^0 \to J/\psi p K^+$
subtracting kaon and proton detection asymmetries
JHEP 07(2014) 103

Systematic uncertainties

Source of uncertainty	a_{sl}^{d}	A_P(7 TeV)	A_P(8 TeV)
Detection asymmetry	0.26	0.20	0.14
B^+ background	0.13	0.06	0.06
Λ_b^0 background	0.07	0.03	0.03
B_s^0 background	0.03	0.01	0.01
Combinatorial D background	0.03	-	-
k-factor distribution	0.03	0.01	0.01
Decay time acceptance	0.03	0.07	0.07
Knowledge on Δm_d	0.02	0.01	0.01
Quadratic sum	0.30	0.22	0.17

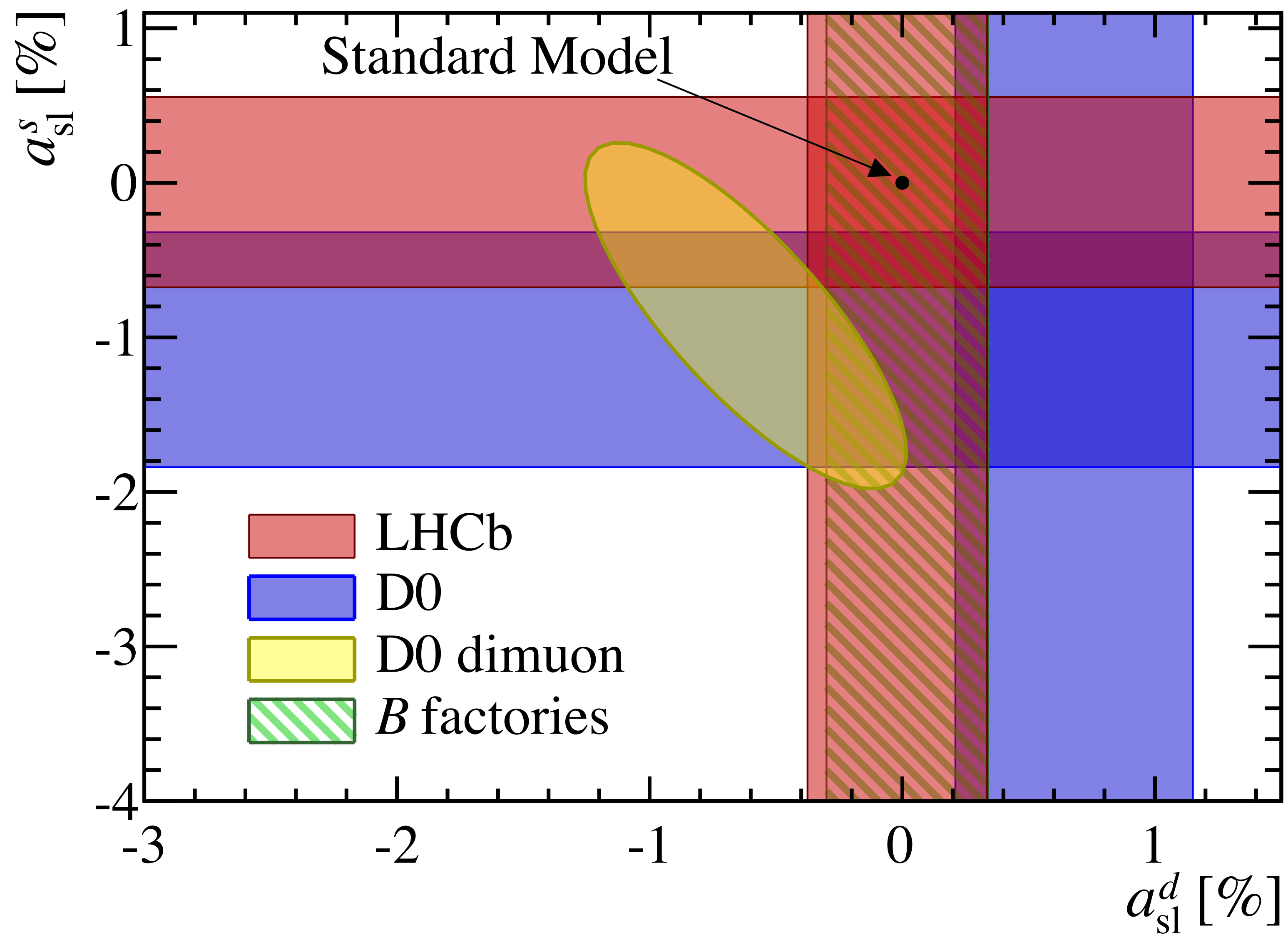
- Leading contribution: uncertainty on the measurement of the detection asymmetries

	statistical	systematic
$A_{K\pi}$	0.18%	0.13%
$A_{\mu}^{trg,PID}$	0.06%	0.06%
A_{π}^{nucl}	0.07%	
$A_{\mu\pi}^{trk\ residual}$	0.04%	

example (for D+ mode)

- B+ background second largest contribution. Different strategy foreseen for the future
- In general the systematics related to the fit model are small.

Results (I)



$$a_{sl}^{s} = (-0.06 \pm 0.50(\mathrm{stat}) \pm 0.36(\mathrm{syst}))\%$$

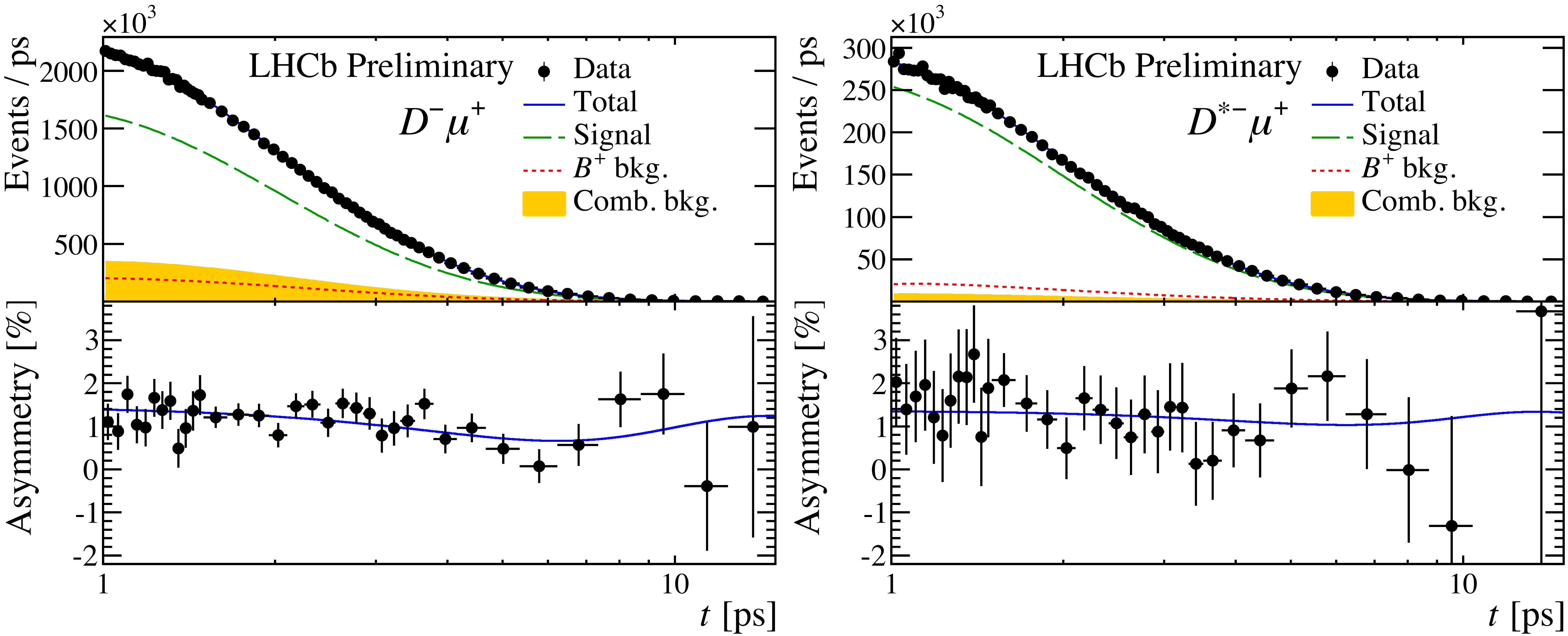
NEW preliminary

$$a_{sl}^{d} = (-0.02 \pm 0.19(\mathrm{stat}) \pm 0.30(\mathrm{syst}))\%$$

SM!!

MOST PRECISE VALUE FROM A SINGLE MEASUREMENT

Results (II)



$$A_{\mathrm{P}}(7\ \mathrm{TeV}) = (-0.66 \pm 0.26(\mathrm{stat}) \pm 0.22(\mathrm{syst}))\%$$

$$A_{\mathrm{P}}(8\ \mathrm{TeV}) = (-0.48 \pm 0.15(\mathrm{stat}) \pm 0.17(\mathrm{syst}))\%$$

USEFUL INPUT FOR OTHER CP ASYMMETRY MEASUREMENTS AT LHCb

Conclusions

- Measurements of the semileptonic CP asymmetry in the *Bs* and *Bd* sectors from LHCb have been shown today:

$$a_{\rm sl}^{s} = (-0.06 \pm 0.50({\rm stat}) \pm 0.36({\rm syst}))\% \quad 1\ {\rm fb}^{-1}\ {\rm analysis}$$

$$a_{\rm sl}^{d} = (-0.02 \pm 0.19({\rm stat}) \pm 0.30({\rm syst}))\% \quad 3\ {\rm fb}^{-1}\ {\rm analysis}$$

NEW preliminary

- Both measurements are in good agreement with the Standard Model
- The update of $a_{\rm sl}^{s}$ using the full $3\ {\rm fb}^{-1}$ of data is coming soon!
- Still room for improvement! (studies to improve the detection asymmetries determination on going, plan to include more decay modes....)

Backup slides

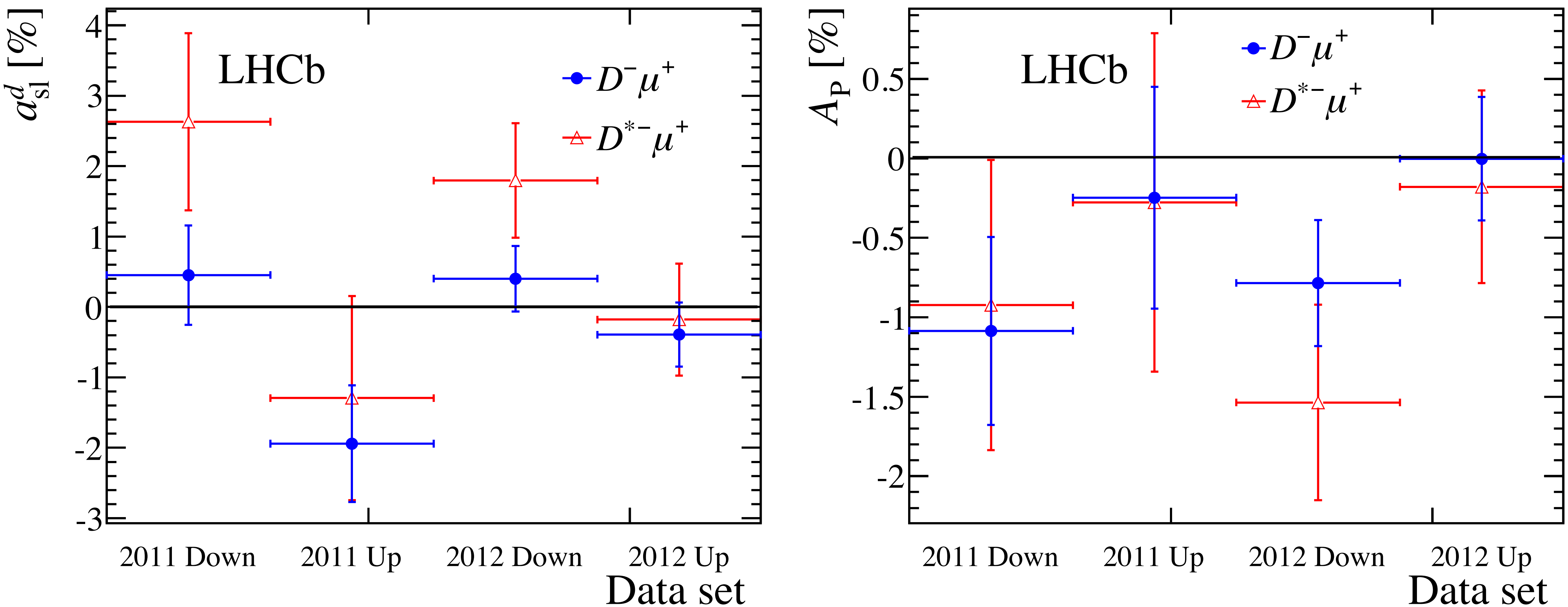
Experimental status

Exp. & Ref.	Method	Measurement
CLEO [1]	Dileptons + partial hadronic	$a_{sl}^d = (1.4 \pm 4.1 \pm 0.6)\%$
Belle [2]	Dileptons	$a_{sl}^d = (-0.11 \pm 0.79 \pm 0.85)\%$
BaBar [3]	Full hadronic rec.	$a_{sl}^d = (-5.8 \pm 2.6 \pm 2.2)\%$
BaBar [4]	Dileptons	$a_{sl}^d = (0.16 \pm 0.54 \pm 0.38)\%$
BaBar [5]	Partial semilept.	$a_{sl}^d = (0.06 \pm 0.17^{+0.38}_{-0.32})\%$
Average of B factories above [6]		$a_{sl}^d = (0.02 \pm 0.32)\%$
D0 [7]	Partial semilept.	$a_{sl}^d = (0.68 \pm 0.45 \pm 0.14)\%$
D0 [8]	Dimuon	$a_{sl}^d = (-0.62 \pm 0.42)\%$
		$a_{sl}^s = (-0.86 \pm 0.74)\%$
		$\rho = -0.79$
D0 [9]	Partial semilept.	$a_{sl}^s = (-1.12 \pm 0.74 \pm 0.17)\%$
LHCb [10]	Partial semilept.	$a_{sl}^s = (-0.06 \pm 0.50 \pm 0.36)\%$
Average of all measurements above [6]		$a_{sl}^d = (-0.09 \pm 0.21)\%$
		$a_{sl}^s = (-0.77 \pm 0.42)\%$

[1] Phys. Rev. Lett. 86 (2001) 5000
[2] Phys. Rev. D73 (2006) 112002
[3] Phys. Rev. 321 (2004) 012007
[4] Phys. Rev. Lett. 96 (2006) 251802
[5] Phys. Rev. Lett. 111 (2013) 101802
[6] http://www.slac.stanford.edu/xorg/hfag/
[7] Phys. Rev. D86 (2012) 072009
[8] Phys. Rev. D89 (2014) 012002
[9] Phys. Rev. Lett.110(2013) 011801
[10] Phys. Lett.B 728 (2014) 607

Stability checks

- The analysis is performed independently in (Up,Down)*(2011,2012)*(D+*D*)

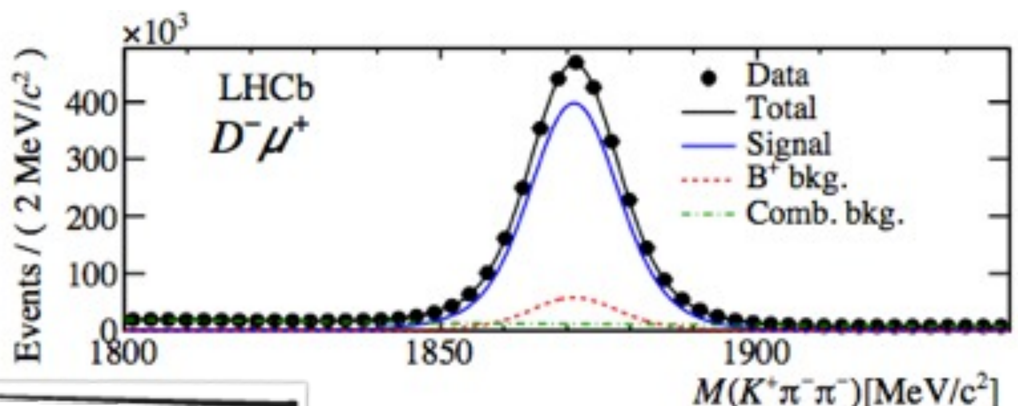


- The detection asymmetries are statistically highly correlated in the two modes.
- More crosschecks documented in the analysis note
- For the final result: arithmetic average of the magnet polarities, weighted average of the years and decay modes)

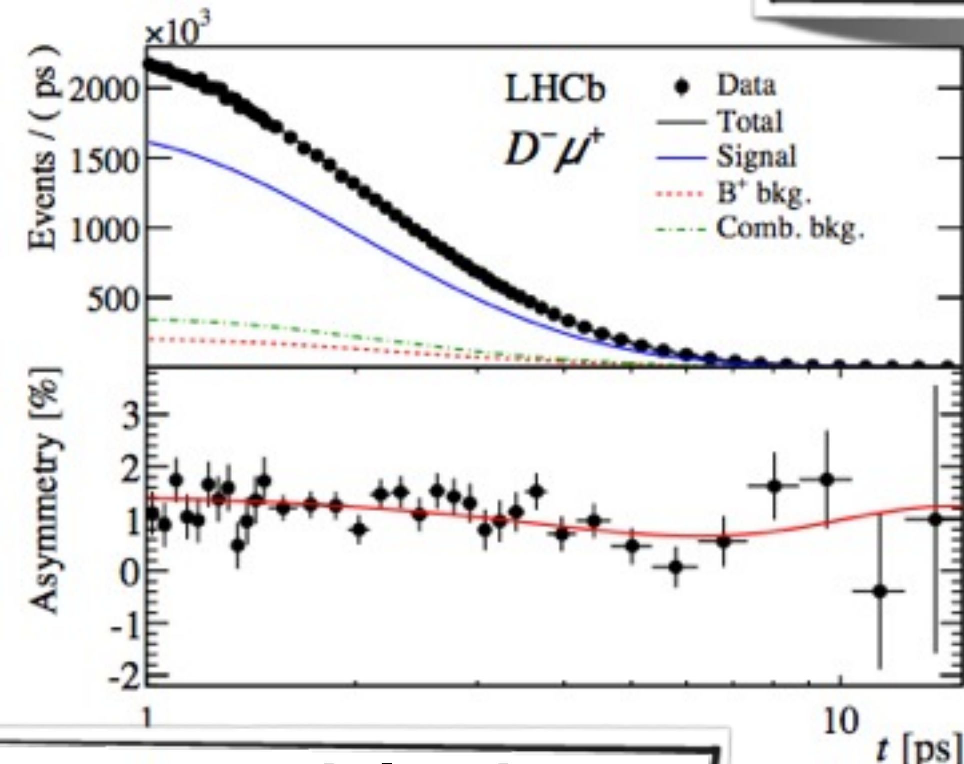
Time dependent fit

- Time-dependent binned maximum likelihood fit to:

B decay time



D+ mass



final state particle charge

signal $\mathcal{P}_{sig}(t,q) = \mathcal{N}e^{-\Gamma_d t}\left(1 \pm A_D \pm \frac{a^d_{sl}}{2} \mp \left(A_P + \frac{a^d_{sl}}{2}\right)\cos(\Delta m_d t)\right)$

B+ bkg $\mathcal{P}_{B+}(t,q) = \mathcal{N}e^{-\Gamma_u t}\left(1 \pm A_{D,B+} \mp A_{P,B+}\right)$

sidebands bkg $\mathcal{P}_{SB}(t,q) = \mathcal{N}e^{-\Gamma_{SB} t}\left(1 \pm A_{D,SB} \pm A_{P,SB}\cos(\Delta m_{SB} t)\right)$

- External input for the detection asymmetries and the B+ production asymmetry

+ Need to account for all resolution and acceptances