CP violation in mixing at LHCb

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on behalf of the LHCb collaboration

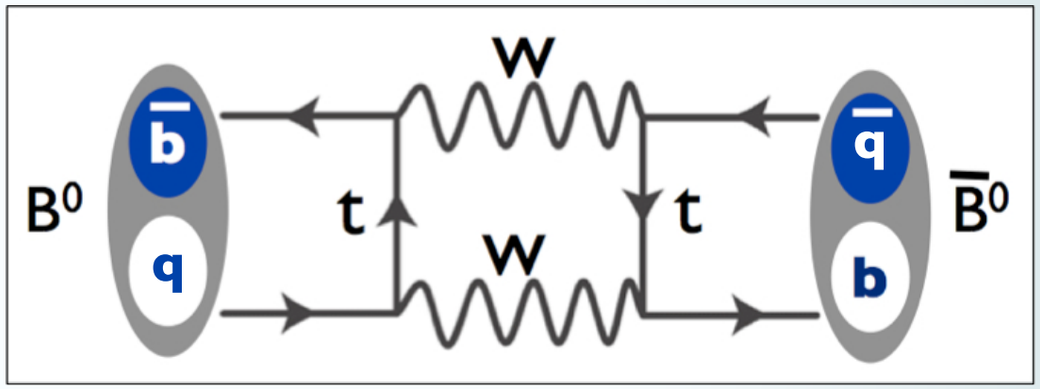
OUTLINE

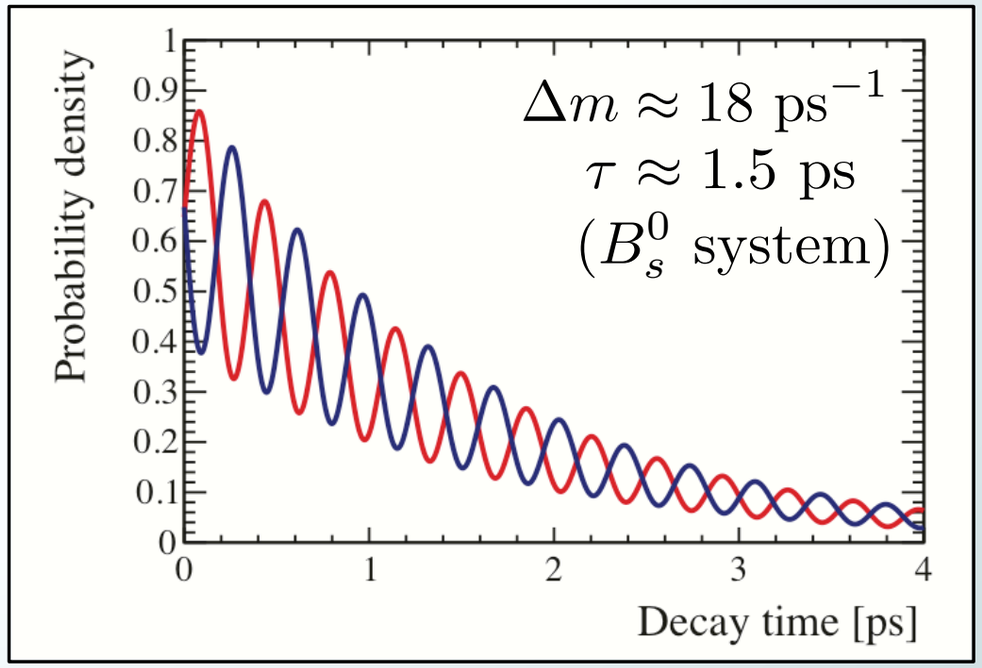
- Introduction
- a_{sl}^{d} (2015)
- a_{sl}^{s} (**new result**)

CPV IN MIXING

- Neutral mesons:
  mass eigenstates vs flavour eigenstates
  $|B_{\mathrm{H,L}}\rangle = p\,|B\rangle \pm q\,|\bar{B}\rangle$

- Mixing due to $\Delta\Gamma$, Δm





- CP violation in mixing:
  $\mathcal{P}(B \to \bar{B}) \neq \mathcal{P}(\bar{B} \to B)$
  $\longrightarrow |q/p| \neq 1$

- So far only observed in kaon system:
  ($\varepsilon_K = 0.2\%$)

PDG, Chin. Phys. C, 38, 090001 (2014)

CPV IN MIXING

- CP Violation in mixing: $\mathcal{P}(B_q \to \bar{B}_q) \neq \mathcal{P}(\bar{B}_q \to B_q)$

$$a^q_{sl} = \frac{P(\overline{B}_q \to B_q) - P(B_q \to \overline{B}_q)}{P(\overline{B}_q \to B_q) + P(B_q \to \overline{B}_q)} \qquad (q = d, s)$$

$$= \frac{1 - |q/p|^4}{1 + |q/p|^4} \approx \frac{\Delta\Gamma_q}{\Delta m_q} \tan(\phi_q^{12})$$

Lenz, Nierste [JHEP 0706:072 (2007)]

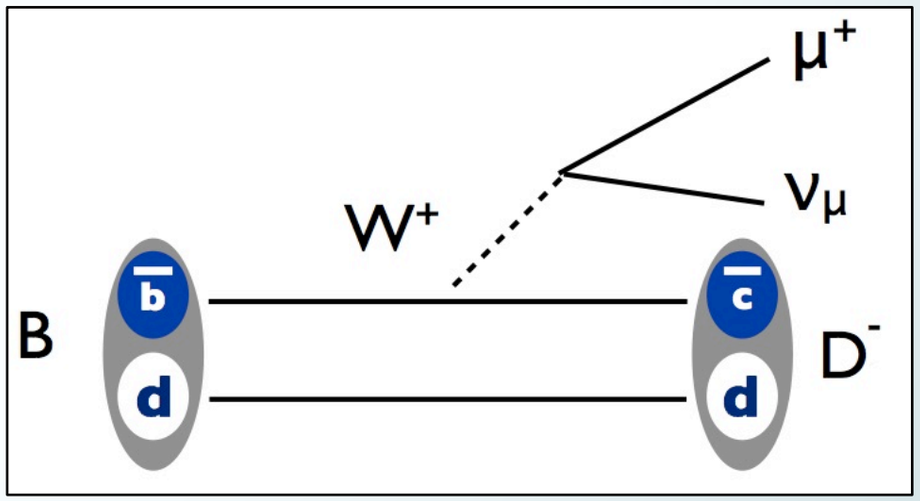
- Semileptonic inclusive final state (flavour specific)

- 2 neutral B mesons:

$$B^0_d \to D^- \mu^+ \nu_\mu X \qquad a^d_{\rm sl}$$
$$B^0_s \to D^-_s \mu^+ \nu_\mu X \qquad a^s_{\rm sl}$$

$$a^d_{sl} = (-4.7 \pm 0.6) \times 10^{-4}$$
$$a^s_{sl} = (2.22 \pm 0.27) \times 10^{-5}$$

Artuso, Borissov, Lenz [arXiv:1511.09466]



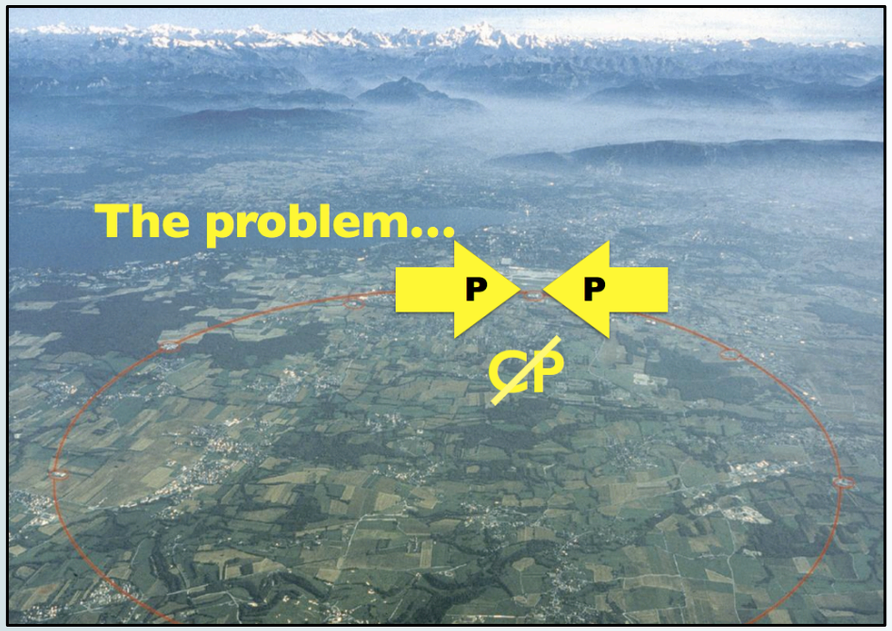
MEASURING a_{sl}

'Raw' untagged asymmetry:

$$A_{\rm raw} = \frac{N(D^-\mu^+) - N(D^+\mu^-)}{N(D^-\mu^+) + N(D^+\mu^-)} = \frac{a_{\rm sl}}{2} + ...$$

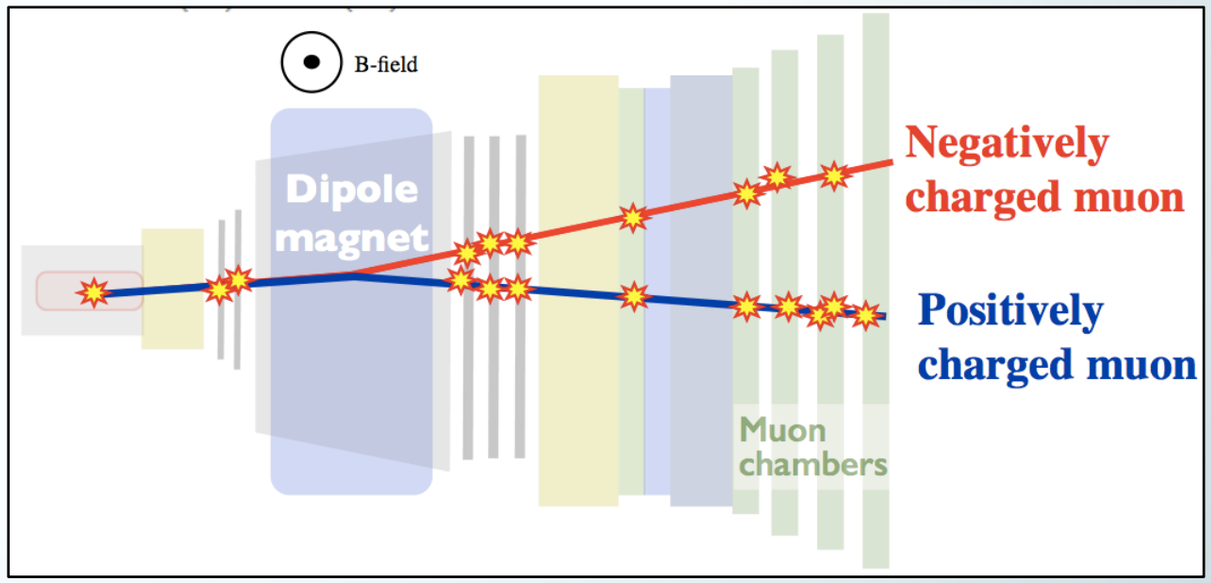
Production asymmetry:

$$A_P = \frac{N(B) - N(\bar{B})}{N(B) + N(\bar{B})}$$



Detection asymmetry:

$$A_D = \frac{\epsilon(D^-\mu^+) - \epsilon(D^+\mu^-)}{\epsilon(D^-\mu^+) + \epsilon(D^+\mu^-)}$$



TIME DEPENDENCE

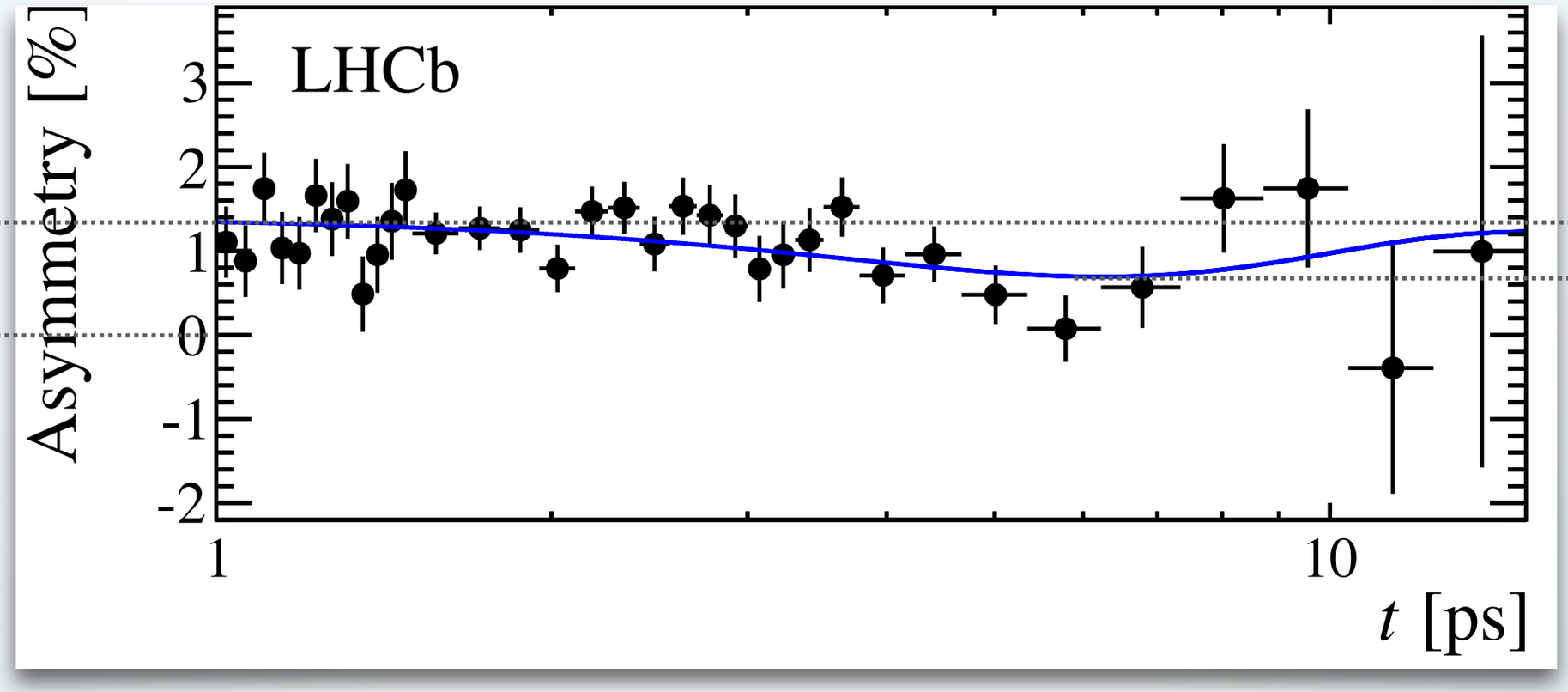
$$A_{\rm raw}(t) = \frac{N(f,t) - N(\bar{f},t)}{N(f,t) + N(\bar{f},t)} \approx \underbrace{A_D + \frac{a^d_{\rm sl}}{2}}_{\text{Offset}} + \underbrace{\left(A_P - \frac{a^d_{\rm sl}}{2}\right)}_{\text{Amplitude}} \cos(\Delta m_d t)$$

Mixing oscillation

For a_{sl}^d: measure offset and amplitude to disentangle A_P and a_{sl}^d

a_{sl}^d

$$A_{\rm raw}(t) = \frac{N(f,t) - N(\bar{f},t)}{N(f,t) + N(\bar{f},t)} \approx A_D + \frac{a^d_{\rm sl}}{2} + \left(A_P - \frac{a^d_{\rm sl}}{2} \right) \cos(\Delta m_d t)$$



$A_D + A_P$

$2A_P - a_{sl}^d$

LHCb, PRL 114 (2015) 041601

THE STORY SO FAR

SM:

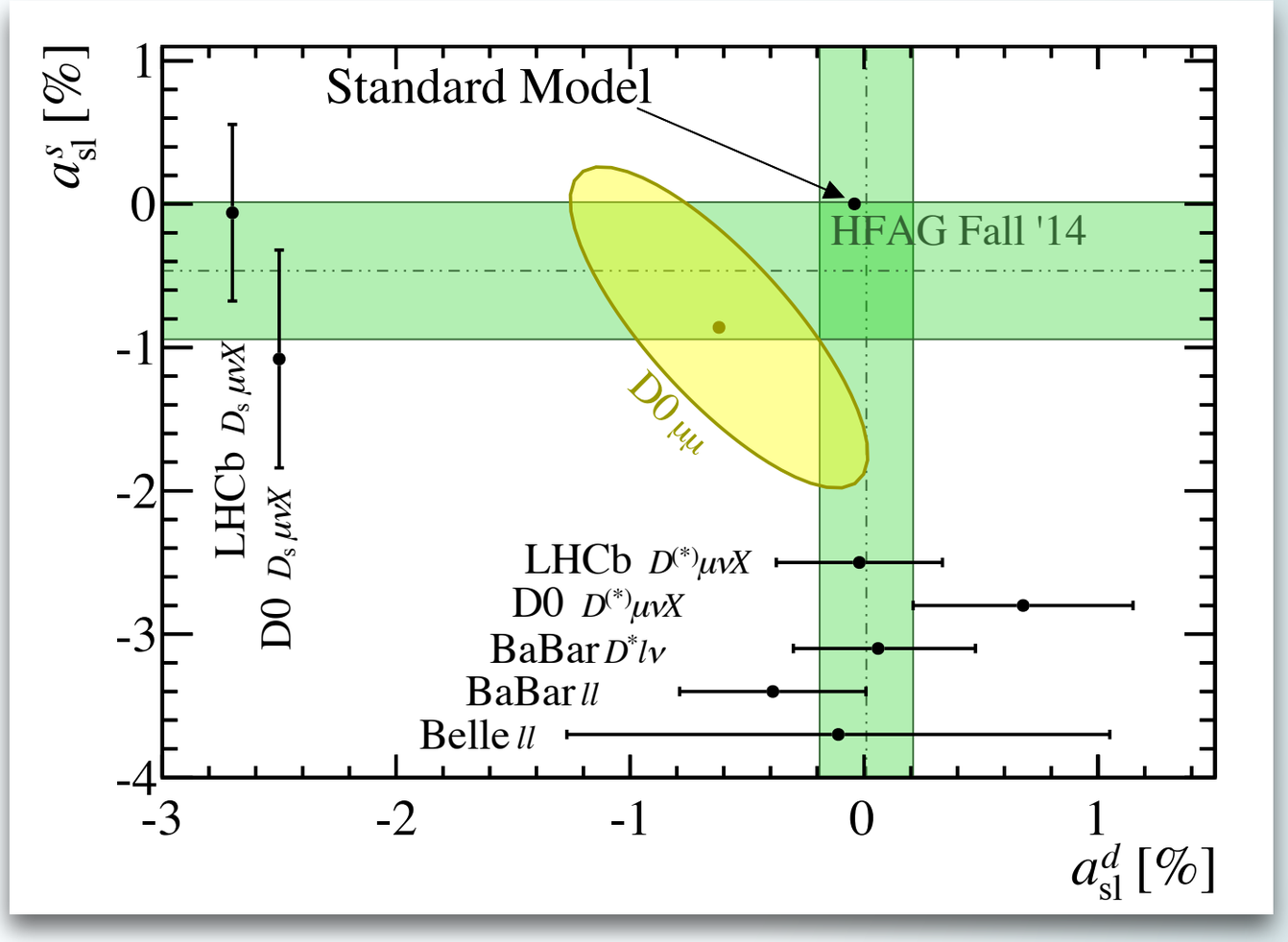
$$a^d_{sl} = (-4.7 \pm 0.6) \times 10^{-4}$$
$$a^s_{sl} = (2.22 \pm 0.27) \times 10^{-5}$$

Artuso, Borissov, Lenz [arXiv:1511.09466]

HFAG*:

$$a^d_{sl} = (0.01 \pm 0.20) \times 10^{-2}$$
$$a^s_{sl} = (-0.48 \pm 0.48) \times 10^{-2}$$

HFAG [arXiv:1412.7515]
*without D0 dimuon result
[PRD 89, 012002 (2014)]



LHCb:

$$\mathbf{a^d_{sl}} = (-\mathbf{0.02} \pm \mathbf{0.19}(\mathrm{stat}) \pm \mathbf{0.30}(\mathrm{syst}))\%$$
$$\mathbf{a^s_{sl}} = (-\mathbf{0.06} \pm \mathbf{0.50}(\mathrm{stat}) \pm \mathbf{0.36}(\mathrm{syst}))\%$$

1 fb^{-1}

LHCb, PRL 114, 041601 (2015)
LHCb, PLB 728C (2014) 607

New result!

a_{sl}^{s} - 3/fb

OVERVIEW

- Inclusive $\overline{B}{}^0_s \to D^+_s \mu^- \overline{\nu}_\mu X$

- Untagged, time-integrated analysis:

$$A_{\rm raw} \approx A_D + \frac{a^s_{\rm sl}}{2} + \left(A_P - \frac{a^s_{\rm sl}}{2} \right) \int \cos(\Delta m_s t) dt$$

$\mathcal{O}(10^{-4})$

- Adding backgrounds:

$$\frac{a^s_{\rm sl}}{2} = \frac{1}{1 - f_{\rm bkg}} (A_{\rm raw} - A_D - f_{\rm bkg} A_{\rm bkg})$$

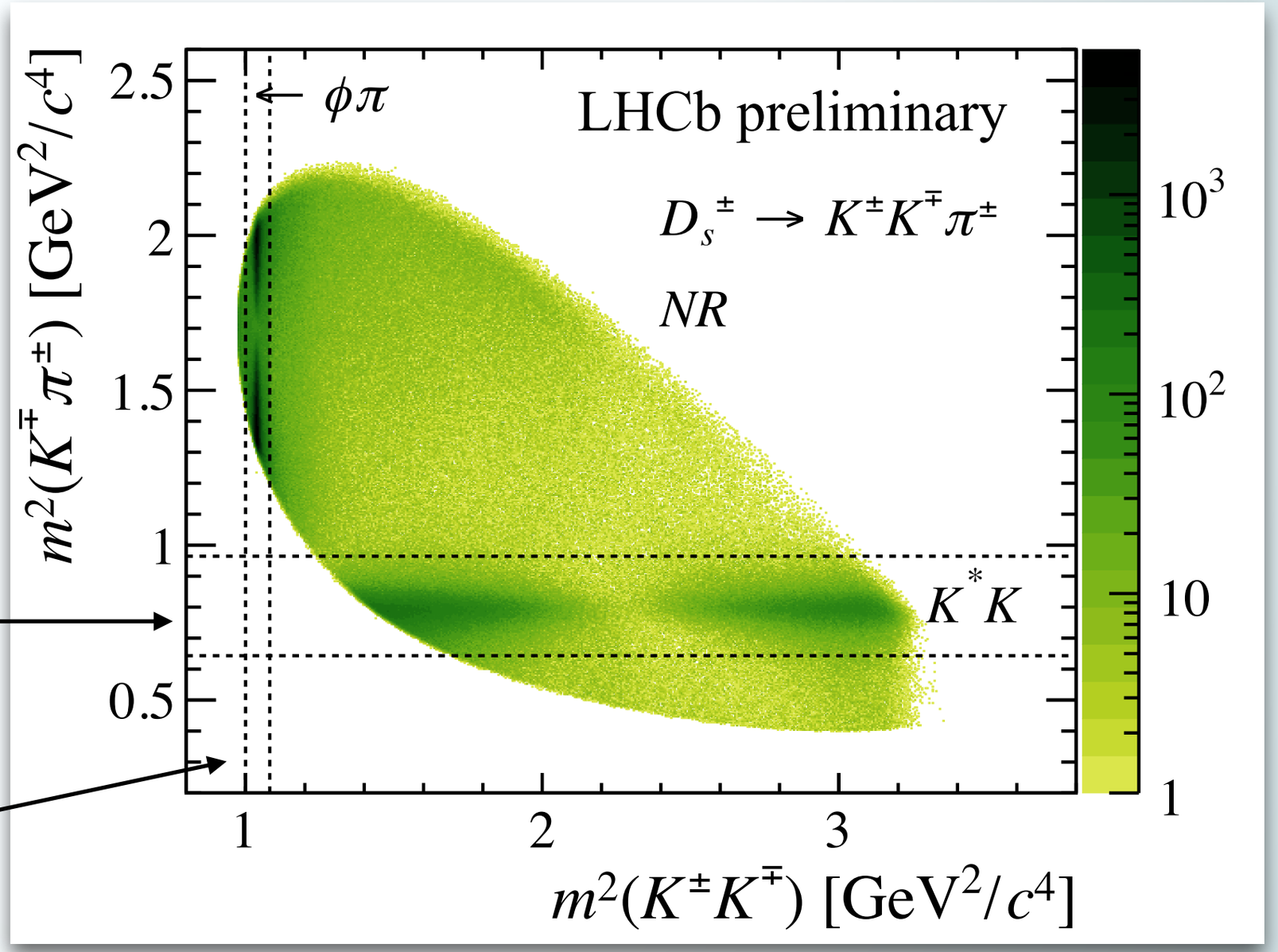
D_S SELECTION

<u>3 Dalitz regions</u>

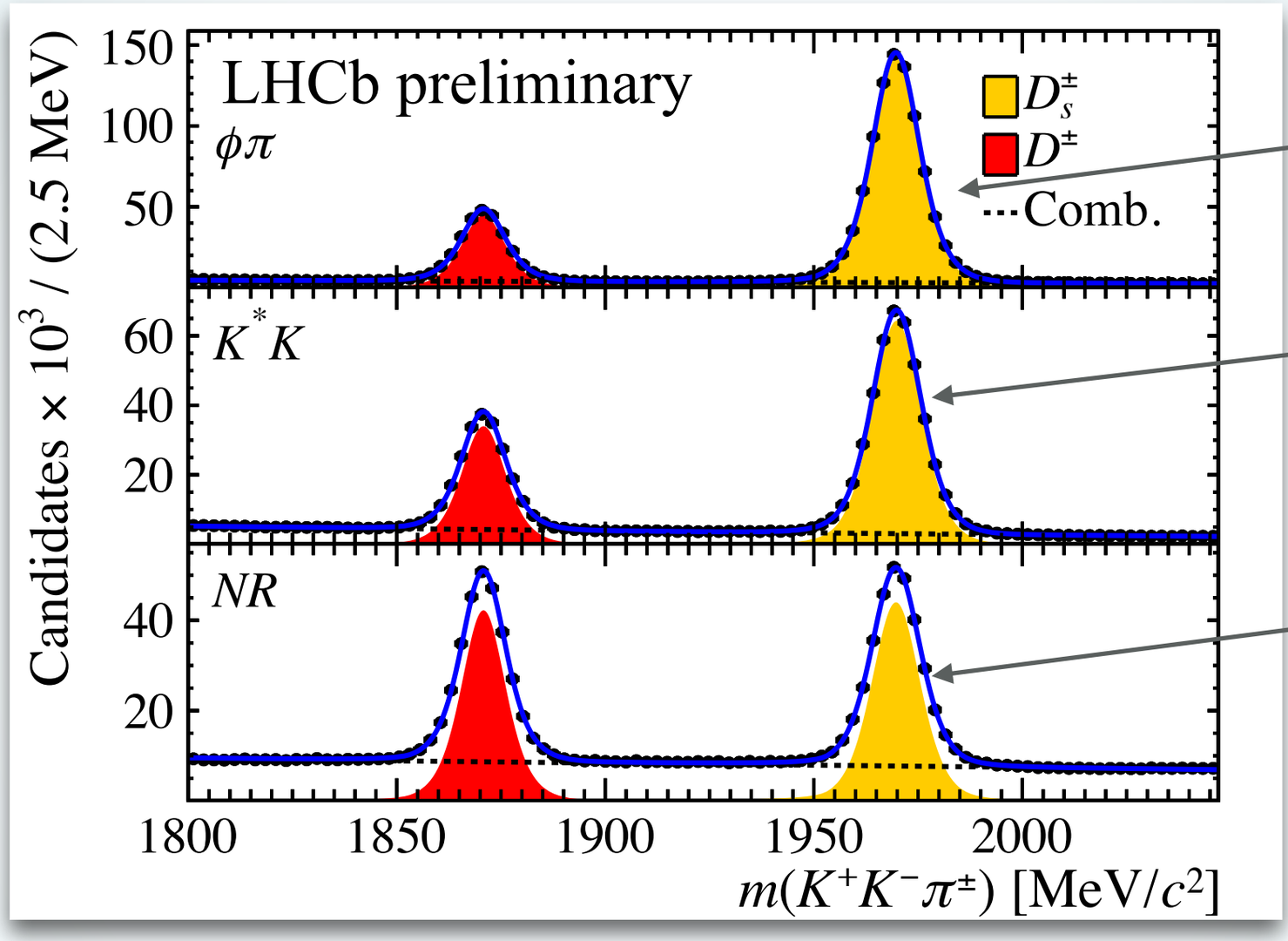
Various levels of backgrounds in $M(D_s^-)$. Regions treated separately.

m(Kπ) in [806, 986] MeV

m(KK) in [1000, 1040] MeV



D_S YIELDS



899 x 10^3

413 x 10^3

280 x 10^3

- Select ($D_s^-\mu^+$), fit D_s^- mass peaks
- Directly produced Ds is removed
- Raw yield contains peaking backgrounds

PEAKING BACKGROUNDS

Peaking backgrounds dilute and bias the measurement

$$\frac{a^s_{\rm sl}}{2} = \frac{1}{1-f_{\rm bkg}}(A_{\rm raw} - A_D - f_{\rm bkg}A_{\rm bkg})$$

$B^+ \to D^{(*)0} D_s^{(*)+} X$
$B^0 \to D^0 D_s^{(*)+} X$
$B^0 \to D^- D_s^{(*)+} X$
$B_s^0 \to D_s^{(*)-} D_s^{(*)+}$
$\Lambda_b^0 \to \Lambda_c^+ D_s^{(*)+} X$

} ‘double-D’

$B^- \to D_s^+ K^- \mu^- \nu X$
$\overline{B}^0 \to D_s^+ K_{\rm S}^0 \mu^- \nu X$

} ‘DsK’

f_{bkg}: branching ratios (PDG) and efficiency

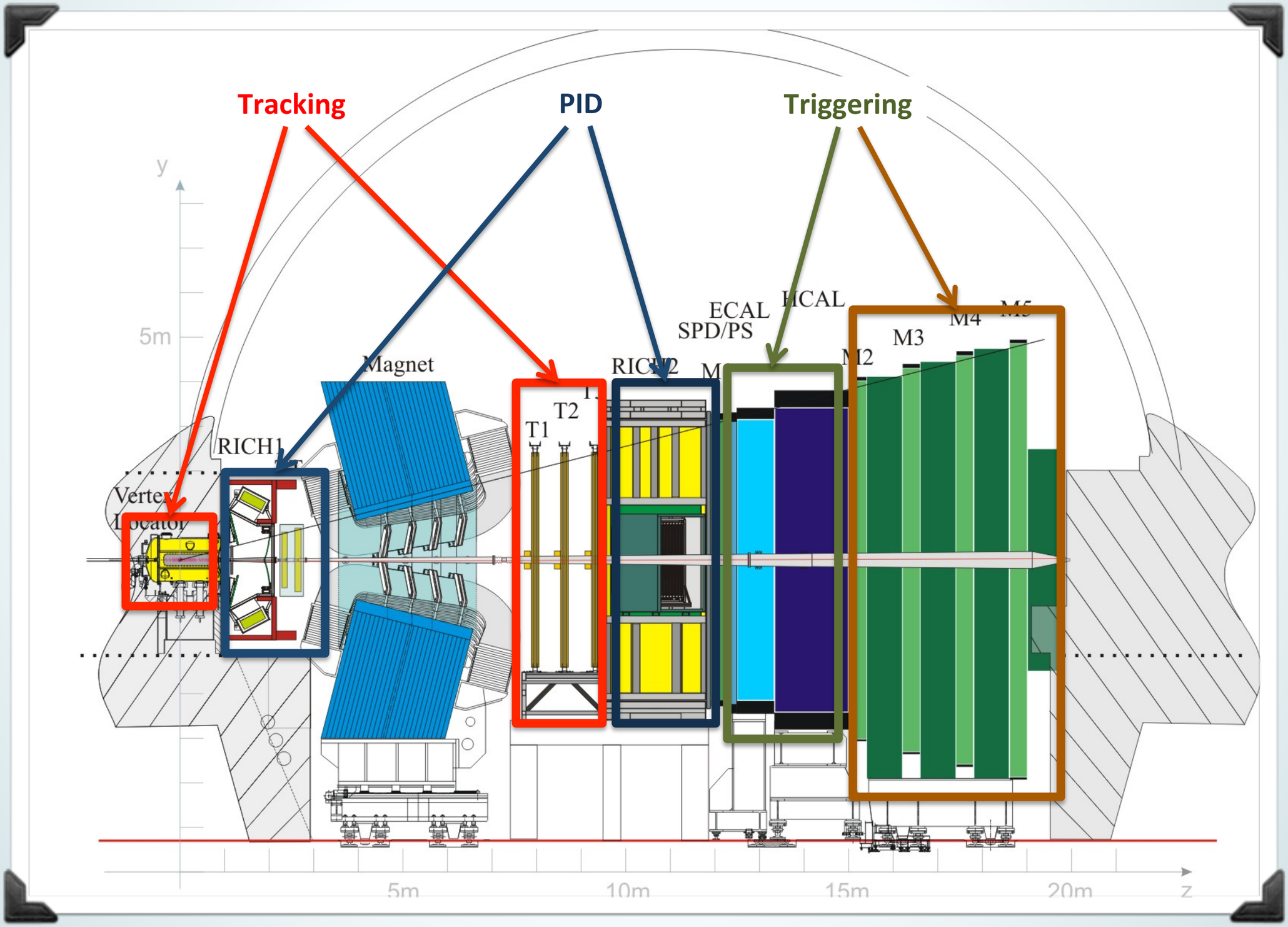
A_{bkg} mainly from production asymmetries:

LHCb, JHEP 09 177 (2014)
LHCb, PRL 114, 041601 (2015)
LHCb, Chin.Phys.C 40, 1, 011001(2016)

Taken into account: $f_{\rm bkg} = (18.4 \pm 6.0)\%$,

$$\sum_i f^i_{\rm bkg} A^i_{\rm bkg} = f_{\rm bkg} A_{\rm bkg} = (-0.045 \pm 0.033)\%$$

DETECTION ASYMMETRIES

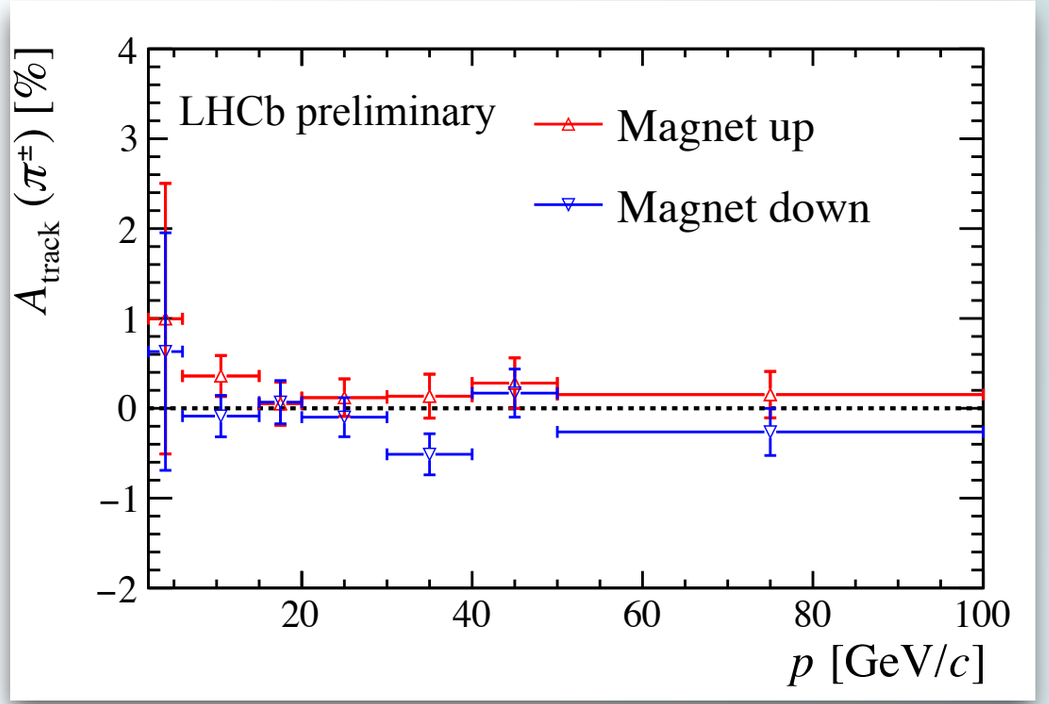


TRACKING ASYMMETRY

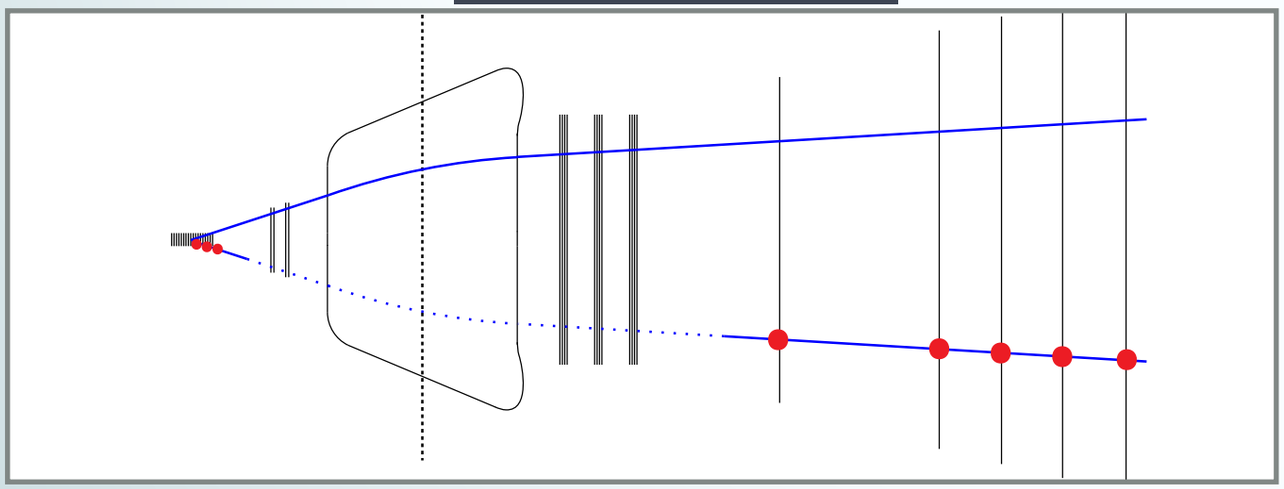
Largest systematic in previous analysis
Combine 2 methods:

- J/ψ tag-and-probe
- D^* partially reconstructed

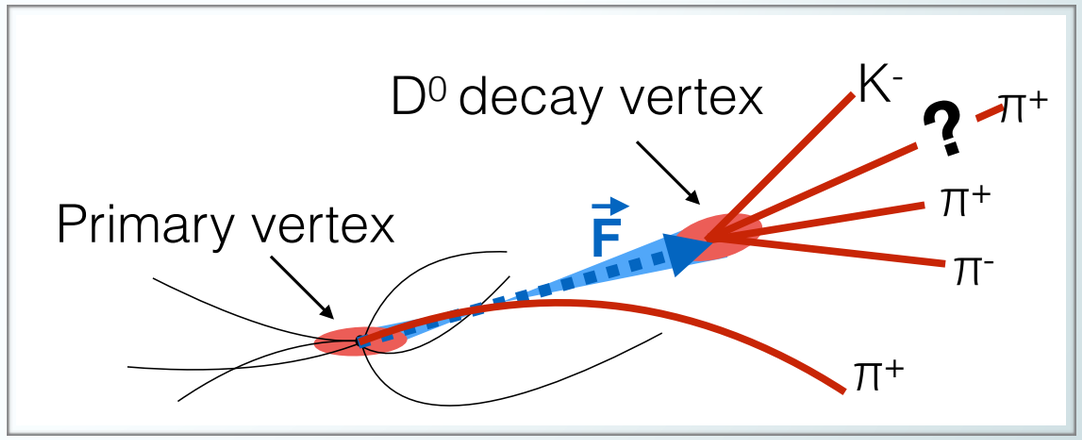
+ simulation studies



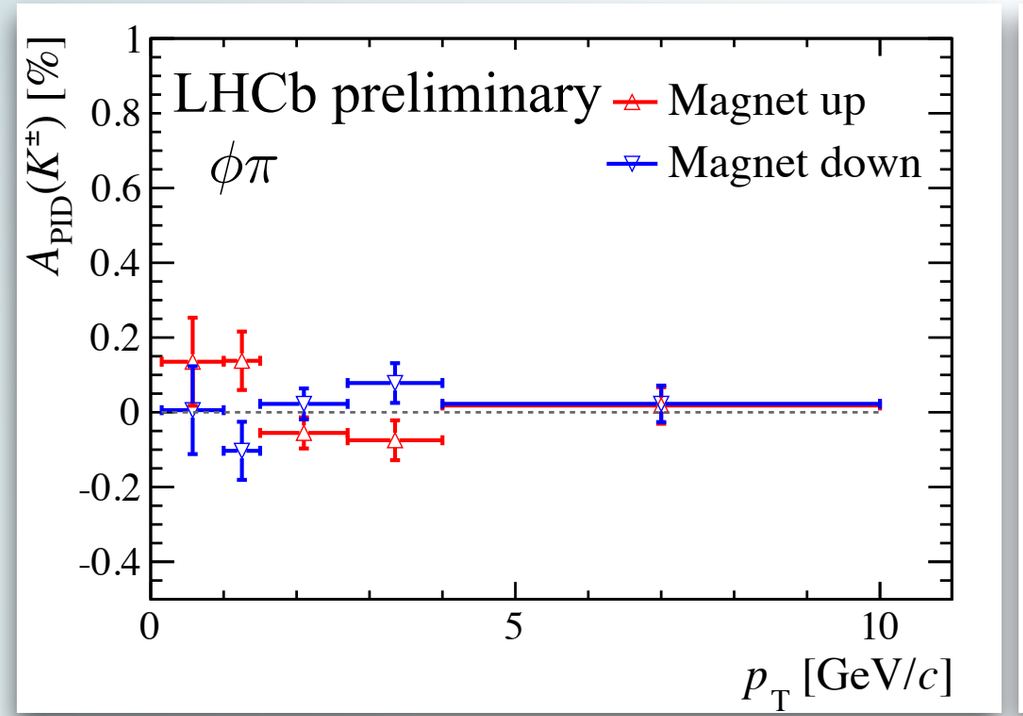
J/ψ method

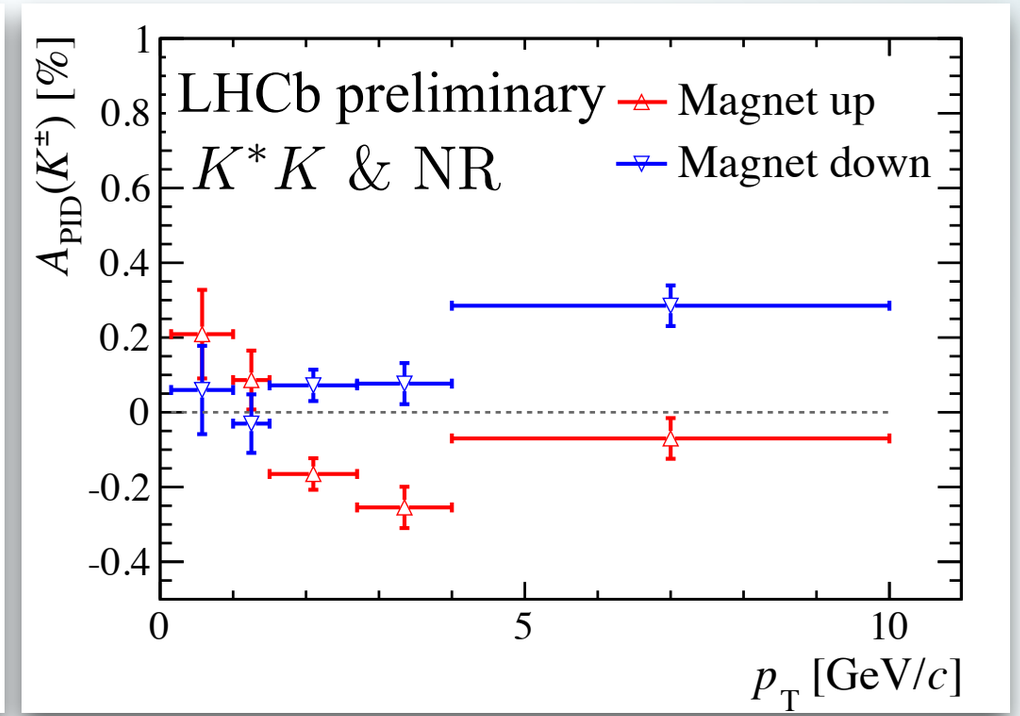


D^* method



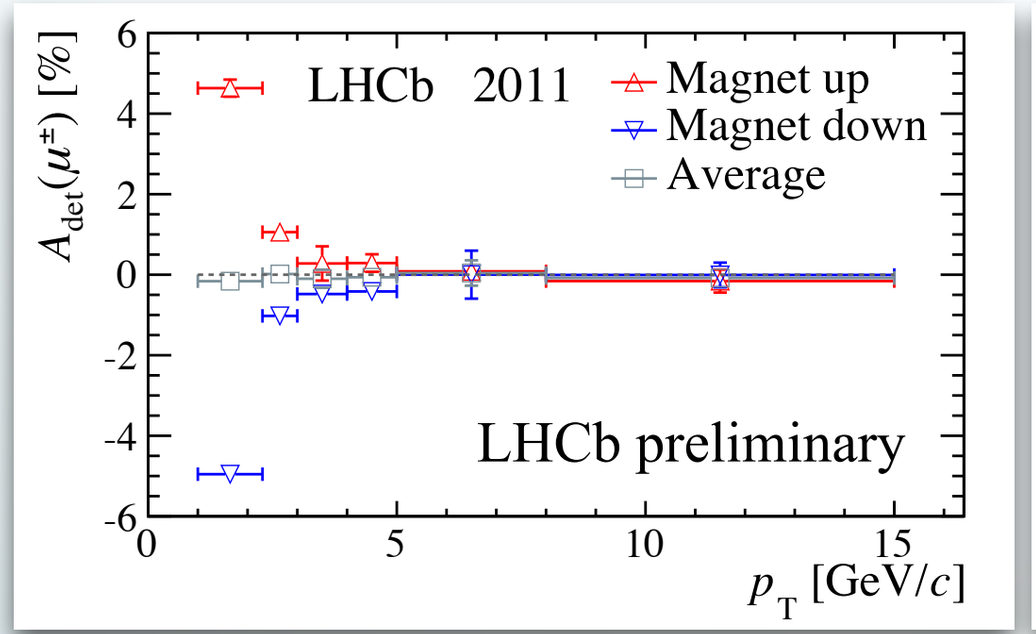
PID & TRIGGER

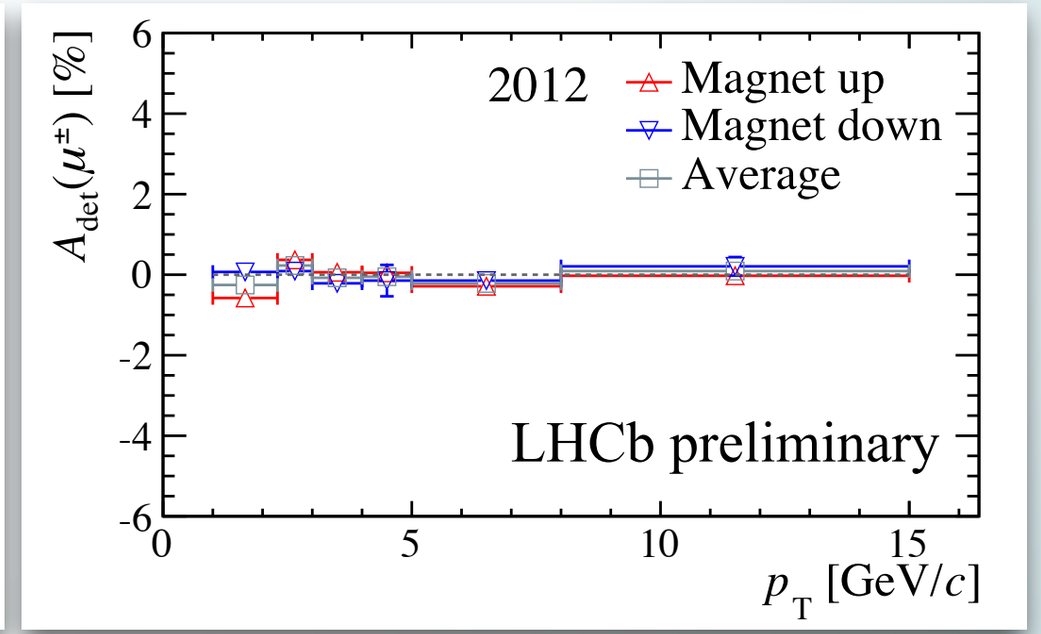




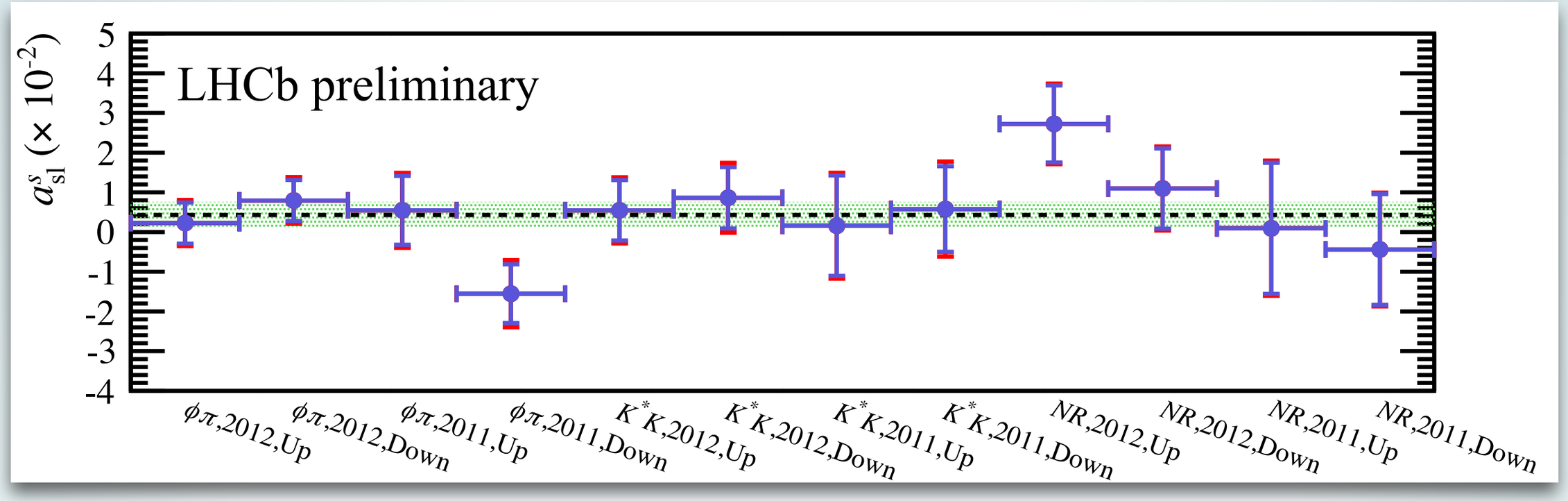
PID

Trigger





RESULTS

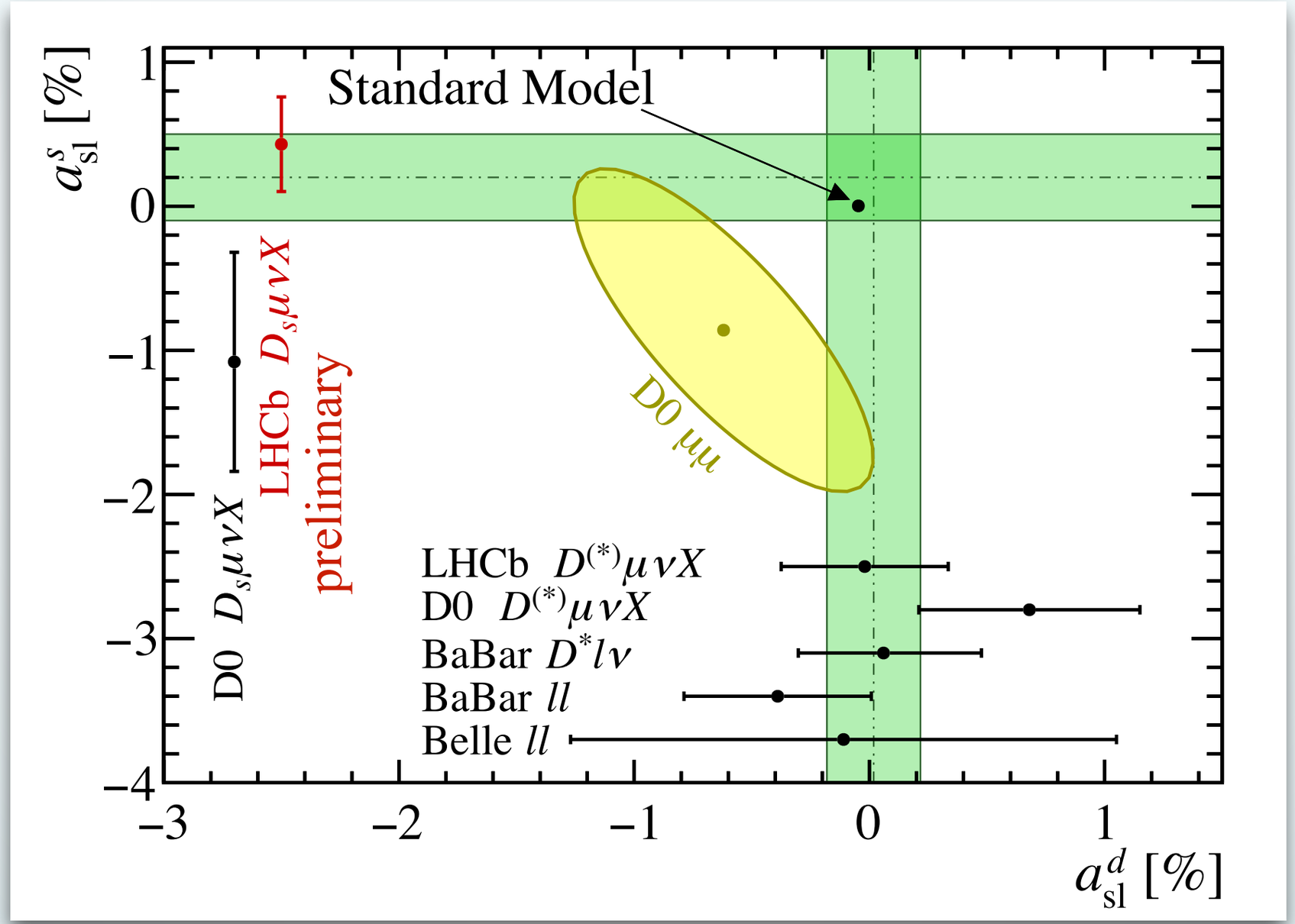


Source	Value	Stat. uncert.	Syst. uncert. (%)
$A_{\rm raw}$	0.11	0.09	0.02
$A_{\rm track}(K^+K^-)$	-0.01	0.00	0.03
$A_{\rm track}(\pi^-\mu^+)$	-0.01	0.05	0.04
$A_{\rm PID}$	0.01	0.02	0.03
$A_{\rm trig}$(hardware)	-0.03	0.02	0.02
$A_{\rm trig}$(software)	0.00	0.01	0.02
$f_{\rm bkg}$ $A_{\rm bkg}$	-0.05	-	0.03
$f_{\rm bkg}$	-	-	0.06
Total $a^s_{\rm sl}$	0.45	0.26	0.20

RESULTS

New result! (preliminary)

$$a^s_{\rm sl} = (0.45 \pm 0.26({\rm stat}) \pm 0.20({\rm syst}))\%$$



CLOSING STATEMENTS

- Measured a_{sl}^s with full Run I dataset (3/fb)

$$a_{\rm sl}^s = (0.45 \pm 0.26({\rm stat}) \pm 0.20({\rm syst}))\%$$

New result! (preliminary)

- Most precise value of CPV in mixing in the B_s system

- Result compatible with Standard Model prediction

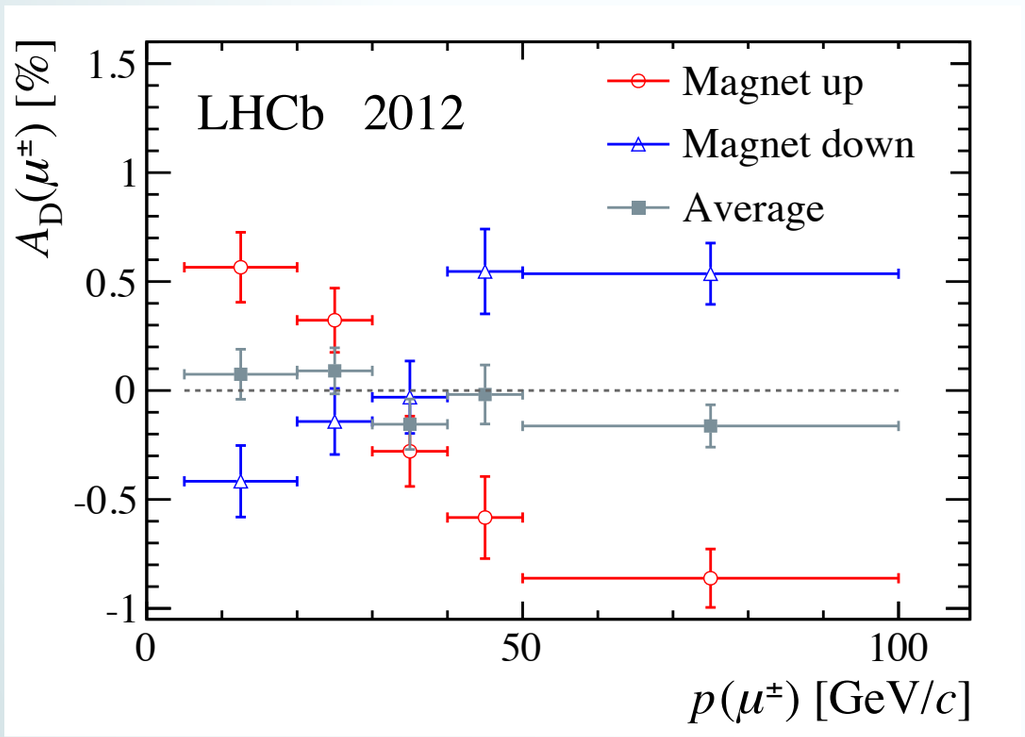
- Statistics limited!

BACKUP

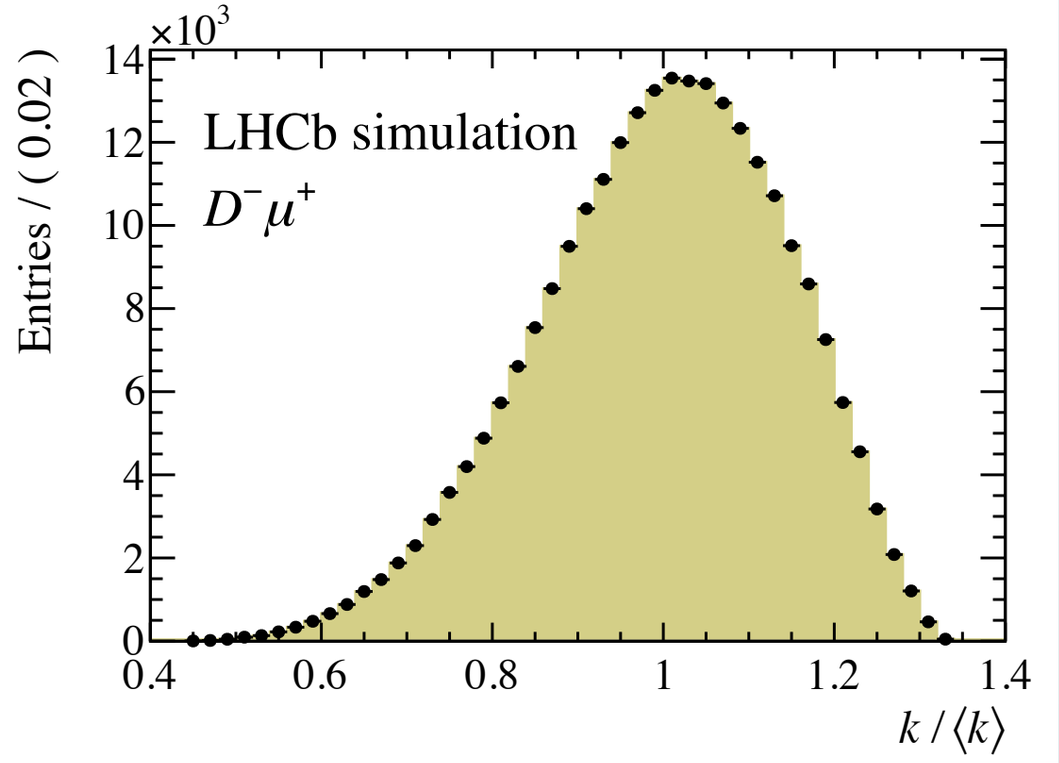
a_{sl}^d

$$A_{\rm meas}(t) = \frac{N(f,t) - N(\overline{f},t)}{N(f,t) + N(\overline{f},t)} \approx A_D + \frac{a^d_{\rm sl}}{2} + \left(A_P - \frac{a^d_{\rm sl}}{2}\right) \cos(\Delta m_d t)$$

Muon detection asymmetry



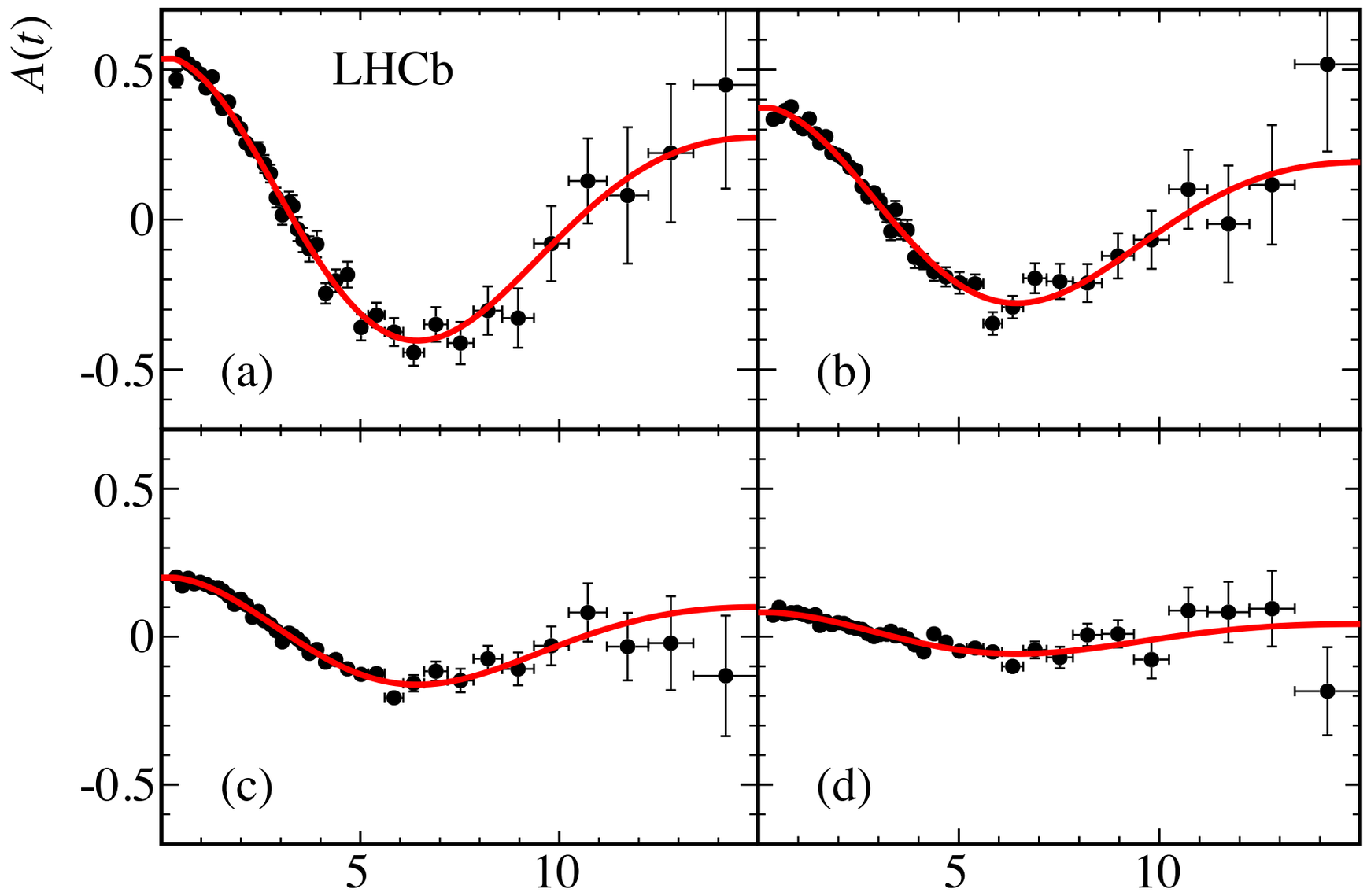
Time correction (k-factor)



LHCb, PRL 114 (2015) 041601

a_{sl}^d

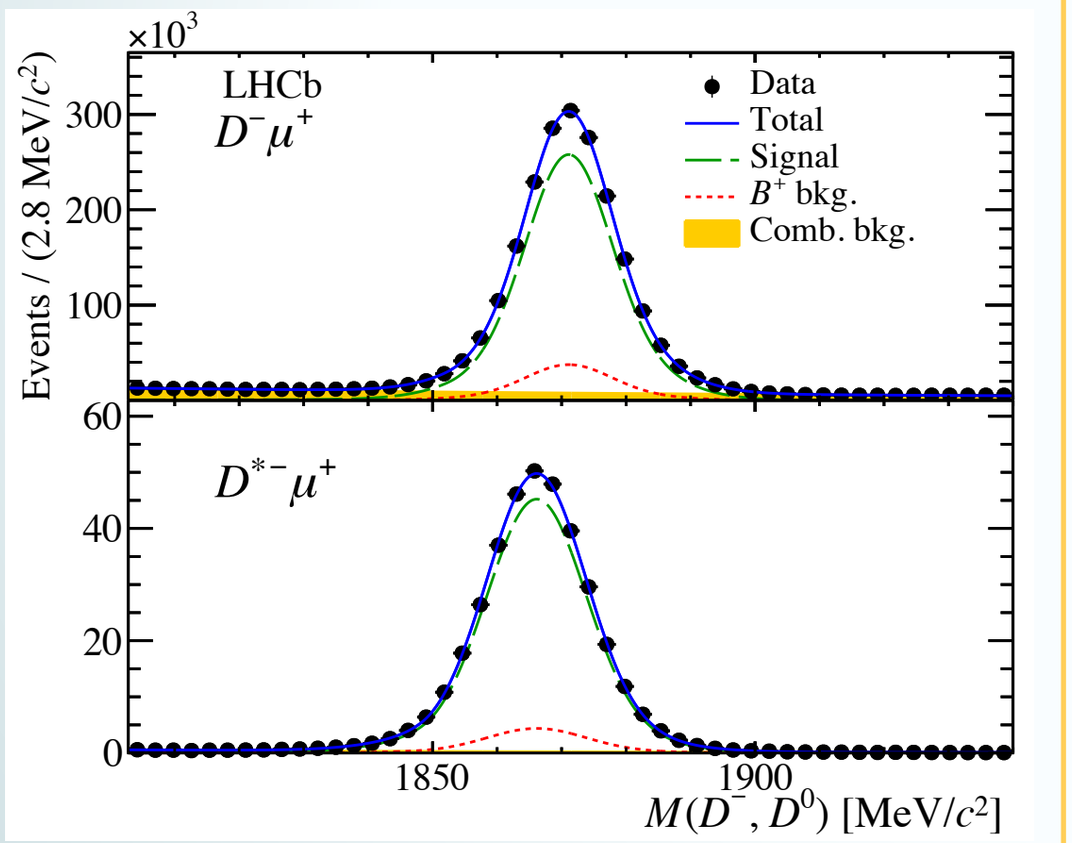
[arXiv:1604.03475]



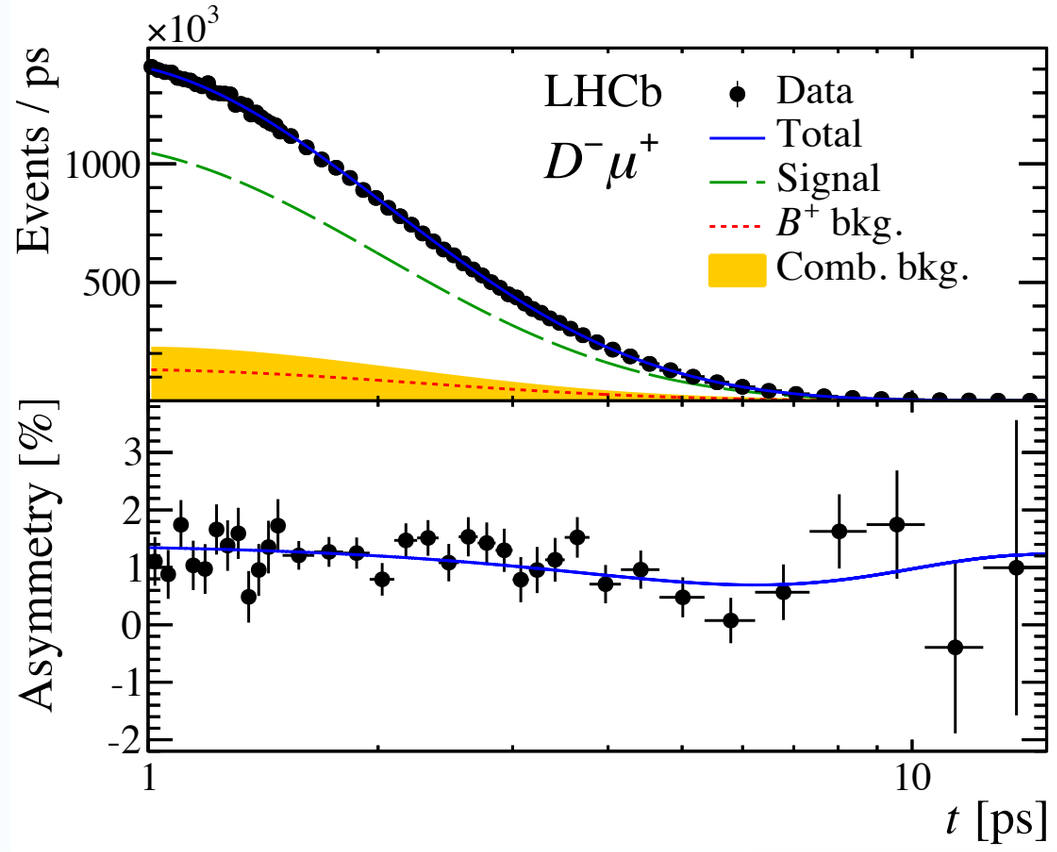
a_{sl}^d

$$A_{\text{meas}}(t) = \frac{N(f,t) - N(\overline{f},t)}{N(f,t) + N(\overline{f},t)} \approx A_D + \frac{a^d_{\text{sl}}}{2} + \left(A_P - \frac{a^d_{\text{sl}}}{2} \right) \cos(\Delta m_d t)$$

$D^{(*)-}$ mass



time dependence



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ASLS PEAKING BKG DETAILS

Mode	$\mathcal{B}$ [%]	$\mathcal{B}(c \to \mu)$ [%]	$\varepsilon_{\rm sig}/\varepsilon_{\rm bkg}$	$f_{\rm bkg}/f_{\rm sig}$ [%]	$A_{\rm bkg}$ [%]
$B^+ \to D^{(*)0} D_s^{(*)+} X$	7.9 ± 1.4	6.5 ± 0.1	4.34	5.8 ± 1.1	-0.6 ± 0.6
$B^0 \to D^0 D_s^{(*)+} X$	5.7 ± 1.2	6.5 ± 0.1	4.08	4.4 ± 1.0	-0.18 ± 0.13
$B^0 \to D^- D_s^{(*)+} X$	4.6 ± 1.2	16.1 ± 0.3	6.41	5.6 ± 1.5	-0.18 ± 0.13
$B_s^0 \to D_s^{(*)-} D_s^{(*)+}$	4.5 ± 1.4	8.1 ± 0.4	3.68	1.0 ± 0.3	–
$\Lambda_b^0 \to \Lambda_c^+ D_s^{(*)+} X$	$10.3^{+2.1}_{-1.8}$	4.5 ± 1.7	4.51	3.0 ± 1.4	-0.4 ± 0.9
$B^- \to D_s^+ K^- \mu^- \nu X$	0.061 ± 0.010	–	2.43	1.3 ± 0.2	0.6 ± 0.6
$\overline{B}^0 \to D_s^+ K_{\rm S}^0 \mu^- \nu X$	0.061 ± 0.010	–	2.89	1.1 ± 0.2	0.18 ± 0.13