Experimental overview of recent mixing and *CP*-violation results in semileptonic *B* decays

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LHCb Implications workshop
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Neutral *B* meson mixing

- Oscillation and decay description:

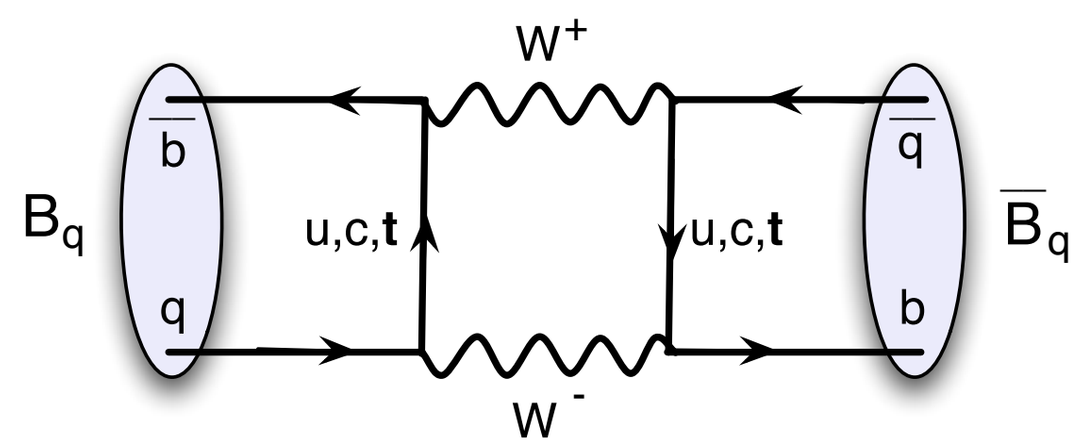
$$i\frac{d}{dt}\begin{pmatrix} |B_q(t)\rangle \\ |\overline{B_q}(t)\rangle \end{pmatrix} = \begin{pmatrix} M_{11} - i\frac{\Gamma_{11}}{2} & M_{12} - i\frac{\Gamma_{12}}{2} \\ M_{12}^* - i\frac{\Gamma_{12}^*}{2} & M_{22} - i\frac{\Gamma_{22}}{2} \end{pmatrix}\begin{pmatrix} |B_q(t)\rangle \\ |\overline{B_q}(t)\rangle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

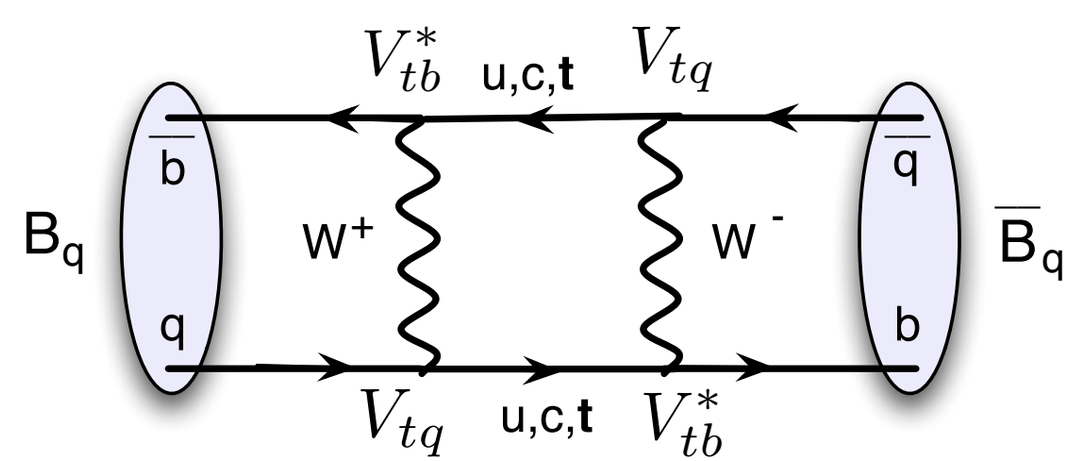
- Mass eigenstates are superpositions of flavor eigenstates:

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

- Mixing observables

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





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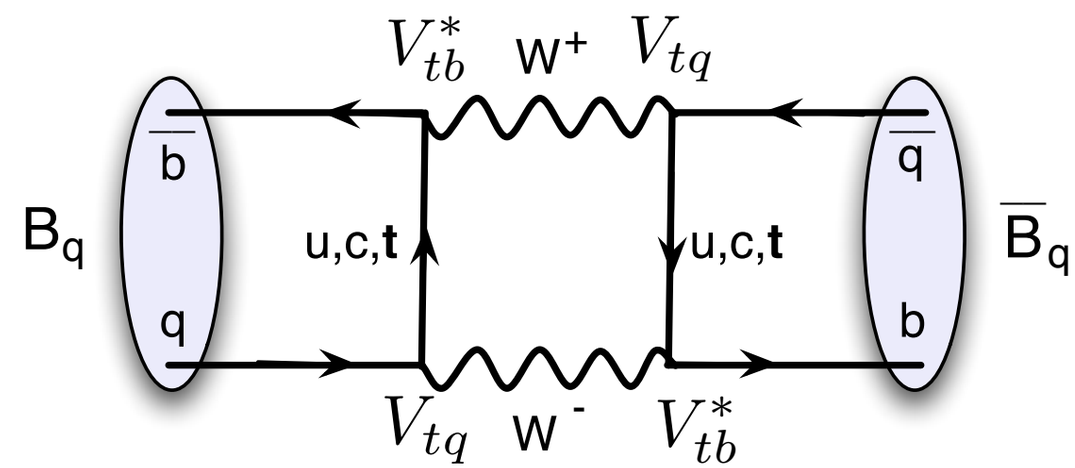

- Mixing observables

$$\Delta\Gamma = \Gamma_L - \Gamma_H$$
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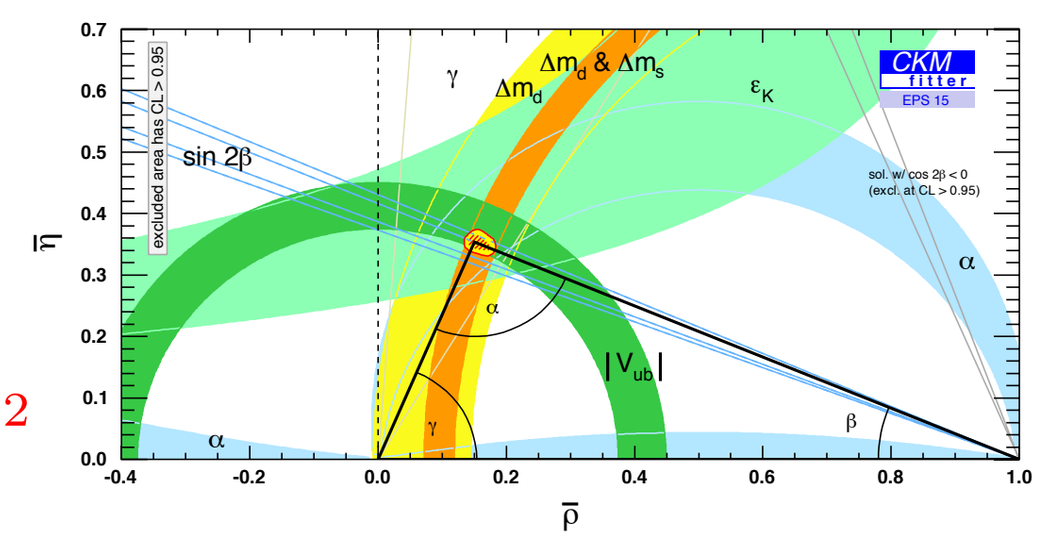
$$\Delta m \propto (V_{tb}^* V_{tq})^2$$



LHCB-CONF-2015-003

Precision measurement of Δm_d

- Oscillation frequency measured with 2.2(0.8)·10⁶ $B^0 \to D^{(*)-}\mu^+\nu_\mu X$ decays

CP violation in mixing
$\sim 10^{-4}(SM)$

$$A(t) = \frac{N^{unmix}(t) - N^{mix}(t)}{N^{unmix}(t) + N^{mix}(t)} = \frac{\cos(\Delta m_d t)}{\cosh(\Delta\Gamma_d t/2)} + \frac{a}{2}\left[1 - \frac{\cos^2(\Delta m_d t)}{\cosh^2(\Delta\Gamma_d t/2)}\right]$$

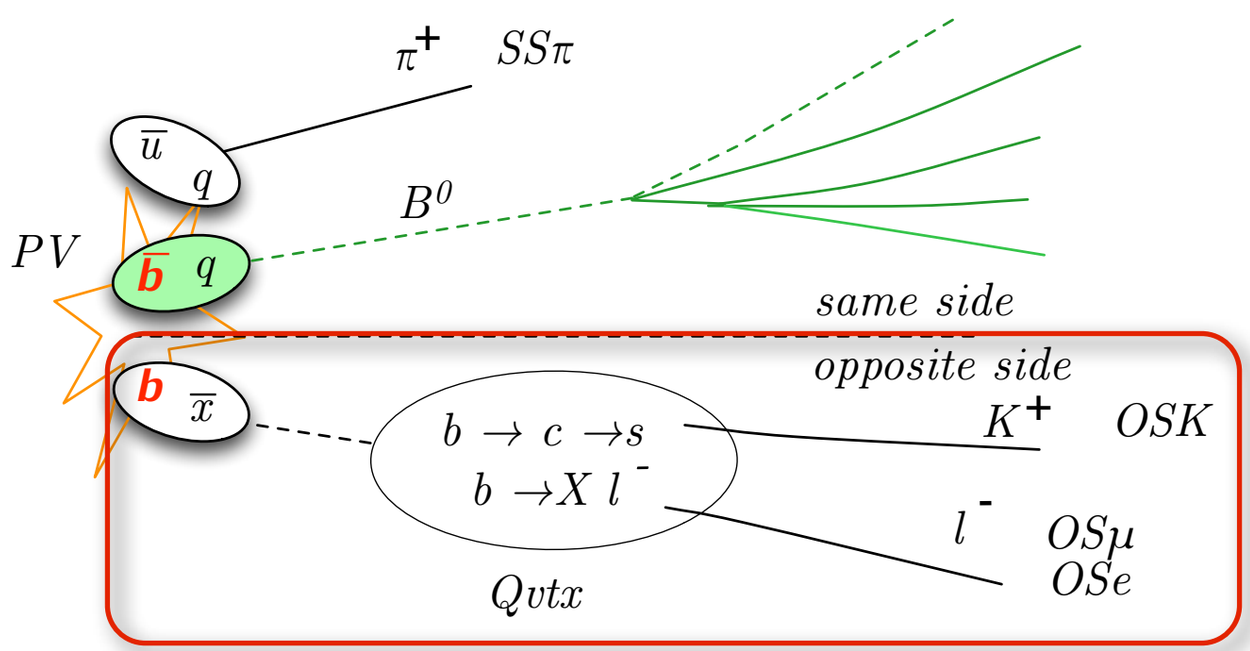
$$\Delta\Gamma_d \sim 0$$

Precision measurement of Δm_d

- Mixing asymmetry measured with 2.2(0.8)·10^6 $B^0 \to D^{(*)-}\mu^+\nu_\mu X$ decays

$$A(t) = \frac{N^{unmix}(t) - N^{mix}(t)}{N^{unmix}(t) + N^{mix}(t)} = \cos(\Delta m_d t)$$

- Flavor tagging $\mathcal{P} = \epsilon_{tag}(1-2\omega)^2 \sim 2.4\%$



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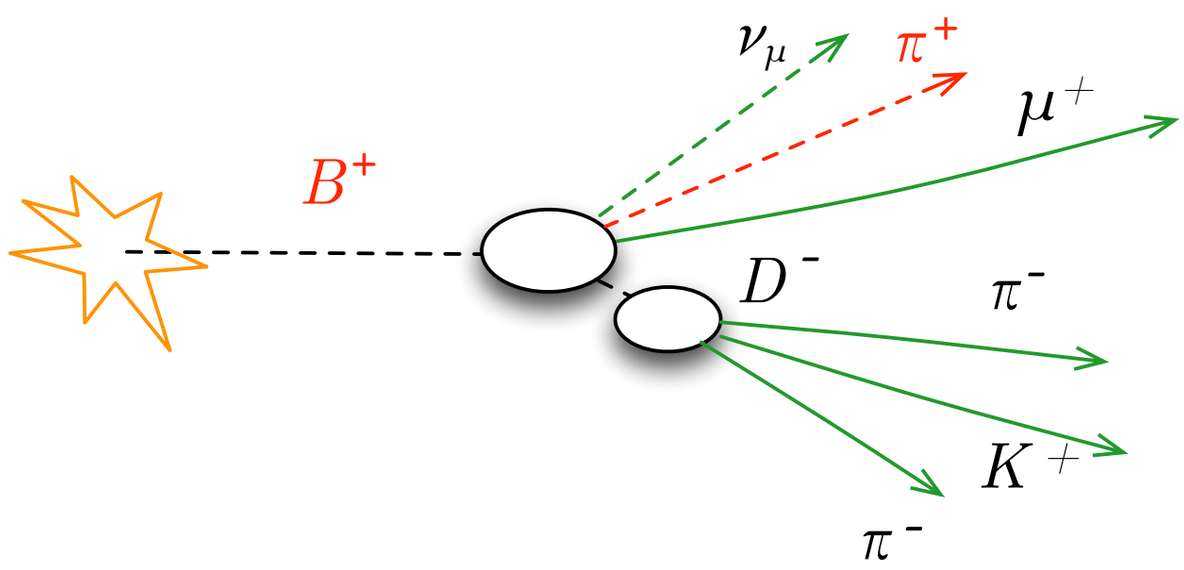
$$A(t) = \frac{N^{unmix}(t) - N^{mix}(t)}{N^{unmix}(t) + N^{mix}(t)} = \cos(\Delta m_d t)$$

- Flavor tagging

- Background rejection $B^+ \to D^{(*)-}\mu^+\nu_\mu X^+$ background rejection with a Multivariate Classifier



LHCB-CONF-2015-003

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- Flavor tagging
- Background rejection
- Decay time reconstruction

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Phys. Rev. Lett. 114 (2015) 041601

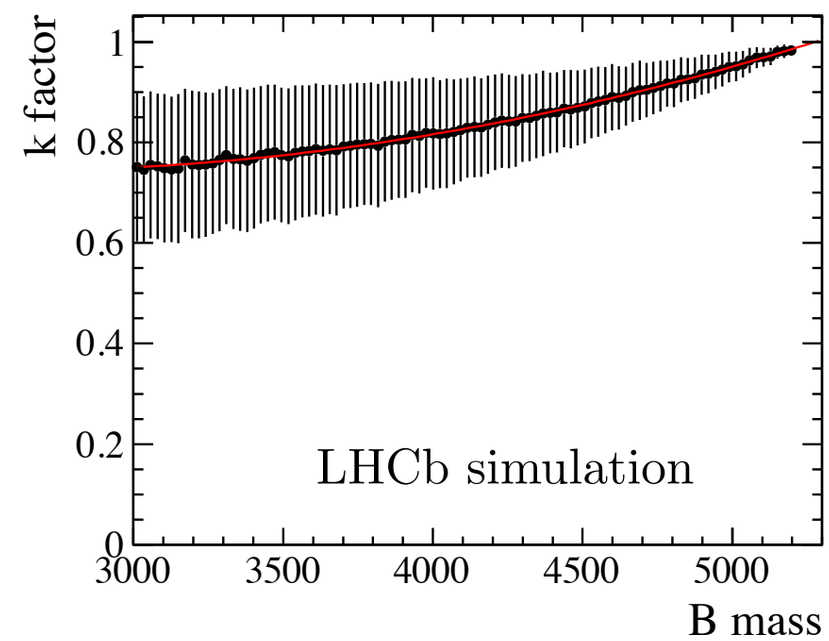
B decay time and resolutions (Δm_d and $a_{\rm sl}^d$)

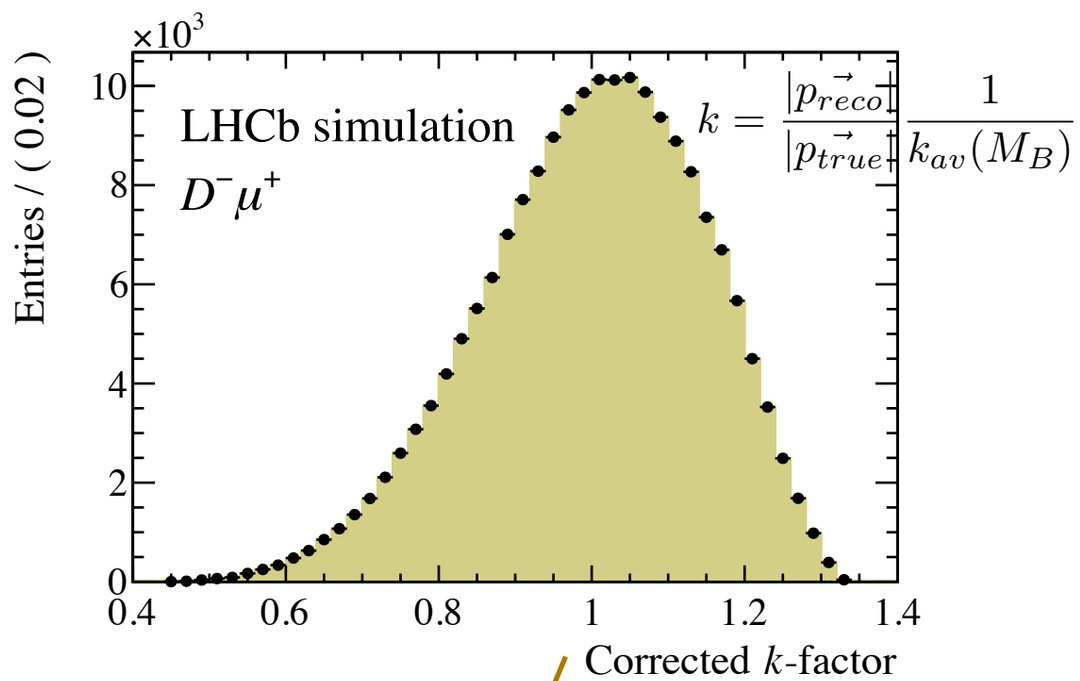
- The momentum of the B meson cannot be measured precisely due to the partial reconstruction of the decay.
- The B decay time is corrected using the factor:

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

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

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



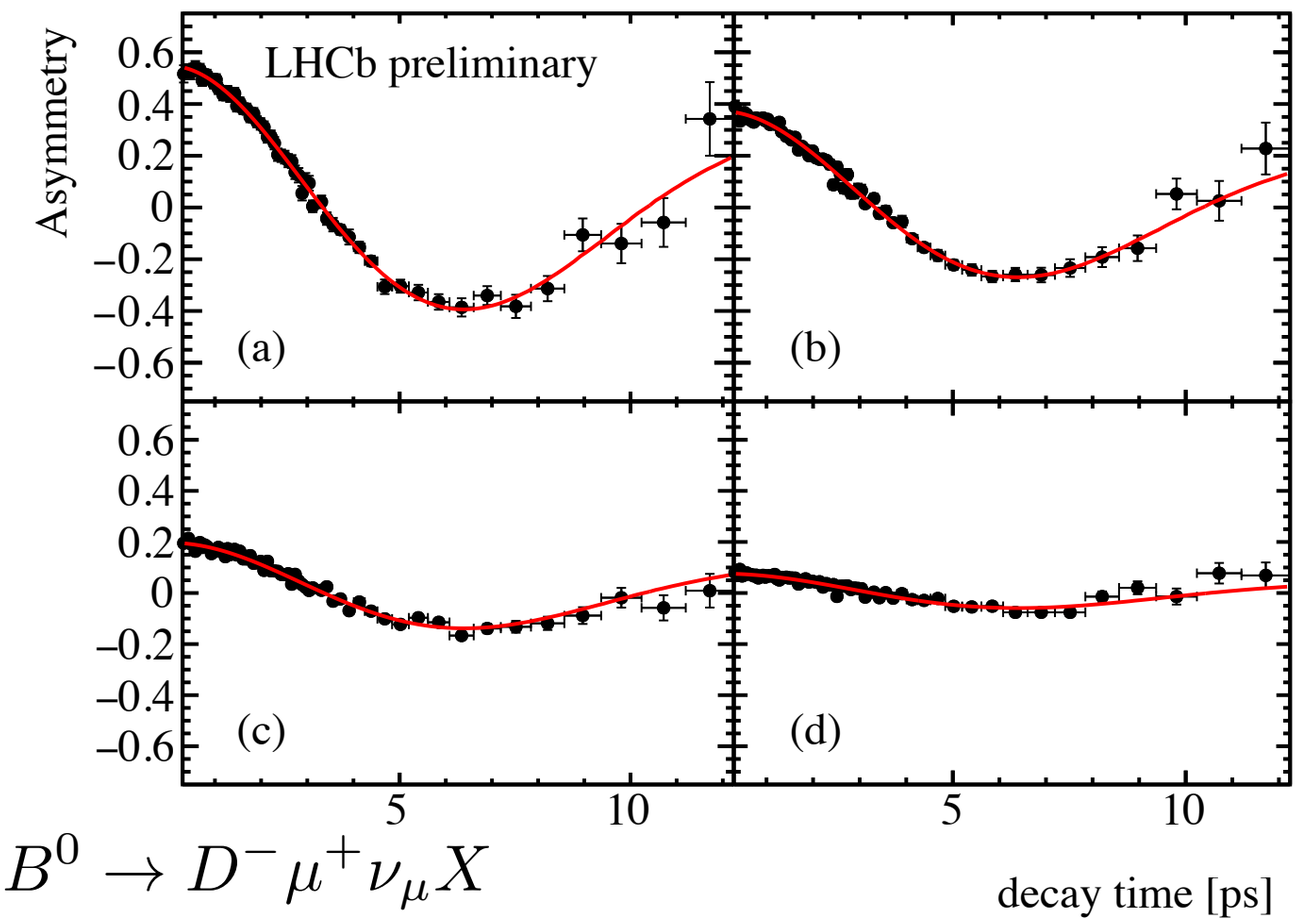


"L resolution"

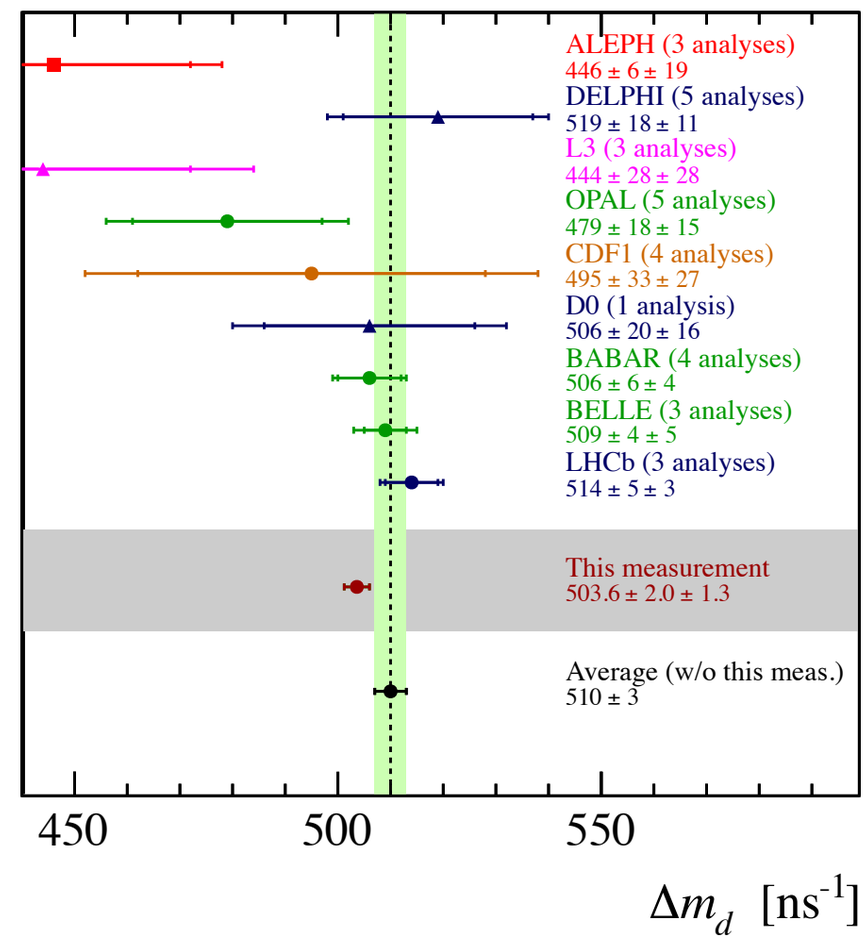
$$\mathcal{P}_{sig} = \boxed{(T(t) \otimes_t R(t) \otimes_k F(k))} \cdot A(t)$$

Precision measurement of Δm_d

- Fit to the mixing asymmetry distributions in four bins of increasing mistag probability



$B^0 \to D^- \mu^+ \nu_\mu X$



$$\Delta m_d = 503.6 \pm 2.0(\text{stat}) \pm 1.3(\text{syst})\text{ns}^{-1}$$

$$\Delta m_d^{HFAG\ 2015} = 505.5 \pm 2.0\ \text{ns}^{-1}$$

$$\Delta m_d^{SM} = 543 \pm 91\ \text{ns}^{-1}$$

A.Lenz, arXiv:1409.6963

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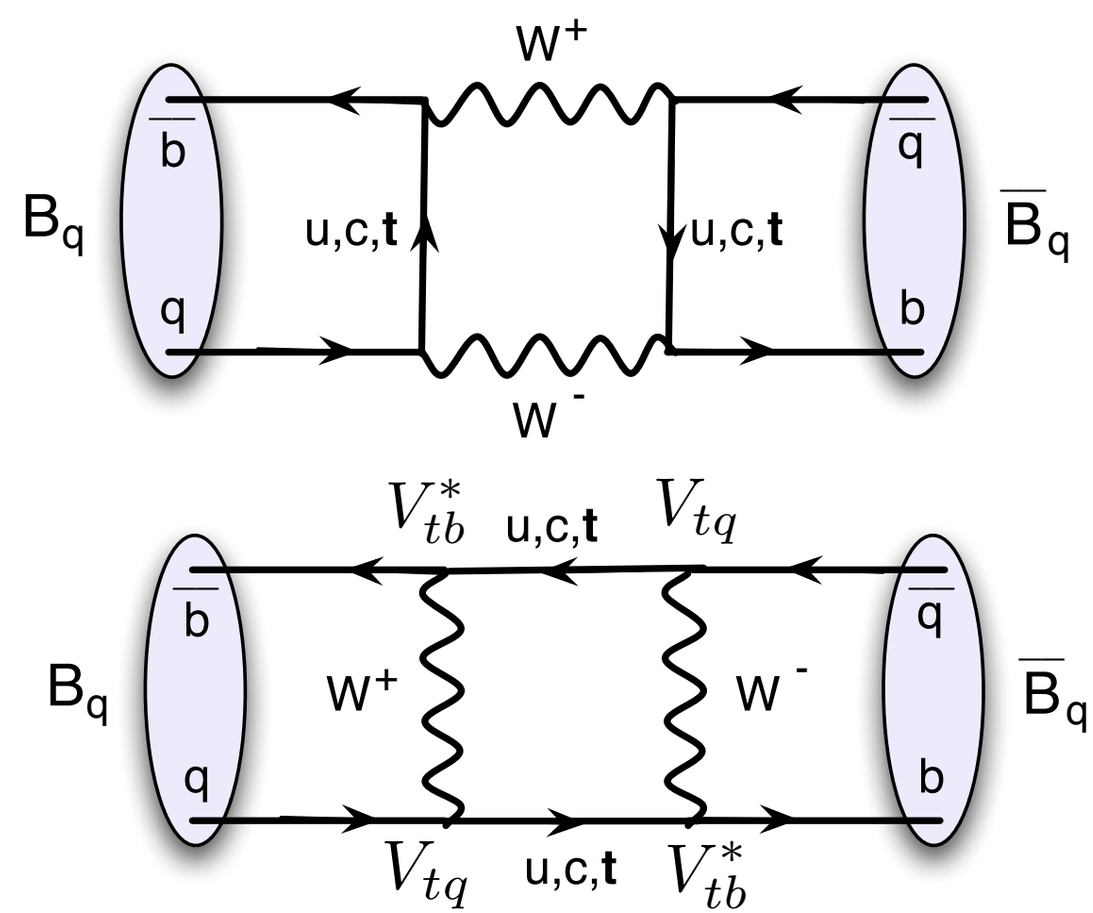

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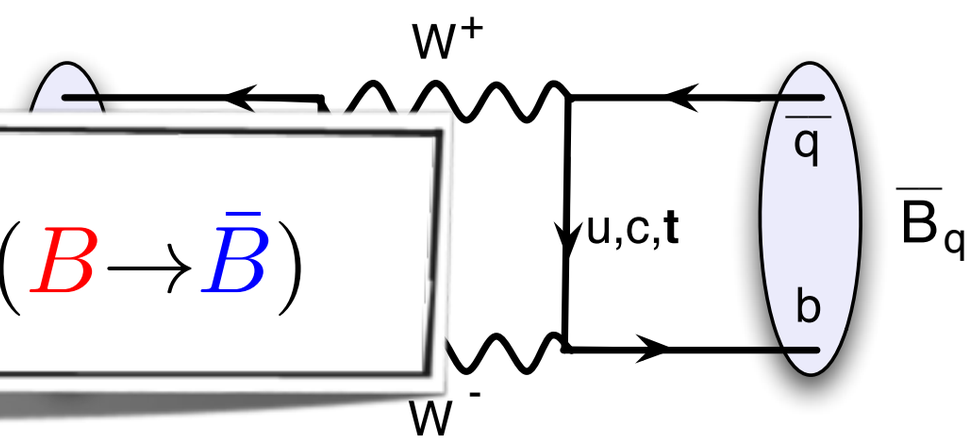
- Mass eigenstates are superpositions of flavor eigenstates:

$$|B_L\rangle = p|$$
$$|B_H\rangle = p|$$

$$\mathcal{P}(\bar{B}\to B) \overset{?}{\neq} \mathcal{P}(B\to\bar{B})$$



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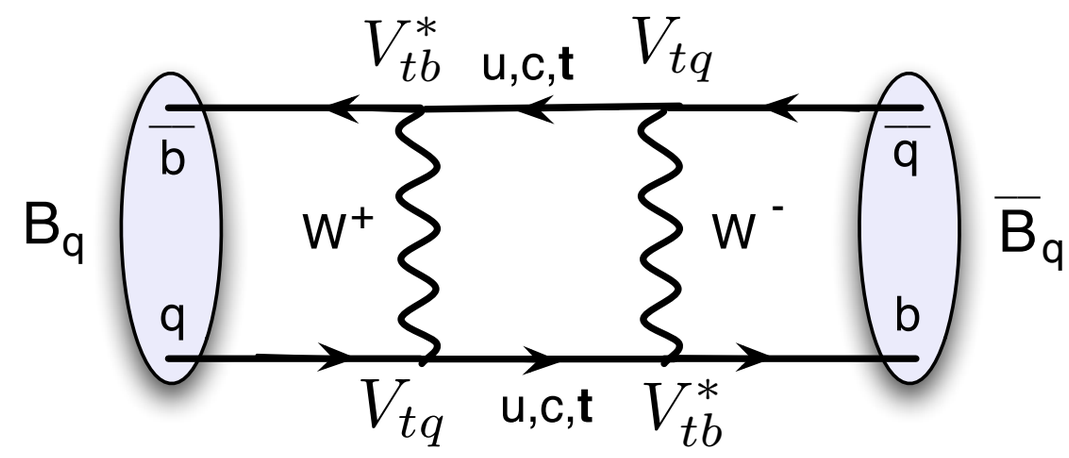
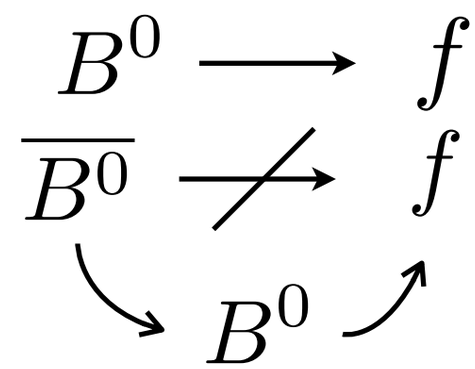


Semileptonic *CP* asymmetries

- Using semileptonic flavor specific *B* meson decays:

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



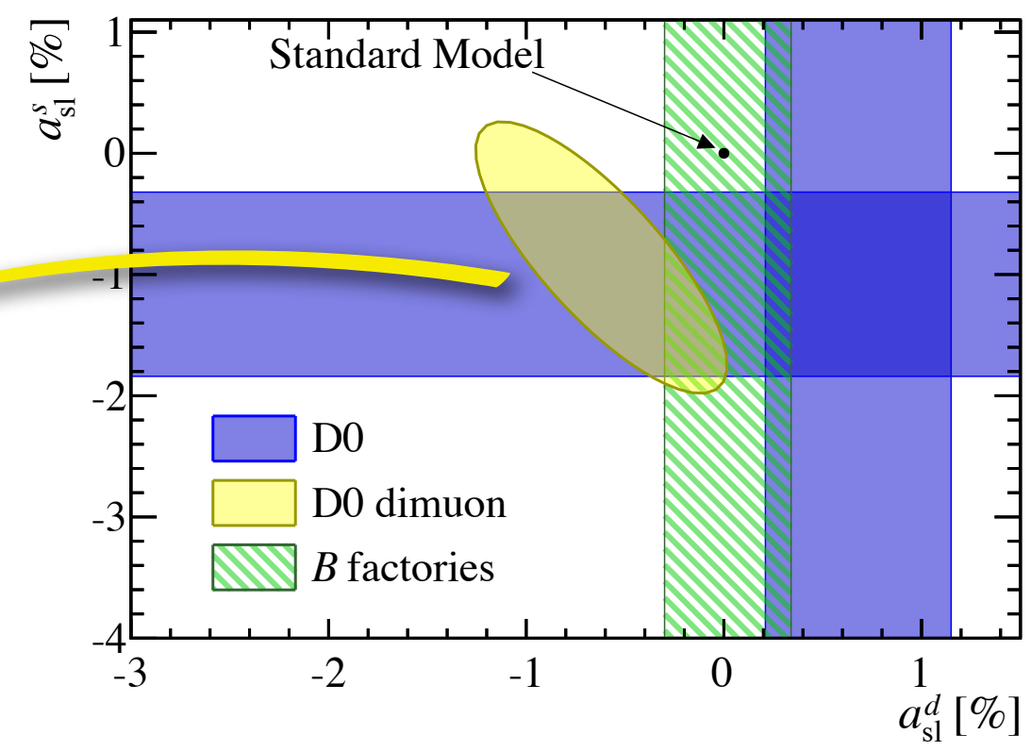
- SM predictions:

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

TINY!!!

A. Lenz and U. Nierste, arXiv:1102.4274

- Experimental landscape without LHCb



New asymmetries (and $\Delta\Gamma_d$) measurements needed

arXiv:1409.6963

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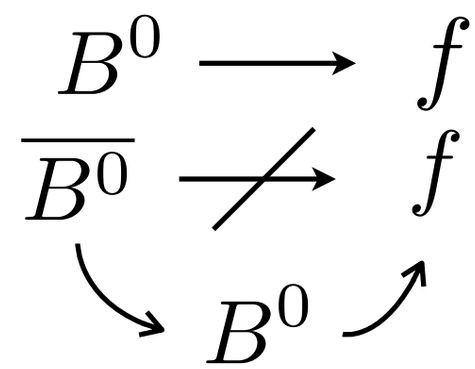

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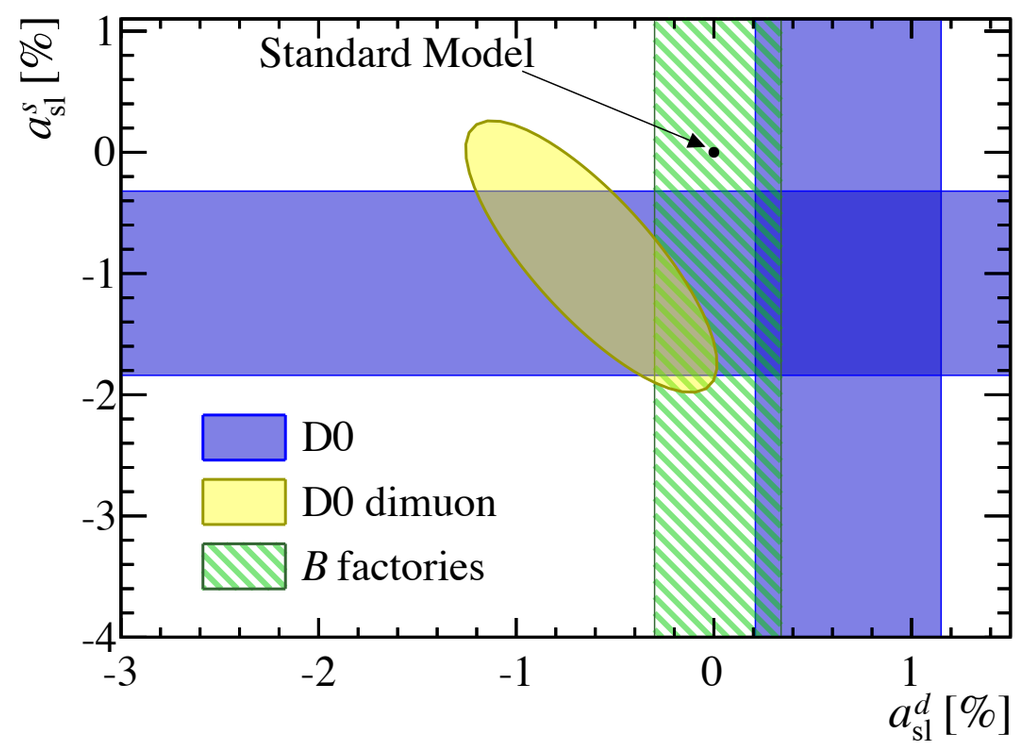

$a^d_{\rm sl}$ and $a^s_{\rm sl}$ measurement from LHCb using 3 fb^{-1} of data

Semileptonic *CP* asymmetries @ LHCb

- Using semileptonic flavor specific *B* meson decays:

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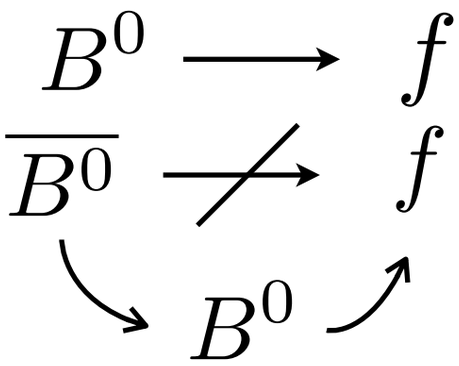
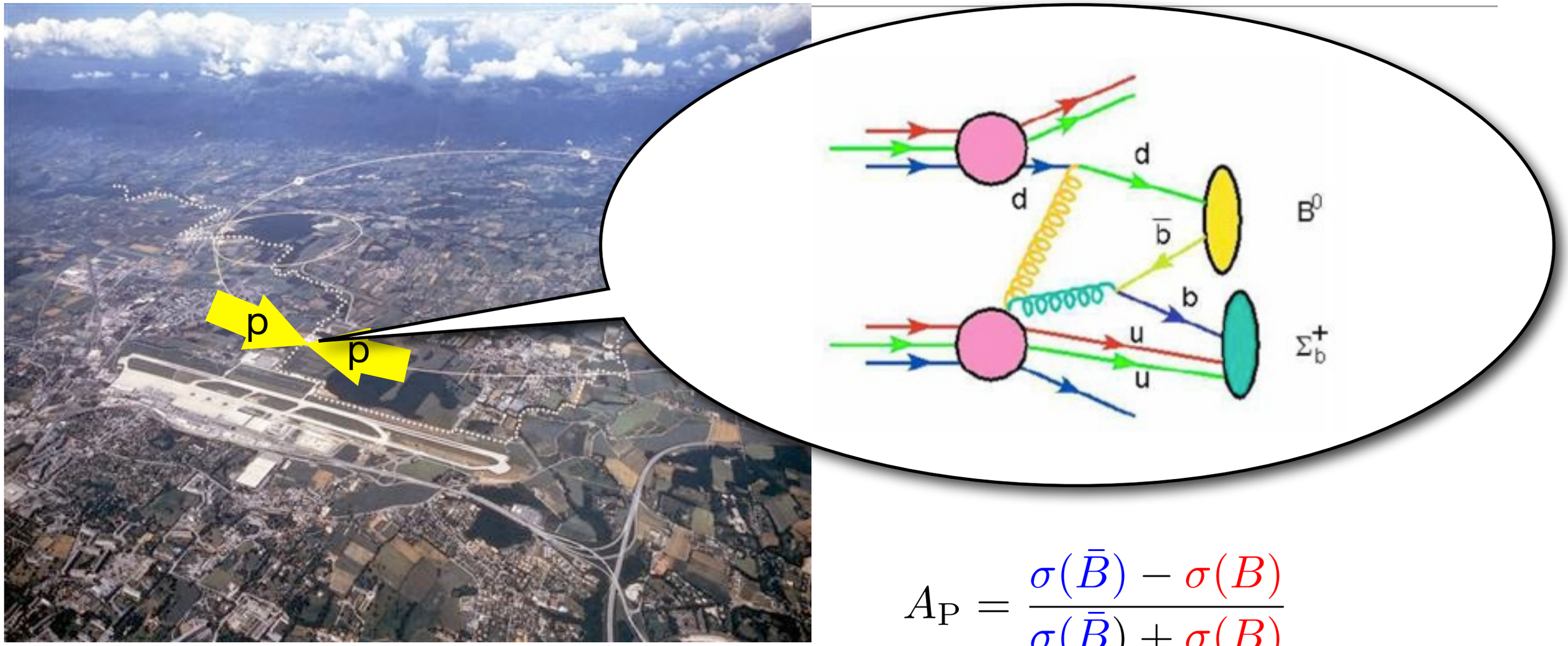


- Untagged charge asymmetry:

$$A_{\rm meas}(t) = \frac{\Gamma(f,t) - \Gamma(\bar{f},t)}{\Gamma(f,t) + \Gamma(\bar{f},t)} = \frac{a^q_{\rm sl}}{2} - \frac{a^q_{\rm sl}}{2}\frac{\cos(\Delta m_q t)}{\cosh(\Delta\Gamma_q t/2)}$$

No need to know the flavor of the B meson at the production

Hadron production asymmetries



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

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

Phys. Rev. Lett. 114 (2015) 041601

Time-dependent: $a_{\rm sl}^d$

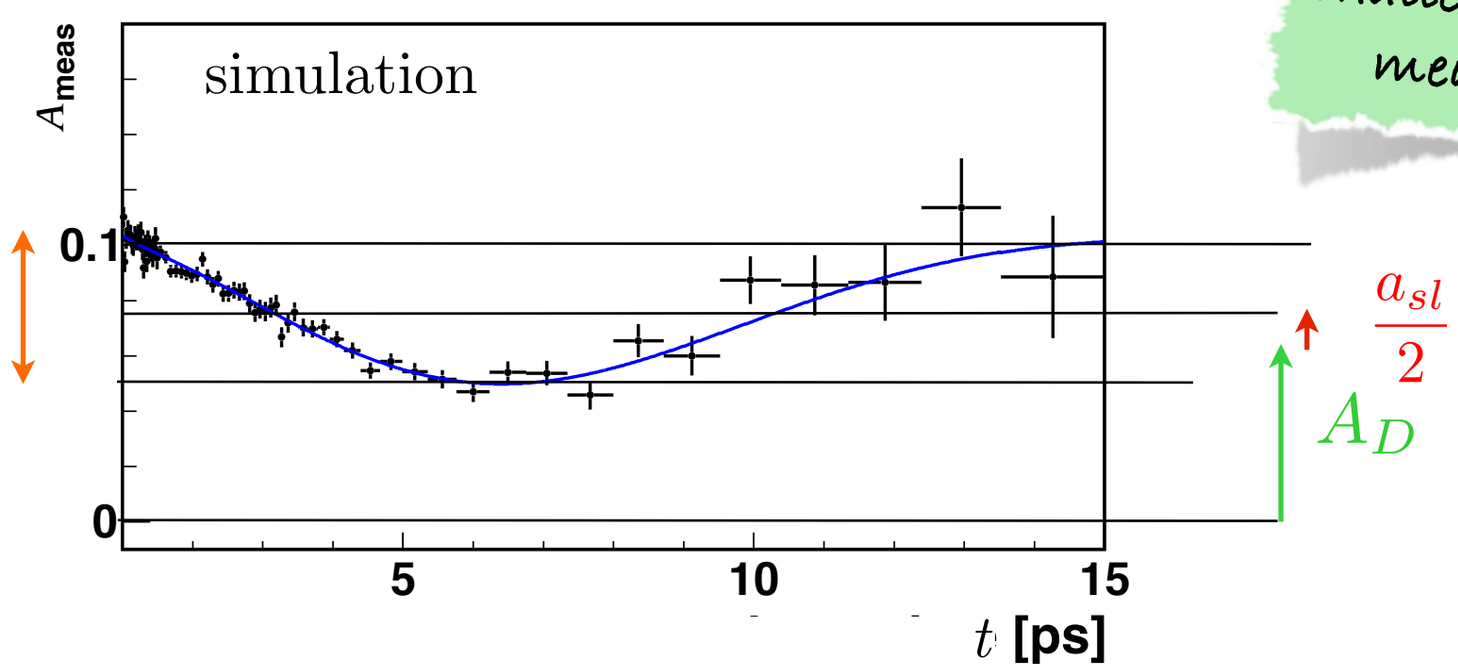
- Untagged, time dependent, charge asymmetry of the final state particles:

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

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

major experimental challenge for many measurements

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



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

Time-integrated: $a^s_{\rm sl}$

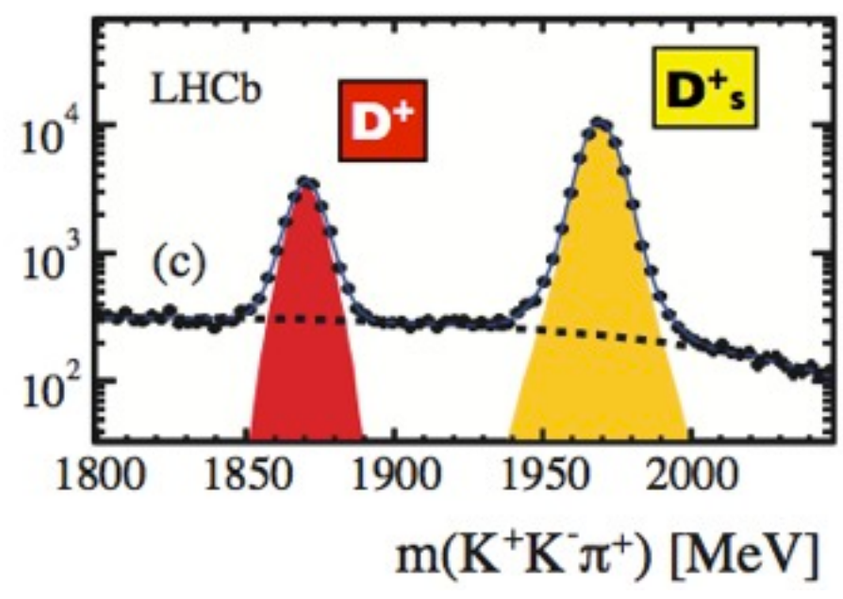
- Untagged, time integrated semileptonic asymmetry:

$$A_{\rm meas} = \frac{\Gamma(f) - \Gamma(\bar{f})}{\Gamma(f) + \Gamma(\bar{f})} = \frac{a^s_{\rm sl}}{2} + A_{\rm D} - \underbrace{\left(A_{\rm P} + \frac{a^s_{\rm sl}}{2}\right) \frac{\int e^{\Gamma_s t}\cos(\Delta m_s t)\epsilon(t)dt}{\int e^{\Gamma_s t}\cosh(\Delta\Gamma_s t/2)\epsilon(t)dt}}_{\sim 10^{-4}}$$

- Fast B^0_s oscillation dilutes second term below precision of this measurement
- $\mathcal{L} = 1\ {\rm fb}^{-1}$ analysis

  1.8 ·10^5 $B^0_s \to D_s \mu \nu_\mu X$ decays

- Signal yields for each charge extracted from KKπ invariant mass distributions
- Correct raw asymmetry for detection and background asymmetries



$$a^s_{\rm sl} = (-0.06 \pm 0.50({\rm stat}) \pm 0.36({\rm syst}))\%$$

Time-integrated: $a^s_{\rm sl}$

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- Fast B^0_s oscillation dilutes second term below precision of this measurement

- $\mathcal{L} = 3\ {\rm fb}^{-1}$ analysis

$B^0_s \to D_s \mu \nu_\mu X$

$$\frac{a^s_{\rm sl}}{2} = \frac{S+B}{S}(A_{\rm meas} - A_{\rm D}) - \frac{B}{S} A_{\rm bkg}$$

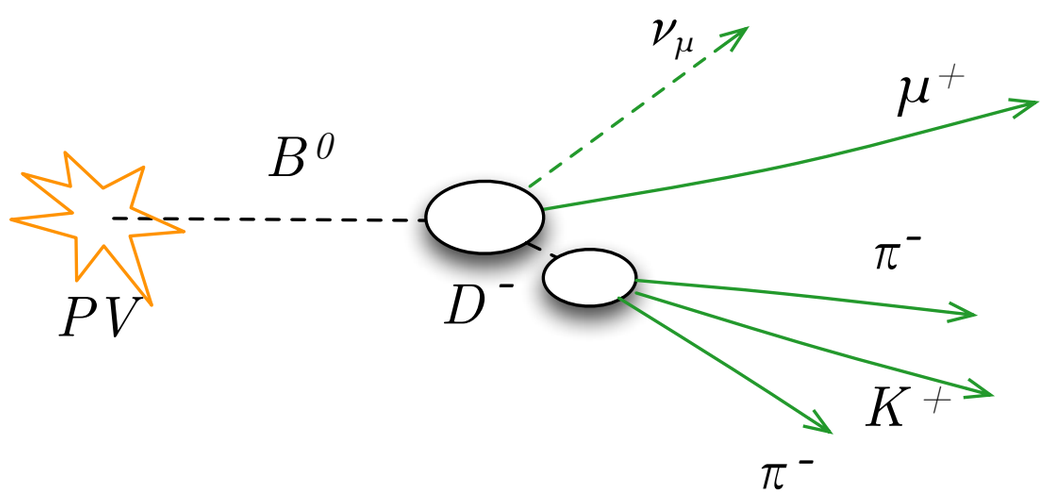
  - Inclusion of the full KKπ Dalitz region
  - Novel techniques to control detection asymmetries

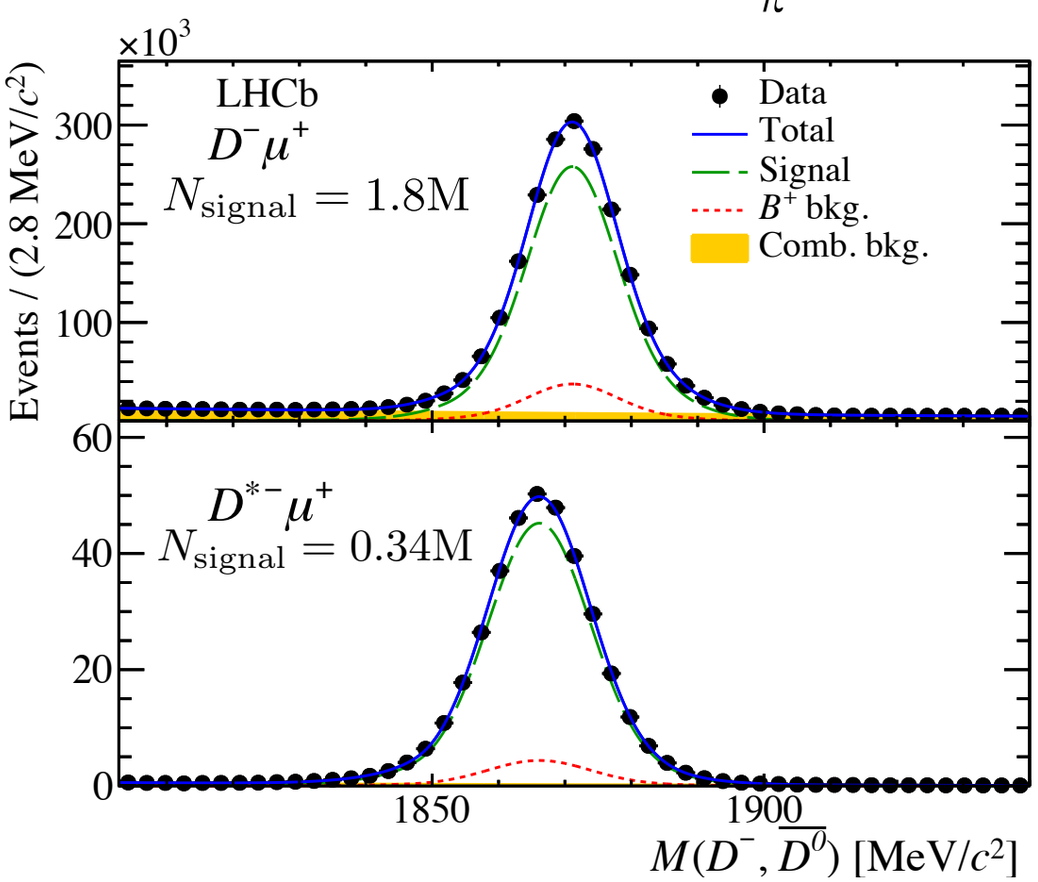
COMING SOON ...

Data samples

$a_{\rm sl}^{d}$

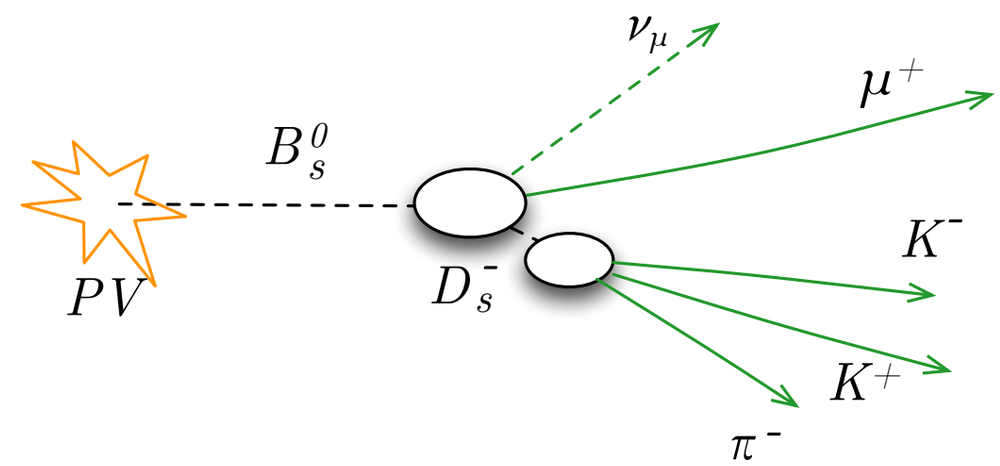
- $B^0 \to D^{(*)-}\mu^+\nu_\mu X$ decays in Run-I



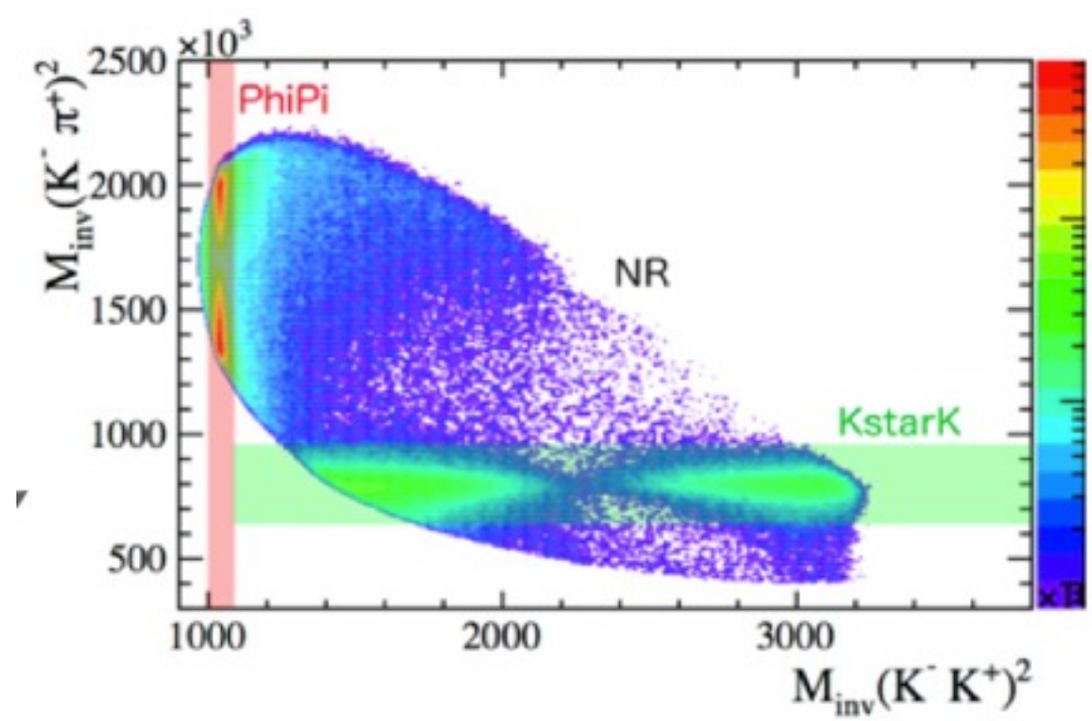


$a_{\rm sl}^{s}$

- $B_s^0 \to D_s^-\mu^+\nu_\mu X$ decays in Run-I



- Using the full KKπ Dalitz region for $3\ \mathrm{fb}^{-1}$



A factor 6 MORE SIGNAL wrt 1 fb^{-1}

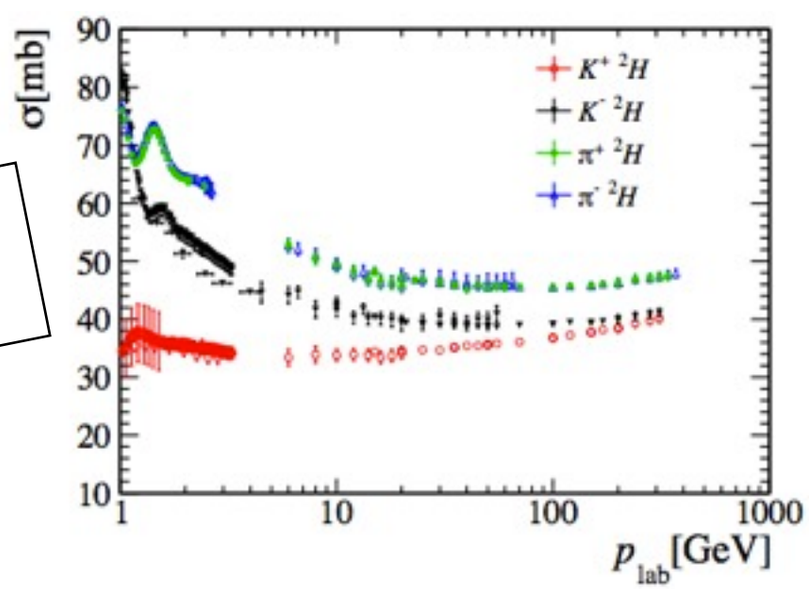
Detection asymmetries

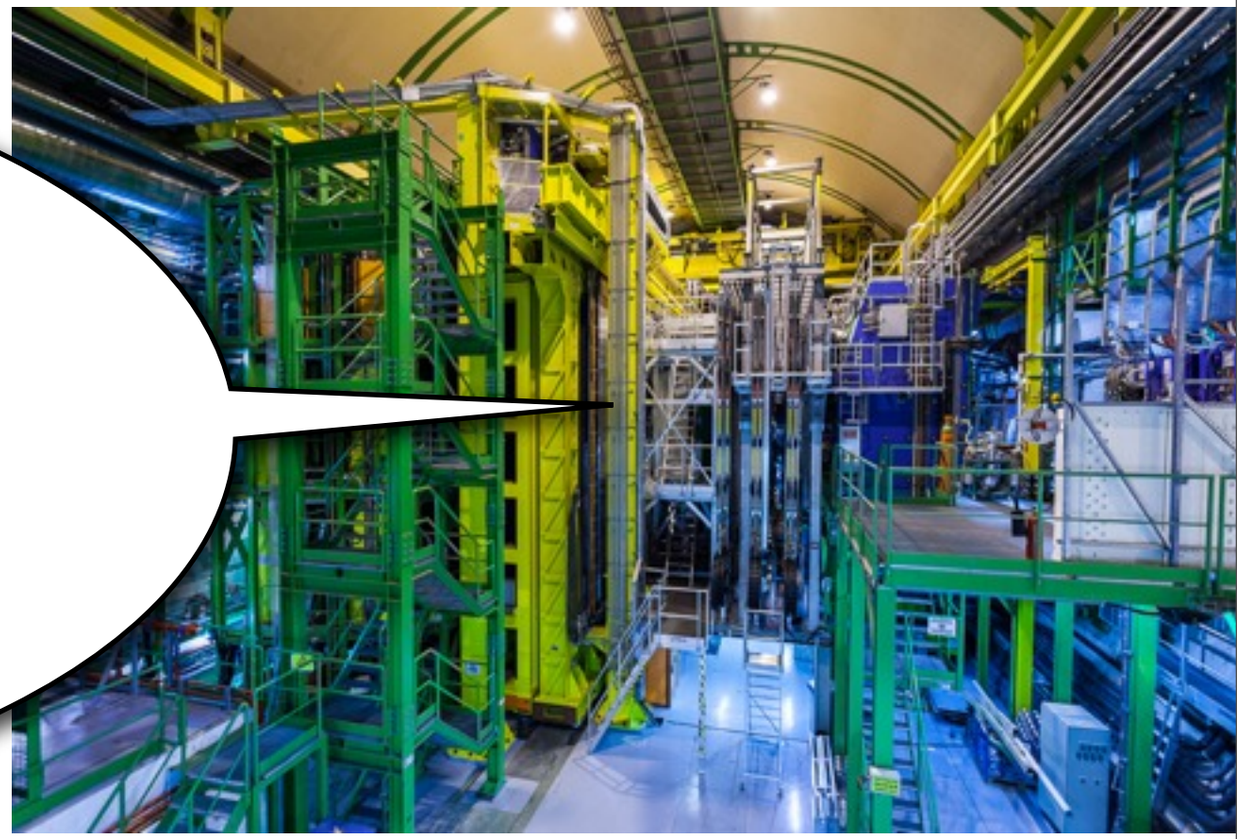
- Detection/reconstruction asymmetry of the final state:

$$A_{\mathrm{D}} = \frac{\epsilon(f) - \epsilon(\bar{f})}{\epsilon(f) + \epsilon(\bar{f})}$$

- Sources of asymmetry:
  - Different interaction with the detector material
  - Detector inefficiency/mis-alignment/inhomogeneities

E.g. : charged kaons





- Evaluated by using data-driven techniques on dedicated samples

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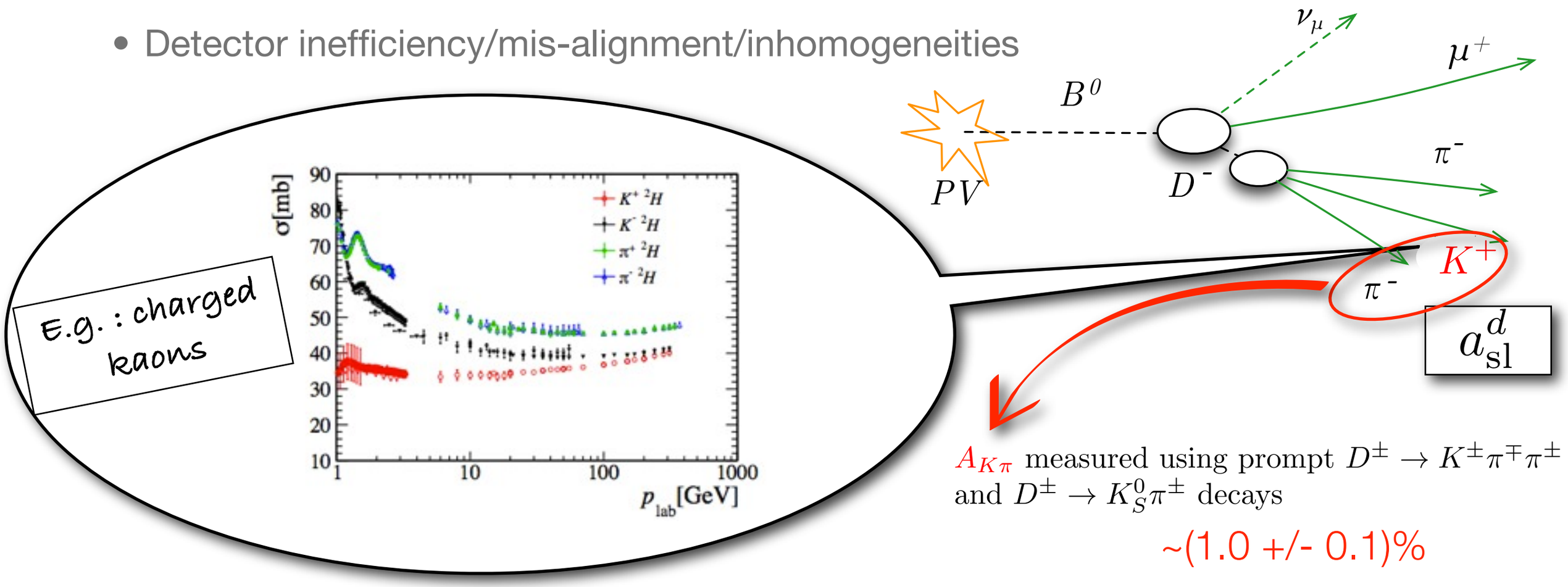

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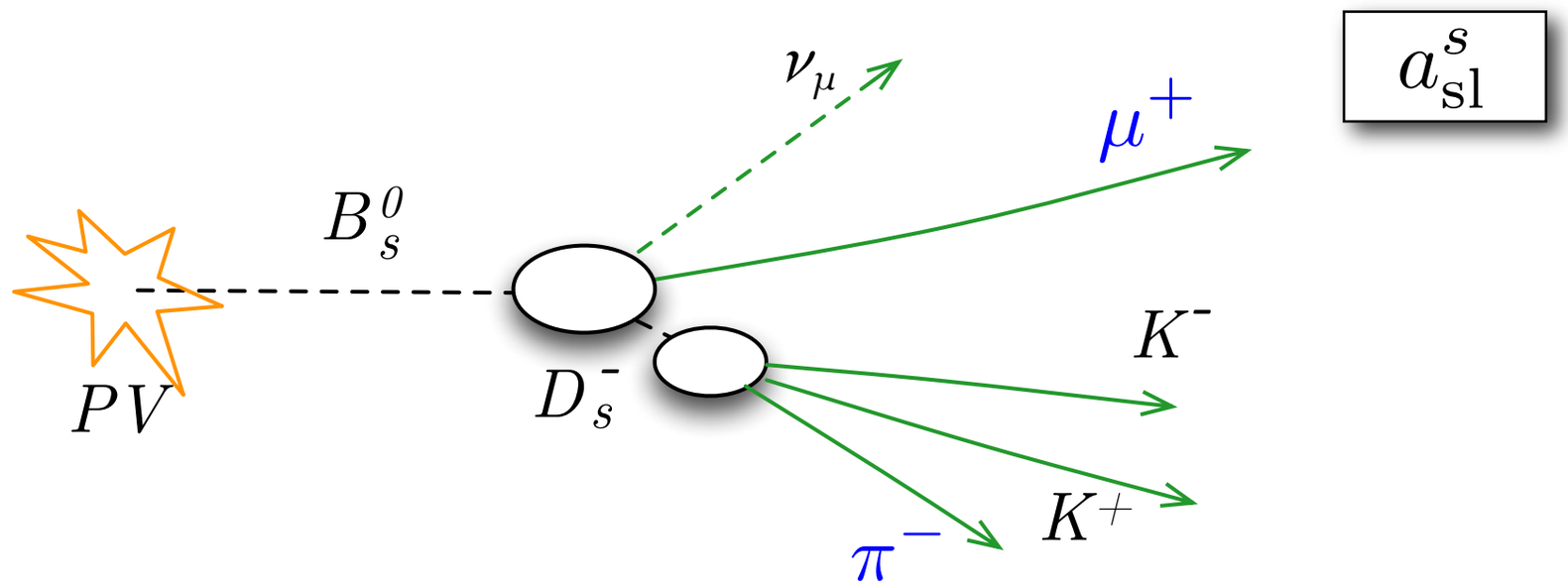
Detection asymmetries

- Need to account for all possible detection and reconstruction asymmetries: *nuclear interaction, particle identification, tracking, trigger*



$$A_{\rm D} = A^{\mu\pi}_{(track)} + A^{\pi}_{(PID|track)} + A^{KK}_{(track+PID)} + A^{\mu}_{(PID+L0|track)}$$

- Novel tag-and-probe method using using $J/\psi \to \mu^+\mu^-$ decays combined with the method using partially reconstructed $D^* \to (D^0 \to K\pi\pi\pi)\pi$ decays

expected uncertainty on $A^{\mu\pi}_{(track)} < 0.1\%$ in 3 fb^{-1} analysis

Results

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

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$$\text{expected } a_{\rm sl}^{s} = (X.XX \pm 0.2({\rm stat}) \pm 0.25({\rm syst}))\%$$

COMING SOON ...

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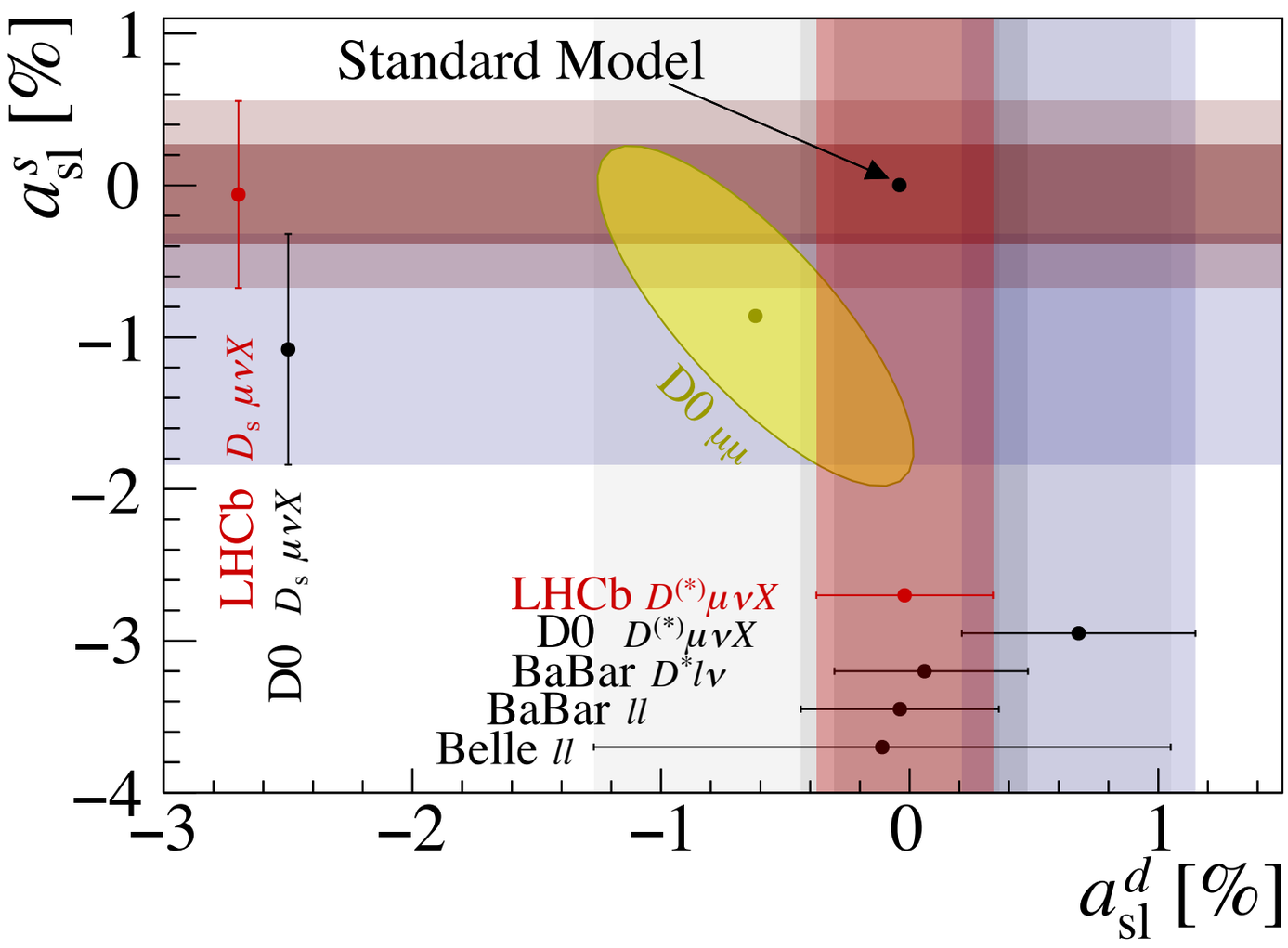

Results

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

Phys. Rev. Lett. 114 (2015) 041601

$$\text{expected } a_{\rm sl}^s = (X.XX \pm 0.2({\rm stat}) \pm 0.25({\rm syst}))\%$$

COMING SOON ...

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

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

$a_{\rm sl}^d$

source	δ(%)
A_D	0.26
B+ bkg	0.13
Λ_b bkg	0.07
fit model	0.05
other bkg	0.04
quadratic sum	0.30

Phys. Rev. Lett. 114 (2015) 041601

$a_{\rm sl}^s$

source	δ(%)
tracking asym.	~~0.26~~
muon asym.	0.16
fit model	0.15
backgrounds	0.10
quadratic sum	0.36

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

E.g. :

~0.16

$3\ {\rm fb}^{-1}$

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Phys. Rev. Lett. 114 (2015) 041601

limited by control sample statistics (0.19%)

limited by assumptions, e.g. production asymmetries

E.g. :

tracking asym.	~~0.26~~
muon asym.	0.16
quadratic sum	0.36

~0.16

$3\ {\rm fb}^{-1}$

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

B+ Production asymmetry

- Samples: $B^+ \to [K^-\pi^+]\pi^+$ and $B^+ \to [K^-\pi^+\pi^-\pi^+]\pi^+$
- Charge asymmetry:

$$A^{B_u}_{\rm meas} = \frac{N(B^- \to D^0\pi^-) - N(B^+ \to \bar{D}^0\pi^+)}{N(B^- \to D^0\pi^-) + N(B^+ \to \bar{D}^0\pi^+)}$$

- Production asymmetry

$$\boxed{A_{\rm P}(B^+) = A^{B_u}_{\rm meas} - A_{\rm D} - A^{D\pi^\pm}_{CP}}$$

- Expected uncertainty ~ 0.33% (8 TeV), 0.47% (7 TeV)
  to be compared with 0.6%
  (systematic on $a^d_{\rm sl}$ ~0.07% (8 TeV) ~0.09% (7 TeV)

And Measurement of $A_{CP}(B^\pm \to J/\psi K^\pm)$

defining $\Delta A_{CP} = A^{J\psi K}_{CP} - A^{D\pi}_{CP} = A^{J\psi K}_{\rm meas} - A^{D\pi}_{\rm meas} + \delta A^{K\pi}_{\rm D}$

and assuming no CPV in $B \to D\pi$ decays

Summary and perspectives

- ***B^0 mixing frequency***: world's best measurement and uncertainty well below the theory uncertainty

- ***Semileptonic asymmetries***:
  - Run-I measurement of $a_{\rm sl}^s$ is coming soon!
  - A number of improvements are available to improve the $a_{\rm sl}^d$ measurement (about at least 15% reduction of the current systematic uncertainty is expected)
  - Increase in the statistics of the samples to come...

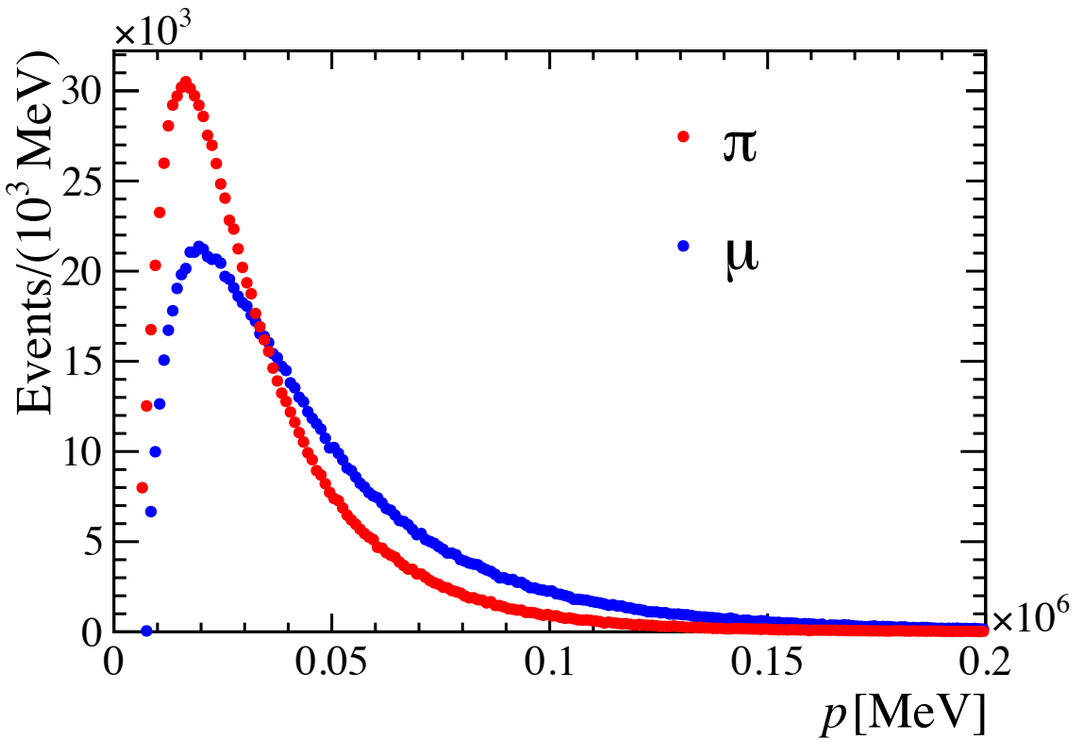
  With the current techniques and tools:

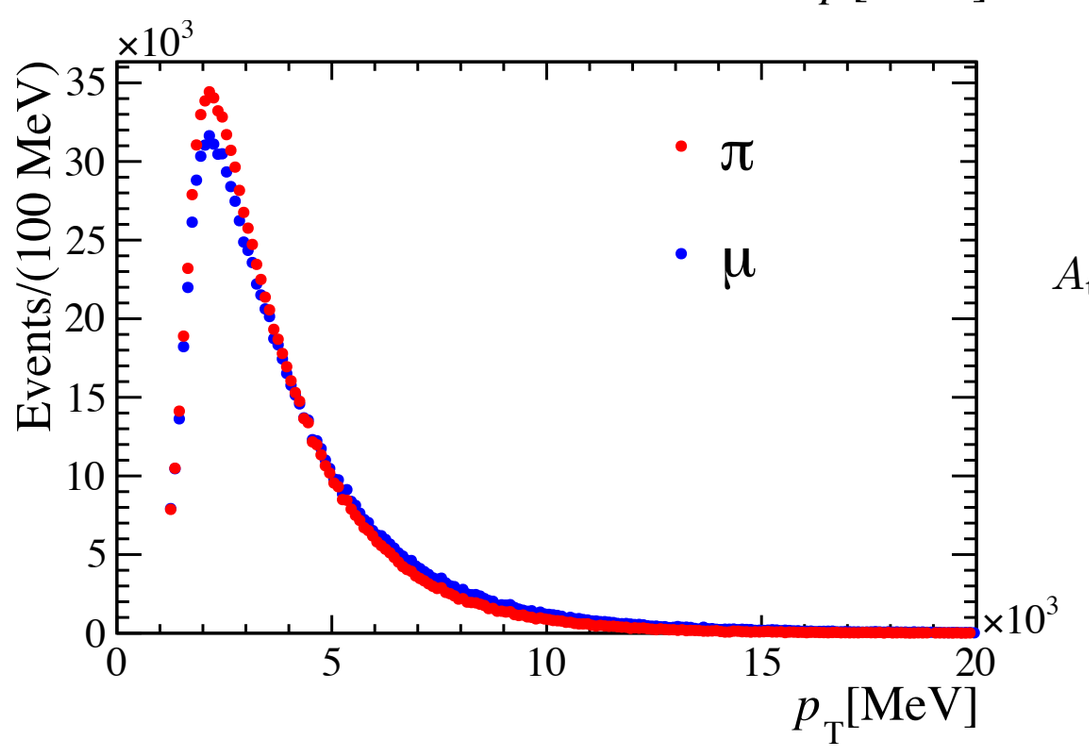
  At the end of Run-II uncertainties on $a_{\rm sl}^s$ and $a_{\rm sl}^d$ are expected to be ~50-60% of the current Run-I uncertainties

  With additional 50 fb^{-1} (upgrade), uncertainties on $a_{\rm sl}^s$ and $a_{\rm sl}^d$ are expected to be at the order of one per mille or below

Backup

a_{sl}^{d} Measurement: Tracking asymmetries





- Efficiency of track reconstruction depends on the momentum of the particle

$$A_{\mathrm{tracking}}(\mu^+\pi^-) = \int_{\mu\ p_T\ range} P_\mu(p_T)dp_T A_{\mathrm{tracking}}(\mu^+, p_T) + \int_{\pi\ p_T\ range} P_\pi(p_T)dp_T A_{\mathrm{tracking}}(\pi^-, p_T)$$

$$A_{\mathrm{tracking}}(\mu^+, p_T) = -A_{\mathrm{tracking}}(\pi^-, p_T)$$

$$A_{\mathrm{tracking}}(\mu^+\pi^-) = \int_0^\infty (P_\mu(p_T) - P_\pi(p_T))A_{\mathrm{tracking}}(\mu^+, p_T)dp_T$$

$$w(p_T(\pi)) = \frac{P_\mu(p_T(\pi))}{P_\pi(p_T(\pi))}$$

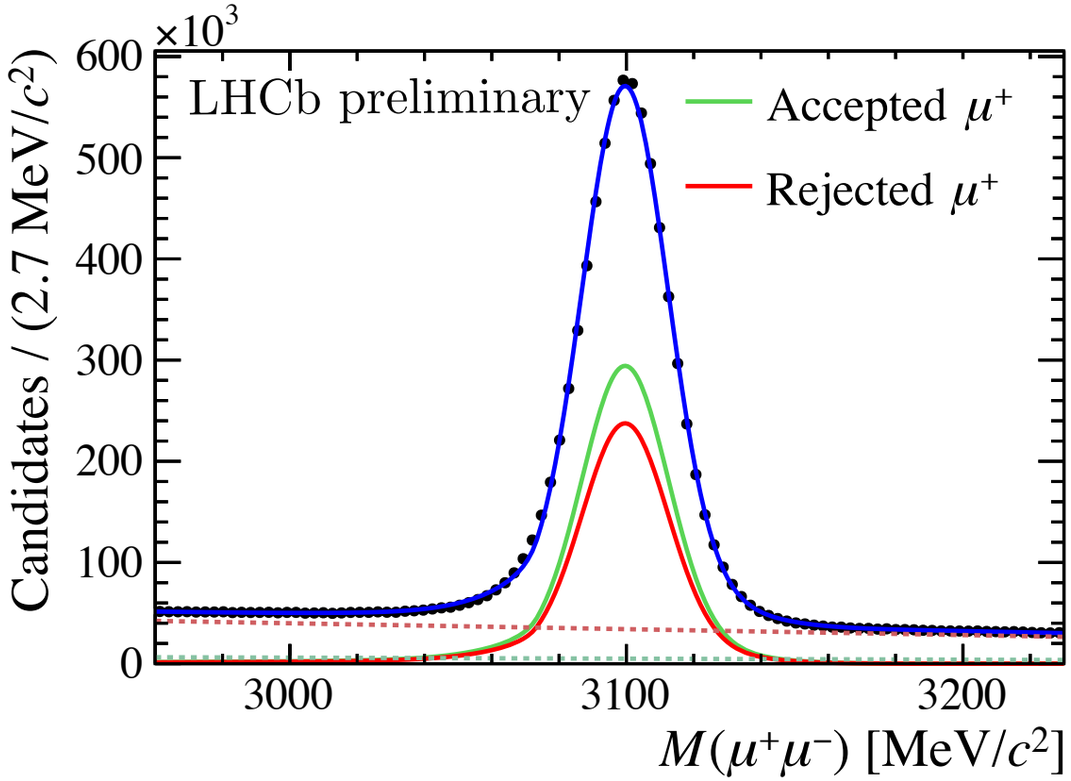
- Checked with pseudo-experiments

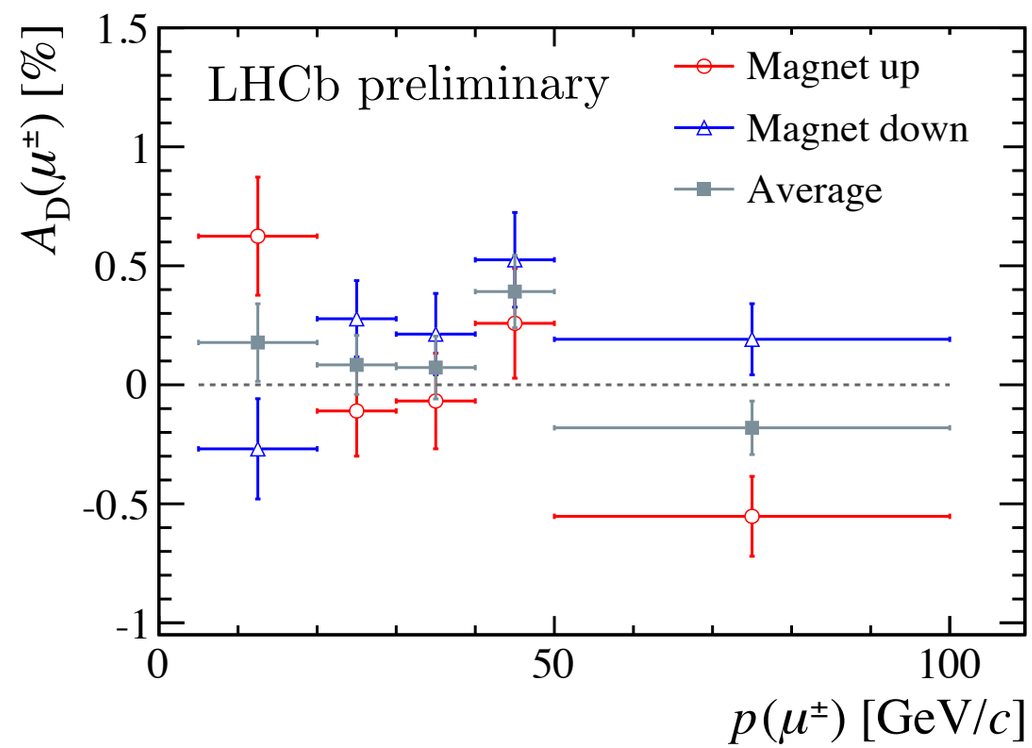
a_{sl}^{d} Measurement: μπ detection asymmetry

- 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/ψ→μμ decays





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

$a_{\rm sl}^d$ Measurement: Kπ detection asymmetry

- Using prompt D+ decays into Kππ and $K_S\pi$

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

- 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

$a_{\rm sl}^d$ Measurement: 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)

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

- 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

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

raw asymmetry in $\Lambda_b^0 \to J/\psi p K^+$
subtracting kaon and proton detection asymmetries

JHEP 07(2014) 103

$a_{\rm sl}^d$ Measurement: Systematic uncertainties

Source of uncertainty	$a_{\rm sl}^d$	$A_{\rm P}(7\,\text{TeV})$	$A_{\rm P}(8\,\text{TeV})$
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

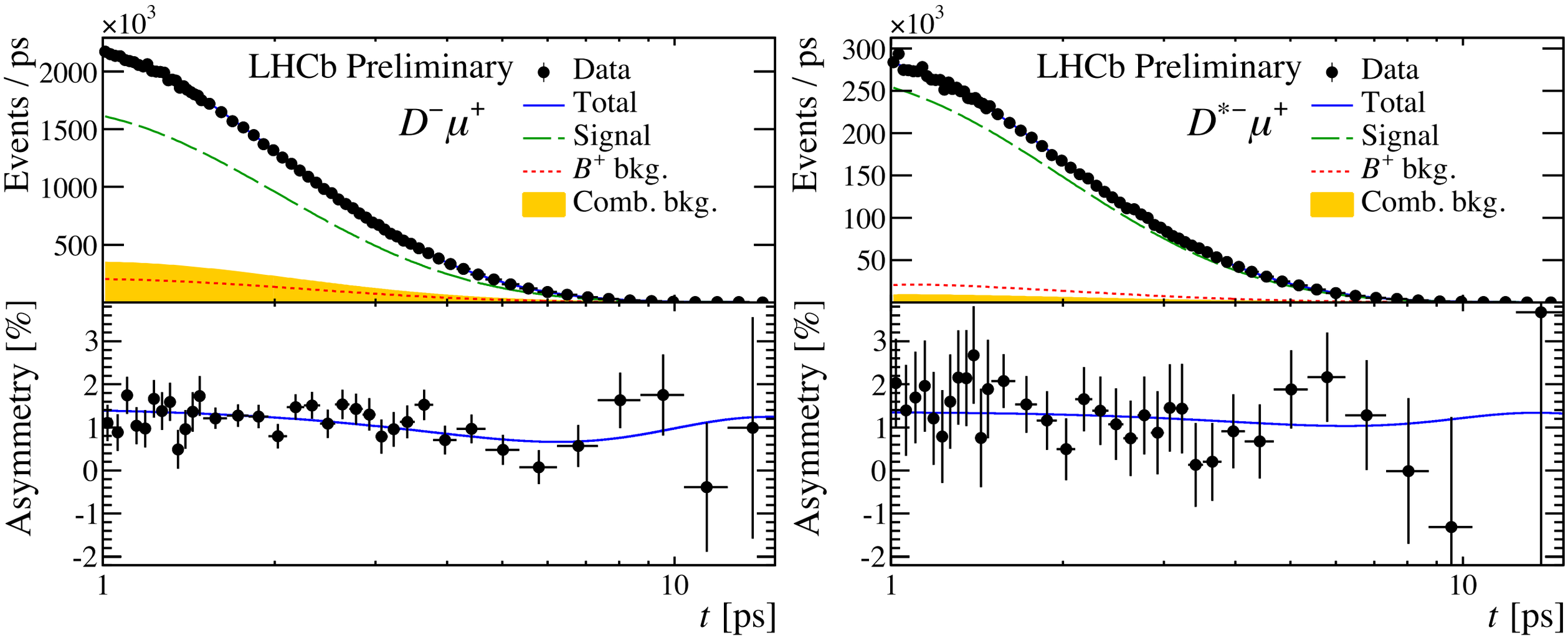
- Leading contribution: uncertainty on the measurement of the detection asymmetries

	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.

a_{sl}^{d} Measurement: Results (II)



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

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