# Semileptonic $B$ decays at LHCb

Beauty 14-18 July 2014,
University of Edinburgh

Katharina Kreplin,
on behalf of the LHCb collaboration

Heidelberg University

2014-07-14

$B_c^+$ lifetime measurement using $B_c^+ \to J/\psi\, \mu^+ \nu_\mu X$ decays

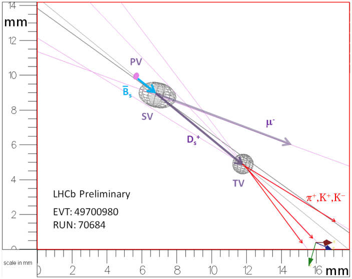
Measurement of the flavour-specific *CP*-violating asymmetry $a_{SL}^s$

# Semileptonic *B* decays

- high trigger efficiency + large branching fractions

⇒ high statistics, precise measurements

- event topology: low backgrounds
- flavour specific final state provides tagging for charm *CPV* measurements (see Angelo Carbone's talk)




⇒ LHCb has unique opportunity to study $B_s^0$ (only partially explored at *B* factories) and $B_c^+$ (previously only explored at Tevatron) semileptonic decays

# $B_c^+$ lifetime physics motivation

- precise measurement of $B_c^+$ lifetime essential input to theoretical models

| Group | prediction | approach | |
|---|---|---|---|
| Beneke and Buchalla | 0.4–0.7 ps | OPE based | PRD 53 4991 |
| Anisimov et. al. | 0.59±0.06 ps | constituent quark model, light-front | PLB 452 129 |
| Kiselev et. al. | 0.48±0.05 ps | QCD sum rules | Nucl. PB 585 353 |

- $B_c^+$ experimental analyses: uncertainty on lifetime becomes dominant systematic for relative branching fractions measurement and affects the determination of production cross-section

| Experiment | $\tau_{B_c}$ (ps) | | | Mode | |
|---|---|---|---|---|---|
| CDF | 0.46 | $^{+0.18}_{-0.16}(stat)$ | $\pm 0.03(syst)$ | $J/\psi\ \ell^+\ \nu$ | PRL 81 2432 |
| CDF II | 0.463 | $^{+0.073}_{-0.065}(stat)$ | $\pm 0.036(syst)$ | $J/\psi\ e^+\ \nu_e$ | PRL 97 012002 |
| D0 | 0.448 | $^{+0.038}_{-0.036}(stat)$ | $\pm 0.032(syst)$ | $J/\psi\ \mu^+\ \nu_\mu$ | PRL 102 092001 |
| CDF II | 0.452 | $\pm 0.048(stat)$ | $\pm 0.027(syst)$ | $J/\psi\ \pi^+$ | PRD 87 011101 |
| PDG 2013 | 0.452 | $\pm 0.033$ | | | |

# Semileptonic vs. hadronic channel

$$B_c^+ \to J/\psi\, \mu^+ \nu_\mu X$$

## semileptonic pro's:

- high statistics ($\sim$ x 20)
- clear signature: 3 $\mu$
- lifetime unbiased selection
- no lifetime acceptance

## semileptonic con's:

- partial reconstruction
- rely on MC for $\nu$ correction (k-factor)
- dependence on form factor
- feed-down contributions

$$B_c^+ \to J/\psi\, \pi^+$$

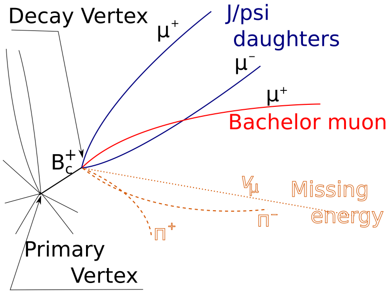
## hadronic con's:

- helicity suppressed
- large $\pi$ from PV background
- min IP cuts required
- correction for lifetime acceptance

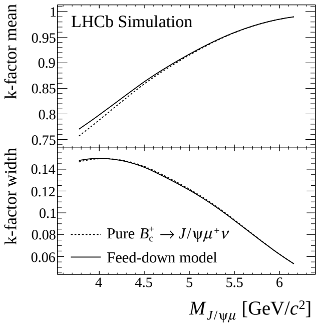
## hadronic pro's:

- full reconstruction
- simple data model
- easy background subtraction
- no feed-down contributions

# $B$ momentum correction by k-factor




- missing $\nu$ track
- correct $B$ momentum by
  $k = p_{rec}/p_{true}$
- folded into decay time resolution
- calculated as function of visible $B$ mass

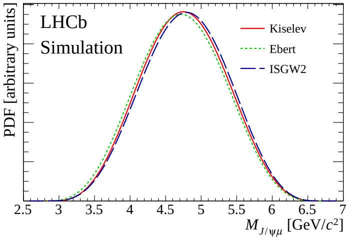



Eur. Phys. J. C (2014) 74:2839

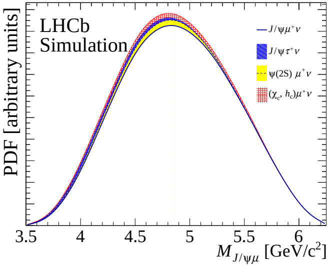
# Simulation inputs to the measurement

$(t, M_{J/\psi\,\mu})$ distribution for signal decays depends on:

- form factor model
- simple phase space model not sufficient, Kiselev best

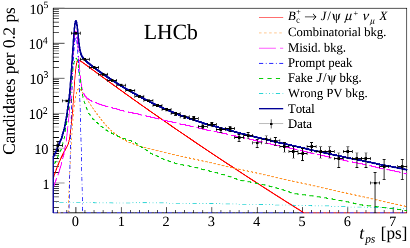



- contributions from feed-down modes
- modify $M_{J/\psi\,\mu}$ distribution to lower values

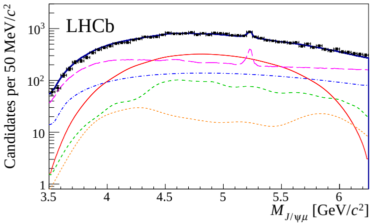



Eur. Phys. J. C (2014) 74:2839

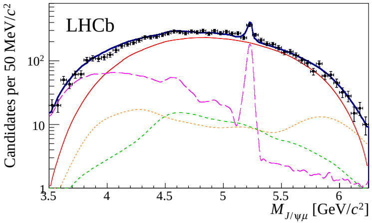
# $B_c^+ \to J/\psi\, \mu^+ \nu_\mu X$ lifetime fit




$-1.5 < t_{ps} < 8\,\mathrm{ps}$




$0.15 < t_{ps} < 8\,\mathrm{ps}$




backgrounds determined on data:

- misID of bachelor $\mu$
- prompt: true $\mu$, $J/\psi$ from PV
- fake $J/\psi$'s (sidebands)
- wrong PV association

backgrounds determined on MC:

- combinatorial: true $\mu$, $J/\psi$ from different vertices

Eur. Phys. J. C (2014) 74:2839

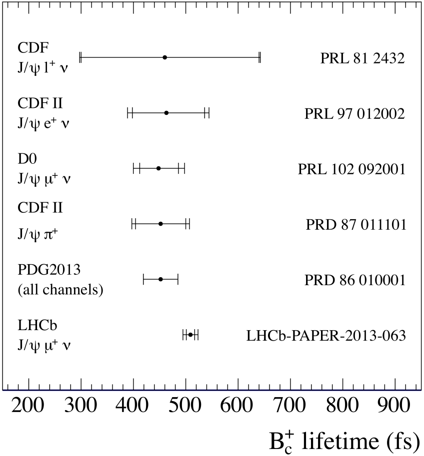
# $B_c^+$ lifetime result

$\tau = (509 \pm 8(\text{stat}) \pm 12(\text{syst}))\,\text{fs}$

dominant systematics:

| Source | $\sigma(B_c^+\tau)[\text{ fs }]$ |
|---|---|
| Combinatorial background shape | 7.3 |
| Prompt background model | 6.4 |
| $B_c^+$ decay model | 5.0 |

- most precise measurement to date
- consistent with world average, less than half the uncertainty
- used $2\,\text{fb}^{-1}$ of LHCb data
- further improvements expected from $B_c^+ \to J/\psi\,\pi^+$ decays



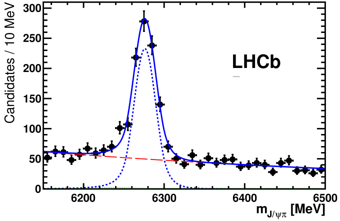

Eur. Phys. J. C (2014) 74:2839

# Measurement of the ratio of $B_c^+$ branching fractions

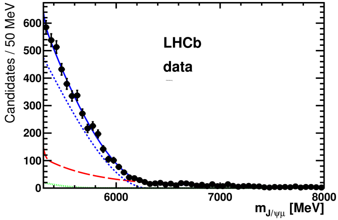
☞NEW

arXiv:1407.2126v1

$B_c^+ \to J/\psi\, \pi^+$




$B_c^+ \to J/\psi\, \mu^+ \nu_\mu$




$$\mathcal{R} = \frac{\mathcal{B}(B_c^+ \to J/\psi\, \pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\, \mu^+ \nu_\mu)}$$

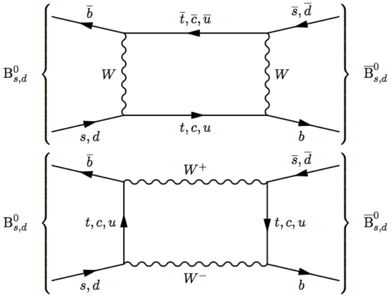
- $m_{J/\psi\,\mu} > 5.3\,\mathrm{GeV}$: many reconstruction uncertainties cancel
- $\mathcal{R}$ extrapolated to full phase space using theoretical predictions
- $\mathcal{R} = 0.0469 \pm 0.0028 \pm 0.0046$ using 1 $\mathrm{fb}^{-1}$ data @ 7 $\mathrm{TeV}$

# $B_q^0$- $\overline{B}_q^0$ oscillations

$$i\frac{d}{dt}\begin{pmatrix}|B_q^0(t)\rangle\\ |\overline{B}_q^0(t)\rangle\end{pmatrix} = \mathcal{H}_{eff}\begin{pmatrix}|B_q^0(t)\rangle\\ |\overline{B}_q^0(t)\rangle\end{pmatrix}$$

$$\mathcal{H}_{eff} = \begin{pmatrix}M_{11} - \frac{i}{2}\Gamma_{11} & M_{12} - \frac{i}{2}\Gamma_{12}\\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & M_{22} - \frac{i}{2}\Gamma_{22}\end{pmatrix}$$

$$\phi_{12} \equiv \arg\left(-M_{12}/\Gamma_{12}\right)$$



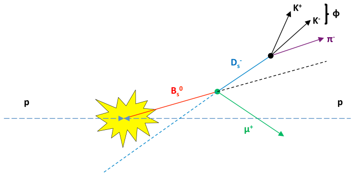

- flavour-specific *CP* asymmetry:

$$a_{SL}^q = \frac{\Gamma(\overline{B}_q^0 \to B_q^0 \to f_{SL}) - \Gamma(B_q^0 \to \overline{B}_q^0 \to \overline{f_{SL}})}{\Gamma(\overline{B}_q^0 \to B_q^0 \to f_{SL}) + \Gamma(B_q^0 \to \overline{B}_q^0 \to \overline{f_{SL}})} \simeq \frac{\Delta\Gamma}{\Delta M}\tan\phi_{12}$$

- precise SM prediction: $a_{SL}^s|^{SM} = (1.9 \pm 0.3) \times 10^{-5}$

A. Lenz, U. Nierste [arXiv:1102.4274 [hep-ph]]

# Time integrated measurement of $a_{SL}^s$




- using $B_s^0 \to D_s^- X \mu^+ \nu_\mu$ decays
- production asymmetry $a_\mathrm{P}$
- fast $B_s^0$ oscillation frequency

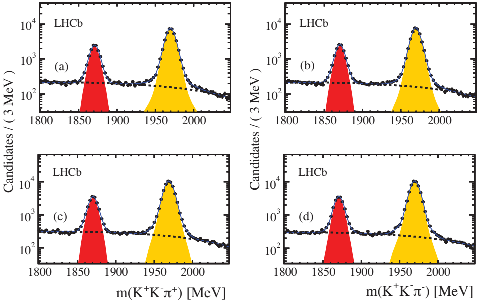
$$A_\mathrm{meas} \equiv \frac{\Gamma[D_s^-\mu^+]-\Gamma[D_s^+\mu^-]}{\Gamma[D_s^-\mu^+]+\Gamma[D_s^+\mu^-]}$$

$$= \frac{a_{SL}^s}{2} + \Big[\underbrace{a_\mathrm{P}}_{\sim 1\%} - \frac{a_{SL}^s}{2}\Big] \underbrace{\frac{\int_{t=0}^{\infty} e^{-\Gamma_s t}\cos(\Delta M_s\, t)\epsilon(t)dt}{\int_{t=0}^{\infty} e^{-\Gamma_s t}\cosh(\frac{\Delta\Gamma_s\, t}{2})\epsilon(t)dt}}_{\sim 0.2\%,\quad (\sim 80\%\quad a_{SL}^d)}$$

$$A_\mathrm{meas} \approx \frac{a_{SL}^s}{2} = \frac{N(D_s^-\mu^+) - N(D_s^+\mu^-)\times\frac{\epsilon(\mu^+)}{\epsilon(\mu^-)}}{N(D_s^-\mu^+) + N(D_s^+\mu^-)\times\frac{\epsilon(\mu^+)}{\epsilon(\mu^-)}} - A_\mathrm{track} - A_\mathrm{bkg}$$

while the measurement of $a_{SL}^d$ is time-dependent

# Ingredients I: signal yields




- $D^+$ mass, $D_s^+$ mass

(a) $K^+K^-\pi^+$ magnet up

(b) $K^+K^-\pi^-$ magnet up

(c) $K^+K^-\pi^+$ magnet down

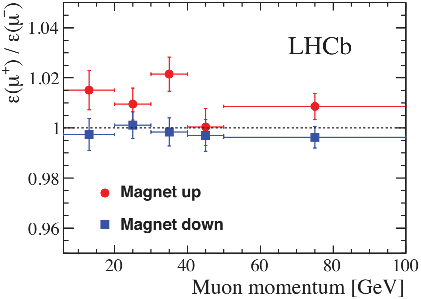
(d) $K^+K^-\pi^-$ magnet down

PLB 728 607 (2014)

- reverse magnetic field: average out residual charge asymmetries in detection efficiency
- background sources: prompt charm production, fake $\mu$ associated with real $D_s^+$ produced in $b$ hadron decays, $B \rightarrow DD_s^+$ where $D$ decays semileptonically

# Ingredients II: detection asymmetries

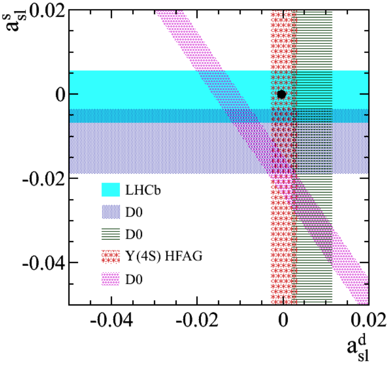
- tag & probe methods to measure $\mu$ efficiencies (trigger and ID)




PLB 728 607 (2014)

- independent of momentum
- small difference due to alignment of muon stations, affects predominantly hardware muon trigger

# $a_{SL}^s$ result




PLB 728 607 (2014)

- most precise measurement to date: $a_{SL}^s = (-0.06 \pm 0.50 \pm 0.36)\%$
- using $1\,\text{fb}^{-1}$ of data @ 7 TeV
- consistent with SM: $a_{SL}^s|^{SM} = (0.0019 \pm 0.0003)\%$
  A. Lenz, U. Nierste [arXiv:1102.4274 [hep-ph]]
- $3\,\text{fb}^{-1}$ analyses on $a_{SL}^s$ and $a_{SL}^d$ in preparation:
  - $\sigma(a_{SL}^s) \sim 0.2 - 0.3\%$
  - $\sigma(a_{SL}^d) \sim 0.36\%$

# Summary

LHCb has performed the most precise measurements:

- for the $B_c^+$ lifetime using $B_c^+ \to J/\psi\,\mu^+\nu_\mu X$ decays (on 2 $\text{fb}^{-1}$ data):

  $$\tau = (509 \pm 8(\text{stat}) \pm 12(\text{syst}))\,\text{fs}$$

  expect further improvements from $B_c^+ \to J/\psi\,\pi^+$ decays
- for the flavour-specific *CP*-violating asymmetry $a_{SL}^s$ (on 1 $\text{fb}^{-1}$ data):

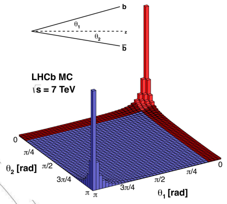
  $$a_{SL}^s = (-0.06 \pm 0.50 \pm 0.36)\%$$

  update on $a_{SL}^s$ and measurement of $a_{SL}^d$ using 3 $\text{fb}^{-1}$ data coming soon

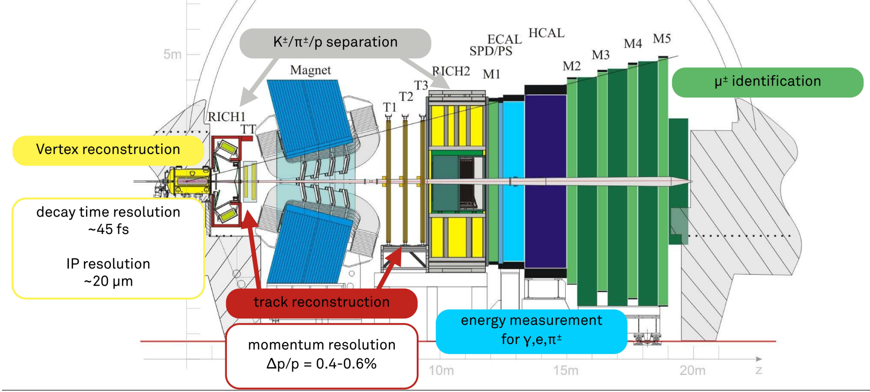
Ongoing studies:

- measurement of $|V_{ub}|$ using $\Lambda_b^0 \to p\mu^-\nu$ and $B_s^0 \to K^+\mu^-\nu$ decays

# The LHCb Detector



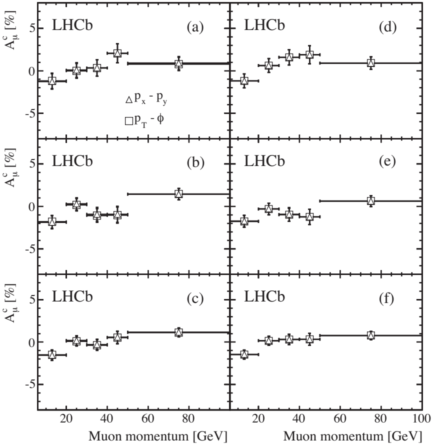

- single arm spectrometer ($2 < \eta < 5$)
- correlated (incoherent) production of *b* quark pairs in *pp*-collisions
  - harsh hadronic environment requires efficient triggers
  - dedicated for the study of *b* and *c* hadrons



# $B_c^+$ lifetime systematics

| Source | Assigned systematic [fs] |
|---|---|
| $B_c^+$ production model | 1.0 |
| $B_c^+$ decay model | 5.0 |
| Signal resolution model | 1.3 |
| Prompt background model | 6.4 |
| Fake $J/\psi$ background yield | 0.4 |
| Fake $J/\psi$ background shape | 2.3 |
| Combinatorial background yield | 3.4 |
| Combinatorial background shape | 7.3 |
| Misidentification background yield | 0.8 |
| Misidentification background shape | 1.2 |
| Length scale calibration | 1.3 |
| Momentum scale calibration | 0.2 |
| Efficiency function ($\beta$ factor) | 2.6 |
| Incorrect association to PV | 1.8 |
| Multiple candidates | 1.0 |
| Fit validation | 0.5 |
| Quadratic sum | 12.4 |

# $\mu$ corrected asymmetry




PLB 728 607 (2014)

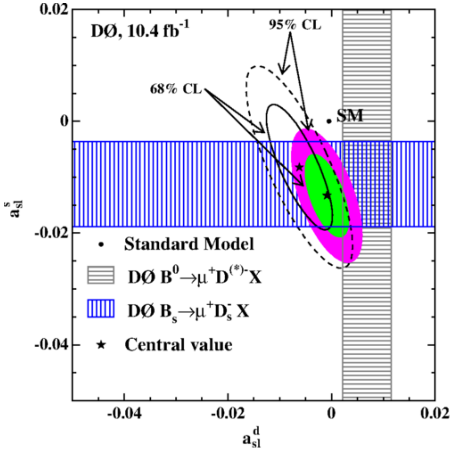
$$A_{\text{meas}} = \frac{a_{SL}^s}{2} = A_\mu^c - A_{\text{track}} - A_{\text{bkg}}$$

$$A_{\text{track}} = (+0.02 \pm 0.13)\%$$
$$A_{\text{bkg}} = (+0.05 \pm 0.05)\%$$
$$A_\mu^c = (+0.04 \pm 0.25)\%$$

$$a_{SL}^s = (-0.06 \pm 0.50 \pm 0.36)\%$$

| Source | $\sigma(A_{\mathbf{meas}})$[%] |
|---|---|
| Signal modelling and muon correction | 0.07 |
| Statistical uncertainty on the efficiency ratios | 0.08 |
| Background asymmetry | 0.05 |
| Asymmetry in track reconstruction | 0.13 |
| Field-up and field-down run conditions | 0.01 |
| Software trigger bias (topological trigger) | 0.05 |
| Total | 0.18 |

# D0 update

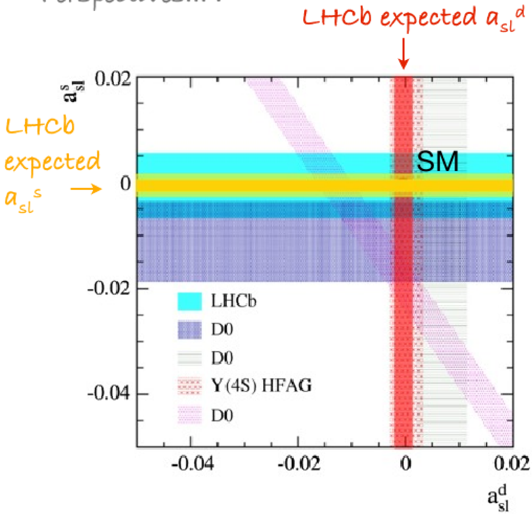



PRD 89 012002 (2014)

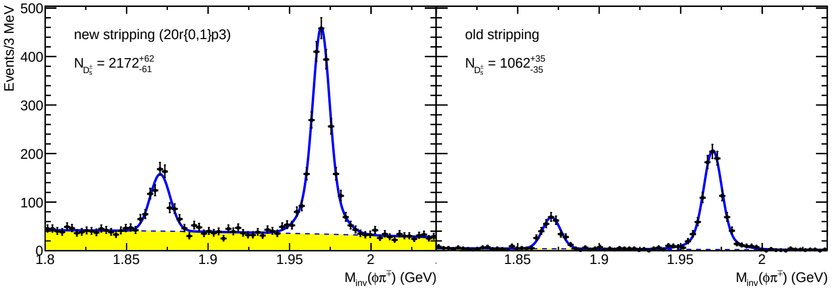
- 68% (full line) and 95% (dashed line) confidence level contours: best fit value of $\frac{\Delta\Gamma_d}{\Gamma_d} = 0.0050$
- filled contours: combination of all D0 measurements at best fit value of $\frac{\Delta\Gamma_d}{\Gamma_d} = 0.0079$
- 3.0 standard deviations difference from SM expectation

# $a_{SL}^s$ and $a_{SL}^d$ expectations – not official LHCb

Perspectives... :



# Improvement in statistical uncertainty for $a_{SL}^s$




- Double the $B_s^0 \to D_s^-(\phi\pi^+)\mu^+$ signal candidates with a loose stripping selection
- Add full $D_s^\mp \to KK\pi$ and $D_s^\mp \to 3\pi$ Dalitz plots

# New analysis strategy for $a_{SL}^s$

- Factorize $\mu$ and $\pi$ detection asymmetries in tracking-, interaction-, PID and trigger-asymmetries

$$\frac{a_{SL}^s}{2} = A_{\mathrm{raw}} - A_{\mathrm{det}}^{\pi} - A_{\mathrm{det}}^{\mu} - A_{\mathrm{det}}^{KK} - A_{\mathrm{bkg}}$$

with

$$A_{\mathrm{raw}} = \frac{N(\overline{B}_s^0 \to \mu^+ \nu_\mu D_s^-) - N(B_s^0 \to \mu^- \bar{\nu}_\mu D_s^+)}{N(\overline{B}_s^0 \to \mu^+ \nu_\mu D_s^-) + N(B_s^0 \to \mu^- \bar{\nu}_\mu D_s^+)}$$

and

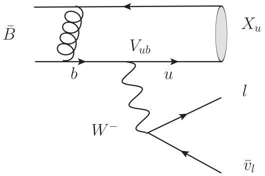
$$A_{\mathrm{det}} = A_{\mathrm{track}} + A_{\mathrm{interaction}} + A_{\mathrm{PID}} + A_{\mathrm{trigger}}$$

- $K$'s in $D_s^- \to \phi\pi^+$ are expected to be symmetric

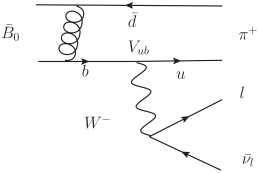
# $|V_{ub}|$ current status

- Semi-Leptonic B Decays:

Inclusive ($\bar{B} \to X_u l \bar{\nu}_l$)

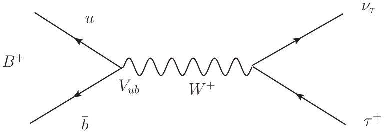



Exclusive ($\bar{B}_0 \to \pi^+ l \bar{\nu}_l$)



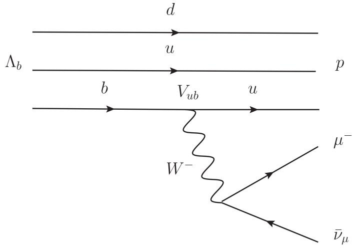

$|V_{ub}| = (4.41 \pm 0.15^{+0.15}_{-0.17}) \times 10^{-3}$ $\quad$ $|V_{ub}| = (3.23 \pm 0.31) \times 10^{-3}$

- Leptonic B decays ($B^+ \to \tau^+ \nu_\tau$):



# $|V_{ub}|$ at LHCb

- Large pion backgrounds hinder $B \to \pi\mu\nu_\mu$.
- Other possible decays: $\Lambda_b \to p\mu^-\bar{\nu}_\mu$ and $\bar{B}_s \to K^+\mu^-\bar{\nu}_\mu$




- Advantages of $\Lambda_b \to p\mu^-\bar{\nu}_\mu$:
  - $f_{\Lambda_b}/(f_u + f_d) \sim 0.40$ and $f_{\Lambda_b}/f_s \sim 3$
  - Proton provides a more distinctive final-state.