Semileptonic b-hadron decays at LHCb

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Outlines

1. LHCb experiment
2. Semileptonic @ LHCb
3. Summary

LHCb

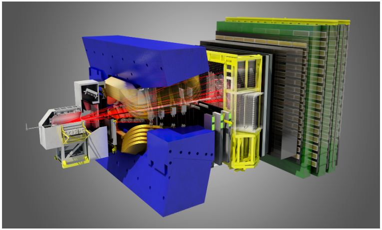
- LHCb experiment:
  - Indirect search for New Physics: probe effects of new particles in loops
  - Single-arm forward spectrometer
  - Unique η coverage ($2 < \eta < 5$)
- LHCb physics:
  - Designed to search for CP violation & Rare decays in Beauty & Charm
    - $\sigma(b\bar{b}) = (288 \pm 4 \pm 48)\,\mu\mathrm{b}^{-1}$@$7\,\mathrm{TeV}$

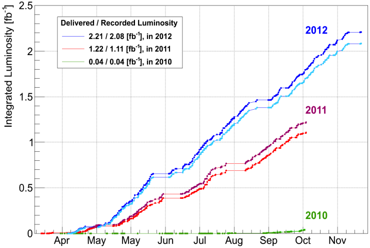
      Eur. Phys. J. C71 (2011) 1645

      $\sigma(b\bar{b}) = (298 \pm 3 \pm 36)\,\mu\mathrm{b}^{-1}$@$8\,\mathrm{TeV}$

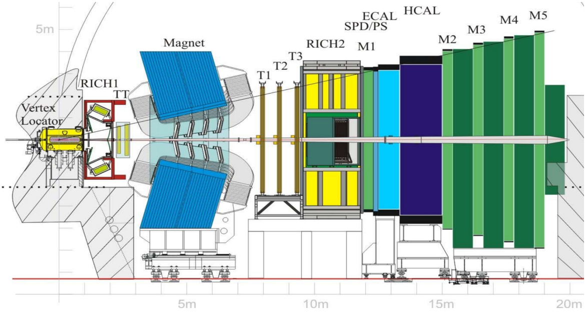
      J. High Energy Phys. 06 (2013) 064
    - $\sigma(c\bar{c}) = (1419 \pm 12 \pm 116 \pm 65)\,\mu\mathrm{b}^{-1}$@$7\,\mathrm{TeV}$

      Nucl. Phys. B871 (2013)
- LHCb luminosity:
  - Run I: $37\,\mathrm{pb}^{-1}$(2010), $1\,\mathrm{fb}^{-1}$(2011), $2\,\mathrm{fb}^{-1}$(2012)
  - data taking eff. $> 90\%$





LHCb detector



- VELO : $20\,\mu\mathrm{m}$ for high p_{T} tracks
- Tracking system : $\delta(p)/p = (0.4 - 0.6)\%$, reversible magnet polarity
- RICH system : ϵ(K ID) $\sim$ 95%, 5% $\pi \rightarrow$ K mis-id probability
- Calorimeter : Energy measurement, identify π^0,γ
- Muon detector : $\epsilon(\mu$ ID)$\sim$ 97%, $(1-3)\%, \pi \rightarrow \mu$ mis-id probability
- Trigger : $40\,\mathrm{MHz} \rightarrow 5\,\mathrm{kHz}$, efficiency($\mu$ trigger) $\sim$ 90%

Smoking guns from Semileptonics

- D0: Semileptonic asymmetries $a_{\mathrm{sl}}^{\mathrm{s}}$, $a_{\mathrm{sl}}^{\mathrm{d}}$ 3.σ from SM

  (Phys. Rev. D89 (2014) 012002)

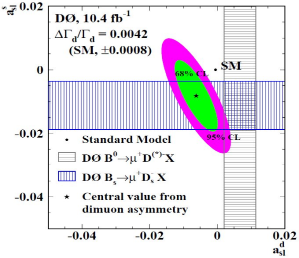
- BaBar: Combined semitaunic $\mathcal{R}(\mathrm{D}^*)$ & $\mathcal{R}(\mathrm{D})$ using $\mathrm{B}^0 \to \mathrm{D}\tau\nu$ 3.σ from SM prediction

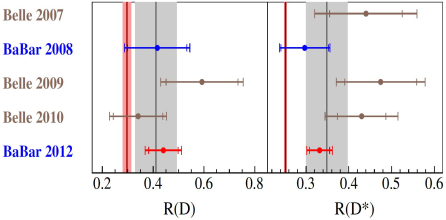
  (Phys. Rev. D88 (2013) 7, 072012)

- V_{ub} puzzle
  - $V_{\mathrm{ub}}(\mathrm{incl}) = (4.41 \pm 0.15) \times 10^{-3}$

    (Phys. Rev. Lett.104, 011802 (2010))
  - $V_{\mathrm{ub}}(\mathrm{excl}) = (3.28 \pm 0.29) \times 10^{-3}$

    (HFAG)





Semileptonic program at LHCb

- *b*-hadron cross sections, production fractions & production asymmetries
- Measuring the mixing frequencies $\Delta m_{\rm d}$ and $\Delta m_{\rm s}$
- Semileptonic asymmetries $a_{\rm sl}^{\rm s}$ and $a_{\rm sl}^{\rm d}$ in the neutral $\rm B_s^0$ and $\rm B^0$ systems
  - $a_{\rm sl}^{\rm d}$ measurement at LHCb: Lucia Grillo talk https://indico.cern.ch/event/253826/session/7/contribution/80
- Branching fraction in semileptonic channels $\rm B^0 \to D^{*-}\tau^+\nu$ and $\rm B^0 \to D^-\tau^+\nu$
- Measurement of CKM elements $V_{\rm ub}/V_{\rm cb}$

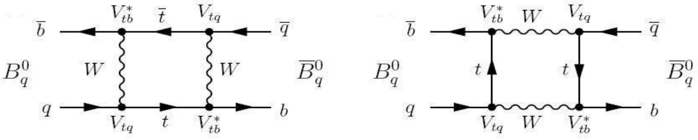
Δm_{s} & Δm_{d}

Observation of Δm_{s} and measuring Δm_{d}

Eur. Phys. J. C (2013) 73:2655

Measuring Δm_{d} & Δm_{s}

- Flavour oscillation through electroweak interaction in neutral B mesons



$$N_{\pm}(t) \propto e^{\frac{-t}{\tau}}(\cosh(\Delta\Gamma_{\mathrm{q}} t/2) \quad \pm \quad q\cos(\Delta m_{\mathrm{q}} t))$$

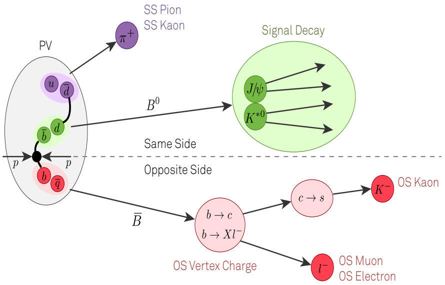
- Tagged time-dependent analysis in $\mathrm{B}^0_{(\mathrm{s})} \to \mathrm{D}^-_{(\mathrm{s})}\mu^+\nu$ decays
  - q: mixing state of $\mathrm{B_q}$ $\to$ determine $\mathrm{B_q}$ flavour at production
  - t: proper time of $\mathrm{B_q}$ $\to$ determine $t = \frac{\text{Decay length} \times \text{mass}}{\text{momentum}}$ correctly

Flavour tagging

- Determine the flavour of $\mathrm{B_q}$ at production in LHCb

  (Eur. Phys. J. C72 (2012) 2022)

  - Opposite B: μ, e from semileptonics, K from cascade, inclusive secondary vertex form B decay products
  - Fragmentation: π or K associated to signal B

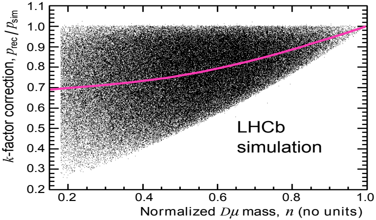


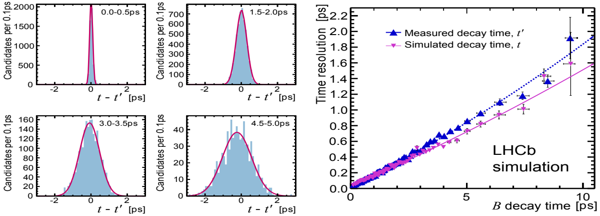
- Tag Decision ($q_i = \pm 1, 0$): NNet output
- Flavour tagging is Not perfect
  - Mistag probability: ω

$$N_{\pm}(t) \propto e^{\frac{-t}{\tau}} (\cosh(\Delta\Gamma_{\mathrm{q}} t/2) \quad + \quad q(1-2\omega) \cos(\Delta m_{\mathrm{q}} t))$$

Determination of B decay time

- Wrong B momentum due to missing particle $\rightarrow$ wrong t
- Correct t using k-factor method
  - $k(m_{\mathrm{B}})$: p_{rec}/p_{true} as a function of B mass from simulation
  - Apply correction function on data
- Time-dependent resolution function

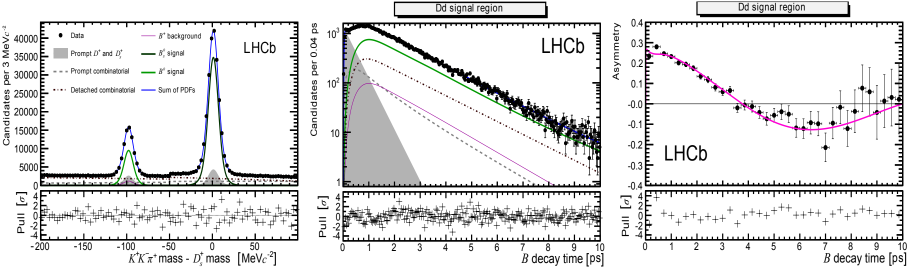




$$N_{\pm}(t) \propto e^{\frac{-t}{\tau}}(\cosh(\Delta\Gamma_{\mathrm{q}} t/2) \quad + \quad q(1-2\omega)\cos(\Delta m_{\mathrm{q}} t)) \otimes \mathcal{R}(t, \sigma_t)$$

Δm_{d} measurement

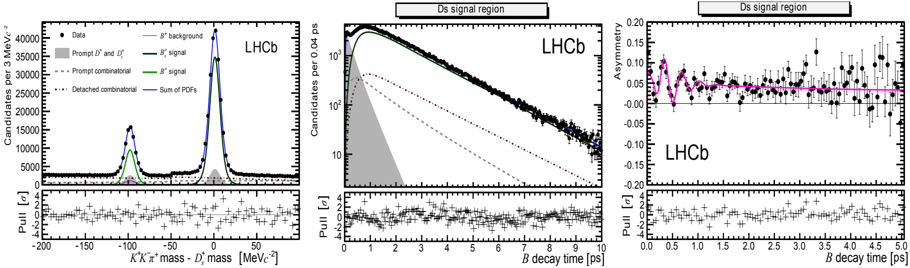
- Binned fit in Time, $KK\pi$ invariant mass and flavour tag, $1\,\mathrm{fb}^{-1}$ of 2011 data
- $\Delta m_{\mathrm{d}} = (0.503 \pm 0.011(\mathrm{stat}) \pm 0.013(\mathrm{syst}))\,\mathrm{ps}^{-1}$
  - PDG world average $\Delta m_{\mathrm{d}} = (0.510 \pm 0.003)\,\mathrm{ps}^{-1}$
  - World best by LHCb $\Delta m_{\mathrm{d}} = (0.5156 \pm 0.0051 \pm 0.0033)\,\mathrm{ps}^{-1}$ (Phys. Lett. B719'(2013) 318-325)



- $B^+ \to D^- \mu^+ \nu$ background: dominant systematic source
- Update using Cabibbo-favored modes $D^+ \to K^- \pi^+ \pi^+$ & $D^{*-} \to D^0(K^- \pi^+)\pi^-$

Δm_s observation

- Binned fit in Time, KKπ invariant mass and flavour tag, $1\,\mathrm{fb}^{-1}$ of 2011 data
- $\Delta m_s = (17.93 \pm 0.22(\mathrm{stat}) \pm 0.15(\mathrm{syst}))\,\mathrm{ps}^{-1}$
  - PDG world average $\Delta m_s = (17.768 \pm 0.023)\,\mathrm{ps}^{-1}$
  - World best by LHCb $\Delta m_s = (17.769 \pm 0.023 \pm 0.006)\,\mathrm{ps}^{-1}$ (New J. Phys. 15 (2013) 053021)



- Parametrization of the time-dependent resolution: dominant systematic source

a_{sl}^{s} & a_{sl}^{d}

Semileptonic asymmetries in the neutral $\mathrm{B_q}$ system: a_{sl}^{q}

Phy. Lett B 728 (2014) 607-615

Semileptonic asymmetries in the neutral $\mathrm{B_q}$ system

- Flavour specific Asymmetry in neutral $\mathrm{B_q}$ semileptonic decays:

$$a_{\mathrm{sl}}^{\mathrm{q}} = \frac{\Gamma(\overline{\mathrm{B_q}}(t) \to f) - \Gamma(\mathrm{B_q}(t) \to \overline{f})}{\Gamma(\overline{\mathrm{B_q}}(t) \to f) + \Gamma(\mathrm{B_q}(t) \to \overline{f})} \simeq \frac{\Delta\Gamma_{\mathrm{q}}}{\Delta m_{\mathrm{q}}} \tan \phi_{\mathrm{M}}^{\mathrm{q}}$$

  - $\overline{\mathrm{B_q}}(t) \to f$ reachable via mixing, $\phi_{\mathrm{M}}^{\mathrm{q}}$: CP violating phase
- Small & known in Standard Model
  - $a_{\mathrm{sl}}^{\mathrm{s}} = (1.9 \pm 0.3) \times 10^{-5}$ (arXiv:1102.4274)
  - $a_{\mathrm{sl}}^{\mathrm{d}} = (-4.1 \pm 0.6) \times 10^{-4}$ (arXiv:1102.4274)
- $\Rightarrow$ Probe for New Physics

Measured semileptonic asymmetry at LHCb

- Measure $a_{\rm sl}^{\rm s}$ in semileptonic $\mathrm{B_s^0} \to \mathrm{D_s^-}\mu^+\nu$
- LHC is pp collider $\to$ account for particle-antiparticle production asymmetry

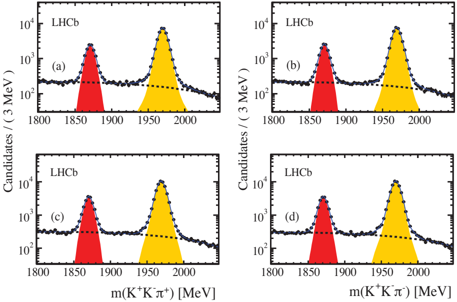
$$\mathrm{A_{meas}} = \frac{\Gamma(\mathrm{D_s^-}\mu^+) - \Gamma(\mathrm{D_s^+}\mu^-)}{\Gamma(\mathrm{D_s^-}\mu^+) + \Gamma(\mathrm{D_s^+}\mu^-)} = \frac{a_{\rm sl}^{\rm s}}{2} + \left(a_{\rm p} - \frac{a_{\rm sl}^{\rm s}}{2}\right)\frac{\int_0^\infty e^{-\Gamma_{\rm s}t}\cos(\Delta m_{\rm s}t)dt}{\int_0^\infty e^{-\Gamma_{\rm s}t}\cosh(\frac{\Delta\Gamma_{\rm s}t}{2})dt} \sim \frac{a_{\rm sl}^{\rm s}}{2}$$

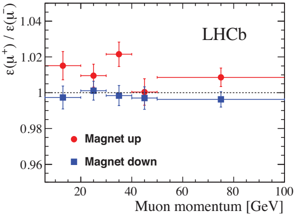
  - Large $\Delta m_{\rm s}$ $\to$ integral ratio ($\sim 0.2\%$), $a_{\rm p} \sim \mathcal{O}(1\%)$
- But $\mathrm{A_{meas}}$ is spoiled by other asymmetries
  - Magnet bends Oppositely charged particles in different detector halves
    - Charge induced asymmetries, solution: reverse the magnet polarity!
  - Tracking asymmetries: different cross section with detector material $\to$ data-driven techniques
  - Background asymmetry $\to$ data-driven techniques

$$\mathrm{A_{meas}} = \frac{\mathrm{N(D_s^-}\mu^+) - \mathrm{N(D_s^+}\mu^-) \times \frac{\epsilon^{\rm C}(\mu^+)}{\epsilon^{\rm C}(\mu^-)}}{\mathrm{N(D_s^-}\mu^+) + \mathrm{N(D_s^+}\mu^-) \times \frac{\epsilon^{\rm C}(\mu^+)}{\epsilon^{\rm C}(\mu^-)}} - \mathrm{A_{Tracking}} - \mathrm{A_{Bkg}}$$

Measured semileptonic asymmetry at LHCb

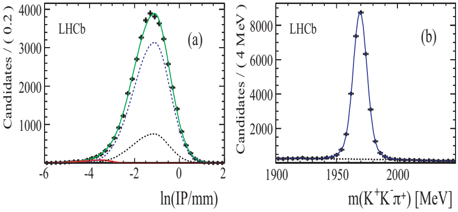
- Estimate the yield for $D_s^-\mu^+, D_s^+\mu^-$ in opposite magnet polarities separately
  - Binned fit into $KK\pi$ invariant mass
- Estimate Trigger and PID asymmetries for each polarity sample from data
  - Use $b \to J/\psi(\mu\mu)\ X$ calibration sample binned in p, px, py
- Calculate asymmetry for each magnet polarity:
  - $A_\mu^C(Up) = (+0.49 \pm 0.38)\%$
  - $A_\mu^C(Down) = (-0.41 \pm 0.32)\%$
- Average the two asymmetries:
  - $A_\mu^C = (+0.04 \pm 0.25)\%$





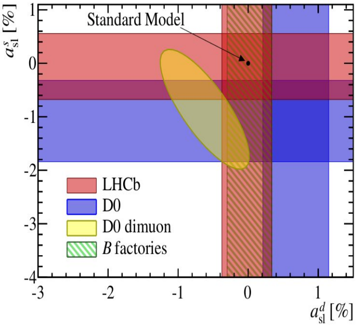
Measured semileptonic asymmetry at LHCb

- Final state $D_s^-(\to \phi(\to K^-K^+)\pi^-)\mu^+$: benefits from asymmetries cancellation
  - K^+K^-, $\pi^\pm\mu^\mp$ charge asymmetry in track reconstruction
  - Kinematic asymmetries around ϕ mass
- But cancellation is imperfect:
  - Small residual $A^{\pi\mu}_{track}$: estimated from $D^{*-} \to D^0\pi^+$
- $A_{Tracking} = (+0.02 \pm 0.13)\%$
- Background: Prompt charm, D_s + fake μ, semileptonic charm in $B \to DD_s$
- 2-D binned fit to D_s mass & $\log(IP)$
- $A_{Bkg} = (+0.05 \pm 0.05)\%$



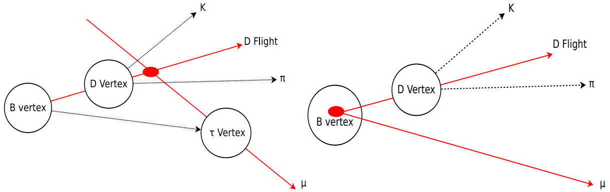
Experimental status of: a_{sl}^{s} & a_{sl}^{d}

- $a_{sl}^{s} = (+0.06 \pm 0.5(\text{stat.}) \pm 0.36(\text{syst.}))\%$ with $1\,\text{fb}^{-1}$
- $a_{sl}^{d} = (-0.04 \pm 0.19(\text{stat.}) \pm 0.30(\text{syst.}))\%$ with $3\,\text{fb}^{-1}$ (Preliminary!)
  - https://indico.cern.ch/event/253826/session/7/contribution/80
- Good agreement with SM
- Both measurements are most precise to date
- Results from LHCb + B-factories + D0:



Present quests

- Measurement of $\mathcal{R}(\mathrm{D}^{*-}) = \mathrm{B}^0 \to \mathrm{D}^{*-}\tau^+\nu / \mathrm{B}^0 \to \mathrm{D}^{*-}\mu^+\nu$ branching ratio
  - Theoretically clean but experimentally challenging: missing neutrinos
  - $\tau \to \pi\pi\pi\nu$:
    - Rich statistics but high background levels
    - Rely on relative position of τ and D vertex
  - $\tau \to \mu\nu\nu$:
    - Low statistics but low background
    - Rely on μD topology & τ flight



- Extract yields using Multi-dimensional fit:
  - Visible & corrected(Phys. Rev. D66 (2002) 079905) mass in bins of q^2 and isolation

Present quests

- $V_{\rm ub}$ at LHCb: investigating $\Lambda_{\rm b} \to {\rm p}\mu\nu$, ${\rm B}^0_{\rm s} \to {\rm K}^{-(*-)}\mu\nu$
  - Measuring $V_{\rm ub}/V_{\rm cb}$
- Use normalization modes: $\Lambda_{\rm b} \to \Lambda_{\rm c}\mu\nu$, ${\rm B}^0_{\rm s} \to {\rm D}^-_{\rm s}({\rm K}^-{\rm K}^0_{\rm S})\mu\nu$

$$\frac{\mathcal{B}(\Lambda_{\rm b} \to {\rm p}\mu\nu)}{\mathcal{B}(\Lambda_{\rm b} \to \Lambda_{\rm c}\mu\nu)} = \frac{|V_{\rm ub}|^2}{|V_{\rm cb}|^2} \times \frac{G(\Lambda_{\rm b} \to {\rm p}\mu\nu)}{G(\Lambda_{\rm b} \to \Lambda_{\rm c}\mu\nu)}$$

- Form factor are precisely predicted by lattice
- Use MVA to distinguish between signal and normalization modes
- Yields: binned Fit to corrected mass

Summary

- Thriving semileptonic program at LHCb experiment albeit challenging
- Provided measurements for $\Delta m_{\rm d}$ and $\Delta m_{\rm s}$ in neutral $\rm B_q$ systems using $1\,\rm fb^{-1}$
- Provided the most precise measurements for $a_{\rm sl}^{\rm d}$ using $3\,\rm fb^{-1}$ and $a_{\rm sl}^{\rm s}$ using $1\,\rm fb^{-1}$
  - Measurements are in agreement with Standard Model
- More results to come from LHCb
  - Update $a_{\rm sl}^{\rm s}$ and $\Delta m_{\rm d}$ measurements using $3\,\rm fb^{-1}$
  - Measurements of $V_{\rm ub}/V_{\rm cb}$, $\mathcal{R}(\rm D^{*-})$ & $\Lambda_{\rm b}$ form factors