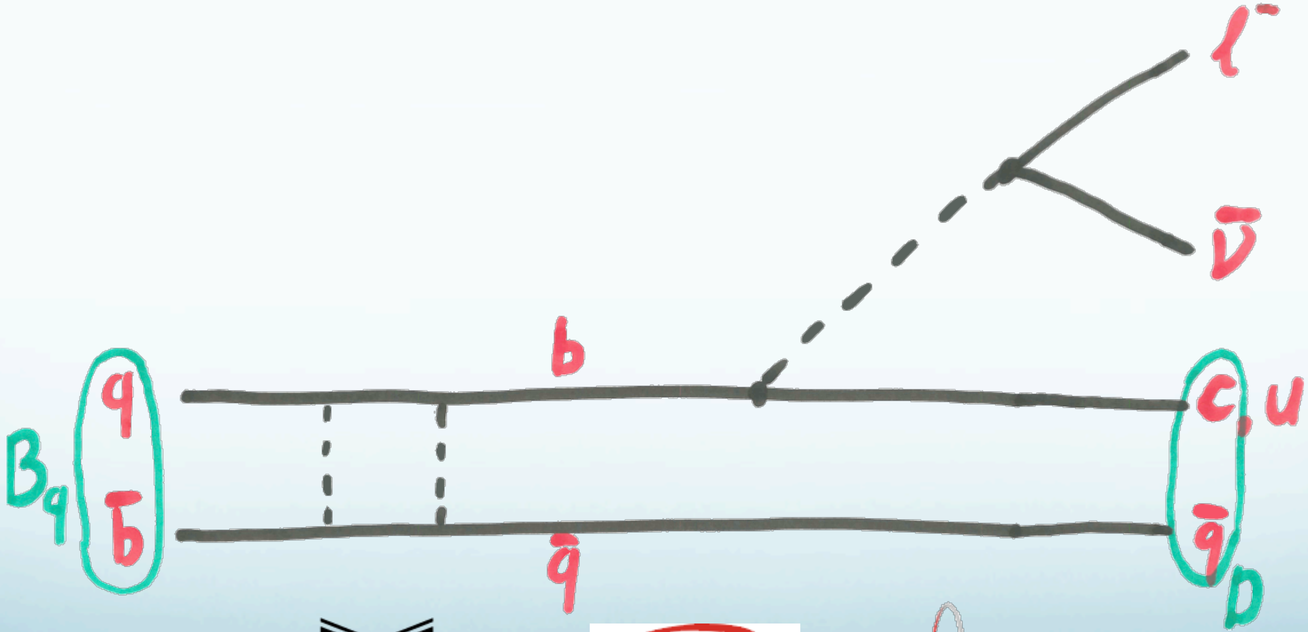
Exclusive $|V_{cb}|$

Experimental issues @ LHCb

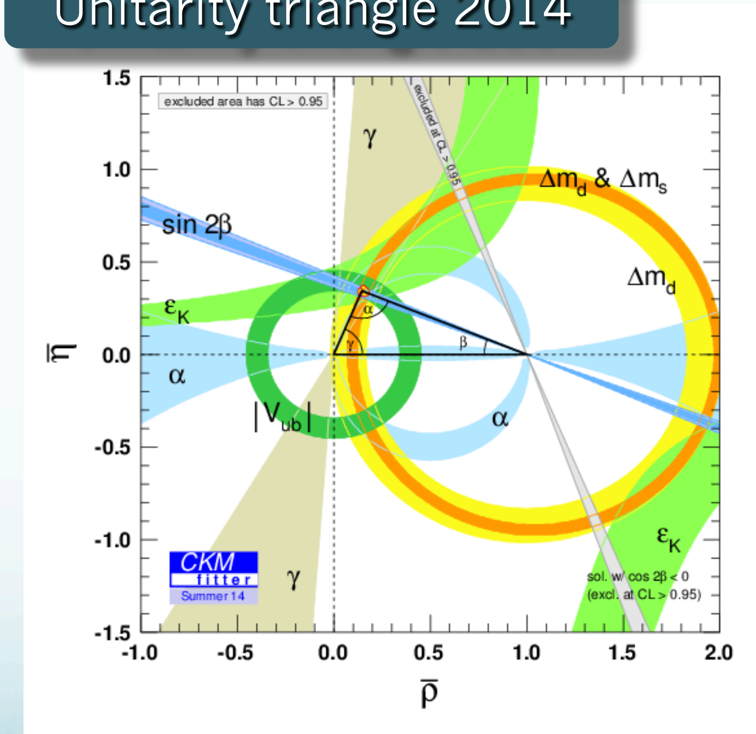
Jeroen van Tilburg



Why measure $|V_{cb}|$?

- Large part of uncertainty in ε_K
- Normalisation for UT sides
  - "Δm_d, Δm_s side"
  - "V_{ub} side"
- Theoretical side:
  - FF parametrization
  - Understanding of $R(D^{(*)})$.
- Ultimate test of CKM unitarity
  - In particular comparing with $\sin 2\beta$.
- Whole picture a bit confused…

Unitarity triangle 2014



Inclusive vs exclusive

- Unitarity test is disturbed by inclusive – exclusive discrepancy (both for V_{ub} and V_{cb}):

PDG:

$$|V_{cb}| = (42.2 \pm 0.7) \times 10^{-3} \text{ (inclusive)}$$
$$|V_{cb}| = (39.5 \pm 0.8) \times 10^{-3} \text{ (exclusive)}$$

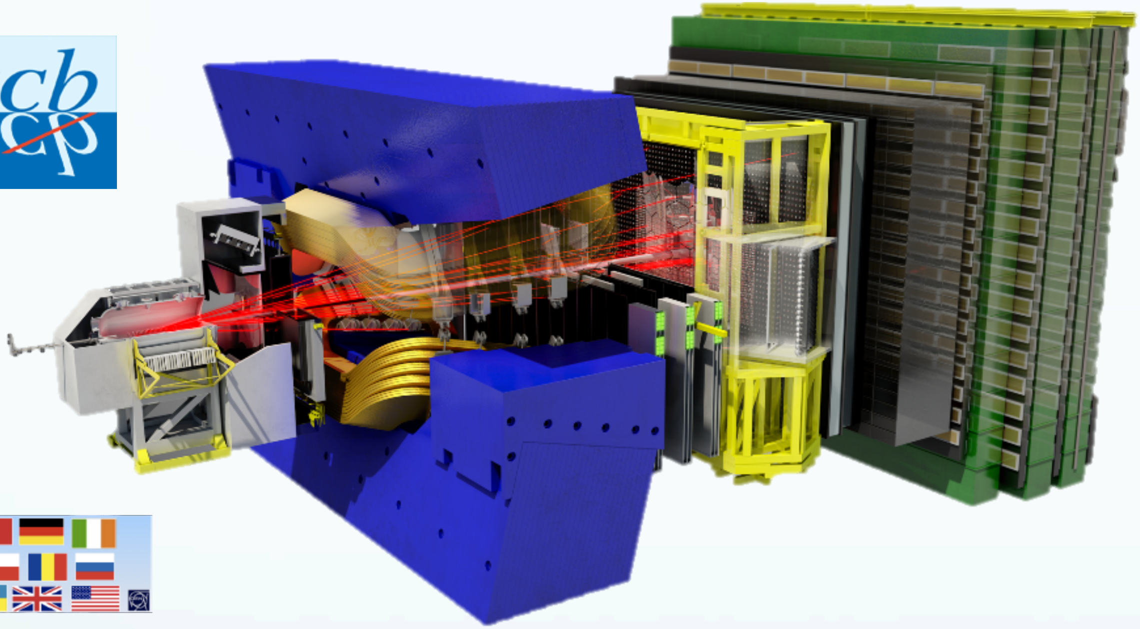
- PDG scales uncertainty by 2.6. Inclusive dominates the average.
- Latest FNAL/MILC calculation further increases the tension:

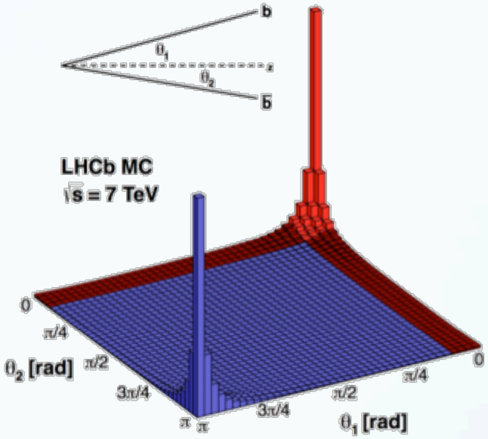
$$|V_{cb}|_{\text{excl.}} = (39.04 \pm 0.75) \times 10^{-3}$$

[Phys. Rev. D 89, 114504 (2014)]

What can the LHC contribute?

Designed to study *b* and c decays





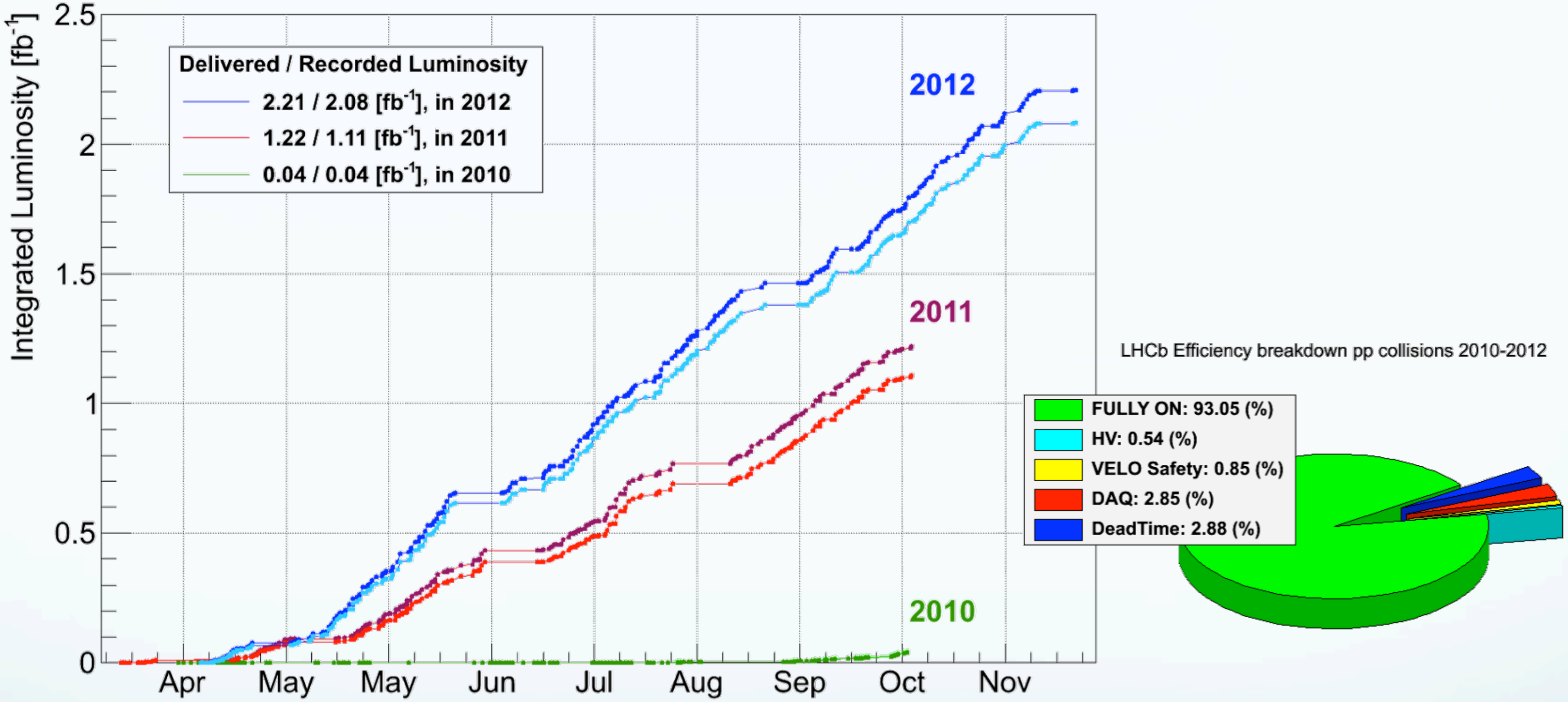
All *b*-hadrons produced
B^0, B^+, B_s, B_c, Λ_b, ...

Large production of beauty quarks:

$$\sigma(pp \to b\bar{b}X) = (284 \pm 20 \pm 49)\mu\mathrm{b} \quad @ \quad \sqrt{s} = 7\,\mathrm{TeV}$$

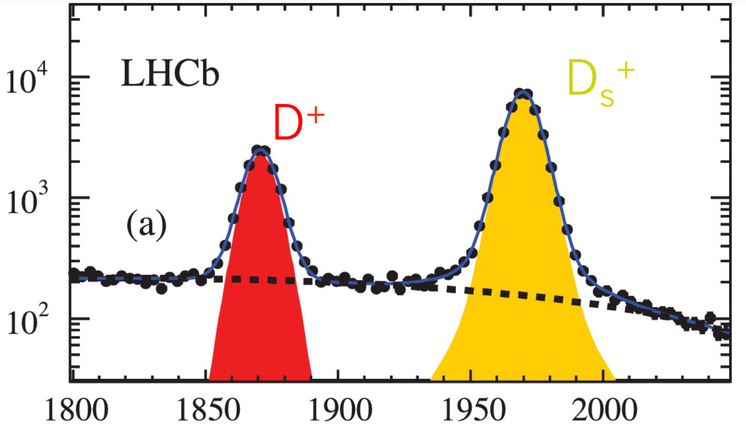
Phys. Lett. B 694 (2010) 209 (obtained from semileptonic decays).

Excellent performance

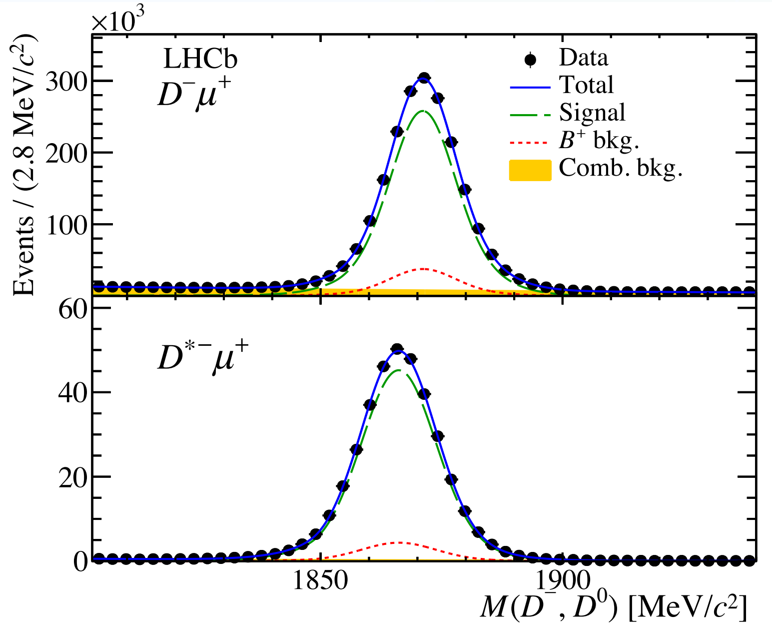


- Collected 3/fb in run 1 at 7-8 TeV.
- Expect to collect another 5/fb in run 2.
  - Note that at 13 TeV $b\bar{b}$ cross-section roughly doubles.
  - i.e. 4 times larger data sample than current.

Large and clean samples



[LHCb: PLB 728 (2014) 607-615]



[LHCb: PRL 114, 041601 (2015)]

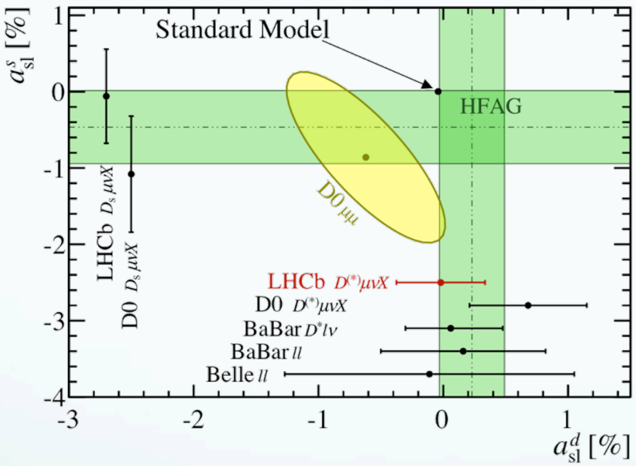
Millions of *B* candidates available.

Allow precision measurements

- Semileptonic asymmetries a_{sl}^{d} and a_{sl}^{s}.

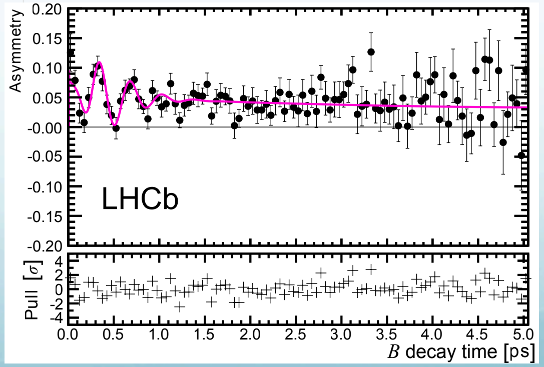
[LHCb: PLB 728 (2014) 607-615]

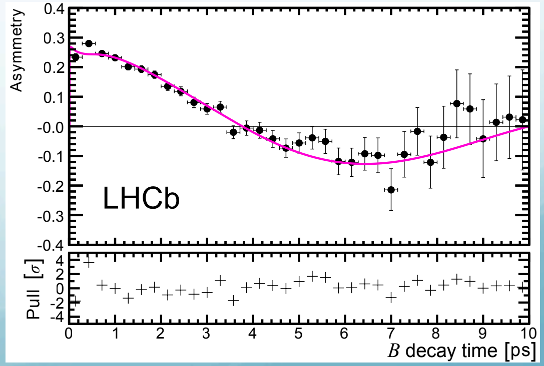
[LHCb: PRL 114, 041601 (2015)]



- B oscillation frequencies (esp. Δm_d).

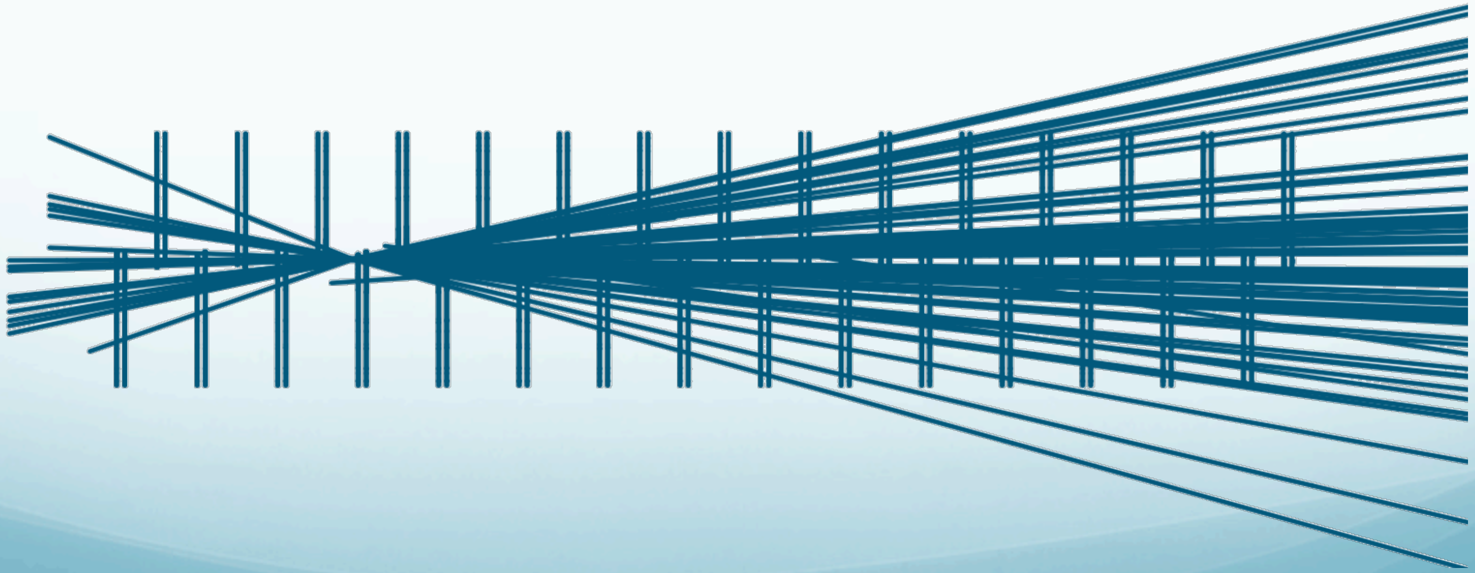
$\Delta m_{d,s}$ [EPJC 73 (2013) 12, 2655]





But… dirty hadronic enviroment

- Many other particles produced in the *pp* collision.
  - No possibility to use beam energy constraints.
- No kinematic constraints from other (tagging) *B*.
  - Also *b*-hadron production fractions poorly known.



What is possible at LHCb?

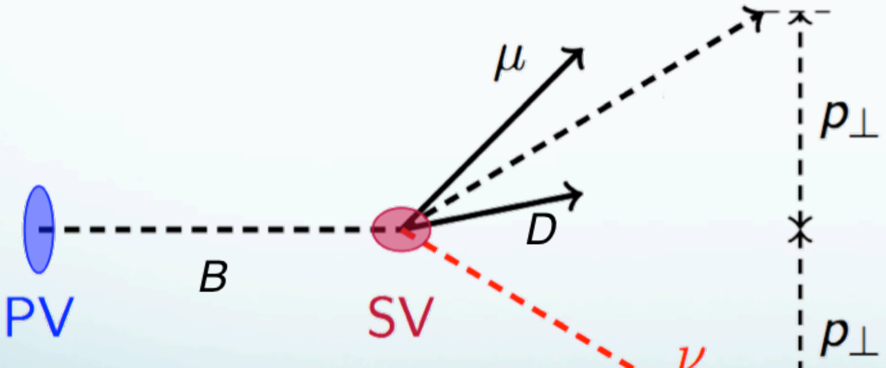
- Exclusive measurements already challenging
  - Fully inclusive measurements impossible?
- First exclusive $|V_{ub}|$ using $\Lambda_b \rightarrow p\,\mu\,\nu$
  - See talk by Ulrik on Thursday!
  - Well-identified proton gives clean signature
    - … but combinatoric background is relatively low.
- Paves the way for other semileptonic decays
  - $\Lambda_b \rightarrow \Lambda_c\,\mu\,\nu$
  - $B_s \rightarrow K\mu\nu$ and $B_s \rightarrow D_s\mu\nu$
  - $B \rightarrow \rho(\pi\pi)\mu\nu$
  - Other options: B_c?

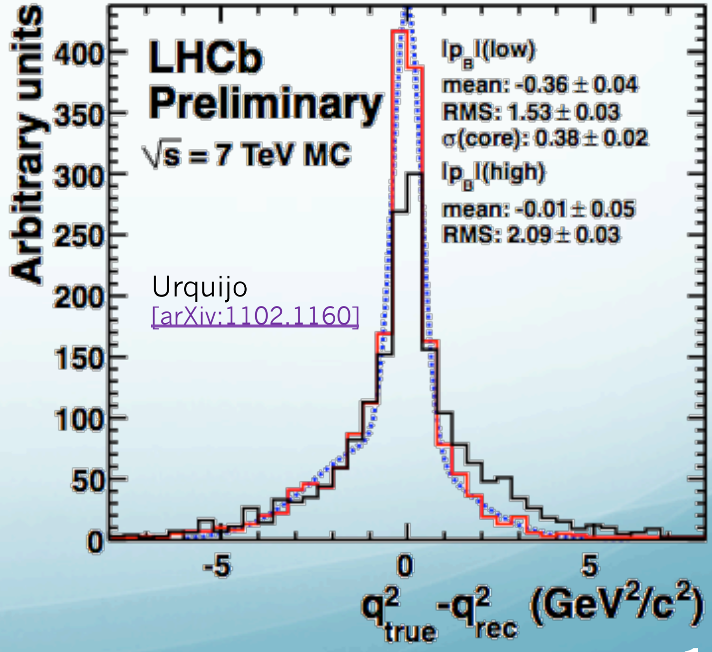
Exclusive V_{cb} at LHCb?

- Problem: cannot normalize to CF decay (as in V_{ub}).
- Normalization uncertainties:
  - $b\bar{b}$ cross-section → 19% LHCb: [PLB 694 (2010) 209]
    - Need normalization channel, or
    - use (almost) fully reconstructed OS tag.
  - b-hadron production fractions LHCb: [PRD 85 (2012) 032008]
    - Branching fractions for B_s and Λ_b not well known.
- Precision on rest-frame observables (q^2).
  - Neutrino reconstruction
  - Same-side tagging

Neutrino reconstruction

- Use pointing constraint to solve q^2 up to 2-fold ambiguity.
- Need to pick one solution.
- Need to worry about resolution effects (unfolding, bin-to-bin migration).

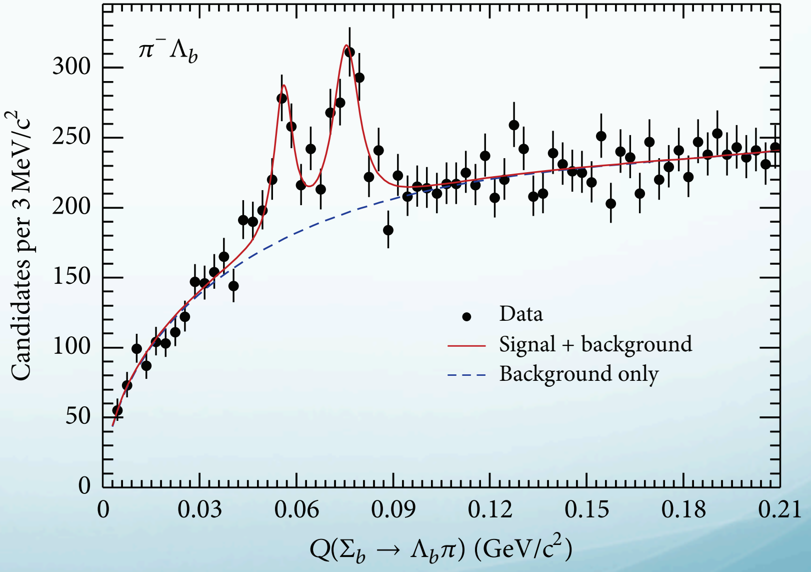




Urquijo [arXiv:1102.1160]

Same-side tagging (Σ_b)

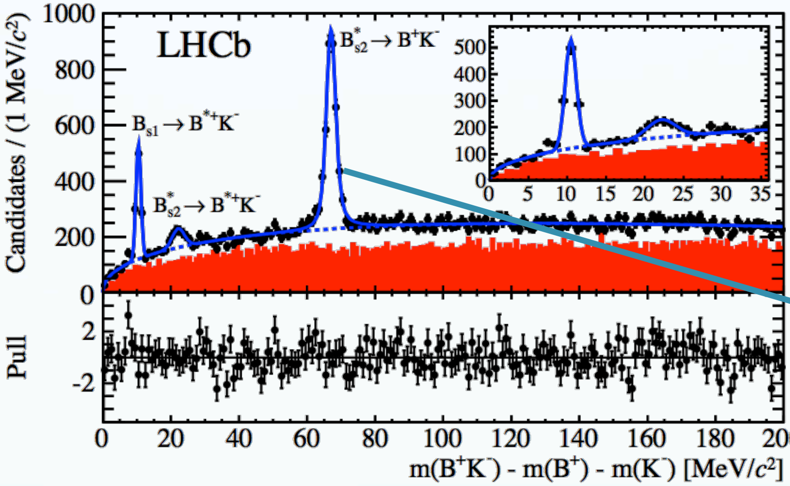
- Use $\Sigma_b \to \Lambda_b \pi$. Stone & Zhang: [Adv.High Energy Phys. 2014 (2014) 931257]
- Narrow width gives additional kinematic constraint.
- Challenge from the 4 overlapping states: $\Sigma_b^{\pm}$ and $\Sigma_b^{*\pm}$.
- Possible usage:
  - Study backgrounds in $\Lambda_b \to p\mu\nu$.
  - Branching fraction of $\Lambda_b \to \Lambda_c \tau \nu$.



From CDF: [Phys. Rev. D 85, 092011 (2012)]

Same-side tagging ($B_{s2}{}^{*}$)

- Also narrow width: $B_{s2}{}^{*} \rightarrow B^{+} K^{-}$



[Phys. Rev. Lett. 110 (2013) 151803]

~3000 candidates/fb

- Possible use for:
  - $B^{+} \rightarrow \rho(\pi\pi)\, \mu\, \nu$: Angular analysis to extract FFs and V_{ub}
  - $B^{+} \rightarrow D\, \mu\, \nu$: Study of D^{**} states and in $D^{0}\tau\nu$.
  - $B^{+} \rightarrow KK\, \mu\, \nu$: $s\bar{s}$-popping in $b \rightarrow u$. First measurement of $B^{+} \rightarrow \varphi\, \mu\, \nu$
- Extend to neutral B mesons: $B_{s2}{}^{*} \rightarrow B^{0} K^{0}$

b-hadron production fractions

[PRD 85 (2012) 032008]

- Use charm tag to determine *b*-hadron species
  - $B^{0+} \to D^{+0} \mu \nu X$, $B_s \to D_s \mu \nu X$, $\Lambda_b \to \Lambda_c \mu \nu X$
- Subtract prompt bkg and cross-feed, e.g.

$$B_s \to (D_s^{**} \to DK) X \mu^- \nu \rightleftarrows B^{0/+} \to D_s K X \mu^- \nu$$

  - Do not separate B^+ and B^0 to avoid $D^0 - D^+$ cross-feed.
- Assume semileptonic widths are universal
  - Small chromomagnetic correction for Λ_b.

$$\boxed{f_q = BR(b \to B_q)}$$

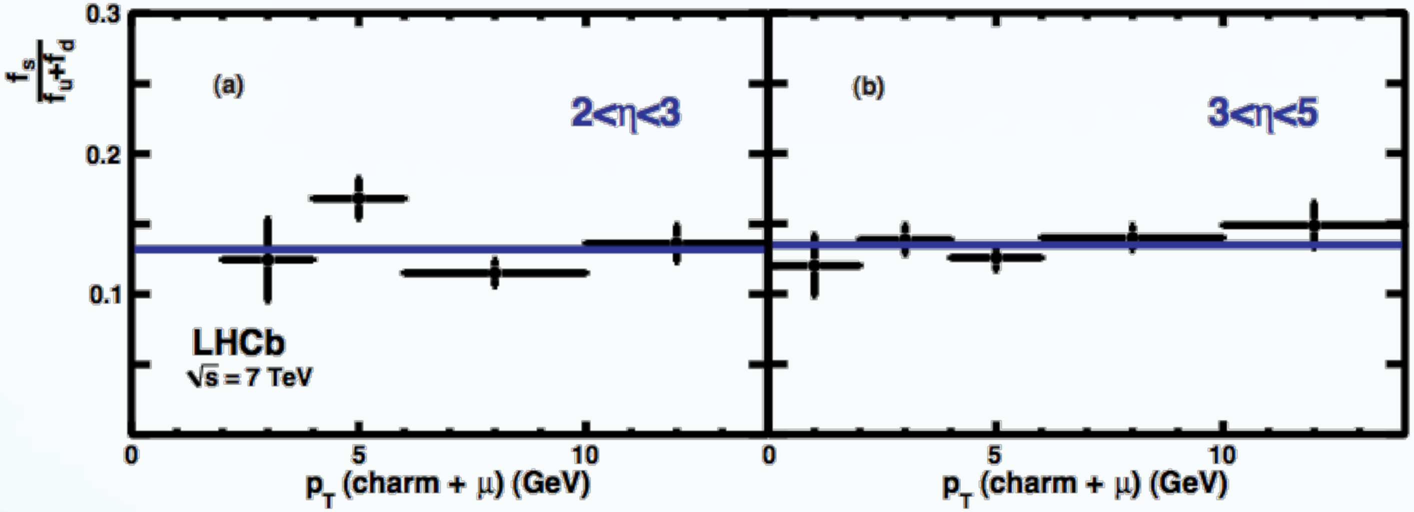
$$\frac{f_s}{f_u + f_d} = \frac{n_{\text{corr}}(\bar{B}_s^0 \to D \mu)}{n_{\text{corr}}(B \to D^0 \mu) + n_{\text{corr}}(B \to D^+ \mu)} \frac{\tau_{B^-} + \tau_{\bar{B}^0}}{2\tau_{\bar{B}_s^0}},$$

$$\frac{f_{\Lambda_b}}{f_u + f_d} = \frac{n_{\text{corr}}(\Lambda_b^0 \to D \mu)}{n_{\text{corr}}(B \to D^0 \mu) + n_{\text{corr}}(B \to D^+ \mu)} \times \frac{\tau_{B^-} + \tau_{\bar{B}^0}}{2\tau_{\Lambda_b^0}} (1 - \xi)$$

$$\boxed{\xi = 4 \pm 2\%}$$

B_s production fraction (from SL decays)

LHCb, 3 pb^{-1}
[PRD 85 (2012) 032008]



Flat in p_T

$$f_s/(f_u+f_d) = 0.134 \pm 0.004^{+0.011}_{-0.010}$$

Compare with:

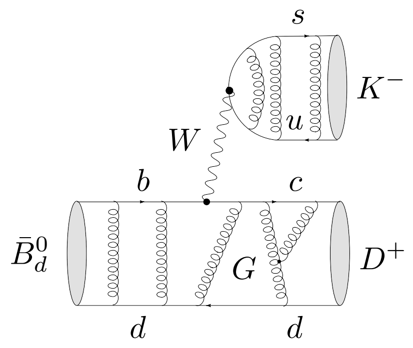
$$\frac{f_s}{f_u+f_d} = 0.128 \pm 0.012 \quad (LEP)$$
$$= 0.164 \pm 0.026 \quad (Tevatron)$$

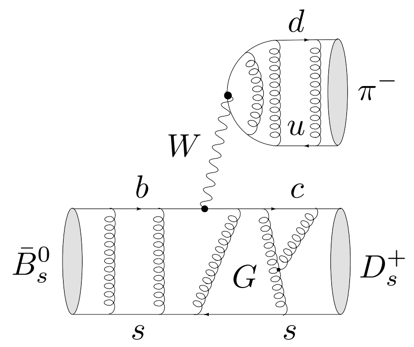
B_s production fraction (from hadronic decays)

- Alternative method

(Fleischer, Tuning and Serra [PRD82 (2010) 034038])

- Use branching ratio of $B_s \to D_s^- \pi^+$ over $B^0 \to D^- K^+$





$$
\begin{aligned}
\frac{f_s}{f_d} &= \frac{\mathcal{B}(B^0 \to D^- K^+)}{\mathcal{B}(B_s^0 \to D_s^- \pi^+)} \frac{\epsilon_{DK}}{\epsilon_{D_s\pi}} \frac{N_{D_s\pi}}{N_{DK}} \\
&= \Phi_{\mathrm{PS}} \left| \frac{V_{us}}{V_{ud}} \right|^2 \left(\frac{f_K}{f_\pi} \right)^2 \frac{\tau_{B^0}}{\tau_{B_s^0}} \frac{1}{\mathcal{N}_a \mathcal{N}_F} \frac{\mathcal{B}(D^- \to K^+\pi^-\pi^-)}{\mathcal{B}(D_s^- \to K^+K^-\pi^-)} \frac{\epsilon_{DK}}{\epsilon_{D_s\pi}} \frac{N_{D_s\pi}}{N_{DK}}
\end{aligned}
$$

Non-factorizable corrections:

$$\left| \frac{a_1(D_s\pi)}{a_1(D_dK)} \right|^2$$

Form factor ratio

$$\left[\frac{F_0^{(s)}(m_\pi^2)}{F_0^{(d)}(m_K^2)} \right]^2 \rightarrow$$

FNAL/MILC prediction:
1.046±0.044±0.015
[PRD85, 114502]

B_s production fraction (from hadronic decays)

- Measurement

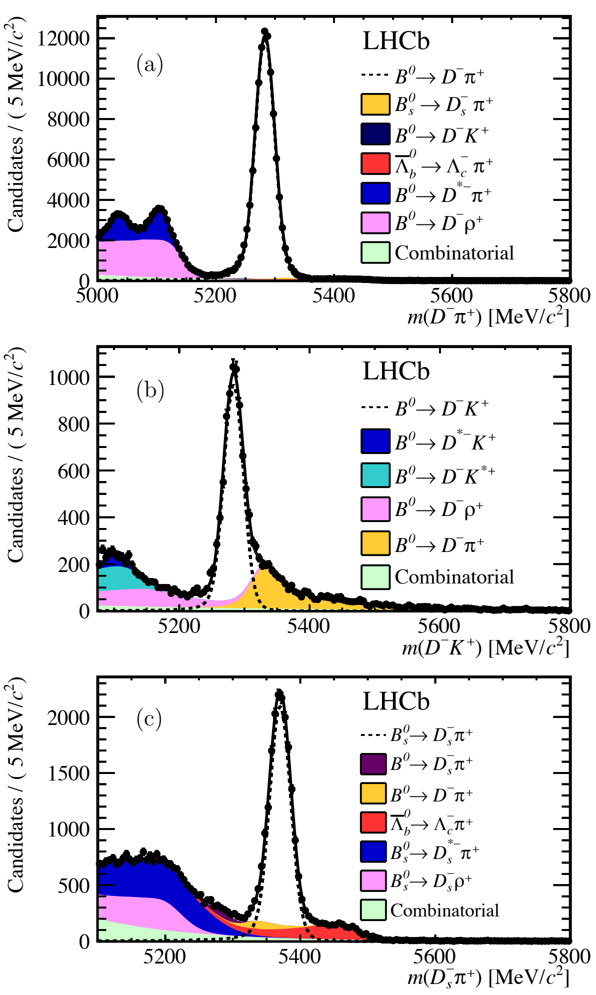
(LHCb, 1/fb [JHEP 1304 (2013) 001])

- Result:

$$
\begin{aligned}
\frac{f_s}{f_d} &= (0.261 \pm 0.004 \pm 0.017) \times \frac{1}{\mathcal{N}_a \mathcal{N}_F} \\
&= 0.238 \pm 0.004 \pm 0.015 \pm 0.021\,,
\end{aligned}
$$

Detector systematics: mainly trigger efficiency

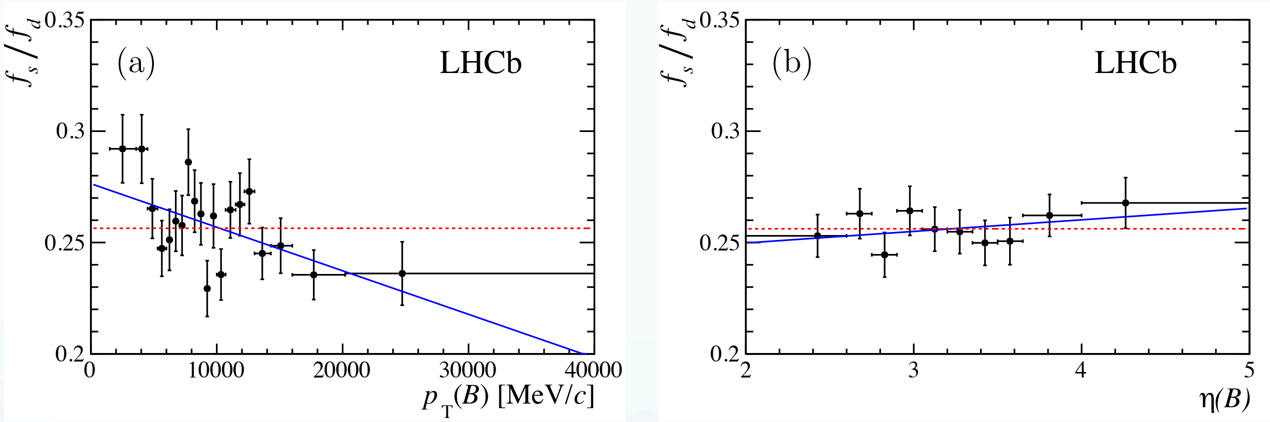
Theory error: Uncertainty of FF ratio.



B_s production fraction (from hadronic decays)

- Improved kinematic dependence
  - Using ratio: $B_s \to D_s^- \pi^+$ over $B^0 \to D^- \pi^+$

(LHCb, 1/fb [JHEP 1304 (2013) 001])



$$
\boxed{\begin{aligned}
f_s/f_d\ (p_\mathrm{T}) &= (0.256 \pm 0.020) + (-2.0 \pm 0.6) \times 10^{-3}/\ \mathrm{GeV}/c \times (p_\mathrm{T} - \langle p_\mathrm{T} \rangle) \\
f_s/f_d\ (\eta) &= (0.256 \pm 0.020) + (0.005 \pm 0.006) \times (\eta - \langle \eta \rangle),
\end{aligned}}
$$

B_s production fraction (combined)

- Combined measurement gives:
  - Assuming isospin f_u=f_d
  - Updated $\mathcal{B}(D_s \to KK\pi)$

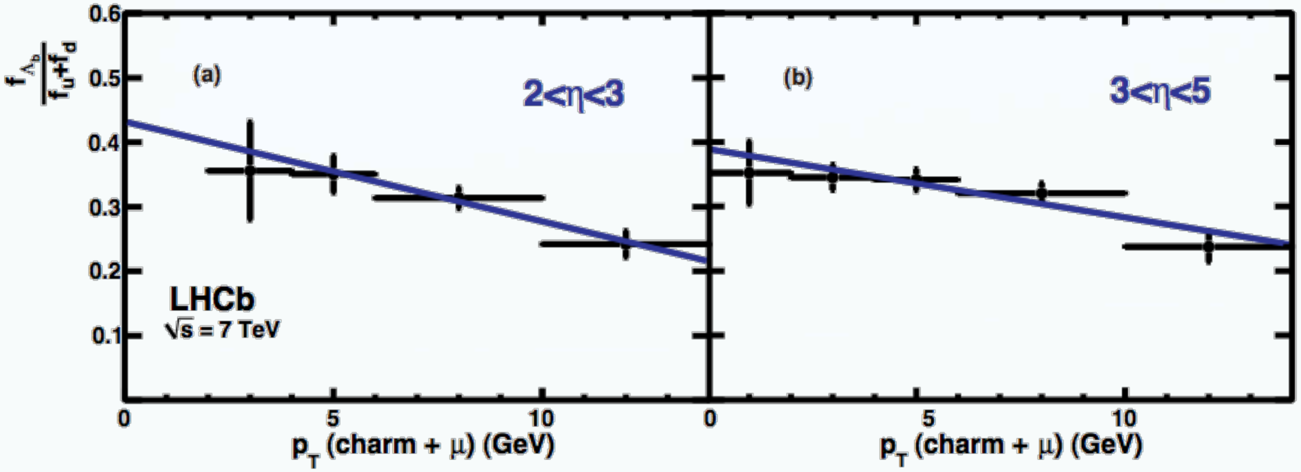
$$\frac{f_s}{f_d} = 0.259 \pm 0.015$$

See [LHCb-CONF-2013-011]

- Systematics dominated by
  - SU(3) breaking of FF ratio (hadronic)
  - Backgrounds, FFs, cross feeds (SL)
  - $\mathcal{B}(D_s \to KK\pi)$ and $\mathcal{B}(D^- \to K\pi\pi)$ (correlated)

Λ_b production fraction (from SL decays)

LHCb, 3 pb^{-1}
[PRD 85 (2012) 032008]



Depends on p_T

$$\left[\frac{f_{\Lambda_b}}{f_u+f_d}\right](p_T) = (0.404 \pm 0.017 \pm 0.027 \pm \boxed{0.105}) \times [1 - (0.031 \pm 0.004 \pm 0.003) \times p_T(\text{GeV})],$$

Systematics dominated by $\mathcal{B}(\Lambda_c \to pK\pi) = (5.0 \pm 1.3)\%$

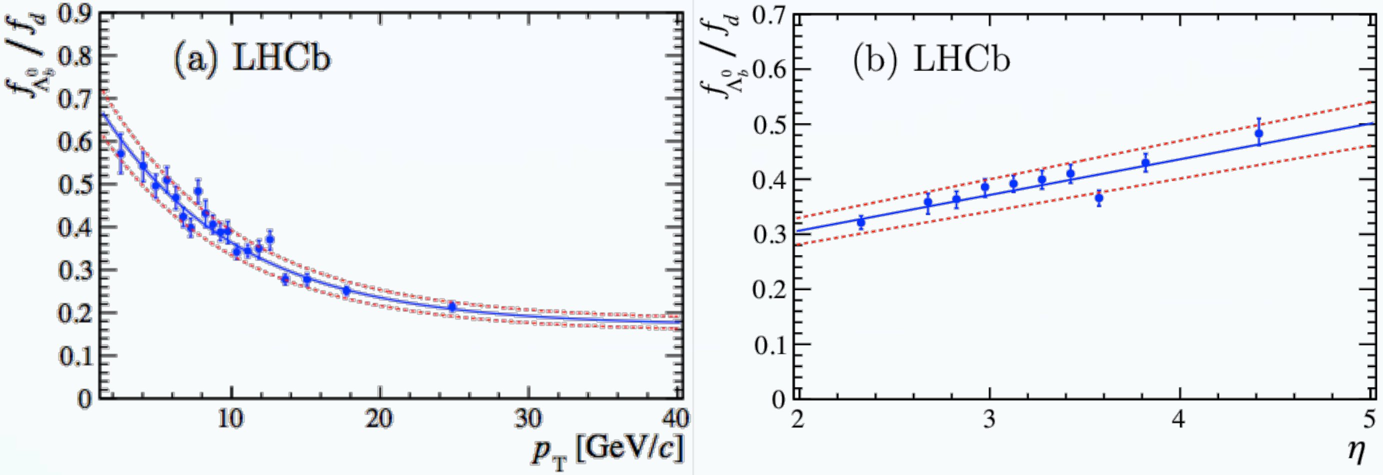
… but updates from Belle: $\mathcal{B}(\Lambda_c \to pK\pi) = (6.84^{+0.32}_{-0.34})\%$ [PRL113, 042002 (2014)]
and lifetime ratio: $(\tau_{B^+} + \tau_{B^0})/2\tau_{\Lambda_b^0} = 1.071 \pm 0.008$

Λ_b production fraction

Shape updated using $\Lambda_b \to \Lambda_c \pi$ and normalization from scaled SL measurement

[PRD 85 (2012) 032008]

[JHEP 08(2014)143]



Depends on p_T and η

$$f_{\Lambda_b^0}/f_d(p_T) = a' + \exp(b' + c' \times p_T[\mathrm{GeV}/c])$$

$$\begin{aligned} a' &= +0.151 \pm 0.016\,^{+0.024}_{-0.025}, \\ b' &= -0.573 \pm 0.040\,^{+0.101}_{-0.097}, \\ c' &= -0.095 \pm 0.007 \pm 0.014\ [\mathrm{GeV}/c]^{-1} \end{aligned}$$

$$f_{\Lambda_b^0}/f_d(\eta) = a' + b' \times (\eta - \overline{\eta})$$

$$\boxed{a' = 0.387 \pm 0.013\,^{+0.028}_{-0.030},}$$

$$b' = 0.067 \pm 0.005\,^{+0.012}_{-0.009},$$

Source	Error (%)
Bin dependent errors	2.2
$\mathcal{B}(\Lambda_b^0 \to D^0 p X \mu^- \overline{\nu})$	2.0
Monte Carlo modelling	1.0
Backgrounds	3.0
Tracking efficiency	2.0
$\Gamma_{\rm sl}$	2.0
Lifetime ratio	2.6
PID efficiency	2.5
Subtotal	6.3

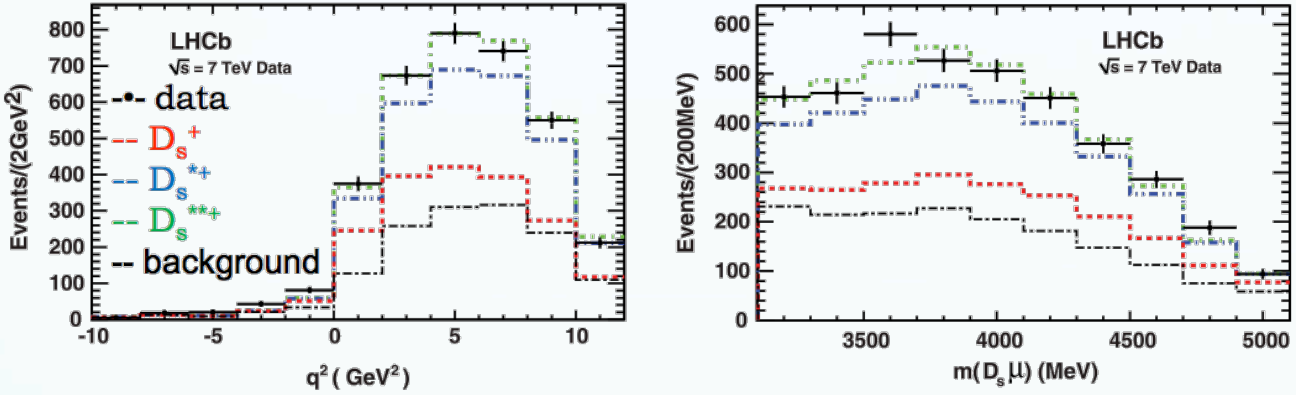
- Overall uncertainty reduced to 8%
- Systematics mainly $\mathcal{B}(\Lambda_c \to pK\pi)$, but rest is scattered
- Possible LHCb measurement using kinematic constraints in $B^+ \to p\pi^+\pi^+\Sigma_c^{--}(\Lambda_c\,\pi)$ see [Eur.Phys.J.C 74 (2014) 3194]

Separate higher D_s & Λ_c resonances

2D fit to q^2 and m_{vis}

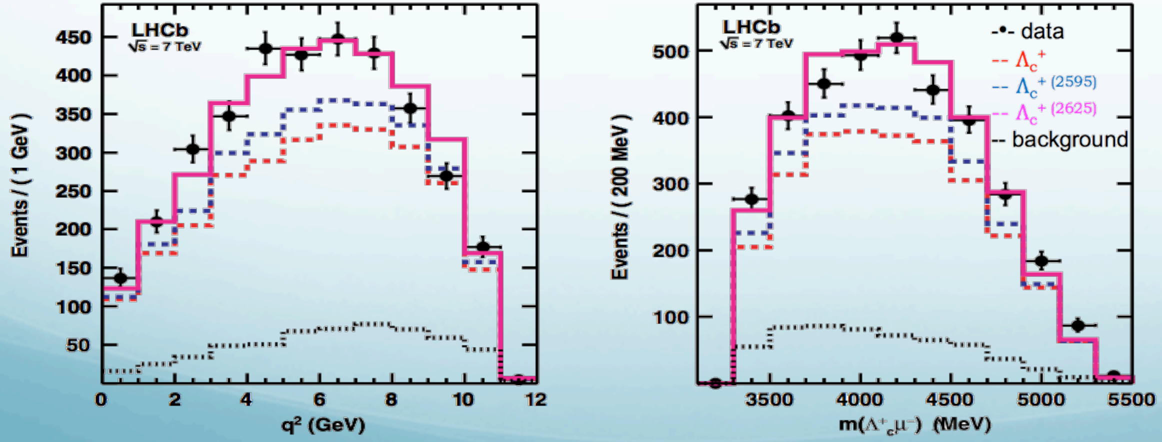
[PRD 85 (2012) 032008]

$\overline{B}_s^0 \rightarrow D_s^{+(*)(**)} \mu^- \overline{\nu}$



- Use D and D^{*+} form factors for D_s and D_s^*
- Fix fraction D_s^*/D_s=D^*/D=2.42

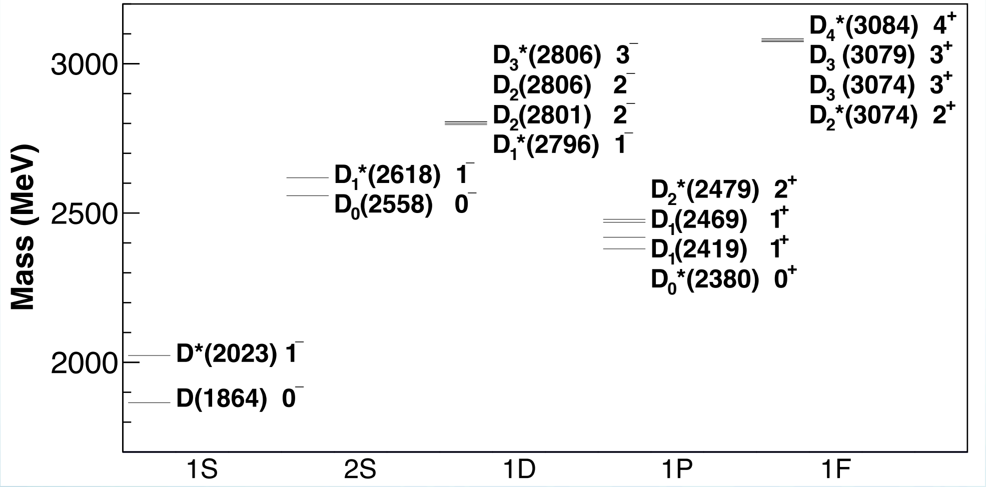
$\Lambda_b^0 \rightarrow \Lambda_c^{+(**)} \mu^- \overline{\nu}$

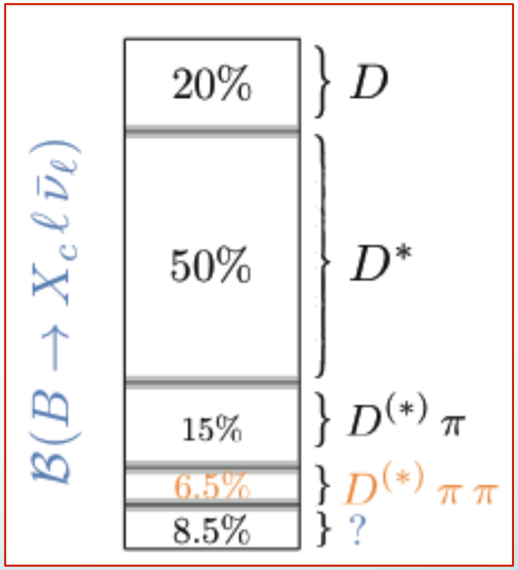


Ratio $\Lambda_c(2595)/\Lambda_c(2625)$ fixed to prediction:
[Phys. Rev. C 72 035201 (2005)]

Composition of SL width

- Composition of inclusive $B \to X_c l \nu$ width not fully understood.
  - Recent update by BaBar bridges half of the gap.
  - 8.5% still unknown.



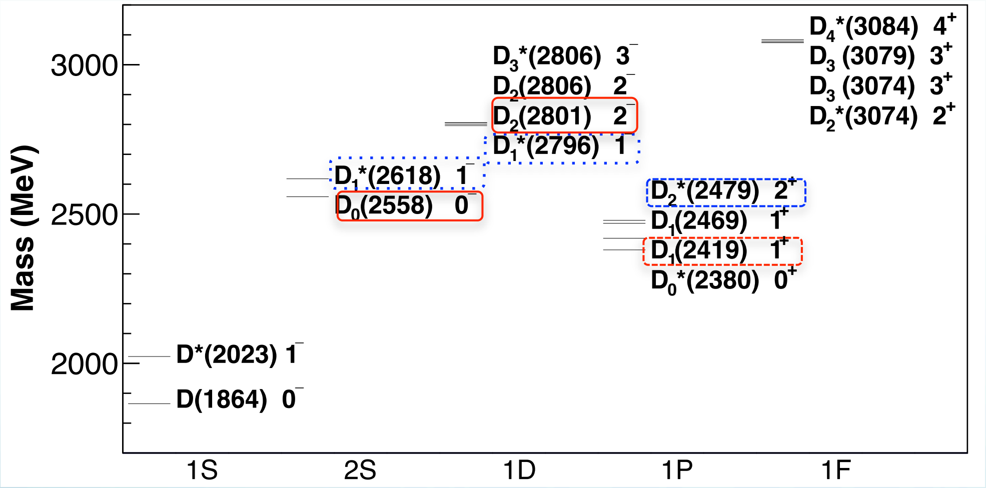


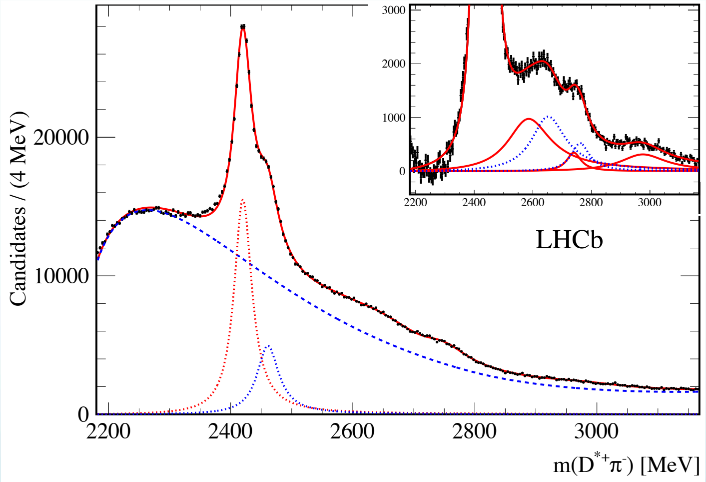
From F. Bernlocher, CKM14

Composition of SL width

- LHCb can study for resonant $B \to X_c l \nu$ structure
  - Including radial excitations $D^{(*)\prime}$
  - High statistics invariant mass spectrum
- **Example**: spectroscopy from **prompt** samples:

LHCb [JHEP 09 (2013) 145]



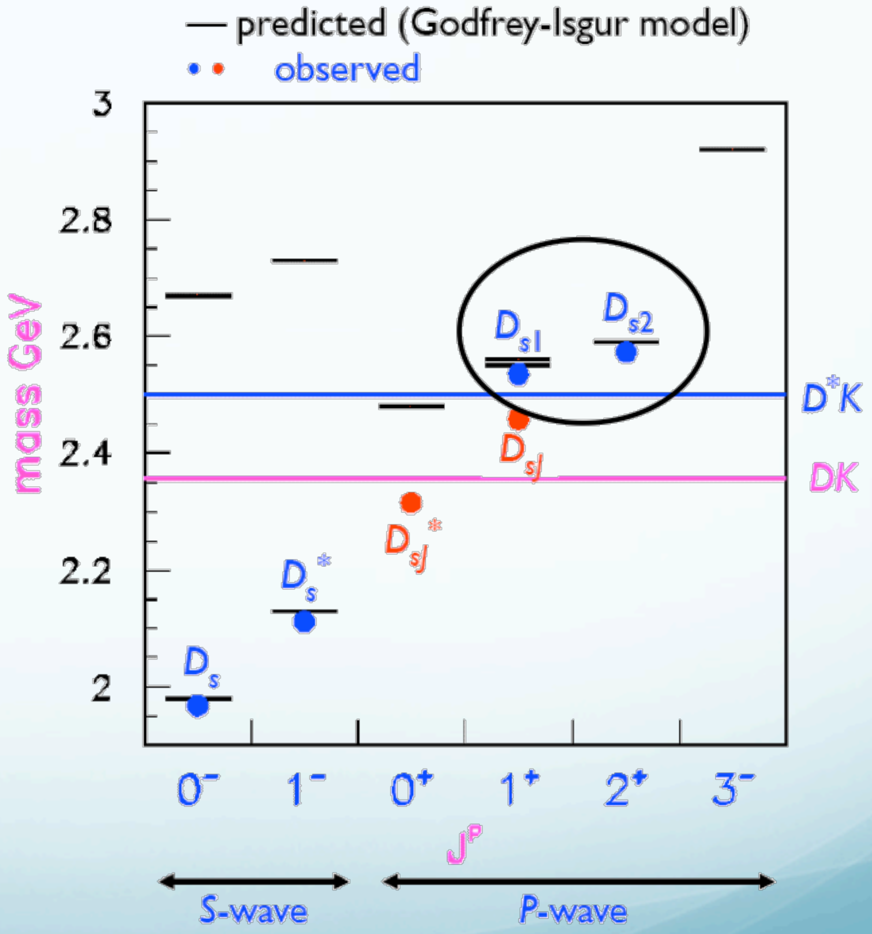


Composition of SL width

- Even less experimental information of exclusive B_s decays.
- Final states with D^0K can be used to measure $B_s \rightarrow D_s^{**} \mu\, \nu$.

$$\boxed{D'_{s1}, D^*_{s2} \rightarrow D^{(*)}K}$$

$$\boxed{D^{(*)}_{sJ} \rightarrow D^{(*)+}_s + n(\pi^0 \; or \; \gamma)}$$



Composition of SL width

- Observed D^0K spectrum from $B_s \to D_s^{**} \mu\, \nu$

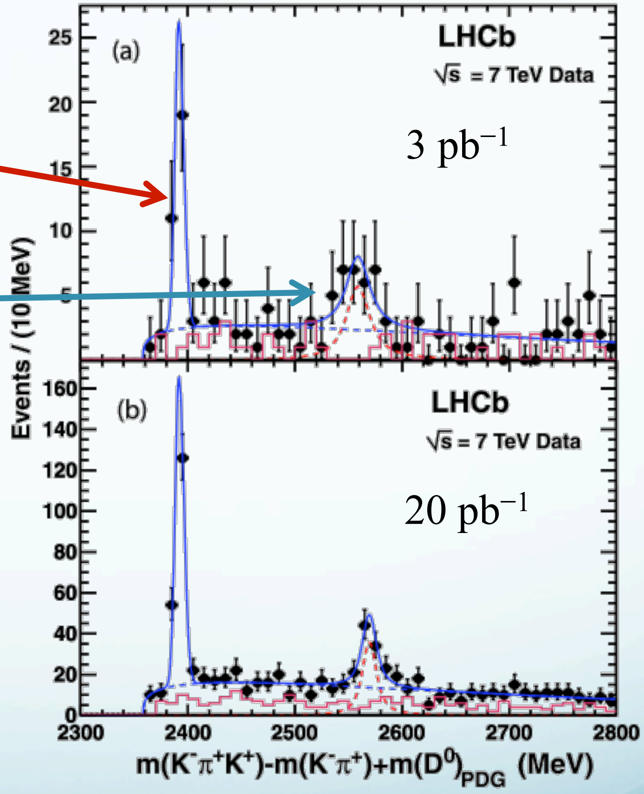
LHCb [PLB 698 (2011) 14]

$$D_{s1}(2536)^+ \to D^*(2007)^0 K^+$$

(missed π^0 or γ)

$$D_{s2}(2573)^+ \to D^0 K^+$$

Significance: 8.3σ



$$\frac{\mathcal{B}(\bar{B}_s^0 \to D_{s2}^{*+} X \mu^- \bar{\nu})}{\mathcal{B}(\bar{B}_s^0 \to D_{s1}^{+} X \mu^- \bar{\nu})} = 0.61 \pm 0.14 \pm 0.05.$$

$$\frac{\mathcal{B}(\bar{B}_s^0 \to D_{s2}^{*+} X \mu^- \bar{\nu})}{\mathcal{B}(\bar{B}_s^0 \to X \mu^- \bar{\nu})} = (3.3 \pm 1.0 \pm 0.4)\%$$

$$\frac{\mathcal{B}(\bar{B}_s^0 \to D_{s1}^{+} X \mu^- \bar{\nu})}{\mathcal{B}(\bar{B}_s^0 \to X \mu^- \bar{\nu})} = (5.4 \pm 1.2 \pm 0.5)\%,$$

$\Lambda_b \to \Lambda_c$ form factor

- Λ_b form factors important for understanding of HQET.
  - Light di-quark has spin 0: not affected by chromomagnetic correction
- Form factor can be parameterized by a universal “Isgur-Wise” function $\xi(w)$

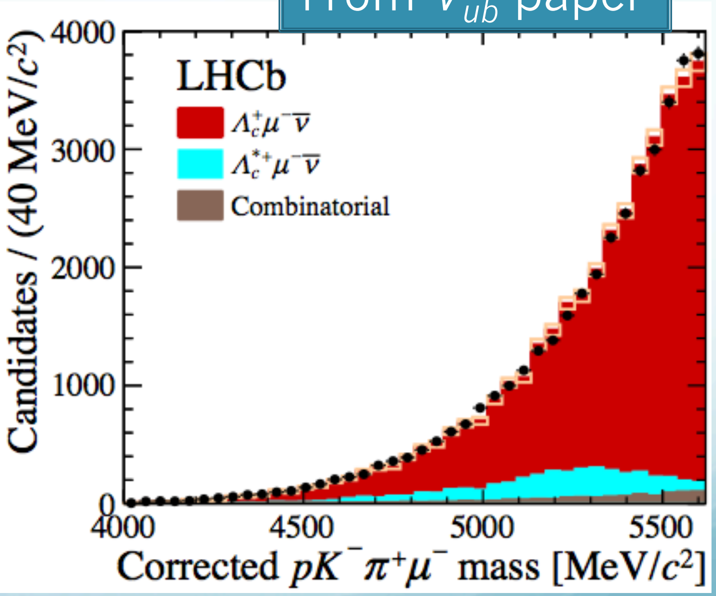
$$\frac{d\Gamma(\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu)}{dw} = \frac{G_F^2 m_{\Lambda_b}^5 |V_{cb}|^2}{24\pi^3} K(w) \xi_{\Lambda_b}^2(w)$$

$$\xi_{\Lambda_b}(w) = e^{-\rho^2 (w-1)}$$

- Measure differential rate to extract slope ρ^2 parameter
  - QCD sum rules $\rho^2 > 1.5$

$\Lambda_b \to \Lambda_c$ form factor

- Use $\Lambda_b \to \Lambda_c \, \mu \, \nu$, with $\Lambda_c \to p \, K \, \pi$.
- Add 2 pions to observe of excited $\Lambda_c(2595)$ and $\Lambda_c(2625)$
  - Subtract from inclusive $\Lambda_c \, \mu \, X$
- Use neutrino-reconstruction to get 4-velocity transfer, *w*
  - Use SVD method for deconvolution
- Analysis in advanced state.
  - Expect uncertainty on $\rho^2 \approx 0.08$
  - Systematics from w resolution, detector efficiencies and Λ_c^* modeling
- Is there a good normalization channel to extract V_{cb} ?

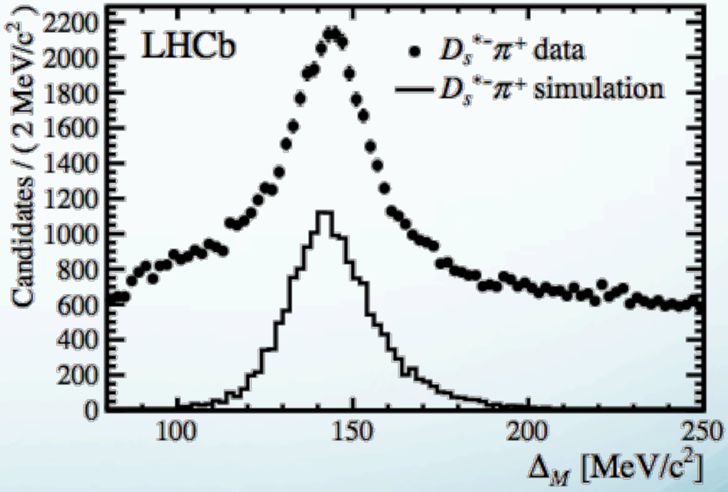


From V_{ub} paper

$B_s \rightarrow D_s$ form factor

- Form factor shape for $B_s \rightarrow D_s$ can also be measured.
- Need to subtract $D_s^{*(*)}$ contributions.
  - $D_s^*/D_s = 2.41$
- Possibly reconstruct $D_s^* \rightarrow D_s \gamma$
  - Recent LHCb paper on $B_s \rightarrow D_s^* h$
- Easier normalisation than $\Lambda_b \rightarrow \Lambda_c$?
  - Use favoured B^{0+} mode and take f_s/f_d (from hadronic measurement)

LHCb [arXiv:1503.09086]



Normalization channel?

- Need B^{0+} decays.
  - All B_s and Λ_b decays already normalized to B^{0+}.
- SL decays not possible (already used for V_{cb})
  - To what extend is the ratio a test of LQCD or HQET?
- Possible hadronic channels:
  - $B^0 \to D^- \pi^+$ or $B^+ \to J/\psi K^+$?
- For B_s and Λ_b need *b*-hadron fractions (f_s/f_d or Λ_b/f_d)
  - From SL decays or from hadronic f_s/f_d

    → Does this work?

Take *b*-fraction from …?

- From SL decays:

$$\frac{f_s}{f_u + f_d} = \frac{N(B_s^0 \to D\mu X)}{N(B \to D^0\mu X) + N(B \to D^+\mu X)} \frac{\tau_{B^-} + \tau_{B^0}}{2\tau_{B_s^0}}$$

$$\mathcal{B}(B_s^0 \to D_s\mu\nu) = \frac{f_u + f_d}{f_s} \frac{N(B_s^0 \to D_s\mu\nu)}{N(\mathrm{norm})} \mathcal{B}(\mathrm{norm})$$

$$= \boxed{\frac{N(B_s^0 \to D_s\mu\nu)}{N(B_s^0 \to D\mu X)}} \frac{N(B \to D^0\mu X) + N(B \to D^+\mu X)}{N(\mathrm{norm})} \mathcal{B}(\mathrm{norm}) \frac{2\tau_{B_s^0}}{\tau_{B^-} + \tau_{B^0}}$$

SL width composition

  - If norm is $B^{+,0} \to D^{-,0}\,\mu\,X$ → measurement of SL width composition.
    - Are these ratios interesting for V_{cb}?

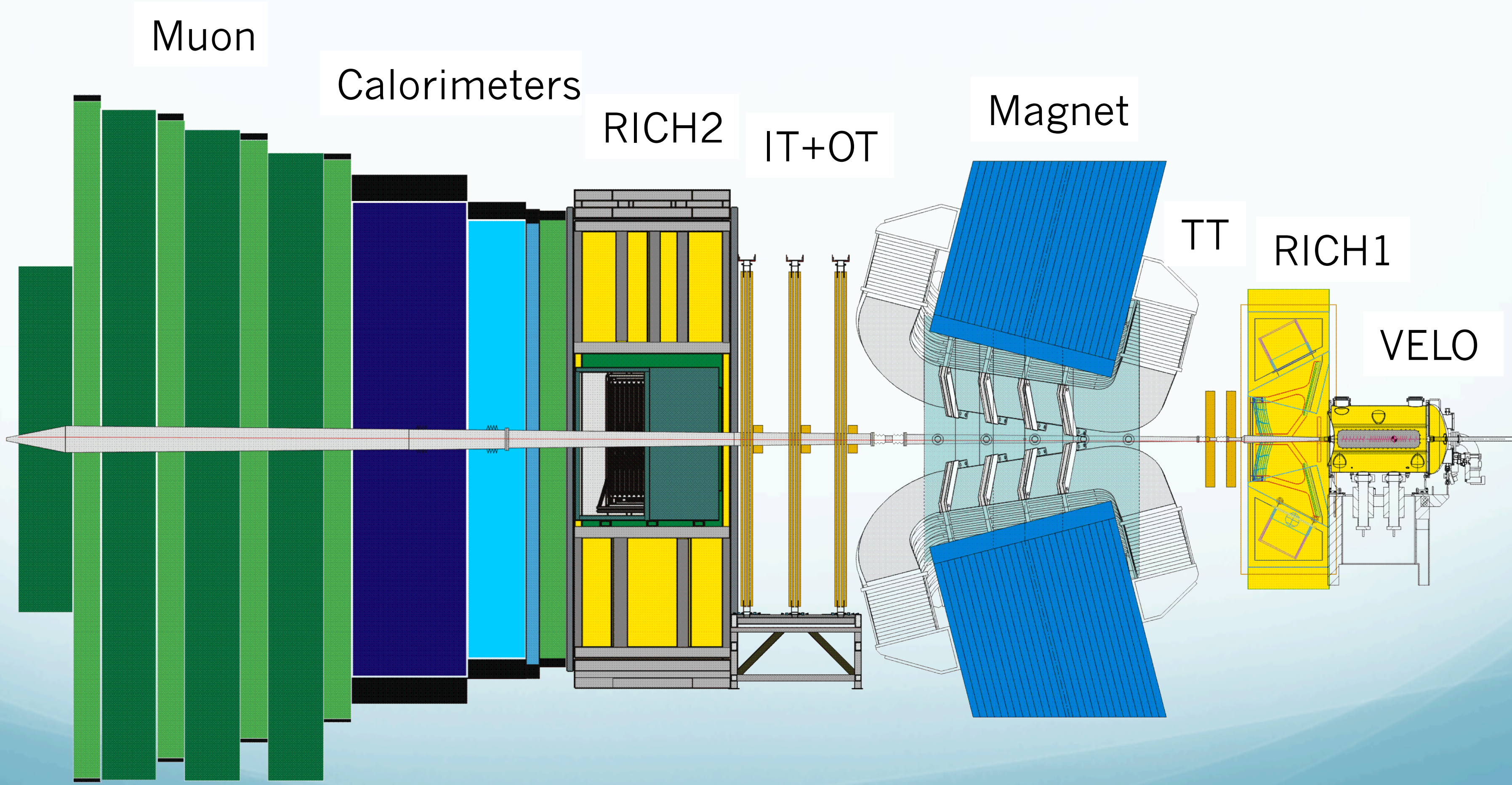
- From hadronic f_s/f_d → Systematic from SU(3) breaking relies on SL decays
  - Effectively measures ratios like: $\frac{N(B_s^0 \to D_s\mu\nu)}{N(\mathrm{norm})} \frac{N(B^0 \to D^-K^+)}{N(B_s^0 \to D_s^-\pi^+)}$
    - Can these ratios help V_{cb}?

Conclusions

- Better understanding of SL decays crucial for V_{cb} (and V_{ub})
- Experimental issues for LHCb
  - Normalization difficult
  - Partial reconstruction challenging in pp collider
  - Long lead time between data taking a d publication
  - ... but large statistics and access to other b-hadron species
- Experimental efforts at LHCb
  - b-hadron production fractions
  - Resonant structure of B^{0+}, B_s and Λ_b.
  - Λ_b form factor analysis
  - ...
- Future will tell what LHCb can say on V_{cb}.

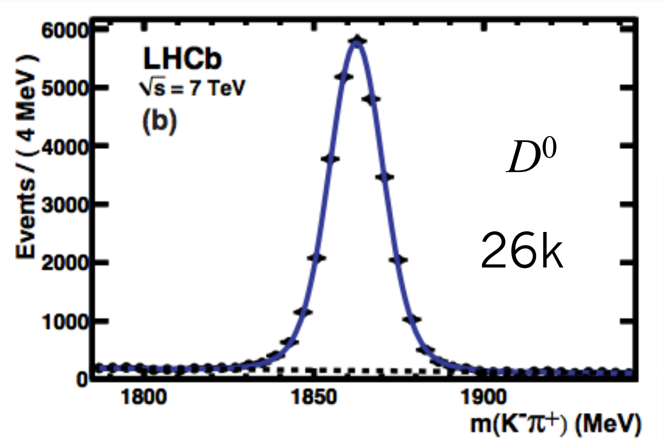
Backup

Setup



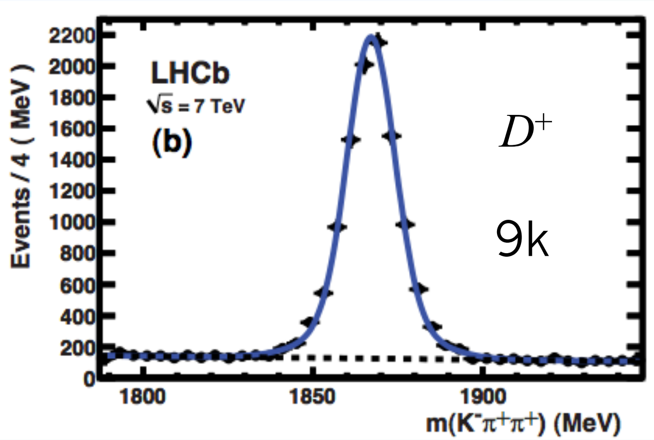
b-hadron production fractions

[PRD 85 (2012) 032008]



D^0

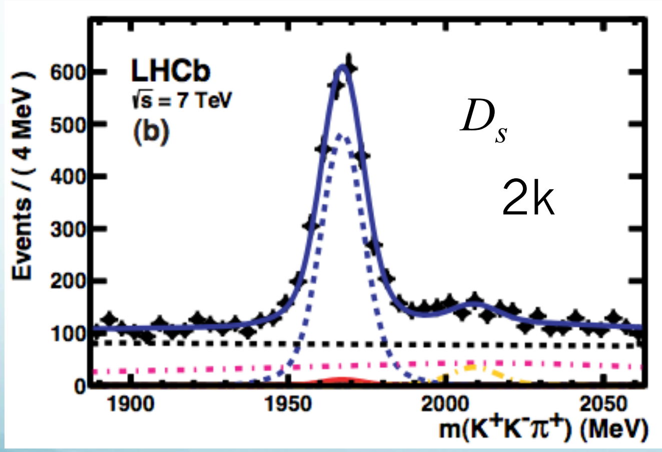
26k



D^+

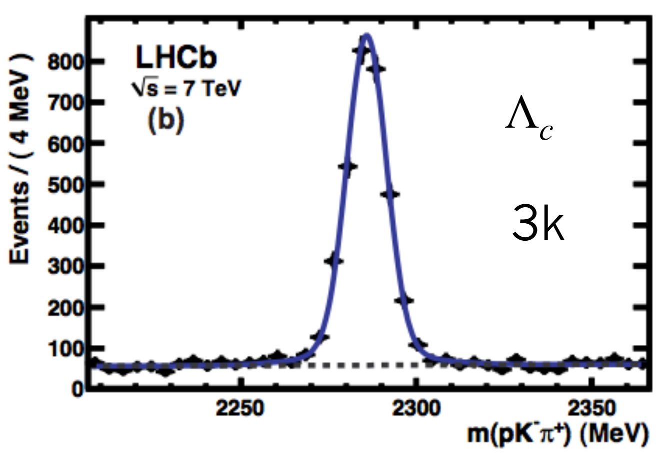
9k

3 pb^{-1}



D_s

2k



Λ_c

3k

Semileptonic publications

- CP violation and $\Delta m_{d,s}$ studies
  - Semileptonic asymmetries
    a_{sl}^{d} [PRL 114, 041601 (2015)]
    a_{sl}^{s} [PLB 728 (2014) 607]
  - CP violation in charm
    ΔA_{CP} [JHEP 07 (2014) 041] and [PLB 723 (2013) 33]
    A_{Γ} [arXiv:1501.06777]
  - B_s, B_d oscillations
    $\Delta m_{d,s}$ [EPJC 73 (2013) 12, 2655]
- $b\underline{b}$ cross section at 7 TeV [PLB 694 (2010) 209]
- *b*-hadron production fractions [PRD 85 (2012) 032008]
- $B_s \rightarrow D_s^{**} X \mu \nu$ branching ratio [PLB 698 (2011) 14]
- V_{ub} measurement [arXiv:1504.01568]