

# Flavor physics with $\Lambda_b$ baryons

Stefan Meinel



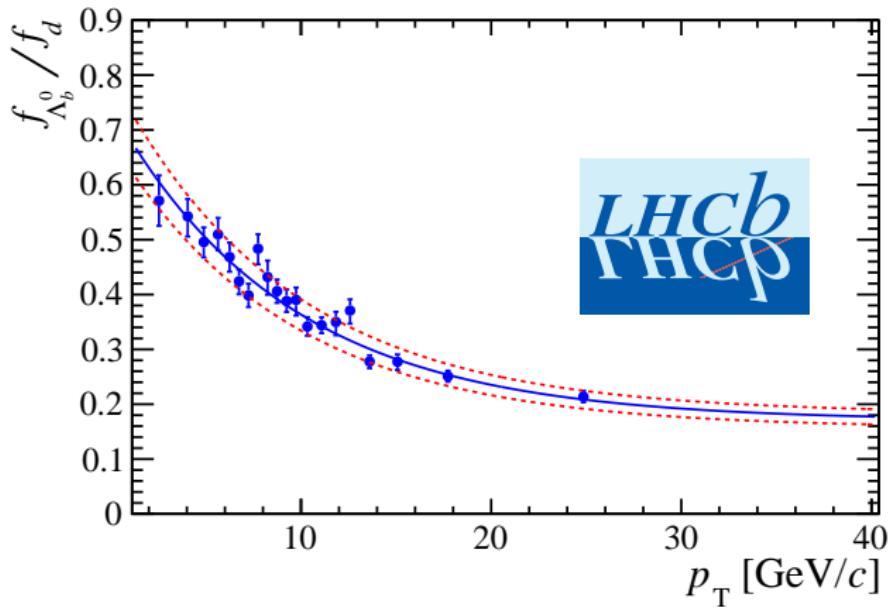
RIKEN BNL  
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THE UNIVERSITY  
OF ARIZONA

ICHEP 2016, Chicago

$$\frac{\text{Production fraction of } \Lambda_b}{\text{Production fraction of } B^0}$$

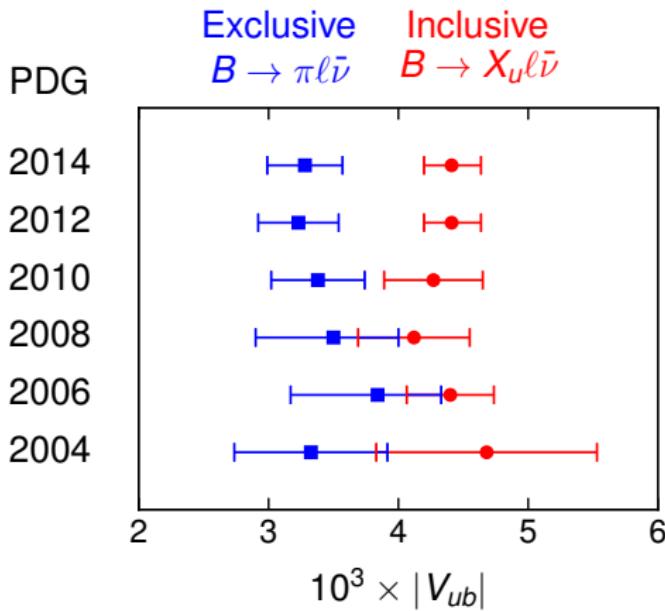
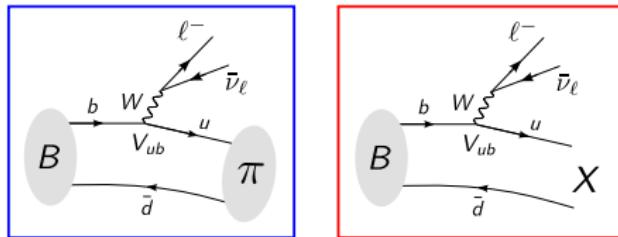


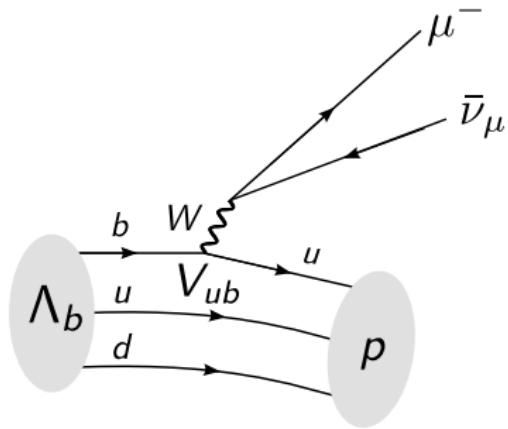
[LHCb Collaboration, JHEP 08, 143 (2014)]

**1**  $|V_{ub}|$  and  $|V_{cb}|$

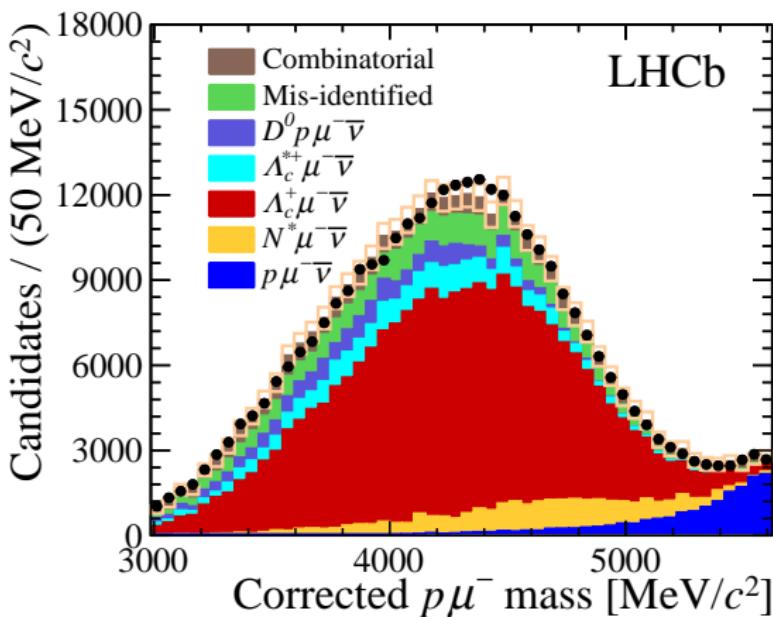
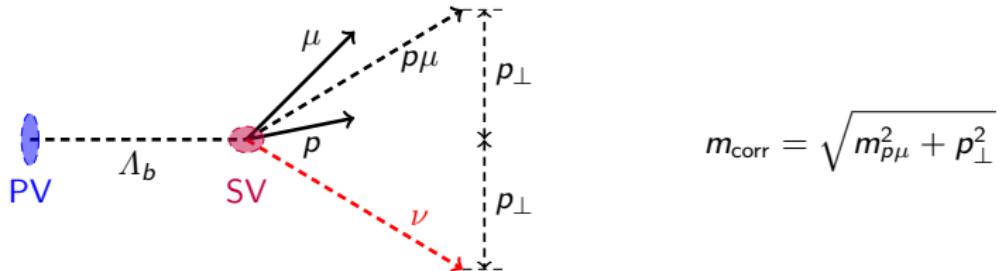
**2**  $b \rightarrow c\tau^-\bar{\nu}$

**3**  $b \rightarrow s\mu^+\mu^-$





At LHCb,  $p\mu\bar{\nu}$  final state easier to identify than  $\pi\mu\bar{\nu}$



[LHCb Collaboration, Nature Physics 11, 743-747 (2015)]

LHCb result:

$$\frac{\int_{15 \text{ GeV}^2}^{q^2_{\text{max}}} \frac{d\Gamma(\Lambda_b \rightarrow p \mu^- \bar{\nu}_\mu)}{dq^2} dq^2}{\int_7 \text{ GeV}^2} = (1.00 \pm 0.04 \pm 0.08) \times 10^{-2}$$
$$(q = p - p').$$

To extract  $|V_{ub}/V_{cb}|$  from this, need

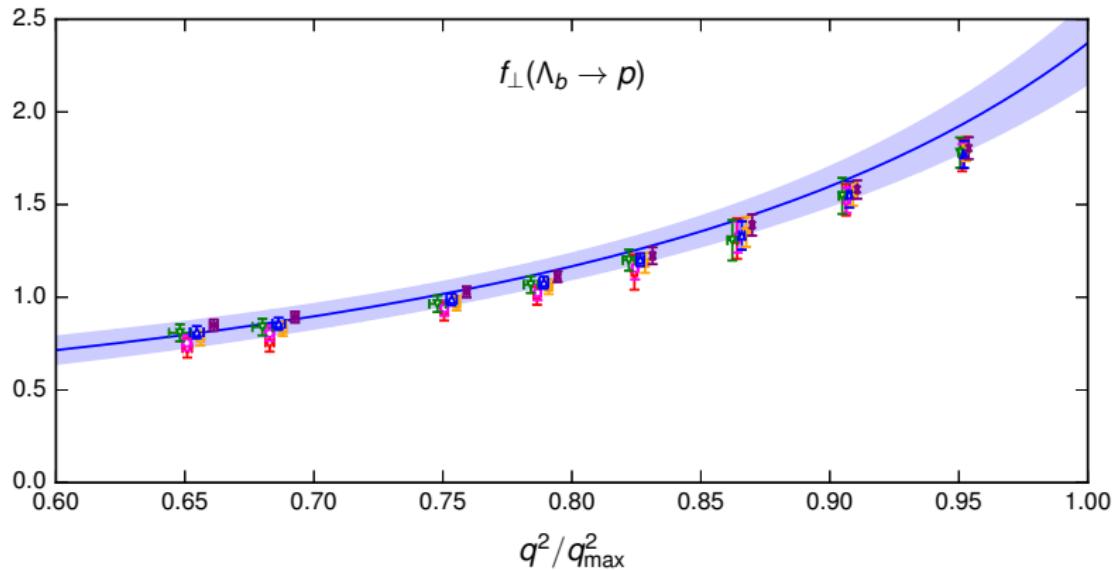
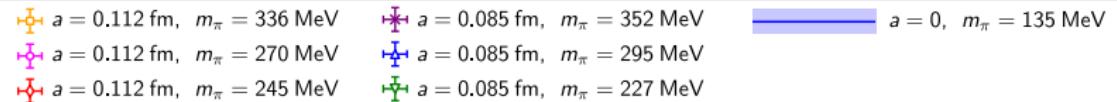
$$\begin{aligned} & \langle p | \bar{u} \gamma^\mu b | \Lambda_b \rangle, \quad \langle p | \bar{u} \gamma^\mu \gamma_5 b | \Lambda_b \rangle, \\ & \langle \Lambda_c | \bar{c} \gamma^\mu b | \Lambda_b \rangle, \quad \langle \Lambda_c | \bar{c} \gamma^\mu \gamma_5 b | \Lambda_b \rangle \end{aligned}$$

from lattice QCD.

$$\begin{aligned}
\langle p | \bar{u} \gamma^\mu b | \Lambda_b \rangle &= \bar{u}_p \left[ (m_{\Lambda_b} - m_p) \frac{q^\mu}{q^2} f_0(q^2) \right. \\
&\quad + \frac{m_{\Lambda_b} + m_p}{s_+} \left( p^\mu + p'^\mu - (m_{\Lambda_b}^2 - m_p^2) \frac{q^\mu}{q^2} \right) f_+(q^2) \\
&\quad \left. + \left( \gamma^\mu - \frac{2m_p}{s_+} p^\mu - \frac{2m_{\Lambda_b}}{s_+} p'^\mu \right) f_\perp(q^2) \right] u_{\Lambda_b}, \\
\langle p | \bar{u} \gamma^\mu \gamma_5 b | \Lambda_b \rangle &= -\bar{u}_p \gamma_5 \left[ (m_{\Lambda_b} + m_p) \frac{q^\mu}{q^2} g_0(q^2) \right. \\
&\quad + \frac{m_{\Lambda_b} - m_p}{s_-} \left( p^\mu + p'^\mu - (m_{\Lambda_b}^2 - m_p^2) \frac{q^\mu}{q^2} \right) g_+(q^2) \\
&\quad \left. + \left( \gamma^\mu + \frac{2m_p}{s_-} p^\mu - \frac{2m_{\Lambda_b}}{s_-} p'^\mu \right) g_\perp(q^2) \right] u_{\Lambda_b},
\end{aligned}$$

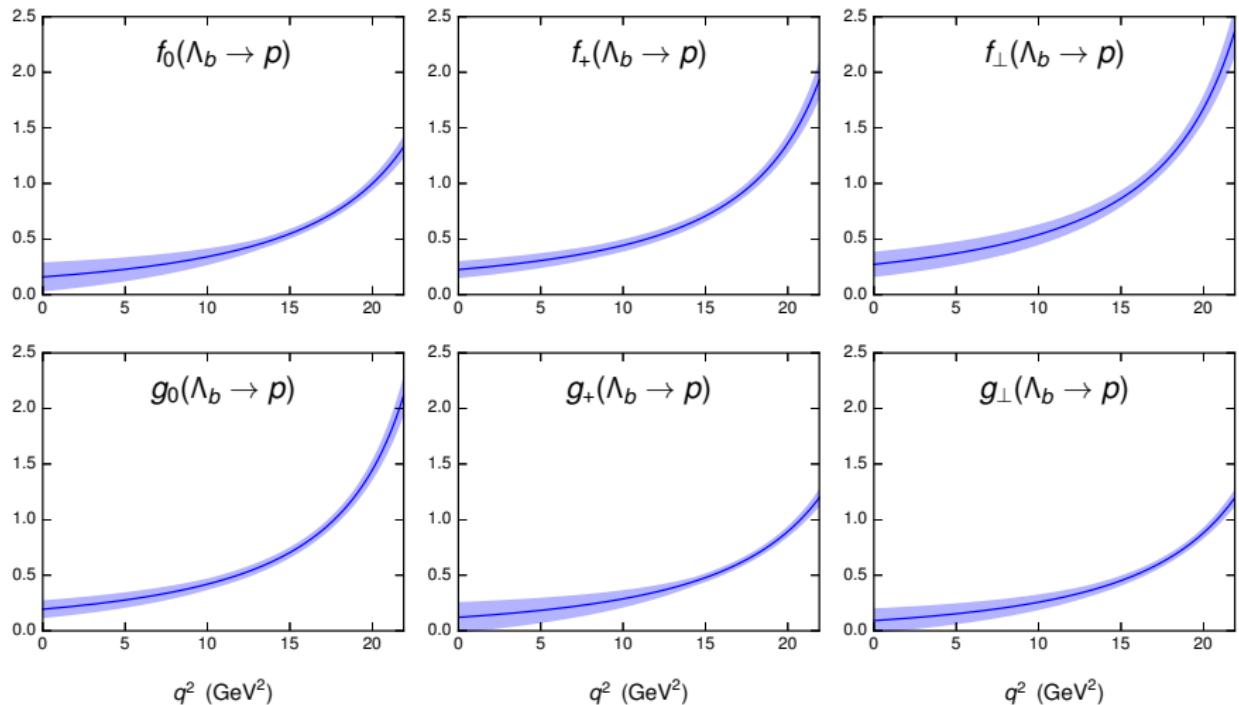
where  $s_\pm = (m_{\Lambda_b} \pm m_p)^2 - q^2$

[T. Feldmann and M. Yip, PRD **85**, 014035 (2012)]

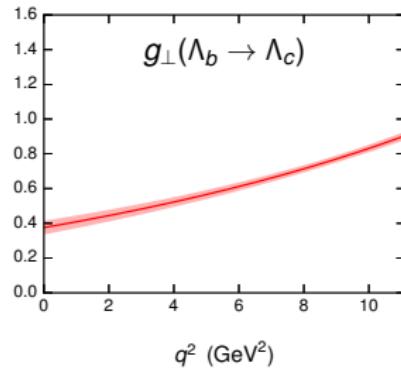
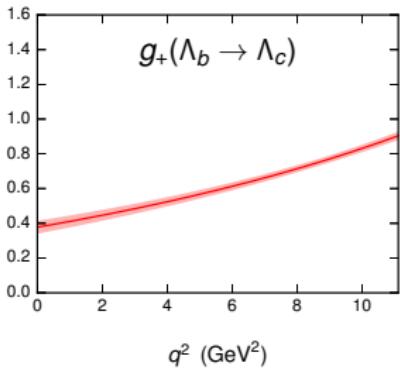
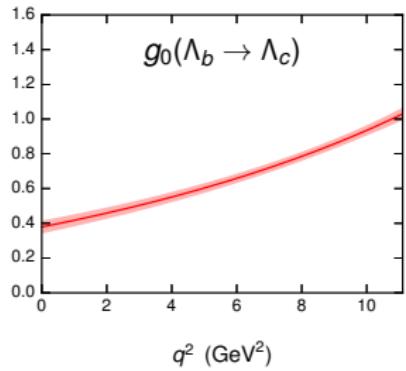
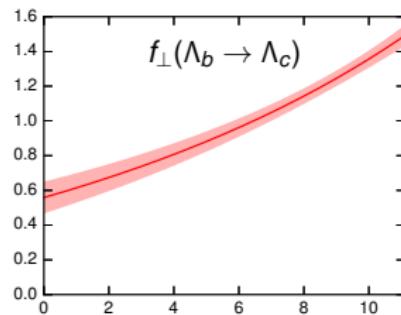
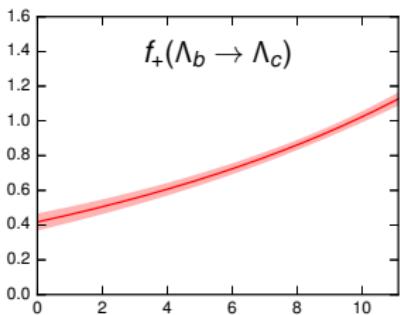
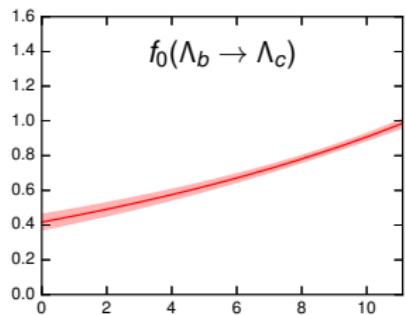


[W. Detmold, C. Lehner, S. Meinel, PRD **92**, 034503 (2015)]

(Using gauge-field configurations generated by RBC/UKQCD)

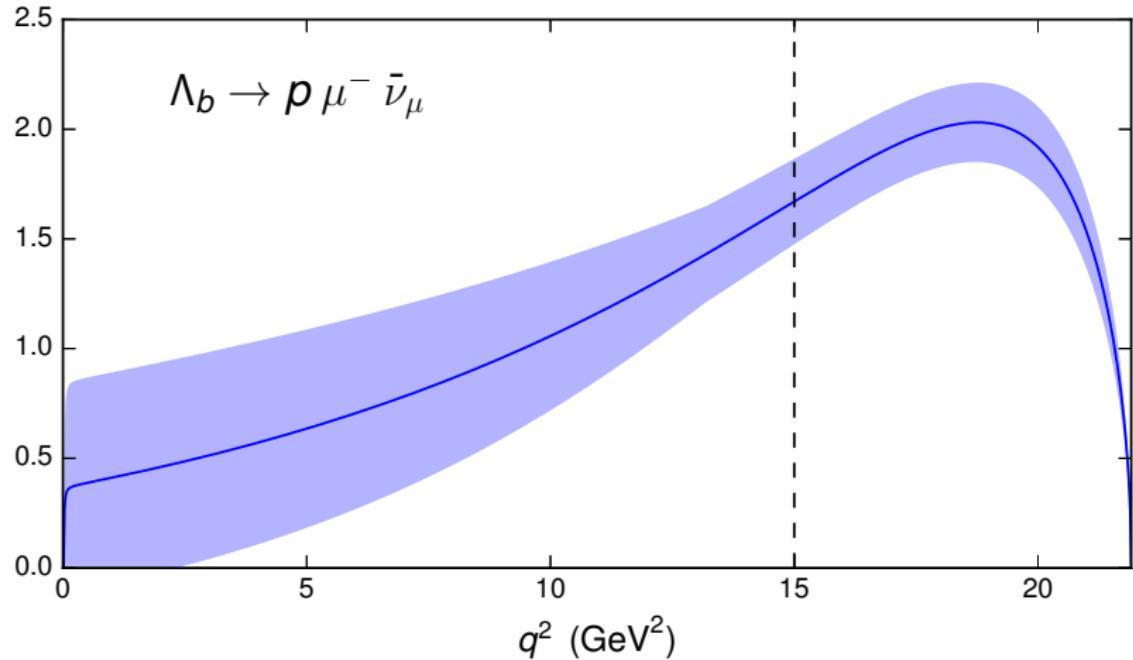


[W. Detmold, C. Lehner, S. Meinel, PRD **92**, 034503 (2015)]

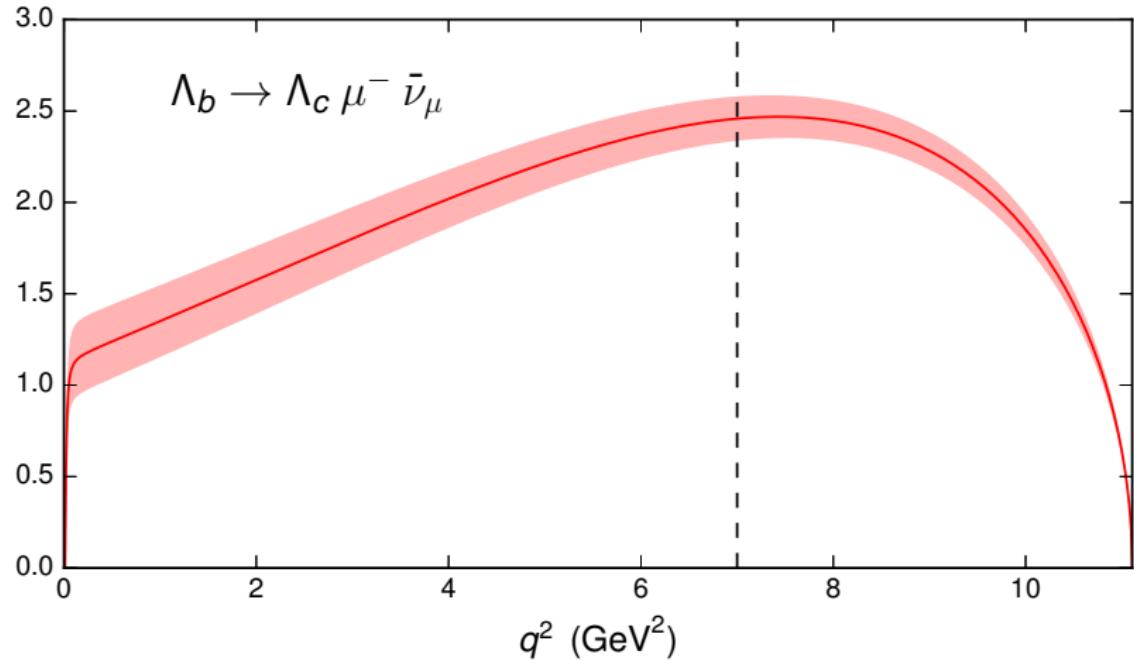


[W. Detmold, C. Lehner, S. Meinel, PRD **92**, 034503 (2015)]

$$\frac{d\Gamma/dq^2}{|V_{ub}|^2} \text{ (ps}^{-1} \text{ GeV}^{-2}\text{)}$$



$$\frac{d\Gamma/dq^2}{|V_{cb}|^2} \text{ (ps}^{-1} \text{ GeV}^{-2}\text{)}$$



$$\frac{|\mathcal{V}_{cb}|^2}{|\mathcal{V}_{ub}|^2} \frac{\int_{15 \text{ GeV}^2}^{q_{\max}^2} \frac{d\Gamma(\Lambda_b \rightarrow p \mu^- \bar{\nu}_\mu)}{dq^2} dq^2}{\int_{7 \text{ GeV}^2}^{q_{\max}^2} \frac{d\Gamma(\Lambda_b \rightarrow \Lambda_c \mu^- \bar{\nu}_\mu)}{dq^2} dq^2}$$

$$= 1.471 \pm 0.095_{\text{stat.}} \pm 0.109_{\text{syst.}}$$

[W. Detmold, C. Lehner, S. Meinel, PRD **92**, 034503 (2015)]

Systematic uncertainties in the ratio of decay rates:

Finite volume	4.9 %
Continuum extrapolation	2.8 %
Chiral extrapolation	2.6 %
RHQ parameters	2.3 %
Matching & improvement	2.1 %
Isospin breaking/QED	2.0 %
Scale setting	1.8 %
$z$ expansion	1.3 %
<b>Combined</b>	<b>7.3 %</b>

Note: the combined uncertainty takes into account the correlations between the individual uncertainties

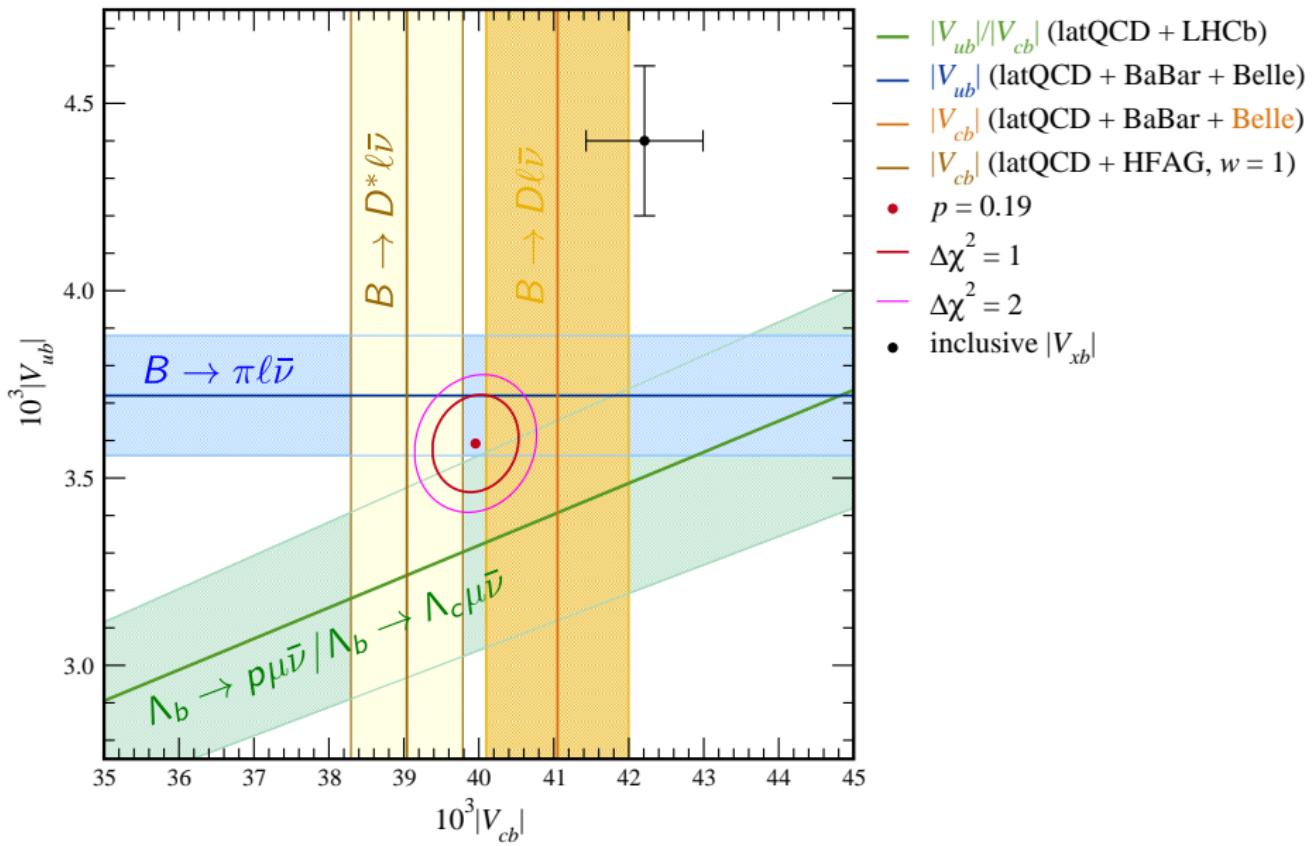
[W. Detmold, C. Lehner, S. Meinel, PRD **92**, 034503 (2015)]

Combine with LHCb measurement:

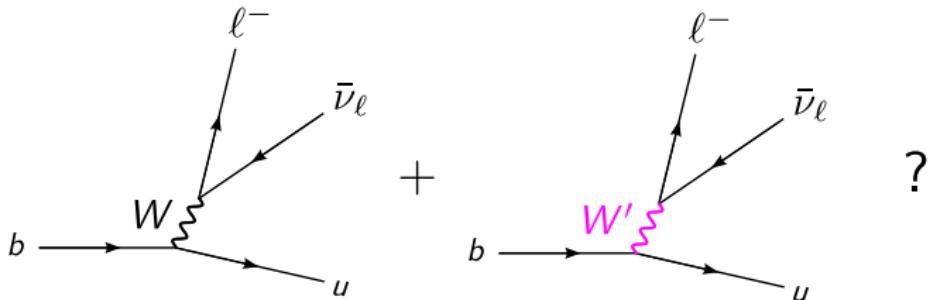
$$\frac{|\mathcal{V}_{ub}|}{|\mathcal{V}_{cb}|} = 0.083 \pm 0.004_{\text{expt}} \pm 0.004_{\text{lat}}$$

[LHCb Collaboration, Nature Physics 11, 743-747 (2015)]

$|V_{ub}|$ ,  $|V_{cb}|$  status as of November 2015: Plot from Andreas Kronfeld



Right-handed  $b \rightarrow u$  currents beyond the Standard Model?



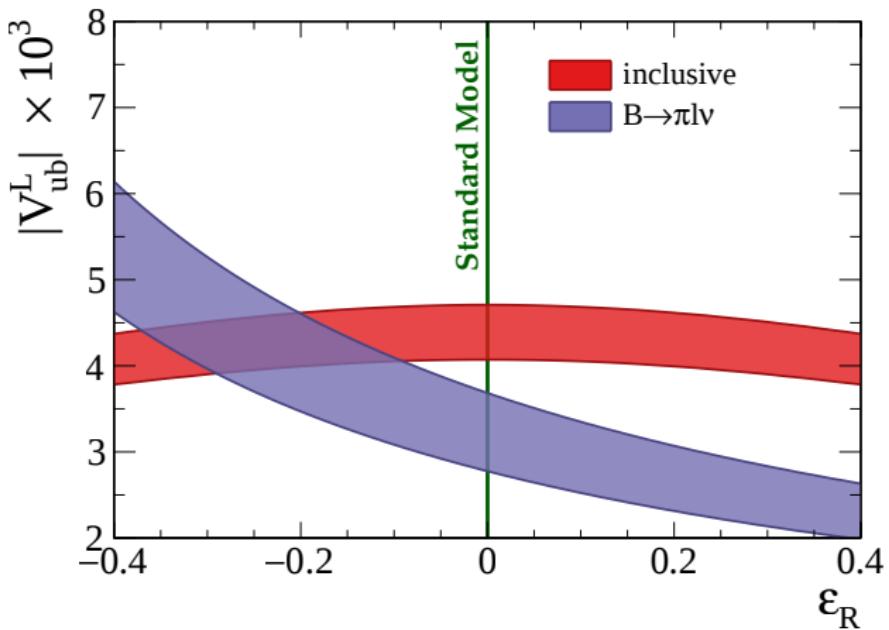
This could replace

$$V_{ub} \underbrace{\bar{u}_L \gamma^\mu b_L}_{V-A}$$

by

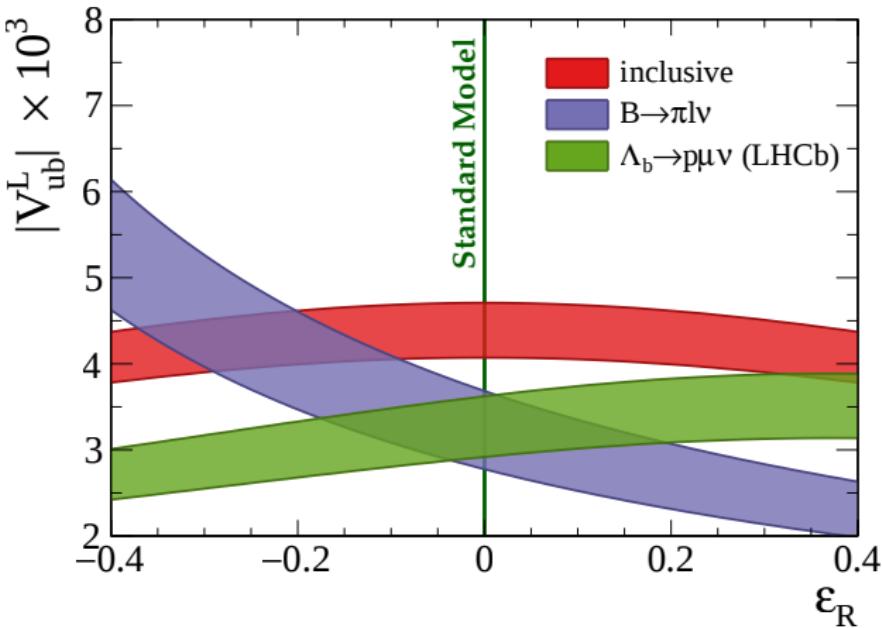
$$V_{ub}^L \left( \underbrace{\bar{u}_L \gamma^\mu b_L}_{V-A} + \epsilon_R \underbrace{\bar{u}_R \gamma^\mu b_R}_{V+A} \right)$$

Process	Vector current	Axial vector current
$B \rightarrow \pi \ell \bar{\nu}_\ell$	✓	✗
$B \rightarrow X_u \ell \bar{\nu}_\ell$	✓	✓
$\Lambda_b \rightarrow p \ell \bar{\nu}_\ell$	✓	✓



(using 2014 PDG values)

[LHCb Collaboration, Nature Physics 11, 743-747 (2015)]



(using 2014 PDG values;  $\Lambda_b \rightarrow p \mu \bar{\nu}$  result normalized using  $|V_{cb}|_{\text{excl.}}$ )

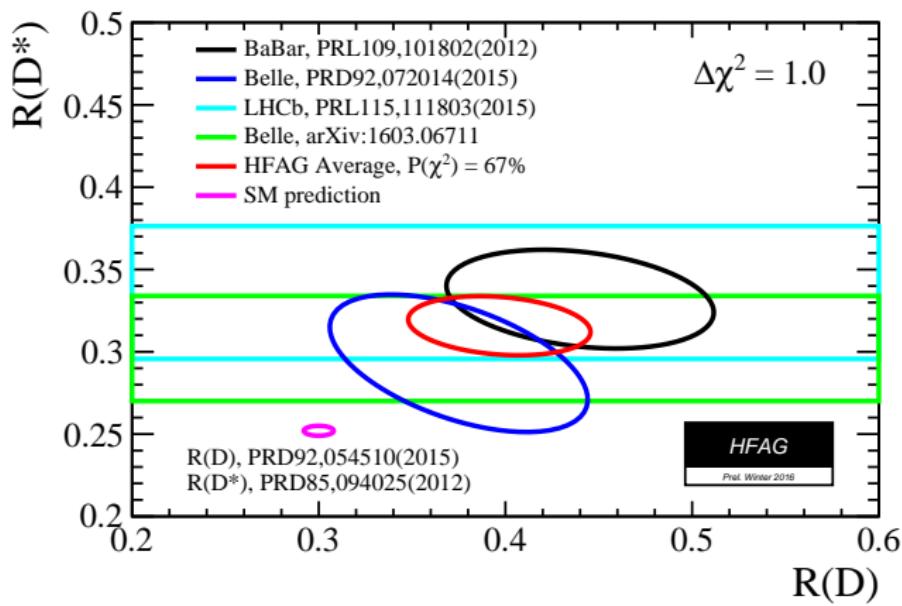
[LHCb Collaboration, Nature Physics 11, 743-747 (2015)]

**1**  $|V_{ub}|$  and  $|V_{cb}|$

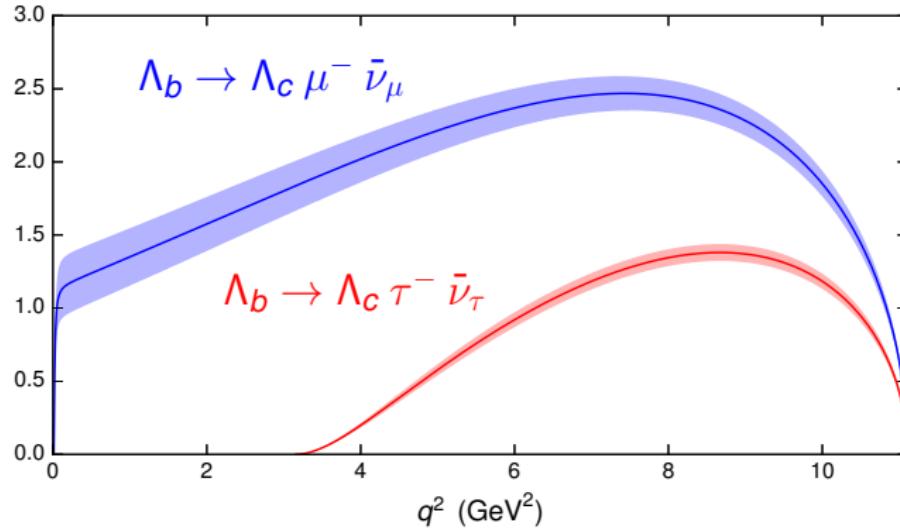
**2**  $b \rightarrow c\tau^-\bar{\nu}$

**3**  $b \rightarrow s\mu^+\mu^-$

$$R[D^{(*)}] = \frac{\Gamma \left( \begin{array}{c} \text{Diagram with } \tau^- \text{ and } \bar{\nu}_\tau \\ \text{B to W to c} \\ \text{D}^{(*)} to d \end{array} \right)}{\Gamma \left( \begin{array}{c} \text{Diagram with } \mu^- \text{ and } \bar{\nu}_\mu \\ \text{B to W to c} \\ \text{D}^{(*)} to d \end{array} \right)}$$



$$\frac{d\Gamma/dq^2}{|V_{cb}|^2} \text{ (ps}^{-1} \text{ GeV}^{-2}\text{)}$$



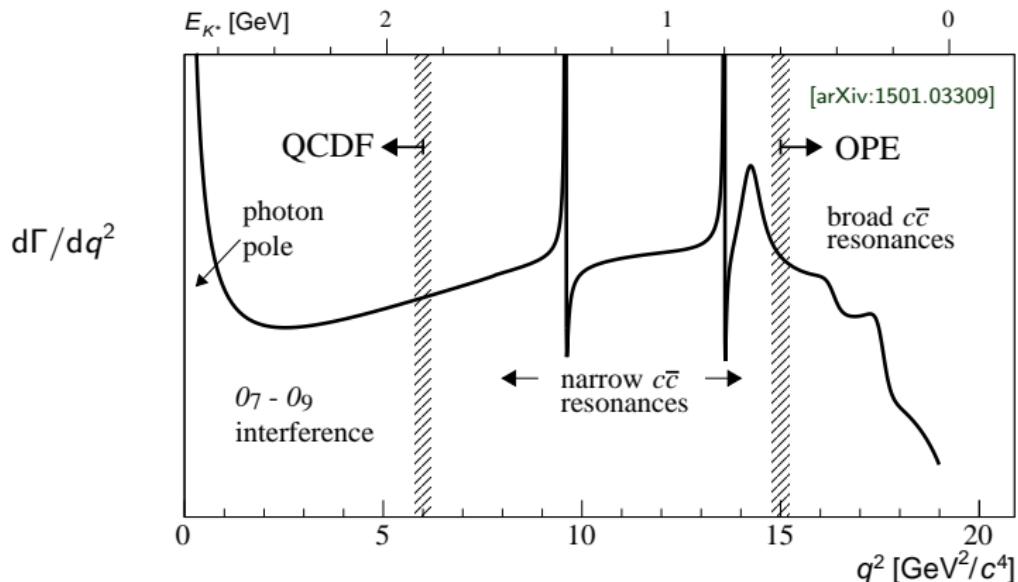
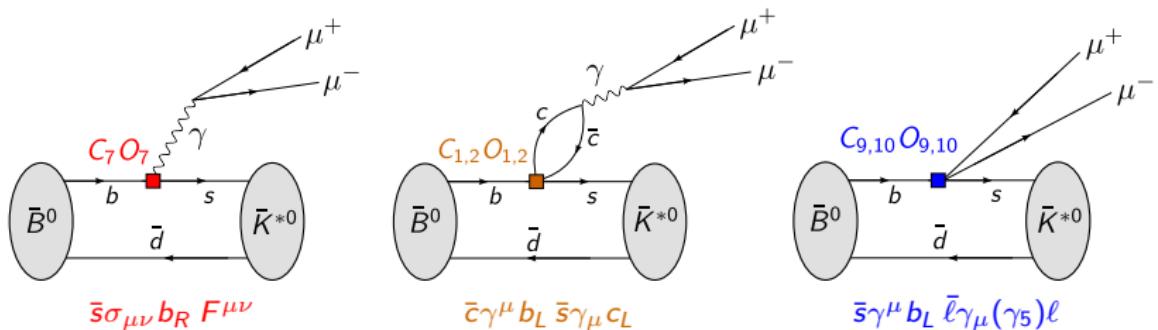
$$R[\Lambda_c] = \frac{\Gamma(\Lambda_b \rightarrow \Lambda_c \tau^- \bar{\nu}_\tau)}{\Gamma(\Lambda_b \rightarrow \Lambda_c \mu^- \bar{\nu}_\mu)} = 0.3328 \pm 0.0074 \pm 0.0070$$

[W. Detmold, C. Lehner, S. Meinel, PRD **92**, 034503 (2015)]

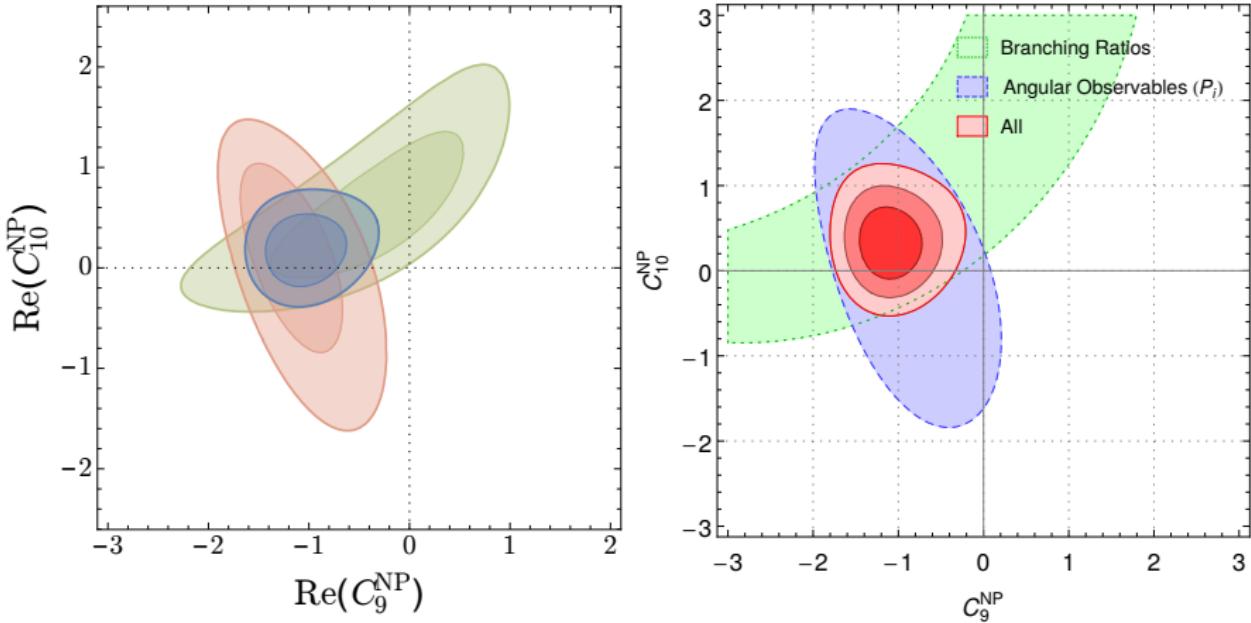
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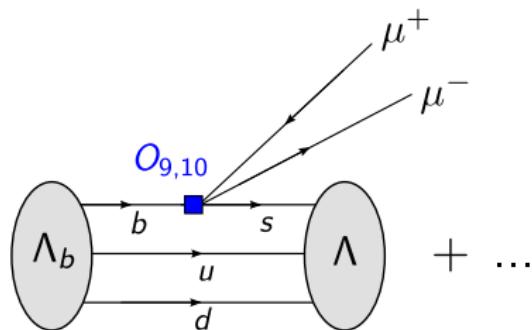
Fits of  $C_i^{\text{NP}} = C_i - C_i^{\text{SM}}$   
 to experimental data for mesonic  $b \rightarrow s\mu^+\mu^-$  decays



[W. Altmannshofer, D. Straub,  
 EPJC **75**, 382 (2015) and arXiv:1503.06199]

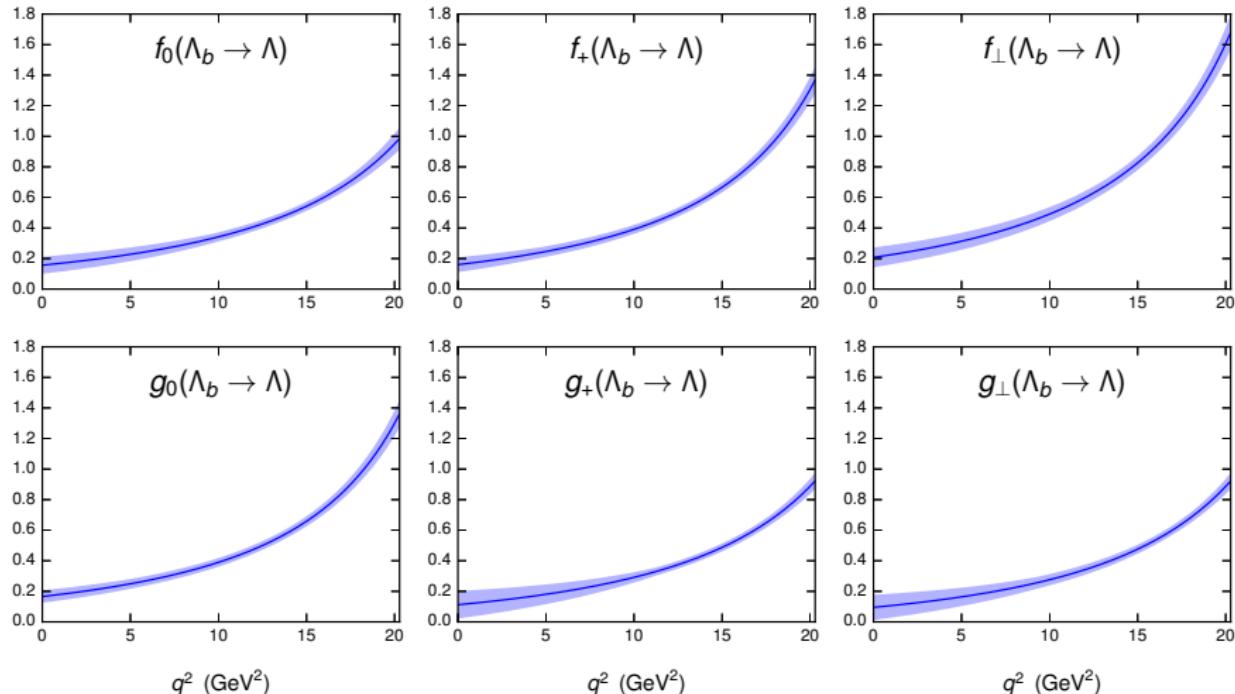
[S. Descotes-Genon, L. Hofer, J. Matias, J. Virto,  
 JHEP **1606**, 092 (2016)]

Complementary information can be obtained from  $\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$



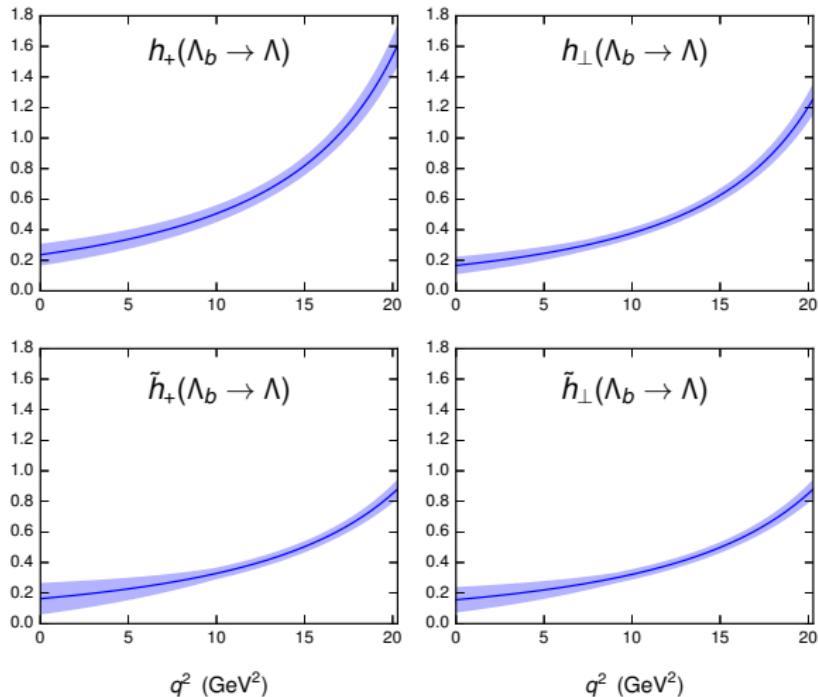
Combines the best aspects of  $B \rightarrow K^* \mu^+ \mu^-$  and  $B \rightarrow K \mu^+ \mu^-$ :  
 $\Lambda$  has nonzero spin **and** is stable under strong interactions.

## $\Lambda_b \rightarrow \Lambda$ vector and axial vector form factors

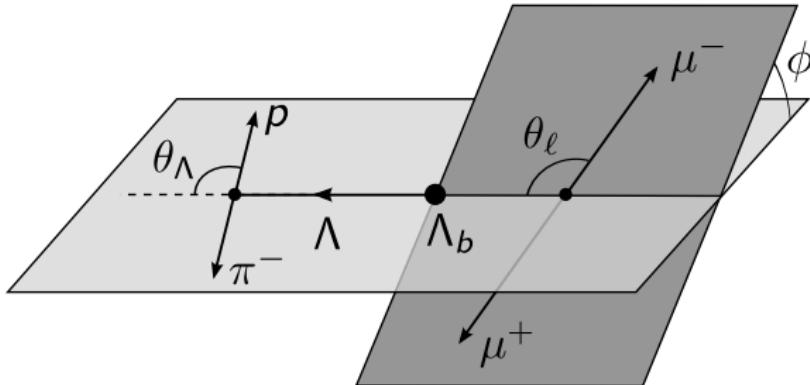


[W. Detmold and S. Meinel, PRD 93, 074501 (2016)]

## $\Lambda_b \rightarrow \Lambda$ tensor form factors

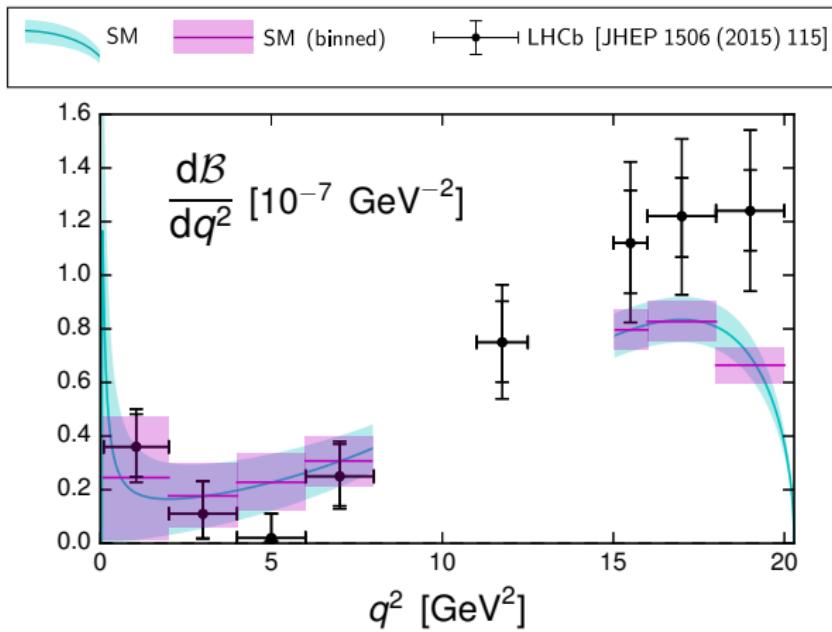


[W. Detmold and S. Meinel, PRD 93, 074501 (2016)]



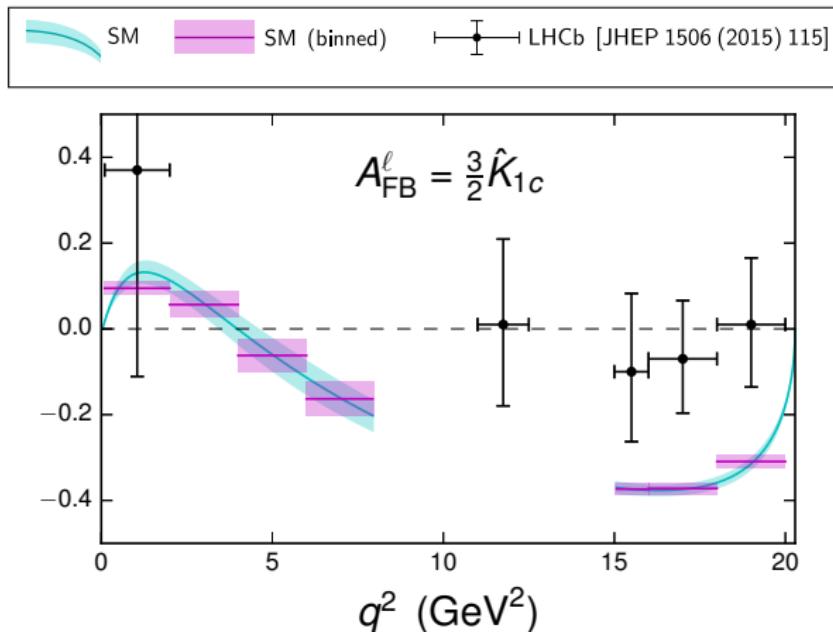
For unpolarized  $\Lambda_b$ :

$$\begin{aligned}
 \frac{d^4\Gamma}{dq^2 d\cos\theta_\ell d\cos\theta_\Lambda d\phi} &= \frac{3}{8\pi} \left[ \right. & (K_{1ss} \sin^2\theta_\ell + K_{1cc} \cos^2\theta_\ell + K_{1c} \cos\theta_\ell) \\
 &+ (K_{2ss} \sin^2\theta_\ell + K_{2cc} \cos^2\theta_\ell + K_{2c} \cos\theta_\ell) \cos\theta_\Lambda \\
 &+ (K_{3sc} \sin\theta_\ell \cos\theta_\ell + K_{3s} \sin\theta_\ell) \sin\theta_\Lambda \sin\phi \\
 &\left. + (K_{4sc} \sin\theta_\ell \cos\theta_\ell + K_{4s} \sin\theta_\ell) \sin\theta_\Lambda \cos\phi \right] \\
 \Rightarrow \frac{d\Gamma}{dq^2} &= 2K_{1ss} + K_{1cc}
 \end{aligned}$$

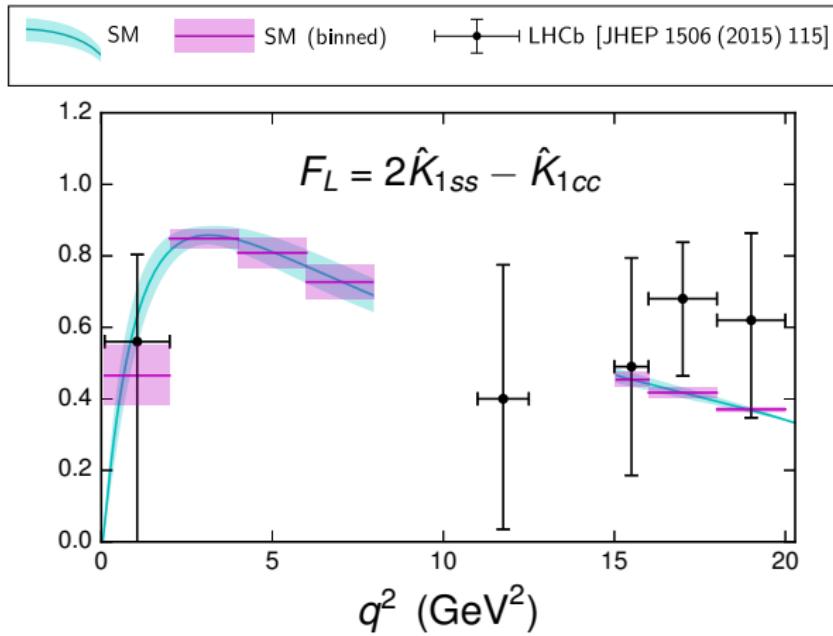


Hint of an excess at high  $q^2$  – contrary to mesonic  $b \rightarrow s\mu^+\mu^-$  decays.

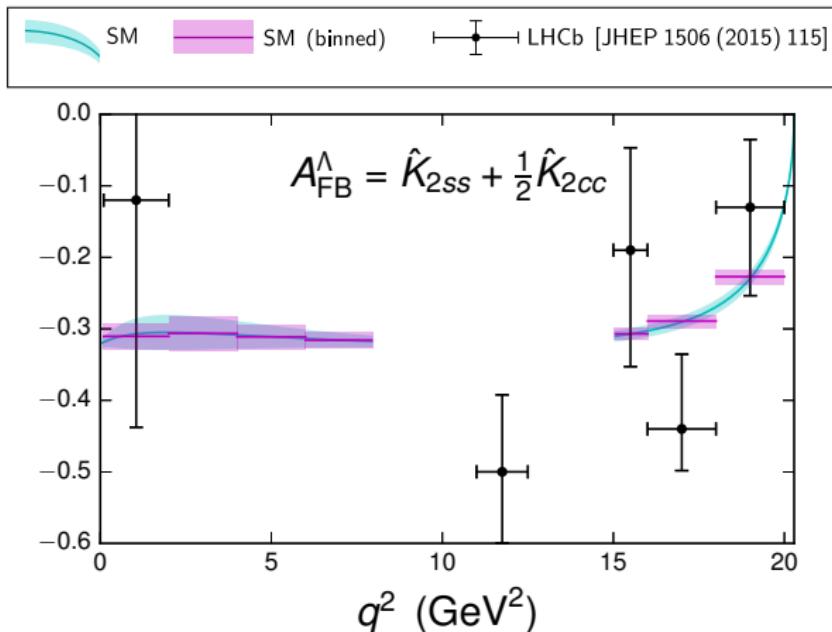
[W. Detmold and S. Meinel, PRD 93, 074501 (2016)]



[W. Detmold and S. Meinel, PRD 93, 074501 (2016)]



[W. Detmold and S. Meinel, PRD 93, 074501 (2016)]



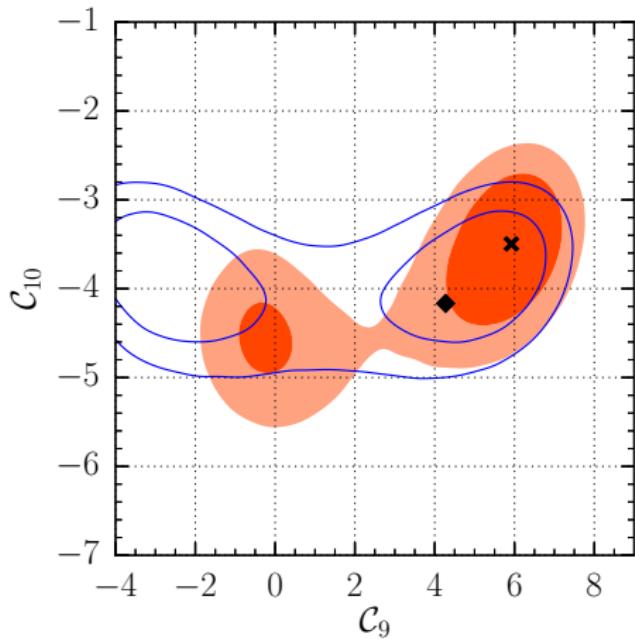
This is nonzero because  $\Lambda \rightarrow p^+ \pi^-$  is a parity-violating weak decay.

[W. Detmold and S. Meinel, PRD 93, 074501 (2016)]

Using  $\Lambda_b \rightarrow \Lambda\mu^+\mu^-$  data within a Bayesian analysis of  $|\Delta B| = |\Delta S| = 1$  decays

Constraint	Scenario		
	SM( $\nu$ -only)	(9, 10)	(9, 9', 10, 10')
$\Lambda_b \rightarrow \Lambda\mu^+\mu^-$	Pull value [ $\sigma$ ]		
$\langle \mathcal{B} \rangle_{15,20}$	+0.86	-0.17	-0.08
$\langle F_L \rangle_{15,20}$	+1.41	+1.41	+1.41
$\langle A_{FB}^\ell \rangle_{15,20}$	+3.13	+2.60	+0.72
$\langle A_{FB}^\Lambda \rangle_{15,20}$	-0.26	-0.24	-1.08
$\bar{B}_s \rightarrow \mu^+\mu^-$	Pull value [ $\sigma$ ]		
$\int \mathcal{B}(\tau) d\tau$	-0.72	+0.75	+0.37
$\bar{B} \rightarrow X_s \ell^+ \ell^-$	Pull value [ $\sigma$ ]		
$\langle \mathcal{B} \rangle_{1,6}$ (BaBar)	+0.47	-0.26	-0.10
$\langle \mathcal{B} \rangle_{1,6}$ (Belle)	+0.17	-0.35	-0.24
	$\chi^2$ at best-fit point		
	13.40	9.60	3.87

[S. Meinel and D. van Dyk, PRD **94**, 013007 (2016)]



[S. Meinel and D. van Dyk, PRD **94**, 013007 (2016)]

Opposite shift in  $C_9$  compared to fits of only mesonic decays!

- Statistical fluctuation?
- Breakdown of OPE for charm-loop effects?

# Conclusions and Outlook

- $\Lambda_b$  decays provide powerful new constraints on important quantities in flavor physics. I look forward to new experimental results ( $R[\Lambda_c]$ ,  $|V_{cb}|$  from  $\Lambda_b \rightarrow \Lambda_c \mu \bar{\nu}$ , full angular analysis of  $\Lambda_b \rightarrow \Lambda(\rightarrow p^+ \pi^-) \mu^+ \mu^-$ , ...).
- Form factors from lattice QCD are available for  $\Lambda_b \rightarrow p, \Lambda, \Lambda_c$ . Additional computations directly at the physical pion mass are currently underway to reduce systematic uncertainties.
- We have also started a lattice QCD calculation of form factors for

$$\Lambda_b \rightarrow \Lambda(1520)(\rightarrow p^+ K^-) \mu^+ \mu^-.$$

See the slides of my talk at Lattice 2016 [[link](#)].