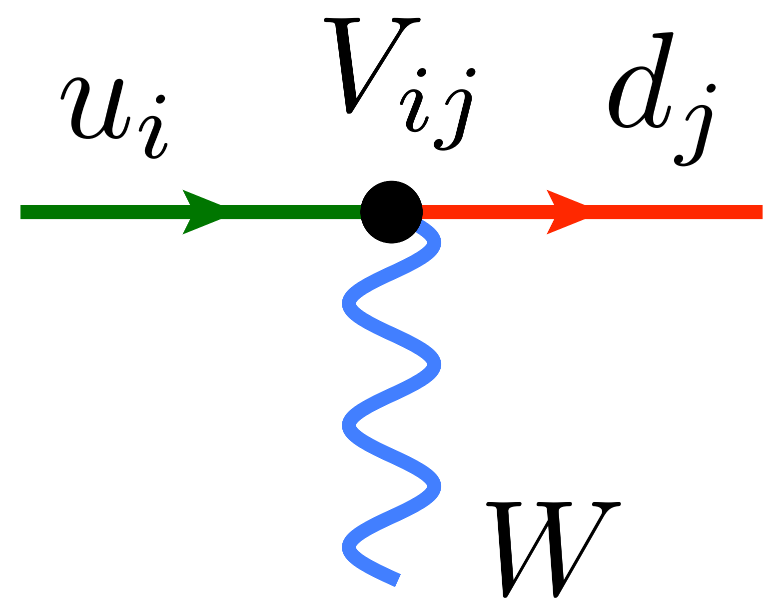
Semileptonic B decays - Experimental Status
FPCP-2019

Eiasha Waheed
University of Melbourne
(On behalf of Belle Collaboration also including material from LHCb and BaBar)

CKM Quark Mixing

Importance of |V$_{cb}$| and |V$_{ub}$|

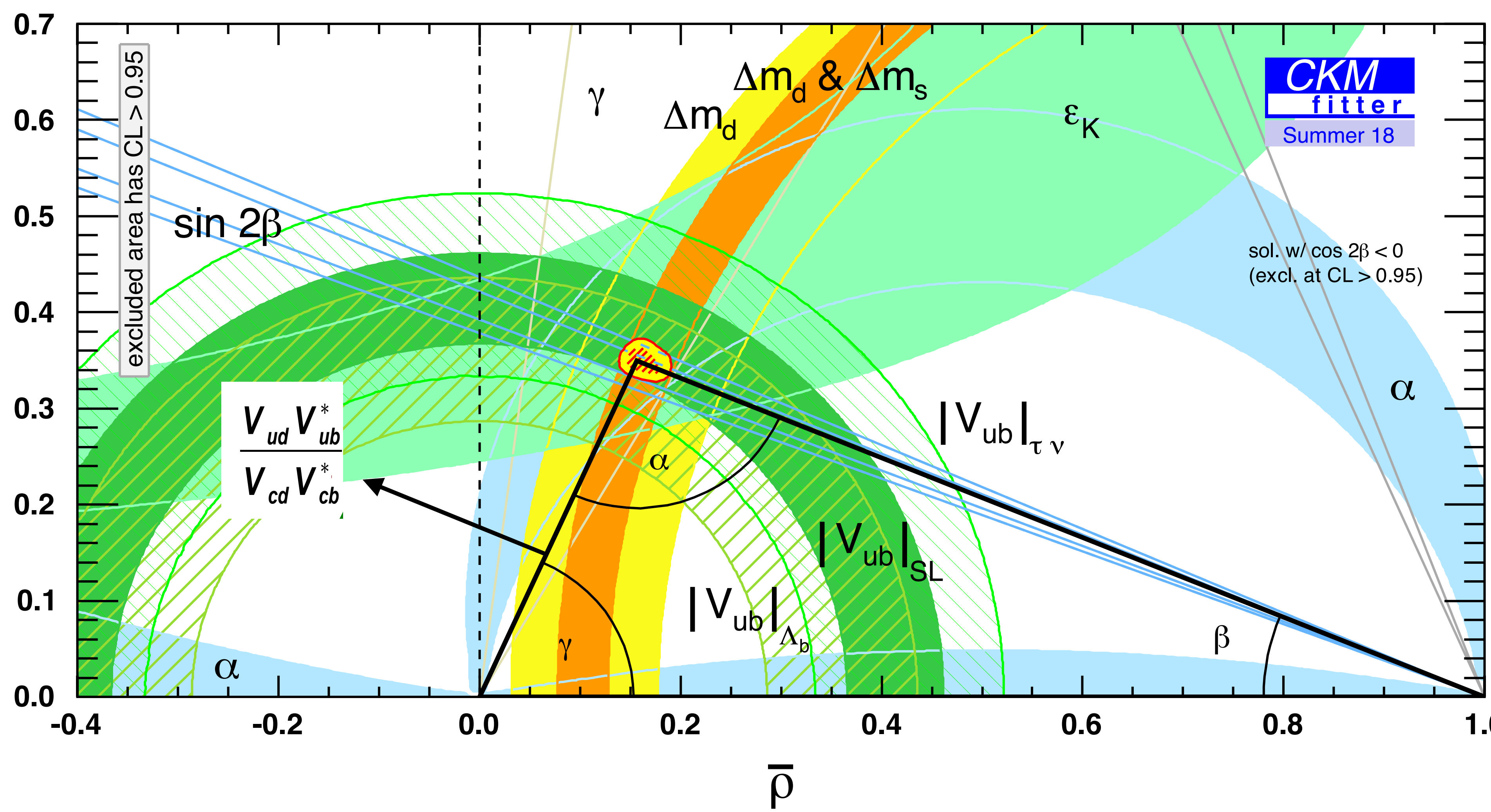
- Test of CKM sector
- So far huge success for SM
- New Physics still possible within current precision
- |V$_{ub}$| has largest error among parameters of UT



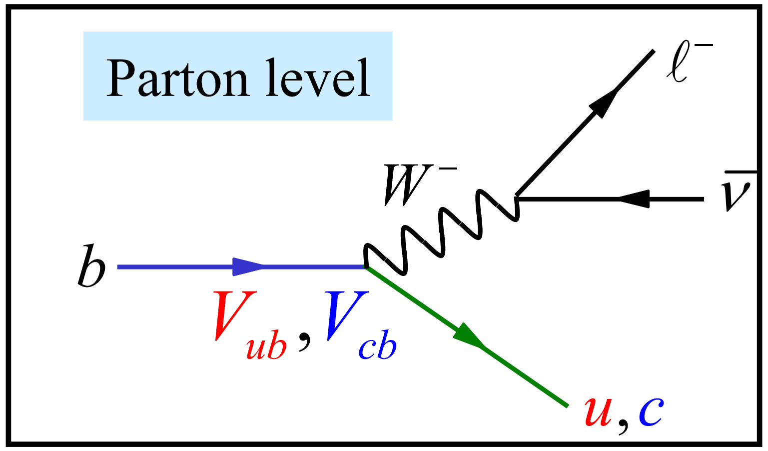
|V$_{qb}$| current precision

$|V_{ub}|_{\text{exlc.}} \sim 4\,\%\,,$

$|V_{cb}| \sim 2\,\%\,,$

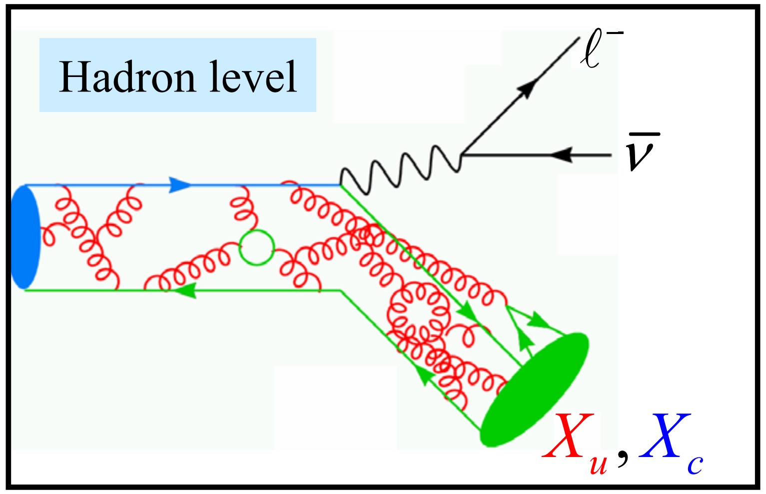


Semileptonic B decays



Decay properties depend on $|V_{cb}|$ & $|V_{ub}|$ and m_b

perturbative regime



But quarks are bounded by soft gluons: non-perturbative

+long distance interactions of b quark with light quark

Semileptonic B decays from HFLAV[1]

$$B^0 \to D^{*-}\ell\nu_\ell = 5.05 \pm 0.02 \pm 0.14$$
$$B^+ \to \bar{D}^{*0}\ell\nu_\ell = 5.66 \pm 0.07 \pm 0.21$$

$$B^0 \to D^-\ell\nu_\ell = 2.31 \pm 0.04 \pm 0.09$$
$$B^+ \to \bar{D}^0\ell\nu_\ell = 2.35 \pm 0.03 \pm 0.09$$

$$\mathcal{B}(\bar{B} \to X_c\ell^-\bar{\nu}_\ell) = (10.65 \pm 0.16)\%$$

$$\mathcal{B}(\bar{B} \to \pi\ell^-\bar{\nu}_\ell) = (1.47 \pm 0.06) \times 10^{-4}$$

$$\mathcal{B}(B \to X_u\ell\nu) = (1.86 \pm 0.10 \pm 0.14) \times 10^{-3}$$

- Decay rate $\Gamma_X \equiv \Gamma(b \to xl\nu) \propto |V_{xb}|^2$
- Γ_c larger than Γ_u by a factor ~50
  - Extracting $b \to \mu l\nu$ signal challenging

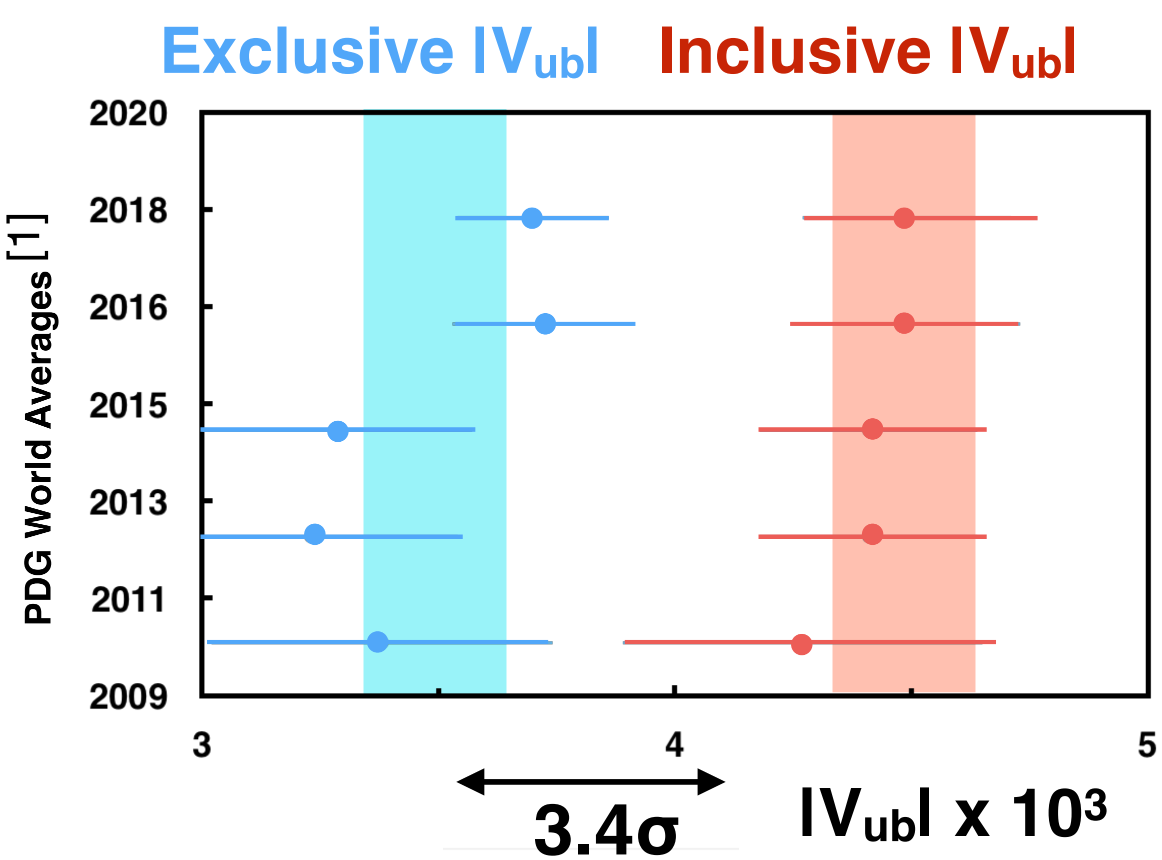
A persistent puzzle in $|V_{xb}|$ determination

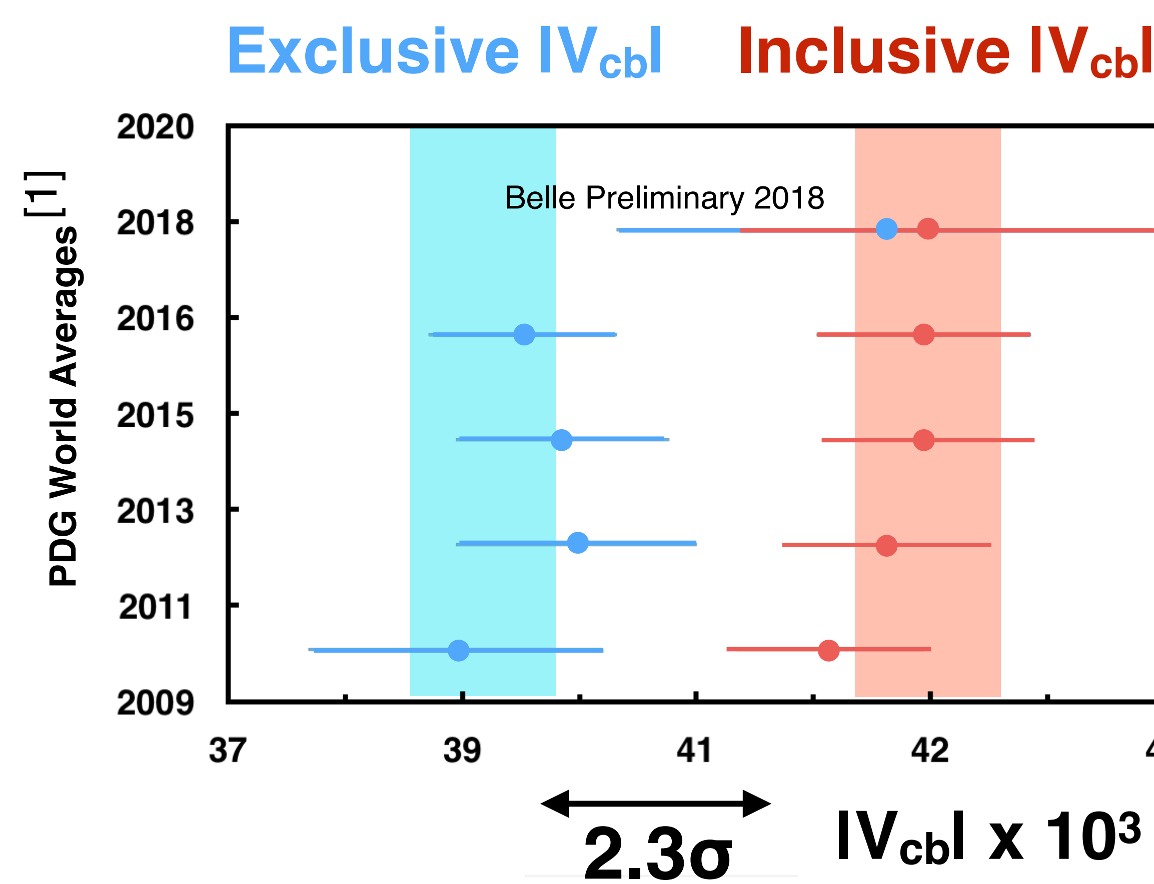
Inclusive Approach ($B\rightarrow X_c l\nu$)

- B Meson acts like a b quark which means that the decay can be described as $b\rightarrow c$, u quark transition.
- Calculated with Heavy Quark Expansion. (Phys.Rev.Lett. 114 (2015), 061802)

Exclusive Approach $B\rightarrow D^* l\nu$ / $B\rightarrow \pi l\nu$

- Hadronic transitions for $B\rightarrow D^*/B\rightarrow \pi$ described with form factors. LQCD and LCSR
  - Theoretically calculable at kinematical limits
  - Lattice QCD works if D^* or π is at rest relative to B (arXiv:1203.1204)



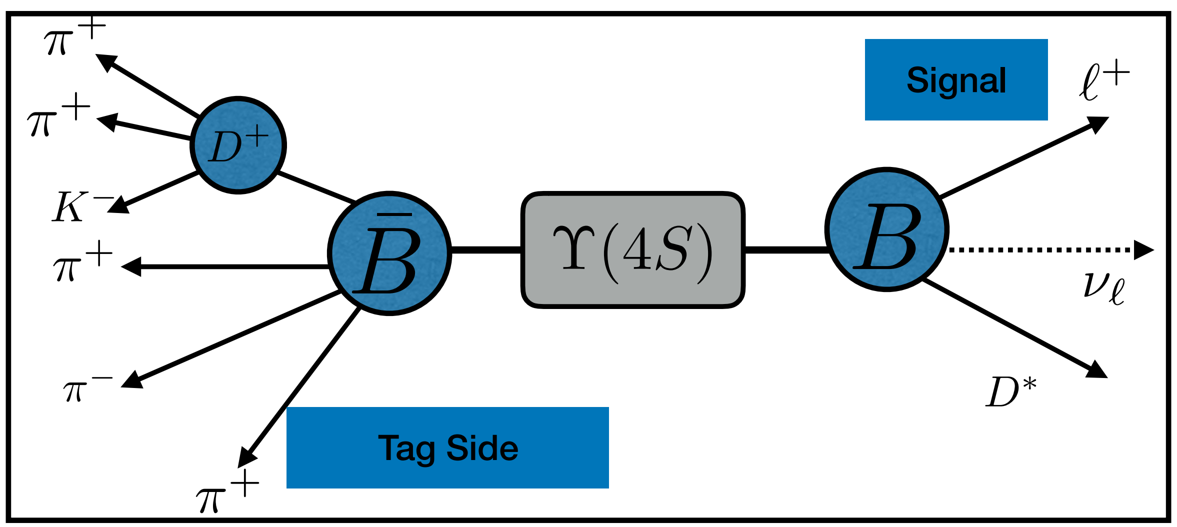


Experimental Measurements at Belle/BaBar

Tagged Measurement

One B reconstructed completely in a known b→c mode without ν. "B-meson Beam"

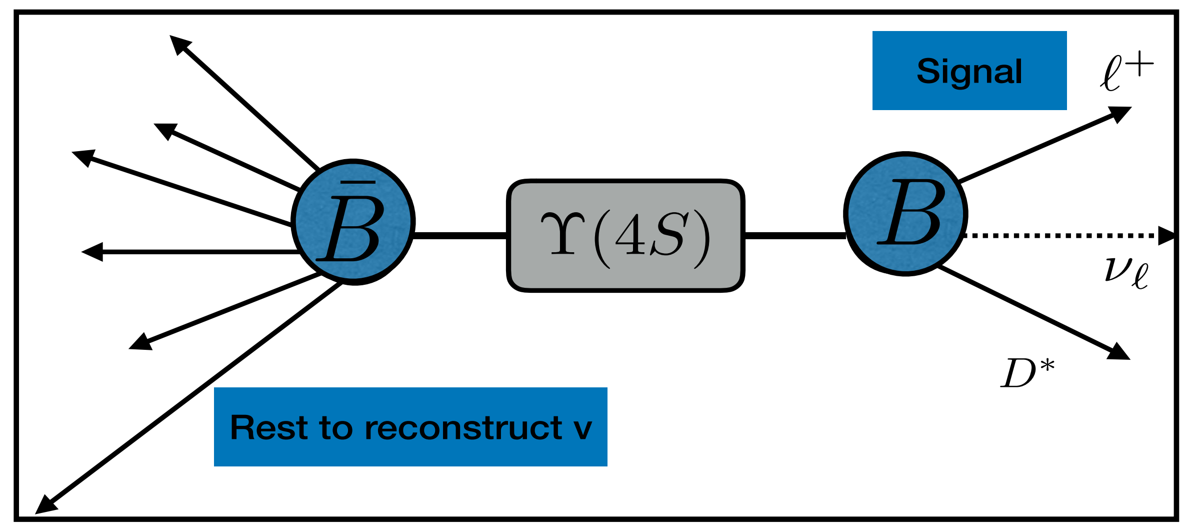
- **High purity, very small background**
- **Low Efficiency , large stat. errors**



Untagged Measurement

Initial 4 momentum known, missing 4-momentum = ν
Reconstructed B → X_q lν
Other side information to constrain signal B flight direction

- **High efficiency**
- **Low purity, large background**



Basic Analysis Steps

- Reconstruction
- Projection into bins of kinematic variables
- Fitting signal yield
- Compare measured events to expected events (Fit to calculate $|V_{cb}|$ and $|V_{ub}|$)

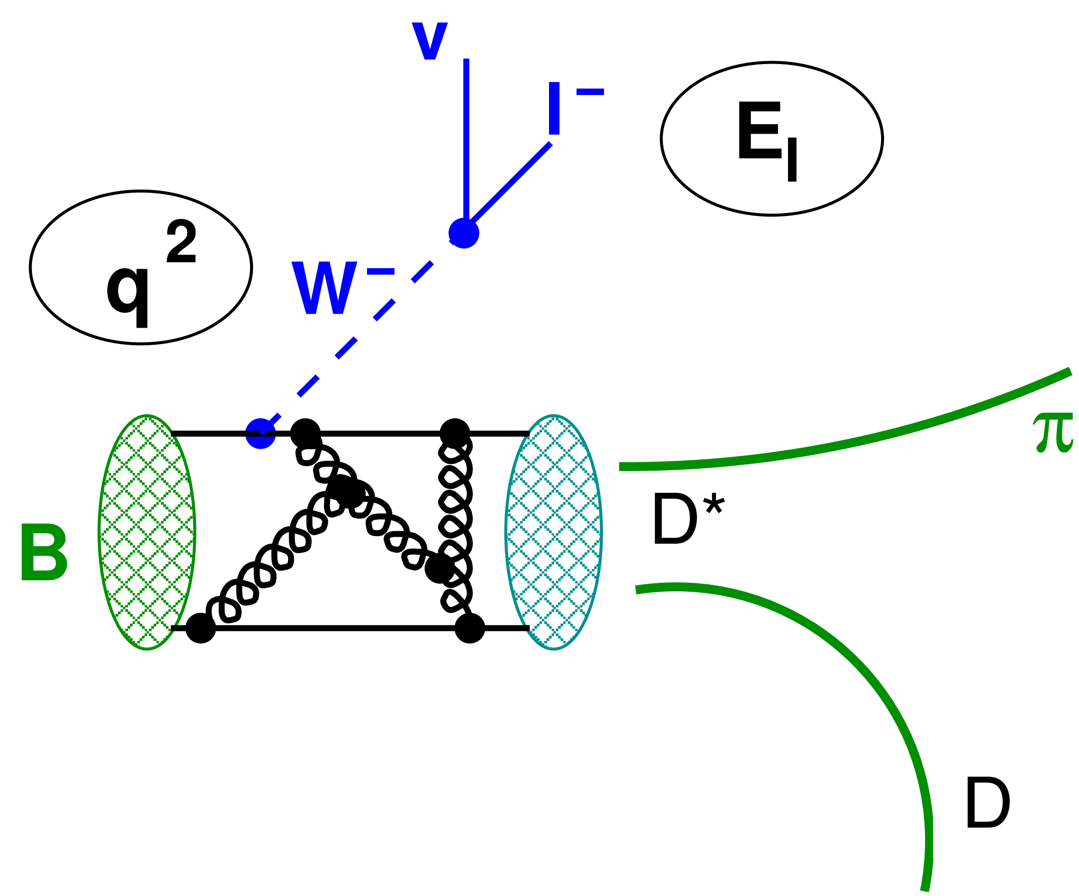
Recent Semileptonic Measurements at B Factories

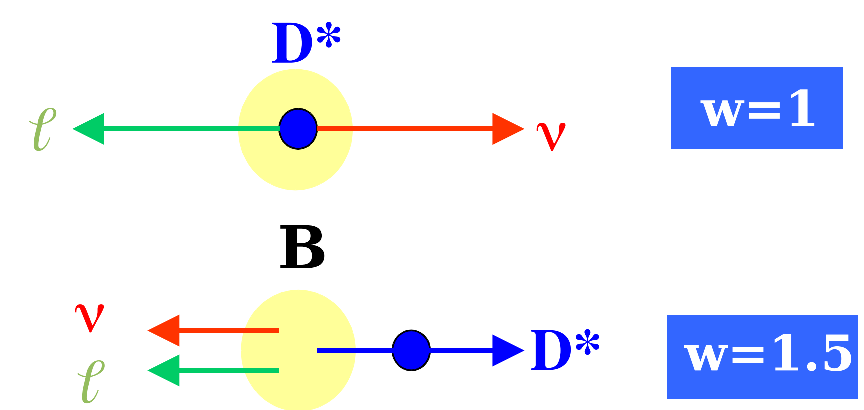
- $B \to D^* \ell \nu$ BaBar tagged 2019 **(arXiv:1903.10002, submitted to PRL)**
- $B^0 \to D^{*-} \ell^+ \nu_\ell$ Belle untagged 2018/2019 **(arXiv:1809.03290, submitted to PRD)**
- Measurement of shape of $\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}$ differential decay rate **(arXiv:1709.01920 Phys. Rev. D 96, 112005 (2017))**
- D^{*-} polarisation in $B^0 \to D^{*-} \tau^+ \nu_\tau$ **arXiv:1903.03102**
- $B \to D^* \pi \ell \nu_\ell$ Belle hadronic tagged 2018 **(arXiv:1803.06444, Phys. Rev. D 98, 012005 (2018))**
- Relative $B^- \to D^0/D^{*0}/D^{**0} \mu^- \nu_\mu$ branching fractions **(arXiv:1807.10722, submitted to PRD)**
- Inclusive $|V_{ub}|$ BaBar tagged 2019 **(arXiv:1611.05624, Phys. Rev. D 95, 072001(2017))**

$|V_{cb}|$

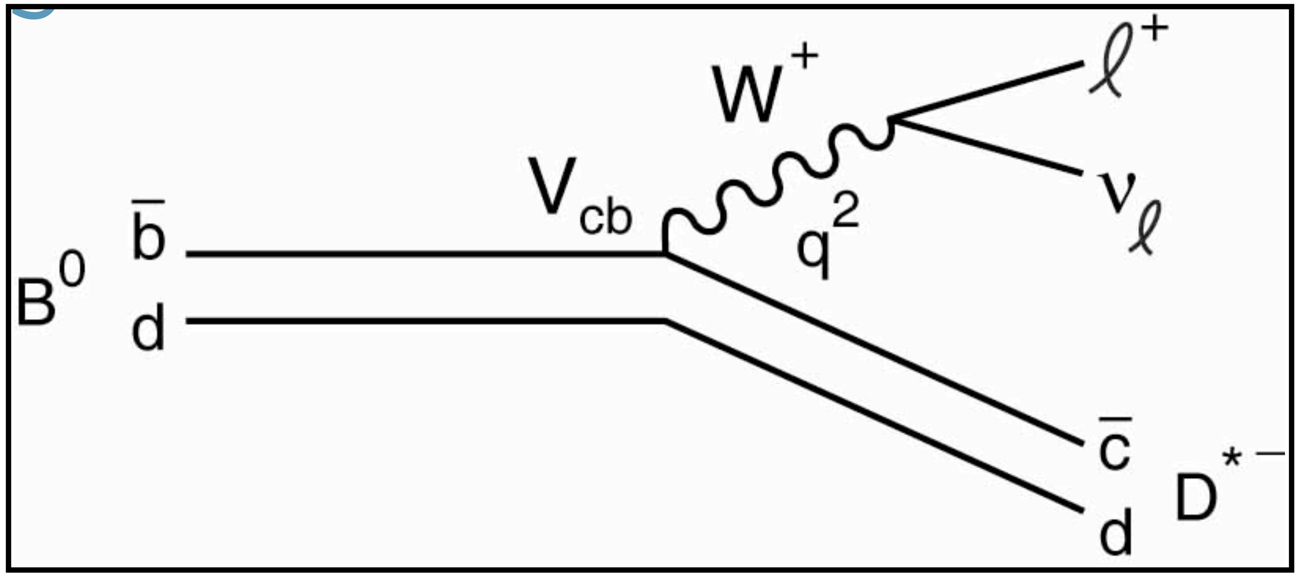
Semileptonic Observables

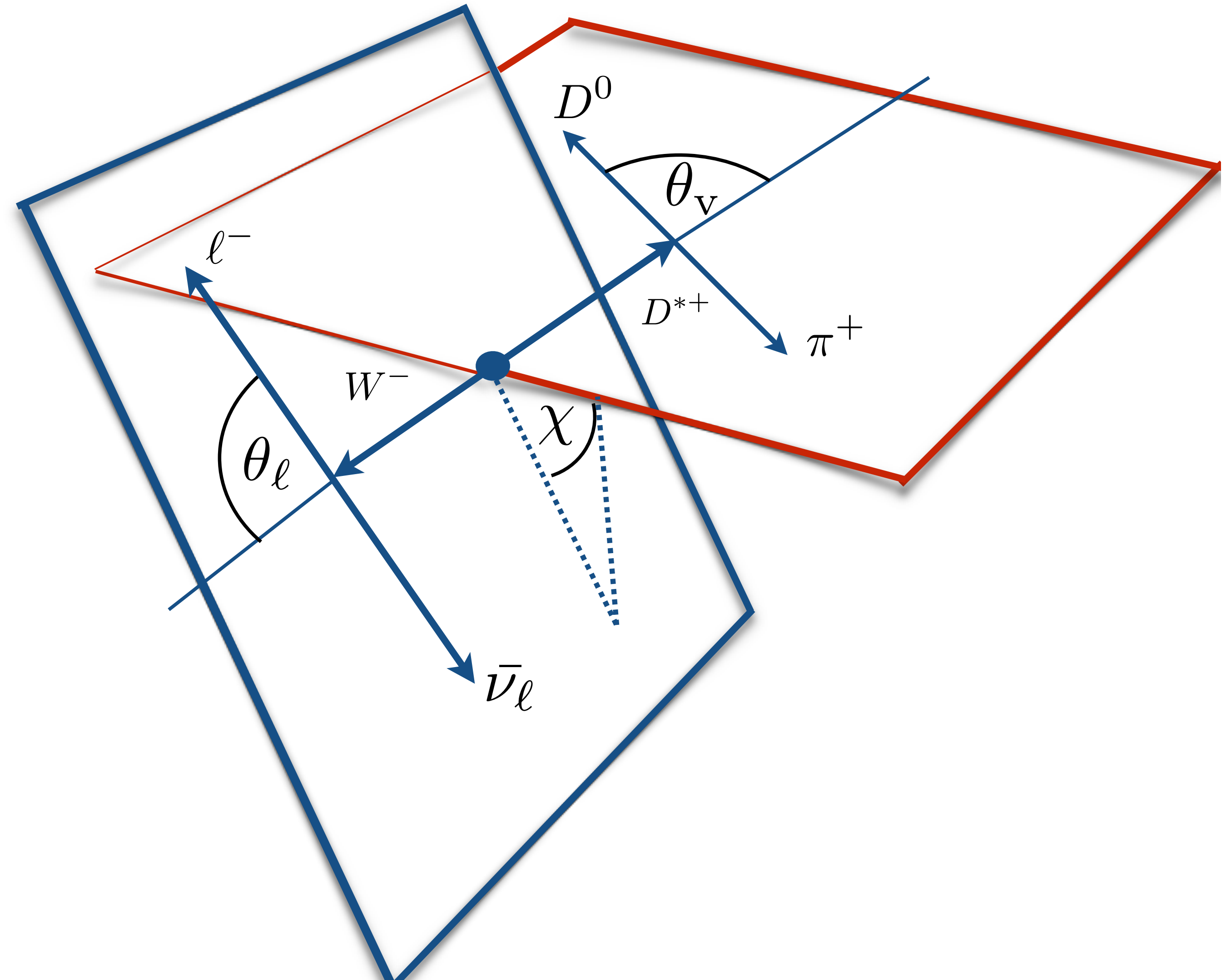
- Four momentum of charged lepton
  - Experimentally: good LeptonID to minimise fakes
- Four momentum of hadronic system
  - Experimentally: slow pion momentum - important for measurement at low recoil
- Momentum transfer to leptonic system
  - $q^2 = (p_l+p_v)^2$
  - Hadronic recoil
    - $w \equiv v_B.v_{D^*} = \dfrac{m_B^2 + m_{D^*}^2 - q^2}{2m_B m_{D^*}}$
    - For $B^0 \to D^{*-}\ell^+\nu : 1 < w < 1.504$
  - Normalisation (w = 1) = 1 (Heavy quark limit)





$|V_{cb}|$ and Decay Rate of $B^0 \to D^{*-}\ell^+\nu_\ell$





Differential Decay rate

$$\frac{d\Gamma(B^0 \to D^*\ell^+\nu_\ell)}{dw\,d\cos\theta_\ell\cos\theta_V d_\chi} = \frac{G_F^2|V_{cb}|^2}{48\pi^3} F(w,\theta_\ell,\theta_V,\chi) G(w)$$

Form factor of B→ D* transition phase space (known)

In case of $B \to D\ell\nu$ decay rate only depend on w.

Form factor parameterisation

Caprini, Lelouch, Neubert (CLN)

arXiv:hep-ph/9712417, Nucl.Phys. B530 (1998)

Theoretical assumptions used to reduce the number of free parameters describing form factors: to measure $|V_{cb}|$ with a smaller data set

$F(w, \theta_\ell, \theta_V, \chi)$ → 3 non trivial form factors $A_1(w)$, $A_2(w)$ and $V(w)$

$$R_1(w) = V/A_1$$
$$R_2(w) = A_2/A_1$$
$$\rho^2(w) = -dF/dw|_{w=1}$$

F(w) normalised at zero recoil (w=1)

Boyd Grinstein Lebed (BGL)

arXiv:hep-ph/9504235, Phys.Lett.B353:306-312,1995

$F(w, \theta_\ell, \theta_V, \chi)$ is written as the most generic parameterisation with minimal theory assumptions, the expansion is constrained by unitarity (can have more coefficients than CLN at O(3))

Form factor parameterisation: CLN Vs BGL

- CLN — **arXiv:hep-ph/9712417, Nucl.Phys. B530 (1998)**
  - HQET relations + corrections in powers of Λ_{QCD}/m_b,
- For $B \to D^* l\nu$

$$h_{A_1}(w) = h_{A_1}(1)\left(-z^3\left(231\rho^2_{D^*} - 91\right) + \right.$$
$$\left. + z^2\left(53\rho^2_{D^*} - 15\right) - 8z\rho^2_{D^*} + 1\right),$$
$$R_1(w) = R_1(1) + 0.05(w-1)^2 - 0.12(w-1),$$
$$R_2(w) = R_2(1) - 0.06(w-1)^2 + 0.11(w-1)$$

- For $B \to Dl\nu$

$$\mathcal{G}(w) = \mathcal{G}(1)(1 - 8\rho^2_D z + (51\rho^2_D - 10)z^2$$
$$-(252)\rho^2_D - 84)z^3$$

- BGL — **Phys.Lett. B771 (2017), Phys.Lett. B769 (2017)**
  - No HQET input
- For $B \to D^* l\nu$

$$h_{A_1}(w) = \frac{f(w)}{\sqrt{m_B m_{D^*}}(1+w)}$$
$$R_1(w) = (w+1)m_B m_{D^*}\frac{g(w)}{f(w)}$$
$$R_2(w) = \frac{w-r}{w-1} - \frac{\mathcal{F}_1(w)}{m_B(w-1)f(w)}$$

where f, g and F_1 are

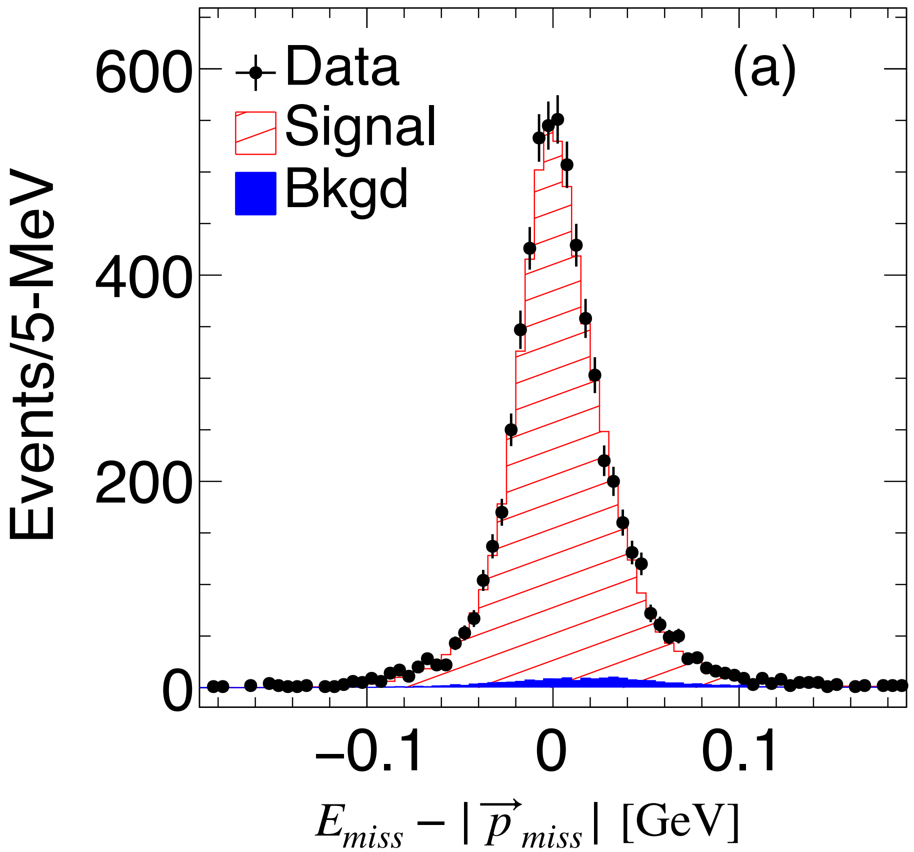
parameterised as ….

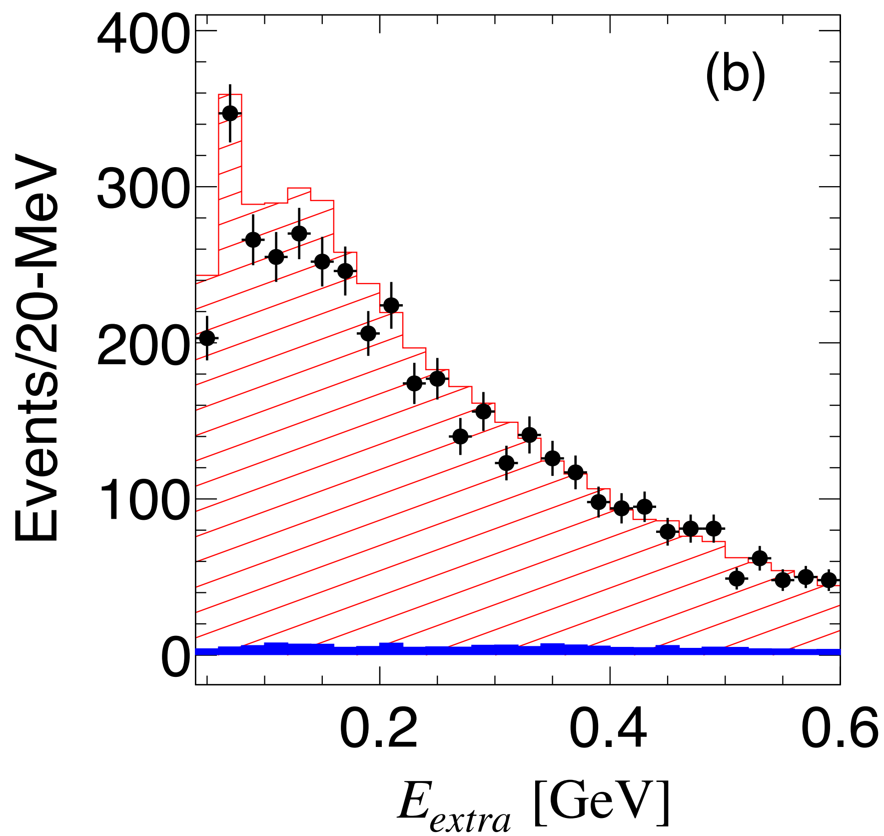
$$f(z) = \frac{1}{P_i(z)\phi_i(z)}\sum_{n=0}^{N} a_{i,n} z^n$$

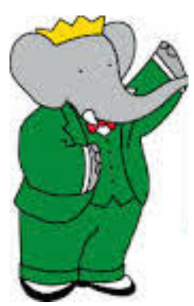
cut off at n=1,2 …

Exclusive $|V_{cb}|$ from $B \to D^* \ell \nu$ tagged

- Tag side B reconstructed (hadronically) to reconstruct unknown neutrino momentum
- Reconstruct Bsignal (comprised of D^*e, $D^*\mu$ and $D^{*0}e$, $D^{*0}\mu$ where D^0 from $D^{*(0)}$ decays to $K^-\pi^+, K^-\pi^-\pi^0, K^-\pi^+\pi^-\pi^+$ combined with π^0 and π^+)
- Signal selection using $\Delta m = (m_{D*} - m_D)$ and p_{lep}
- Kinematic fit to $e^+e^- \to \Upsilon(4S) \to B_{\text{tag}}\bar{B}_{\text{sig}}(\to D^*\ell^-\bar{\nu}_l)$







BaBar 469 fb^{-1}

$N_{\text{signals}} = 5932$

Exclusive |Vcb| from $B \to D^* \ell \nu$ tagged

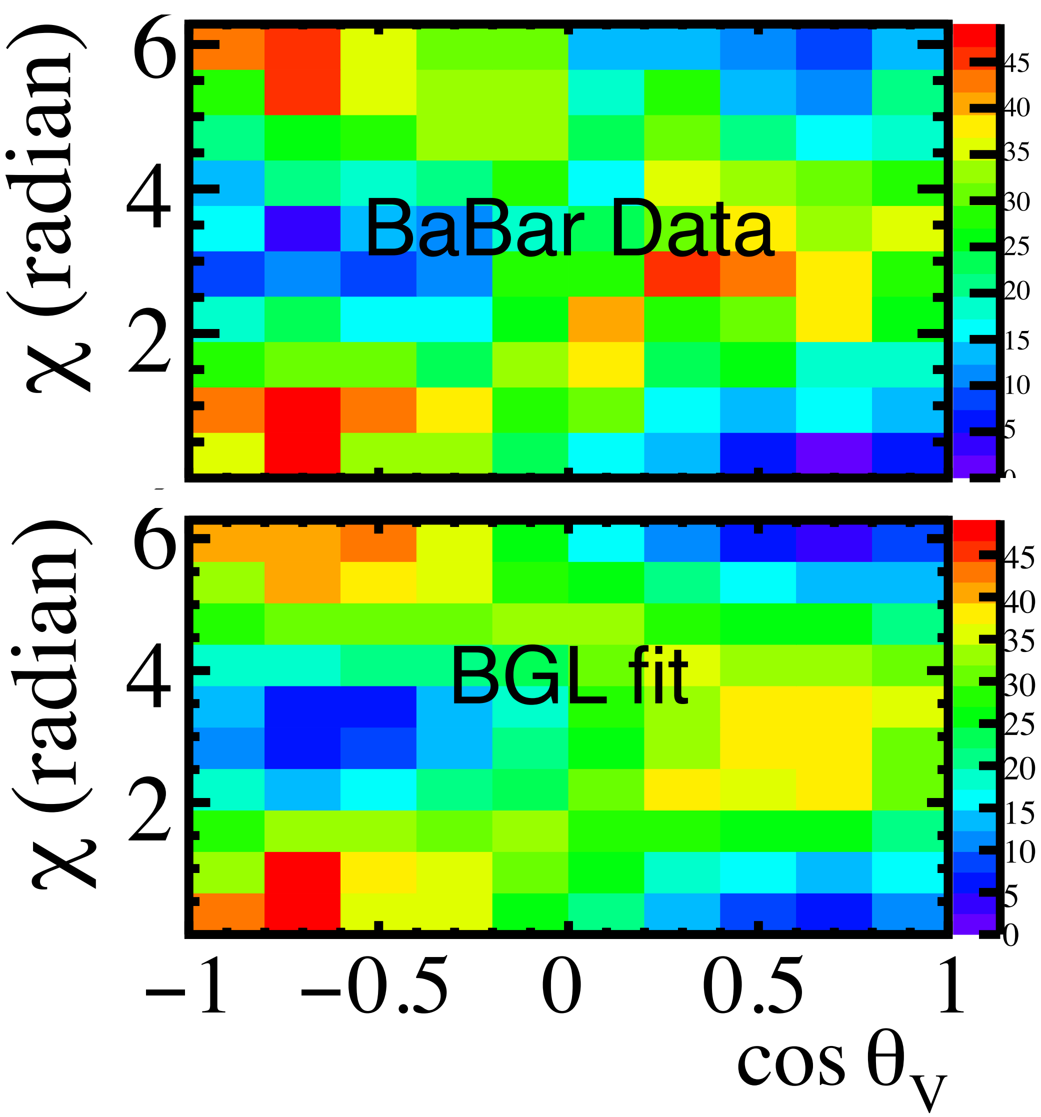
arXiv:1903.10002, submitted to PRL

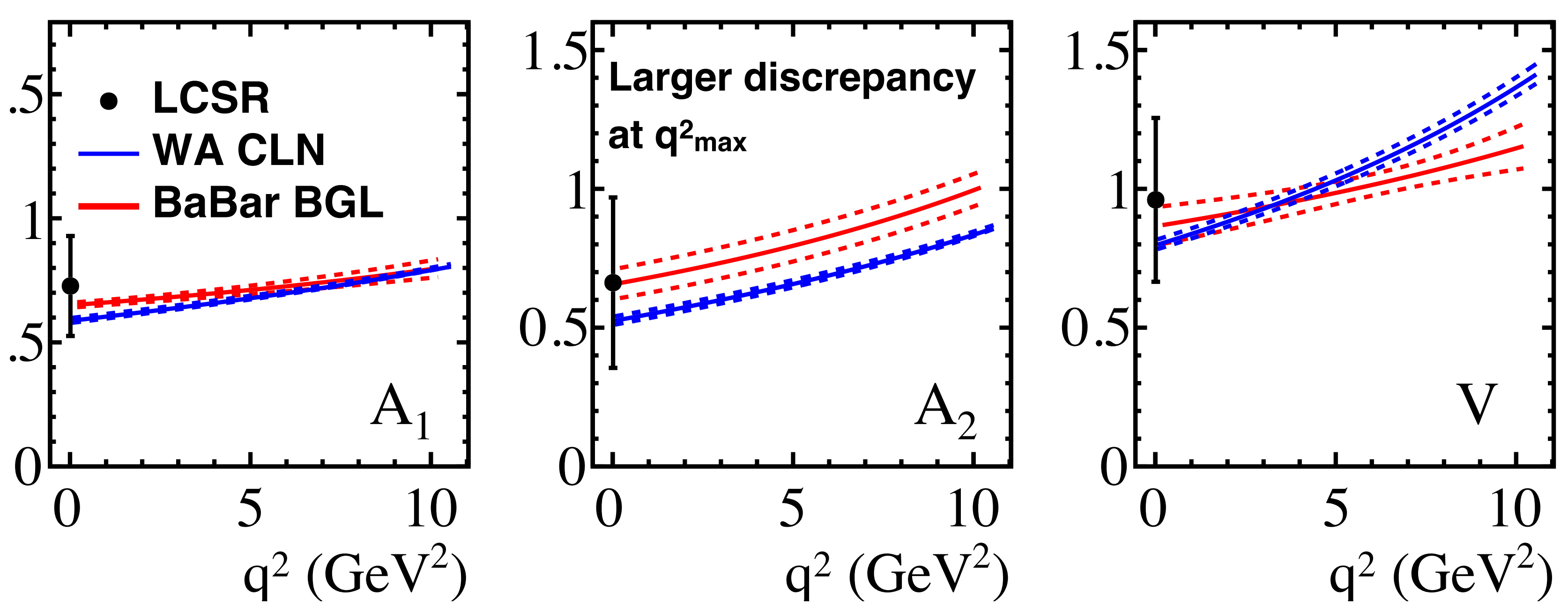
- Measure $|V_{cb}|$ and form factor parameters
- First unbinned (ML) fit in 4-D of q^2, $\cos\theta_l$, $\cos\theta_V$, χ for BGL expansion (N=1)
- Tension remain between inclusive and exclusive $|V_{cb}|$

$|V_{cb}|$ consistent with CLN-WA

$$|V_{cb}| \times 10^3 = 38.03 \pm 1.05 \ (B^- - e)$$
$$|V_{cb}| \times 10^3 = 38.68 \pm 1.16 \ (B^- - \mu)$$
$$|V_{cb}| \times 10^3 = 38.59 \pm 1.15 \ (B^0 - e)$$
$$|V_{cb}| \times 10^3 = 38.24 \pm 1.05 \ (B^0 - \mu)$$

$a_0^f \times 10^2$	$a_1^f \times 10^2$	$a_1^{F_1} \times 10^2$	$a_0^g \times 10^2$	$a_1^g \times 10^2$	$\lvert V_{cb}\rvert \times 10^3$
1.29 $\pm$0.03	1.63 $\pm$1.00	0.03 $\pm$0.11	2.74 $\pm$0.11	8.33 $\pm$6.67	38.36 $\pm$0.90

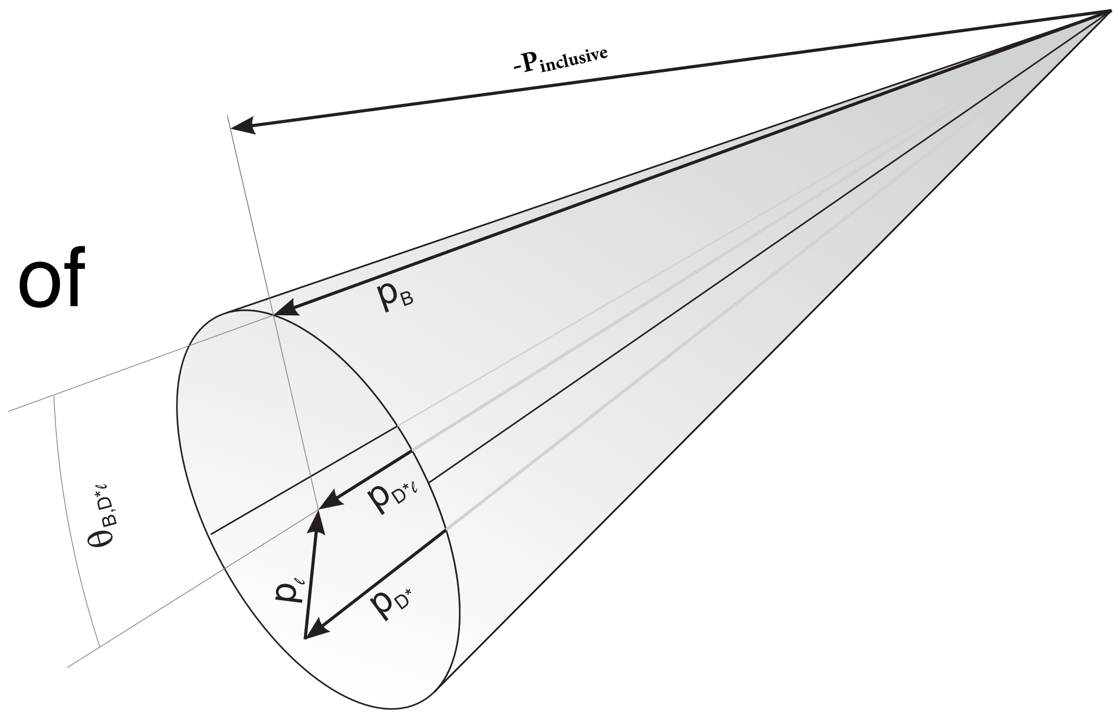




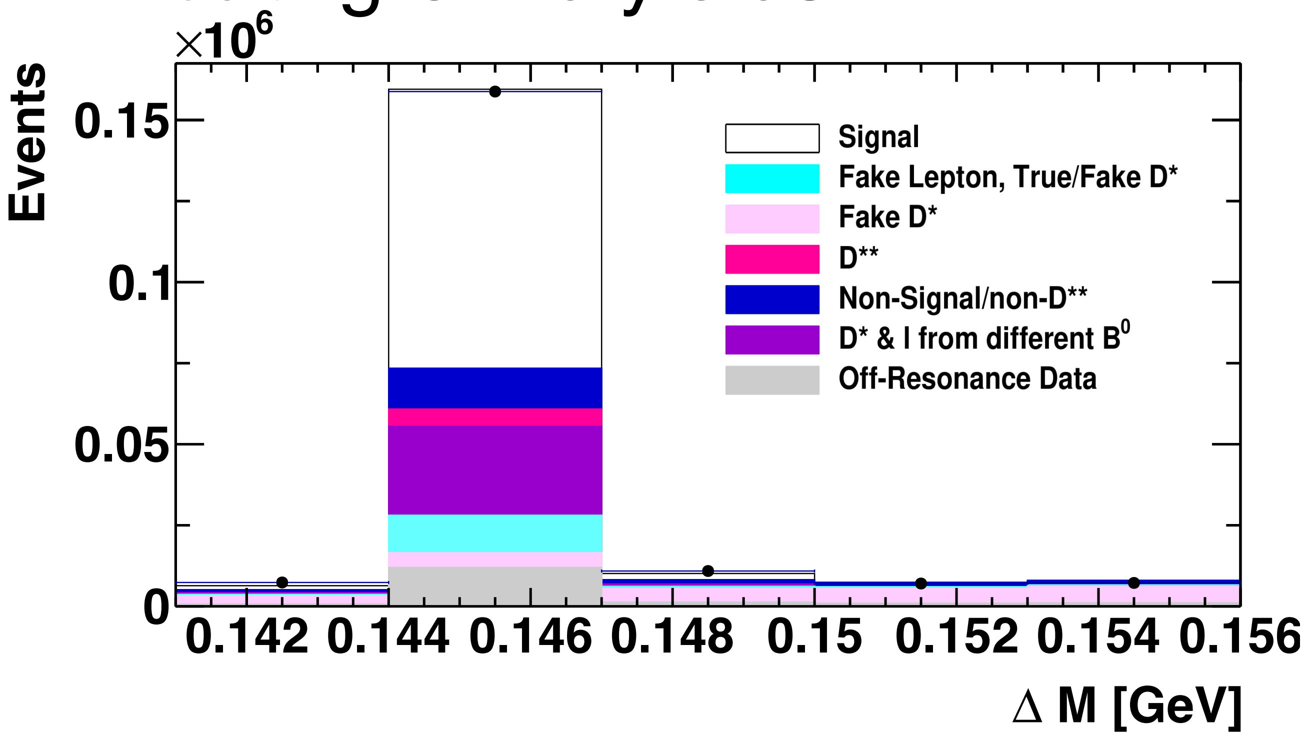
$B^0 \to D^{*-}\ell^+\nu_\ell$ using untagged approach

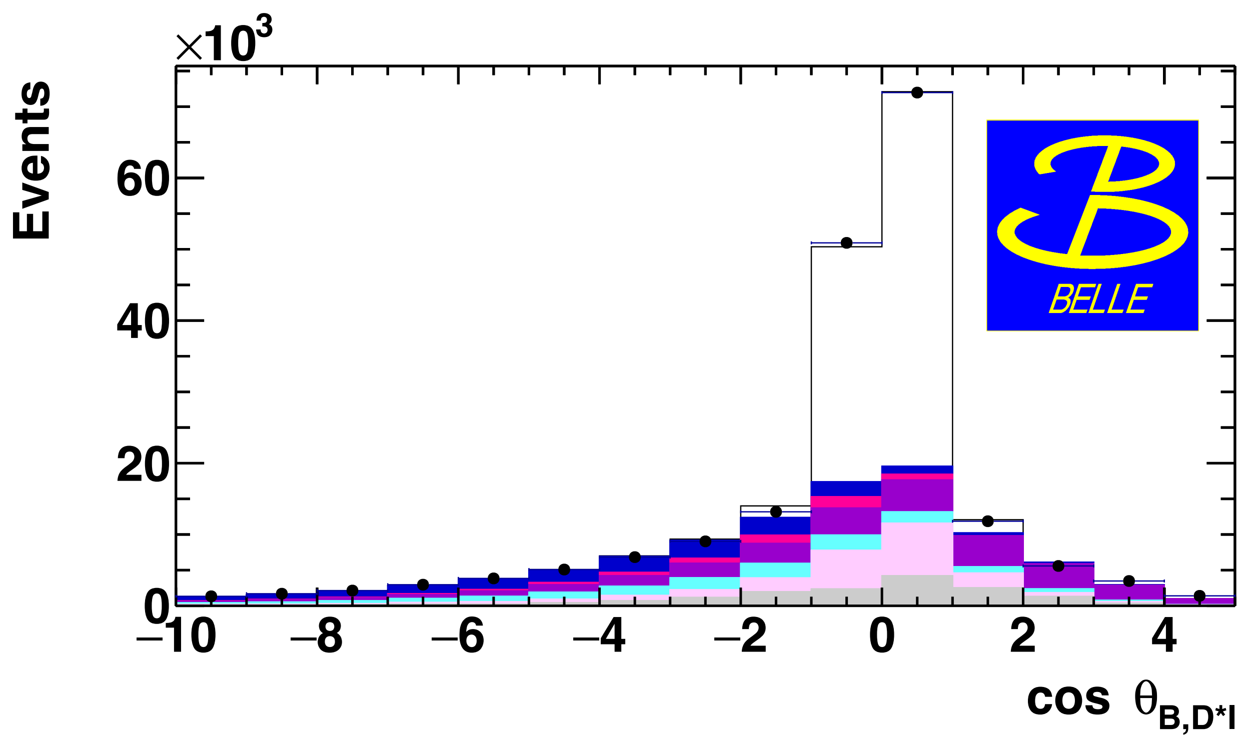
arXiv:1809.03290 , submitted to PRD

- Measure $|V_{cb}|$ using **Belle** 711fb^{-1}.
- Signal Selection using
  - 3D - Binned Maximum Likelihood fit of
  - $(\cos\theta_{B,D^*l})$
  - ΔM = mass $(D^*\text{-}D^0)$
  - lepton momentum



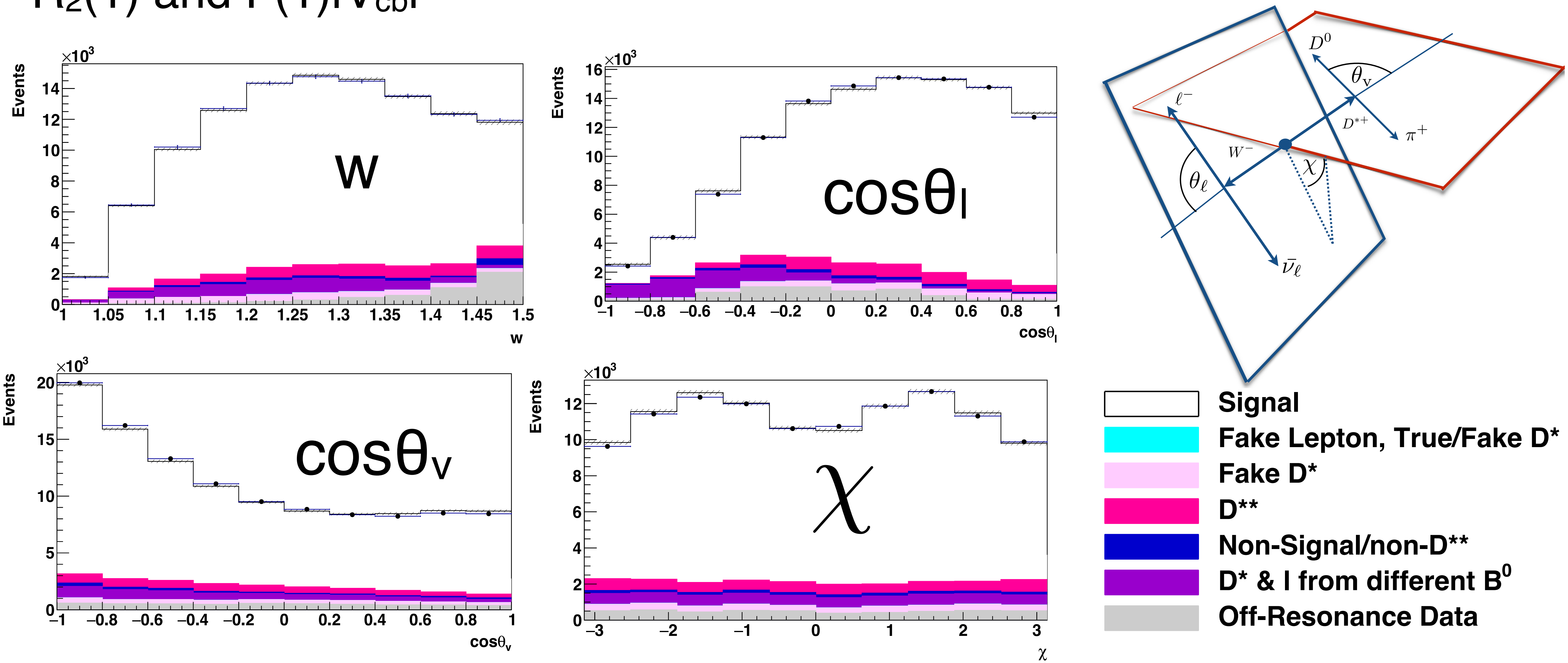
- Float Signal & Backgrounds components from MC to extract background yields





FF parameters and $|V_{cb}|$ from CLN

Simultaneous fit of 1D projections of w, $\cos\theta_l$, $\cos\theta_v$, X to extract ρ^2, $R_1(1)$, $R_2(1)$ and $F(1)|V_{cb}|$



$$\rho^2 = 1.106 \pm 0.031 \pm 0.007$$
$$R_1(1) = 1.229 \pm 0.028 \pm 0.009$$
$$R_2(1) = 0.852 \pm 0.021 \pm 0.006$$

$F(1)|V_{cb}|\eta_{EW} \times 10^3 = 35.1 \pm 0.2 \pm 0.6$

FF parameters and $|V_{cb}|$ from BGL

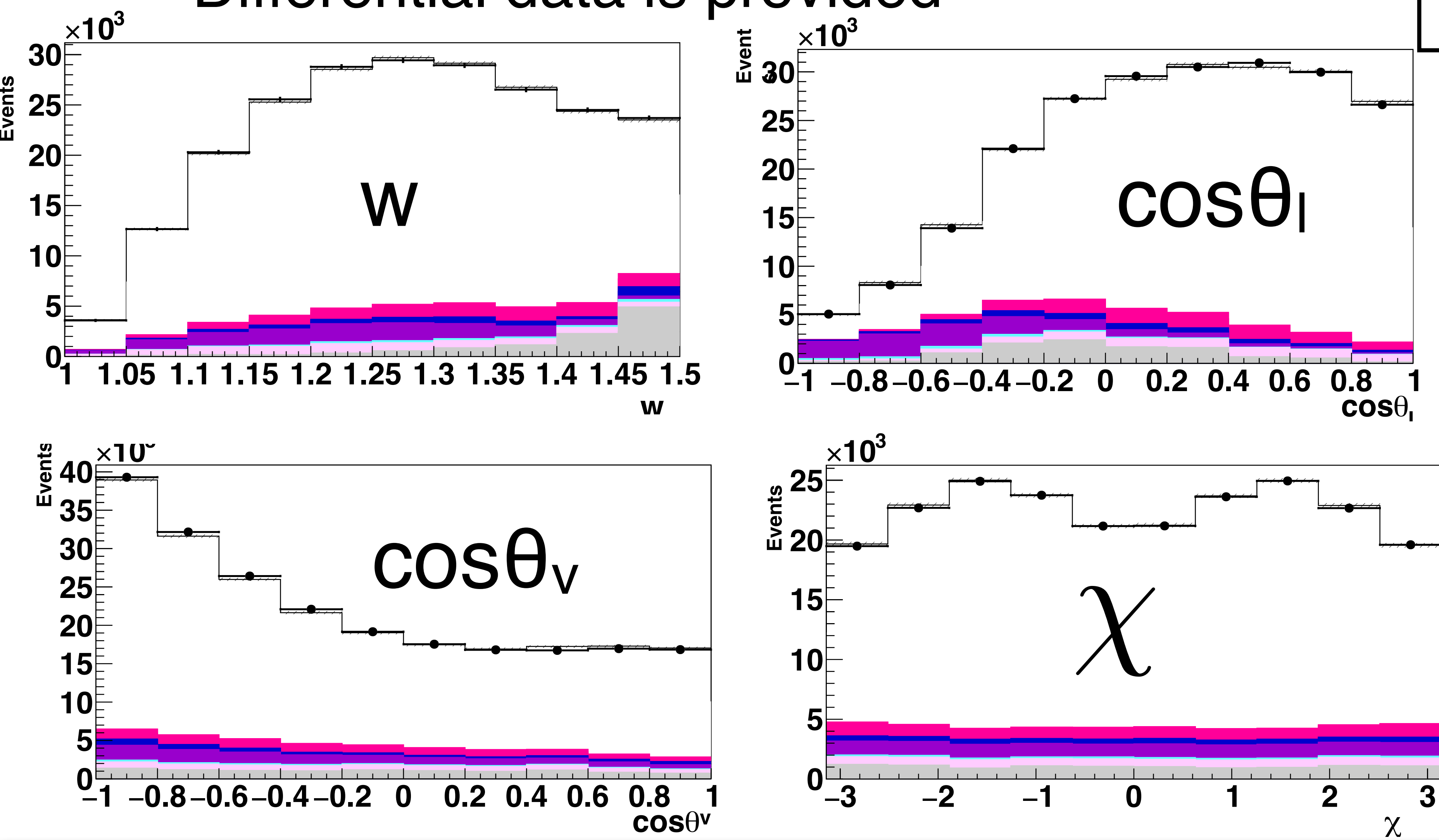
arXiv:1809.03290, submitted to PRD

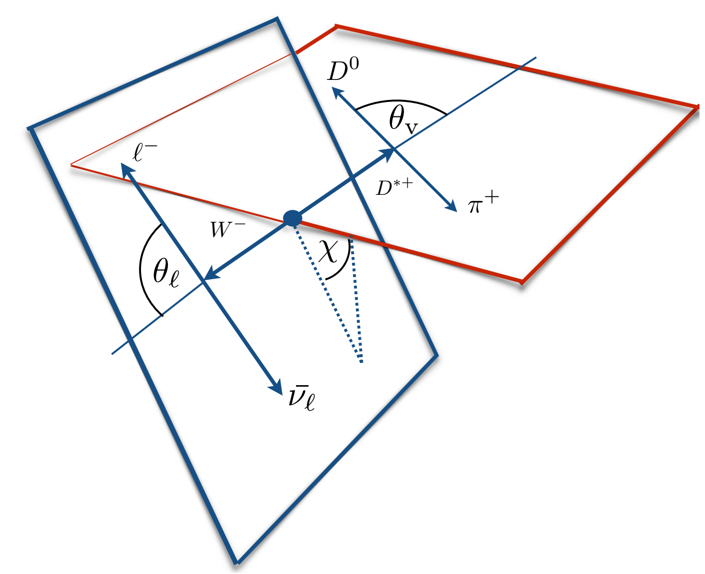
Simultaneous fit of 1D projections of w, $\cos\theta_l$, $\cos\theta_v$, X to extract the coefficients of the BGL expansion (up to 3rd order) and $F(1)|V_{cb}|$

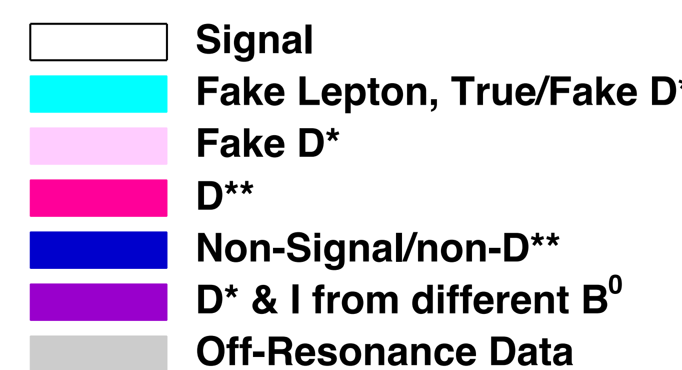
$$F(1)|V_{cb}|\eta_{EW} \times 10^3 = 34.9 \pm 0.2 \pm 0.6$$

- Consistent with CLN
- Differential data is provided

$$\begin{aligned}
\tilde{a}_0^f \times 10^3 &= -0.506 \pm 0.004 \pm 0.008, \\
\tilde{a}_1^f \times 10^3 &= -0.65 \pm 0.17 \pm 0.09, \\
\tilde{a}_1^{F_1} \times 10^3 &= -0.270 \pm 0.064 \pm 0.023, \\
\tilde{a}_2^{F_1} \times 10^3 &= +3.27 \pm 1.25 \pm 0.45, \\
\tilde{a}_0^g \times 10^3 &= -0.929 \pm 0.018 \pm 0.013,
\end{aligned}$$







THE UNIVERSITY OF MELBOURNE

$|V_{cb}|$ from BaBar and Belle From CLN and BGL

Last 10 years…

$|V_{cb}| \times 10^3 = 38.4 \pm 0.6$ (CLN-Belle2019) ($B \to D^* l\nu$)[1]

$|V_{cb}| \times 10^3 = 38.3 \pm 0.8$ (BGL-Belle2019) ($B \to D^* l\nu$)[1]

$|V_{cb}| \times 10^3 = 38.4 \pm 0.9$ (BGL-BaBar2019) ($B \to D^* l\nu$)[2]

$|V_{cb}| \times 10^3 = 39.9 \pm 1.3$ (CLN-Belle2016) ($B \to D l\nu$)[3]

$|V_{cb}| \times 10^3 = 40.8 \pm 1.1$ (BCL-Belle2016)($B \to D l\nu$)[3]

$|V_{cb}| \times 10^3 = 42.2 \pm 0.8$ (Inclusive-HFLAV)[4]

- CLN and BGL agree for both Belle and BaBar
- Inclusive and Exclusive tension still persistent !!!
- CLN and BGL form factor differences at zero-recoil (minimum higher order HQET corrections) need to be investigated further.

$\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}$ differential decay rate

arXiv:1709.01920, Phys. Rev. D 96, 112005 (2017)

- Differential decay rate (as function of q^2) is compared with expectations from HQET and unquenched lattice QCD predictions.
- $\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu$ described by (6) form factors (FF) corresponding to the vector and axial-vector components.

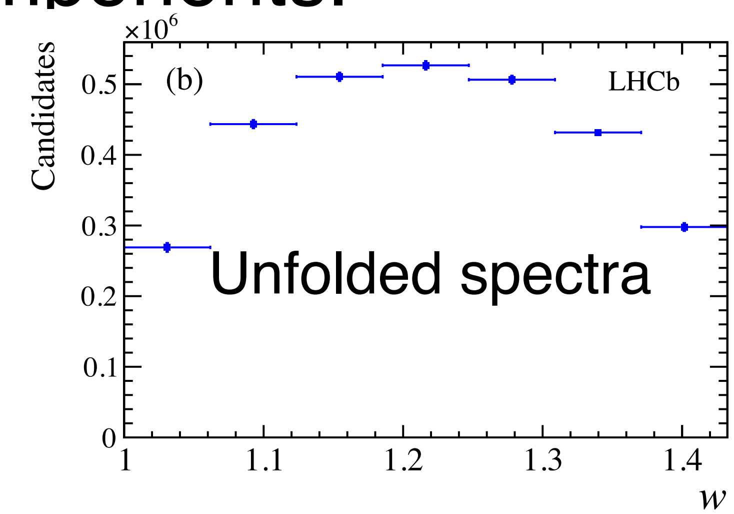
$$\frac{d\Gamma}{dw} = G K(w) \xi_B^2$$

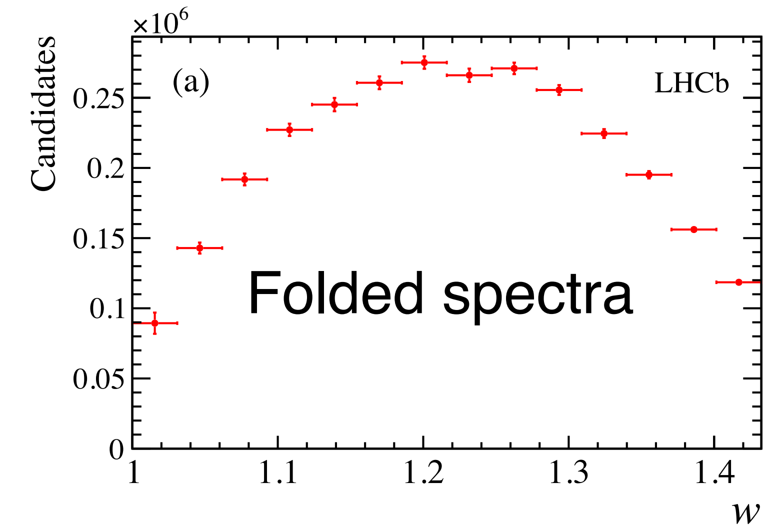
$$G = \frac{2}{3}\frac{G_F^2}{(2\pi)^3}|V_{cb}|^2 (m_{\Lambda_b^0})^4 r^2$$

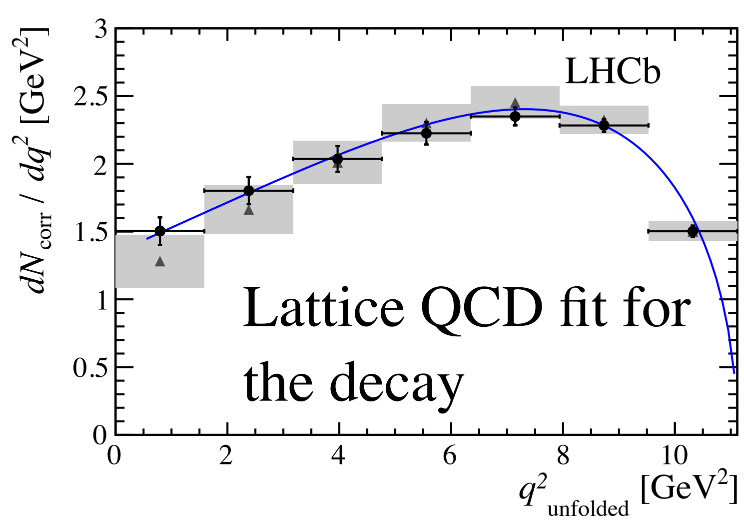
$$\xi_B(w) = 1 - \rho^2(w-1) + \frac{1}{2}\sigma^2(w-1)^2 + \ldots,$$

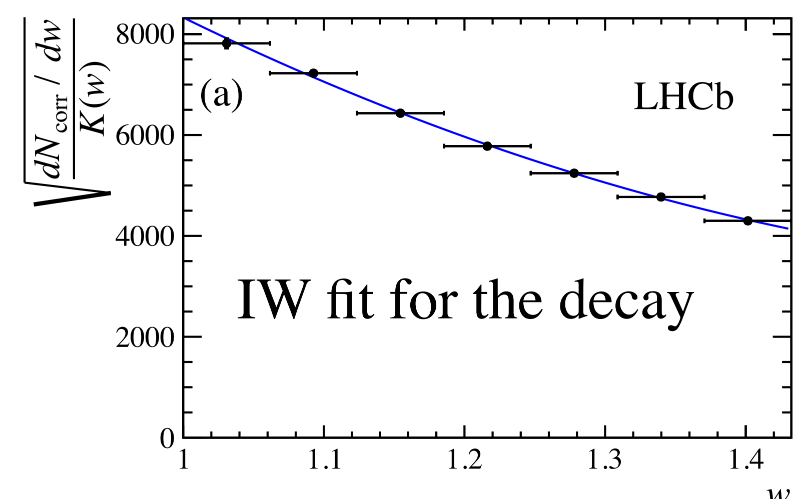
$$K(w) = m_{\Lambda_c^+}\sqrt{w^2-1}\,[3w(1-2rw+r^2) + 2r(w^2-1)].$$

ρ^2 = 1.63 ± 0.07 ± 0.08,
consistent with Lattice[1], QCD[2], and relativistic quark model[3]









Further studies with a suitable normalisation channel will lead to a precise independent determination of the CKM parameter $|V_{cb}|$.

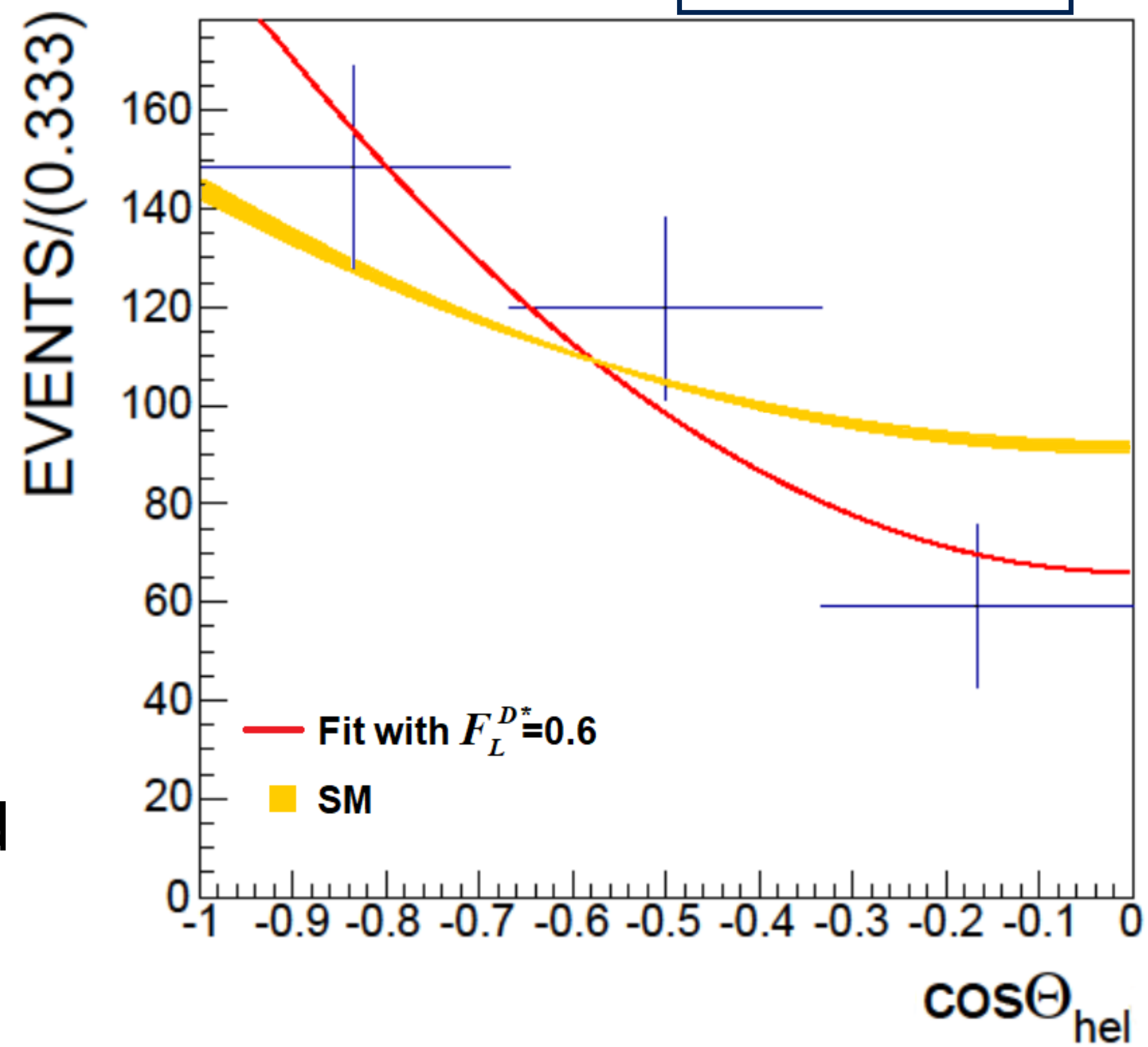
D^{*-} polarisation in $B^0 \to D^{*-}\tau^+\nu_\tau$ arXiv:1903.03102

- $F_L^{D^*}$ is fraction of D* polarisation in $B^0 \to D^{*-}\tau^+\nu_\tau$ decay from angular distribution in $D^{*-} \to \bar{D}^0\pi^-$
- SM prediction[1]: $F_L^{D^*} = 0.45$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\rm hel}} = \frac{3}{4}(2F_L^{D^*}\cos^2\theta_{\rm hel} + (1 - F_L^{D^*})\sin^2\theta_{\rm hel})$$

  - θ_{hel} is angle between D^0 and direction opposite to B^0 in D^{*-} rest frame
- Rest of event information to reconstruct B_{tag}
- Calculate helicity angle in 3 bins
- Signal yield in bins of $\cos\theta_{hel}$ is extracted from extended unbinned ML fit to M_{tag}

Belle 711fb⁻¹



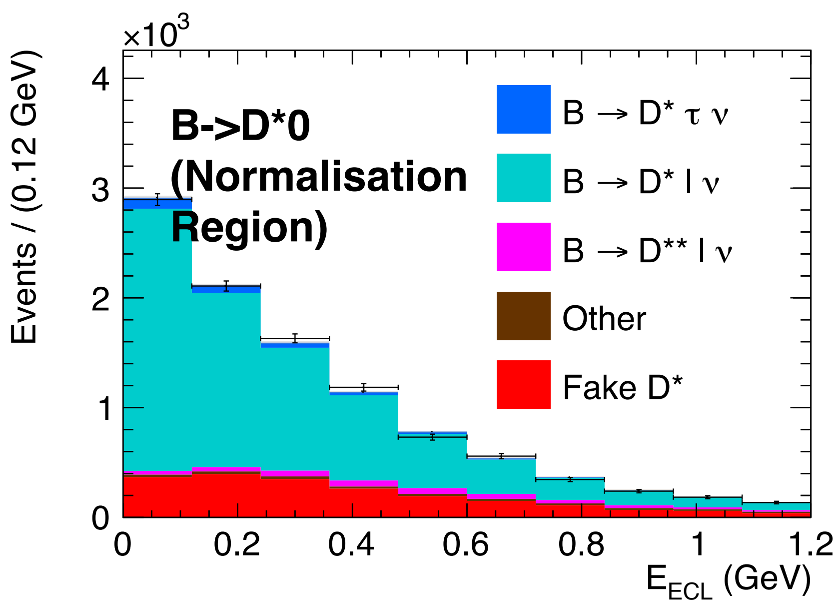
$$F_L^{D^*} = 0.60 \pm 0.08(\text{stat}) \pm 0.04(\text{sys})$$

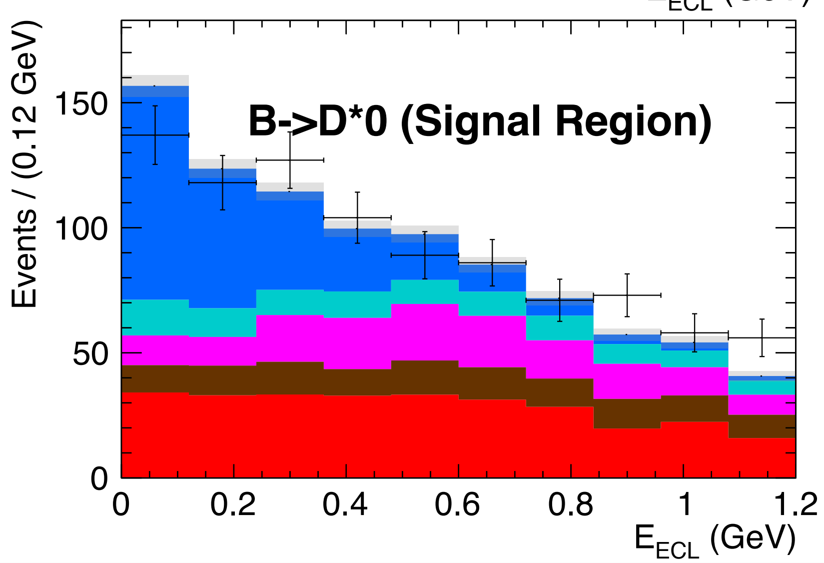
agrees within about 1.7σ with SM

Importance of B→D** lν Measurement

- D** is important background for both semileptonic (B→D*lν) and semitonic (B→D*τ ν) measurements
- D** is leading systematic error for both measurement
- Can mimic signal while measuring R(D) and R(D*)

arXiv:1904.08794





Source	$\Delta R(D)$ (%)	$\Delta R(D^*)$ (%)
D^{**} composition	0.76	1.41
Fake $D^{(*)}$ calibration	0.19	0.11
B_{tag} calibration	0.07	0.05
Feed-down factors	1.69	0.44
Efficiency factors	1.93	4.12
Lepton efficiency and fake rate	0.36	0.33
Slow pion efficiency	0.08	0.08
MC statistics	4.39	2.25
B decay form factors	0.55	0.28
Luminosity	0.10	0.04
$\mathcal{B}(B \to D^{(*)}\ell\nu)$	0.05	0.02
$\mathcal{B}(D)$	0.35	0.13
$\mathcal{B}(D^*)$	0.04	0.02
$\mathcal{B}(\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau)$	0.15	0.14
Total	5.21	4.94

$B \to D^{(*)}\pi\ell\nu$ hadronic tagged

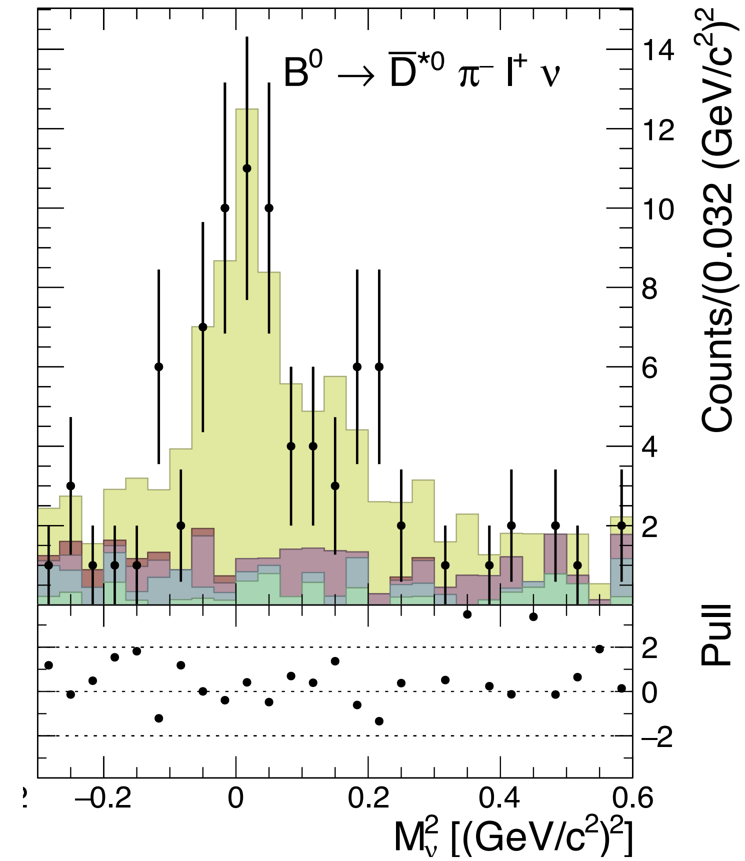
arXiv:1803.06444, Phys. Rev. D 98, 012005 (2018)

Important background for B→ D*τν and R(D*) measurement

Belle 711fb^{-1}

$$B \to (D^{**} \to D^{(*)}\pi\ell\nu_\ell)$$

- $D^{**} \to D\pi \longrightarrow D^{*0} \to D^0\pi^0,$
- $D^{**} \to D^*\pi \longrightarrow D^{*+} \to D^+\pi^0, D^0\pi^+$

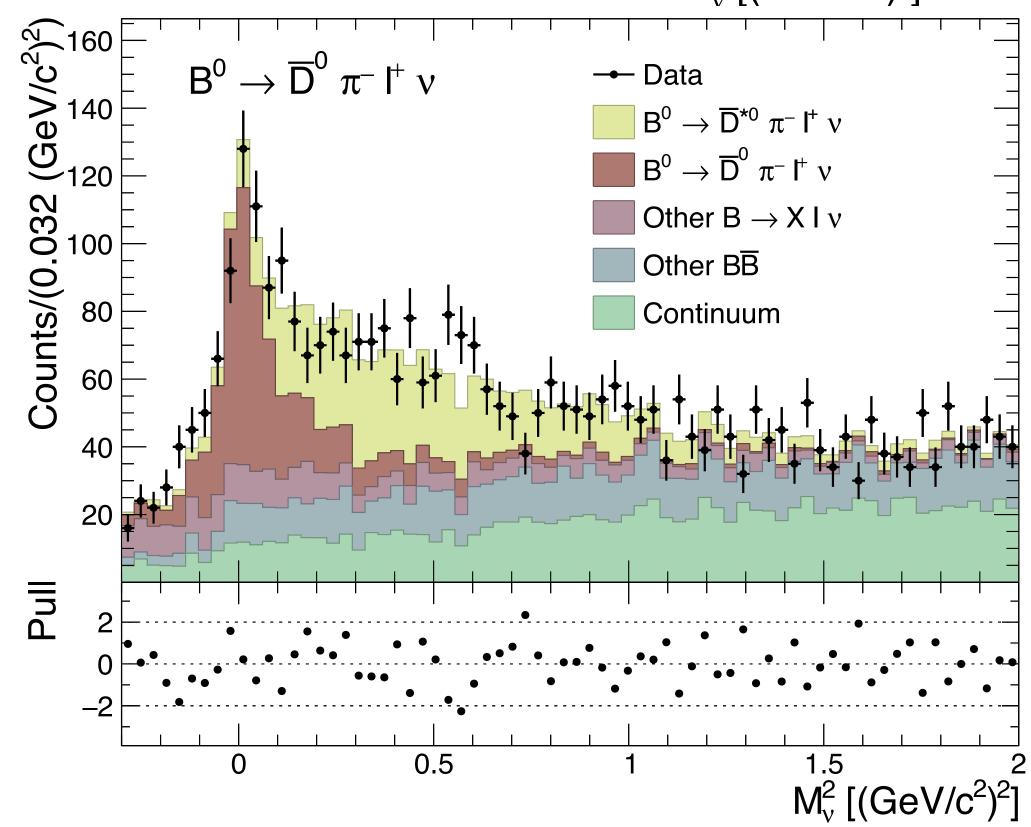


$$\mathcal{B}(B^+ \to D^-\pi^+\ell^+\nu) = [4.55 \pm 0.27\ (\text{stat.}) \pm 0.39\ (\text{syst.})]\ \times 10^{-3},$$

$$\mathcal{B}(B^0 \to \bar{D}^0\pi^-\ell^+\nu) = [4.05 \pm 0.36\ (\text{stat.}) \pm 0.41\ (\text{syst.})] \times 10^{-3},$$

$$\mathcal{B}(B^+ \to D^{*-}\pi^+\ell^+\nu) = [6.03 \pm 0.43\ (\text{stat.}) \pm 0.38\ (\text{syst.})] \times 10^{-3},$$

$$\mathcal{B}(B^0 \to \bar{D}^{*0}\pi^-\ell^+\nu) = [6.46 \pm 0.53\ (\text{stat.}) \pm 0.52\ (\text{syst.})] \times 10^{-3}.$$



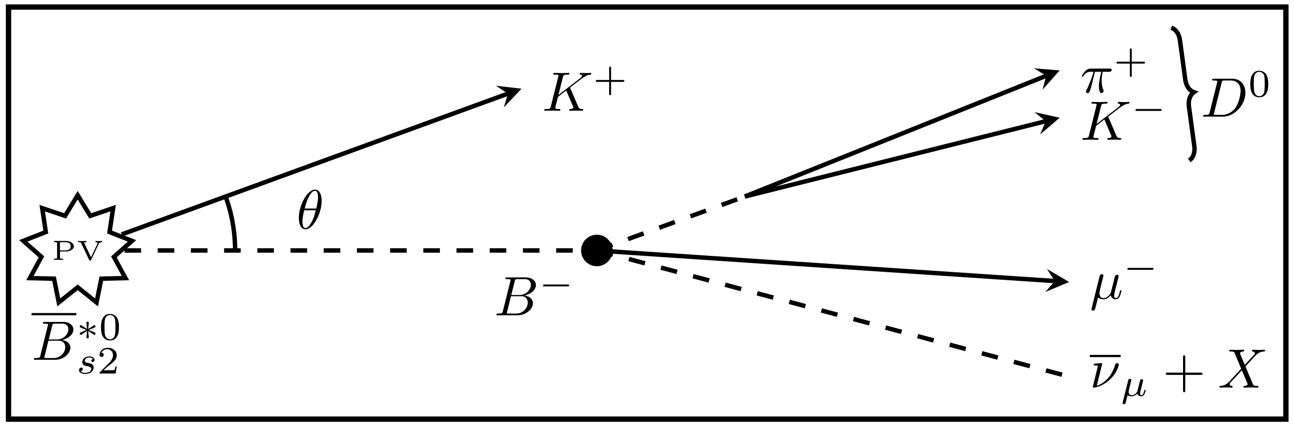
within 1σ of WA

Relative $B^- \to D^0/D^{*0}/D^{**0}\mu^-\nu_\mu$ branching fractions using B^- from B^{*0}_{s2} decays

arXiv:1807.10722, submitted to PRD

- First LHCb measurement of f($D^0/D^{*0}/D^{**0}$) → distinguishes $D^0/D^{*0}/D^{**0}$ in semileptonic B decay
- Useful input for B production rate at LHCb.
- B^{*0}_{s2} decay used to separate the three components
- B.F relative to the inclusive

$$B^- \to D^0 X \mu^- \bar{\nu}_\mu$$

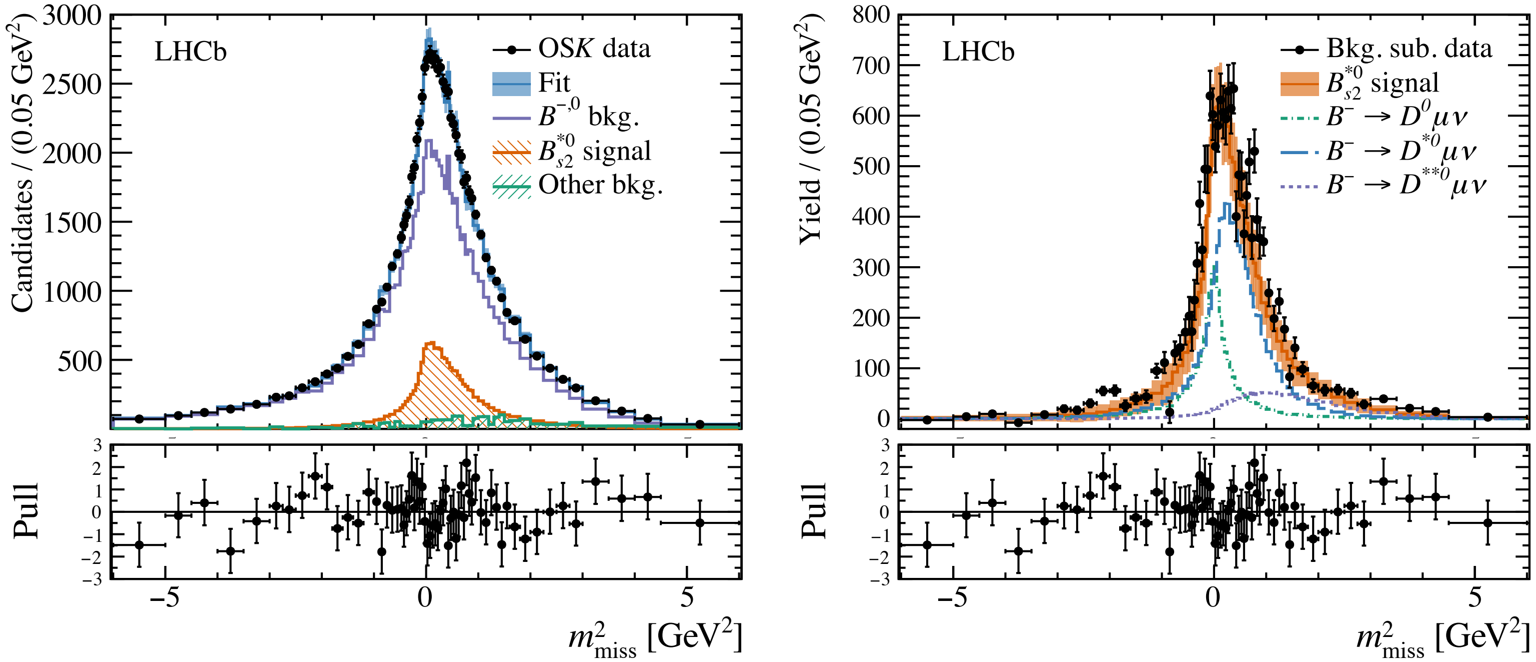


Data 3 fb[-1] collected at 7-8 TeV

$$f_{D^{**0}} = \frac{\mathcal{B}(B^- \to (D^{**0} \to D^0 X)\mu^-\bar{\nu}_\mu)}{\mathcal{B}(B^- \to D^0 X \mu^-\bar{\nu}_\mu)} = 0.21 \pm 0.07.$$

$$f_{D^0} = \frac{\mathcal{B}(B^- \to D^0\mu^-\bar{\nu}_\mu)}{\mathcal{B}(B^- \to D^0 X \mu^-\bar{\nu}_\mu)} = 0.25 \pm 0.06.$$

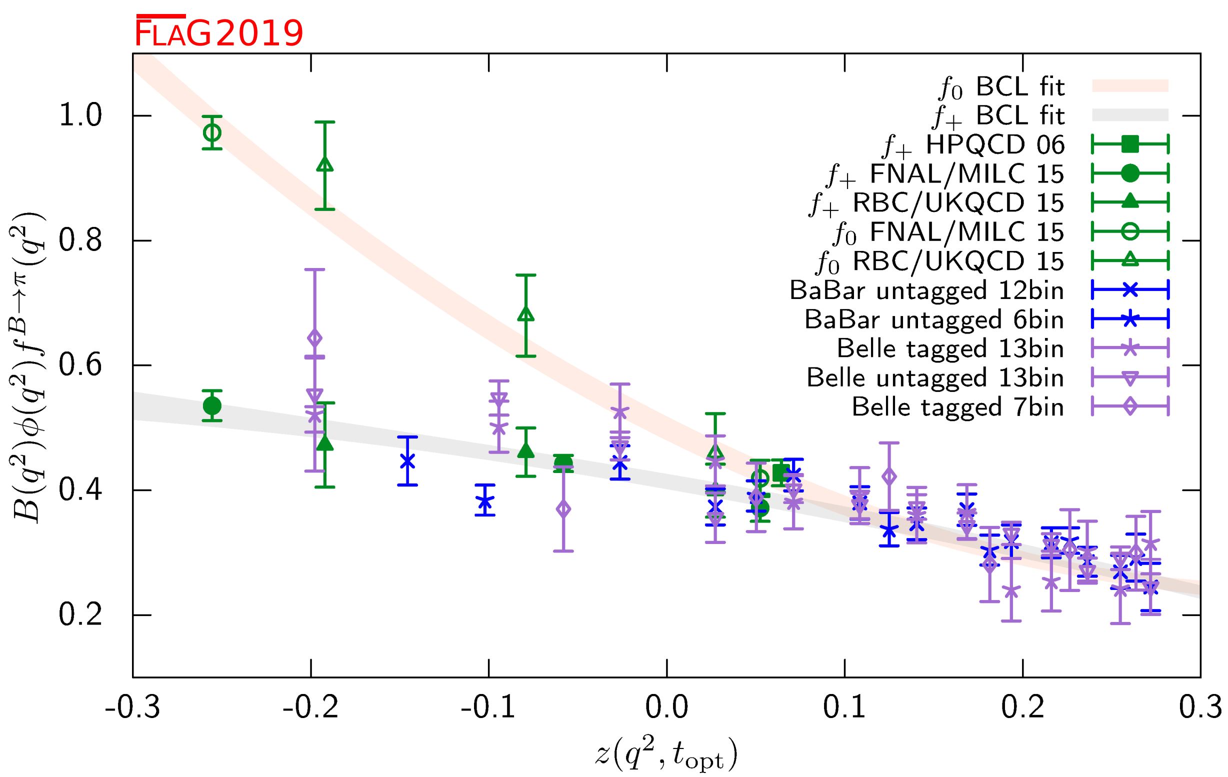
$$\longrightarrow \quad f_{D^{*0}} = 1 - f_{D^0} - f_{D^{**0}}$$

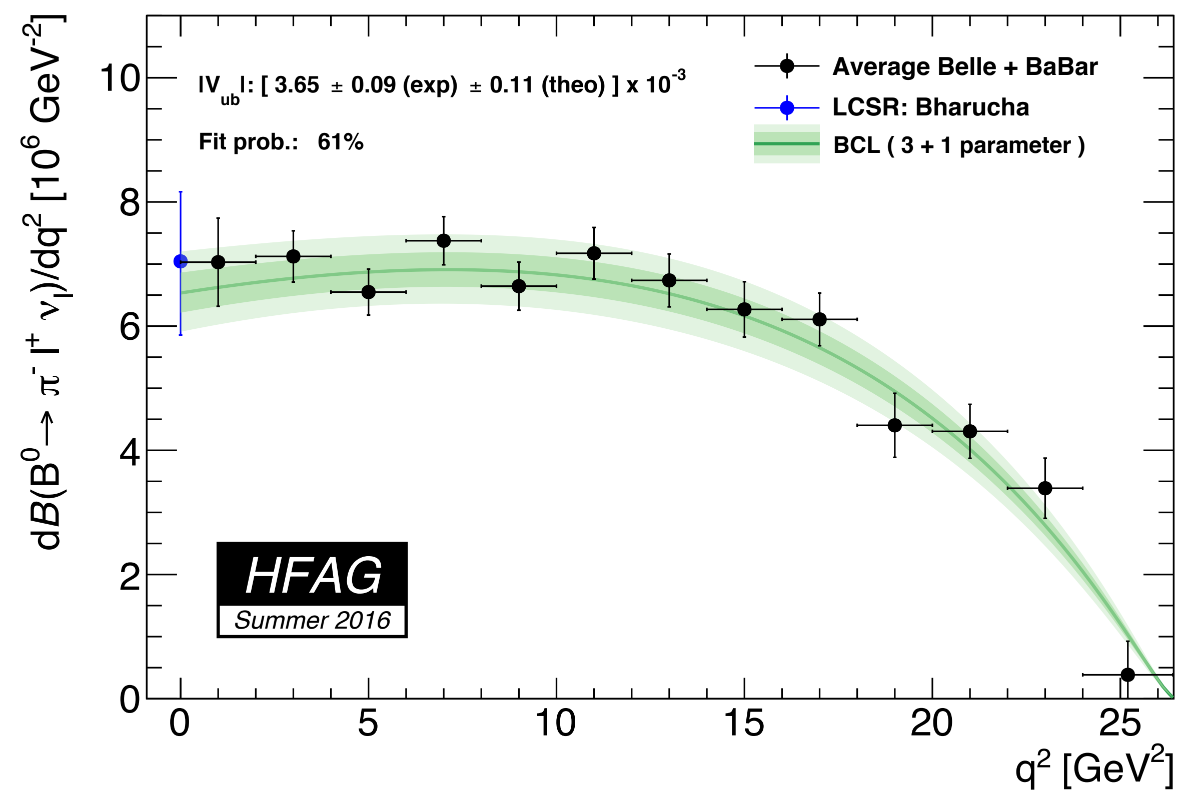


$|V_{ub}|$

$|V_{ub}|$ Status

- Clean signal in missing mass for exclusive modes to measure $|V_{ub}|$
- Form factors $f_i(q^2)$ computed with Light Cone Sum Rules or LQCD
- $b \rightarrow u\, l\, \nu$ signal enhanced w.r.t. $b \rightarrow c$ backgrounds in low M_X and high q^2
- systematics effects the charm background composition and u quark fragmentation



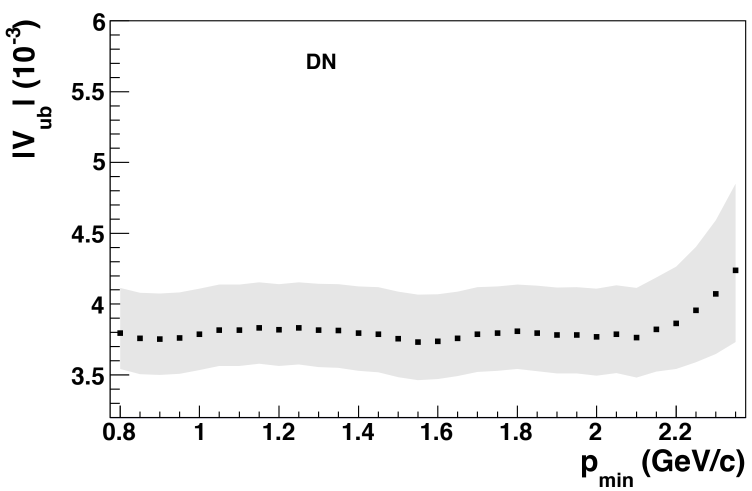


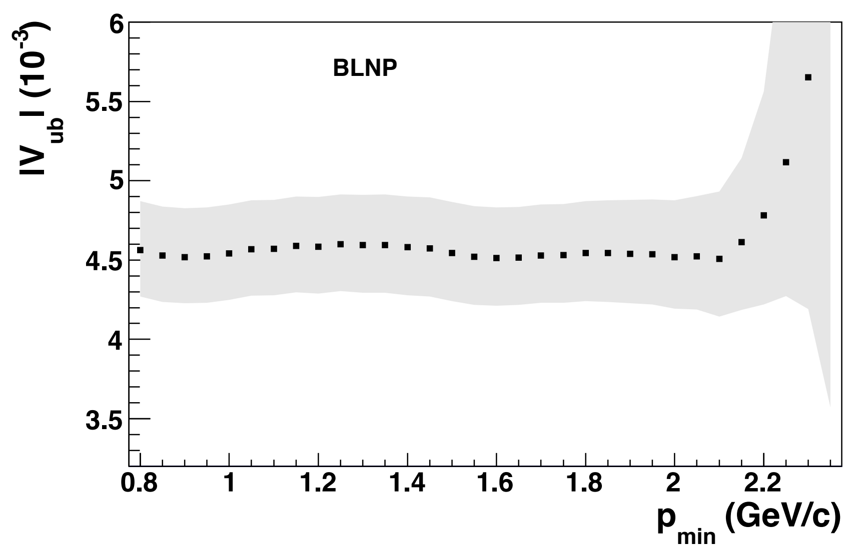
Summary of $|V_{ub}|$ determined from leptonic decay, exclusive modes compared with lattice QCD

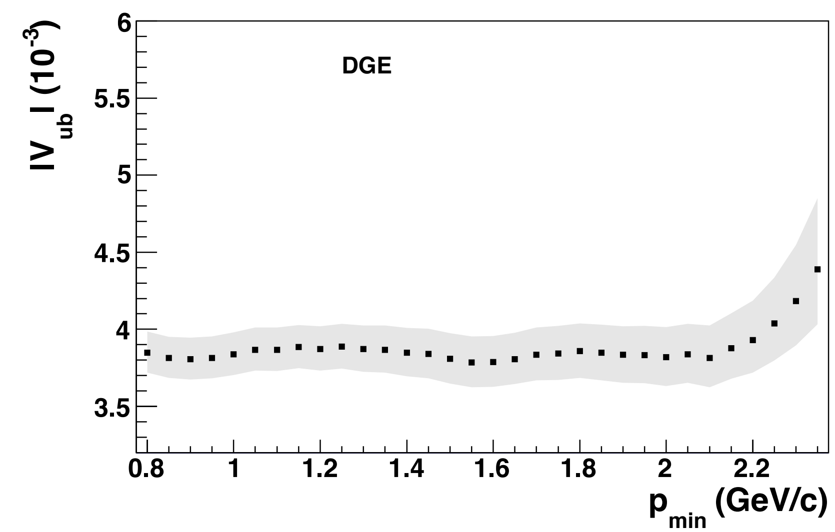
Inclusive $|V_{ub}|$ from BaBar

arXiv:1611.05624, Phys. Rev. D 95, 072001(2017)

- Inclusive $B \to Xe\nu$ measurement from full BaBar data set of 424 fb^{-1}
- Cut applied to electron momentum to seperate signal $B \to X_u e\nu$ (~ 2.6 GeV/c) to background $B \to X_c e\nu$ (~ 2.3 GeV/c)
- Perform fit to the inclusive electron momentum spectrum averaged over charged and neutral B meson.







- $|V_{ub}|$ is extracted as a function of plep.
- $|V_{ub}| = (3.794 \pm 0.107_{\rm exp} \,{}^{+0.292}_{-0.219}\,{\rm SF} \,{}^{+0.078}_{-0.068}\,{\rm theory}) \times 10^{-3}$ (DeFazio and Neubert)
- $|V_{ub}| = (4.563 \pm 0.126_{\rm exp} \,{}^{+0.230}_{-0.208}\,{\rm SF} \,{}^{+0.162}_{-0.163}\,{\rm theory}) \times 10^{-3}$ (Bosch, Lange, Neubert, Paz)
- $|V_{ub}| = (3.959 \pm 0.104_{\rm exp} \,{}^{+0.164}_{-0.154}\,{\rm SF} \,{}^{+0.042}_{-0.079}\,{\rm theory}) \times 10^{-3}$ (DGE)

Belle II prospects of $|V_{ub}|$

More Detail in Markus Prim Talk

- Improvement of experimental uncertainties expected in both inclusive and exclusive determination

Mode and dataset	Uncertainty (%) EXP. ONLY
|Vub| exclusive (tagged)	
Belle	3.8
Belle II 5 ab^{-1}	1.8
Belle II 50 ab^{-1}	1.2
|Vub| exclusive (untagged)	
Belle	2.7
Belle II 5 ab^{-1}	1.2
Belle II 50 ab^{-1}	0.9
|Vub| inclusive (tagged)	
Belle	6.0
Belle II 5 ab^{-1}	2.6
Belle II 50 ab^{-1}	1.7

- Expect theory error to decrease to 1% for exclusive and 2-4% for inclusive
- Exclusive analyses (hadronic tags)→ perform clean and detailed exploration of exclusive b→u modes spectra
- Untagged $B\to\pi l \nu$ competitive for $|V_{ub}|$
- Exploit at maximum the differential distributions for a global V_{ub} fit (inclusive measurement)

Summary

- New B→D* l ν tagged measurement from BaBar 2019 (BGL)
  - $|V_{cb}| \times 10^3 = 38.4 \pm 0.6$ (BGL)
- B^0→D* l ν untagged measurement from Belle,2018/2019 (BGL and CLN)
  - $|V_{cb}| \times 10^3 = 38.4 \pm 0.6$ (CLN)
  - $|V_{cb}| \times 10^3 = 38.3 \pm 0.8$ (BGL)
- Shape parameters of $d\Gamma(\Lambda^0_b \to \Lambda^+_c \mu^- \nu_\mu)/dq^2$
- D* polarisation $F_L^{D^*} = 0.60 \pm 0.08(\mathrm{stat}) \pm 0.04(\mathrm{sys})$
- $f(D^0/D^{*0}/D^{**0})$ by LHCb
- Result of inclusive $B \to X_u l \nu$ from BaBar
- Measurements are coming up from Belle on inclusive $|V_{ub}|$
- Belle II will collect ~ $5ab^{-1}$ data by 2020, enough to look for NP
- Precise model independent measurement of $|V_{cb}|$ and $|V_{ub}|$

Thank you

References

- Slide 3
  1. Eur. Phys. J. C77 (2017) 895
- Slide4
  1. M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018).
- Slide 8
  1. Phys. Rev. D57 (1998) 6948, arXiv:hep-lat/9709028.
  2. Phys. Lett. B629 (2005) 27, arXiv:hep-ph/0502004.
  3. Phys. Rev. D73 (2006) 094002, arXiv:hep-ph/0604017
- Slide 17
  4. arXiv:1809.03290
  5. arXiv:1903.10002
  6. Phys. Rev. D 93, 032006
  7. Eur. Phys. J. C77 (2017) 895
- Slide 19
  1. Phys. Rev. D 87, 034028 (2013).

BACKUP

Exclusive |Vcb| from $B \to D^{*}\ell\nu$ untagged

Source	ρ^2	$R_1(1)$	$R_2(1)$	$\mathcal{F}(1)\lvert V_{cb}\rvert$ [%]	$\mathcal{B}(B^0 \to D^{*-}\ell^+\nu_\ell)$ [%]
Slow pion efficiency	0.005	0.002	0.001	0.65	1.29
Lepton ID combined	0.001	0.006	0.004	0.68	1.38
$\mathcal{B}(B \to D^{**}\ell\nu)$	0.002	0.001	0.002	0.26	0.52
$B \to D^{**}\ell\nu$ form factors	0.003	0.001	0.004	0.11	0.22
f_{+-}/f_{00}	0.001	0.002	0.002	0.52	1.06
Fake e/μ	0.004	0.006	0.001	0.11	0.21
Continuum norm.	0.002	0.002	0.001	0.03	0.06
K/π ID	< 0.001	< 0.001	< 0.001	0.39	0.77
Fast track efficiency	-	-	-	0.53	1.05
$N\Upsilon(4S)$	-	-	-	0.68	1.37
B^0 lifetime	-	-	-	0.13	0.26
$\mathcal{B}(D^{*+} \to D^0\pi_s^+)$	-	-	-	0.37	0.74
$\mathcal{B}(D^0 \to K\pi)$	-	-	-	0.51	1.02
Total systematic error	0.008	0.009	0.007	1.60	3.21

CLN systematic

Source	$\tilde{a}_0^f$ [%]	$\tilde{a}_1^f$ [%]	$\tilde{a}_1^{F1}$ [%]	$\tilde{a}_2^{F1}$ [%]	$\tilde{a}_0^g$ [%]	$\eta_{EW}\mathcal{F}(1)\lvert V_{cb}\rvert$ [%]	$\mathcal{B}(B^0 \to D^{*-}\ell^+\nu_\ell)$ [%]
Slow pion efficiency	0.79	9.59	5.61	4.46	0.18	0.79	1.57
Lepton ID combined	0.67	5.45	1.35	0.73	0.38	0.67	1.33
$\mathcal{B}(B \to D^{**}\ell\nu)$	0.05	5.02	4.34	9.31	0.37	0.05	0.10
$B \to D^{**}\ell\nu$ form factors	0.08	2.08	3.56	6.78	0.12	0.08	0.16
f_{+-}/f_{00}	0.56	0.46	0.50	0.48	0.56	0.56	1.05
Fake e/μ	0.07	6.43	3.03	5.92	0.14	0.07	0.11
K/π ID	0.39	0.39	0.39	0.39	0.39	0.39	0.77
Fast track efficiency	0.53	0.53	0.53	0.53	0.53	0.53	1.05
$N(\Upsilon(4S))$	0.69	0.69	0.69	0.69	0.69	0.69	1.37
B^0 lifetime	0.13	0.13	0.13	0.13	0.13	0.13	0.26
$\mathcal{B}(D^{*+} \to D^0\pi_s^+)$	0.37	0.37	0.37	0.37	0.37	0.37	0.74
$\mathcal{B}(D^0 \to K\pi)$	0.51	0.51	0.51	0.51	0.51	0.51	1.02
Total systematic error	1.65	13.93	8.69	13.77	1.40	1.65	3.26

BGL systematic

$B \to D^{(*)}\pi\ell\nu$ hadronic tagged

arXiv:1803.06444

	$B^+ \to D^- \pi^+ \ell^+ \nu$	$B^0 \to \bar{D}^0 \pi^- \ell^+ \nu$
Charged PID	4.8	6.9
π^0 PID	1.2	6.0
Tracking efficiency	2.6	3.6
D^{**} form factors	0.3	0.2
D meson BRs	1.7	1.6
B meson BRs	0.0	0.1
Number of $B\bar{B}$	1.4	1.4
Tag efficiency	4.6	3.2
$\Upsilon(4S)$ BR	1.2	1.2
Combined	**8.3**	**9.7**

	$B^+ \to D^{*-} \pi^+ \ell^+ \nu$	$B^0 \to \bar{D}^{*0} \pi^- \ell^+ \nu$
Charged PID	2.1	6.5
π^0 PID	2.0	5.2
Tracking efficiency	2.9	3.2
D^{**} form factors	0.2	0.1
D meson BRs	1.8	1.1
B meson BRs	0.0	0.1
Number of $B\bar{B}$	1.4	1.4
Tag efficiency	4.2	2.8
$\Upsilon(4S)$ BR	1.2	1.2
Combined	**5.8**	**7.2**

The table lists the relative uncertainties in the branching fractions in percent for each channel for the combined fits. The last row gives the combined variation of all sources.

D*- polarisation in $B^0 \to D^{*-}\tau^+\nu_\tau$

arXiv:1903.03102

Source		$\Delta F_L^{D^*}$
Monte Carlo statistics	AR shape and peaking background	±0.032
	CB shape	±0.010
	Background scale factors	±0.001
Background modeling	$B \to D^{**}\ell\nu$	±0.003
	$B \to D^{**}\tau\nu$	±0.011
	$B \to$ hadrons	±0.005
	$B \to \bar{D}^* M$	±0.004
Signal modeling	Form factors	±0.002
	$\cos\theta_{\mathrm{hel}}$ resolution	±0.003
	Acceptance non-uniformity	$^{+0.015}_{-0.005}$
Total		$^{+0.039}_{-0.037}$

Measurement of the relative $B^- \to D^0/D^{*0}/D^{**0}\mu^-\nu_\mu$ branching fractions using B^- mesons from B^{*0}_{s2} decays

arXiv:1807.10722

	Source of uncertainty	f_{D^0}	$f_{D^{**0}}$
Statistical	OSK sample	0.025	0.027
	Templates	0.047	0.052
Floating syst.	Signal form-factors	0.006	0.004
	Non-B^-, $\overline{B}^0$ backgrounds	0.004	0.004
	B^-, $\overline{B}^0$ background normalization	0.003	0.015
	$\overline{B}^0$ fraction and m^2_{miss} shape	0.004	0.030
Fixed syst.	D^{**0} branching fractions	0.025	0.044
	Relative signal efficiency	0.003	0.003
Total uncertainty		0.056	$^{+0.070}_{-0.074}$

Measurement of R(D) and R(D*) with a semileptonic tag

arXiv:1904.08794

TABLE I. Systematic uncertainties contributing to the $\mathcal{R}(D^{(*)})$results.

Source	$\Delta R(D)$ (%)	$\Delta R(D^*)$ (%)
D^{**} composition	0.76	1.41
Fake $D^{(*)}$ calibration	0.19	0.11
B_{tag} calibration	0.07	0.05
Feed-down factors	1.69	0.44
Efficiency factors	1.93	4.12
Lepton efficiency and fake rate	0.36	0.33
Slow pion efficiency	0.08	0.08
MC statistics	4.39	2.25
B decay form factors	0.55	0.28
Luminosity	0.10	0.04
$\mathcal{B}(B \to D^{(*)}\ell\nu)$	0.05	0.02
$\mathcal{B}(D)$	0.35	0.13
$\mathcal{B}(D^*)$	0.04	0.02
$\mathcal{B}(\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau)$	0.15	0.14
Total	5.21	4.94

Source	Uncertainty (%)
$\bar{B} \to \pi \ell^- \bar{\nu}_\ell$ form-factor	0.9
$\bar{B} \to \rho \ell^- \bar{\nu}_\ell$ form-factor	12
$B^- \to K_L^0 \pi^-$	5.5
$B^- \to \mu^- \bar{\nu}_\mu \gamma$	6
Continuum shape	15
Signal peak shape	11
Trigger	8
$\mathcal{B}(\bar{B} \to \pi \ell^- \bar{\nu}_\ell)$	3.4
Total	24.6

$B \to \eta \ell \nu$ and $B \to \eta' \ell \nu$ hadronic tagged

Phys. Rev. D 96, 091102(R) 2017

Mode q^2 [GeV^2]	$\eta \to \gamma\gamma$ All	< 12	> 12	$\eta \to \pi^+\pi^-\pi^0$ All	< 12	> 12	Both η modes All	< 12	> 12	$\eta' \to \eta(\gamma\gamma)\pi^+\pi^-$ All
Track finding	±0.35	±0.35	±0.35	±1.05	±1.05	±1.05	±0.5	±0.5	±0.5	±1.05
Photon finding	±4.0	±4.0	±4.0	±0.0	±0.0	±0.0	±3.1	±3.1	±3.1	±4.0
π^0 reconstruction	±0.0	±0.0	±0.0	±2.5	±2.5	±2.5	±0.5	±0.5	±0.5	±0.0
π^0 veto	±2.5	±2.5	±2.5	±0.0	±0.0	±0.0	±2.0	±2.0	±2.0	±0.0
Pion ID	±0.0	±0.0	±0.0	±1.0	±1.0	±1.0	±0.20	±0.20	±0.20	±1.0
Lepton ID	±2.0	±2.0	±2.0	±2.0	±2.0	±2.0	±2.0	±2.0	±2.0	±2.0
Lepton fake rate	±0.36	$^{+0.19}_{-0.13}$	±0.11	$^{+0.46}_{-0.50}$	$^{+0.42}_{-0.47}$	$^{+0.18}_{-0.16}$	$^{+0.47}_{-0.44}$	±0.51	$^{+0.02}_{-0.07}$	$^{+1.6}_{-1.8}$
Signal model	±0.83	±0.75	±1.0	±0.50	±0.70	±0.46	±0.88	±0.71	±2.0	±0.28
$b \to u \ell \nu_\ell$ form factors	±1.1	±0.49	±0.72	$^{+1.8}_{-2.6}$	$^{+0.14}_{-0.16}$	$^{+0.82}_{-1.4}$	$^{+0.31}_{-0.43}$	$^{+0.73}_{-1.1}$	$^{+0.77}_{-0.70}$	$^{+0.92}_{-0.56}$
$b \to u \ell \nu_\ell$ branching fractions	$^{+0.26}_{-0.20}$	±1.0	$^{+1.4}_{-1.3}$	$^{+0.04}_{-0.05}$	±0.05	$^{+0.85}_{-0.95}$	$^{+0.50}_{-0.45}$	$^{+1.5}_{-1.8}$	$^{+0.86}_{-1.2}$	$^{+1.9}_{-2.4}$
$b \to c \ell \nu_\ell$ form factors	$^{+1.0}_{-0.15}$	$^{+2.3}_{-0.60}$	±0.0	$^{+0.21}_{-0.06}$	$^{+0.70}_{-0.22}$	±0.0	$^{+1.1}_{-0.10}$	$^{+1.3}_{-0.24}$	±0.0	$^{+0.18}_{-0.23}$
$b \to c \ell \nu_\ell$ branching fractions	±0.14	±0.80	±0.29	±0.28	$^{+0.43}_{-0.45}$	$^{+0.18}_{-0.28}$	±0.13	±0.64	$^{+0.21}_{-0.27}$	±0.62
Secondary leptons	$^{+0.00}_{-0.06}$	±0.12	$^{+0.01}_{-0.03}$	$^{+0.07}_{-0.04}$	$^{+0.15}_{-0.13}$	$^{+0.02}_{-0.12}$	$^{+0.03}_{-0.01}$	±0.08	$^{+0.06}_{-0.04}$	$^{+0.01}_{-0.00}$
$\mathcal{B}(\eta^{(\prime)})$ [29]	±0.50	±0.50	±0.50	±1.2	±1.2	±1.2	±0.50	±0.50	±0.50	±1.7
Hadronic tag	±4.2	±4.2	±4.2	±4.2	±4.2	±4.2	±4.2	±4.2	±4.2	±4.2
N($B\bar{B}$)	±1.4	±1.4	±1.4	±1.4	±1.4	±1.4	±1.4	±1.4	±1.4	±1.4
Continuum	$^{+0.77}_{-0.80}$	$^{+0.98}_{-0.96}$	$^{+0.24}_{-0.30}$	$^{+0.66}_{-0.64}$	$^{+1.1}_{-1.2}$	$^{+0.71}_{-0.62}$	±0.47	±0.83	$^{+1.2}_{-1.3}$	±3.9
Fit procedure	±2.9	±9.8	±2.0	±6.3	±8.7	±9.6	±2.2	±5.6	±3.2	±5.2
Total	±7.6	$^{+12.3}_{-12.1}$	±7.3	$^{+8.8}_{-9.0}$	±10.6	$^{+11.3}_{-11.4}$	±6.7	±8.7	$^{+7.4}_{-7.5}$	$^{+9.7}_{-9.8}$

Measurement of R(D) and R(D*) with a semileptonic tag

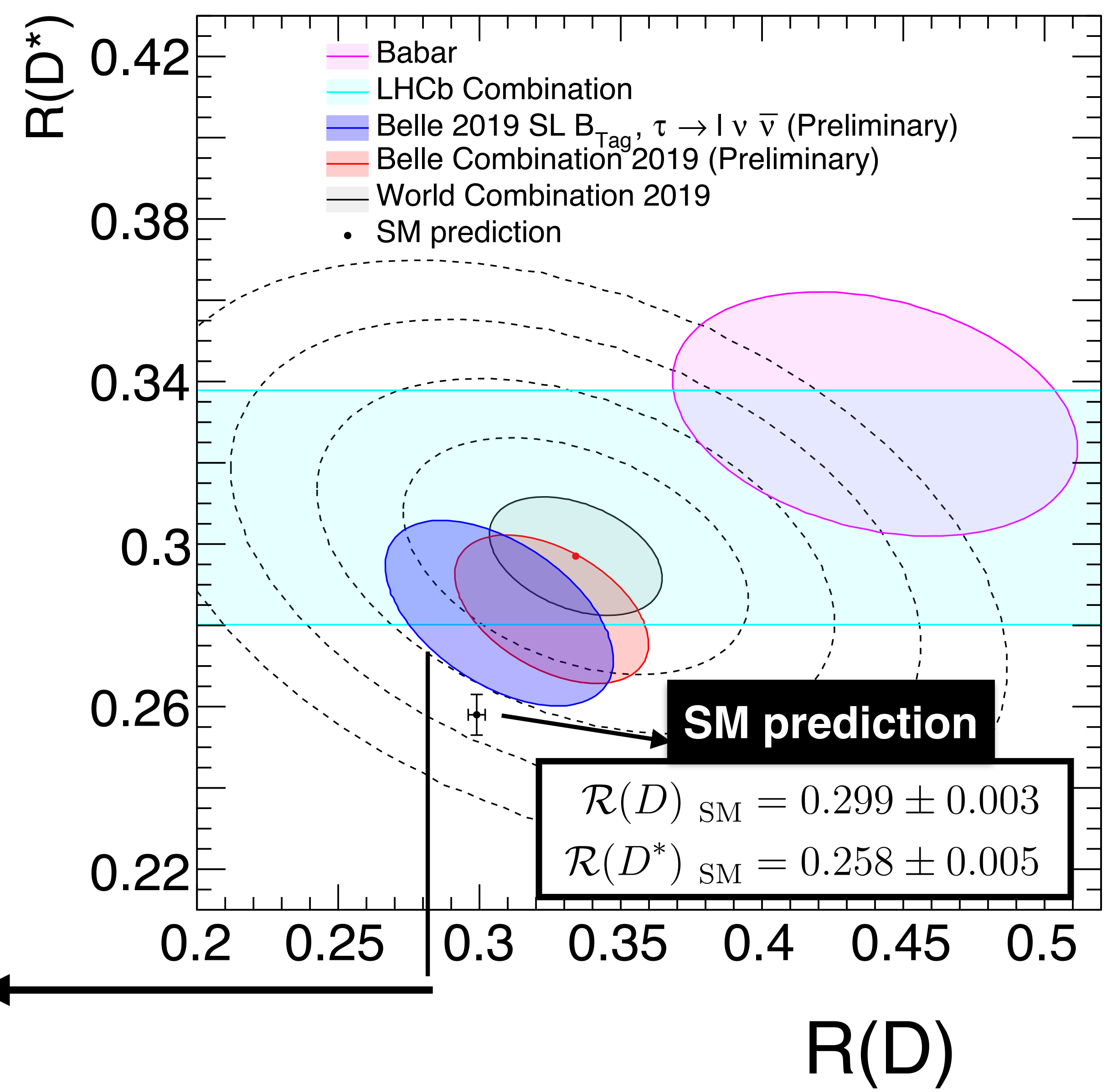
arXiv:1904.08794

$$R(D) \equiv \frac{\mathcal{B}(\bar{B} \to D^+\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^+\ell^-\bar{\nu}_\ell)} \quad R(D^*) \equiv \frac{\mathcal{B}(\bar{B} \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{*+}\ell^-\bar{\nu}_\ell)}$$

where $\ell = e, \mu$

Signal: $B^{0/\pm} \to D^{(*)}\tau^-\nu$ **Normalisation:** $B^{0/\pm} \to D^{(*)}\ell^-\nu$ **B-tag:** $B^{0/\pm} \to D^{(*)}\ell^-\nu$

- First R(D) and R(D*) measurement with semileptonic tag
- Most Precise Measurement till date !!!
- Results compatible with SM expectations within 1.2 sigma
- R(D) and R(D*) WA tension reduces to 3.1sigma



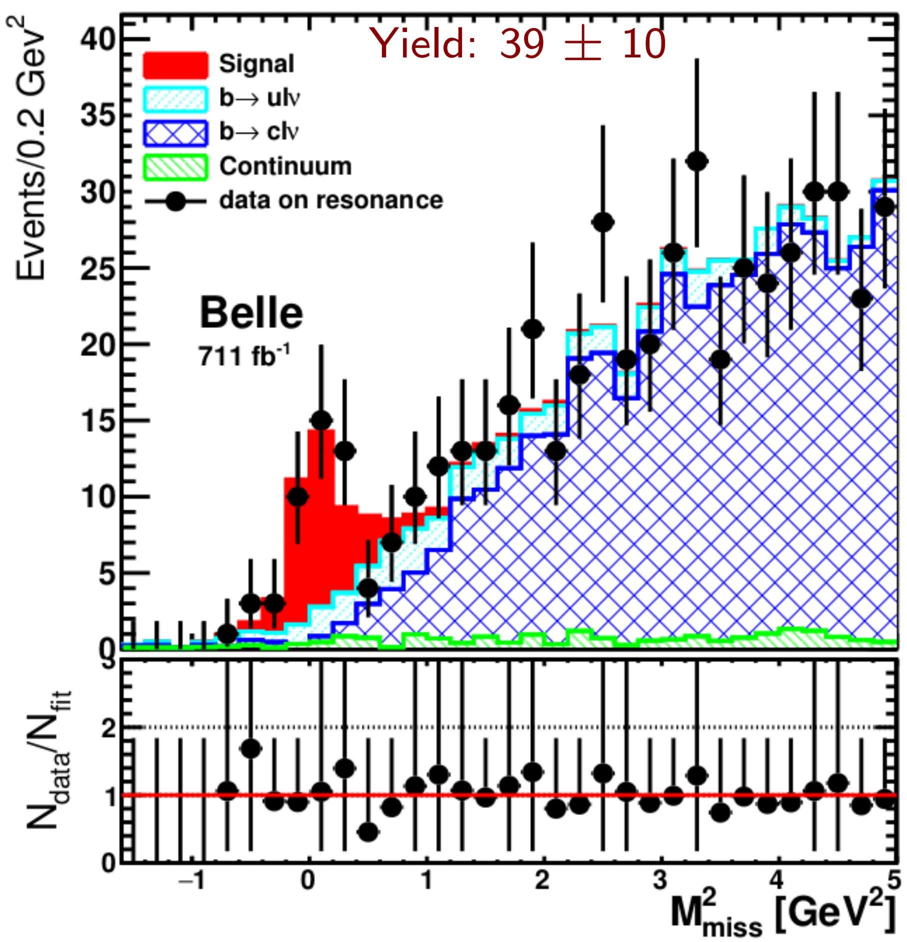
$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016$$
$$\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014$$

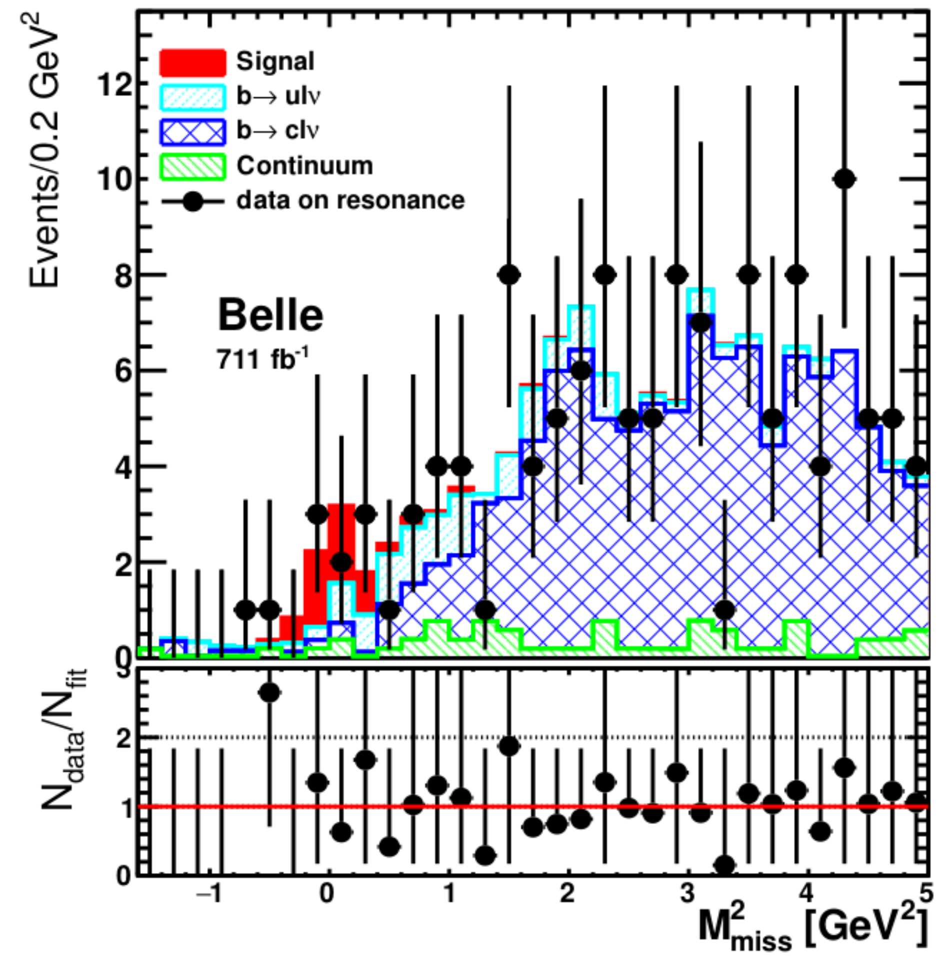
$B \to \eta \ell \nu$ and $B \to \eta' \ell \nu$ hadronic tagged

Phys. Rev. D 96, 091102(R) 2017

$B \to \eta \ell \nu_\ell$ $\qquad$ $B \to \eta' \ell \nu_\ell$

To measure the inclusive b→ulv rate we must understand exclusive components.





$\eta \to \gamma\gamma$, $\pi^+\pi^-\pi^0$
$\eta' \to \pi^+\pi^-\gamma$, $\eta\,\gamma$

BACKUP

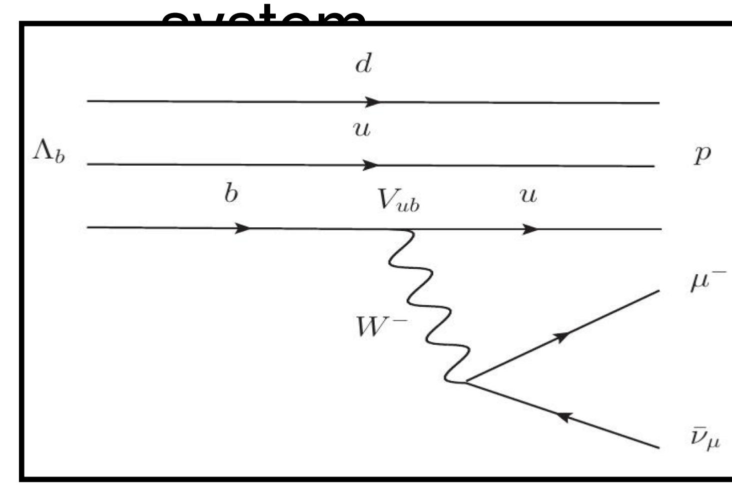
$$\mathcal{B}(B^+ \to \eta \ell^+ \nu) = (4.2 \pm 1.1_{stat} \pm 0.3_{syst}) \times 10^{-5}$$
$$\mathcal{B}(B^+ \to \eta' \ell^+ \nu) < 0.72 \times 10^{-4} \quad 90\% \quad \text{C.L.}$$

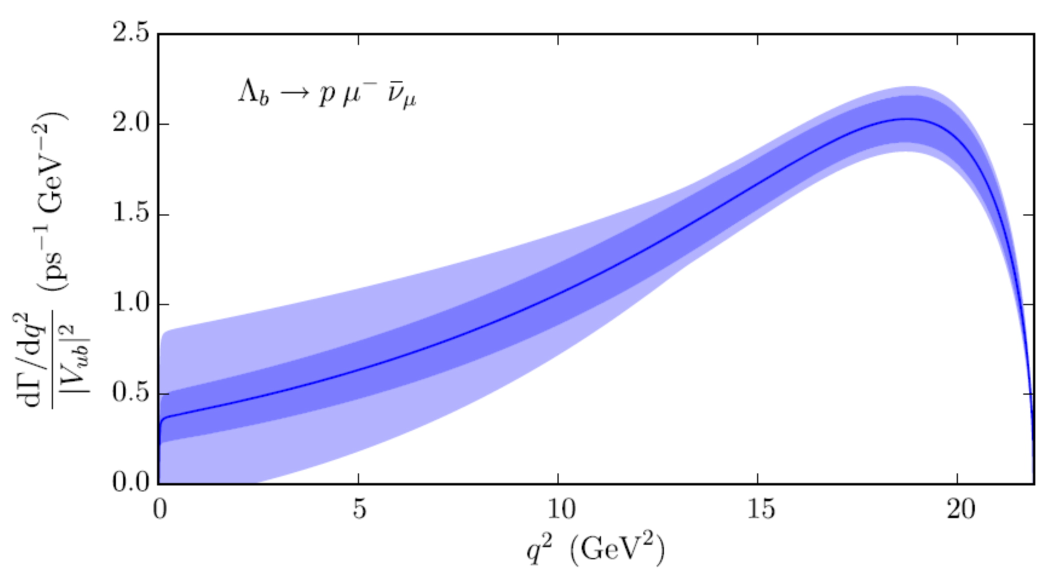
$$|V_{ub}| = (3.59 \pm 0.58_{stat} \pm 0.13_{syst}\,{}^{+0.29}_{-0.32}{}_{theo}) \times 10^{-3}$$

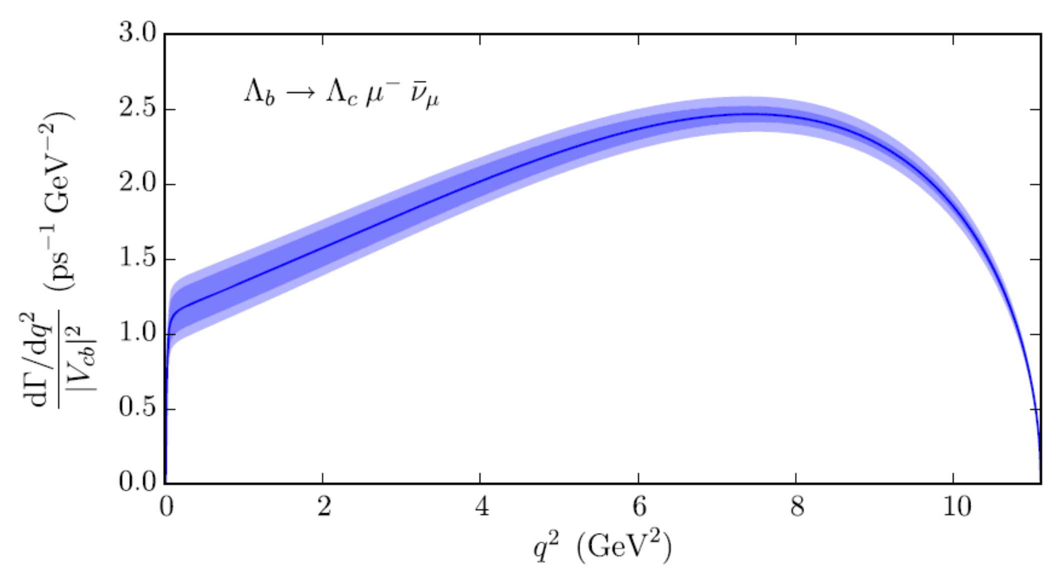
|V$_{ub}$| measurement at LHCb $\Lambda_b \to p\mu^-\nu_\mu$

arXiv:1503.01421

- Missing neutrino momentum → B not fully reconstructed
- Generally affected by much higher (x10) X_b → X_c μν backgrounds
- Excellent μ and p PID LHCb from RICH/Muon system
- precision vertexing and tracking used
  - displaced p$_\mu$ vertex as signature in detector
- High production fraction of Λ_b : ~20% of b-hadron
- Normalise signal yield to a |V$_{cb}$| decay $\Lambda_b \to \Lambda_c\, \mu^-\nu_\mu$
  - cancels many systematic uncertainties → the production rate of Λ_b
- Improved FF calculations from theory for $\Lambda_b \to p\mu^-\nu_\mu$ and $\Lambda_b \to \Lambda^+_c\, \mu^-\nu_\mu$ in high q^2 region → there FF calculations from theory are most precise







Analysis Strategy $\Lambda_b \to p\mu^- \nu_\mu$

- Determine yields of $\Lambda_b \to p\mu^- \nu_\mu$ and $\Lambda_b \to (\Lambda_c^+ \to pK^-\pi^+)\mu^-\nu_\mu$
- Estimate relative experimental efficiency with high precision
  - Measuring B.F:

$$\frac{\mathcal{B}(\Lambda_b \to p\mu^-\nu_\mu)_{q^2>15\,\mathrm{GeV}^2}}{\mathcal{B}(\Lambda_b \to \Lambda_c^+\mu^-\nu_\mu)_{q^2>7\,\mathrm{GeV}^2}} = (1.00 \pm 0.04(stat) \pm 0.08(syst)) \times 10^{-2}$$

with

$$\frac{\mathcal{B}(\Lambda_b \to p\mu^-\nu_\mu)}{\mathcal{B}(\Lambda_b \to \Lambda_c^+\mu^-\nu_\mu)} = R_{\mathrm{FF}} \times \frac{|V_{ub}|^2}{|V_{cb}|^2} \text{ with } R_{\mathrm{FF}} = 0.68 \pm 0.07$$

implies

$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004(exp.) \pm 0.004(theo.)$$

using WA $|V_{cb}| = (39.5 \pm 0.8) \times 10^{-3}$ gives

$$|V_{ub}| = (3.27 \pm 0.15(exp.) \pm 0.16(theo.) \pm 0.06(|V_{cb}|)) \times 10^{-3}$$