Conference on Flavour Physics and CP violation 2020, 8-12 June 2020

Experimental status of $|V_{cb}|$ and $|V_{ub}|$ with semileptonic b-hadron decays

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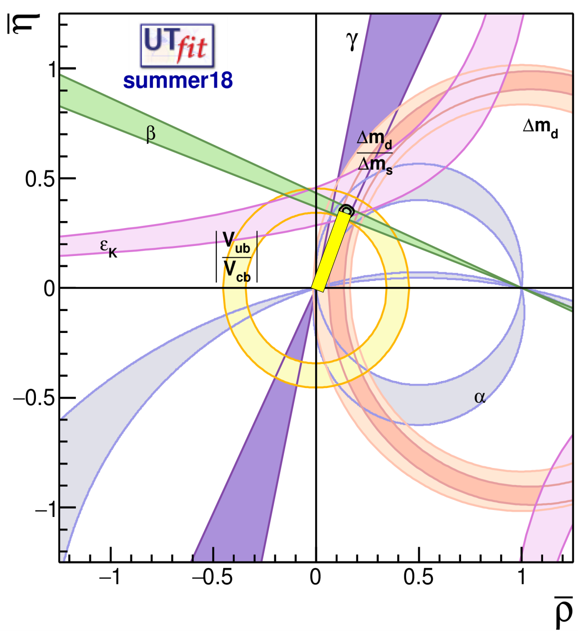
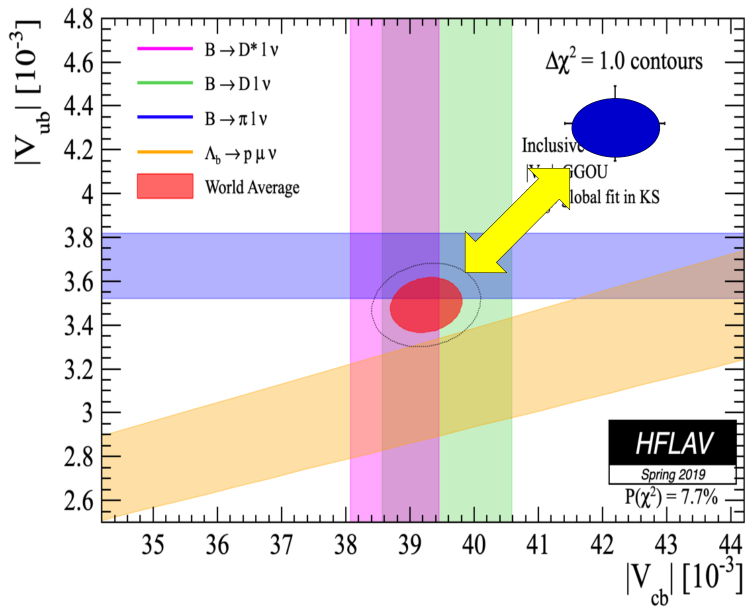
Why $|V_{cb}|$ and $|V_{ub}|$?

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

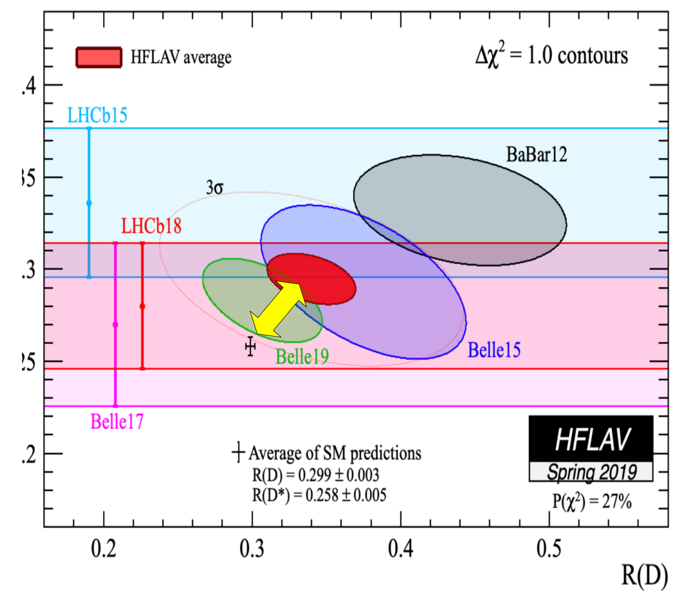
$$\frac{\Gamma(B \to D^{(*)}\tau\nu_\tau)}{\Gamma(B \to D^{(*)}\ell\nu_\ell)}$$



$|V_{xb}|$ provide crucial inputs for indirect search of New Physics

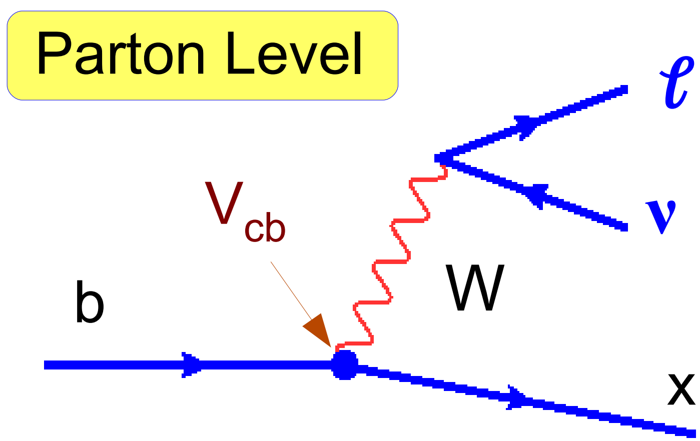


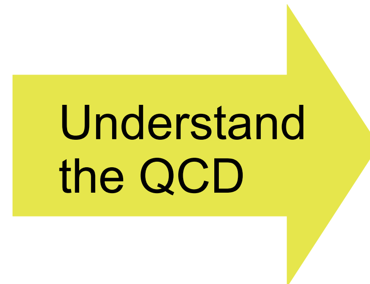
$|V_{ub}|$ and $|V_{cb}|$ significant tensions between different determinations

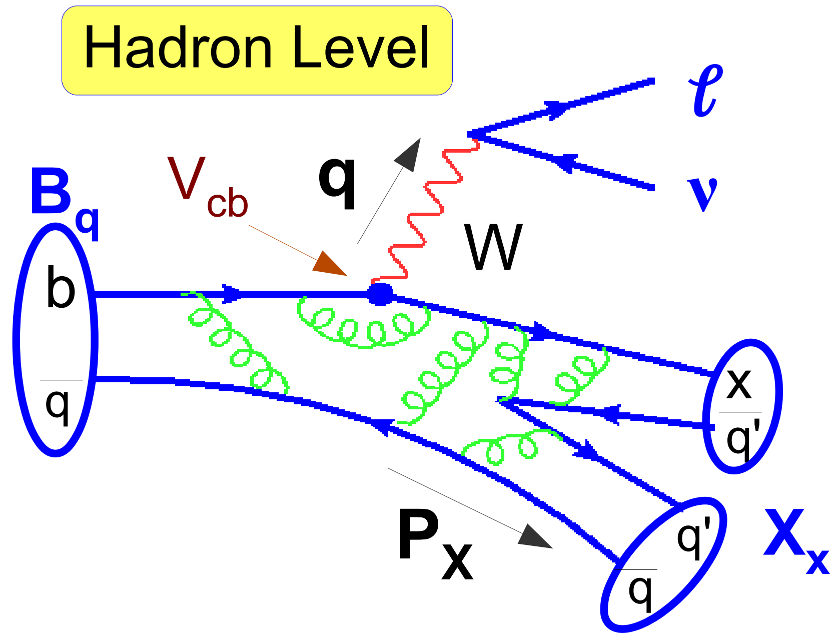


Difference with expectations @ about 3σ.
Study of semileptonic B decays provide Form-Factors, crucial for SM predictions on R(D)-R(D*) and signal model

Measurements of $|V_{xb}|$







Inclusive decays $B \to X_c \ell \nu$, $B \to X_u \ell \nu$

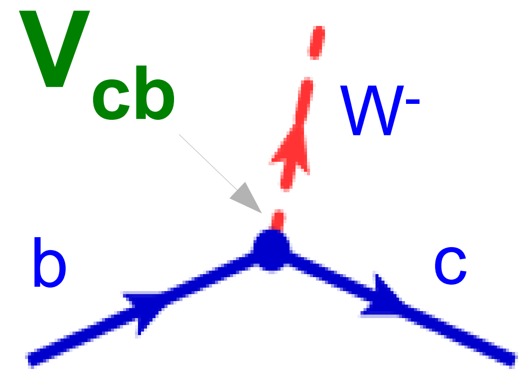
- Need to know QCD corrections to parton level decay rate
- Operator Product Expansion in α_s and $\Lambda_{QCD}/m_{b,c}$ predicts the total rate Γ_c

Exclusive decays $B \to D/D^* \ell \nu$, $B \to \pi/\rho\, \ell \nu$

- QCD effects are embedded in the form factors
- Lattice-QCD, LCSR

$$\frac{d\mathcal{B}(B \to H_x \ell \nu)}{dq^2} \propto |V_{xb}|^2 \cdot |f_{B \to H_x}(q^2)|^2$$

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



$|V_{cb}|$ with inclusive $B \to X_c \ell \nu$

- HQE is the successful tool to include perturbative and non-perturbative QCD corrections that allow to connect measurements of semileptonic B-meson decays to $|V_{cb}|^2$

$$\Gamma_{sl} = \Gamma_0 \Big[1 + a^{(1)} \frac{\alpha_s(m_b)}{\pi} + a^{(2,\beta_0)} \beta_0 \left(\frac{\alpha_s}{\pi}\right)^2 + a^{(2)} \left(\frac{\alpha_s}{\pi}\right)^2 + \left(-\frac{1}{2} + p^{(1)} \frac{\alpha_s}{\pi}\right) \frac{\mu_\pi^2}{m_b^2} + \left(g^{(0)} + g^{(1)} \frac{\alpha_s}{\pi}\right) \frac{\mu_G^2(m_b)}{m_b^2} + d^{(0)} \frac{\rho_D^3}{m_b^3} - g^{(0)} \frac{\rho_{LS}^3}{m_b^3} + \text{higher orders} \Big]$$

+ Moments of the lepton spectrum
+ Moments of the X_c invariant mass squared

No new experimental results since 2010

Gambino, Schwanda
PhysRevD 89,014022 (2014)
Include charm-quark mass from sum-rule results (PRD80,074010 (2009))

Alberti, Gambino, Healey, Nandi
PhysRevLett 114,061802 (2015)
- Includes corrections of $O(\alpha_s^2 \Lambda_{QCD}^2/m_b^2)$

HFLAV Latest fit in Kinetic Scheme:

$$|V_{cb}| = (42.19 \pm 0.78) \cdot 10^{-3}$$

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

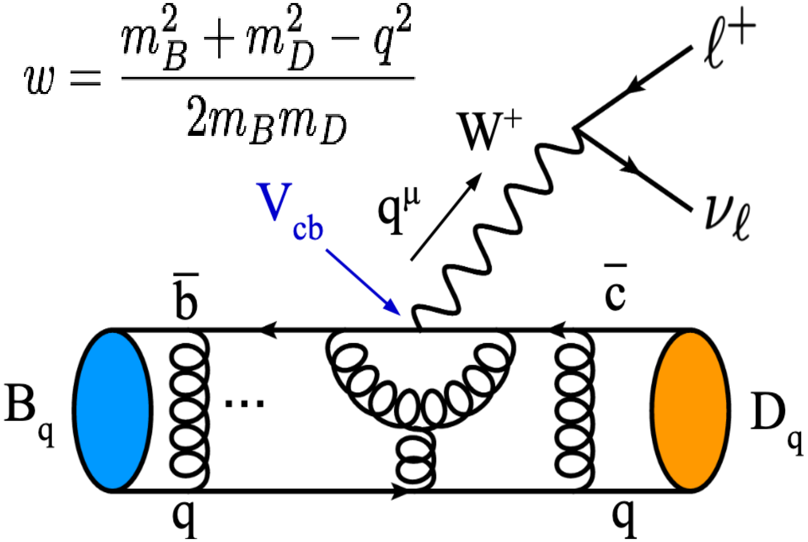
$$m_b^{kin} = 4.544 \pm 0.018\ GeV$$

$$\mu_\pi^2 = 0.464 \pm 0.076\ GeV^2$$

$|V_{cb}|$ with exclusive $B \to D^{(*)}\ell\,\nu$

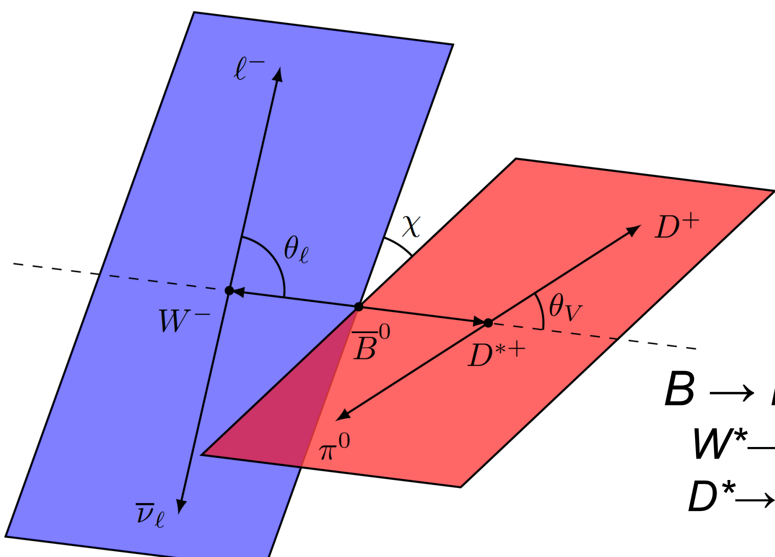
- $B \to D\ell\nu$ and $B \to D^*\ell\nu$ provide clean way to extract $|V_{cb}|$

$$w = \frac{m_B^2 + m_D^2 - q^2}{2 m_B m_D}$$

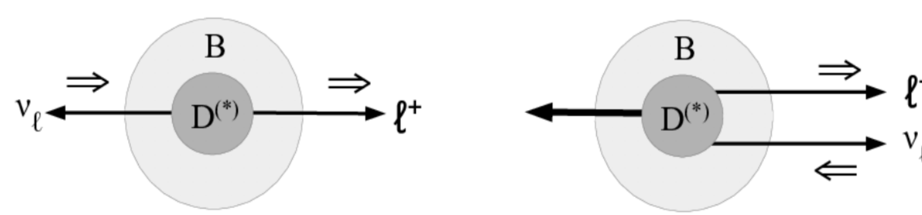


$$\frac{d\Gamma(B \to D^{(*)}\ell\bar{\nu})}{dw} \propto \eta_{EW}^2 |V_{cb}|^2 \begin{cases} (w^2-1)^{1/2}\, F^2(w) & \boldsymbol{B \to D^*} \\ (w^2-1)^{3/2}\, G^2(w) & \boldsymbol{B \to D} \end{cases}$$

- $B \to D\ell\nu$ decay is described by w
  - ℓ=e, μ only one form factor is needed
- $B \to D^*\ell\nu$ with $D \to D\pi/\gamma$: requires w and helicity angles $\{\theta_\ell, \theta_V, \chi\}$
  - ℓ=e, μ three form factors are required



B → D W**
W→ ℓν*
D→ Dπ*



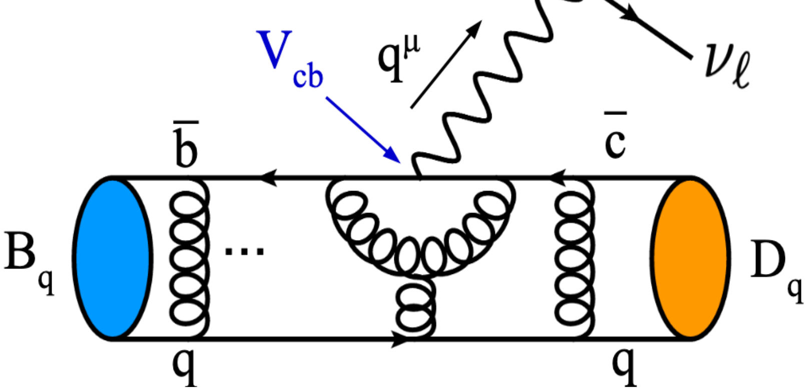
$q^2 = q^2_{max}$ $q^2 = q^2_{min} = m_\ell^2 \approx 0$

$w = 1$ $w \approx 1.5$

$|V_{cb}|$ with exclusiv

- $B \to D\ell\nu$ and $B \to D^*\ell\nu$ provi

$$w = \frac{m_B^2 + m_D^2 - q^2}{2 m_B m_D}$$



$B \to D^*\ell\nu$

Unquenched lattice FF calculation available only at zero-recoil

HPQCD, Phys.Rev.D97, 054502 (2018)
F(1) = 0.895 ± 0.026

MILC/FNAL Phys.Rev.D89, 115404 (2014)
F(1) = 0.906 ± 0.013

Ongoing calculations at large recoil by various lattice groups

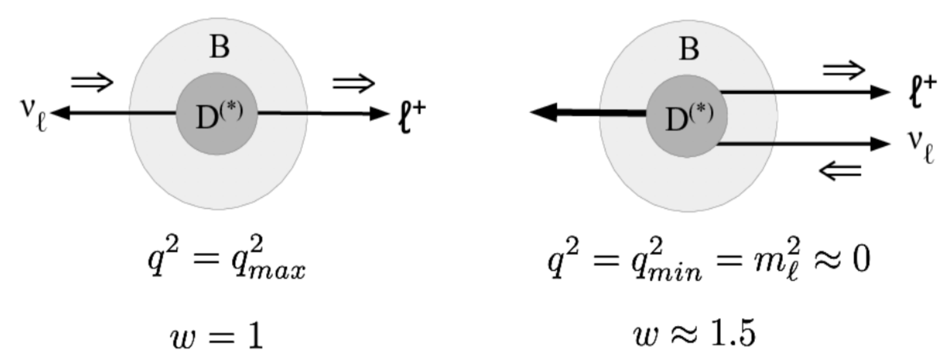
$B \to D\ell\nu$

Unquenched lattice FF calculation also at moderately large recoil
MILC/FNAL Phys.Rev.D92, 034506 (2015)
HPQCD Phys.Rev.D92, 054510 (2015)

- FF normalization requires non perturbative QCD calculations

► Lattice-QCD reliables close to zero-recoil w~1

► LCSR reliables at $w \sim w_{max}$



$|V_{cb}|$ and Form Factors parameterizations

- Phase space is reduced to 0 in the zero-recoil region
- Need an extrapolation to w=1 which has to rely on a form factor parameterization

- BGL Boyd, Grinstein, Lebed Phys.Rev.Lett 74, 4603 (1995)
  - Generic parameterization with minimal theoretical assumptions

$$f_i(z) = \frac{1}{P_i(z)\phi_i(z)} \sum_{n=0}^{N} a_{i,n} z^n, \qquad z(w) = \frac{\sqrt{w+1} - \sqrt{2}}{\sqrt{w+1} + \sqrt{2}}$$

Coefficient $a_{i,n}$ are free parameters to a certain order
The unitarity and analyticity of the FFs assure bounds on the coefficients $\sum_{n=0}^{\infty} a_{i,n}^2 \leq 1$

- CLN Caprini, Lellouch, Neubert Nucl.Phys.B530, 153 (1998)
  - Additional assumptions to reduced the number of parameters
    - $F(1)=h_{A1}(1)$
    - R_1 and R_2 are ratios of FFs

$B \to D^* \ell \nu$

$$h_{A_1}(w) = h_{A_1}(1)\left[1 - 8\rho^2 z + (53\rho^2 - 15)z^2 - (231\rho^2 - 91)z^3\right],$$

$$R_1(w) = R_1(1) - 0.12(w-1) + 0.05(w-1)^2$$

$$R_2(w) = R_2(1) + 0.11(w-1) - 0.06(w-1)^2$$

Belle B→D*lν analysis

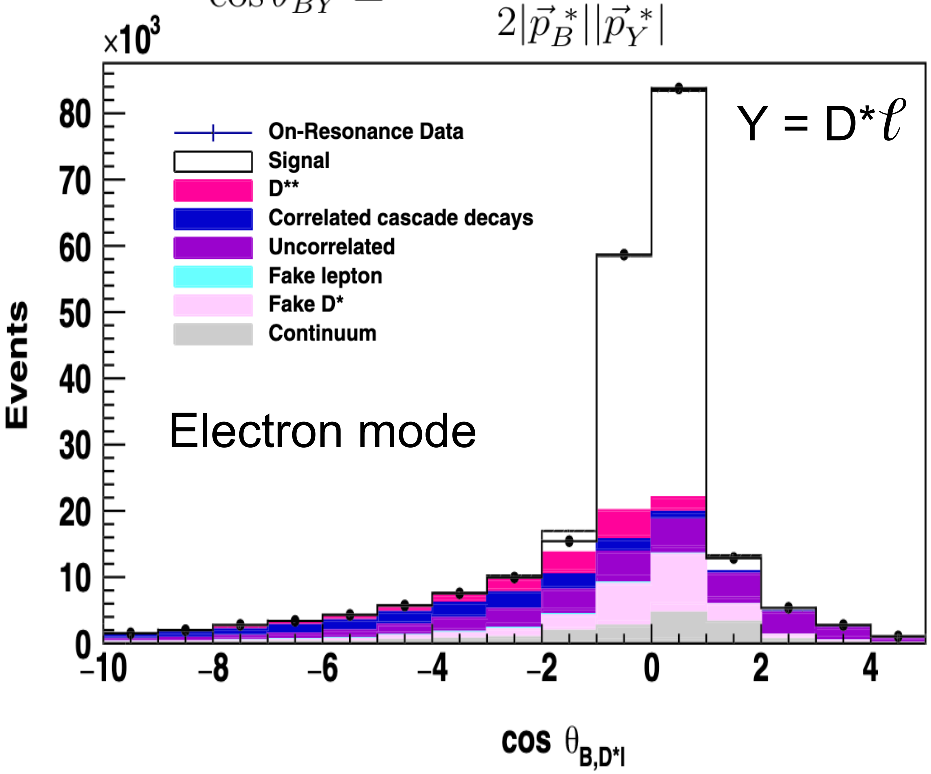
Phys. Rev. D 100 (2019) 052007

- Based on 711 fb^{-1}
- Using $D^{*-} \to D^0\pi_s$, $D^0 \to K\pi$
- Requiring a well reconstructed lepton
  - P_e > 0.80 GeV
  - P_μ > 0.85 GeV

$$N(B \to D^* e\nu_e) = 91 \cdot 10^3$$
$$N(B \to D^* \mu\nu_\mu) = 90 \cdot 10^3$$

Purity ~80%

$$\cos\theta_{BY} = \frac{2E_B^* E_Y^* - m_B^2 - m_Y^2}{2|\vec{p}_B^*||\vec{p}_Y^*|}$$



- Signal yields extracted from a 3D fit of

  $\cos\theta_{BY}$
  $\Delta M = m(D^*) - m(D)$
  P_ℓ

- In 40 bins in $w, \theta_\ell, \theta_V, \chi$

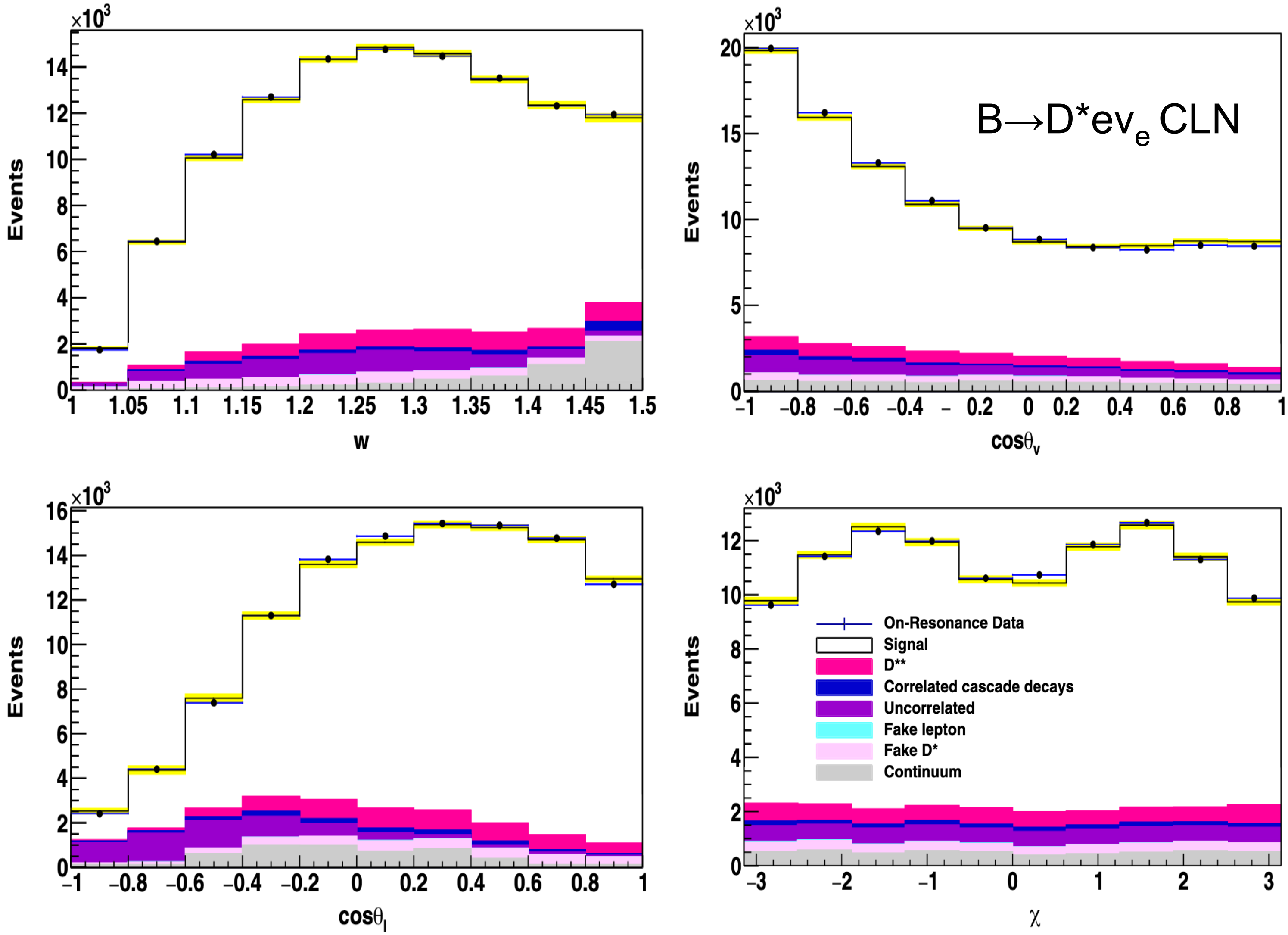
  (10 bins for each projection)

Computation of kinematic quantities requires the knowledge of the B direction → estimated by $\cos\theta_{BY}$ and information from the rest of the event

B→D*lν: fit results

Phys. Rev. D 100 (2019) 052007

- Simultaneous fit of 1D projections of w, θ_ℓ, θ_V, χ
  - CLN: $F(1)|V_{cb}|$ + 3 f.f. parameters ρ^2, $R_1(1)$, $R_2(1)$
  - BGL[(120)]: $|V_{cb}|$ and 5 f.f. coefficients, a_0^f, a_1^f, a_1^{F1}, a_2^{F1}, a_0^g



Correlations across the 4 dimensions evaluated from the overlapping events between each pair of bins
The 40x40 covariance matrix is properly accounted in the χ^2

Good χ^2/ndf for both CLN and BGL

$$\frac{\mathcal{B}(B^0 \to D^{*-} e^+ \nu)}{\mathcal{B}(B^0 \to D^{*-} \mu^+ \nu)} = 1.01 \pm 0.01 \pm 0.03$$

FF parameters and $|V_{cb}|$

Phys. Rev. D 100 (2019) 052007

$$|V_{cb}|_{CLN} = (38.4 \pm 0.2 \pm 0.6 \pm 0.6) \times 10^{-3}$$

FNAL/MILC F(1)=0.906 ± 0.013

$$|V_{cb}|_{BGL} = (38.3 \pm 0.2 \pm 0.7 \pm 0.6) \times 10^{-3}$$

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

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

- Consistent results between CLN and BGL
- With additional parameters free in the BGL
  - The unitarity constrains are violated
  - Large correlations between parameters cause fit instability

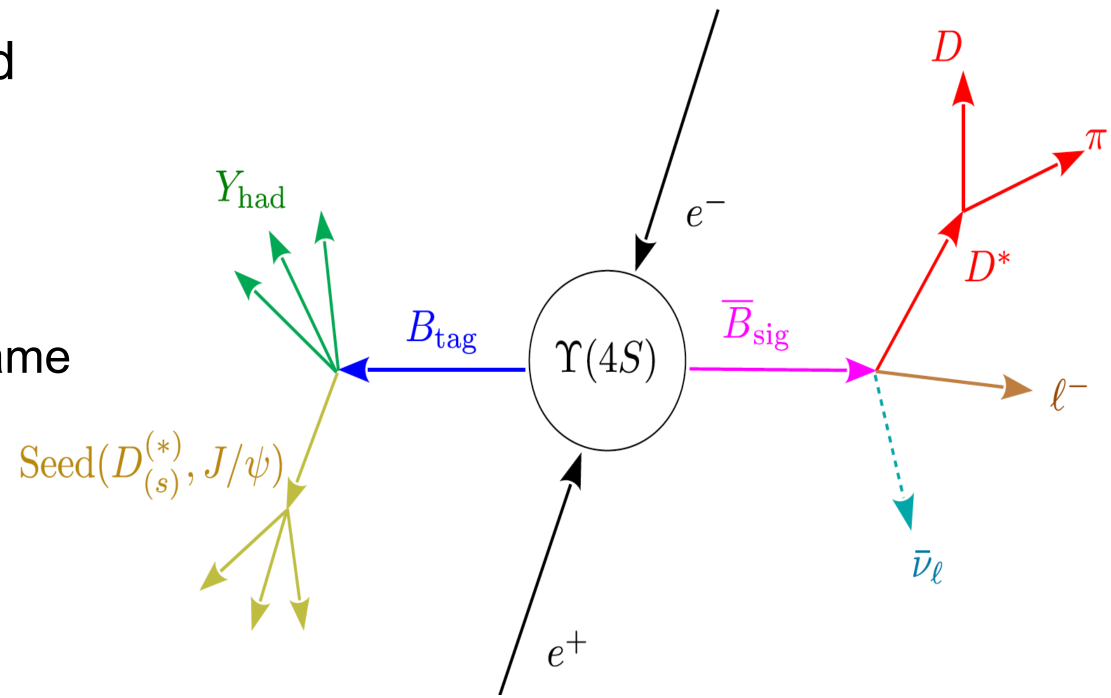
- Spectrum is not unfolded, but information about bin-bin migration matrix and efficiency maps are available for independent fits

BaBar B→D*lν analysis

Phys.Rev.Lett. 123 (2019) no.9, 091801

- Analysis based on 426 fb^{-1} at Y(4S)
- Hadronic B-tagging
  - Suppress continuum $e^+e^- \to q\bar{q}$ and combinatorial background
  - Improve the resolution on the kinematics of the signal decay
    - Boost kinematics in the B_{sig} rest frame
    - Increase the signal/background separation

$$\Upsilon(4S) \to B_{tag}B_{sig}(\to D^*\ell\nu_\ell)$$

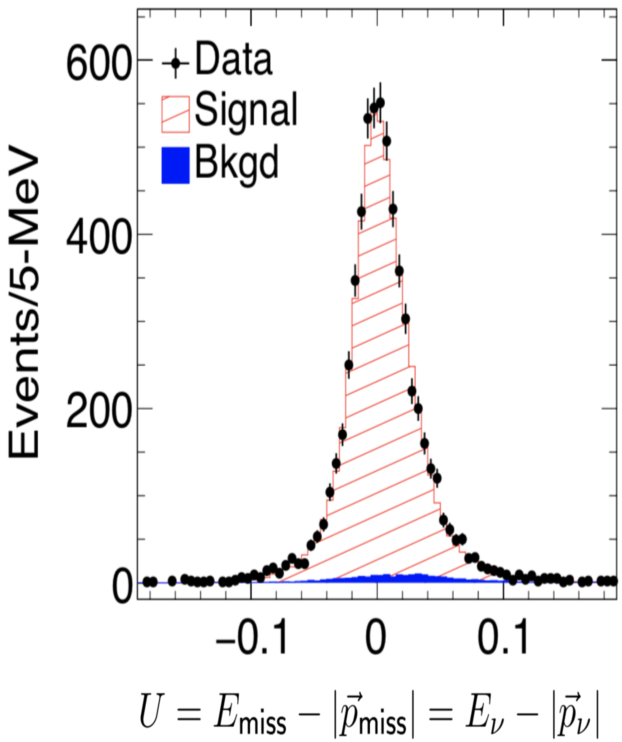


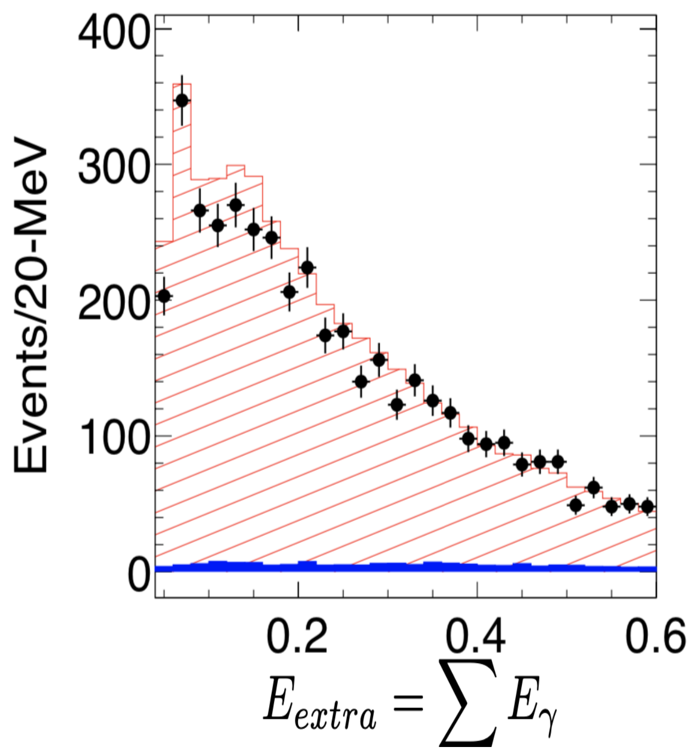
- Improved B_{tag} algorithm used also in
  - B→D(*)ππℓν PRL 116 (2016) 041801
  - R(D)-R(D*) PRL 109 (2012) 101802

- Full exclusive event topology reconstructed: no additional tracks
  - B_{tag}^0 & $B^0 \to D^{*-}\ell^+\nu$, with $D^{*-} \to D^0\pi^-$, ℓ=e,μ
  - B_{tag}^- & $B^+ \to D^{*0}\ell^+\nu$, with $D^{*0} \to D^0\pi^0$, ℓ=e,μ
    - D^0 reconstructed in the cleanest mode: $K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+$

Signal yield

- Kinematic fit of the full event topology: $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B_{tag}$ && $B \rightarrow D^* \ell \nu$
  - Mass constraint: B_{tag}, B_{sig}, D, D*, ν
  - Vertex constraint: beam spot, secondary vertices
  - Probability of the χ^2 of the kinematic fit used as discriminating variable
  - Event further cleaned requiring E_{extra} < 0.4-0.6 GeV (depending on the mode)





Requiring |U|<90 MeV

- 6112 total candidates

- signal purity 98%

- the background of 2% is all due to BB events

FF parameters and $|V_{cb}|$

- Form factors parameters extracted from an unbinned Maximum Likelihood fit using the full 4D differential rate

$$\frac{d\Gamma}{dq^2 d\Omega}$$

- $BF(B^0 \to D^{*-}\ell^+\nu)$ included as gaussian constraints in the likelihood to extract $|V_{cb}|$

$$\Gamma_{tot} \equiv \int \frac{d\Gamma}{dq^2 d\Omega} dq^2 d\Omega = \frac{BF(B \to D^* \ell \nu)}{\tau_B}$$

- CLN

$\rho^2_{D^*}$	$R_1(1)$	$R_2(1)$	$\lvert V_{cb}\rvert \times 10^3$
0.96 ± 0.08	1.29 ± 0.04	0.99 ± 0.04	38.40 ± 0.84

- BGL(111)

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

- Higher order terms have large uncertainties and violate unitarity

- BGL and CLN give consistent $|V_{cb}|$ results
  - Result consistent with HFLAV average (based on CLN)
  - Form Factor parameters not included in HFLAV yet

Comments on B→D*lν measurements

- Most precise previous measurements from BaBar and Belle

Phys.Rev.D77:032002(2008)

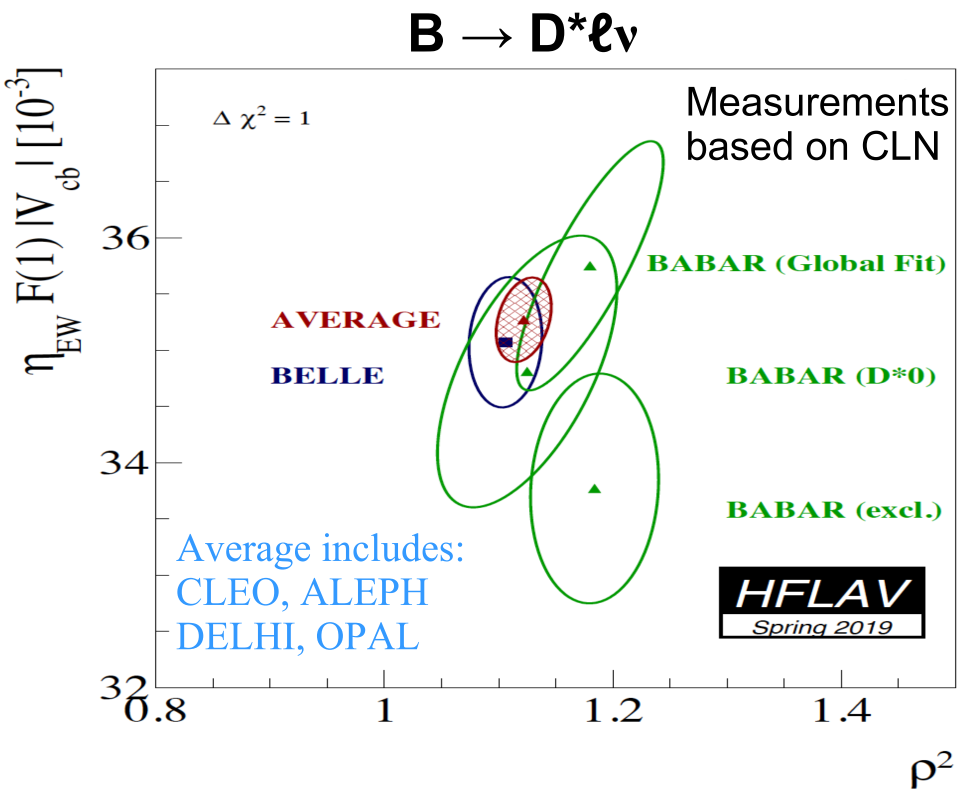
Phys.Rev.D100:052007(2019)

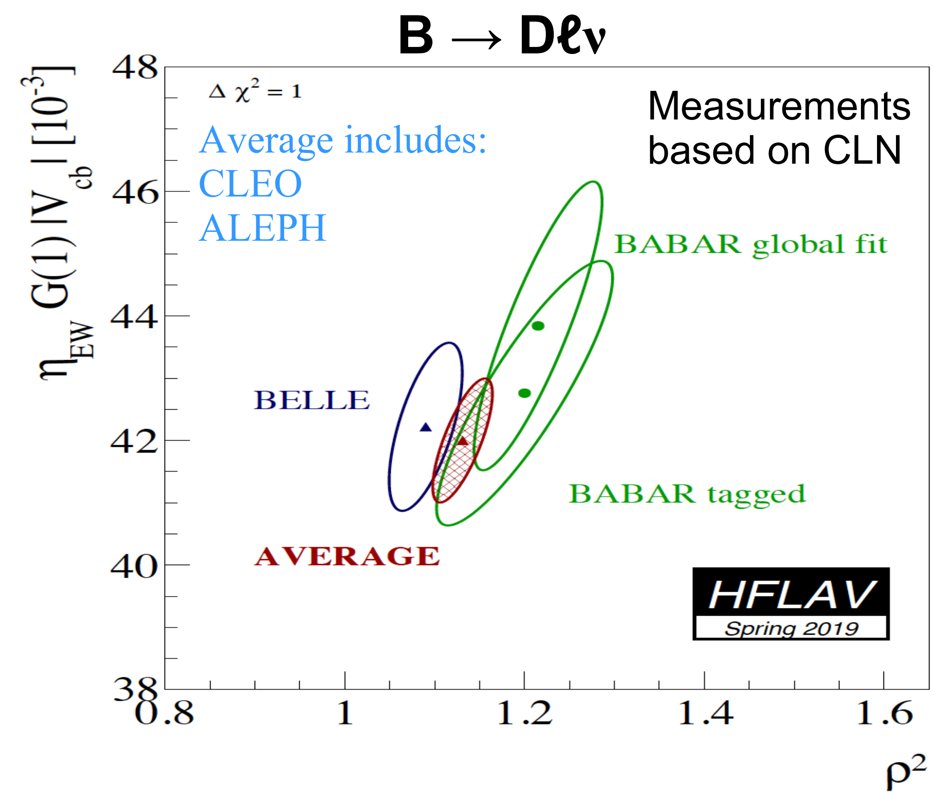
  - Untagged sample: high efficiency but higher background and unconstrained kinematics
  - Fit the projections to the 4-dimensions w, θ_ℓ, θ_V, χ
    - Strong statistical correlation between the bins in the various projections need to be considered
    - Reduced sensitivity to form factors shapes

- The BaBar measurement with only $1/20^{th}$ of the signal yield achieved a sensitivity to form factors similar to Belle analysis
  - Tagged sample: better resolutions, smaller background, 4-D fit to q^2, θ_ℓ, θ_V, χ

    - Caveat: for a $|V_{cb}|$ measurement, the hadronic B-tagging suffers from systematics due to calibration of the B_{tag} efficiencies

HFLAV Average





$$\eta_{EW}\mathcal{F}(1)|V_{cb}| = (35.27 \pm 0.38) \times 10^{-3}$$
$$\rho^2 = 1.122 \pm 0.024$$
$$R_1(1) = 1.270 \pm 0.026$$
$$R_2(1) = 0.852 \pm 0.018$$

$$\eta_{EW}\mathcal{G}(1)|V_{cb}| = (42.00 \pm 1.00) \times 10^{-3}$$
$$\rho^2 = 1.131 \pm 0.033$$

$$|V_{cb}| = (38.76 \pm 0.42_{exp} \pm 0.55_{th}) \cdot 10^{-3}$$

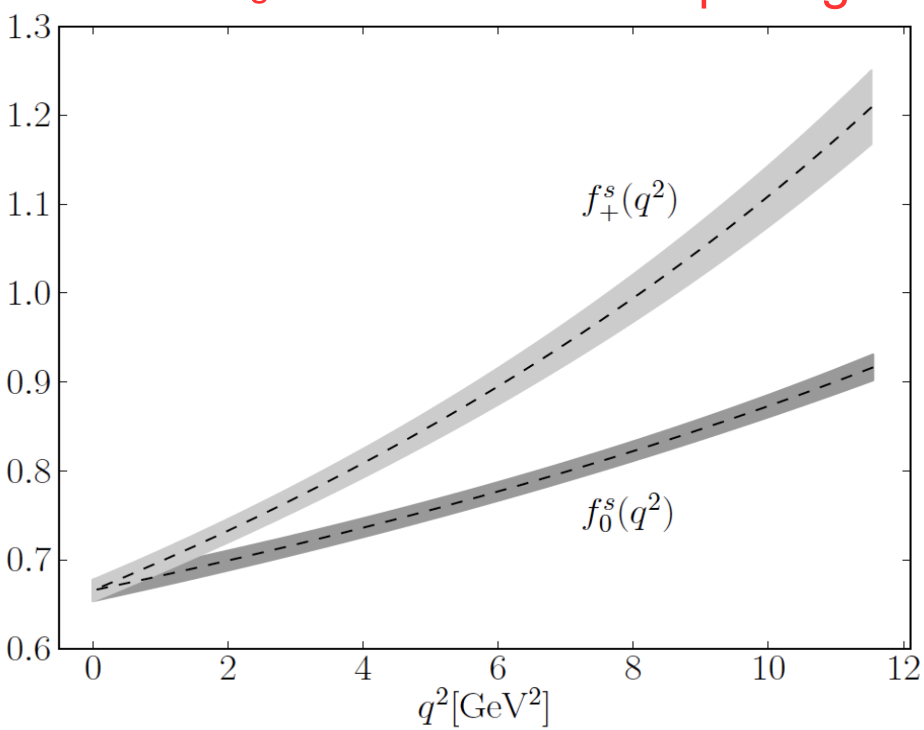
$$|V_{cb}| = (39.58 \pm 0.94_{exp} \pm 0.37_{th}) \cdot 10^{-3}$$

B_s semileptonic decays

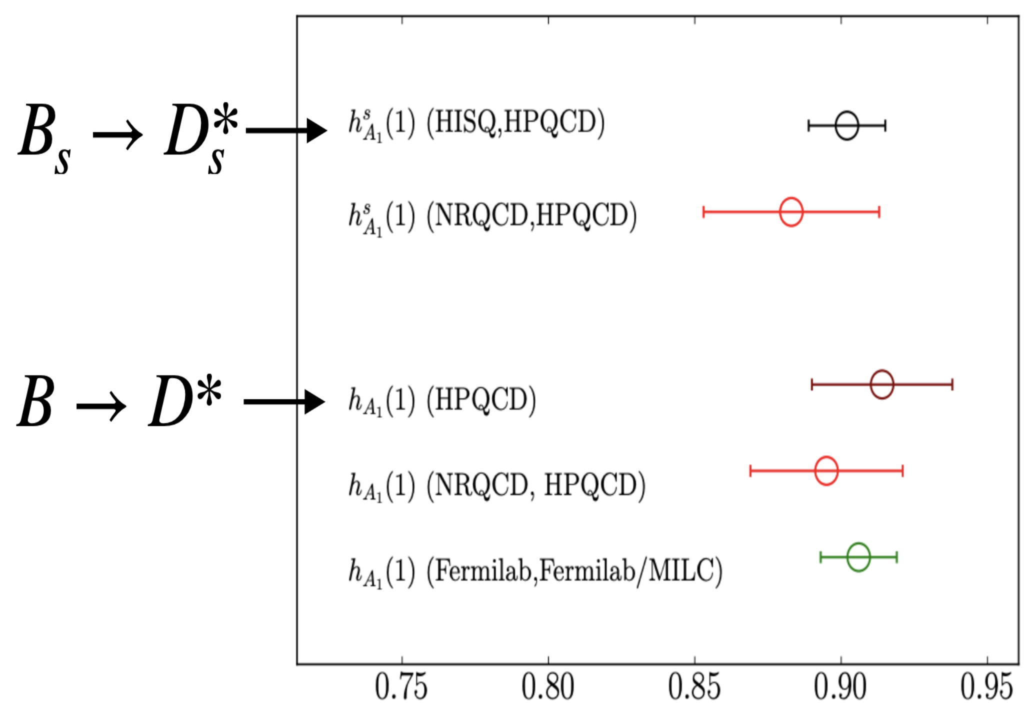
- Complementary measurements to those from B^0 and B^+
- Advantages:
  - Lattice calculations easier due to heavier spectator quark: predictions are more precise
  - For the $B_s \to D_s^*$: the *zero-width* approximation of the D_s^* should work better than the B case (no Dπ pollution)

Golden modes for Lattice-QCD

HPQCD, PRD 101 (2020) 7, 074513
$B^0 \to D_s \ell^+ \nu$ FF in the full q^2 range



HPQCD, PRD 99 (2019), 114512



LHCb Measurement of $|V_{cb}|$

Phys.Rev.D 101 (2020) 7, 072004

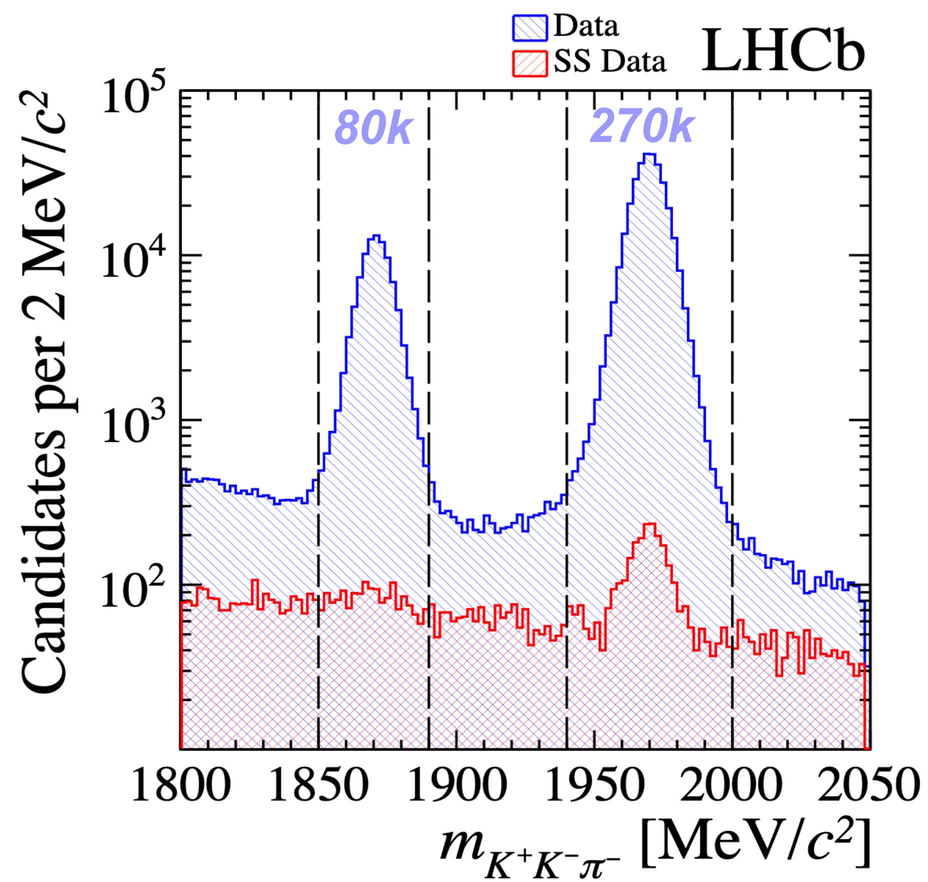
- Based on Run1, $3fb^{-1}$
- Extract $|V_{cb}|$ from B_s decays $B_s \to D_s^- \mu\nu$ and $B_s \to D_s^{*-} \mu\nu$
- Normalized to $B^0 \to D^- \mu\nu$ and $B^0 \to D^{*-} \mu\nu$
  - The $BF(B^0 \to D^{(*)-} \mu\nu)$ are known well from B-Factories

$$\mathcal{R} \equiv \frac{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)}{\mathcal{B}(B^0 \to D^- \mu^+ \nu_\mu)}$$

$$\mathcal{R}^* \equiv \frac{\mathcal{B}(B_s^0 \to D_s^{*-} \mu^+ \nu_\mu)}{\mathcal{B}(B^0 \to D^{*-} \mu^+ \nu_\mu)}$$

- The D^- and the D_s^- are reconstructed in the same final state $D_{(s)}^- \to K^- K^+ \pi^-$
- Decrease the systematic uncertainties: same particles and similar kinematic in the final state

- Only the $D^- \mu\nu$ and $D_s^- \mu\nu$ samples are reconstructed
  - The $D_s^- \mu\nu$ and the $D_s^{*-} \mu\nu$ components (and $D^- \mu\nu$ and $D^{*-} \mu\nu$) are separated kinematically



LHCb Measurement of $|V_{cb}|$

Phys.Rev.D 101 (2020) 7, 072004

$$\mathcal{R} \equiv \frac{\mathcal{B}(B_s \to D_s \mu\nu)}{\mathcal{B}(B^0 \to D^- \mu\nu)} = \frac{N_s}{N_d} \cdot \frac{\epsilon_d}{\epsilon_s} \cdot \frac{f_d}{f_s} \cdot \frac{\mathcal{B}(D^- \to KK\pi)}{\mathcal{B}(D_s \to KK\pi)}$$

External inputs

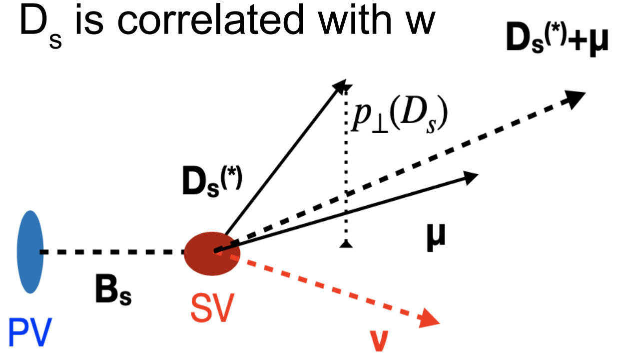
f_s/f_d from PRD(2019)031102

BFs from PDG

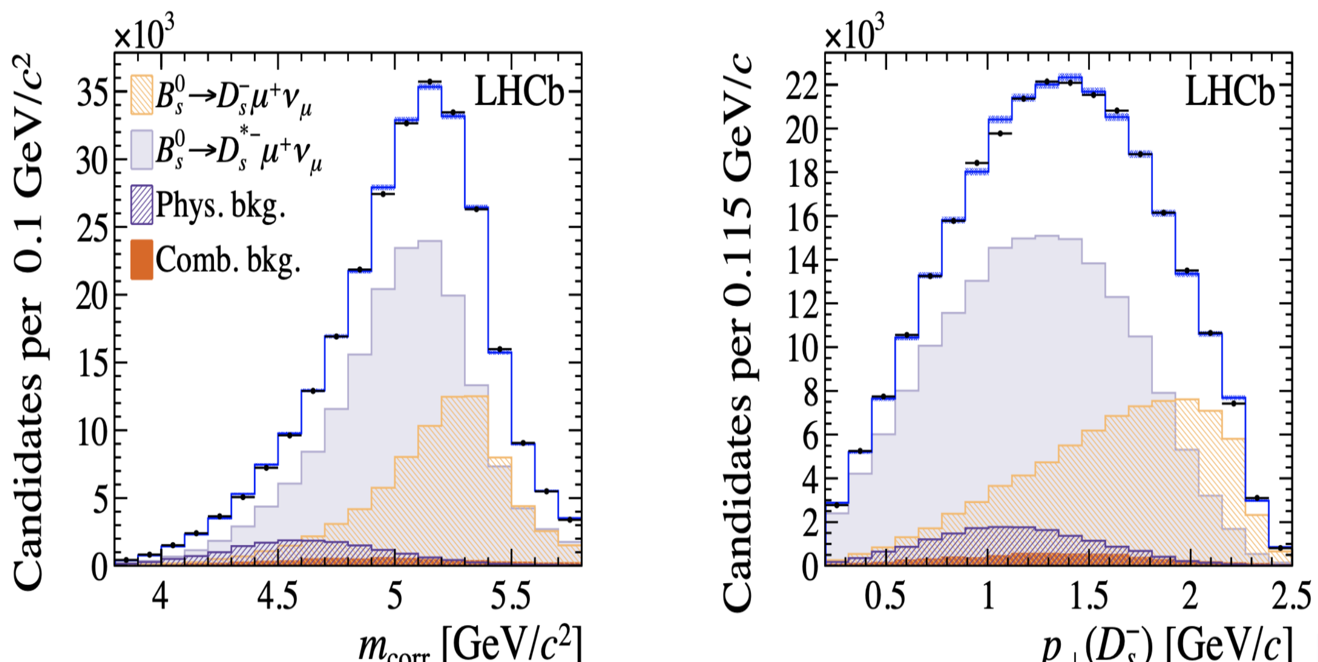
- N_s is written in terms of $|V_{cb}|$ and the form factors
- 2-D template fit to m_{corr} and $p_\perp(D_s)$ identify the signal yields and provides a simultaneous measurement of the ratios R(*) and the form factors

More details in the dedicated talk by Dawid Gerstel on June 10th /parallel session on B-anomalies

- The transverse momentum of the D_s is correlated with w



$$m_{Mcorr} = \sqrt{m(Y)^2 + |p_T(Y)|^2} + |p_T(Y)|$$



Results on $|V_{cb}|$

Phys.Rev.D 101 (2020) 7, 072004

$$|V_{cb}|_{\rm CLN} = (41.4 \pm 0.6({\rm stat}) \pm 0.9({\rm syst}) \pm 1.2({\rm ext})) \times 10^{-3}$$

$$|V_{cb}|_{\rm BGL} = (42.3 \pm 0.8({\rm stat}) \pm 0.9({\rm syst}) \pm 1.2({\rm ext})) \times 10^{-3}$$

First measurement of $|V_{cb}|$ using B_s

First measurement of $|V_{cb}|$ in an hadronic environment

- The results are consistent between CLN and BGL
- Compatible with world average for both inclusive and exclusive determinations

- Uncertainty not competitive with b-factories: limited by knowledge of f_s/f_d

The approach can be applied also to B^0 decays!

Results on $|V_{cb}|$

Phys.Rev.D 101 (2020) 7, 072004

$$|V_{cb}|_{\mathrm{CLN}} = (41.4 \pm 0.6(\mathrm{stat}) \pm 0.9(\mathrm{syst}) \pm 1.2(\mathrm{ext})) \times 10^{-3}$$

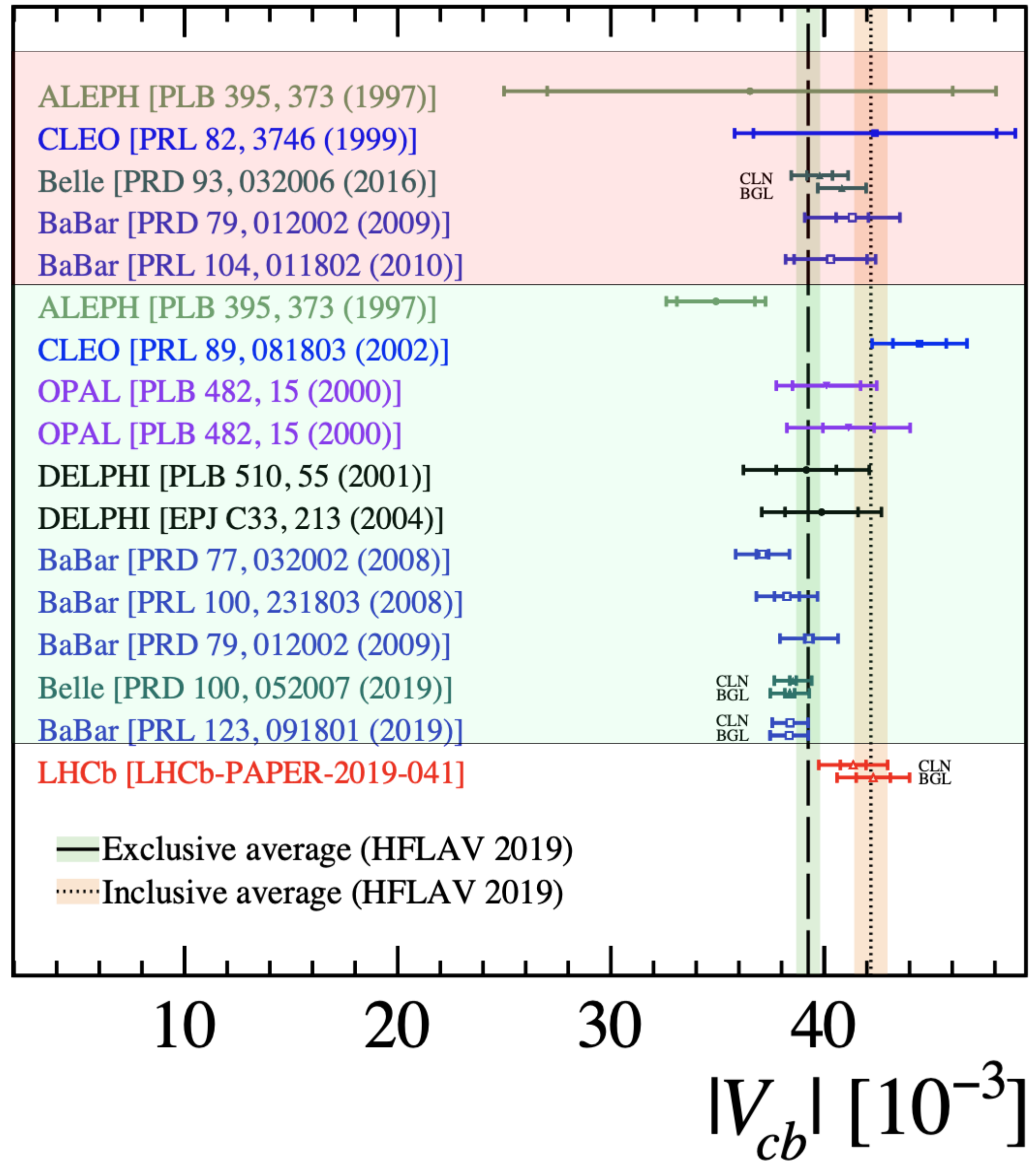
$$|V_{cb}|_{\mathrm{BGL}} = (42.3 \pm 0.8(\mathrm{stat}) \pm 0.9(\mathrm{syst}) \pm 1.2(\mathrm{ext})) \times 10^{-3}$$

First measurement of $|V_{cb}|$ using B_s

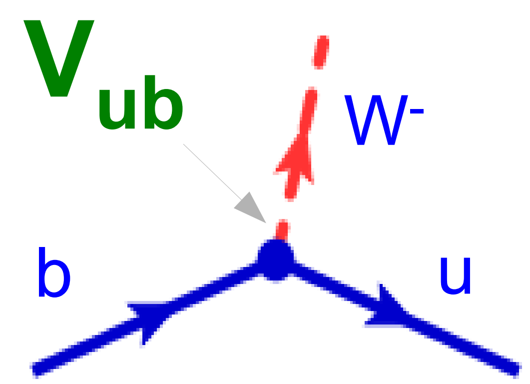
First measurement of $|V_{cb}|$ in an hadronic environment

- The results are consistent between CLN and BGL
- Compatible with world average for both inclusive and exclusive determinations
- Uncertainty not competitive with b-factories: limited by knowledge of f_s/f_d

The approach can be applied also to B^0 decays!

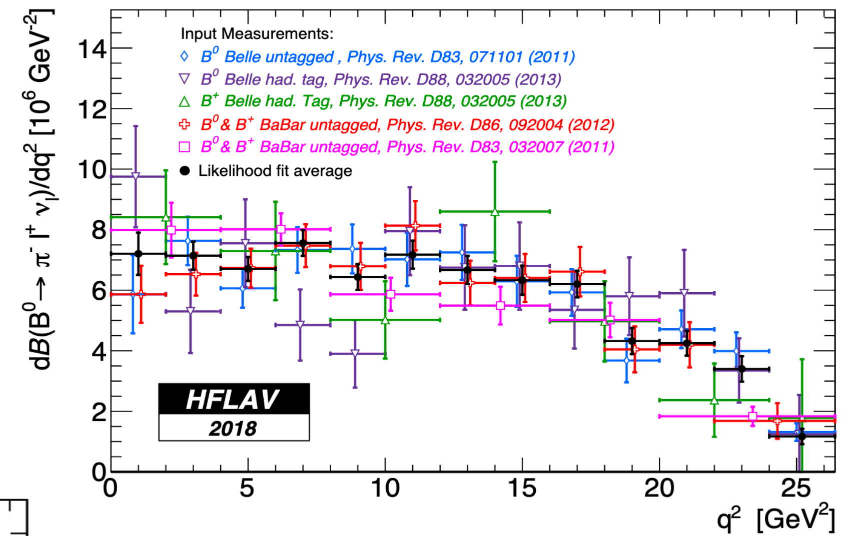


$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



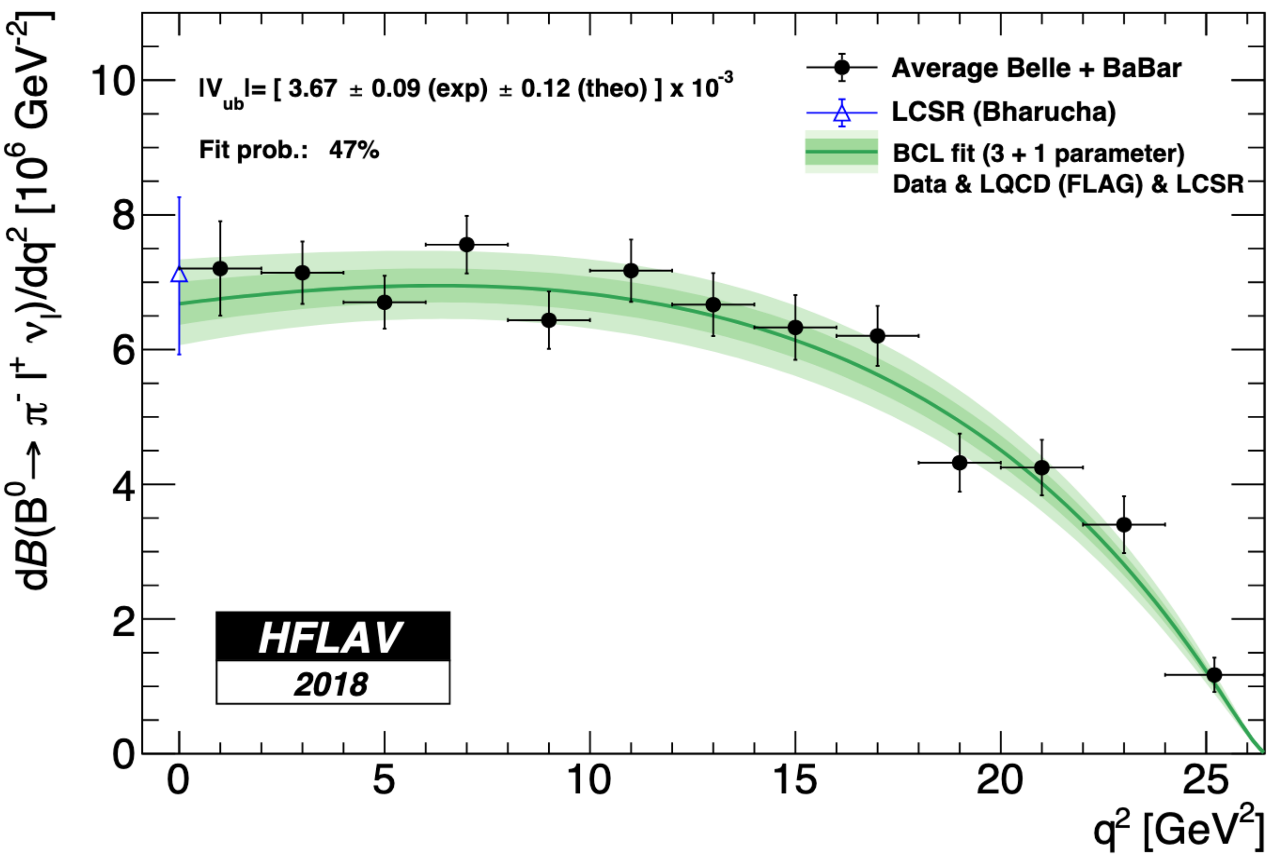
The state of the art at the B-Factories

$$B^0 \rightarrow \pi^+ \ell^- \bar{\nu}$$
$$B^- \rightarrow \pi^0 \ell^- \bar{\nu}$$



Using both tagged and untagged approaches

Untagged provide most precise results



Results of the HFLAV combined fit of the experimental data and theoretical inputs:

- Lattice QCD (HPQCD, MILC/FNA) at high q^2
- Light Cone Sum Rules at low q^2

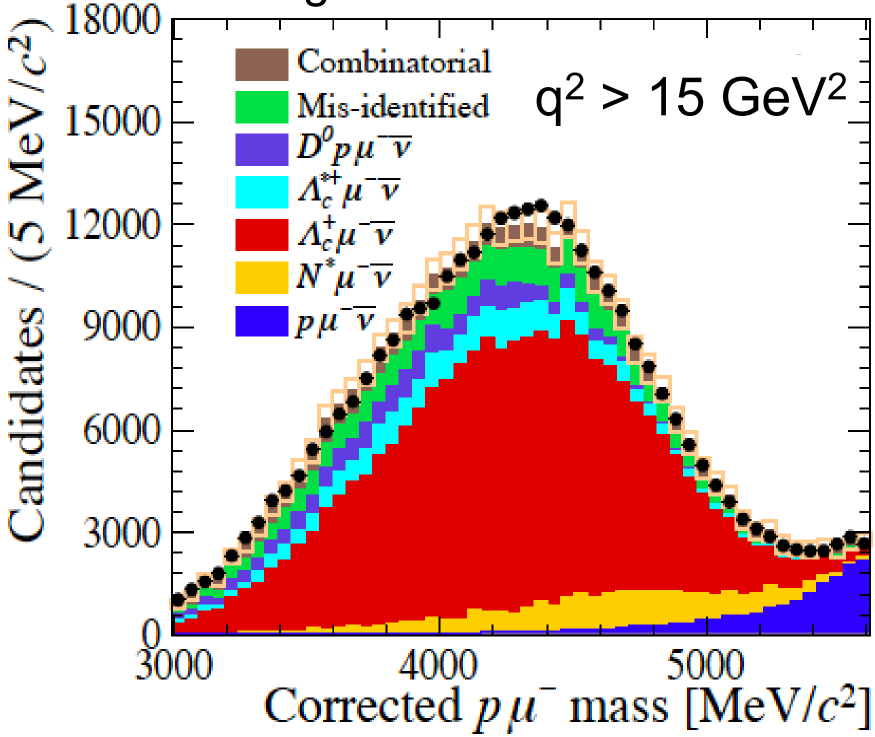
$$|V_{ub}| = (3.67 \pm 0.09_{exp.} \pm 0.12_{th.}) \cdot 10^{-3}$$

$\Lambda_b \to p\mu\nu$: signal fits

Nature Phys.11(2015)743

- The b-baryon decays provided complementary information to B mesons
- Using Run1 (2 fb^{-1})
- Large background from $\Lambda_b \to \Lambda_c\mu\nu$
- LHCb determines the ratio

Signal N=17687 ± 733



$$R_{exp} = \frac{\mathcal{B}(\Lambda_b \to p\mu\nu)}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu\nu)}$$

Signal $q^2 > 15$ GeV^2

Normalization $q^2 > 7$ GeV^2

$R_{exp} = (0.92 \pm 0.04_{stat} \pm 0.07_{syst}) \times 10^{-2}$

$$\frac{V_{ub}}{V_{cb}} = \sqrt{\frac{R_{exp}}{R_{TH}}}$$

Detmold et al. PRD92 (1015) 034503

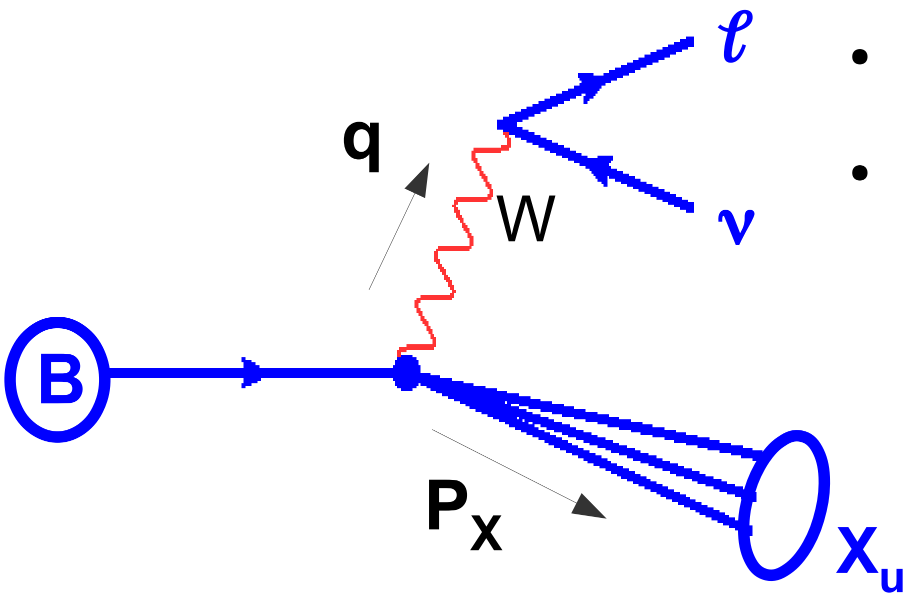
$$\frac{|V_{ub}|}{|V_{cb}|} = 0.079 \pm 0.004_{exp} \pm 0.004_{F.F}$$

First measurement of $\Lambda_b \to p\,\mu\nu$

First $|V_{ub}|$ measurement in hadronic environments

$|V_{ub}|$ from inclusive decays

$$\frac{\Gamma(b \to c\ell\nu)}{\Gamma(b \to u\ell\nu)} \approx 50$$



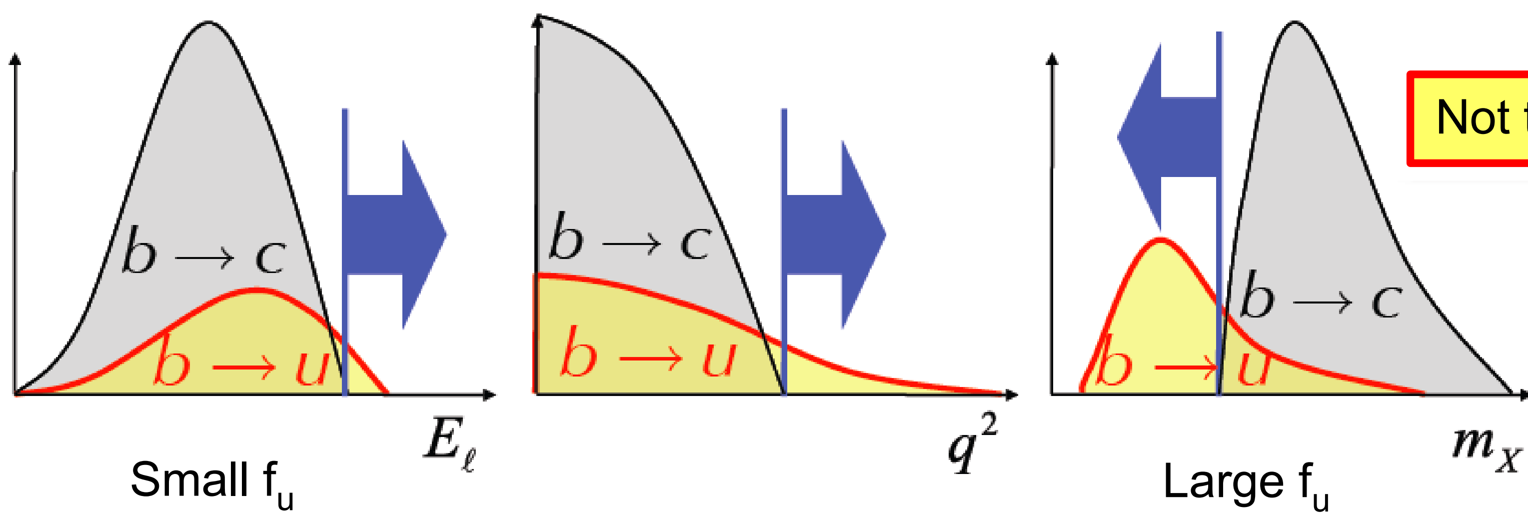
- Large background from $B \to X_c \ell \nu$
- Kinematics to extract the signal: $m_u \ll m_c$
  - Cut limited region of phase space (f_u)
    - Non perturbative shape-function needed
    - Universal only at leading order in Λ/m_b

E_ℓ = lepton energy

$q^2 = (P_B - P_X)^2 = (P_\ell - P_\nu)^2$

M_X = X_u hadronic mass

$$|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}(\overline{B} \to X_u \ell \bar{\nu})}{\tau_B \, \Delta\Gamma_{\rm theory}}}$$



Experimental resolution leads to “irreducible” $b \to c\ell\nu$ contamination
- partially suppressed with K and D* vetos

$|V_{ub}|$ from inclusive decays

$$\frac{\Gamma(b \to c\ell\nu)}{\Gamma(b \to u\ell\nu)} \approx 50$$

- Large background from $B \to X_c \ell\nu$
- Kinematics to extract the signal: $m_u \ll m_c$
- Cut limited region of phase space (f_u)
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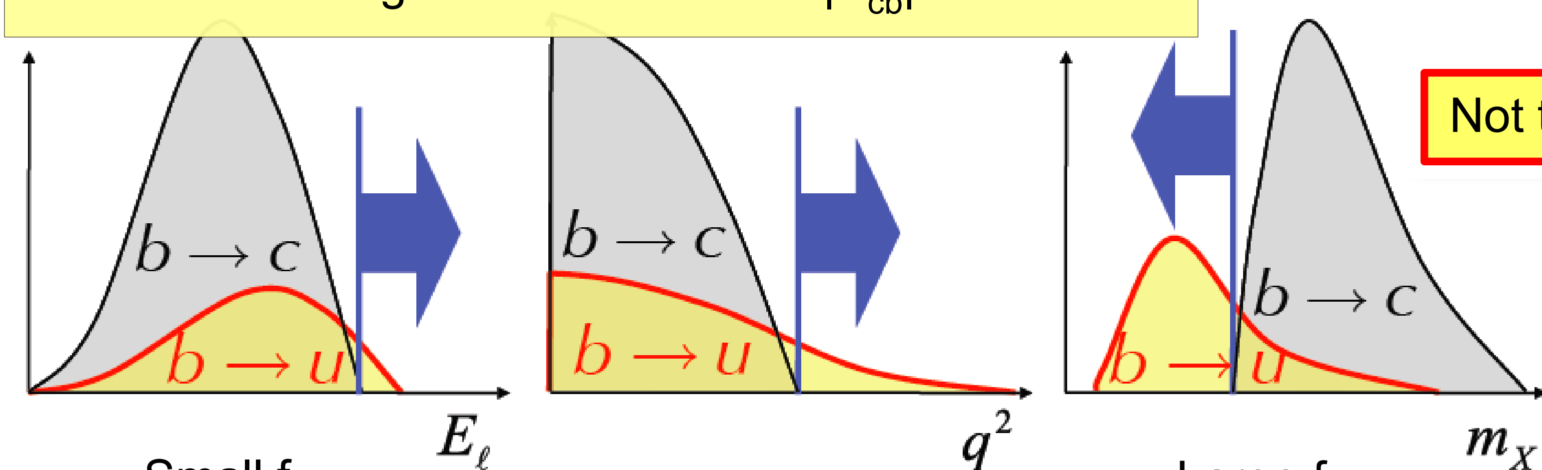
$$|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}(\overline{B} \to X_u \ell\bar{\nu})}{\tau_B \, \Delta\Gamma_{\text{theory}}}}$$

DN De Fazio, Neubert JHEP9905,017 (1999)
Claimed in BLNP to be superseeded
BLNP Bosh, Lange, Neubert, Paz, Nulc.Phys.B699,335(2004)
GGOU Gambino, Giordano, Ossola, Uraltsev, JHEP908 10, 058 (2007)
DGE Andersen, Gardi, JHEP 0601, 097 (2006)
ADFR Aglietti, Di Ludovico, Ferrara, Ricciardi EPJC, Vol. 59 (2009)
BLL Bauer, Ligeti, Luke Phys. Rev. D64,113004 (2001)
Only valid in the mx-q[2] two-dimensions cut

Inputs on m_b and non perturbative parameters, from the global fit of inclusive $|V_{cb}|$



Not to scale!

Experimental resolution leads to "irreducible" $b \to c\ell\nu$ contamination
- partially suppressed with K and D* vetos

$B \to X_u e\nu$: electron spectrum

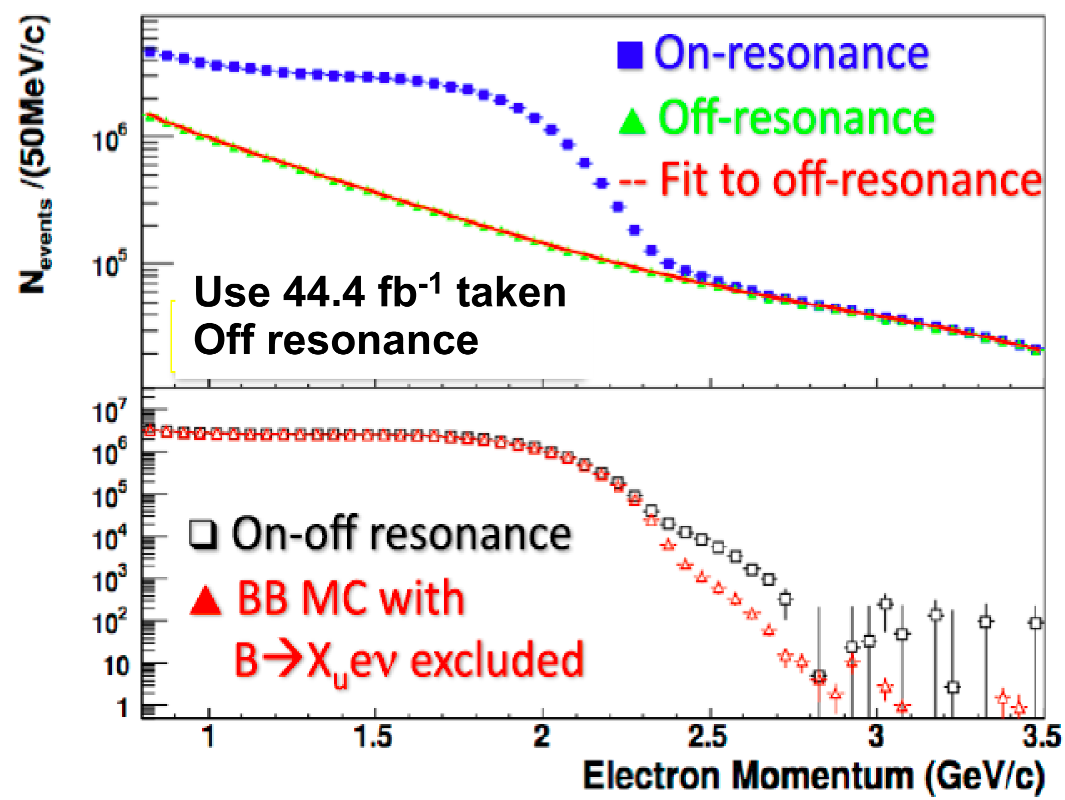
Phys.Rev.D 95, 072001 (2017)

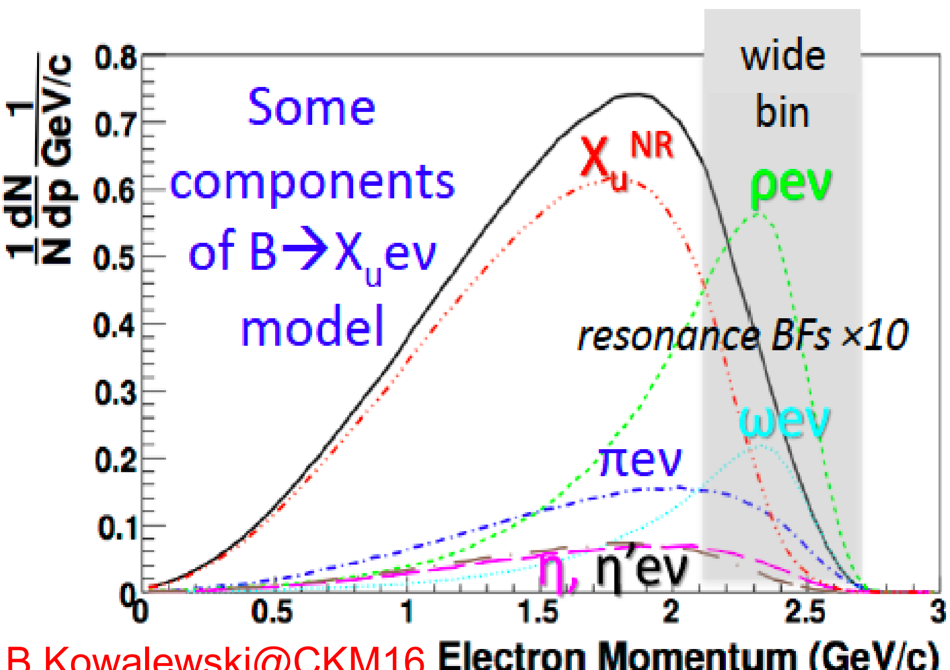
- Inclusive electron spectrum measurement
- Dataset: 467M Υ(4S)

Fit Strategy

- Fit simultaneously on-Υ(4S) and off-Υ(4S)
  - 5 separate $b \to c$ components
  - Secondary leptons $b \to c \to e$
  - $b \to X_u e \nu$
- Spectrum range [p_{min}, 2.7] GeV, p_{min} from 0.8 GeV

Large statistics: >10⁶ events / 50 MeV bin; statistical uncertainties dominated by continuum subtraction





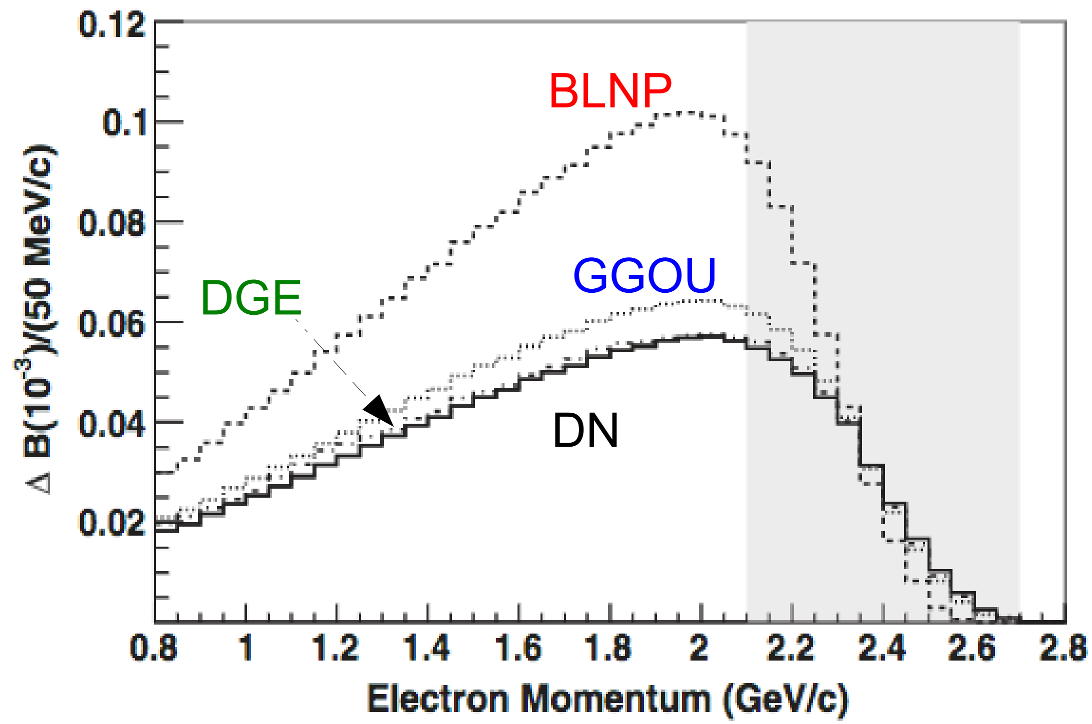
Signal model obtained mixing known existing exclusive final states with calculations for $B \to X_u e \nu$ (Hybrid model). Four different calculations considered for $B \to X_u e \nu$ Inclusive spectrum

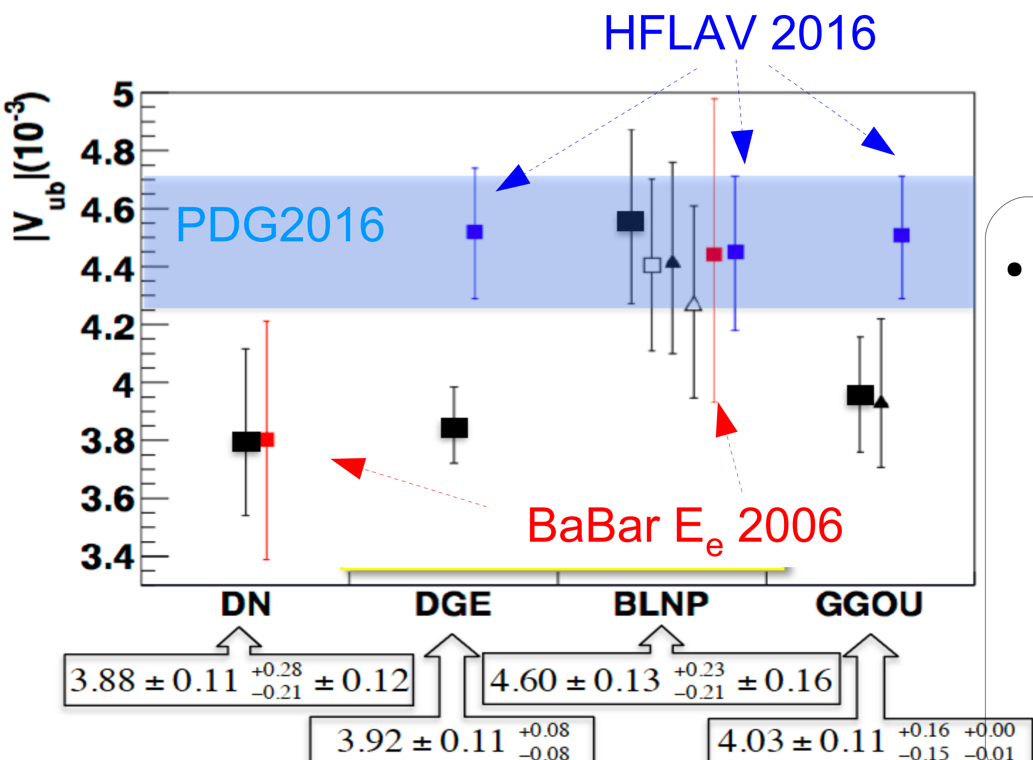
B.Kowalewski@CKM16

Results on total rate and $|V_{ub}|$

Phys.Rev.D 95, 072001 (2017)

- Highest sensitivity to $B \to X_u e\nu$ in the wide bin 2.1-2.7 GeV
- Models make different predictions for the fractional rate in this bin
- This dependence on the signal model impacts any measurement that extends in the $B \to X_c e\nu$ region





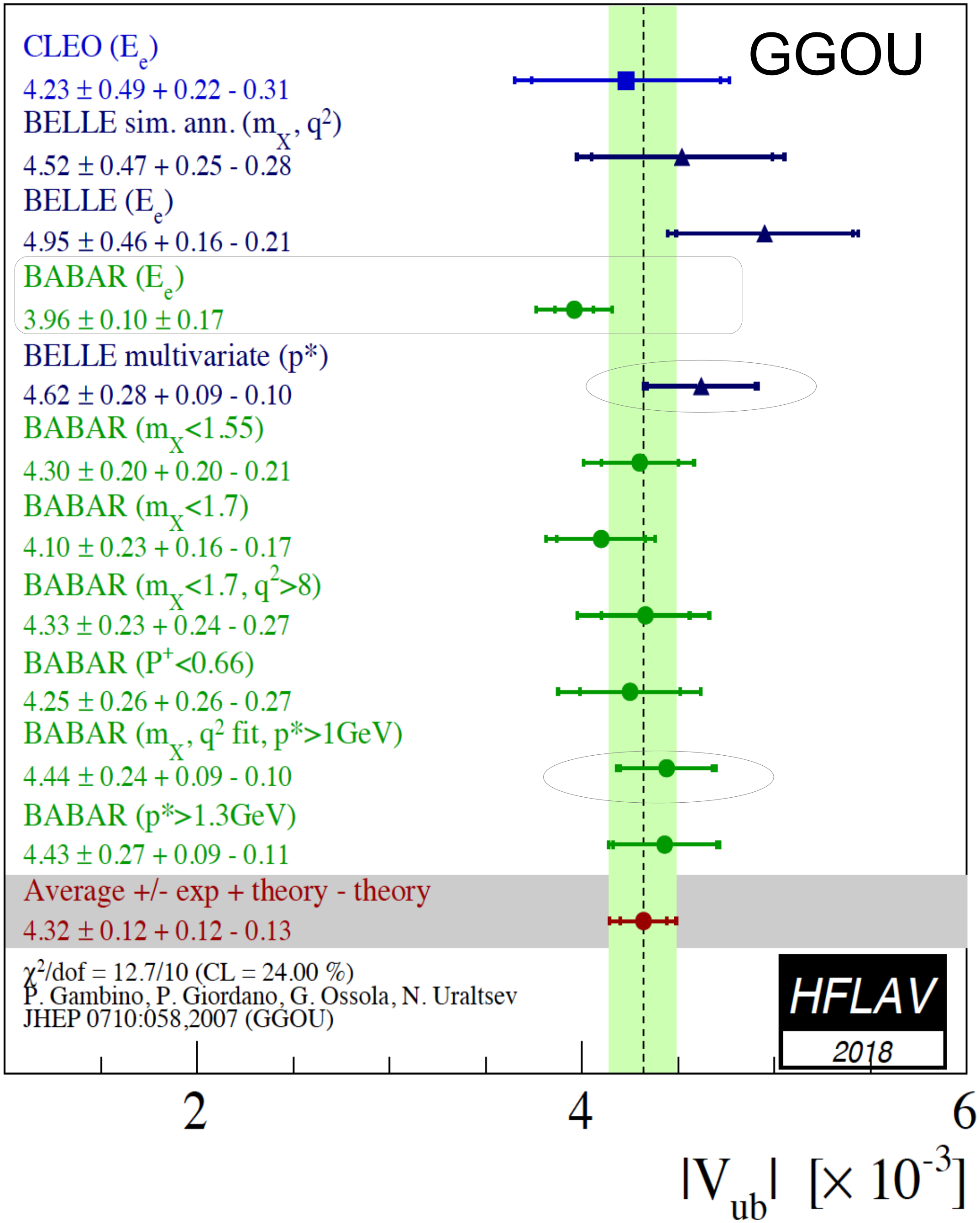
- In the future it will be crucial to improve
  - Knowledge about $B \to X_c$ composition and kinematics: rates and FFs for D/D*/D**...
  - Constrain the signal model measuring exclusive $B \to n\pi\, e\nu$: up to now resonant and non-resonant contributions are combined with an ad-hoc procedure

Status of inclusive $|V_{ub}|$: HFLAV 2018

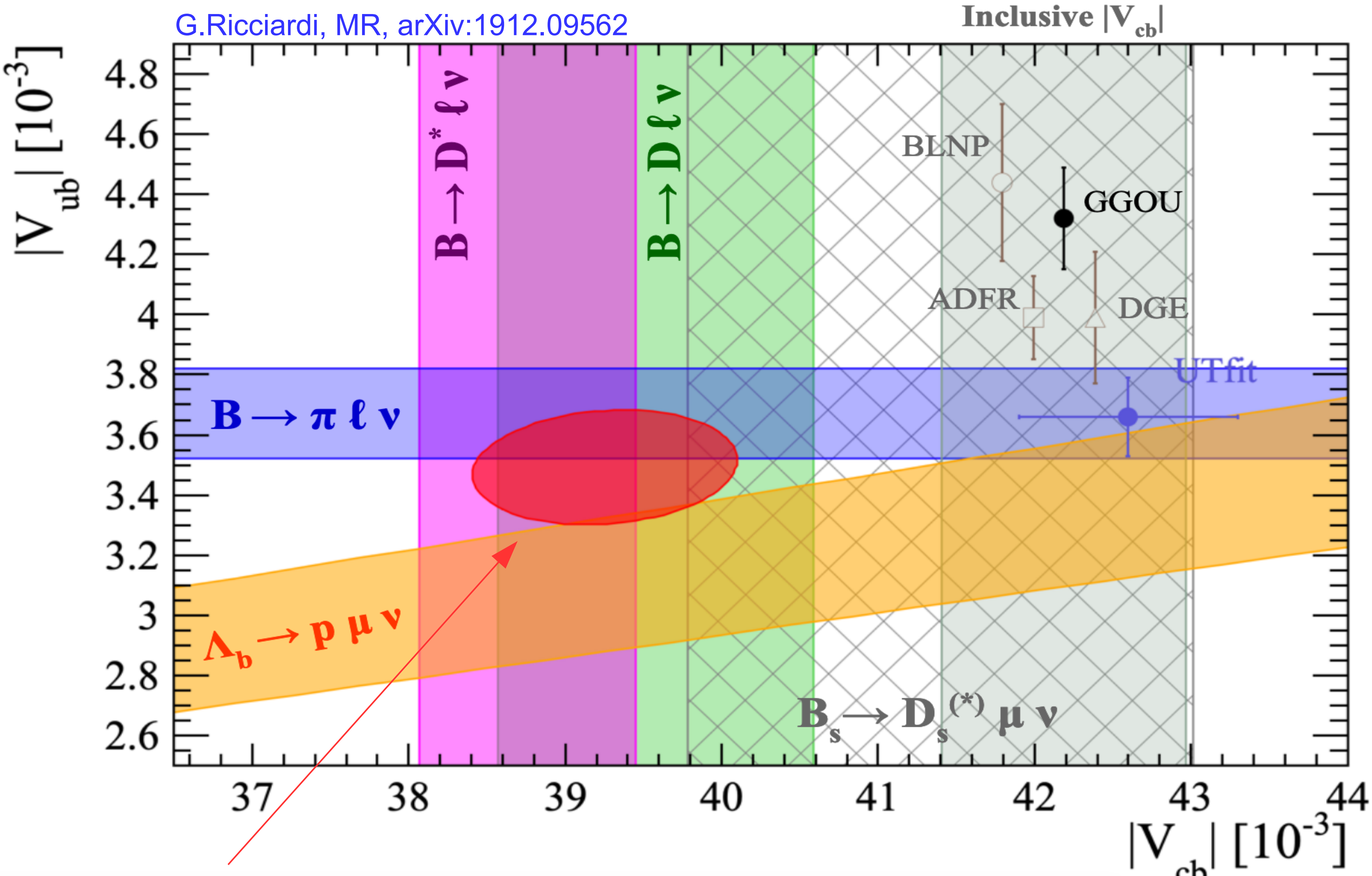
Compared with HFLAV 2016
BLNP is unchanged
DGE, GGOU decrease
ADFR is almost unchanged (not included in the BaBar analysis)

Framework	$\lvert V_{ub}\rvert[10^{-3}]$
BLNP	$4.44^{+0.13+0.21}_{-0.14-0.22}$
DGE	$3.99 \pm 0.10^{+0.09}_{-0.10}$
GGOU	$4.32 \pm 0.12^{+0.12}_{-0.13}$
ADFR	$3.99 \pm 0.13^{+0.18}_{-0.12}$
BLL (m_X/q^2 only)	$4.62 \pm 0.20 \pm 0.29$

- BLNP and GGOU are based on QCD with a mild dependence on the way the shape functions are modeled
- DGE and ADFR are model dependent: they compute the shape function with assumptions on the QCD couplings
  - → Uncertainties are probably underestimated



Summary of the $|V_{ub}|$-$|V_{cb}|$ measurements



HFLAV average of the exclusive $|V_{ub}|$ and $|V_{cb}|$

Indirect determination of $|V_{cb}|$
D.King et al. JHEP05(2019)034

$$|V_{cb}| = (41.6 \pm 0.7) \cdot 10^{-3}$$

Conclusions

- Semileptonic decays require close interplay between theorists and experimentalists
  - Eagerly waiting for calculations at non-zero recoil for $B \to D^*$ and $B \to D_s^*$
- Inclusive-Exclusive puzzle has to be understood
  - Many published results are based on 10-year old analyses and cannot be easily re-analyzed
    - Crucial to provide results in a format that can be re-analyzed
  - Inclusive measurements will be dominated by Belle II in the near future
  - Λ_b and B_s decays into the game (B_c in the future): many opportunities

Backup

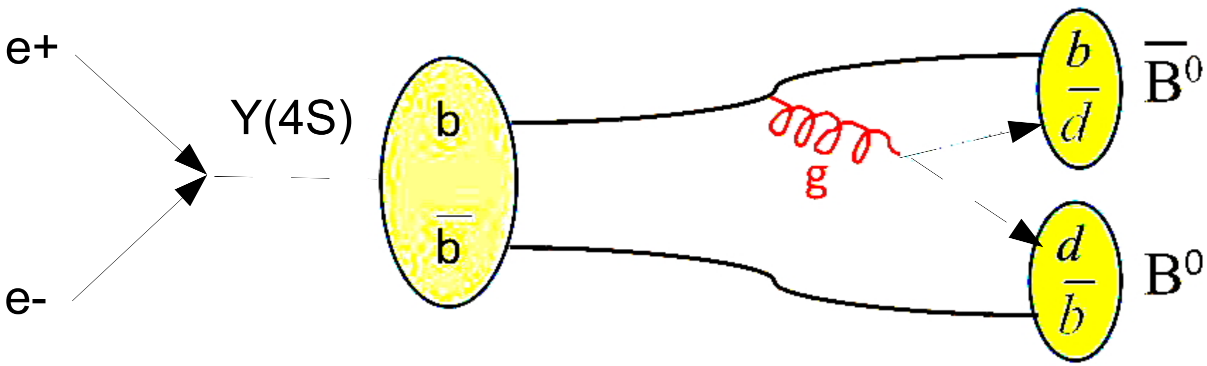
B-hadron production

$$\mathcal{N} \propto \mathcal{L} \cdot \sigma$$

- B-Factories: e^+e^- running at $\sqrt{s} \sim 10.58$ GeV

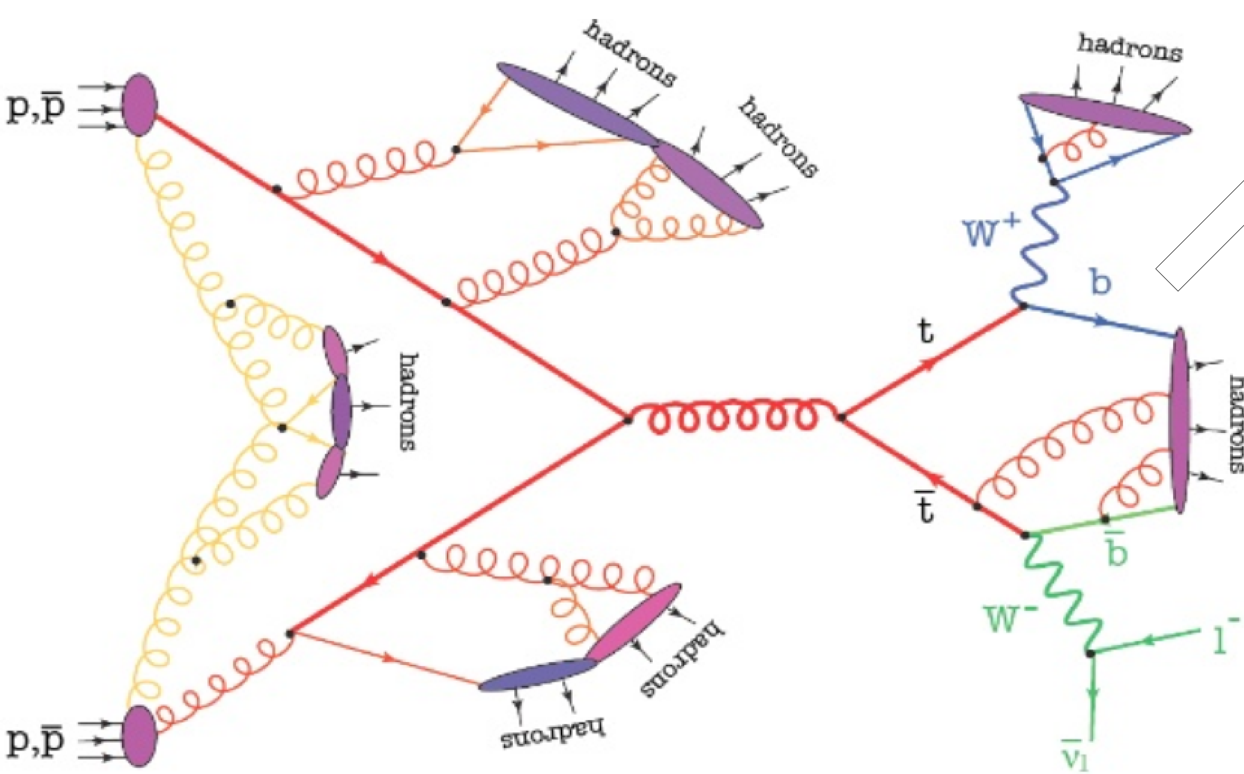
$$\sigma(e^+e^- \to \Upsilon(4S)) = 1.06 \text{ nb}$$

$$BF(\Upsilon(4S) \to B\overline{B}) \approx 100\%$$



BaBar: 430 fb^{-1}
Belle: 711 fb^{-1}
Belle-II expected 50 ab^{-1}

- Hadron machines: high energy pp (or $p\bar{p}$) collision



b-hadrons

$$\sigma(pp \to b\bar{b})_{7\ TeV} \approx 295 \cdot 10^3 \text{nb}$$

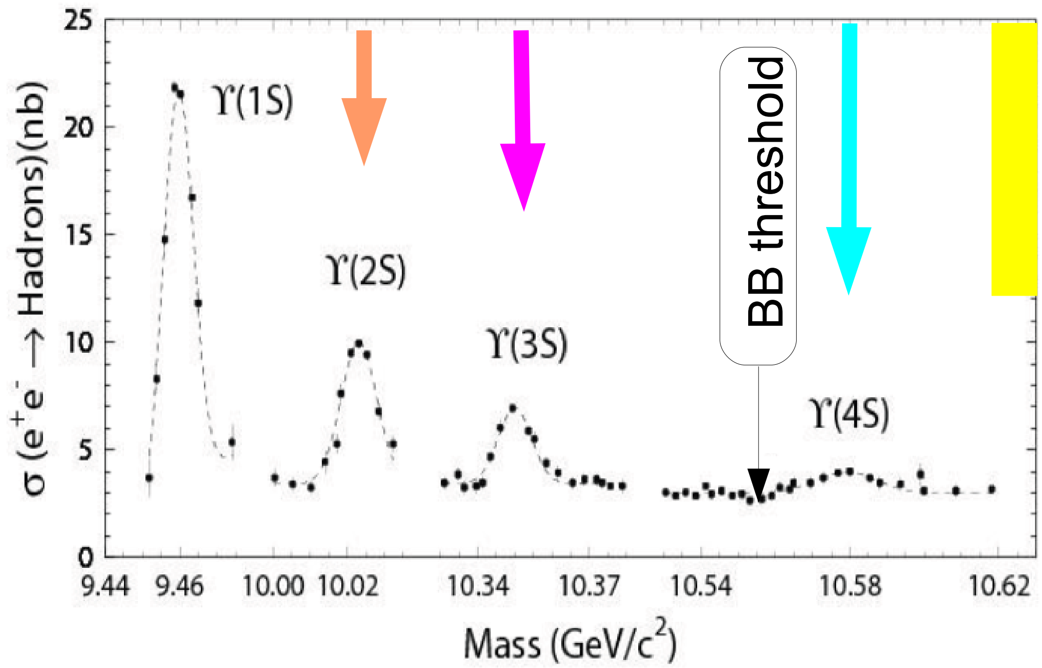
$$\sigma(pp \to b\bar{b})_{13\ TeV} \approx 600 \cdot 10^3 \text{nb}$$

The b-quarks can hadronize in any kind of b-hadron
B_d, B_u, Λ_b, B_s, Ξ_b, Σ_b, Ω_b, B_c ...

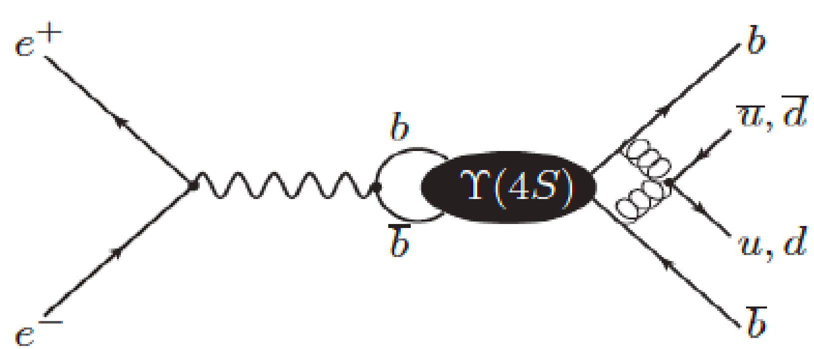
LHCb: 3 fb^{-1} + 6 fb^{-1}

B-Factories BaBar and Belle

- CM energy of the Y(4S) = 10.58 GeV most of the time
  - Large production of B meson from Y decays
  - $\sigma_{10.58GeV}(e^+e^- \rightarrow bb)$ = 1.06nb
  - Run at Y(5S) allows to access the B_s mesons



$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\overline{B}$$



B-Factories: hermetic detectors, low background, Excellent PID, access (mainly) at $B^{0/+}$

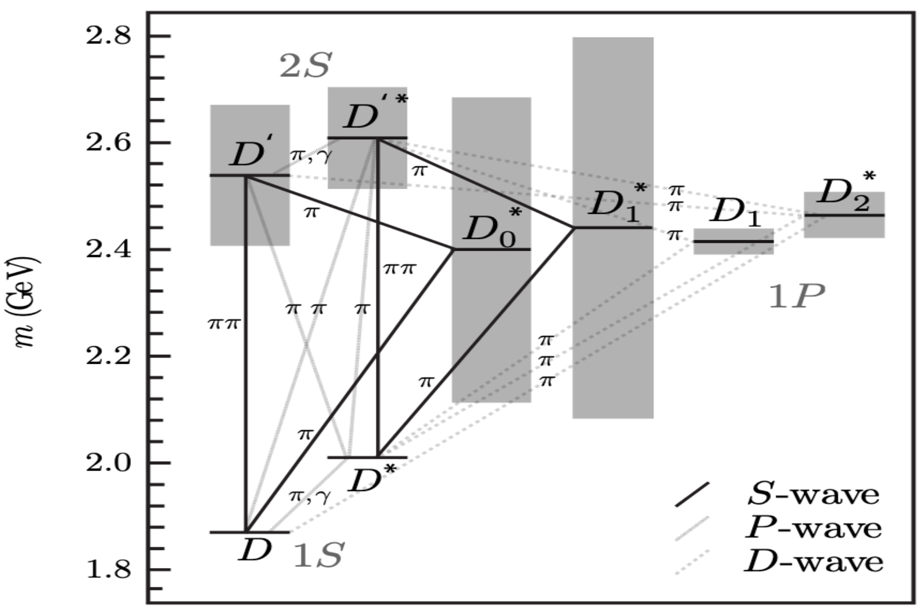
About (771 + 467)x10^6 $e^+e^- \rightarrow$ BB events in the Belle+BaBar data

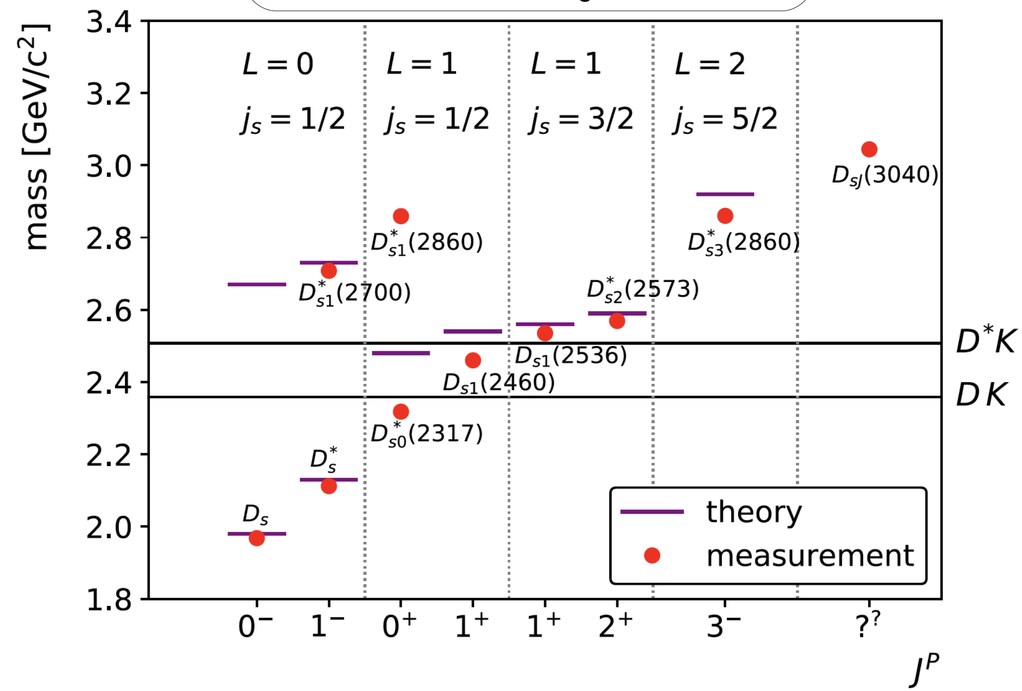
B_s semileptonic decays

Golden modes for Lattice-QCD

- Advantages:
  - Lattice calculations easier due to heavier spectator quark, so predictions are more precise
  - For the $B_s \to D_s^*$: the *zero-width* approximation of the D_s^* is more valid than the B case (no $D\pi$ pollution)
  - Experimental point: different background composition from excited D_s states than in the $B \to D^*$ case

$D_s(2317) \to D_s \pi^0$ >90%
$D_{s1}(2460) \to D_s^* \pi^0$ ~50%
$D_s X$ ~50%

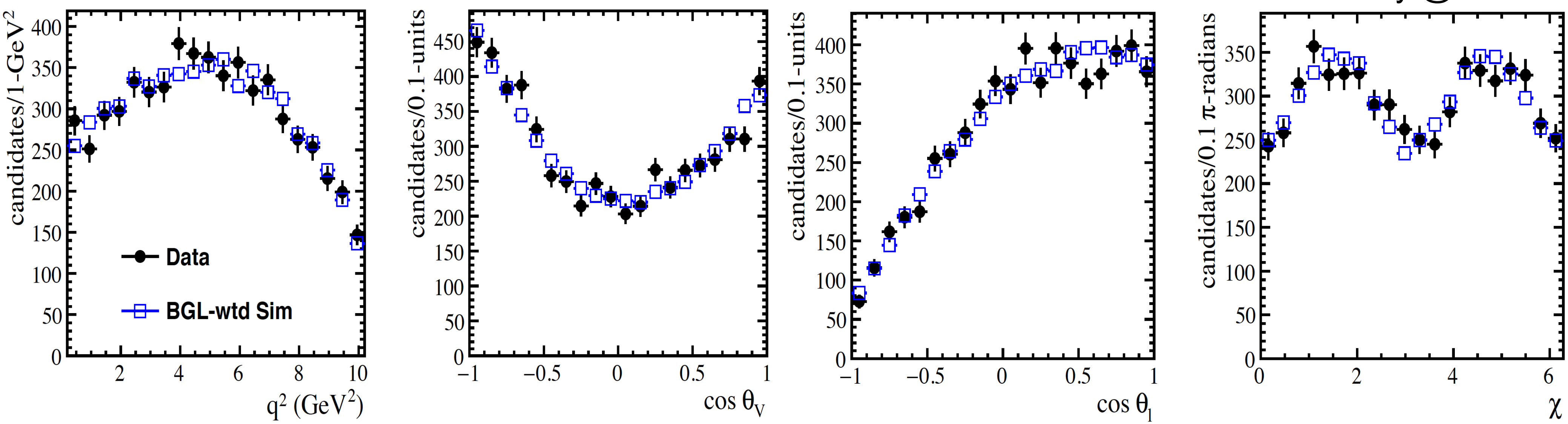




Data/MC comparison

Phys.Rev.Lett. 123 (2019) no.9, 091801

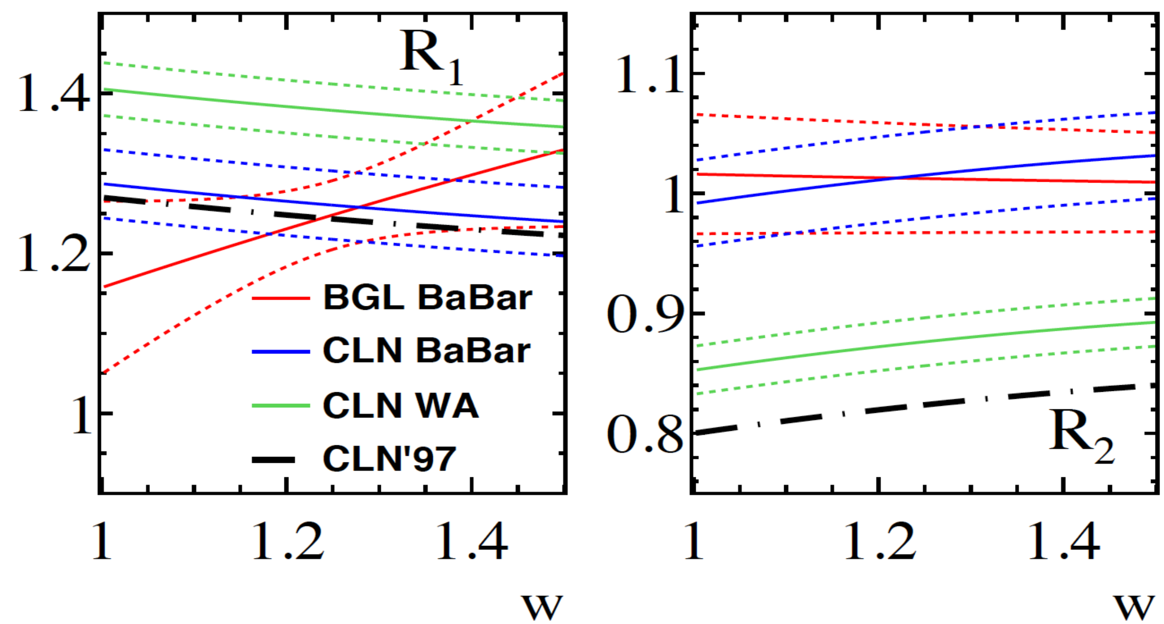
B.Day @ EPS19



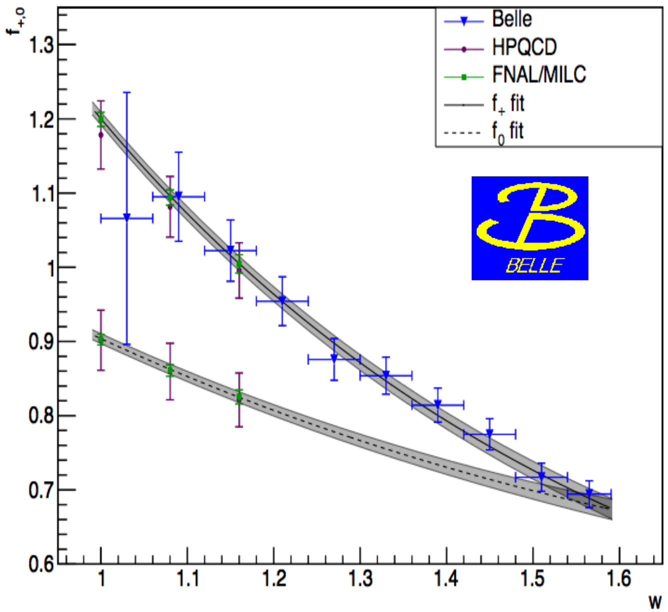
- BGL FF's differ from CLN-WA both in scale and in shape
- In terms of ratios R_1 and R_2
  - R_1 has positive slope, R_2 is flat

$$R_1 = (w+1) m_B m_{D^*} \frac{g}{f}$$

$$R_2 = \frac{w-r}{w-1} - \frac{F_1}{m_B (w-1) f}$$



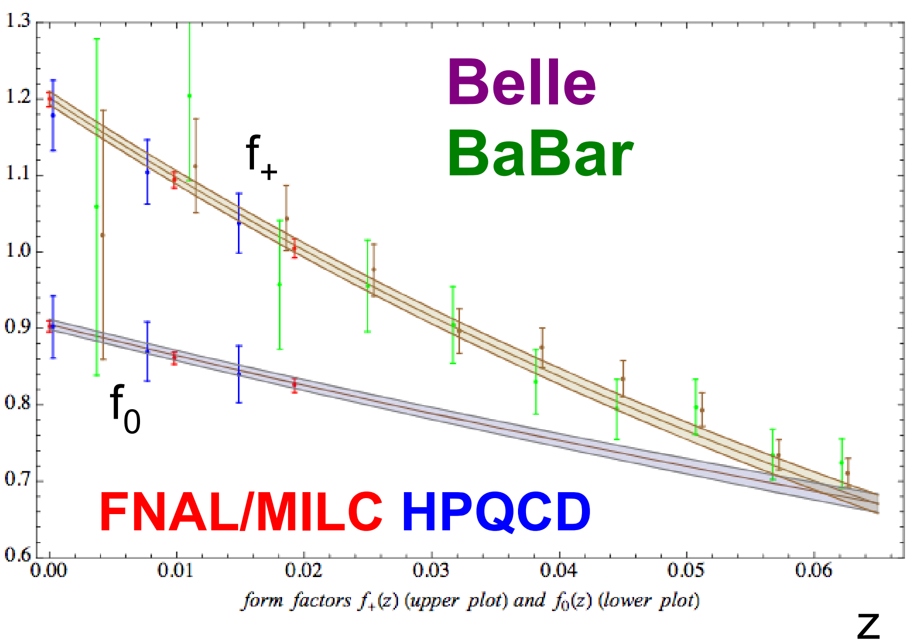
G(1)|V_{cb}|: effect of the parameterization



- Combined fit with Lattice data beyond zero-recoil using BGL parameterization

Series truncated at n=3

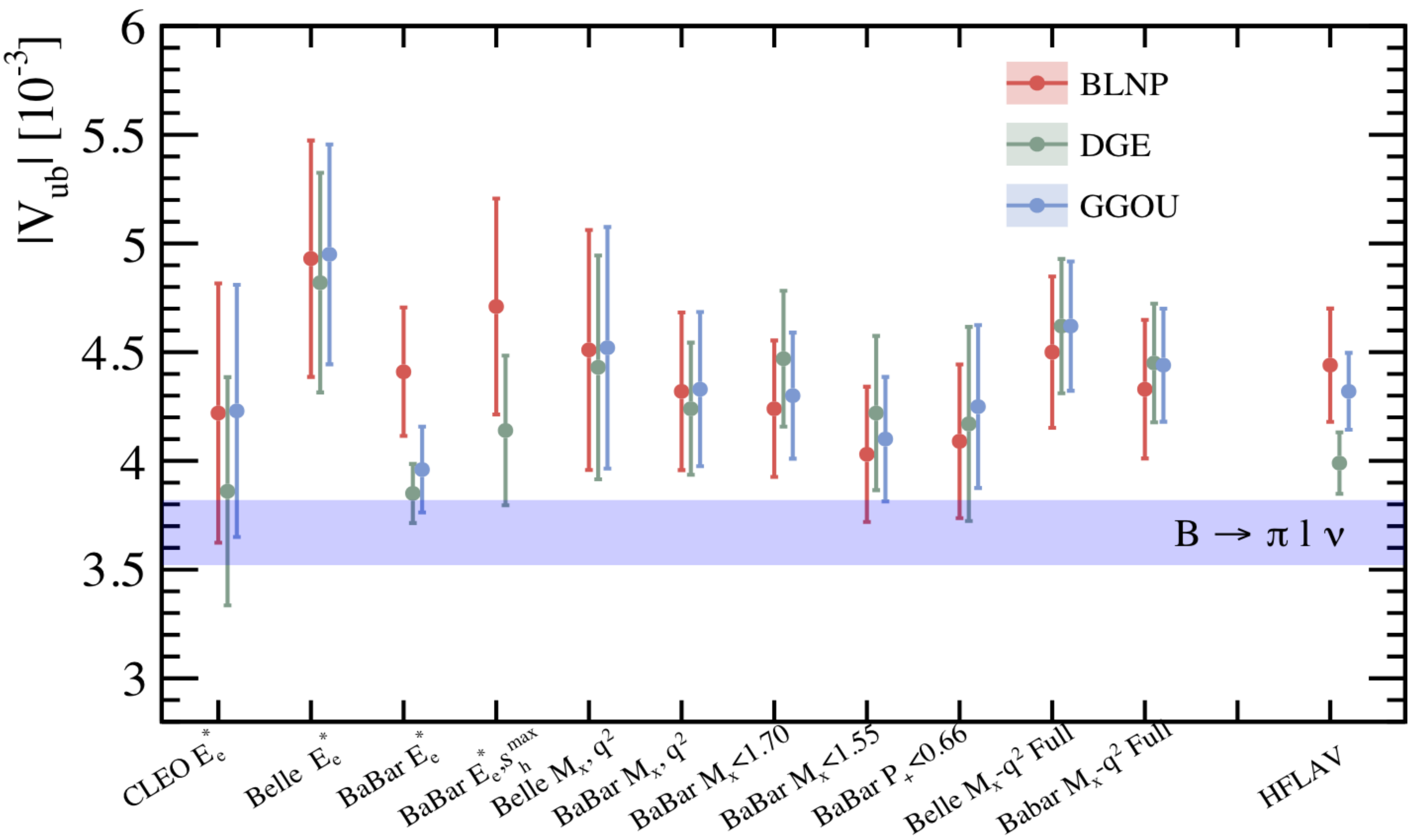
Lattice data	$\eta_{EW}\|V_{cb}\|[10^{-3}]$	χ^2/n_{df}	Prob.
FNAL/MILC [15]	40.96 ± 1.23	6.01/10	0.81
HPQCD [32]	41.14 ± 1.88	4.83/10	0.90
FNAL/MILC & HPQCD [15, 32]	41.10 ± 1.14	11.35/16	0.79



Critical discussion on the FF parameterizations, using both Belle and BaBar data reported in Bigi, Gambino Phys.Rev.D 94,094008(2016)

exp data	lattice data	N,par	$10^3 \times \|V_{cb}\|$	χ^2
all	all	2,BGL	40.62(98)	22.1/26
all	all	3,BGL	40.47(97)	18.2/24
all	all	4,BGL	**40.49(97)**	19.0/22
Belle	all	3,BGL	40.92(1.12)	11.6/14
BaBar	all	3,BGL	40.11(1.55)	12.6/14

BGL and CLN give consistent results. Because of the present accurate Lattice calculation, CLN is no longer a satisfactory parametrization



$|V_{ub}|$ [10^{-3}]
6
5.5
5
4.5
4
3.5
3
BLNP
DGE
GGOU
$B \to \pi l \nu$
CLEO E_e^*
Belle E_e^*
BaBar E_e^*
BaBar E_e^*, s_h^{max}
Belle M_x, q^2
BaBar M_x, q^2
BaBar M_x<1.70
BaBar M_x<1.55
BaBar P_+<0.66
Belle M_x-q^2 Full
Babar M_x-q^2 Full
HFLAV