Recent Results of the Magnitudes of the CKM Matrix Elements $|V_{cb}|$ and $|V_{ub}|$ from Belle

PIC-2019

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(On behalf of Belle Collaboration)

The Cabibbo-Kobayashi-Maskawa (CKM) Matrix

- Mixing of quarks of different generations
- Important test of CKM sector
- So far huge success for SM
- Precise determination of V_{ub} / V_{cb} provides a benchmark for testing NP in other processes

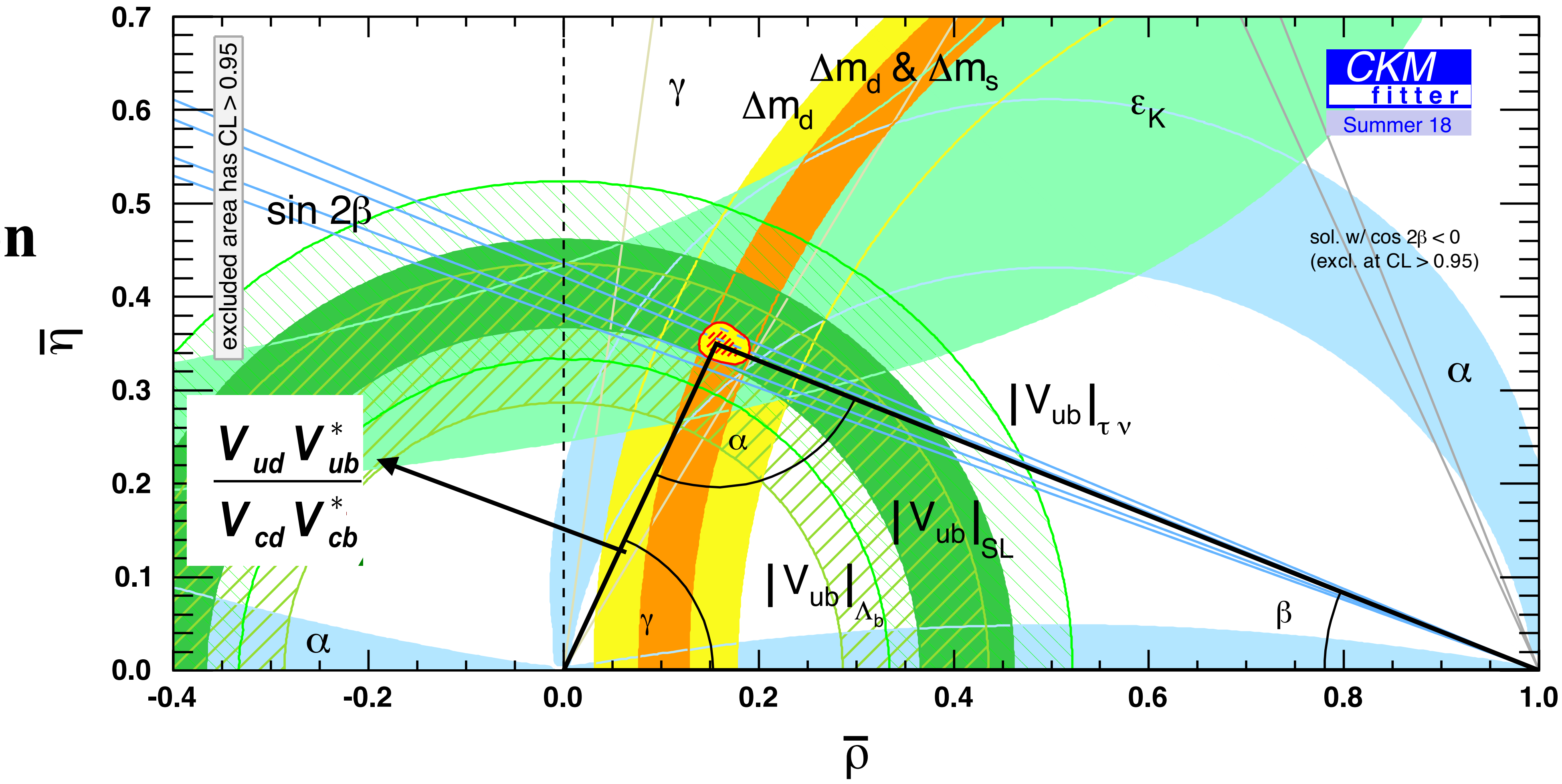
$$V_{\mathrm{CKM}}=\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

What we measure

$|V_{qb}|$ current precision

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

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



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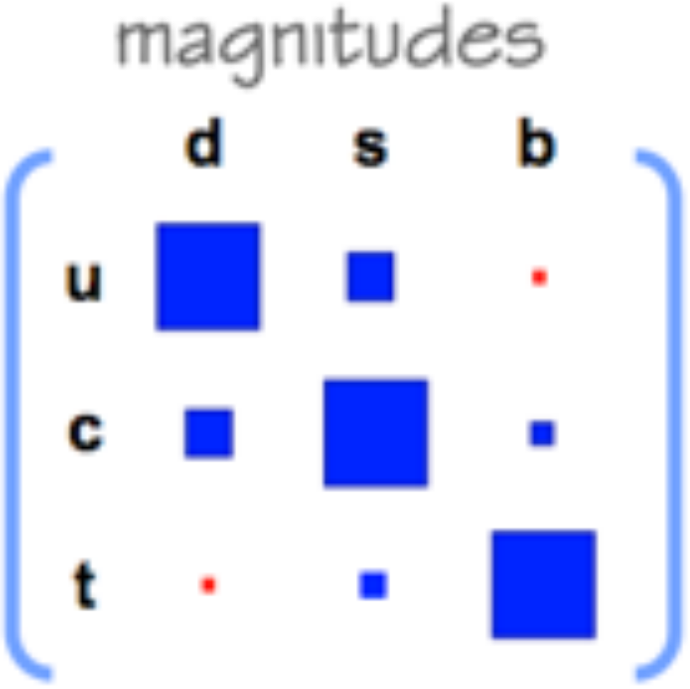
$V_{CKM} =$



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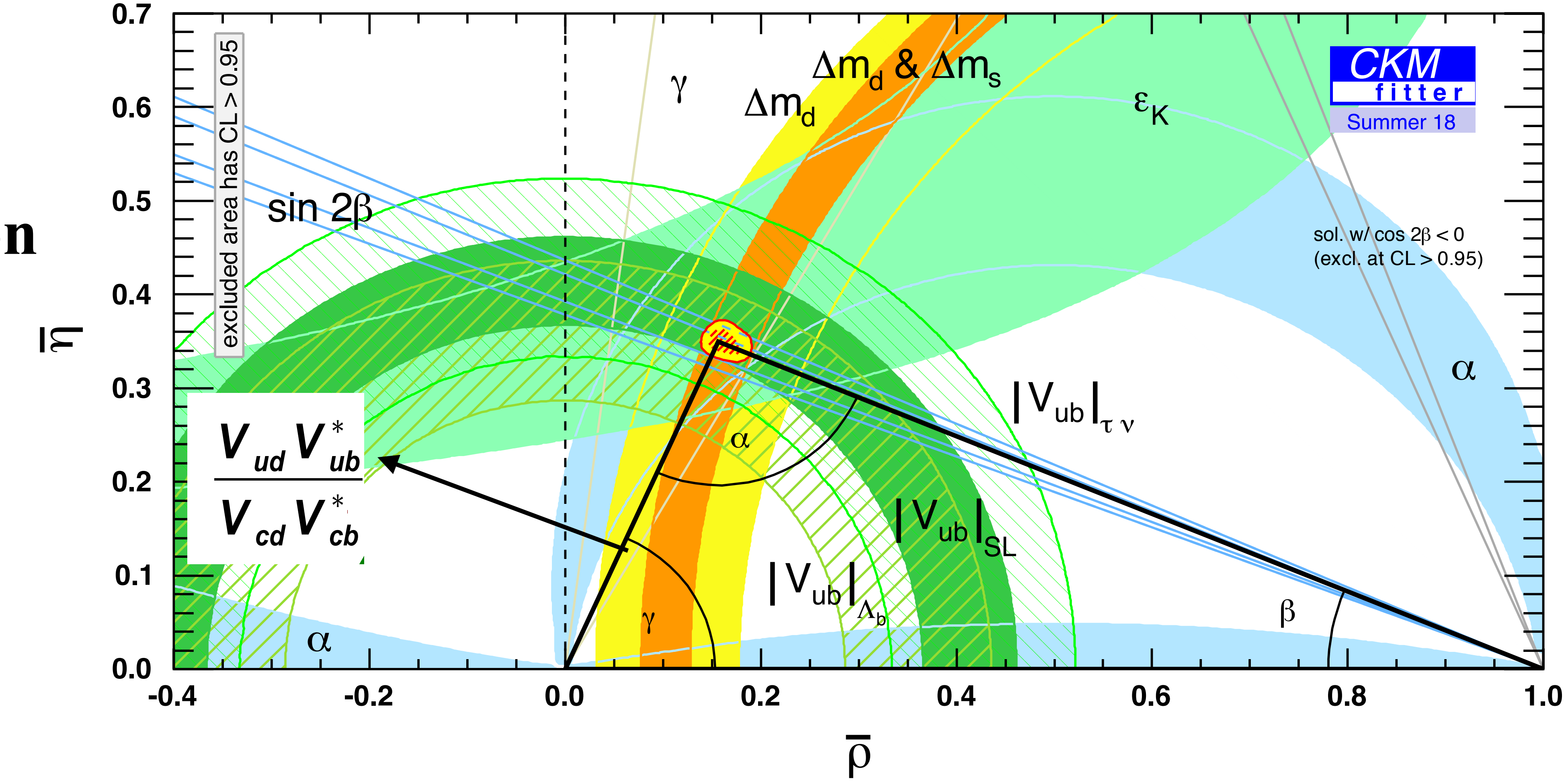
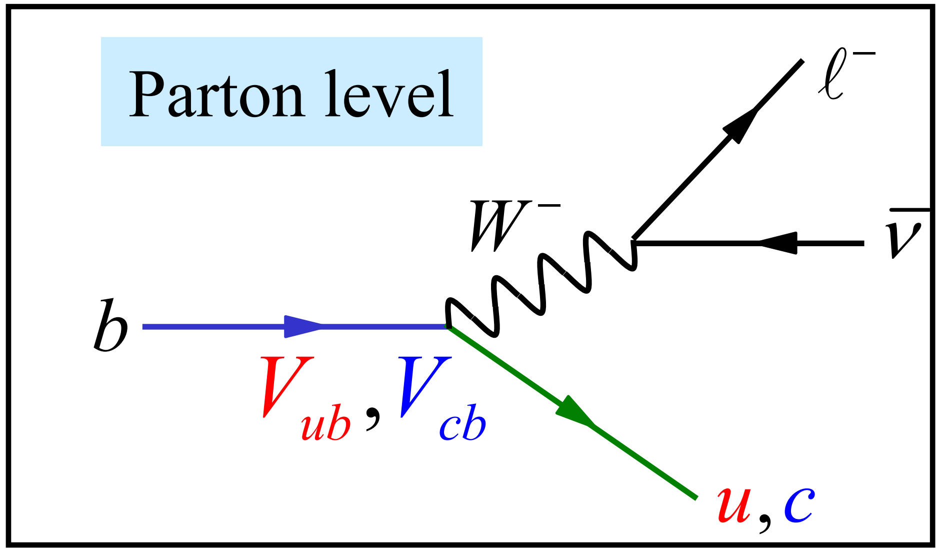
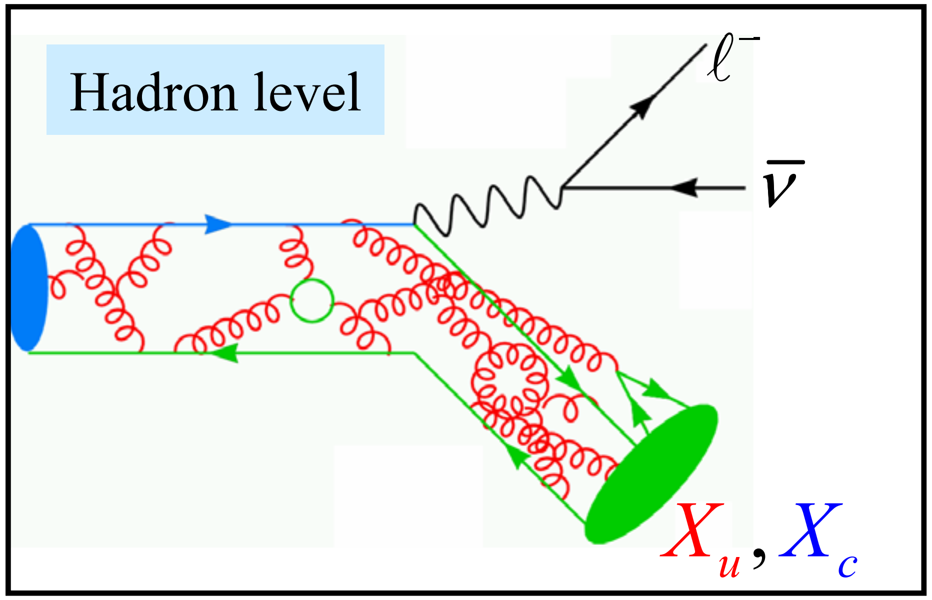


Semileptonic B decays



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

perturbative regime (α_s^n)



But quarks are bound by soft gluons: non-perturbative

long distance interactions of b quark with light quark

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

The decay channels used to study $|V_{ub}|$, $|V_{cb}|$ and their relative phase are all dominated by tree diagrams

Semileptonic methods to measure $|V_{xb}|$

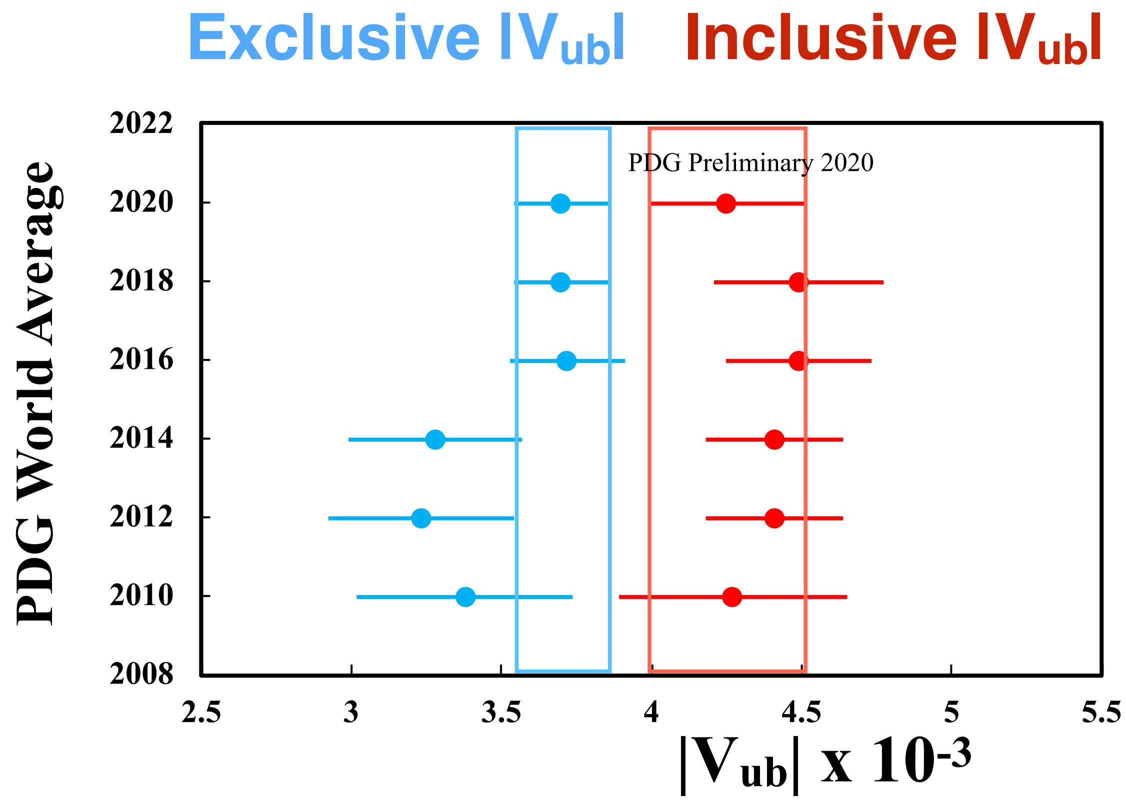
Inclusive Approach ($B \rightarrow X_c l\nu$)

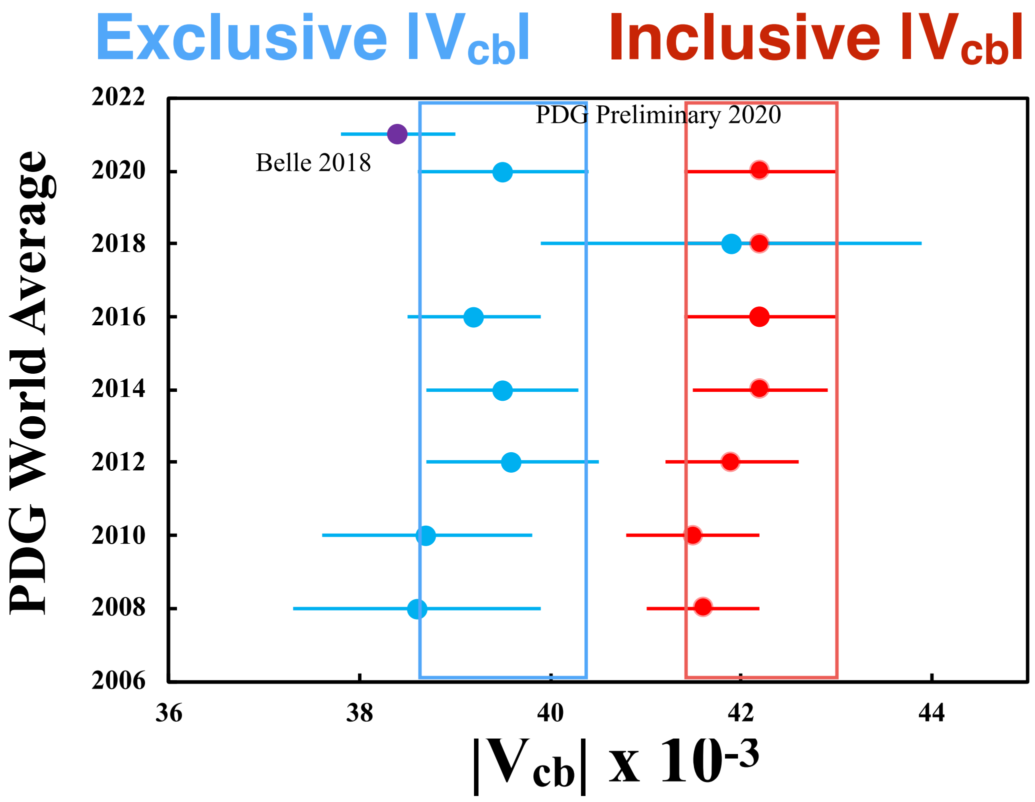
- B Meson acts like a b quark which means that the decay can be described as b→c, u quark transition.
- Calculated with Heavy Quark Expansion. (Phys.Rev.Lett. 114 (2015), 061802)

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)

- Measurements come from $\Upsilon(4S) \rightarrow B\bar{B}$
- Determine non-B contributions using data below $B\bar{B}$ threshold.


Exclusive $|V_{ub}|$ **Inclusive $|V_{ub}|$**


Exclusive $|V_{cb}|$ **Inclusive $|V_{cb}|$**

Recent Measurements of $|V_{cb}|$ and $|V_{ub}|$ at Belle

1. Measurement of the CKM matrix element $|V_{cb}|$ from $B^0 \to D^{*-} \ell^+ \nu_\ell$ at Belle

Phys. Rev. D 100, 052007

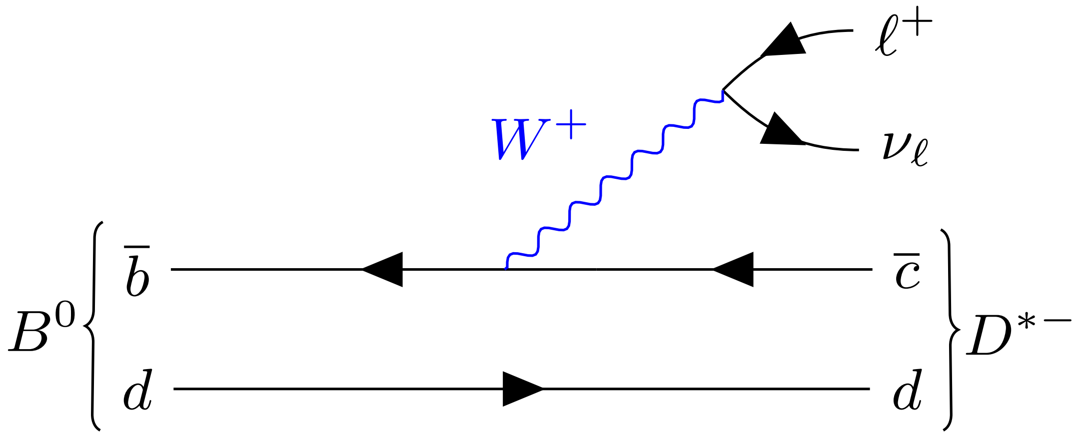
2. Measurement of the $|V_{ub}|$ from $B \to \mu \bar{\nu}$

Presented at EPS 2019

$|V_{cb}|$

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

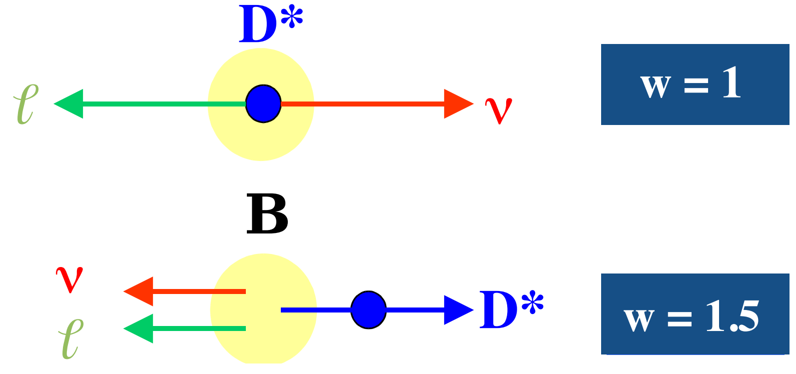
Differential decay rate



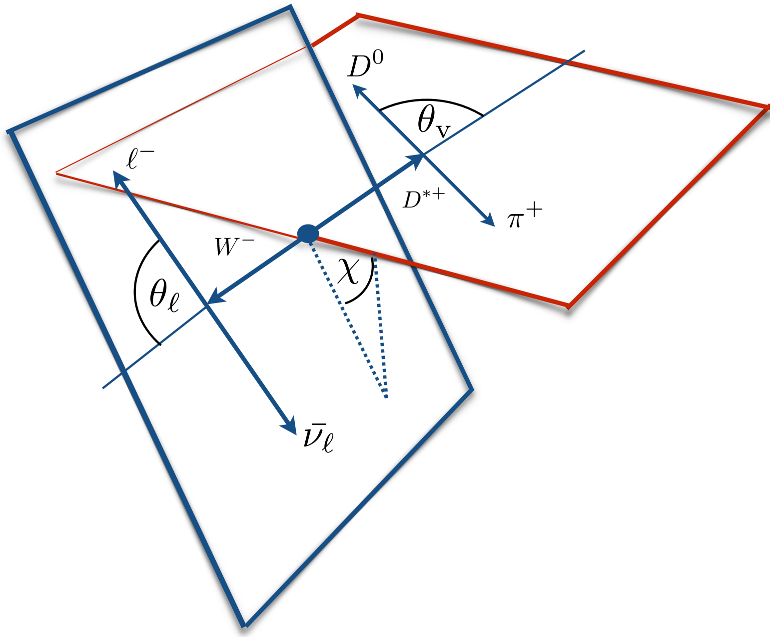
$$\frac{d\Gamma(B^0 \to D^*\ell^+\nu_\ell)}{dw\, d\cos\theta_\ell \cos\theta_V d_\chi} = \frac{G_F^2|V_{cb}|^2}{48\pi^3} F(w,\theta_\ell,\theta_V,\chi) G(w)$$

Form factor of B⁰⟶ D* transition phase space (known)

Heavy quark limit



- $w \equiv v_B . v_{D^*} = \frac{m_B^2 + m_{D^*}^2 - q^2}{2m_B m_{D^*}}$: $1 < w < 1.504$
- $\cos\theta_\ell$: angle between lepton and B meson
  - **Requirement**: good LeptonID to minimise fakes
- $\cos\theta_\mathrm{v}$: angle between D⁰ and B meson
  - **Requirement**: slow pion momentum - important for measurement at low recoil
- χ : Angle between two decay planes formed by D* and W



Form factor parameterisation

Caprini, Lelouch, Neubert (CLN)

arXiv:hep-ph/9712417

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 $V(w)$

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

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

Boyd Grinstein Lebed (BGL)

arXiv:hep-ph/9504235

$F(w, \theta_\ell, \theta_V, \chi)$ 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→ D*lν

$$\boxed{z(w) = \frac{(\sqrt{w+1}-\sqrt{2})}{(\sqrt{w+1}+\sqrt{2})}}$$

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

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

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

- BGL

Phys.Lett. B771 (2017)
Phys.Lett. B769 (2017)

  - No HQET input

$$\boxed{z(w) = \frac{(\sqrt{w+1}-\sqrt{2})}{(\sqrt{w+1}+\sqrt{2})}}$$

- For B→ D*lν

$$h_{A_1}(w) = \frac{f(w)}{\sqrt{m_B m_{D^*}}(1+w)}$$

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

$$R_2(w) = \frac{w-r}{w-1} - \frac{\mathcal{F}_1(w)}{m_B(w-1)f(w)}$$

where f, g and F_1 are parameterized as ….

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

  - cut off at n=1,2 …(for X^2/ndf is satisfying)

Belle un-tagged Measurement 2018

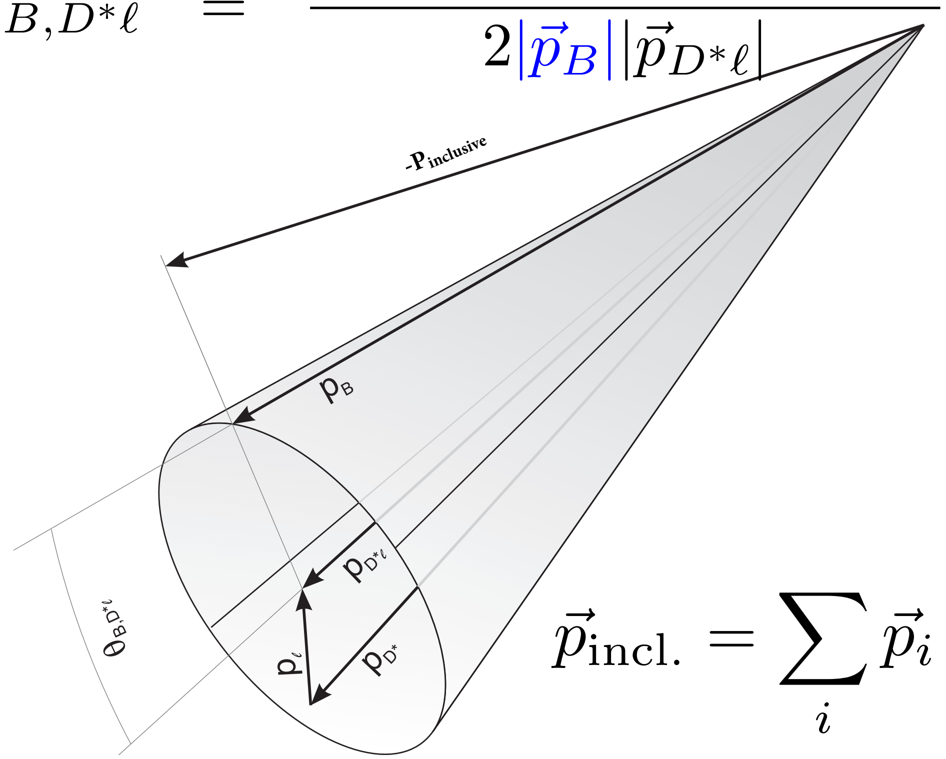
Phys. Rev. D 100, 052007

- Measure $|V_{cb}|$ using Belle 711fb^{-1}.
  - $D^{*-} \to D^0\pi_s, D^0 \to K\pi$ (vertex fit)
- **Signal Selection**
  - $|\cos\theta_{B,D^*\ell}|<1$
  - $|m_{D^0} - m_{D^0_{\mathrm{PDG}}}|<14\ \mathrm{MeV/c^2}$
  - $144\ \mathrm{MeV/c^2}<|\mathrm{m_{D^*}} - \mathrm{m_{D^0}}|<147/\mathrm{c^2}\ \mathrm{MeV/c^2}$
  - $p_e>0.80\mathrm{GeV/c}$
    $p_\mu>0.85\mathrm{GeV/c}$
- e & μ modes are reconstructed separately

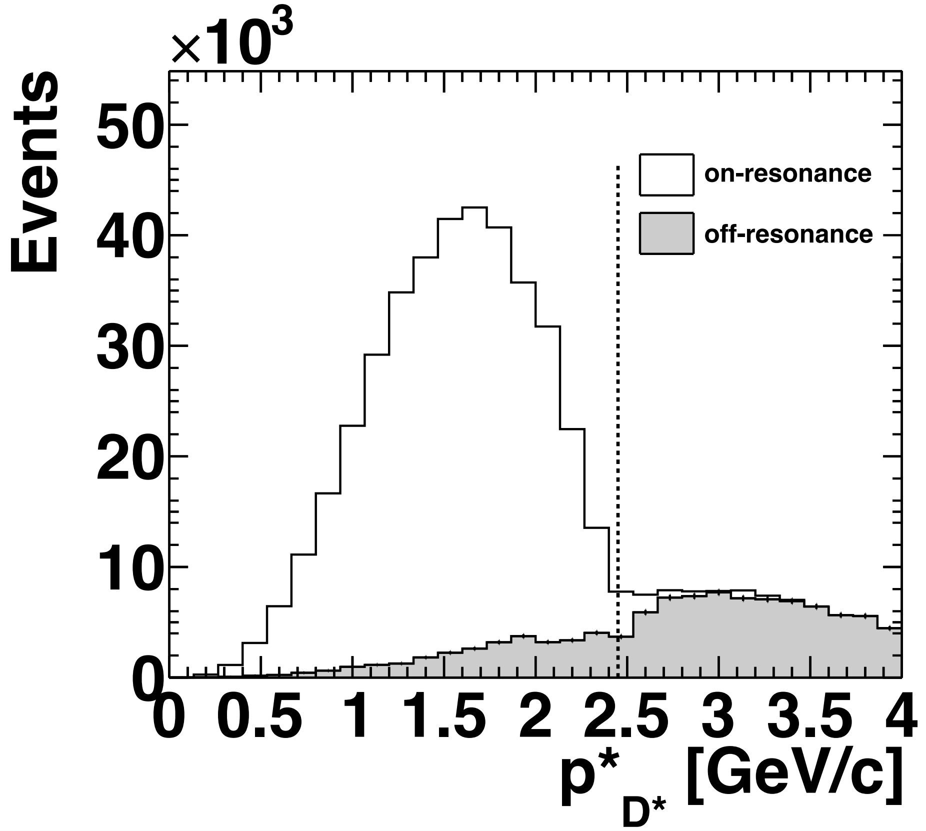
  N(B→D* e ν) = 91381

  N(B→D* μ ν) = 89965
- Split data into 2 SVD configurations (3 layer, 4 layer) as tracking/slow π tracking are dominant systematics
- Suppress continuum with p$^*_{\mathrm{D}^*}$>2.45 GeV/c

$$\cos\theta_{B,D^*\ell} = \frac{2E_B E_{D^*\ell} - m_B^2 - m_{D^*\ell}^2}{2|\vec{p}_B||\vec{p}_{D^*\ell}|}$$



$$\vec{p}_{\mathrm{incl.}} = \sum_i \vec{p}_i$$

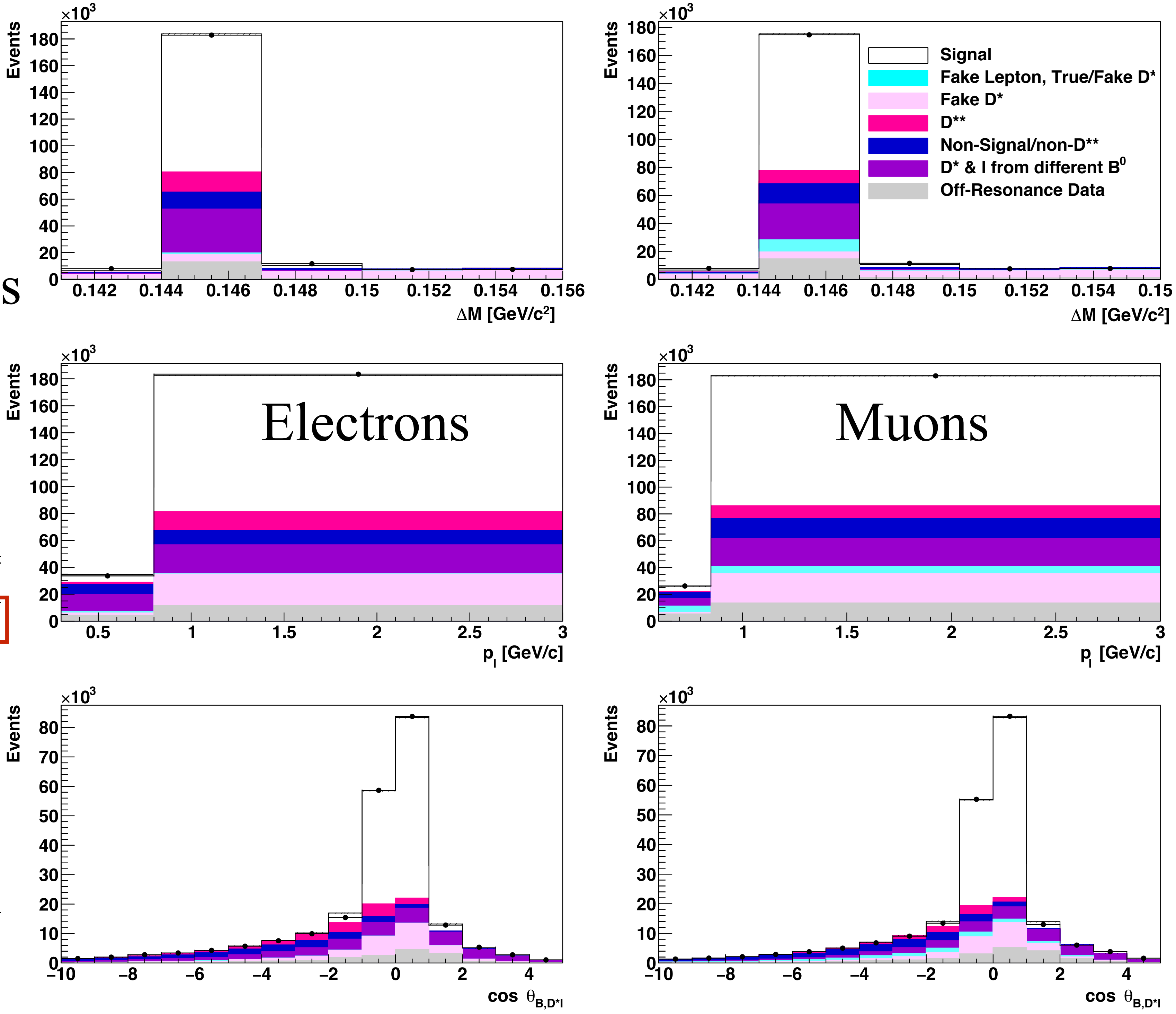


$B^0 \to D^{*-}\ell^+\nu_\ell$ using un-tagged approach

Phys. Rev. D 100, 052007

- Signal selection using 3D - Binned Maximum Likelihood fit of
  - $(\cos\theta_{B,D^*l})$
  - $\Delta M = mD^* - mD^0$)
  - lepton momentum
- Float Signal & Backgrounds components from MC to extract background yields

	SVD2 (e)	SVD2 (μ)
Signal yield	88622	87060
Signal	81.00 ± 0.19	79.86 ± 0.20
Fake ℓ	0.10 ± 0.79	1.15 ± 0.38
Fake D^*	2.94 ± 0.01	2.81 ± 0.01
D^{**}	5.08 ± 0.14	3.62 ± 0.08
Signal corr.	1.42 ± 0.07	2.39 ± 0.14
Uncorrelated	4.96 ± 0.15	5.00 ± 0.24
Continuum	4.48 ± 0.38	5.16 ± 0.46

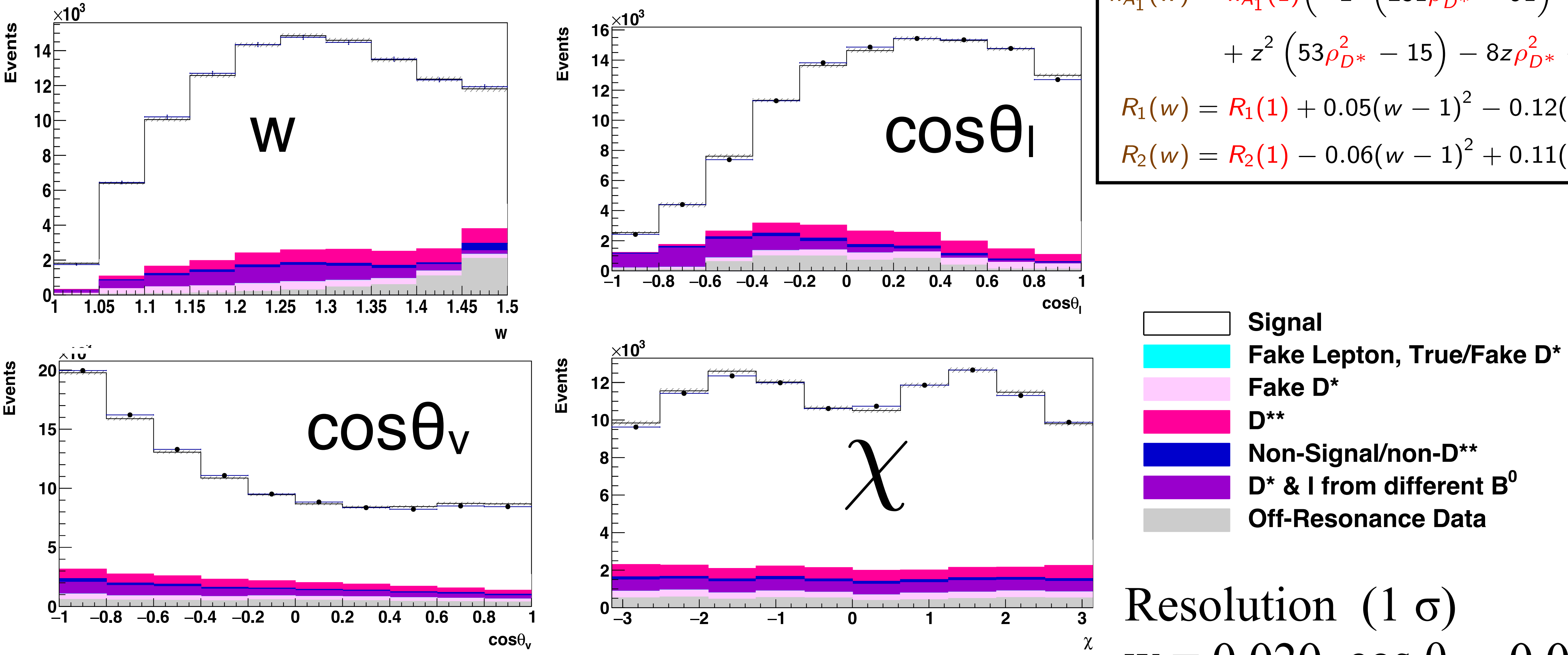


Extraction of $|V_{cb}|$ from CLN (1)

Phys. Rev. D 100, 052007

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

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



Resolution (1 σ)

$w = 0.020$ $\cos\theta_l = 0.038$

$\cos\theta_V = 0.044$ $\chi = 0.210$

$$
\begin{aligned}
\rho^2 &= 1.106 \pm 0.031 \pm 0.007 \\
R_1(1) &= 1.229 \pm 0.028 \pm 0.009 \\
R_2(1) &= 0.852 \pm 0.021 \pm 0.006
\end{aligned}
$$

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

Extraction of $|V_{cb}|$ from CLN (2)

Phys. Rev. D 100, 052007

- Good χ/ndf (stat errors only)
- No hint of different behaviour between e and μ.

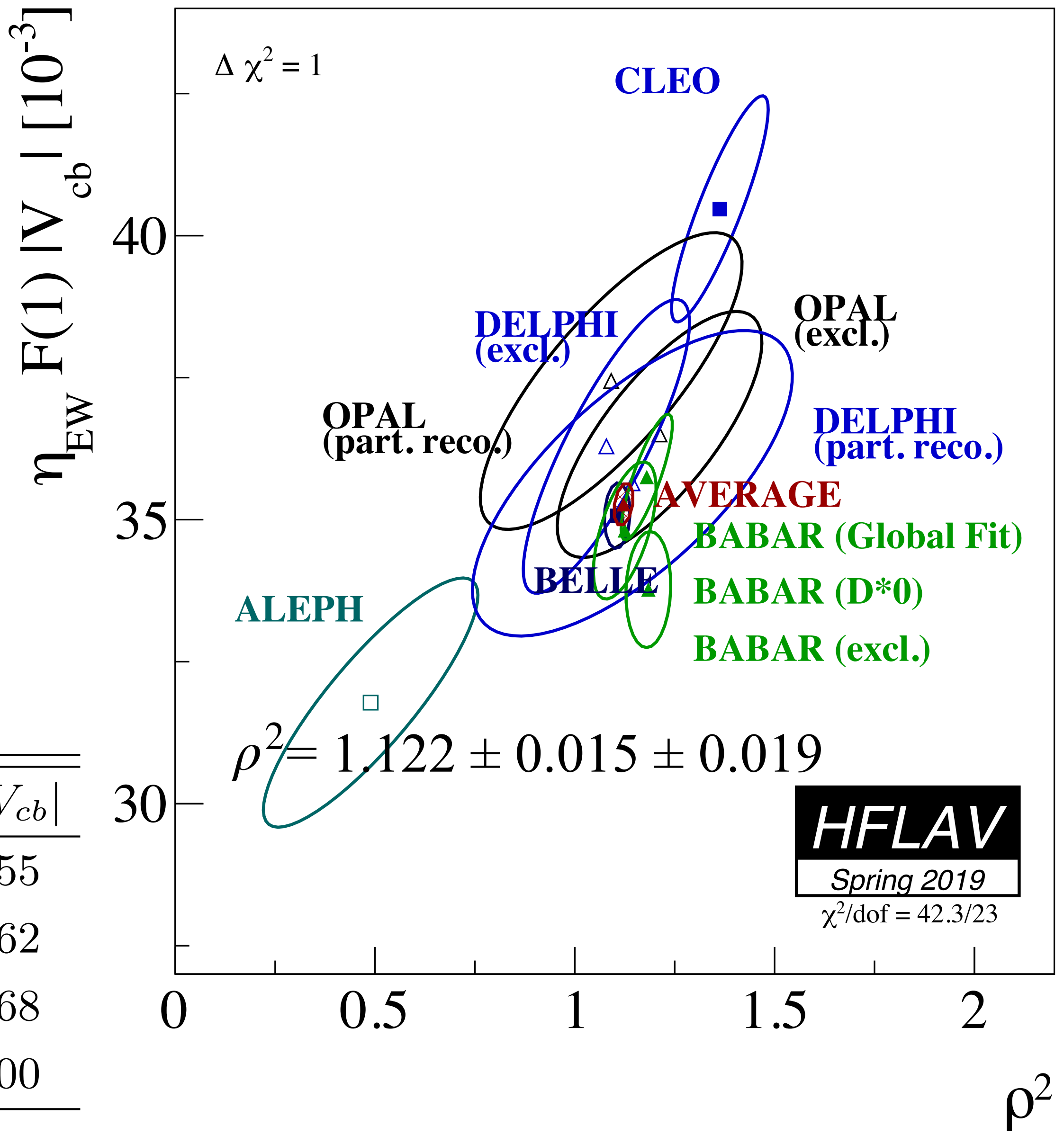
	SVD1 e	SVD1 μ	SVD2 e	SVD2 μ
ρ^2	1.165 ± 0.099	1.165 ± 0.102	1.087 ± 0.046	1.095 ± 0.051
$R_1(1)$	1.326 ± 0.106	1.336 ± 0.103	1.117 ± 0.040	1.287 ± 0.047
$R_2(1)$	0.767 ± 0.073	0.777 ± 0.074	0.861 ± 0.030	0.884 ± 0.034
$\mathcal{F}(1)\|V_{cb}\|\eta_{\rm EW} \times 10^3$	34.66 ± 0.48	35.01 ± 0.50	35.25 ± 0.23	34.98 ± 0.25
χ^2/ndf	35/36	36/36	44/36	43/36
p-value	0.52	0.47	0.17	0.20
$\mathcal{B}(B^0 \to D^{*-}\ell^+\nu_\ell)$ [%]	4.89 ± 0.06	4.96 ± 0.06	4.93 ± 0.03	4.86 ± 0.03

- HFLAV p-value 0.8% - large pulls from ALEPH and CLEO.

Fit correlations.

	ρ^2	$R_1(1)$	$R_2(1)$	$\mathcal{F}(1)\|V_{cb}\|$
ρ^2	$+1.000$	$+0.593$	-0.883	$+0.655$
$R_1(1)$		$+1.000$	-0.692	-0.062
$R_2(1)$			$+1.000$	-0.268
$\mathcal{F}(1)\|V_{cb}\|$				$+1.000$

$F(1)|V_{cb}|\eta_{EW} = 35.27 \pm 0.11 \pm 0.36$



- First measurement of spectra from "forward folding" is proposed - avoids smearing effect from unfolded spectra

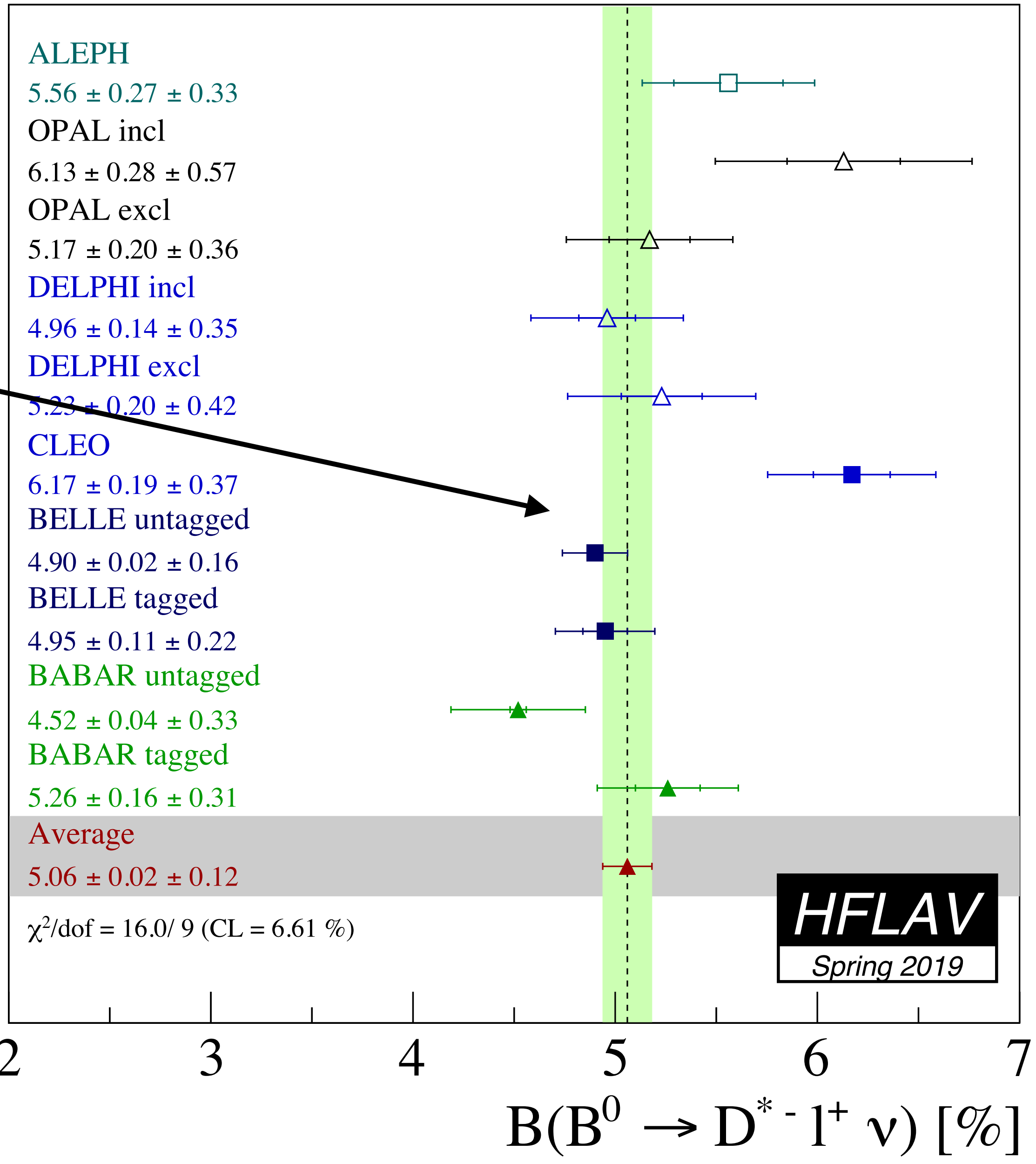
Branching Ratio and LFUV tests

Phys. Rev. D 100, 052007

- Extract BR from yield for e and μ and the total BR of the decay.

$$\mathcal{B} = \frac{N_{\text{signal}}}{N_{B^0} \times \epsilon \times \mathcal{B}(D^{*+} \to D^0\pi^+) \times \mathcal{B}(D^0 \to K^-\pi^+)}$$

$$\boxed{\mathcal{B}(B^0 \to D^{*-}\ell^+\nu_\ell) = (4.90 \pm 0.02 \pm 0.16)\%}$$



- First direct e/μ LFUV measurement - cancelling common systematics where only remaining are dominated by e and μ ID.

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

Extraction of $|V_{cb}|$ from BGL

Phys. Rev. D 100, 052007

- Our nominal result uses a_0f, a_1f, a_1F, a_2F, a_0g (1 more parameter than CLN).

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

- More studies can/have been done with more floating parameters.
- Possibility of pull when floating without more LQCD constraints.

$$|V_{cb}|\eta_{EW}\mathcal{F}(1) = \frac{1}{2\sqrt{m_B m_{D^*}}}\left(\frac{|\tilde{a}_0^f|}{P_f(0)\phi_f(0)}\right)$$

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

Consistent with CLN!!!

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

Fit correlations.

	$\tilde{a}_0^f$	$\tilde{a}_1^f$	$\tilde{a}_1^F$	$\tilde{a}_2^F$	$\tilde{a}_0^g$
$\tilde{a}_0^f$	+1.000	−0.790	−0.775	+0.669	−0.038
$\tilde{a}_1^f$		+1.000	+0.472	−0.411	−0.406
$\tilde{a}_1^F$			+1.000	−0.981	+0.071
$\tilde{a}_2^F$				+1.000	−0.057
$\tilde{a}_0^g$					+1.000

- When additional parameters are added correlations >>0.95 causing fit instability.
- This should be resolved with LQCD at non-zero recoil!

$|V_{cb}|$ Summary

$\mathcal{F}(1) = 0.906 \pm 0.013$

10.1103/PhysRevD.89.114504

Last 10 years…

$|V_{cb}|$ x 10^3 = 38.4 ± 0.6 (CLN-Belle2019) (B→D*lv)[1]

$|V_{cb}|$ x 10^3 = 38.3 ± 0.8 (BGL-Belle2019) (B→D*lv)[1]

$|V_{cb}|$ x 10^3 = 38.4 ± 0.9 (BGL-BaBar2019) (B→D*lv)[2]

$|V_{cb}|$ x 10^3 = 39.9 ± 1.3 (CLN-Belle2016) (B→Dlv)[3]

$|V_{cb}|$ x 10^3 = 40.8 ± 1.1 (BCL-Belle2016)(B→Dlv)[3]

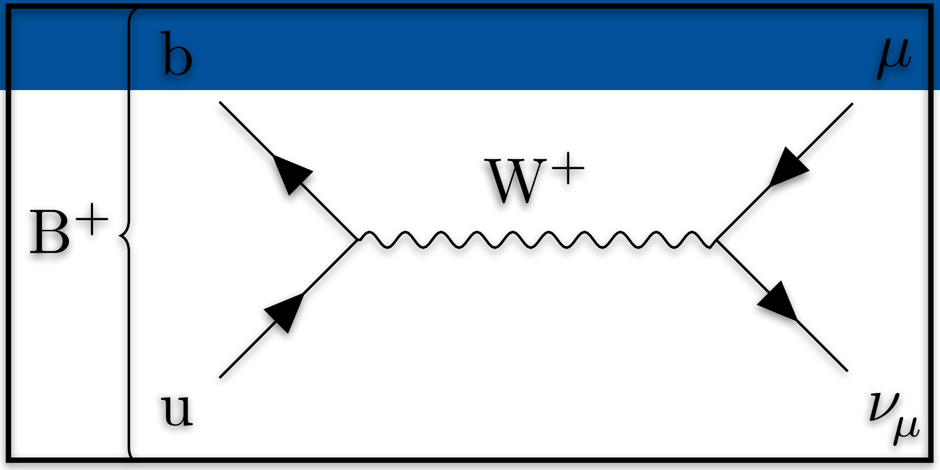
$|V_{cb}|$ x 10^3 = 42.2 ± 0.8 (Inclusive-HFLAV)[4]

- 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.

$|V_{ub}|$

$|V_{ub}|$ from $B \to \mu\bar{\nu}$

To be submitted to PRD



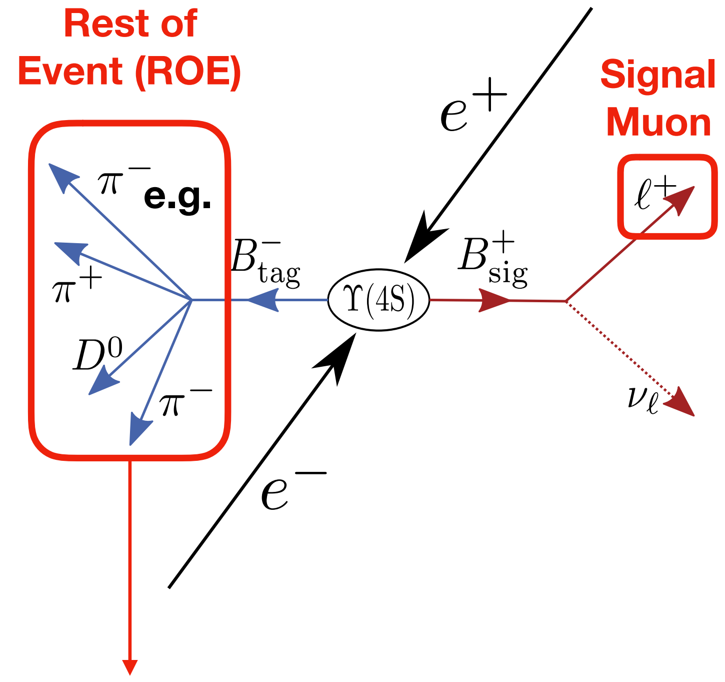
- Helicity and CKM suppressed

$$\mathcal{B}(B \to \ell\nu_\ell)_{SM} = \frac{G_F^2 m_B m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

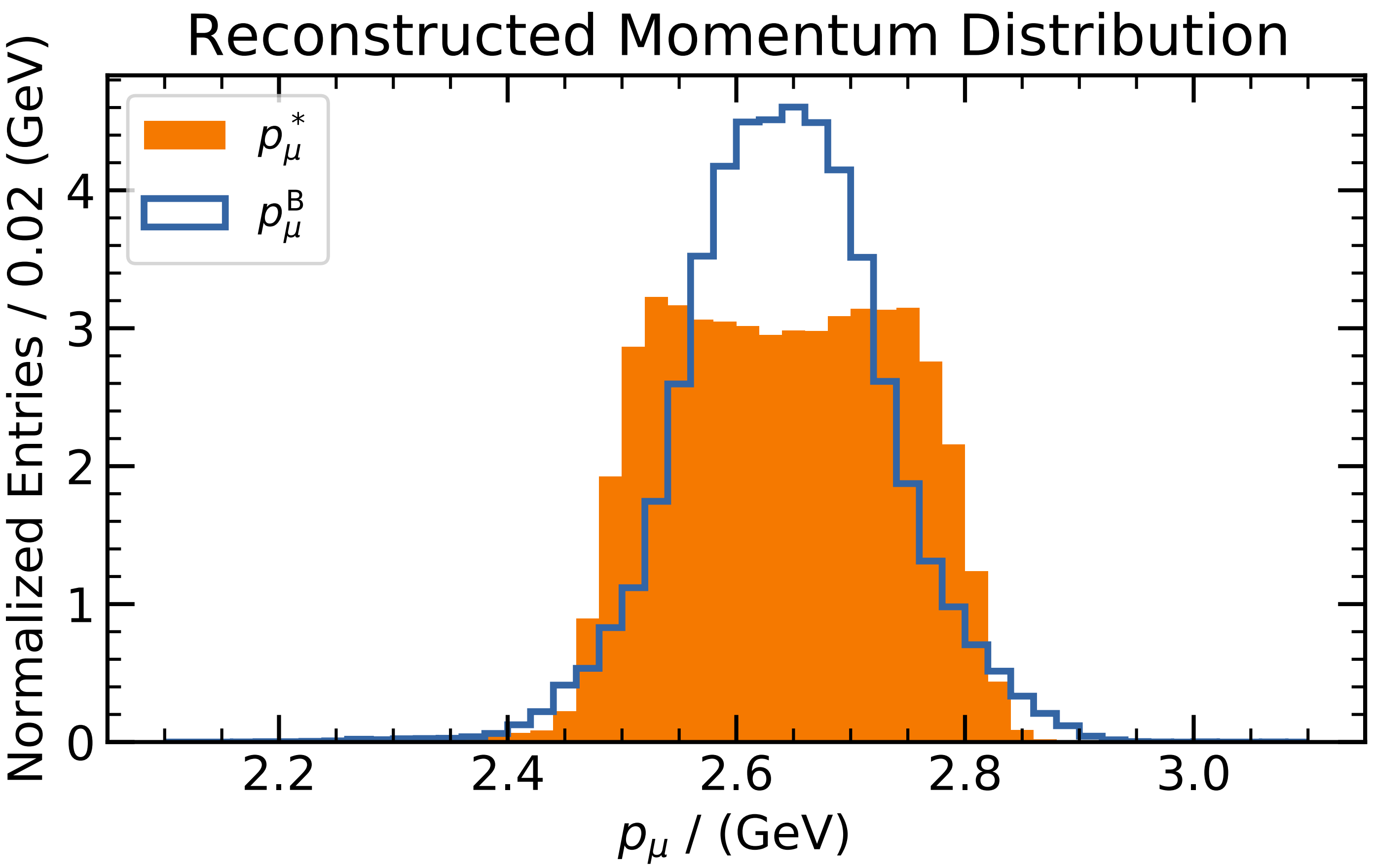
$$\mathcal{B}(B \to \mu\nu_\mu)_{SM} = (4.26 \pm 0.81) \times 10^{-7}$$

only ~300 decays in entire Belle data set ~700 x 10^6 B-Meson decays

- Measurement is done using Inclusive tagging method



$$\mathbf{p}_{tag}^{lab} = \sum_i^{tracks} \mathbf{p}_i^{lab} + \sum_j^{photons} \mathbf{E}_j^{lab},$$



$|V_{ub}|$ from $B \to \mu\bar{\nu}$ results

To be submitted to PRD

- Binned likelihood fit is performed the p^B_μ spectra with all the systematics incorporated

	$\mathcal{B}(B \to \mu\nu_\mu)$
SM	4.26×10^{-7}
Belle (2018)[a]	$(6.6 \pm 2.2 \pm 1.6) \times 10^{-7}$ @ $2.4\,\sigma$
Result (this)	$\mathbf{(5.3 \pm 2.0 \pm 0.9) \times 10^{-7}}$ **@ 2.8 σ**
Frequentist UL	$< 8.64 \times 10^{-7}$ @ 90% CL

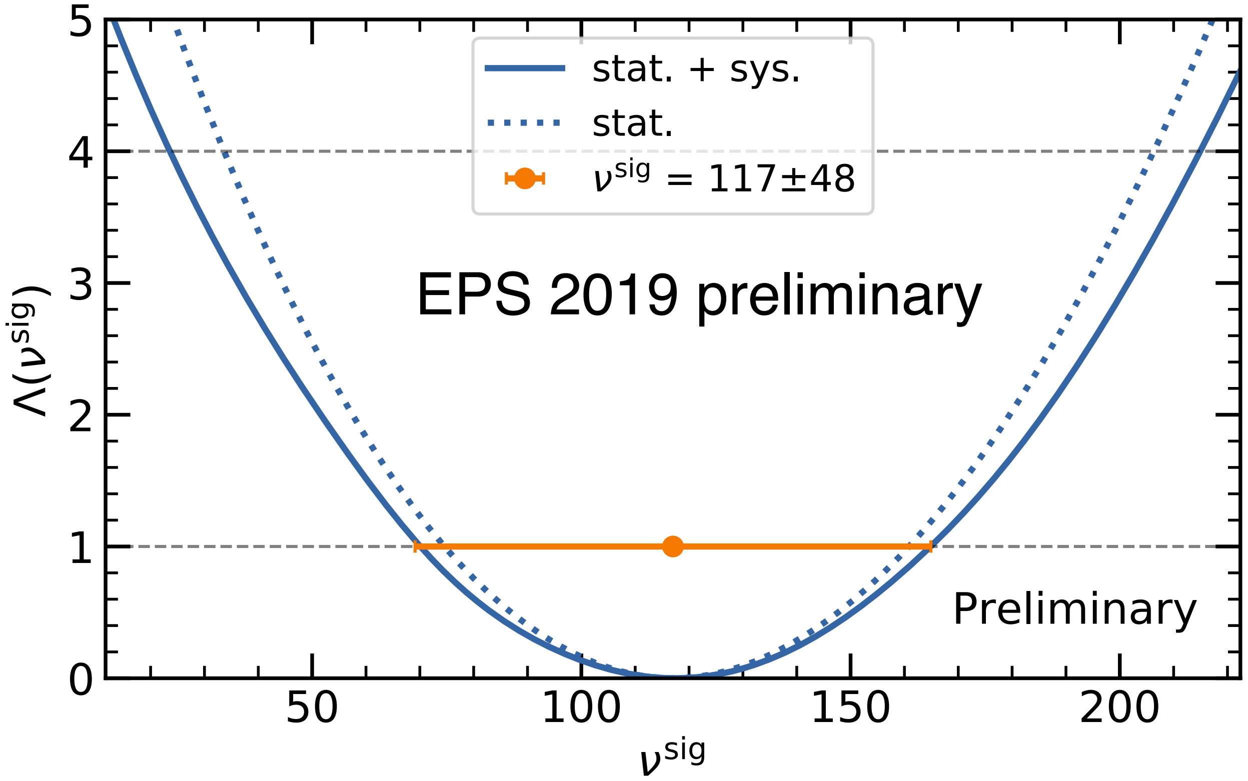
a: *Sibidanov et al.*, Phys. Rev. Lett. 121, 031801 (2018)

For $f_B = 184 \pm 4$ MeV

S. Aoki et al. (2017)

$$\boxed{|V_{ub}| = \left(4.4^{+0.8}_{-0.9} \pm 0.4 \pm 0.1\right) \times 10^{-3}}$$

Extracted Signal Yield



New result supersedes Belle (2018):

- Analysis in B-Frame boosts sensitivity
- Improved description of Continuum backgrounds.
- Improved modelling of $b \to u\ell\bar{\nu}_\ell$

$|V_{ub}|$ Summary

- **Exclusive Measurement**
  - Clean signal in missing mass to measure exclusive $|V_{ub}|$
  - Form factors $f_i(q^2)$ computed with Light Cone Sum Rules or LQCD
- **Inclusive Measurement**
  - $b \to u \ell \nu$ signal enhanced w.r.t. $b \to c$ backgrounds in low M_X and high q^2

Interplay between theory and experiment crucial

Exclusive $|V_{ub}|$ average: $(3.49 \pm 0.13) \times 10^{-3}$

Inclusive $|V_{ub}|$ averages:

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

Leptonic Decay $|V_{ub}| = 4.12(37)(9) \times 10^{-3}$ (PDG 2019)

$|V_{ub}|$ Summary

- **Exclusive Measurement**
  - Clean signal in missing mass to measure exclusive $|V_{ub}|$
  - Form factors $f_i(q^2)$ computed with Light Cone Sum Rules or LQCD
- **Inclusive M**
  - $b \to u\ell\nu$

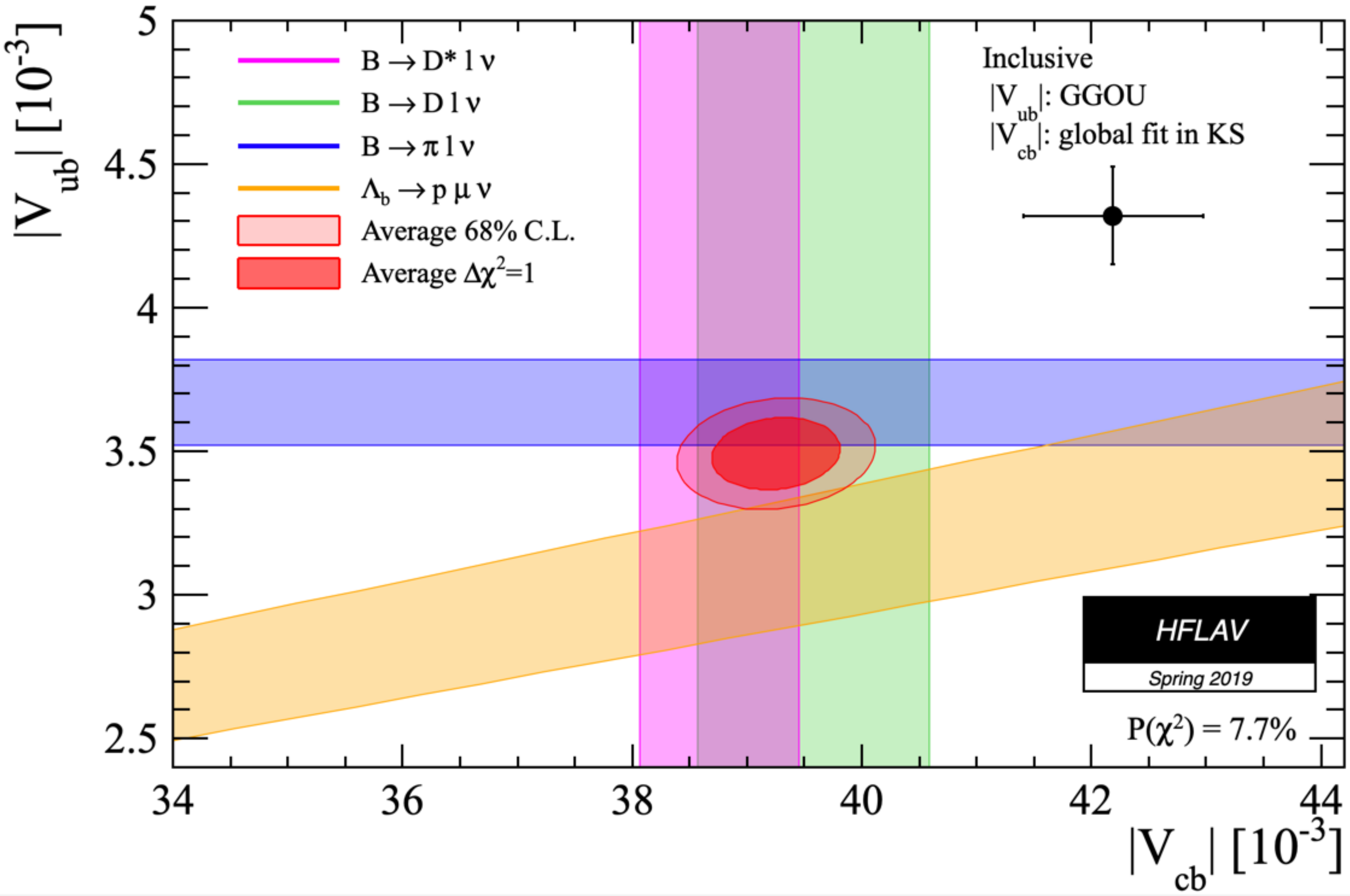
    high q^2

Interplay betw

Exclusive $|V_{ub}$

Inclusive $|V_{ub}|$

- $|V_{ub}| =$ $(3.79$
- $|V_{ub}| =$ $(4.56$
- $|V_{ub}| =$ $(3.95$



Conclusion

- B→D* l ν analysis 2018 from Belle (published in PRD)
  - Tested both CLN and BGL parameterisation

$|V_{cb}|$ x 10^3 = 38.4 ± 0.6 CLN
$|V_{cb}|$ x 10^3 = 38.3 ± 0.8 BGL

- B→μ ν analysis 2019 (presented at EPS), to be submitted to PRD soon

$$\boxed{|V_{ub}| = \left(4.4^{+0.8}_{-0.9} \pm 0.4 \pm 0.1\right) \times 10^{-3}}$$

- Measurements are coming up from Belle on inclusive $|V_{ub}|$
- Belle II will collect ~ 50ab^{-1} data
  - Measurement at $|V_{cb}|$ at zero recoil, more stats required.
- Precise model independent measurement of $|V_{cb}|$ and $|V_{ub}|$

Thank you

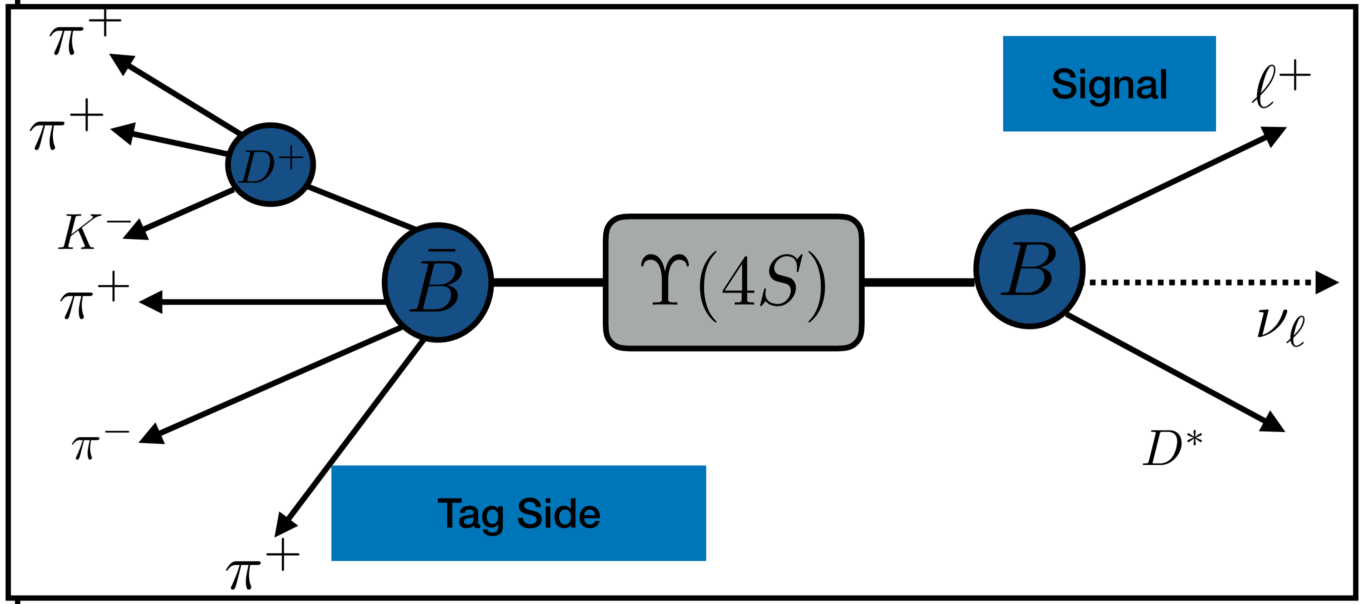
BACKUP

Experimental Measurements at Belle

Tagged Measurement: One B reconstructed completely in a known b→c,u mode without ν. “B-meson Beam”

Pro: High purity, very small background.

Con: Low Efficiency, large stat. errors



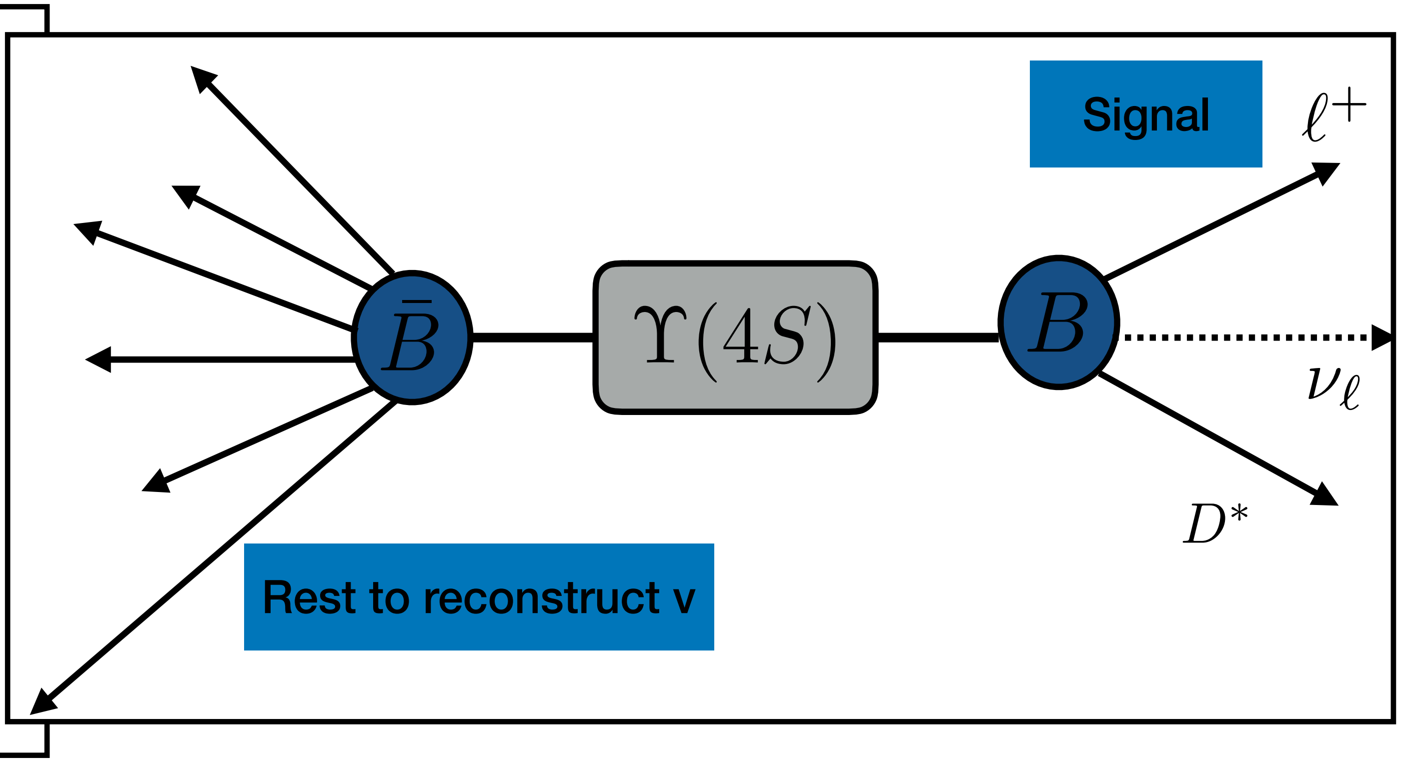
Untagged Measurement: Initial 4 momentum known, missing 4-momentum = ν

Reconstructed B → X_q lν

Other side information to constrain signal B flight direction

Pro: High efficiency

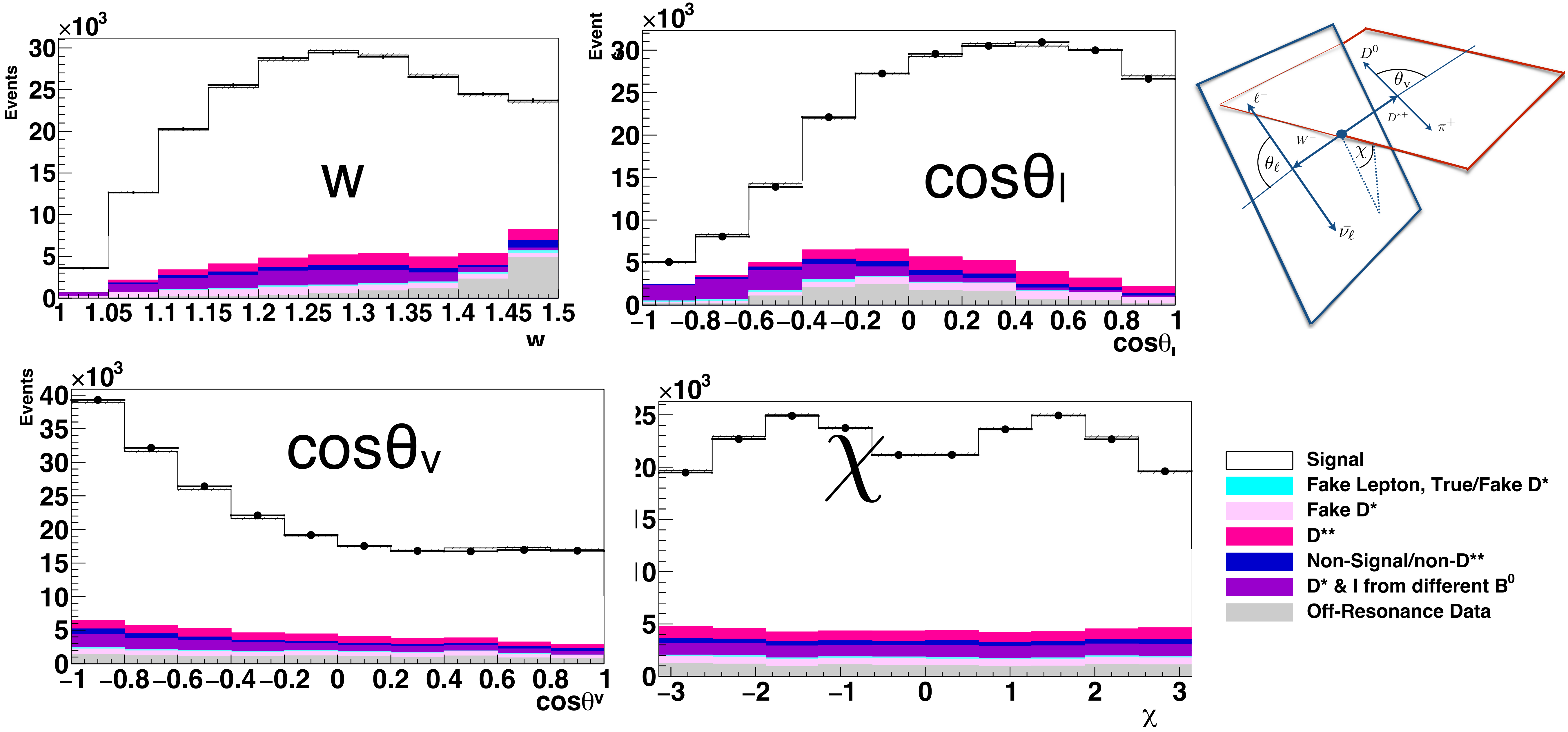
Con: Low purity, large background



Extraction of $|V_{cb}|$ from BGL

arXiv:1809.03290, accepted by PRD

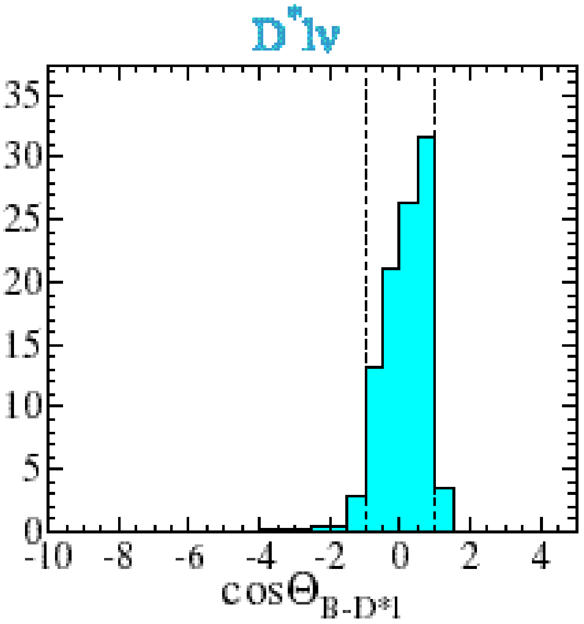
- Simultaneous fit of 1D projections of w, $\cos\theta_l$, $\cos\theta_v$, χ to extract the coefficients of the BGL expansion (up to 3rd order) and $F(1)|V_{cb}|$

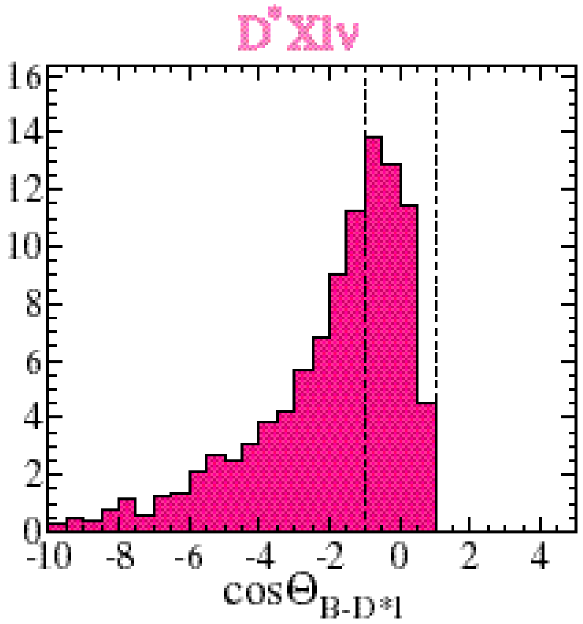


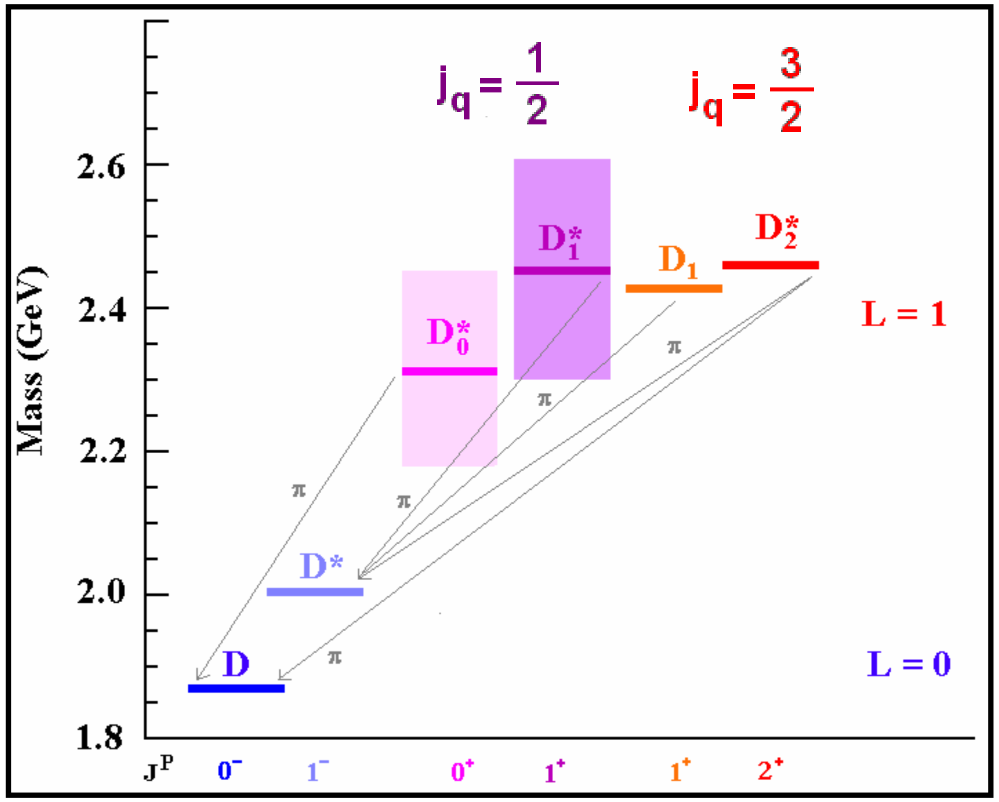
Belle Un-tagged Measurement 2018

Phys. Rev. D 100, 052007

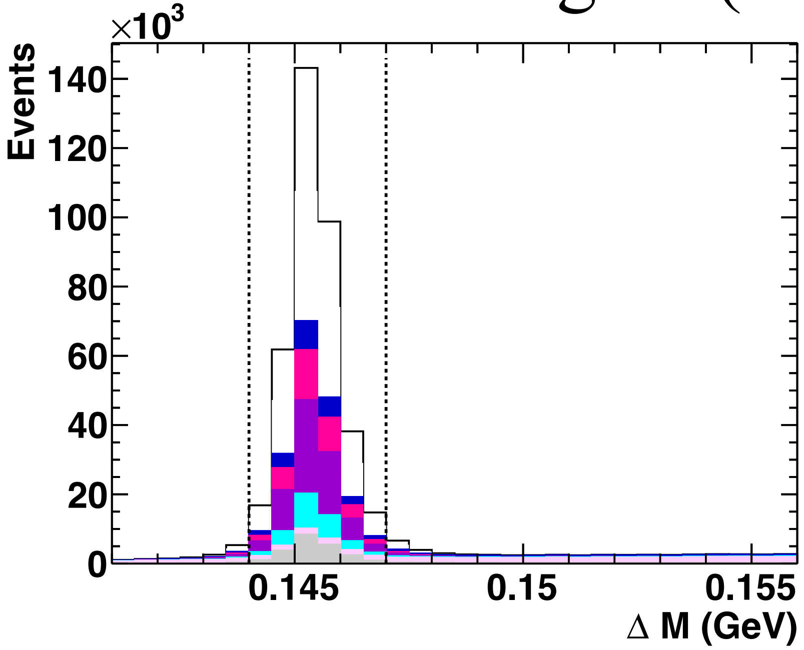
- Major source of Background $B \rightarrow D^{**} l \nu$
  - BF not known precisely
  - Disentangle D* from D** states using cos $\theta_{(B,D^*l)}$







- D** decay to D*→ could mimic signal (very poorly understood)



Measurement of spectra, correlations

- "Forward folding" rather than unfolding is proposed - avoids smearing effect from unfolded spectra.
  - Yields (N^{measured}), efficiencies (ε), Erorrs (σ)
  - Detector response (R)
  - Stat correlation (ρ^{stat})
  - Systematics correlations (ρ^{sys})

$$\mathrm{Cov}_{ij} = \rho_{ij}^{\text{stat}} \sigma_i^{\text{stat}} \sigma_j^{\text{stat}} + \rho_{ij}^{\text{sys}} \sigma_i^{\text{sys}} \sigma_j^{\text{sys}}$$

$$N_i^{\text{exp.}} = \sum_{j=1}^{40} (R_{ij} \epsilon_j N_j^{\text{theory}})$$

	Electrons		**Muons**	
Bin	Yield	Efficiency (%)	Yield	Efficiency (%)
1	1421 ± 41	2.72 ± 0.02	1494 ± 43	2.68 ± 0.02
2	5319 ± 85	5.72 ± 0.02	5062 ± 89	5.66 ± 0.02
3	8563 ± 113	7.70 ± 0.03	8385 ± 120	7.66 ± 0.03
4	10685 ± 129	9.10 ± 0.03	10734 ± 142	9.05 ± 0.03
5	11971 ± 156	10.03 ± 0.03	11961 ± 159	9.91 ± 0.03
6	12275 ± 167	10.61 ± 0.03	12090 ± 167	10.43 ± 0.03
7	11888 ± 166	10.74 ± 0.03	11803 ± 168	10.60 ± 0.03
8	11096 ± 151	10.67 ± 0.03	10501 ± 155	10.52 ± 0.03
9	9751 ± 159	10.23 ± 0.03	9378 ± 160	10.04 ± 0.03
10	7770 ± 215	9.10 ± 0.03	7673 ± 213	9.14 ± 0.03

R

W reco

W true

Bin	1	2	3	4	5	6	7	8	9	10
1	0.803	0.053	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	0.197	0.778	0.098	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3	0.000	0.168	0.717	0.126	0.002	0.000	0.000	0.000	0.000	0.000
4	0.000	0.001	0.182	0.667	0.149	0.006	0.000	0.000	0.000	0.000
5	0.000	0.000	0.004	0.199	0.626	0.167	0.011	0.000	0.000	0.000
6	0.000	0.000	0.000	0.009	0.207	0.592	0.177	0.015	0.000	0.000
7	0.000	0.000	0.000	0.000	0.016	0.215	0.575	0.183	0.018	0.000
8	0.000	0.000	0.000	0.000	0.000	0.021	0.213	0.567	0.186	0.017
9	0.000	0.000	0.000	0.000	0.000	0.000	0.024	0.214	0.598	0.186
10	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.022	0.198	0.797

Exclusive $|V_{cb}|$ from $B^0 \to D^{*-}\ell^+\nu_\ell$ untagged

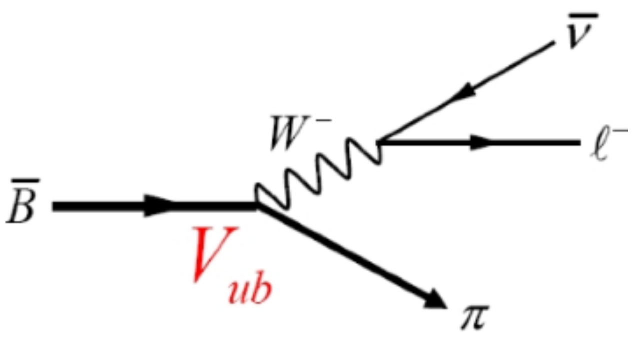
Source	ρ^2	$R_1(1)$	$R_2(1)$	$\mathcal{F}(1)\lvert V_{cb}\rvert$ [%]	$\mathcal{B}(B^0 \to D^{*-}\ell^+\nu_\ell)$ [%]
Slow pion efficiency	0.005	0.002	0.001	0.65	1.29
Lepton ID combined	0.001	0.006	0.004	0.68	1.38
$\mathcal{B}(B \to D^{**}\ell\nu)$	0.002	0.001	0.002	0.26	0.52
$B \to D^{**}\ell\nu$ form 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

- Tracking, slow π tracking, lepton ID dominate. Tracking errors 3x smaller than in 2010 paper.

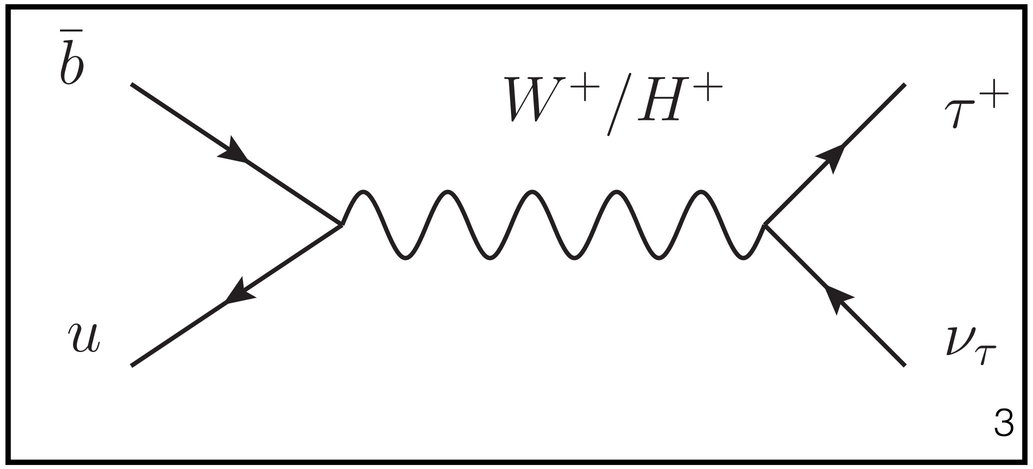
$|V_{ub}|$ Determination $b \to u$

Calculate $|V_{ub}|$ from

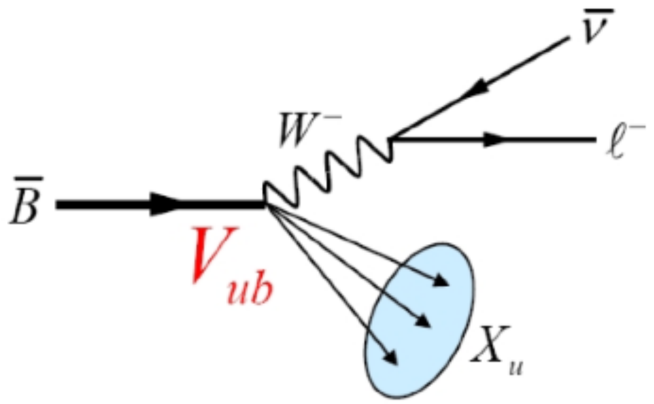
Exclusive $|V_{ub}|$



pure leptonic



Inclusive $|V_{ub}|$



$$\frac{d\Gamma(B \to \pi l \nu)}{dq^2} = \frac{G_F^2}{24\pi^3} p_\pi^3 |V_{ub}|^2 \times |f(q^2)|^2$$

- Theory input: form factors (Lattice and sum rules)
- Experimentally more constrained
- Both untagged and tagged analysis

$$\Gamma_{SL} = |V_{ub}|^2 \frac{G_F^2 m_b^5}{192\pi^3} \times A_{pert} \times A_{non-pert}(1/m_b)$$

- Theory input: OPE
- High background b→clν background
  - Must select phase space region (M_x,q^2,p_l) to enhance B→u signal
- Need theoretical input to extrapolate to full rate

Continuum Background

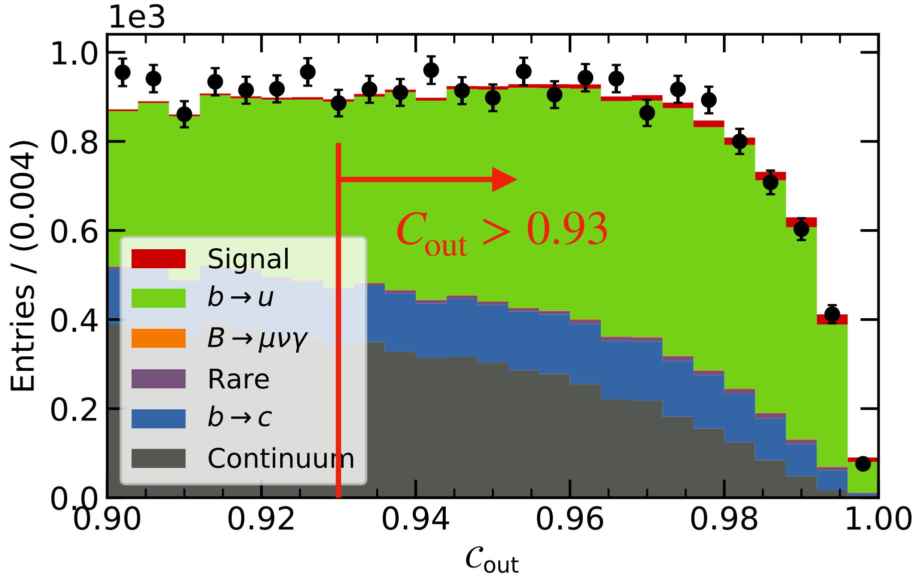
Category	C_{out}	$\cos\Theta_{B\mu}$	Signal Efficiency
I	[0.98,1.00)	[-0.13,1.00)	6.5 %
II	[0.98,1.00)	[-1.00,-0.13)	5.9 %
III	[0.93,0.98)	[0.04,1.00)	7.1 %
IV	[0.93,0.98)	[-1.00,0.04)	8.3 %

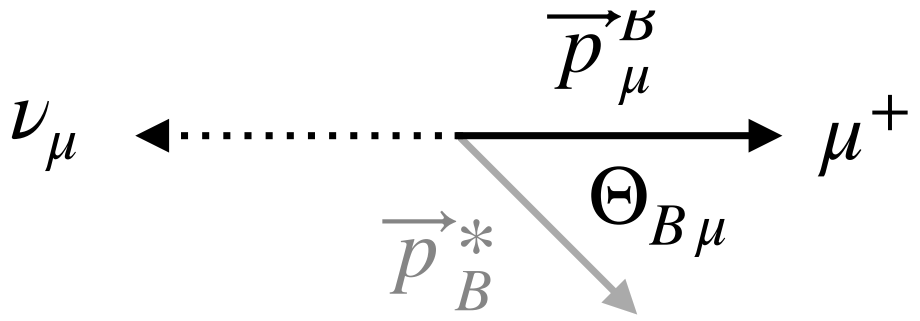
Signal Enriched

Background Enriched

9 variables characterizing the event →

Multivariate Classifier trained to separate Signal and Continuum

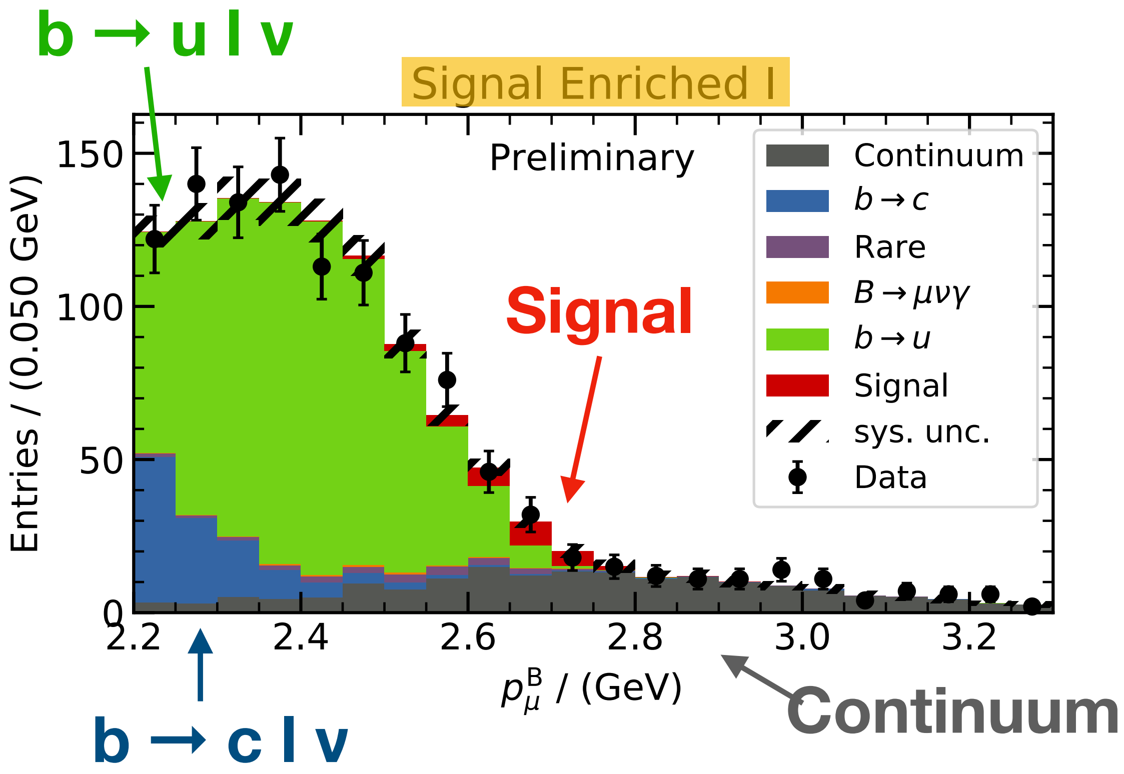




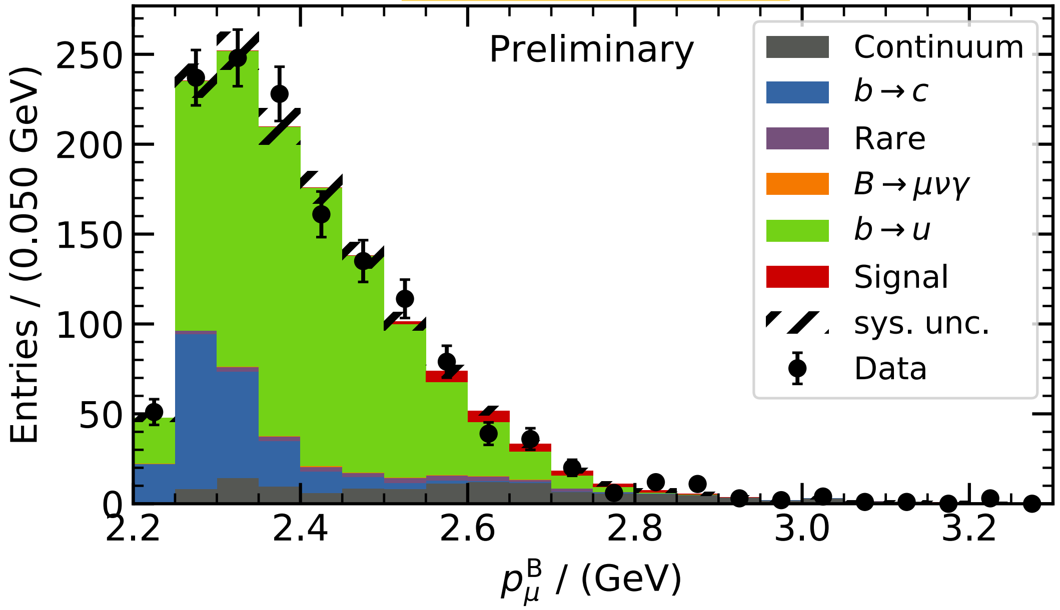
Efficiency	$B^+ \to \mu^+\nu_\mu$	$b \to u\,\ell\,\nu_\ell$	Continuum
$B\,\bar{B}$ & Muon reco.	99 %	10 %	0.9 %
ROE Presel.	55 %	1.4 %	0.03 %
C_{out} cut	28 %	0.2 %	0.001 %

Four Signal Categories

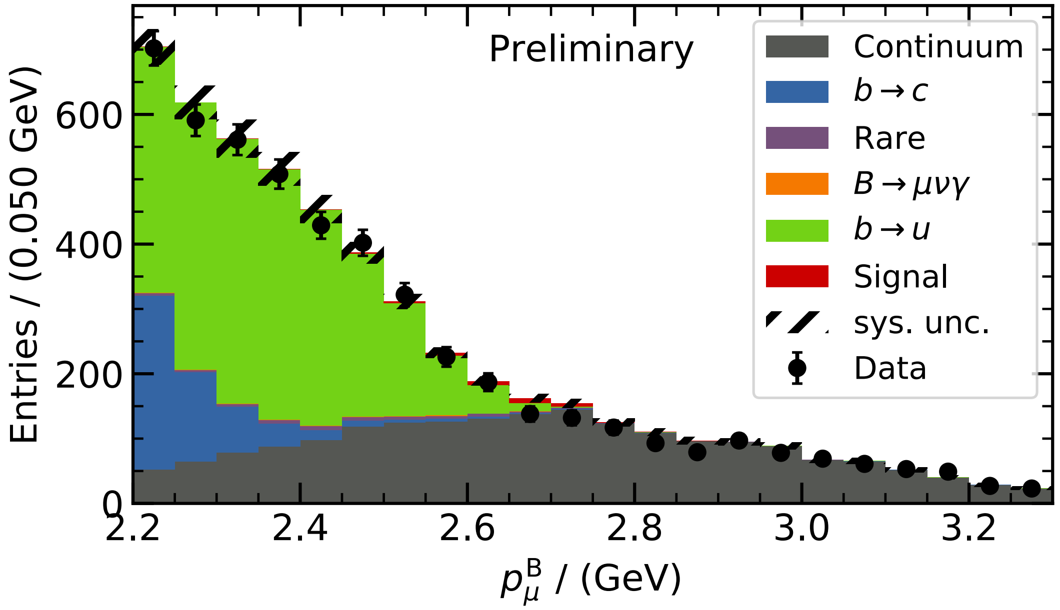
Signal Enriched I



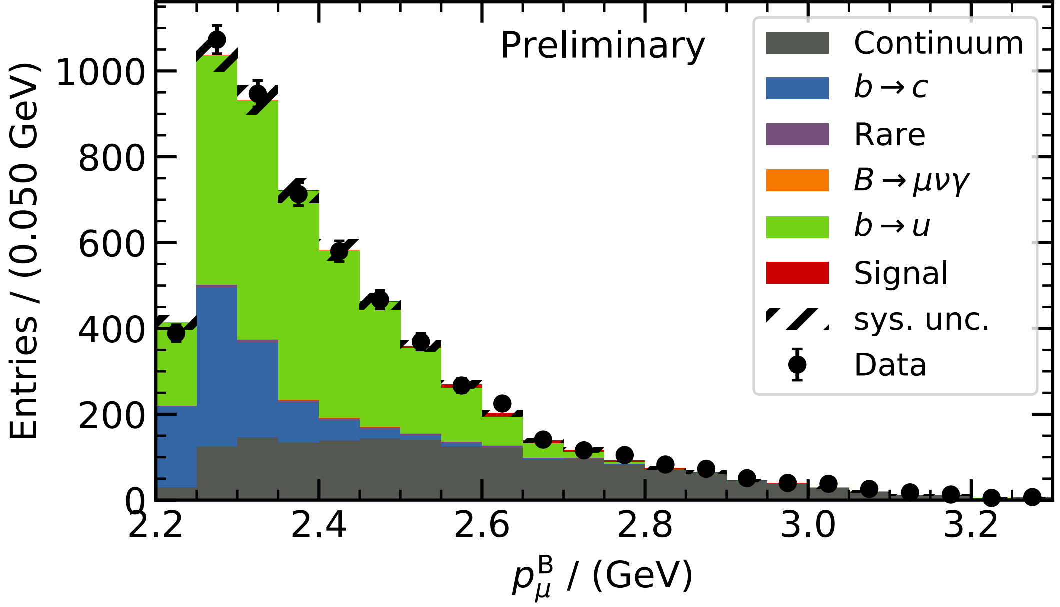
Signal Enriched II



Background Enriched III



Background Enriched IV

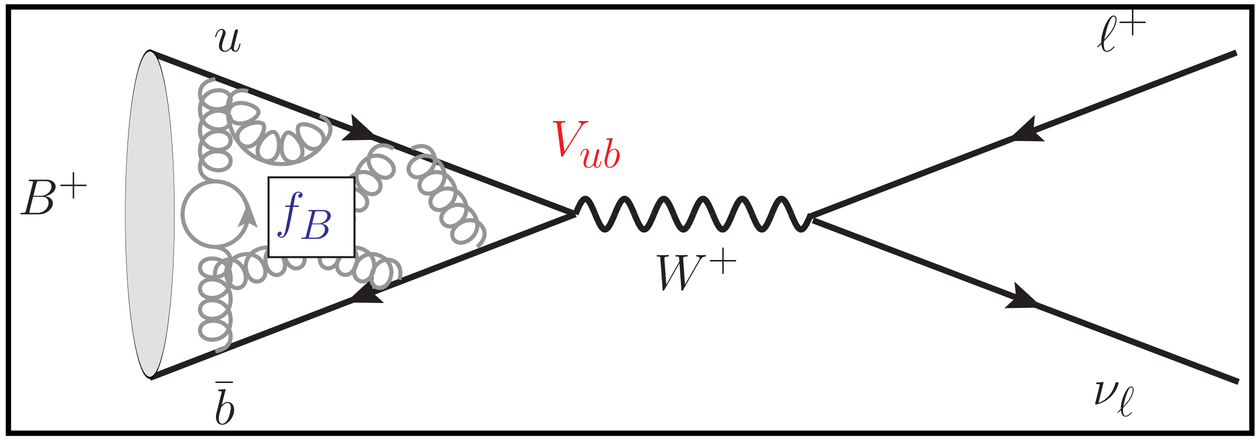


$B \to \mu\nu$ untagged

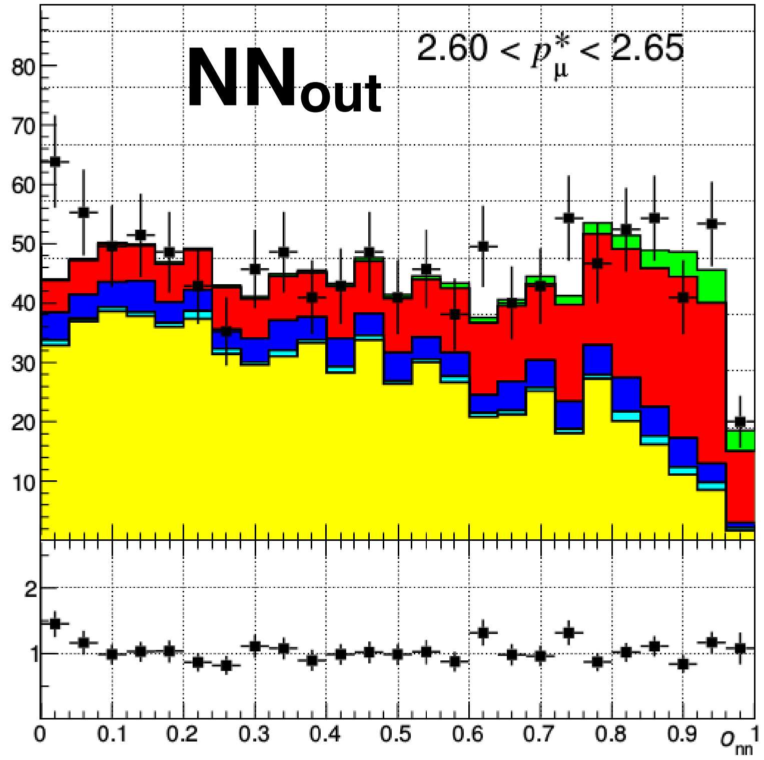
arXiv:1712.04123, to appear in PRL

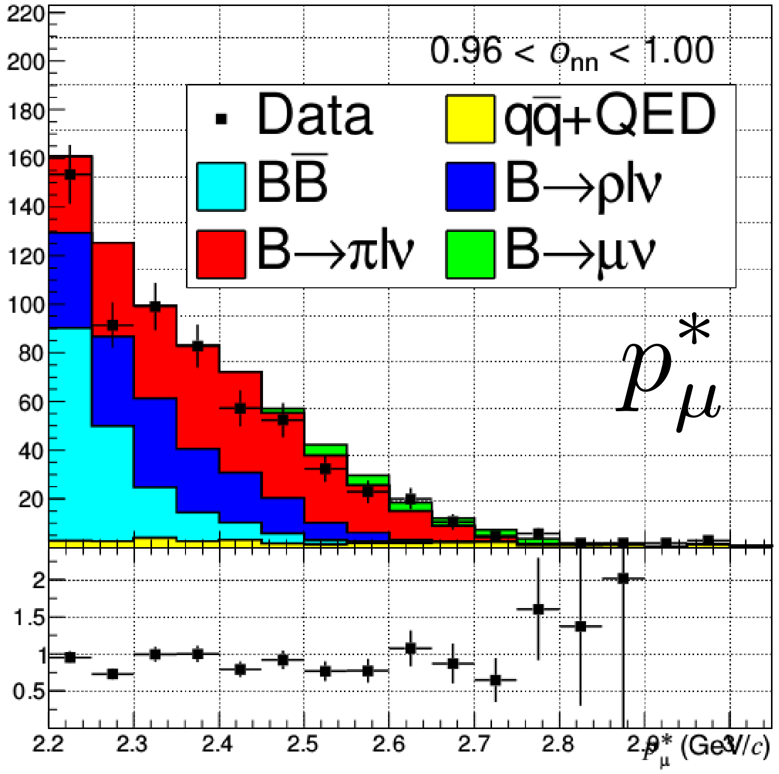
- Theoretically very clean

$$\mathcal{B}(B^- \to \ell^- \bar{\nu}_\ell) = \frac{G_F^2 m_B m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 \boxed{|V_{ub}|}^2 \tau_B,$$



- Reconstruct B_{signal}
- Rest of event used to reconstruct other B
- NN for signal & background separation
- 2D fit b/w p^*_μ & NN_{out}
- SM prediction from $B \to \pi l \nu$ $|V_{ub}|$ value.





$$\mathcal{B}(B^+ \to \mu^+ \nu_\mu) = (6.46 \pm 2.22 \pm 1.60) \times 10^{-7} \quad \Leftarrow 2.4\ \sigma \text{ significance}$$

$$\mathcal{B}(B^+ \to \mu^+ \nu_\mu) \in [2.9, 10.7] \times 10^{-7} \text{ at } 90\% \text{ C.L.} \quad \Leftarrow \text{Expressed as limit}$$

$$\mathcal{B}(B^+ \to \mu^+ \nu_\mu) = (3.80 \pm 0.31) \times 10^{-7} \quad \Leftarrow \text{SM prediction}$$

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

Inclusive Approach

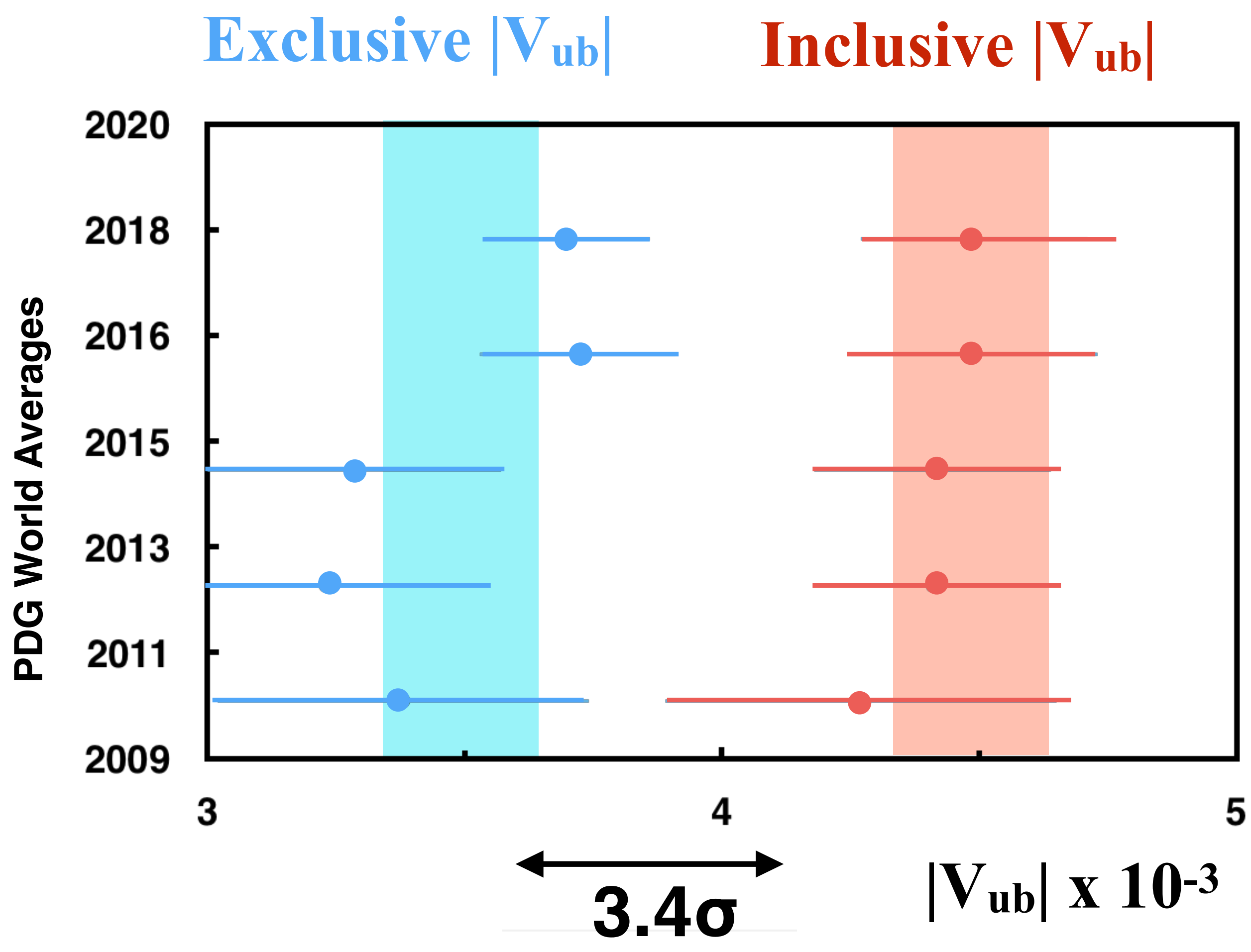
$B \rightarrow X_c l\nu$

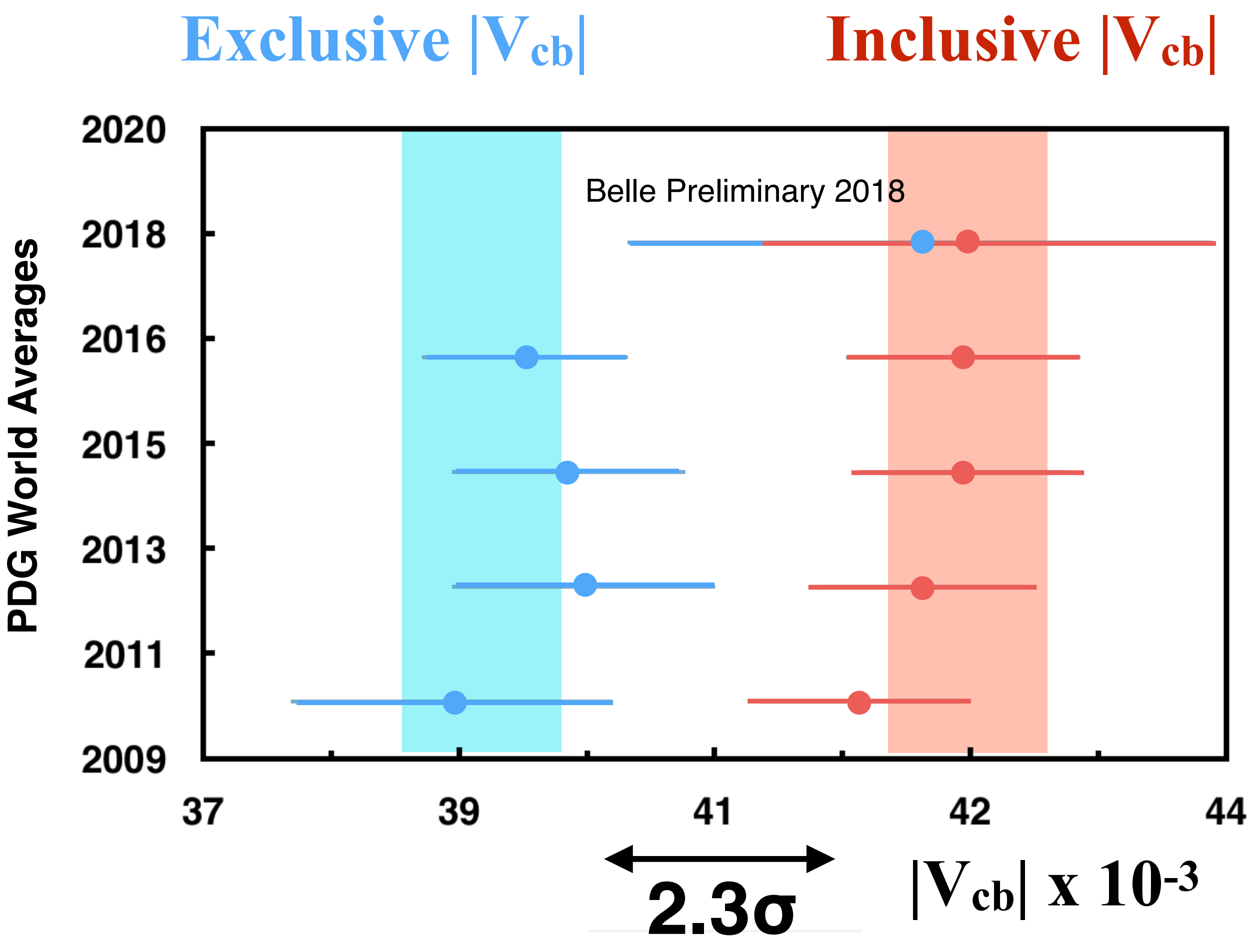
$B \rightarrow X_u l\nu$

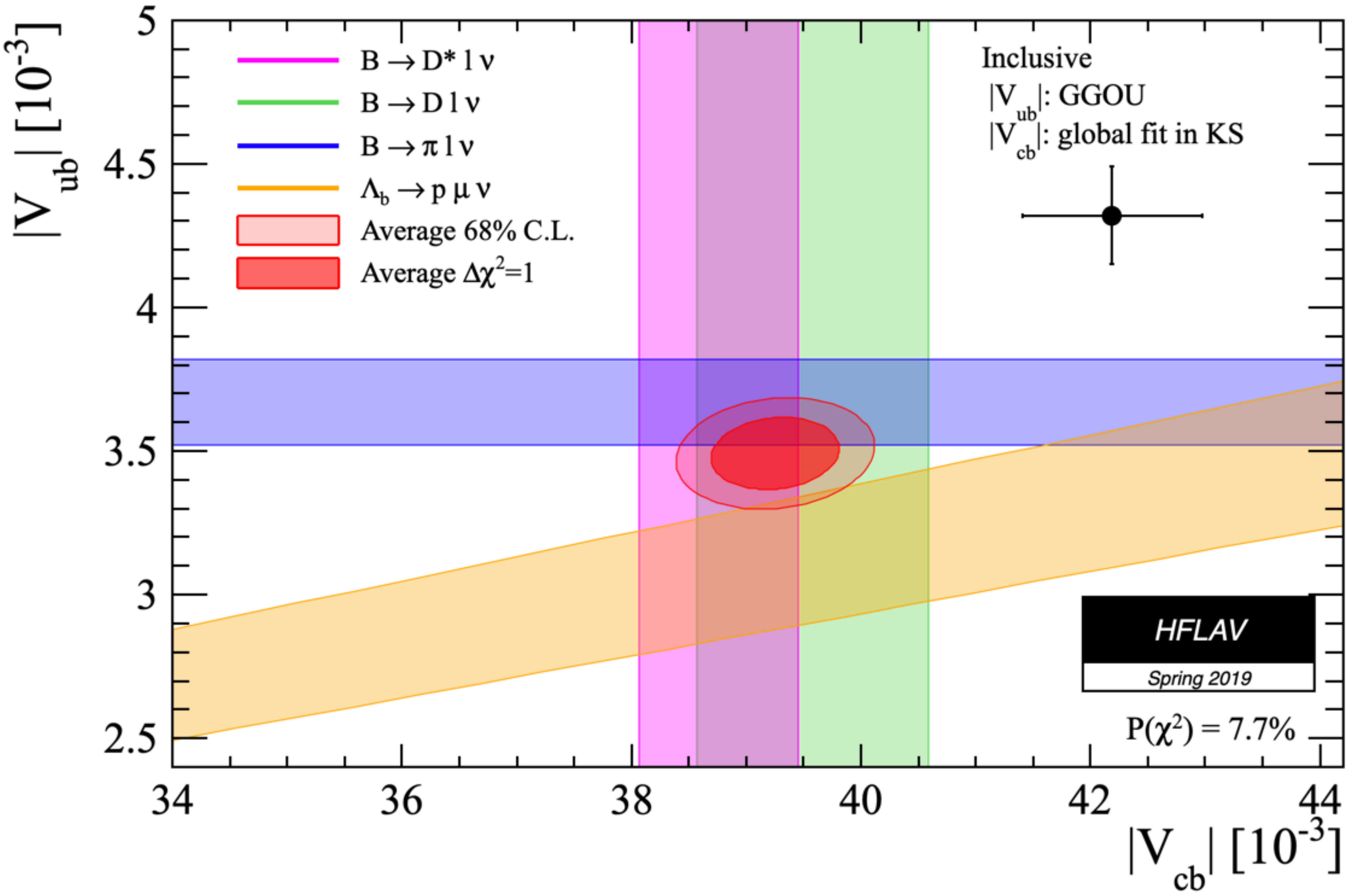
Exclusive Approach

$B \rightarrow D l\nu$, $B \rightarrow D^* l\nu$ for $|V_{cb}|$

$B \rightarrow \pi l\nu$ for $|V_{ub}|$






B → D* l ν
B → D l ν
B → π l ν
$\Lambda_b \to p \mu \nu$
Average 68% C.L.
Average $\Delta\chi^2$=1
Inclusive
$|V_{ub}|$: GGOU
$|V_{cb}|$: global fit in KS
HFLAV
Spring 2019
$P(\chi^2) = 7.7\%$
$|V_{ub}|$ $[10^{-3}]$
5
4.5
4
3.5
3
2.5
34
36
38
40
42
44
$|V_{cb}|$ $[10^{-3}]$