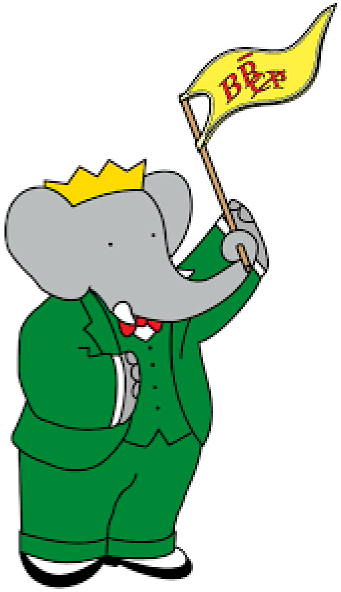

Semileptonic B decays at the B Factories

Franco Simonetto

INFN &
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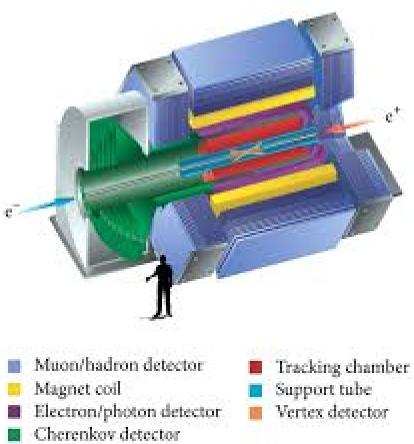
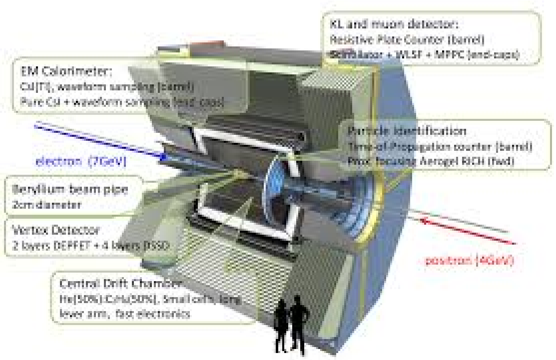


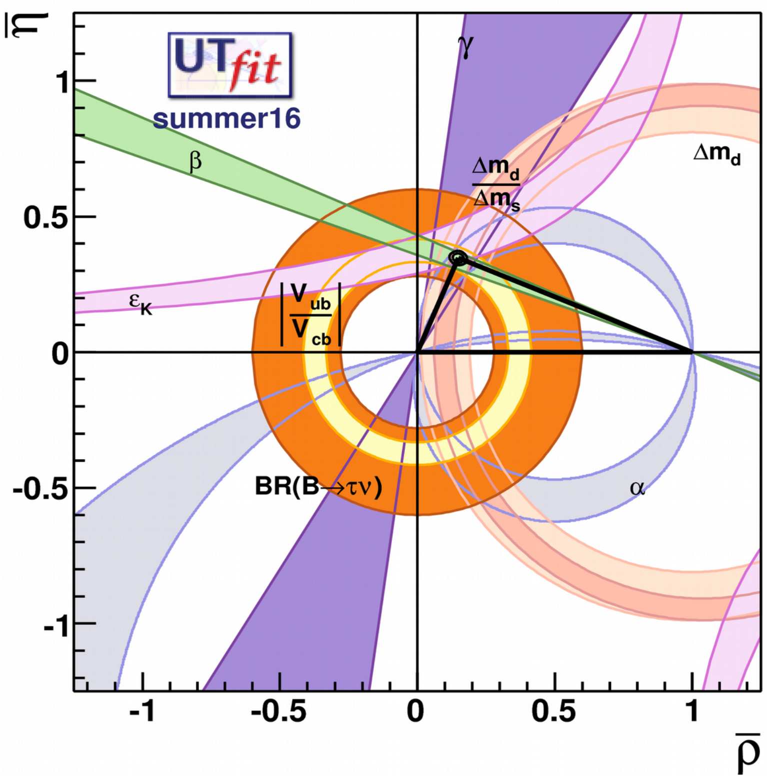


Talk Outlook

- Motivations
- Overview
- Tools :
  - Theory
  - Experiment
- $B \to c\ell\nu$ and $|V_{cb}|$, ℓ=e,m
- $B \to u\ell\nu$ and $|V_{ub}|$, ℓ=e,m
- $B \to D^{(*)}\tau\nu$
- Conclusions

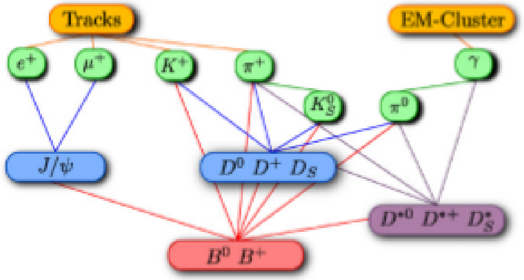
Motivations

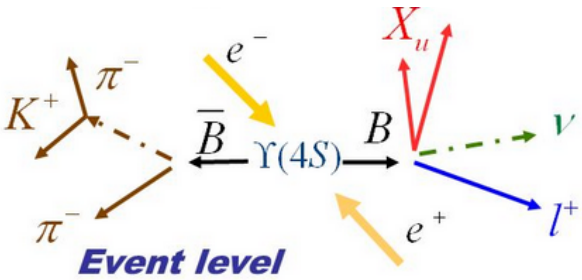
- Semileptonic decays provide the most precise determinations of V_{xb} (x=c,u)
- $|V_{cb}|$ sets the scale for :
  - a unitarity triangle
  - FCNC $\propto |V_{tb}V_{ts}| \approx |V_{cb}|^2[1+O(\lambda^2)]$
  - Kaon CP $\epsilon_K \approx x|V_{cb}|^2 + \ldots$
- $|V_{ub}/V_{cb}|$
  - the side opposite to sin $2\phi_1$
- $B \to D^{(*)} \tau\nu$ test :
  - 3rd generation coupling
  - New form factor
  - Larger sensitivity to new Physics effects ?



- Fully reconstruct the tag B in more than 1000 hadronic final states

- $\varepsilon \sim 0.5$ % (B^+)
- $\varepsilon \sim 0.3$ % (B^0)



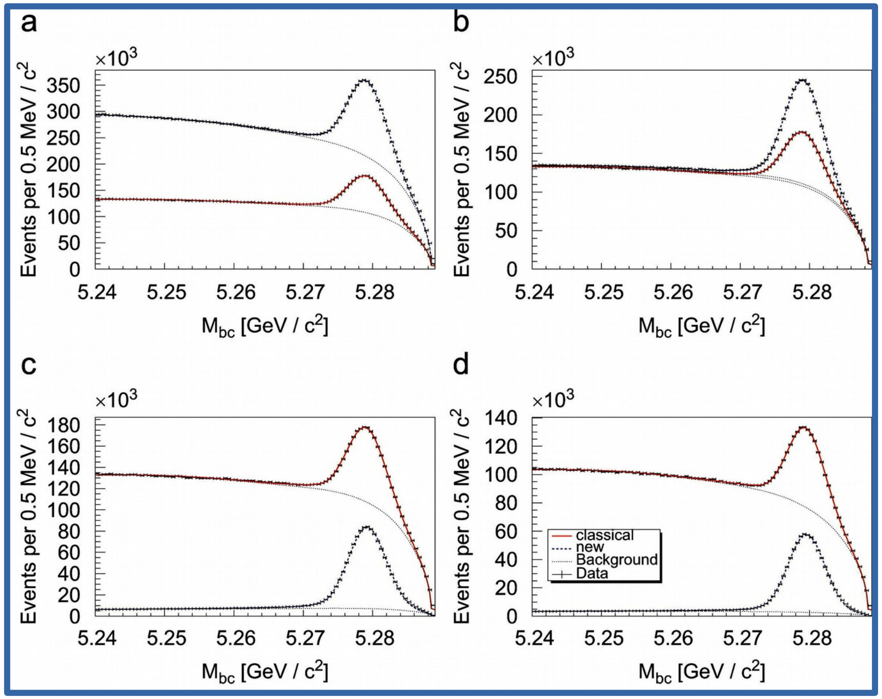


- (almost) unbiased measurement side, with :

$$P^{\mu}_{Meas} = P^{\mu}_{\Upsilon(4S)} - P^{\mu}_{Tag}$$

  - $B \to \ell \nu D/\pi$: full ν reconstruction
  - $B \to \ell \nu X$: improved bck rejection, partial reconstruction of the event

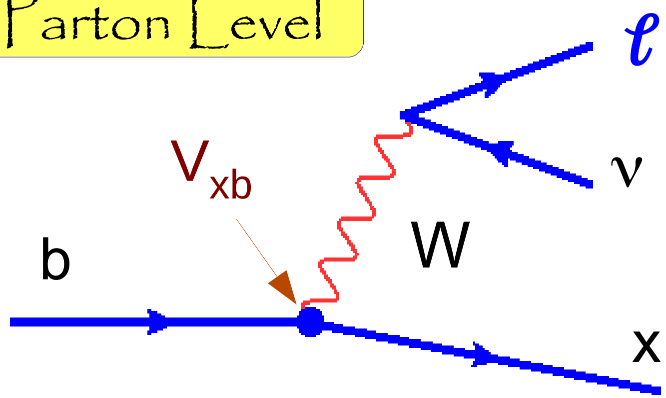
- Belle (only):
  - Hierarchical Neuro Based algo improves tag perfomances by ~ x 2



Blue points : HNB selection
Red points : old selection

Theoretical tools

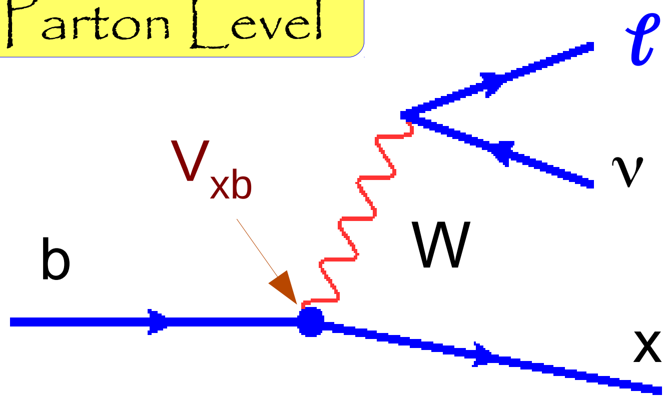
Parton Level



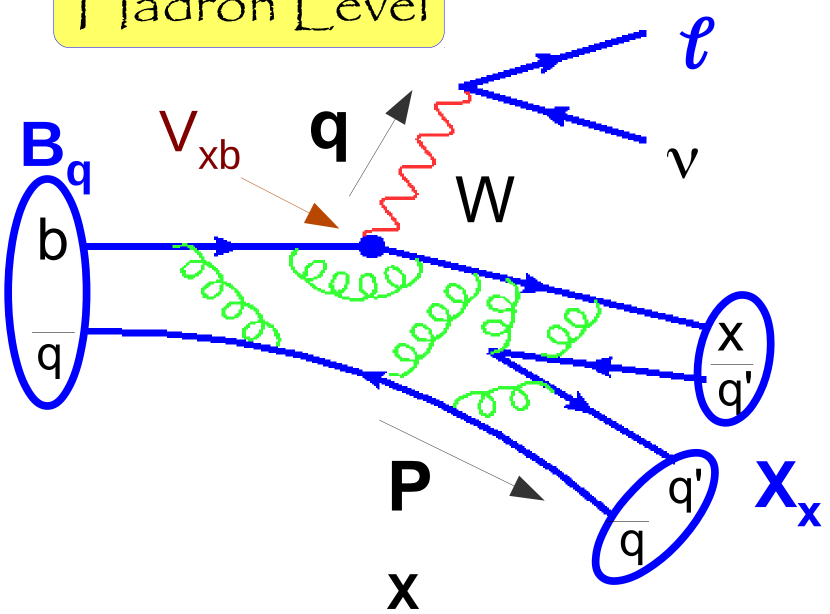
$$\Gamma = |V_{cb}|^2 \frac{G_F^2 m_b^5(\mu)}{192\pi^3}(1 + A_{\mathrm{ew}})$$

Trivial diagram, as for μ decay

Parton Level



Hadron Level



Hadronization and other QCD Effects :

- Inclusive decays ($B \to \ell \nu X_{c/u}$)
  - Operator Product Expansion in α_s and $\Lambda_{QCD} / m_{b,c}$
- Exclusive decays ($B \to \ell \nu D^{(*)} / \pi$)
  - Form factors from Lattice QCD, Light Cone Sum Rules
- Fit measured spectra to reduce theoretical errors

$|V_{cb}|$ from $b \to X_c \ell \nu$: theory

- Sizable QCD corrections to simple spectator model
- Computed with OPE + pQCD expansion in powers of :
  - α_s

$$\Gamma = |V_{cb}|^2 \frac{G_F^2 m_b^5(\mu)}{192\pi^3}(1 + A_{\rm ew})\times$$
$$\Big[z_0^{(0)}(r) + \frac{\alpha_s(\mu)}{\pi} z_0^{(1)}(r) + \left(\frac{\alpha_s(\mu)}{\pi}\right)^2 z_0^{(2)}(r) + \cdots$$
$$+ \frac{\mu_\pi^2}{m_b^2}\left(z_2^{(0)}(r) + \frac{\alpha_s(\mu)}{\pi} z_2^{(1)}(r) + \cdots\right)$$
$$+ \frac{\mu_G^2}{m_b^2}\left(y_2^{(0)}(r) + \frac{\alpha_s(\mu)}{\pi} y_2^{(1)}(r) + \cdots\right)$$
$$+ \frac{\rho_D^3}{m_b^3}\left(z_3^{(0)}(r) + \frac{\alpha_s(\mu)}{\pi} z_3^{(1)}(r) + \cdots\right)$$
$$+ \frac{\rho_{LS}^3}{m_b^3}\left(y_3^{(0)}(r) + \frac{\alpha_s(\mu)}{\pi} y_3^{(1)}(r) + \cdots\right) + \ldots \Big]$$

$$\overline{\Lambda} = M_B - m_b\,,$$
$$\mu_\pi^2 = -\langle B|\bar{b}(iD_\perp)^2 b|B\rangle\,,$$
$$\mu_G^2 = \langle B|\bar{b}(iD_\perp^\mu)(iD_\perp^\nu)\sigma_{\mu\nu} b|B\rangle\,,$$
$$\rho_D^3 = \langle B|\bar{b}(iD_{\perp\mu})(ivD)(iD_\perp^\nu) b|B\rangle\,,$$
$$\rho_{LS}^3 = \langle B|\bar{b}(iD_\perp^\mu)(ivD)(iD_\perp^\nu)\sigma_{\mu\nu} b|B\rangle$$

$|V_{cb}|$ from $b \to X_c \ell\nu$: theory

- Sizable QCD corrections to simple spectator model
- Computed with OPE + pQCD expansion in powers of :
  - α_s
  - $1/m_b$, $1/m_c$
- Fit to spectra allows the determination of unknown operators
- Fit in fact moments to smooth resonances away

$$\Gamma = |V_{cb}|^2 \frac{G_F^2 m_b^5(\mu)}{192\pi^3}(1 + A_{\rm ew})\times$$

$$\Big[z_0^{(0)}(r) + \frac{\alpha_s(\mu)}{\pi} z_0^{(1)}(r) + \left(\frac{\alpha_s(\mu)}{\pi}\right)^2 z_0^{(2)}(r) + \cdots$$

$$+ \frac{\mu_\pi^2}{m_b^2}\left(z_2^{(0)}(r) + \frac{\alpha_s(\mu)}{\pi} z_2^{(1)}(r) + \cdots \right)$$

$$+ \frac{\mu_G^2}{m_b^2}\left(y_2^{(0)}(r) + \frac{\alpha_s(\mu)}{\pi} y_2^{(1)}(r) + \cdots \right)$$

$$+ \frac{\rho_D^3}{m_b^3}\left(z_3^{(0)}(r) + \frac{\alpha_s(\mu)}{\pi} z_3^{(1)}(r) + \cdots \right)$$

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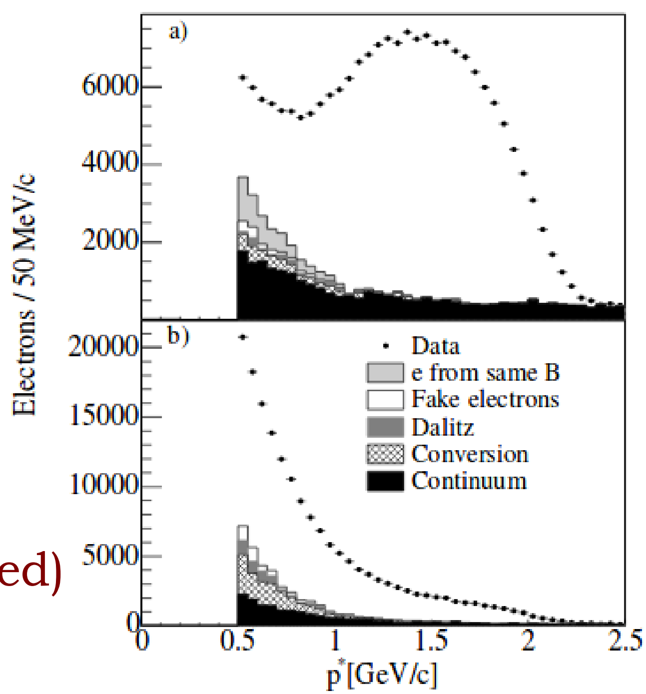
$$\rho_{LS}^3 = \langle B|\bar{b}(iD_\perp^\mu)(ivD)(iD_\perp^\nu)\sigma_{\mu\nu} b|B\rangle$$

$|V_{cb}|$ from $b \to X_c \ell \nu$: measurement

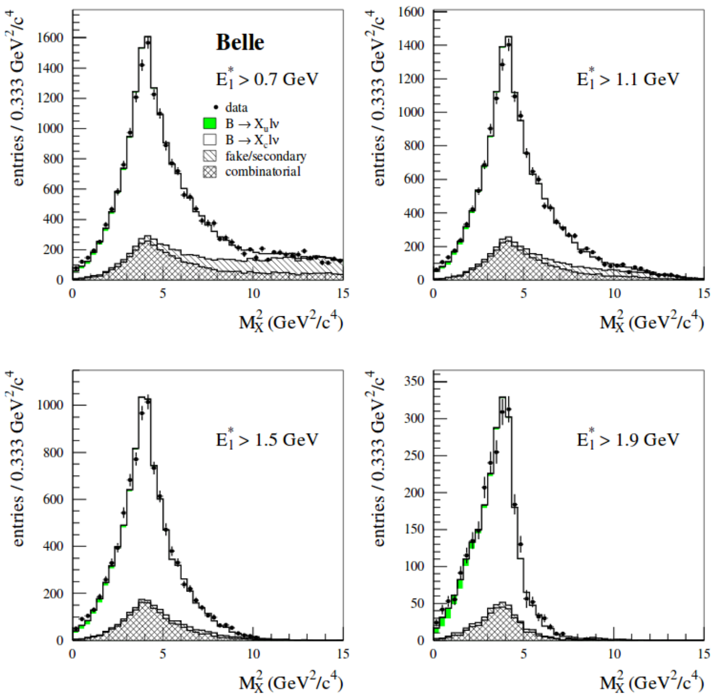
- Untagged measurements : large data size
- Tagged measurements provide :
  - ℓ moments in B rest frame (instead of Y(4S))
  - X_c moments from residual hadrons in the event

$$\langle E_\ell^n \rangle = \frac{1}{\Gamma_{E_\ell > E_{\rm cut}}} \int_{E_\ell > E_{\rm cut}} E_\ell^n \frac{d\Gamma}{dE_\ell} \, dE_\ell \, ,$$

$$\langle m_X^{2n} \rangle = \frac{1}{\Gamma_{E_\ell > E_{\rm cut}}} \int_{E_\ell > E_{\rm cut}} m_X^{2n} \frac{d\Gamma}{dm_X^2} \, dm_X^2$$



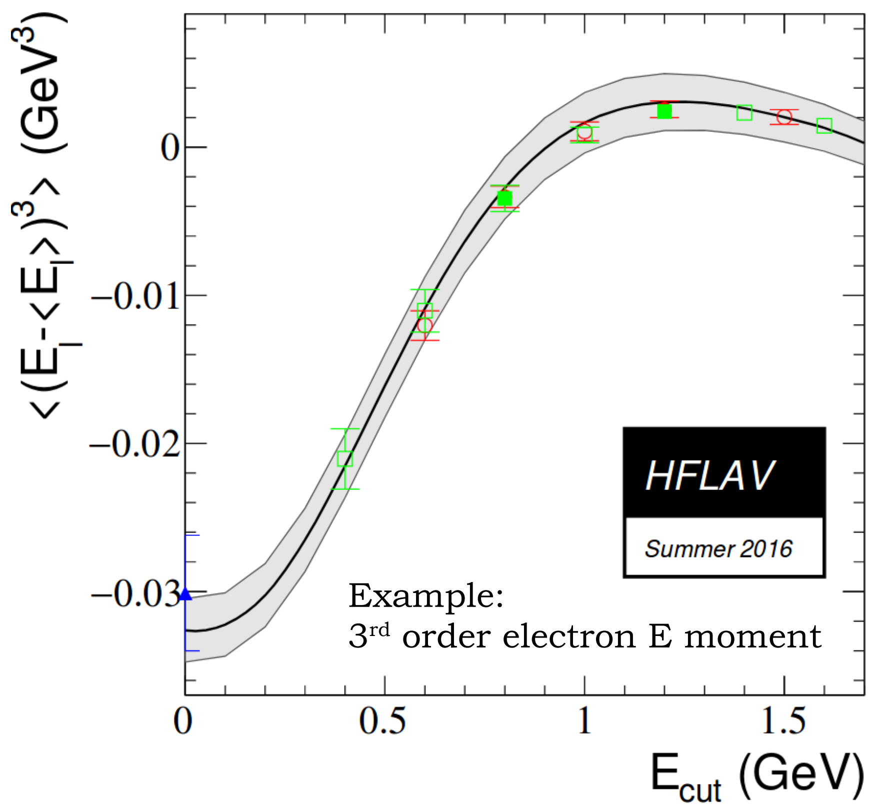
Lepton Spectra (untagged)

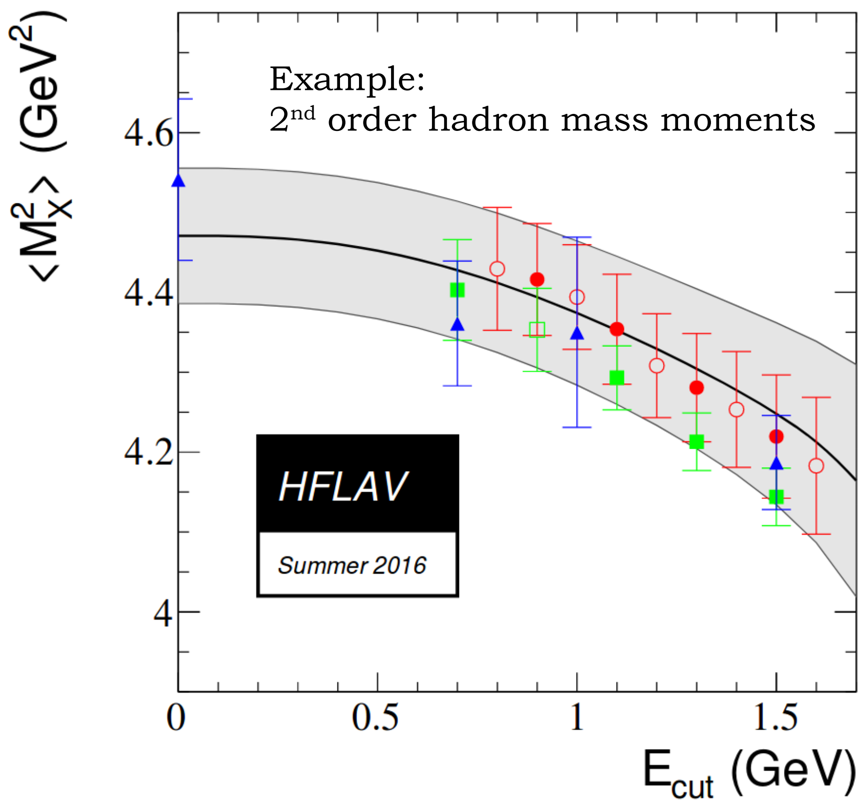


Hadron Spectra (tagged)

- HFLAV averages :

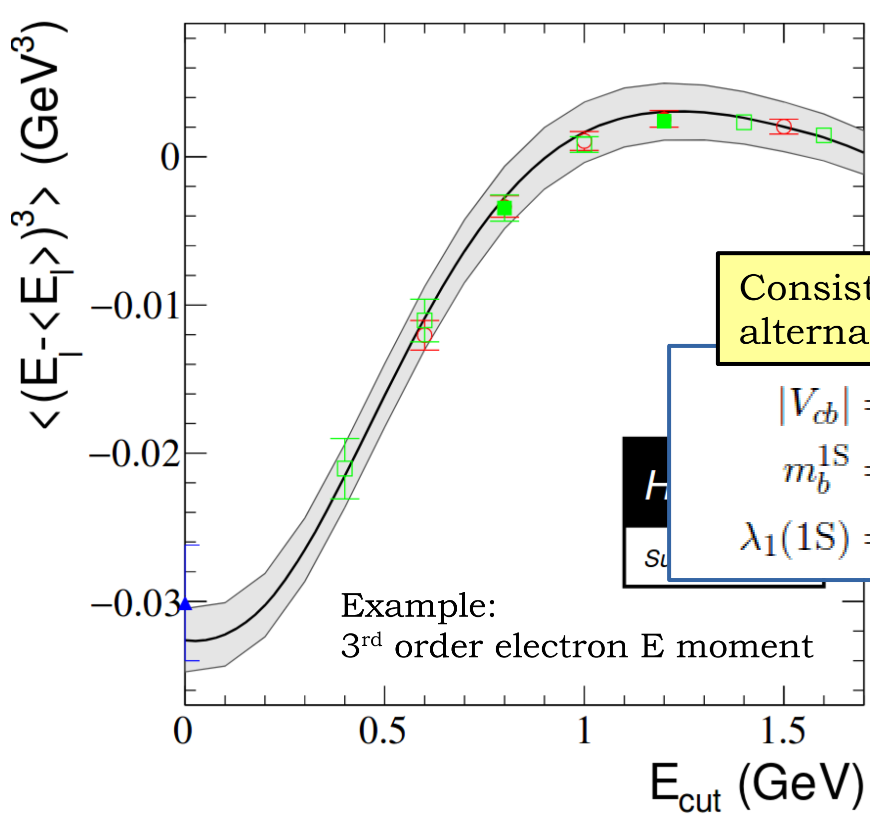
Circles : BABAR
Squares : Belle
Triangles : LEP, CLEO





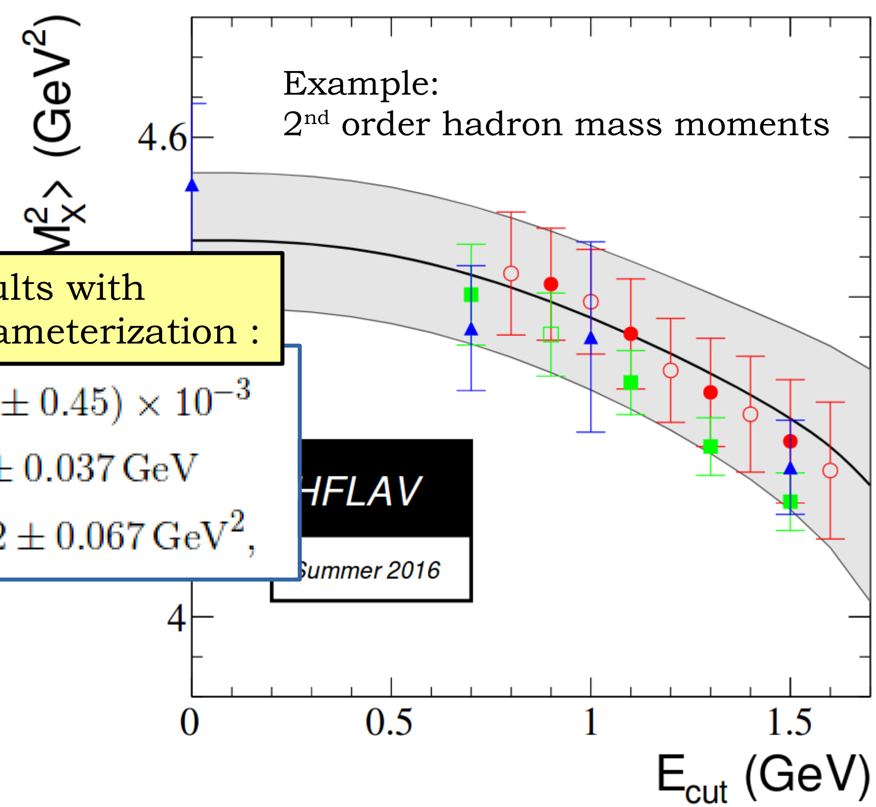
Br(B -> $X_c$lnu) (%)	$\|V_{cb}\|$ (10^{-3})	m_b^{kin} (GeV)	mu$^2_{pi}$ (GeV^2)
10.65 +/- 0.16	42.19 +/- 0.78	4.554 +/- 0.018	0.464 +/- 0.076

- HFLAV averages :



Consistent results with alternative parameterization :

$$|V_{cb}| = (41.98 \pm 0.45) \times 10^{-3}$$
$$m_b^{1S} = 4.691 \pm 0.037 \,\text{GeV}$$
$$\lambda_1(1S) = -0.362 \pm 0.067 \,\text{GeV}^2,$$



Br(B -> $X_c$lnu) (%)	$\|V_{cb}\|$ (10^{-3})	m_b^{kin} (GeV)	mu$^2_{pi}$ (GeV^2)
10.65 +/- 0.16	42.19 +/- 0.78	4.554 +/- 0.018	0.464 +/- 0.076

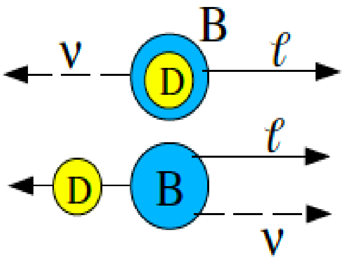
$|V_{cb}|$ from $B \rightarrow D^{(*)}\ell\nu$: theory

Phase space

$$\frac{d\Gamma}{dw}(\bar{B} \rightarrow D^{*}\ell\bar{\nu}_{\ell}) = \frac{G_F^2 m_B^5}{48\pi^3}|V_{cb}|^2(w^2-1) \;\alpha\; P(w)(\eta_{ew}\mathcal{F}(w))^2$$

Form Factors

- ... where :
  - $w = v_B^{\mu} v_{\mu D} = \frac{m_B^2 - m_D^2 - q^2}{2 m_B m_D} = \gamma_D \; (B\, rest\, frame)$
  - , w mapped onto $z(w) = (\sqrt{w+1} - \sqrt{2})/(\sqrt{w+1} + \sqrt{2})$



W = 1

W (max)

- $\mathcal{F}$(w) represent the (unknown) form factors
  - Power series expansions z^n
  - HQET : bounds between parameters
  - LQCD : $F(1) = 1 + O\left(\frac{m_B - m_D}{m_B + m_D}\frac{\Lambda_{QCD}}{m_c}\right) = 1 + O(\%)$
- Extraplation to *w=1* provides $F(1) \cdot |V_{cb}|$

$|V_{cb}|$ from $B \to D^{(*)} \ell \nu$: theory

Phase space

$$\frac{d\Gamma}{dw}(\bar{B} \to D^* \ell \bar{\nu}_\ell) = \frac{G_F^2 m_B^5}{48\pi^3} |V_{cb}|^2 (w^2 - 1)^{\alpha} P(w) (\eta_{ew} \mathcal{F}(w))^2$$

Form Factors

- D (pseudoscalar) :
  - . $\alpha = 3/2$: helicity suppression near $w=1$ 
  - One form factor : $\mathcal{G}(z) = \mathcal{G}(1)(1 - 8\rho^2 z + (51\rho^2 - 10)z^2 - (252\rho^2 - 84)z^3)$ 

Form Factors from :
Caprini, Lellouch, Neubert (CLN)
Nucl.Phys.B530, 153 (1998):

Use Heavy Quark Symmetry to constrain higher oder parameters

$|V_{cb}|$ from $B\to D^{(*)}\ell\nu$: theory

Phase space

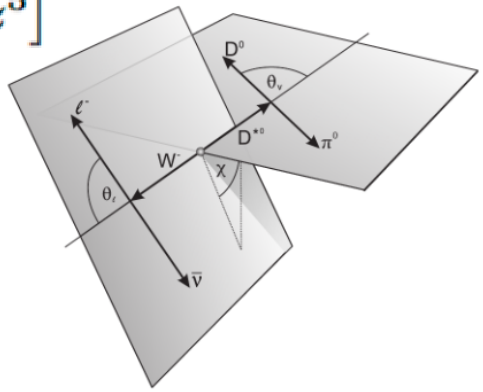
$$\frac{d\Gamma}{dw}(\bar{B}\to D^*\ell\bar{\nu}_\ell) = \frac{G_F^2 m_B^5}{48\pi^3}|V_{cb}|^2(w^2-1)^{\alpha} P(w)(\eta_{ew}\mathcal{F}(w))^2$$

Form Factors

- D (pseudoscalar) :
  - . α= 3/2 : helicity suppression near w=1
  - One form factor : $\mathcal{G}(z) = \mathcal{G}(1)(1-8\rho^2 z + (51\rho^2-10)z^2 - (252\rho^2-84)z^3)$
- D* (vector)
  - . α= 1/2 : larger event rate near end point
  - Three helicity amplitudes (f.f.) :

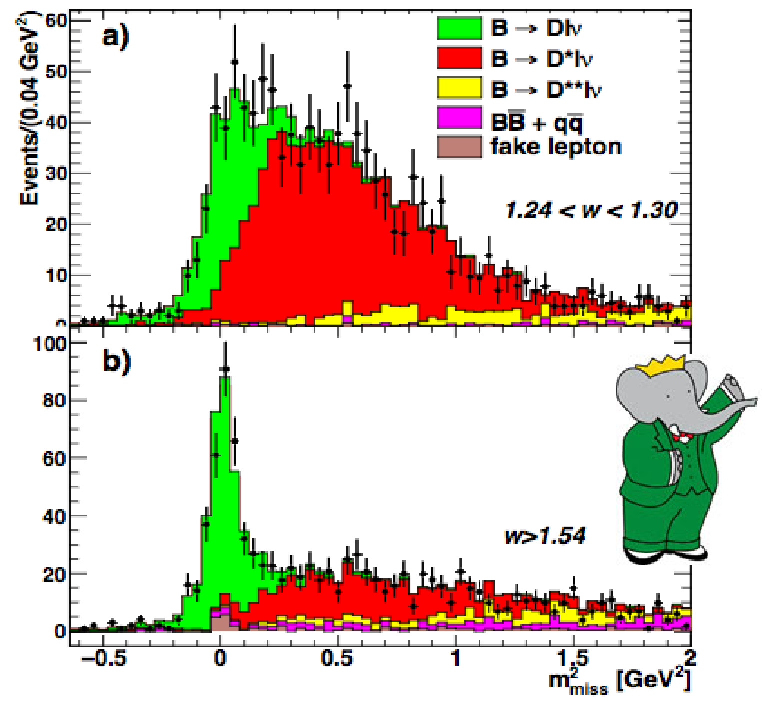
Form Factors from :
Caprini, Lellouch, Neubert (CLN)
Nucl.Phys.B530, 153 (1998)

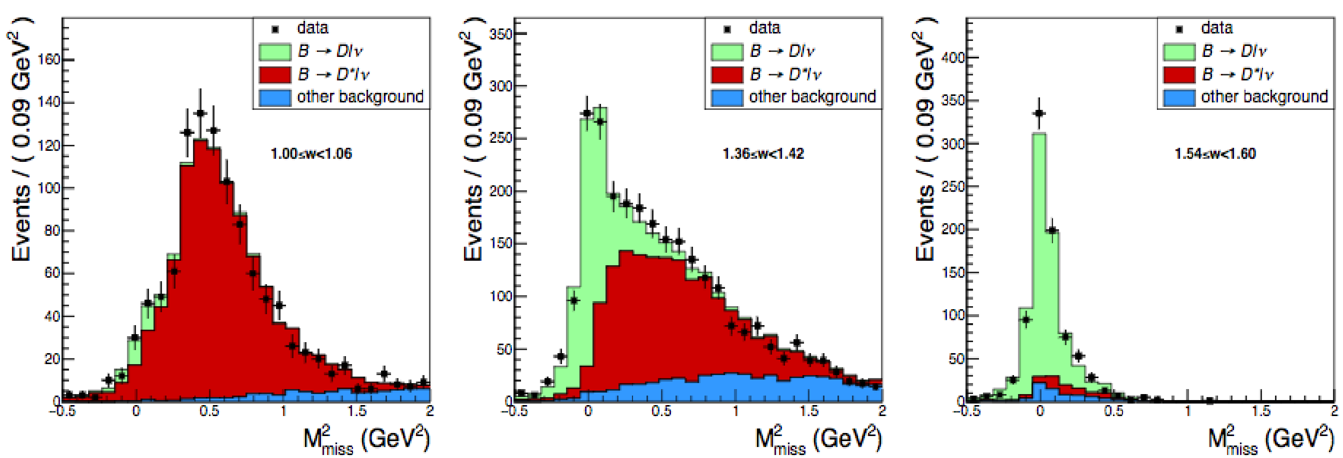
$$\begin{aligned} h_{A_1}(w) &= h_{A_1}(1)\left[1-8\rho^2 z+(53\rho^2-15)z^2-(231\rho^2-91)z^3\right] \\ R_1(w) &= R_1(1)-0.12(w-1)+0.05(w-1)^2 \\ R_2(w) &= R_2(1)+0.11(w-1)-0.06(w-1)^2 \end{aligned}$$



- Angular analysis, in addition to w, to determine R_1, R_2

- State of art : tagged events
  - Improve kinematic
  - Reduce D* background (with missed π/γ)
- BaBar (PRL 104:011802 (2010))
  - 460 M BB, 3200 signal events
- Belle (PRD93:032006 (2016))
  - 770 MBB , 17000 signal events
- Signal tag : (missing mass)² (= m_ν^2)





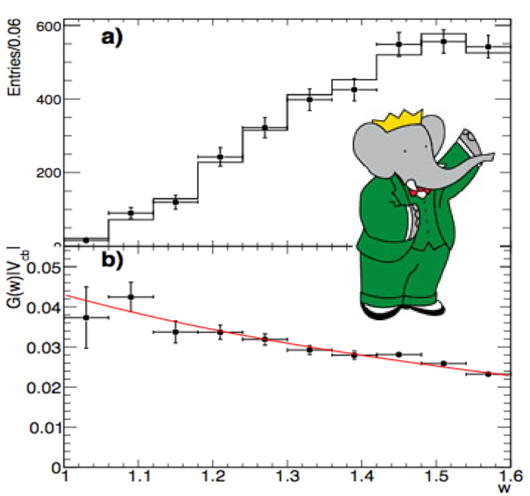
$|V_{cb}|$ from $B \to D\ell\nu$:results

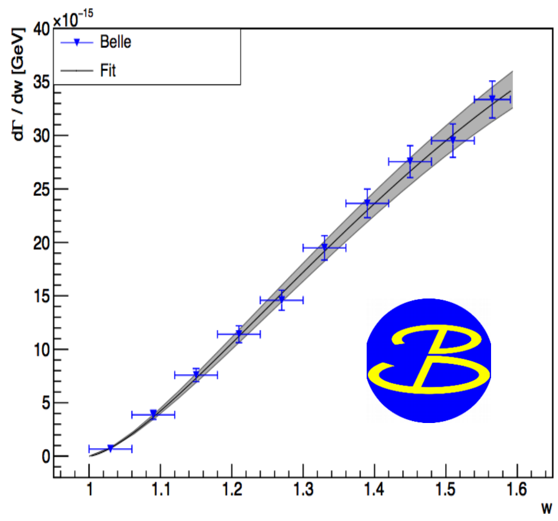
	$B^- \to D^0\ell^-\bar{\nu}_\ell$	$\bar{B}^0 \to D^+\ell^-\bar{\nu}_\ell$	$\bar{B} \to D\ell^-\bar{\nu}_\ell$
$\mathcal{G}(1)\|V_{cb}\| \cdot 10^3$	41.7±2.1 ±1.3	45.6± 3.3±1.6	43.0± 1.9±1.4
ρ^2	1.14± 0.11±0.04	1.29± 0.14±0.05	1.20± 0.09±0.04
ρ_{corr}	0.943	0.950	0.952
χ^2/ndf	3.4/8	5.6/8	9.9/18
Signal Yield	2147 ± 69	1108 ± 45	-
...ency	$(1.99 \pm 0.02) \times 10^{-4}$	$(1.09 \pm 0.02) \times 10^{-4}$	-
	(2.31± 0.08 ± 0.09)%	(2.23± 0.11 ± 0.11)%	(2.17± 0.06 ± 0.09)%

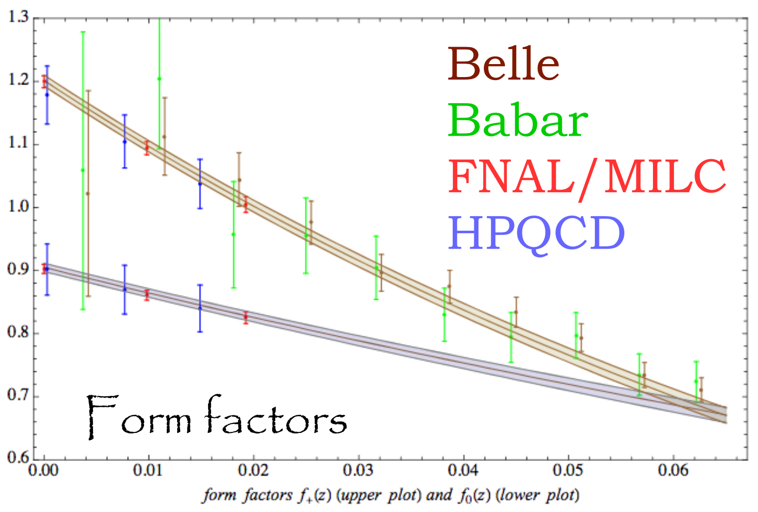
	$B^+ \to \bar{D}^0 e^+\nu_e$	$B^+ \to \bar{D}^0\mu^+\nu_\mu$	$B^0 \to D^- e^+\nu_e$	$B^0 \to D^-\mu^+\nu_\mu$	$B \to D\ell\nu_\ell$
$\eta_{EW}\mathcal{G}(1)\|V_{cb}\|[10^{-3}]$	42.31 ± 1.94	45.48 ± 1.96	41.84 ± 2.14	42.99 ± 2.18	42.29 ± 1.37
ρ^2	1.05 ± 0.08	1.22 ± 0.07	1.01 ± 0.10	1.08 ± 0.10	1.09 ± 0.05
Correlation	0.81	0.77	0.85	0.84	0.69
$\eta_{EW}\|V_{cb}\|[10^{-3}]$	40.14 ± 1.86	43.15 ± 1.89	39.69 ± 2.05	40.78 ± 2.09	40.12 ± 1.34
χ^2/n_{df}	2.19/8	2.71/8	9.65/8	4.36/8	4.[illegible]
Prob.	0.97	0.95	0.29	0.82	0[illegible]

$$\mathcal{G}(1) = 1 + \mathcal{O}\left(\frac{m_B - m_D}{m_B + m_D}\frac{\Lambda_{QCD}}{m_c}\right) = 1.054 \pm 0.004 \pm 0.008$$

FNAL Lattice & MILC Coll.
PhysRevD92, 034506 (2015)







$|V_{cb}|$ from $B \to D \ell \nu$:results

	$B^- \to D^0 \ell^- \bar{\nu}_\ell$	$\bar{B}^0 \to D^+ \ell^- \bar{\nu}_\ell$	$\bar{B} \to D \ell^- \bar{\nu}_\ell$
$\mathcal{G}(1)\lvert V_{cb}\rvert \cdot 10^3$	41.7±2.1 ±1.3	45.6± 3.3±1.6	43.0± 1.9±1.4
ρ^2	1.14± 0.11±0.04	1.29± 0.14±0.05	1.20± 0.09±0.04
ρ_{corr}	0.943	0.950	0.952
χ^2/ndf	3.4/8	5.6/8	9.9/18
Signal Yield	2147 ± 69	1108 ± 45	-
[illegible]ncy	$(1.99 \pm 0.02) \times 10^{-4}$	$(1.09 \pm 0.02) \times 10^{-4}$	-
[illegible]	$(2.31 \pm 0.08 \pm 0.09)\%$	$(2.23 \pm 0.11 \pm 0.11)\%$	$(2.17 \pm 0.06 \pm 0.09)\%$

	$B^+ \to \bar{D}^0 e^+ \nu_e$	$B^+ \to \bar{D}^0 \mu^+ \nu_\mu$	$B^0 \to D^- e^+ \nu_e$	$B^0 \to D^- \mu^+ \nu_\mu$	$B \to D \ell \nu_\ell$
$\eta_{EW}\mathcal{G}(1)\lvert V_{cb}\rvert[10^{-3}]$	42.31 ± 1.94	45.48 ± 1.96	41.84 ± 2.14	42.99 ± 2.18	42.29 ± 1.37
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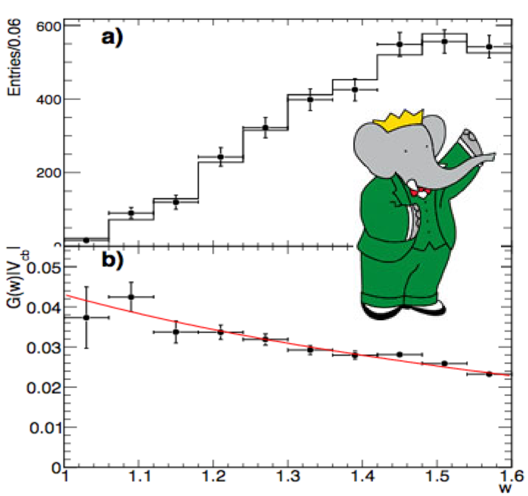
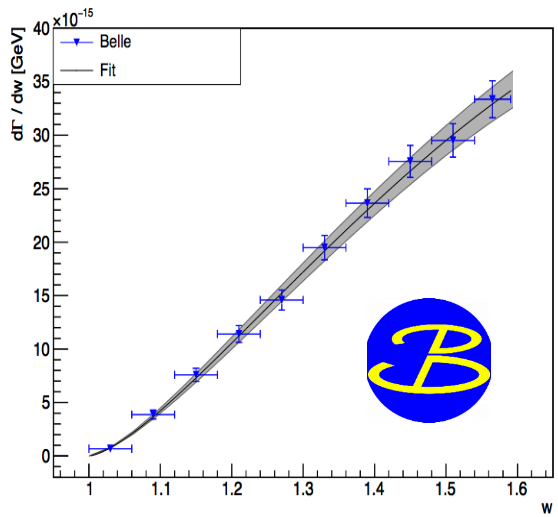
Prob.	0.97	0.95	0.29	0.82	0[illegible]

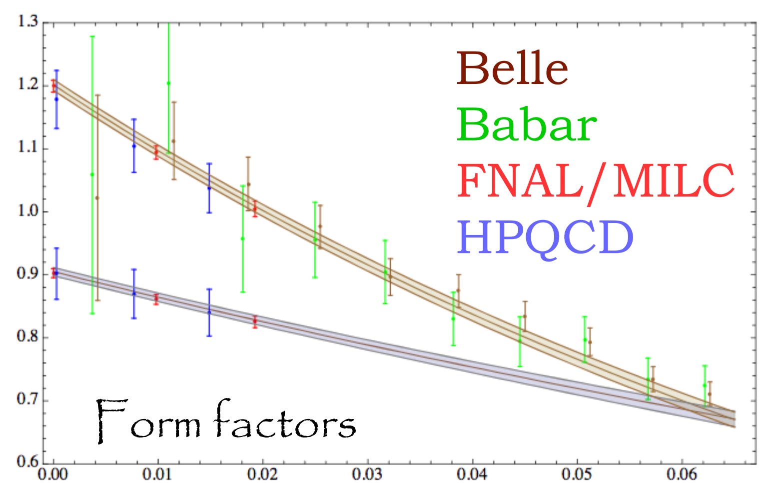
$$\mathcal{G}(1) = 1 + \mathcal{O}\left(\frac{m_B - m_D}{m_B + m_D}\frac{\Lambda_{QCD}}{m_c}\right) = 1.054 \pm 0.004 \pm 0.008$$

FNAL Lattice & MILC Coll. PhysRevD92, 034506 (2015)

$$|V_{cb}| = (39.18 \pm 0.94 \pm 0.36) \times 10^{-3}$$



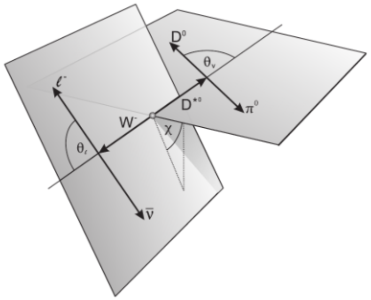




form factors $f_+(z)$ (upper plot) and $f_0(z)$ (lower plot)

$|V_{cb}|$ from $B \to D^*\ell\nu$: Untagged

- Babar, Belle select $\bar{B}^0 \to l^- \bar{\nu}_l D^{*+} (\pi^+ D^0)$
- Fit on projections, accounting for correlations



Babar:

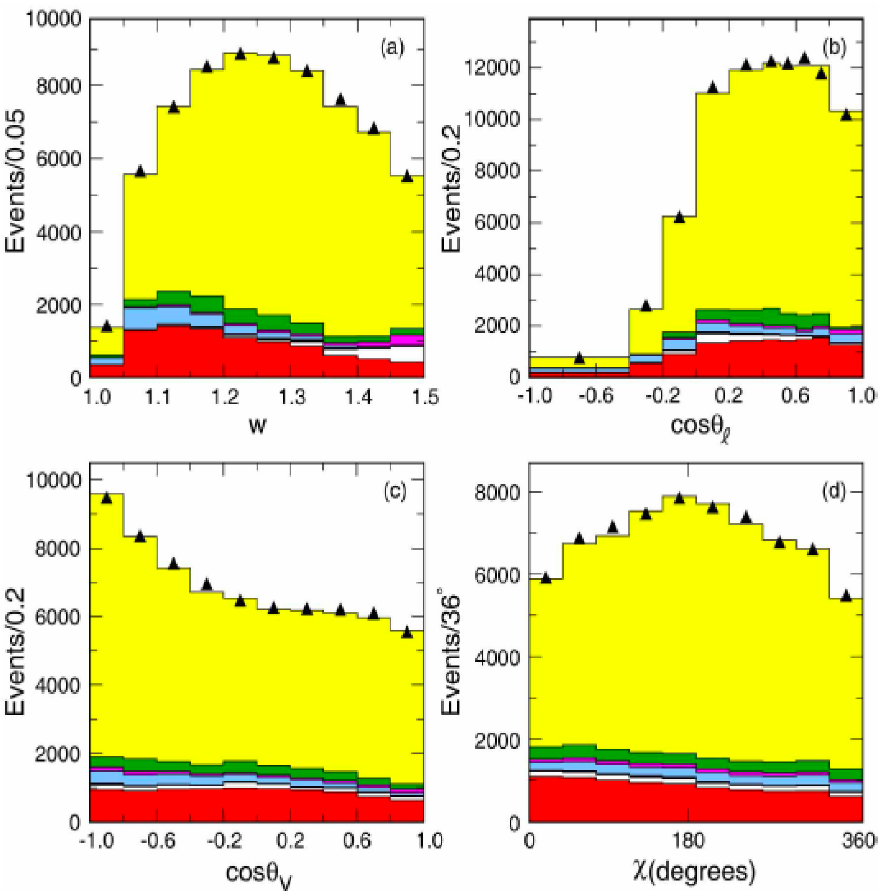
$D^0 \to K^- \pi^+, K^- \pi^+ \pi^0, K 3\pi, K_s \pi^- \pi^+$

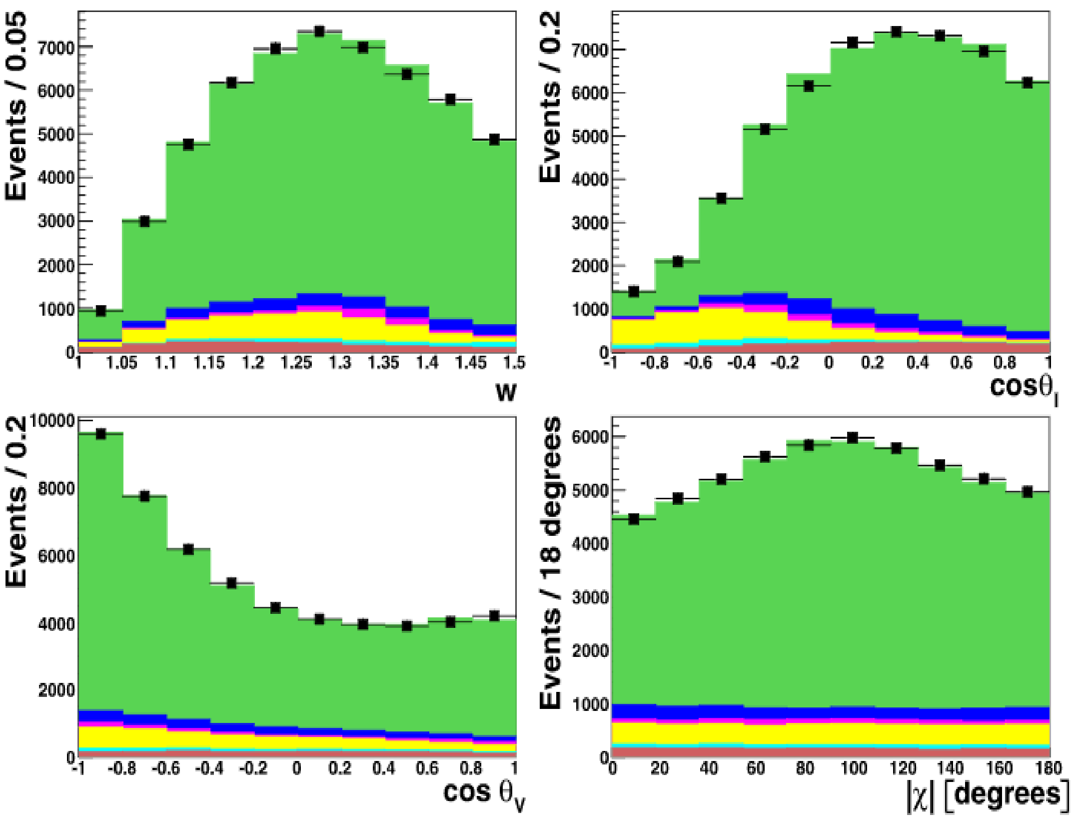
$51\, fb^{-1}$, 53000 signal events

Belle:

$D^0 \to K^- \pi^+$ only

$711\, fb^{-1}$, 120 000 signal events





$|V_{cb}|$ from $B \to D^* \ell \nu$: Untagged

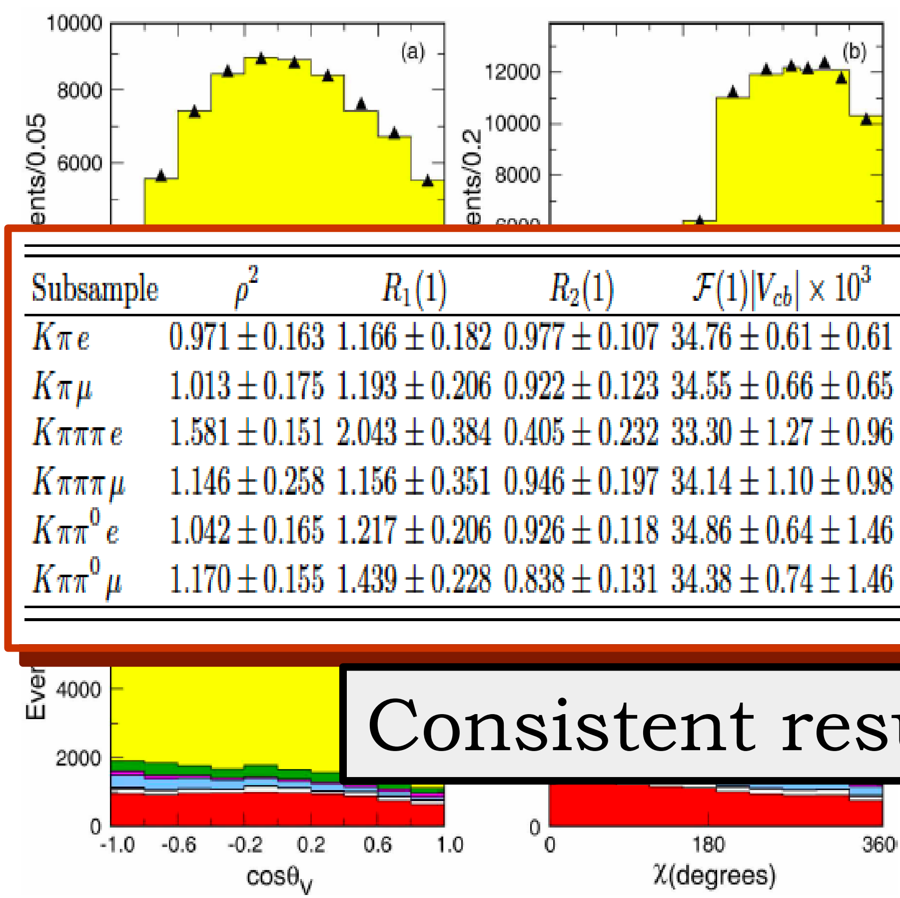
- Babar, Belle select $\bar{B}^0 \to l^- \bar{\nu}_l D^{*+}(\pi^+ D^0)$
- Fit on projections, accountig for correlations

$D^0 \to K^- \pi^+, K^- \pi^+ \pi^0, K 3\pi, K_s \pi^- \pi^+$

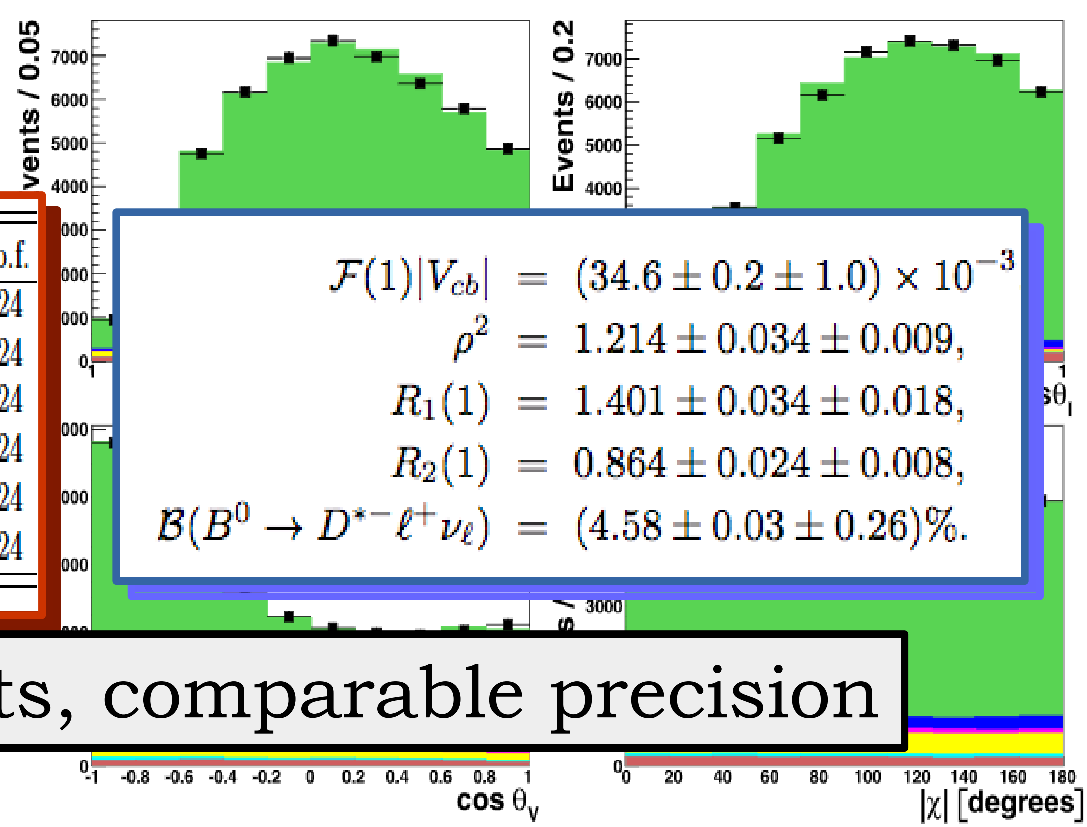
$51\, fb^{-1}$, 53000 signal events

$D^0 \to K^- \pi^+$ only

$711\, fb^{-1}$, 120 000 signal events



Subsample	ρ^2	$R_1(1)$	$R_2(1)$	$\mathcal{F}(1)\|V_{cb}\| \times 10^3$	χ^2/d.o.f.
$K\pi e$	0.971 ± 0.163	1.166 ± 0.182	0.977 ± 0.107	$34.76 \pm 0.61 \pm 0.61$	23.9/24
$K\pi\mu$	1.013 ± 0.175	1.193 ± 0.206	0.922 ± 0.123	$34.55 \pm 0.66 \pm 0.65$	37.9/24
$K\pi\pi\pi e$	1.581 ± 0.151	2.043 ± 0.384	0.405 ± 0.232	$33.30 \pm 1.27 \pm 0.96$	15.6/24
$K\pi\pi\pi\mu$	1.146 ± 0.258	1.156 ± 0.351	0.946 ± 0.197	$34.14 \pm 1.10 \pm 0.98$	28.0/24
$K\pi\pi^0 e$	1.042 ± 0.165	1.217 ± 0.206	0.926 ± 0.118	$34.86 \pm 0.64 \pm 1.46$	26.9/24
$K\pi\pi^0 \mu$	1.170 ± 0.155	1.439 ± 0.228	0.838 ± 0.131	$34.38 \pm 0.74 \pm 1.46$	24.8/24

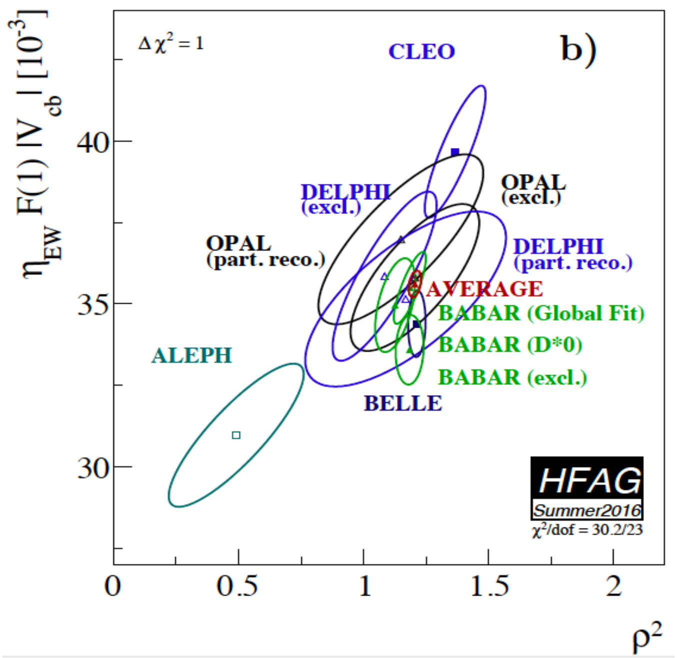


$$\mathcal{F}(1)|V_{cb}| = (34.6 \pm 0.2 \pm 1.0) \times 10^{-3}$$
$$\rho^2 = 1.214 \pm 0.034 \pm 0.009,$$
$$R_1(1) = 1.401 \pm 0.034 \pm 0.018,$$
$$R_2(1) = 0.864 \pm 0.024 \pm 0.008,$$
$$\mathcal{B}(B^0 \to D^{*-}\ell^+\nu_\ell) = (4.58 \pm 0.03 \pm 0.26)\%.$$

Consistent results, comparable precision

B-factories + LEP + CLEO average :

$$\eta_{EW}\mathcal{F}(1)|V_{cb}| = (35.61 \pm 0.43)\times 10^{-3} ,$$
$$\rho^2 = 1.205 \pm 0.026 ,$$
$$R_1(1) = 1.404 \pm 0.032 ,$$
$$R_2(1) = 0.854 \pm 0.020 ,$$



With :

$$\eta_{ew} = 1.0066 \pm 0.0050$$

$$\mathcal{F}(1) = 0.906 \pm 0.013,$$ Bailey et al., FNAL+MILC coll. Phys.Rev.D89,114504(2014)

HFLAV quotes :

$$|V_{cb}| = (38.71 \pm 0.47_{\rm exp} \pm 0.59_{\rm th}) \times 10^{-3} \qquad B \to D^*\ell\nu$$

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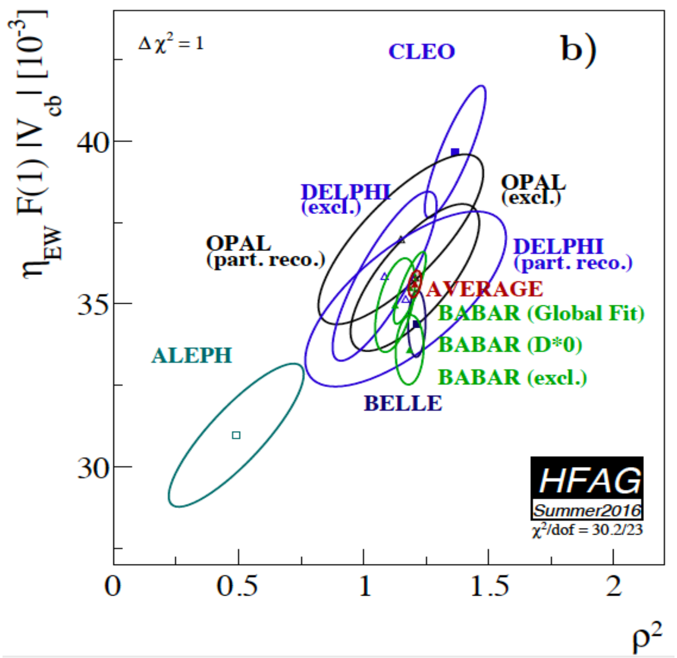

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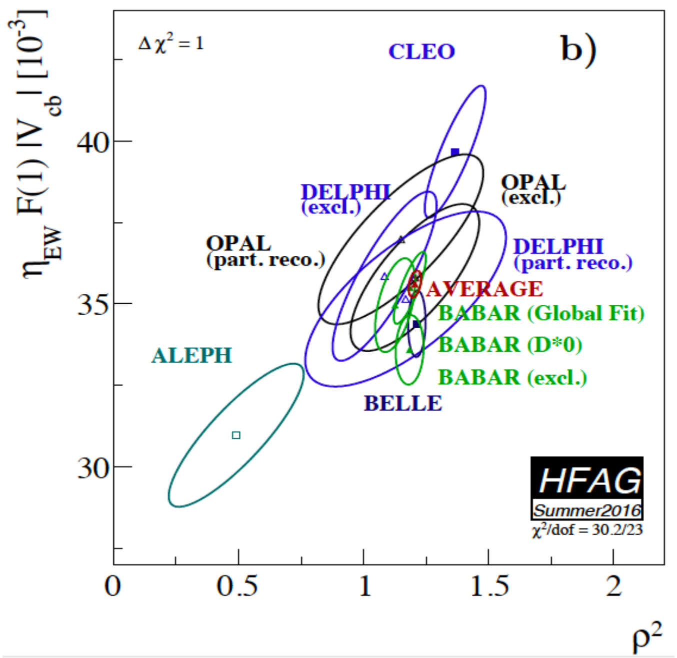

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$$|V_{cb}| = (42.19 \pm 0.78) \times 10^{-3}$$ $B \to X_c \ell \nu$

$|V_{cb}|$ tension ?

- New Belle D* tagged analysis, with about 2000 signal events
- Consistent with (but less precise than) untagged results
- Provide UNFOLDED data

Parameter	folded result	unfolded result	World Average
$\lvert V_{cb}\rvert \times 10^3$	37.4 ± 1.3	38.2 ± 1.5	39.2 ± 0.7
$\rho^2_{D^*}$	1.04 ± 0.13	1.17 ± 0.15	1.21 ± 0.03
$R_1(1)$	1.38 ± 0.07	1.39 ± 0.09	1.40 ± 0.03
$R_2(1)$	0.86 ± 0.10	0.91 ± 0.08	0.85 ± 0.02

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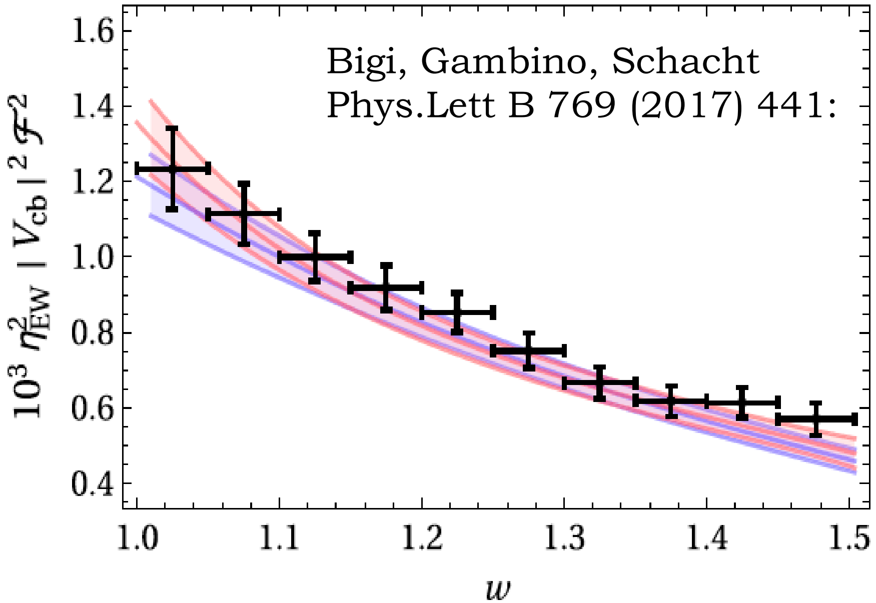

- Fit unfolded Belle data, relaxing constraints from HQS :

$$|V_{cb}| \times 10^3 = 38.2 \pm 1.5 \quad \text{CLN param.}$$
$$|V_{cb}| \times 10^3 = 41.7 \pm 2.0 \quad \text{BGL param.}$$

- "Strong possibility that the tension between inclusive & exclusive V_{cb} ... is due to CLN parameterization"

Grinstein, Kobach
PLB771 (2017) 359-364

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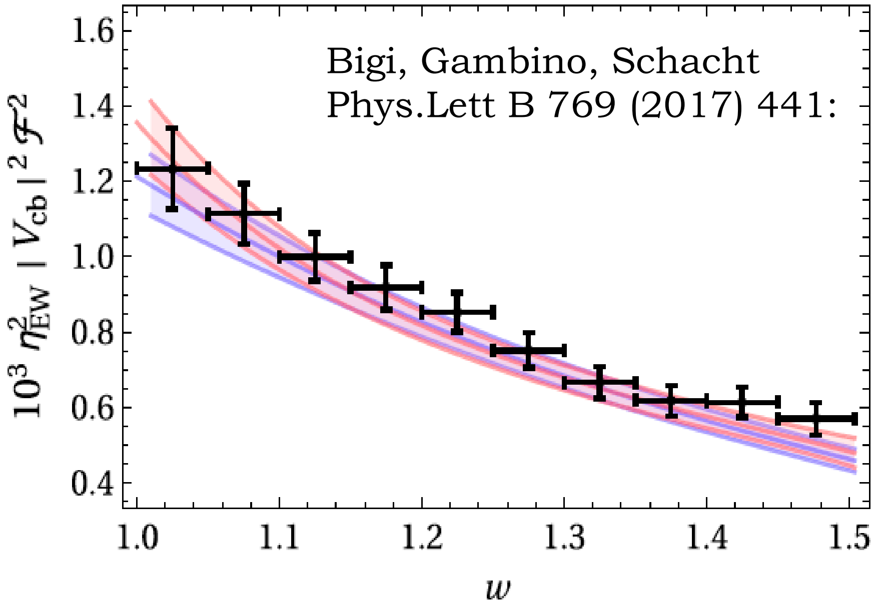

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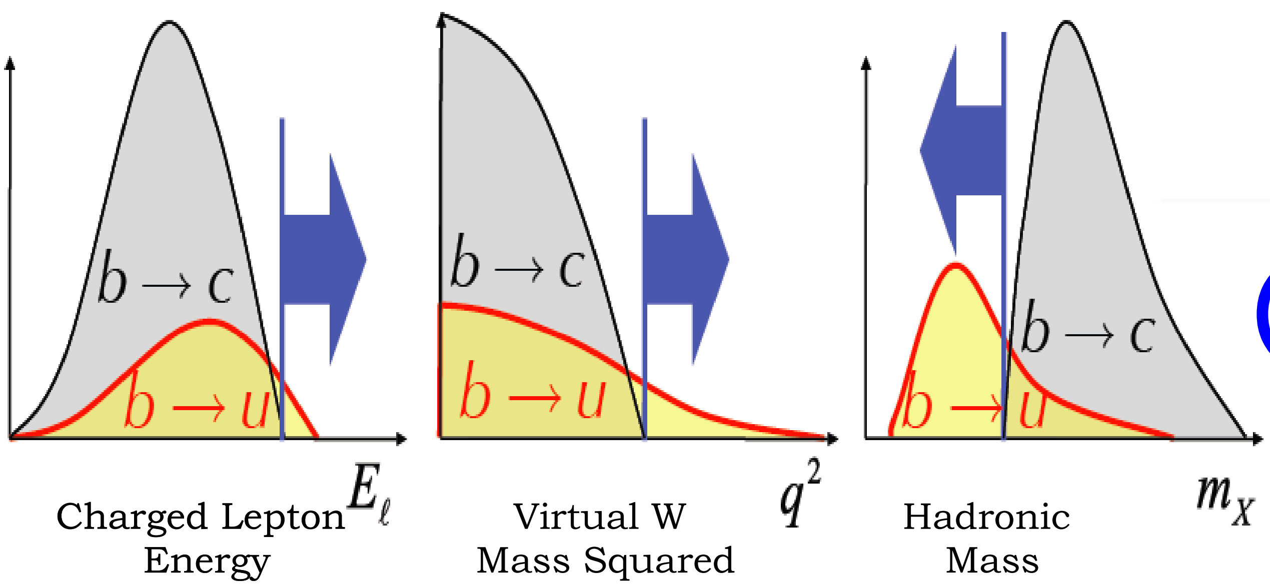
$$|V_{cb}| \times 10^3 = 41.7 \pm 2.0 \quad \text{BGL param.}$$

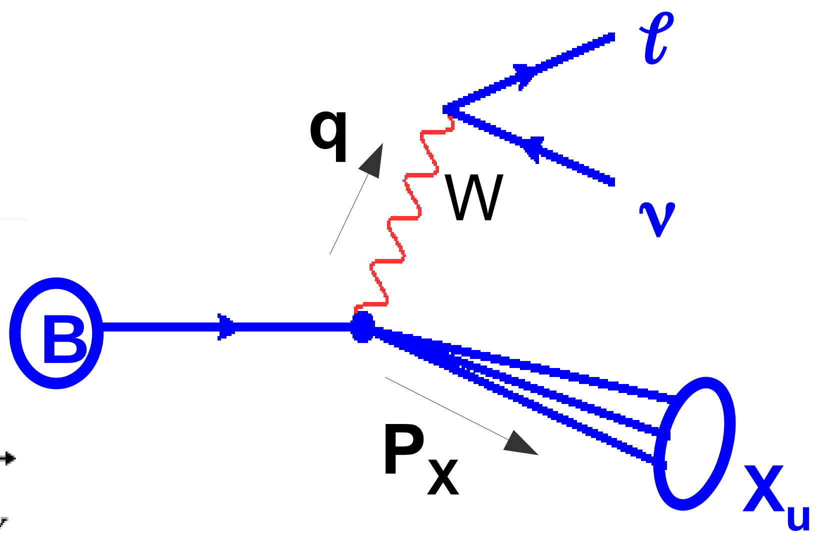
- “The central values of the BGL,..., suggest possibly large deviations from heavy quark symmetry.”

Bernlochner et al.
PhysRevD.96.091503

$|V_{ub}|$ from inclusive decays

- $$\frac{\Gamma(b \to c\ell\nu)}{\Gamma(b \to u\ell\nu)} \approx 50$$
- Need hard cuts to reduce charm background
- Select tiny fraction of the space phase, described by a"shape function"
- Large uncertainties from extrapolation to full space phase : $|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}(\overline{B} \to X_u \ell \bar{\nu})}{\tau_B \, \Delta\Gamma_{\text{theory}}}}$





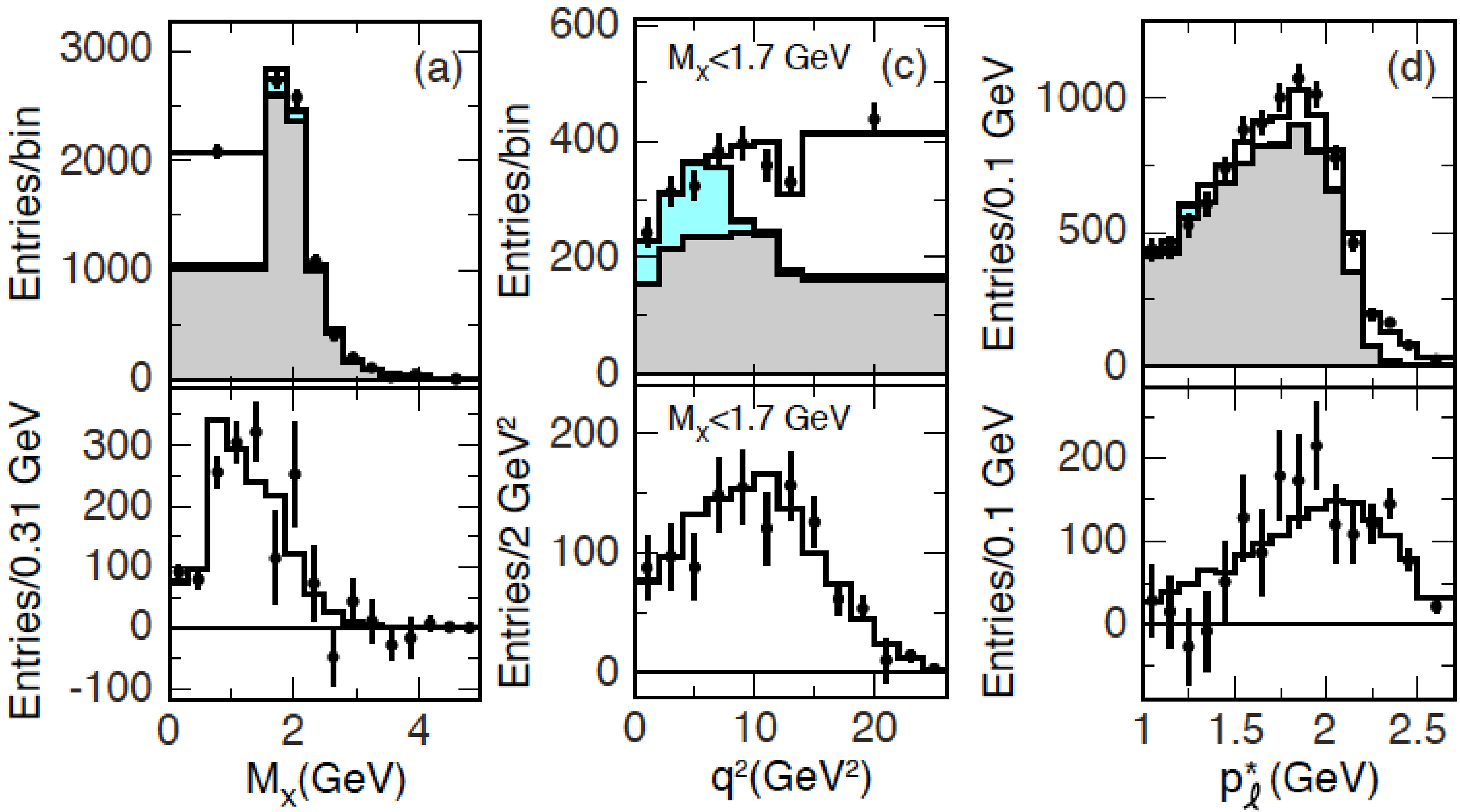
An example : tagged measurement

White : $B \to X_u \ell \nu$ signal

Grey : $B \to X_c \ell \nu$ + fakes + cascade

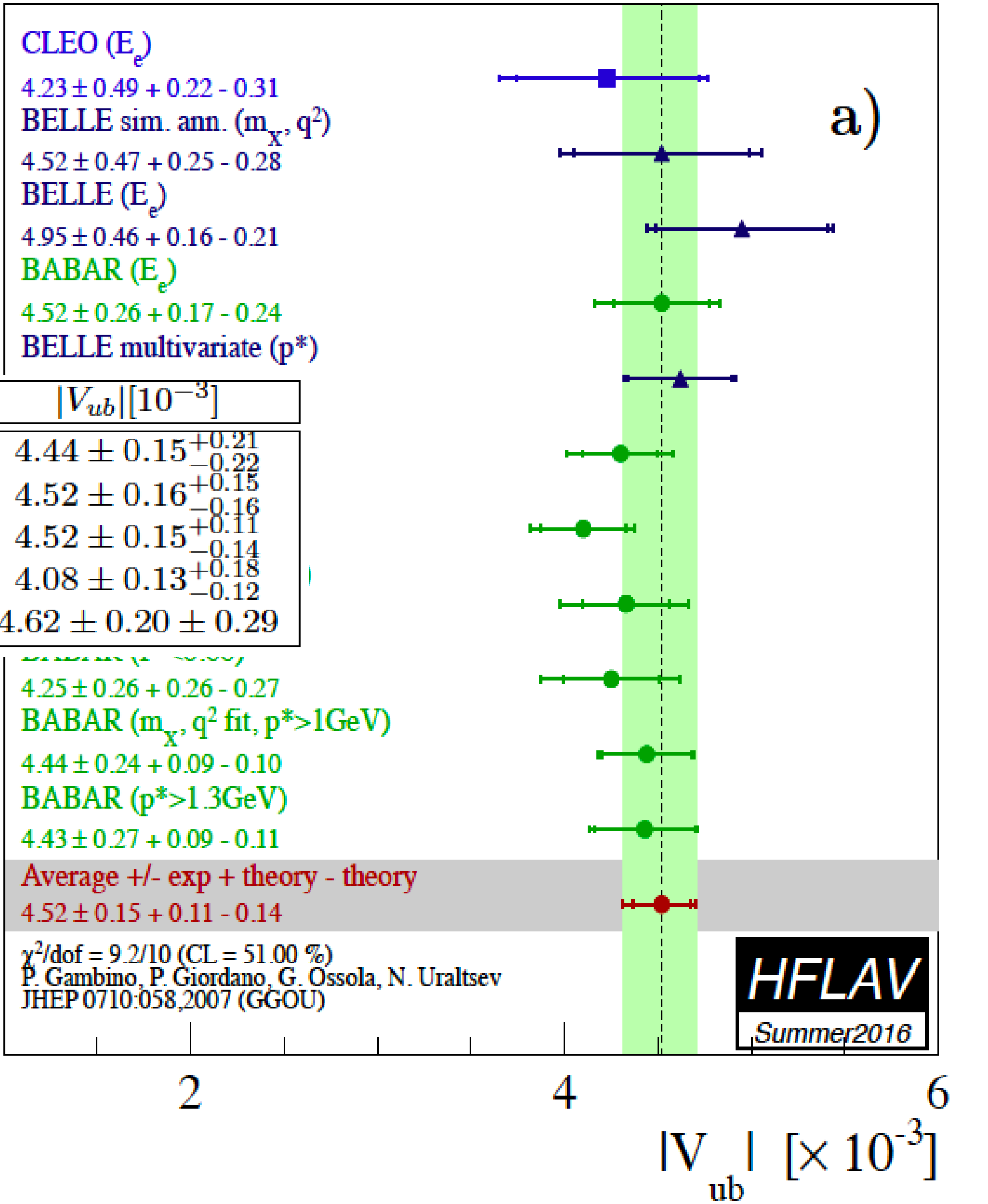
Cyan : signal feed down

Phys.Rev. D86 (2012) 032004



- Several different measurements
  - Tagged / untagged
  - Different variables
  - Different portions of phase space
- Consistent results
  - For different measurer
  - For different models
- Correlated uncertainties
  - HQE parameters (from V_{cb} fits)
  - Common tools (Jetset, background)

Framework	$\lvert V_{ub}\rvert [10^{-3}]$
BLNP	$4.44 \pm 0.15^{+0.21}_{-0.22}$
DGE	$4.52 \pm 0.16^{+0.15}_{-0.16}$
GGOU	$4.52 \pm 0.15^{+0.11}_{-0.14}$
ADFR	$4.08 \pm 0.13^{+0.18}_{-0.12}$
BLL (m_X/q^2 only)	$4.62 \pm 0.20 \pm 0.29$



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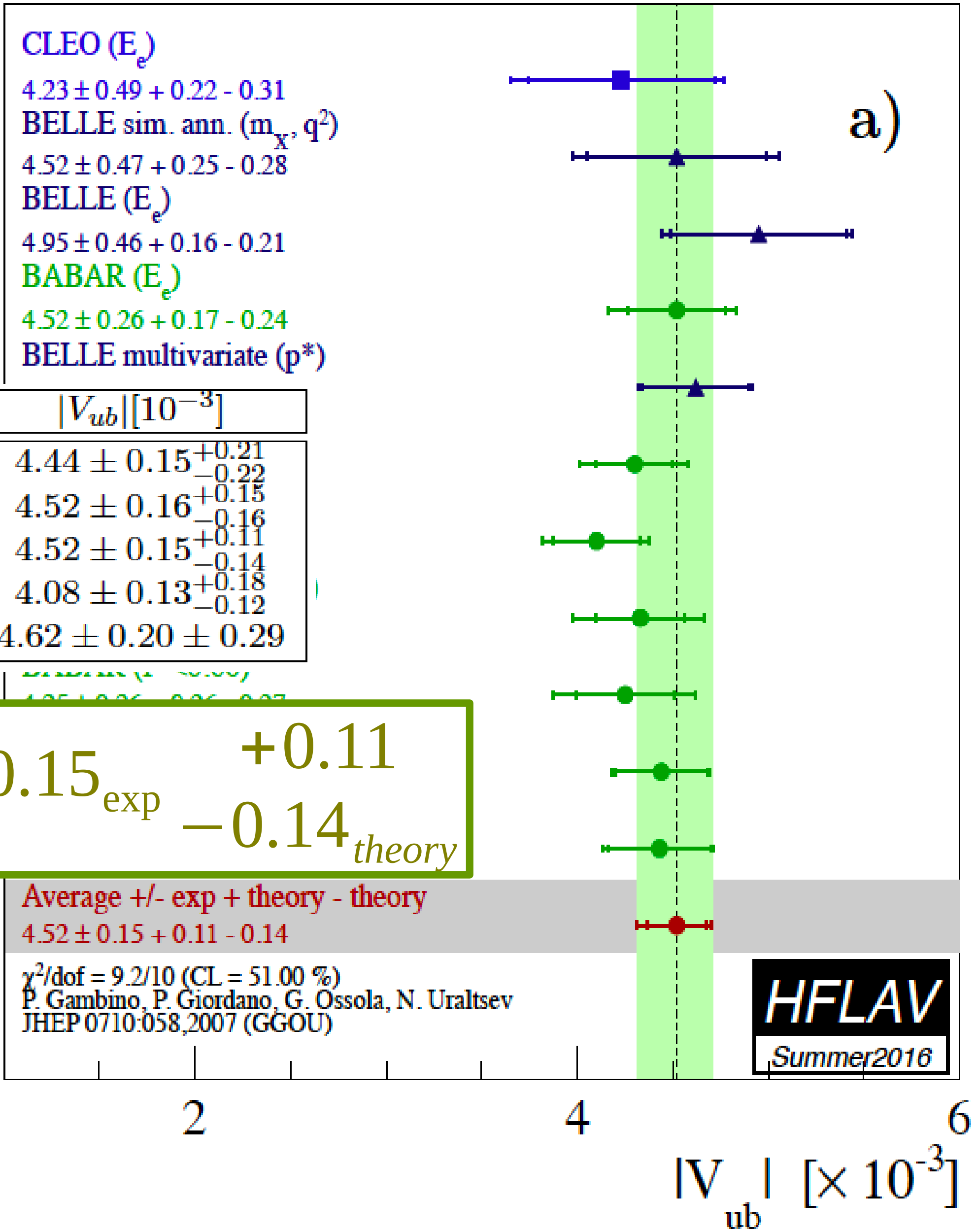

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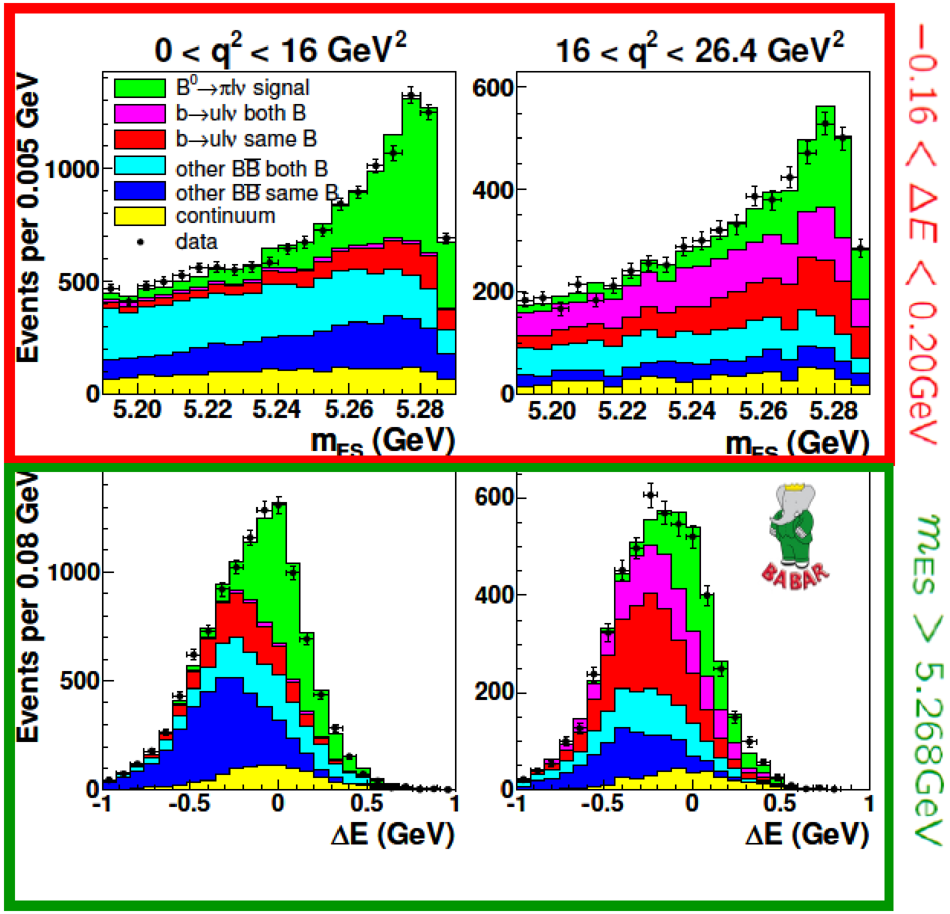
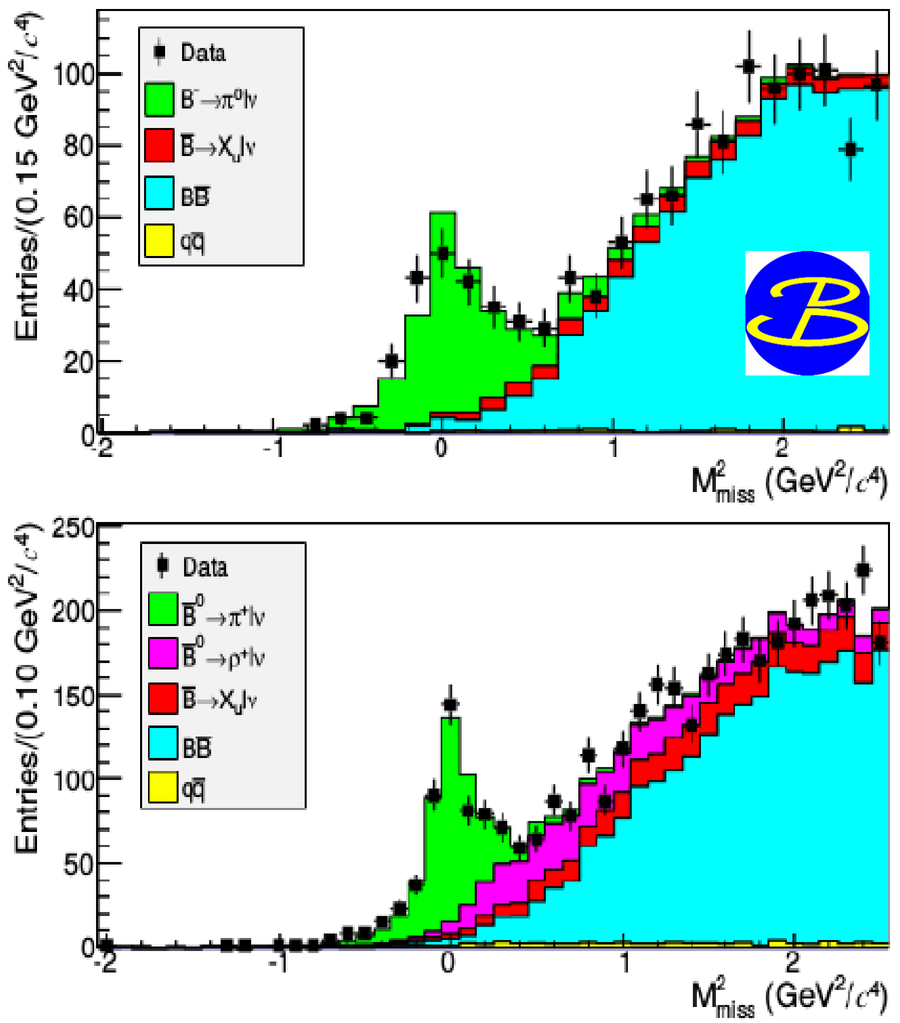
$$|V_{ub}| \times 10^3 = 4.52 \pm 0.15_{exp} \; {}^{+0.11}_{-0.14}{}_{theory}$$

$|V_{ub}|$ from $B \to \ell\nu\,\pi$

- Untagged analysis: $\vec{p}_\nu = \vec{p}_{miss}$
- Tagged analysis: use kinematic constraints



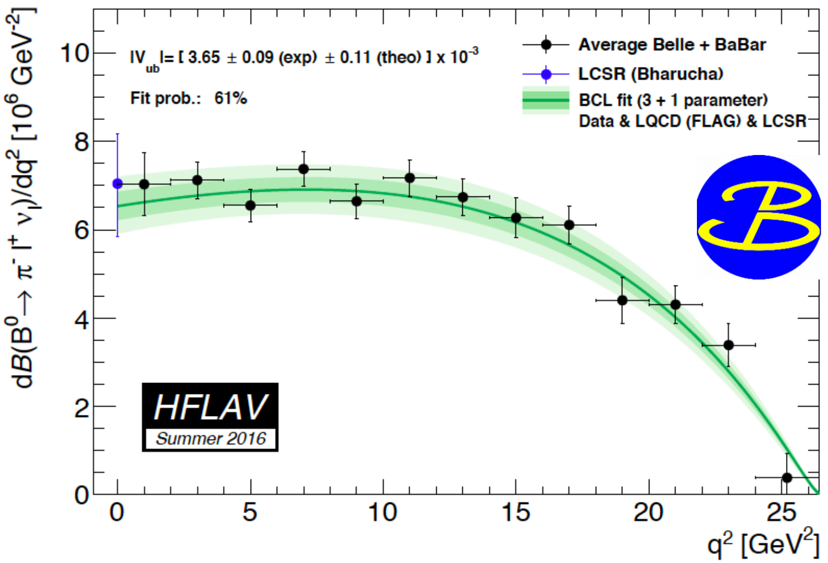


$$m_{ES} = \sqrt{E^{*2}_{beam} - \mathbf{p}^{*2}_{\pi\ell\nu}} \qquad \Delta E = E^*_{\pi\ell\nu} - E^*_{beam}$$

$|V_{ub}|$ from $B \to \ell\, \nu\, \pi$: results

- Measurements performed in q^2 bins
- Results from different measurements combined in a single distribution
- Theory constraints:
  - LQCD at high q^2 — FNAL/MILC EurPhysJ C77(2017)2,112
  - LCSR at $q^2 = 0$ — Bharucha JHEP 1205(2012)092
- FF parameterization as in : Bourrely, Caprini, Lellouch, PRD79, 013008 (2009)

$$f_+(q^2, \vec{b}) = \frac{1}{1 - q^2/m_{B^*}^2} \sum_{k=0}^{K} b_k(t_0)\, z(q^2)^k$$



Parameter	Value
$\lvert V_{ub}\rvert$	$(3.65 \pm 0.14) \times 10^{-3}$
b_1^+	0.421 ± 0.017
b_2^+	-0.390 ± 0.033
b_3^+	-0.650 ± 0.126

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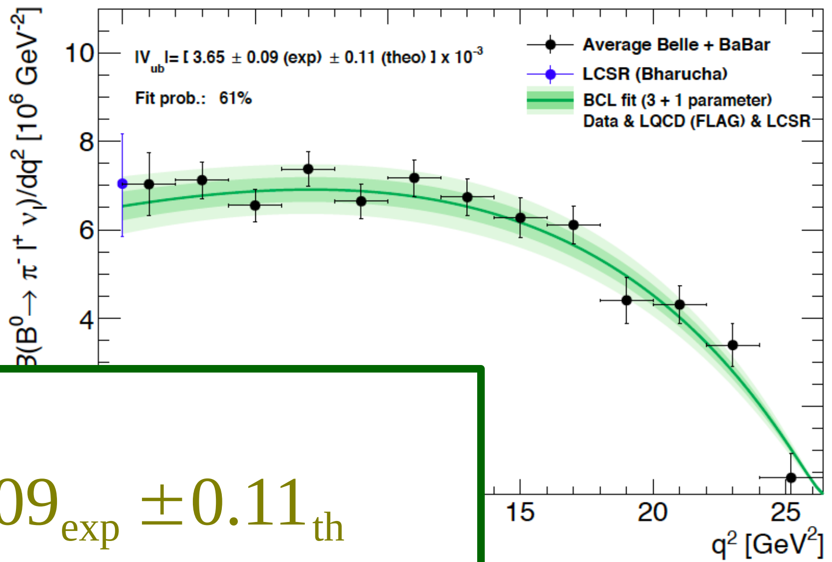
Bourrely, Caprini,
PRD79, 013008 (2



$$|V_{ub}| \times 10^3 = 3.65 \pm 0.09_{exp} \pm 0.11_{th}$$

$$Br(B \to \pi l \nu) \times 10^4 = 1.47 \pm 0.02_{exp} \pm 0.06_{th}$$

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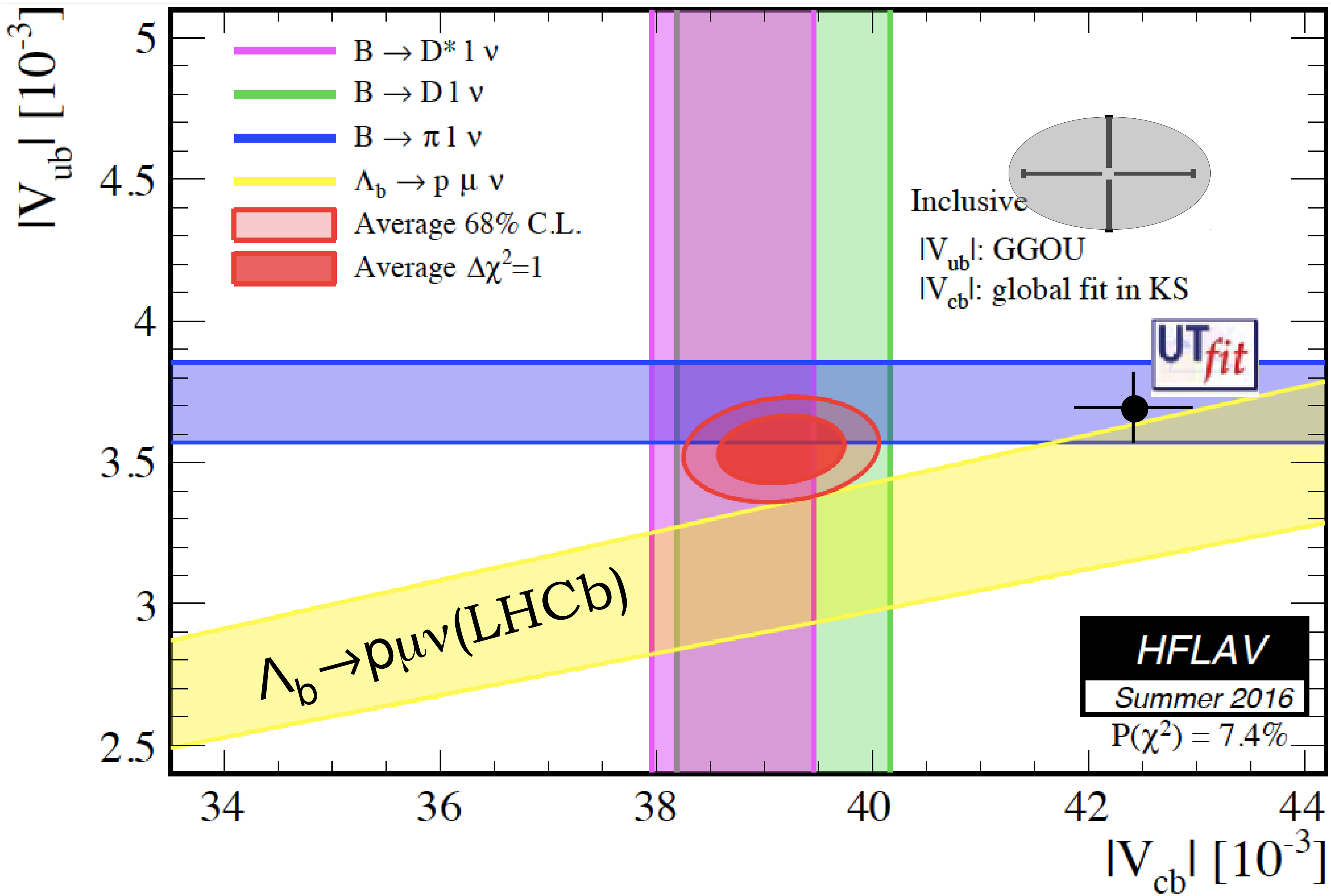

B → D* l ν
B → D l ν
B → π l ν
Λb → p μ ν
Average 68% C.L.
Average Δχ²=1
Inclusive
|Vub|: GGOU
|Vcb|: global fit in KS
UTfit
Λb→pμν(LHCb)
HFLAV
Summer 2016
P(χ²) = 7.4%
|Vub| [10⁻³]
|Vcb| [10⁻³]
5
4.5
4
3.5
3
2.5
34
36
38
40
42
44

$B \to D^* \tau \nu_\tau$

- Heavy lepton :
  - One more Form Factor (no exp. constraint, use LQCD)
  - Reduced Phase space
  - Focus on semileptonic τ decays
  - Lower event rate : $\frac{\Gamma(B \to X_c \tau \bar{\nu}) \times B(\tau \to l \nu \bar{\nu}_l)}{\Gamma(B \to X_c l \bar{\nu})} \simeq \frac{1}{5} x 0.34 \simeq 7\%$

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- Tag variables :
  - Large missing mass (three neutrinos)
  - Softer lepton momentum
  - Residual energy (apart B_{TAG} , $D^{(*)}$ τ)

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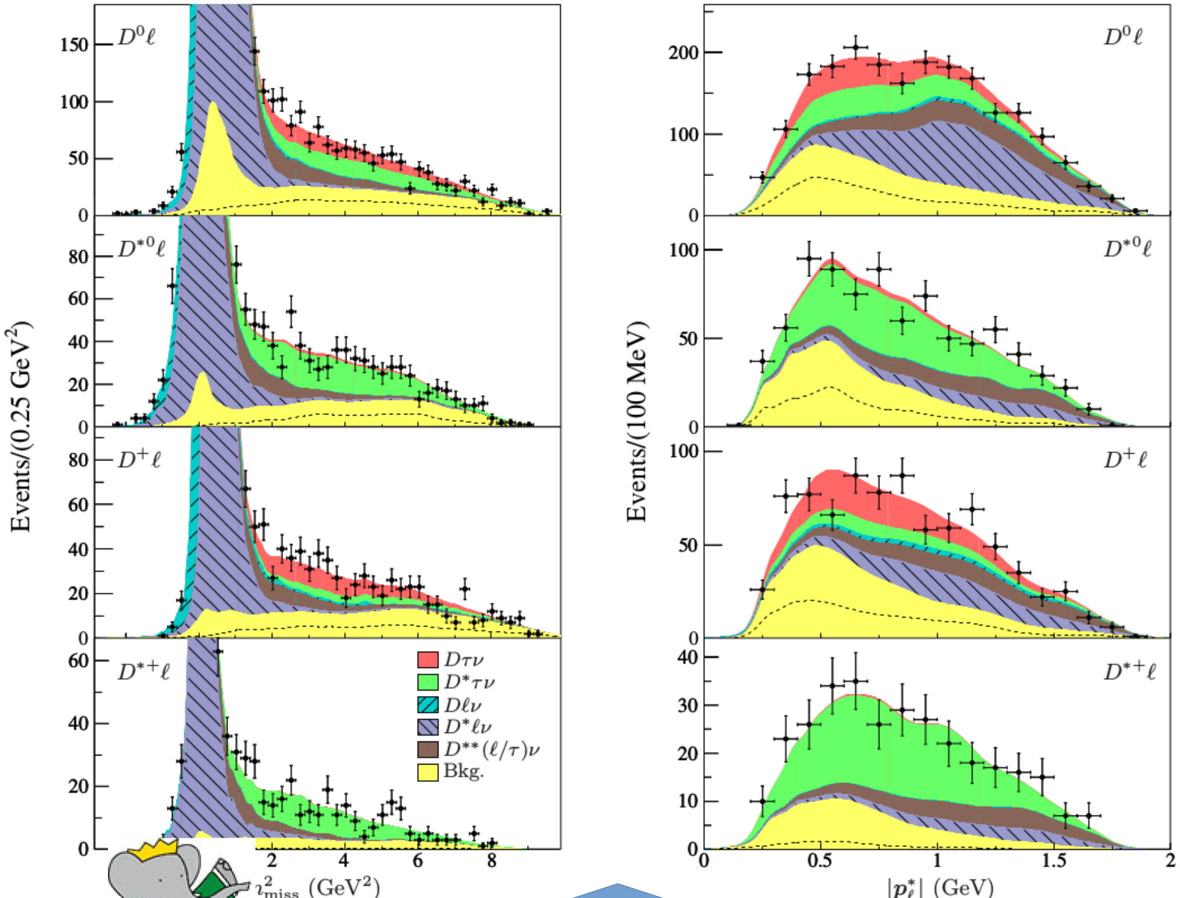
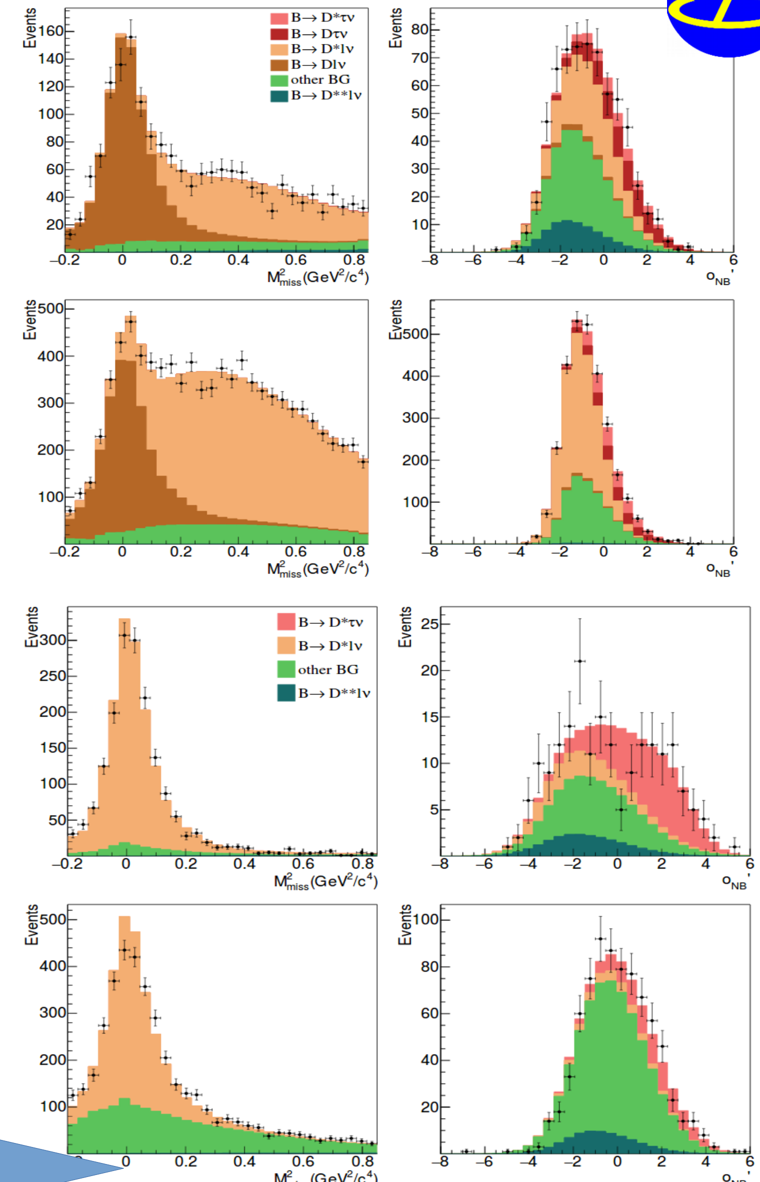
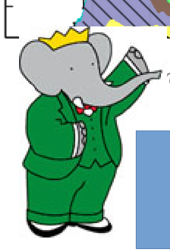
  - Residual energy (apart B_{TAG} , $D^{(*)}$ τ)

- Measure ratios : $R(D^{(*)}) = \frac{\Gamma(B\to X_c \tau \bar{\nu}) \times B(\tau \to l \nu \bar{\nu}_l)}{\Gamma(B \to X_c l \bar{\nu}_l)}$



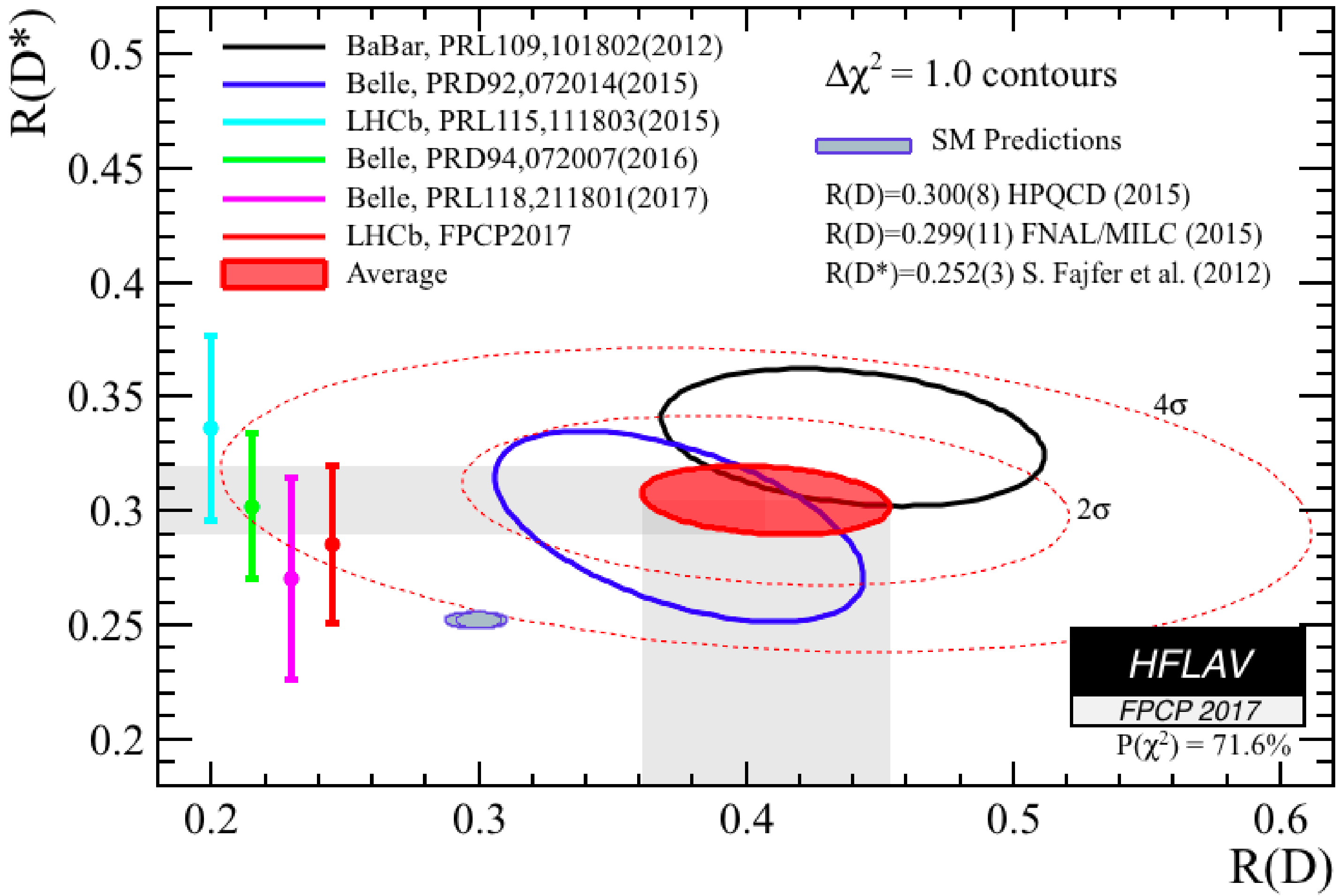




2d fit to m^2_{miss} p_{lep}

Normalize bck. (m^2_{miss} <0.8)
Fit MVA for (m^2_{miss} >0.8)

B → D* τ ν_τ : results



- Combined measurement of R(D) and R(D*) ~ 4 σ away from SM !

Conclusions (1)

- Semileptonic B decays are studied since more than 30 years
- Despite noticeable progressess
  - Sofisticated detectors, huge event size, tagged analysis, MVA discriminators
  - Precise LQCD, HQE, HQET, LCSR calculations
- ... still many inconsistencies around :
  - Inclusive vs exclusive V_{cb}
  - Inclusive vs exclusive V_{ub}
  - $R(D^{(*)})$
  - $\Sigma i\, B(\ell\nu D_i) < B(\ell\nu X_c)$ (not discussed here)

UT fits prefer :
- Inclusive V_{cb}
- Exclusive V_{ub}

(that's not the way we want to play it)

Conclusions (2)

- Exclusive V_{cb}:
  - Reanalysis of high statistics data set with alternative parameterizations of FF
  - Complete angular analysis on 4d space instead of fit to projections
- Inclusive V_{ub} :
  - Improve control of $B \to X_c \ell \nu$ background
  - Consistent use of signal and background models in extracting results
- $R(D^{(*)})$:
  - Improve understanding of $B \to \ell \nu D^{**} (\to Dnh)$ background
  - ... hints of new Physics ?


THE ELEVENTH COMMANDMENT
XI
THOU SHALT MAKE BACK-UPS!

$|V_{cb}|$ tension ? (Backup)

$$\langle D^* | \bar{c}\gamma^\mu b | \overline{B}\rangle = i\sqrt{m_B m_{D^*}}\, h_V\, \varepsilon^{\mu\nu\alpha\beta}\, \epsilon^*_\nu v'_\alpha v_\beta\,,$$

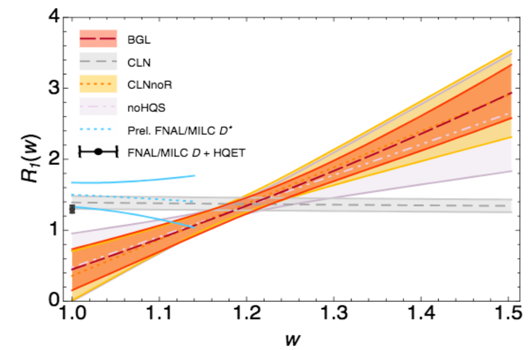
$$\langle D^* | \bar{c}\gamma^\mu \gamma^5 b | \overline{B}\rangle = \sqrt{m_B m_{D^*}}\, \big[h_{A_1}(w+1)\epsilon^{*\mu} - h_{A_2}(\epsilon^*\cdot v)v^\mu - h_{A_3}(\epsilon^*\cdot v)v'^\mu\big]$$

- Exact Heavy Quark Symmetry : $h_V = h_{Ai} = Z(w)$ (Isgur Wise function)
- HQS bounds :

$$R_1(w) = \frac{h_V}{h_{A_1}}\,, \qquad R_2(w) = \frac{h_{A_3} + r_{D^*} h_{A_2}}{h_{A_1}} = 1 + \mathcal{O}(\Lambda_{QCD}/m_{c,b},\, \alpha_s)$$

$$h_{A_1}(w) = h_{A_1}(1)\big[1 - 8\rho^2_{D^*} z + (53.\, c_{D^*} - 15.)z^2\big] \quad c_{D^*} = \rho^2_{D^*}$$

	CLN	CLNnoR	noHQS	BGL
$\lvert V_{cb}\rvert \times 10^3$	38.2 ± 1.5	41.5 ± 1.9	41.8 ± 1.9	41.5 ± 1.8
$\rho^2_{D^*}$	1.17 ± 0.15	1.6 ± 0.2	1.8 ± 0.4	1.54 ± 0.06
c_{D^*}	$\rho^2_{D^*}$	$\rho^2_{D^*}$	2.4 ± 1.6	fixed: $15./53.$
$R_1(1)$	1.39 ± 0.09	0.36 ± 0.35	0.48 ± 0.48	0.45 ± 0.28
$R_2(1)$	0.91 ± 0.08	1.10 ± 0.19	0.79 ± 0.36	1.00 ± 0.18
$R'_1(1)$	fixed: -0.12	5.1 ± 1.8	4.3 ± 2.6	4.2 ± 1.2
$R'_2(1)$	fixed: 0.11	-0.89 ± 0.61	0.25 ± 1.3	-0.53 ± 0.42
χ^2 / ndf	35.2 / 36	27.9 / 34	27.6 / 33	27.7 / 34



Bernlochner et al. PhysRevD.96.091503

$|V_{cb}|$ tension ? (Backup)

$$\langle D^*|\,\bar{c}\gamma^\mu b\,|\overline{B}\rangle = i\sqrt{m_B m_{D^*}}\,h_V\,\varepsilon^{\mu\nu\alpha\beta}\,\epsilon^*_\nu v'_\alpha v_\beta\,,$$

$$\langle D^*|\,\bar{c}\gamma^\mu\gamma^5 b\,|\overline{B}\rangle = \sqrt{m_B m_{D^*}}\,\big[h_{A_1}(w+1)\epsilon^{*\mu} - h_{A_2}(\epsilon^*\cdot v)v^\mu - h_{A_3}(\epsilon^*\cdot v)v'^\mu\big]$$

- Exact Heavy Quark Symmetry : $h_V = h_{A_i} = Z(w)$ (Isgur Wise function)
- HQS bounds :

$$R_1(w) = \frac{h_V}{h_{A_1}}\,, \qquad R_2(w) = \frac{h_{A_3} + r_{D^*} h_{A_2}}{h_{A_1}} = 1 + \mathcal{O}(\Lambda_{\rm QCD}/m_{c,b},\,\alpha_s)$$

$$h_{A_1}(w) = h_{A_1}(1)\big[1 - 8\rho^2_{D^*} z + (53.\,c_{D^*} - 15.)z^2\big]$$