Measurements of $|V_{cb}|$ @ ***BaBar***

Session: Heavy Flavour Physics I

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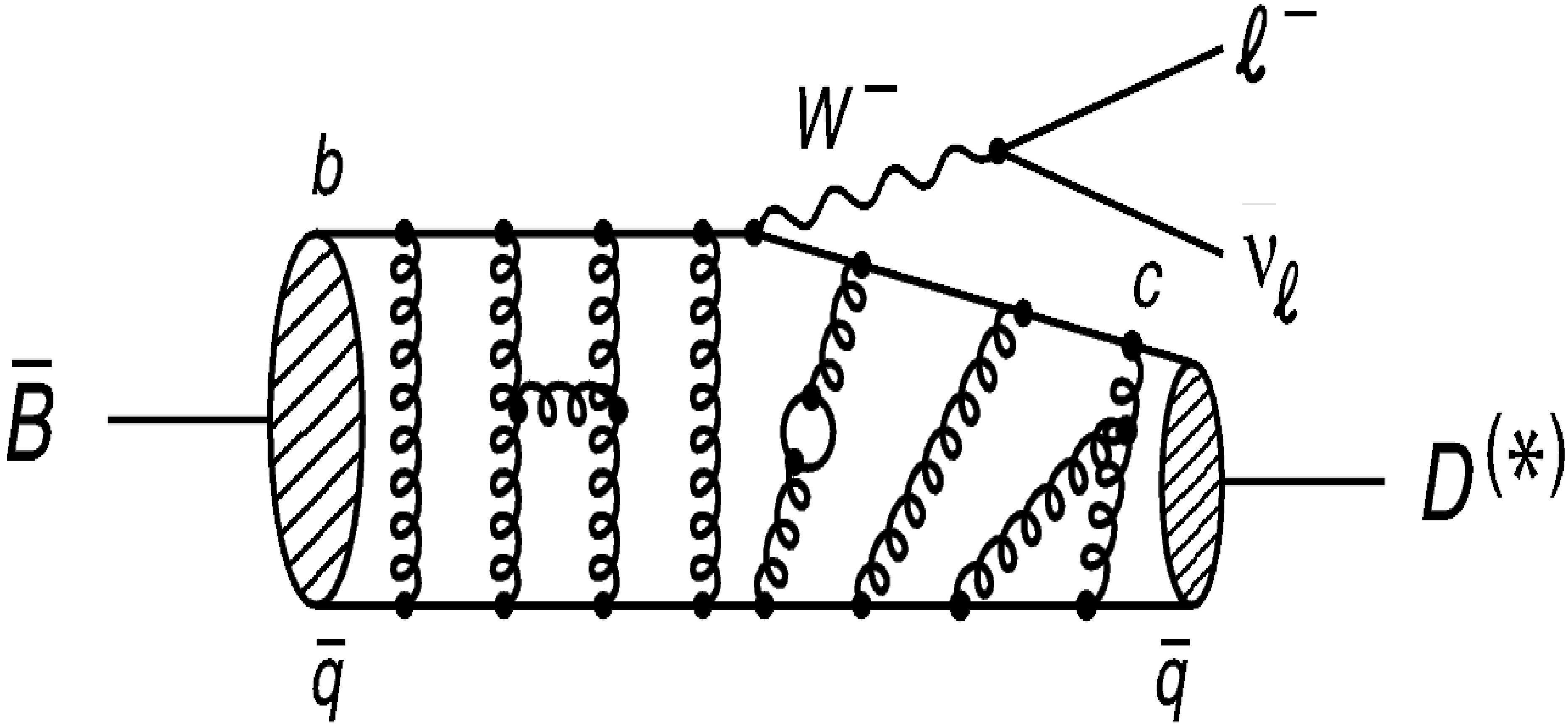
On Behalf of the BaBar Collaboration:
Enrico Feltresi
(INFN Padova)

Outline

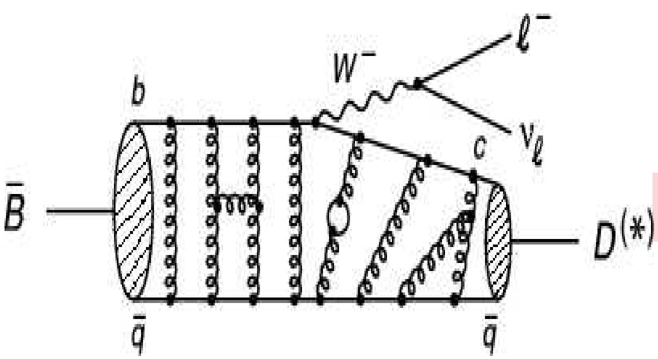
- $|V_{cb}|$ and ***FF*** from exclusive $B \to D\ell\nu$ decays
  - Hadronic tagged $B \to D\ell\nu$
  - Untagged global fit to $B \to DX\ell\nu$
- Measurements of Moments in inclusive Semileptonic Decay $B \to X_c\ell\nu$:
  - Extraction of $|V_{cb}|$, m_b, m_c, $\mathcal{B}(B \to X_c\ell\nu)$ and leading non perturbative QCD parameters
- Conclusions

Exclusive B → $D^{(*)}\ell\nu$ decays



Why B $\rightarrow D\ell\nu$ decays?

Simple and Clean way to get $|V_{cb}|$ and B FF parameter (ρ)



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

Phase Space

$$K(w) = m_D^3 (m_B + m_D)^2 \cdot (w^2 - 1)^{3/2}$$

$$\frac{d\Gamma}{dw} = \frac{G_f^2}{48\pi^3} \cdot K(w) \cdot |V_{cb}|^2 \cdot G_D^2(w).$$

- Form Factors describe Hadronization processes.
- Only one FF in the limit of very small lepton mass
- Expression of $G_D(w)$ from Lattice QCD and HQET

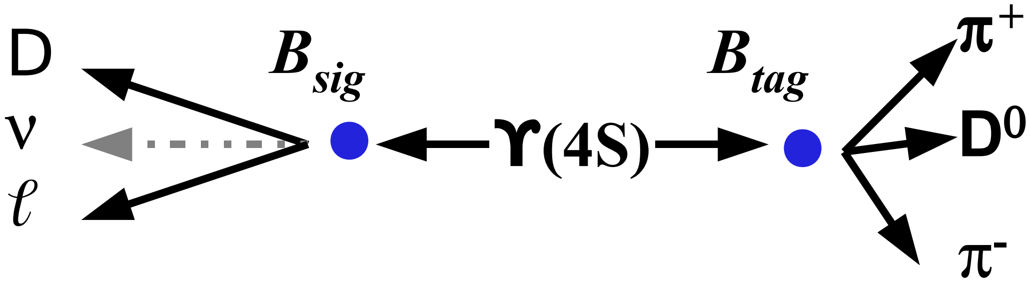
Using Caprini et al. parameterization (CLN): Nucl.Phys.B 530 (1998), 153

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

$$G(w) = G(1)[1 - 8\rho^2 z + (51\rho^2 - 10) z^2 - (252\rho^2 - 84) z^3]$$

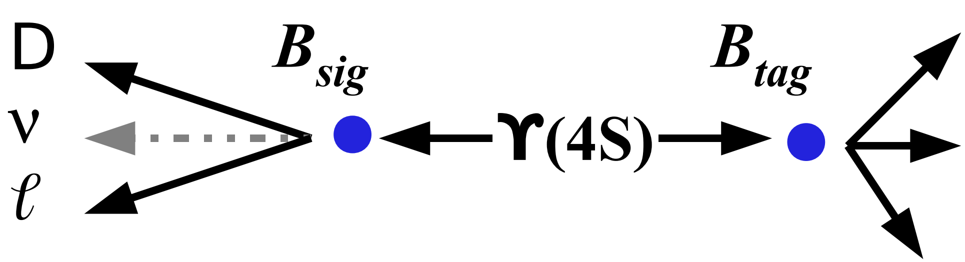
Experimental Methods

Hadronic tag

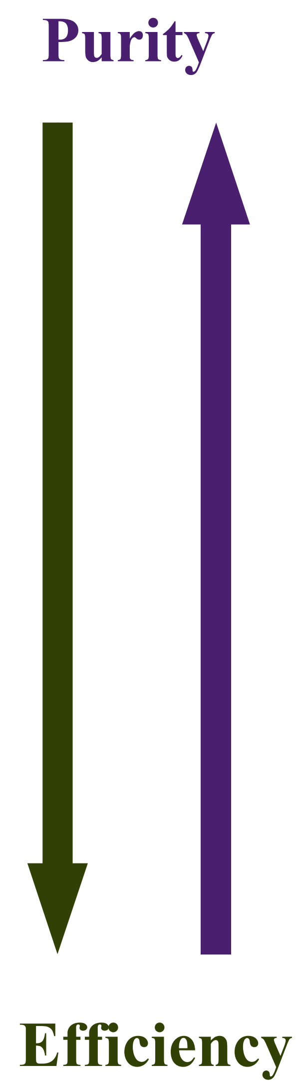


- Reco. B→D(*)Y
- Y=π,K
- Several decays mode
- Kinematic, charge and flavour known

Untagged



- Only signal reco.
- High statistic



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Hadronic tagged $B \to D\ell\nu$

- Reconstruct $\mathbf{B^{+/0} \to D^{0/+}\ell\nu}$ on the recoil of about 1000 fully reco. B final states ($\mathbf{D^{0/+}}$ reco. in 9/7 different final states)

  ☺ High purity (S/S+B)

  ☺ Good Resolution

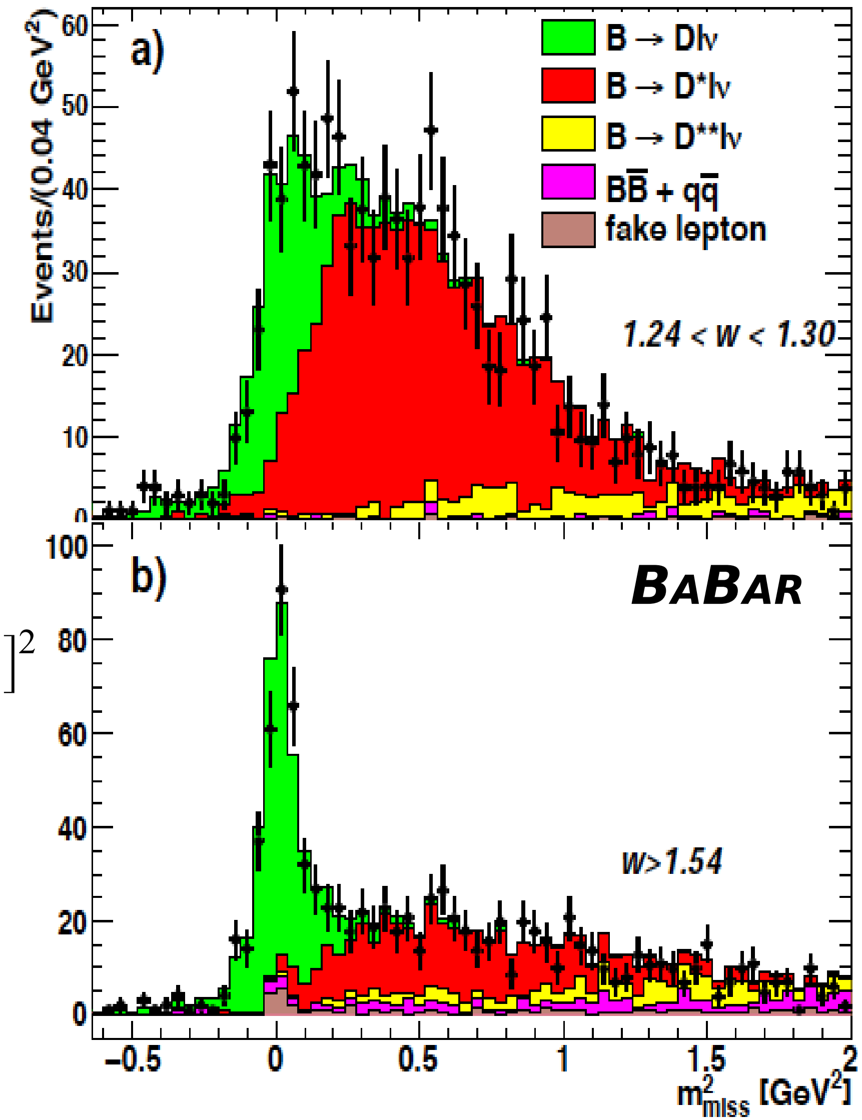
  ☹ Very Low efficiency (0.2%÷0.5%)

- Missing Mass squared (MM^2)used to identify semileptonic B decay

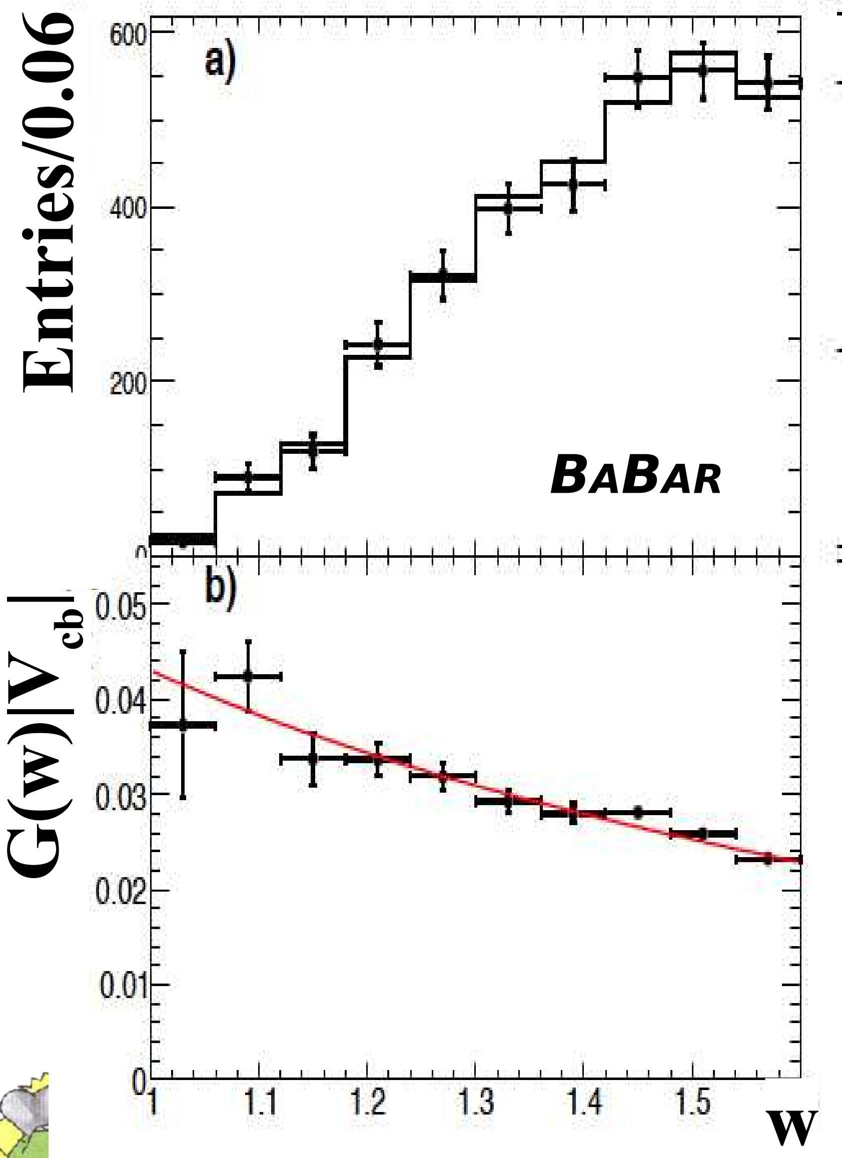
$$m^2_{miss} = [P(\Upsilon(4S)) - P(B_{tag}) - P(D) - P(lepton)]^2$$

- Signal Events Yields from a binned maximum likelihood fit to MC sources in 10 bins of w

- $G(1)|V_{cb}|$ and ρ^2 extracted with a χ^2-fit to the w-distribution



Tagged $B \to D\ell\nu$: Results



	$B^- \to D^0\ell^-\bar{\nu}_\ell$	$\bar{B}^0 \to D^+\ell^-\bar{\nu}_\ell$
$\mathcal{G}(1)\|V_{cb}\| \cdot 10^3$	41.0±2.1 ±1.3	44.9± 3.2±1.6
ρ^2	1.14± 0.11±0.04	1.29± 0.14±0.05
ρ_{corr}	0.943	0.950
χ^2/ndf	3.4/8	5.6/8
Signal Yield	2147 ± 69	1108 ± 45
Recon. efficiency	$(1.99 \pm 0.02) \times 10^{-4}$	$(1.09 \pm 0.02) \times 10^{-4}$
$\mathcal{B}$	(2.29± 0.08 ± 0.09)%	(2.21± 0.11 ± 0.11)%

Combined Results:

$G(1)|V_{cb}| = (42.3 \pm 1.9 \pm 1.4)\text{x}10^3$

$\rho^2 = 1.20 \pm 0.09 \pm 0.04$

$Br(B^0 \to D\ell\nu) = (2.15 \pm 0.06 \pm 0.07)\%$

5.6% total error on $G(1)|V_{cb}|$

Untagged $B \to D^{(*)}\ell\nu$

- Select $B^{+/0} \to D^{0/+}\ell\nu$ with $p_\ell > 1.2$GeV/c, no D(*,**) reco.

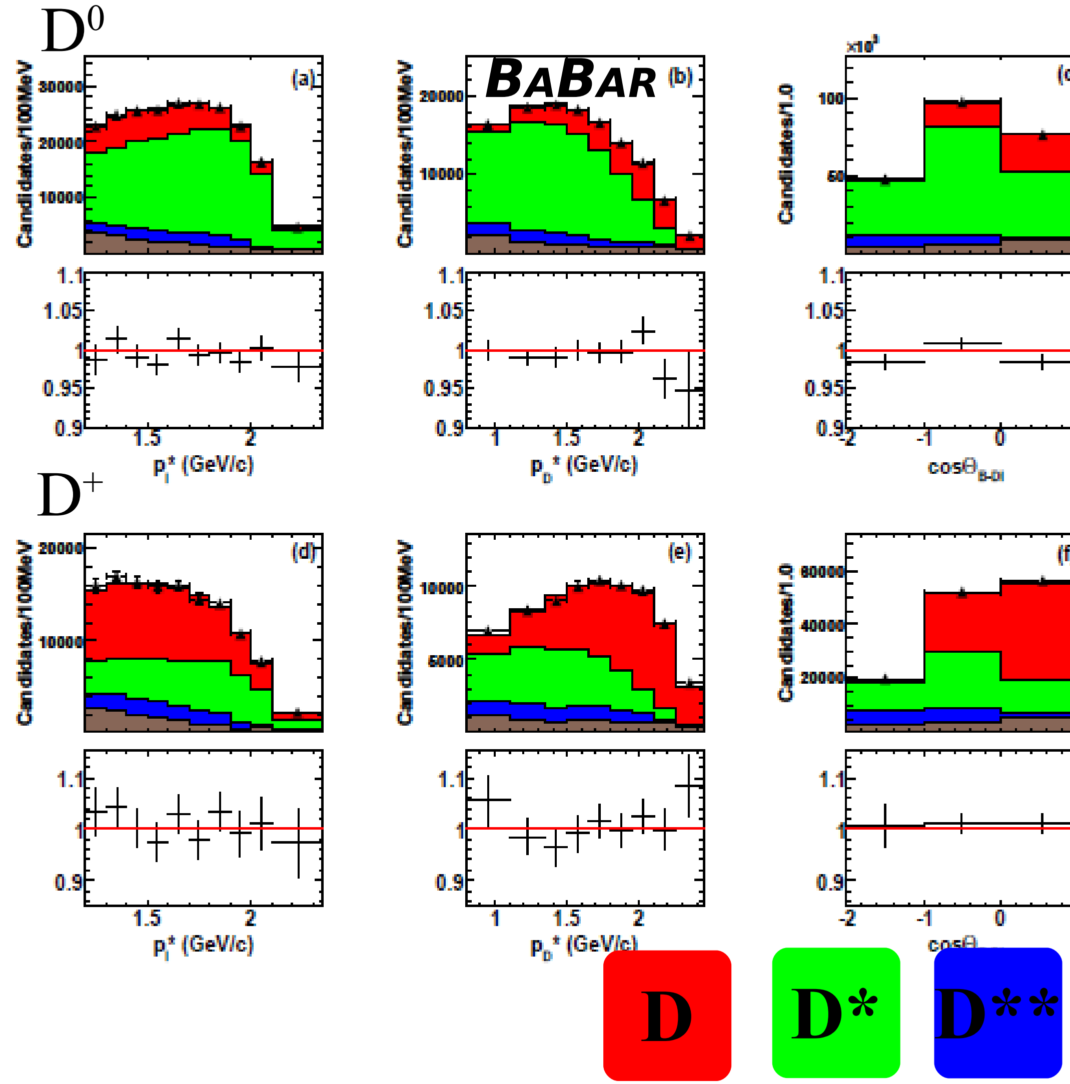
  ☺ High Signal yields

  ☹ High Systematics:

  Physics Modeling: FF and BR for $B \to D(*)\pi l\nu$, $B \to D(*)\pi\pi l\nu$, D* and D .

- Get D/D* rates and FF slope (ρ_D^2,ρ_{D*}^2) with a binned 3D fit to p_ℓ,p_D,$\cos\theta_{BY}$
- Relate BR(B^0) to BR(B^+) using lifetime ratio
- The analysis is sensitive to $|V_{cb}|$

- 1-D projections for p_ℓ,p_D,$\cos\theta_{BY}$



Untagged $B \to D^{(*)}\ell\nu$: Results

$\mathcal{G}(1)|V_{cb}| = (43.1 \pm 0.8 \pm 2.3) \times 10^{-3}$ 5.5% total error (mainly sys)

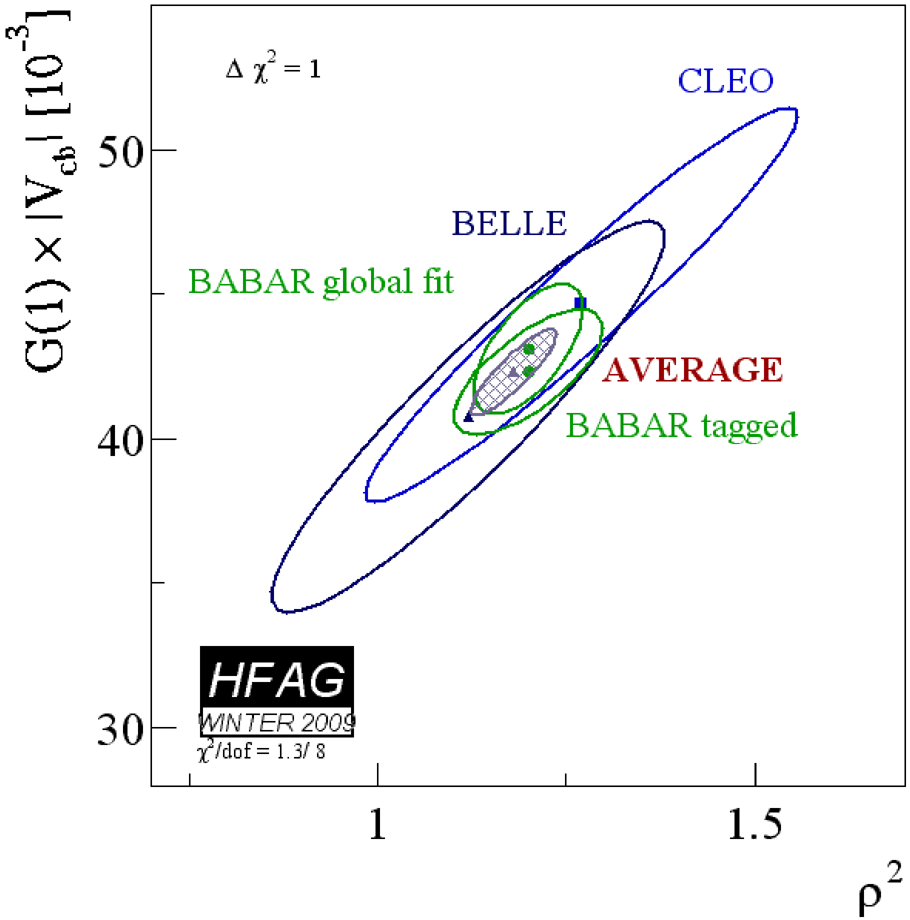
$\mathcal{F}(1)|V_{cb}| = (35.9 \pm 0.2 \pm 1.2) \times 10^{-3}$. 3.3% total error (mainly sys)

	Combined Fit
ρ^2_D	$1.20 \pm 0.04 \pm 0.07$
ρ^2_{D*}	$1.22 \pm 0.02 \pm 0.07$
$BR(D^0 l\nu)(\%)$	$2.34 \pm 0.03 \pm 0.13$
$BR(D^{*0} l\nu)(\%)$	$5.40 \pm 0.02 \pm 0.21$

Interesting results validation:

- G(1)/F(1) in agreement with lattice calculation:
  - $G(1)/F(1)_{Theory} = 1.17 \pm 0.04$
  - $G(1)/F(1)_{untag} = 1.20 \pm 0.09$
- Slope difference ($\rho_D^2 - \rho_{D*}^2$) compatible with zero

BaBar Results on B→ Dℓν



Combined BaBar Results:

$$G(1)|V_{cb}| = (42.4 \pm 0.7 \pm 1.6)x10^{-3}$$

$$\rho^2 = 1.18 \pm 0.04 \pm 0.04$$

$$Br(B^0 \to D\ell\nu) = (2.16 \pm 0.08)\%$$

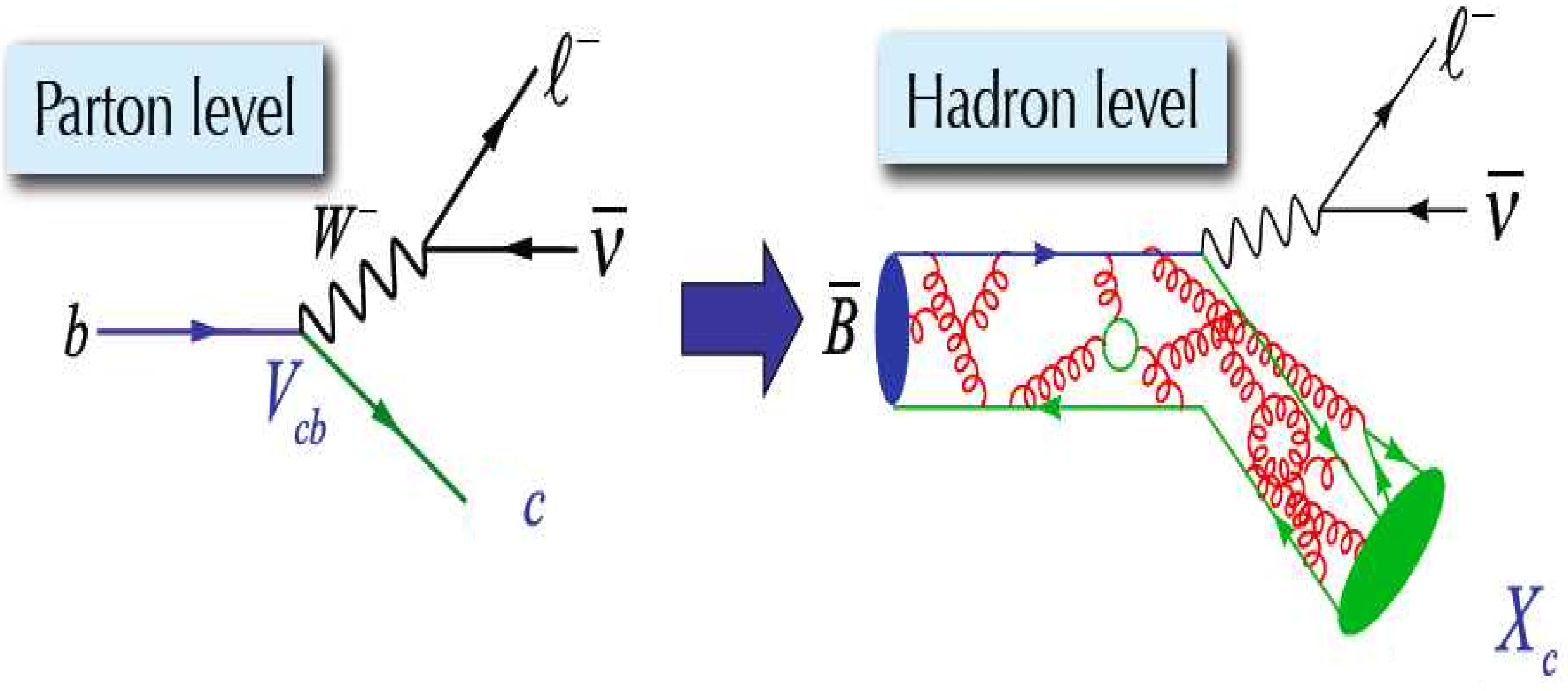
Using the Okamoto et al. (FNAL05) LQCD

$$\mathcal{G}(1) = 1.074 \pm 0.018 \pm 0.016$$

$$|V_{cb}| = (39.2 \pm 1.6 \pm 0.9_G)x10^{-3}$$

In good Agreement with exclusive B →D*

Inclusive Semileptonic b→c decays



Inclusive Semileptonic $B \to X_c l \nu$ decays

- Study of Semileptonic $B \to X_c l \nu$ decay offers laboratory for studying the ***b*** quark in the ***B*** meson
- The Inclusive decay rate can be written in terms of a Heavy Quark Expansion (HQE) in $1/m_b^n$ and α_s :

$$\Gamma_{sl}(B \to X_c l \nu) = \frac{G_F^2 m_b^5}{192\pi^3} \cdot |V_{cb}|^2 \cdot \left[z_0(r) + \frac{0}{m_b} + z_2\left(r, \frac{\mu_\pi^2}{m_b^2}, \frac{\mu_G^2}{m_b^2}\right) + z_3\left(r, \frac{\rho_D^3}{m_b^3}, \frac{\rho_{LS}^3}{m_b^3}\right) + O(1/m_b^4) \right]$$

$r = \frac{m_c^2}{m_b^2}$ m_b and m_c are the quark masses

$\mu_\pi^2, \mu_G^2, \rho_D^3, \rho_{LS}^3$ are Non-perturbative parameters, matrix elements of local operators in HQET

Moments of Inclusive Distributions

- Hadronic Mass Moments

$$\langle m_X^n \rangle_{E>E_0} = \frac{\int_{E>E_0} m_X^n \left(\frac{d\Gamma_c}{dm_X} \right) dm_X}{\int_{E>E_0} \frac{d\Gamma_c}{dm_X} dm_X}$$

- Energy Moments of X_c system

$$\langle E_X^n \rangle_{E>E_0} = \frac{\int_{E>E_0} (E_X - \langle E_X \rangle)^n \left(\frac{d\Gamma_c}{dE_X} \right) dE_X}{\int_{E>E_0} \frac{d\Gamma_c}{dE_X} dE_X}$$

- Mixed Moments

$$n_X^2 = m_X^2 c^4 - 2\tilde{\Lambda} E_X + \tilde{\Lambda}^2$$

$$\tilde{\Lambda} = 0.65\, GeV$$

$E>E_0$:lepton or photon energy cut

- Moments, like the total rate are also described in term of an HQE in ***$1/m_b^n$*** and ***α_s*** by quark masses (m_b,m_c) and Nonperturbative parameters, matrix elements of local operators in HQET (μ_π^2, μ_G^2, ρ_D^3,ρ_{LS}^3)

$$\langle m_X^n \rangle_{E>E_0} = f\,(E_0, m_b, m_c \mu_\pi^2, \mu_G^2, \rho_D^3, \rho_{LS}^3)$$

Interpretation of Moments

Moments Measurements:

- Mass or Mixed moments
- Electron Energy moments
- Photon Energy Moments

Heavy Quark Expansions:

- Kinetic Scheme [1]
- 1S Scheme [2]

HQE-Fit

External Parameter:

$\tau_B = (1.585 \pm 0.007)$ps

constrain on μ_G^2 and ρ_{LS}^3

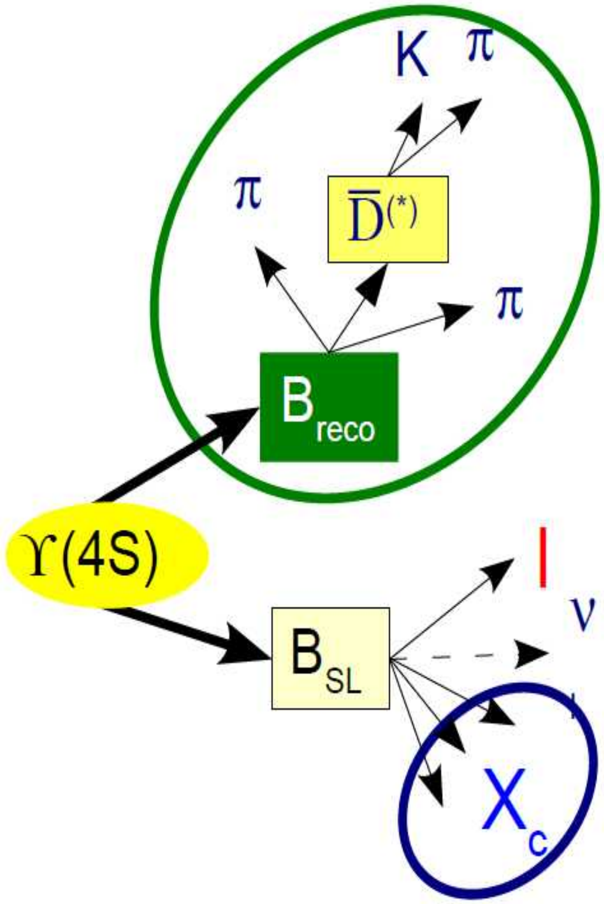
$$|V_{cb}|, m_b, m_c, \mu_\pi^2, \mu_G^2, \rho_D^3, \rho_{LS}^3$$

- [1] P.Gambino, N.Uraltsev, Eur.Phys.J. C34, 181 (2004)
  D.Beson, I.Bigi, N.Uraltsev, Nucl.Phys. B710, 371 (2005)
- [2] C.Bauer, Z.Ligeti, M.Luke, A.Manohar, M.Trott, Phys.Rev. D70, 094017 (2004)

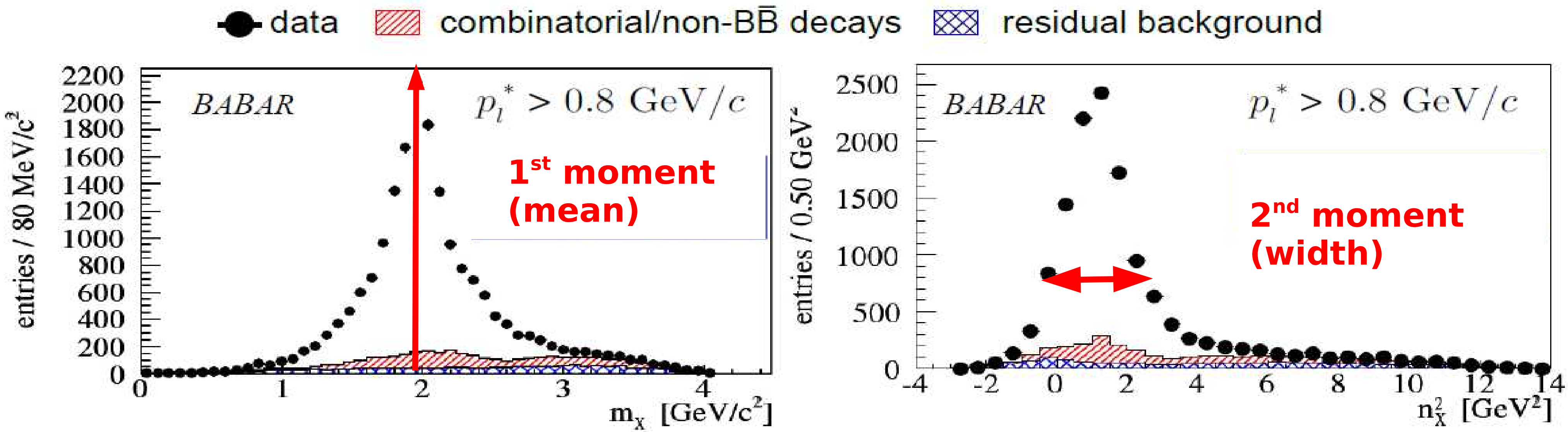
0707.2670[hep-ex]
submitted to PRD

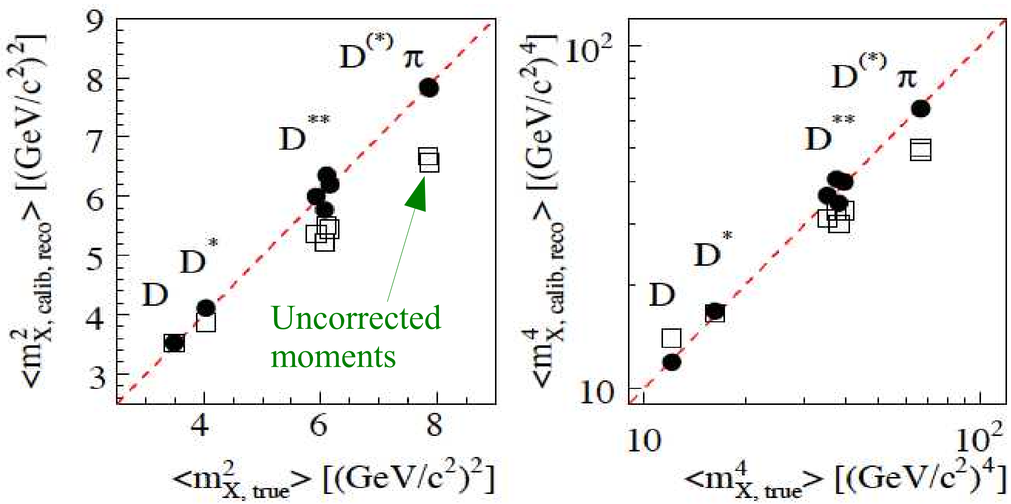
Moments: Analysis Strategy

- Dataset: 230 million B pairs
- On the recoil of **fully reconstructed B**
- Measure one recoiling lepton with minimum $p^*>0.8GeV$ in the B rest-frame
- Remaining particles form inclusive hadronic X_c-system
- Missing mass and Energy consistent with semileptonic decay
- Improve resolution with kinematic fit to the total event



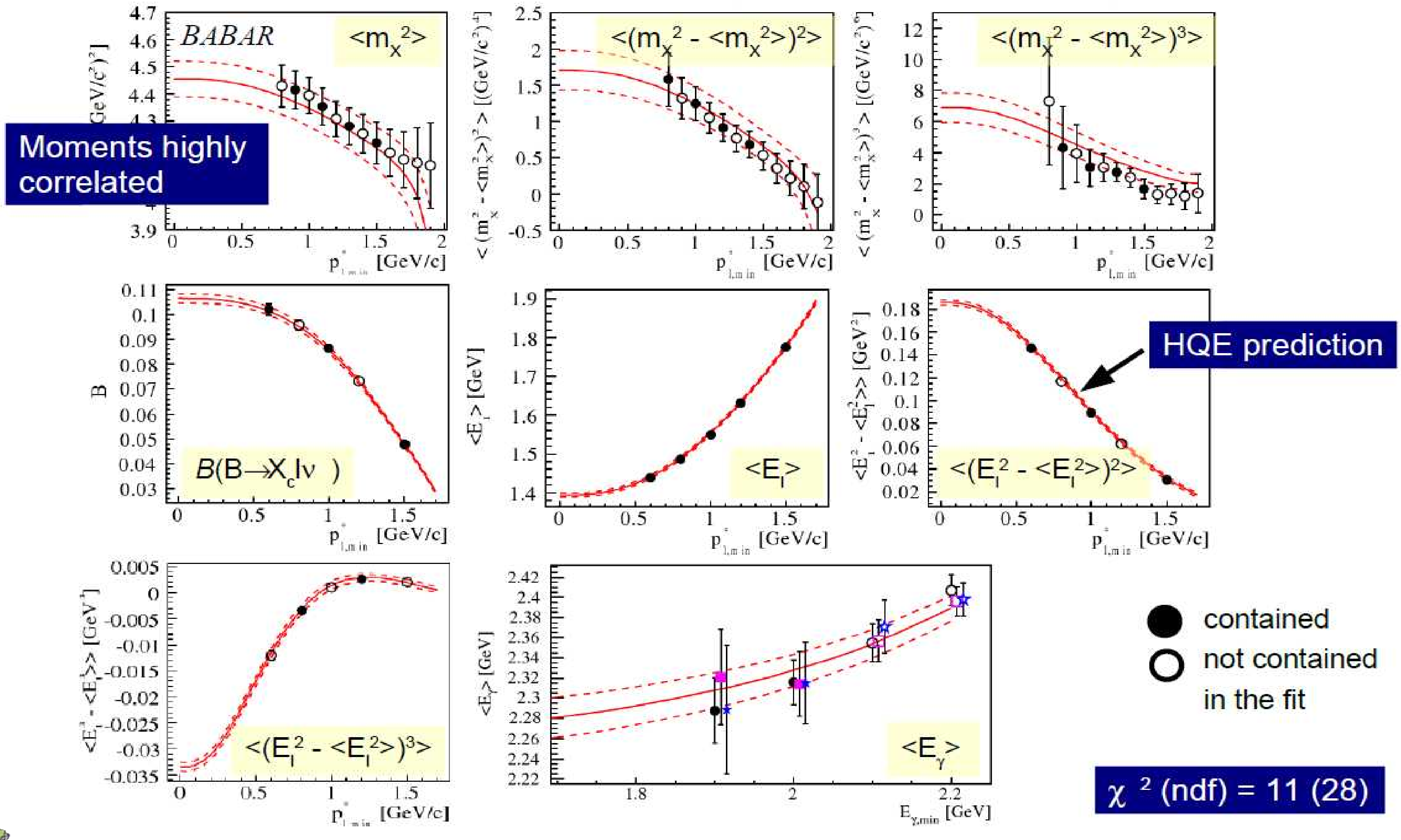
Moments: Spectra





Event by event m_X calibration functions to relate reconstructed m_X to true m_X, in bins of:
- charged tracks multiplicity, E_{miss}-$|\mathbf{P}_{miss}|$ and P_ℓ

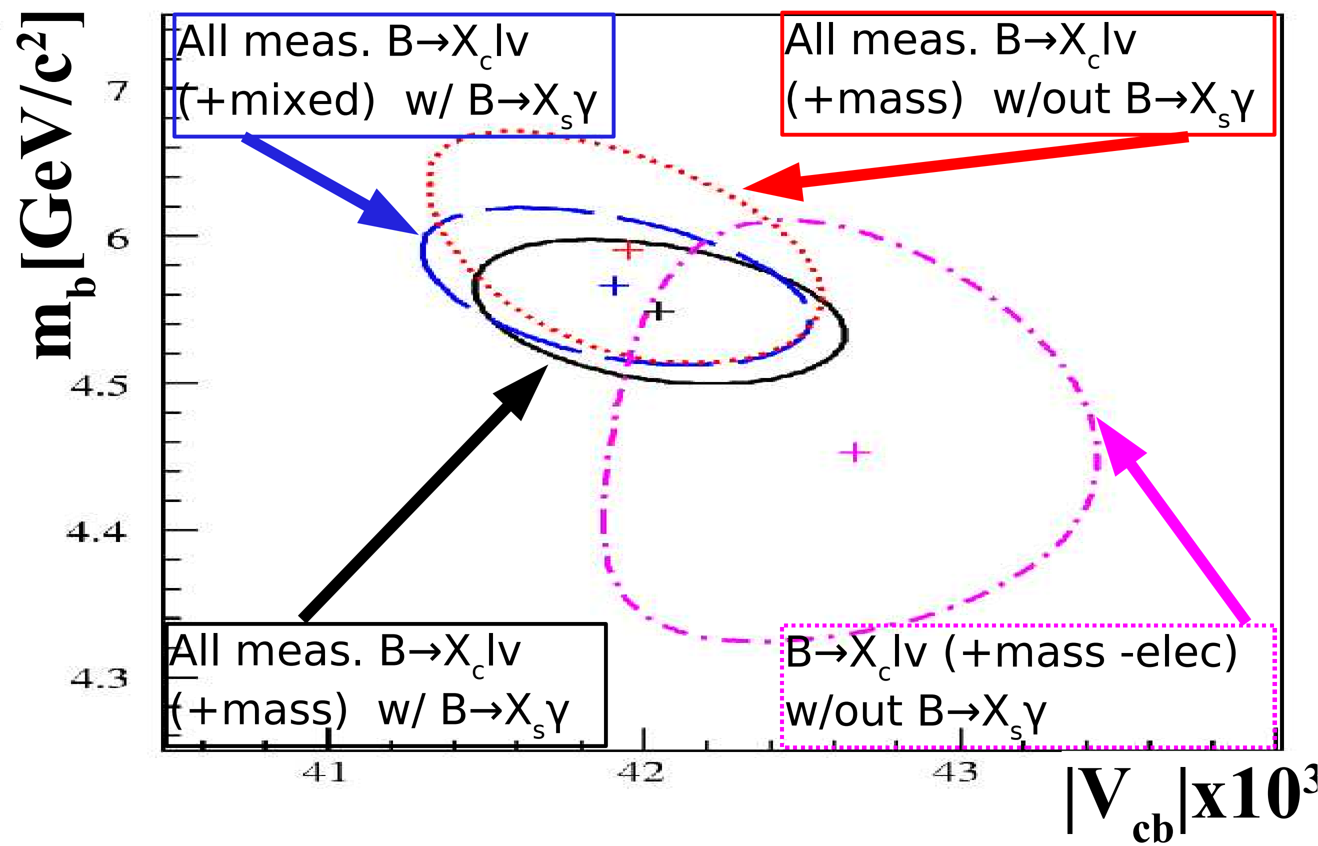
Mass Moments: HQE-Prediction



HQE-Fit results
(kinetic scheme)

	$\lvert V_{cb}\rvert$ x 10^3	m_b [GeV]	m_c [GeV]	μ_π^2 [GeV^2]
mass moments	42.05±0.83	4.549±0.049	1.077±0.074	0.476±0.063
mixed moments	41.91±0.85	4.566±0.053	1.101±0.078	0.452±0.069
HFAG (Winter 2009)*	41.54±0.73	4.620±0.035	1.190±0.052	0.424±0.042
BELLE 2008 [Phys.Rev. D78,032016]	41.58±0.90	4.543±0.075	1.055±0.118	0.539±0.079

- Agreement with other measurements and world average
- Good agreement of results of mixed and mass moments:
  - Indicating that higher order corrections have been treated correctly for the calculation of the mass moments



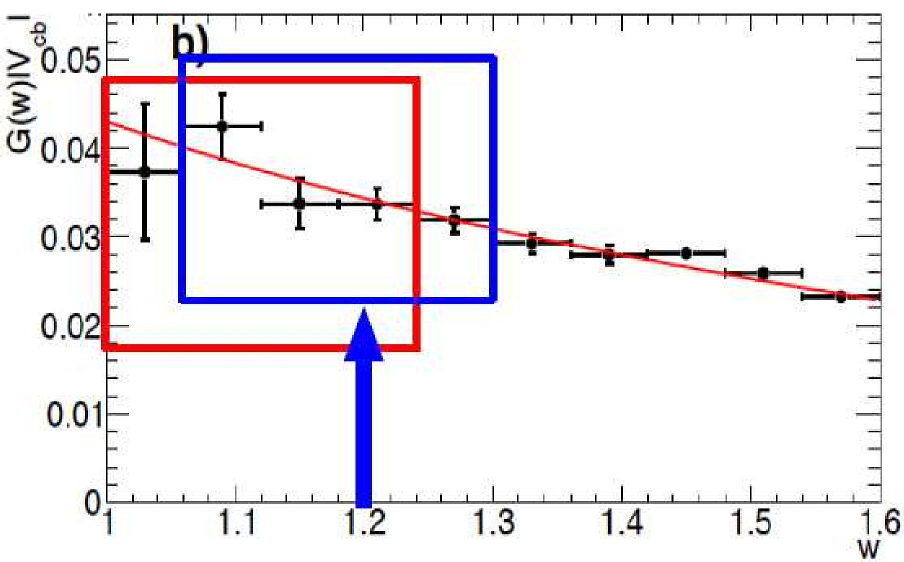
Conclusion

- Many exciting results on $B \rightarrow D l \nu$ decays
  - Recent BaBar measurements have improve the total error on the world average $G(1)|V_{cb}|$ (4%)
  - Interesting validation in the comparison with $B \rightarrow D^* l \nu$ $[(\rho_D^2 - \rho_{D*}^2)$ and $G(1)/F(1)]$
  - Precision on $|V_{cb}|$ measurements limited by form factor knowledge
- Inclusive $|V_{cb}|$ precision now at 2% level
- Agreement between Exclusive ($B \rightarrow D l \nu$) and Inclusive measurements

Back-up

Back-up:Tagged $B \rightarrow D\ell\nu$ at w>1

Reduce the model dependence determining $G(w')|V_{cb}|$ from a fit in a limited region of phase-space



w'	$\lvert V_{cb}\rvert G(w')/G(w')\ 10^{-3}$	
	unquenched (FNAL)	Full PS
1.00	39.2 ± 1.8 ± 1.3 ± 0.9	
	quenched (Tantalo)	
1.00	40.9 ± 1.8 ± 1.3 ± 0.7	
1.03	40.2 ± 5.6 ± 1.3 ± 0.8	4 bins
1.05	40.0 ± 5.0 ± 1.4 ± 0.6	
1.10	40.0 ± 3.4 ± 1.4 ± 0.5	
1.20	**40.7 ± 1.3 ± 1.4 ± 1.0**	**4 bins**
	stat syst FF	

- *Experimental error* ***interpolating*** *4 bins around w=1.2 is competitive with the* ***extrapolation*** *to w=1 using the full phase-space*
- ***We expect lattice community provide un-quenched (2+1) computation of the FF at w=1 and at w>1***

Back-up: Tagged $B \to D\ell\nu$ Sys

	Systematic uncertainty on $\lvert V_{cb}\rvert$ and ρ^2					
	$D^0\ell^-\bar{\nu}_\ell$		$D^+\ell^-\bar{\nu}_\ell$		$D\ell^-\bar{\nu}_\ell$	
	$\lvert V_{cb}\rvert(\%)$	ρ^2	$\lvert V_{cb}\rvert(\%)$	ρ^2	$\lvert V_{cb}\rvert(\%)$	ρ^2
Tracking efficiency	0.5	0.008	1.1	0.003	0.7	0.004
Neutral reconstruction	1.	0.003	0.8	0.006	0.9	0.004
Lepton ID	1.0	0.009	0.9	0.009	0.95	0.009
PHOTOS	0.13	0.005	0.10	0.005	0.12	0.005
Cascade $\overline{B} \to X \to \ell^-$ decay background	0.6	-	1.0	-	0.75	-
$\overline{B} - B^-$ cross-feed	0.24	0.003	0.24	0.003	0.24	0.003
$\overline{B} \to D^*\ell^-\bar{\nu}_\ell$ Form factors	0.56	0.008	0.20	0.003	0.38	0.006
$\overline{B} \to D^{**}\ell^-\bar{\nu}_\ell$ Form factors	0.24	0.007	0.34	0.006	0.29	0.007
D branching fractions	1.0	-	1.35	-	1.12	-
$\mathcal{B}(\overline{B} \to D^{**}\ell^-\bar{\nu}_\ell)$	1.18	0.023	0.96	0.011	1.08	0.019
$\mathcal{B}(\overline{B} \to X\ell^-\bar{\nu}_\ell)$	0.95	-	0.95	-	0.85	-
$B_{\rm tag}$ selection	1.1	0.021	1.8	0.036	1.5	0.028
$\overline{B} \to X\ell^-\bar{\nu}_\ell$ yield	0.7	-	1.1	-	0.85	-
$\overline{B} \to D\ell^-\bar{\nu}_\ell$ yield	1.27	0.018	1.06	0.027	1.25	0.020
Total systematic error	3.1	0.04	3.6	0.05	3.3	0.04

Back-up: Untagged $B \to D\ell\nu$ Sys

Item	Electron sample ρ_D^2	$\rho_{D^*}^2$	$\mathcal{B}(D\ell\bar{\nu})$	$\mathcal{B}(D^*\ell\bar{\nu})$	$\mathcal{G}(1)\|V_{cb}\|$	$\mathcal{F}(1)\|V_{cb}\|$	Muon sample ρ_D^2	$\rho_{D^*}^2$	$\mathcal{B}(D\ell\bar{\nu})$	$\mathcal{B}(D^*\ell\bar{\nu})$	$\mathcal{G}(1)\|V_{cb}\|$	$\mathcal{F}(1)\|V_{cb}\|$
R_1'	0.44	2.74	0.71	−0.38	0.60	0.71	0.50	2.67	0.74	−0.40	0.63	0.70
R_2'	−0.40	1.02	−0.18	0.30	−0.32	0.49	−0.45	0.96	−0.19	0.30	−0.33	0.48
D^{**} slope	−1.42	−2.52	−0.07	−0.09	−0.82	−0.87	−1.42	−2.58	−0.10	−0.10	−0.77	−0.92
D^{**} FF approximation	−0.87	0.33	−0.12	0.19	−0.54	0.20	−0.99	0.59	−0.12	0.21	−0.59	0.30
$\mathcal{B}(B^- \to D^{(*)}\pi\ell\bar{\nu})$	0.28	−0.27	−0.22	−0.80	0.04	−0.49	0.59	−0.32	−0.13	−0.86	0.24	−0.54
$f_{D_2^*/D_1}$	−0.39	0.16	−0.38	0.16	−0.41	0.13	−0.50	0.17	−0.41	0.18	−0.47	0.15
$f_{D_0^*D\pi/D_1D_2^*}$	−2.30	1.12	−1.53	0.97	−2.07	0.85	−3.13	1.23	−1.53	1.02	−2.41	0.93
$f_{D_1'D^*\pi/D_1D_2^*}$	1.82	−1.14	1.30	−0.65	1.65	−0.70	2.44	−1.15	1.35	−0.72	1.91	−0.75
$f_{D\pi/D_0^*}$	−0.88	−1.28	0.36	0.17	−0.31	−0.34	−0.83	−1.23	0.31	0.18	−0.27	−0.33
$f_{D^*\pi/D_1'}$	−0.21	−0.05	−0.13	0.21	−0.18	0.09	−0.30	−0.04	−0.15	0.23	−0.23	0.10
NR D^*/D ratio	0.58	−0.16	0.11	−0.09	0.38	−0.04	0.66	−0.16	0.11	−0.09	0.40	−0.03
$\mathcal{B}(B^- \to D^{(*)}\pi\pi\ell\bar{\nu})$	1.19	−1.97	0.25	−1.28	0.78	−1.28	1.98	−1.71	0.40	−1.20	1.20	−1.18
X^*/X and Y^*/Y ratio	0.61	−1.15	0.09	−0.27	0.39	−0.52	0.74	−1.02	0.08	−0.24	0.42	−0.47
X/Y and X^*/Y^* ratio	0.76	−0.83	0.21	−0.65	0.52	−0.60	1.09	−0.76	0.25	−0.63	0.68	−0.57
$D_1 \to D\pi\pi$	2.22	−1.54	0.74	−1.08	1.63	−1.05	2.74	−1.48	0.76	−1.06	1.81	−1.03
$f_{D_2^*}$	−0.14	−0.01	−0.10	0.07	−0.12	0.03	−0.16	−0.01	−0.10	0.07	−0.13	0.03
$\mathcal{B}(D^{*+} \to D^0\pi^+)$	0.73	−0.01	0.43	−0.34	0.62	−0.17	0.80	−0.00	0.41	−0.33	0.61	−0.17
$\mathcal{B}(D^0 \to K^-\pi^+)$	0.69	0.02	−0.21	−1.63	0.29	−0.80	0.92	0.12	−0.27	−1.68	0.35	−0.80
$\mathcal{B}(D^+ \to K^-\pi^+\pi^+)$	−1.46	−0.42	−2.17	0.30	−1.89	0.01	−1.43	−0.42	−2.10	0.28	−1.77	−0.01
τ_{B^-}/τ_{B^0}	0.26	0.16	0.63	0.27	0.46	0.19	0.22	0.16	0.58	0.28	0.41	0.19
f_{+-}/f_{00}	0.88	0.43	0.66	−0.53	0.82	−0.12	0.91	0.48	0.57	−0.52	0.75	−0.10
Number of $B\bar{B}$ events	0.00	−0.00	−1.11	−1.11	−0.55	−0.55	0.00	−0.00	−1.11	−1.11	−0.55	−0.55
Off-peak luminosity	0.05	0.01	−0.02	−0.00	0.02	0.00	0.07	0.00	−0.02	−0.00	0.02	−0.00
B momentum distribution	−0.96	0.63	1.29	−0.54	−1.15	0.48	1.30	−0.10	1.27	−0.64	1.31	−0.35
Lepton PID efficiency	0.52	0.16	1.21	0.82	0.90	0.46	3.30	0.06	5.11	5.83	1.99	2.90
Lepton mis-ID	0.03	0.01	−0.01	−0.01	0.01	−0.00	2.65	0.70	−0.59	−0.50	1.06	−0.01
Kaon PID	0.07	0.80	0.28	0.23	0.18	0.38	1.02	0.71	0.35	0.29	0.70	0.39
Tracking efficiency	−1.02	−0.43	−3.35	−2.00	−2.25	−1.15	−0.63	−0.28	−3.37	−2.09	−2.02	−1.14
Radiative corrections	−3.13	−1.04	−2.87	−0.74	−3.02	−0.71	−0.76	−0.61	−0.82	−0.25	−0.79	−0.33
Bremsstrahlung	0.07	0.00	−0.13	−0.28	−0.04	−0.14	0.00	0.00	0.00	0.00	0.00	0.00
Vertexing	0.83	−0.64	0.63	0.60	0.78	0.09	1.79	−0.76	0.97	0.54	1.41	0.01
Background total	1.39	1.12	0.64	0.34	1.07	0.51	1.58	1.09	0.67	0.38	1.16	0.49
Total	6.25	5.66	6.01	4.03	5.99	3.20	8.12	5.47	7.35	7.07	6.06	4.23