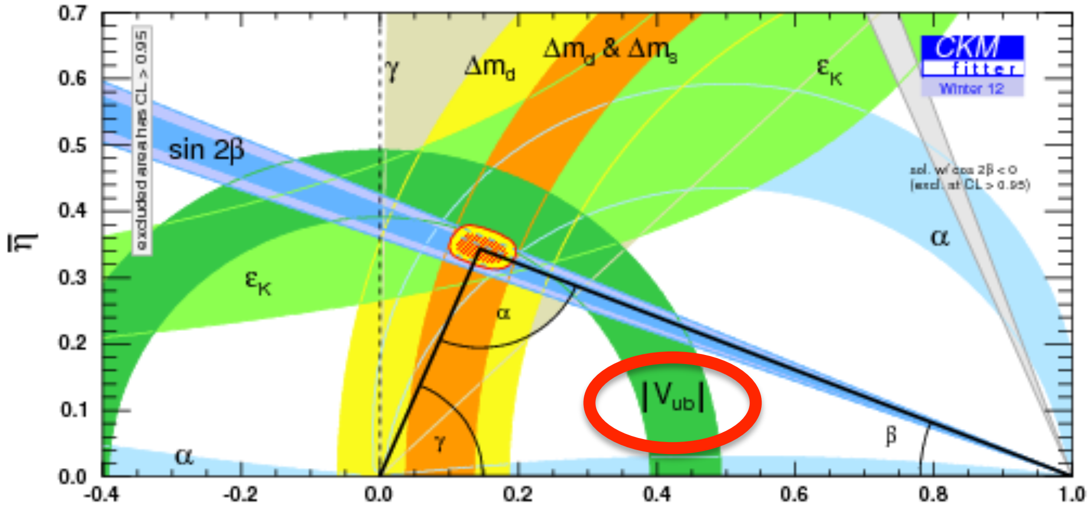
Mini-review of Inclusive B Semileptonic Decays, and $B \to D(*) \tau \nu$ at BaBar

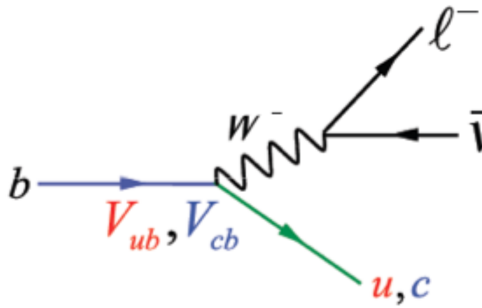
Concezio Bozzi
INFN Sezione di Ferrara

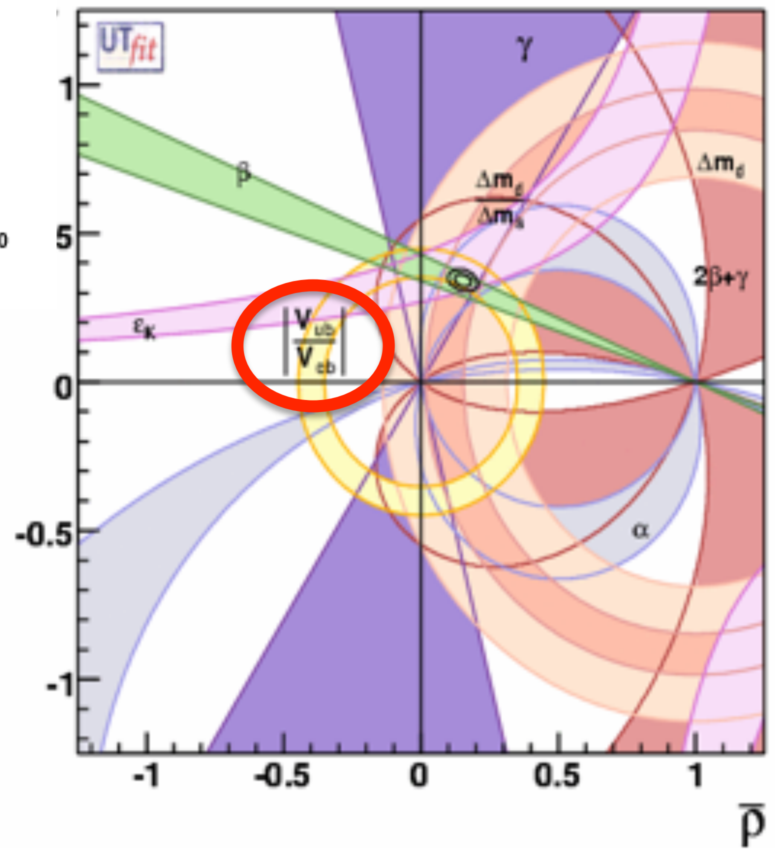
(gratefully acknowledging V. Lüth, P. Gambino, C. Schwanda, R. Kowalewski, G. Ricciardi, M. Franco Sevilla)

The relevance of semileptonic decays



(Vcb normalizes the whole UT) $\bar{\rho}$





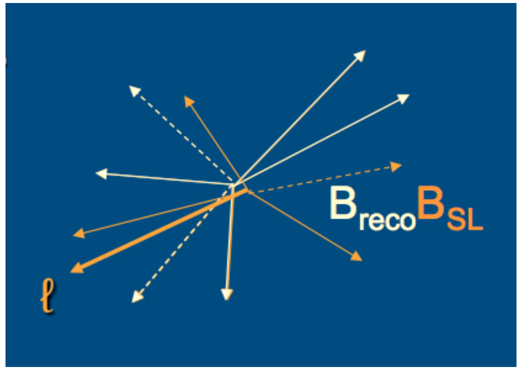
$|V_{qb}|$ precisely determined from semileptonic B decays

Also input for measurements sensitive to new physics (e.g. $B \rightarrow \tau\nu$)

The advantages of B-Factories

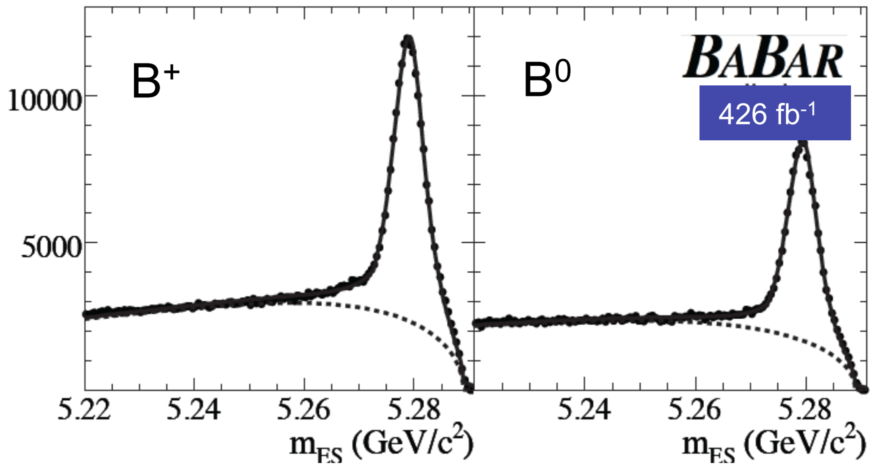
- Clean experimental environment: $e^+e^- \to \Upsilon(4S) \to B\overline{B}$
  $\sigma_{\Upsilon(4S)} \approx 1.05\,nb \qquad (\sigma_{\Upsilon(4S)} / \sigma_{had} \sim 1/4)$
- Large samples: $L \approx 500\ fb^{-1}, \quad BR(B \to X\ell\nu) \approx 10\%$
- Reconstruction of s.l. decays:
  - Charged lepton ID: $e^\pm$, $\mu^\pm$
  - Hadronic system: X_c, X_u, D, D^*, π, ρ…
  - ν inferred from $E_{\rm miss}$, $p_{\rm miss}$:

$$(E_{\rm miss}, \vec{p}_{\rm miss}) = (E_{e^+e^-}, \vec{p}_{e^+e^-}) - \left(\sum_i E_i, \sum_i \vec{p}_i\right)$$



- **Full reconstruction of one B decay, e.g.**
  $B^+_{reco} \to D^- \pi^+ \pi^-$, $B^-_{SL} \to X_u^0\, l^- \nu$
  - Reduction of combinatorial backgrounds
  - improved ν reconstruction
  - kinematics of hadronic system completely determined
  - Low efficiency (0.3-0.6%)

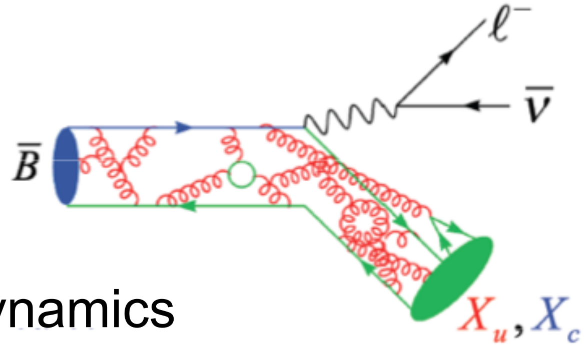
Typical yields ~ 4000 B/fb^{-1}



$$m_{\rm ES} = \sqrt{s/4 - \vec{p}_B^{\,2}}$$

Resulting inclusive samples:
$O(100k)\ B_{SL} \to X_c\, l^- \nu$
$O(1k)\ B_{SL} \to X_u\, l^- \nu$

Inclusive s.l. decays



- **OPE factorization** of **short-** and **long-**distance dynamics
  - Non-perturbative contributions from matrix elements of **local operators**
  - **Coefficients** of the operators calculated perturbatively
  - double series in powers of α_s and Λ/m_b
- Total **decay rate**:

$$\Gamma(b \to q\ell\nu) = \frac{G_F^2 m_b^5}{192\pi^3}|V_{qb}|^2(1 + A_{ew})A^{pert}(r,\mu)\left[z_0(r) + z_2(r)\left(\frac{\mu_\pi^2}{m_b^2}, \frac{\mu_G^2}{m_b^2}\right) + z_3(r)\left(\frac{\rho_D^3}{m_b^3}, \frac{\rho_{LS}^3}{m_b^3}\right) + \ldots\right] \quad \left(r = m_q/m_b\right)$$

- Conceptually similar expression for **differential rates**
- Non-perturbative input appears in experimentally accessible **spectral moments**

$$\langle E_\ell^n M_X^{2m} \rangle = \frac{1}{\Gamma_0}\int_{E_0}^{E_{\max}} dE_\ell \int dM_X^2 \frac{d\Gamma(\mu_\pi^2, \mu_G^2, \rho_D^3, \ldots)}{dE_\ell dM_X^2} E_\ell^n M_X^{2m}$$

- **Global fit to moments** to determine $|V_{qb}|$ and **hadronic parameters**

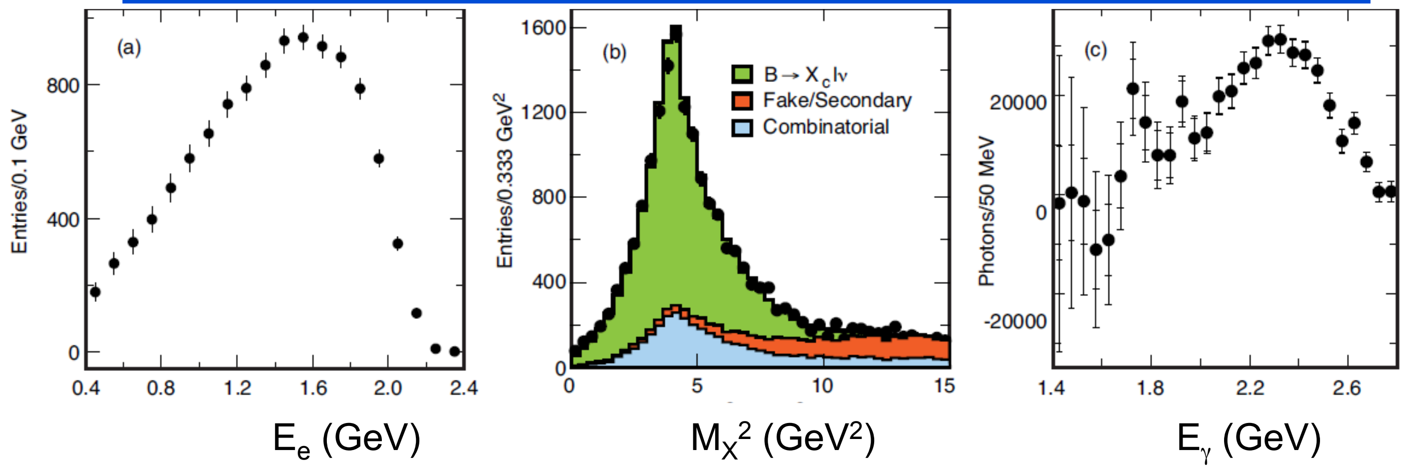
  $m_b, m_c, \mu^2_\pi, \mu^2_G, \rho^3_D, \rho^3_{LS}$

$|V_{cb}|$ from inclusive $B \to X_c \, l \, \nu$

- Measure spectra of lepton momentum p^*_l and hadronic mass m_X or energy E_X in events **tagged with a fully reconstructed B**
- S/B discrimination: neutrino momentum, missing mass squared
- Calibration and unfolding required for hadronic observables, e.g. m_X
- Measurements from Babar, Belle, CLEO, CDF, DELPHI

Belle: PRD 75, 032001 (2007), PRD 75, 032005(2007), PRL 103, 241801 (2009)

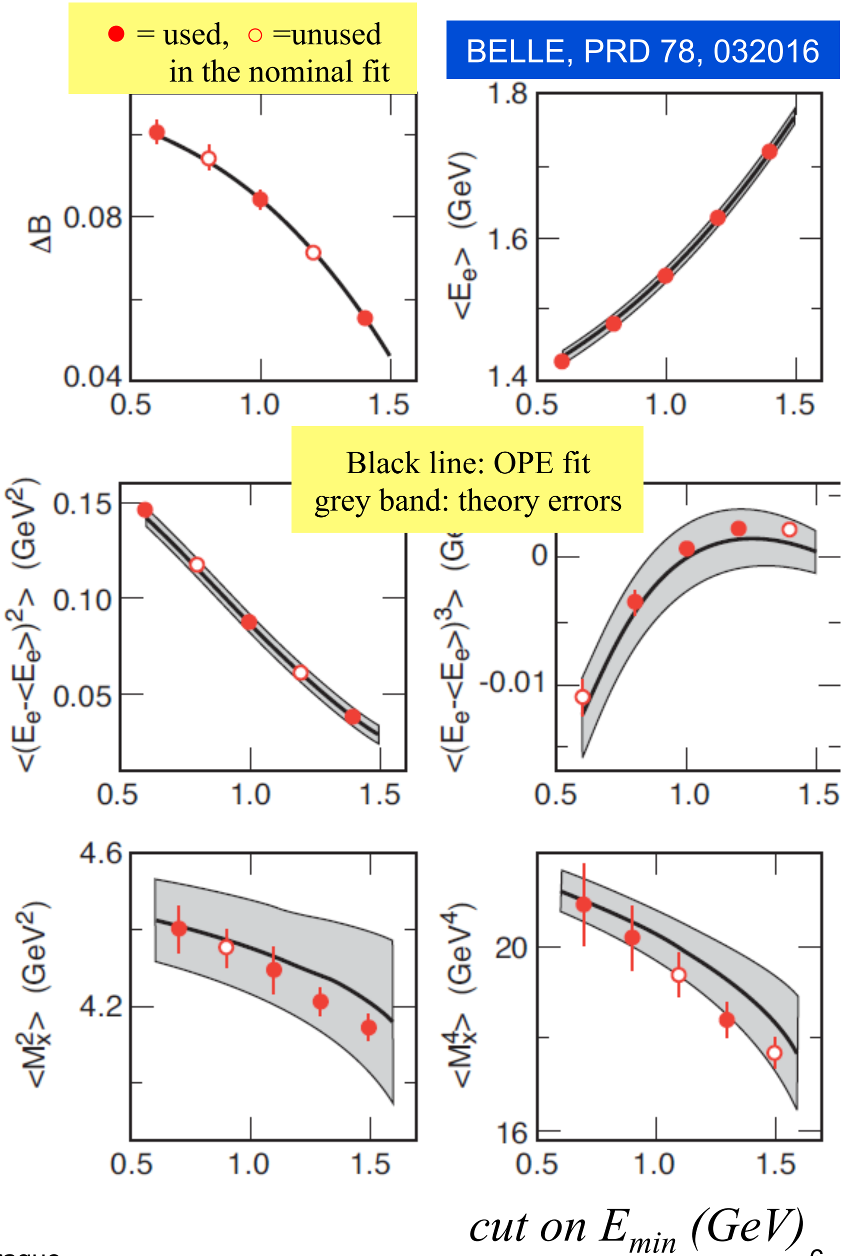
Examples of inclusive distributions used in Moments Analysis by Belle



Global fit to mass, energy moments

- Extract **many moments** from a single distribution (high correlations)
- Each point integrates data above E_{min}
- Leading experimental systematics due to **detector modeling**, **B&D decays**

- Determine $|V_{cb}|$, m_b, m_c and other hadronic parameters by fitting with theory predictions
- all terms through $O(\alpha_s^2, 1/m_b^3)$ are included
- two renormalization schemes in use
  - ***kinetic*** (Benson, Bigi, Gambino, Mannel, Uraltsev)
  - ***1S*** (Bauer, Ligeti, Luke, Manohar, Trott)



Updated HFAG global fit

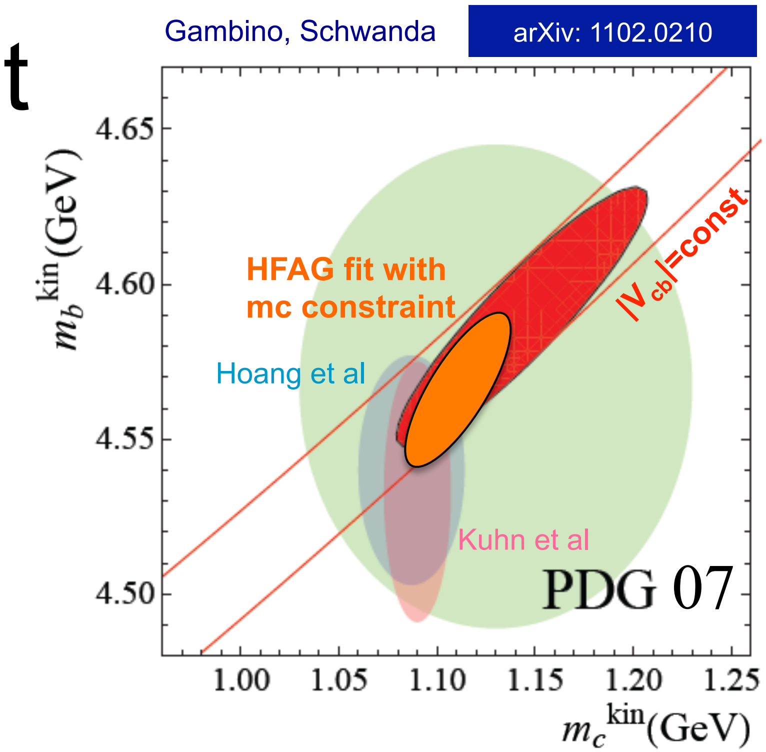
- Rather than measuring precisely m_b, the fit identifies rather well a ***strip in the (m_b,m_c) plane***
- Precision measurement of m_b important for inclusive $|V_{ub}|$; can be improved by external knowledge of m_c
- In the past, $b \to s\gamma$ ***moments*** were used
- Now, use (conservative) input on $m_c(3GeV) = 0.998(29)$ **GeV** (MS Scheme)

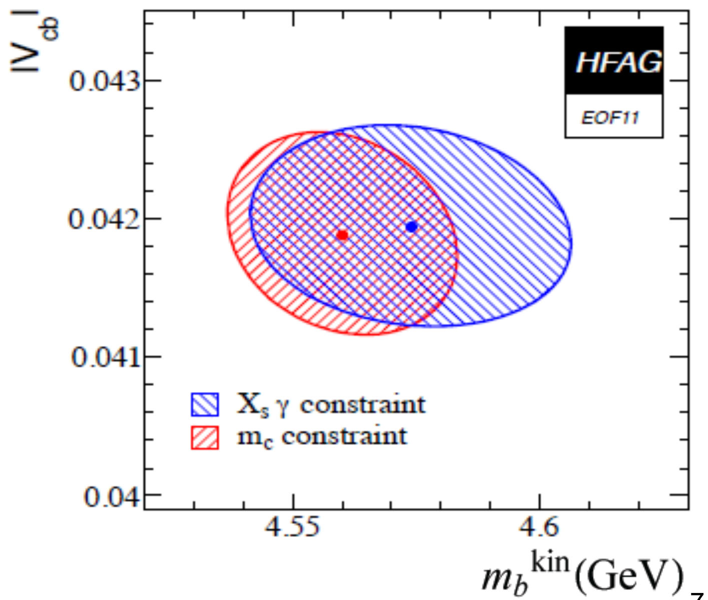
  Hoang et al, arXiv:1102.2264

- Global fit gives

$$|V_{cb}| = (41.88 \pm 0.44_{\rm fit} \pm 0.59_{\rm theory}) \times 10^{-3}$$
$$m_b = 4.560 \pm 0.023 \text{ GeV}$$
$$\mu_\pi^2 = 0.453 \pm 0.036 \text{ GeV}^2$$

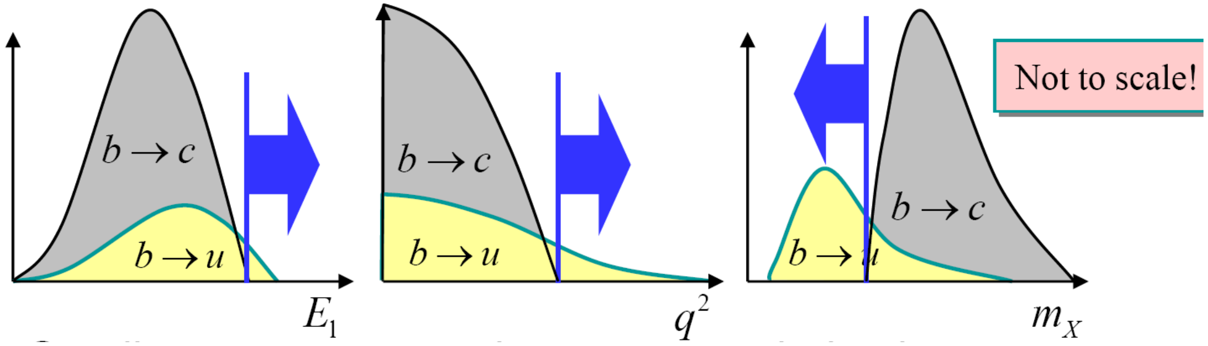
- Similar results in 1S scheme





Inclusive charmless s.l. decays

- **Experimentally challenging:** 50x larger $B \to X_c l^- \nu$ background
  - Cut in phase space and measure partial branching fractions
  - Fully reconstruct one B to access m_X, q^2



E_l = lepton energy

q^2 = dilepton mass squared

m_X = hadron system mass

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

- **Theoretically challenging:** in limited phase space
  - OPE **breaks down**
  - "shape function" is needed to **resum non-perturbative physics**
  - sensitivity to m_b **increases** from $\Gamma \sim |V_{ub}|^2 m_b^5$ up to $\Delta\Gamma \sim |V_{ub}|^2 m_b^{10}$
- Theoretical calculations predicting $\Delta\Gamma$

OPE-inspired:

BLNP NP B699, 335 (2004)

GGOU JHEP 0710, 058 (2007)

resummed perturbation theory:

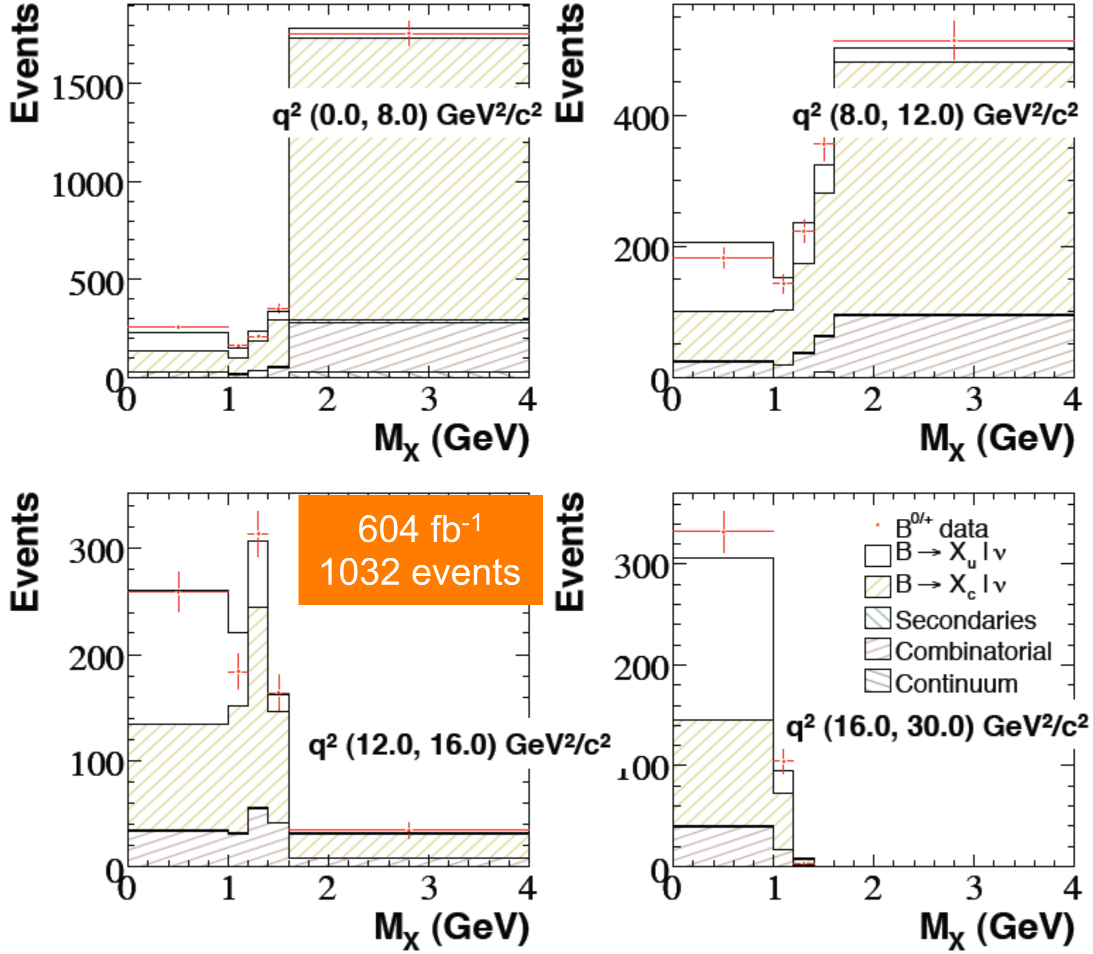
DGE JHEP 0601, 096 (2006)

ADFR Eur. Phys. J. C59, 831 (2009)

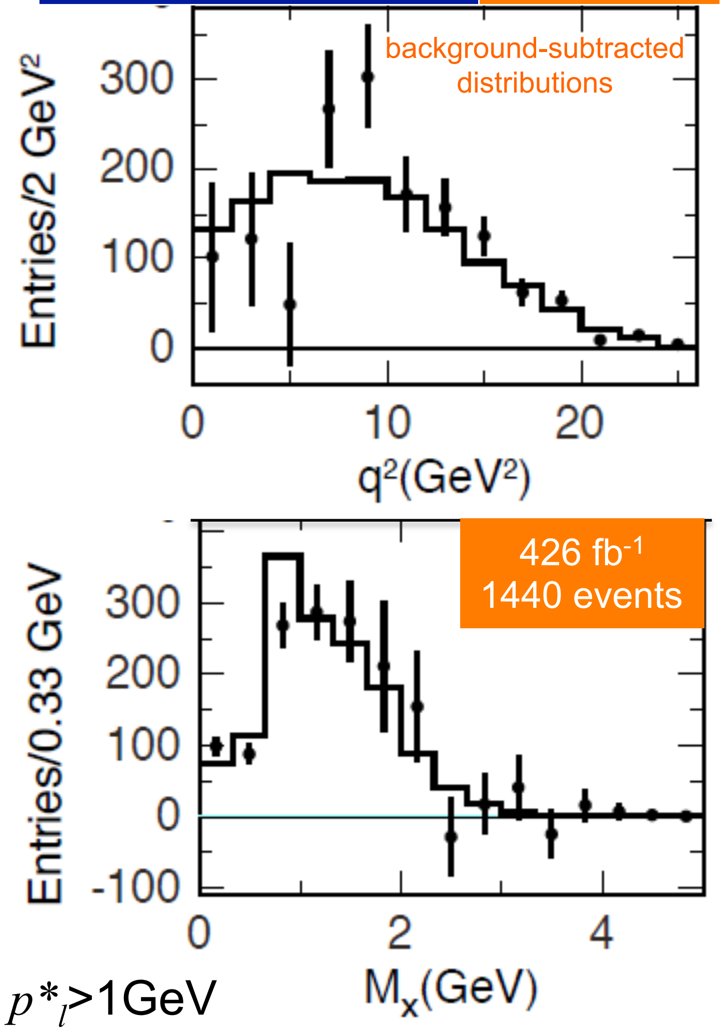
- Measure in as many phase space regions as possible
- Be as inclusive as possibly allowed by background knowledge

Best measurements

Belle — Phys.Rev.Lett.104:021801,2010



Babar — arXiv:1112.0702 submitted to PRD



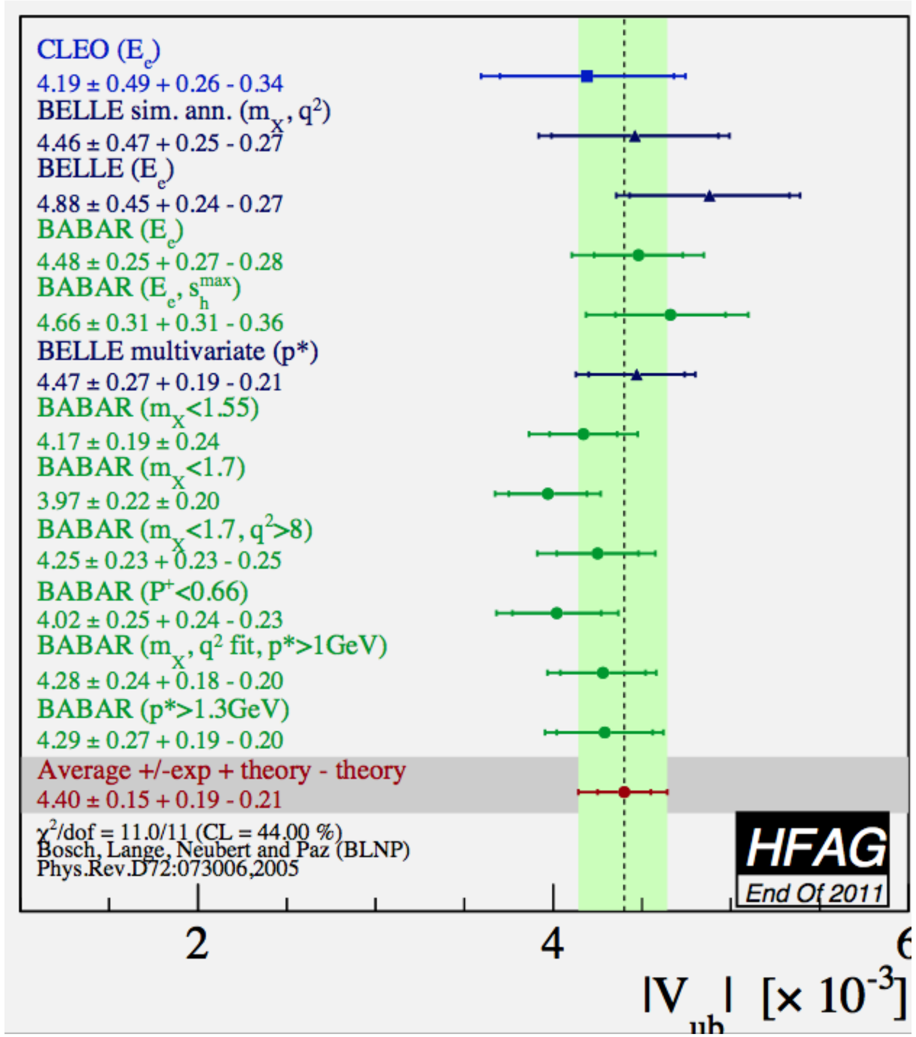
- Fit the (M_X, q^2) distributions in the region defined by $p^*_l > 1$GeV
- Systematic uncertainties dominated by signal modeling
- Total uncertainties on partial branching fractions: 11-12%

An example of HFAG average

BLNP

$|V_{ub}|$ = 4.40 ± 0.15 +0.19 -0.21

~6% total error



Good consistency between different measurements

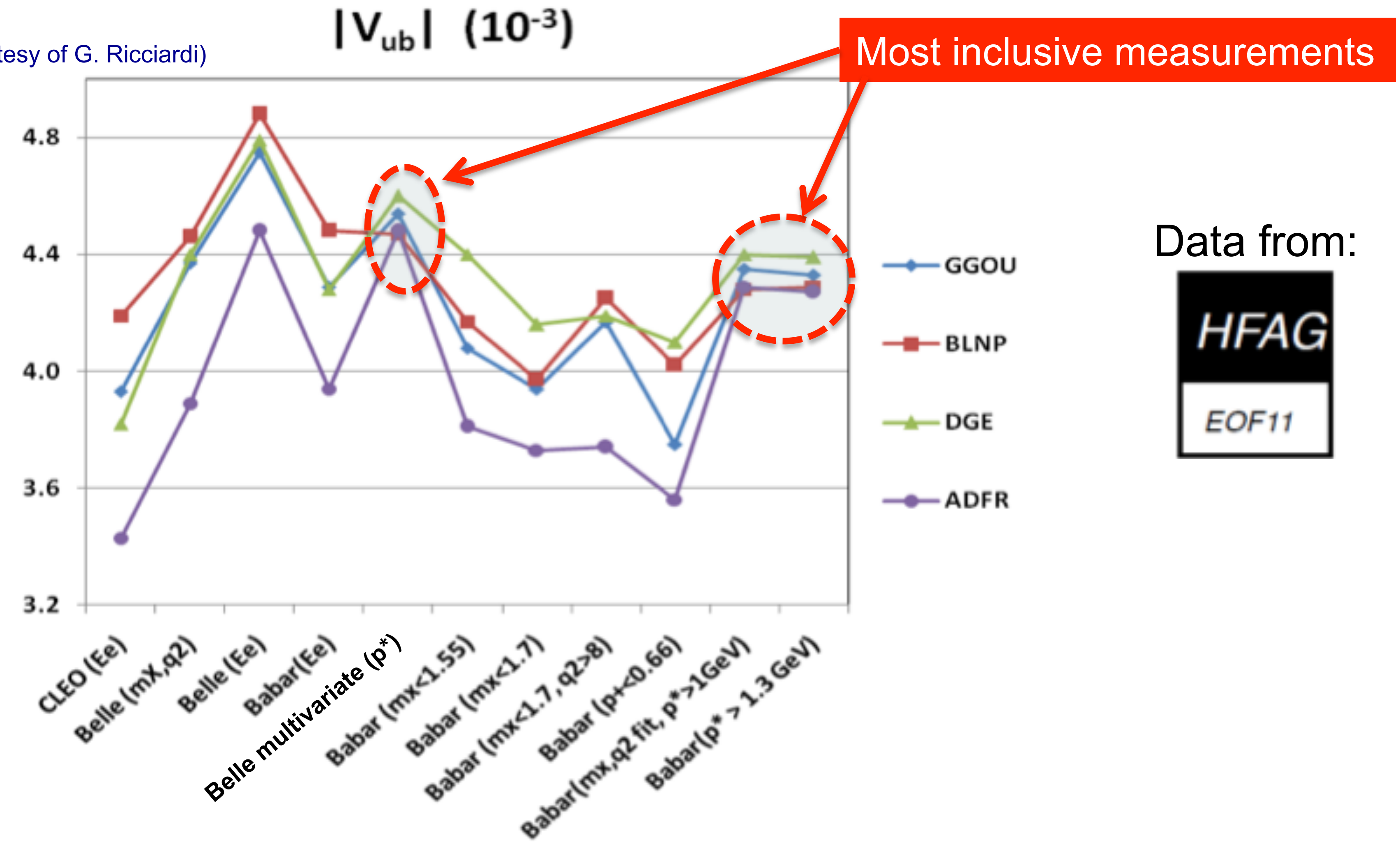
Error budget:

$+2.1_{stat}$ $+1.5_{exp}$ $+1.2_{b2c\ model}$ $+1.5_{b2u\ model}$ $+2.1_{HQE\ param}$ $+0.3_{SF\ func}$ $+0.7_{sub\ SF}$ $+0.0_{WA}$ $+3.7_{matching}$ $= +5.5_{tot}$

-2.2_{stat} -1.6_{exp} $-1.2_{b2c\ model}$ $-1.8_{b2u\ model}$ $-3.2_{HQE\ param}$ $-0.5_{SF\ func}$ $-0.8_{sub\ SF}$ -1.7_{WA} $-3.7_{matching}$ $= -6.1_{tot}$

Good consistency

(Courtesy of G. Ricciardi)



Data from:

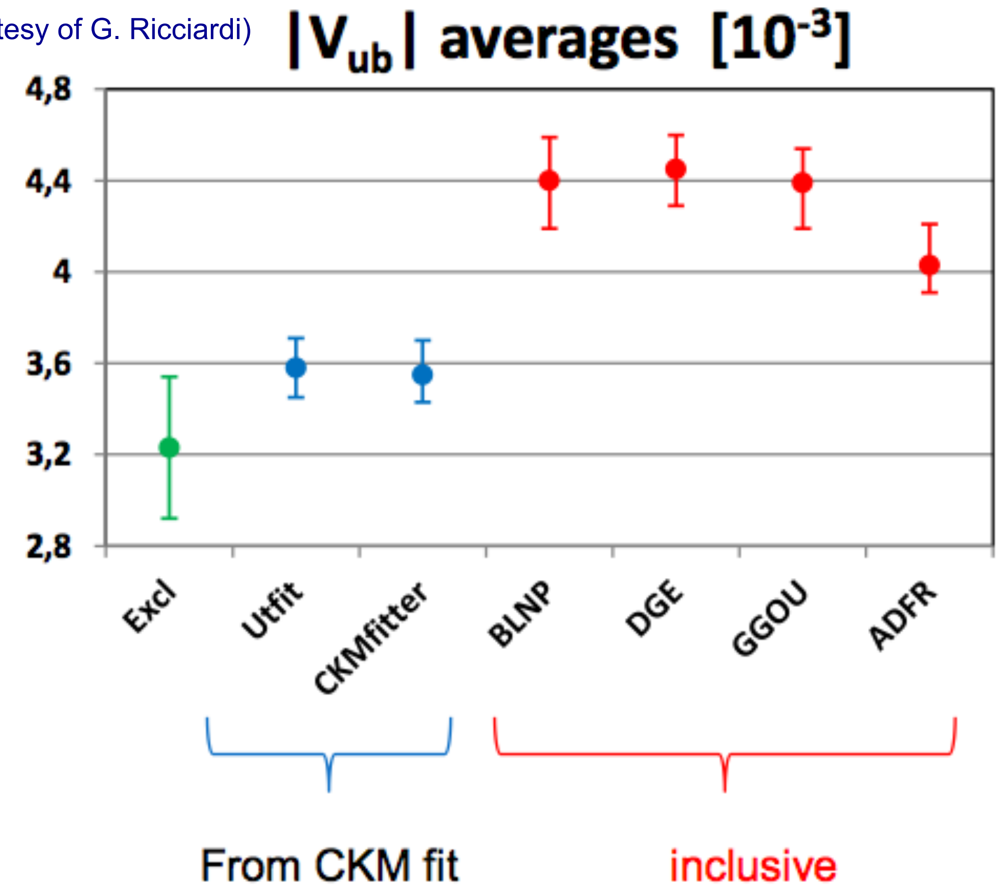
HFAG

EOF11

Spread among calculations comparable to quoted theoretical (non-parametric) errors

Tension™

(Courtesy of G. Ricciardi)



Exclusive and **inclusive** $|V_{ub}|$ differ at **~2.5σ level**

Current $B\rightarrow\tau\nu$ average calls for $|V_{ub}|$~$5\ 10^{-3}$!

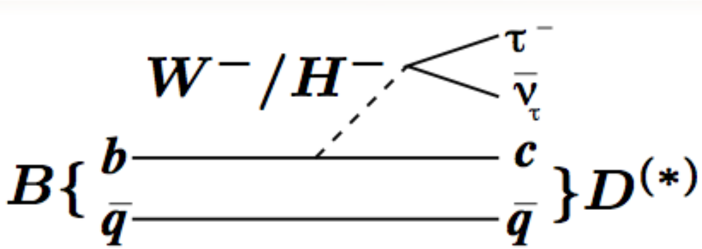
Similar tension between exclusive and inclusive $|V_{cb}|$

Arithmetic average of inclusive $|V_{ub}|$ =$(4.33 \pm 0.24_{exp} \pm 0.15_{theo})$ x10^{-3}

Evidence for an excess of $B \to D^{(*)}\tau^- \bar{\nu}_\tau$ decays

BABAR
arXiv:1205.5442
submitted to PRL

Introduction



- Semileptonic decays with τ lepton in the final state are **sensitive to charged Higgs**
- The ratios $R(D)$ and $R(D^*)$ are both **theoretically and experimentally clean**
- SM predictions are:

$$R(D) = \frac{Br(\bar{B} \to D\tau\nu)}{Br(\bar{B} \to D\ell\nu)}$$

$$R(D^*) = \frac{Br(\bar{B} \to D^*\tau\nu)}{Br(\bar{B} \to D^*\ell\nu)}$$

$$R(D) = 0.297 \pm 0.017, \qquad R(D^*) = 0.252 \pm 0.003$$

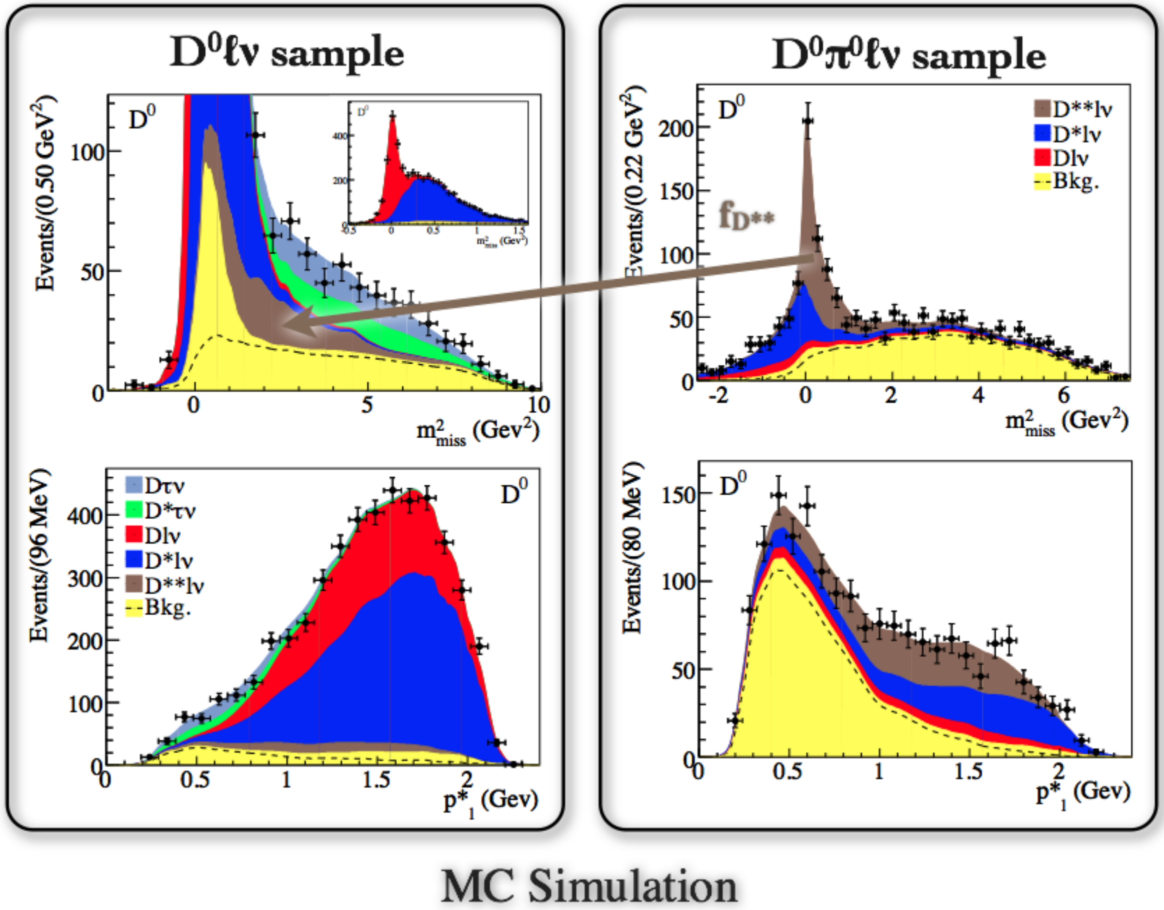
- $B \to D\tau\nu$ and $B \to D^*\tau\nu$ have been previously established with 3.8σ and 8.1σ significances, but sensitivity was not enough to give meaningful constraints on new physics
- This analysis updates the previous Babar measurements by
  - using the **entire dataset** (426 fb^{-1})
  - improving (x2) the reconstruction of the **hadronic B decay**
  - extending ***e* and *μ* ID** to lower momentum
  - using a **multivariate selection** (BDT) to reject backgrounds
    - most important variable: E_{extra} (unused energy in calorimeter)

Analysis strategy

- Reconstruct $D^{(*)}$ mesons: 4 $(D^0, D^{*0}, D^+, D^{*+})l\nu$ samples
  - Consider only $\tau \to l\nu\nu$: $D^{(*)}\tau\nu$ and $D^{(*)}l\nu$ have same detectable particles in final state
- Remaining $D^{**}l\nu$ background is poorly known:
  - Select 4 **$D^{(*)}\pi^0 l\nu$ control samples** (one for each **signal sample)**
- 2D ML fit to p_ℓ^* and

$$m_{miss}^2 = (P_{ee} - P_{Btag} - P_{D(*)} - P_\ell)^2$$

- Fit gives 4 **$D^{(*)}\tau\nu$ signal yields**, 4 **$D^{(*)}l\nu$ normalization yields**, and 4 **control channel ($D^{**}l\nu$) yields**
- Keep **other background yields** fixed
  - B^0-B^+ cross-feed
  - $B\underline{B}$ combinatorial
  - $(q\underline{q})$ continuum
- PDFs taken from MC
- data-driven corrections



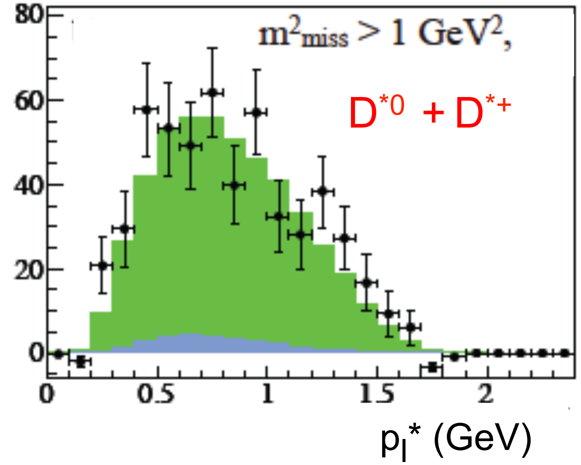
Fit results: $B \rightarrow D^{*}\tau\nu$

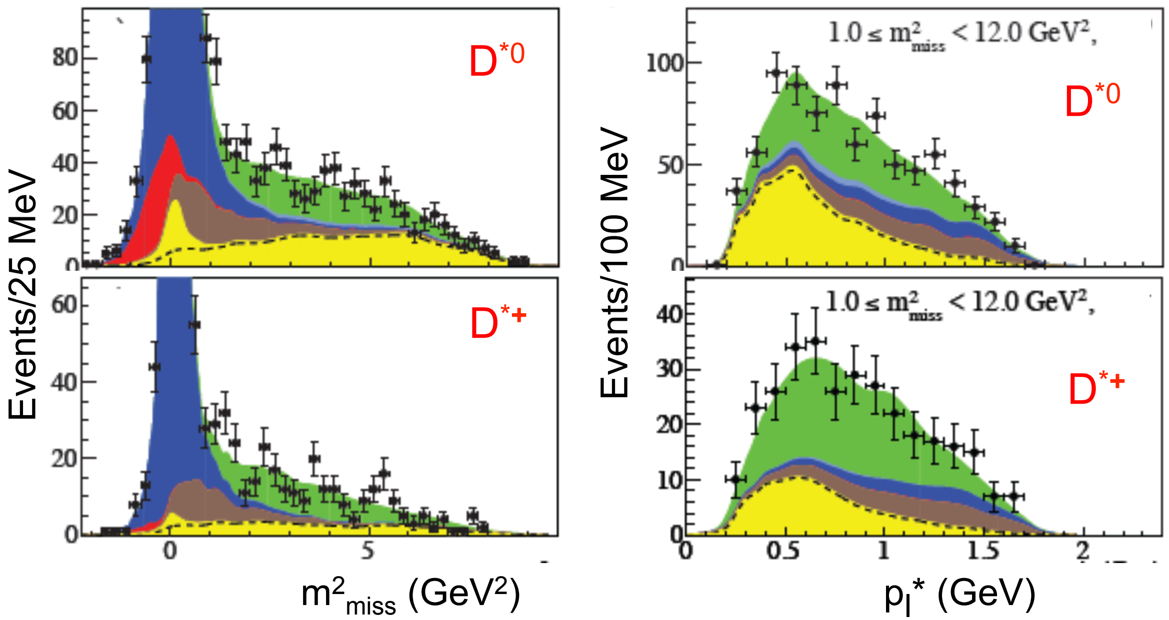
BABAR, arXiv:1205.5442
submitted to PRL

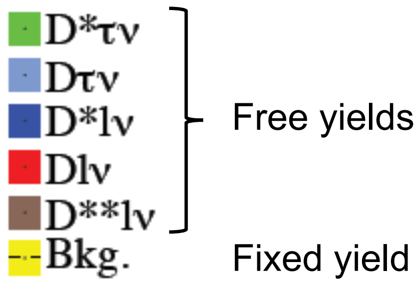
Statistical errors only

	$D^{*0}\tau\nu$	$D^{*+}\tau\nu$	$D^{*}\tau\nu$
N_{sig}	639 ± 62	245 ± 27	888 ± 63
Significance (σ)	11.3	11.6	16.4
$R(D^{*})$	0.322 ± 0.032	0.355 ± 0.039	0.332 ± 0.024

(isospin constrained)







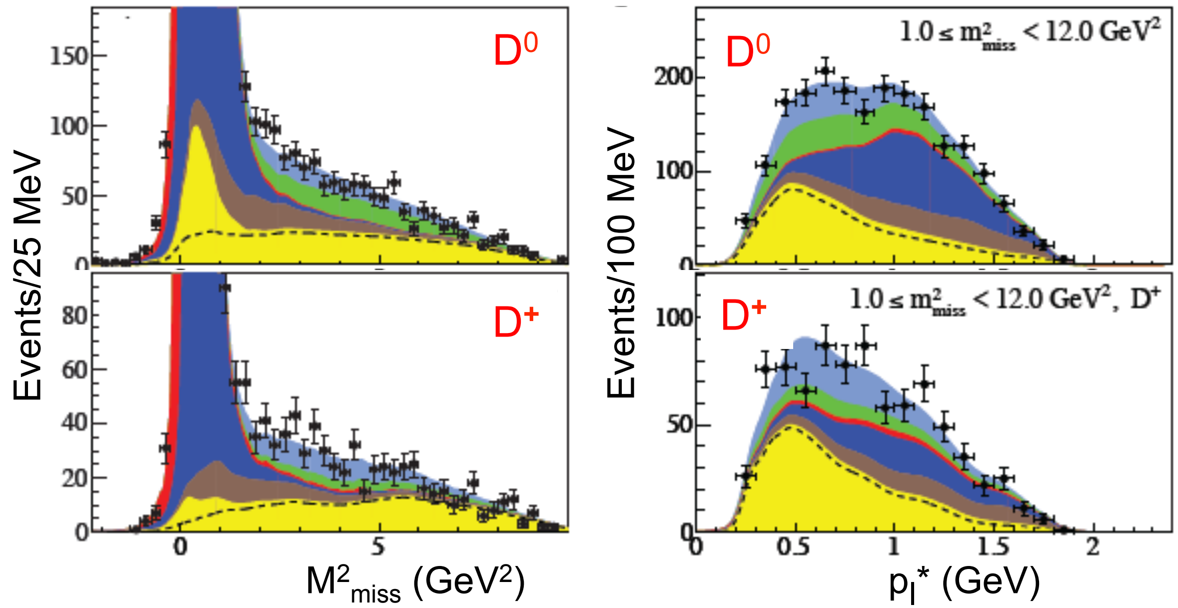
Fit results: $B \to D\tau\nu$

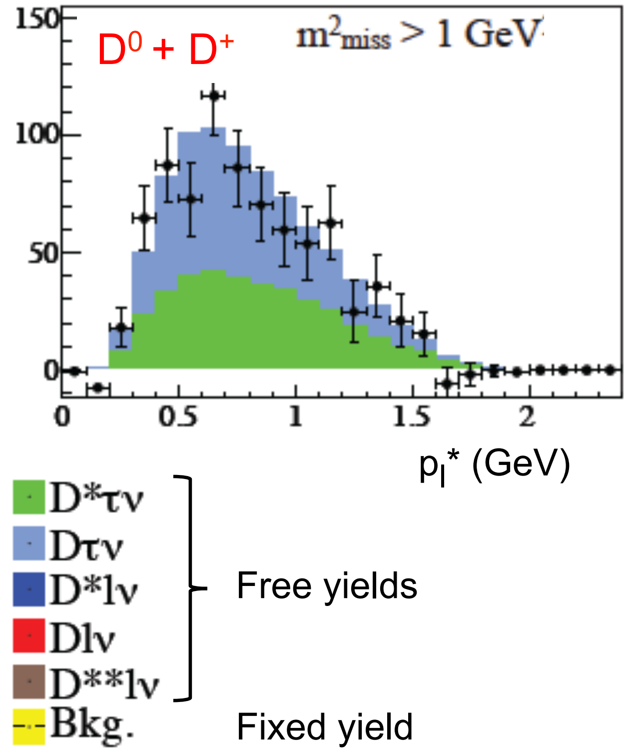
BABAR, arXiv:1205.5442
submitted to PRL

Statistical errors only

	$D^0\tau\nu$	$D^+\tau\nu$	$D\tau\nu$
$N_{\rm sig}$	314 ± 60	177 ± 31	489 ± 63
Significance (σ)	5.5	6.1	8.4
$R(D)$	0.429 ± 0.082	0.469 ± 0.084	0.440 ± 0.058

(isospin constrained)





Systematic Uncertainties

Source	Uncertainty (%) $R(D)$	Uncertainty (%) $R(D^*)$	ρ
$D^{**}\ell\nu$ background	5.8	3.7	0.62
MC statistics	5.0	2.5	-0.48
Cont. and $B\overline{B}$ bkg.	4.9	2.7	-0.30
$\varepsilon_{\mathrm{sig}}/\varepsilon_{\mathrm{norm}}$	2.6	1.6	0.22
Systematic uncertainty	9.5	5.3	0.05
Statistical uncertainty	13.1	7.1	-0.45
Total uncertainty	16.2	9.0	-0.27

BABAR, arXiv:1205.5442
submitted to PRL

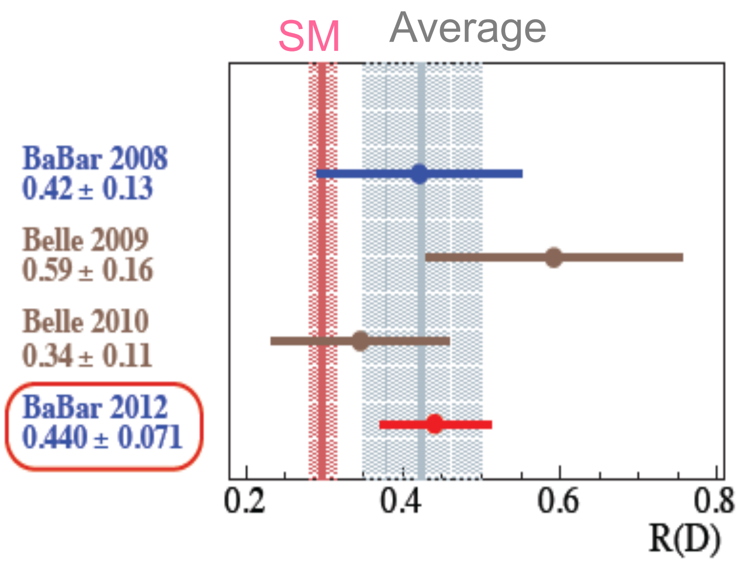
ρ is the correlation between $R(D)$ and $R(D^*)$

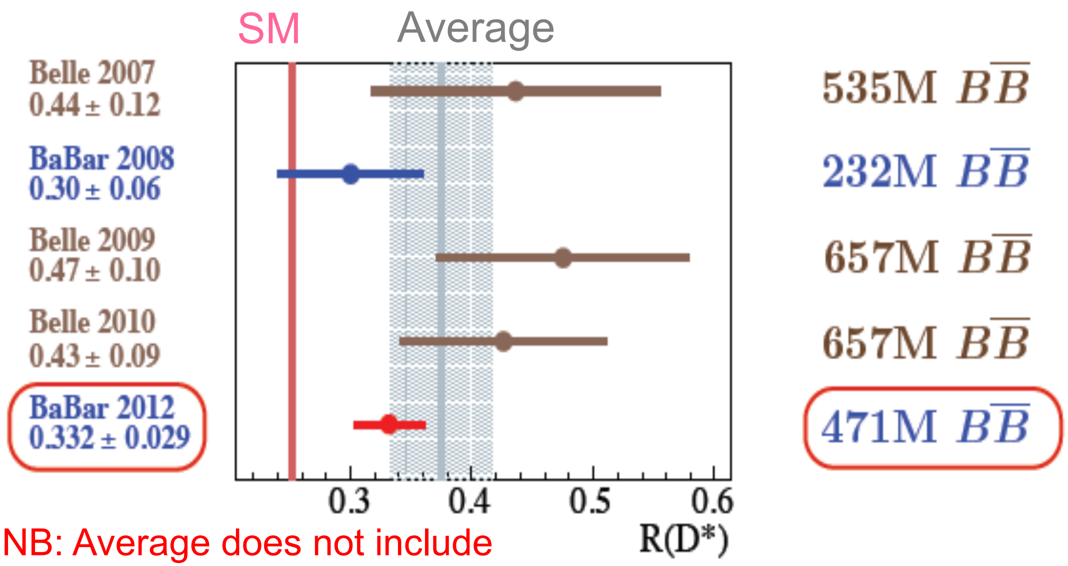
Largest errors are Gaussian distributed

Main uncertainties:

- $D^{**}l\nu$: 15% (conservative)
- No dedicated signal MC sample (impacts PDF parameterization)
- Continuum and BB background: corrections and MC statistics

Summary of $R(D^{(*)})$ Measurements



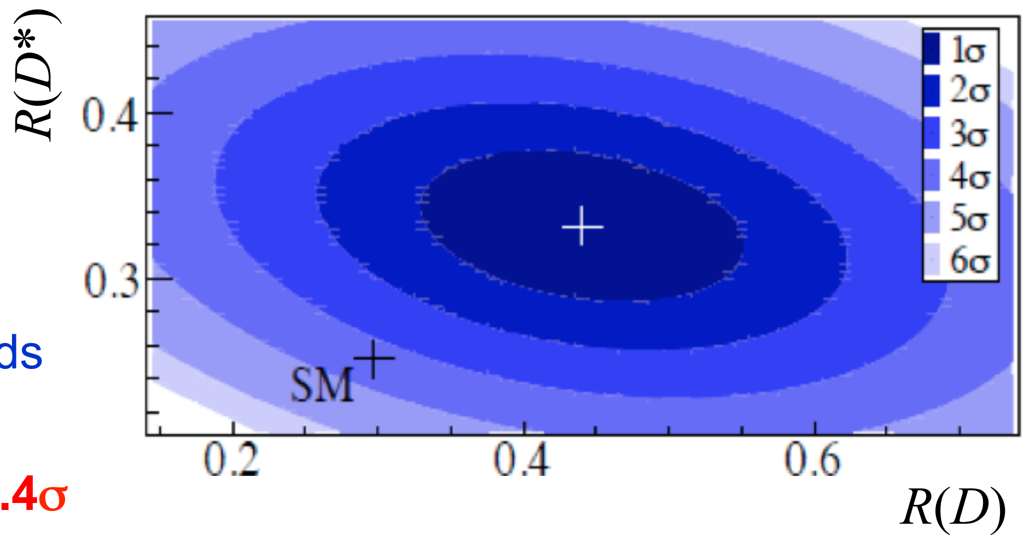


NB: Average does not include this measurement

Comparison with SM calculation:

	$R(D)$	$R(D^*)$
BABAR	0.440 +/- 0.071	0.332 +/- 0.029
SM	0.297 +/- 0.017	0.252 +/- 0.003
Δ	**2.0 σ**	**2.7 σ**

BABAR, arXiv:1205.5442 submitted to PRL



The combination of the two measurements (-0.27 correlation) yields χ^2=14.6/2, i.e. Prob. = 6.9 10^{-4} !!

The SM prediction is excluded at 3.4σ

Comparison to the 2HDM (type II)

- SM matrix element:

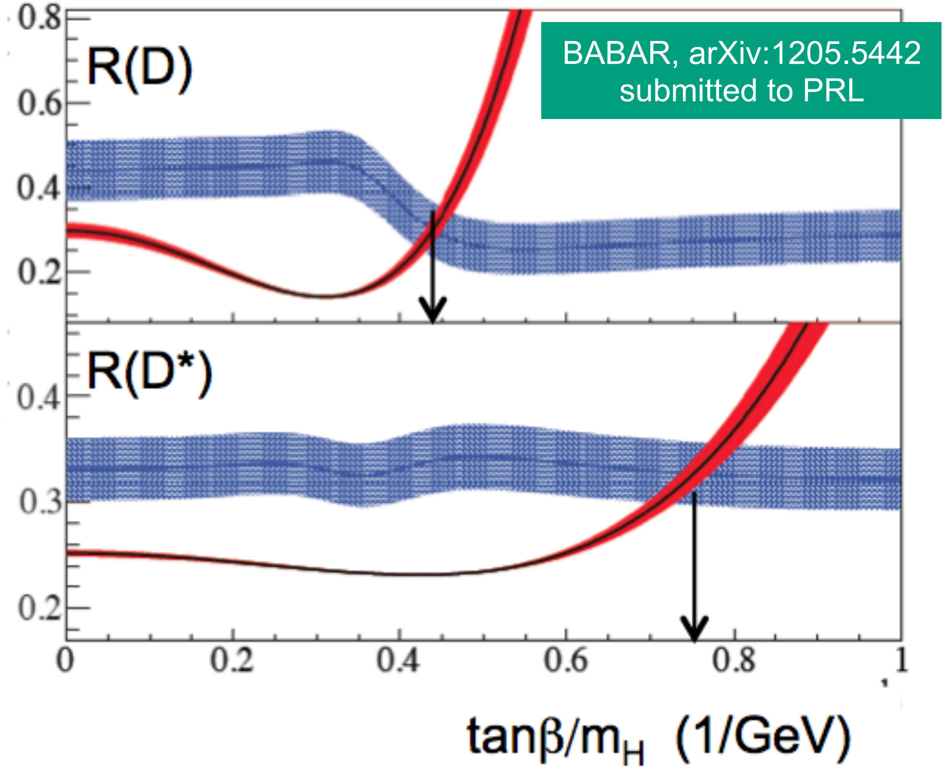
(L and H: leptonic and hadronic currents)

$$\mathcal{M}^{\lambda_\ell}_{\lambda_M}(q^2,\theta_\ell)\Big|_W = \frac{G_F V_{cb}}{\sqrt{2}} \sum_{\lambda_W} L^{\lambda_\ell}_{\lambda_W} H^{\lambda_M}_{\lambda_W}$$

- H^+ enters through the **zero-helicity current**

$$H_t^{2\text{HDM}} = H_t^{\text{SM}} \times \left(1 - \frac{\tan^2\beta}{m^2_{H\pm}} \frac{q^2}{1 \mp m_c/m_b}\right)$$

- **Reweight simulation** accordingly and repeat fit for several values of **$\tan\beta/m_H$**
- Allowed regions:
  - $\tan\beta/m_H = 0.44 \pm 0.02$ for $R(D)$
  - $\tan\beta/m_H = 0.75 \pm 0.04$ for $R(D^*)$
- Combination of $R(D)$ and $R(D^*)$ **excludes full parameter space with 99.8% probability** (m_H>10GeV)



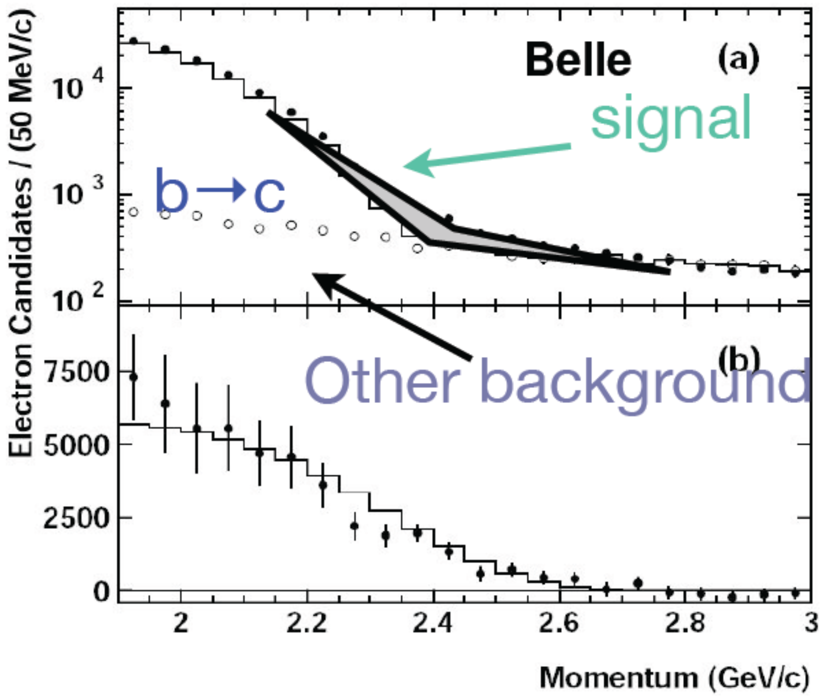
Conclusions

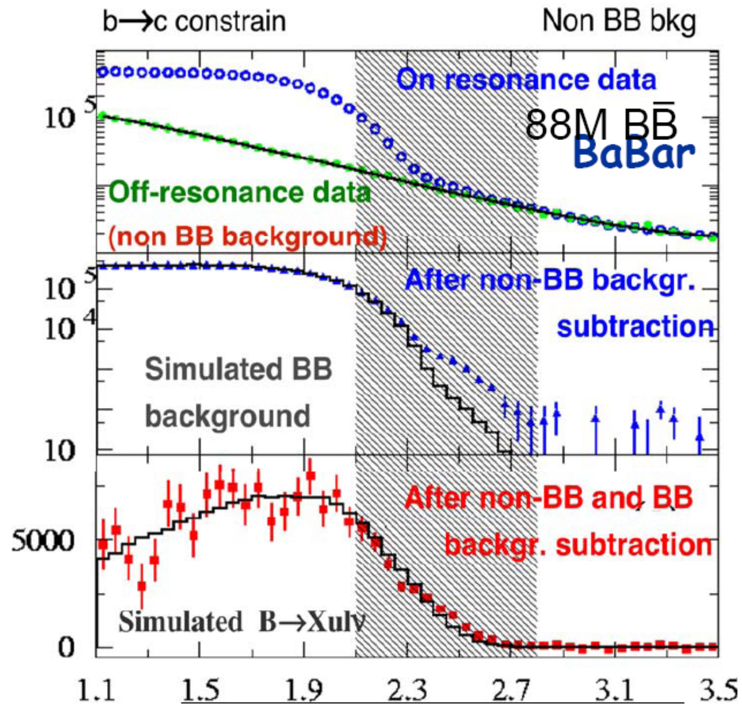
- After ***ten years of efforts***, the determination of $|V_{cb}|$, $|V_{ub}|$ and b quark mass with inclusive decays has ***improved substantially*** both from the ***theoretical*** and the ***experimental*** point of view
- Accuracies are at the (few) ***percent level***
- ***Long-standing 2-3σ "tensions" between inclusive and exclusive determinations/CKM fits*** are still with us
  - Do we understand QCD at the percent level?
  - Is there any new physics in $b \to u$ transitions?
- ***Significant excess of events in $B \to D\tau\nu$ and $B \to D^*\tau\nu$, marginally compatible with the SM and clearly disfavoring a 2-Higgs Doublet Model of type II***
- ***Final measurements from the B-Factories***: further progress will come from current experiments (LHCb) and future B-Factories

Backup

“Classic” endpoint analyses

- Typical requirements: missing momentum, event shape
- S/B ~ 1/10, ε<~40%, measurements limited by background knowledge





	$\mathcal{L}(\mathrm{fb}^{-1})$	$E_\ell(\mathrm{GeV})$	$\Delta\mathcal{B}(10^{-4})$
BaBar	81.4	2.0–2.6	5.72±0.41±0.65
Belle	27.0	1.9–2.6	8.5±0.4±1.5
CLEO	9.13	2.2–2.6	2.30±0.15±0.35

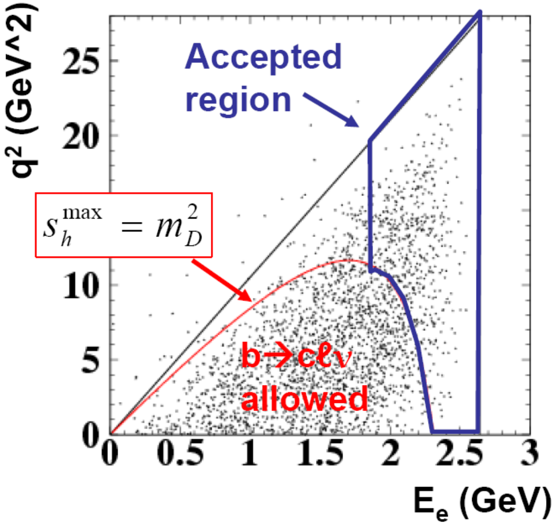
PRD 73, 012006 (2006)
PL B 621 (2005) 28
PRL 88, 231803 (2002)

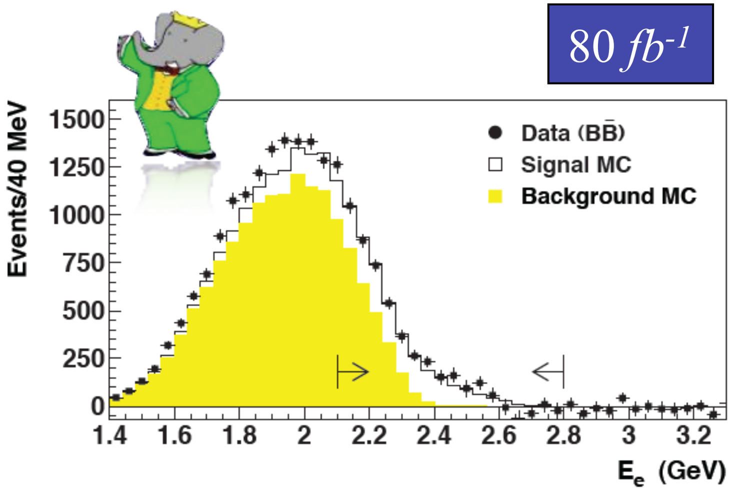
"improved" endpoint analysis

- Separate $b \to c l \nu$ background by using

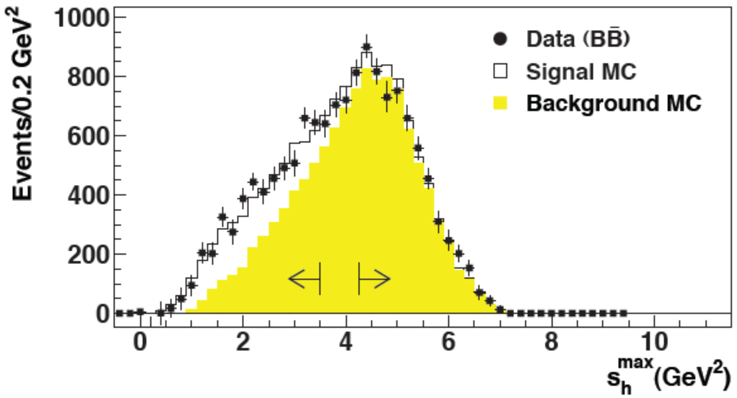
$$s_h^{\max} = m_B^2 + q^2 - 2m_B\left(E_e + \frac{q^2}{4E_e}\right)$$

- S/B~1/2, ε~25%





BaBar (PRL 95, 111801, 2005
PRL 97, 019903 (2006) Err.)



$$\Delta\mathcal{B}(2.0, 3.5) = (4.41 \pm 0.42 \pm 0.42) \times 10^{-4}$$

Systematics dominated by K_L and neutral particle ID, charm SL decays

Systematic uncertainties

BABAR preliminary

Source $\sigma(\Delta\mathcal{B}(B \to X_u \ell\nu))$	$M_X < 1.55$ GeV/c^2	$M_X < 1.70$ GeV/c^2	$P_+ < 0.66$ GeV	$M_X < 1.70$ GeV/c, $q^2 > 8$GeV^2/c^4	(M_X, q^2) $p_\ell^* > 1.0$ GeV/c	$p_\ell^* > 1.0$ GeV/c	$p_\ell^* > 1.3$ GeV/c
Statistical error	7.1	8.9	8.9	8.0	7.1	9.4	8.9
MC statistics	1.3	1.3	1.3	1.6	1.1	1.1	1.2
Detector-related:							
Tracking efficiency	0.4	1.0	1.1	1.7	0.7	1.2	0.1
Neutral efficiency	1.3	2.1	4.0	0.7	1.0	0.9	0.9
π^0 efficiency	1.2	0.9	1.1	0.9	0.9	2.9	1.1
PID eff. & misID	1.9	2.4	3.3	2.9	2.3	2.9	2.2
K_L	0.9	1.3	1.1	2.1	1.6	1.3	0.6
Fit related: (tbu)							
m_{ES} fit parameters	2.0	2.7	1.9	2.6	1.9	2.0	2.5
combinatorial backg.	1.8	1.8	2.6	1.8	1.0	2.1	0.5
Signal knowledge:							
SF parameters	$^{2.4}_{-1.6}$	$^{1.8}_{-0.9}$	$^{0.6}_{-1.8}$	$^{0.6}_{-0.9}$	$^{6.0}_{-4.9}$	$^{5.8}_{-7.1}$	$^{7.1}_{-6.1}$
SF form	1.2	1.6	2.6	1.2	1.5	1.1	1.1
Exclusive $B \to X_u \ell\nu$	0.6	1.3	1.6	0.7	1.9	5.3	3.4
Gluon splitting	1.2	1.6	1.1	1.0	2.7	3.1	2.4
Background knowledge:							
K_S veto	0.8	1.4	1.7	2.1	1.2	1.3	0.3
B SL branching ratio	0.9	1.4	1.5	1.4	1.0	0.8	0.7
D decays	1.1	0.6	1.1	0.6	1.1	1.6	1.5
$B \to D\ell\nu$ form factor	0.5	0.5	1.3	0.4	0.4	0.1	0.2
$B \to D^*\ell\nu$ form factor	0.7	0.7	0.9	0.7	0.7	0.7	0.7
$B \to D^{**}\ell\nu$ form factor	0.8	0.9	1.3	0.4	0.9	1.0	0.3
$B \to D^{**}$ reweight	0.4	1.0	1.1	0.7	1.6	0.1	1.2
Total systematics:	$^{5.3}_{-5.0}$	$^{6.4}_{-6.2}$	$^{8.0}_{-8.1}$	$^{6.2}_{-6.2}$	$^{8.5}_{-7.7}$	$^{10.5}_{-11.2}$	$^{9.4}_{-8.7}$
Total error:	$^{9.0}_{-8.8}$	$^{11.0}_{-10.9}$	$^{12.0}_{-12.1}$	$^{10.2}_{-10.3}$	$^{11.1}_{-10.5}$	$^{14.1}_{-14.6}$	$^{12.9}_{-12.4}$

BABAR preliminary

Correlation matrix for Babar analysis

TABLE V: Matrix of statistical correlations between different analyses. The $p_\ell^* > 1\,\mathrm{GeV}/c$ requirement is implicitly assumed in the definitions of phase space regions, unless otherwise noted. The entries above the main diagonal refer to correlations between measurements of partial branching fractions; the entries below the main diagonal (in boldface) refer to correlations on $|V_{ub}|$ measurements. In the latter case, theoretical correlations have been included, as described in the text.

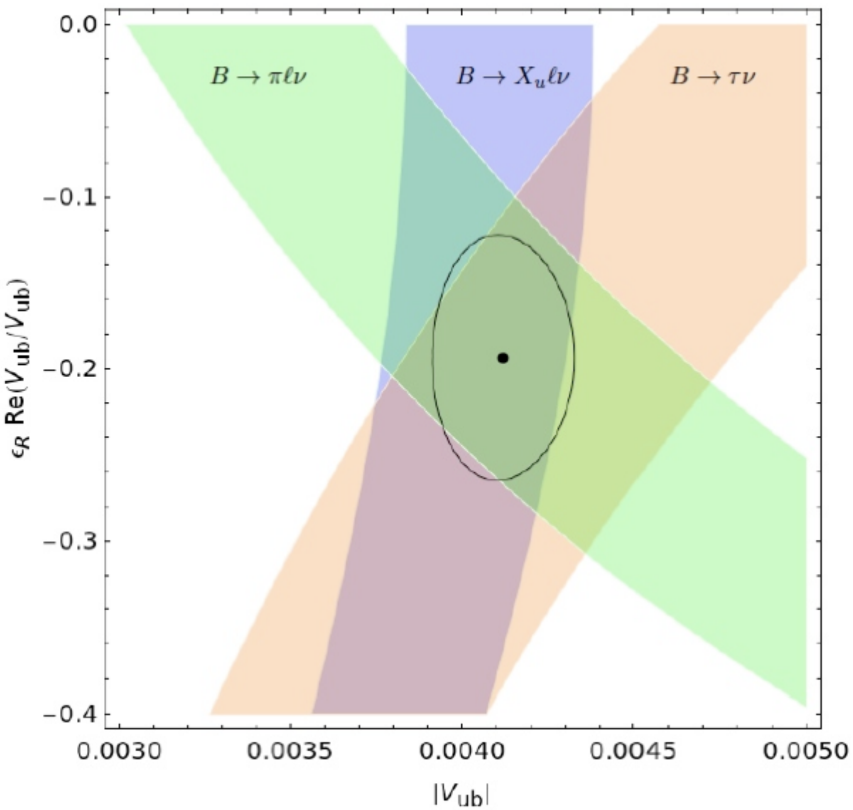
Analysis	$M_X < 1.55$ GeV/c^2	$M_X < 1.70$ GeV/c^2	$P_+ < 0.66$ GeV	$M_X < 1.70\,\mathrm{GeV}/c^2$, $q^2 > 8\mathrm{GeV}^2/\mathrm{c}^4$	(M_X, q^2) $p_\ell^* > 1.0\,\mathrm{GeV}/c$	$p_\ell^* > 1.3$ GeV/c
$M_X < 1.55\,\mathrm{GeV}/c^2$	1	0.77	0.74	0.50	0.72	0.57
$M_X < 1.70\,\mathrm{GeV}/c^2$	**0.81**	1	0.86	0.55	0.94	0.73
$P_+ < 0.66\,\mathrm{GeV}$	**0.69**	**0.81**	1	0.46	0.78	0.61
$M_X < 1.70\,\mathrm{GeV}/c^2, q^2 > 8\mathrm{GeV}^2/\mathrm{c}^4$	**0.40**	**0.46**	**0.38**	1	0.52	0.46
(M_X, q^2), $p_\ell^* > 1\,\mathrm{GeV}/c$	**0.58**	**0.88**	**0.67**	**0.34**	1	0.74
$p_\ell^* > 1.3\,\mathrm{GeV}/c$	**0.53**	**0.72**	**0.58**	**0.40**	**0.72**	1

This is a backup slide

Divertissement

(stolen from P. Gambino)

- LR models can explain a difference between inclusive and exclusive V_{ub} determinations [Chen,Nam]
- Also in MSSM [Crivellin]
- BUT the RH currents affect predominantly the exclusive V_{ub}, making the conflict between V_{ub} and sin2β (J/ψK_S) stronger...



Buras, Gemmler, Isidori 1007.1993