Experimental Results on $|V_{cb}|$ and $b \to c\ell\nu$ Transitions at *BABAR*

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BABAR

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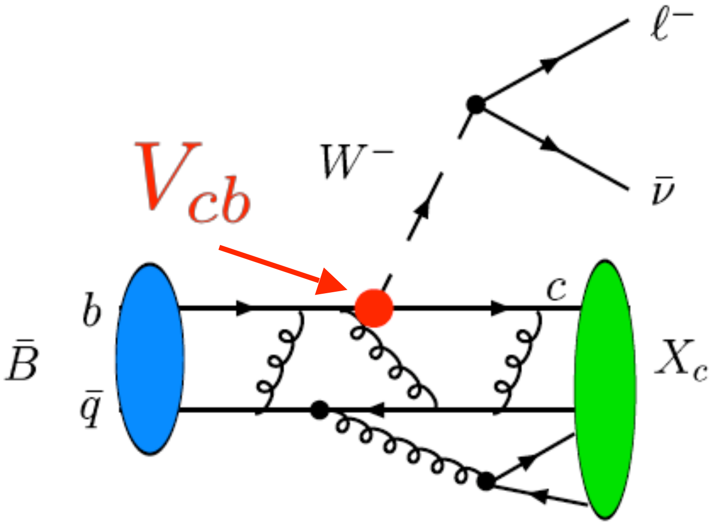
TECHNISCHE UNIVERSITÄT DRESDEN

bmb+f - Förderschwerpunkt
BABAR
Großgeräte der physikalischen Grundlagenforschung

The 2007 Europhysics Conference on High Energy Physics
Manchester, England, 19-25 July 2007

Outline

- Inclusive semileptonic decays
  - Updated hadronic-mass moments and mixed hadronic-mass and -energy moments
  - HQE Fit



- Exclusive semileptonic decays
  - Measurement of $B^- \to D^{*0} e^- \bar{\nu}$

- Exclusive semileptonic decays containing a τ lepton
  - Measurement of $\mathcal{B}(\bar{B}^0 \to D^+ \tau \nu)$, $\mathcal{B}(B^- \to D^0 \tau \nu)$ and $\mathcal{B}(\bar{B}^0 \to D^{*+} \tau \nu)$, $\mathcal{B}(B^- \to D^{*0} \tau \nu)$

Sensitivity to New Physics

HQE and Semileptonic B Decays

$$\Gamma_{sl}(B \to X_c \ell \nu) = \frac{G_F^2 m_b^5}{192\pi^3} |V_{cb}|^2 (1 + A_{EW}) A_{pert} A_{nonpert}$$

$$\frac{\mathcal{B}(B \to X_c \ell \nu)}{\tau_B} = f_{HQE}^{(0)} |V_{cb}|^2$$

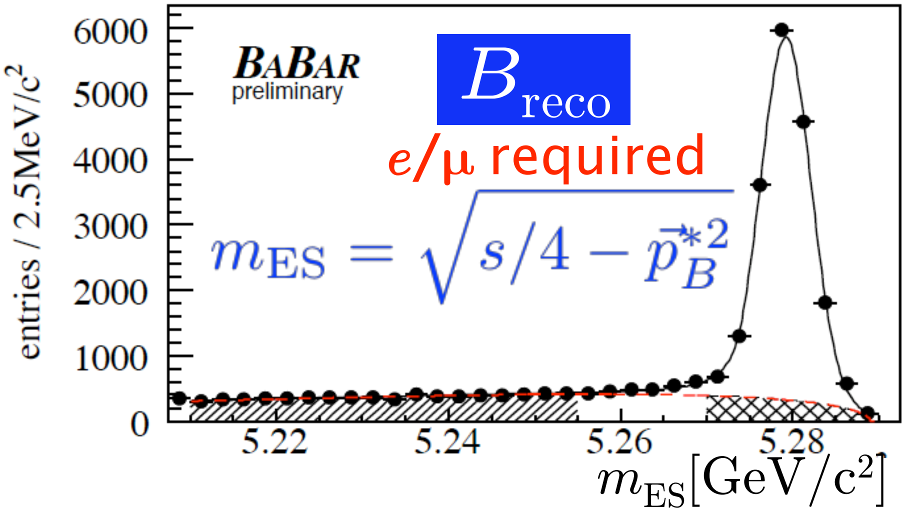
depends on m_b, m_c and HQE parameters

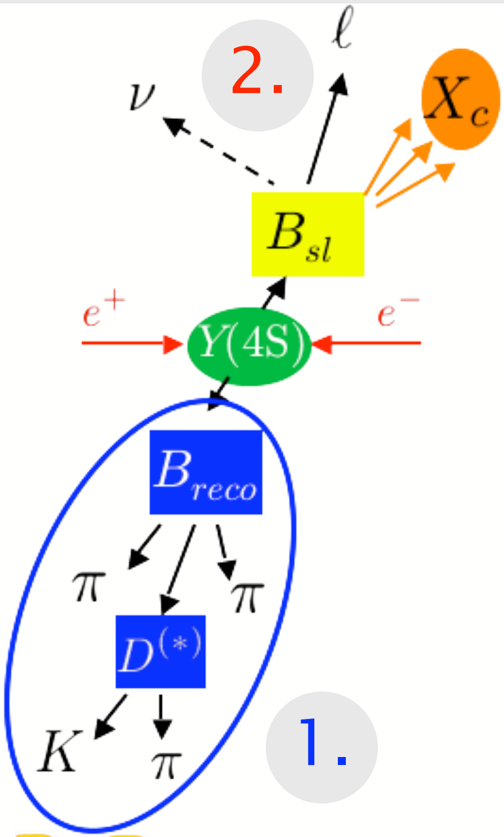
$$\langle m_X^n \rangle = f_{HQE}^{(n)}(p_\ell^* > p_{\ell,\min}^*; m_b, m_c, \mu_\pi^2, \mu_G^2, \rho_D^3, \rho_{LS}^3)$$

- Measurement of
  - hadronic mass, lepton energy moments in $b \to c l \nu$
    - mixed hadronic moments $n_X^2 = m_X^2 - 2\tilde{\Lambda} E_X + \tilde{\Lambda}^2$
  - Photon energy moments in $b \to s\gamma$

Inclusive $B \to X_c l\nu$ Hadronic Moments

1. Inclusive reconstruction in tagged events with fully reconstructed B_{reco} meson, quality checked with m_{ES}



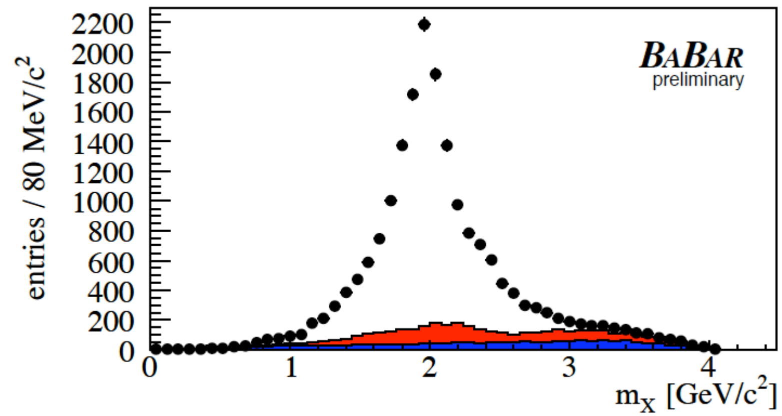


2. Measure exactly one e/μ ($q_{lep} \times q_{breco} < 0$) in remaining particles with $p_l^* > 0.8$ GeV/c
3. All remaining particles combined to inclusive X_c system
4. Kinematic fit (2C):
   - Energy- and momentum-conservation
   - E_{miss} and p_{miss} consistent with neutrino hypothesis

Extraction of Hadronic Moments

232 M $B\bar{B}$ pairs

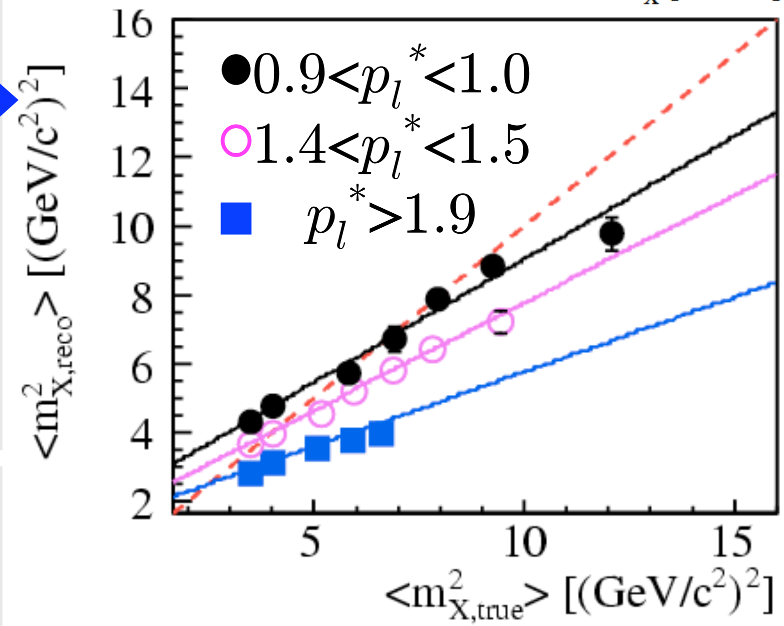
- Requirements on neutrino observables E_{miss} and p_{miss}
- Background (about 20%)
  - Combinatorial B_{reco} → m_{ES} sideband
  - B_{reco} correct, B_{sl} not signal → MC simulations



- Distortion of hadronic system:
  - Unmeasured particles
- Linear correction functions measured on MC

$$\langle n^k_{X,\mathrm{reco}} \rangle \leftrightarrow \langle n^k_{X,\mathrm{true}} \rangle \quad \langle m^k_{X,\mathrm{reco}} \rangle \leftrightarrow \langle m^k_{X,\mathrm{true}} \rangle$$

applied event-by-event

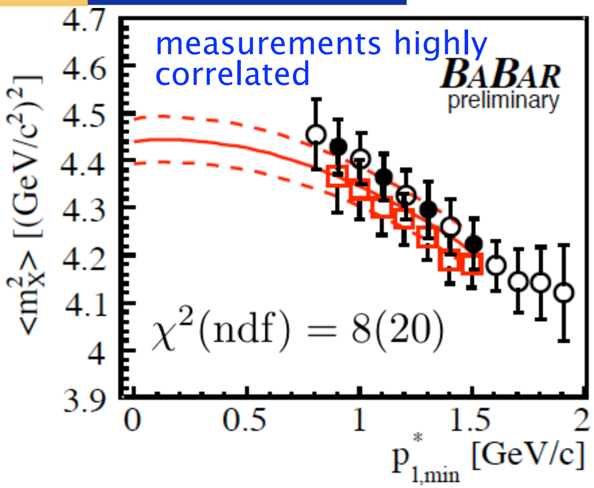


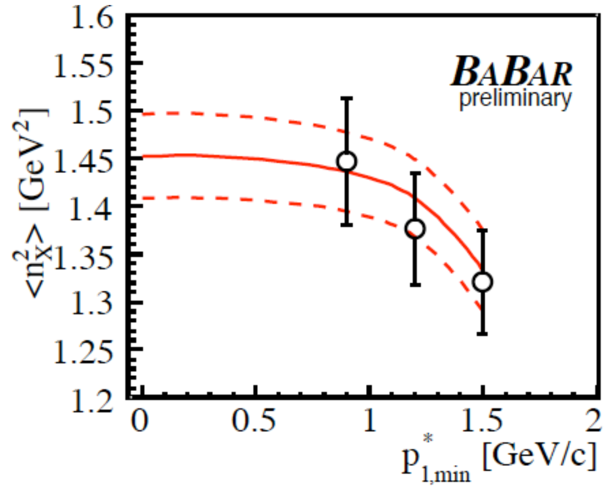
- Main systematic uncertainties:
  - Reconstruction efficiency impact on inclusive full event reconstruction

HQE Fit

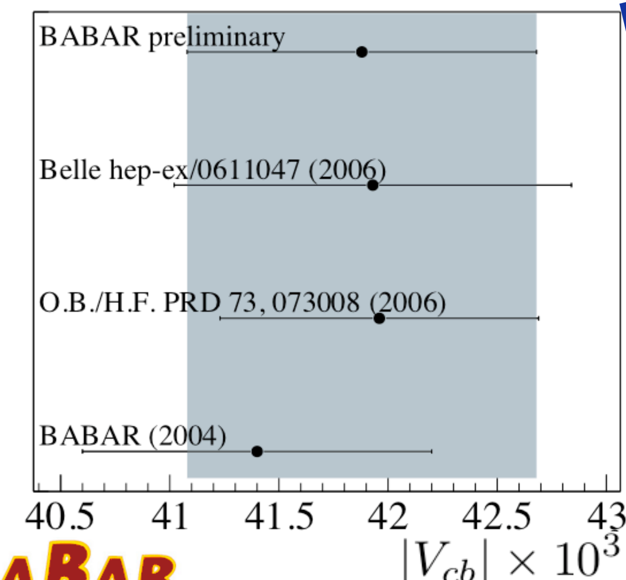
- 27 input moments
  - 8 mass moments
  - 13 E_l moments
  - 6 photon moments
- further input: τ_B
- 8 fit parameters
  - $|V_{cb}|$, m_b, m_c, B_{sl}
  - 4 HQE parameters

○● This measurement (open symbols not fitted)
□ BABAR 2004





Benson,Bigi,Mannel,Uraltsev, Nucl.Phys.B**665**:367;
Gambino and Uraltsev, hep-ph/0401063, hep-ph/0403166



preliminary

	$\vert V_{cb}\vert$ $\times 10^3$	m_b [GeV/c^2]	m_c [GeV/c^2]	$\mathcal{B}$ [%]
Results	41.88	4.552	1.070	10.597
Δ_{exp}	0.44	0.038	0.055	0.171
Δ_{theo}	0.35	0.040	0.065	0.053
$\Delta_{\Gamma_{sl}}$	0.59			
Δ_{tot}	0.81	0.055	0.085	0.179
Δ_{tot} [%]	1.9	1.2	7.9	1.7

BABAR, arXiv:0707.2670 [hep-ex] (2007)

Measurement of $B^- \to D^{*0} e^- \bar{\nu}$

- Theory connects $|V_{cb}|$ with the differential rate

$$\frac{d\Gamma}{dw}(B \to D^* \ell \nu) = \frac{G_F^2 |V_{cb}|^2}{48\pi^3} \mathcal{F}^2(w)\mathcal{G}(w)$$

- $w = \mathbf{v_B} \cdot \mathbf{v_{D^*}}$
- $\mathcal{G}(w) \propto \sqrt{w^2 - 1}$ (phase space)
- $\mathcal{F}(w)$ form factor expressed in terms of D^* helicity amplitudes parametrized with
  - measured FF ratios $R_1(1), R_2(1)$
  - and parameter related to slope at $w=1$: $\rho^2{}_{A1}$

BABAR, hep-ex/0607067

Caprini, Lellouch, Neubert NPB**530** (1998) 153

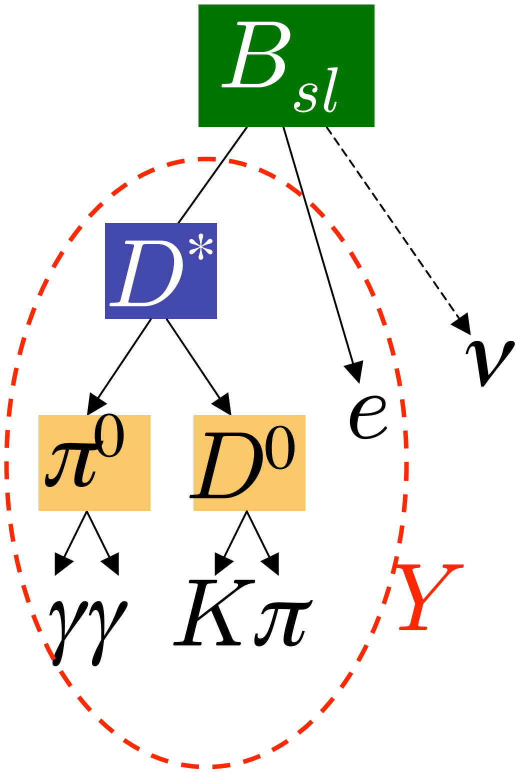
- Branching fraction from $\mathcal{B} = \int \frac{d\mathcal{B}}{dw} dw$

So Far

- Mainly B^0 decays including a slow $\pi^\pm$

➲ Independent B^- measurement with a slow π^0

Analysis for $B^- \to D^{*0} e^- \bar{\nu}$



- Discriminating variables:
  - $\Delta m = m(K\pi\pi^0) - m(K\pi)$
  - $\cos\theta^*_{BY} = \dfrac{2E^*_B E^*_Y - m^2_B - m^2_Y}{2p^*_B p^*_Y}$
- Estimate for w

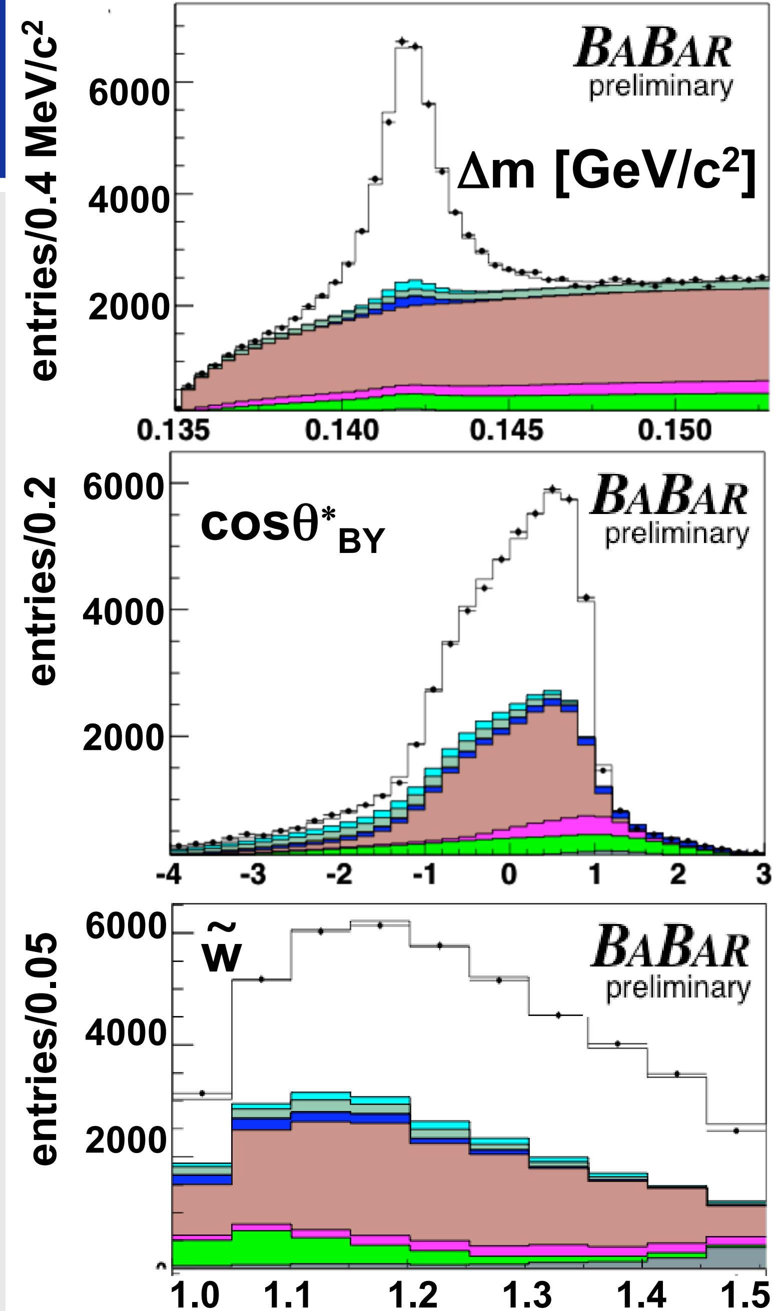
$$\Rightarrow \tilde{w} = \frac{1}{2}\left(w(\beta^*_{\min}) + w(\beta^*_{\max})\right)$$

β^* angle between B and D^* in CM

- Binned maximum likelihood fit to 3-dim. distribution in
  - Δm, $\cos\Theta^*_{BY}$, and $\tilde{w}$
  - 49 free parameters:
    - $F(1)|V_{cb}|$, ρ^2_{A1},
    - shapes and normalizations

Fit to $B^- \to D^{*0} e^- \bar{\nu}$

- Fit Results
  - Obtained χ^2 (dof) = 4436 (4095)
    - No accumulation of high χ^2 in any region
  - 23500±330 signal events
- Main background
  - Misreconstructed $B^{\pm 0} \to D^{*\pm 0} e\nu$ decays
  - $B \to De\nu$ decays
  - Combinatorial D^{*0}
  - Other BG peaking in Δm: D^{**}, $D^{*0}\,e$ from different B mesons
- Main systematic uncertainties
  - π^0 reconstruction efficiency
  - $\mathcal{B}(D^{*0} \to D^0 \pi^0)$
  - $R_1(1)$ and $R_2(1)$ for ρ^2_{A1}



226 M BB̄ pairs

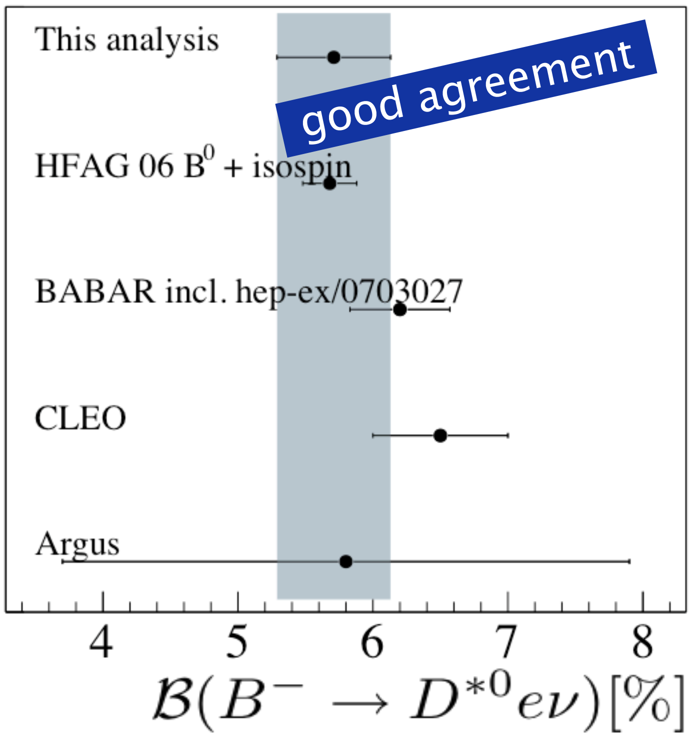
Results for $B^- \to D^{*0} e^- \bar{\nu}$

BABAR, arXiv:0707.2655 [hep-ex] (2007)

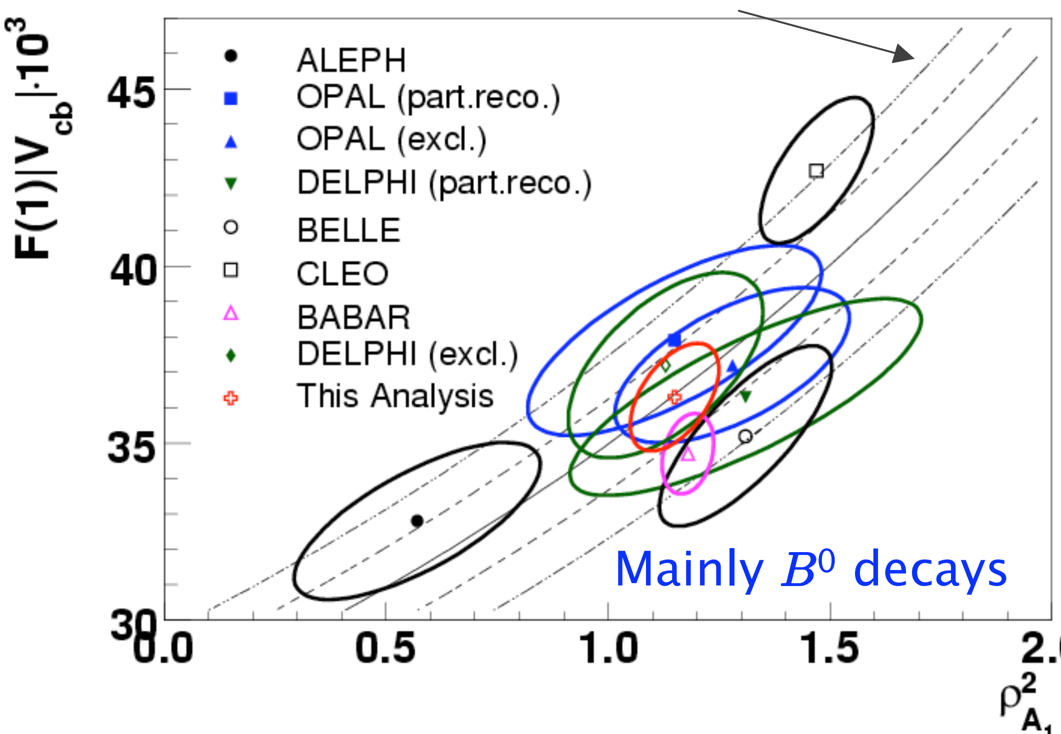
preliminary

$$F(1)\cdot|V_{cb}| = (36.3 \pm 0.6 \pm 1.4)\cdot 10^{-3}$$
$$\rho^2_{A_1} = 1.15 \pm 0.06 \pm 0.08$$
$$\mathcal{B}(B^- \to D^{*0} e^- \bar{\nu}_e) = (5.71 \pm 0.08 \pm 0.41)\ \%$$

correlation $\varrho = 0.52$



lines of constant $\mathcal{B}$

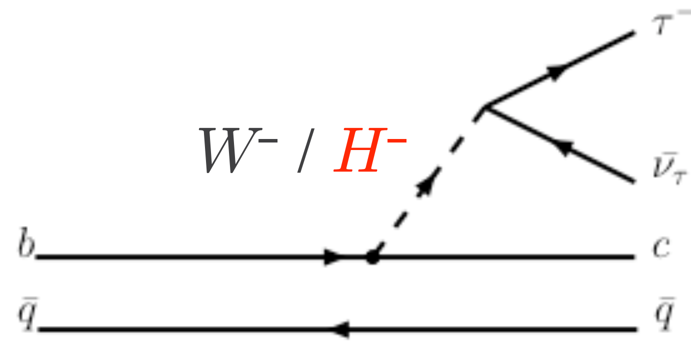


Measurement of $B \to D^{(*)} \tau \nu$

- New physics accessible at tree level
- BFs calculated precisely

Decay Mode	$\mathcal{B}(\%)$
$\overline{B}^0 \to D^+ \tau^- \overline{\nu}_\tau$	0.69 ± 0.04
$\overline{B}^0 \to D^{*+} \tau^- \overline{\nu}_\tau$	1.41 ± 0.07
$B \to X_c \tau^- \overline{\nu}_\tau$	2.3 ± 0.25

- Though BFs are large: Challenge



Chen, Geng, JHEP **0610**, 053 (2006)
Falk et al., PLB **326**,145 (1994)

- Results for inclusive decays from 3 LEP experiments (PDG):

$$\mathcal{B}(b \to X \tau^- \overline{\nu}_\tau) = (2.48 \pm 0.26)\%$$

- Preliminary observation of $B^0 \to D^{*-} \tau \nu$ by Belle:

$$\mathcal{B}(B^0 \to D^{*-} \tau^+ \nu_\tau) = (2.02^{+0.40}_{-0.37} \pm 0.37)\%$$

Belle, arXiv:0706.4429 [hep-ex] (2007)

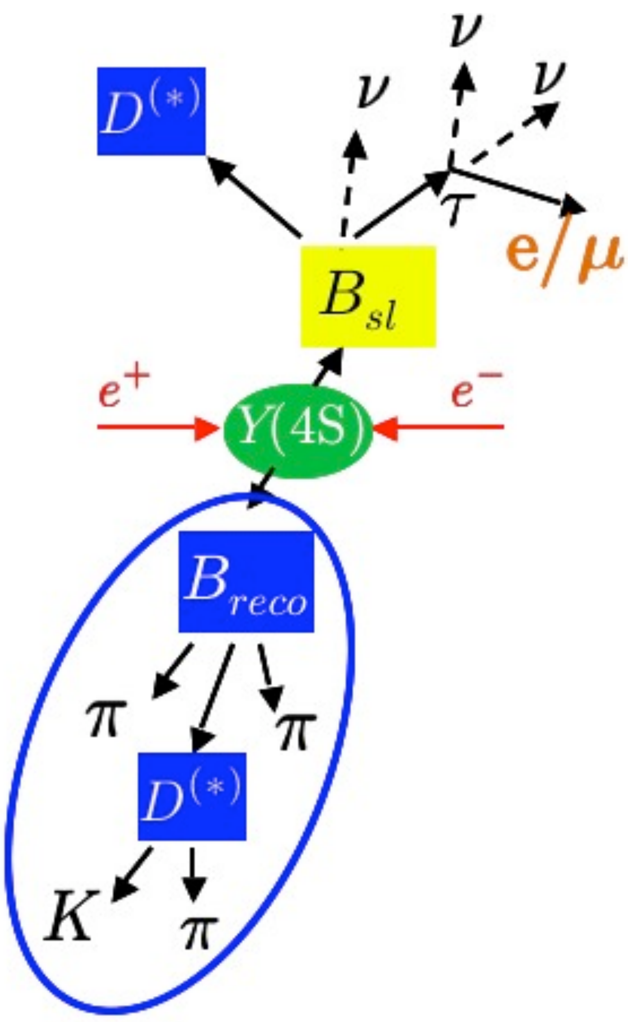
- Measure four channels relative to decays with e/μ

$\Rightarrow B^- \to D^0 / D^{*0} \tau^- \overline{\nu}_\tau$

$\Rightarrow \overline{B}^0 \to D^+ / D^{*+} \tau^- \overline{\nu}_\tau$

$B \to D \tau \nu$ yields more sensitivity to New Physics

Reconstruction of $B \rightarrow D^{(*)}\tau\nu$



- Full event reconstruction allows use of B_{reco} - $D^{(*)}$ flavor correlation
- E_{extra} < 150-300 MeV (sum of additional photons); no additional charged tracks
- Requirements on p_{miss} and q^2
- Sensitivity in $m^2_{\text{miss}} = [p_{\Upsilon(4S)} - p_{\text{tag}} - p_{D(*)} - p_l]^2$

3 neutrinos result in $m^2_{\text{miss}} \sim$ 2-8 GeV$^2/c^4$

- Main background from
  - $D^* e(\mu)\nu$ → peaks near zero in m^2_{miss}
  - $D^{**} e(\mu)\nu$ → accumulates in signal region
    - decays with a lost π^0 and ν
    - construction of D^{**} control samples by adding a π^0
    - used to constrain D^{**} background in signal region

Measurement of $B \to D^{(*)}\tau\nu$

- Discriminating variables: $m^2_{\rm miss}$ and p_l
- Perform extended unbinned maximum likelihood fit in eight reconstruction channels
  - Four signal channels + four D^{**} control samples
  - 18 free parameters in the fit
    (16 event yields for signal & BG, 2 crossfeed constraints)

  - Extract simultaneously yields of
    $D\tau\nu / D^*\tau\nu / D\ell\nu / D^*\ell\nu / D^{**}\ell\nu$

    used for normalization for

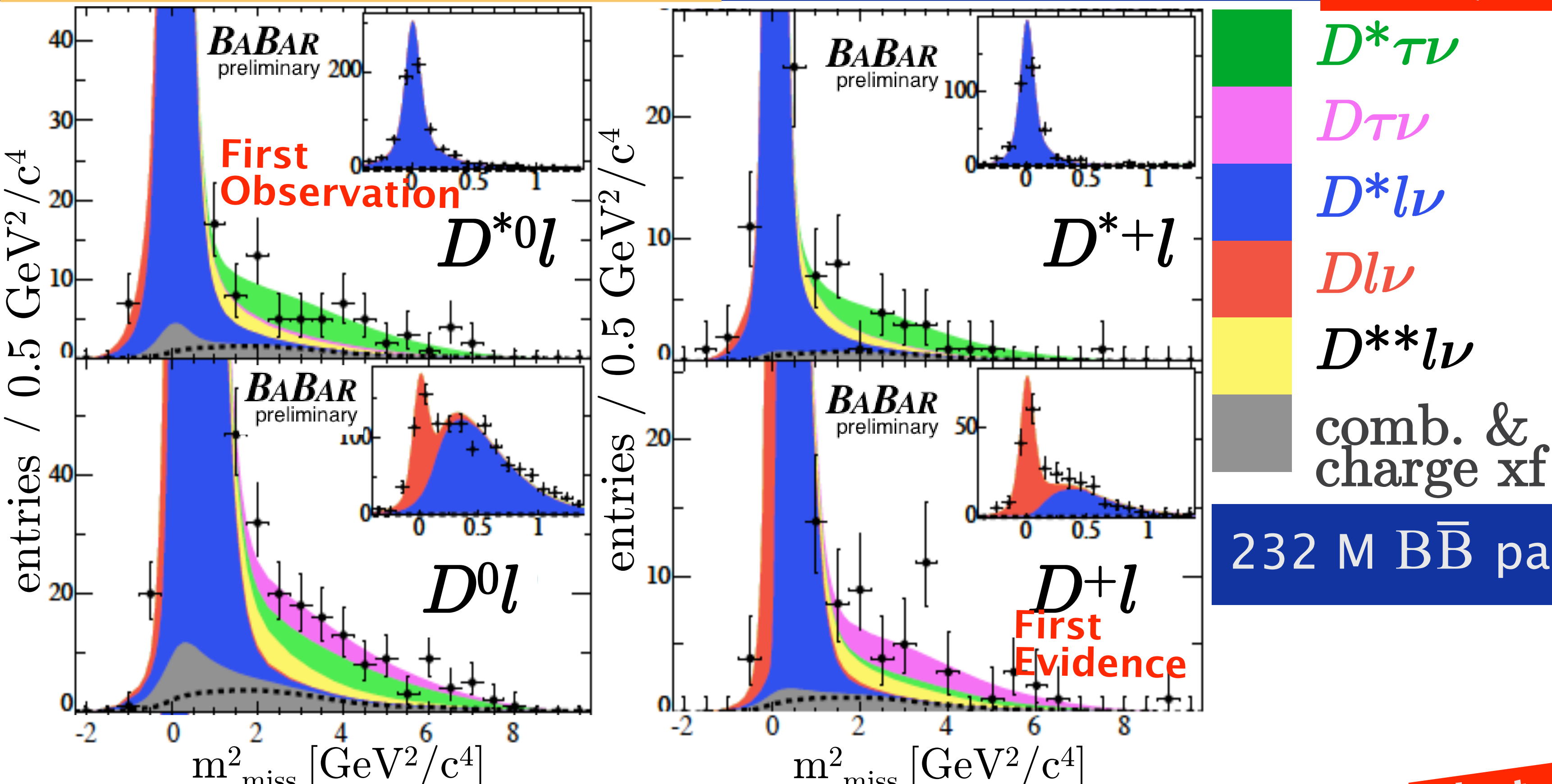
$$R = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)} \qquad \ell = e \text{ or } \mu$$

  - also combined fit with:
    $R(B^0) = R(B^+)$ → isospin symmetry

- Main systematic uncertainties:
  - Parametrization of PDFs and crossfeed constraints
  - Composition of combinatorial background

First Evidence for $B \to D\tau\nu$

BABAR, arXiv:0707.2758 [hep-ex] (2007)



232 M $B\bar{B}$ pairs

preliminary

Combined Fit Results

Mode	N_{sig}	$\mathcal{B}[\%]$ (± stat. ± sys. ± norm.)	sign.
$D\tau\nu$	64.9 ± 19.1	$0.90 \pm 0.26 \pm 0.11 \pm 0.06$	3.5
$D^*\tau\nu$	105.3 ± 19.4	$1.81 \pm 0.33 \pm 0.11 \pm 0.06$	6.2

First Evidence

consistent with Belle measurement

1σ agreement with SM

Summary

BABAR, arXiv:0707.2670 [hep-ex] (2007)

Inclusive semileptonic decays

- Measurement of $<m_X^k>$, k=1…6 and $<(n_X^2)^k>$, k=1,2,3
- HQE Fit (kinetic scheme) to BABAR measurements yields

preliminary

	$\lvert V_{cb}\rvert \times 10^3$	m_b [GeV/c^2]	m_c [GeV/c^2]	$\mathcal{B}$ [%]
Results	41.88	4.552	1.070	10.597
Δ_{tot}	0.81	0.055	0.085	0.179

BABAR, arXiv:0707.2655 [hep-ex] (2007)

Exclusive semileptonic decays: $B^- \to D^{*0} e^- \overline{\nu}$

preliminary

$$F(1) \cdot |V_{cb}| = (36.3 \pm 0.6 \pm 1.4) \cdot 10^{-3}$$
$$\rho^2_{A_1} = 1.15 \pm 0.06 \pm 0.08$$
$$\mathcal{B}(B \to D^{*0} e\nu) = (5.71 \pm 0.08 \pm 0.41)\ \%$$

Measurement of B ($B \to D\tau\nu$) and $\mathcal{B}$ ($B \to D^*\tau\nu$)

preliminary

Mode	$\mathcal{B}$[%]	sign.
$D\tau\nu$	$0.90 \pm 0.26 \pm 0.11 \pm 0.06$	3.5
$D^*\tau\nu$	$1.81 \pm 0.33 \pm 0.11 \pm 0.06$	6.2

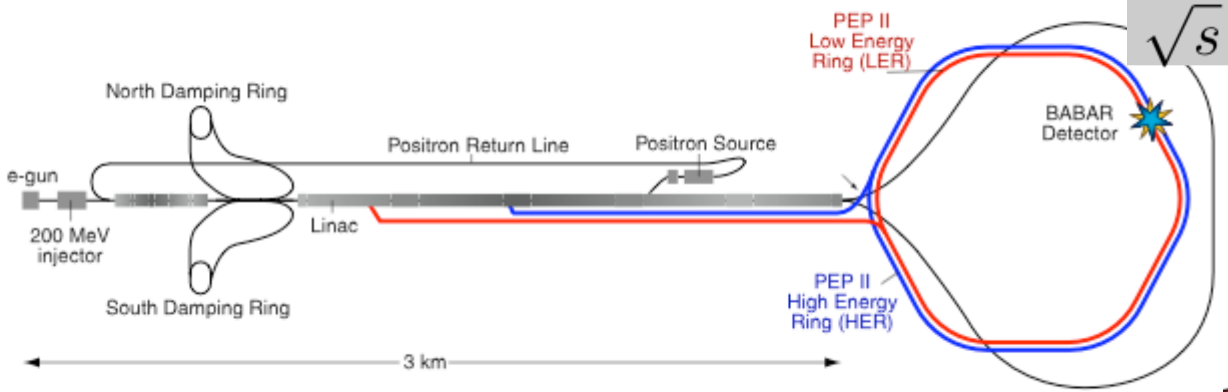
First Evidence for $B \to D\tau\nu$

First Observation of $B^- \to D^{*0}\tau\nu$

BABAR, arXiv:0707.2758 [hep-ex] (2007)

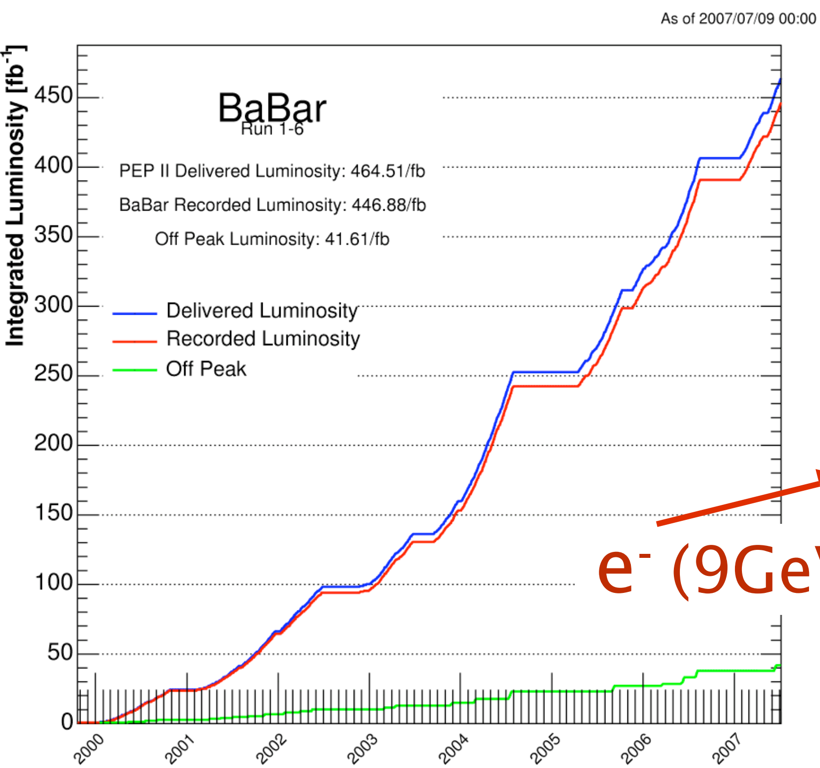
Backup Slides

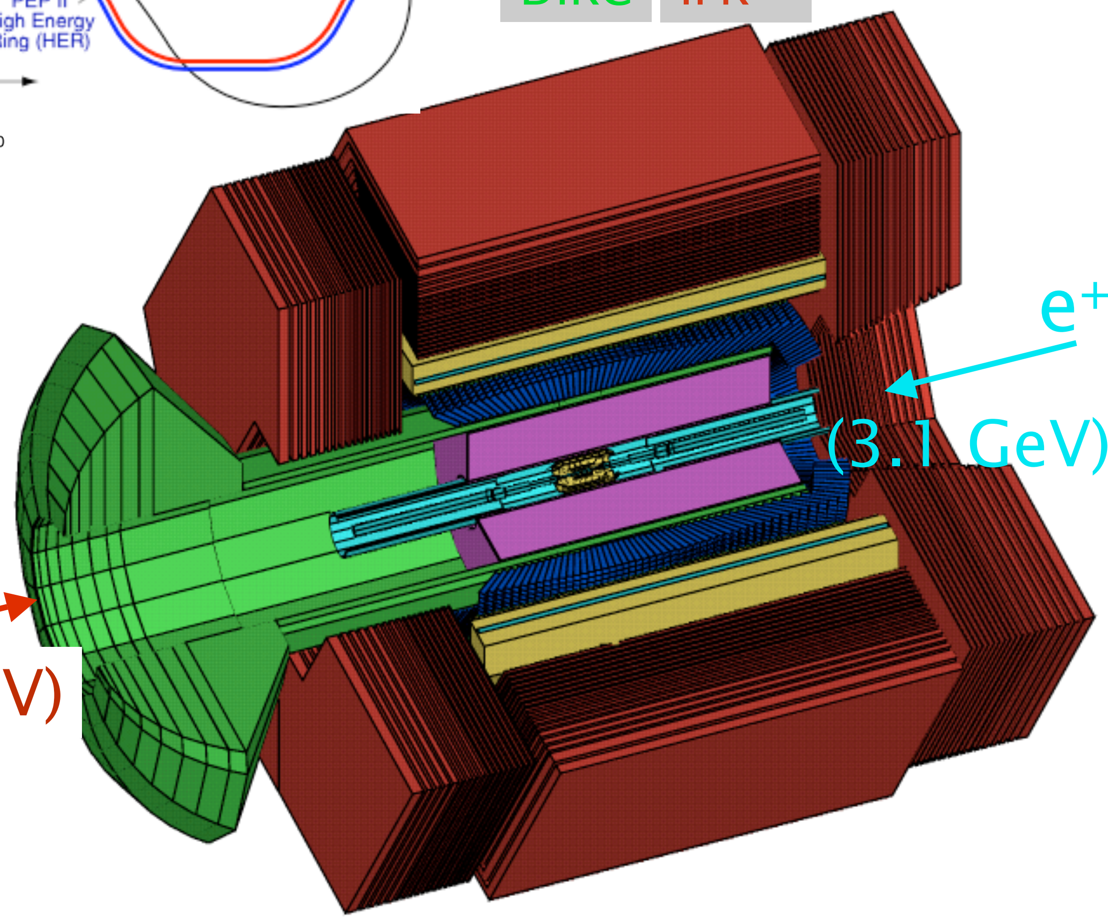
PEP-II and BABAR



$\sqrt{s} = 10.58\,\mathrm{GeV} = m(\Upsilon(4S))$

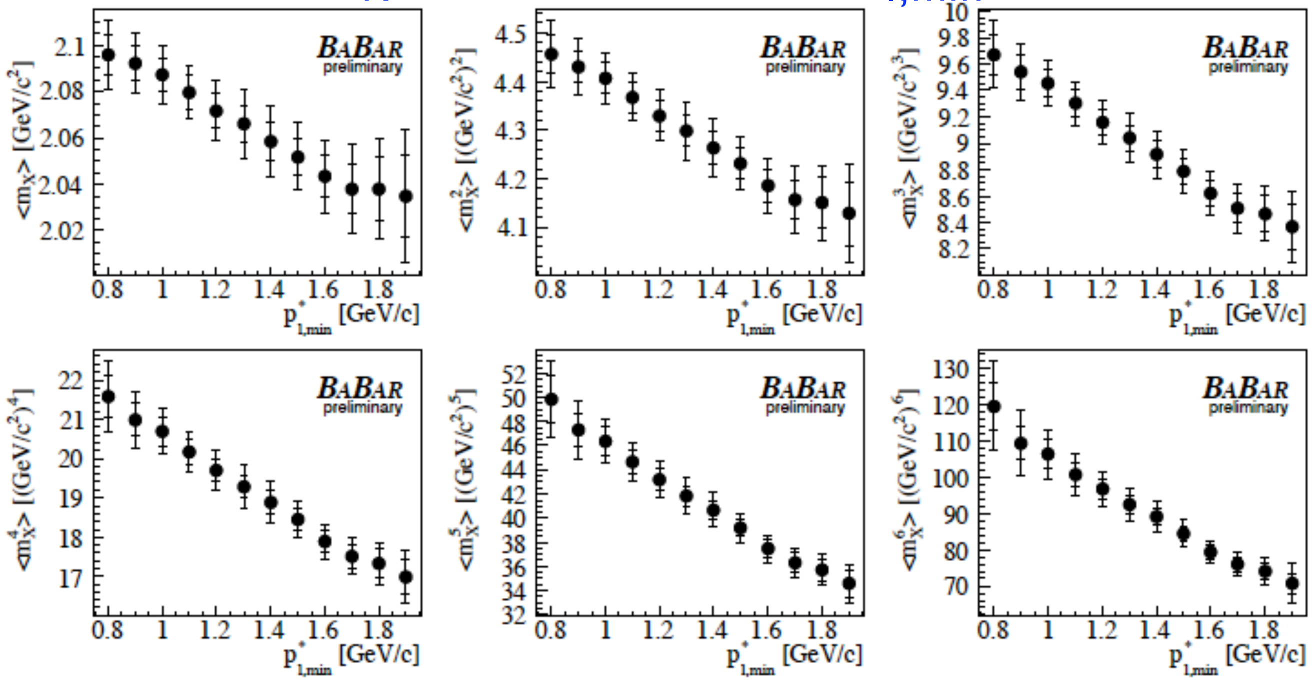
SVT | EMC
DCH | 1.5 T Solenoid
DIRC | IFR



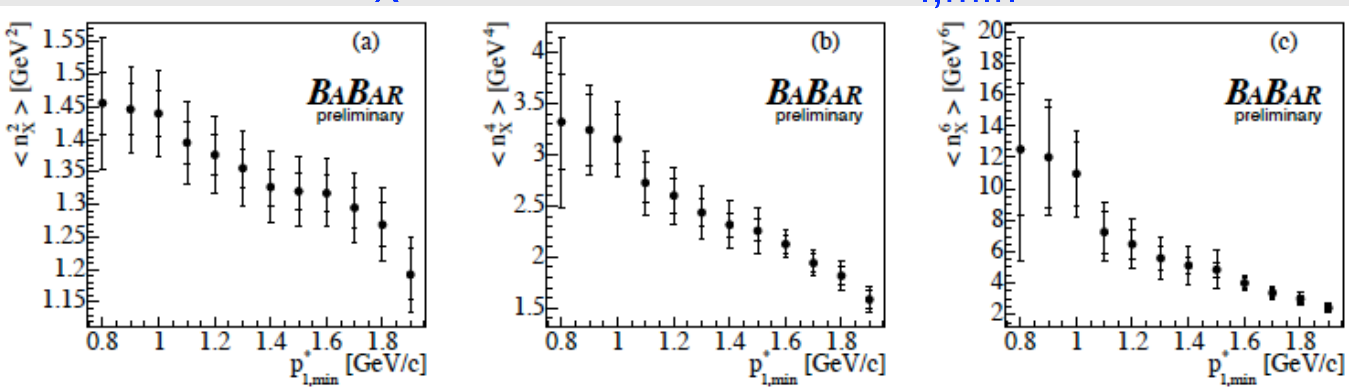


Large Set of Hadronic Moments

Mass moments $<m_X^k>$ for k=1,…,6, $p_{l,min}$ =0.8….1.9 GeV/c

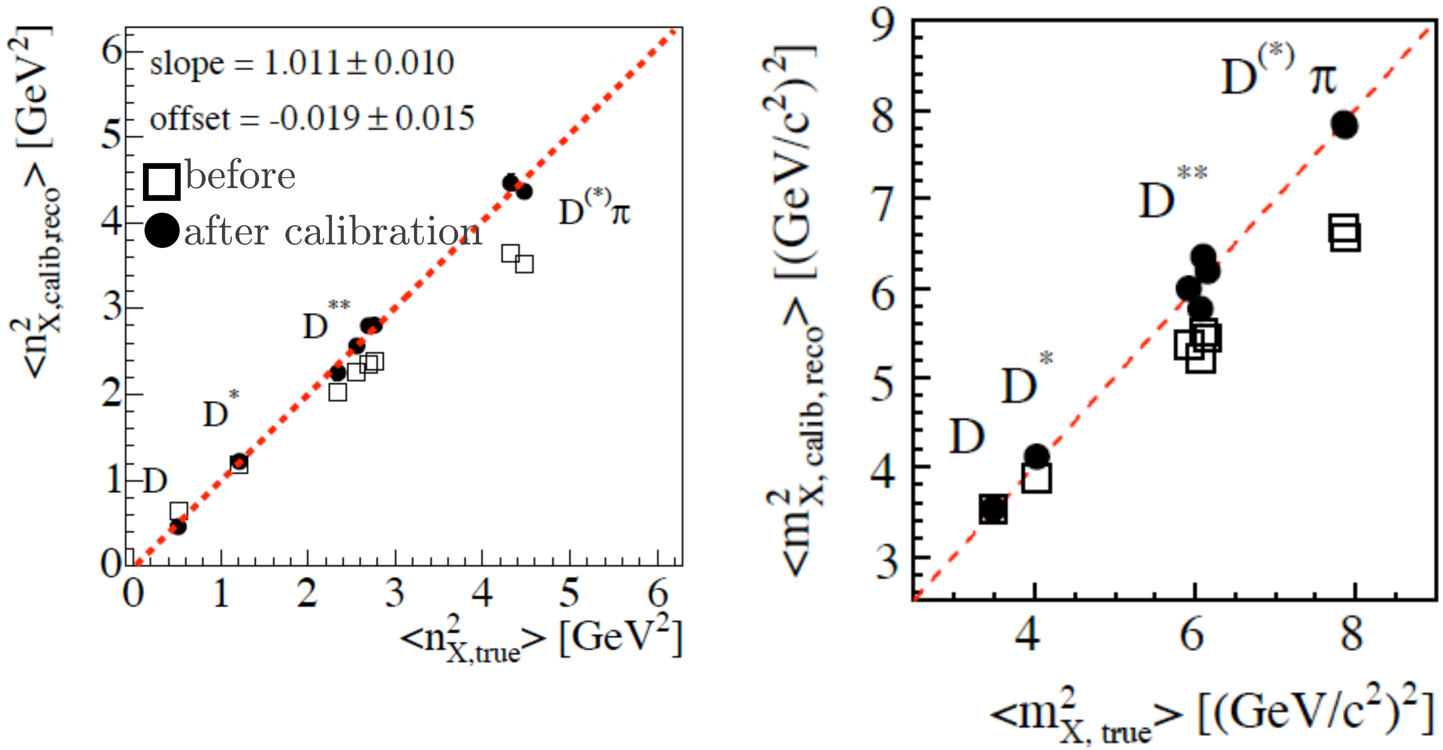


Mixed moments $<(n_X^2)^k>$ for k=1,2,3, $p_{l,min}$ =0.8….1.9 GeV/c



Hadronic Moments – Verification

- Extraction method uses inclusive $b \to c l \nu$ mixture
- Verification on MC simulations with exclusive final states



Systematic Uncertainties Moments

k=1

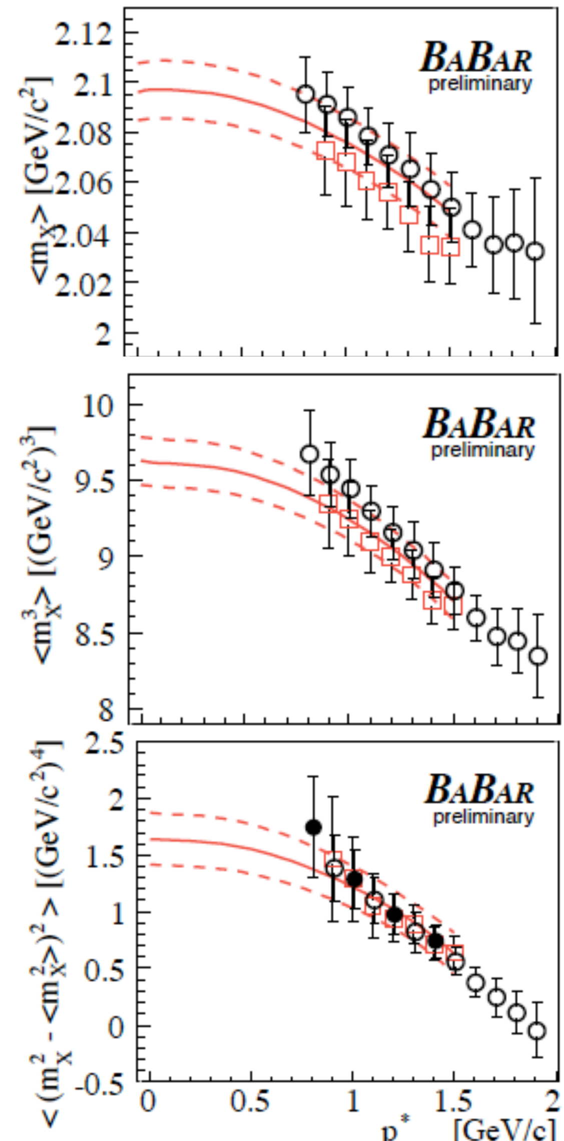
$p_{l,min}$	$\langle m_X^k \rangle$	σ_{stat}	σ_{sys}	Signal Model	C_{calib}	BG subtr.	Detector	Stability
0.8	2.0958	±0.0083	±0.0121	0.0045	0.0042	0.0044	0.0095	0.0000
0.9	2.0920	±0.0075	±0.0107	0.0039	0.0040	0.0042	0.0082	0.0000
1.0	2.0872	±0.0072	±0.0099	0.0038	0.0041	0.0041	0.0070	0.0009
1.1	2.0796	±0.0072	±0.0093	0.0036	0.0035	0.0041	0.0066	0.0000
1.2	2.0717	±0.0075	±0.0104	0.0035	0.0047	0.0043	0.0067	0.0032
1.3	2.0661	±0.0078	±0.0128	0.0032	0.0054	0.0045	0.0067	0.0077
1.4	2.0583	±0.0081	±0.0128	0.0028	0.0059	0.0048	0.0065	0.0075
1.5	2.0518	±0.0080	±0.0121	0.0025	0.0063	0.0053	0.0071	0.0045
1.6	2.0433	±0.0089	±0.0128	0.0025	0.0077	0.0060	0.0079	0.0000
1.7	2.0378	±0.0105	±0.0162	0.0024	0.0075	0.0073	0.0080	0.0091
1.8	2.0379	±0.0139	±0.0168	0.0025	0.0070	0.0089	0.0096	0.0075
1.9	2.0350	±0.0179	±0.0225	0.0020	0.0098	0.0121	0.0121	0.0107

- main systematic uncertainty:
  - neutral selection efficiency → impact on full event rec.
  - $b \to u l \nu$ background at high cuts on $p_{l,min}$

Data - HQE Comparison

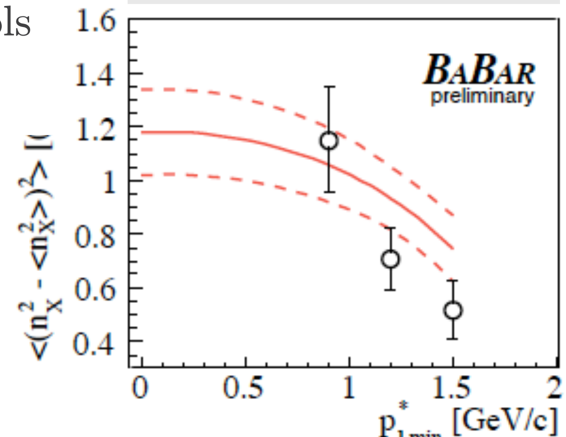
mass moments

- Hadronic mass moments:
  - $\langle m_X^2 \rangle$ $\quad p^*_{l,min}$ = 0.9, 1.1, 1.3, 1.5 GeV/c
  - $\langle m_X^4 \rangle$ $\quad p^*_{l,min}$ = 0.8, 1.0, 1.2, 1.4 GeV/c
- Lepton energy moments:
  - partial BF $\quad p^*_{l,min}$ = 0.6, 1.2, 1.5 GeV/c
  - $\langle E_l \rangle$ $\quad p^*_{l,min}$ = 0.6, 0.8, 1.0, 1.2, 1.5 GeV/c
  - $\langle E_l^2 \rangle$ $\quad p^*_{l,min}$ = 0.6, 1.0, 1.5 GeV/c
  - $\langle E_l^3 \rangle$ $\quad p^*_{l,min}$ = 0.8, 1.2 GeV/c
- Photon energy moments (inclusive and semi-excl.):
  - $\langle E_\gamma \rangle$ $\quad E_{g,min}$ = 1.9, 2.0 GeV
  - $\langle E_\gamma^2 \rangle$ $\quad E_{g,min}$ = 1.9 GeV
- B-meson lifetime
  - τ_B =(1.585 ± 0.007) ps

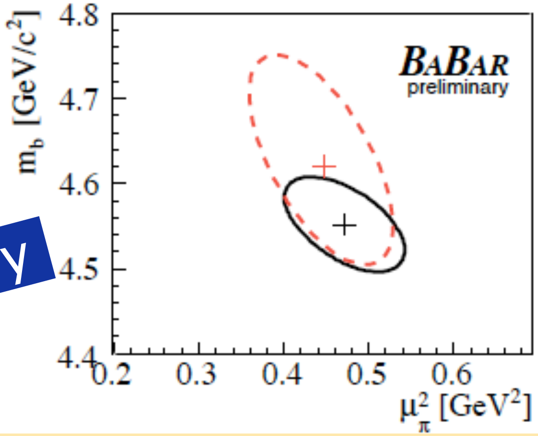


mixed moments

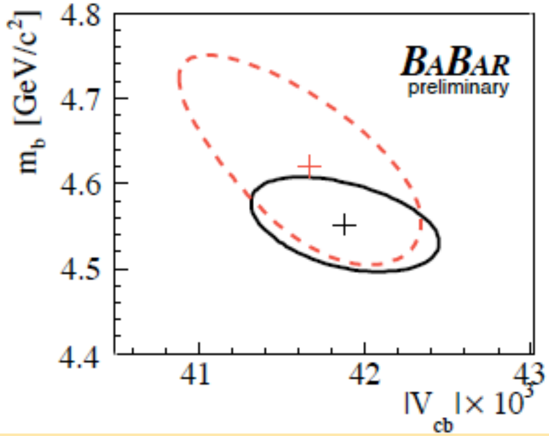
○● This measurement (open symbols not fitted)
□ BABAR 2004



Results from HQE Fit



preliminary



presented fit
fit without $b \to s\gamma$

	$\lvert V_{cb}\rvert \times 10^3$	m_b [GeV/c^2]	m_c [GeV/c^2]	$\mathcal{B}$ [%]	μ_π^2 [GeV^2]	μ_G^2 [GeV^2]	ρ_D^3 [GeV^3]	ρ_{LS}^3 [GeV^3]
Results	41.88	4.552	1.070	10.597	0.471	0.330	0.220	-0.159
Δ_{exp}	0.44	0.038	0.055	0.171	0.034	0.042	0.021	0.081
Δ_{theo}	0.35	0.040	0.065	0.053	0.062	0.043	0.042	0.050
$\Delta_{\Gamma_{SL}}$	0.59							
Δ_{tot}	0.81	0.055	0.085	0.179	0.070	0.060	0.047	0.095
$\lvert V_{cb}\rvert$	1.00	-0.42	-0.27	0.75	0.42	-0.28	0.25	0.10
m_b		1.00	0.96	0.09	-0.56	-0.07	-0.38	-0.24
m_c			1.00	0.15	-0.63	-0.32	-0.51	-0.15
$\mathcal{B}$				1.00	0.09	-0.10	0.02	-0.04
μ_π^2					1.00	0.40	0.87	0.10
μ_G^2						1.00	0.41	-0.05
ρ_D^3							1.00	-0.21
ρ_{LS}^3								1.00

Systematic Uncertainties $B^- \to D^{*0} e \nu$

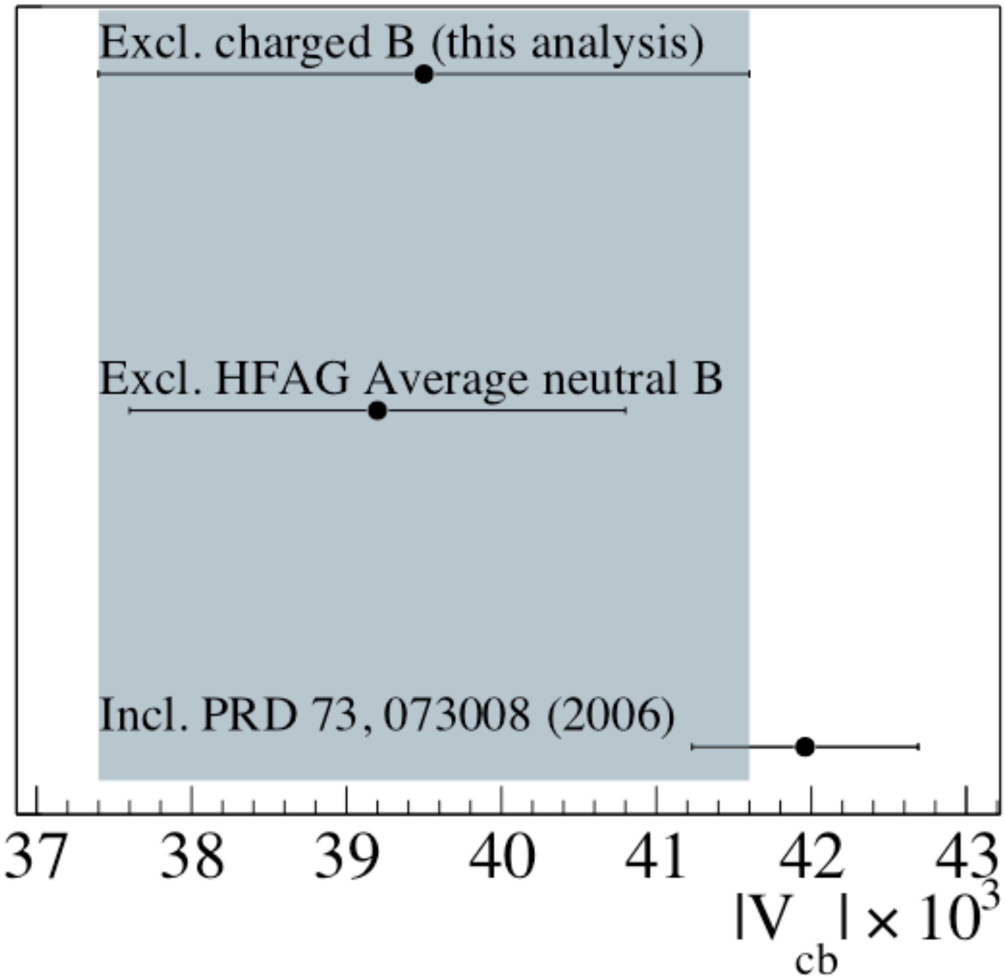
preliminary

	$\Delta V/V$	$\Delta\rho^2/\rho^2$	$\Delta\mathcal{B}/\mathcal{B}$
tracking efficiency (ϵ_{tr})	1.2	-	2.4
p_T dependence of ϵ_{tr}	0.3	0.5	0.2
particle ID efficiency	0.9	2.0	1.6
extrapolated π^0 efficiency (ϵ_{π^0})	1.8	-	3.6
p_{π^0} dependence of ϵ_{π^0}	1.0	3.5	0.4
Δm shape of D^{**} background	0.1	0.1	0.2
shape parameters	1.0	2.5	0.6
number of $B\overline{B}$ events	0.6	-	1.1
off-peak luminosity	0.1	0.4	<0.1
total internal	**2.8**	**4.8**	**4.8**
$R_1(1)$ and $R_2(1)$	0.1	4.7	0.3
$\mathcal{B}(\Upsilon(4S) \to B^+B^-)$	0.8	-	1.6
$\mathcal{B}(D^{*0} \to D^0\pi^0)$	2.3	-	4.7
$\mathcal{B}(D^0 \to K^-\pi^+)$	0.9	-	1.8
B^- life time	0.3	-	-
D^{**} decay fractions	0.3	0.7	0.3
number of D^{*0} in $c\bar{c}$ events	0.2	0.7	<0.1
total external	**2.6**	**4.8**	**5.3**
total	**3.9**	**6.8**	**7.2**

Comparison Inclusive vs. Exclusive V_{cb}

with $F(1) = 0.919 \pm 0.033$

S. Hashimoto et al., Phys. Rev. D **66**, 014503 (2002).



39.5 ± 2.1

39.2 ± 1.6

42.0 ± 0.7

Detailed Results for $B \to D^{(*)}\tau\nu$

preliminary

	Mode	N_{sig}	N_{norm}	$\varepsilon_{sig}/\varepsilon_{norm}$	$(\Delta R/R)_{fit}$ [%]	$(\Delta R/R)_{\varepsilon}$ [%]
exclusive channels	$B^- \to D^0\tau^-\overline{\nu}_\tau$	33.1±19.6	346.7±23.0	1.85	15.2	1.5
	$B^- \to D^{*0}\tau^-\overline{\nu}_\tau$	95.9±19.8	1628.6±63.5	0.98	9.4	1.4
	$\overline{B}^0 \to D^+\tau^-\overline{\nu}_\tau$	23.0±7.9	149.9±13.3	1.83	13.4	1.7
	$\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$	16.2±7.3	481.8±25.5	0.93	3.4	1.5
combined fit	$B \to D\tau^-\overline{\nu}_\tau$	64.9±19.1	496.3±26.4	1.85	12.0	1.3
	$B \to D^*\tau^-\overline{\nu}_\tau$	105.3±19.4	2109.4±68.0	0.93	5.7	1.2

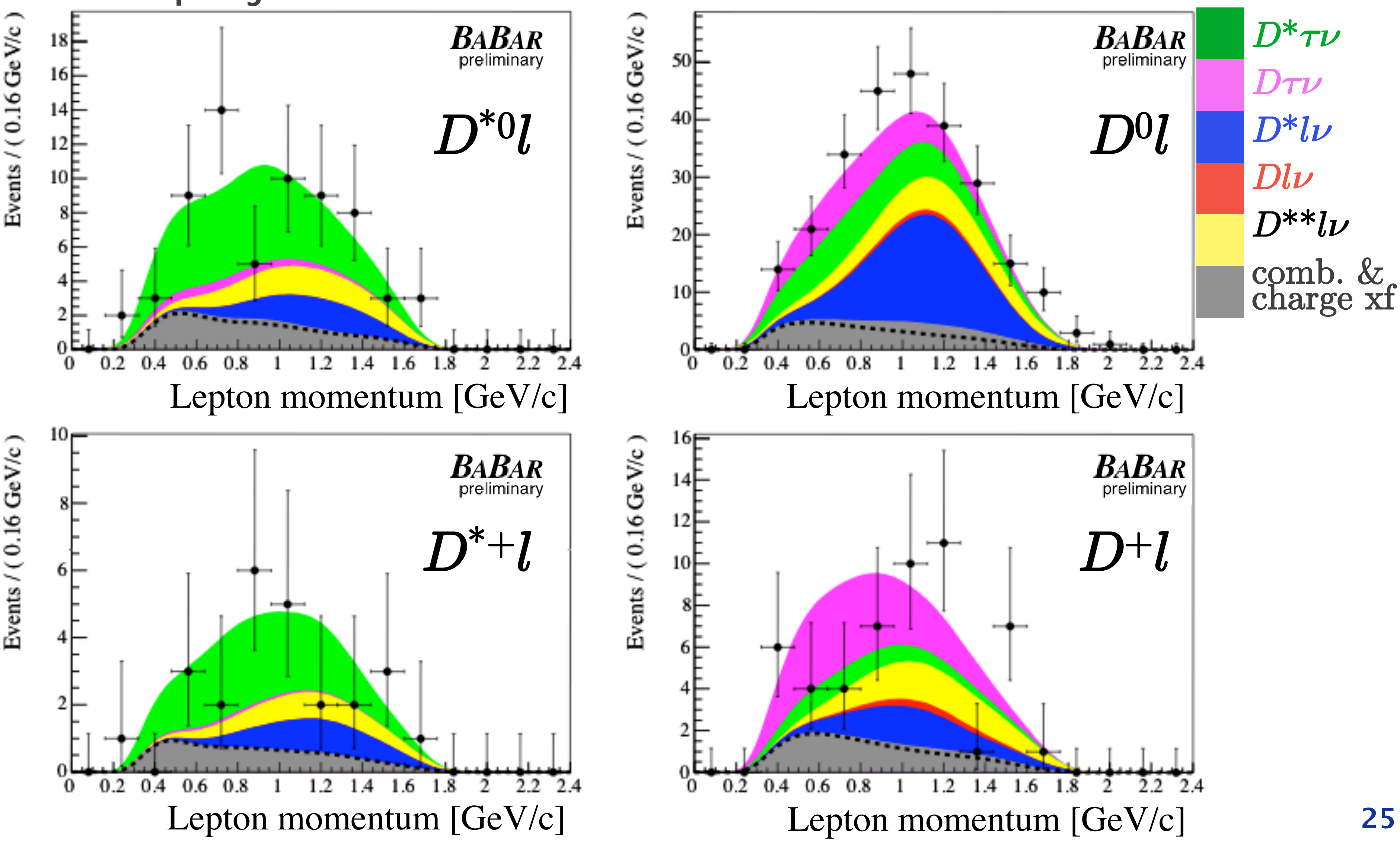
	Mode	R [%]	$\mathcal{B}$ [%]	σ_{tot} (σ_{stat})
exclusive channels	$B^- \to D^0\tau^-\overline{\nu}_\tau$	29.5±17.4±4.5	0.63±0.38±0.10±0.06	1.7(1.7)
	$B^- \to D^{*0}\tau^-\overline{\nu}_\tau$	36.2± 7.5±3.4	2.35±0.49±0.22±0.18	5.3(5.8)
	$\overline{B}^0 \to D^+\tau^-\overline{\nu}_\tau$	48.6±16.7±6.6	1.03±0.35±0.14±0.10	3.3(3.5)
	$\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$	21.4± 9.7±0.8	1.15±0.52±0.04±0.04	2.7(2.7)
combined fit	$B \to D\tau^-\overline{\nu}_\tau$	40.7±12.0±4.9	0.90±0.26±0.11±0.06	3.5(3.8)
	$B \to D^*\tau^-\overline{\nu}_\tau$	31.0± 5.7±1.8	1.81±0.33±0.11±0.06	6.2(6.5)

First Observation of $B^- \to D^{*0}\tau\nu$

First Evidence for $B \to D\tau\nu$

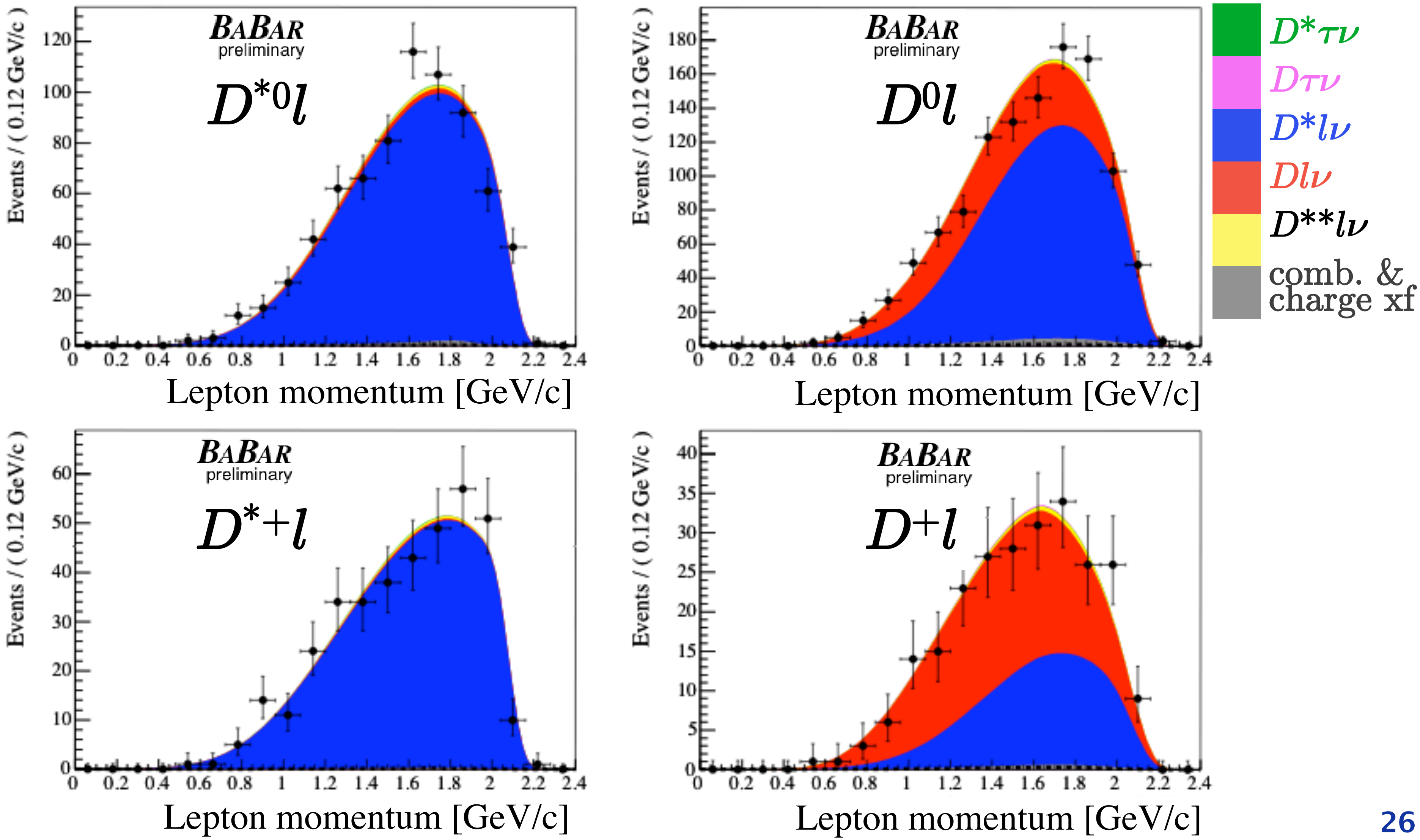
Fit Projections Lepton Momentum

cut on $m^2_{miss} > 1\ GeV^2/c^4$,
projections for constrained fit



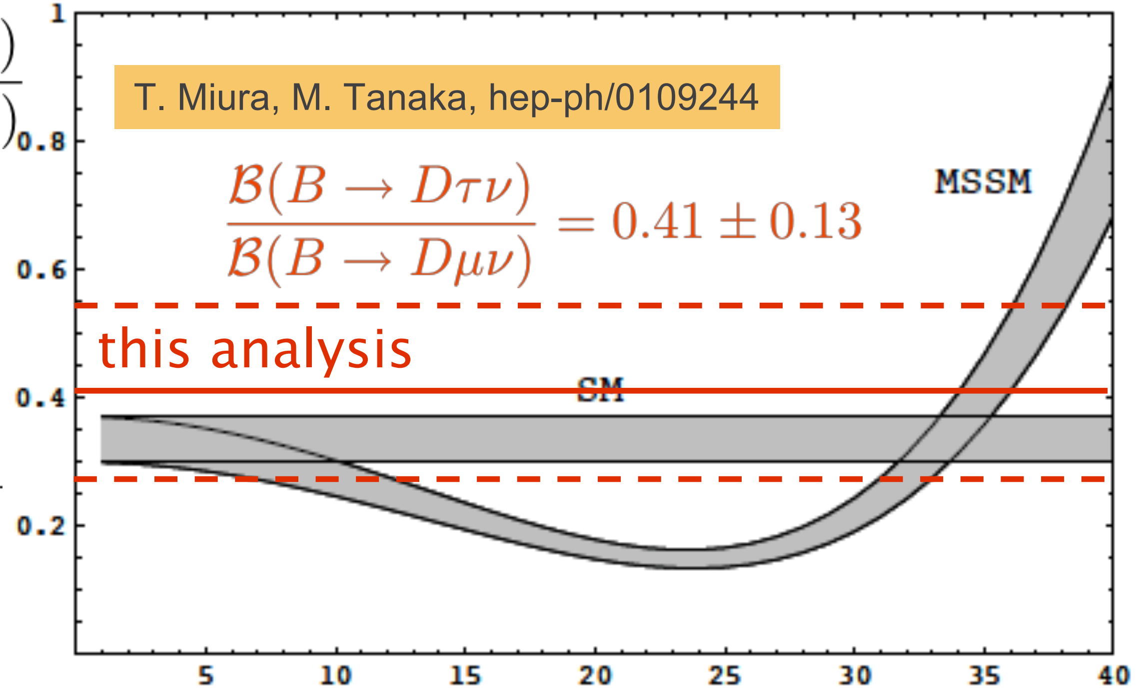
Fit Projections Lepton Momentum

cut on $m^2_{miss} < 1\ GeV^2/c^4$,
projections for constrained fit



New Physics Expectations

$$\frac{\mathcal{B}(B \to D\tau\nu)}{\mathcal{B}(B \to D\mu\nu)}$$



$$R = \frac{m_W}{m_H} \tan\beta$$