Leptonic and Semileptonic decays at BaBar

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on behalf of BaBar

Fourth Workshop on Theory, Phenomenology and Experiments in Flavour Physics

Villa Orlandi, Anacapri 11-14 June 2012

BABAR

INFN Istituto Nazionale di Fisica Nucleare
Sezione di Roma

Outline

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- Tagging
- Semileptonic Exclusive Measurements
  - $B \rightarrow D^{(*)}\tau\nu$ — arXiv:1205.5442
- Semileptonic Inclusive Measurements
  - $B^+ \rightarrow X_u l \nu$ — arXiv:1112.0702v1
- Leptonic B decays
  - $B^0 \rightarrow$ invisible $(+\gamma)$ — Preliminary
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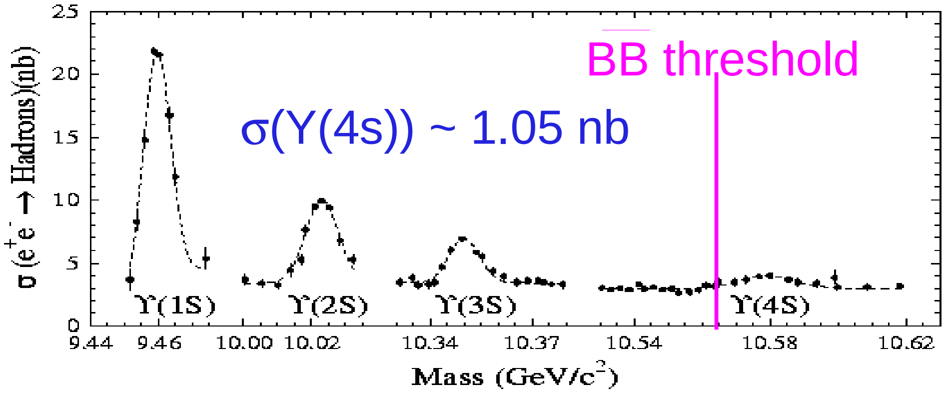
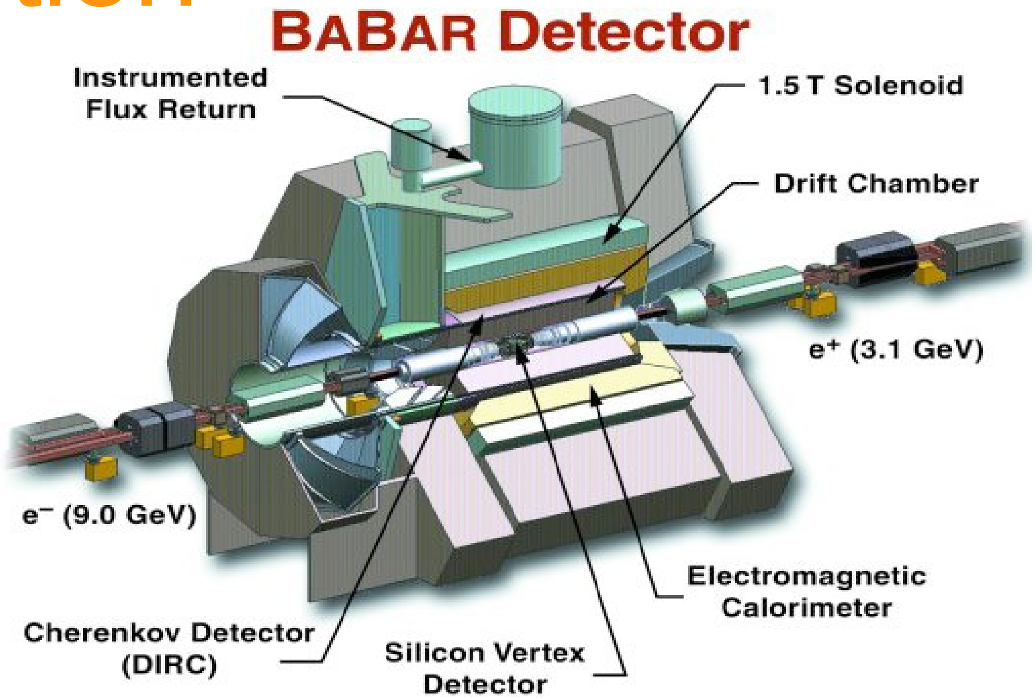
  - $D^0 \rightarrow l^+l^-$ — Preliminary
- Tests of SM and NP
- Conclusions and Outlook

Introduction

Multipurpose, asymmetric 4π detector at e^+e^- collider (PEP-II @SLAC)

$\int d\mathscr{L}$ = 432 fb^{-1} @Y(4s)





- 472×10^6 $B\bar{B}$ pairs produced in e^+e^- collisions at Y(4S) ~ at rest in CM
- asymmetric CM energy (boost β=0.55) ⇒ we can separate the B decay vertices
- exclusive B decays : kinematics variables

$$\Delta E = E_B - E_{beam} \quad \text{centered at 0}$$

$$m_{ES} = \sqrt{E_{beam}^2 - \vec{p}_B^{\,2}} \quad \text{centered at } m_B$$

- low background : $\sigma(B\bar{B})$ ~ 1/5 σ(had)
  Continuum contribution measured by off-resonance runs during data taking
- low-multiplicity (~11 tracks /evt) ⇒ "easy" to fully reconstruct B decay
- very good particle ID and separation

Tagging method

Weak signal signature

Decay with p_{mis} (one or more ν in final state) → lack of kinematics constraints in final state

→ background rejection improved identifying the companion B

→ kinematics from the companion B

Look for signal in the rest of the event

Semileptonic B decays

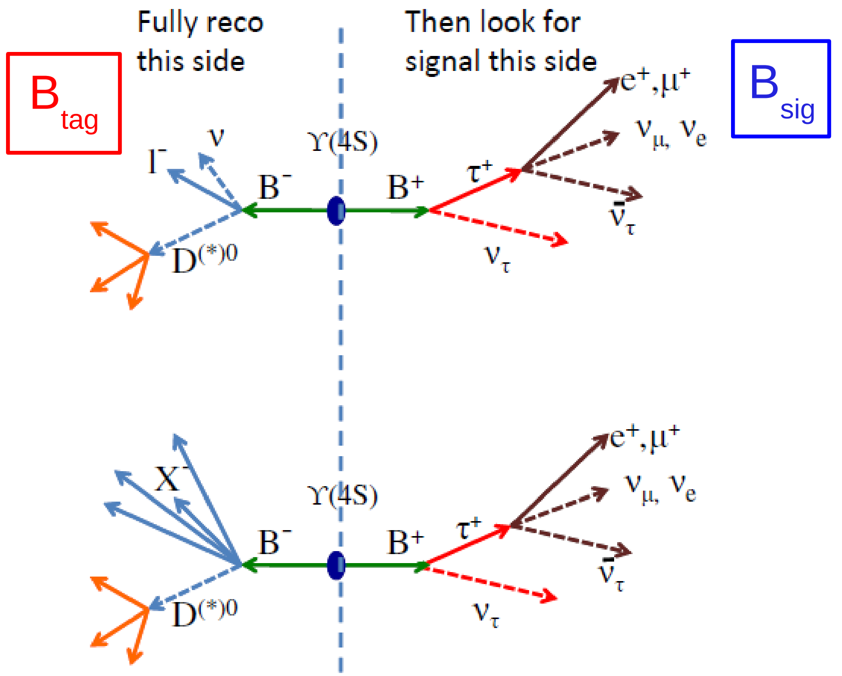
Ex : B →D*/ ν

- PRO: Higher efficiency $\varepsilon_{tag} \sim O(10^{-2})$
- CON: more backgrounds, B momentum unmeasured

Hadronic B decays (with charm)

Ex : $B^+ \to D^{(*)0} X^+$ or $B^0 \to D^{(*)+} X^-$

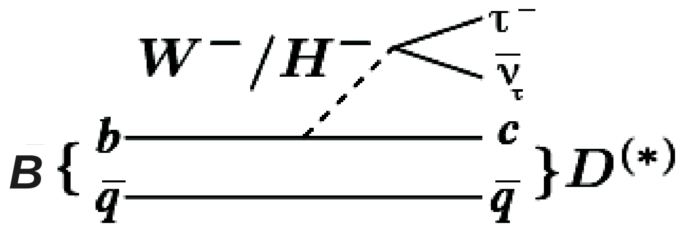
- X charged system of hadrons : among (π, K, π^0, K_s) up to 5-6 charged and 2-3 neutrals
- PRO: cleaner events, B momentum reconstructed
- CON: smaller efficiency $\varepsilon_{tag} \sim O(10^{-3} - 10^{-2})$



ArXiv:1205-5442
submitted to PRL

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

NEW



Semileptonic decays to τ sensitive to charged Higgs at tree level → less model dependence
Have an additional helicity amplitude H_t

For $D\tau\nu$, only H_{00} and H_t contribute

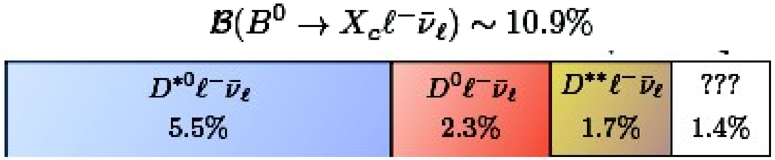
$$\frac{d\Gamma_\tau}{dq^2} = \frac{G_F^2|V_{cb}|^2|\mathrm{p}|q^2}{96\pi^3 m_B^2}\left(1-\frac{m_\tau^2}{q^2}\right)^2\left[(|H_{++}|^2+|H_{--}|^2+|H_{00}|^2)\left(1+\frac{m_\tau^2}{2q^2}\right)+\frac{3}{2}\frac{m_\tau^2}{q^2}|H_t|^2\right]$$

Z. Phys, C46, 93 (1990)

Test of SM : measure of $R(D) = \frac{Y(\bar{B} \to D\tau\nu)}{Y(\bar{B} \to D\ell\nu)}$ $\quad R(D^*) = \frac{Y(\bar{B} \to D^*\tau\nu)}{Y(\bar{B} \to D^*\ell\nu)}$

many uncertainties cancel in ratio

- Fully reconstruct B_{tag} in $B \to D^{(*)}X$, $D_s^{(*)}X$, $J/\Psi X$ ($X = \pi$, K modes, $n_X < 6$)
- B_{sig} : reco of $D^{(*)}$ and *e* or μ + no additional charged particles
- Kinematic selection : $q^2 > 4$ GeV^2
- Background suppression by Boosted Decision Tree (combinatorial and $D^{**}l\nu$)
- E_{Extra} : important variable **but** has large uncertainties
  → Not used in the fit
- MC correction based on data distributions
- Fit unbinned M.L. fit on 2-D distributions:
  $m^2_{miss} = (P_{e+e-} - P_{Btag} - P_{D(*)} - P_l)^2$, P^*_l in B rest frame



$B \to D^{*}\tau\nu$

Full BABAR dataset : 472 million BB pairs

4 signal samples : $D^{0}l$, $D^{*0}l$, $D^{+}l$, $D^{*+}l$ ($l = e$ or μ)

PDF's from MC

Fitted Yelds : 4 $D^{(*)}\tau\nu$ Signal + 4 $D^{(*)}l\nu$ Normalization + 4 $D^{**}l\nu$ Background

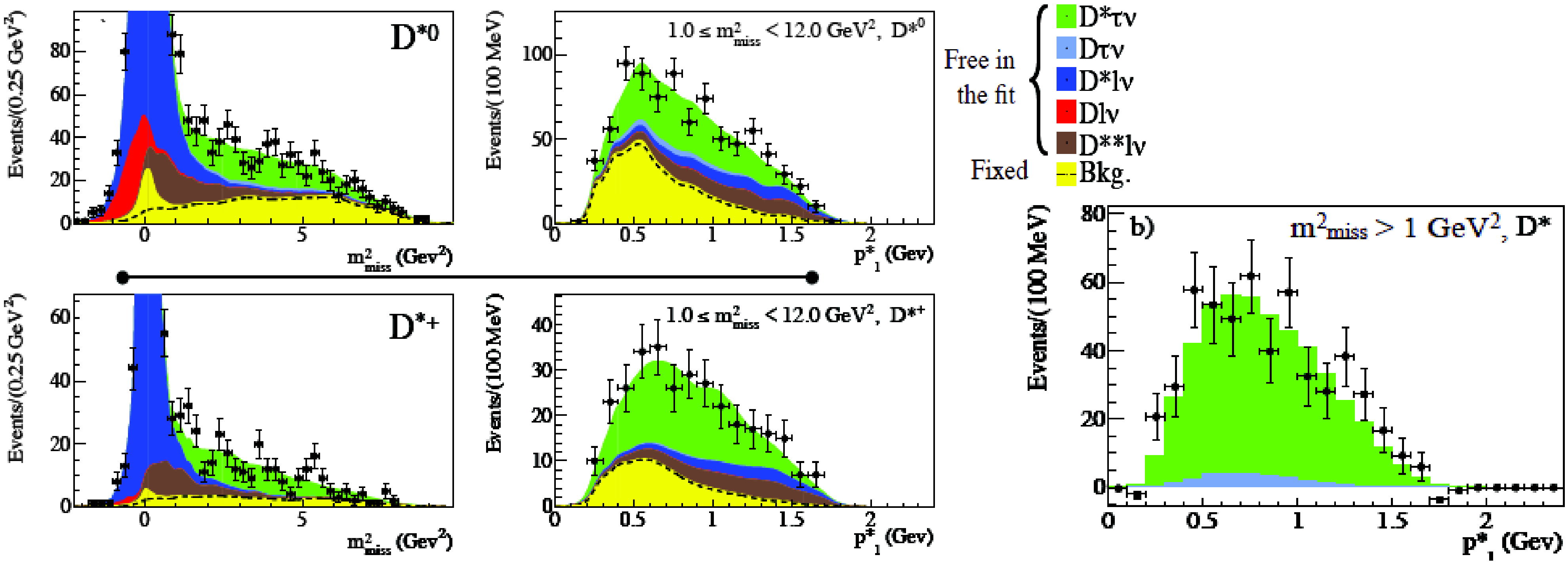
Fixed Backgrounds : $B^{0}-B^{+}$ cross feed + BB combinatorial BG+ Continuum $e^{+}e^{-} \to ff(\gamma)$

Stat error 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

good consistency between charged and neutral modes

Isospin constrained fit



B → Dτν

Full BABAR dataset : 472 million BB pairs

4 signal samples : $D^0 l$, $D^{*0} l$, $D^+ l$, $D^{*+} l$ (l = e or μ)

PDF's from MC

Fitted Yelds : 4 $D^{(*)}\tau\nu$ Signal + 4 $D^{(*)} l\nu$ Normalization + 4 $D^{**} l\nu$ Background

Fixed Backgrounds : B^0–B^+ cross feed + BB combinatorial BG+ Continuum $e^+e^- \to f\bar{f}(\gamma)$

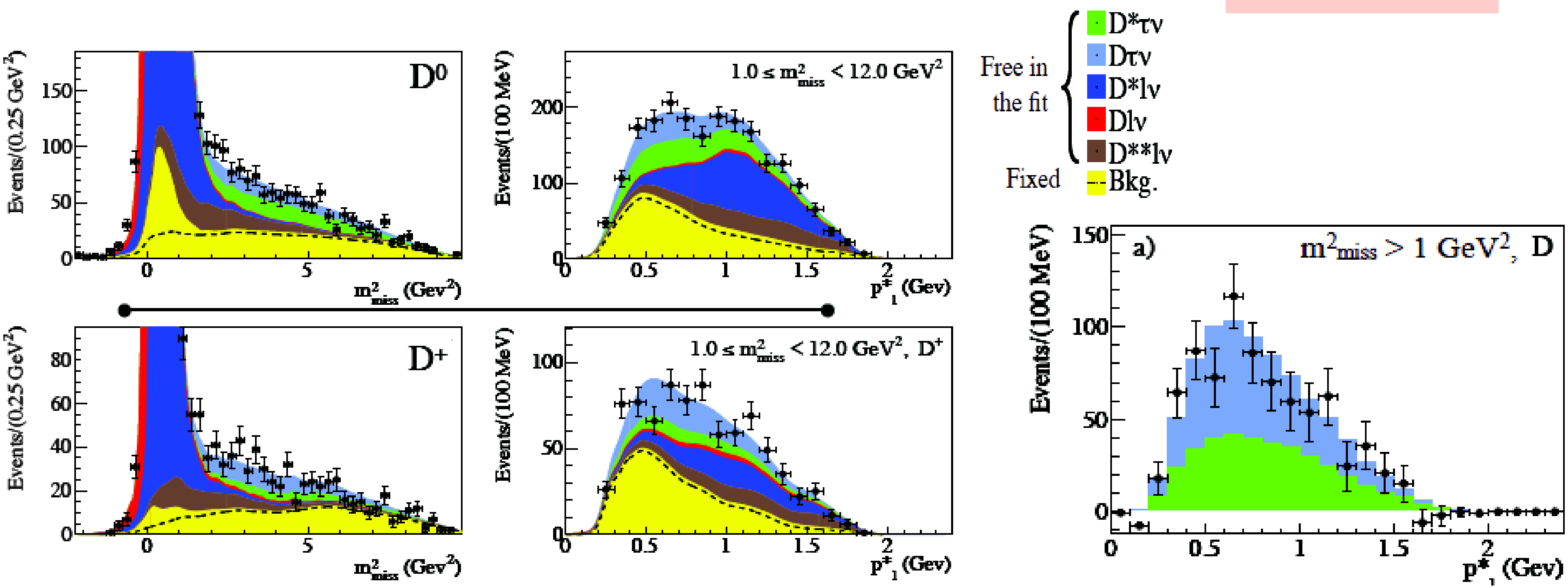
Stat error only

	$D^0\tau\nu$	$D^+\tau\nu$	$D\tau\nu$
N_{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

good consistency between charged and neutral modes

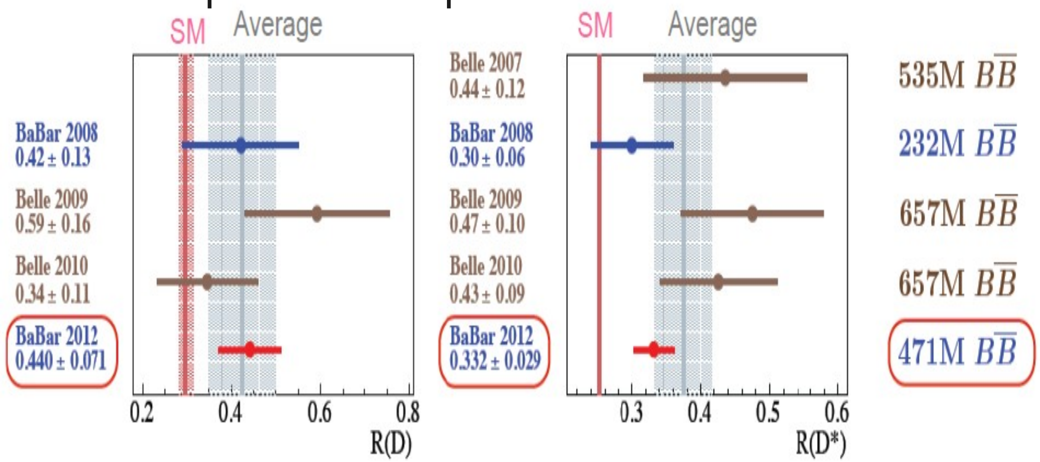
First > 5 σ observation

Isospin constrained fit



Summary of R(D) and R(D*) Measurement

Comparison with previous measurements



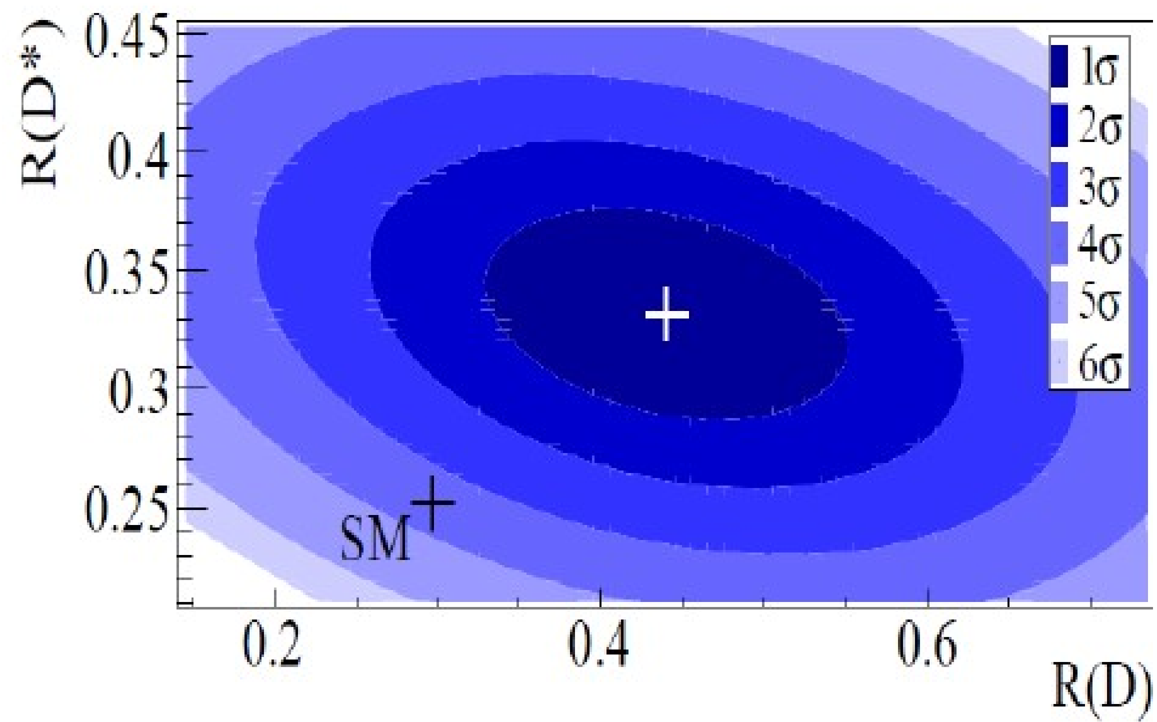
	R(D)	R(D*)
BABAR	0.440 ± 0.072	0.332 ± 0.029
SM*	0.297 ± 0.017	0.252 ± 0.003
Δ	2.0 σ	2.7 σ

* Z. Phys, C46, 93 (1990)
PRD 82, 0340276 (2010)
PhD 85, 094025 (2012)
and recent updates

R(D) and R(D*) correlated (-0.27)

Combination yields χ^2/NDF=14.6/2
i.e. Prob = 6.9×10^{-4} !

Data exclude SM by 3.4 σ !!



Including syst errors
$B \rightarrow D\tau\nu$: 6.8 σ significance

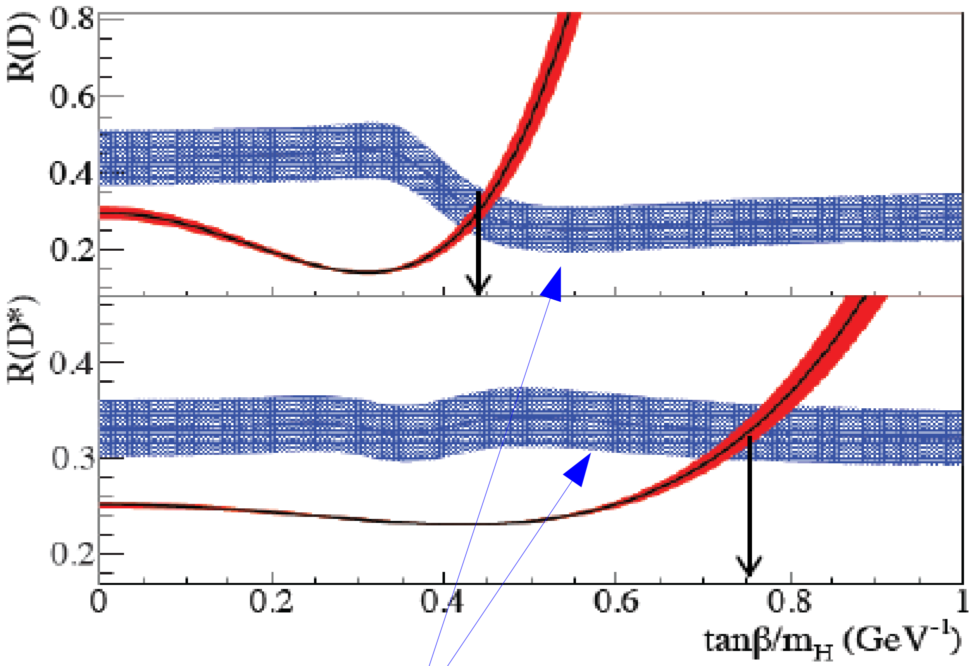
Implications for the Higgs sector

Individual measurement exceeds SM by > 2σ : 2Higgs Doublet Model may explain excesses individually.
A charged Higgs (2HDM type II) of spin 0 coupling to τ will affect H_t

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

\+ Dτν
\- D*τν

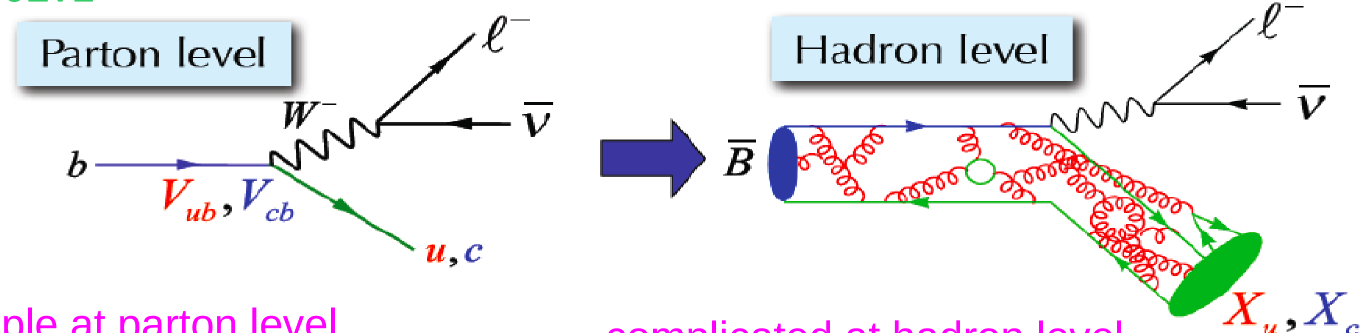
Combination of R(D) and R(D*) inconsistent and excludes type II 2HDM with a probability > 99.8% in the full tan2β-m_H parameter space !!
(provided m_H> 10 GeV)



2HDM changes kinematic distributions as a fct of tanβ/m_H, hence the efficiencies change

Inclusive $|V_{ub}|$ with hadronic tag

arXiv:1112-0702v1



Simple at parton level

complicated at hadron level

q^2 = dilepton inv mass

M_X = hadronic inv mass

Semileptonic tree-level B decays provide the cleanest environment to study V_{ub}

Experimental challenges :

- Large $B \rightarrow X_c l \nu$ background (~ 50 times larger)
- Variables like M_X and q^2 require full event reconstruction
- Background BF, bkg and signal distributions not that well understood

Theoretical challenges :

- OPE convergence destroyed in limited phase space
- Rates are sensitive to b-quark dynamics inside B meson.
- Uncertainties in input parameters

Fully reconstruct B_{tag} in $B \rightarrow D^{(*)}X$ ($X = \pi$, K modes, $n_X < 6$ charged + < 3 neutrals)

$\rightarrow$ kinematics and flavour of B_{sig} known (high purity,low efficiency $O(10^{-3})$)

Look for a lepton ($p^*_l > 1$ GeV/c) and neutrino (missing momentum) in B_{sig}

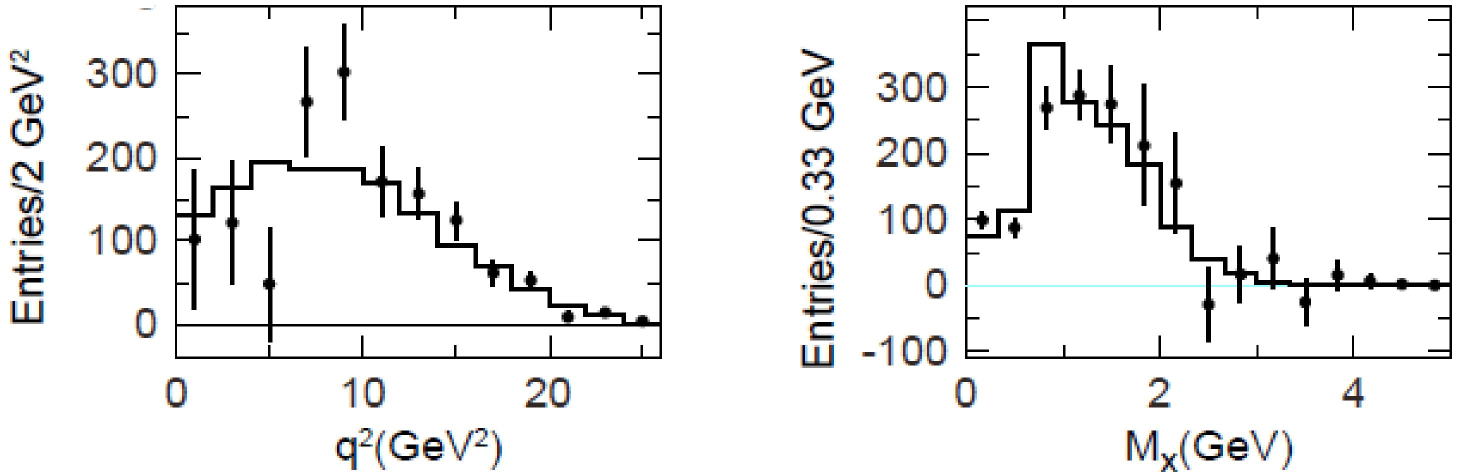
Inclusive $|V_{ub}|$ with hadronic tag

Full BABAR dataset : 472 million BB pairs

Precision of V_{ub} limited by theory uncertainties due to phase space cuts

Performed a (M_X , q^2) 2-dim unbinned ML fit **without** phase space cuts

(except $p^*_l > 1.0$ GeV → 88-90% of phase space where theo uncertainites are smaller)



Data bkg subtracted
Not efficiency corrected

$\Delta\mathcal{B}(B \to X_u l \nu)$ (10^{-3}) = 1.80 ± 0.13 stat ± 0.15 syst ± 0.02 theo

$|V_{ub}| = (4.31 \pm 0.25\ \text{exp} \pm 0.16\ \text{theo}) \times 10^{-3}$ [avg 4 QCD predictions *]

Systematic error mostly from $B \to X_u l \nu$ and BG simulation

BaBar measurement in different kinematic regions agree !

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

* BLNP	: multi-scale OPE based on SCET	NP B699, 335 (2004)
DGE	: resummed perturbations theory	JHEP 0601, 096 (2006)
GGOU	: large range of distributions fct.	JHEP 0710, 058 (2007)
ADFR	: partial BF in terms of $|V_{cb}|^2/|V_{ub}|^2$	Eur. Phys. J. C 59, 831 (2009)

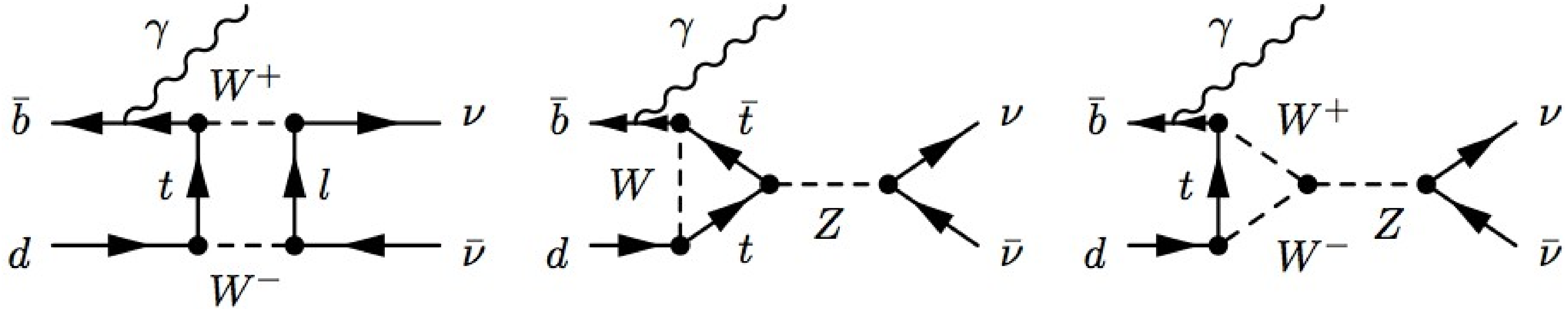
Preliminary

B → invisible

NEW

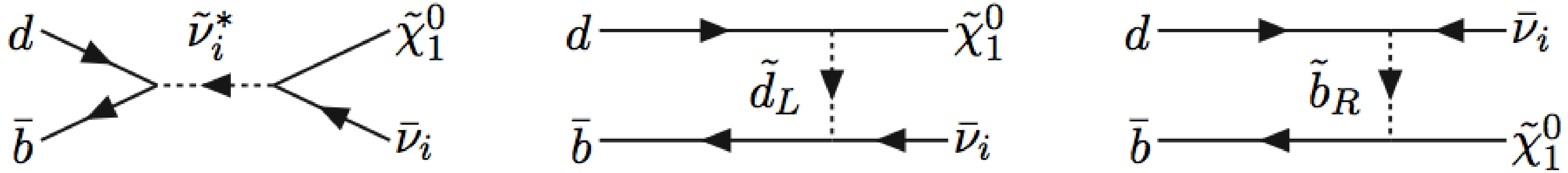
SM : $B^0 \to \nu\nu$ decay suppressed by a factor $(m_\nu/m_B)^2$

BF($B^0 \to \nu\nu\gamma$) is of the order of 10^{-9}



In SUSY model BR($B^0 \to$ Invisible) can be enhanced up to 10^{-7}-10^{-6} due to neutrino+neutralino production in the final state

A. Dedes, H. Dreiner, and P. Richardson, hep-ph/0106199, Phys. Rev.D65, 015001 (2001)



Semileptonic tag: B_{tag} in $B^0 \to D^{(*)-} l^+ \nu$

Look for consistency with an invisible(+γ) decay of the other neutral B_{sig}

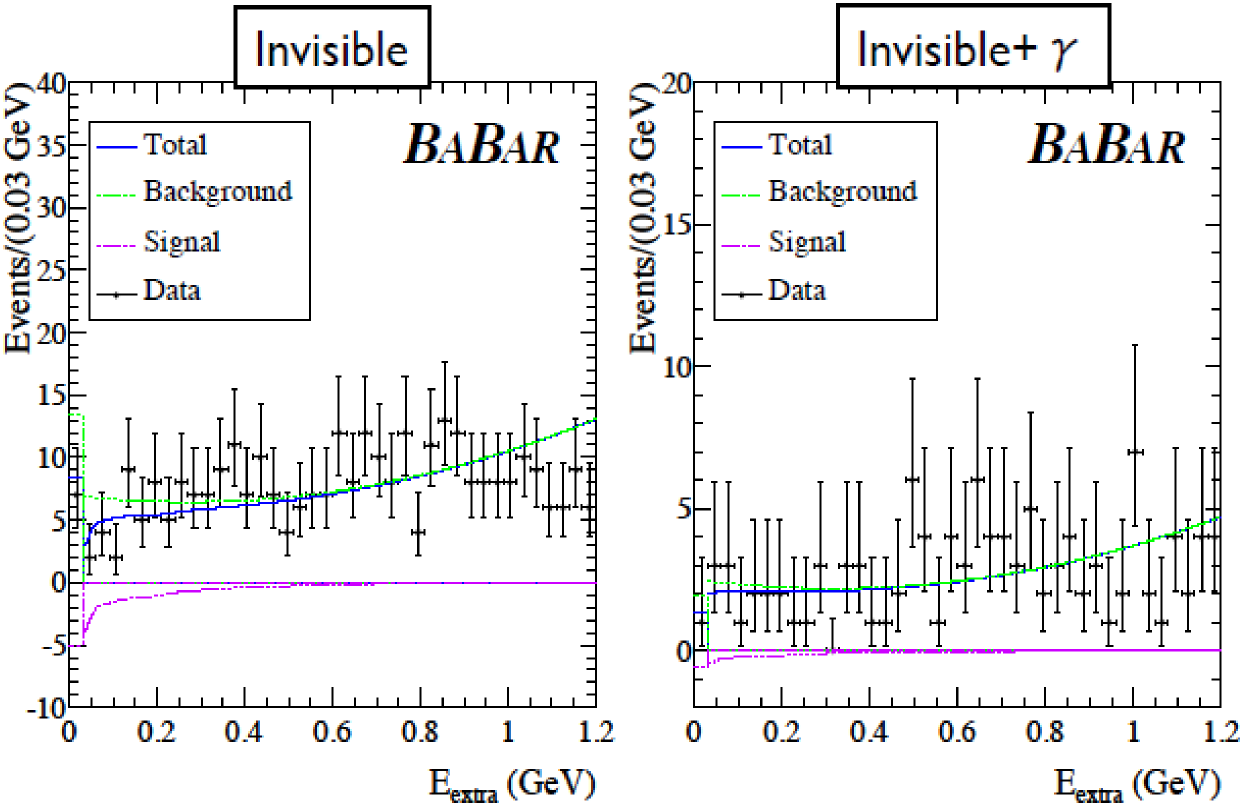
B → invisible

Full BABAR dataset : 472 million BB pairs

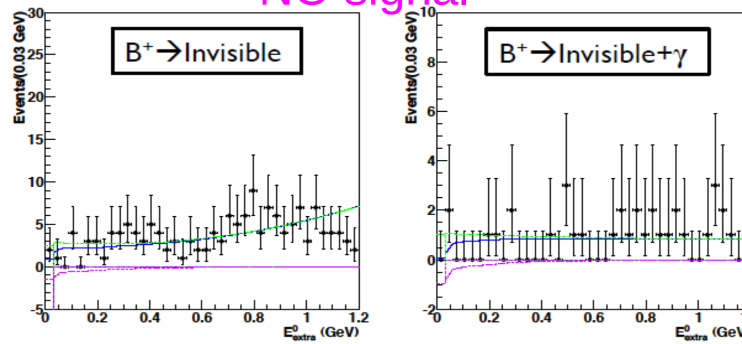
Most discriminating variable : total residual energy - unassociated clusters in the calo (E_{extra})

Unbinned Maximum Likelihood fit to E_{extra}

Mode	N_{sig}	N_{bkg}
$B^0 \to$ invisible	-22 ± 9	334 ± 21
$B^0 \to$ invisible+γ	-3.1 ± 5.2	113 ± 12



B⁺→ invisible(+γ) control sample
NO signal



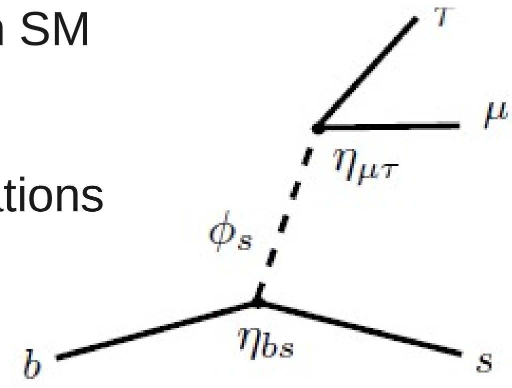
1 order of magnitude improvement over previous limits:

$$\mathcal{B}(B^0 \to \text{invisible}) < 2.4 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to \text{invisible} + \gamma) < 1.7 \times 10^{-5}$$

Submitted to PRD
arXiv:1204.2852

Search for Lepton-Flavor Violation: $B^+ \rightarrow K^+\tau e$, $B^+ \rightarrow K^+\tau\mu$, $B^+ \rightarrow \pi^+\tau e$, $B^+ \rightarrow \pi^+\tau\mu$

Tree-level Flavor-Changing Neutral-Currents (FCNC) **forbidden** in SM



Well-motivated extensions of the SM include LFV in FCNCs :
$\rightarrow$ NP may enhance interactions coupling to 2nd and 3rd generations
Phys. Rev. D 44, 1461 (1991)

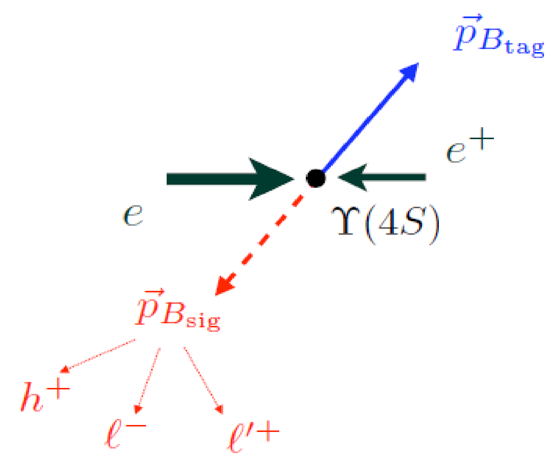
Experimental constraints involving τ in B meson decays weak
$\rightarrow$ difficulty : reconstruct τ daughters (involving neutrinos)

From Black et al.* on τ-μ flavor violation, using full BABAR data and expected sensitivity on $\mathcal{B}(B^\pm \rightarrow K^\pm\tau\mu)$ the NP energy scale in FC operators can be pushed to $\Lambda > 15$ TeV

* Phys.Rev.D66, 053002 (2002)

8 final states looked

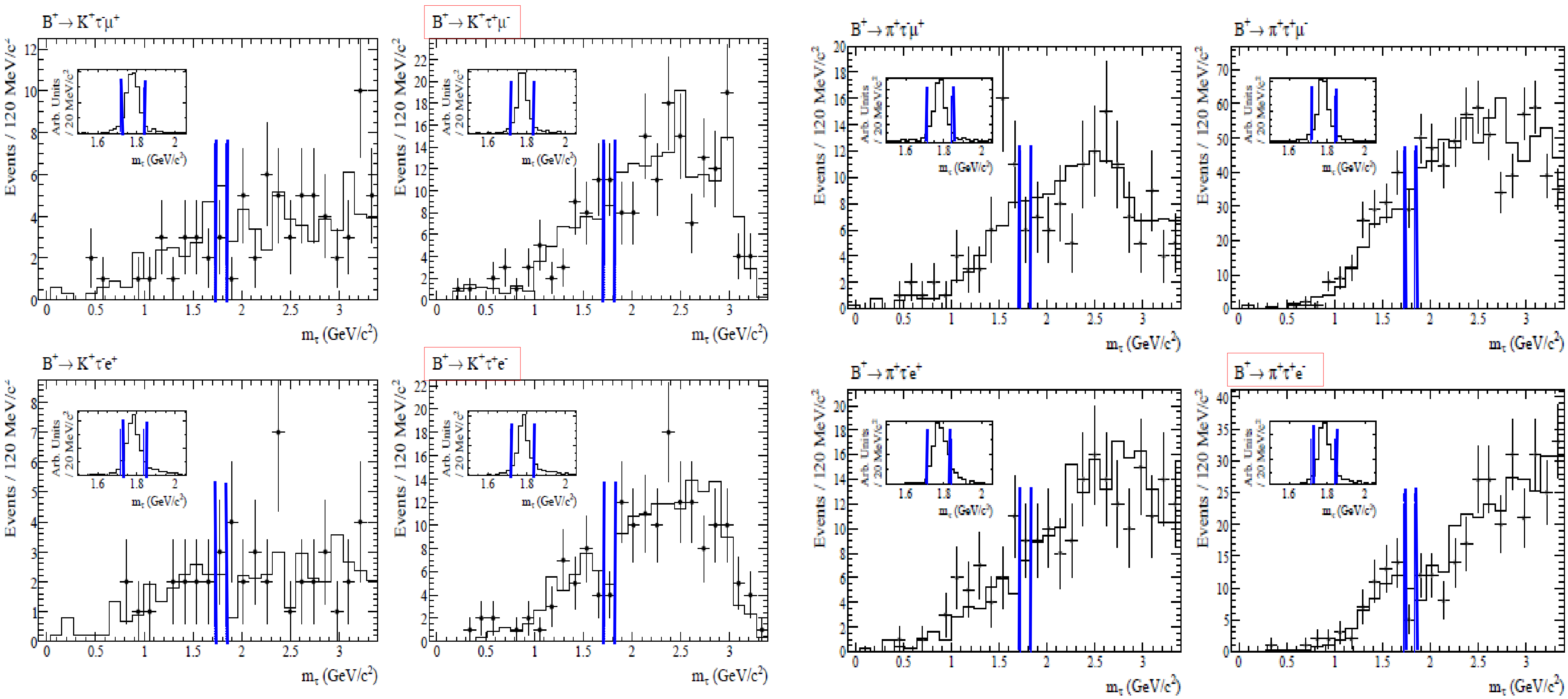
Fully reconstruct hadronic $B_{tag} \rightarrow D^{(*)0}X^-$ decays
Determine B_{tag} momentum $\rightarrow$ known B_{sig} momentum
Combinatoric background rejection performed with likelihood ratio
Studied 3 single prong τ decays (e,μ,π^- [$\geq$0 π^0]) channels
Fully reconstruct τ invariant mass using E_{beam} in Υ(4S) CM frame



Search for Lepton-Flavor Violation: $B^+ \to K^+\tau e$, $B^+ \to K^+\tau\mu$, $B^+ \to \pi^+\tau e$, $B^+ \to \pi^+\tau\mu$

Full BABAR dataset : 472 million BB pairs

Results for all modes : first time measurement for these 3 decay modes



Signal region : $m_\tau \pm 60$ MeV

Count events in τ regions : **No evidence** for signals

Search for Lepton-Flavor Violation: $B^+ \to K^+\tau e$, $B^+ \to K^+\tau\mu$, $B^+ \to \pi^+\tau e$, $B^+ \to \pi^+\tau\mu$

Mode	$\mathcal{B}(B \to h\tau l)$ ($\times 10^{-5}$) central value		90% CL UL
$B^+ \to K^+\tau^-\mu^+$	+0.8	$^{+1.9}_{-1.4}$	< 4.5
$B^+ \to K^+\tau^+\mu^-$	-0.4	$^{+1.4}_{-0.9}$	< 2.8
$B^+ \to K^+\tau^-e^+$	+0.2	$^{+2.1}_{-1.0}$	< 4.3
$B^+ \to K^+\tau^+e^-$	-1.3	$^{+1.5}_{-1.8}$	< 1.5
$B^+ \to \pi^+\tau^-\mu^+$	+0.4	$^{+3.1}_{-2.0}$	< 6.2
$B^+ \to \pi^+\tau^+\mu^-$	0.0	$^{+2.6}_{-2.0}$	< 4.5
$B^+ \to \pi^+\tau^-e^+$	2.8	$^{+2.4}_{-1.9}$	< 7.4
$B^+ \to \pi^+\tau^+e^-$	-3.1	$^{+2.4}_{-2.1}$	< 2.0

Conservative constraints on NP parameters from "clean" modes

Used Feldman-Cousins UL

Black et al.* : estimate NP energy scales for 3rd generation flavor changing couplings

$\mathcal{B}(B^+ \to \pi^+\tau^-\mu^+) < 6.2 \times 10^{-5} \to \Lambda_{bd} > 12$ TeV

$\mathcal{B}(B^+ \to K^+\tau^-\mu^+) < 4.5 \times 10^{-5} \to \Lambda_{bs} > 15$ TeV

* Phys.Rev.D66, 053002 (2002)

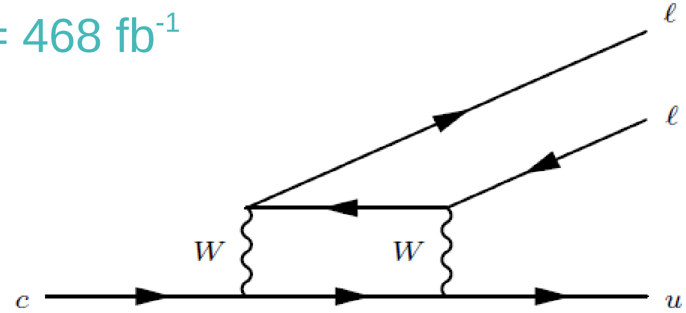
1 order of magnitude improvement over old limits

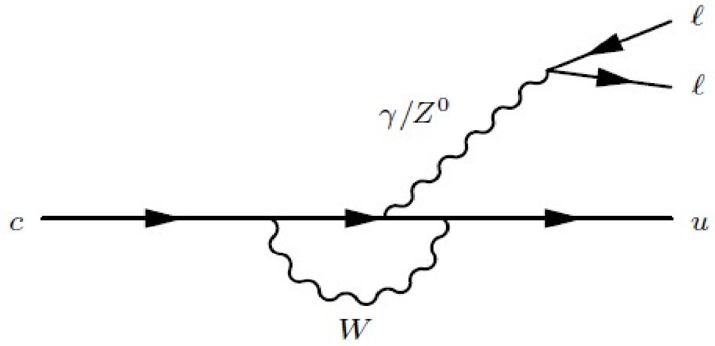
$D^0 \to l^+ l^-$

NEW

Preliminary

$\int d\mathscr{L}$ = 468 fb^{-1}





FCNC decay highly GIM suppressed in SM.
Long-distance corrections raise $D^0 \to \mu^+\mu^-$ BF to as high as 10^{-13} within SM

BF could be enhanced by many orders of magnitude by NP.

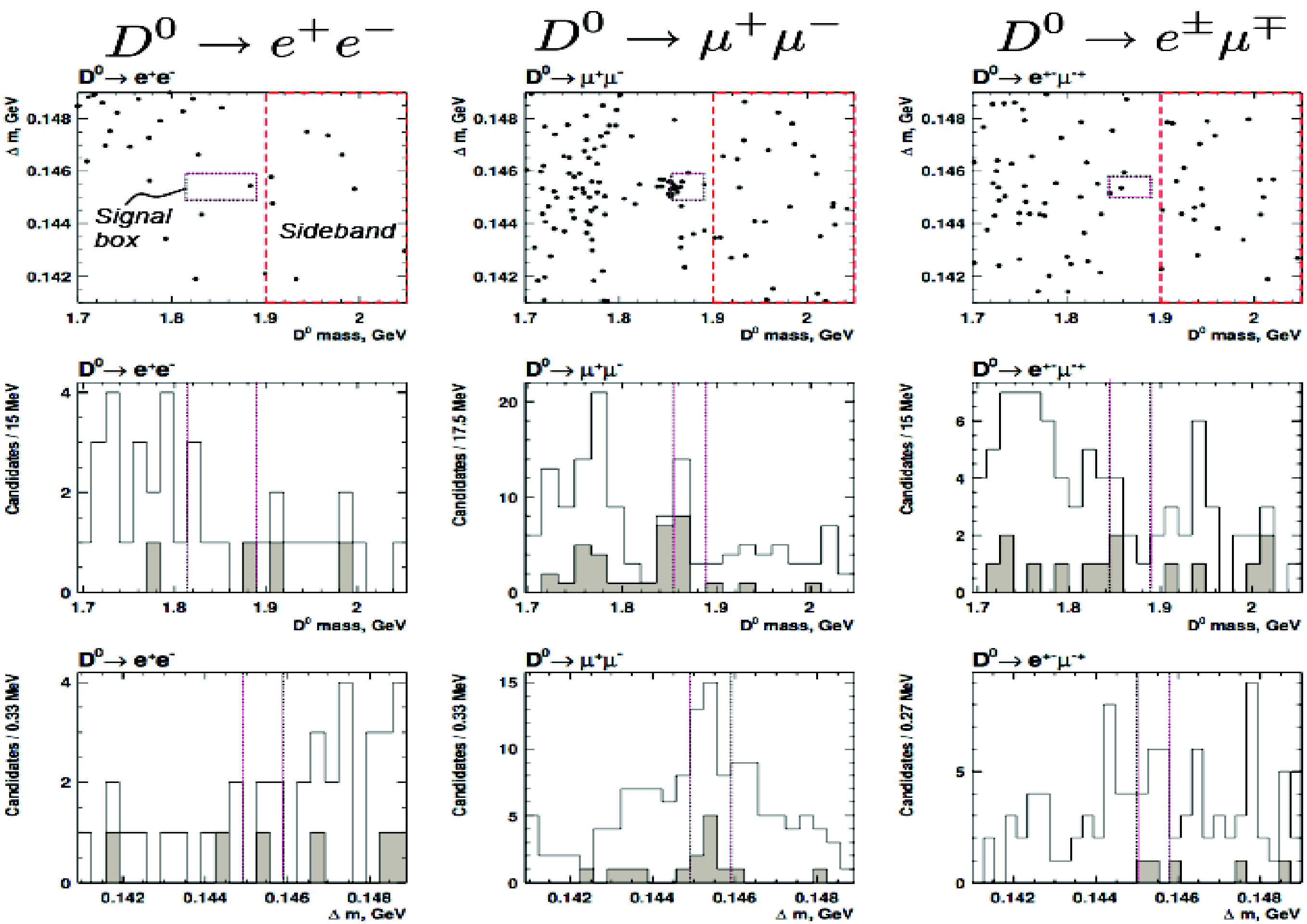
Sensitivity with full dataset and improved analysis expected to be ~10^{-7}

- D^0 candidates from $D^{*+} \to D^0\pi^+$ to reduce combinatoric BG.
  - p*(D^0) > 2.4 GeV to remove D^0 from B decay
- Lepton particle ID to help BG separation
- Combinatoric background mostly has real leptons in it
  - BB background : Fisher discriminant ,continuum BG : helicity angle cut
- *Peaking* background from $D^0 \to h^+h^-$
  - $D^0 \to K^-\pi^+$ and $D^0 \to K^+K^-$ modes are far away in m(D^0) (*not a problem*).
  - $D^0 \to \pi^+\pi^-$ is a *dominant* BG for the $D^0 \to \mu^+\mu^-$ mode.

$D^0 \rightarrow l^+l^-$

Very few events survive all cuts -- use cut-and-count approach
Normalize signal BF relative to $D^0 \rightarrow \pi^+\pi^-$

$\Delta m = m(D^*) - m(D)$



Combinatoric BG in signal window from upper SB

Peaking $D^0 \rightarrow \pi^+\pi^-$ in μμ signal window from *misid* rates measured in data

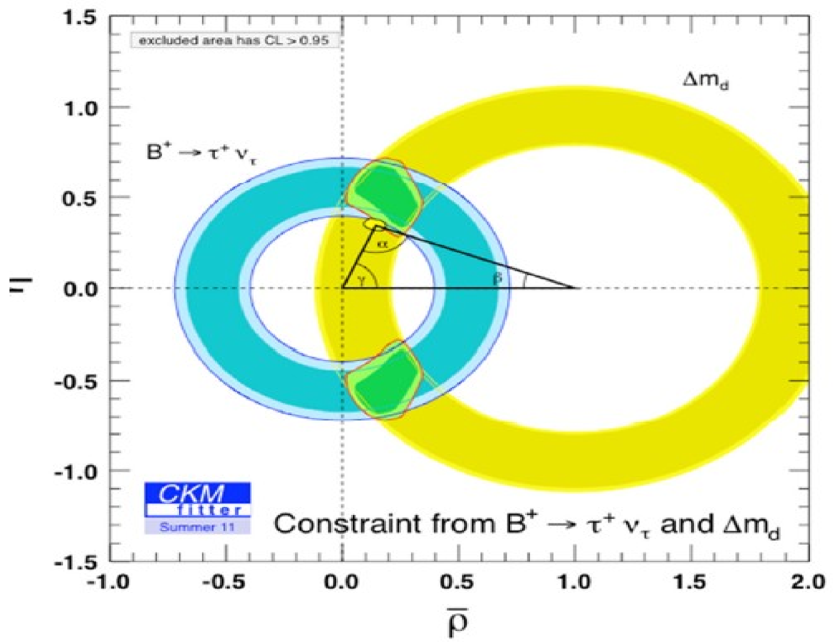
Mode	N_{BG}	$N_{\rm obs}$	$\mathcal{B}_{\ell\ell}$, 90% CL	$\mathcal{B}_{\ell\ell}$
$D^0 \rightarrow e^+e^-$	$1.0 \pm 0.4 \pm 0.4$	1	$< 1.7 \times 10^{-7}$	$\left(0.1\ ^{+0.7}_{-0.4}\right) \times 10^{-7}$
$D^0 \rightarrow \mu^+\mu^-$	$3.9 \pm 0.4 \pm 0.5$	8	$[0.6, 8.1] \times 10^{-7}$	$\left(3.3\ ^{+2.6}_{-2.0}\right) \times 10^{-7}$
$D^0 \rightarrow e^\pm\mu^\mp$	$1.4 \pm 0.3 \pm 0.2$	2	$< 3.3 \times 10^{-7}$	$\left(0.5\ ^{+1.3}_{-0.9}\right) \times 10^{-7}$

For μμ channel Feldman-Cousins UL procedure results in a 2-sided 90% CL interval

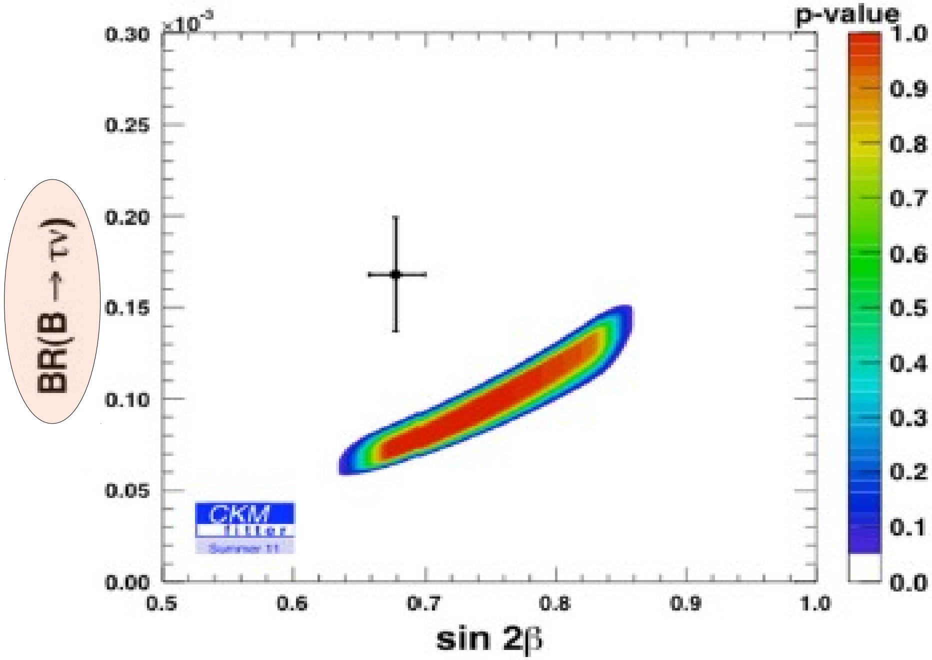
Superseeds PRL 93, 191801 (2004)

Tests of SM and NP

General striking overall consistency of UT constraints



However .....
some measurements show "tensions"



$\|V_{cb}\|$ exclusive ($D^*l\nu$)	$\|V_{cb}\| = (39.04 \pm 0.55 \pm 0.73) \cdot 10^{-3}$	2.4 σ
$\|V_{cb}\|$ inclusive	$\|V_{cb}\| = (41.88 \pm 0.44 \pm 0.59) \cdot 10^{-3}$	
$\|V_{ub}\|$ exclusive (π/ν)	$\|V_{ub}\| = (3.28 \pm 0.18 \pm 0.24) \cdot 10^{-3}$	2.7 σ
$\|V_{ub}\|$ inclusive	$\|V_{ub}\| = (4.41 \pm 0.15 \pm 0.17) \cdot 10^{-3}$	

$|V_{ub}| = (4.31 \pm 0.25 \pm 0.16) \cdot 10^{-3}$

Another problem : $B \to \tau\nu$ $|V_{ub}| = (5.0 \pm 0.6) \cdot 10^{-3}$

Caveat: based on BF average of 4 low statistics measurements

... and now also the rates for $B \to D^{(*)}\tau\nu$ exceed the SM by 3.4 σ

Conclusions and outlook - I

Study of leptonic and semileptonic decays continues to be a very active area for both theory and experiment and has recently greatly improved

- Use of B tagging technique : substantially reduces backgrounds + improves systematic uncertainties
- Major improvements in analysis + larger data sets : reduced uncertainties on BF, $|V_{ub}|$ and $|V_{cb}|$
- Stringent new limits on rare and forbidden B decays and New Physics

Yet found no evidence for New Physics : overall consistency of UT constraints

BUT

some ”tensions” are visible :

- ➔ values of inclusive and exclusive $|V_{ub}|$ and $|V_{cb}|$ differ by more than 2 sigma
- ➔ $\mathcal{B}(B \to \tau\nu)$ [vs sin 2β and V_{ub}] do not agree with SM expectations
- ➔ A significant excess of events has been observed in $B \to D\tau\nu$ and $B \to D^*\tau\nu$
  - ➔ cannot be explained in terms of a 2DHM of type II

Statistical fluctuations, unknown systematic uncertainties or hints of NP around the corner?

Conclusions and outlook - II

Impressive number of new results from BaBar [and Belle] still produced

BaBar still well and alive long after end of data-taking (2008)

Physics Book of B-Factories in preparation by BaBar and Belle jointly

SM very well verified by UT constraints

BUT

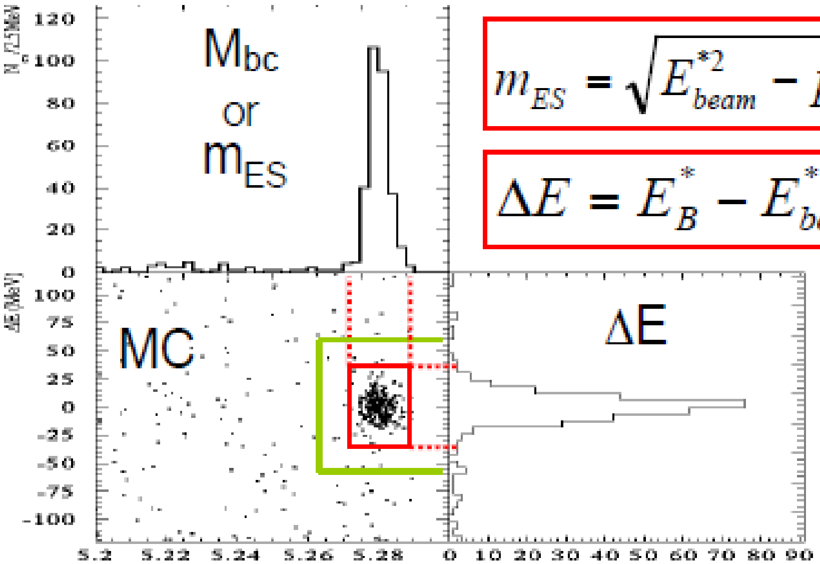
”tensions” present : NP could be near

We need more data and better precision
Major advances are expected from LHCb and
future B Factories !

Backup slides

The BaBar detector

Exclusive reconstruction of B decay; kinematic constraint from beam energies

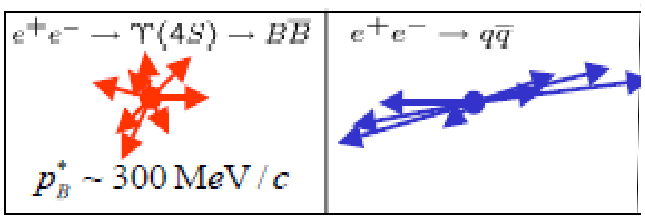


$$m_{ES} = \sqrt{E_{beam}^{*2} - p_B^{*2}}$$

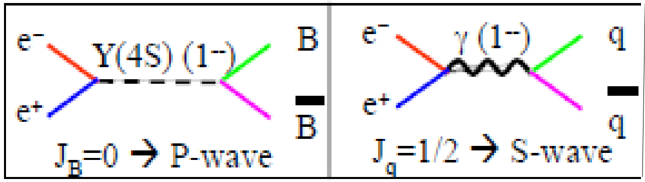
$$\Delta E = E_B^* - E_{beam}^*$$

Continuum ($q\bar{q}$) bkg suppression

Topology:

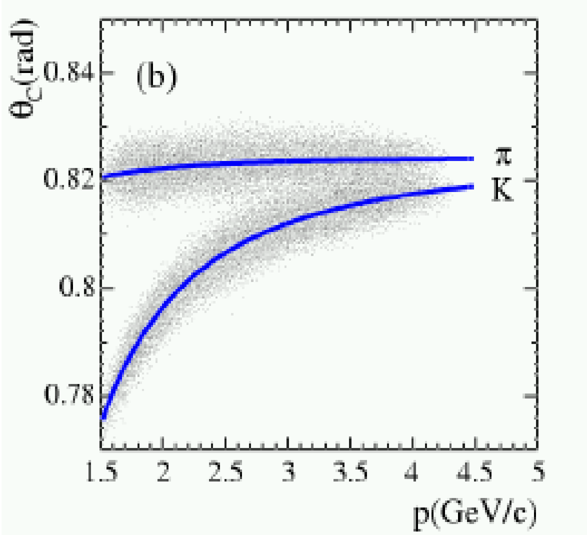


Angular distribution:



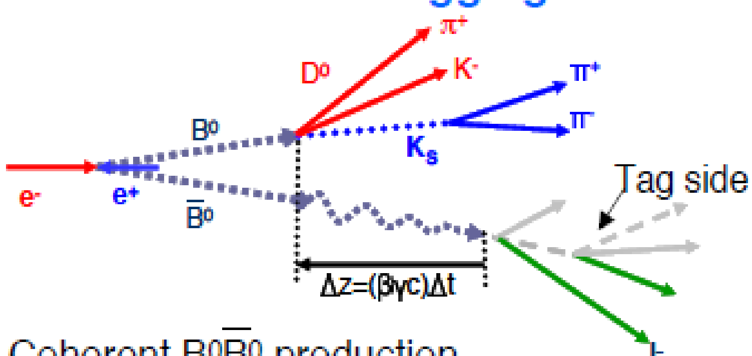
Multivariate analysis (NN, Fisher)

K/π separation: Cherenkov angle + dE/dx



Excellent separation between 1.5 and 4 GeV/c

Flavor tagging



Coherent $B^0\bar{B}^0$ production

Boost $\beta\gamma \approx 0.55$ allows Δt measurement

Leptons and kaons tag flavor of other B

Search for Lepton-Flavor Violation: $B^+ \to K^+\tau e$, $B^+ \to K^+\tau\mu$, $B^+ \to \pi^+\tau e$, $B^+ \to \pi^+\tau\mu$

Mode	$\mathcal{B}(B \to h\tau l)$ ($\times10^{-5}$) central value		90% CL UL
$B^+ \to K^+\tau^-\mu^+$	+0.8	$^{+1.9}_{-1.4}$	< 4.5
$B^+ \to K^+\tau^+\mu^-$	-0.4	$^{+1.4}_{-0.9}$	< 2.8
$B^+ \to K^+\tau^-e^+$	+0.2	$^{+2.1}_{-1.0}$	< 4.3
$B^+ \to K^+\tau^+e^-$	-1.3	$^{+1.5}_{-1.8}$	< 1.5
$B^+ \to \pi^+\tau^-\mu^+$	+0.4	$^{+3.1}_{-2.0}$	< 6.2
$B^+ \to \pi^+\tau^+\mu^-$	0.0	$^{+2.6}_{-2.0}$	< 4.5
$B^+ \to \pi^+\tau^-e^+$	2.8	$^{+2.4}_{-1.9}$	< 7.4
$B^+ \to \pi^+\tau^+e^-$	-3.1	$^{+2.4}_{-2.1}$	< 2.0

Avg of $\mathcal{B}(B\text{-}> h\tau l)$ assuming
$\mathcal{B}(B\text{-}> h\tau l^+) = \mathcal{B}(B\text{-}> h\tau l^-)$

Mode	$\mathcal{B}(B \to h\tau\ell)$ ($\times10^{-5}$) central value	90% C.L. UL
$B^+ \to K^+\tau\mu$	$0.0^{+2.7}_{-1.4}$	< 4.8
$B^+ \to K^+\tau e$	$-0.6^{+1.7}_{-1.4}$	< 3.0
$B^+ \to \pi^+\tau\mu$	$0.5^{+3.8}_{-3.2}$	< 7.2
$B^+ \to \pi^+\tau e$	$2.3^{+2.8}_{-1.7}$	< 7.5

Conservative constraints on NP parameters
from "clean" modes
Used Feldman-Cousins UL

Black et al.* : estimate NP energy scales for 3rd generation flavor changing couplings

$\mathcal{B}(B^+ \to \pi^+\tau^-\mu^+) < 6.2 \times 10^{-5} \to$ bound on $\Lambda_{bd} > 12$ TeV

$\mathcal{B}(B^+ \to K^+\tau^-\mu^+) < 4.5 \times 10^{-5} \to$ bound on $\Lambda_{bs} > 15$ TeV

* Phys.Rev.D66, 053002 (2002)

Inclusive $|V_{ub}|$ with hadronic tag

Theoretical challenges :

- OPE convergence destroyed in limited phase space
- Rates become sensitive to b-quark dynamics inside B meson.
  - Unknown higher orders terms in α_s and $1/m_b$ expansions
  - Shape functions (SF) – to be extracted from data
    - Leading order in $1/m_b$: universal SF
    - Order Λ_{QCD}/m_b: several subleading SF
- Uncertainties in input parameters
  - m_b : total rate $\Gamma \sim |V_{ub}|^2 m_b^5$, partial rates $\Delta\Gamma \sim |V_{ub}|^2 m_b^{10}$

Systematics of R(D) and R(D*) Measurement

Systematic errors

Source	Uncertainty (%) $R(D)$	$R(D^*)$	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
$\varepsilon_{sig}/\varepsilon_{norm}$	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

- D**l ν: conservative 15% constraints + fit to Dπ sample
- Limited MC signal samples 2-dim PDFs ~2000 events

Largest errors are Gaussian distributed !

correlation !

Decay	$\mathcal{R}(D^{(*)})$
$B^- \rightarrow D^0\tau^-\overline{\nu}_\tau$	$0.429 \pm 0.082 \pm 0.052$
$B^- \rightarrow D^{*0}\tau^-\overline{\nu}_\tau$	$0.322 \pm 0.032 \pm 0.022$
$\overline{B}^0 \rightarrow D^+\tau^-\overline{\nu}_\tau$	$0.469 \pm 0.084 \pm 0.053$
$\overline{B}^0 \rightarrow D^{*+}\tau^-\overline{\nu}_\tau$	$0.355 \pm 0.039 \pm 0.021$
$\overline{B} \rightarrow D\tau^-\overline{\nu}_\tau$	$0.440 \pm 0.058 \pm 0.042$
$\overline{B} \rightarrow D^*\tau^-\overline{\nu}_\tau$	$0.332 \pm 0.024 \pm 0.018$