Semileptonic *B* decays at *BaBar*

On behalf of the *BaBar* collaboration

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Outline

- Introduction
- Inclusive semileptonic B decays
  - Measurements of moments of the hadronic mass, and combined hadronic mass and energy distribution from $B \to X_c l \nu$
  - Measurements of moments of the unfolded hadronic mass distribution from $B \to X_u l \nu$
  - Inclusive results
- Exclusive semileptonic B decays
  - $|V_{cb}|$ and Form Factors from $B \to D l \nu$ (tagged measurement)
  - $|V_{cb}|$ and Form Factors from $B \to D^{(*)} l \nu$ (untagged measurement)
  - Exclusive results
- Conclusion

Introduction

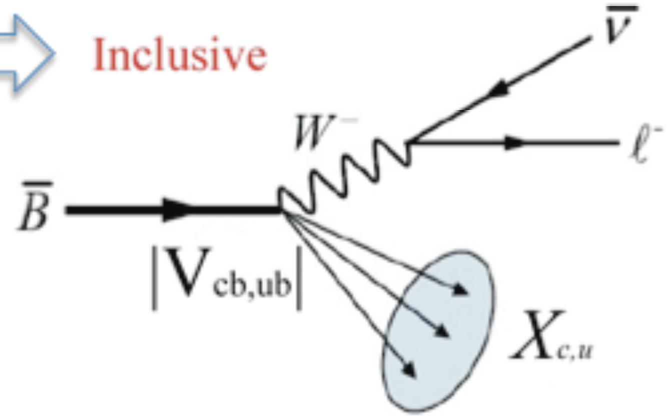
Semileptonic $B \to X_{c(u)}\, l\nu$ decays provide a clean environment for studies on the b quark inside the B meson.

As well as a method for measuring CKM elements $|V_{ub}|, |V_{cb}|$

Can be split into two distinct groups

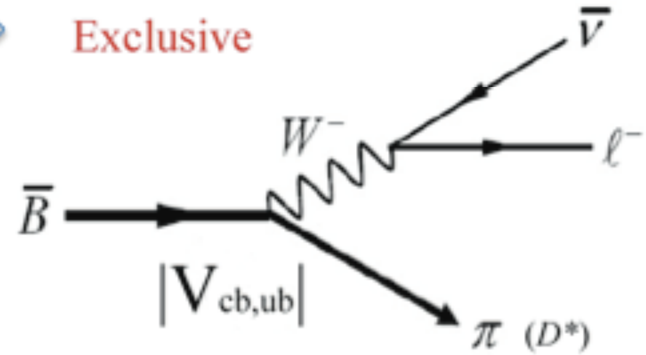
- Inclusive decays
  - Sum over all possible final state hadrons.
  - Use Operator Product Expansion (OPE) and Heavy Quark Expansion (HQE) to calculate decay rates.

Inclusive



- Exclusive decays
  - Specifically reconstruct $X_{c(u)}$
  - Better background rejection
  - Less statistics
  - Use Heavy Quark Effective Theory (HQET) and Form Factors (FF) to describe hadronization

Exclusive



Inclusive semileptonic

HQE calculates the relation between the total rate $\Gamma_{c(u)}$ and $|V_{c(u)b}|$

$$\Gamma(B \to X_{c(u)} l\nu) = \frac{G^2{}_F}{192\pi^3} m_B{}^5 \, |V_{c(u)b}|^2 \, (1 + A_{ew}) A^{pert} A^{nonpert}$$

- Non perturbative parameters need to be measured precisely in order to extract $|V_{ub}|$ and $|V_{cb}|$ precisely.
  - Kinetic energy of b quark, $\mu_{\pi}{}^2$;
  - Chromomagnetic moment, $\mu_G{}^2$;
  - Higher order terms: $\rho_{LS}{}^3$, $\rho_D{}^3$.

- Moments have a sensitivity to these quark masses and same non-perturbative parameters
  - Use moments for hadronic mass $<m_X{}^k>$, lepton energy $<E_l{}^k>$, and mixed moments

Inclusive semileptonic

- **Lepton moments**

$$\langle E_l^{\,n} \rangle = N \int (E_l - \langle E_l \rangle)^n \left(\frac{d\Gamma_{c(u)}}{dE_l} \right) dE_l$$

- **Hadronic mass moments**

$$\langle m_X^{\,n} \rangle = N \int m_X^{\,n} \left(\frac{d\Gamma_{c(u)}}{dm_X} \right) dm_X$$

- **Mixed moments**
  Give a more precise determination of higher order non-perturbative parameters

$$n_X^{\,2} = m_X^{\,2} - 2\Lambda E_X + \Lambda^2$$
$$\Lambda = 0.65 GeV$$

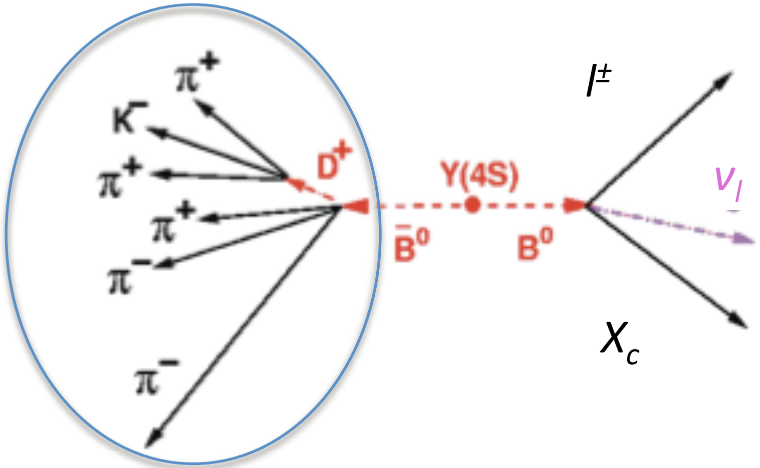
- Translations from moments to non-perturbative parameters available in kinetic and 1S schemes
  - All results in this presentation are calculated in the kinetic scheme

Moments from $B \to X_c l \nu$

230 million $B\overline{B}$ events

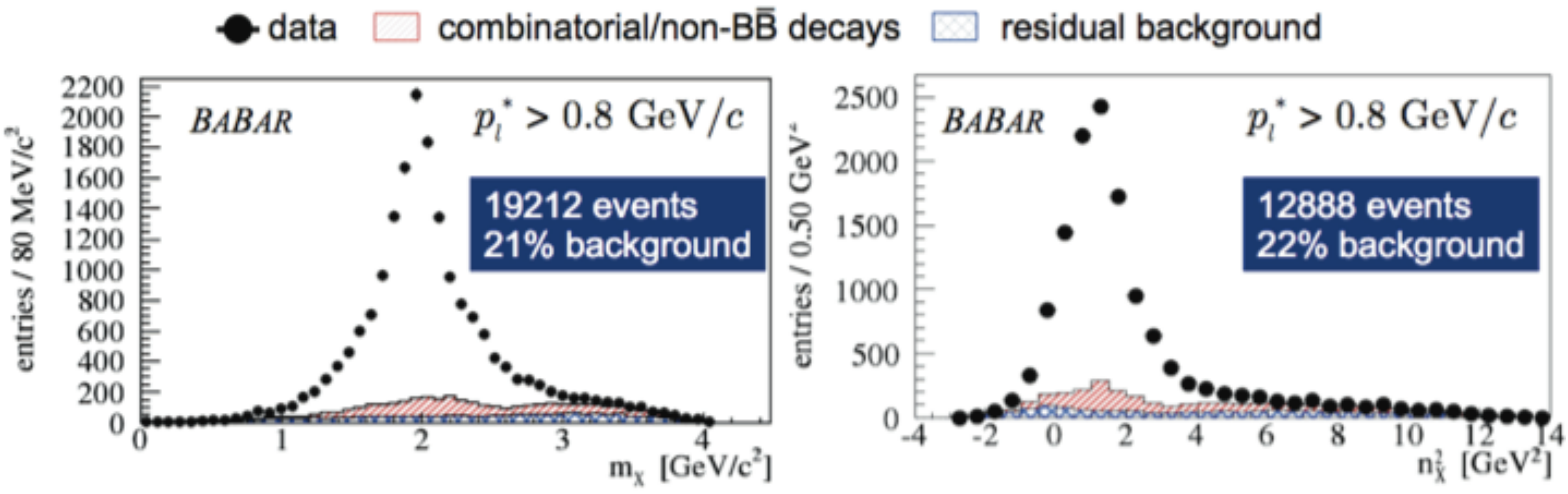
0908.2670 [hep-ex]
(submitted to PRD)

- **Tagged side**
  - Fully reconstruct one B meson
- **Recoil side**
  - Select lepton with $p^*_l > 0.8$ GeV/c ($l = e, \mu$)
  - Missing mass consistent with neutrino
  - Remaining particles form X_c system
  - Improve resolution with kinematic fit
- **Residual background**
  - $B \to X_u l \nu$ decays
  - Secondary semileptonic D decays
  - Semileptonic τ decays
  - Leptons from $J/\Psi \to l\bar{l}$
- **Combinatorial background**
- **BB background**
  - $e^+e^- \to c\bar{c}$ or $l\bar{l}$



Moments measured as lower limits on p_l^* (0.8 - 1.9 GeV)

Moments from $B \to X_c l \nu$



Apply correction factors (calculated from MC) to m_X and n_X^2 spectrum to correct for unmeasured/missing particles

Moments from $B \to X_c l \nu$

- **Perform combined χ^2 fit in kinetic scheme:**
  - Hadronic mass moments/mixed moments;
  - Lepton energy moments in $B \to X_c l \nu$;
  - Photon energy moments in $B \to X_s \gamma$;
- **Fit on subsets of measurements** to reduce correlation
- **Uneven mass/mixed moments not used** to provide an unbiased comparison with fitted HQE prediction
- 8 fit parameters:
  - $|V_{cb}|$, m_b, m_c, $BF(B \to X_c l \nu)$, μ_π^2, μ_G^2, ρ_{LS}^3, ρ_D^3

Additionally:

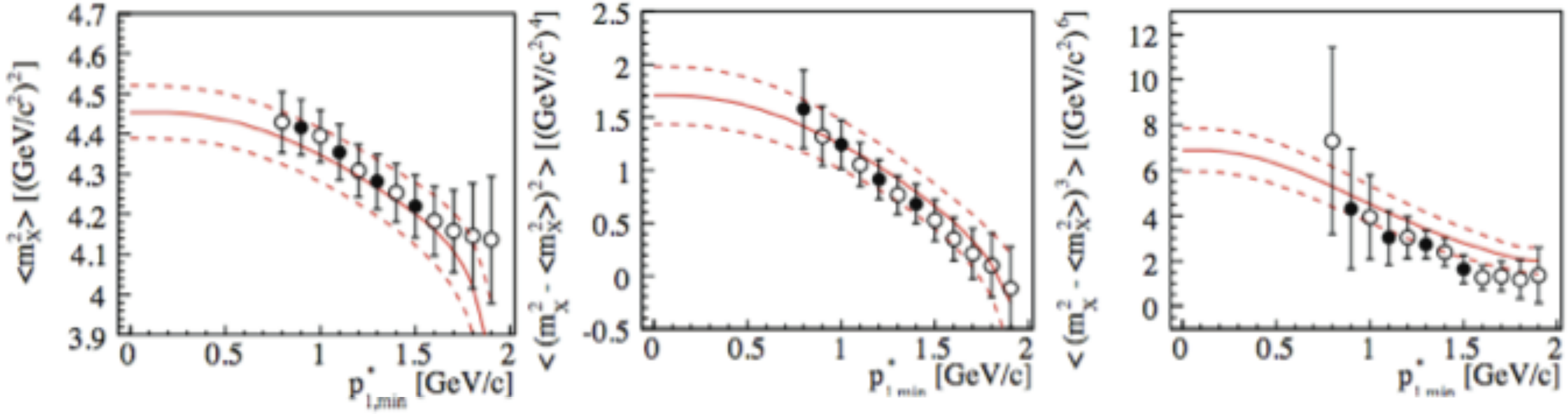
$\tau_B = (1.585 \pm 0.007) \times 10^{-12}$ s	(B lifetime) Input parameter
$\mu_G^2 = (0.35 \pm 0.07)$ GeV^2	Constraint
$\rho_{LS}^3 = (-0.15 \pm 0.10)$ GeV^3	Constraint

Moments from $B \to X_c l \nu$

Mass moments

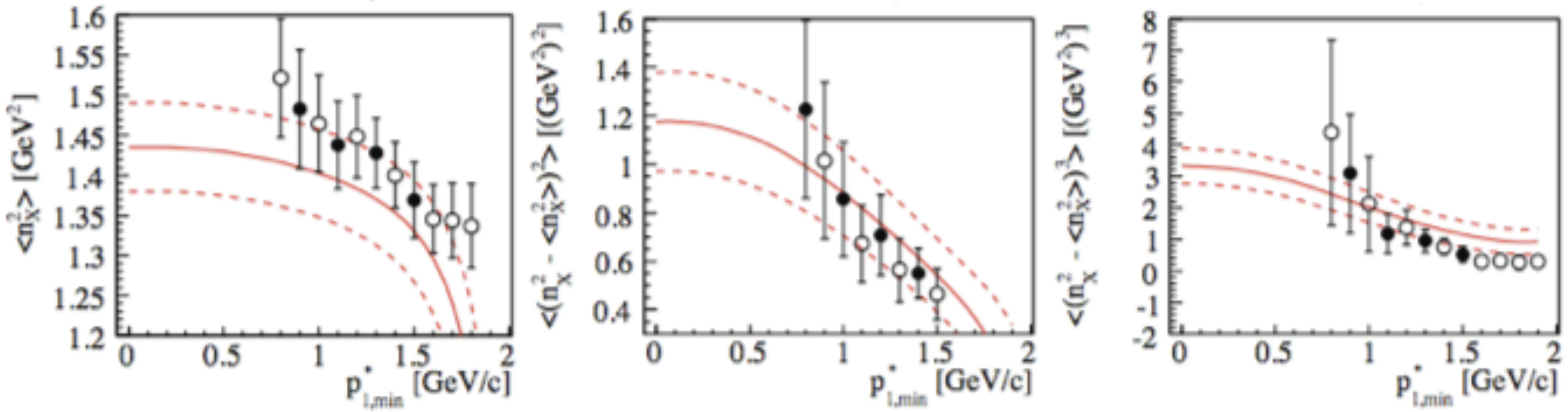
● contained
○ not contained
in the fit

χ^2 (ndf) = 11 (28)



Mixed moments

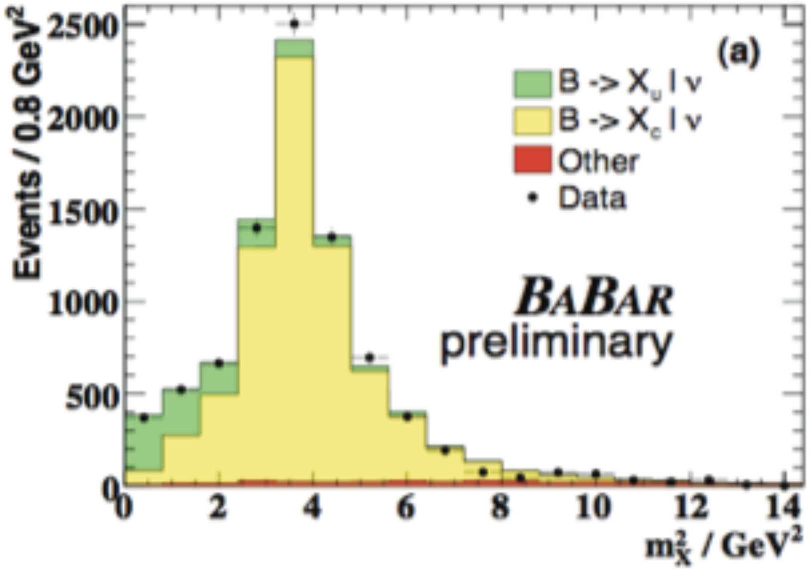
χ^2 (ndf) = 8 (28)



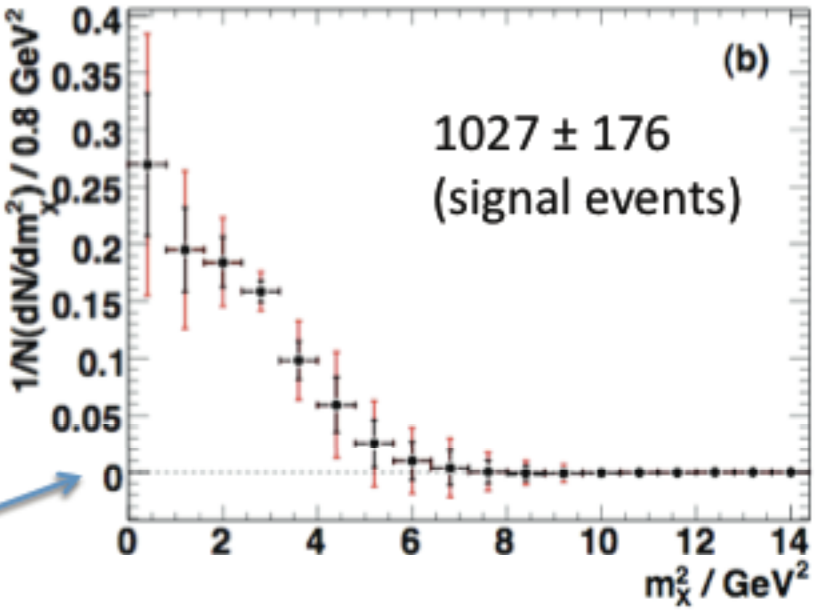
Moments from $B \to X_u l \nu$

383 million $B\overline{B}$ events

- **Tagged side**
  - Fully reconstruct one B meson
- **Recoil side**
  - Select lepton with $p^*_l > 1.0$ GeV/c ($l = e, \mu$)
  - Remaining particles form X_u system
  - Missing mass consistent with neutrino
  - Veto $K^{\pm}$, K_S and partially reconstructed D^*
- **Large $B \to X_c l \nu$ background**
  - Subtract using a χ^2 fit to the hadronic mass spectrum **(a)**



Unfold background subtracted spectrum **(a)** for detector acceptance, resolution and efficiency to get unfolded spectrum **(b)**.
Then extract moments from **(b)** for $m^2_X < 6.4$ GeV^2



Statistical error (inner bar)
Experimental (outer bar)

Summary of inclusive results

*FPCP

Results from $B \to X_c l \nu$ and $B \to X_u l \nu$ moments analyses

	$\lvert V_{cb}\rvert \times 10^3$	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
$B \to X_u l\nu$ moments		4.604±0.250		0.398±0.240
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

- Good agreement of results from mixed and mass moments
- Good agreement of results with the HFAG world average
- Good agreement for $B \to X_c l \nu$ and $B \to X_u l \nu$ results

Exclusive semileptonic

HQET calculates the relation between the total rate Γ and $|V_{cb}|G^2(w)$

$$\frac{d\Gamma}{dw}(D) = \frac{G^2{}_F}{48\pi^3}(m_B + m_D)2m_D{}^3(w^2-1)^{3/2}|V_{cb}|G^2(w)$$

– $G^2(w)$ is the only relevant form factor (FF) in null lepton mass limit.

$$w = V_B \cdot V_D = \frac{(M^2{}_B + M^2{}_D - q^2)}{2M_B M_D}$$

– (D meson produced at rest) $1.0 < w < 1.6$ (D momentum opposite to W)

- HQET expansion of FF *(Caprini el al. parameterization: Nucl.Phys.B530 (1998),153)*

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

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

- Slope of $G(w)$ at $w=1$, ρ^2 is extracted with fit along with $G(1)|V_{cb}|$

Tagged $B \to D\, l\, \nu$

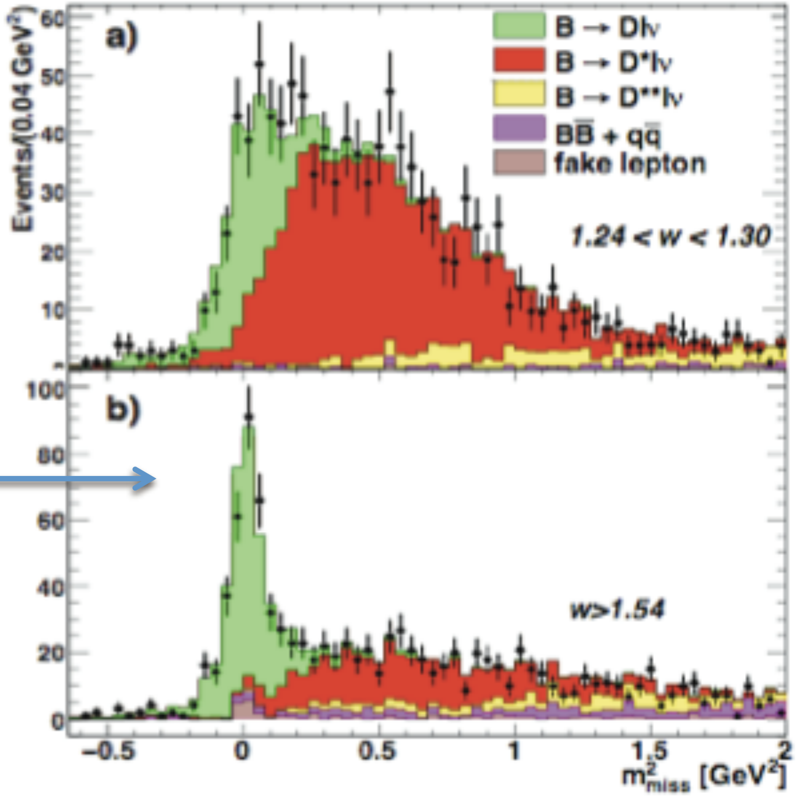
0904.4063 [hep-ex]
(submitted to PRL)

460 million $B\bar{B}$ events

- **Tagged side**
  - Fully reconstruct one B meson

- **Recoil side**
  - Select lepton with $p^*_l > 0.6$ GeV/c ($l = e, \mu$)
  - Reconstruct D^0 (9 final states)
  - Reconstruct D^+ (7 final states)
  - Identify semileptonic B decays from the missing mass squared

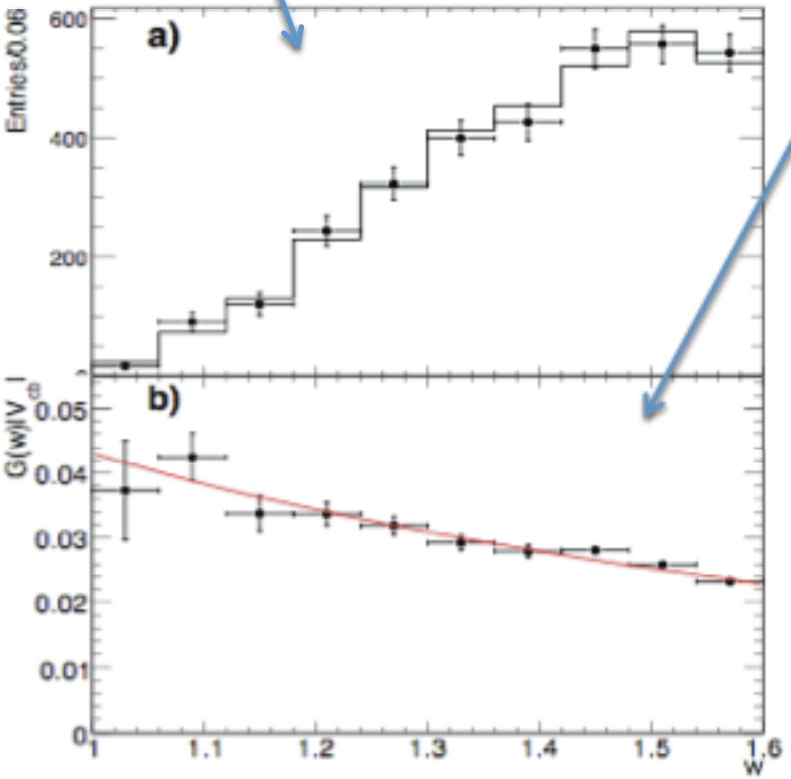
$$m^2_{miss} = [p(\Upsilon(4S)) - p(B_{tag}) - p(D) - p(\ell)]^2$$



- Extract $B \to D\, l\, \nu$ for each bin of w using a binned maximum likelihood fit to m^2_{miss}
  - 10 bins of w
  - $1.0 < w < 1.6$

Tagged $B \to D\, l\, \nu$

Background subtracted spectrum (~3250 signal events)



Use χ^2 fit to w spectrum to calculate $G(1)\,|V_{cb}|$ and ρ^2

	$B^- \to D^0 \ell^- \bar{\nu}_\ell$	$\overline{B}^0 \to D^+ \ell^- \bar{\nu}_\ell$
$\mathcal{G}(1)\|V_{cb}\| \cdot 10^3$	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

$G(1)\,|V_{cb}| = (43.0 \pm 1.9 \pm 1.4) \times 10^{-3}$

(5.5% error) – Mainly statistics

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

$BR(B^0 \to D\, l\, \nu) = (2.17 \pm 0.06 \pm 0.09)$ %

Untagged $B \rightarrow D^{(*)} l \nu$

PRD79, 012002 (2009)

230 million $B\bar{B}$ events

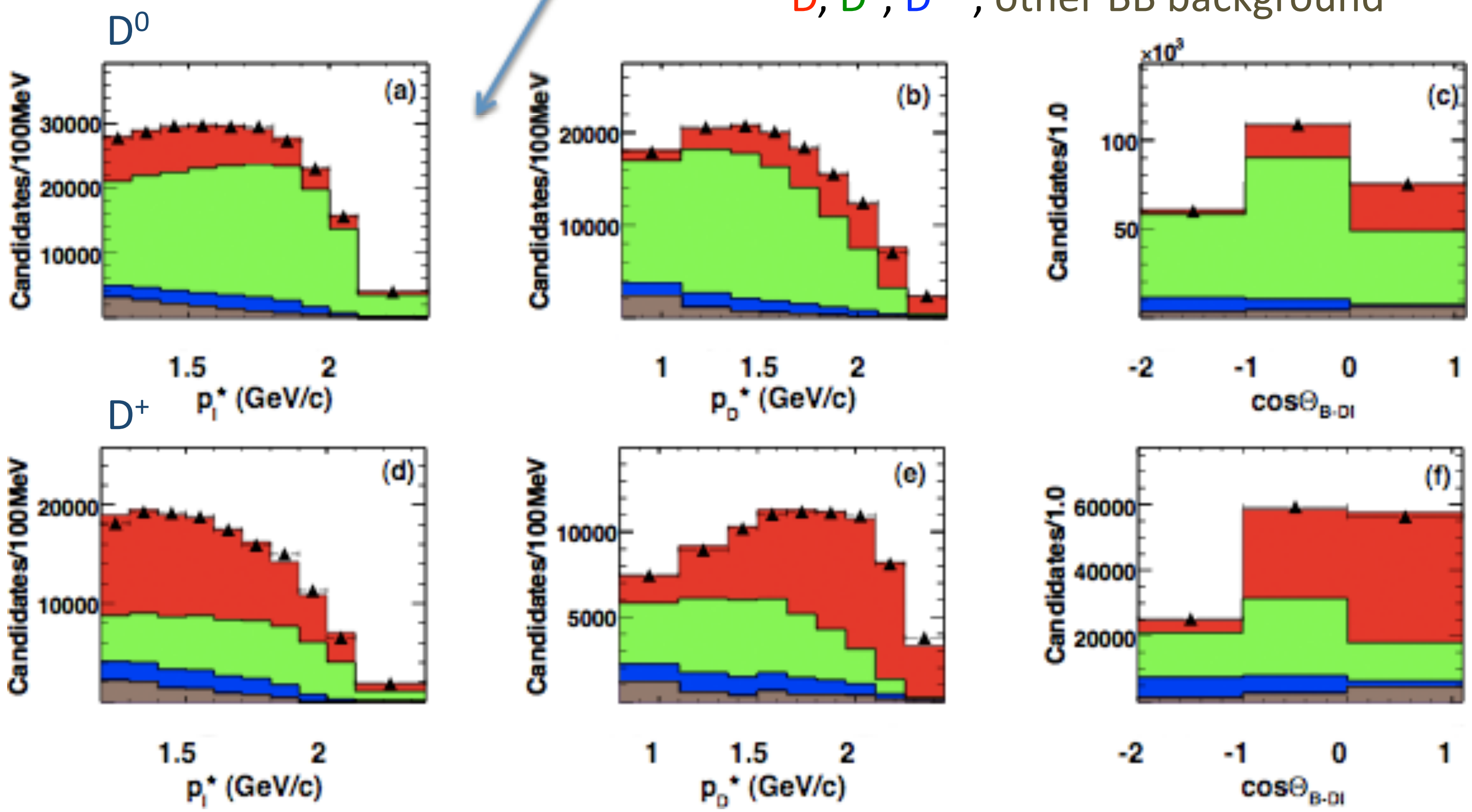
Select $B^{+/0} \rightarrow D^{0/+} l \nu$
from $D^0 l$ or $D^+ l$ pairs
select lepton with
$p^*_l > 1.2$ GeV/c $(l = e, \mu)$

Extract $B \rightarrow D^{(*)} l \nu$ from binned 3D fit to:

- p^*_l (momentum of lepton)
- p_D (momentum of D)
- $cos\vartheta_{B-Dl}$

Analysis has sensitivity to ρ_D^2, $\rho_{D^*}^2$ and $|V_{cb}|$

D, D*, D**, other BB background



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

- Result from combined fit from electron and muon samples.
- BR($\overline{B}^0$) obtained from BR(B^-) results using lifetime ratio.

Parameters	combined result
ρ_D^2	$1.20 \pm 0.04 \pm 0.07$
$\rho_{D^*}^2$	$1.22 \pm 0.02 \pm 0.07$
$\mathcal{B}(D^0 \ell \overline{\nu})(\%)$	$2.34 \pm 0.03 \pm 0.13$
$\mathcal{B}(D^{*0} \ell \overline{\nu})(\%)$	$5.40 \pm 0.02 \pm 0.21$
χ^2/n.d.f. (probability)	2.2/4 (0.71)

D : $G(1)|V_{cb}| = (43.1 \pm 0.8 \pm 2.3) \times 10^{-3}$

(5.5% error) – Mainly systematics

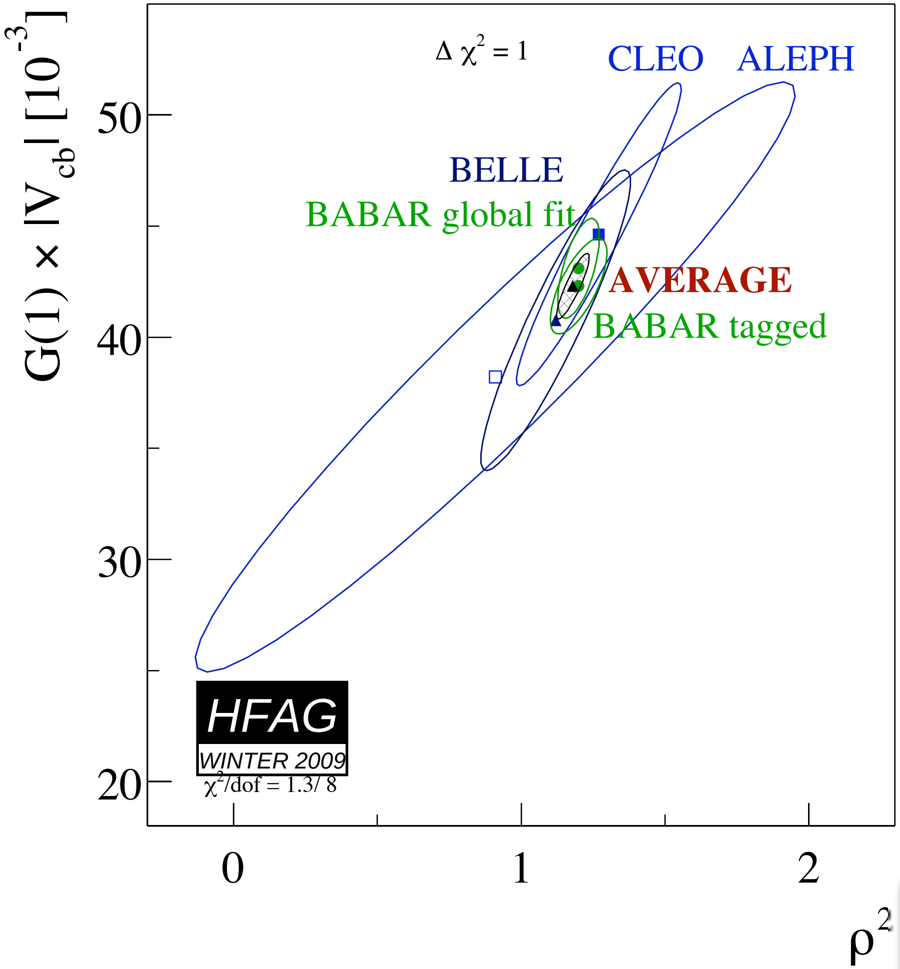
D*: $F(1)|V_{cb}| = (35.9 \pm 0.2 \pm 1.2) \times 10^{-3}$

- Consistent with existing measurements.

Theory Validation

- $G(1)/F(1) = 1.20 \pm 0.09$ agrees well with lattice computation (1.17 ± 0.04).
- Slope difference $\rho_D^2 - \rho_{D^*}^2 = 0$. Consistent with prediction.

Summary of exclusive results



Combine tagged and untagged measurements for $B \to D\, l\, \nu$

$G(1)|V_{cb}| = (42.4 \pm 0.7 \pm 1.6) \times 10^{-3}$

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

$BR(B^0 \to D\, l\, \nu) = (2.16 \pm 0.08)\%$

Using Okamoto et al. (FNAL05) LQCD:

$G(1) = 1.074 \pm 0.018 \pm 0.016$

$\mathbf{|V_{cb}| = (39.2 \pm 1.6 \pm 0.9_G) \times 10^{-3}}$

Consistent with existing measurements

$|V_{cb}|\ (B \to D^*\, l\, \nu) = (38.1 \pm 0.5 \pm 1.0_F) \times 10^{-3}$

$|V_{cb}|$ (inclusive) $= (41.5 \pm 0.7) \times 10^{-3}$

Conclusion

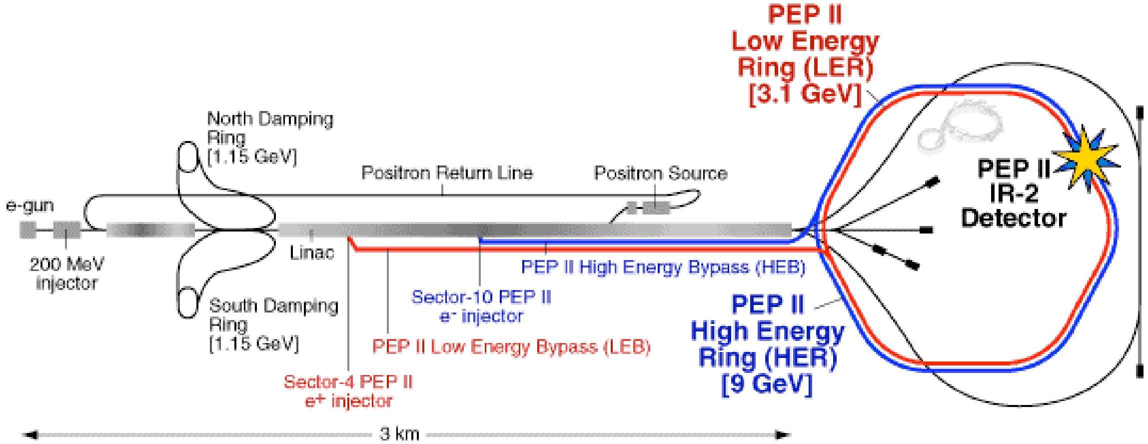
- **Presented are inclusive measurements of:**
  - The first six moments of hadronic mass spectrum for $B \rightarrow X_c l \nu$
  - The first measurements of mixed hadronic moments $<n_x^k>$ k = 2, 4, 6
  - Moments from the unfolded mass spectrum in $B \rightarrow X_u l \nu$
  - Good consistency between measured parameters from both moments analyses
- **Presented are exclusive measurements of:**
  - $G(1)|V_{cb}|$ from $B \rightarrow D l \nu$ using tagged and untagged sample.
  - Combined measurements of $|V_{cb}|$ are compatible with existing measurements
  - Recent BaBar results have improved total error on world average of $G(1)|V_{cb}|$ (4%)
  - Inclusive $|V_{cb}|$ is at currently at 2%

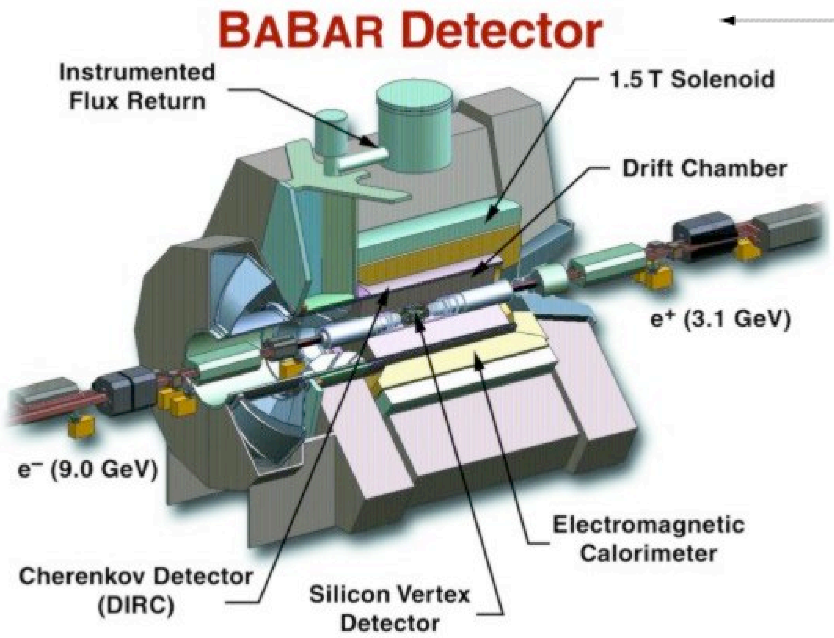
END

Overview of the BaBar experiment

E_{CM} = 10.58 GeV

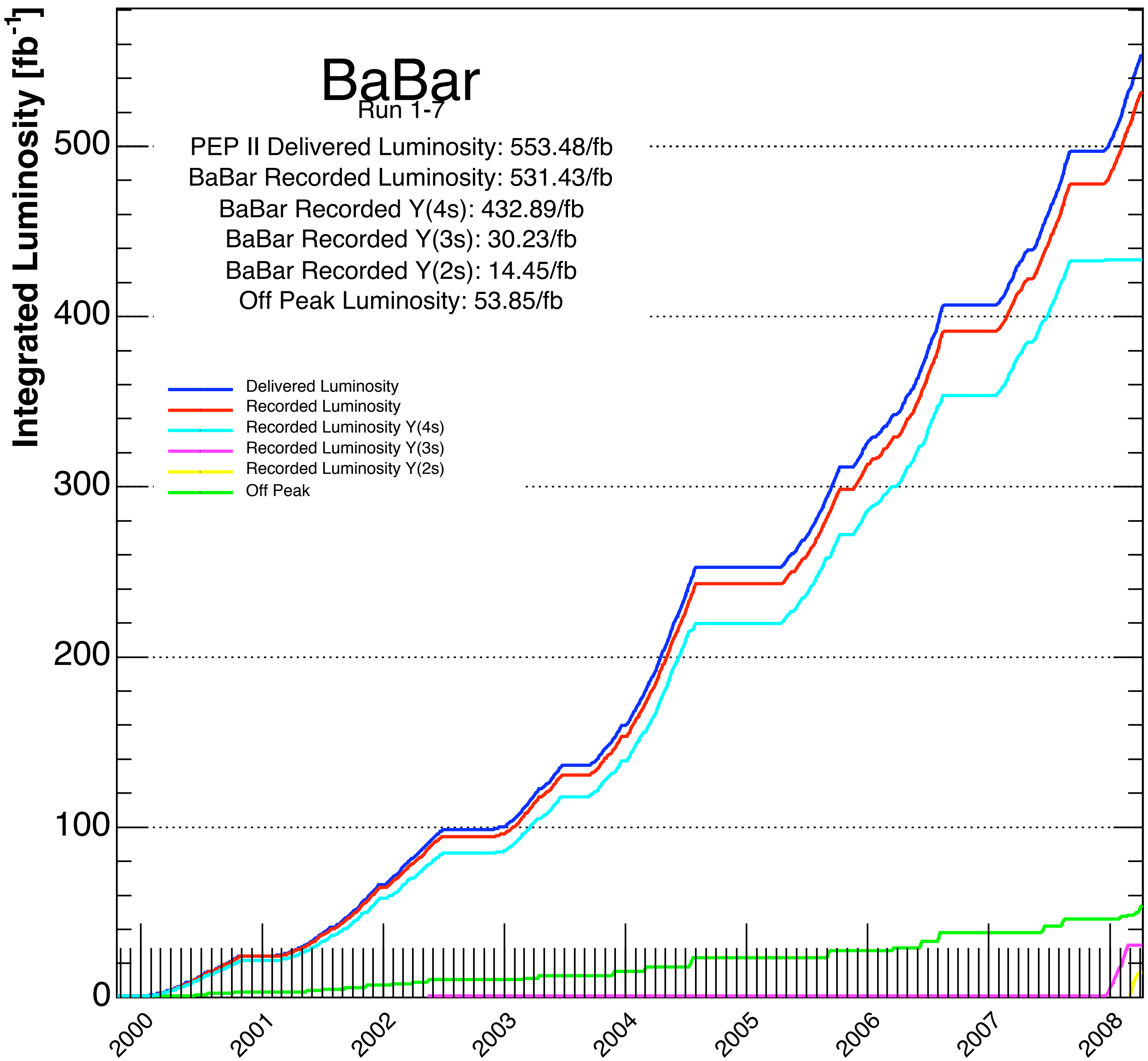
$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$





- SVT – 5 layers of double-sided silicon strips
- DCH – 40 stereo layers of drift/sense wires in helium/isobutane gas mix (dE/dx)
- DIRC – Provides π/K separation (above 700 MeV)
- EMC – 6580 CsI(Tl) crystals. Energy/position measurements for $e^{\pm}$, γ, K_L
- IFR – Identifies μ and neutral hadrons (primarily K_L and neutrons)

As of 2008/04/11 00:00



Collaboration:

~500 physicists

Data-taking:

October 1999 – April 2008

Peak luminosity:

1.2 x 10^{34} cm^{-2} s^{-1} (4 x design)

Integrated Υ(4S) sample:

433 fb^{-1}

Motivation

CP Violation is accounted for in the SM using V_{CKM}.

Appears as complex phase in η

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

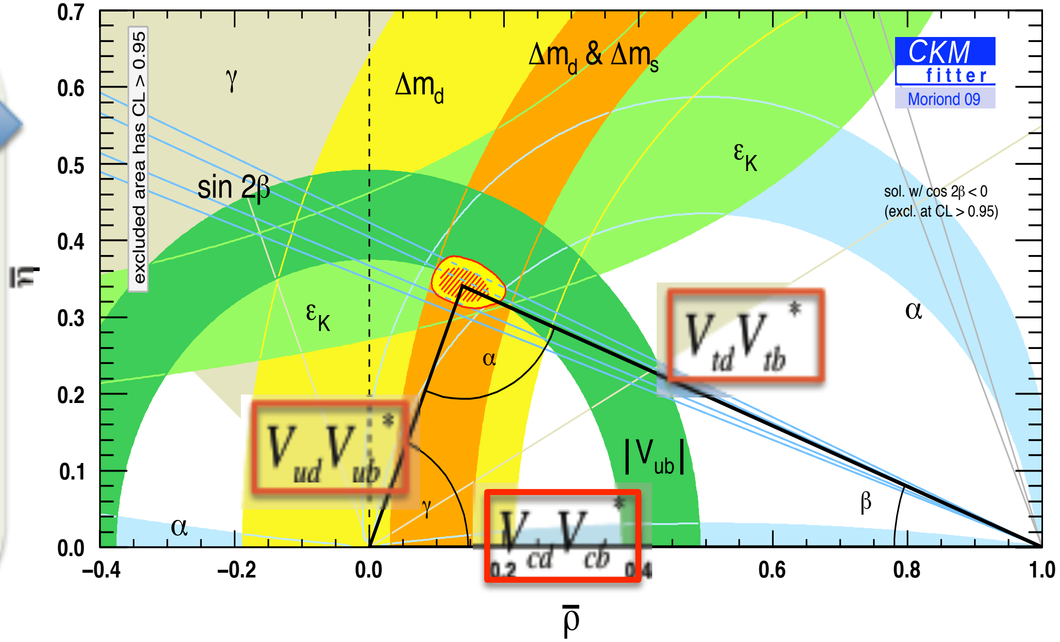
Unitarity of V_{CKM} gives rise to various relations such as: $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$

Can be represented as a 'unitarity triangle'

Measurement of left side compliments measurements of Sin2β

Goal is to over-constrain triangle

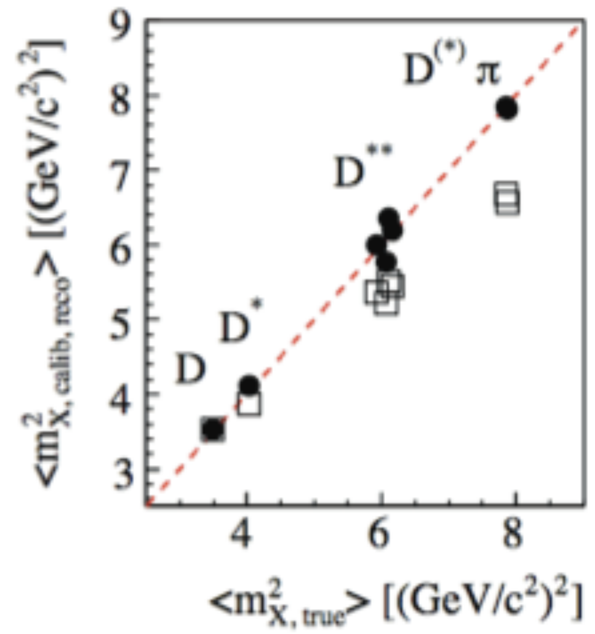
BSM possibilities in 



Calibration

To extract moments additional corrections are applied which distort m_X spectrum

- Correct fitted $\langle m_X^k \rangle$ by:
  - Using the observed relationship (from MC) between : $\langle m_{X,reco} \rangle$ to $\langle m_{X,true} \rangle$ and $\langle n_{X,reco} \rangle$ to $\langle n_{X,true} \rangle$
  - Then apply correction factors on an event by event basis



Other moments measurements