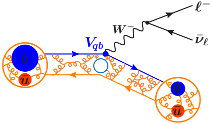
Recent results on charmless semileptonic decays at BaBar



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Melbourne

Australia

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Overview

I. Why explore the Flavor sector of the Standard Model in the first place?

II. Inclusive measurement of $B \to X_u \ell \bar{\nu}_\ell$
[arXiv:1112.0702]

III. Exclusive measurements for $B \to h \ell \bar{\nu}_\ell$ with $h = \pi, \omega, \rho, \eta, \eta'$
[PRD:83032007], [arXiv:1205.6245], 2× [to be submitted]

IV. $|V_{ub}|$ from both approaches

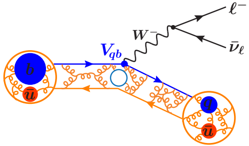
V. The status of charmless semileptonic decays at BaBar

I.a Motivation

Why explore the Flavor sector of the Standard Model (SM) and measure charmless semileptonic decays?

[cf. Backup A.a for a slightly longer introduction]

I. Charmless semileptonic decay rate allows determination of $|V_{ub}|$

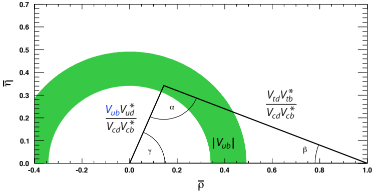


II. $|V_{ub}|$ important input for global CKM fits.

a What are the contributions from the Flavor sector to CP violation in the Universe?

b Violation of CKM unitarity $\Leftrightarrow$ new physics

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



III. Inclusive vs Exclusive measurements:

a Fairly independent experimental and theoretical methods

b Probe our understanding of non-perturbative and perturbative QCD

I.b Semileptonic decays

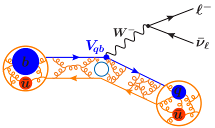
Semileptonic $b \to u$ decays are characterized by

a $q^2 = (p_B - p_X)^2 = (p_\ell + p_{\bar\nu})^2$

b θ: Angular variables (helicity,...)

c m_X: Invariant hadronic mass

$\mathcal{B}(B \to X_u \, \ell \, \bar\nu_\ell) \propto |V_{ub}|^2 \times$ 'Something we can predict from Theory'



a Challenges:

$\Rightarrow$ Much more abundant $b \to c \, \ell \, \bar\nu_\ell$ decays:

Force e.g. inclusive measurements into regions with larger theory uncertainties. Orbital or other modes poorly known.

$\Rightarrow$ Very low signal yields

b Experimental techniques:

$\Rightarrow$ Neutrino reconstruction:

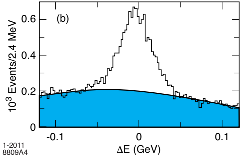
$$(E_{\text{miss}}, \vec{p}_{\text{miss}}) = (E_{\text{beam}}, \vec{p}_{\text{beam}}) - \sum_i (E_i, \vec{p}_i)$$

Missing mass squared: $MM^2 = E^2_{\text{miss}} - |\vec{p}_{\text{miss}}|^2$

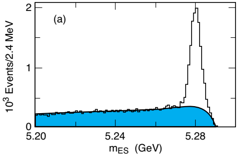
$\Rightarrow$ Beam constraints: ΔE and m_{ES}

$\left(E^*_B, \vec{p}^{*2}_B\right) = p_X + p_\ell + p_{\text{miss}}$ or inferred from the tag side *if present*; $^* =$ in $\Upsilon(4S)$ rest frame; E^*_{beam} beam energy

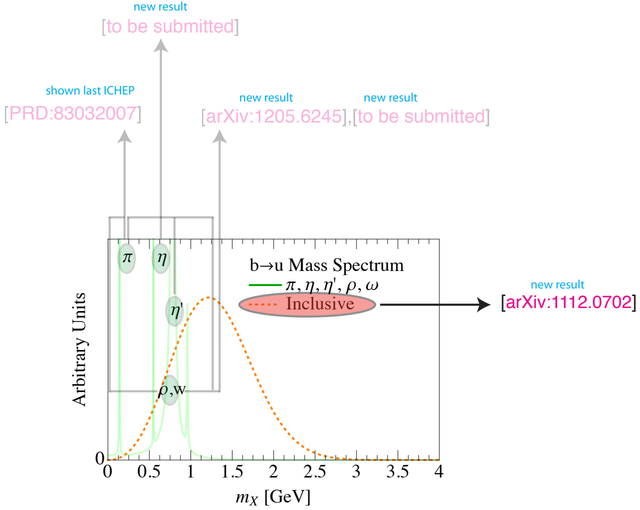
$$\Delta E = E^*_B - E^*_{\text{beam}}/2$$



$$m_{ES} = \sqrt{E^{*2}_{\text{beam}}/4 - \vec{p}^{*2}_B}$$



BaBar charmless overview:



II. *New* inclusive measurement

[arXiv:1112.0702]

At a glance:

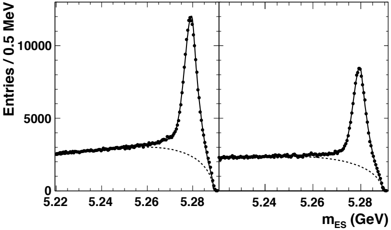
- Full BaBar dataset of 467.8×10^6 $B\bar{B}$
- Inclusive $B \to X_u \ell \bar{\nu}_\ell$ using hadronic tags to reconstruct p_B, require lepton
- $p_X = \sum_i p_i^{\text{tracks}} + \sum_j p_j^{\text{calo}}$

  The sum excludes the lepton and all tracks and calo. clusters associated with the tagged B
- Cut based Bkg suppression, e.g. MM^2, total charge, D^* veto based on partial reco.
- $q^2 = (p_B - p_X)^2$; $m_X^2 = p_X^2$; p_ℓ: $P_+ = E_X - |\vec{p}_X|$

tag Unbinned LH Fit in m_{ES} for comb. & continuum Bkg ($\to$ top plot)

recoil χ^2 Fit ($\to$ List) for signal and $B\bar{B}$ Bkg

Step 1 Fit # of $B \to X_u \ell \bar{\nu}_\ell$ evts. in given bins
Step 2 Determine # of $B \to X \ell^- \nu_\ell$ evts. in reco sample



Signal regions of phase-space:

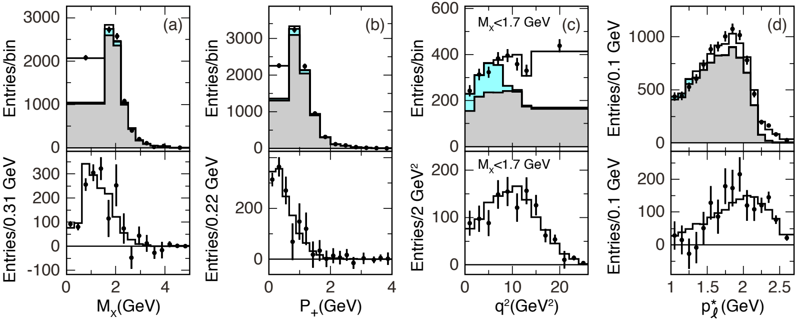
1) $m_X < 1.55$ GeV
2) $m_X < 1.70$ GeV
3) $P_+ < 0.66$ GeV
4) $m_X < 1.70$ GeV & $q^2 > 8$ GeV^2
5) $m_X - q^2$, $p_\ell^* > 1.0$ GeV
6) $p_\ell^* > 1.0$ GeV
7) $p_\ell^* > 1.3$ GeV

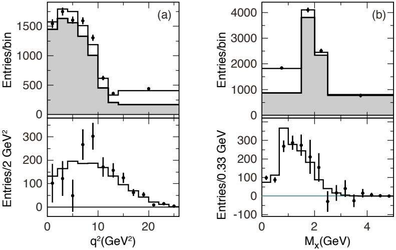
$* = B$ rest frame

$\Rightarrow$ Measure ratio $\Delta\mathcal{B}(B \to X_u \ell \bar{\nu}_\ell)/\mathcal{B}(B \to X \ell \bar{\nu}_\ell)$ ($\to$ many systematics cancel)

II. *New* inclusive measurement

[arXiv:1112.0702]





↑

a) $m_X < 1.55$ GeV or $m_X < 1.70$ GeV

b) $P_+ < 0.66$ GeV

c) $m_X < 1.70$ GeV & $q^2 > 8$ GeV^2

d) $p^*_\ell > 1.0$ GeV or $p^*_\ell > 1.3$ GeV

← a) & b) $m_X - q^2$, $p^*_\ell > 1.0$ GeV

(White) $B \to X_u \ell \bar{\nu}_\ell$; (Cyan) $B \to X_u \ell \bar{\nu}_\ell$ leakage into signal region; (Grey) Bkg from $B \to X_c \ell \bar{\nu}_\ell$ and other sources

II. *New* inclusive measurement

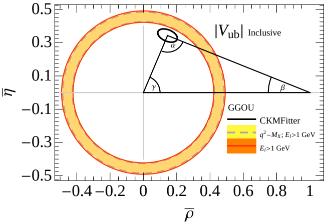
[arXiv:1112.0702]

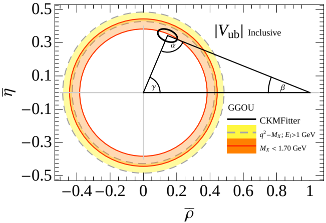
- $|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}}{\tau_B\,\Delta\Gamma_{\text{theory}}}}$ with $\Delta\Gamma_{\text{theory}}$ from ADFR [EPJC:59;831], BLNP [NPB:699;335], DGE [JHEP:0601097], GGOU[JHEP:0710:058]
- $m_X - q^2$, $p_\ell^* > 1.0$ GeV vs $p_\ell^* > 1.0$ GeV

  Events overlap completely; Very nice agreement between theory predictions and signal regions → large region of phase space, very reduced sensitivity to non-pert. corrections ($\widehat{=}$ shape function)
- $m_X - q^2$, $p_\ell^* > 1.0$ GeV vs $m_X < 1.7$ GeV

  Large overlap, cut on m_X increases sensitivity to non-pert. corrections ($\widehat{=}$ shape function)

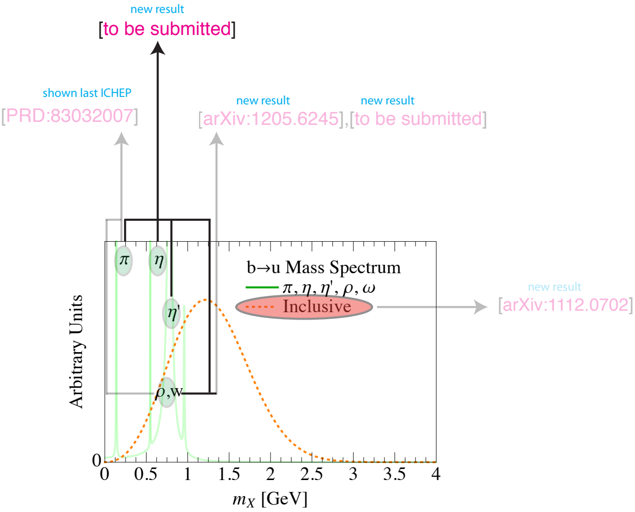
$\lvert V_{ub}\rvert \times 10^3$	$p_l^* > 1.0$ GeV	$m_X - q^2$	$m_X < 1.7$ GeV
ADFR	$4.3 \pm 0.3^{+0.2}_{-0.2}$	$4.3 \pm 0.2^{+0.2}_{-0.2}$	$3.7 \pm 0.2^{+0.2}_{-0.2}$
BLNP	$4.3 \pm 0.3^{+0.2}_{-0.2}$	$4.3 \pm 0.2^{+0.2}_{-0.2}$	$4.0 \pm 0.2^{+0.2}_{-0.2}$
DGE	$4.4 \pm 0.3^{+0.1}_{-0.1}$	$4.4 \pm 0.2^{+0.1}_{-0.1}$	$4.2 \pm 0.2^{+0.3}_{-0.2}$
GGOU	$4.4 \pm 0.3^{+0.1}_{-0.1}$	$4.4 \pm 0.2^{+0.1}_{-0.1}$	$3.9 \pm 0.2^{+0.2}_{-0.2}$





The apex of the UT from the Moriond 2012 CKMFitter result is compared to the constraints from the new BABAR inclusive measurement as determined by the QCD calculation from [JHEP:0710:058], $A = 0.812 \pm 0.022$, and $\lambda = 0.22543 \pm 0.00095$. → other calculations in Backup

BaBar charmless overview:



III.a *New* $B \to h\,\ell\,\bar{\nu}_\ell$ measurement

[to be submitted]

At a glance:

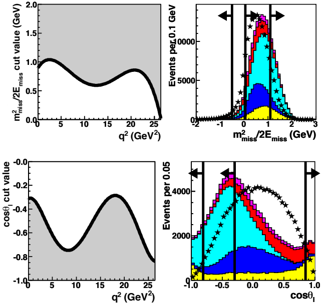
- Full *BaBar* dataset of 467.8×10^6 $B\bar{B}$
- $B \to h\,\ell\,\bar{\nu}_\ell$ with $h = \pi, \eta, \eta', \omega$
- Untagged; loose neutrino reconstruction
- $q^2 = (p_B - p_h)^2$, p_B from average over directions; resolution unfolded
- q^2 dependent selection $\to$ Figure
- Binned LH Fit in $\Delta E - m_{ES} - q^2$:

  $h = \pi$: Signal in 12 bins of q^2; Bkg in two bins of q^2

  $h = \omega$: Signal in 5 bins of q^2; Bkg in one q^2 bin

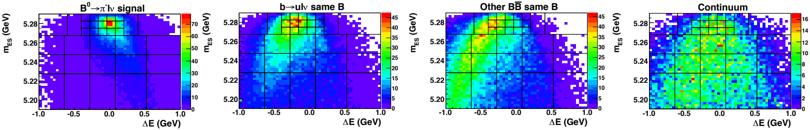
  $h = \eta$: Signal in 5 bins of q^2; fixed or in one q^2 bin

  $h = \eta'$: Signal in 1 bins of q^2; Bkg fixed



cuts(q^2) for $MM^2/(2E_{miss})$ and the cosine of the lepton helicity angle $\cos\theta_l$. The shaded region is excluded.

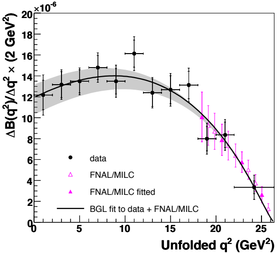
- $\Delta E - m_{ES}$ Signal & Background PDFs :

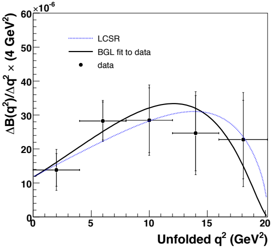


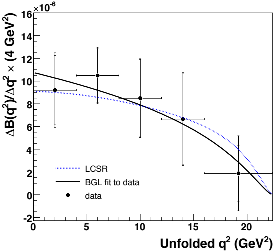
III.b *New* $B \to h\,\ell\,\bar{\nu}_\ell$ measurement

[to be submitted]

$\Delta\mathcal{B}(B \to \pi\,\ell\,\bar{\nu}_\ell)/\Delta q^2$; $\Delta\mathcal{B}(B \to \omega\,\ell\,\bar{\nu}_\ell))/\Delta q^2$; $\Delta\mathcal{B}(B \to \eta\,\ell\,\bar{\nu}_\ell))/\Delta q^2$







$|V_{ub}|$ from $B \to \pi\,\ell\,\bar{\nu}_\ell$ two methods:

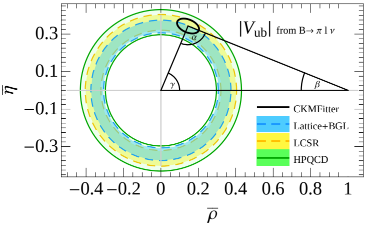
a Sum rule or lattice based QCD prediction of decay rate:

	q^2/GeV^2	$\lvert V_{ub}\rvert \times 10^3$
[PRD:73074502]	> 16	$\mathbf{3.47 \pm 0.13^{+0.60}_{-0.39}}$
[PRD:830904021]	< 12	$\mathbf{3.46 \pm 0.10^{+0.37}_{-0.32}}$
[arXiv:1203.1359]	0	$\mathbf{3.34 \pm 0.11^{+0.29}_{-0.26}}$

b Combined lattice and data fit of whole q^2 range with model independent form factor parametrization:

$$|V_{ub}| = \mathbf{3.25 \pm 0.31} \times 10^{-3}$$

[PRD:56303],[PRD:80034026],[PRD:79054507]



[CKM Fitter Moriond 2012]

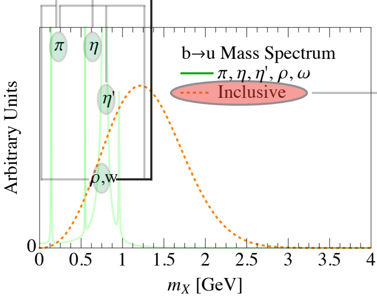
BaBar charmless overview:

new result
[to be submitted]

shown last ICHEP
[PRD:83032007]

new result
[arXiv:1205.6245],

new result
[to be submitted]



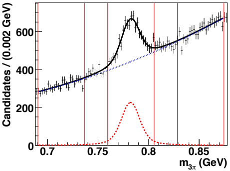
new result
[arXiv:1112.0702]

III.c *New* $B \to \omega\,\ell\,\bar{\nu}_\ell$ measurement

[arXiv:1205.6245]

At a glance:

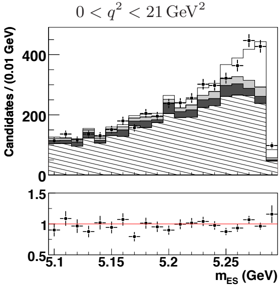
- Full BaBar dataset of 467.8×10^6 $B\bar{B}$
- Untagged $B \to \omega\,\ell\,\bar{\nu}_\ell$; loose neutrino reconstruction.
- $q^2 = (p_\ell + p_{\rm miss})^2$
- Neural Network based selection to suppress continuum and $B \to X_c\,\ell\,\bar{\nu}_\ell$
- $B\bar{B}$ comb. Bkg from ω-mass sideband

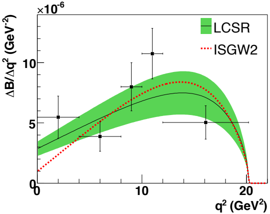


- Binned LH Fit in $\Delta E - m_{ES} - q^2$ (→ Plot)

	$q^2\,/\,\mathrm{GeV}^2$	$\lvert V_{ub}\rvert \times 10^3$
[PRD:71014029]	< 12	$\mathbf{3.41 \pm 0.28 \pm 0.38}$

Signal in 5 bins of q^2; $B\bar{B}$ Bkg with true ω in 5 bins of q^2





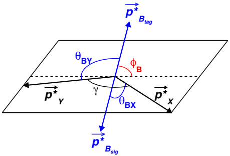
Fitted m_{ES} and q^2 spectrum

III.c *New* $B \to \omega\,\ell\,\bar{\nu}_\ell$ measurement

At a glance:

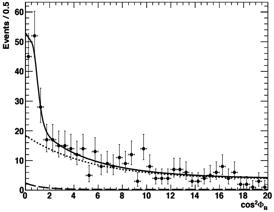
[to be submitted]

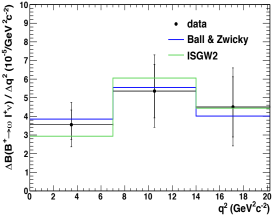
- Full *BaBar* dataset of 467.8×10^6 $B\bar{B}$
- Tagged measurement of $B \to \omega\,\ell\,\bar{\nu}_\ell$
- Partial reconstruction of secondary B meson kinematic via $B \to D^{(*)}\,\ell\,\bar{\nu}_\ell$
- Kinematics of B-mesons inferred from beam constraints + $D^{(*)}\,\ell$ and $\omega\,\ell$ candidates
- $q^2 = (p_B - p_\omega)^2$, meas. in B rest frame.
- Binned LH fit in $\cos\phi_B^2 - q^2$:



$\cos\phi_B$: angle of tag B 3-momentum and the plane spanned by the $D^{(*)}(n\,\pi)\,\ell$ and $\omega\,\ell$ 3-momenta

	q^2/GeV^2	$\lvert V_{ub}\rvert \times 10^3$
[PRD:71014029]	full	**3.39 ± 0.32 ± 0.65**





Fitted $\cos\phi_B$ and q^2 spectrum

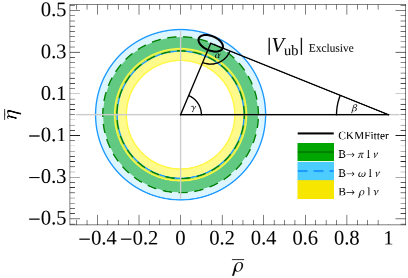
IV. Comparison of $|V_{ub}|$ from both approaches

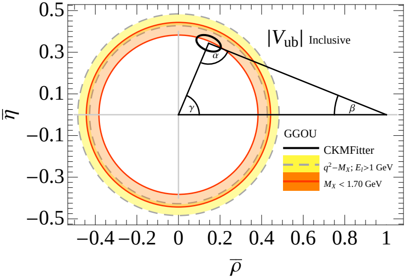
I. Good agreement between $|V_{ub}|$ from different exclusive measurements.

Unquenched Lattice predictions for form factors for $B \to \omega\, \ell\, \bar{\nu}_\ell$ and $B \to \rho\, \ell\, \bar{\nu}_\ell$ highly desirable, considerable width of ρ might make the ω easier target.

II. Tension between exclusive vs inclusive $|V_{ub}|$

Many ideas floating in the room: poorly understood QCD ($\to$ **SIMBA**), new physics (e.g. right-handed currents), poorly understood backgrounds (e.g. $B \to X_c\, \ell\, \bar{\nu}_\ell$ which has its own mysteries), experimental uncertainties underestimated, etc.





$|V_{ub}|$ from the combined data-lattice fit from page X for $B \to \pi\, \ell\, \bar{\nu}_\ell$ is compared to the values for $B \to \omega\, \ell\, \bar{\nu}_\ell$ and $B \to \rho\, \ell\, \bar{\nu}_\ell$ determined using the Sum rule calculation of [PRD:71014029]; The right-hand side shows the inclusive result from page Y for two phase-space regions and using the QCD calculation from [JHEP:0710:058].

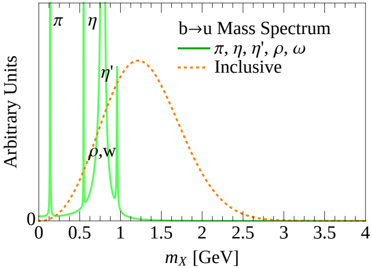
V. Summary: The status of charmless decays and $|V_{ub}|$

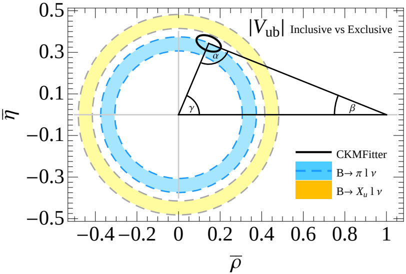
I. Measurements using the full *BABAR* dataset for 4 exclusive modes

Understand what makes up $\approx 44\%$ of the inclusive $B \to X_u \ell \bar{\nu}_\ell$ spectra for $m_X < 1.55$ GeV

II. Inclusive $b \to u \ell \bar{\nu}_\ell$ measurement using the full *BABAR* dataset

Tension between inclusive and exclusive values of $|V_{ub}|$ remain:





Inclusive $|V_{ub}|$ from [arXiv:1112.0702] from GGOU with $q^2 - m_X$ fit with $E_l^* > 1.0$ GeV is compared with the combined $B \to \pi \ell \bar{\nu}_\ell$ data-lattice fit from slide 10. The CKMFitter result is from Moriond 2012 result.

Future plans at *BABAR* : tagged $B \to \rho \ell \bar{\nu}_\ell$; $B \to h\bar{h} \ell \bar{\nu}_\ell$ with $h = p, K, pi, \ldots$
Studies for a better understanding of exclusive $b \to c \ell \bar{\nu}_\ell$ background.

Backup

A.a Motivation

Flavor sector of Standard Model (SM):

$$\mathcal{L} = \frac{g_2}{\sqrt{2}} W_\mu^+ \, \bar{u}'_L \, \gamma^\mu \, V_{\text{CKM}} \, d'_L + \text{h.c.}$$

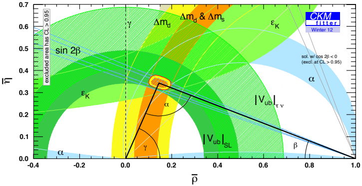
V_{CKM} couples Weak and Mass eigenstates

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$V_{\text{CKM}} \, V_{\text{CKM}}^\dagger = 1 \to 6$ triangle equations, e.g.

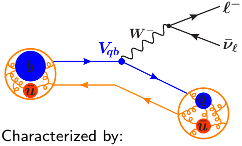
Unitary triangle: $V_{ud} V_{ub}^* + V_{td} V_{tb}^* + V_{cd} V_{cb}^* = 0$

Complex phase of V_{CKM}: $(\bar{\rho} + i\bar{\eta})$



[CKMFitter Moriond 2012 result]

Semileptonic $b \to q$ decays:



Characterized by:

$q^2 = (p_B - p_X)^2 = (p_\ell + p_{\bar{\nu}})^2$

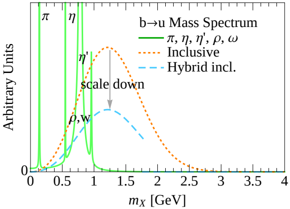
m_X: Invariant hadronic mass

θ: Angular variables

Decay rate for $b \to u \, \ell \, \bar{\nu}_\ell$:

$$d\Gamma \propto |V_{ub}|^2 \times \left| \mathcal{A}(q^2, \theta) \right|^2 \, dq^2 \, d\theta \, (dm_X)$$

m_X-Spectrum: Inclusive vs Exclusive states



⇒ 'Hybrid' simulation of $b \to u \, \ell \, \bar{\nu}_\ell$

⇒ Amplitudes can be predicted using QCD; fairly independent approaches for Inclusive vs Exclusive

A.b Experimental Methods

Reconstruction of q^2:

$$q^2 = (p_B - p_X)^2$$
$$= (p_\ell + p_{\text{miss}})^2$$

→ Tagged: full or partial reconstruct second B-meson:

$$p_B = \left(E_{B_{tag}}, -\vec{p}_{B_{tag}}\right)$$

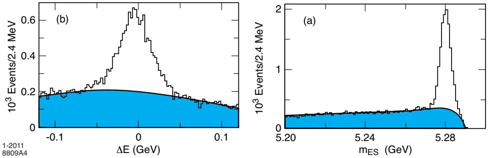
Incl.: p_X from $\sum$ over recoil side particles
Excl.: $p_X = p_h$ from $h = \pi, \ldots$ candidate

→ Untagged: average over unknown direction of B-meson using beam constraints

or p_ℓ + missing 4-momentum p_{miss} of event.

Isolation of signal decays:

$\Delta E = E_B^* - E_{\text{beam}}^*$ $\qquad$ $m_{ES} = \sqrt{E_{\text{beam}}^{*2} - \vec{p}_B^{*2}}$:



$\left(E_B^*, \vec{p}_B^{*2}\right) = p_X + p_\ell + p_{\text{miss}}$; $^* = \Upsilon(4S)$ rest frame;
E_{beam}^* beam energy

Loose neutrino reconstruction:

(used in untagged)

Infer neutrino kinematics from missing 4-momentum:

$$(E_{\text{miss}}, \vec{p}_{\text{miss}}) = (E_{\text{beam}}, \vec{p}_{\text{beam}}) - \sum_i (E_i, \vec{p}_i)$$

sum runs over reconstructed particles from all charged tracks and unmatched calorimeter clusters in event.

Missing mass squared $MM^2 = E_{\text{miss}}^2 - |\vec{p}_{\text{miss}}|^2$
→ $MM^2/(2E_{\text{miss}})$ has better resolution
→ Multivariate techniques (NN); cut; or cut(q^2)

Other Backgrounds

$e^+ e^- \to q\bar{q}$ cuts or NN; validation with off-resonance
$e^+ e^- \to b\bar{b}$ cuts or NN; validation with sidebands

→ Semileptonic $b \to c\, \ell\, \bar{\nu}_\ell$

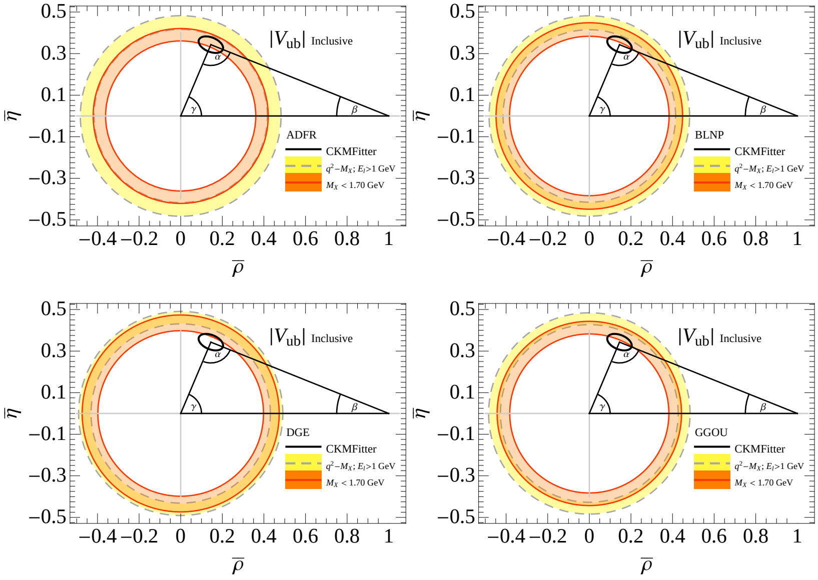
$50 - 500\ \times$ more abundant than signal decays

$m_X > 1.85$; lower lepton energy endpoint

Measurements in phase space regions where $b \to c$ strongly suppressed or forbidden

→ inclusive decays: model dependence due to unknown parton distribution function

B.a New inclusive $|V_{ub}|$ gallery



B.b New inclusive $|V_{ub}|$ gallery