$|V_{ub}|$, $|V_{cb}|$ and m_b from Inclusive B Decays

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Flavor Physics and New Physics

Central questions for Flavor Physics

- Does the SM (weak interactions and CKM mechanism) describe all existing flavor changing interactions?

  Expect New Flavor Physics

  - ⋆ SM does not explain hierarchies in masses and CKM mixing angles
  - ⋆ SM CP violation insufficient to explain observed baryon asymmetry
    - Does not strictly need new flavor physics
  - ⋆ Most SM extensions have new sources of flavor and CP violation

- What can we learn about flavor structure of New Physics?

  Important complement to direct and other indirect searches

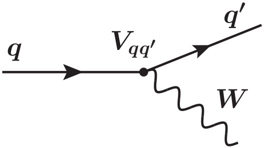
  - ⋆ New Physics with generic flavor structure strongly constrained

$$\frac{(s\bar{d})^2}{\Lambda_{\mathrm{FV}}^2}, \frac{(d\bar{b})^2}{\Lambda_{\mathrm{FV}}^2} \qquad \Rightarrow \qquad \Lambda_{\mathrm{FV}} \gtrsim 10^{4,3}\,\mathrm{TeV} \gg \Lambda_{\mathrm{NP}} \lesssim \mathrm{TeV}$$

  - ⋆ Distinguish (classes of) models (e.g. SUSY breaking mechanism)

CKM Matrix and the Unitarity Triangle

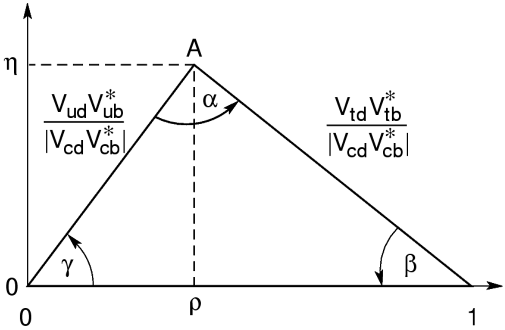
- Quarks: mass eigenstates $\neq$ weak eigenstates
- Mixing described by CKM matrix:



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

Unitarity:

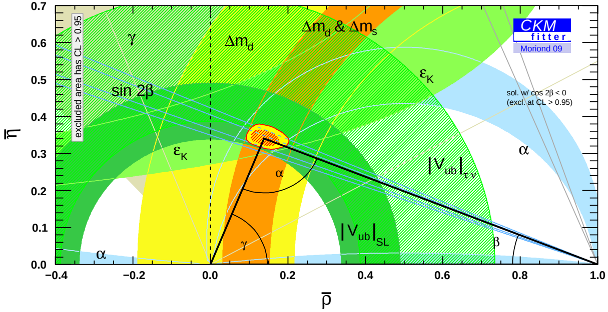
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



Test consistency of CKM picture by overconstraining with measurements in K and $B_{(s)}$ decays

Why Care About $|V_{ub}|$ and $|V_{cb}|$?

- New Physics expected to show up in rare processes
  - ⋆ Flavor changing neutral currents: neutral meson mixing, rare decays
  - ⋆ CP violation
- Overconstraining SM flavor sector constrains New Physics
  - ⋆ Compare tree-level (NP insensitive) processes ($|V_{xb}|$) to loop (NP sensitive) processes ($\sin 2\beta$)



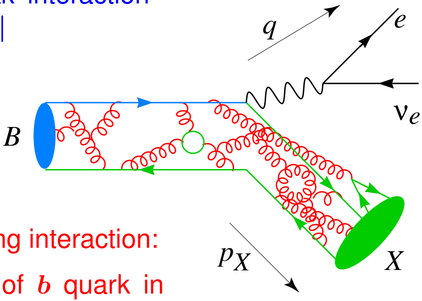
$|V_{ub}|$ and $|V_{cb}|$:

- $|V_{ub}|/|V_{cb}|$ determines side opposite β
- $|V_{cb}|$ enters ϵ_K constraint as $|V_{cb}|^4$

Semileptonic B Meson Decays

- Quark levels decays: $b \to c\ell\nu$ and $b \to u\ell\nu$
- Hadronic decays: $B \to X_c\ell\nu$ and $B \to X_u\ell\nu$

Study weak interaction
$|V_{cb}|$, $|V_{ub}|$



Study strong interaction:

Dynamics of b quark in B meson

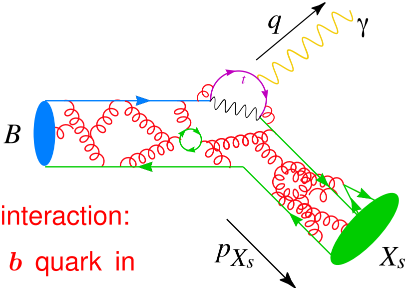
$\to$ "B meson PDF", nonperturbative parameters

$\to$ b-quark mass

Radiative Penguin B Meson Decays

- Quark levels decays: $b \to s\gamma$
- Hadronic decays: $B \to X_s\gamma$

Sensitive to New Physics
(loop process)



Study strong interaction:

Dynamics of b quark in B meson

→ "B meson PDF", nonperturbative parameters

→ b-quark mass

→ Study in $B \to X_s\gamma$ and use for $|V_{ub}|$

Inclusive vs Exclusive Measurements: Techniques

- Rate factorizes into hadronic and leptonic subprocesses

$$\Gamma = G_F^2 |V_{xb}|^2 m_b^5 |L_\mu|^2 |\langle X | J_L^\mu | B \rangle|^2$$

Exclusive	Inclusive
Reconstruct specific final state $|V_{cb}|$: $X = D^*, (D)$ $|V_{ub}|$: $X = \pi, (\rho)$	Sum over all X
Parametrize $\langle D^* | J_L^\mu | B \rangle$, $\langle \pi | J_L^\mu | B \rangle$, ...	Perform Operator Product Expansion (HQE) in $1/m_b$
Different form factors $f_i(q^2)$ Lattice QCD, QCD sum rules, Measurements	Universal nonpert. parameters: Measure in $B \to X \ell \nu$ and $B \to X_s \gamma$

- $\mathcal{B}(B \to X_c \ell \nu) \approx 50 \times \mathcal{B}(B \to X_u \ell \nu) \Rightarrow$ Large background in $|V_{ub}|$ analyses

Inclusive vs Exclusive Measurements: Results

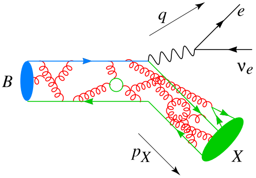
Small but persistent systematic difference between inclusive and exclusive $|V_{cb}|$ and $|V_{ub}|$ determinations

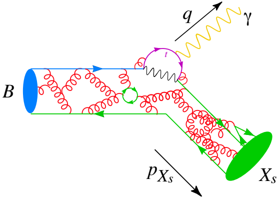
Inclusive SCET:	$10^3|V_{ub}|_{\mathrm{BLNP}} = 4.06 \pm 0.15_{[\mathrm{exp}]}\ {}^{+0.25}_{-0.27}{}_{[\mathrm{theory}]}$
Inclusive OPE:	$10^3|V_{ub}|_{\mathrm{BLL}} = 4.87 \pm 0.24_{[\mathrm{exp}]} \pm 0.38_{[\mathrm{theory}]}$
Exclusive:	$10^3|V_{ub}|_{B\to\pi\ell\nu} = 3.34 \pm 0.12_{[\mathrm{exp}]}\ {}^{+0.55}_{-0.37}{}_{[\mathrm{lattice}]}$
Leptonic:	$10^3|V_{ub}|_{B\to\tau\nu} = 5.2 \pm 0.5_{[\mathrm{exp}]} \pm 0.4_{[f_B]}$

Inclusive OPE:	$10^3|V_{cb}|_{\mathrm{kinetic}} = 41.31 \pm 0.50_{[\mathrm{exp}]} \pm 0.58_{[\mathrm{theory}]}$
Exclusive:	$10^3|V_{cb}|_{\mathrm{B\to D^*}\ell\nu} = 38.3 \pm 0.5_{[\mathrm{exp}]} \pm 1.0_{[\mathrm{lattice}]}$
Exclusive:	$10^3|V_{cb}|_{\mathrm{B\to D}\ell\nu} = 39.1 \pm 1.4_{[\mathrm{exp}]} \pm 0.9_{[\mathrm{lattice}]}$

Fluctuation? Problems with measurements or theory? New Physics?

Inclusive B Meson Decays





Inclusive decay rate can be systematically calculated

$$\Gamma_{x\ell\nu} \propto |V_{xb}|^2 m_b^5 \left[A - B\frac{\mu_\pi^2}{m_b^2} - C\frac{\mu_G^2}{m_b^2} + \mathcal{O}(\frac{1}{m_b^3}) \right]$$

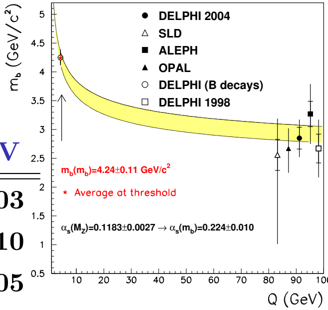
$$\mathrm{d}\Gamma_{s\gamma}/\mathrm{d}E_\gamma \propto |V_{tb}V_{ts}^*|^2 m_b^2 E_\gamma^3 \left[F(m_B - 2E_\gamma) + \mathcal{O}(\Lambda_{\mathrm{QCD}}/m_b) \right] + \ldots$$

- Moments of differential decay distributions of $B \to X_{c,u}\ell\nu$, $B \to X_s\gamma$
  - ⋆ Only depend on m_b and same universal nonperturbative parameters ($\longrightarrow$ dynamics of b in B)
  - ⋆ $\mu_\pi^2 \propto$ kinetic energy of b quark in B
  - ⋆ $\mu_G^2 \propto$ chromomagnetic moment of b in B ($B - B^*$ mass splitting)
  - ⋆ Moments of F given by nonperturbative parameters

Determinations of the b-Quark Mass

- Confinement makes mass definition difficult
- Pole mass yields ill-converging expansions
- Different renormalization schemes used
  - ⋆ Here: kinetic scheme, 1S scheme

Year	Method and Scheme		m_b^{1S} / GeV
2007	spectral sum rules	$\overline{\mathrm{MS}}$	4.64 ± 0.03
2001	$\Upsilon(1S)$ system	1S	4.69 ± 0.10
2007	lattice QCD		4.83 ± 0.05
2006	3 jet evts (Z, DELPHI)	$\overline{\mathrm{MS}}$	4.66 ± 0.45
2005	HQE fit (DELPHI)	$\overline{\mathrm{MS}}$	4.82 ± 0.20
2002	HQE fit (CLEO)	1S	4.82 ± 0.13
2004	HQE fit (BABAR)	kin	4.72 ± 0.07
2006	HQE fit (Belle)	1S	4.73 ± 0.05
2004	global fit (Bauer et al.)	1S	4.68 ± 0.03

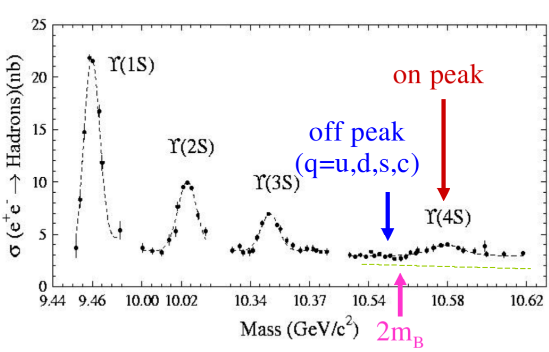


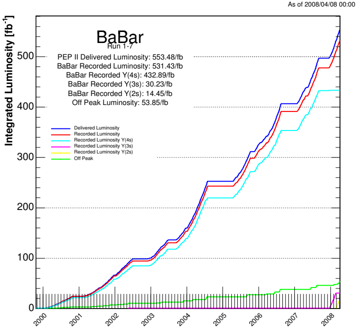
HQE = Heavy Quark Expansion

[PDG 2009]

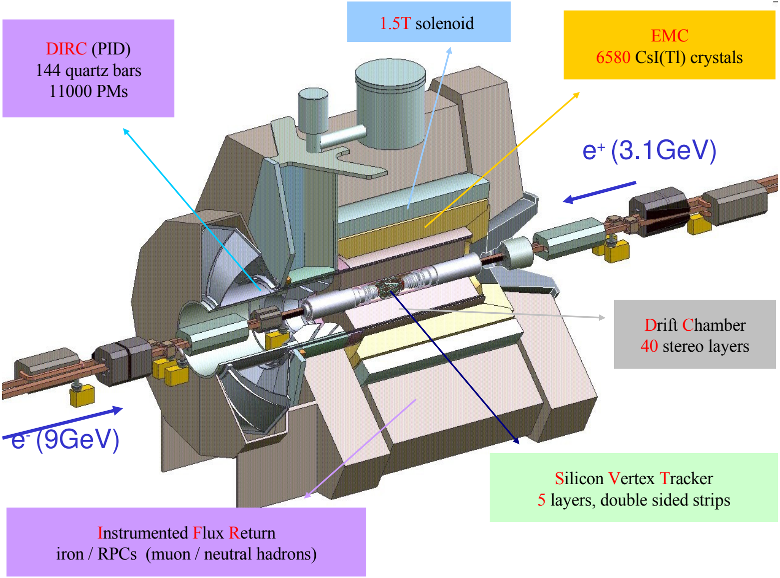
The *BaBar* Experiment

- PEP-II is "asymmetric B-factory":
  - ⋆ $e^-(9\,\mathrm{GeV})e^+(3.1\,\mathrm{GeV}) \to \Upsilon(4S) \to B\bar{B}$
  - ⋆ Collected $\sim 433\,\mathrm{fb}^{-1}$ (475 million $B\bar{B}$) between 1999 and 2007
- Data taking at $\Upsilon(3S)$ and $\Upsilon(2S)$ in 2008 (140 million each)
  - ⋆ Bottomoniom spectroscopy and searches for rare decays





The BABAR Detector



Particle Reconstruction and Identification

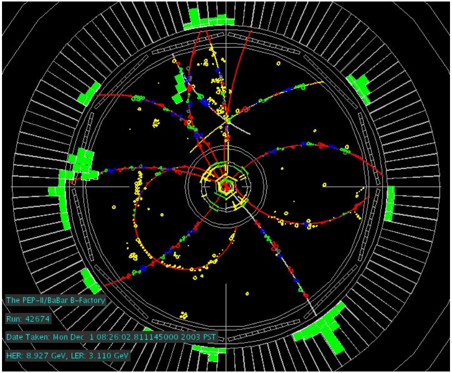
Charged Particles

- Silicon Vertex Tracker (SVT)
  - ⋆ Vertexing and low momentum tracking
- Drift Chamber (DCH)
  - ⋆ Main tracking system, momentum measurement for charged particles with $p_T > 100\,\mathrm{MeV}$

(Charged and) Neutral Particles

- Electromagnetic Calorimeter (EMC)
  - ⋆ Neutral Particle: EMC cluster not matching any track

Angular Coverage 91% in CMS



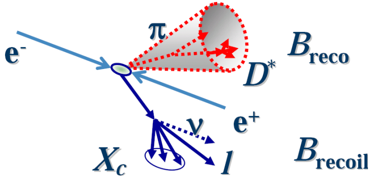
- Kaon and Lepton ID:
  - ⋆ dE/dx in SVT and DCH
  - ⋆ Cherenkov angle
- e: Shower shape, energy in EMC
- μ: Instrumented Flux Return

Analyses on the Recoil

- Hadronic decay of non-signal B fully reconstructed: $B_{\mathbf{reco}} \to D^{(*)}Y$

  $Y = n_1 K^{\pm} + n_2 K_S + n_3 \pi^{\pm} + n_4 \pi^0$

  - ⋆ Low efficiency, $\epsilon \approx 0.3\%$
  - ⋆ Inclusive measurement of X system (with good resolution)
  - ⋆ Measure kinematic quantities in B rest frame
  - ⋆ Charge and flavor determined

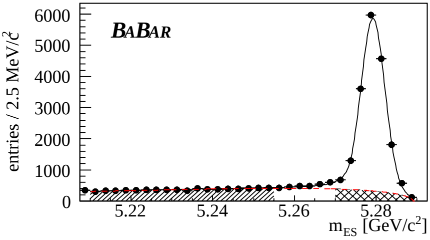


Backgrounds:

- Combinatorial $B_{\mathbf{reco}}$
- Continuum: $e^+e^- \to q\bar{q}$, $q = u, d, s, c$

Energy-substituted mass:

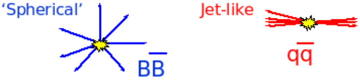
$$m_{\mathbf{ES}} = \sqrt{E^2_{\mathbf{beam}} - \vec{p}^2_B}$$



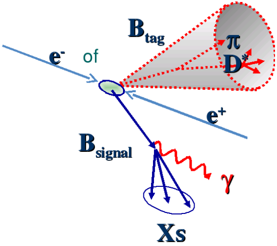
$B \to X_s\gamma$: Analysis

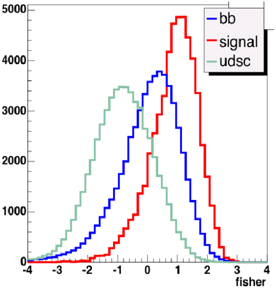
232M $B\bar{B}$ [BABAR, Phys. Rev. D **77** 051103 (2008)]

- Events tagged by hadronic B decay
- Well reconstructed high energy photon $E_\gamma > 1.3\,\mathrm{GeV}$
  - ⋆ Photon energy measured in B rest frame
- Veto γ compatible with π^0, η, ρ decays
- Suppress continuum with Fisher discriminant (mostly event shape variables)
  - ⋆ $B\bar{B}$ isotropic vs. light $q\bar{q}$ jetty

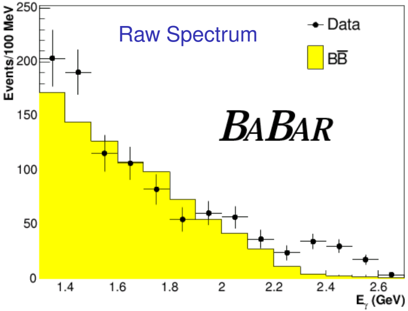


- Subtract B_{reco} combinatorial and remaining continuum background in bins of E_γ

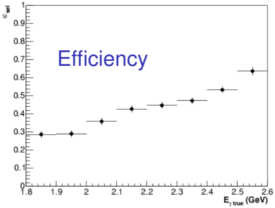




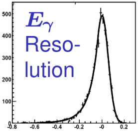
$B \to X_s\gamma$: The E_γ Spectrum

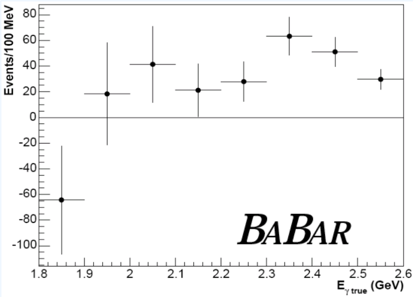


- $E_\gamma < 1.9\,\mathrm{GeV}$ for background control
- Main background γ from π^0 decays
- 119 ± 22 $B \to X\gamma$ signal decays for $E_\gamma > 1.9\,\mathrm{GeV}$



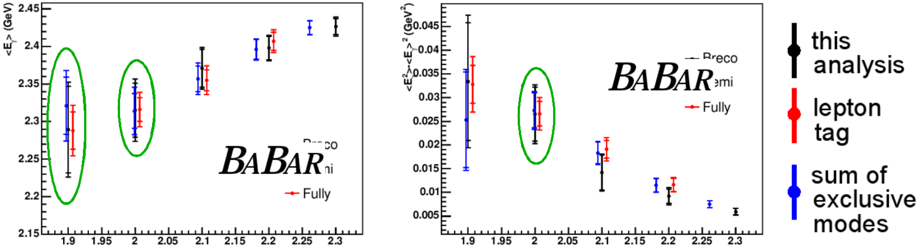
Efficiency and resolution $\Longrightarrow$ Correction





$B \to X_s\gamma$: Moments and HQE Fits

$\langle E_\gamma \rangle (\mathrm{GeV})$ $\quad\quad$ $\langle E_\gamma^2 \rangle - \langle E_\gamma \rangle^2 (\mathrm{GeV}^2)$



$E_\gamma^{\min} / \mathrm{GeV}$ $\quad\quad$ $E_\gamma^{\min} / \mathrm{GeV}$

- Consistency between measured moments in different analyses
- Limited by statistics
- Much cleaner environment leads to potential for reduced systematics

$$m_b^{\mathrm{kin}} = (4.46^{+0.21}_{-0.23})\,\mathrm{GeV}$$

$$\mu_\pi^{2\mathrm{kin}} = (0.64^{+0.39}_{-0.38})\,\mathrm{GeV}^2$$

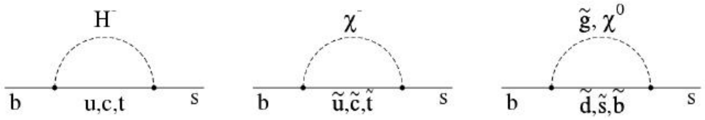
$$\rho = -0.94$$

$$\mathcal{B}(E_\gamma > 1.9\,\mathrm{GeV}) = (3.65 \pm 0.85_{[\mathrm{stat}]} \pm 0.60_{[\mathrm{syst}]}) \times 10^{-4}$$

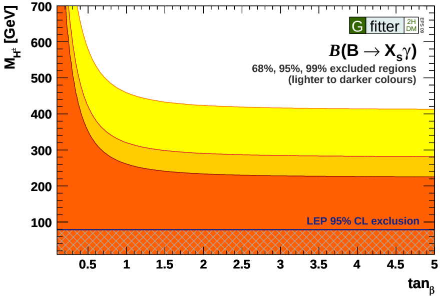
$\to$ in agreement with SM prediction (need extrapolation to $E_\gamma > 1.6\,\mathrm{GeV}$)

$B \to X_s\gamma$: Searching for New Physics

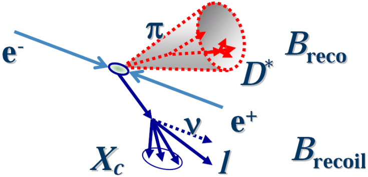
- Flavor-changing neutral current
  - $\Rightarrow$ New Physics can appear at same order as SM process



- $B \to X_s\gamma$ BF constrains parameter space of beyond SM models
- New Physics can change rate
  - ⋆ E_γ distribution determined by low energy physics



$B \to X_c \ell \nu$: Analysis

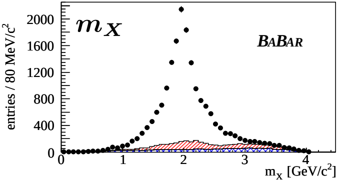


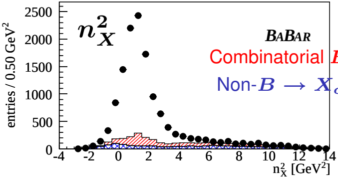
- Events tagged by hadronic B decay
- Require exactly 1 lepton (e, μ) in recoil with energy $E_\ell > 0.8\,\mathrm{GeV}$ in B rest frame

[arXiv:0908.0415]

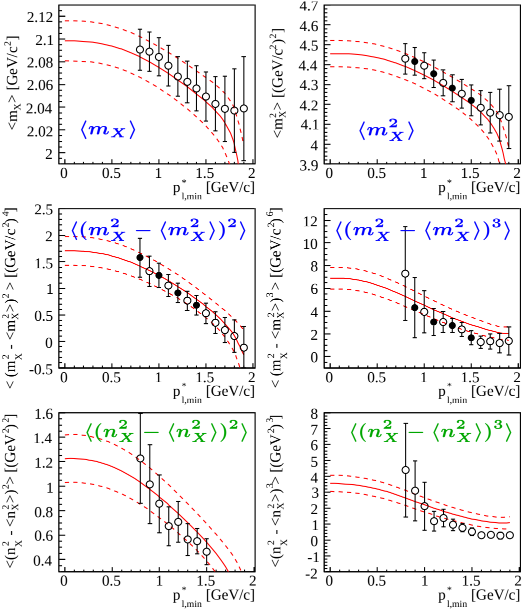
232M $B\bar{B}$

- Remaining charged and neutral particles form inclusive X_c system
- Measure moments of hadronic mass m_X and mixed mass-and-energy moments $n_X = m_X^2 c^4 - 2\bar{\Lambda}E_X + \bar{\Lambda}^2$
  - ⋆ $\bar{\Lambda} = 0.65\,\mathrm{GeV}$
- Improve resolution with kinematic fit
  - ⋆ Energy-momentum conservation
  - ⋆ $E_{\mathrm{miss}}, p_{\mathrm{miss}}$ consistent with ν





$B \to X_c \ell \nu$: Measurement of Moments



As function of lower cut on $E_{\ell,\gamma}$

- Moments in m_X, n_X, E_ℓ
- Partial BF
- $B \to X_s \gamma$ E_γ moments

[BABAR, Phys. Rev. D **72**, 052004 (2005), Phys. Rev. Lett. **97** 171803 (2006), Phys. Rev. D **77** 051103 (2008)]

Fit to predictions from Heavy Quark Effective Theory

- ● Included in fit
- ○ Not included in fit

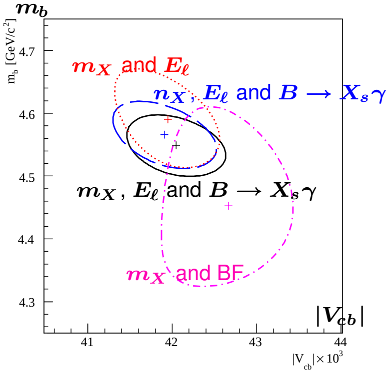
$B \to X_c \ell \nu$: Moments and HQE Fit

- Global *BaBar*-HQE fit
  - ⋆ Mass moments
  - ⋆ E_ℓ moments and BFs
  - ⋆ E_γ moments
  - ⋆ B lifetime τ_B

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

	m_b / GeV	m_c / GeV	μ_π^2 / GeV^2
	4.55	1.08	0.48
σ(exp)	0.03	0.04	0.02
σ(theo)	0.04	0.06	0.06
σ(tot)	0.05	0.07	0.06

(kinetic scheme, $\mu = 1\,\mathrm{GeV}$)



Determine

$\mathcal{B}(B \to X_c \ell \nu) = (10.64 \pm 0.17 \pm 0.06)\%$

$m_b^{\mathrm{kin}} = (4.55 \pm 0.03 \pm 0.04)\ \mathrm{GeV}$

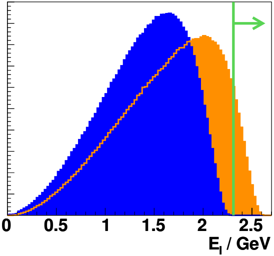
and use τ_B

$\Rightarrow |V_{cb}| = (42.05 \pm 0.45 \pm 0.70) \times 10^{-3}$

$B \to X_u \ell \nu$: Challenges

Experimental challenge

- Background from $B \to X_c \ell \nu \approx 50\times$ signal
- Use kinematics to suppress background
  - ⋆ Hadronic mass m_X, lepton energy E_ℓ
  - ⋆ $P_+ = E_X - p_X$, Dilepton mass q^2

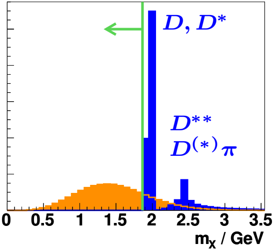


Theory challenge

- Expansion breaks down in endpoint region

⇒ Enhanced dependence on m_b

⇒ Need nonperturbative shape function ("B PDF")
  - ⋆ Describes dynamics of b in B
  - ⋆ To leading order given by E_γ spectrum in $B \to X_s \gamma$
  - ⋆ Several more function at subleading order ($\mathcal{O}(1/m_b)$)
  - ⋆ Moments given by m_b, μ_π^2, ...

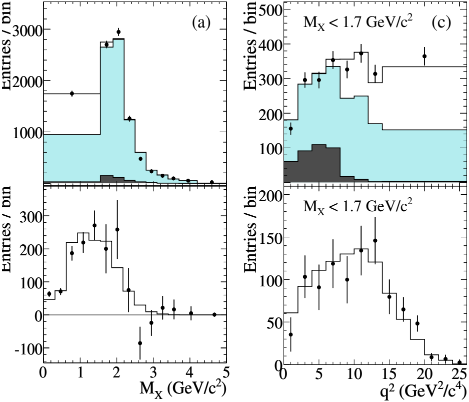


(Ideal resolution, not to scale)

$B \to X_u \ell \nu$: Analysis

- Hadronic tags to improve resolution and background suppression
- Require exactly 1 lepton (e or μ) with $E_\ell > 1\,\mathrm{GeV}$
- Veto events with $K^\pm$, K_S and partially reconstructed $D^{*\pm}$
- Different kinematic cuts to test consistency
  - ⋆ $m_X < 1.55\,\mathrm{GeV}$
  - ⋆ $m_X < 1.7\,\mathrm{GeV}$, $q^2 > 8\,\mathrm{GeV}^2$
  - ⋆ $P_+ < 0.66\,\mathrm{GeV}$

m_X q^2



$B \to X_c \ell \nu$

$B \to X_u \ell \nu$ (outside signal region)

383M $B\bar{B}$ [arXiv:0708.3702]

$B \to X_u \ell \nu$: $|V_{ub}|$ Results

Method	N_u	$|V_{ub}| \times (10^3)$
m_X	803 ± 60	$4.27 \pm 0.16 \pm 0.13 \pm 0.30$
		$4.56 \pm 0.17 \pm 0.14 \pm 0.32$
P_+	633 ± 63	$3.88 \pm 0.19 \pm 0.16 \pm 0.28$
		$3.99 \pm 0.20 \pm 0.16 \pm 0.24$
m_X, q^2	562 ± 55	$4.57 \pm 0.22 \pm 0.19 \pm 0.30$
		$4.64 \pm 0.23 \pm 0.19 \pm 0.25$
		$4.93 \pm 0.24 \pm 0.20 \pm 0.36$

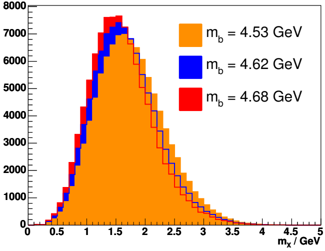
[Bosch, Neubert and Paz, JHEP **0411**, 073 (2004)]

[Andersen and Gardi, JHEP **0601**, 097 (2006)]

[Bauer, Ligeti and Luke, Phys. Rev. D **64**, 113004 (2001)]

- $\approx 9\%$ uncertainty for a single measurement
- $|V_{ub}|$ based on $P_+ \approx 2.5\sigma$ lower than other measurements
- Dominant uncertainty from knowledge of m_b
  - ⋆ Use m_b from $B \to X_c \ell \nu$ and/or $B \to X_s \gamma$
- Uncertainty from assumed functional form of shape function

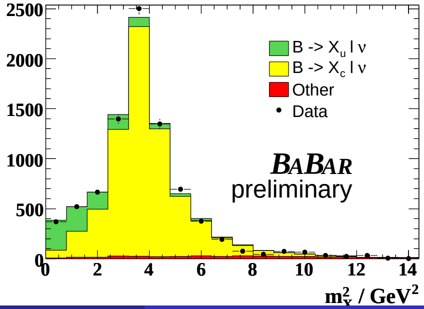
$B \to X_u \ell \nu$: Hadronic Mass Spectrum (I)



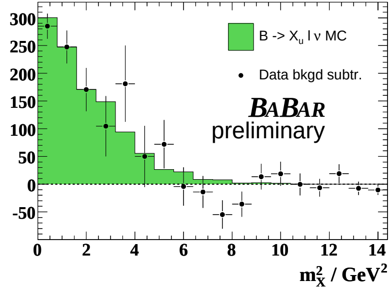
- Spectrum (directly) sensitive to m_b and shape function
  - ⋆ Best sensitivity in $B \to X_c \ell \nu$ to $m_b - m_c$
- Determine m_b, μ_π^2, ... in the same mode as $|V_{ub}|$ as test of theory

383M $B\bar{B}$ [arXiv:0801.2985]

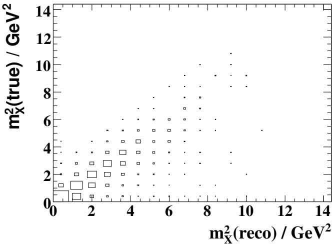
- Hadronic tags, lepton $E_\ell > 1\,\mathrm{GeV}$
- $B \to X_c \ell \nu$ background suppression: veto events with $K^\pm$, K_S andpartially reconstructed $D^{*\pm}$
- Subtract remaining $B \to X_c \ell \nu$ and non-semileptonic backgrounds



$B \to X_u \ell \nu$: Hadronic Mass Spectrum (II)



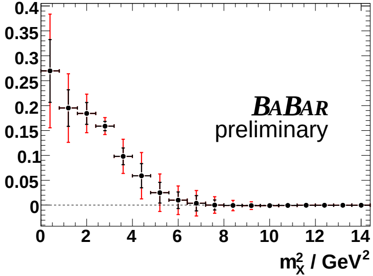
- 1027 ± 176 signal events
- Unfold spectrum for detector acceptance, efficiency and resolution
- Significant bin-by-bin correlations due to unfolding



Efficiency and Resolution Correction

$\Longrightarrow$

[Höcker, Kartvelishvili, Nucl.Instrum.Meth. A **372**, 469-481 (1996)]



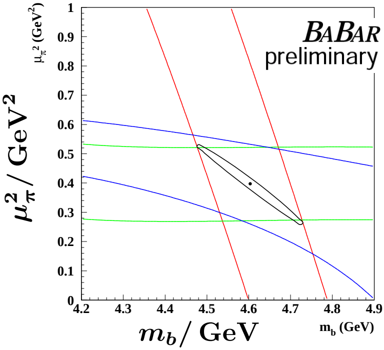
$B \to X_u \ell \nu$: Moments and HQE Fit

- Extract mass moments with upper cut: $m_X^2 < 6.4\,\mathrm{GeV}^2$

Central Moments

$$M_1 = (1.96 \pm 0.34_{[\mathrm{stat}]} \pm 0.53_{[\mathrm{syst}]})\ \mathrm{GeV}^2$$
$$U_2 = (1.92 \pm 0.59_{[\mathrm{stat}]} \pm 0.87_{[\mathrm{syst}]})\ \mathrm{GeV}^4$$
$$U_3 = (1.79 \pm 0.62_{[\mathrm{stat}]} \pm 0.78_{[\mathrm{syst}]})\ \mathrm{GeV}^6$$

Highly correlated: $\rho_{12} = 0.99$, $\rho_{23} = 0.94$ and $\rho_{13} = 0.88$



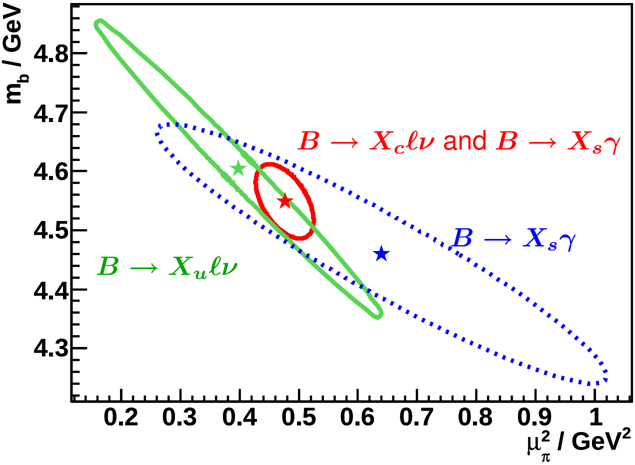
[Gambino, Ossola, Uraltsev, JHEP **0509**, 010 (2005)]

	$m_b /$ GeV	$\mu_\pi^2 /$ GeV^2
	4.604	0.398
σ(stat)	0.125	0.135
σ(syst)	0.193	0.195
σ(theo)	0.097	0.036
σ(tot)	0.250	0.240

(kinetic scheme, $\mu = 1\,\mathrm{GeV}$)

First measurement in $B \to X_u \ell \nu$
Consistent with $B \to X_c \ell \nu$

Compare Results in Different Modes



[arXiv:0801:2985]

[arXiv:0908.0415, Phys. Rev. D **72** 052004 (2005), Phys. Rev. Lett. **97** 171803 (2006), Phys. Rev. D **77** 051103 (2008)]

[Phys. Rev. D **77** 051103 (2008)]

- m_b and μ_π^2 extracted in different decay modes compatible
- m_b from $B \to X_s \gamma$ systematically lower

Strategy Towards Precision $|V_{ub}|$

Precision of inclusive $|V_{ub}|$ depends on

- How well we know m_b and SF and correlation between them
- Ability to (consistently) combine many different measurements
  - ⋆ Different kinematic cuts: E_ℓ, m_X, q^2, P_+

First, reduce SF uncertainties by incorporating all available information on it

- Perturbative constraints (perturbative tail and RGE)
- Moment constraints (m_b, $\lambda_1 \sim -\mu_\pi^2$ from $B \to X_c \ell \nu$)
- Shape information from $B \to X_s \gamma$ and $B \to X_u \ell \nu$ spectra

Then repeat success strategy of inclusive $|V_{cb}|$

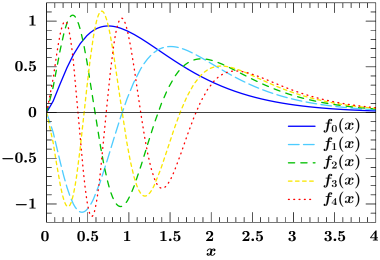
- Perform global fit to all available data
- Simultaneously determine $|V_{ub}|$ and inputs (m_b, SF)

  [Bernlochner, Lacker, Ligeti, Stewart, F Tackmann, KT (work in progress)]

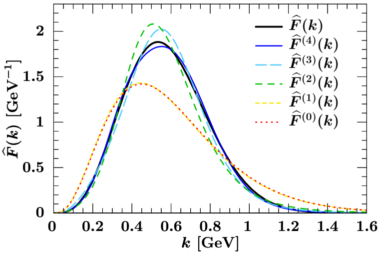
SIMBA - Analysis of B-Meson Inclusive Spectra

Modeling the Shape Function

Basis



Expansion of Gaussian $\hat{F}(k)$



Design suitable orthonormal basis for $\hat{F}(k)$ (formally model independent)

$$\hat{F}(\lambda x) = \frac{1}{\lambda}\left[\sum_{n=0}^{\infty} c_n f_n(x)\right]^2 \qquad \text{with} \qquad \int \mathrm{d}k\, \hat{F}(k) = \sum_{n=0}^{\infty} c_n^2 = 1$$

- Builds an orthonormal basis on top of any given model function
- Keep terms up to $n \leq N$ as required by precision of data
- Experimental uncertainties and correlations can be properly captured by uncertainties and correlations in basis coefficients c_n

[Ligeti, Stewart, F Tackmann (2008)]

Setup for Global $|V_{ub}|$ Fit

Use expansion $\hat{F}(k) = \left[\sum_n c_n f_n(k)\right]^2$ in master formula and moments

$$\mathrm{d}\Gamma = |V_{ub}|^2 \sum_{n,m} c_n c_m K(E_\ell, P_\pm) \int \mathrm{d}k\, \widehat{W}_{\mathrm{pert}}(P_\pm, k) f_n(k) f_m(k)$$

$$M_j(m_b^{1S}, \lambda_1^{\mathrm{i}}) = \sum_{n,m} c_n c_m \int \mathrm{d}k\, k^j\, f_n(k) f_m(k)$$

Perform combined fit (similar to $|V_{cb}|$)

- $B \to X_u \ell \nu$ partial rates
  - ⋆ Normalization determines $|V_{ub}|$
- $B \to X_s \gamma$ and $B \to X_u \ell \nu$ spectra
  - ⋆ Shapes of distributions constrain $\hat{F}(k)$ through basis coefficients c_n
- Known moments of $\hat{F}(k)$
  - ⋆ Consistently combines existing constraints on m_b^{1S}, λ_1^{i} (from $B \to X_c \ell \nu$ or anywhere else) with $B \to X_u \ell \nu$ and $B \to X_s \gamma$ data

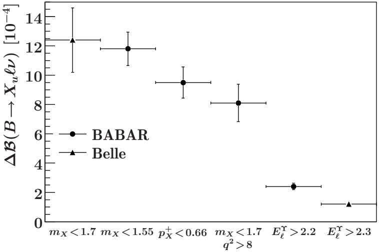
Proof-of-Concept

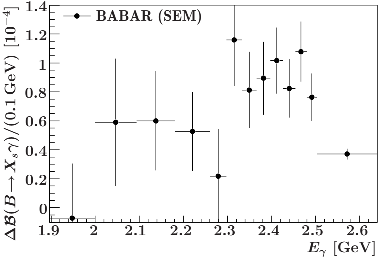
[Bernlochner, Lacker, Ligeti, Stewart, F Tackmann, KT (work in progress)]

As proof-of-concept, fit to

- $B \to X_u \ell \nu$ hadronic tag
  - ⋆ BABAR: $m_X, m_X - q^2, P_+$
  - ⋆ Belle: m_X
- $B \to X_u \ell \nu$ lepton endpoint
  - ⋆ BABAR: $E_\ell^\Upsilon > 2.2\,\mathrm{GeV}$
  - ⋆ Belle: $E_\ell^\Upsilon > 2.3\,\mathrm{GeV}$
- $B \to X_s \gamma$ spectra
  - ⋆ BABAR sum over exclusive modes
  - ⋆ BABAR hadronic tag (not shown)
- m_b^{1S}, λ_1 from $B \to X_c \ell \nu$
  - ⋆ Belle fit in 1S scheme

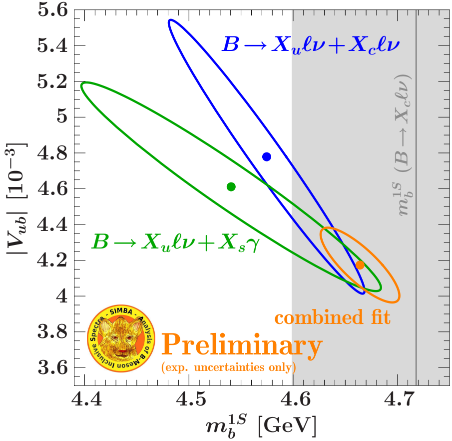
$$m_b^{1S} = (4.72 \pm 0.12)\,\mathrm{GeV}$$
$$\lambda_1 = (-0.31 \pm 0.09)\,\mathrm{GeV}^2$$

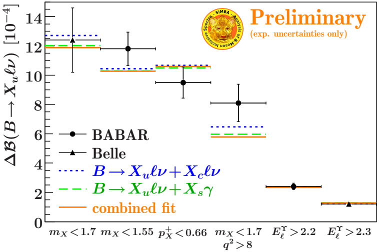


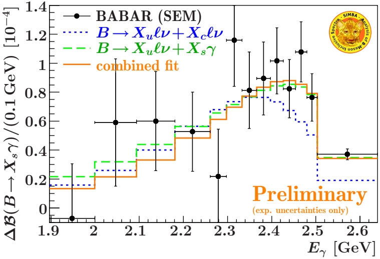


Proof-of-Concept

[Bernlochner, Lacker, Ligeti, Stewart, F Tackmann, KT (work in progress)]





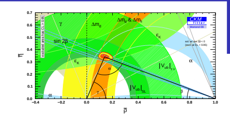


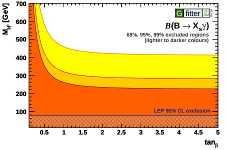
- Wrong E_γ spectrum without $B \to X_s \gamma$
- Significant improvement from combining $B \to X_s \gamma$ and $B \to X_c \ell\nu$

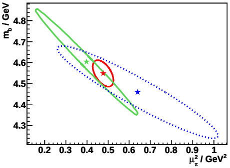
(Caution: Fits do not include theory uncertainties yet)

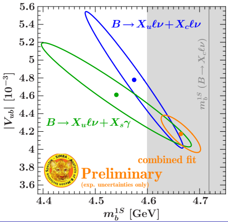
Conclusions

- Semileptonic and radiative penguin B-meson decays are a good tool to study quark couplings and B-meson structure and to search for New Physics
- Inclusive determinations of $|V_{cb}|$ and $|V_{ub}|$ down to 2% and 9%
  - ⋆ CKM fit shows impressive consistency with SM
    - ▶ Open issue: discrepancy between exclusive and inclusive measurements (and $B \to \tau\nu$)
- $\mathcal{B}(B \to X_s\gamma\ )$ constrains beyond SM models
- m_b and nonperturbative parameters extracted from semileptonic and radiative penguin decays consistent
- Work in progress towards global fit for $|V_{ub}|$, combining different experimental inputs with improved theory
  - ⋆ Reduce role of leading shape function modeling and decouple SF shape and m_b uncertainties







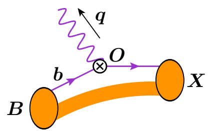


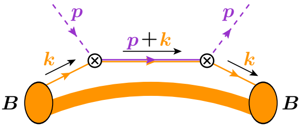
Backup

OPE for Inclusive Decays

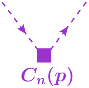
Dependence on final state X drops out when summing over all X

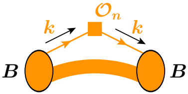
$$\mathrm{d}\Gamma = \sum_X \left| \quad \right|^2 = \mathrm{Im}$$





$$= \sum_n \quad \times$$



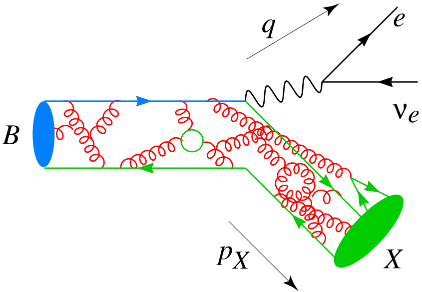


$$= \frac{G_F^2 m_b^5}{192\pi^3} |V_{cb}|^2 \left[C_0(\alpha_s) 1 + \frac{0}{m_b} + C_1(\alpha_s) \frac{\mu_\pi^2}{m_b^2} + C_2(\alpha_s) \frac{\mu_G^2}{m_b^2} + \cdots \right]$$

- LD properties of B meson parametrized by MEs of local operators
  - ⋆ $\mu_\pi^2 \sim -\lambda_1 \sim \langle k^2 \rangle, \quad \mu_G^2 \sim 3\lambda_2 \sim \langle \sigma_{\mu\nu} G^{\mu\nu} \rangle \sim m_{B^*}^2 - m_B^2$
- SD physics contained in perturbative coefficients $C_n(p)$
  - ⋆ $C_0(\alpha_s)$ given by perturbative quark decay
  - ⋆ To get well-behaved α_s series need a SD mass $m_b^{1S}, m_b^{\mathrm{kin}}, \ldots$

Kinematic Variables

Dilepton mass $q^2 = (p_\ell + p_\nu)^2 = (p_B - p_X)^2$

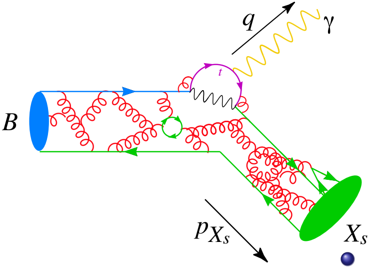


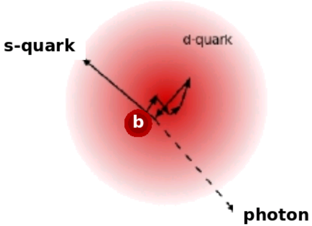
Lepton Energy E_ℓ

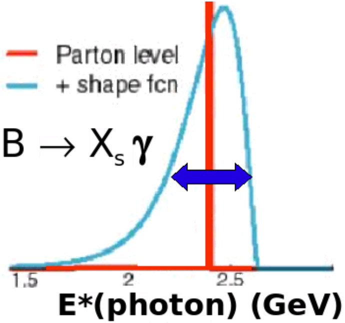
Neutrino from missing energy and momentum

Hadronic mass m_X
Hadronic energy E_X
Hadronic momentum p_X

Radiative Penguin B Decays





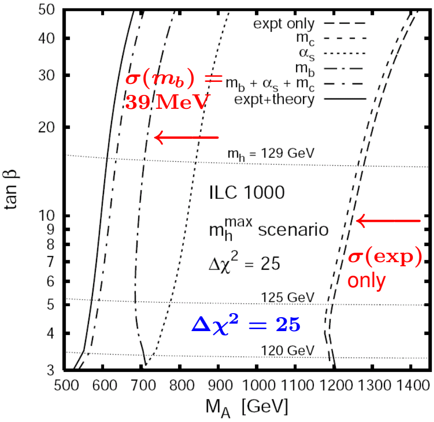


- Parton level: $E_\gamma = m_b/2$
- Hadron level: E_γ smeared out by residual motion of b in B:
  - ⋆ Mean of E_γ: $\langle E_\gamma \rangle = m_b$
  - ⋆ Width of $E_\gamma \to \mu_\pi^2$ $\propto$ kinetic energy of b quark in B meson
- Indirect sensitivity to m_b, μ_π^2, ... in kinematic distributions of "3-body" $B \to X_{c,u} \ell \nu$ decays

The b-Quark Mass

- Dependence of $|V_{ub}|$ measurements on m_b: $\sigma(m_b) = 40\,\mathrm{MeV}$
  - ⋆ $\sigma(|V_{ub}|)/|V_{ub}| \approx 2\%$ without phase space cuts
  - ⋆ $\sigma(|V_{ub}|)/|V_{ub}| \approx \mathcal{O}(5\%)$ with necessary phase space cuts
- Learn about dynamics of b quark in B meson through nonperturbative parameters
- Renormalization scheme: kinetic scheme ($\mu = 1\,\mathrm{GeV}$) unless marked otherwise

- Good knowledge of m_b important when studying New Physics effects in Higgs sector
  - ⋆ SM – MSSM Higgs separation



[Droll, Logan, Phys. Rev. D **76**:015001 (2007)]

Hadronic Mass Spectrum in $B \to X_u \ell \nu$

- Mass spectrum relies on non-local OPE
  - ⋆ Nonperturbative "parameters" are shape functions (SF)
  - ⋆ SF encode momentum distribution of b in B
  - ⋆ Leading order shape function is $\mathcal{O}(1)$, several functions at $\mathcal{O}(1/m_b)$
- Mass spectrum very sensitive to
  - ⋆ m_b
  - ⋆ Shape function tail
    - ▶ Not accessible in $B \to X_s \gamma$ because of large backgrounds
  - ⋆ α_s corrections
- Moments can be obtained from local OPE
  - ⋆ Give access to m_b, μ_π^2, ...

[De Fazio, Neubert, JHEP 9906:017 (1999)]