Inclusive B Decays

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Outline

- Introduction
- Semileptonic: $\bar{B} \to X_c \, \ell \, \bar{\nu}$ and $|V_{cb}|$
- Semileptonic: $\bar{B} \to X_u \, \ell \, \bar{\nu}$ and $|V_{ub}|$
- Radiative: $\bar{B} \to X_s \gamma$
- Radiative: $\bar{B} \to X_s \, \ell^+ \ell^-$ (Backup Slides)
- Conclusions and outlook

Introduction

Motivation

- **Why study inclusive B decays?**

- Determination of fundamental parameters

- Important probe of new physics

- Theoretically clean

- Theoretically interesting

- Large impact

Determination of fundamental parameters

- Inclusive semileptonic B decays

$\Rightarrow$ precision determination of $|V_{cb}|$ &$|V_{ub}|$

- PDG 2012:

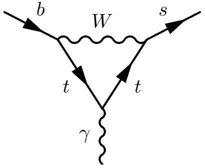
  Inclusive $|V_{cb}| = 41.9 \pm 0.7 \times 10^{-3}$ (exclusive $|V_{cb}| = 39.6 \pm 0.9 \times 10^{-3}$)

  Inclusive $|V_{ub}| = 4.41 \pm 0.23 \times 10^{-3}$ (exclusive $|V_{ub}| = 3.23 \pm 0.31 \times 10^{-3}$)

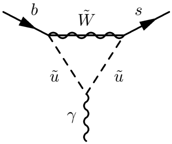
- Unresolved tension for $|V_{cb}|$ &$|V_{ub}|$: Inclusive $>$ Exclusive

Important probe of new physics

- $b \to s\gamma$ is a flavor changing neutral current (FCNC)
  In SM no FCNC at tree level, arises as a loop effect:



- $b \to s\gamma$ can have contribution from new physics e.g. SUSY (only one diagram shown):



- Inclusive radiative B decays constrain many models of new physics

Theoretically Clean

Since $5\,\mathrm{GeV} \sim m_b \gg \Lambda_{\mathrm{QCD}} \sim 0.5\,\mathrm{GeV}$

Observables expanded as a power series in $\Lambda_{\mathrm{QCD}}/m_b \sim 0.1$

$$d\Gamma = \sum_n c_n \frac{\langle O_n \rangle}{m_b^n}$$

c_n perturbative, $\langle O_n \rangle$ non-perturbative

- Improvable:
- Calculate c_n to higher order in α_s
- Expand to higher orders in $\Lambda_{\mathrm{QCD}}/m_b$

Theoretically Interesting

- Theoretically Interesting: test of basic QFT tools
  - Factorization theorems
  - Operator product expansion

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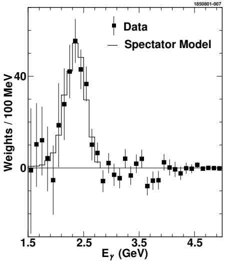
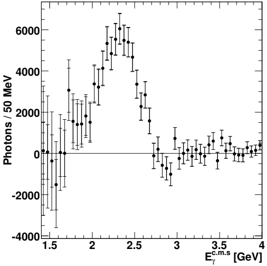
- Theoretically Interesting: window to non-perturbative physics

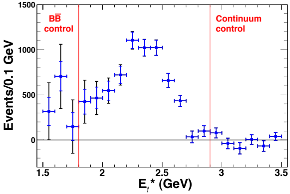
CLEO (2001)



Belle (2008)



BaBar (2012)



- At leading twist the photon spectrum is the B-meson pdf

Large Impact

- CLEO top cited papers: #1 ($b \to s\gamma$ '95)
- Belle top cited papers: #3 ($b \to s\gamma$ '01)
- BaBar top cited papers: #18 ($b \to s\ell^+\ell^-$ '04)
- Theoretical predictions: hundreds of citations

Take home message

- 1990's -2000's: Next to Leading Order (NLO) Era:

  c_0 at $\mathcal{O}(\alpha_s)$ + first power corrections at $\mathcal{O}(\alpha_s^0)$

- 2010's: Next to Next to Leading Order (NNLO) Era

  c_0 at $\mathcal{O}(\alpha_s^2)$ + first power corrections at $\mathcal{O}(\alpha_s)$+ ...

  New level of precision!

Questions

- What is the current status of the theory of Inclusive B decays?
- What theory advances can we expect in the near future?
- What measurements will be useful?

$\bar{B} \to X_c\, \ell\, \bar{\nu}$ and $|V_{cb}|$

$\bar{B} \to X_c \, \ell \, \bar{\nu}$

- At the quark level the process $\bar{B} \to X_c \, l \, \bar{\nu}$ is $b \to c \, l \, \bar{\nu}$
- Simplest approximation: free quark decay

$$d\Gamma(\bar{B} \to X_c \, l \, \bar{\nu}) \approx d\Gamma(b \to c \, l \, \bar{\nu})$$

- "Muon Decay"

$$\Gamma = \frac{G_F^2 |V_{cb}|^2 m_b^5}{192\pi^3}$$

- How good is this approximation?

  What are the corrections?

$\bar{B} \to X_c \, \ell \, \bar{\nu}$

- Answer: free quark is the zeroth term in a series Operator Product Expansion for $\bar{B} \to X_c \, l \, \bar{\nu}$

$$d\Gamma = \sum_n c_n \frac{\langle O_n \rangle}{m_b^n}$$

- c_n can be calculated in perturbation theory in α_s
- $\langle O_n \rangle$ are *local* operators, non-perturbative input

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- No $1/m_b$ corrections, at order $1/m_b^2$ two operators
- Kinetic: $\langle O_2^K \rangle = \langle \bar{B} | \bar{b} \, (iD)^2 \, b | \bar{B} \rangle$ must be fitted to spectra
- Chromomagnetic: $\langle O_2^G \rangle = \langle \bar{B} | \bar{b} \, \sigma_{\mu\nu} G^{\mu\nu} \, b | \bar{B} \rangle$ related to $M_B - M_{B^*}$

$\bar{B} \to X_c \, \ell \, \bar{\nu}$: Present

- Currently *implemented* calculations by two theory groups:
  "Kinetic" scheme and "1S" scheme

- c_0 calculated at $\mathcal{O}(\alpha_s)$
  [Trott '04; Aquila, Gambino, Ridolfi, Uraltsev '05]
- c_2^K, c_2^G calculated at $\mathcal{O}(\alpha_s^0)$
  [Blok, Koyrakh, Shifman, Vainshtein '93; Manohar, Wise '93]
- c_3^j with $j = 1, 2$ calculated at $\mathcal{O}(\alpha_s^0)$
  [Gremm, Kapustin '96]

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    [Gremm, Kapustin '96]
- PDG 2012: Extracted inclusive $|V_{cb}|$ using these calculations
  - $|V_{cb}| = (41.88 \pm 0.73) \cdot 10^{-3}$ in the kinetic scheme
  - $|V_{cb}| = (41.96 \pm 0.45) \cdot 10^{-3}$ in the 1S scheme
  - Consistent with each other, marginally consistent with exclusive $|V_{cb}| = (39.6 \pm 0.9) \cdot 10^{-3}$

$\bar{B} \to X_c \, \ell \, \bar{\nu}$: Future

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$\bar{B} \to X_c \, \ell \, \bar{\nu}$: Future

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- Calculate c_n to higher order in α_s
- Expand to higher orders in $\Lambda_{\rm QCD}/m_b$
- More recently
- c_0 calculated at $\mathcal{O}(\alpha_s^2)$ [Melnikov '08; Pak, Czarnecki '08]
- c_2^K calculated *numerically* at $\mathcal{O}(\alpha_s)$ [Becher, Boos, Lunghi '07]
- c_2^K calculated *analytically* at $\mathcal{O}(\alpha_s)$ [Alberti, Ewerth, Gambino, Nandi, '12]
- c_2^G at $\mathcal{O}(\alpha_s)$ in progress [Alberti, Ewerth, Gambino, Nandi, '##]
- $c_4^j, j = 1\ldots 9$ and $c_5^j, j = 1\ldots 18$ calculated at $\mathcal{O}(\alpha_s^0)$ [Mannel, Turczyk, Uraltsev '09]
- Of these *only* c_0 at $\mathcal{O}(\alpha_s^2)$ was implemented

  [Gambino '11; Gambino, Schwanda '13]

$\bar{B} \to X_c \, \ell \, \bar{\nu}$: Future

- With the completion of c_2^G at $\mathcal{O}(\alpha_s)$ we will have α_s^2, $\alpha_s \Lambda_{\rm QCD}^2/m_b^2$, $\Lambda_{\rm QCD}^3/m_b^3$, $\Lambda_{\rm QCD}^4/m_b^4$, and $\Lambda_{\rm QCD}^5/m_b^5$ terms for the theoretical prediction

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- NNLO Era!

  Allow for high precision $|V_{cb}|$

$\bar{B} \to X_u \, \ell \, \bar{\nu}$ and $|V_{ub}|$

$\bar{B} \to X_u \, \ell \, \bar{\nu}$

- In principle local OPE describes $\bar{B} \to X_u \, \ell \, \bar{\nu}$ observables

  Assuming $M_X^2 \sim m_b^2 \Rightarrow$ local OPE

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- In practice, to reject $\bar{B} \to X_c \, \ell \, \bar{\nu}$ background need cuts: $M_X^2 < M_D^2$

  $M_X^2 < M_D^2 \sim m_b \, \Lambda_{\rm QCD} \Rightarrow$ non-local OPE

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- Observables described by B meson PDFs: shape functions

$$d\Gamma = \sum_n \frac{1}{m_b^n} \sum_i h_i^{(n)} \cdot j_i^{(n)} \otimes s_i^{(n)}$$

$h_i^{(n)}$, $j_i^{(n)}$ perturbative, $s_i^{(n)}$ non-perturbative *functions*

$\bar{B} \to X_u \ell \bar{\nu}$: Present

- Based on

$$d\Gamma \sim H \cdot J \otimes S + \frac{1}{m_b} \sum_i H \cdot J \otimes s_i + \ldots$$

- Leading power H, J at $\mathcal{O}(\alpha_s)$

  [Bauer, Manohar '03; Bosch, Lange, Neubert, GP '04]

- Subleading shape functions: $H \cdot J \otimes s_i$ at $\mathcal{O}(\alpha_s^0)$

  [K. Lee, Stewart '04; Bosch, Neubert, GP '04; Beneke, Campanario, Mannel,Pecjak '04]

- S extracted from $\bar{B} \to X_s \gamma$, s_i modeled ($\sim$ 700 models)

- Precision determination of $|V_{ub}|$ ("NLO")

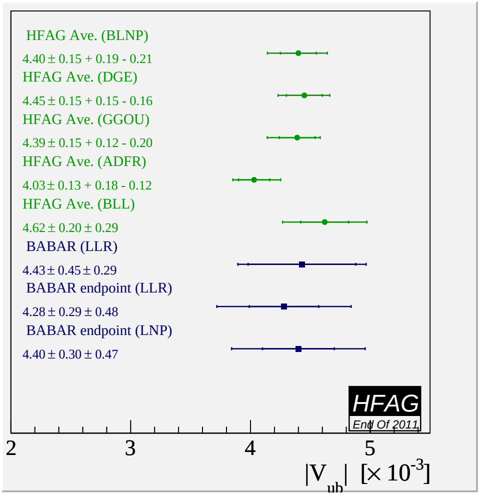
  Lange, Neubert, GP PRD **72** 073006 (2005)

  Error on $|V_{ub}|$: **18%** (PDG 2004) $\Rightarrow$ **8%** (PDG 2006)

$\bar{B} \to X_u \ell \bar{\nu}$: Present

- Consistent extractions based on various theoretical approaches

  (Another group, SIMBA (Global fit approach) doesn't have results yet)



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  exclusive $|V_{ub}| \quad = 3.23 \pm 0.31 \times 10^{-3}$

$\bar{B} \to X_u \, \ell \, \bar{\nu}$: Future

$$d\Gamma \sim H \cdot J \otimes S + \frac{1}{m_b} \sum_i H \cdot J \otimes s_i + \frac{1}{m_b} \sum_i H \cdot j_i \otimes S + \mathcal{O}\left(\frac{\Lambda^2_{\mathrm{QCD}}}{m_b^2}\right)$$

- More recently
- J calculated at $\mathcal{O}(\alpha_s^2)$ [Becher, Neubert '06]
- H calculated at $\mathcal{O}(\alpha_s^2)$ [Bonciani, Ferroglia '08; Asatrian, Greub, Pecjak '08; Beneke, Huber, Li '08; Bell '08]
- j_i calculated at $\mathcal{O}(\alpha_s)$ [GP '09]
- Calculations not fully combined yet

$\bar{B} \to X_u \ell \bar{\nu}$: Future

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  - j_i calculated at $\mathcal{O}(\alpha_s)$ [GP '09]
- Calculations not fully combined yet
- NNLO Era!

  Allow for high precision $|V_{ub}|$

$\bar{B} \to X_u \, \ell \, \bar{\nu}$: Future

- What if we could relax the cuts?
  E.g. Belle's $p_\ell^{*B} > 1.0$ GeV [Belle, Urquijo et al. '10]
  Relaxing the cuts makes the measurement more inclusive

- Three options:

1) Use the same calculations as the end point region
   e.g. BLNP smoothly merges to local OPE
2) Use local OPE
   Recently free quark $d\Gamma(b \to u \, \ell \, \bar{\nu})$ was calculated at $\mathcal{O}(\alpha_s^2)$
   [Burcherseifer, Caola, Melnikov '13]
3) Multi Scale OPE [Neubert '05]
   interpolating between local and non-local OPE

- My personal preference: try a variety of approaches
  Data with different *cuts* will allow to test these options

$$\bar{B} \to X_s \gamma$$

$\bar{B} \to X_s\gamma$: Present

- Brief discussion, for details
  [GP talk at KEK Flavor Factory Workshop (KEK-FF2013)]

- Latest (May 2013) HFAG BR
  $\Gamma(b \to s\gamma) = (3.43 \pm 0.21 \pm 0.07) \times 10^{-4}, \quad E_\gamma > 1.6 \text{ GeV}$

- Published value [Misiak et. al. '07]
  $\Gamma(b \to s\gamma) = (3.15 \pm 0.23) \times 10^{-4}, \quad E_\gamma > 1.6 \text{ GeV}$

- Recent update [Misiak, FPCP 2013]
  $\Gamma(b \to s\gamma) = (3.14 \pm 0.22) \times 10^{-4}, \quad E_\gamma > 1.6 \text{ GeV}$

- Largest uncertainty: non-perturbative (5%) from $\mathcal{O}\left(\Lambda_{\rm QCD}/m_b\right)$

$\bar{B} \to X_s\gamma$: Present

- Like semileptonic expect non-perturbative effects at $\mathcal{O}\left(\Lambda^2_{\mathrm{QCD}}/m_b^2\right)$

- Direct $Q_{7\gamma}$: $b \to s\gamma$ is only one possible process

$\bar{B} \to X_s\gamma$: Present

- Like semileptonic expect non-perturbative effects at $\mathcal{O}\left(\Lambda^2_{\rm QCD}/m_b^2\right)$
- Direct $Q_{7\gamma}$: $b \to s\gamma$ is only one possible process
- "Resolved" (indirect) photon production, e.g

- Q_1 : $b \to s\,\bar{q}q \to s\,g\,\gamma$
- Q_{8g} : $b \to s\,g \to s\,\bar{q}q\,\gamma$

Lead to $\mathcal{O}\left(\Lambda_{\rm QCD}/m_b\right)$ non-perturbative effects

[S. Lee, Neubert, GP '06; Benzke, S. Lee, Neubert, GP '10]

Δ_{0-}

- Hard to estimate the resolved photon contributions

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- The uncertainty due to Q_{8g} can be extracted from data
  Assuming $SU(3)$ flavor symmetry it is determined by charge (isospin) asymmetry [Misiak '09]

$$\Delta_{0-} = \frac{\Gamma(\bar{B}^0 \to X_s\gamma) - \Gamma(B^- \to X_s\gamma)}{\Gamma(\bar{B}^0 \to X_s\gamma) + \Gamma(B^- \to X_s\gamma)}$$

- Including 30% $SU(3)$ flavor breaking
  [Benzke, S. Lee, Neubert, GP '10]

$$Q_{8g}\,\text{uncertainty} = -(1 \pm 0.3)\frac{\Delta_{0-}}{3}$$

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$$Q_{8g}\,\mathrm{uncertainty} = -(1 \pm 0.3)\frac{\Delta_{0-}}{3}$$

- So far Δ_{0-} *only* measured by BaBar, $\Delta_{0-} = (-1.3 \pm 5.9)\%$
  Error on $\Gamma(\bar{B} \to X_s\gamma)$ increase/decrease depending on size of Δ_{0-}

CP asymmetry

- Latest (May 2013) HFAG value

$$\mathcal{A}_{X_s\gamma} = \frac{\Gamma(\bar{B} \to X_s\gamma) - \Gamma(B \to X_{\bar{s}}\gamma)}{\Gamma(\bar{B} \to X_s\gamma) + \Gamma(B \to X_{\bar{s}}\gamma)} = -(0.8 \pm 2.9)\%$$

- Perturbative only : $\mathcal{A}_{X_s\gamma} \approx 0.5\%$

  [Soares '91; Kagan, Neubert '98; Ali et al.; '98; Hurth et al. '05]

- Resolved photons have dramatic effect on $\mathcal{A}_{X_s\gamma}$

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- CP asymmetry dominated by non-perturbative effects!

$$-0.6\% < \mathcal{A}^{\mathrm{SM}}_{X_s\gamma} < 2.8\%$$

  [Benzke, S. Lee, Neubert, GP, '11]

$\Delta\mathcal{A}_{X_s}$: Theory

- **New** test of physics beyond the SM

$$\Delta\mathcal{A}_{X_s} = \mathcal{A}_{X_s^-\gamma} - \mathcal{A}_{X_s^0\gamma} \approx 4\pi^2\alpha_s \frac{\tilde{\Lambda}_{78}}{m_b} \,\mathrm{Im}\, \frac{C_{8g}}{C_{7\gamma}} \approx 12\% \times \frac{\tilde{\Lambda}_{78}}{100\,\mathrm{MeV}} \,\mathrm{Im}\, \frac{C_{8g}}{C_{7\gamma}}$$

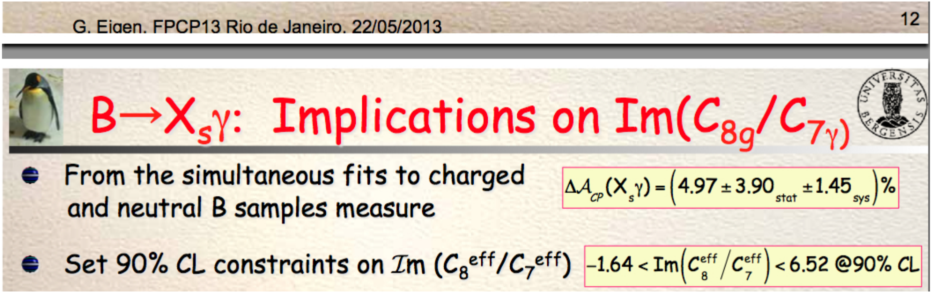
  where 17 MeV $< \tilde{\Lambda}_{78} <$ 190 MeV [Benzke, S. Lee, Neubert, GP, '11]

- BaBar $\Delta\mathcal{A}_{X_s}$ analysis

$\Delta\mathcal{A}_{X_s}$: Experiment

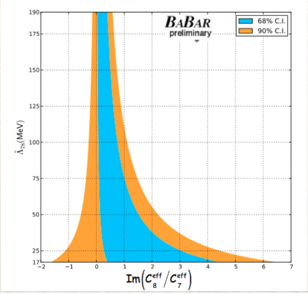
- BaBar talk at FPCP 2013

  (Also Piti Ongmongkolkul, Caltech thesis, http://inspirehep.net/record/1243753/files/thesis.pdf)

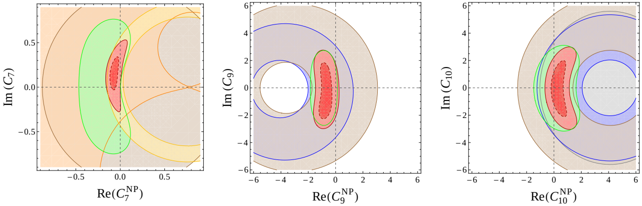


$\Delta\mathcal{A}_{X_s}$: Experiment

- First constraint on Im $C_{8g}/C_{7\gamma}$



- Complement similar $b \to s$ constraints on $C_{7\gamma}$, C_9, and C_{10} [Altmannshofer, Straub '12]



$\bar{B} \to X_s\gamma$: Future

- Current status for total rate $\Gamma(\bar{B} \to X_s\gamma)$

- leading power NNLO $\mathcal{O}(\alpha_s^2)$ [Misiak et. al. '07]
- $\Lambda_{\rm QCD}/m_b$ corrections at $\mathcal{O}(\alpha_s^0)$ [Benzke, S. Lee, Neubert, GP '10]
- Some $\Lambda^2_{\rm QCD}/m_b^2$ corrections [Kaminski, Misiak, Poradzinski '12]
- Some $\alpha_s\Lambda^2_{\rm QCD}/m_b^2$ corrections [Ewerth, Gambino, Nandi '10]

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  - $\Lambda_{\rm QCD}/m_b$ corrections at $\mathcal{O}(\alpha_s^0)$ [Benzke, S. Lee, Neubert, GP '10]
  - Some $\Lambda_{\rm QCD}^2/m_b^2$ corrections [Kaminski, Misiak, Poradzinski '12]
  - Some $\alpha_s\Lambda_{\rm QCD}^2/m_b^2$ corrections [Ewerth, Gambino, Nandi '10]

- Spectrum $d\Gamma(\bar{B} \to X_s\gamma)$:
  - Resolved photon effects not known numerically
    relevant for HQET parameters and $|V_{cb}|$ and $|V_{ub}|$
  - Comparison between theory and experiment relays on extrapolation
    from measured $E_\gamma \sim 1.9$ GeV to $E_\gamma > 1.6$ GeV
    The issue of extrapolation should be revisited
  - Both can benefit from detailed E_γ *cut* effects

Conclusions and outlook

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  New level of precision!

What theorist(s) hope for

- *Reduction of experimental error* motivates theoretical advances
  Currently $\delta\Gamma_{\rm exp} \approx \delta\Gamma_{\rm th}$ for both $\bar{B} \to X_s\gamma$ and $\bar{B} \to X_u\,\ell\,\bar{\nu}$

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- *Cut effects*: dependence of observables on cuts helps improve theoretical predictions (or make them more reliable)

- *Isospin asymmetries*

- Δ_{0-} helps constrain error on $\Gamma(\bar{B} \to X_s\gamma)$
  so far only measured by BaBar, $\Delta_{0-} = (-1.3 \pm 5.9)\%$
- $\Delta\mathcal{A}_{X_s}$: test of new physics
- so far only measured by BaBar $\Delta\mathcal{A}_{X_s} = (4.97 \pm 3.90 \pm 1.45)\%$

What theorist(s) hope for

- *Reduction of experimental error* motivates theoretical advances
  Currently $\delta\Gamma_{\rm exp} \approx \delta\Gamma_{\rm th}$ for both $\bar{B} \to X_s\gamma$ and $\bar{B} \to X_u\,\ell\,\bar{\nu}$

- *Cut effects*: dependence of observables on cuts helps improve theoretical predictions (or make them more reliable)

- *Isospin asymmetries*
  - Δ_{0-} helps constrain error on $\Gamma(\bar{B} \to X_s\gamma)$
    so far only measured by BaBar, $\Delta_{0-} = (-1.3 \pm 5.9)\%$
  - $\Delta\mathcal{A}_{X_s}$: test of new physics
  - so far only measured by BaBar $\Delta\mathcal{A}_{X_s} = (4.97 \pm 3.90 \pm 1.45)\%$

- Surprises both from experiment and theory...

Backup Slides

Comments on

$$\bar{B} \to X_s\,\ell^+\ell^-$$

$\bar{B} \to X_s \, \ell^+ \ell^-$

- Region of low $q^2 \in [1...6]\,\mathrm{GeV}^2$ and $m_X \leq m_X^{\mathrm{cut}}$
  $d\Gamma_i$ factorizes similarly to $d\Gamma_{77}$ of $\bar{B} \to X_s\gamma$

$$d\Gamma_i \sim H_i \cdot J \otimes S + \mathcal{O}\left(\frac{\Lambda_{\mathrm{QCD}}}{m_b}\right), \quad i = T, A, L$$

  [K. Lee, Stewart '05]

- Recent progress:

- K. Lee, Tackmann
  Calculation of $\mathcal{O}\left(\frac{\Lambda_{\mathrm{QCD}}}{m_b}\right)$ "primary" SSF
  [PRD **79**, 114021 (2009)]
- Bell, Beneke, Huber and Li
  Two loop calculation of H_i
  [NPB **843**, 143 (2011)]

$\bar{B} \to X_s\,\ell^+\ell^-$: Power Corrections

- [K. Lee, Tackmann, PRD **79**, 114021 (2009)]:

  Contribution of SSF that appear also in $\bar{B} \to X_u\, l\bar{\nu}$ ("primary")

- Sizable power corrections of order 5% to 10%

- Cause a shift of $\sim\ -0.05\,\mathrm{GeV}^2$ to $-0.1\,\mathrm{GeV}^2$
  in the zero of the forward-backward asymmetry

$\bar{B} \to X_s \ell^+\ell^-$: Perturbative Corrections

- [Bell, Beneke, Huber, Li , NPB **843**, 143 (2011)]

  Two loop calculation of H_i

- Shift in zero of the forward-backward asymmetry:

  NLO: -2.2% NNLO: -3%

- Final result, *including* the "primary" $1/m_b$ corrections

$$q_0^2 = (3.34 \ldots 3.40)^{+0.22}_{-0.25}\,\mathrm{GeV}^2 \quad \text{for} \quad m_X^{\rm cut} = (2.0 \ldots 1.8)\,\mathrm{GeV}$$

$\bar{B} \to X_s\,\ell^+\ell^-$: Future Directions

- Following the completed analysis for $\Gamma(\bar{B} \to X_s\gamma)$

  What is the effect from "non-primary" SSF?

- For example, soft gluon attachments to the charm-loop diagrams:

$$\langle \bar{B}|\bar{b}(0)\cdots G(s\bar{n})\cdots b(0)|\bar{B}\rangle$$

- Point also stressed in

  [Bell, Beneke, Huber, Li , NPB **843**, 143 (2011)]