Sides of the Unitarity Triangle with a (few) dozen GB's

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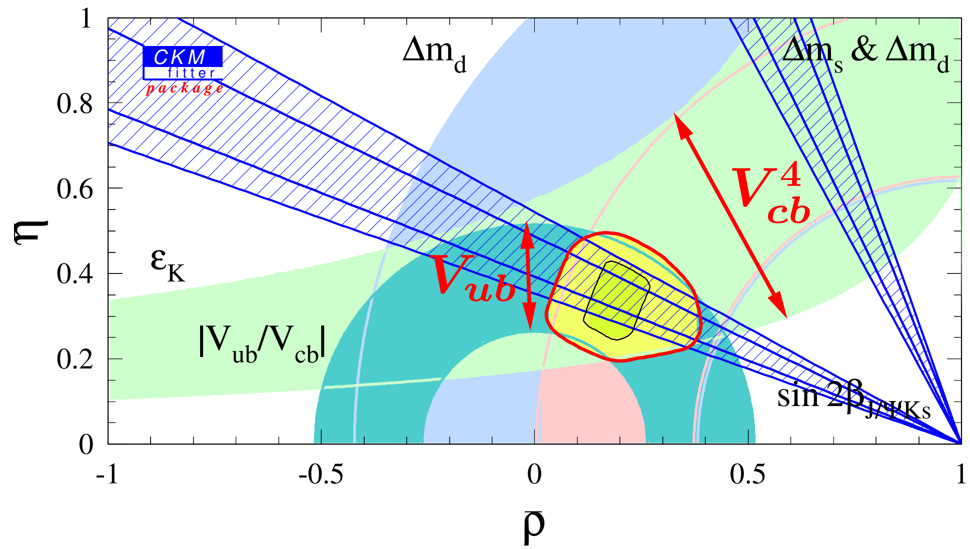
- Introduction
- $|V_{cb}|$ — will be skipped
- $|V_{ub}|$ — excl., incl. ($\lesssim 10\%$ theory error)
  ... concentrate on theoretical limitations
- $|V_{td}|$ and $|V_{ts}|$ — from other than mixing
- Conclusions

Why care about $|V_{ub}|$ and $|V_{cb}|$?

$|V_{ub}|$: dominant uncertainty of the side opposite to $\beta \equiv \phi_1$

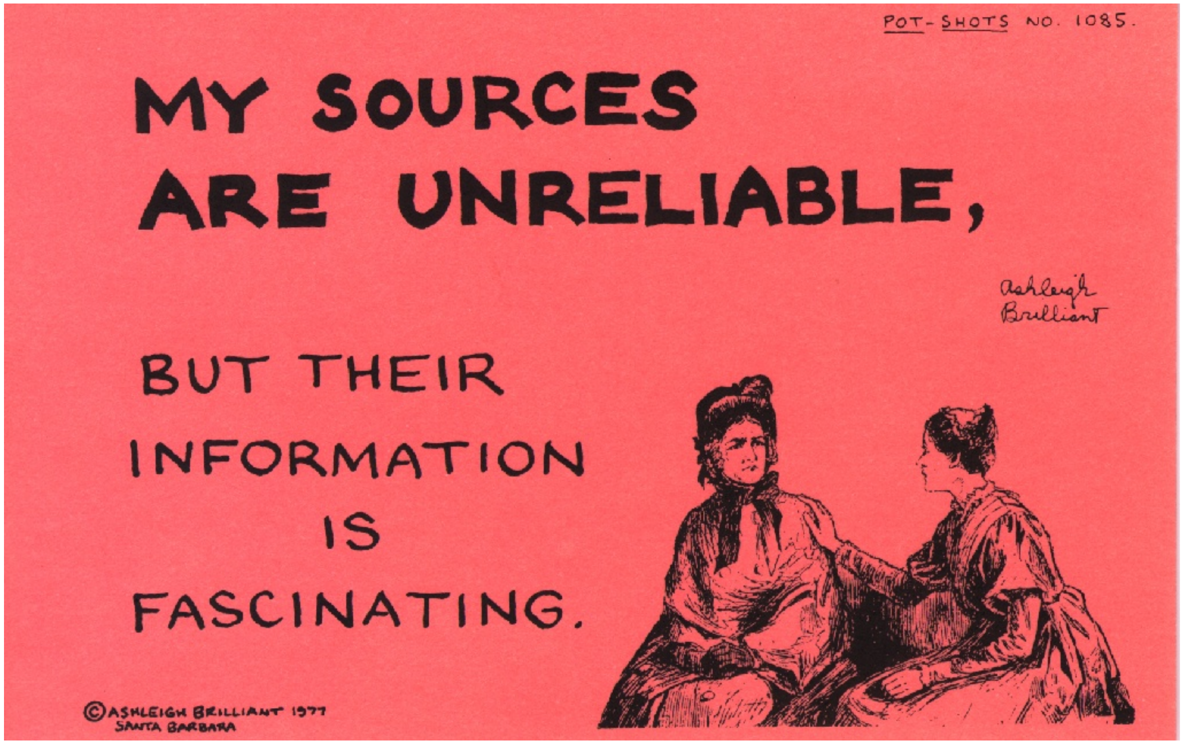
$|V_{cb}|$: large part of the uncertainty in ϵ_K constraint, and in $K \to \pi\nu\bar{\nu}$ in the future



Look for New Physics: compare (i) angles with sides; (ii) tree and loop processes ... semileptonic decays crucial for this

$b \to q\gamma$, $b \to q\,\ell^+\ell^-$, and $b \to q\,\nu\bar{\nu}$ ($q = s, d$) are sensitive probes of the SM theoretical tools same as for $|V_{xb}|$ — accuracy of theory limits sensitivity to NP

The name of the game



Success of SM impressive ($\sin 2\beta$, kaons, $B \to X_s\gamma$)

Only truly convincing deviations are likely to be interesting

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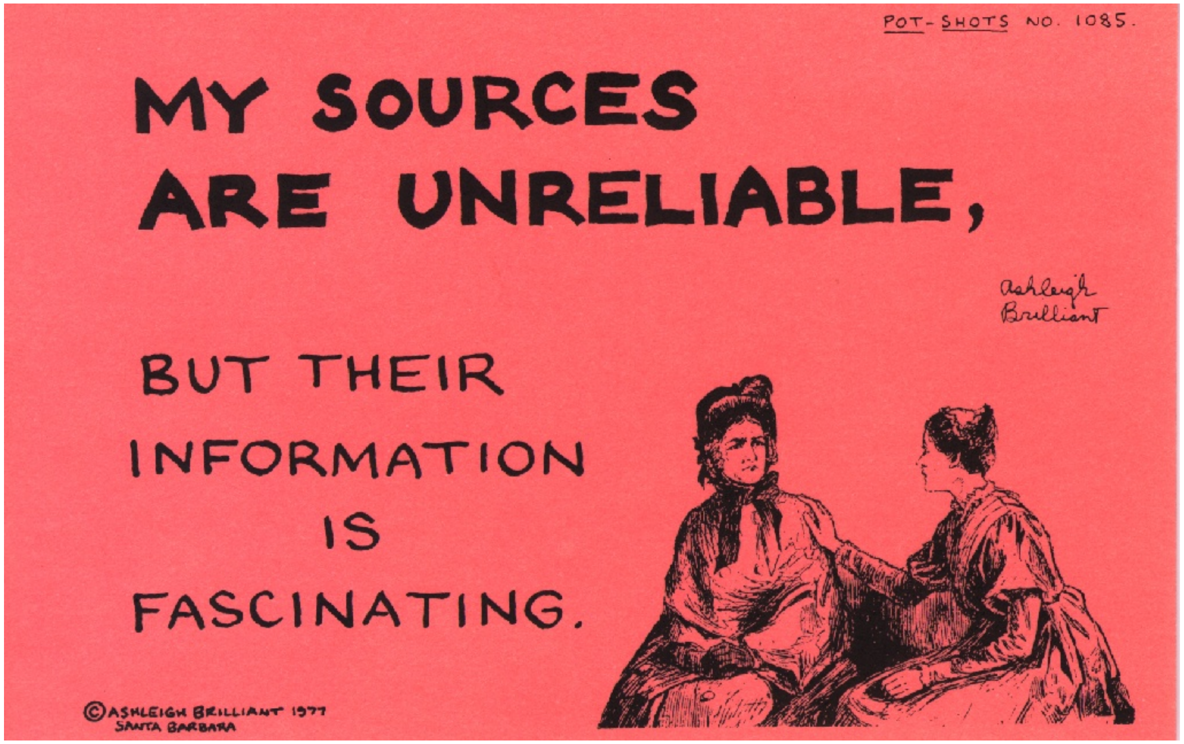

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Only truly convincing deviations are likely to be interesting

2σ: 50 theory papers 3σ: 200 theory papers 5σ: strong sign of effect

Status of exclusive $|V_{ub}|$

Experiment	Average [10^{-3}]	ISGW2 [1] [10^{-3}]	LCSR [2] [10^{-3}]	UKQCD [3] [10^{-3}]	Ligeti/Wise + E791 [4] [10^{-3}]	Beyer/Melikhov [5] [10^{-3}]	Reference
CLEO	3.23 +/-0.24 +0.23-0.26 +/-0.58	3.14 +/-0.24 +0.22-0.25	3.48 +/-0.26 +0.24-0.28	3.29 +/-0.25 +0.23-0.26	2.83 +/-0.21 +0.20-0.23	3.38 +/-0.25 +0.24-0.27	Phys.Ref.D61:052001-,2000
BELLE		3.50 +/-0.20 +/-0.28					Preliminary, ICHEP 2002
BABAR	3.64 +/-0.22 +/-0.25 +0.39-0.56	3.55 +/-0.21 +/-0.25 +0.80-1.04	3.85 +/-0.24 +/-0.27 +0.57-0.67	3.62 +/-0.22 +/-0.25 +0.36-0.26	3.09 +/-0.19 +/-0.22 +0.42-0.49	3.84 +/-0.24 +/-0.27 +0.28-0.30	Phys.Rev.Lett.90:181801,2003

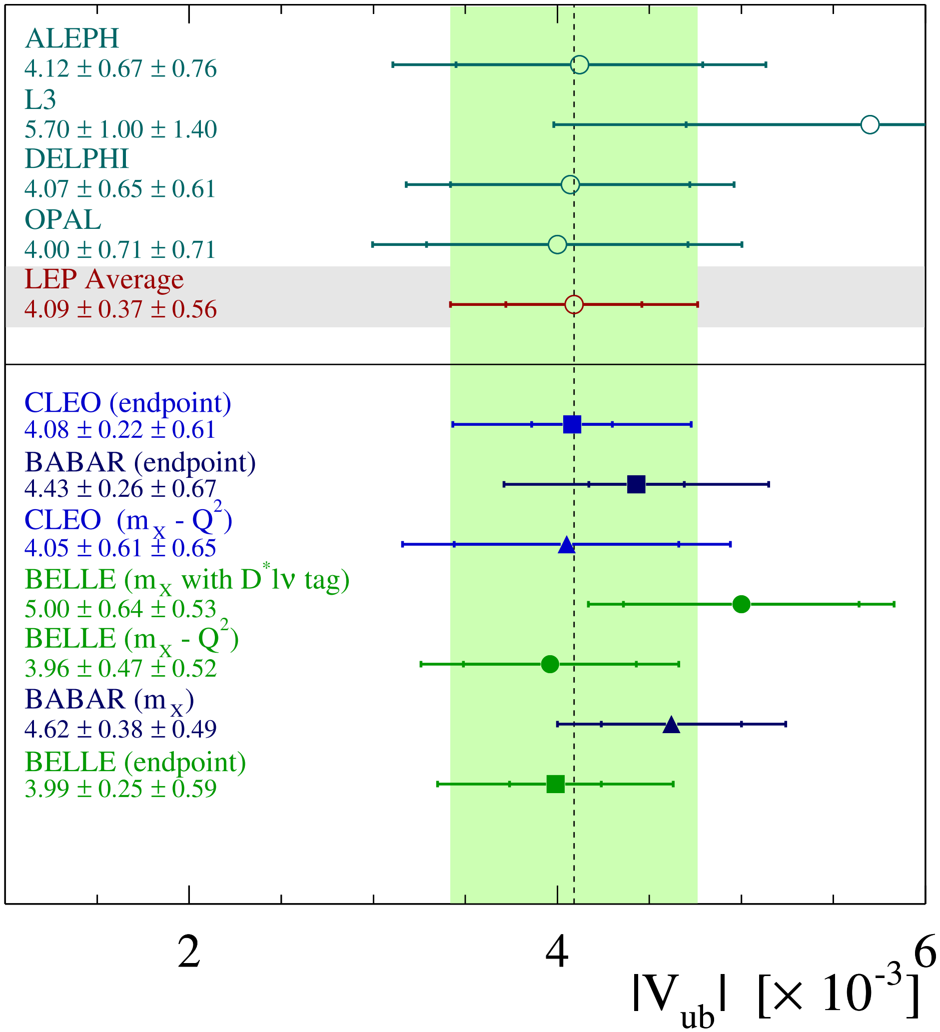
References on the formfactor models:

[$B \to \rho \ell \bar{\nu}$, similar for $B \to \pi \ell \bar{\nu}$]

- [1] D.Scora and N.Isgur, Phys.Rev.D52, 2783(1995).
- [2] P.Ball and V.M.Braun, Phys.Rev.D58, 094016 (1998).
- [3] L.delDebbio et al, Phys.Lett.B416, 392 (1998).
- [4] Z.Ligeti and M.Wise, Phys.Rev.D53, 4937 (1996); E.M.Aitala et al, Phys.Rev.Lett. 80, 1393 (1998).
- [5] M.Beyer and D.Melikhov, Phys.Lett.B436, 344 (1998).

Model dependent errors dominate until unquenched lattice form factors available

Status of inclusive $|V_{ub}|$



HFAG provides no average, as probably no one quite knows how to do it right

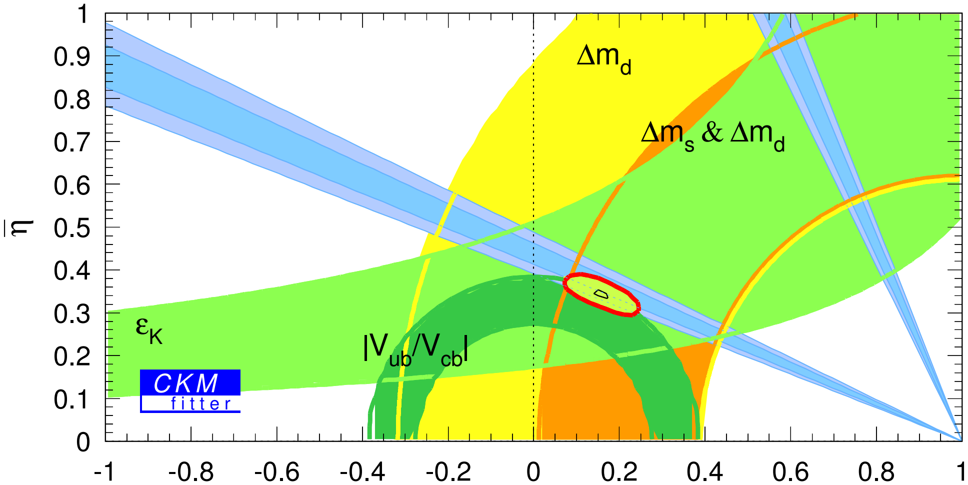
Results partially correlated; some contain model dependent or unquantifiable errors more than others

$\Downarrow$

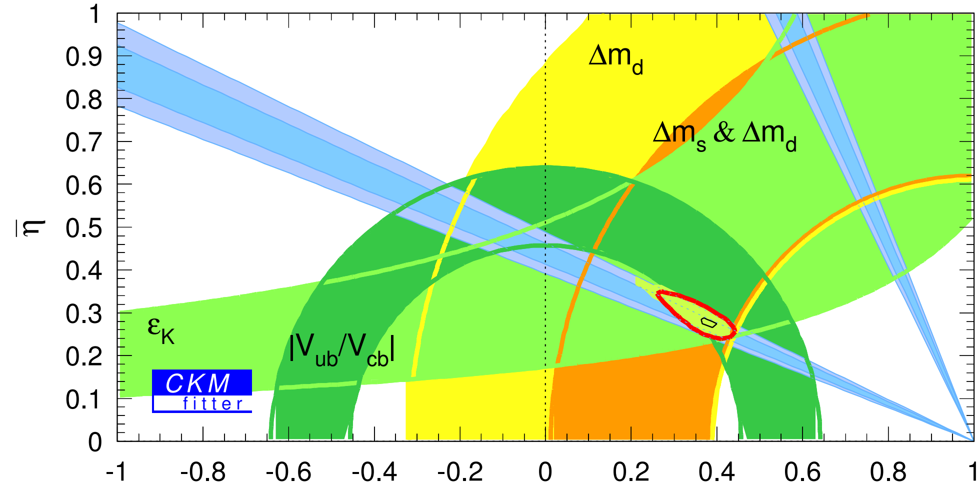
Move toward extractions with theoretical errors that can be reliably estimated

Some “extreme” scenarios for $|V_{ub}|$

$|V_{ub}| = (3.0 \pm 0.15 \pm 0.15) \times 10^{-3}$



$|V_{ub}| = (5.0 \pm 0.25 \pm 0.25) \times 10^{-3}$



and $\sigma(\sin 2\beta) = \text{present}/2$

(Not realistic, by this time B_s mixing should be measured)

Recent incl. [excl.] measurements of $|V_{ub}|$ tend to be high [low]

Both fits less good than with average $|V_{ub}|$

Central values: difference of γ about $25°$; require Δm_s near max [min] SM range

$\Rightarrow$ Must aim at $\sigma(|V_{ub}|) \sim 5\%$

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Crucial distinction between V_{xb} and V_{tx}

- $|V_{ub}|$ and $|V_{cb}|$: Dominated by SM tree diagrams, so new physics very unlikely to influence measurements

  Independent measurements of $|V_{xb}|$ are cross-checks

  $\Rightarrow$ Look for "the" best determination(s)

- $|V_{td}|$ and $|V_{ts}|$: Contributions arise from higher dimension operators, generated in SM by loop processes, so new physics could compete with SM

  Independent measurements of $|V_{tx}|$ (with clean interpretation) search for NP

  $\Rightarrow$ Measuring V_{td}, V_{ts} in rare decays is interesting even if uncertainties are larger than from $B_{d,s}$ mixing — such "redundancy" may be the key to finding NP

$|V_{ub}|$ — exclusive

Exclusive $b \to u$ decays

- Less constraints from heavy quark symmetry than in $b \to c$

$\Rightarrow$ $B \to \ell\bar{\nu}$ measures $f_B \times |V_{ub}|$ — need f_B from unquenched lattice

$\Rightarrow$ Useful constraints from unitarity/analyticity

$\Rightarrow$ Ratios $= 1$ in heavy quark or chiral symmetry limit ($+$ study corrections)

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- Deviations of "Grinstein-type double ratios" from unity are more suppressed:

$\dfrac{f_B}{f_{B_s}} \times \dfrac{f_{D_s}}{f_D}$ — lattice: double ratio $= 1$ within few $\%$ (Grinstein, '93)

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$\frac{f^{(B\to\rho\ell\bar{\nu})}}{f^{(B\to K^*\ell^+\ell^-)}} \times \frac{f^{(D\to K^*\ell\bar{\nu})}}{f^{(D\to\rho\ell\bar{\nu})}}$ or q^2 spectra — accessible soon? (ZL & Wise, ’96)

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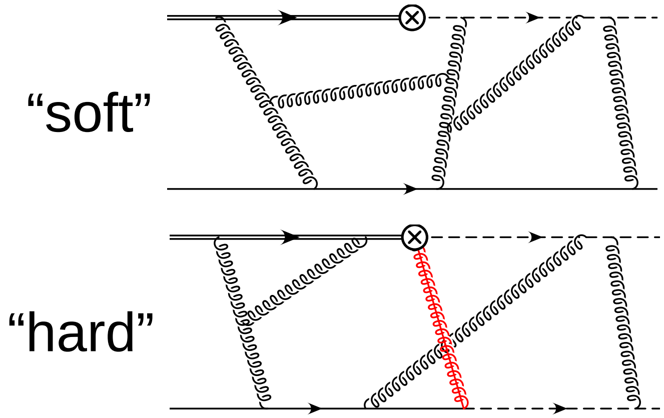
$\frac{\mathcal{B}(B \to \ell\bar{\nu})}{\mathcal{B}(B_s \to \ell^+\ell^-)} \times \frac{\mathcal{B}(D_s \to \ell\bar{\nu})}{\mathcal{B}(D \to \ell\bar{\nu})}$ — very clean... in a decade? (Ringberg workshop, '03)

Soft-collinear effective theory

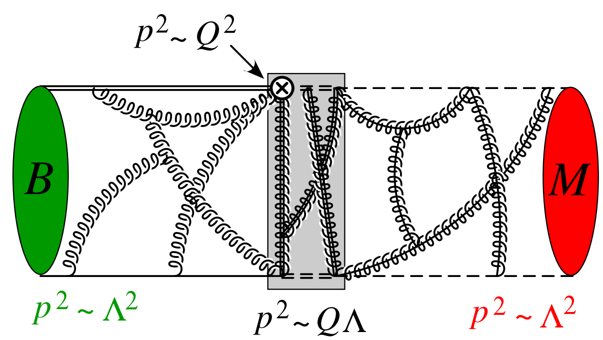
(Talk by Bauer)

- A new EFT to describe the interactions of energetic but low invariant mass particles with soft quanta [“the” connection between heavy quarks and jet physics?]
  ... Operator formulation instead of studying regions of Feynman diagrams
  ... Simplified & new proofs ($B \to D\pi, \pi\ell\bar{\nu}$) of factorization theorems (Bauer, Pirjol, Stewart)

- E.g., $B \to \pi\ell\bar{\nu}$ form factor: Issues: tails of wave fn’s, Sudakov suppression, etc.



$\Rightarrow$

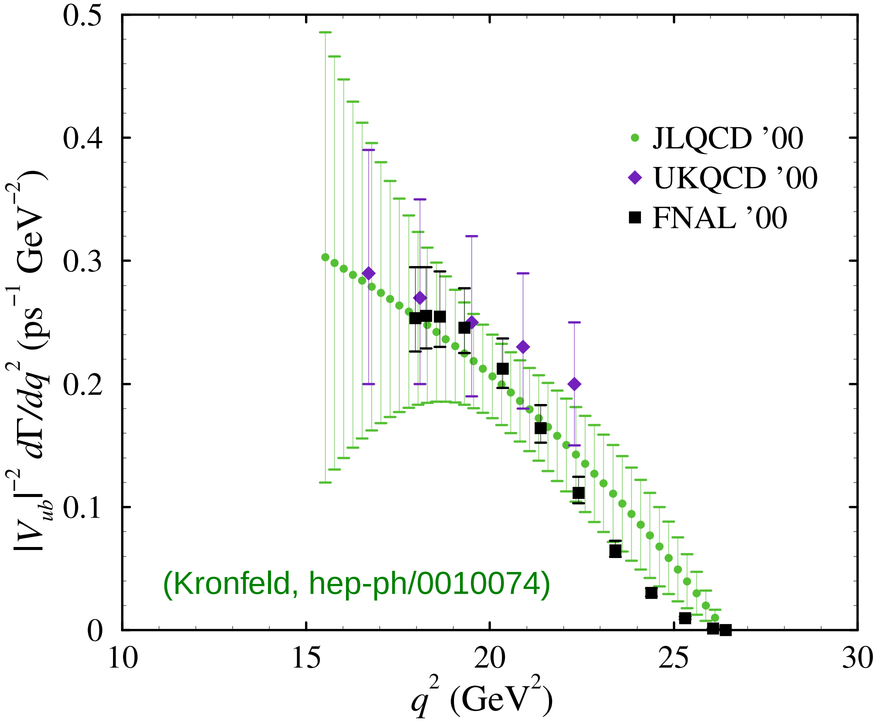


$$F(Q) = f^{\text{non-fact.}}(Q) + f^{\text{fact.}}(Q)$$

Hope to understand accuracy of form factor relations in low q^2 region (Charles *et al.*)

... Will likely impact our understanding of charmless nonleptonic decays

$B \to \pi \ell \bar{\nu}$ will be lattice QCD dominated



Present calculations are quenched

Need unquenched to be model independent

Few – $10\,\%$ errors seem to be achievable

Calculations in larger/full q^2 range may become possible (presently low p_π)

$B \to \rho$ harder due to sizable Γ_ρ / m_ρ

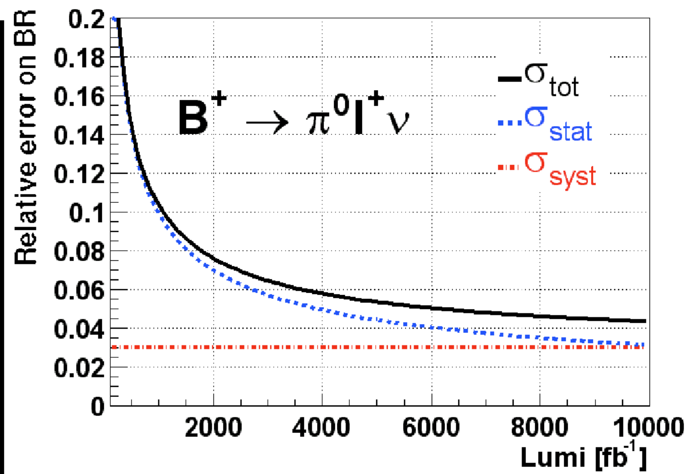
(Covered at previous meetings; many of the World experts are in Japan / in this room)

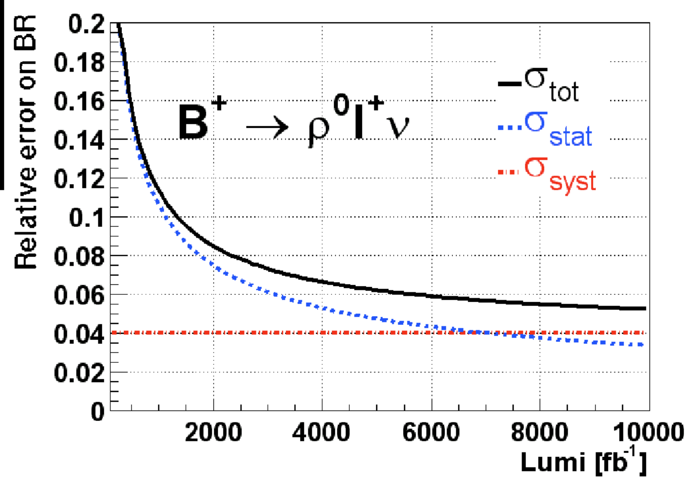
- May ultimately be the most precise determination of $|V_{ub}|$

$B \to u$ exclusive projections from Babar

Excl. Charmless Decays: Perspectives

BR measurement	S/B	σ(tot)500fb^{-1}	σ(tot)10ab^{-1}
$B\to\pi^0 l\nu$	>10	~14%	~4%
$B\to\rho^0 l\nu$	~4	~15%	~5%
$B\to\omega l\nu$	~2.5	~16%	~6%
$B\to\pi^+ l\nu$	>10	~11%	~3%
$B\to\rho^+ l\nu$	~2	~15%	~6%





*Here I assumed negligible systematics from FF and a rough estimate of experimental syst. error

(Improvements up to $\sim 10\,\mathrm{ab}^{-1}$)

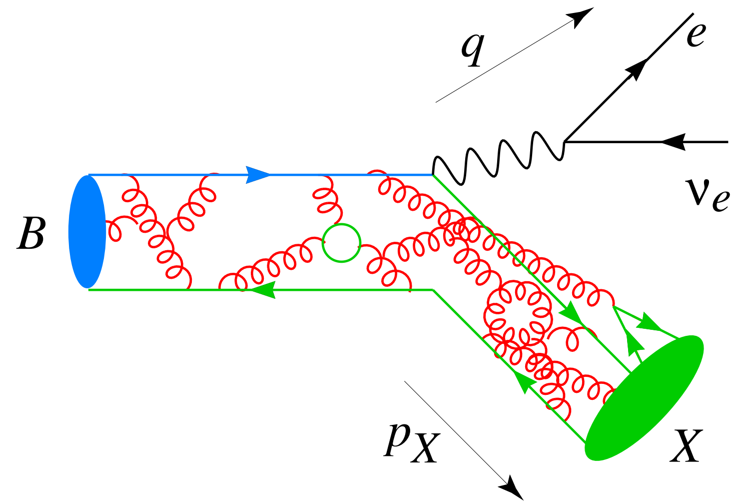
$|V_{ub}|$ — inclusive

Why inclusive decays?

- Sum over hadronic final states, subject to constraints determined by short distance physics

  Decay: short distance (calculable)

  Hadronization: long distance (nonperturbative), but probability to hadronize somehow is unity



- Rates calculable in an OPE, expansion in $\Lambda_{\rm QCD}/m_b$ and $\alpha_s(m_b)$:

$$d\Gamma = \begin{pmatrix} b \text{ quark} \\ \text{decay} \end{pmatrix} \times \left\{ 1 + \frac{0}{m_b} + \frac{f(\lambda_1, \lambda_2)}{m_b^2} + \ldots + \alpha_s(\ldots) + \alpha_s^2(\ldots) + \ldots \right\}$$

  In "most" of phase space, details of b quark wavefunction unimportant, only averages matter: $\lambda_1 \sim \langle k^2 \rangle$ not well-known, $\lambda_2 \sim \langle \sigma_{\mu\nu} G^{\mu\nu} \rangle = (m_{B^*}^2 - m_B^2)/4$, ...

  Interesting quantities computed to order α_s, $\alpha_s^2 \beta_0$, and $1/m^3$

The problem for $B \to X_u \ell \bar\nu$

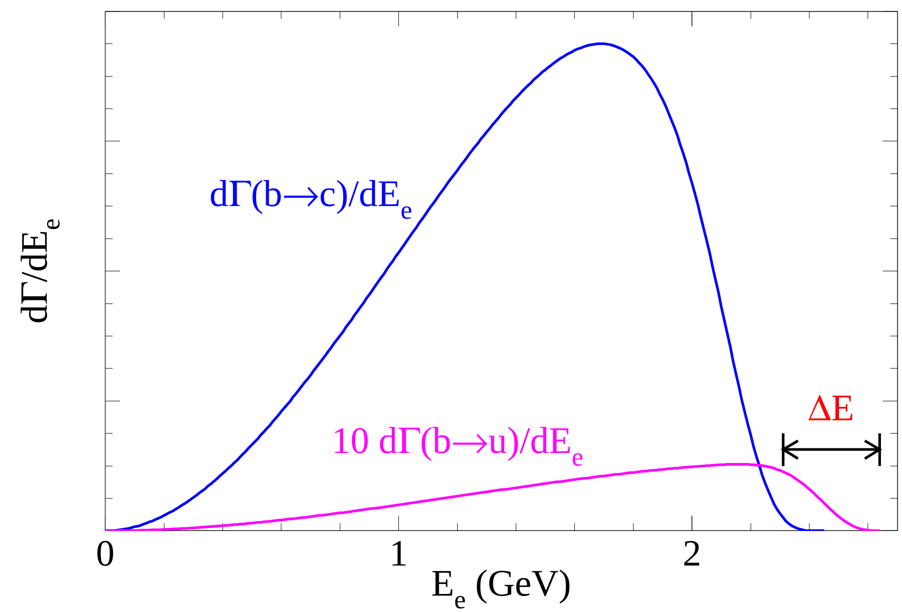
- Total rate known at $\sim 4\%$ level, similar to $\Gamma(B \to X_c \ell \bar\nu)$ (Hoang, ZL, Manohar)

$$|V_{ub}| \sim \left[3.04 \pm 0.08_{m_b} \pm 0.08_{\rm pert}\right] \times 10^{-3} \left(\frac{\mathcal{B}(B \to X_u \ell \bar\nu)}{0.001} \, \frac{1.6\,\rm ps}{\tau_B}\right)^{1/2}$$

Can huge charm background ($|V_{cb}/V_{ub}| \sim 10$) be removed w/o phase space cuts?

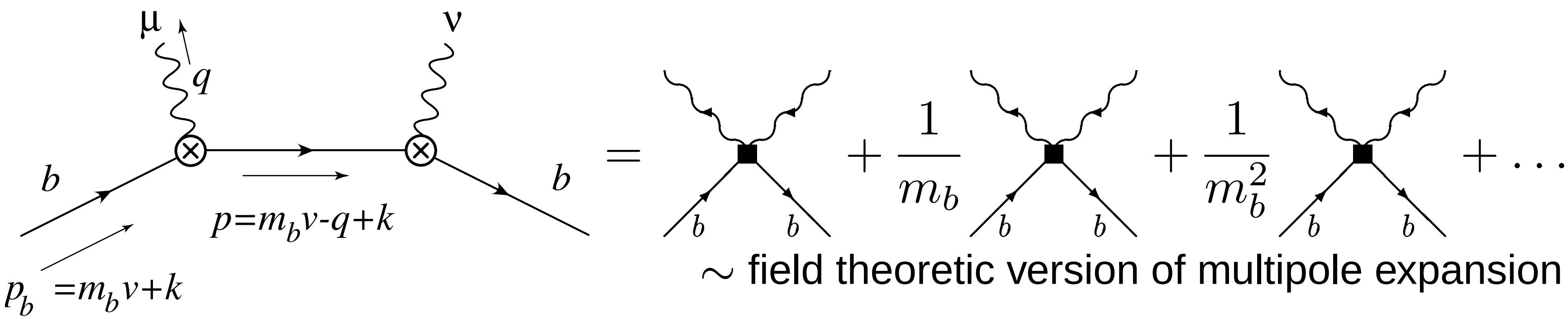
- If cuts needed, life gets more complicated:
  phase space cuts can enhance perturbative and nonperturbative corrections drastically

  E.g.: purely nonperturbative effects shift endpoint from $m_b/2$ to $m_B/2$



OPE: when should it converge?

- Can think of the OPE as expansion of forward scattering amplitude in $k \sim \Lambda_{\rm QCD}$



$\sim$ field theoretic version of multipole expansion

Time ordered product short distance dominated if expansion in k converges:

$$\frac{1}{(m_b v - q + k)^2} = \frac{1}{(m_b v - q)^2 + 2k\cdot(m_b v - q) + k^2}$$

Need to allow: $m_X^2 \gg E_X \Lambda_{\rm QCD} \gg \Lambda_{\rm QCD}^2$

OPE breaks down: m_X restricted to few $\times\,\Lambda_{\rm QCD}$ (trivial — resonances)

$m_X^2 \sim E_X \Lambda_{\rm QCD}$ but $E_X \gg \Lambda_{\rm QCD}$ (nontrivial — many states)

$\Rightarrow$ Design cuts to avoid these regions

5th Workshop on Higher Luminosity B Factory, Sep.24-26,2003 Izu,Japan

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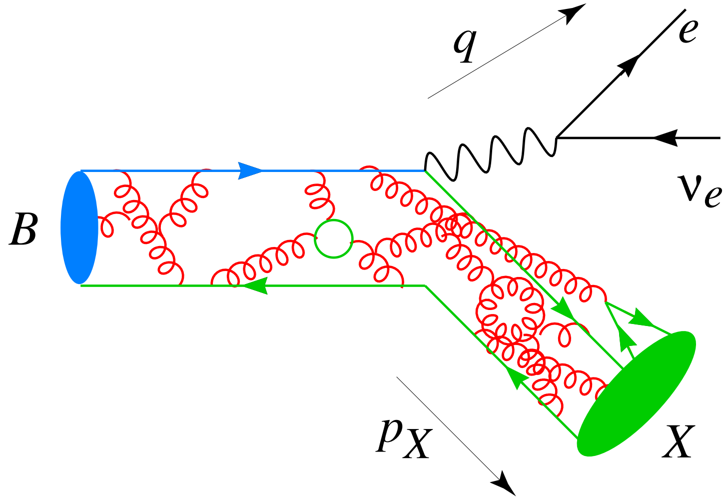
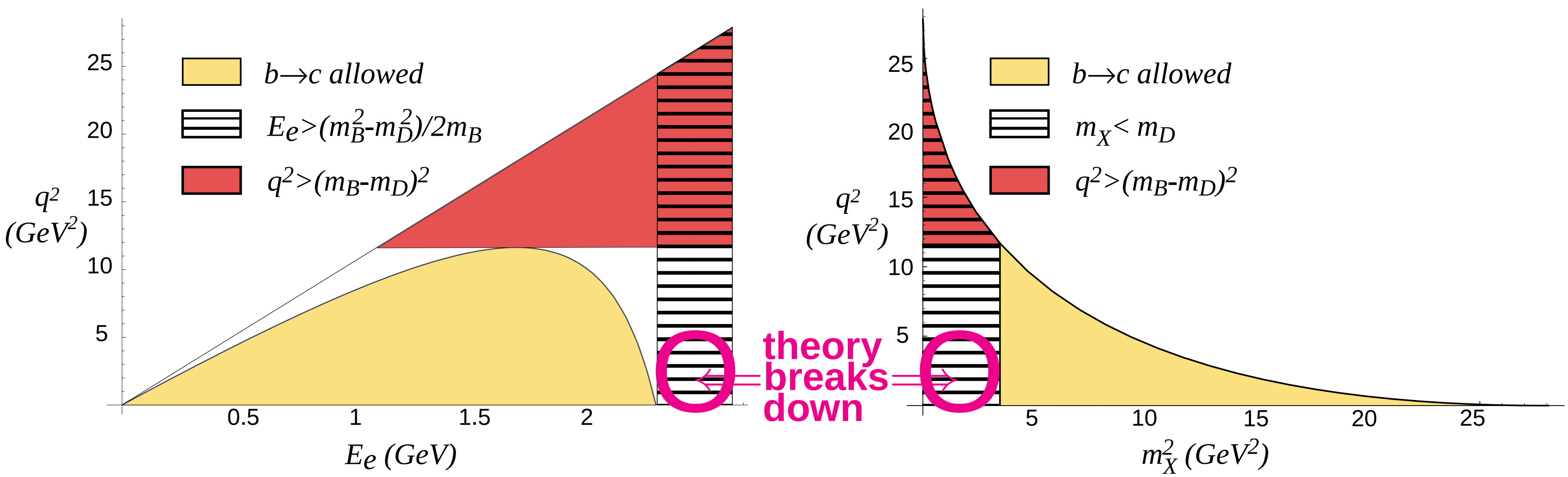
Inclusive $B \to X_u \ell \bar{\nu}$ phase space

Possible cuts to eliminate $B \to X_c \ell \bar{\nu}$ background:

- Lepton spectrum: $E_\ell > (m_B^2 - m_D^2)/2m_B$
- Hadronic mass spectrum: $m_X < m_D$
- Dilepton mass spectrum: $q^2 > (m_B - m_D)^2$
- Combinations of cuts





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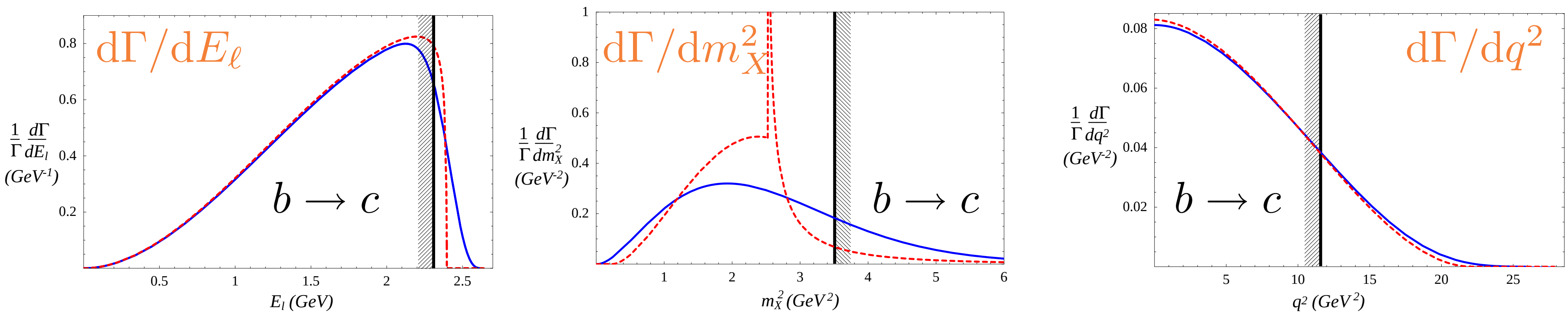
$B \to X_u \ell \bar{\nu}$ spectra

- Troubles come from the coincidence: $m_c^2 \approx m_b \times 400\,$MeV

$E_\ell > (m_B^2 - m_D^2)/2m_B$ or $m_X < m_D$ include $E_X \sim m_b/2 \;\Rightarrow\; m_X^2 \not\gg E_X \Lambda_{\rm QCD}$



— b quark decay to $\mathcal{O}(\alpha_s)$
— incl. "Fermi-motion" (model)

Theory happy →

← Experiment happy

Exp:	"easy"	need neutrino reconstruction	
Rate:	$\sim 10\%$	$\sim 80\%$	$\sim 20\%$
OPE:	infinite set of terms equally important		first few terms converge

Large E_ℓ and small m_X regions

Bad: infinite set of terms in OPE equally important (shape function)

Good: Fermi motion effects universal at leading order in $\Lambda_{\rm QCD}/m_b$
related to $B \to X_s\gamma$ photon spectrum (Neubert; Bigi, Shifman, Uraltsev, Vainshtein)

- $E_\ell > \frac{m_B^2 - m_D^2}{2m_B}$: NLO Sudakov logs resummed (Leibovich, Low, Rothstein)
  Operators other than O_7 in $B \to X_s\gamma$ (Neubert)
  Terms unrelated to $B \to X_s\gamma$ sizable (Leibovich, ZL, Wise; Bauer, Luke, Mannel)

- $m_X < m_D$: lot more rate, but nonperturbative input formally still $\mathcal{O}(1)$
  corrections smaller and inclusive description should be valid, but model dependence increases rapidly as $m_X^{\rm cut}$ lowered (Barger *et al.*; Falk, ZL, Wise; Bigi, Dikeman, Uraltsev)

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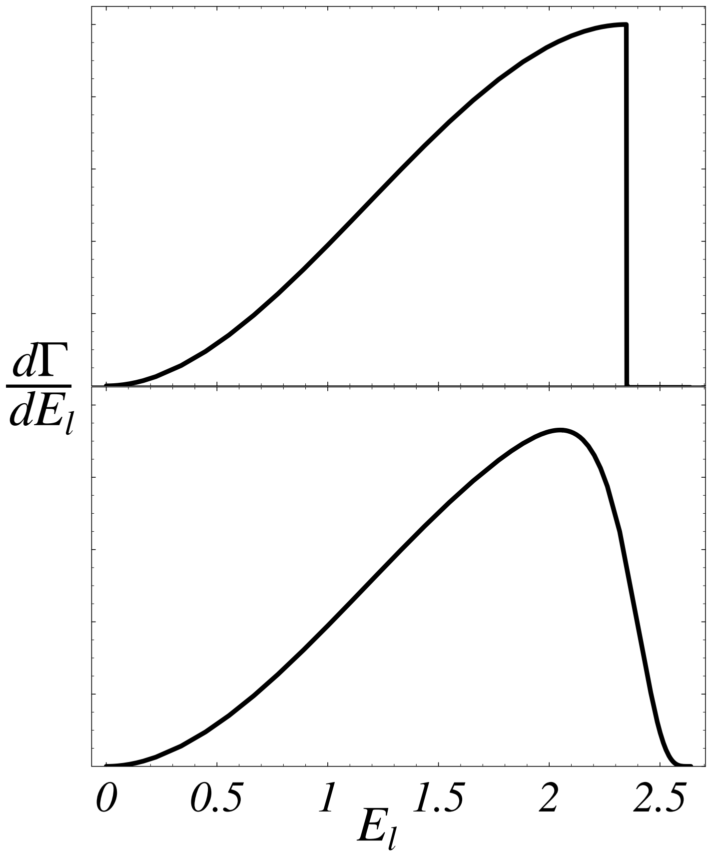
Lepton endpoint vs. $B \to X_s\gamma$

b quark decay spectrum

with a model for Fermi motion



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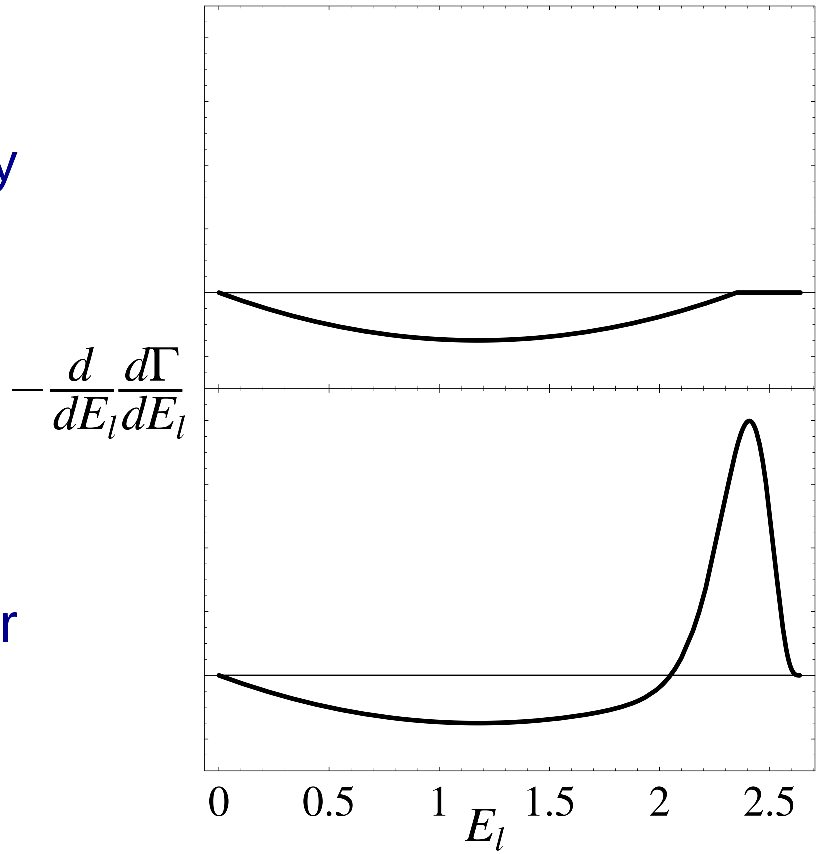

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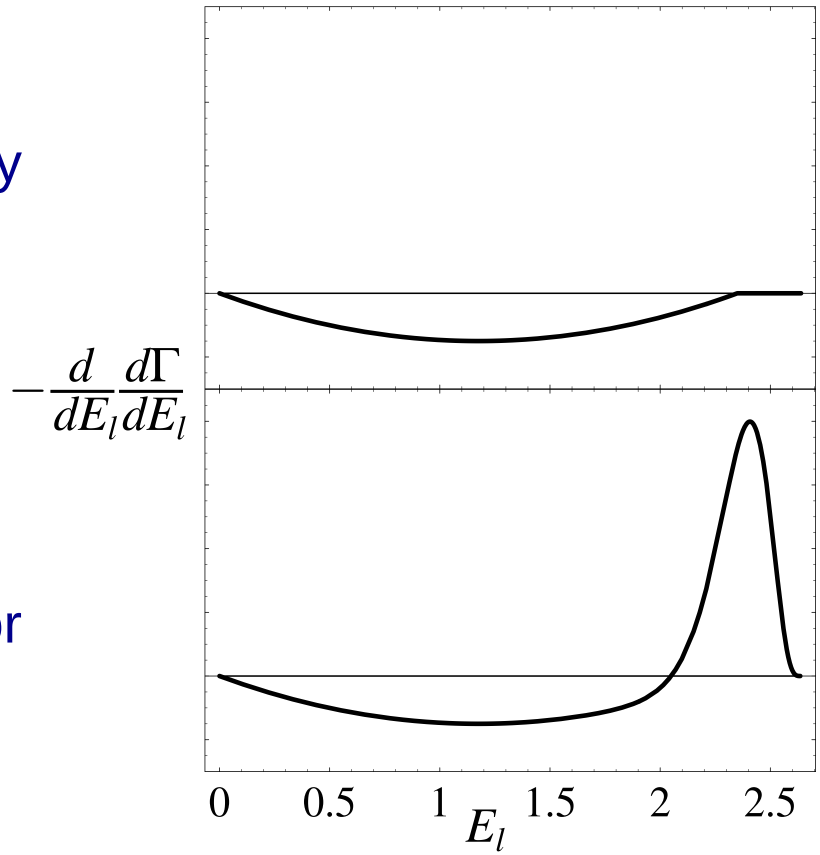
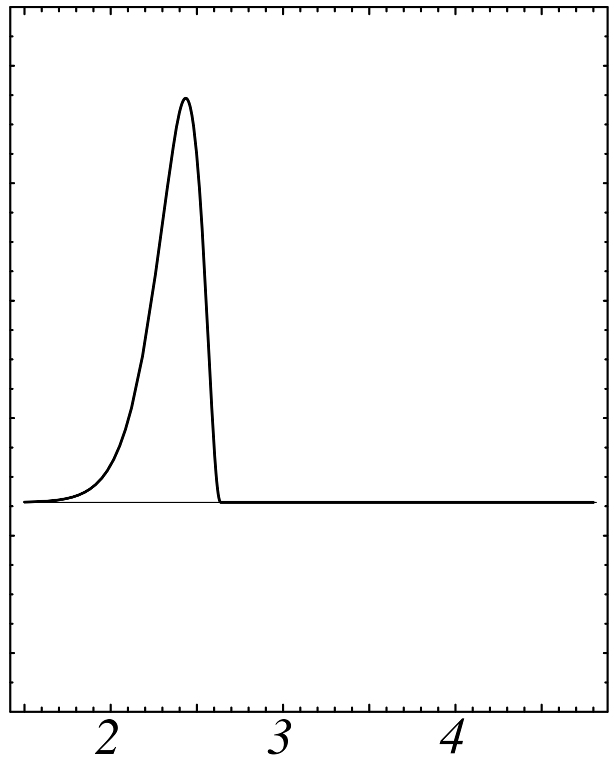


with a model for Fermi motion

difference:



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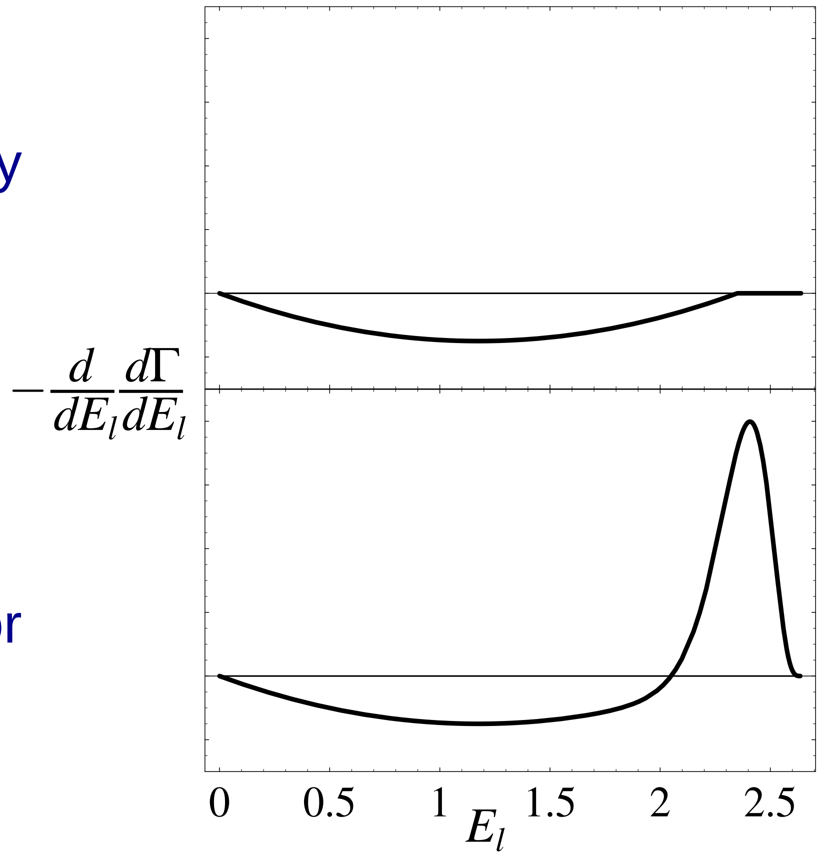

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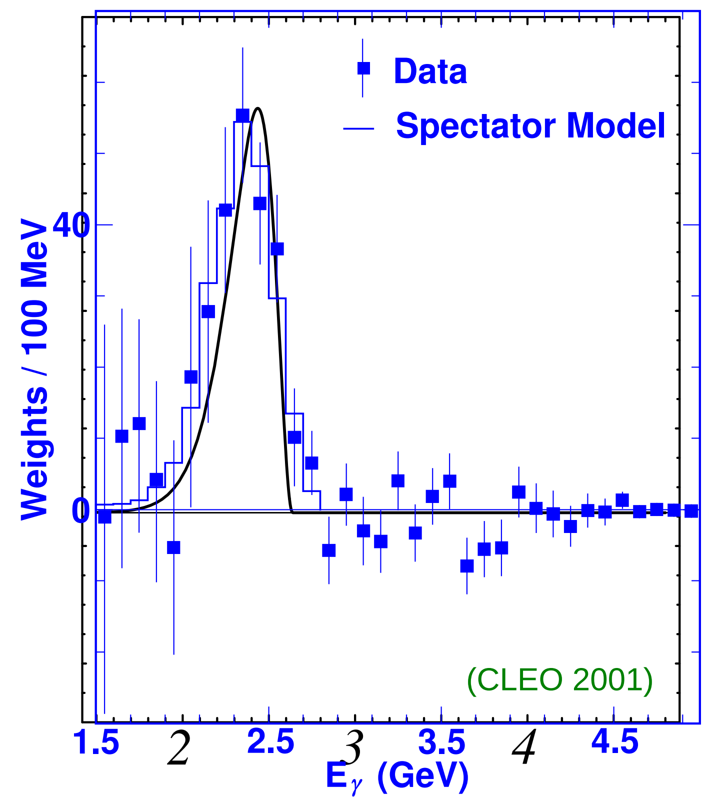

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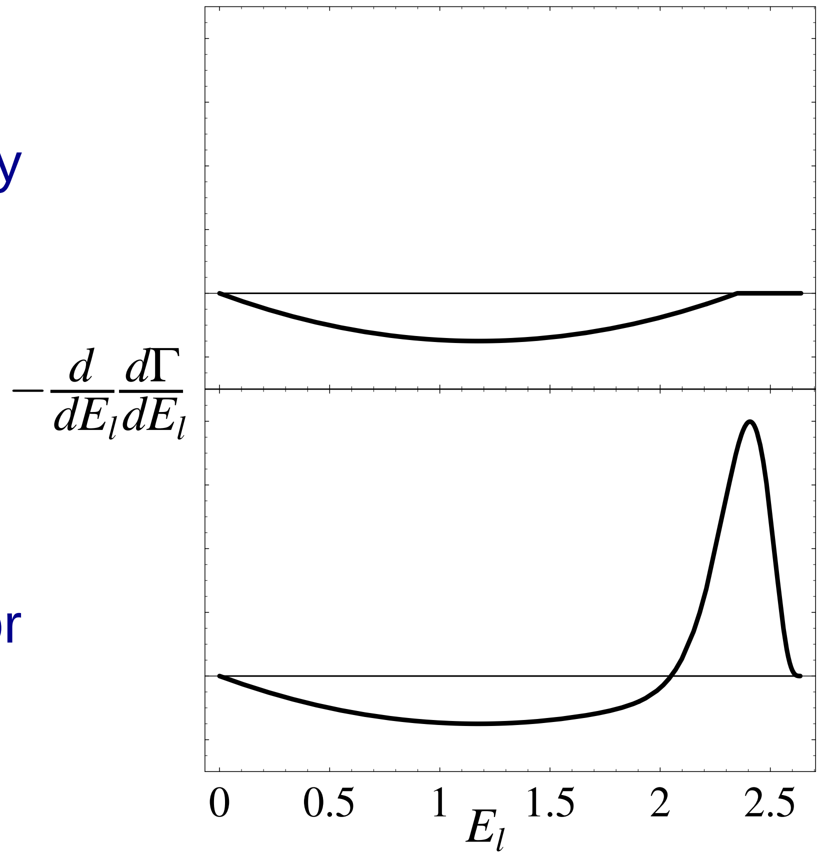

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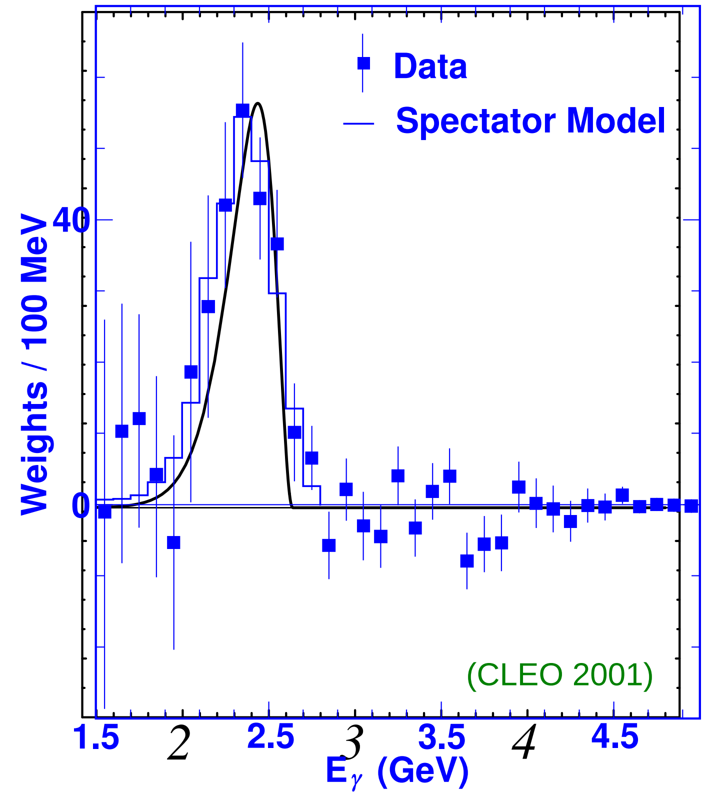


Limiting uncertainties: subleading corrections?
inclusive enough?

$\Downarrow$ (CLEO 2002)

$|V_{ub}| = (4.08 \pm 0.63) \times 10^{-3}$

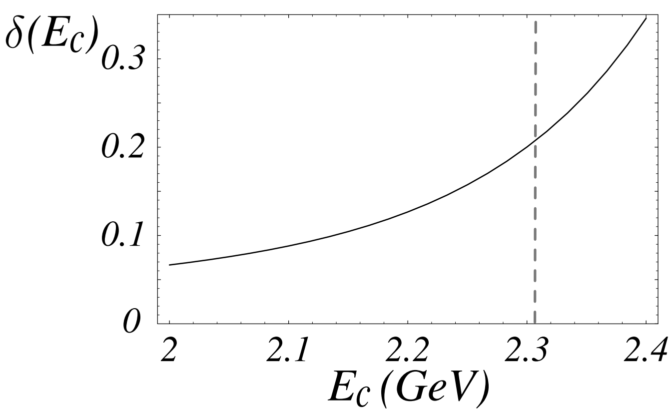
Sizable subleading twist effects

$$\frac{d\Gamma}{dy} = \frac{G_F^2\, m_b^5\, |V_{ub}|^2}{192\,\pi^3} \Bigg\{ y^2(3-2y)\, 2\theta(1-y) - \frac{\lambda_2}{m_b^2}\Big[11\,\delta(1-y) - 2y^2(6+5y)\theta(1-y)\Big]$$

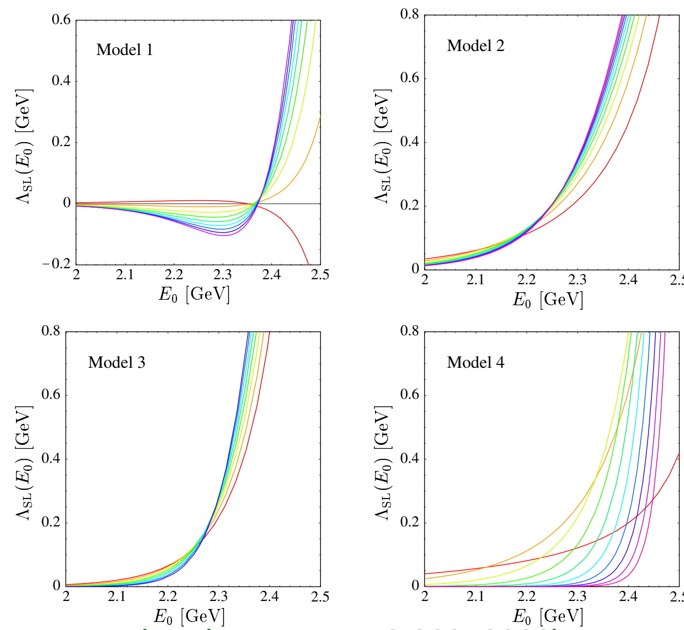
$$- \frac{\lambda_1}{m_b^2}\Big[\frac{1}{3}\,\delta'(1-y) + \frac{1}{3}\,\delta(1-y) - \frac{10}{3}\,y^3\theta(1-y)\Big] + \ldots \Bigg\}$$

Coefficient corresponding to **11** is **3** in $B \to X_s\gamma$ (Leibovich, ZL, Wise, PLB **539** 242, 2002)

Models: $\sim 15\%$ effect in $|V_{ub}|$ for $E_\ell^{\rm cut} = 2.3\,$GeV, decrease with $E_\ell^{\rm cut}$



(Bauer, Luke, Mannel, PLB **543** 261, 2002)

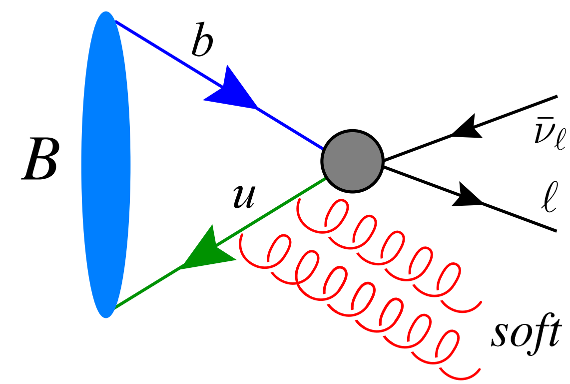


(Neubert, PLB **543** 269, 2002)

What part is “calculable”, what is the “uncertainty”?

Weak annihilation (sub-subleading)

- Bad news: $\mathcal{O}(\Lambda^3_{\rm QCD}/m_b^3)$ in rate, enhanced by $16\pi^2$
  ... concentrated at large E_ℓ, q^2, and small m_X^2
  $\Rightarrow$ enters all $|V_{ub}|$ extractions



(Bigi & Uraltsev; Voloshin; Leibovich, ZL, Wise)

Cancellation between: $\langle B|(\bar b\gamma^\mu P_L u)\,(\bar u\gamma_\mu P_L b)|B\rangle$

$\langle B|(\bar b P_L u)\,(\bar u P_L b)|B\rangle$

Estimated, with large uncertainty, as:

$$\mathcal{O}\left[16\pi^2 \times \left(\frac{\Lambda_{\rm QCD}}{m_b}\right)^3 \times \begin{pmatrix}\text{factorization}\\ \text{violation}\end{pmatrix}\right] \sim 0.03 \left(\frac{f_B}{200\,\text{MeV}}\right)^2 \left(\frac{B_2 - B_1}{0.1}\right)$$

If $\sim 3\%$ uncertainty in total rate, then $\sim 15\%$ in $|V_{ub}|$ from lepton endpoint, $\lesssim 10\%$ in $|V_{ub}|$ from large q^2 region, less for $m_X < m_D$ (more rate included)

- Constrain WA: compare D^0 vs. D_s SL widths, or V_{ub} from $B^\pm$ vs. B^0 decay

Large q^2 region

- Good: first few terms in OPE can be trusted (Bauer, ZL, Luke '00)

  full $\mathcal{O}(\alpha_s^2)$ result known (Czarnecki & Melnikov '01)

  Bad: expansion is more like in $\Lambda_{\rm QCD}/m_c$ and $\alpha_s(m_c)$ than at scale m_b (Neubert '00)

- Combined q^2 & m_X cuts: more rate, expansion behaves better (Bauer, ZL, Luke '01)

Cuts on $(q^2,\ m_X)$	included fraction of $b \to u\ell\bar\nu$ rate	error of $\lvert V_{ub}\rvert$ $\delta m_b = 80/30$ MeV
$6\,\text{GeV}^2,\ m_D$	46%	$8\%/5\%$
$8\,\text{GeV}^2,\ 1.7\,\text{GeV}$	33%	$9\%/6\%$
$(m_B - m_D)^2, m_D$	17%	$15\%/12\%$

Strategy: (i) reconstruct $p_\nu \Rightarrow q^2, m_X$; make cut on m_X as large as possible

(ii) for a given m_X cut, reduce q^2 cut to minimize overall uncertainty

Can get $30 - 40\%$ of events, even with cuts away from $b \to c$ region

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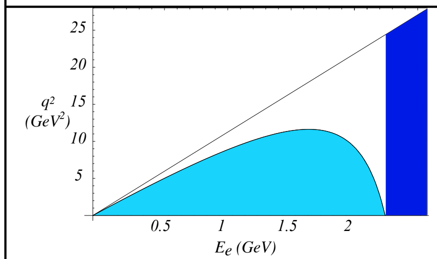
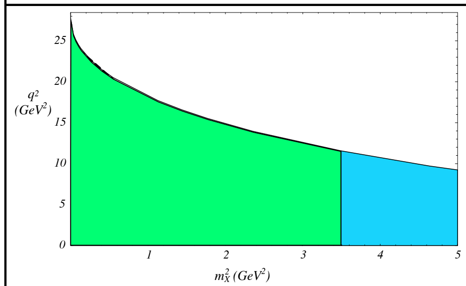
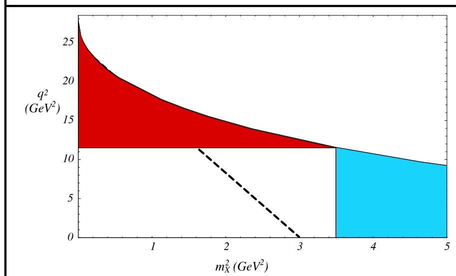
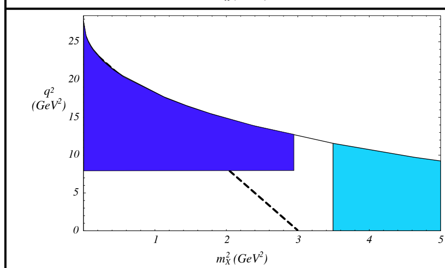
Summary for $B \to X_u \ell \bar{\nu}$ and $|V_{ub}|$

(From M. Luke)

cut	% of rate	good	bad
 $E_\ell > \frac{m_B^2 - m_D^2}{2m_B}$	~10%	don't need neutrino	- depends on $f(k^+)$ (and subleading corrections) - WA corrections may be substantial - reduced phase space - duality issues?
 $s_H < m_D^2$	~80%	lots of rate	- depends on $f(k^+)$ (and subleading corrections)
 $q^2 > (m_B - m_D)^2$	~20%	insensitive to $f(k^+)$	- very sensitive to m_b - WA corrections may be substantial - effective expansion parameter is $1/m_c$
 "Optimized cut"	~45%	- insensitive to $f(k^+)$ - lots of rate - can move cuts away from kinematic limits and still get small uncertainties	- less rate than pure m_X cut - gets worse as cuts are loosened

SLAC workshop: $2(-4)$ ab^{-1} seems enough to reach theory limit around $\sigma(|V_{ub}|) \sim 5\%$

Wishlist for $|V_{ub}|$

Exclusive: precise form factors, $B \to \ell\bar{\nu}$, unquenched lattice

Inclusive: all methods have some uncertainties hard to compute from first principles — need lot of data to constrain / estimate these

- get the cuts as close to the charm threshold as possible
- constrain WA by comparing $|V_{ub}|$ from $B^{\pm}$ vs. B^0, or D^0 vs. D_s SL widths
- improve measurement of $B \to X_s\gamma$ photon spectrum (lower cut) and try to use it directly instead of through parameterizations
- full α_s^2 corrections (beyond $\alpha_s^2\beta_0$) known only for total rate and q^2 spectrum, not for other distributions
- precise determination of m_b — rate $\propto m_b^5$, even stronger sensitivity with cuts

Few comments on $|V_{ts}|$ and $|V_{td}|$

$b \longrightarrow d\gamma$ decays

- I'll concentrate on accuracy of SM predictions, since that will limit sensitivity to NP

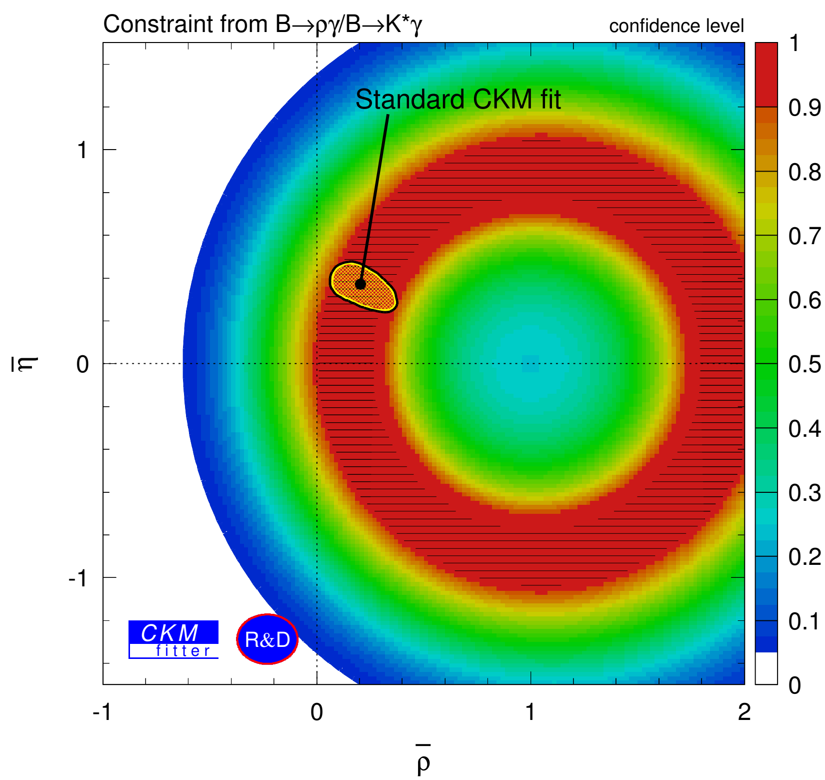
In the SM:

$$R = \frac{\Gamma(B \to X_d\gamma)}{\Gamma(B \to X_s\gamma)} = \left|\frac{V_{td}}{V_{ts}}\right|^2 \times (1 + \text{corrections})$$

... corrections characterized by typical $SU(3)$ breaking in exclusive modes, and by m_s/m_b in inclusive rates

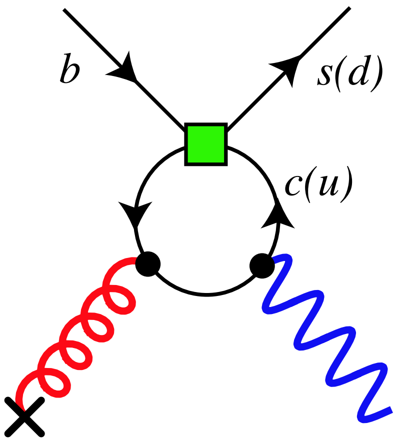
$B \to \rho\gamma$: should be observed in 1–2 years

$B \to X_d\gamma$: SM rate $\sim 1 \times 10^{-5}$; the difficulty is picking signal out from $B \to X_s\gamma$ background



Long distance effects

- Unlike semileptonic decays, inclusive radiative decays are not determined entirely by short distance physics



In $B \to X_s \gamma$, can expand c loop contribution in powers of $\Lambda_{\rm QCD} m_b / m_c^2$, giving $\sim 3\%$ correction to rate (Voloshin; ZL, Randall, Wise)

u quark loops are long distance — cannot perform an OPE

In $B \to \rho\gamma$ VMD and LCSR suggest $\lesssim 10 - 15\%$ effects

Other issues: Does $s\bar{s}$ production from vacuum in $B \to X_d \gamma$ decay mess up vetoing on kaons? Is it needed? How big an effect is this?

Photon fragmentation from $b \to u\bar{u}d$ transition is large at low E_γ

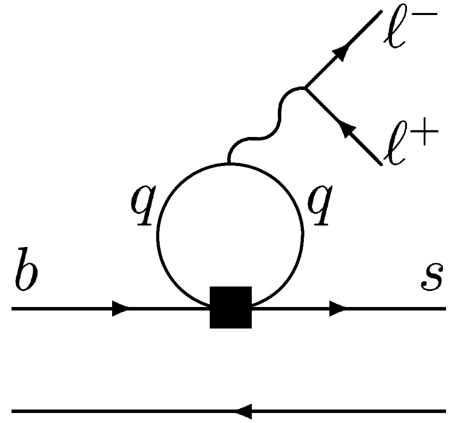
How large a cut is required to control this effect?

$b \to d(s)\ell^+\ell^-$ decays

- Kinematic variable q^2 allows study of more observables; recoil need not be large

Incl.: precise 2-loop calculations — Excl.: not harder in lattice QCD than $b \to u\ell\bar{\nu}$

$$\mathcal{B}(B \to \psi X_s) \sim 4 \times 10^{-3}$$
$$\downarrow$$
$$\mathcal{B}(\psi \to \ell^+\ell^-) \sim 6 \times 10^{-2}$$



Combined BR: $\mathcal{B}(B \to X_s\ell^+\ell^-) \sim 2 \times 10^{-4}$

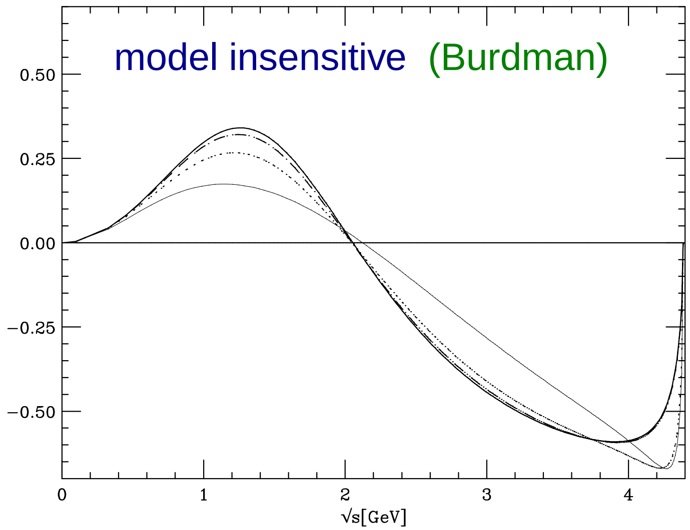
This is ~ 30 times the short distance contribution!

Averaged over a large region of q^2, the $c\bar{c}$ loop expected to be dual to $\psi + \psi' + \ldots$
This is what happens in $e^+e^- \to$ hadrons, in τ decay, etc., but NOT here

Is it consistent to "cut out" the ψ and ψ' regions and then compare data with the short distance calculation? (Maybe..., but understanding is unsatisfactory)

Richness: many more observables

- Forward-backward asymmetry insensitive to the precise values of form factors:



Changes sign (in $B \to K^* \ell^+ \ell^-$):

$$C_9^{\rm eff}(q_0^2) = -C_7^{\rm eff}\,\frac{2 m_B m_b}{q_0^2} \times \left[1 + \mathcal{O}\left(\text{“}\alpha_s\text{”}, \frac{\Lambda_{\rm QCD}}{m_b}\right)\right]$$

$[q^2 = s\, m_b^2 = (p_{\ell^+} + p_{\ell^-})^2]$

1 or $\mathcal{O}(\alpha_s)$ as well?

The “α_s” terms computed (Beneke, Feldman, Seidel)

Measurement of C_9 very sensitive to NP

Theory needs to develop further to reliably understand SM uncertainties

- Same comment holds for isospin breaking (e.g., B^0 vs. $B^\pm \to K^*\gamma,\ \rho\gamma$)
  Arises due to to power suppressed effects, which are not fully understood yet

Summary for $|V_{td}|$ and $|V_{ts}|$

- $b \to q\gamma$ ($q = d, s$) probes different short distance physics than B_q–$\overline{B}_q$ mixing
- $b \to q\ell^+\ell^-$ probes different short distance physics than mixing and $b \to q\gamma$
- $b \to s\nu\bar{\nu}$ ....

  Only measurable four-Fermi interaction involving three 3rd generation fermions
- $B_{d,s} \to \ell^+\ell^-$ ....

- Accurate $|V_{td}|$ measurement challenging both theoretically and experimentally
- $b \to s$ processes are a huge background

  (“Yesterday’s discovery is today’s calibration, and tomorrow’s background”)
- Precise multi-loop calculations exist, but long distance physics poorly understood, limits theoretical precision

Conclusions

Summary

- Inclusive decays are in principle very clean theoretically, but can get complicated by experimental cuts and long distance contributions
- Progress in $|V_{ub}|$ requires neutrino reconstruction with large statistics (inclusive), or/and precise spectra and unquenched lattice (exclusive or $B \to \ell\bar{\nu}$)
- For both $|V_{ub}|$ and $|V_{cb}|$, important to pursue both inclusive and exclusive
- Theoretical limit for $|V_{ub}|$ and $|V_{cb}|$ appear to be about 4% and 1% (without lattice)

- Progress in understanding exclusive heavy $\to$ light form factors for $q^2 \ll m_B^2$
  $B \to \pi/\rho\,\ell\bar{\nu},\ K^*\gamma,\ K^{(*)}\ell^+\ell^-$ below the $\psi \Rightarrow$ increase sensitivity to new physics
  ... will impact our understanding of charmless nonleptonic decays
- $|V_{td}|$ from rare decays is challenging but important

Last comment

Thank you for not asking me to address whether there is a compelling physics case for a super-B-factory in the LHC(B) era

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Thank you for not asking me to address whether there is a compelling physics case for a super-B-factory in the LHC(B) era

... just one point:

If new phenomena are seen at the LHC, "low energy high energy physics" may be crucial not only to understand what the new phenomena are (some couplings may only be measurable in B decays, similar to $|V_{ts}|$ and $|V_{td}|$), but what it is not

Few slides on $|V_{cb}|$

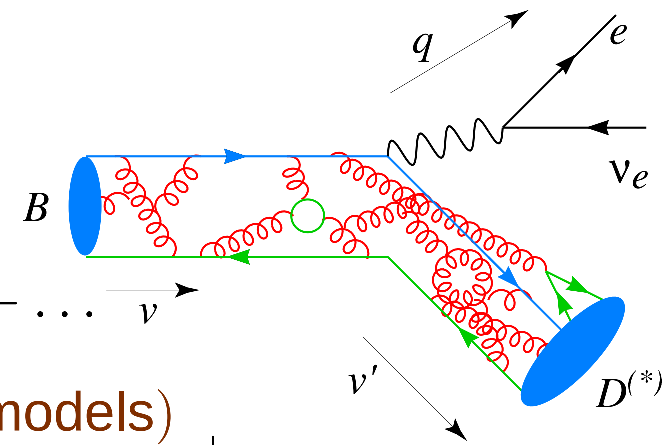
$|V_{cb}|$ — exclusive

$|V_{cb}|$ from $B \to D^{(*)}\ell\bar{\nu}$

- Heavy Quark Symmetry: brown muck only feels $v \to v'$ (not $m_b \to m_c$ or $\vec{s}_b \to \vec{s}_c$)

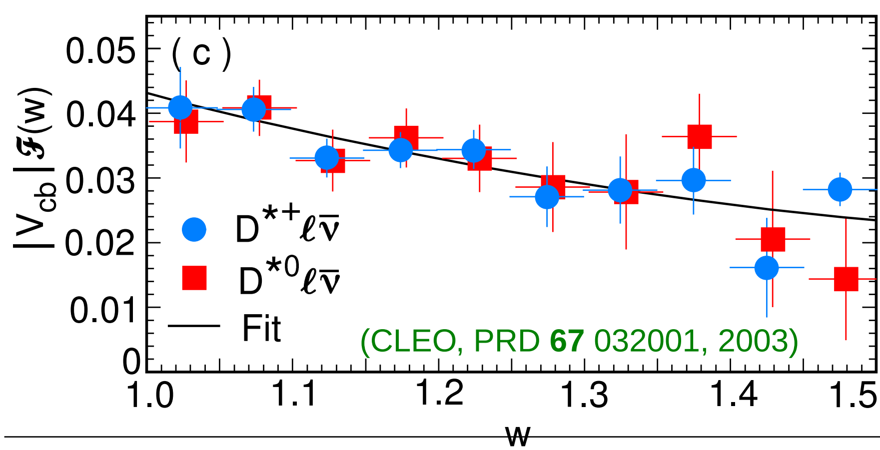
$$\frac{\mathrm{d}\Gamma(B \to D^{(*)}\ell\bar{\nu})}{\mathrm{d}w} = (\dots)\,(w^2-1)^{3(1)/2}\;|V_{cb}|^2\,\mathcal{F}^2_{(*)}(w)$$

$\nwarrow w \equiv v \cdot v'$ $\qquad$ $\nearrow$ Isgur-Wise function $+\dots$



$$\mathcal{F}(1) = 1_{\mathrm{Isgur-Wise}} + 0.02_{\alpha_s,\alpha_s^2} + \frac{\text{(lattice or models)}}{m_{c,b}} + \dots$$

$$\mathcal{F}_*(1) = 1_{\mathrm{Isgur-Wise}} - 0.04_{\alpha_s,\alpha_s^2} + \frac{0_{\mathrm{Luke}}}{m_{c,b}} + \frac{\text{(lattice or models)}}{m^2_{c,b}} + \dots$$



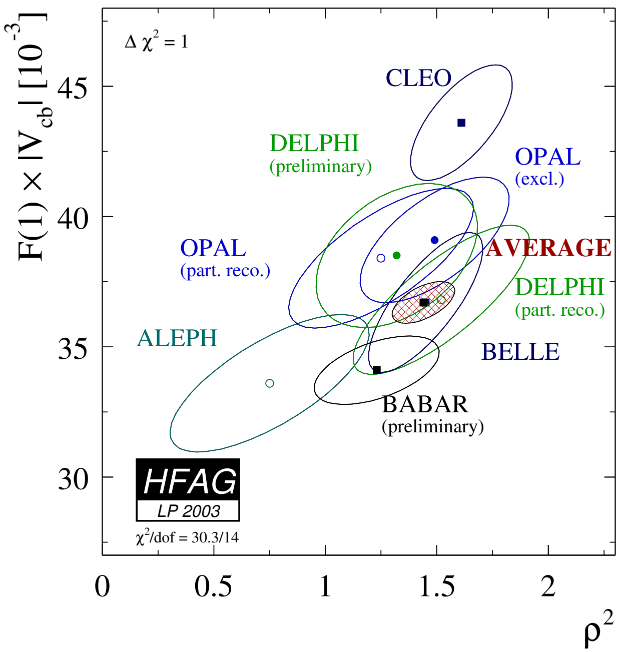
Experiments measure: $|V_{cb}| \times \mathcal{F}_*(w)$

Theory issues: (i) $\mathcal{F}_*(1)$, (ii) shape

Theory predicts: $\mathcal{F}_*(1) = 0.91 \pm 0.04$

[$1 - \mathcal{F}_*(1)$: lattice, sum rules, models]

$|V_{cb}|$ from $B \to D^{(*)} \ell \bar\nu$ (cont.)



$|V_{cb}|$ sensitive to shape of $\mathcal{F}_*(w)$: fits use analyticity constraint (slope vs. curvature at $w = 1$)

(Boyd, Grinstein, Lebed; Caprini, Lellouch, Neubert)

$\Rightarrow |V_{cb}| = (42.1 \pm 1.1_{\rm exp} \pm 1.9_{\rm th}) \times 10^{-3}$ (hep-ph/0304132)

... HQS relates $B \to D$ and D^* shapes (Grinstein, ZL)

... Sum rule relations to $B \to D^{**} \ell \bar\nu$

- New bounds on derivatives of Isgur-Wise function (Le Yaouanc, Oliver, Raynal, PLB **557** 207, 2003)

$$(-1)^n \, \xi^{(n)}(1) \geq \frac{2n+1}{4} \left[(-1)^{n-1} \, \xi^{(n-1)}(1) \right] \quad \Rightarrow \quad (-1)^n \, \xi^{(n)}(1) \geq \frac{(2n+1)!!}{2^{2n}}$$

- Questions: (i) how to best use constraints on shape?

  (ii) if $0^+, 1^+$ D states were $\sim 2.22, 2.36$ GeV with $\Gamma \sim 300$ MeV, could it affect $|V_{cb}|$?

$|V_{cb}|$ — inclusive

Issues relevant for $B \to X_c \ell \bar{\nu}$

- Total semileptonic rate precisely calculable:

$$|V_{cb}| \sim \left[42 \pm (\text{error mostly in } m_b \;\&\; \lambda_1)\right] \times 10^{-3} \left(\frac{\mathcal{B}(B \to X_c \ell \bar{\nu})}{0.105} \, \frac{1.6\,\text{ps}}{\tau_B} \right)^{1/2}$$

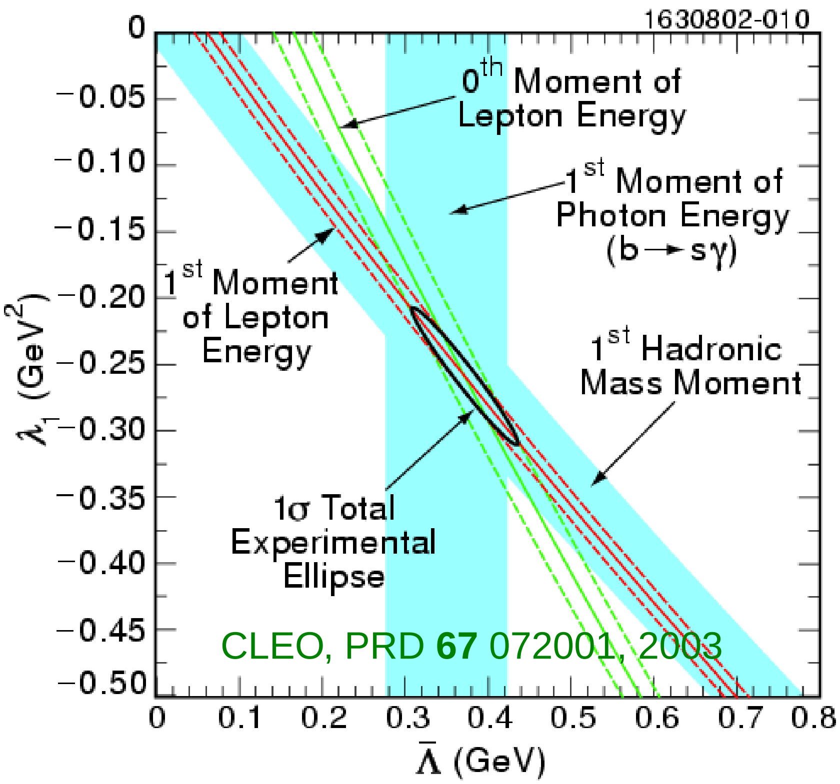
  - Values of m_b and λ_1?
  - Four more nonperturbative parameters at $\mathcal{O}(\Lambda^3_{\text{QCD}}/m_b^3)$
  - Theoretical uncertainties (perturbation theory, masses)
  - In restricted regions, OPE can break down (especially relevant for $|V_{ub}|$)
  - Implicit assumption: quark-hadron duality

- Address these and determine unknown param's and $|V_{cb}|$ from shape variables:

"Moments:" $$\langle X \rangle = \langle X \rangle_{\text{parton}} + \frac{0}{m_b} F_\Lambda + \frac{\lambda_i}{m_b^2} F_{\lambda_i} + \frac{\rho_i}{m_b^3} F_{\rho_i} + \ldots$$

$\langle X \rangle_{\text{parton}}$ and each F_i has an expansion in α_s and depends on m_c/m_b

Shape variables and global fits



They allow: (i) precision extractions of m_b and HQET matrix elements

(ii) testing validity of the whole approach

Results: (Bauer, ZL, Luke, Manohar, PRD **67** 054012, 2003)

$$|V_{cb}| = (40.8 \pm 0.9) \times 10^{-3}$$

$$m_b^{1S} = (4.74 \pm 0.10)\ \text{GeV}$$

$$\overline{m}_b(\overline{m}_b) = (4.22 \pm 0.09)\ \text{GeV}$$

(Similar fits by Battaglia *et al.*, PLB **556** 41, 2003)

Theoretical uncertainties dominate $\Rightarrow$ their correlations are essential when many observables determine hadronic parameters and $|V_{cb}|$

Theoretical limitations: setting all experimental errors to zero, we would obtain

$$\sigma(|V_{cb}|) = 0.35 \times 10^{-3} \qquad \sigma(m_b^{1S}) = 35\ \text{MeV}$$

Summary for $|V_{cb}|$

- Current precision is already at the $\sim 4\%$ level
- Limiting theory errors — inclusive: m_b and matrix elements
  exclusive: $\mathcal{F}_{(*)}(1)$ and shape
- "Duality" hard to quantify — cross-checks are important
- Inclusive and exclusive determinations both important
- If all caveats resolved, $\sigma(|V_{cb}|)$ may be reduced to $\sim 1\%$ level

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Possible improvements:

– better consistenty and precision of m_X and E_ℓ moments in $B \to X_c \ell \bar{\nu}$

– measurement of $B \to X_s \gamma$ to lower E_γ

– full α_s^2 calculation of spectra (surprises unlikely)

– better understanding of $B \to D^{(*)} \ell \bar{\nu}$ shapes; unquenched lattice form factors

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