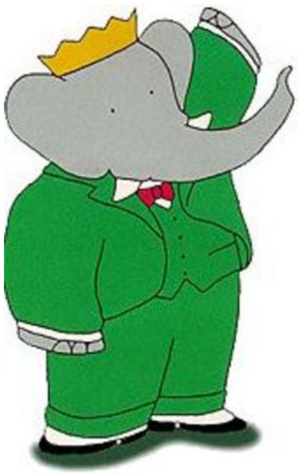
BaBar, Simba & dark matter

Zoltan Ligeti



- Status and future of flavor physics
- Improvements in inclusive $B \to X_s\gamma$ and $B \to X_u\ell\bar{\nu}$
- A somewhat unusual search in $B \to K^{(*)}\ell^+\ell^-$

Disclaimers

- A few weeks ago when I got a phone call about the report from the intensity frontier review, I thought I'd get dis-invited and would not have to prepare this talk

Disclaimers

- A few weeks ago when I got a phone call about the report from the intensity frontier review, I thought I'd get dis-invited and would not have to prepare this talk

  This has not happened, so I thought I should tell you my opinions

Disclaimers

- A few weeks ago when I got a phone call about the report from the intensity frontier review, I thought I'd get dis-invited and would not have to prepare this talk

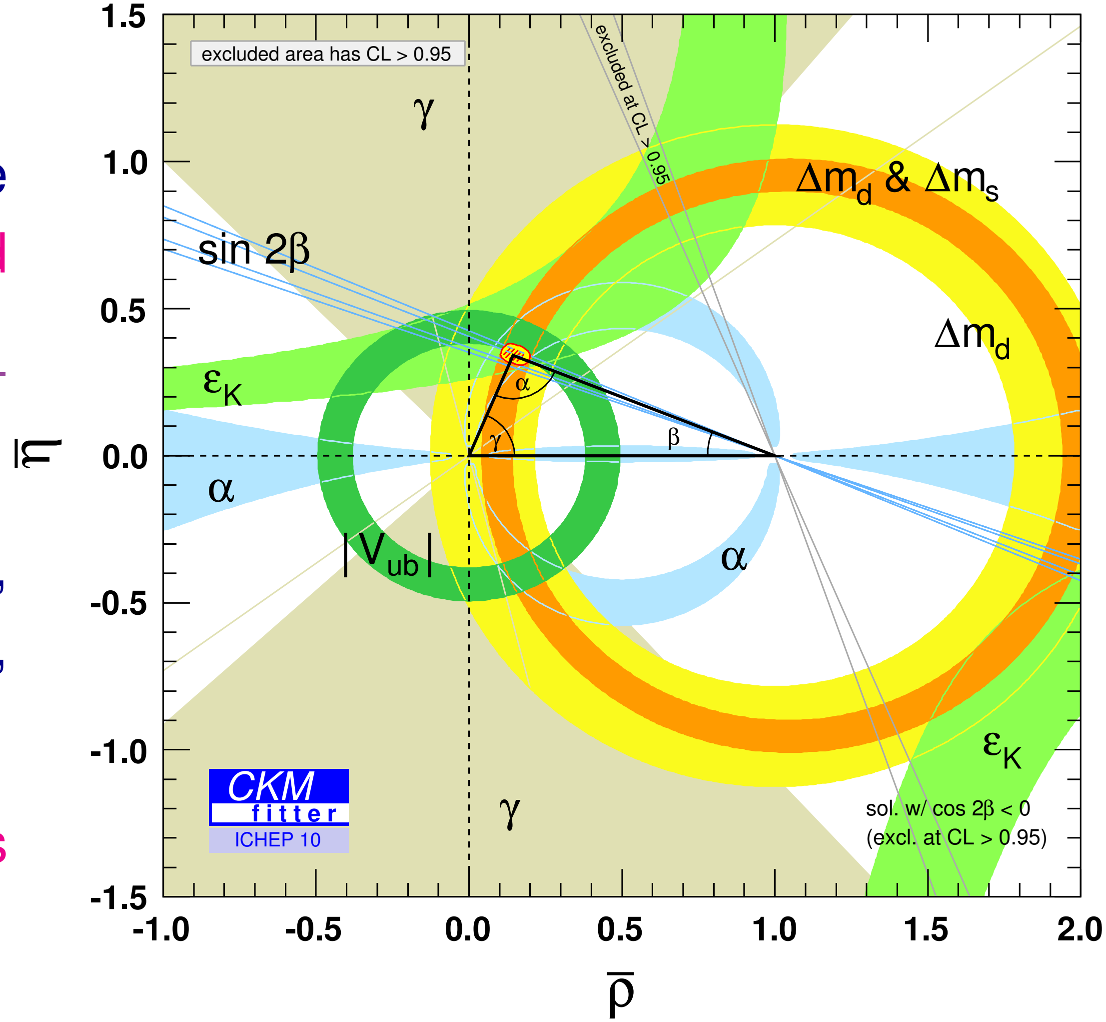
  This has not happened, so I thought I should tell you my opinions

- To me it's obvious that an order of magnitude (or more) improved sensitivity to plausible new short distance physics is worth pursuing

Many people disagree... I don't get it.

The standard model CKM fit

- Very impressive accomplishments
- The level of agreement between the measurements often misinterpreted
- Increasing the number of parameters can alter the fit completely
- Plausible TeV scale NP scenarios, consistent with all low energy data, with sizable flavor physics effects
- CKM is inevitable; the question is not if it's correct, but is it sufficient?



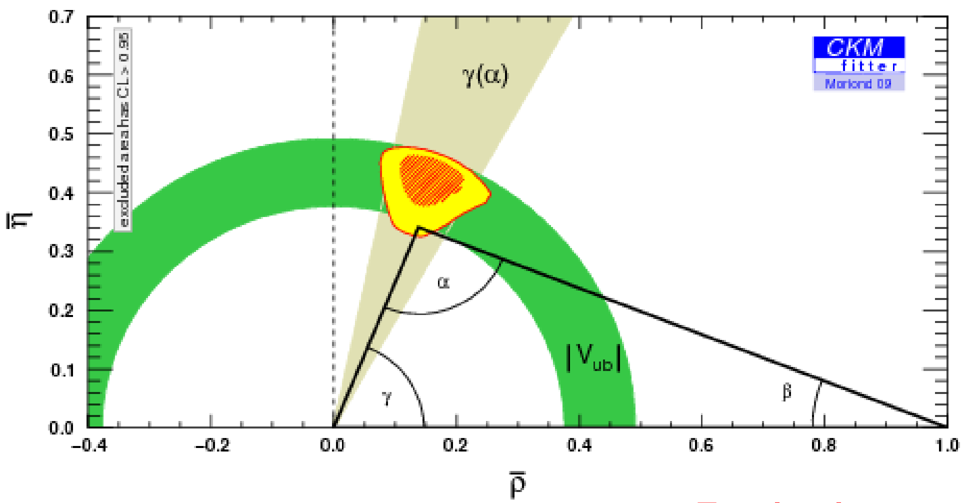
- It will require a lot more data to answer this question at the $< 10\%$ level

An example: new physics in $B-\overline{B}$ mixing

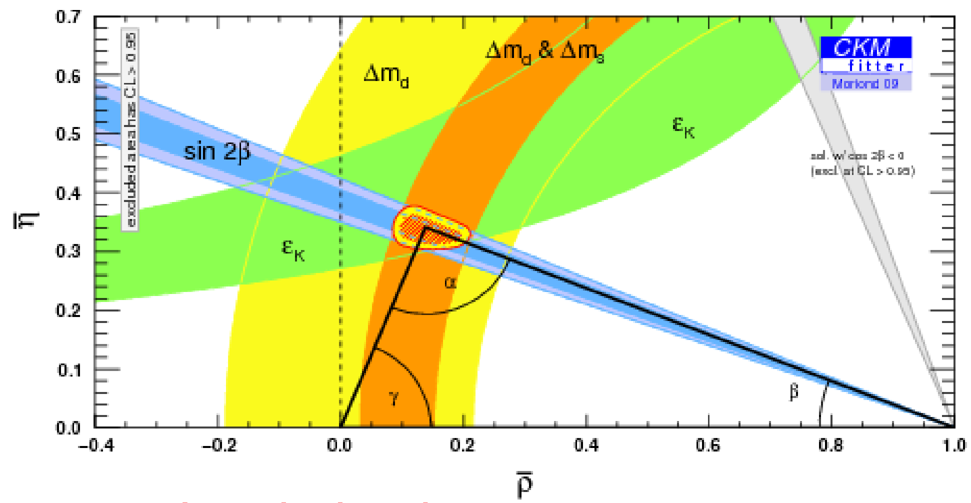
- Large class of models: (i) 3×3 CKM matrix is unitary
  (ii) Tree-level decays dominated by SM

Two parameters for each neutral meson: $M_{12} = M_{12}^{\rm SM}(1 + h\, e^{2i\sigma}) = M_{12}^{\rm SM}(r_d\, e^{2i\theta_d})$

- Tree-level CKM constraints unaffected   Observables sensitive to NP in mixing



Tree-level



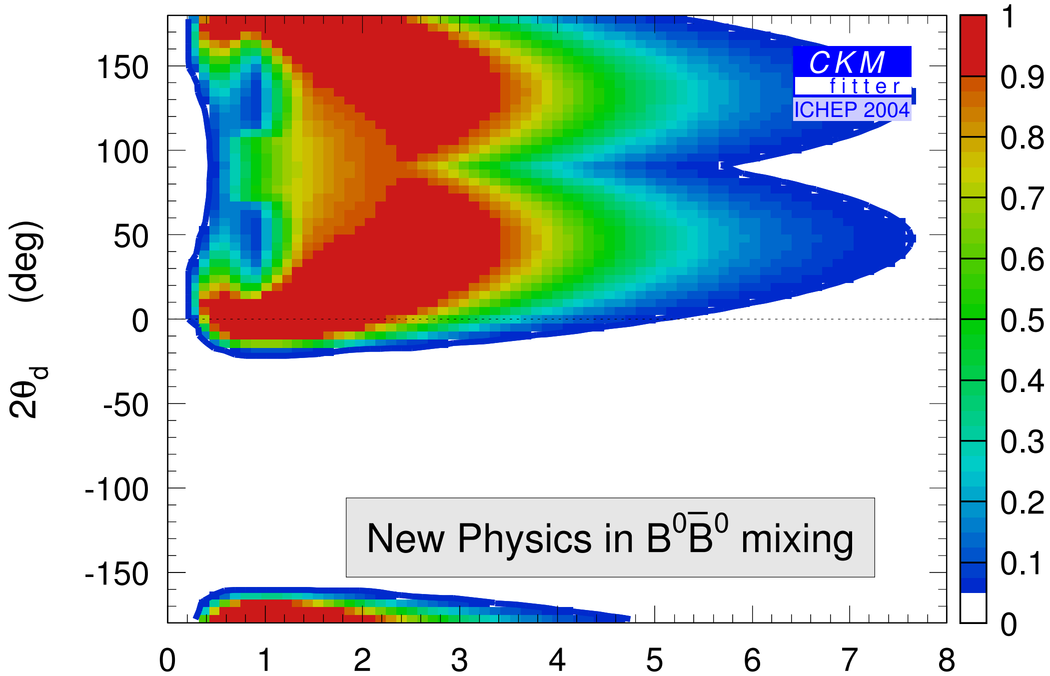
Loop-dominated

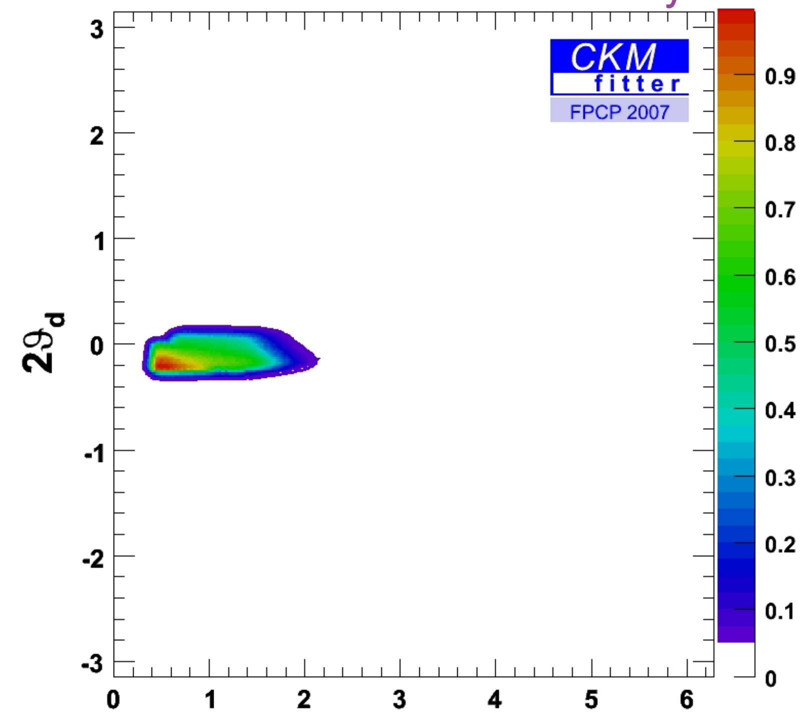
- Isolating modest new physics contributions requires many measurements

The one-page summary of BaBar & Belle

- Strong constraints on NP in many FCNC amplitudes — much more progress in this and more interesting than just the uncertainties of the SM parameters

Qualitative change before vs. after 2004 — the real justification for the Nobel Prize in my mind



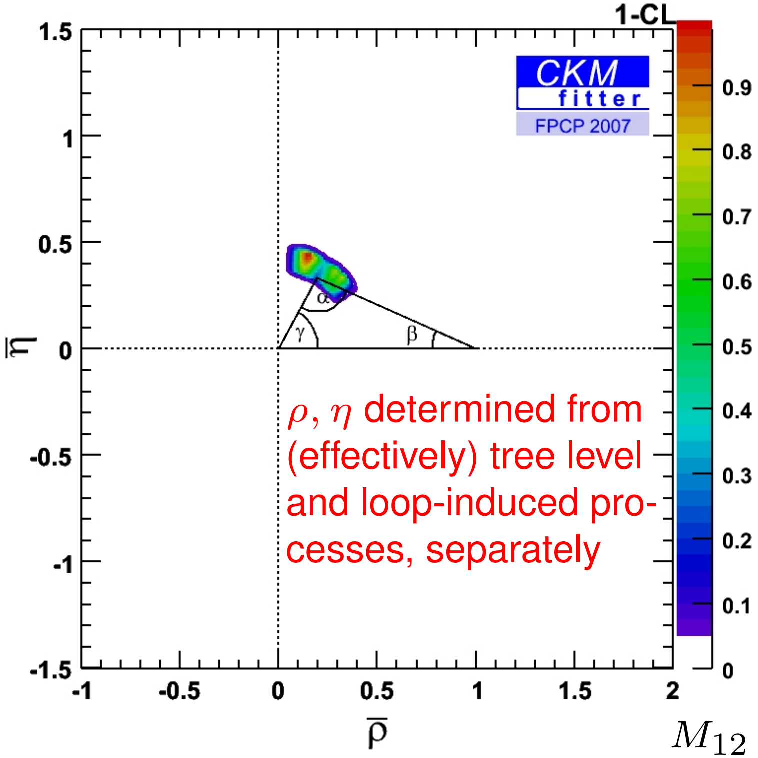


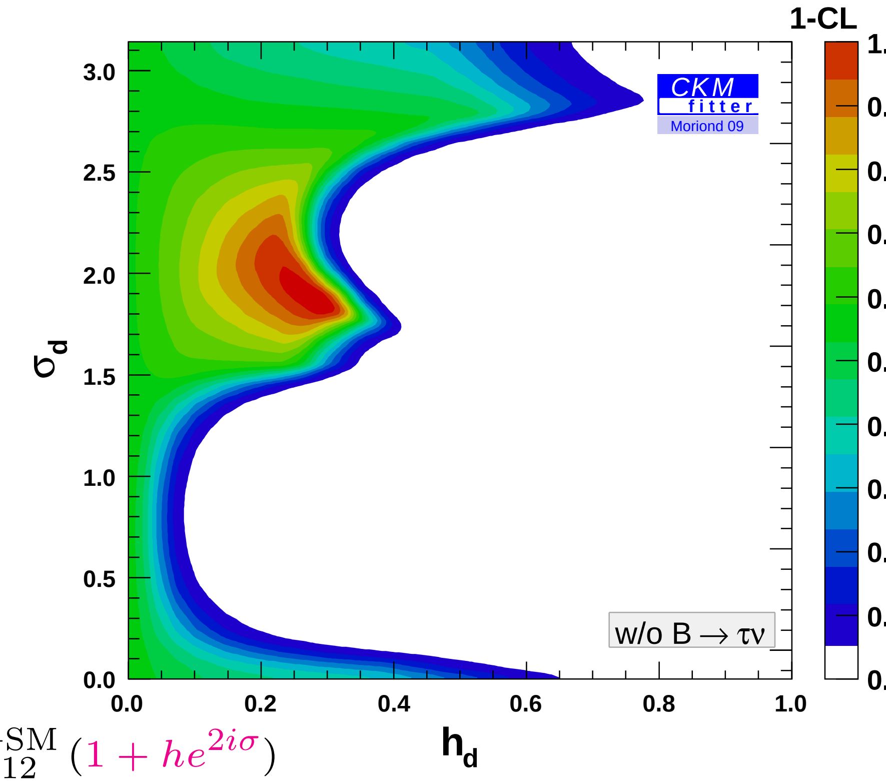
$$M_{12} = M_{12}^{\rm SM}\,(r_d\, e^{2i\theta_d}) = M_{12}^{\rm SM}\,(1 + h_d\, e^{2i\sigma_d})$$

- Despite huge progress $\sim 20\%$ NP contribution to most loop processes still allowed

Constraints on new physics in B_d^0 mixing

- Overconstraining measurements (tree vs. loop) are crucial to bound new physics





$$M_{12} = M_{12}^{\rm SM}\,(1 + h e^{2i\sigma})$$

Only the SM-like region is allowed, even in the presence of NP in mixing

NP ~ SM is still allowed, approaching NP ≪ SM unless $\sigma_d = 0$ (mod $\pi/2$)

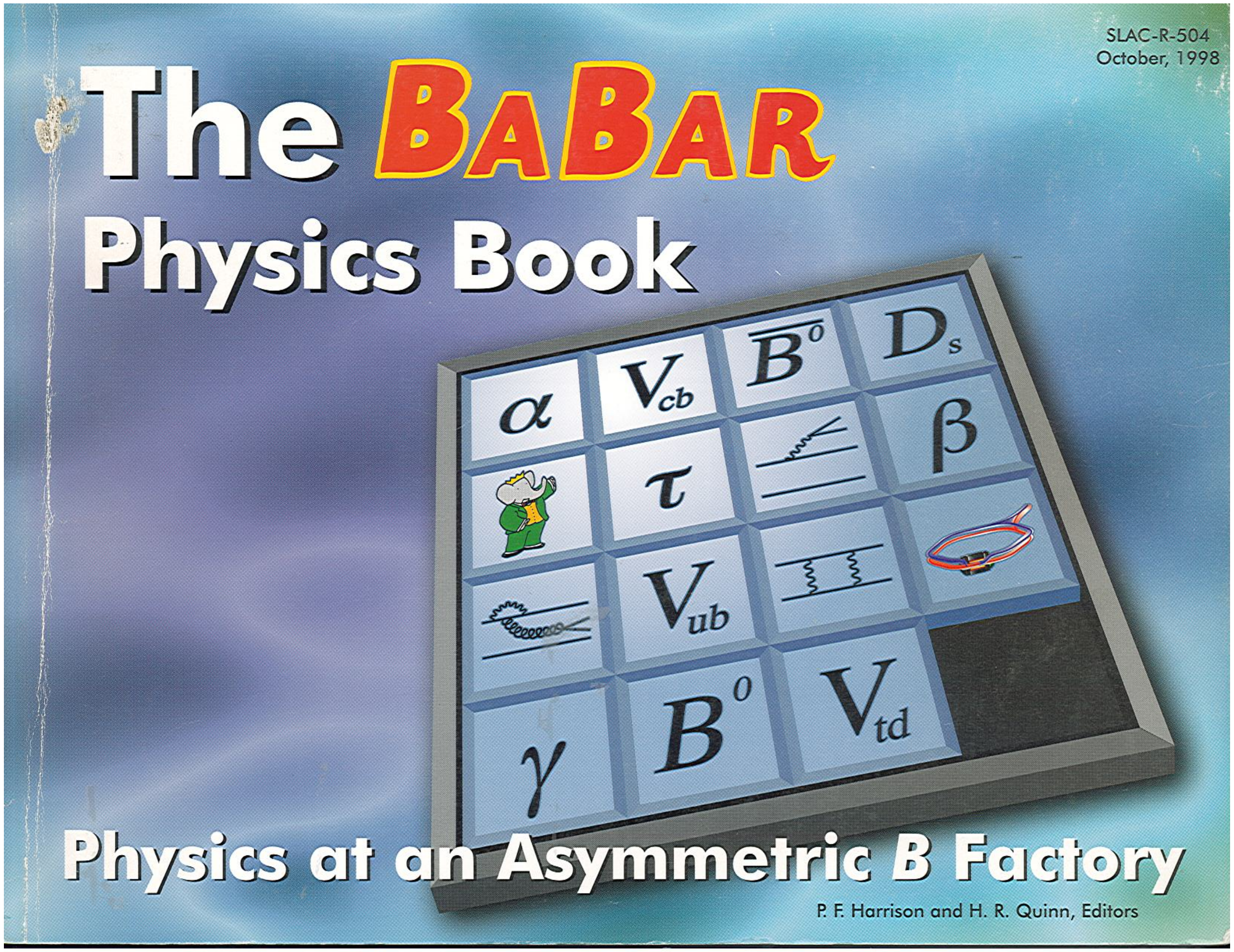
- Question: How small is h? Is $h \lesssim 0.1$? [assume $h \sim (4\pi v/\Lambda_{\rm flav.})^2$ — is $\Lambda_{\rm flav.} \gg \Lambda_{\rm EWSB}$?]

Where do we go from here?

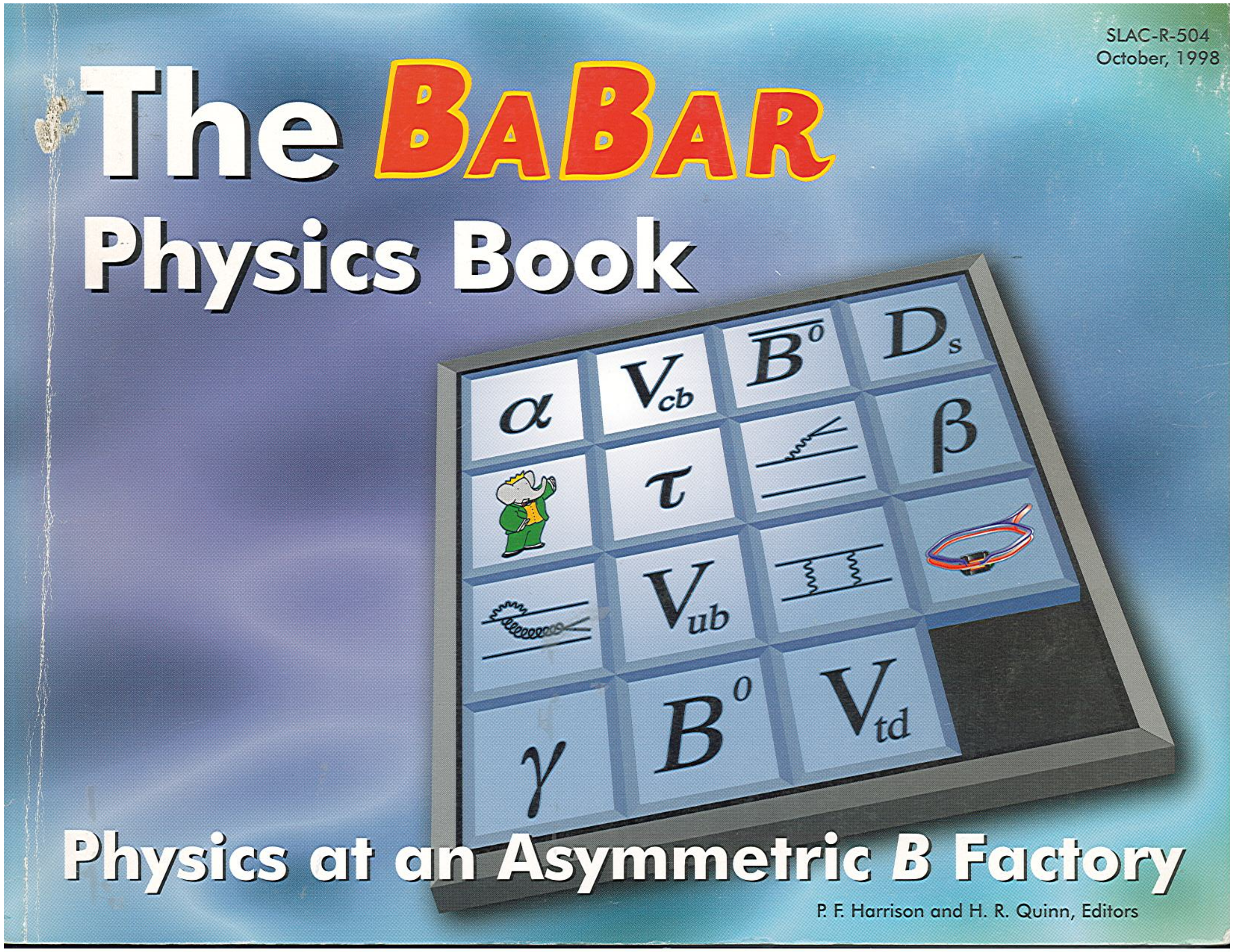
My personal super(-KEK)-B best buy list

- Want observables: (i) sensitive to different NP, (ii) measurements can improve by an order of magnitude, and (iii) not limited by hadronic uncertainties:
  - Difference of CP asymmetries, $S_{\psi K_S} - S_{\phi K_S}$
  - γ from CP asymmetries in tree-level decays vs. γ from $S_{\psi K_S}$ and $\Delta m_d/\Delta m_s$
  - Search for charged lepton flavor violation, $\tau \to \mu\gamma$, $\tau \to 3\mu$, and similar modes
  - Search for CP violation in $D^0 - \overline{D}^0$ mixing
  - The CP asymmetry in semileptonic decay, $A_{\rm SL}$
  - The CP asymmetry in the radiative decay, $S_{K^*\gamma}$
  - Rare decay searches and refinements: $b \to s\nu\bar{\nu}$, $B \to \tau\bar{\nu}$, etc.
- Complementary to LHCb
- Any one of these measurements has the potential to establish new physics

What was it in the BaBar Book?



What was it in the BaBar Book?

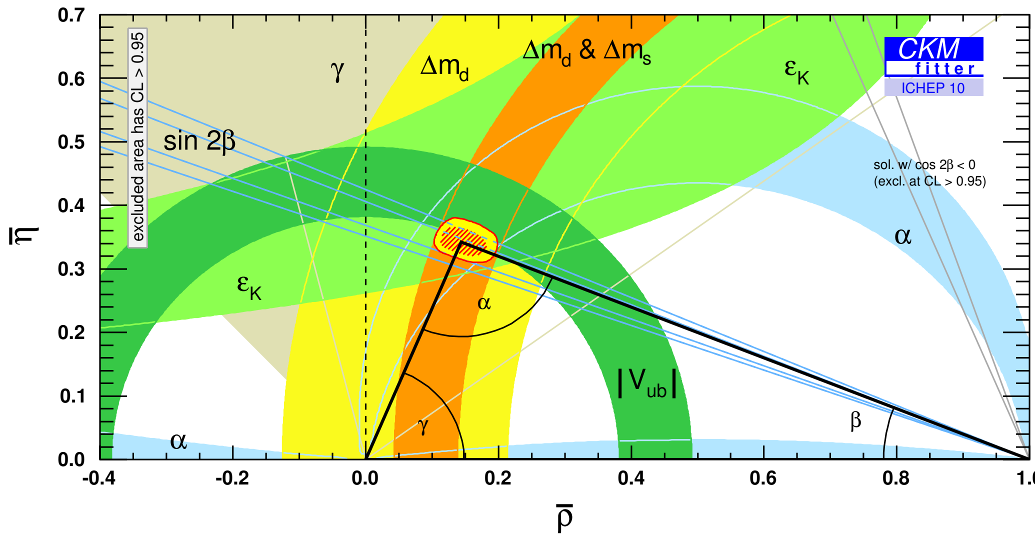


- There was no executive summary! Neither a list of gold-plated measurements...

Outline

- Pick two topics where significant progress could still come from existing data
  - Inclusive semileptonic B decays [Bernlochner, Lacker, ZL, Stewart, Tackmann, Tackmann]
    ... SIMBA [$=$Analysis of B Meson Inclusive Spectra]
  - An unusual dark matter search [Freytsis, ZL, Thaler]
    ... Bump hunting in $B \to K^{(*)}\ell^+\ell^-$
  - Conclusions

Semileptonic and rare B decays



- $|V_{ub}|$ is the dominant uncertainty of the side of the UT opposite to β
- Error of $|V_{cb}|$ is large part of the uncertainty in the ϵ_K constraint, and in $K \to \pi\nu\bar{\nu}$

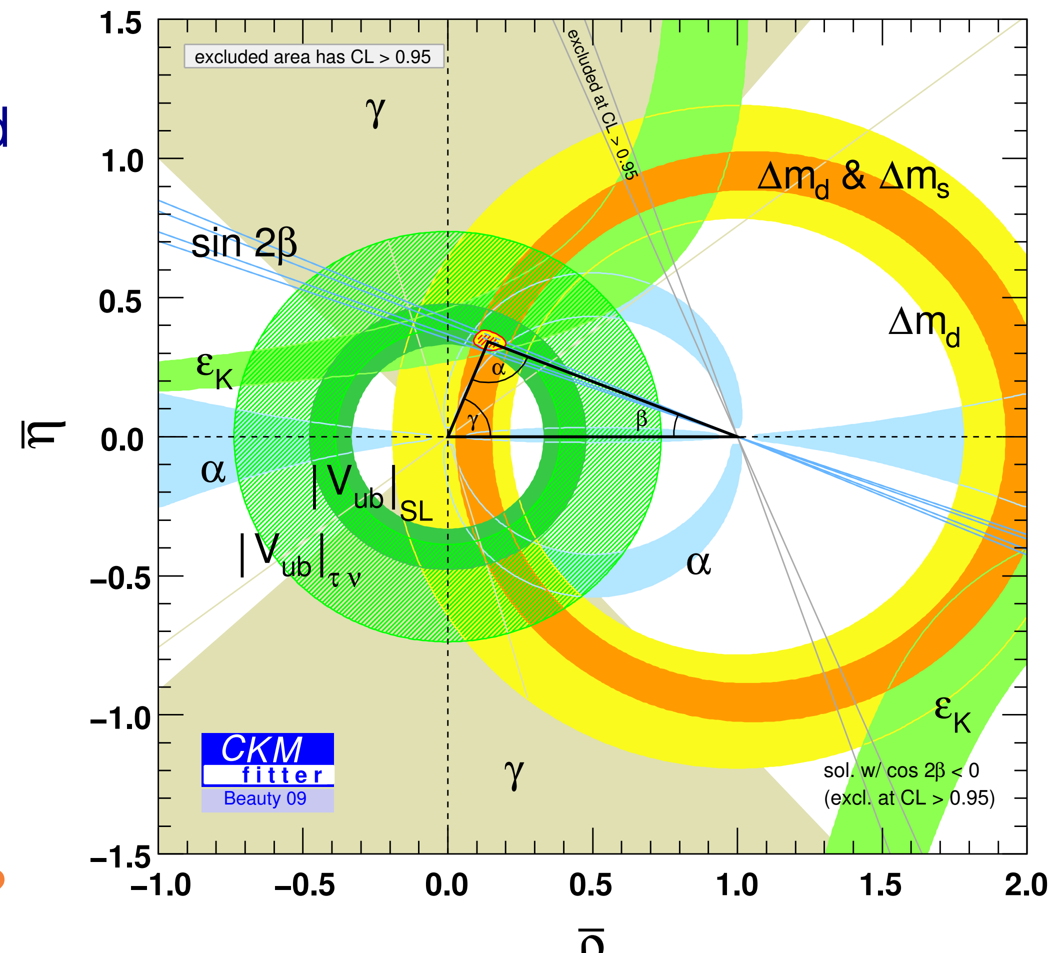
Both $|V_{cb}|$ and $|V_{ub}|$: persistent $\sim 2\sigma$ tension between inclusive & exclusive

Determination of $|V_{ub}|$ is far from settled

- Determined by tree-level decays
  Crucial for comparing tree-dominated and loop-mediated processes

- $|V_{ub}|_{\pi\ell\bar{\nu}-\mathrm{LQCD}} = (3.5 \pm 0.5) \times 10^{-3}$
  $|V_{ub}|_{\mathrm{incl-BLNP}} = (4.3 \pm 0.3) \times 10^{-3}$
  $|V_{ub}|_{\mathrm{incl-BLL}} = (4.9 \pm 0.5) \times 10^{-3}$
  $|V_{ub}|_{\tau\nu} = (5.2 \pm 0.5 \pm 0.4_{f_B}) \times 10^{-3}$
  SM CKM fit: $(3.54 \pm 0.18) \times 10^{-3}$

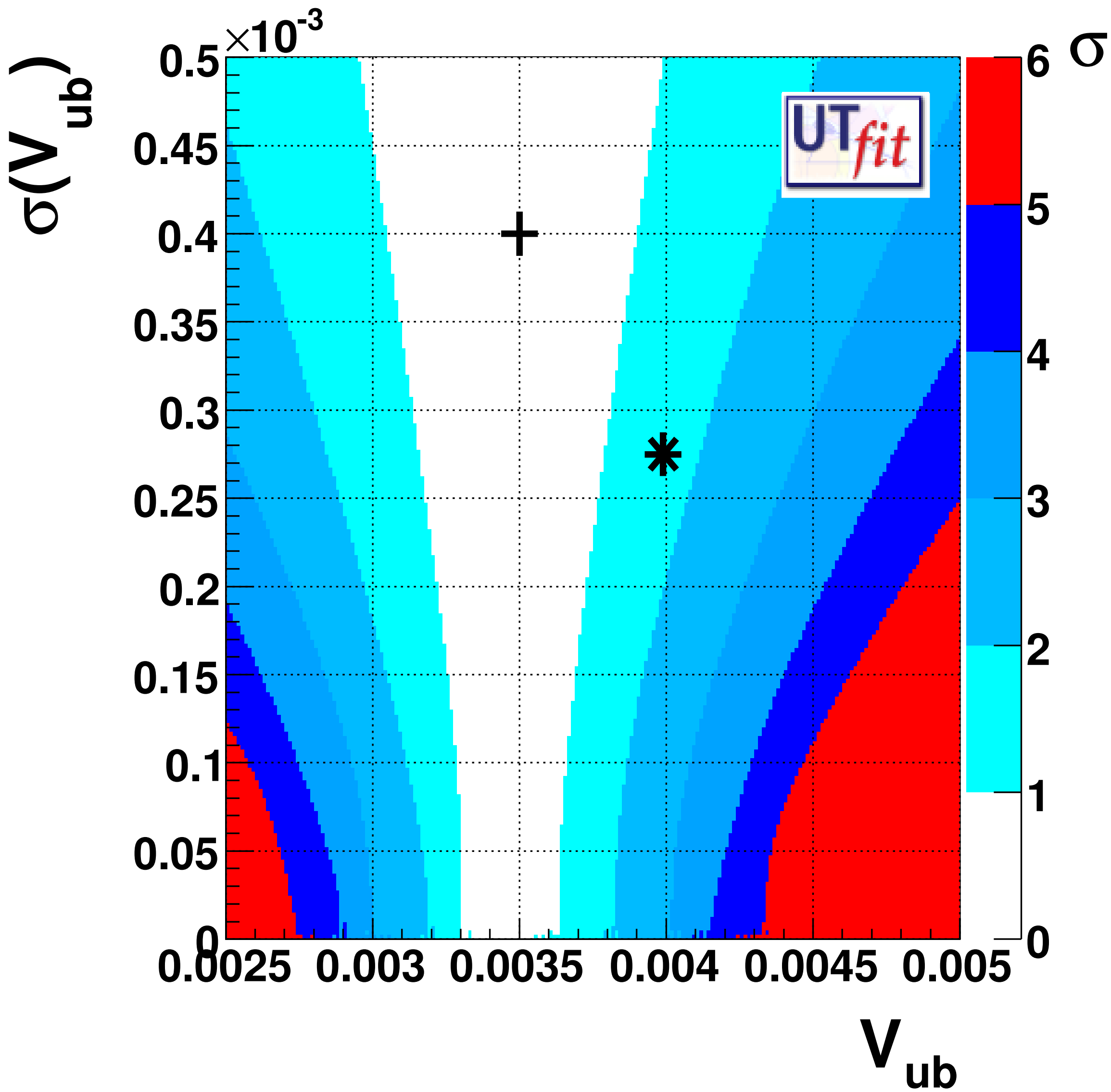
- Fluctuation, bad theory, new physics?



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

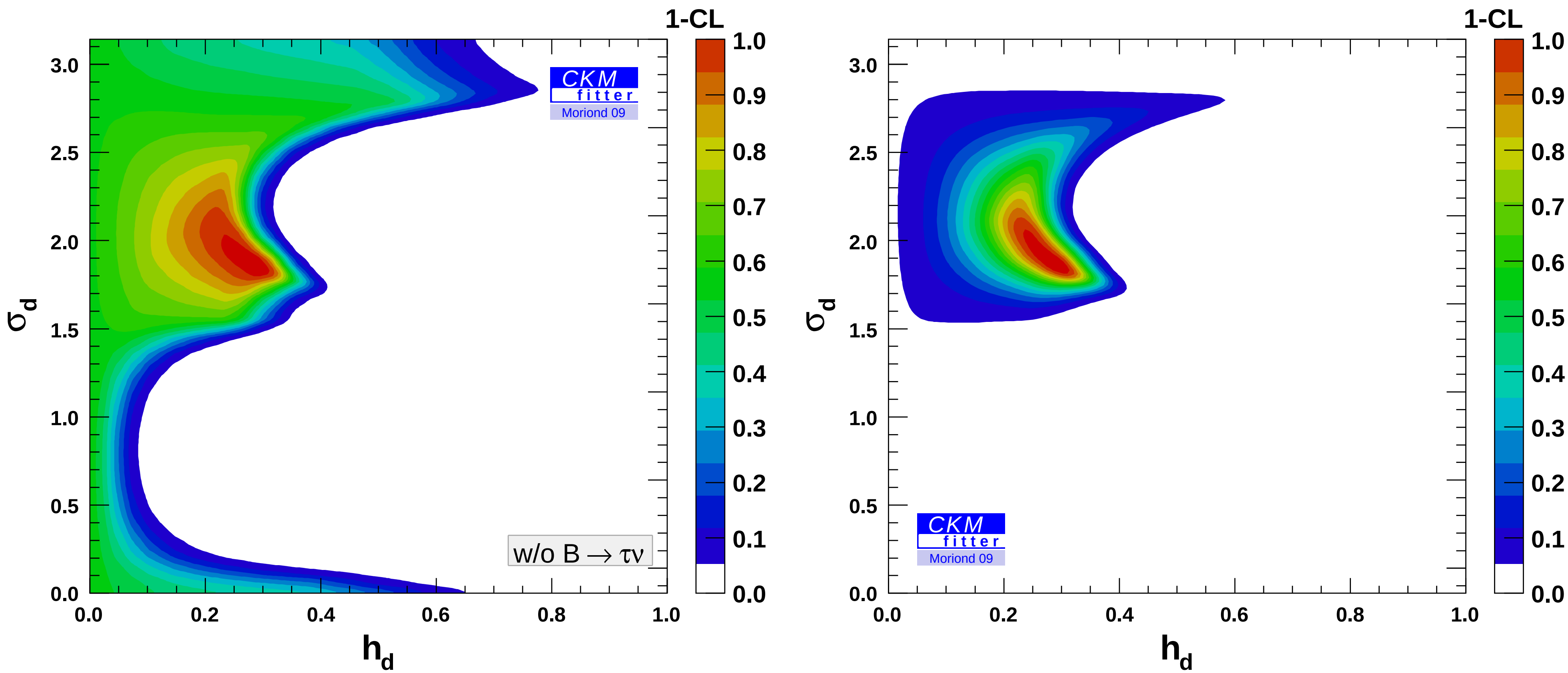
Another way of plotting $\sin 2\beta$ vs. $|V_{ub}|$

- UTfit has talked about this for several years; lingering around since 2003 or so, $\sim 2\sigma$



$|V_{ub}|$ and new physics ...

- At the present time, including $B \to \tau\bar{\nu}$, the SM is "disfavored" at $> 2\sigma$



Parameterize NP in B^0–$\overline{B}^0$ mixing: $M_{12} = M_{12}^{\text{SM}}\,(1 + h_d\, e^{2i\sigma_d})$

- There are NP models that would ease this "tension" (that's not the real question)

How to make sense of this?

- $B \to \pi\ell\bar{\nu}$ ("exclusive"): theory is in the hand of lattice QCD
  - I would not be too worried about QCD sum rules and other model calculations
  - Lattice QCD: f_B is simpler than q^2-dependent form factors

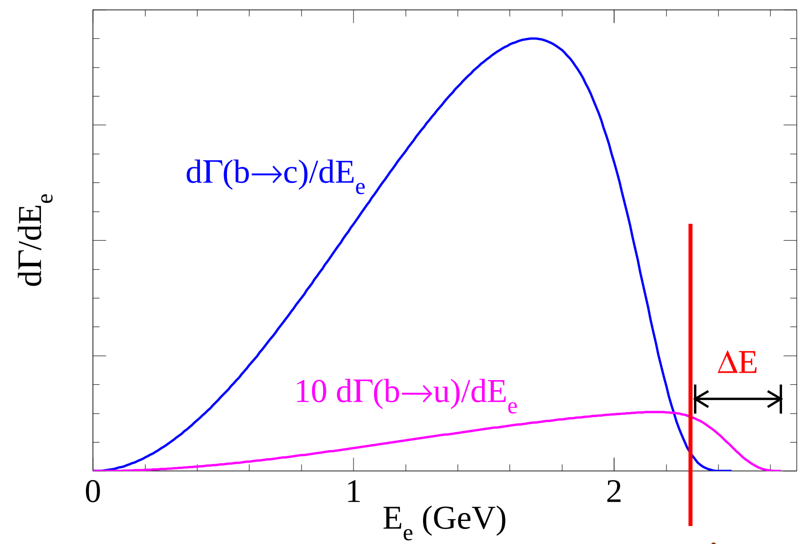
    However, $|V_{ub}|$ from $B \to \tau\nu$ is the highest (could be experimental fluctuation)
- $B \to X_u\ell\bar{\nu}$ ("inclusive"): theoretical improvements possible
  - However, e.g., in BLNP, recently computed NNLO terms increase $|V_{ub}|$
  - Work on better combination of $B \to X_u\ell\bar{\nu}$ and $B \to X_s\gamma$
- For most of these measurements, BaBar and Belle results are consistent

  Statistical fluctuations possible, though results seem fairly steady...
- (My) problem: results I'd trust the least are the ones most consistent with the SM

The challenge of inclusive $|V_{ub}|$ measurements

- Total rate calculable with $\sim 4\%$ uncertainty, similar to $\mathcal{B}(B \to X_c \ell \bar{\nu})$
- To remove the huge charm background $(|V_{cb}/V_{ub}|^2 \sim 100)$, need phase space cuts

  Can enhance pert. and nonpert. corrections

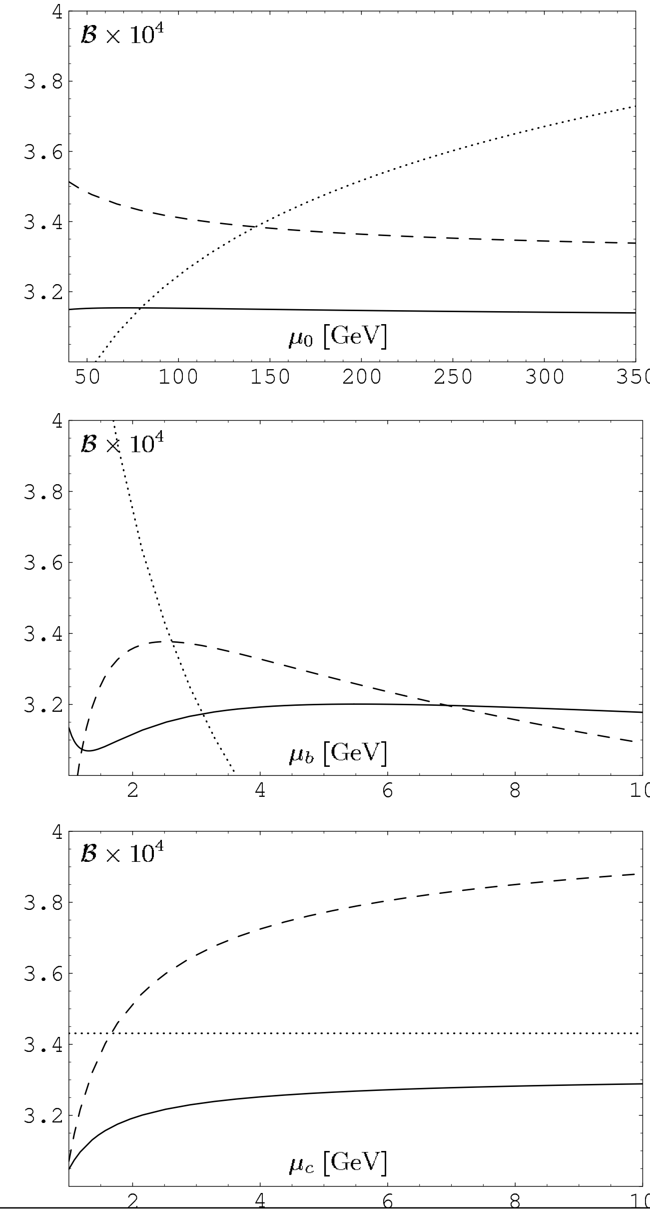


- Instead of being constants, the hadronic parameters become functions (like PDFs)

  Leading order: universal & related to $B \to X_s \gamma$;
  $\mathcal{O}(\Lambda_{\rm QCD}/m_b)$: several new unknown functions

- Nonperturbative effects shift endpoint $\frac{1}{2} m_b \to \frac{1}{2} m_B$ & determine its shape
- Shape in the endpoint region is determined by b quark PDF in B ["shape function"]
  Related to $B \to X_s \gamma$ photon spectrum at lowest order [Bigi, Shifman, Uraltsev, Vainshtein; Neubert]

Astonishing calculations: $B \to X_s\gamma$ rate



- One (if not "the") most elaborate SM calculations

  Constrains many models: 2HDM, SUSY, LRSM, etc.

- NNLO practically completed [Misiak et al., hep-ph/0609232]

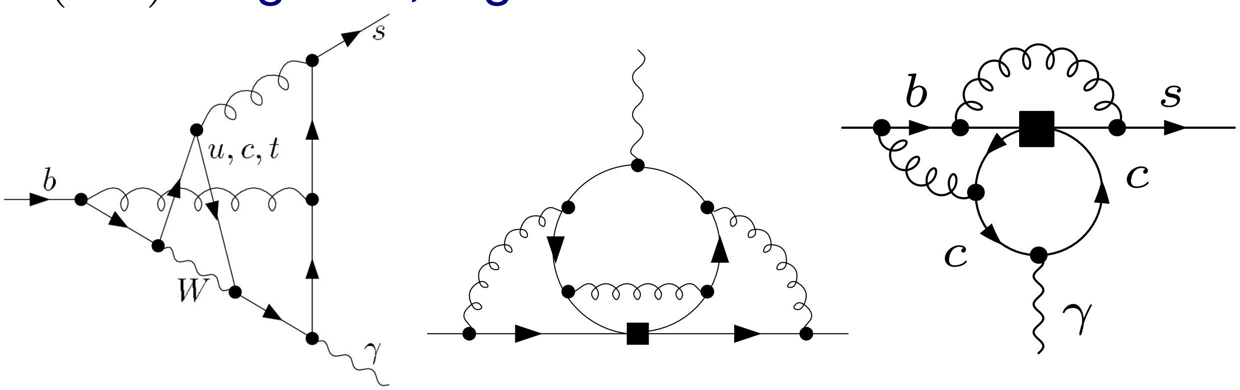
  4-loop running, 3-loop matching and matrix elements

  Scale dependencies significantly reduced $\Rightarrow$

- $\mathcal{B}(B \to X_s\gamma)\big|_{E_\gamma > 1.6\text{GeV}} = (3.15 \pm 0.23) \times 10^{-4}$

  experiment: $(3.55 \pm 0.26) \times 10^{-4}$

$\mathcal{O}(10^4)$ diagrams, e.g.:



Regions of $B \to X_s\gamma$ photon spectrum

- Important both for $|V_{ub}|$ and constraining NP
- The peak is around $E_\gamma \sim 2.3\,\mathrm{GeV}$

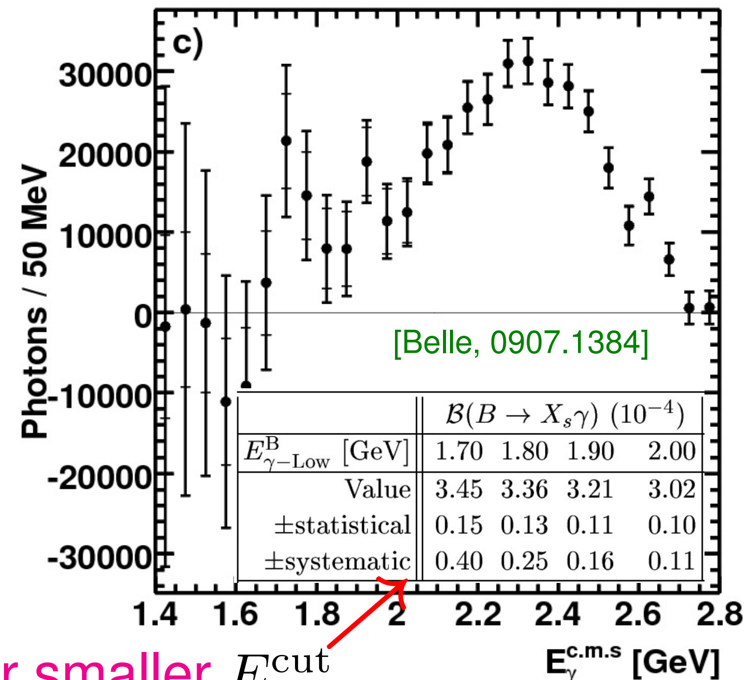
Three cases: 1) $\Lambda_{\rm QCD} \sim m_B - 2E_\gamma \ll m_B$ ["SCET"]

2) $\Lambda_{\rm QCD} \ll m_B - 2E_\gamma \ll m_B$ ["MSOPE"]

3) $\Lambda_{\rm QCD} \ll m_B - 2E_\gamma \sim m_B$

Expansions and theory uncertainties differ in the 3 regions

Neither 1) nor 2) is fully appropriate



- Experimental systematic error rapidly increases for smaller $E_\gamma^{\rm cut}$

- Current practice: Compare rate extrapolated to $1.6\,\mathrm{GeV}$ with theoretical prediction

Con: (i) extrapolation uses theory, so comparison of theory and data is effectively done at the measured values; (ii) best use of the most precise measurements?

Advantages of a global fit

- Optimally combine all information, while consistently treating the uncertainties and their correlations (experimental, theoretical, parameters)
- Simultaneously determine:
  - Overall normalization: $\mathcal{B}(B \to X_s\gamma)$, $|V_{ub}|$
  - Parameters: m_b, shape function(s)
- Utilize all measurements:
  - Different $B \to X_s\gamma$ spectra, or partial rates
  - Different $B \to X_u\ell\bar{\nu}$ spectra, or partial rates
  - Eventually also $B \to X_s\ell^+\ell^-$
  - Include other constraints on m_b, λ_1, etc.
- Same strategy as for $|V_{cb}|$, just a bit more complicated...

The shape function (b quark PDF in B)

- The shape function $S(\omega, \mu)$ contains nonperturbative physics and obeys a RGE

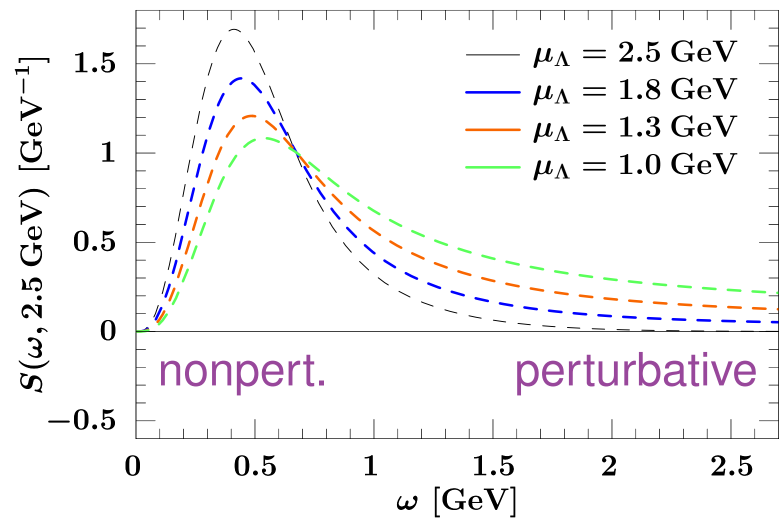
If $S(\omega, \mu_\Lambda)$ has exponentially small tail, but RGE running gives a long tail and divergent moments

[Balzereit, Mannel, Kilian]

$$S(\omega, \mu_i) = \int \mathrm{d}\omega' \, U_S(\omega - \omega', \mu_i, \mu_\Lambda) \, S(\omega', \mu_\Lambda)$$

Constraint: moments (OPE) + $B \to X_s \gamma$ shape

How to combine these?



Model $\left\{ S \right.$ (dash) run to $2.5\mathrm{GeV}$

The shape function (b quark PDF in B)

- The shape function $S(\omega,\mu)$ contains nonperturbative physics and obeys a RGE

If $S(\omega,\mu_\Lambda)$ has exponentially small tail, but RGE running gives a long tail and divergent moments [Balzereit, Mannel, Kilian]

$$S(\omega,\mu_i) = \int \mathrm{d}\omega'\, U_S(\omega-\omega',\mu_i,\mu_\Lambda)\, S(\omega',\mu_\Lambda)$$

Constraint: moments (OPE) + $B \to X_s\gamma$ shape

How to combine these?

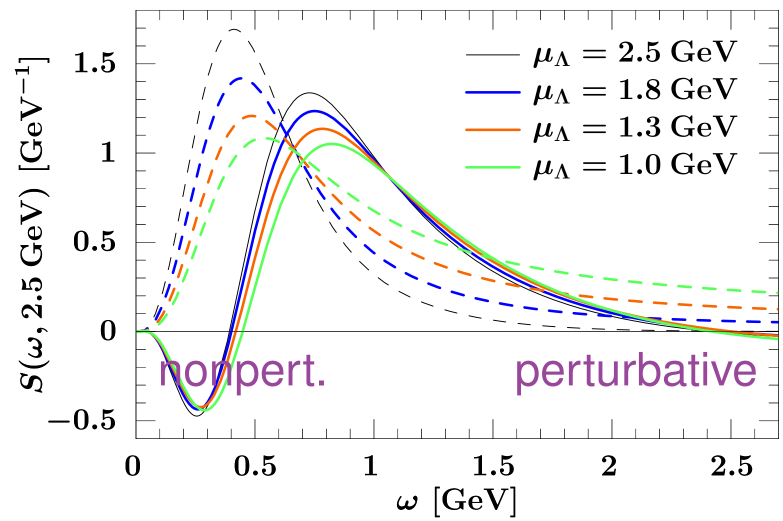
Derive: [ZL, Stewart, Tackmann, 0807.1926]

$$S(\omega,\mu_\Lambda) = \int \mathrm{d}k\, C_0(\omega-k,\mu_\Lambda) F(k)$$

– Consistent setup at any order, in any scheme

– Stable results for varying μ_Λ
 (SF modeling scale, must be part of uncert.)

– Similar to how all matrix elements are defined
 e.g., $B_K(\mu) = \widehat{B}_K \times [\alpha_s(\mu)]^{2/9}(1+\ldots)$



Model $\begin{cases} S & \text{(dash)} \\ F & \text{(solid)} \end{cases}$ run to $2.5\mathrm{GeV}$

- Consistent to impose moment constraints on $F(k)$, but not on $S(\omega,\mu_\Lambda)$ w/o cutoff

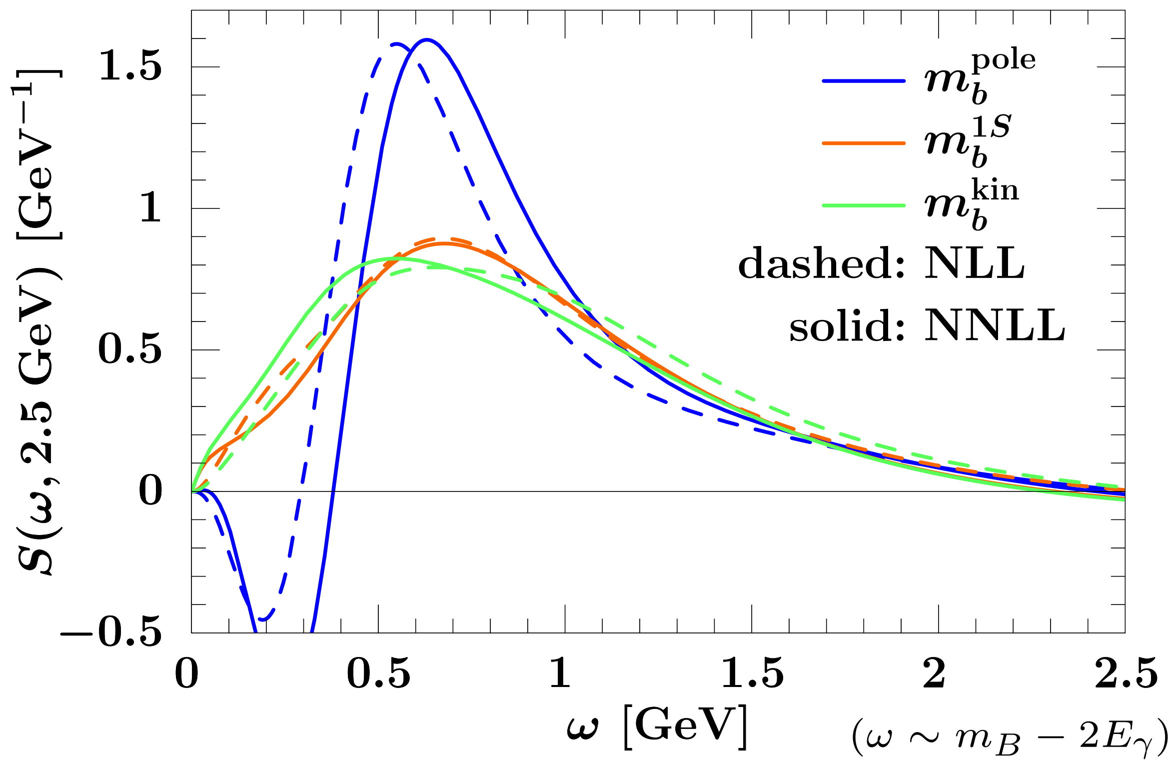
Changing schemes: m_b

- Going to a short distance mass scheme removes the dip at small ω
- Want to define short distance (hatted) quantities such that:

$$S(\omega) = \int \mathrm{d}k\, C_0(\omega - k)\, F(k) = \int \mathrm{d}k\, \widehat{C}_0(\omega - k)\, \widehat{F}(k)$$

Switch from pole to short distance scheme:

$$m_b = \widehat{m}_b + \delta m_b$$
$$\lambda_1 = \widehat{\lambda}_1 + \delta\lambda_1$$



$(\omega \sim m_B - 2E_\gamma)$

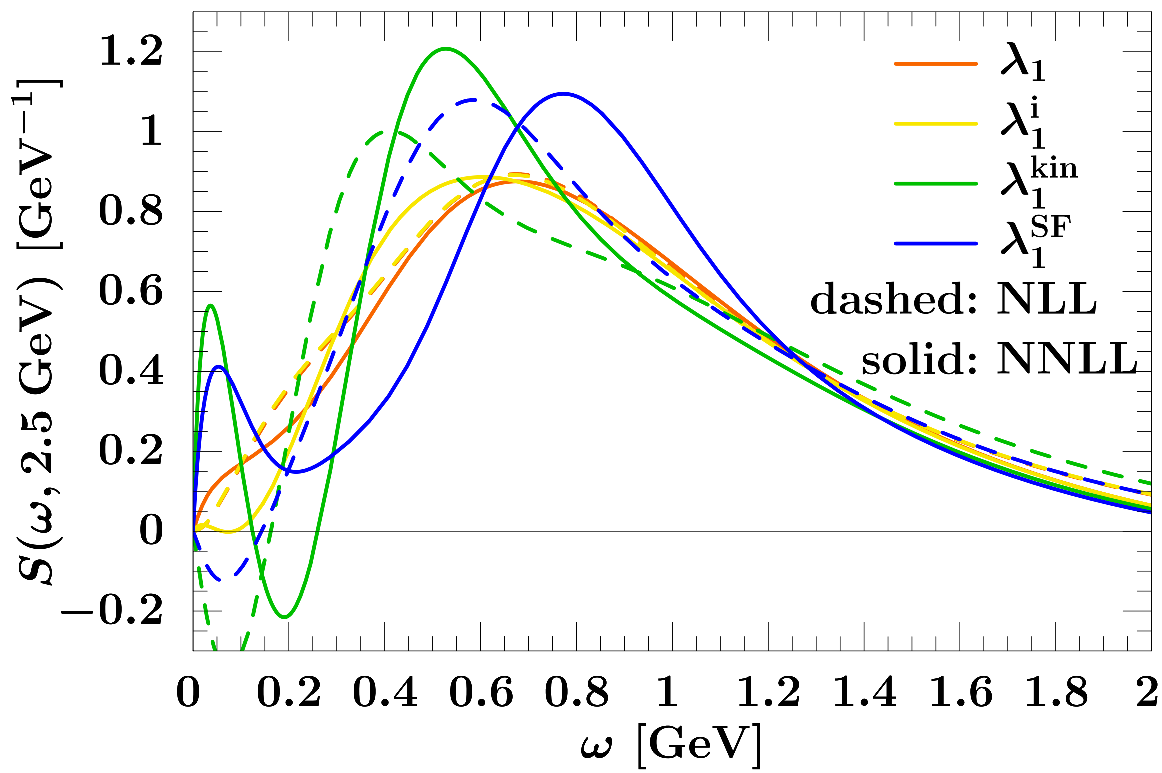
$$\widehat{C}_0(\omega) = C_0(\omega + \delta m_b) - \frac{\delta\lambda_1}{6}\frac{\mathrm{d}^2}{\mathrm{d}\omega^2} C_0(\omega) = \left[1 + \delta m_b \frac{\mathrm{d}}{\mathrm{d}\omega} + \left(\frac{(\delta m_b)^2}{2} - \frac{\delta\lambda_1}{6}\right)\frac{\mathrm{d}^2}{\mathrm{d}\omega^2}\right] C_0(\omega)$$

- Can use any short distance mass scheme ($1S$, kinetic, PS, shape function, ...)

Changing schemes: λ_1

- "Invisible" renormalon in λ_1 at $\mathcal{O}(\alpha_s^2)$? $\Rightarrow$ kinetic and SF schemes for λ_1
- Introduce invisible scheme: $\lambda_1^{\rm i} = \lambda_1 - 0\alpha_s - R^2 \frac{\alpha_s^2(\mu)}{\pi^2} \frac{C_F C_A}{4} \left(\frac{\pi^2}{3} - 1\right) \quad (R = 1\,\text{GeV})$
- The kinetic and shape function scheme definitions oversubtract $(-\mu_\pi^2 \equiv \lambda_1^{\rm kin,\,SF})$

  ... similar to $\overline{m}_b(\overline{m}_b)$ issues



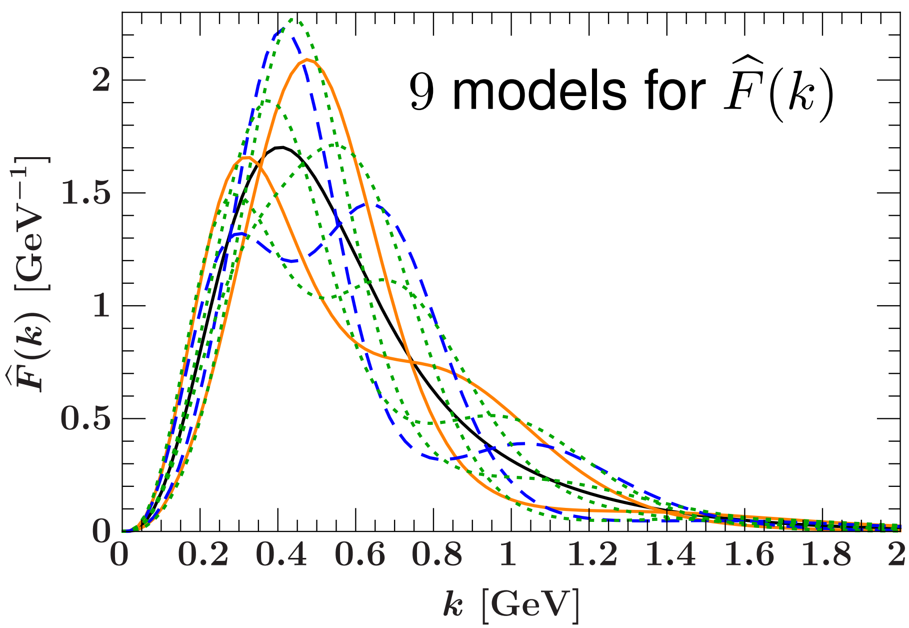
(Curves use $m_b^{1S,\,\text{kin},\,\text{SF}}$, respectively)

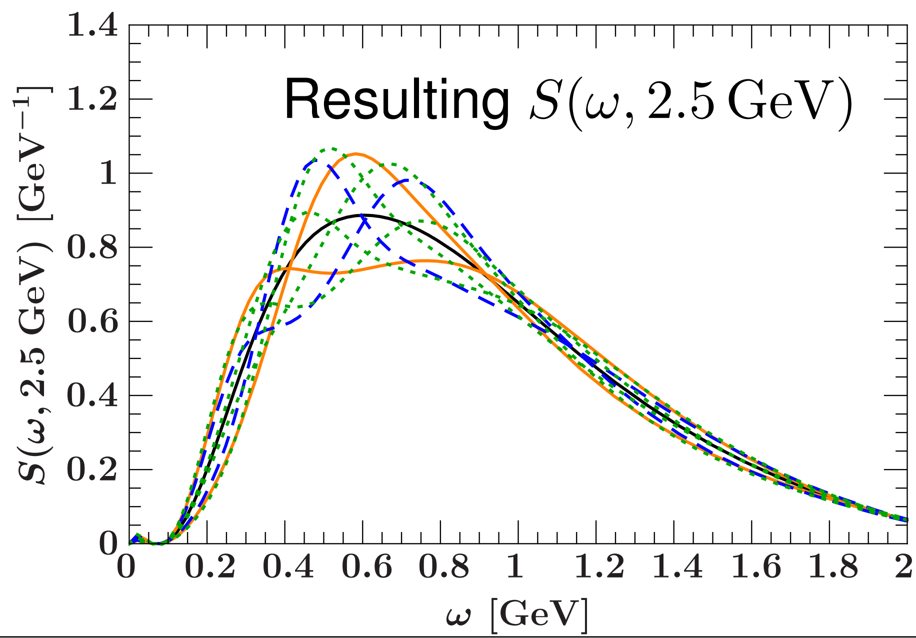
Shape function: the bottom line

$$S(\omega, \mu_\Lambda) = \int \mathrm{d}k \, \widehat{C}_0(\omega - k, \mu_\Lambda) \, \widehat{F}(k)$$

$\widehat{F}$: nonperturbative
- determines peak region
- well-defined moments
- fit from data

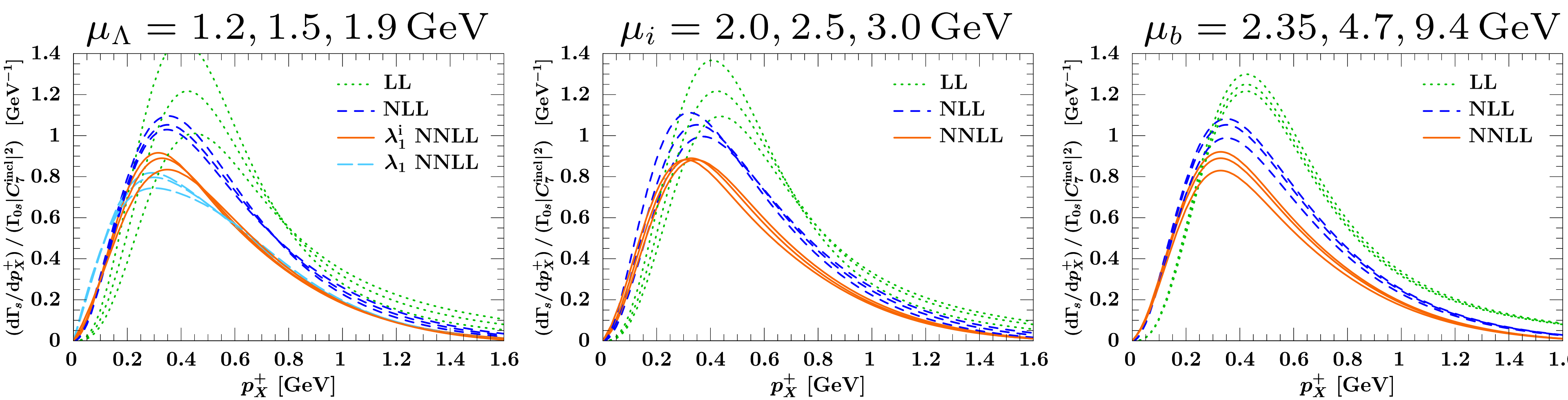
$\widehat{C}_0$: perturbative
- generates tail consistent with RGE
- divergent moments
- calculable





Scale (in)dependence of $B \to X_s\gamma$ spectrum

- Dependence on 3 scales in the problem can be handled appropriately:



$$\frac{\mathrm{d}\Gamma_s}{\mathrm{d}p_X^+} = \Gamma_{0s}\, H_s(p_X^+, \mu_b)\, U_H(m_b, \mu_b, \mu_i) \int \mathrm{d}k\, \widehat{P}(m_b, k, \mu_i)\, \widehat{F}(p_X^+ - k) \qquad \left(p_X^+ = m_B - 2E_\gamma\right)$$

$\widehat{P}$, $\widehat{F}$ indicate use of short distance schemes: m_b^{1S} and $\lambda_1^{\rm i}$

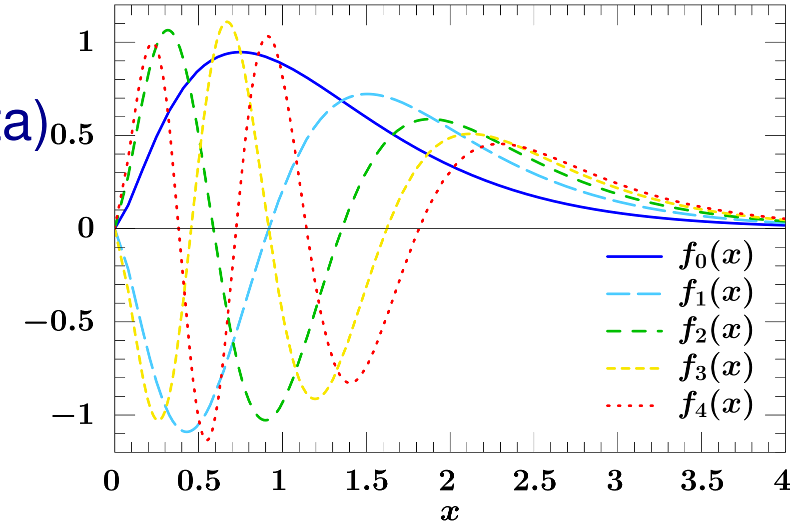
- In other approaches, using models for $S(\omega, \mu_\Lambda)$ run up to μ_i, dependence on μ_Λ ignored so far, but it must be considered an uncertainty $\Rightarrow$ This is how to solve it

Designer orthonormal functions

- Devise suitable orthonormal basis functions (earlier: fit parameters of model functions to data)

$$\widehat{F}(\lambda x) = \frac{1}{\lambda}\Big[\sum c_n f_n(x)\Big]^2, \quad n\text{th moment} \sim \Lambda_{\rm QCD}^n$$

$$f_n(x) \sim P_n[y(x)] \leftarrow \text{Legendre polynomials}$$

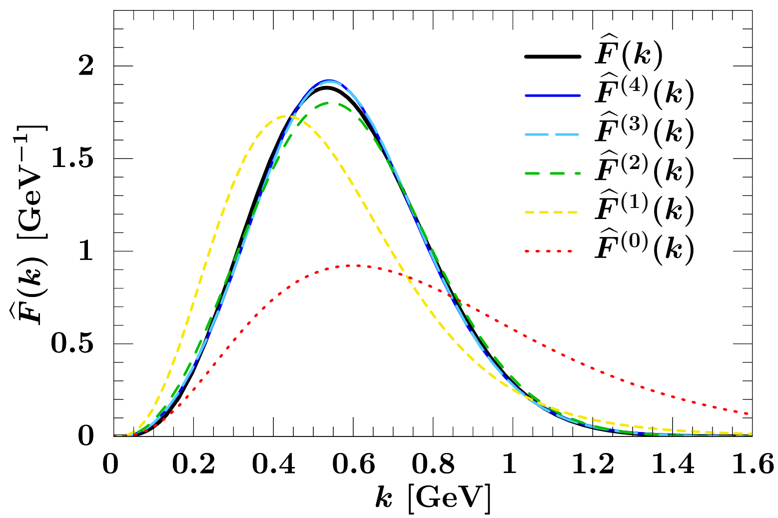


- Approximating a model shape function

Better to add a new term in an orthonormal basis than a new parameter to a model:

– less parameter correlations

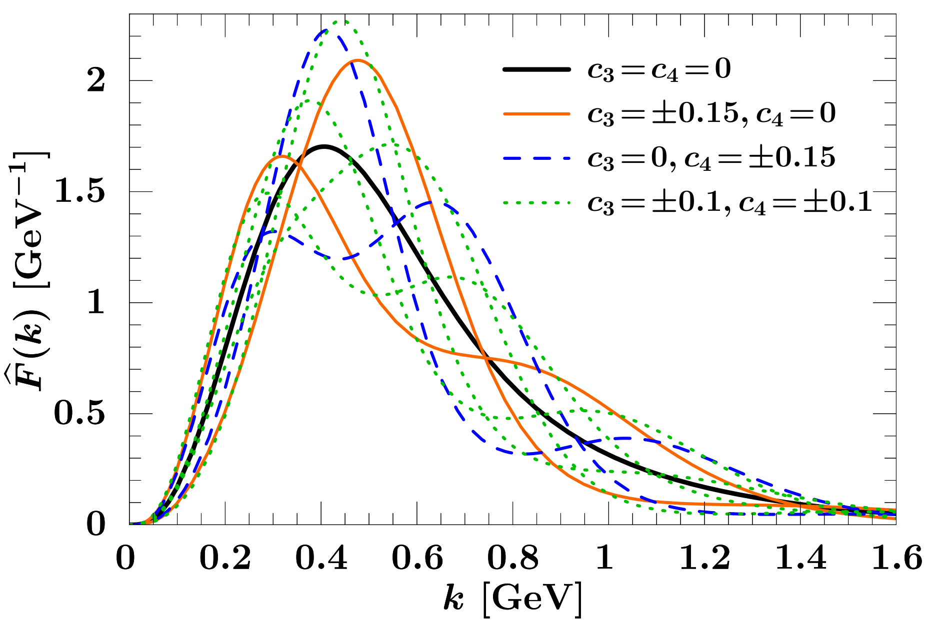
– errors easier to quantify

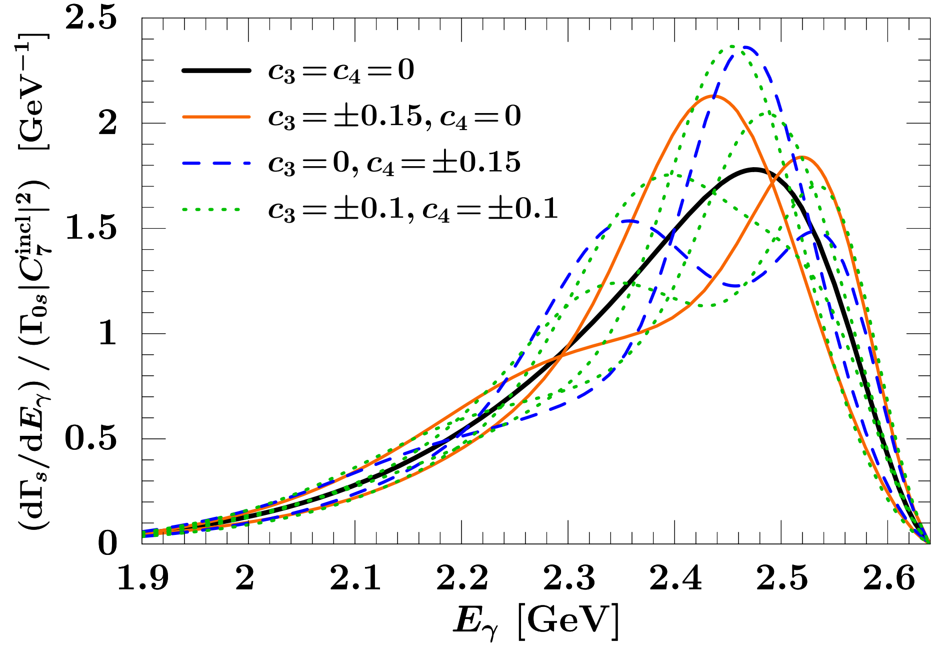


"With four parameters I can fit an elephant, and with five I can make him wiggle his trunk." (John von Neumann)

The $B \to X_s\gamma$ spectrum again

- Same 9 models as before (fixed 0th, 1st, 2nd moments), and the resulting spectra





- At NNLL: Shape in peak region not determined at all by first few moments

  Perturbative tail of shape function starts to dominate for $E_\gamma \lesssim 2.1\,\mathrm{GeV}$

- Not shown: subleading shape functions, subleading corrections not in C_7^{incl}, kinematic power corrections, boost to $\Upsilon(4S)$ frame

Details of fitting the data

- $\widehat{F}(k)$ enters the spectra linearly

  $\Rightarrow$ can calculate independently the contribution of $f_m\, f_n$ in the expansion of $\widehat{F}(k)$:

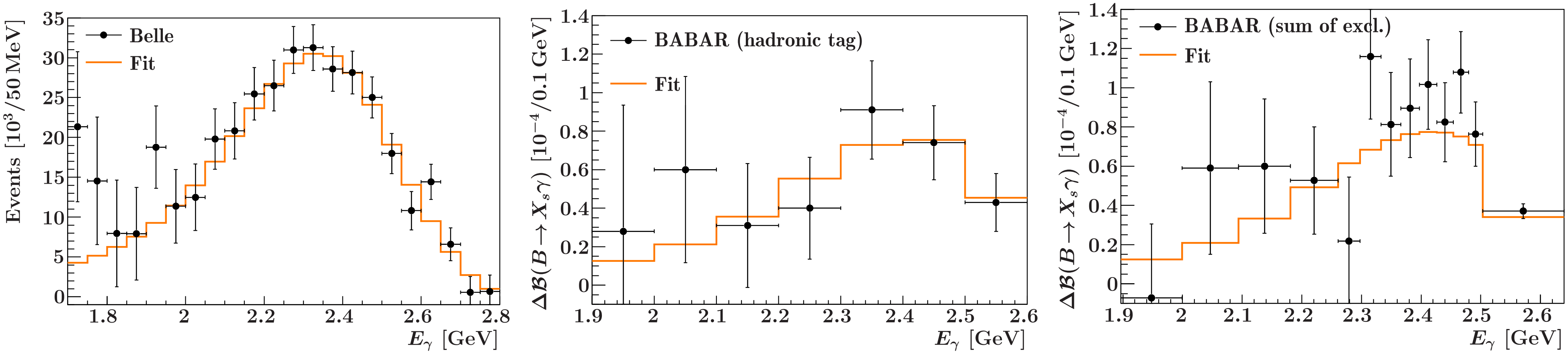
$$\mathrm{d}\Gamma = \sum \underbrace{c_m\, c_n}_{\text{fit}}\ \underbrace{\mathrm{d}\Gamma_{mn}}_{\text{compute}}$$

$$\mathrm{d}\Gamma_{mn} = \Gamma_0\, H(p_X^\pm) \int_0^{p_X^+} \mathrm{d}k\, \frac{\widehat{P}(p^-, k)}{\lambda}\ \underbrace{f_m\!\left(\frac{p_X^+ - k}{\lambda}\right) f_n\!\left(\frac{p_X^+ - k}{\lambda}\right)}_{\text{basis functions}}$$

  Fit the c_i coefficients from all measured (binned) spectra (similar to $|V_{cb}|$ fit)

- SIMBA includes: [all plots preliminary]
  - Simultaneous fit using all available information
  - Correlations in data, propagation of SF uncertainties
  - Validate the fits with pseudo-experiments
  - Check model independence by varying number of basis functions in fit (up to 5)

Fits results for $B \to X_s\gamma$

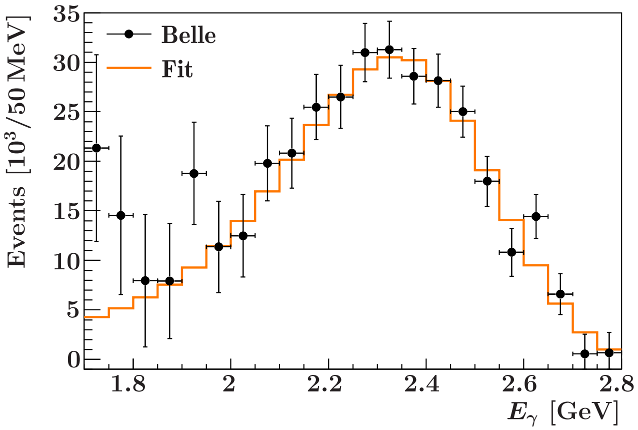


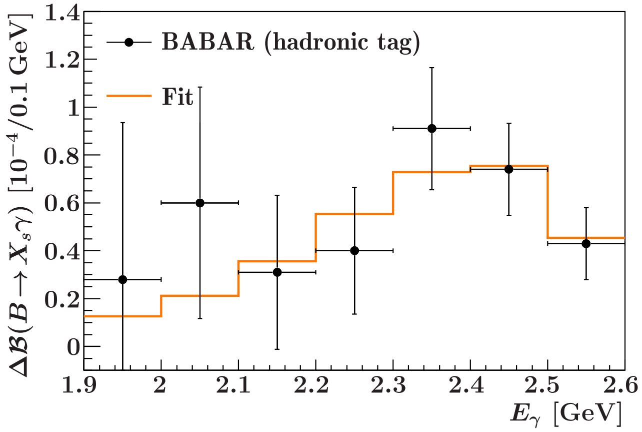
- Belle: $605\,\mathrm{fb}^{-1}$ — they provided the covariance matrix, experimental efficiency, and resolution (latter two folded into theory prediction)

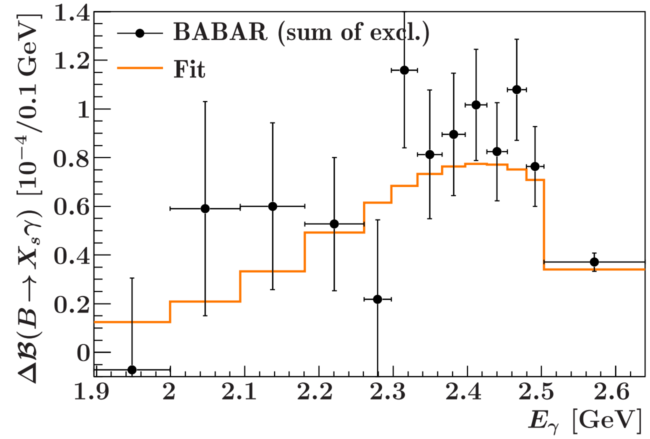
- BaBar: hadronic tag ($210\,\mathrm{fb}^{-1}$) and sum over exclusive modes ($80\,\mathrm{fb}^{-1}$) (spectra efficiency corrected, resolution not an issue)

  leptonic tag data cannot (yet) be included

Fits results for $B \to X_s\gamma$

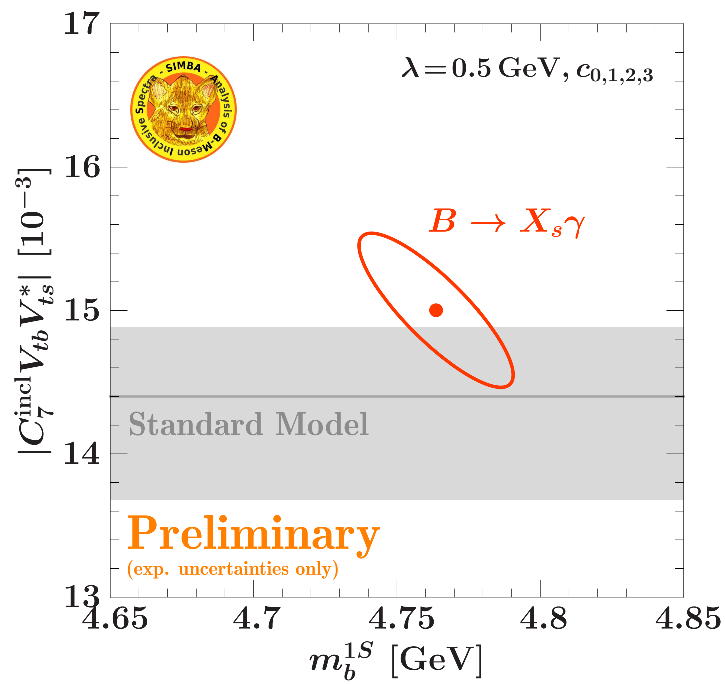




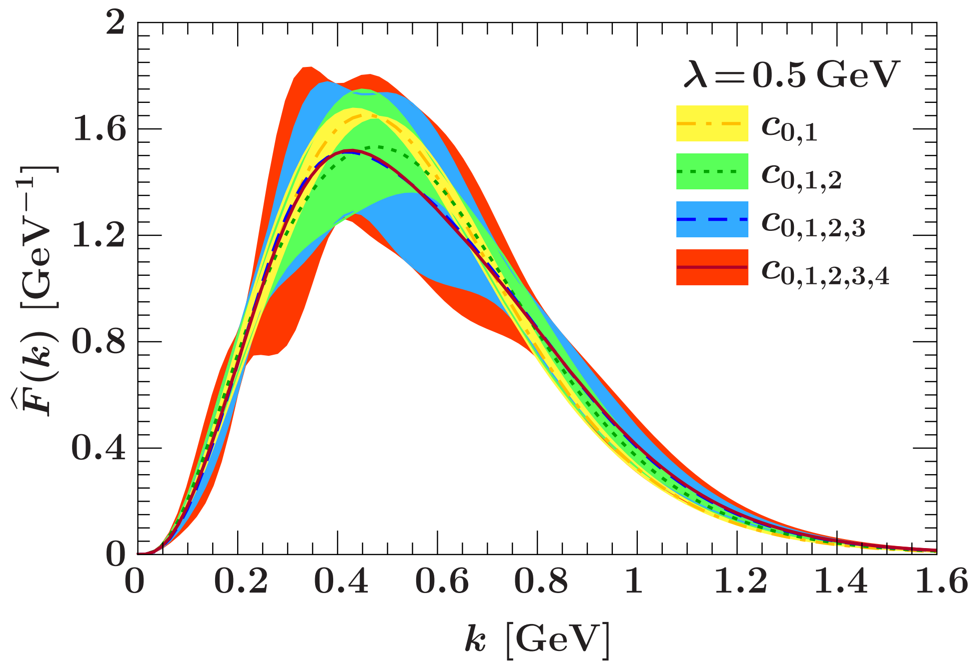


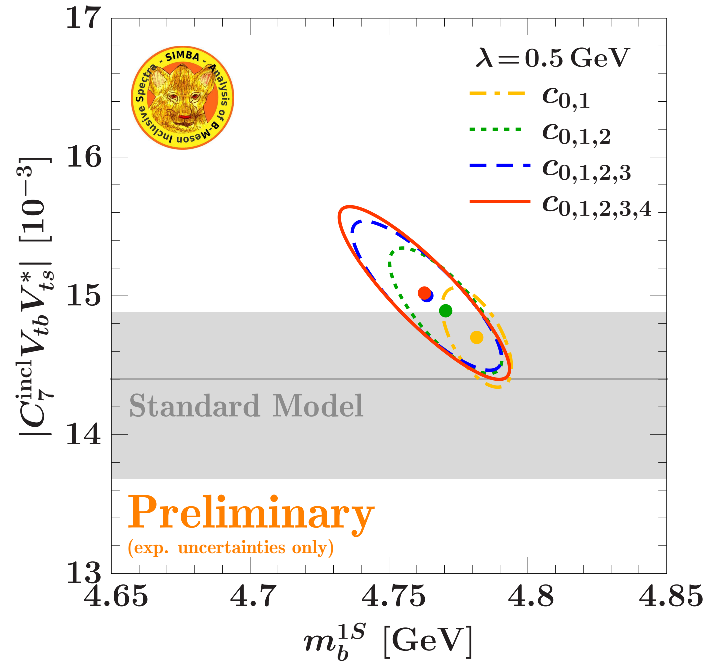
- $\chi^2/\mathrm{ndf} = 27.0/38$
- SM prediction: $\left|C_7^{\mathrm{incl}}\right|^{\mathrm{SM}} = 0.354^{+0.011}_{-0.012}$

  $|V_{tb}V_{ts}| = (40.7^{+0.4}_{-0.5}) \times 10^{-3}$
- Fit result: $\left|C_7^{\mathrm{incl}}\, V_{tb}V_{ts}\right| = (15.00 \pm 0.54_{\mathrm{exp}}) \times 10^{-3}$
- Data slightly above SM prediction, as in HFAG combination vs. Misiak *et al.*



Convergence of basis expansion





- Uncertainties underestimated with too few coefficients
  - Would need to estimate / include additional uncertainty from truncation
- Little change in going from $4 \to 5$ basis functions
  - Truncation uncertainty negligible compared to other uncertainties
- Also varied λ to check basis independence (change form of basis functions)

$B \to X_u \ell \bar\nu$ is more complicated

- "Natural" kinematic variables: $p_X^\pm = E_X \mp |\vec{p}_X|$ — "jettiness" of hadronic final state

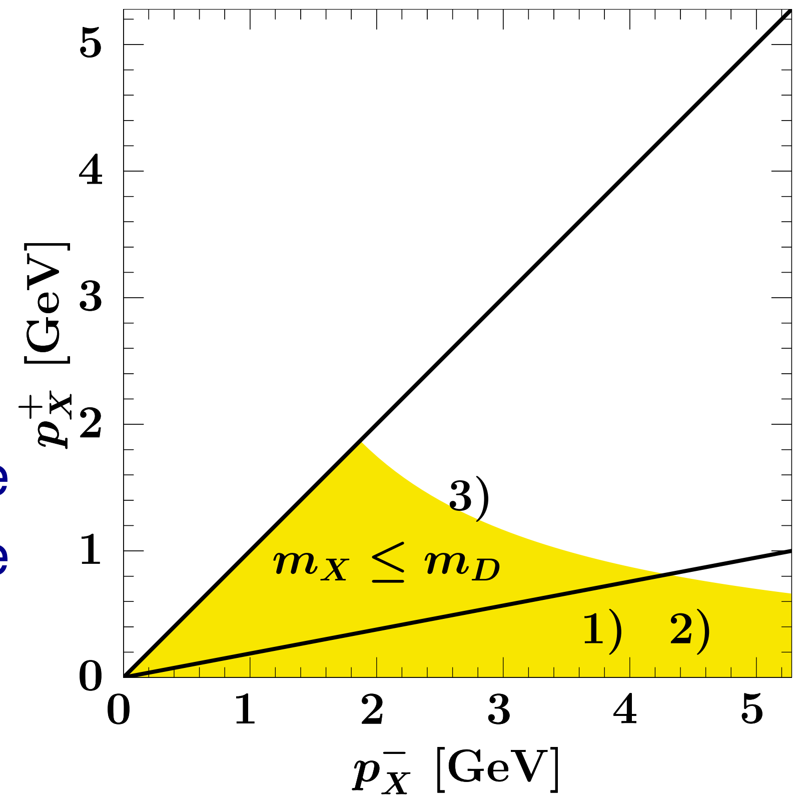
  $B \to X_s\gamma$: $p_X^+ = m_B - 2E_\gamma$ & $p_X^- \equiv m_B$, but independent variables in $B \to X_u \ell \bar\nu$

- Three cases: 1) $\Lambda \sim p_X^+ \ll p_X^-$ } SF region

  2) $\Lambda \ll p_X^+ \ll p_X^-$ } SF region

  3) $\Lambda \ll p_X^+ \sim p_X^-$ local OPE region

  Want to make no assumptions how p_X^- compares to m_B



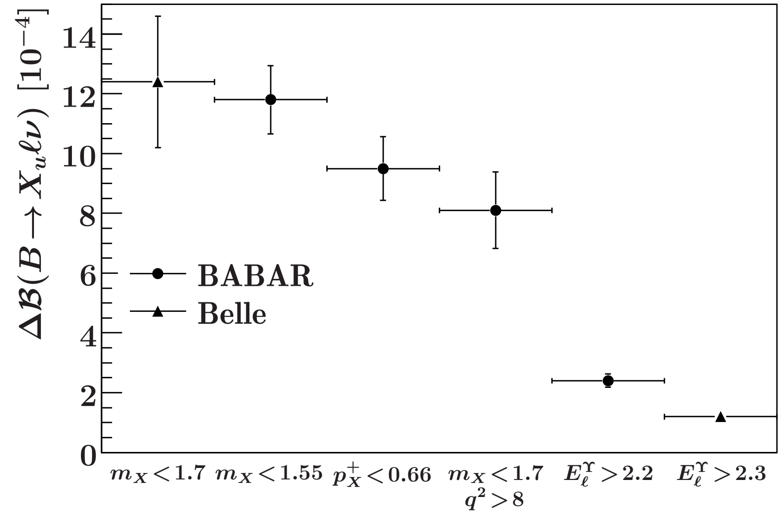
- $B \to X_u \ell \bar\nu$: 3-body final state, appreciable rate in region 3), where hadronic final state not jet-like

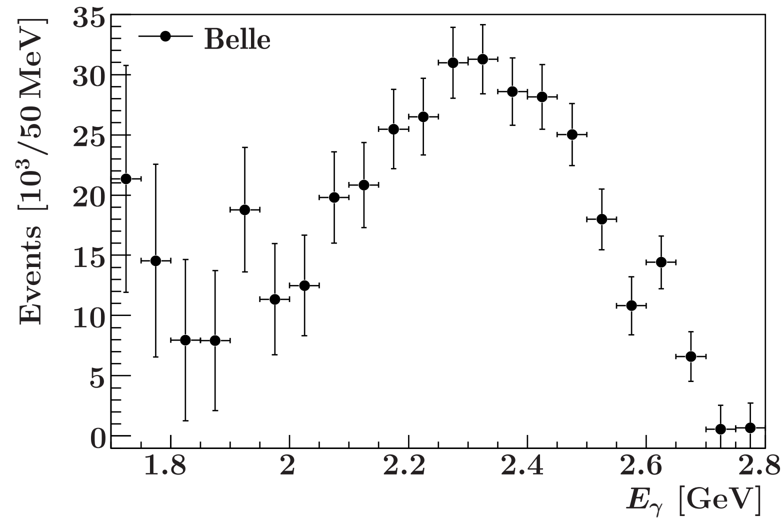
  E.g., $m_X^2 < m_D^2$ does not imply $p_X^+ \ll p_X^-$

- Existing approaches based on theory in one region, extrapolated / modeled to rest

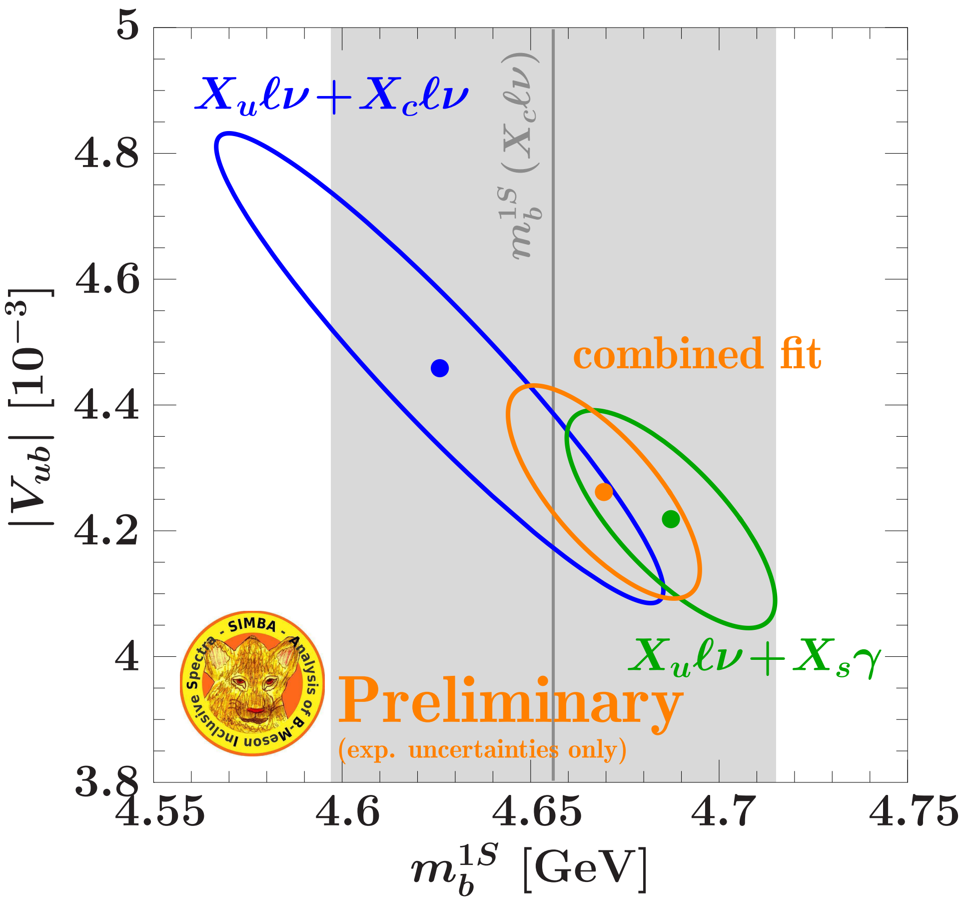
Even more preliminary — $|V_{ub}|$

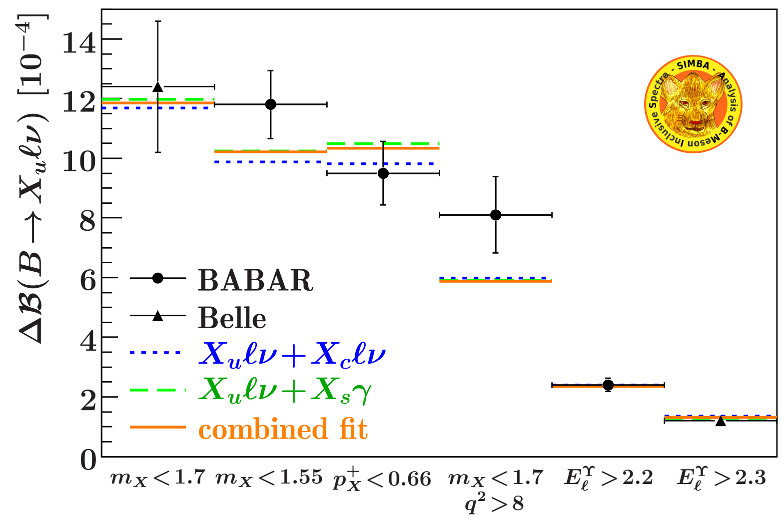
- $B \to X_u \ell \bar{\nu}$ hadronic tag
  - BaBar m_X, $m_X - q^2$, p_X^+
  - Belle m_X
- $B \to X_u \ell \bar{\nu}$ lepton endpoint
  - BaBar $E_\ell^\Upsilon > 2.2\,\mathrm{GeV}$
  - Belle $E_\ell^\Upsilon > 2.3\,\mathrm{GeV}$
- $B \to X_s \gamma$ spectra
  - Belle latest result (shown)
  - BaBar sum over exclusive $+$ hadronic tag
- m_b^{1S}, λ_1 from $B \to X_c \ell \bar{\nu}$ fit
  - $m_b^{1S} = (4.66 \pm 0.05)\,\mathrm{GeV}$
  - $\lambda_1 = (-0.34 \pm 0.05)\,\mathrm{GeV}^2$

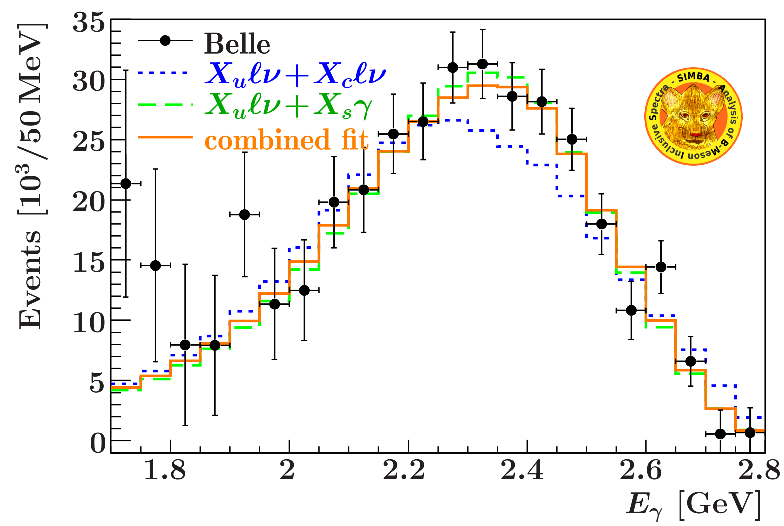




Even more preliminary — $|V_{ub}|$







- E_γ spectrum is off without $B \to X_s\gamma$ in the fit
- Including it, favors lower values of $|V_{ub}|$

If all else fails: “Grinstein-type double ratios”

- Continuum theory may be competitive using HQS + chiral symmetry suppression
- $\dfrac{f_B}{f_{B_s}} \times \dfrac{f_{D_s}}{f_D}$ — lattice: double ratio $= 1$ within few $\%$ [Grinstein ’93]
- $\dfrac{f^{(B\to\rho\ell\bar\nu)}}{f^{(B\to K^*\ell^+\ell^-)}} \times \dfrac{f^{(D\to K^*\ell\bar\nu)}}{f^{(D\to\rho\ell\bar\nu)}}$ or q^2 spectra — accessible soon? [ZL, Wise; Grinstein, Pirjol]

  $D \to \rho\ell\bar\nu$ data still consistent with no $SU(3)$ breaking in form factors [ZL, Stewart, Wise]

  Could lattice QCD do more to pin down the corrections?

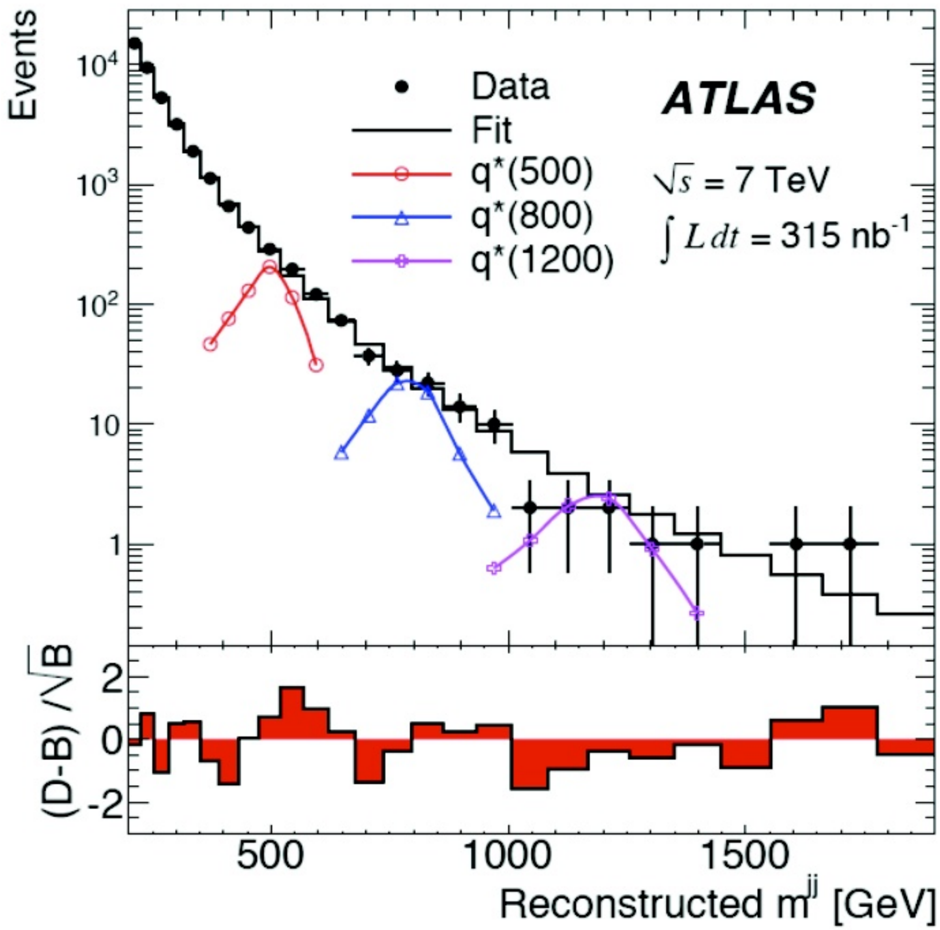
  Worth looking at similar ratio with K, π — role of B^* pole...?
- $\dfrac{\mathcal{B}(B\to\ell\bar\nu)}{\mathcal{B}(B_s\to\ell^+\ell^-)} \times \dfrac{\mathcal{B}(D_s\to\ell\bar\nu)}{\mathcal{B}(D\to\ell\bar\nu)}$ — very clean... after 2016? [Ringberg workshop, ’03]
- $\dfrac{\mathcal{B}(B_u\to\ell\bar\nu)}{\mathcal{B}(B_d\to\mu^+\mu^-)}$ — even cleaner... around 2020? [Grinstein, CKM’06]
- Also useful for probing SUSY parameter space [Akeroyd, Mahmoudi, 1007.2757]

Summary: inclusive $B \to X_s\gamma$ and $|V_{ub}|$

- Qualitatively better analyses are possible than those implemented so far
  - Fitting $F(k)$ instead of modeling $S(\omega,\mu)$
  - Designer orthonormal functions — reduce role of shape function modeling
  - Fully consistent combination of all phase space regions
  - Decouple SF shape variation from m_b variation
- Progress can be made using current data:
  Combine all $B \to X_s\gamma$, $X_u\ell\bar{\nu}$, $X_c\ell\bar{\nu}$ data to constrain short distance physics & SFs
  Need spectra & correlations; so far we had to rely more on Belle than BaBar data
- Refining $|V_{ub}|$ will remain important to constrain new physics in $B^0 - \overline{B}^0$ mixing
  (Uncomfortable $\sim 2\sigma$ tensions, PDG in 2008 inflated error for the first time)
  Recently Λ_b lifetime and $\Gamma(D_s \to X\ell\bar{\nu})$ taught us about what the resolution is not
- $|V_{ub}|$ is tricky: to draw conclusions about new physics, we'll want ≥ 2 extractions with different uncertainties to agree well (inclusive, exclusive, leptonic)

Dark matter in $B \to K^{(*)}\ell^+\ell^-$?

Bump hunting: not only for ATLAS & CMS...



(The first LHC result superseding Tevatron limits)

Dark matter

- Recent observations of cosmic ray excesses led to a flurry of DM model building

  Standard WIMPs unable to fit the data (lack of antiprotons, hard lepton spectrum)

- An idea: DM annihilates to SM through light bosons [Pospelov, Ritz, Voloshin; Arkani-Hamed *et al.*]

$$\chi\chi \to \phi^{(*)}\phi^{(*)}, \qquad \phi \to \ell^+\ell^-,\ \pi^+\pi^-,\ \ldots$$

  "Dark bosons" couple to leptons with $\alpha_X = \lambda_X^2/(4\pi)$, lots of different constraints depending on mass and coupling

- Most popular scenario: ϕ^μ couples to $\bar\psi\gamma_\mu\psi$ and mixes with γ ("dark photons")
  ... other viable models also exist

  A lot of the constraints and phenomenology was worked out here at SLAC

The axion portal

- The new particle could also be a scalar with axion-like couplings [Nomura, Thaler, 0810.5397]

$$\mathcal{L}_{\rm int} = \frac{\lambda}{f_a} (\bar\psi \gamma^\mu \gamma_5 \psi)\, \partial_\mu a \quad \to \quad \frac{\lambda\, m_\psi}{f_a} (\bar\psi \gamma_5 \psi)\, a$$

  The most interesting part of parameter space is thought to be:

$$m_K - m_\pi < m_a \lesssim 800\,\text{MeV}, \qquad f_a \sim (1-3)\,\text{TeV}$$

- Coupling to fermions $\propto m_\psi$, so FCNC $b \to sa$ loops are enhanced by m_t

  With only $\mathcal{L}_{\rm int}$, divergent loops $\Rightarrow$ need to embed in a renormalizable theory

- A simple explicit model: Peccei-Quinn symmetric NMSSM (2HDM $+$ a singlet)

  (SUSY part not directly relevant for us, more general DFSZ-axion)

- At one loop: $\mathcal{M}(b \to sa) \propto \mathcal{M}(b \to sA^0)_{\rm 2HDM}$ (from $tW,\ tH, tHW$ penguins)

The 2HDM calculation

[Hall and Wise, NPB 187 (1981) 397]

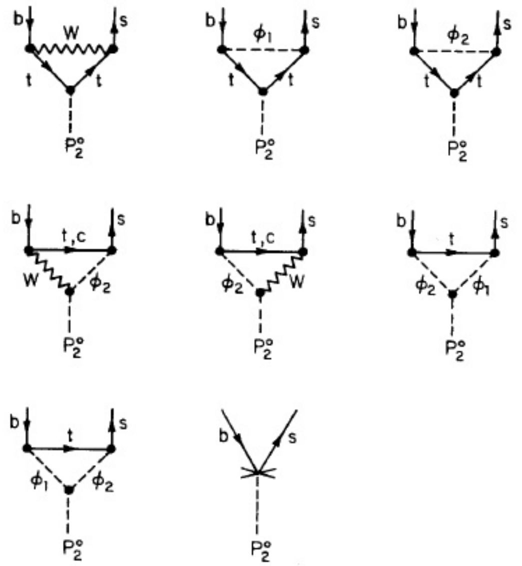
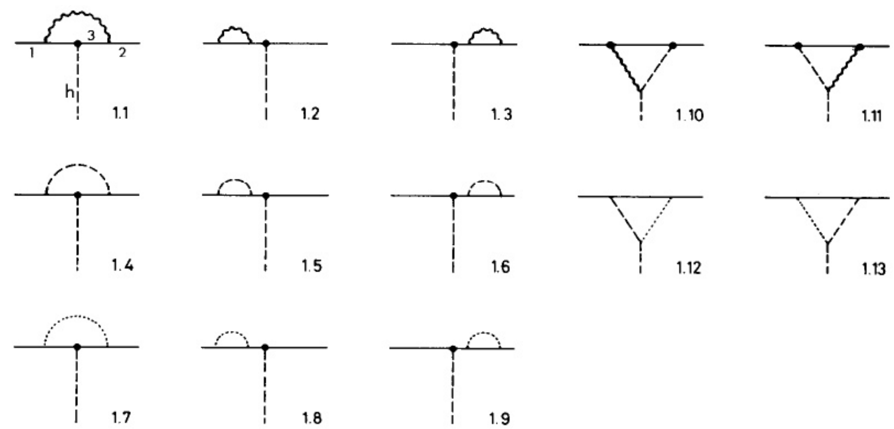


Fig. 2. Feynman diagrams contributing to the b→s P_2^0 amplitude at one-loop.

in both models I and II. The functions $F_i(m, M_{\phi_2}, M_W)$ are

$$
\begin{aligned}
F_1(m, M_{\phi_2}, M_W) = &\left(\frac{M_W^2 - \frac{1}{2}m^2}{M_W^2 - m^2}\right)\left(\frac{M_W^2}{M_W^2 - m^2}\ln\left(\frac{M_W^2}{m^2}\right) - 1\right) \\
&+ \frac{2M_W^2}{M_W^2 - M_{\phi_2}^2}\left(\frac{M_{\phi_2}^2}{M_{\phi_2}^2 - m^2}\ln\left(\frac{M_{\phi_2}^2}{m^2}\right) - \frac{M_W^2}{M_W^2 - m^2}\ln\left(\frac{M_W^2}{m^2}\right)\right) \\
&+ \tfrac{1}{2}(M_W^2 - M_{\phi_2}^2)\left(\frac{-M_{\phi_2}^2}{(M_W^2 - M_{\phi_2}^2)(M_{\phi_2}^2 - m^2)}\right. \\
&+ \frac{M_W^2 M_{\phi_2}^2}{(M_W^2 - m^2)(M_W^2 - M_{\phi_2}^2)^2}\ln\left(\frac{M_W^2}{M_{\phi_2}^2}\right) \\
&+ \frac{M_{\phi_2}^2 m^2}{(M_W^2 - m^2)(M_{\phi_2}^2 - m^2)^2}\ln\left(\frac{M_{\phi_2}^2}{m^2}\right) + \frac{1}{2}\frac{m^2}{(M_W^2 - m^2)(M_{\phi_2}^2 - m^2)} \\
&+ \frac{1}{2}\frac{M_W^4}{(M_W^2 - M_{\phi_2}^2)(M_W^2 - m^2)^2}\ln\left(\frac{M_W^2}{m^2}\right) \\
&\left. - \frac{1}{2}\frac{M_{\phi_2}^4}{(M_W^2 - M_{\phi_2}^2)(M_{\phi_2}^2 - m^2)^2}\ln\left(\frac{M_{\phi_2}^2}{m^2}\right)\right),
\end{aligned}
\qquad (17)
$$

[Frere, Vermaseren, Gavela, PLB 103 (1981) 129]



$$
\begin{aligned}
A_1(m) = &\frac{-3M_W^4}{(M_W^2 - m^2)(M_W^2 - M_H^2)}\left(1 + \frac{M_H^2 - m^2}{M_W^2 - m^2}\right) \\
&\times \ln\frac{m^2}{M_W^2} + \frac{M_H^2}{(M_H^2 - m^2)}\left(\frac{6M_W^2}{M_W^2 - M_H^2} + \frac{M_H^2}{M_H^2 - m^2}\right) \\
&\times \ln\frac{m^2}{M_W^2} + 2 + \frac{3M_W^2}{M_W^2 - m^2} + \frac{M_H^2}{M_H^2 - m^2},
\end{aligned}
\qquad (9)
$$

- Results disagree, neither knew about other
- Many papers cited both, none commented on disagreement... so we computed it all...

The current data

- Considering the combined BaBar/Belle rate measurement and the spectra...

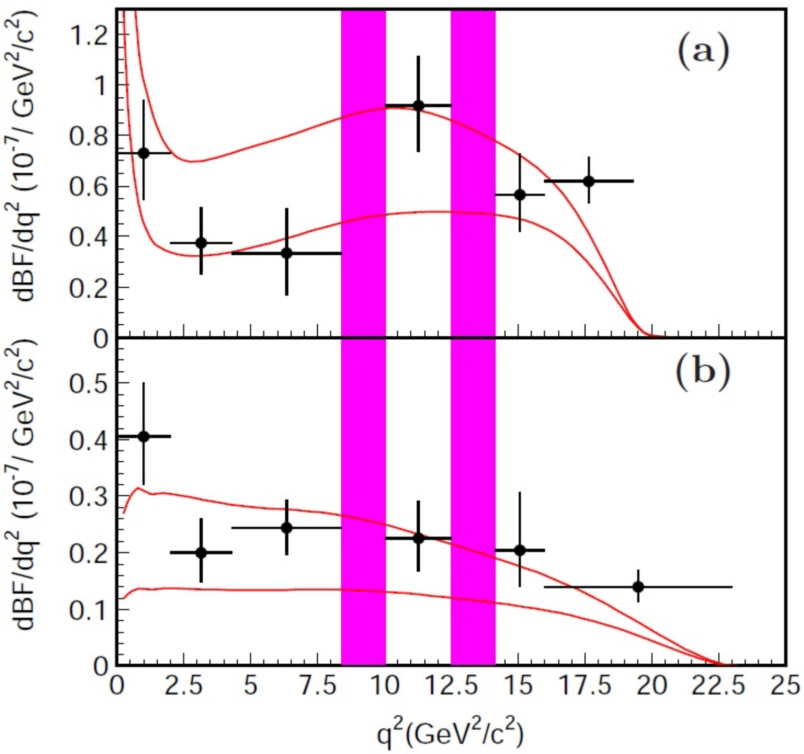
[Wei *et al.*, Belle Collaboration, PRL 103 (2009) 171801]

we used: $\mathcal{B}(B \to Ka) \times \mathcal{B}(a \to \mu^+\mu^-) < 10^{-7}$

[at a high, but who-knows-what CL...]

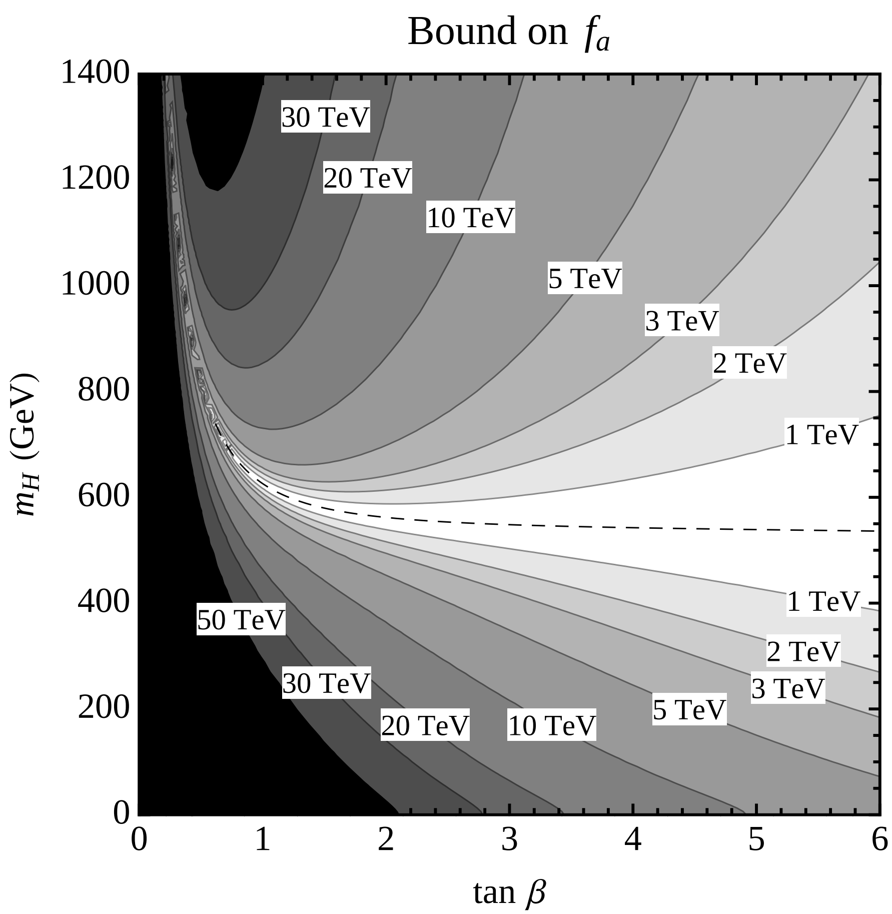
Can improve independent of form factor uncertainties

For this physics $K\ell^+\ell^-$ may be better than $K^*\ell^+\ell^-$, since no O_7 (photon penguin) enhancement at small q^2 in K mode



- BaBar and Belle should be able to set a significantly better bound
- LHCb should be able to improve it substantially

The bound from $B \to K\ell^+\ell^-$



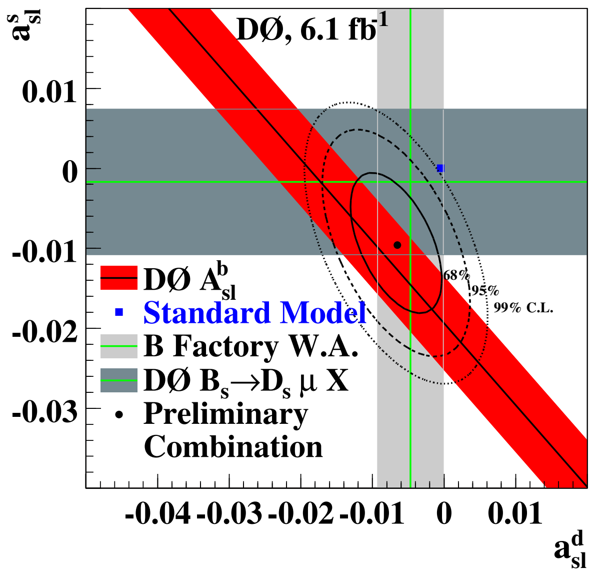
[Freytsis, ZL, Thaler, 0911.5355]

- Cancellation in a narrow region near the dashed line (between $\cot\beta$ and $\cot^3\beta$ terms)
- In most of the parameter space this is the best bound (then $\Upsilon(3S) \to \gamma A^0$) [BaBar, 0902.2176]

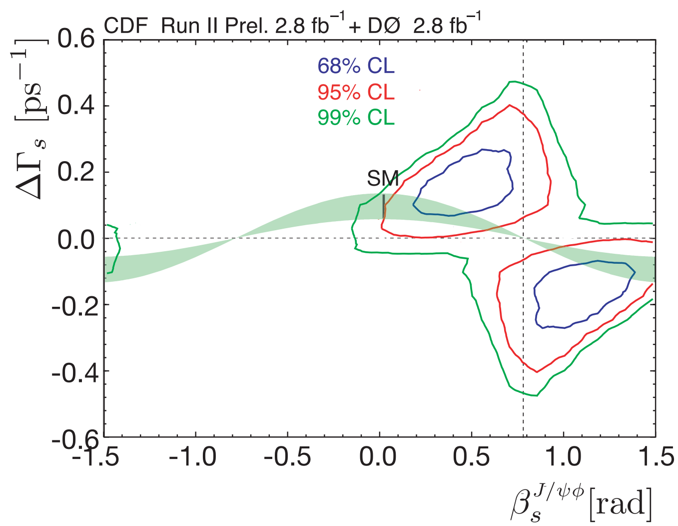
Final comments

Anomalies on the watch list

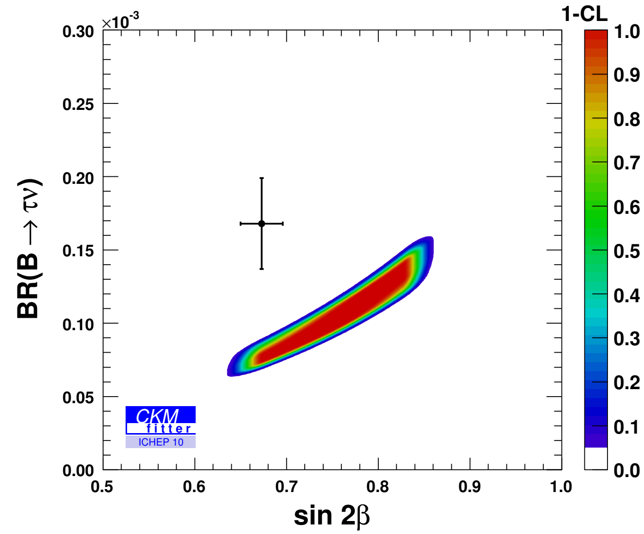
- $A_{\rm SL}$ — CP violation in $B_{d,s}$ mixing: $\sim 3\sigma$



β_s — analog of β, measured in $B_s \to \psi\phi$: $\sim 2\sigma$



$\mathcal{B}(B \to \tau\nu)$ — above the SM prediction: $\sim 2.5\sigma$



- $B \to K\pi$ CP asymmetries: theoretically less clean, but very puzzling (many σ)

- In addition, there are several other measurements where improved experimental sensitivity could unambiguously establish non-SM physics

Conclusions

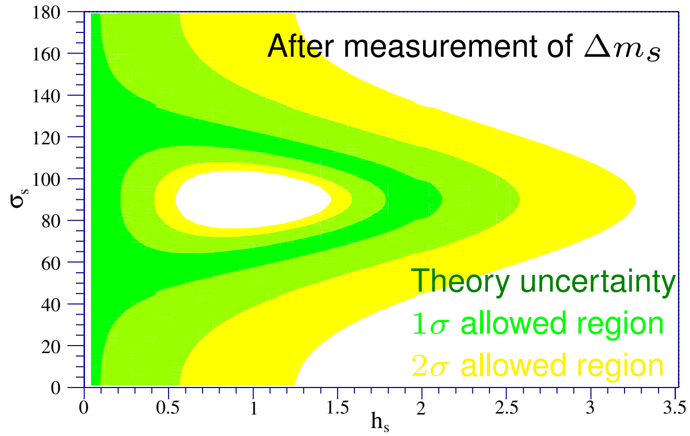
- Substantial improvements in many analyses possible using the existing data
- Few hints of discrepancies — existing data could have shown new physics, compelling reasons to want a lot more data (theoretical uncertainties won't be limiting)
- E.g., if any of the anomalies on the previous page become robust, not only is new physics discovered, but (in case of SUSY) gauge mediation is ruled out
- Consistency of precision flavor measurements with SM is a problem for NP @ TeV

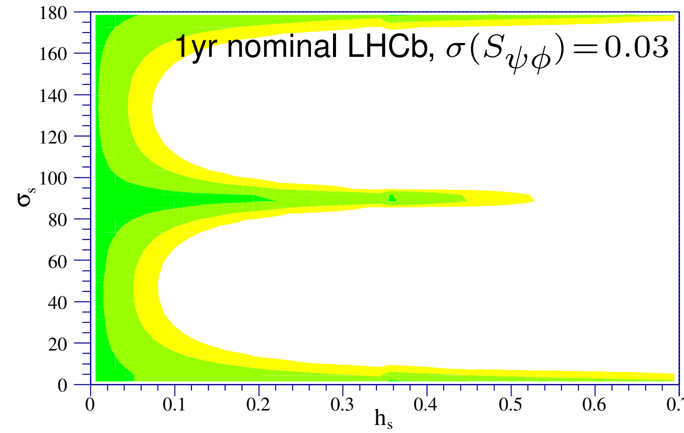
  However, NP in most FCNC processes may still be $> 10\%$ of the SM contributions
- Expect exciting synergies between high-p_T LHC and low energy flavor physics

Backup slides

A personal LHCb best buy list

- After Δm_s measurement, large NP contribution to B_s mixing is still allowed





[ZL, Papucci, Perez, hep-ph/0604112]

- LHCb will probe B_s sector at a level comparable to B_d
  - Difference of CP asymmetries, $S_{B_s \to \psi\phi} - S_{B_s \to \phi\phi}$
  - $B_s \to \mu^+\mu^-$ ($\propto \tan^6\beta$), search for $B_d \to \mu^+\mu^-$, other rare / forbidden decays
  - 10^{4-5} events in $B \to K^{(*)}\ell^+\ell^-$, $B_s \to \phi\gamma, \ldots$ — test Dirac structure, BSM op's
  - γ from $B \to DK$ and $B_s \to D_s K$ (for α probably super-B wins)
  - [Precisely measure τ_{Λ_b} — affects how much we trust $\Delta\Gamma_{B_s}$ calculation, etc.]

And a lot more: the B factory decade

- Q: How many CP violating quantities are measured with $> 3\sigma$ significance?

  A: 15; B: 19; C: 23; D: 27 (with different sensitivity to new physics)

And a lot more: the B factory decade

- Q: How many CP violating quantities are measured with $> 3\sigma$ significance?

  C: 23 (with different sensitivity to new physics)

ϵ_K, ϵ'_K,

$S_{\psi K}$, $S_{\eta' K}$, $S_{f_0 K}$, $S_{\pi K}$, $S_{K^+K^-K^0}$, S_{3K_S}, $S_{\psi\pi^0}$, $S_{D^+D^-}$, $S_{D^{*+}D^{*-}}$, $S_{D^{*+}D^-}$, $S_{\pi^+\pi^-}$

$A_{\rho^0 K^+}$, $A_{\eta K^+}$, $A_{f_2 K^+}$, $A_{K^+\pi^-}$, $A_{\eta K^{*0}}$, $A_{\pi^+\pi^-}$, $A_{\rho^\pm\pi^\mp}$, $\Delta C_{\rho^\pm\pi^\mp}$, $a_{D^{*\pm}\pi^\mp}$, $A_{D_{\rm CP+}K^-}$

- Just because a measurement determines a CP violating quantity, it no longer automatically implies that it is interesting

  (E.g., if $S_{\eta' K}$ was still consistent with 0, it would be a many σ discovery of NP!)

- It doesn't matter if one measures a side or an angle — only experimental precision and theoretical cleanliness for interpretation for short distance physics do

Neutral meson mixings

- Identities, neglecting CPV in mixing (not too important, surprisingly poorly known)

$$K: \text{ long-lived} = CP\text{-odd} = \text{heavy}$$

$$D: \text{ long-lived} = CP\text{-odd } (3.5\sigma) = \text{light } (2\sigma)$$

$$B_s: \text{ long-lived} = CP\text{-odd } (1.5\sigma) = \text{heavy in the SM}$$

$$B_d: \text{ yet unknown, same as } B_s \text{ in SM for } m_b \gg \Lambda_{\rm QCD}$$

Before 2006, we only knew experimentally the kaon line above

- We have learned a lot about meson mixings — good consistency with SM

	$x = \Delta m/\Gamma$ SM theory	$x = \Delta m/\Gamma$ data	$y = \Delta\Gamma/(2\Gamma)$ SM theory	$y = \Delta\Gamma/(2\Gamma)$ data	$A = 1 - \lvert q/p\rvert^2$ SM theory	$A = 1 - \lvert q/p\rvert^2$ data
B_d	$\mathcal{O}(1)$	0.78	$y_s\,\lvert V_{td}/V_{ts}\rvert^2$	-0.005 ± 0.019	$-(5.5 \pm 1.5)10^{-4}$	$(-4.7 \pm 4.6)10^{-3}$
B_s	$x_d\,\lvert V_{ts}/V_{td}\rvert^2$	25.8	$\mathcal{O}(-0.1)$	-0.05 ± 0.04	$-A_d\,\lvert V_{td}/V_{ts}\rvert^2$	$(0.3 \pm 9.3)10^{-3}$
K	$\mathcal{O}(1)$	0.948	-1	-0.998	$4\,{\rm Re}\,\epsilon$	$(6.6 \pm 1.6)10^{-3}$
D	< 0.01	< 0.016	$\mathcal{O}(0.01)$	$y_{CP} = 0.011 \pm 0.003$	$< 10^{-4}$	$\mathcal{O}(0.1)$ bound only

$K^0 - \overline{K}^0$ mixing in supersymmetry

- $$\frac{(\Delta m_K)^{\rm SUSY}}{(\Delta m_K)^{\rm exp}} \sim 10^4 \left(\frac{1\,{\rm TeV}}{\tilde m}\right)^2 \left(\frac{\Delta\tilde m^2_{12}}{\tilde m^2}\right)^2 {\rm Re}\big[(K^d_L)_{12}(K^d_R)_{12}\big]$$

  $K^d_{L(R)}$: mixing in gluino couplings to left-(right-)handed down quarks and squarks

  For ϵ_K, replace: $10^4\,{\rm Re}\big[(K^d_L)_{12}(K^d_R)_{12}\big] \Rightarrow 10^6\,{\rm Im}\big[(K^d_L)_{12}(K^d_R)_{12}\big]$

- Classes of models to suppress each factors

  (i) Heavy squarks: $\tilde m \gg 1\,{\rm TeV}$ (e.g., split SUSY)

  (ii) Universality: $\Delta m^2_{\tilde Q,\tilde D} \ll \tilde m^2$ (e.g., gauge mediation)

  (iii) Alignment: $|(K^d_{L,R})_{12}| \ll 1$ (e.g., horizontal symmetries)

- Has driven SUSY model building — all models incorporate some of the above

- $D^0 - \overline{D}^0$ mixing discovery (BaBar & Belle, 2007) ruled out (iii) as sole explanation

Outlook

- Measurements sensitive to scales $> \text{TeV}$; sensitivity limited by statistics

  The non-observation of NP at $E_{\text{exp}} \sim m_B$ is a problem for NP at $\Lambda_{\text{NP}} \sim \text{TeV}$

  $\Rightarrow$ New physics could show up any time measurements improve

- If NP is seen: Study it in as many different operators as possible

  One / many sources of CPV? Only in CC interactions? NP couples mostly to up / down sector? 3rd / all generations? $\Delta(F) = 2$ or 1?

- If NP is not seen: Achieve what is theoretically possible

  Could teach us a lot whether or not NP is seen at LHC

- Flavor physics will provide important clues to model building in the LHC era

Looking for surprises

- Will LHC see new particles beyond a Higgs?

  SUSY, something else, understand in detail?

- Will NP be seen in the quark sector?

  B_s: large $A^s_{\rm SL}$, β_s or $B_s \to \mu^+\mu^-$?

  B: Semileptonic $|V_{ub}|$ and $B \to \tau\nu$ agree, in conflict with $\sin 2\beta$?

  D: CPV in D^0–$\overline{D}^0$ mixing?

- Will NP be seen in the lepton sector?

  $\mu \to e\gamma$, $\mu \to eee$, $\tau \to \mu\gamma$, $\tau \to \mu\mu\mu$, ...?

- I don't know, but I'm sure it's worth finding out...! Want to keep looking broadly