FPCP into the future

Benjamin Grinstein
FPCP07
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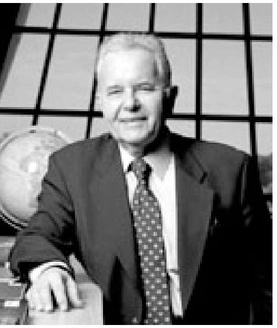
Outline

- The CKM triangle
  - selected inputs (sides, angles)
  - tension in V_{ub}
- Are there problems? No.
- So what now?
  - MFV & MFV-GUTS
  - implications for LHC

Appologies:
Not intended to be inclusive.
Hope to be provocative, insightful.
Will rush through the boring but required review.
Missing many references (ran out of time)



The CKM Matrix

(it is not just a triangle)

$$U = \begin{pmatrix} u \\ c \\ t \end{pmatrix} \qquad D = \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Diagonalize quark mass terms by unitary transformations

$$\bar{U}_L \lambda_U U_R + \bar{D}_L \lambda_D D_R \longrightarrow \bar{U}_L (V^\dagger_{U_L} \lambda_U V_{U_R}) U_R + \bar{D}_L (V^\dagger_{D_L} \lambda_D V_{D_R}) D_R$$

Charged current

$$\bar{U}_L \gamma^\mu D_L \to \bar{U}_L \gamma^\mu (V^\dagger_{U_L} V_{D_L}) D_L, \qquad V_{\mathrm{CKM}} = V^\dagger_{U_L} V_{D_L}$$

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

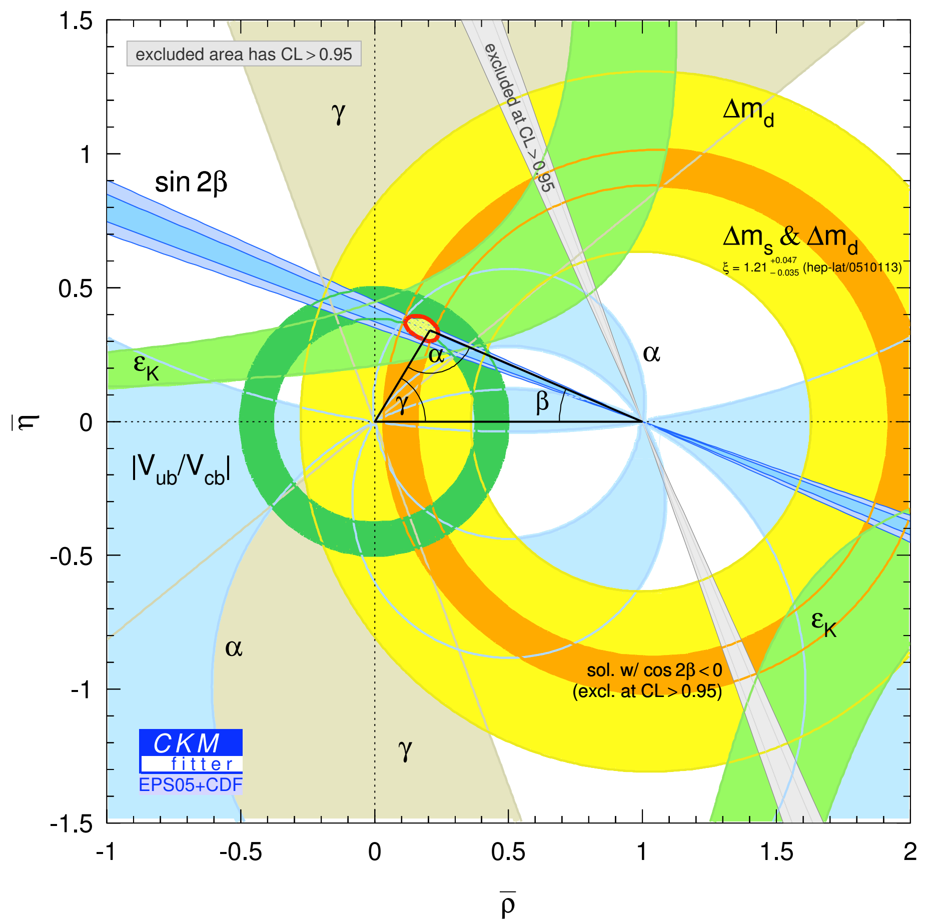
CKM is inevitable. The question is not whether CKM is correct.
It has to be there.
The question is: is it sufficient?

Wolfenstein parametrization

$$V_{\rm CKM} \approx \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\bar\rho - i\bar\eta) \\ -\lambda(1+iA^2\lambda^4\bar\eta) & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\bar\rho-i\bar\eta) & -A\lambda^2(1+i\lambda^2\bar\eta) & 1 \end{pmatrix} + \mathcal{O}(\lambda^6).$$

$\lambda, A\lambda^2$ **determined to ~2%,**

$\bar\rho$ and $\bar\eta$ to:



Sides determination

(Circles in plane)

1. $|V_{td}|$ (B_d/B_s mixing)
2. $|V_{ub}|$ ($B \to X_u \mu\nu$)
3. $|V_{cb}|$ ($B \to X_c \mu\nu$)

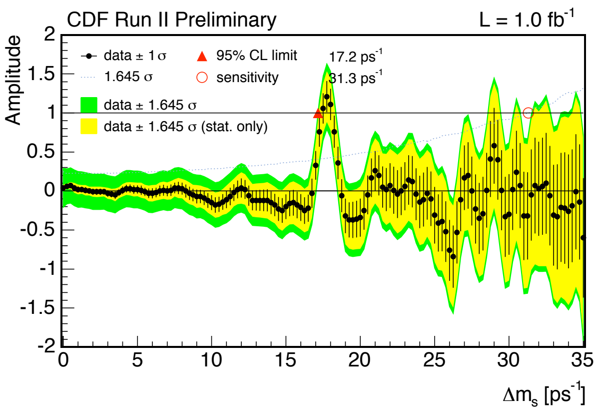
Inclusive+Exclusive
More emphasis on exclusives
(tend to get neglected)

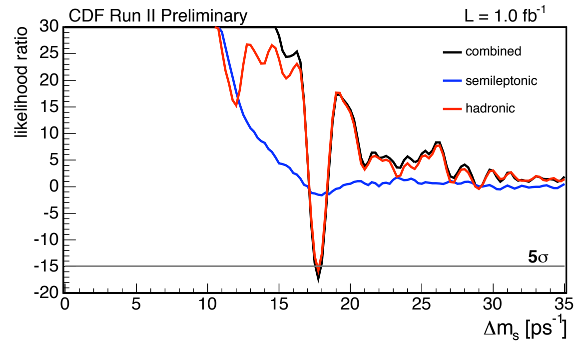
$|V_{cb}|$ ain't a circle. Needed for extraction of $\frac{|V_{ub}|}{|V_{cb}V_{us}|}$

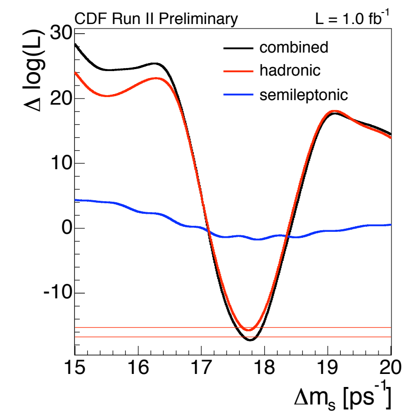
Similarly, $|V_{us}|$ ($K \to \pi e\nu$) needed, but not covered here.
And, of course, should check rest (like magical 1-2% precision in exclusive D decays).

Won't give a compendium of latest numbers (quote only when tension)

$|V_{td}|$







Theory: $$\frac{|V_{td}|}{|V_{ts}|} = \xi \sqrt{\frac{\Delta m_s \; m_{B_s}}{\Delta m_d \; m_{B_d}}} \qquad \xi^2 = \frac{B_{B_s} f_{B_s}^2}{B_{B_d} f_{B_d}^2}$$

Lattice: $$\xi = 1.21 \, {}^{+0.047}_{-0.035}$$

I'll believe a 3% lattice theory error when the lattice has produced one successful prediction and several 3% postdictions
However, here the calculation is really of $\xi^2 - 1$, and the error is 16%
Chiral-PT gives only chiral logs, so error in $\xi^2 - 1 \approx 0.3$ is 100%

$$\frac{|V_{td}|}{|V_{ts}|} = 0.2060 \pm 0.0007(\mathrm{exp}) \, {}^{+0.0081}_{-0.0060} (\mathrm{theory})$$

Rating: Experiment ★★★★★
Theory ★★ (it's a factor of 10 behind experiment and only one method)

$|V_{cb}|$ inclusive - moments

$$\frac{d\Gamma(B \to X_c \ell \nu)}{dx dy} = |V_{cb}|^2 f(x,y)$$

In full QCD rate given in terms of four parameters: $|V_{cb}|^2, \alpha_s, m_b, m_c$

well known

drops out of normalized moments

fix by moments

Get $|V_{cb}|$ from rate

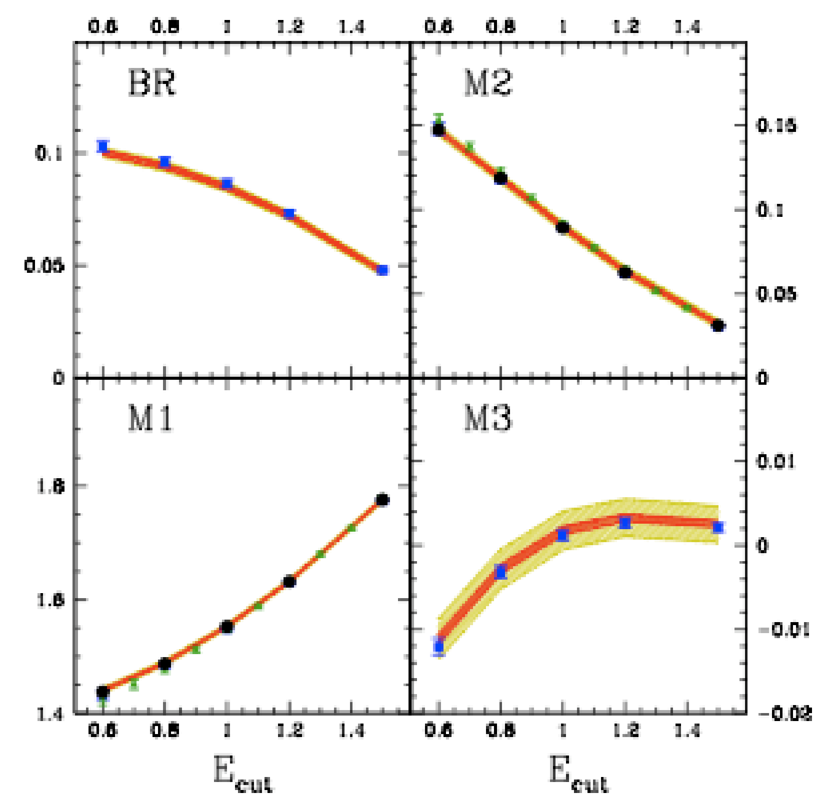
Problem: can't get f(x,y) in QCD
Solution: Use $1/m_b$ expansion (ie Λ/m_b)

$$\Gamma_0 + \quad \Gamma_1 + \quad \Gamma_2 + \quad \Gamma_3 + \quad \ldots$$
$$\downarrow \quad \downarrow \quad \downarrow \quad \downarrow$$
$$m_b \qquad\qquad \lambda_1 \quad \mathcal{T}_{1,2,3}, \rho_1$$

← fit these too

Error: 2%, Understand without magic:
use last term used in expansion to estimate

$$\beta_0 \alpha_s^2,\ \alpha_s \Lambda_{QCD}/m_b,\ (\Lambda_{QCD}/m_b)^3$$



$|V_{cb}|$ exclusive

- Good to confirm inclusive
- HQET-inspired parametrization

$$\frac{d\Gamma(B \to D^* \ell \bar{\nu})}{dw} = \frac{G_F^2 m_B^5}{48\pi^3} r_*^3 (1-r_*)^2 \sqrt{w^2-1}\,(w+1)^2 \times \left[1 + \frac{4w}{1+w}\frac{1-2wr_*+r_*^2}{(1-r_*)^2}\right] |V_{cb}|^2 \mathcal{F}_*{}^2(w)$$

$$\frac{d\Gamma(B \to D \ell \bar{\nu})}{dw} = \frac{G_F^2 m_B^5}{48\pi^3} r^3 (1+r)^2 (w^2-1)^{3/2} |V_{cb}|^2 \mathcal{F}^2(w)$$

- $\mathcal{F}$, $\mathcal{F}_*$: combination of form factors of $V-A$
- At lowest order in HQET $\mathcal{F}(1) = \mathcal{F}_*(1) = 1$
- Luke's Theorem: $\mathcal{F}_*(1) - 1 = \mathcal{O}(\Lambda_{\mathrm{QCD}}/m_c)^2$ (get from lattice)
- Measure at w>1, extrapolate
- Extrapolation uncertainty reduced by theory/dispersion relations

“Good to confirm inclusive” ??

$$|V_{cb}| = 37.6 \pm 0.3 \pm 1.3 \pm 1.5 \times 10^{-3}$$ Exclusive (BABAR Phys.Rev.D74:092004,2006)

$$|V_{cb}| = 41.6 \pm 0.6 \times 10^{-3}$$ Inclusive (PDG)

Form factor tension with theory?

theory

$$\begin{aligned} R_1(w) &= 1.25 - 0.10(w-1) \\ R_2(w) &= 0.81 + 0.09(w-1) \end{aligned}$$

experiment

$$\begin{aligned} R_1 &= 1.396 \pm 0.060 \pm 0.035 \pm 0.027 \\ R_2 &= 0.885 \pm 0.040 \pm 0.022 \pm 0.013 \end{aligned}$$

And, whatever happened to problem with slopes (D* vs D)?

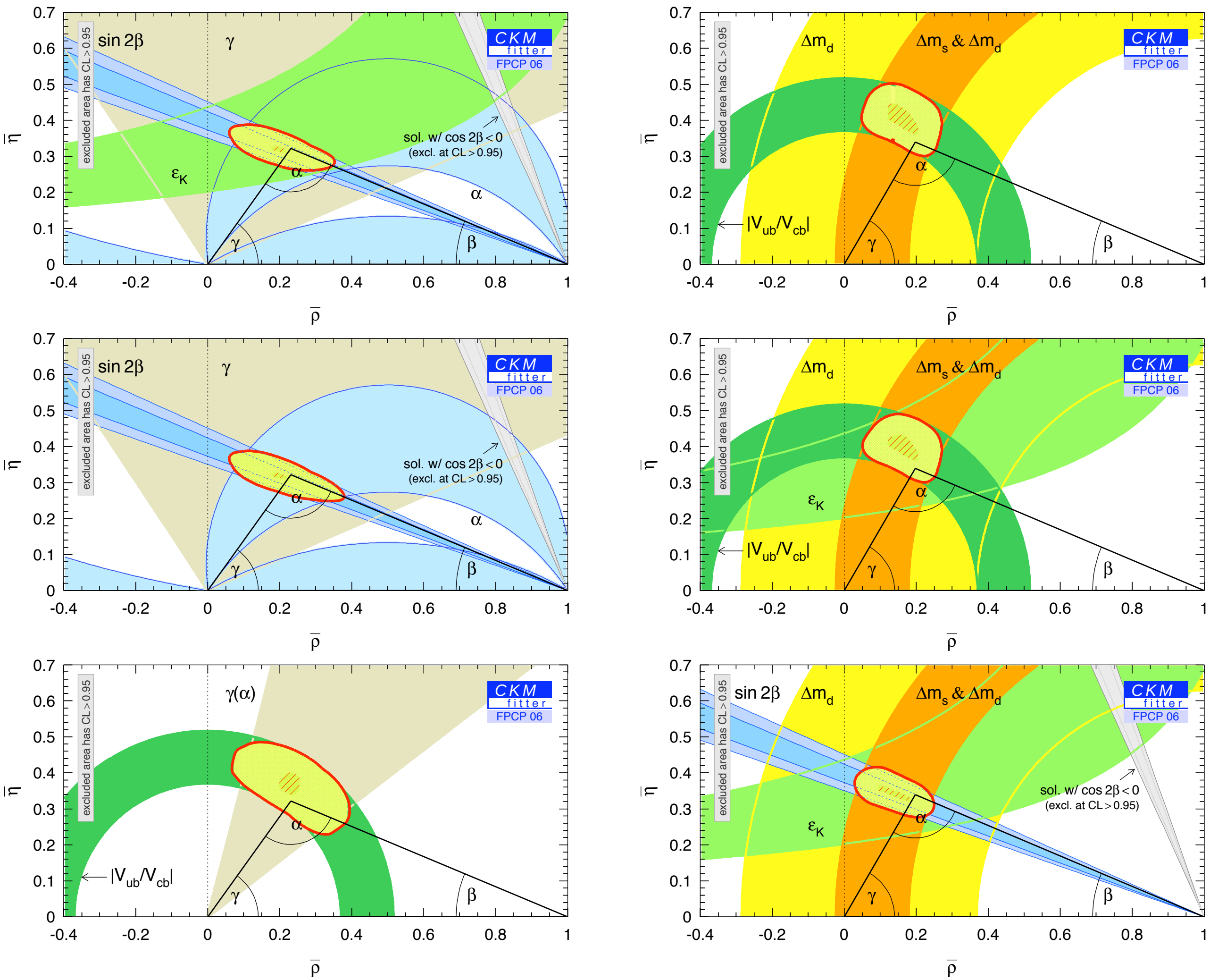
$$\begin{aligned} \rho^2_{\mathcal{F}} - \rho^2_{\mathcal{F}_*} &= 0.203 + 0.053\,\epsilon - 0.013\,\epsilon^2_{\rm BLM} + 0.075\,\eta(1) + 0.14\,\eta'(1) \\ &\quad + 1.0\,\chi_2(1) - 3.0\,\chi_3'(1) - 0.018\,\lambda_1/\mathrm{GeV}^2 \simeq 0.19 \end{aligned}$$ theory

$$\rho^2_{\mathcal{F}} - \rho^2_{\mathcal{F}_*} \simeq -0.22 \pm 0.20$$ experiment

Opportunity for lattice to show they can postdict quantities to 3% and predict slope difference to 3%.

taken from Jerome Charles @ FPCP06,Vancouver

What dominates? Consistency?



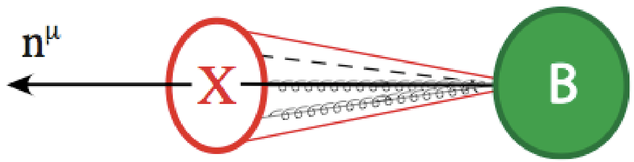
CPV vs non-CPV

non-QCD vs QCD

tree vs loop

Is $|V_{ub}|$ too large?

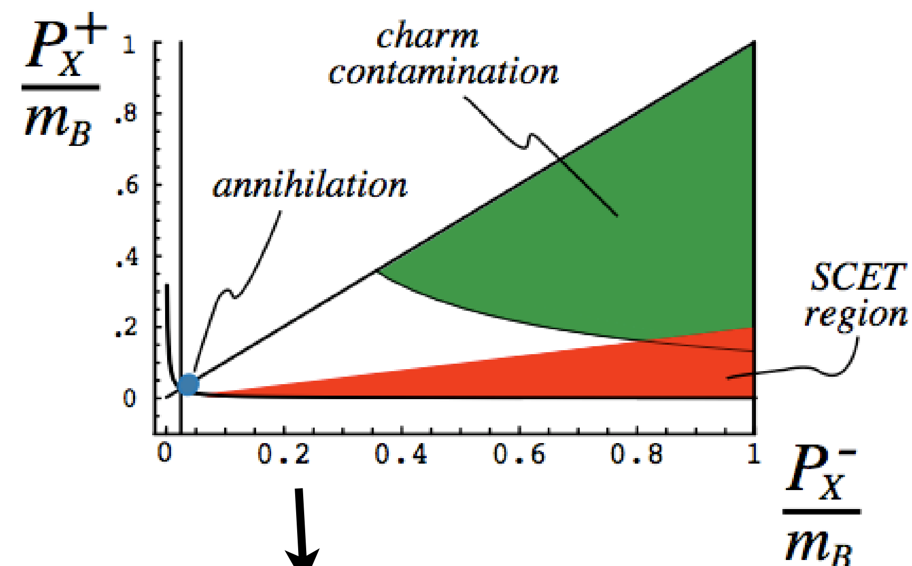
$|V_{ub}|$ inclusive



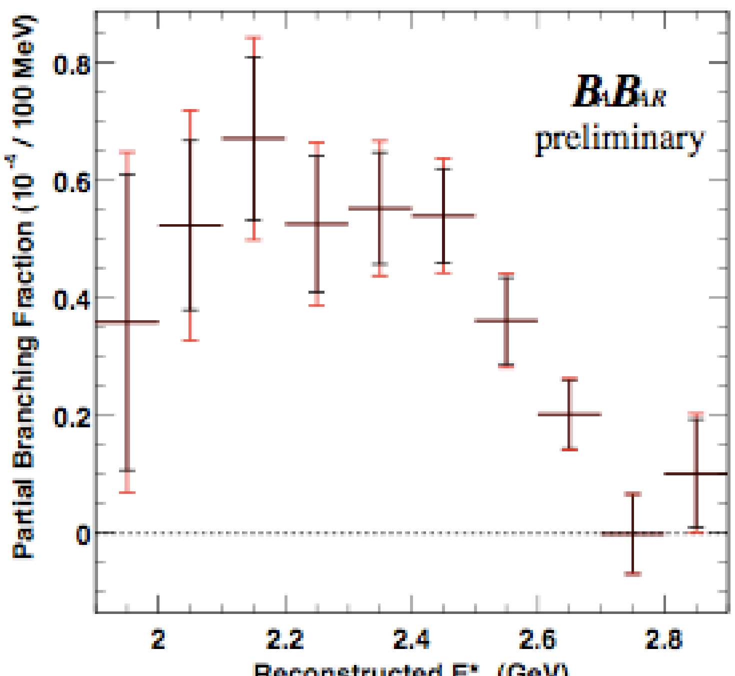
$m_X^2 \sim m_b \Lambda$
$P_X^- \gg P_X^+$

factorization
SCET

$B \to X_u e \bar{\nu}$



$B \to X_s \gamma$



not fully inclusive
need non-pert from exp

the problem is non-universal sub-leading shape functions

more apologies to I.S.

$$
\begin{aligned}
W_i^{(2)} = \; & \frac{h_i^{0f}(\bar{n}\cdot p)}{2m_b} \int_0^{p_X^+} dk^+ \, \mathcal{J}^{(0)}(\bar{n}\cdot p\, k^+,\mu)\, f_0^{(2)}(k^+ + r^+,\mu) \\
& + \sum_{r=1}^{2} \frac{h_i^{rf}(\bar{n}\cdot p)}{m_b} \int_0^{p_X^+} dk^+ \, \mathcal{J}^{(0)}(\bar{n}\cdot p\, k^+,\mu)\, f_r^{(2)}(k^+ + r^+,\mu) \\
& + \sum_{r=3}^{4} \frac{h_i^{rf}(\bar{n}\cdot p)}{m_b} \int dk_1^+ \, dk_2^+ \, \mathcal{J}_{1\pm 2}^{(-2)}(\bar{n}\cdot p\, k_j^+,\mu)\, f_r^{(4)}(k_j^+ + r^+,\mu) \\
& + \sum_{r=5}^{6} \frac{h_i^{rf}(\bar{n}\cdot p)}{\bar{n}\cdot p} \int dk_1^+ dk_2^+ dk_3^+ \, \mathcal{J}_1^{(-4)}(\bar{n}\cdot p\, k_{j'}^+,\mu)\, f_r^{(6)}(k_{j'}^+ + r^+,\mu) \\
& + \frac{h_i^{00f}(\bar{n}\cdot p)}{m_b} \int_0^{p_X^+} dk^+ \, \mathcal{J}^{(0)}(\bar{n}\cdot p\, k^+,\mu)\, g_0^{(2)}(k^+ + r^+,\mu) \\
& + \sum_{r=3}^{4} \frac{h_i^{rf}(\bar{n}\cdot p)}{m_b} \int dk_1^+ \, dk_2^+ \, \mathcal{J}_{3\pm 4}^{(-2)}(\bar{n}\cdot p\, k_j^+,\mu)\, g_r^{(4)}(k_j^+ + r^+,\mu) \\
& + \sum_{r=5}^{6} \frac{h_i^{rf}(\bar{n}\cdot p)}{\bar{n}\cdot p} \int dk_1^+ dk_2^+ dk_3^+ \, \mathcal{J}_2^{(-4)}(\bar{n}\cdot p\, k_{j'}^+,\mu)\, g_r^{(6)}(k_{j'}^+ + r^+,\mu) \\
& + \sum_{r=7}^{8} \frac{h_i^{rf}(\bar{n}\cdot p)}{\bar{n}\cdot p} \int dk_1^+ dk_2^+ dk_3^+ \, \big[\mathcal{J}_3^{(-4)}(\bar{n}\cdot p\, k_{j'}^+,\mu)\, g_r^{(6)}(k_{j'}^+ + r^+,\mu) \\
& \qquad\qquad + \mathcal{J}_4^{(-4)}(\bar{n}\cdot p\, k_{j'}^+,\mu)\, g_{r+2}^{(6)}(k_{j'}^+ + r^+,\mu)\big] \\
& + \sum_{m=1,2} \int dz_1 dz_2 \, \frac{h_i^{[2b]m+8}(z_1,z_2,\bar{n}\cdot p)}{m_b} \int_0^{p_X^+} dk^+ \, \mathcal{J}_m^{(2)}(z_1,z_2,p_X^- k^+)\, f^{(0)}(k^+ + \bar{\Lambda} - p_X^+) \\
& + \sum_{m=3,4} \frac{h_i^{[2c]m+8}(\bar{n}\cdot p)}{m_b} \int_0^{p_X^+} dk^+ \, \mathcal{J}_m^{(2)}(p_X^- k^+)\, f^{(0)}(k^+ + \bar{\Lambda} - p_X^+) \\
& + \sum_{m=5}^{10} \int dz_1 \, \frac{h_i^{[2c]m+8}(z_1,\bar{n}\cdot p)}{m_b} \int_0^{p_X^+} dk^+ \, \mathcal{J}_m^{(2)}(z_1,p_X^- k^+)\, f^{(0)}(k^+ + \bar{\Lambda} - p_X^+) \\
& + W_i^{[2La]f}[g_{11,12}^{(2)}] + W_i^{[2Lb]f}[g_{13,14}^{(2)}] + W_i^{[2LL]f}[g_{15-26}^{(4)}] + W_i^{[2Ga]f}[f_{3,4}^{(4)}]
\end{aligned}
$$

+ phase space & kinematic corrections

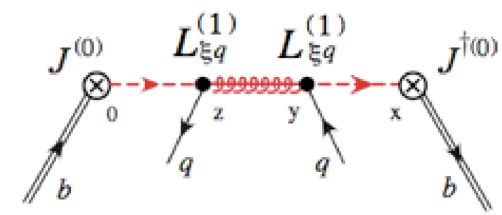
(triple differential spectra)

$h_i(\bar{n}\cdot p)$: $\alpha_s(m_b^2)$

$\mathcal{J}(\bar{n}\cdot p k_j^+)$: $\alpha_s(m_X^2) \sim \alpha_s(m_b\Lambda)$

A brick wall: $\alpha_s \dfrac{\Lambda}{m_b}$

- keep $\dfrac{\Lambda}{m_b}$ and $4\pi\alpha_s \dfrac{\Lambda}{m_b}$

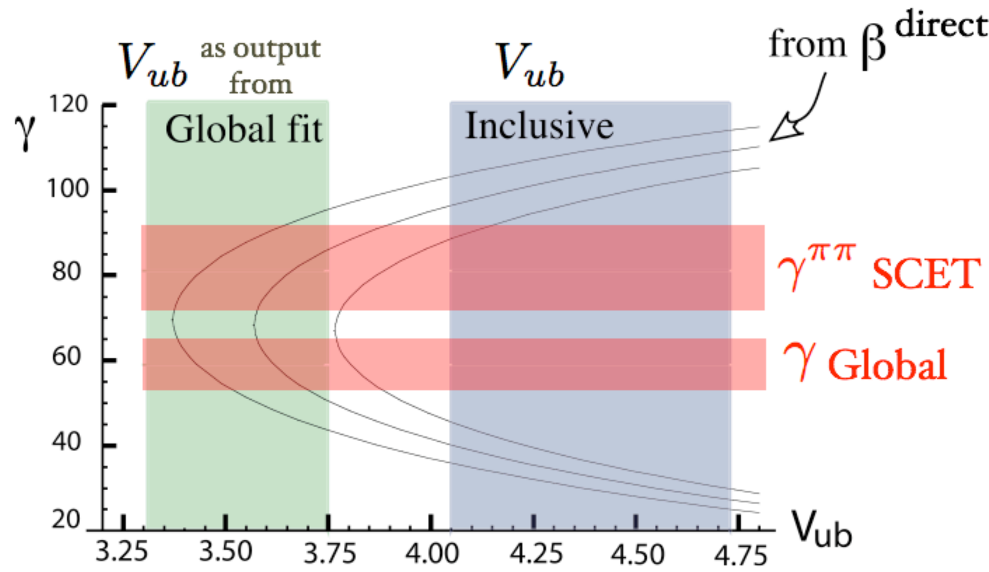


- model these subleading shape functions to get uncertainties

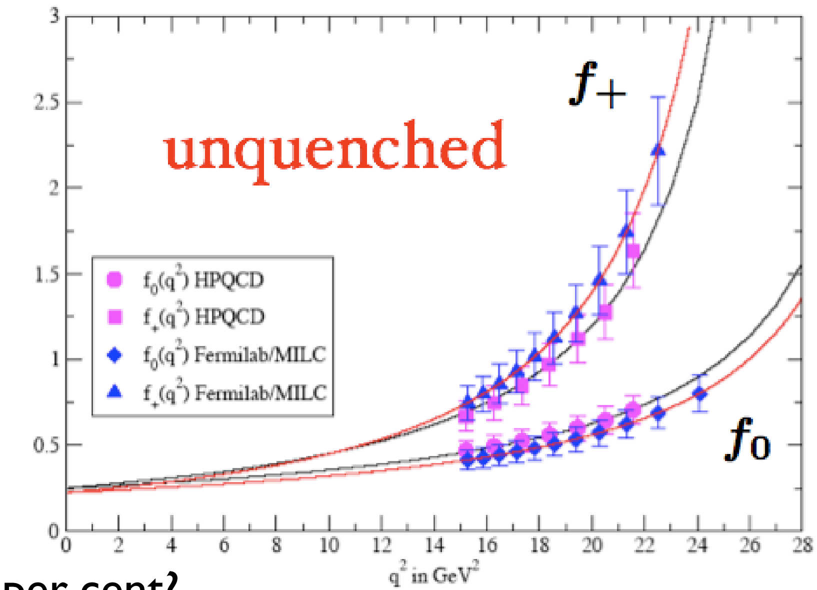
(& interpolate to local OPE)

$|V_{ub}|$ inclusive brown muck

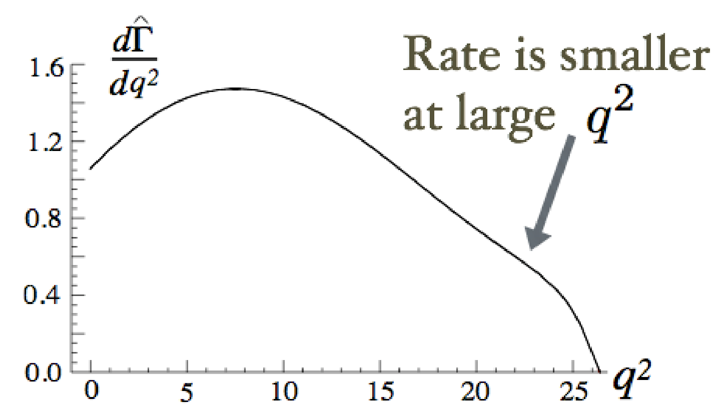
- $\alpha_s(\sqrt{\Lambda m_b})*\Lambda/m_b$ "brick wall"
  - numerics: $\alpha_s(\sqrt{\Lambda m_b})*\Lambda/m_b$ at least 5% but there are ~10 terms so guesstimate $\sqrt{(10)}*5\% = 15\%$
- shape function fit dependence: avoid by using Leibovich, Low, and Rothstein, but slightly larger errors
  (why do we still use parametrized fits???)
- subleading-shape functions
- data



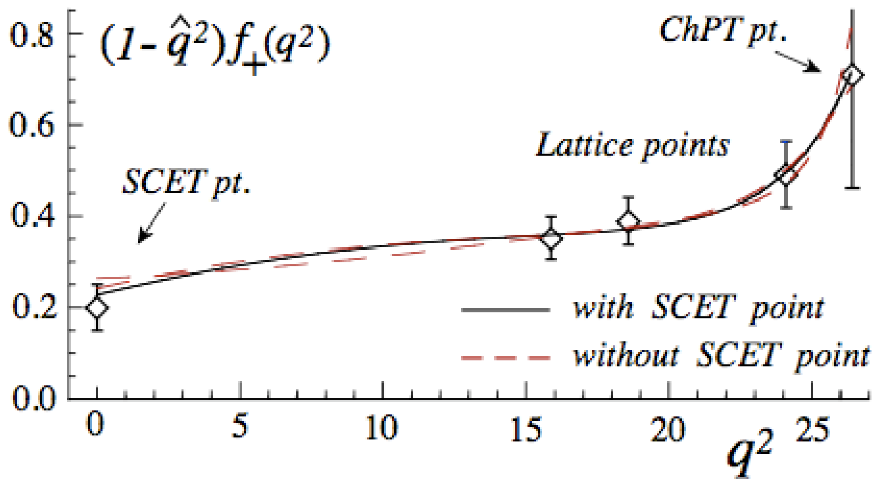
$|V_{ub}|$ exclusive

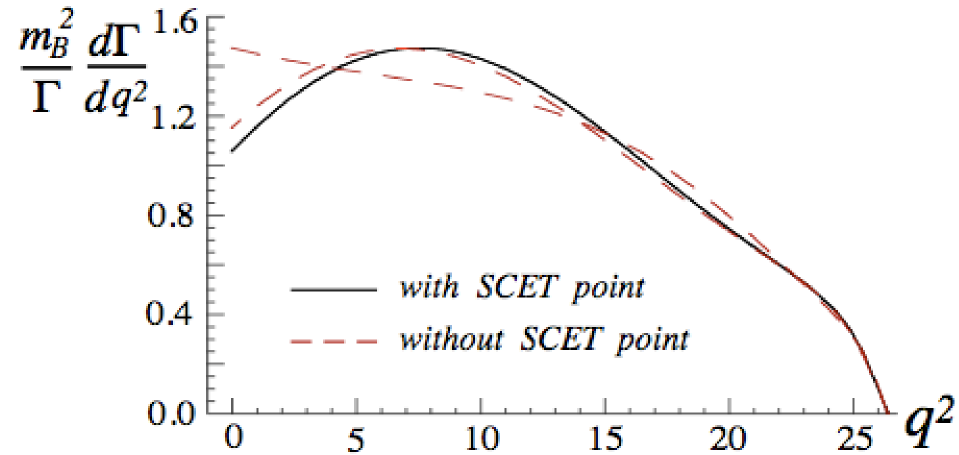


- Br(exp) to 8%, shouldn't we have $|V_{ub}|$ to 4%?
- Normalization of form factor ($f(0)$) from $B \to D\pi$ (SCET)?
  - Will never be better than 10% accurate
- Form factors from lattice: can we trust the lattice to few per-cent?
  - Need a number of successful lattice predictions (vs postdictions)
  - Eventual agreement between lattice groups with full dynamical fermions is not enough (need different methods too)
- Lattice only at $q^2 > 16$ GeV^2. Need either
  - high precision experiment at $q^2 > 16$ GeV^2 where rate is smallest (even though ff is largest)
  - theory of shape of form factor
    - models?
    - QCD sum rules: uncontrolled, not good to few %
    - dispersion relations



Dispersion relations + lattice





Type of Error	Variation From	$\delta\|V_{ub}\|^{q^2}$
Input Points	1-σ correlated errors	$\pm 13\%$
Bounds	F_+ versus F_-	$< 1\%$
m_b^{pole}	4.88 ± 0.40	$< 1\%$
OPE order	2 loop $\rightarrow$ 1 loop	$< 1\%$

$\chi^2/(dof) \sim 1.0$ expt. & theory

$10^3 \times |V_{ub}| = 3.72 \pm 0.52$ FNAL

$10^3 \times |V_{ub}| = 4.11 \pm 0.52$ HPQCD

Error in V_{ub} is ~13% (only 4% experimental)

Challenge: Need third method!

One idea out there: double ratios.
Example of "double ratio:"

- $SU(3)$ flavor symmetry $\Rightarrow$

$$\frac{f_{B_s}}{f_B} = 1 \qquad \text{and} \qquad \frac{f_{D_s}}{f_D} = 1$$

- Heavy Quark Flavor Symmetry $\Rightarrow$

$$\frac{f_{B_s}}{f_{D_s}} = \sqrt{\frac{m_c}{m_b}} \qquad \text{and} \qquad \frac{f_B}{f_D} = \sqrt{\frac{m_c}{m_b}}$$

- Ratio of ratios[a] ("double ratio")

$$R_1 = \frac{f_{B_s}/f_B}{f_{D_s}/f_D} = \frac{f_{B_s}/f_{D_s}}{f_B/f_D} = 1 + \mathcal{O}\left(m_s\left(\frac{1}{m_c} - \frac{1}{m_b}\right)\right)$$

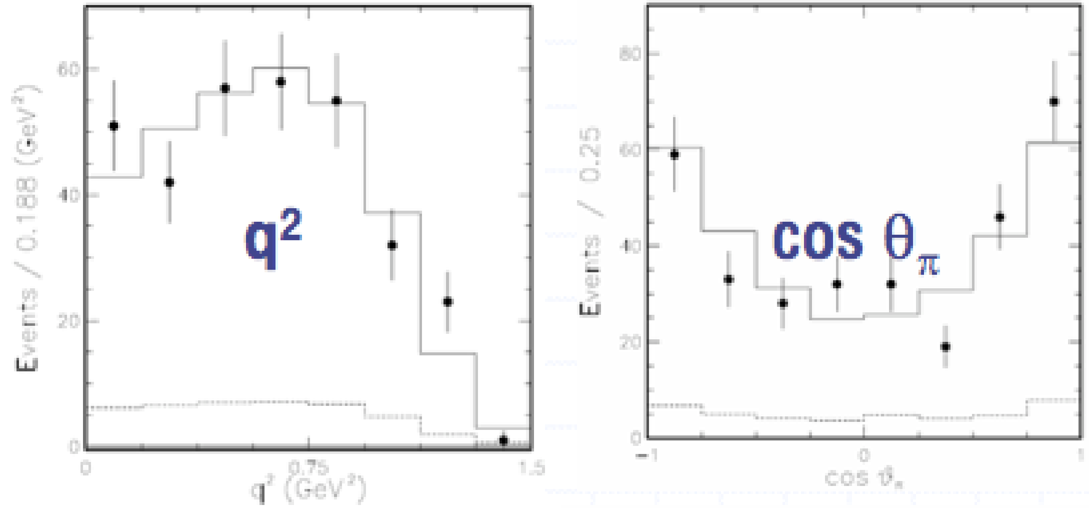
Error is ~ 5%

This is a Unknown Known!

something we don't know
that we know
(although we probably don't
not know it well enough, yet)

$\boxed{D \to \rho \ell \nu}$

CLEO



1. Measure, for q^2 above charmonium resonance region

$$\frac{\mathrm{d}\Gamma(\bar{B} \to \rho e \nu)/\mathrm{d}q^2}{\mathrm{d}\Gamma(\bar{B} \to K^* \ell^+ \ell^-)/\mathrm{d}q^2} = \frac{|V_{ub}|^2}{|V_{tb}V_{ts}^*|^2} \cdot \frac{8\pi^2}{\alpha^2} \cdot \frac{1}{|C_9^{\mathrm{eff}}(1+\delta(q^2))|^2 + |C_{10}|^2} \frac{\sum_\lambda |H_\lambda^{B\to\rho}(q^2)|^2}{\sum_\lambda |H_\lambda^{B\to K^*}(q^2)|^2}$$

2. Measure decays spectra for $D \to \rho \ell \nu$ and $D \to K^* \ell \nu$
3. Express all as functions of $y = E_V/m_V$ $(V = \rho, K^*)$
4. Use double-ratio. Let

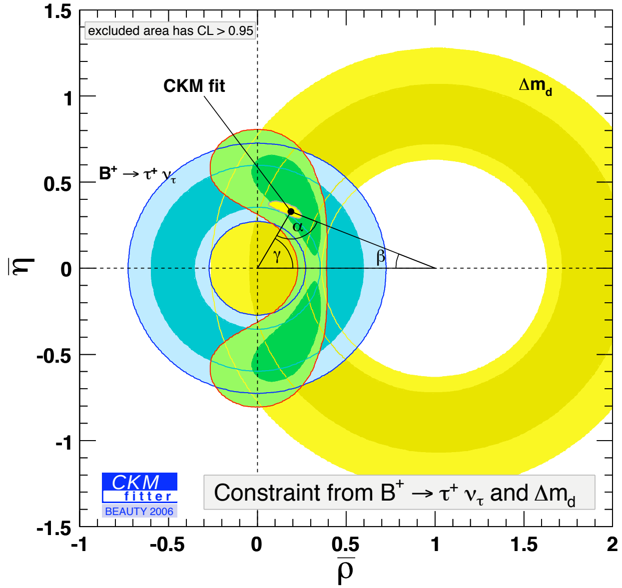
$$R_{B\to V}(y) \equiv \frac{\sum_\lambda |H_\lambda^{B\to\rho}(y)|^2}{\sum_\lambda |H_\lambda^{B\to K^*}(y)|^2} \qquad R_{D\to V}(y) \equiv \frac{\sum_\lambda |H_\lambda^{D\to\rho}(y)|^2}{\sum_\lambda |H_\lambda^{D\to K^*}(y)|^2}$$

then

$$R_{B\to V}(y) = R_{D\to V}(y)\left(1 + \mathcal{O}(m_s(\frac{1}{m_c} - \frac{1}{m_b}))\right)$$

5. Given $N_{\mathrm{eff}}(q^2) = |C_9^{\mathrm{eff}}(1+\delta(q^2))|^2 + |C_{10}|^2$ obtain $|V_{ub}|^2/|V_{tb}V_{ts}^*|^2$

Know how to do this. Not known (not done).



Fourth method:

$$\mathrm{Br}(B_u \to \tau\nu) \sim |V_{ub}|^2 f_{B_u}^2$$

$$\mathcal{B}(B^+ \to \tau^+\nu_\tau) = (0.88^{+0.68}_{-0.67}(\text{stat.}) \pm 0.11(\text{syst.})) \times 10^{-4},$$ BaBar

Can you trust the lattice for f_B?
Could also use double ratio here (method 4.5)

$$\frac{\dfrac{\Gamma(B_u \to \tau\nu)}{\Gamma(B_s \to \ell\bar{\ell})}}{\dfrac{\Gamma(D_d \to \ell\nu)}{\Gamma(D_s \to \ell\nu)}} \sim \left(\frac{f_{B_u}/f_{B_s}}{f_{D_d}/f_{D_s}}\right)^2 \frac{|V_{ub}|^2}{|V_{ts}V_{tb}|^2}$$

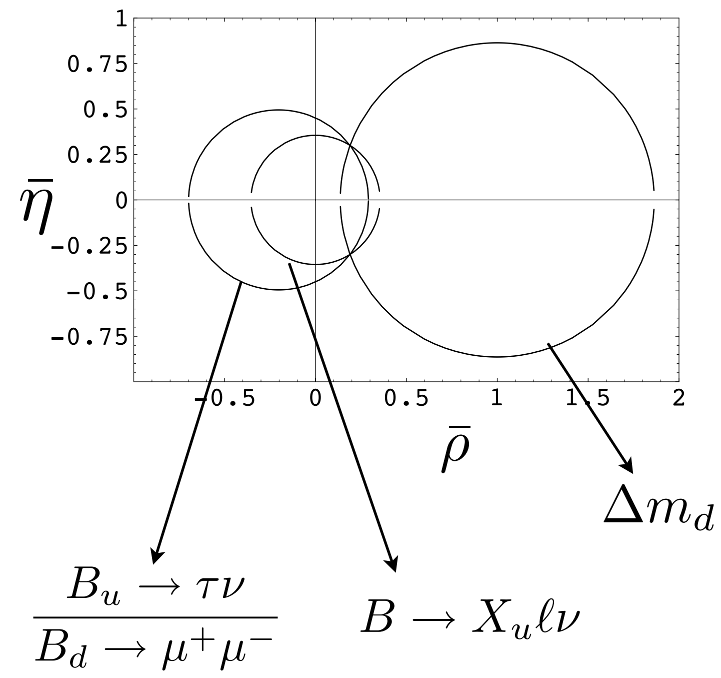
Not an unknown known (yet!):

$$Br(B_s \to \mu^+\mu^-) = 3.5 \cdot 10^{-9} \left[\frac{\tau(B_s)}{1.6\text{ps}}\right] \left[\frac{F_{B_s}}{210\,\text{MeV}}\right]^2 \left[\frac{|V_{ts}|}{0.040}\right]^2 \left[\frac{\overline{m}_t(m_t)}{170\,\text{GeV}}\right]^{3.12}$$

$$Br(B_s \to \mu^+\mu^-) < 2.3 \times 10^{-8} \qquad \text{(CDF)}$$

Fifth method??:

$$\frac{\mathrm{Br}(B_u \to \tau\nu)}{\mathrm{Br}(B_d \to \mu^+\mu^-)} \sim \frac{f_{B_u}^2}{f_{B_d}^2} \frac{|V_{ub}|^2}{|V_{td}V_{tb}|^2}$$



(Almost) no hadronic uncertainty!
(use only isospin symmetry)

Unusual circle (centered at ~ (–0.2,0), radius ~ 0.5)

A challenge for experiment (seems impossible)

Sixth method????:

Wrong charm decays

$$\bar{B}_{d,s} \to \bar{D}^0 X \qquad (b\bar{q} \to u\bar{c})$$

(not unlike DCS D^0 decays in the D^0 mixing case):

- -Exclusive: interesting connection to $B_{d,s}$ mixing matrix elements (lattice check)
- -Inclusive: challenge for experiment?

As it happens
I often hear
“We know $|V_{ub}|$ to 4% ...”

Which reminds me of ...

Happenings

You're going to be told lots of things.
You get told things every day that don't happen.

It doesn't seem to bother people, they don't—
It's printed in the press.
The world thinks all these things happen.
They never happened.

Everyone's so eager to get the story
Before in fact the story's there
That the world is constantly being fed
Things that haven't happened.

All I can tell you is,
It hasn't happened.
It's going to happen.

Donald Rumsfeld—Feb. 28, 2003, DoD briefing

Angles determination

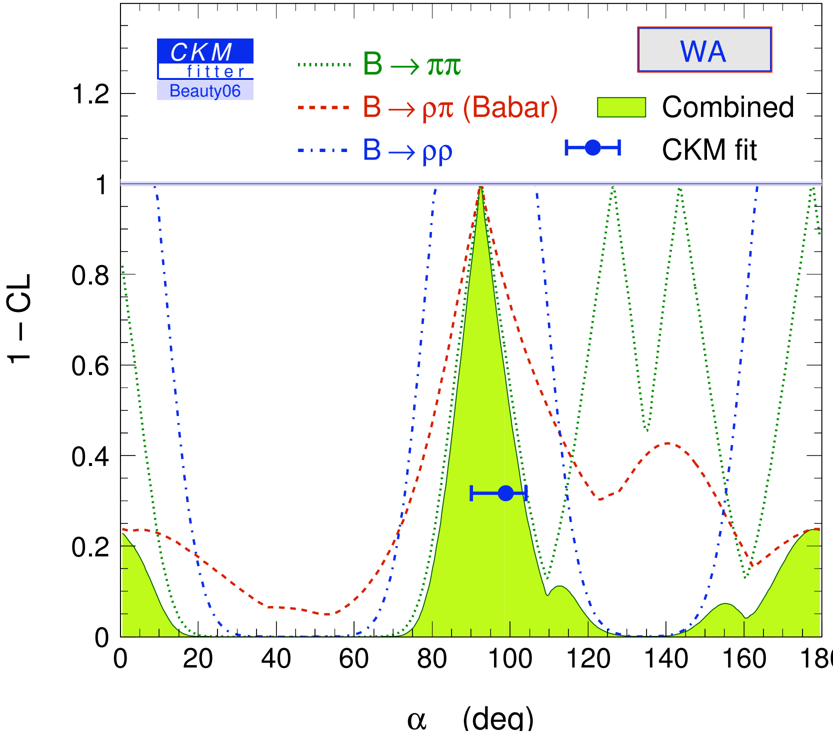
α from $B \to \pi\pi, \pi\rho, \rho\rho$

- Two empirical observations in $\rho\rho$: $S_{\rho^+\rho^-} = \sin[2(\alpha + \Delta\alpha)]$
  - Longitudianl polarization (CP even) dominates
  - Small neutral rate $\mathcal{B}(B \to \rho^0\rho^0) = (1.16 \pm 0.46) \times 10^{-6}$ $\Rightarrow$ small $\Delta\alpha$

$$\frac{\mathcal{B}(B\to\pi^0\pi^0)}{\mathcal{B}(B\to\pi^+\pi^0)} = 0.23 \pm 0.04 \quad \text{vs} \quad \frac{\mathcal{B}(B\to\rho^0\rho^0)}{\mathcal{B}(B\to\rho^+\rho^0)} = 0.06 \pm 0.03$$

- All three modes important
  - Before 2006 $\rho\rho$ dominated
- Effects of finite with of can be constrained with more data [Falk et al]
- All measurements combined:

$$\alpha = (93\,^{+11}_{-9})^\circ$$



γ from $B^\pm \to DK^\pm$

- Tree level: interference between Cabibbo-allowed and suppressed decays

$$b \to c \; (B^- \to D^0 K^-) \qquad b \to u \; (B^- \to \overline{D}^0 K^-)$$

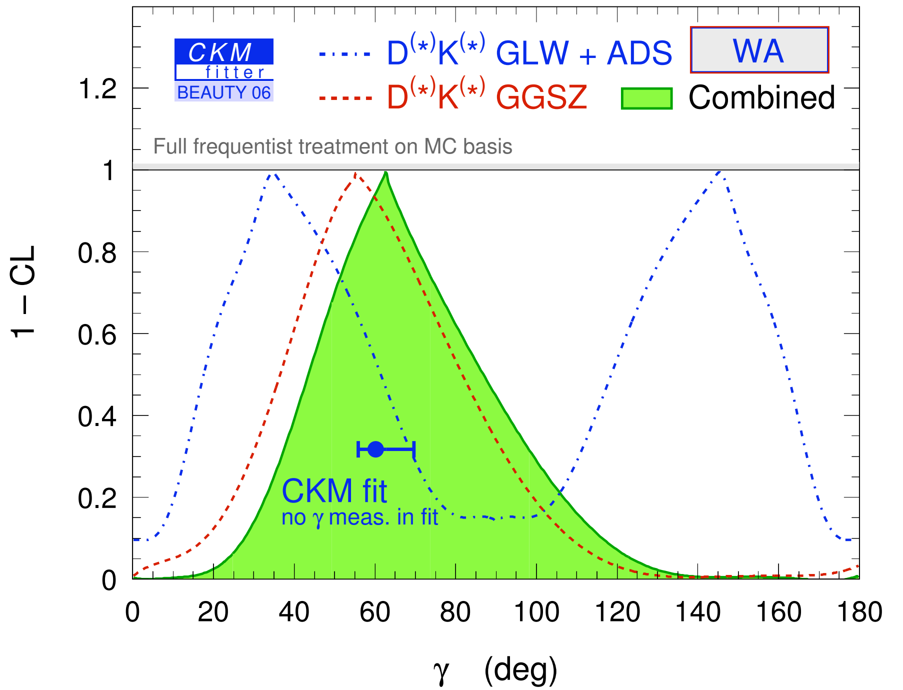
- Need decay of $D^0, \overline{D}^0 \to$ same final state
  - Determine decay amplitudes from data
  - Sensitivity driven by $r_B = |A(B^- \to \overline{D}^0 K^-)/A(B^- \to D^0 K^-)| \sim 0.1 - 0.2$

- Results vary depending on which D decay mode

- Comparable results

- Need more data: all measurements combined give

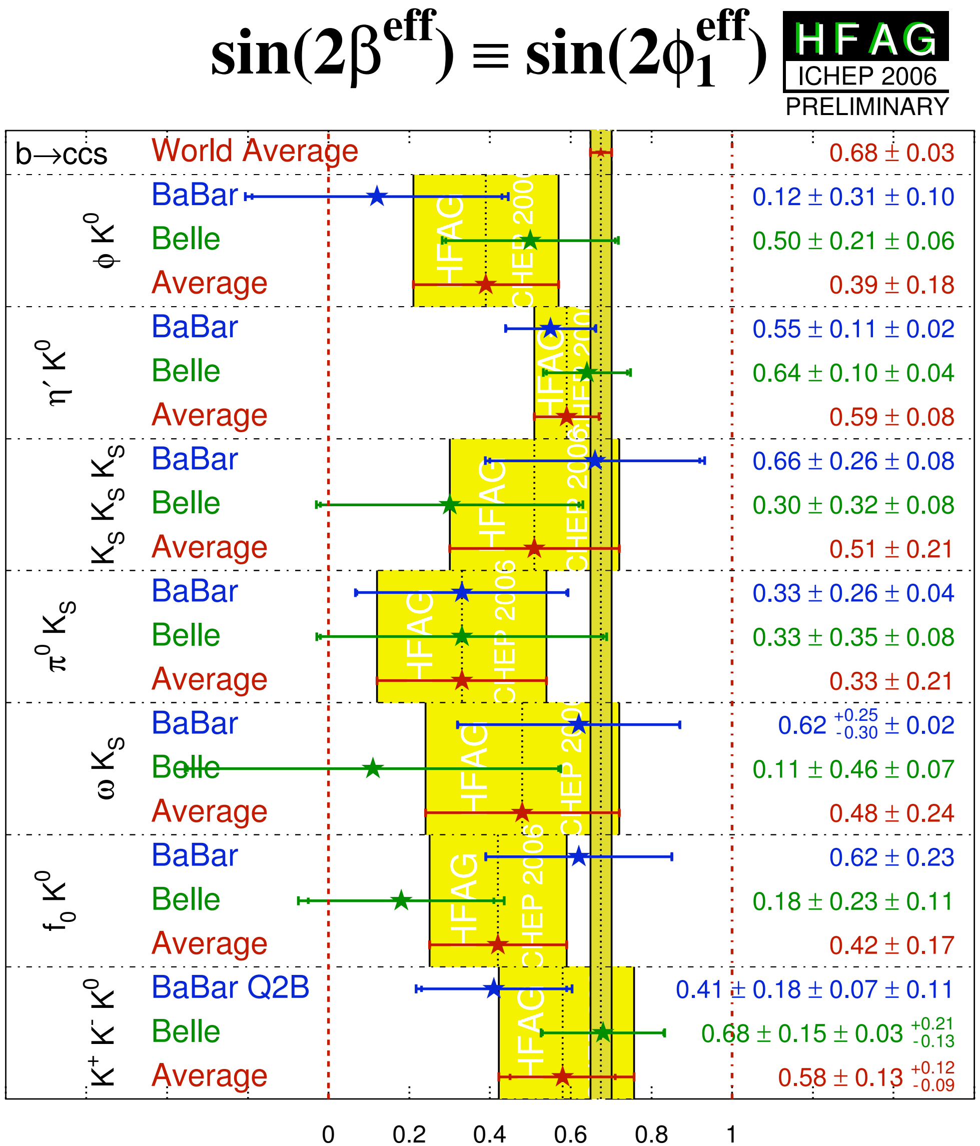
$$\gamma = \left(62\,^{+38}_{-24}\right)^\circ$$



Are there anomalies, *i.e.*, hints of New Physics?

- CPV in $b \to s$
- "$B \to K\pi$ puzzle"

Is there an anomaly in CPV in $b \to s$?



- Amplitude with one weak phase dominates $\Rightarrow$ theoretically clean

- Loop induced $\Rightarrow$ good sensitivity to new physics

- SM, (f = final state)
  $0 < S_f - S_{\psi K_s} \lesssim 0.05, \quad C_f = -A_f \lesssim 0.05$
  [Buchalla et al; Beneke; Williamson & Zupan]

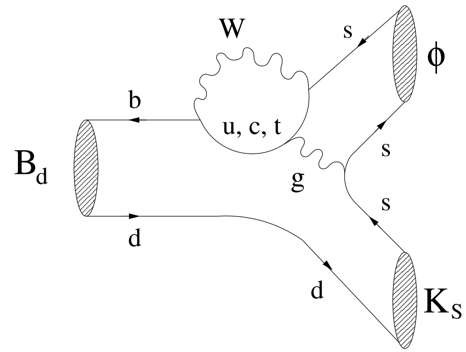
- New Physics: can enter $S_{\psi K}$ mainly in mixing, but S_f in mixing and decay (can be f dependent)

- Is this NP??? To address this let's assume it is not a fluctuation

Let's review the theory:

$$A = e^{i\theta} a + e^{i\chi} b$$

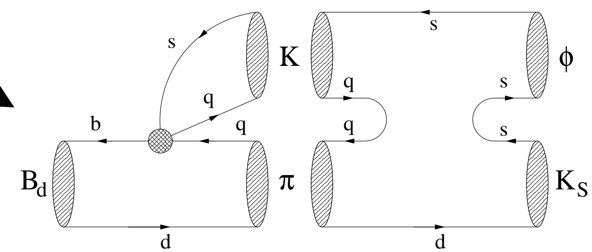
mostly from



$\sim \lambda^2 \frac{\alpha_s}{4\pi}$

about equal

mostly from



$\sim \lambda^4 \times \text{(f.s.i.)}$

how big?
phase?

$$\bar{A} = e^{-i\theta} a + e^{-i\chi} b$$

Assume $b << a$ and expand to linear order in $|b/a|$

$$S_f = \sin(2\beta) + \delta S_f \qquad C_f = 0 + \delta C_f$$

$$\delta S_f = 2\sin(\theta - \chi)\text{Re}\left(\frac{q}{p} e^{-2i\theta}\right)\text{Re}\left(\frac{b}{a}\right) \qquad \delta C_f = 2\sin(\theta - \chi)\text{Im}\left(\frac{b}{a}\right)$$

So, eg, for $f = \phi K_S$

$$\delta S_f = 2\sin(\gamma)\cos(2\beta)\text{Re}\left(\frac{b}{a}\right) \approx 1.5\,\text{Re}\left(\frac{b}{a}\right)$$

Can this be -0.1 give or take 0.1?

$\Rightarrow$ Must understand f.s.i

Calculations done using large m_B expansion (as in SCET, QCDfac, pQCD, etc, i.e., "hard rescattering") find small f.s.i.

By using very general and well established features of soft strong interactions it has been shown (contrary to large m_B expansion expectations), that

[Donoghue et al, '96]

1. Soft FSI do not disappear for large m_B
2. Inelastic re-scattering is expected to be the main source of soft FSI phases
3. FSI which interchange charge and/or flavors are suppressed by a power of m_B, but are quite likely to be significant at $m_B \simeq 5$ GeV

Estimating f.s.i. using measured cross sections give

- effects of order 10-20%, easily
- phases can be large, $O(1)$
- for B $\rightarrow$Kπ (the other "puzzle") [Falk et al, '97]
  direct CP asymmetry A ≈ 0.2 well possible
  and the bound $\sin^2\gamma \leq R$ $\quad R = \frac{\Gamma(B_d \to \pi^{\mp} K^{\pm})}{\Gamma(B^{\pm} \to \pi^{\pm} K)}$
  could easily be violated, $\sin^2\gamma \sim 1.2R$
- *idem* for B $\rightarrow\pi\pi$ [Wolfenstein & Wu, '05]
- *there is no (unambiguous) signal of new physics*
  - nothing if only isospin used in analysis
  - puzzles arise only when additional dynamical inputs used

So now what???
(Have FPCP physicists been *too* successful?)

What can we exclude?
This should dictate some of the goals in this field.
For example:

1. Fourth generation?
   More generally, is the CKM unitary?

2. New CP violating interactions?
   Needed for lepto/baryo-genesis

3. Other new interactions?
   Particularly those related to EW-SB (TeV scale)

LHC $\leftrightarrow$ focus on #3

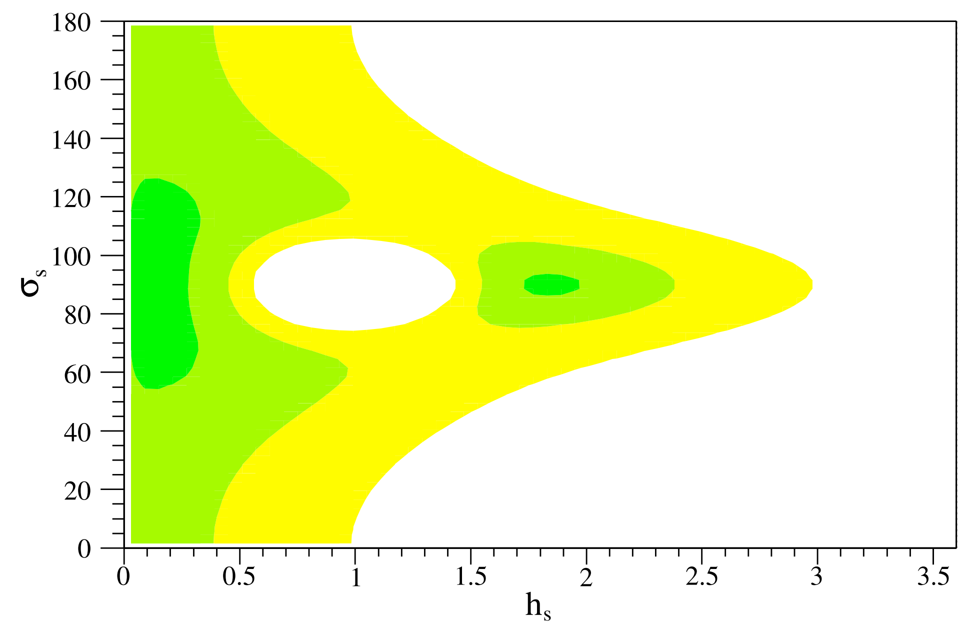
Can we exclude/limit new TeV physics?

Q: how precise do we need $V_{\rm CKM}$ to distinguish CKM from new physics at TeV scale?

Example: B_d mixing

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

[Ligeti et al]



Is there "a lot of room" for new physics?
After all, this is $|h_s| < 40\%$'ish

Address same question, more generally:

(How precisely do we need $V_{\rm CKM}$ to distinguish CKM from new physics at TeV scale?)

Ans 1:

$$\mathcal{A} = \mathcal{A}_{\rm SM} + \mathcal{A}_{\rm New}$$

$$\mathcal{A}_{\rm SM} \sim \frac{g^2}{M_W^2} \times {\rm CKM} \qquad \qquad \mathcal{A}_{\rm New} \sim \frac{1}{\Lambda^2}$$

need roughly, at least

$$\frac{\delta({\rm CKM})}{\rm CKM} \sim \frac{1}{\rm CKM}\frac{1/\Lambda^2}{g^2/M_W^2} \sim \frac{1}{\rm CKM}\frac{v^2}{\Lambda^2} \sim 1\% \times \left(\frac{0.03}{\rm CKM}\right)\left(\frac{10\ {\rm TeV}}{\Lambda}\right)^2$$

---

nota bene: if the NP is weakly coupled, expect $m \sim \Lambda/4\pi$
so even in weakly coupled case we are taking $m \sim 1$ TeV

Ans 2: Use process which are at least one EW-loop in SM, e.g., Flavor Changing Neutral Currents (FCNC)

Restate answer #1:
determination of CKM through SM-tree level process does not get New Physics contamination (to 1% accuracy)

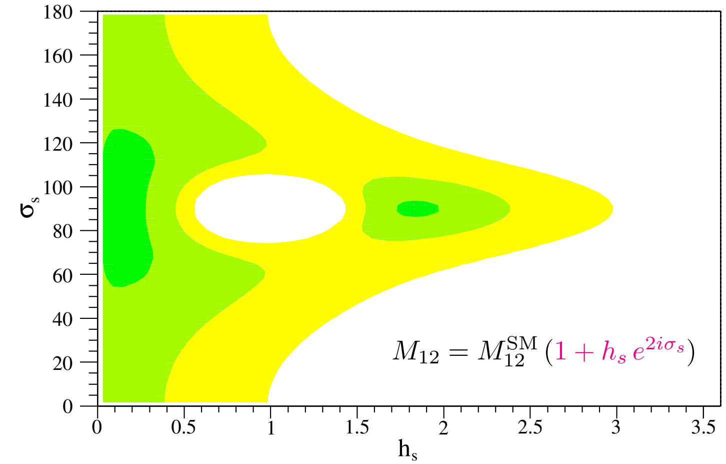
Now

$$\mathcal{A}_{\rm SM} \sim \frac{\alpha}{4\pi \sin^2\theta_w} \frac{g^2}{M_W^2} \times {\rm CKM} \qquad \mathcal{A}_{\rm New} \sim \frac{1}{\Lambda^2}$$

$$\frac{\delta({\rm CKM})}{\rm CKM} \sim \frac{1}{\rm CKM} \frac{1/\Lambda^2}{\alpha/(4\pi\sin^2\theta_w)(1/v^2)} \sim 400\% \times \left(\frac{0.03}{\rm CKM}\right)\left(\frac{10~{\rm TeV}}{\Lambda}\right)^2$$

Don't even need ~10% (tree level) determination of CKMs to be sensitive to new physics from 10 TeV scale, if we use FCNCs as probes!!

Again, example: $B_{d,s}$ mixing



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

$$\Delta m_d^{SM} = \frac{G_F^2}{6\pi^2}\eta_B m_B f_B^2 B_B m_W^2 S(x_t)|V_{td}V_{tb}|^2$$

Now suppose we add to the SM a NewPhysics interaction which at low energies is

$$\mathcal{H}_{NP} = \frac{1}{\Lambda^2}\bar{s}_L\gamma^\mu b_L\,\bar{s}_L\gamma_\mu b_L$$

Estimate:

$$h_d \sim \frac{\frac{1}{\Lambda^2}}{\frac{g^4}{\pi^2 m_W^2}A^2\lambda^6} \sim \left(\frac{5\mathrm{TeV}}{\Lambda}\right)^2\frac{1}{A^2\lambda^6} \sim 10^4\left(\frac{5\mathrm{TeV}}{\Lambda}\right)^2$$

Possibilities:

-ridiculous cancellations among several NP contributions

-large scale Λ (say, Λ~1000 TeV)

-find a reason for coefficient of NP to include $A^2\lambda^6$

So what do we learn from measuring V_{CKM} precisely? Examine the possibilities

- ridiculous cancellations among several NP contributions
  - a moving target
  - not pleasing theoretically
  - yet favored by some model builders

- large scale Λ (say, $\Lambda \sim 1000$ TeV)
  - a solution, but hopeless
  - nothing at LHC?

- find a reason for coefficient of NP to include $A^2\lambda^6$
  - yes: Minimal Flavor Violation (MFV)
  - gives well defined questions, target

- Else?

SUSY

TechniColor
with
ETC
(has other problems, but...)

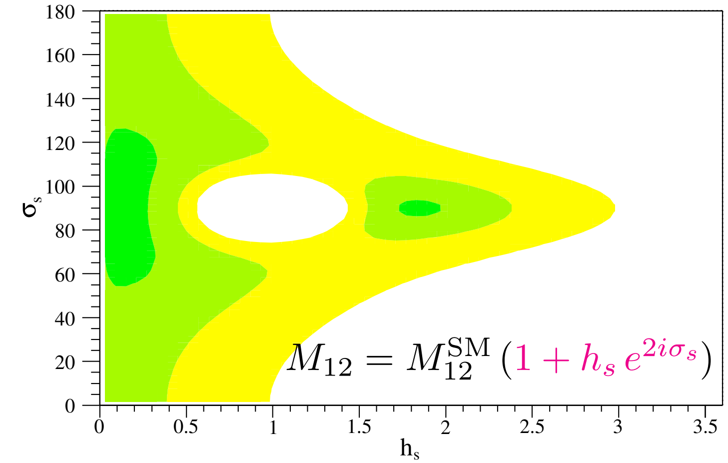
SUSY
(gauge mediated)
with 1+ TeV m's

So what is MFV?

Symmetry Principle which results in the coefficients C (in H_{eff}) include automatic CKM suppression in FCNC's

- Quark sector in SM, in absence of masses has large flavor (global) symmetry: $G_F = SU(3)^3 \times U(1)^2$
- In SM, this symmetry is only broken by Yukawa interactions, parametrized by Yukawa couplings λ_{U} and λ_{D}
- Premise of MFV: This is the unique source of flavor breaking
- New interactions breaking G_F must transform as Yukawa's
- When going to mass eigenstate basis, all mixing is parametrized by CKM and GIM is automatic

Again, back to example: B_d mixing



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

Now the NP interaction $\mathcal{H}_{NP} = \frac{1}{\Lambda^2}\bar{s}_L\gamma^\mu b_L\,\bar{s}_L\gamma_\mu b_L$

which gives

$$h_d \sim \frac{\frac{1}{\Lambda^2}}{\frac{g^4}{\pi^2 m_W^2}A^2\lambda^6} \sim 10^4\left(\frac{5\text{TeV}}{\Lambda}\right)^2$$

With MFV this is replaced by

$$\mathcal{H}_{NP} = \frac{1}{\Lambda^2}\left(\sum_{q=u,c,t} V_{qb}V_{qs}^*\frac{m_q^2}{v^2}\right)^2 \bar{s}_L\gamma^\mu b_L\,\bar{s}_L\gamma_\mu b_L$$

which gives

$$h_d \sim \frac{\frac{1}{\Lambda^2}\left(A^2\lambda^6\frac{m_t^4}{v^4}\right)}{\frac{g^4}{\pi^2 m_W^2}A^2\lambda^6} \sim \left(\frac{5\text{TeV}}{\Lambda}\right)^2$$

digression

plagiarized from
Nir hepph/0703235
Cuccini et al, hepph/0703204

A comment on $D^0 D^0$ mixing

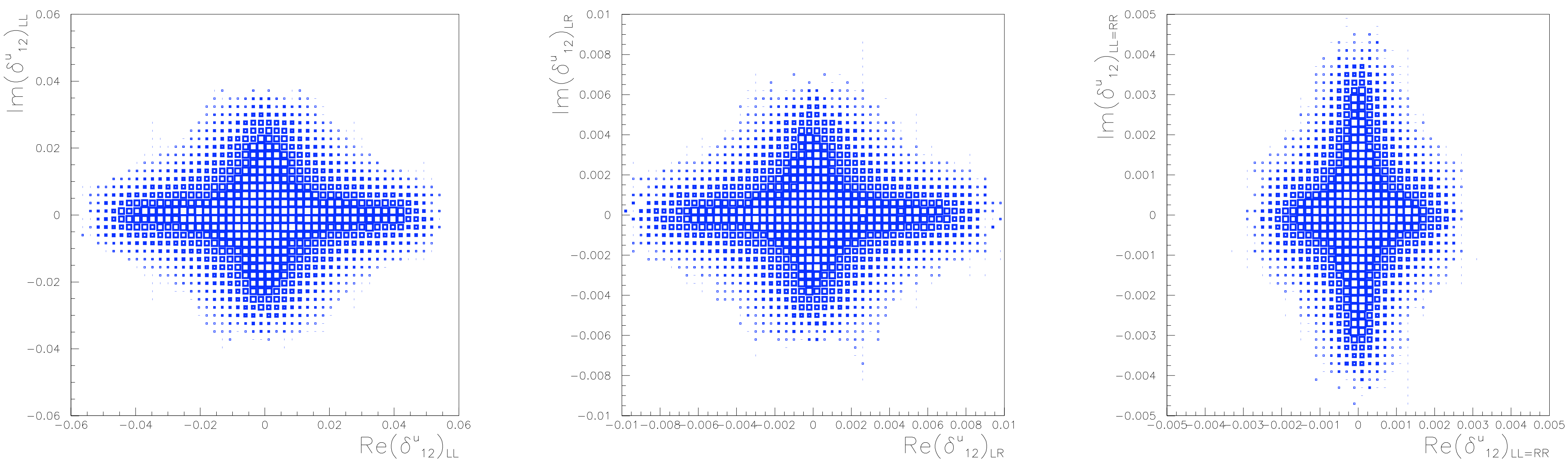
$$|M_{12}^D|^2 = \left(\frac{x\Gamma}{2}\right)^2 \frac{1 + A_m^2 (y/x)^2}{1 - A_m^2}.$$

- Use Belle result to constraint $|x| < 0.015$ (95%CL) (Nir)

$$|M_{12}^D| \lesssim 1.2 \times 10^{-11}\ MeV \quad \text{(CP conservation)},$$

$$|M_{12}^D| \lesssim 2.2 \times 10^{-11}\ MeV \quad \text{(CP violation)},$$

- SUSY: requires very high level of degeneracy between up-squarks
- Barring cancellations, gluino & up-squark masses lower bound ~ 2 TeV



MFV Bounds on Λ (99% CL)

- One operator at a time
- C = 1
- circa 2002, little change, don't expect much (best chance in $\ell\ell$ and $\nu\nu$ modes)

[G.D'Ambrosio, *et al.*, Nucl. Phys. B**645**, 155(2002)]

Minimally flavour violating dimension six operator	main observables	Λ [TeV] $-$	Λ [TeV] $+$
$\mathcal{O}_0 = \frac{1}{2}(\bar{q}_L \lambda_U \lambda_U^\dagger \gamma_\mu q_L)^2$	$\epsilon_K, \quad \Delta m_{B_d}$	6.4	5.0
$\mathcal{O}_{F1} = H^\dagger \left(\bar{d}_R \lambda_D \lambda_U \lambda_U^\dagger \sigma_{\mu\nu} q_L \right) F_{\mu\nu}$	$B \to X_s \gamma$	9.3	12.4
$\mathcal{O}_{G1} = H^\dagger \left(\bar{d}_R \lambda_D \lambda_U \lambda_U^\dagger \sigma_{\mu\nu} T^a q_L \right) G^a_{\mu\nu}$	$B \to X_s \gamma$	2.6	3.5
$\mathcal{O}_{\ell 1} = (\bar{q}_L \lambda_U \lambda_U^\dagger \gamma_\mu q_L)(\bar{L}_L \gamma_\mu L_L)$	$B \to (X)\ell\bar{\ell}, \quad K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	3.1	2.7
$\mathcal{O}_{\ell 2} = (\bar{q}_L \lambda_U \lambda_U^\dagger \gamma_\mu \tau^a q_L)(\bar{L}_L \gamma_\mu \tau^a L_L)$	$B \to (X)\ell\bar{\ell}, \quad K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	3.4	3.0
$\mathcal{O}_{H1} = (\bar{q}_L \lambda_U \lambda_U^\dagger \gamma_\mu q_L)(H^\dagger i D_\mu H)$	$B \to (X)\ell\bar{\ell}, \quad K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	1.6	1.6
$\mathcal{O}_{q5} = (\bar{q}_L \lambda_U \lambda_U^\dagger \gamma_\mu q_L)(\bar{d}_R \gamma_\mu d_R)$	$B \to K\pi, \quad \epsilon'/\epsilon, \ldots$	~ 1	

A modest proposal:

The new aim of FPCP should be to exclude Λ<10 TeV

Here is why this is very interesting:

$$\mathcal{H}_{NP} = \frac{1}{\Lambda^2}\left(\sum_{q=u,c,t} V_{qb}V_{qs}^*\frac{m_q^2}{v^2}\right)^2 \bar{s}_L\gamma^\mu b_L\,\bar{s}_L\gamma_\mu b_L \quad \longleftrightarrow \quad \mathcal{H}_{NP} = \frac{1}{\Lambda^2}\bar{u}_L\gamma^\mu u_L\,\bar{u}_L\gamma_\mu u_L$$

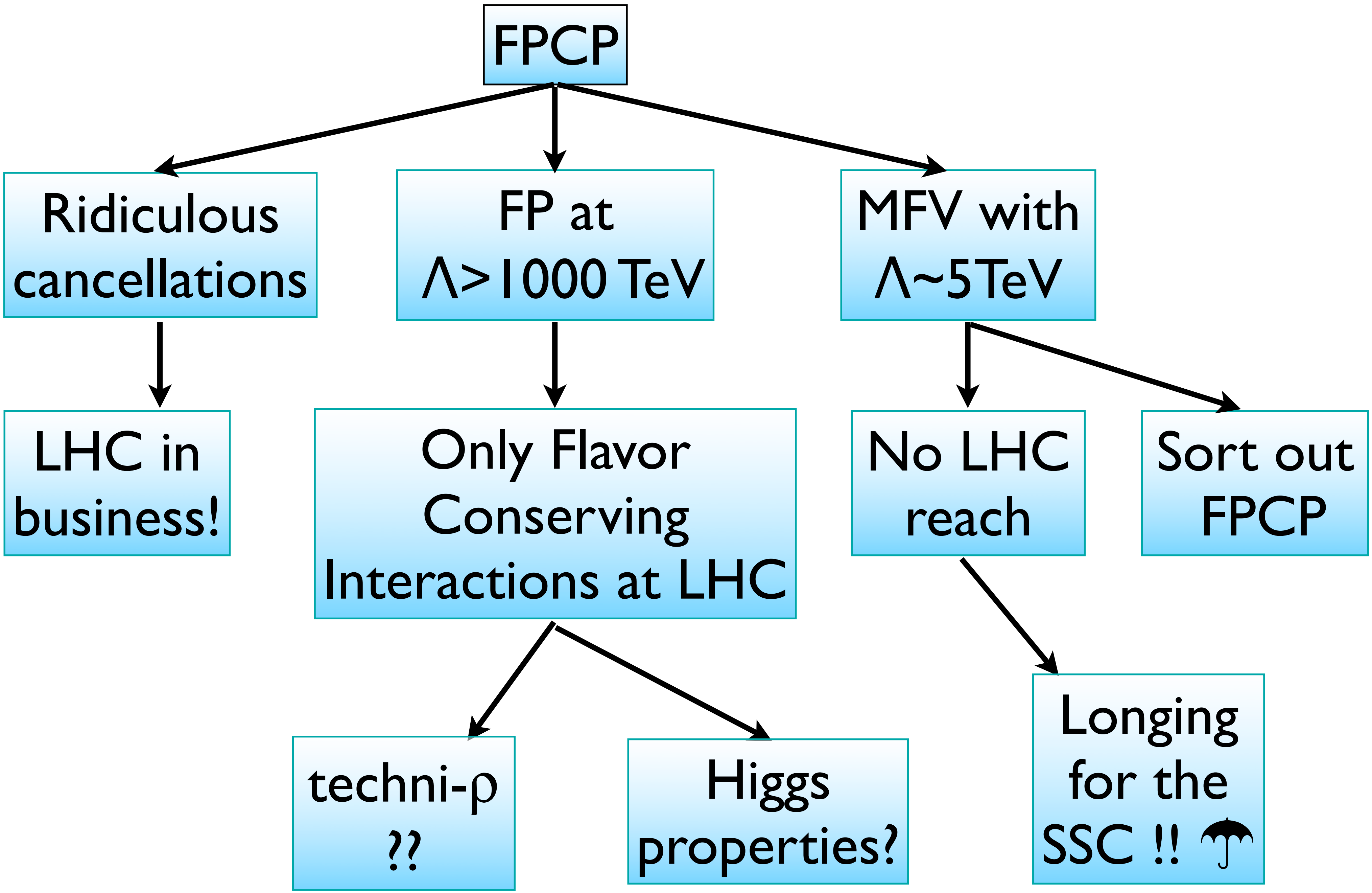
If
Λ<10 TeV is excluded
and
MFV is the mechanism suppressing FCNC

then expect

Λ<10 TeV excluded also for flavor conserving NP

NP found at LHC (even, say, as anomalous higgs or W couplings)
would suggest the scale of FP is large, Λ>1000 TeV

Roadmap


FPCP
Ridiculous cancellations
FP at Λ>1000 TeV
MFV with Λ~5TeV
LHC in business!
Only Flavor Conserving Interactions at LHC
No LHC reach
Sort out FPCP
techni-ρ ??
Higgs properties?
Longing for the SSC !! ☂

MFV and GUTs

- Lepton and quark Yukawas related in GUTs
- Natural to extend MFV principle to include lepton sector
- New interactions in H_{eff} can include leptons, even be purely leptonic
- Lepton Flavor Violation (LFV) in charged leptons predicted at observable levels (10^{30} larger than SM)

quick example (probably out of time by now):

$$\tau \to \mu\gamma, \quad \tau \to e\gamma \quad \& \quad \mu \to e\gamma$$

$$\Delta\mathcal{L}_{\rm eff} = \frac{v}{\Lambda^2}\bar{e}_R\left[\, c_1 \lambda_e\lambda_1^\dagger\lambda_1 + \; c_2 \lambda_u\lambda_u^\dagger\lambda_e + \; c_3 \lambda_u\lambda_u^\dagger\lambda_d^T\right]\sigma^{\mu\nu}e_L F_{\mu\nu}$$

from RH neutrino masses

Generalizes Barbieri-Hall (SUSY-GUT)

New mixing structures

$$C = V_{e_R}^T V_{d_L}$$

$$G = V_{e_L}^T V_{d_R}$$

Independent of M_ν

Hierarchical

Large: for Λ=10TeV

$$\mathrm{Br}(\mu \to e\gamma) \sim 10^{-12}$$

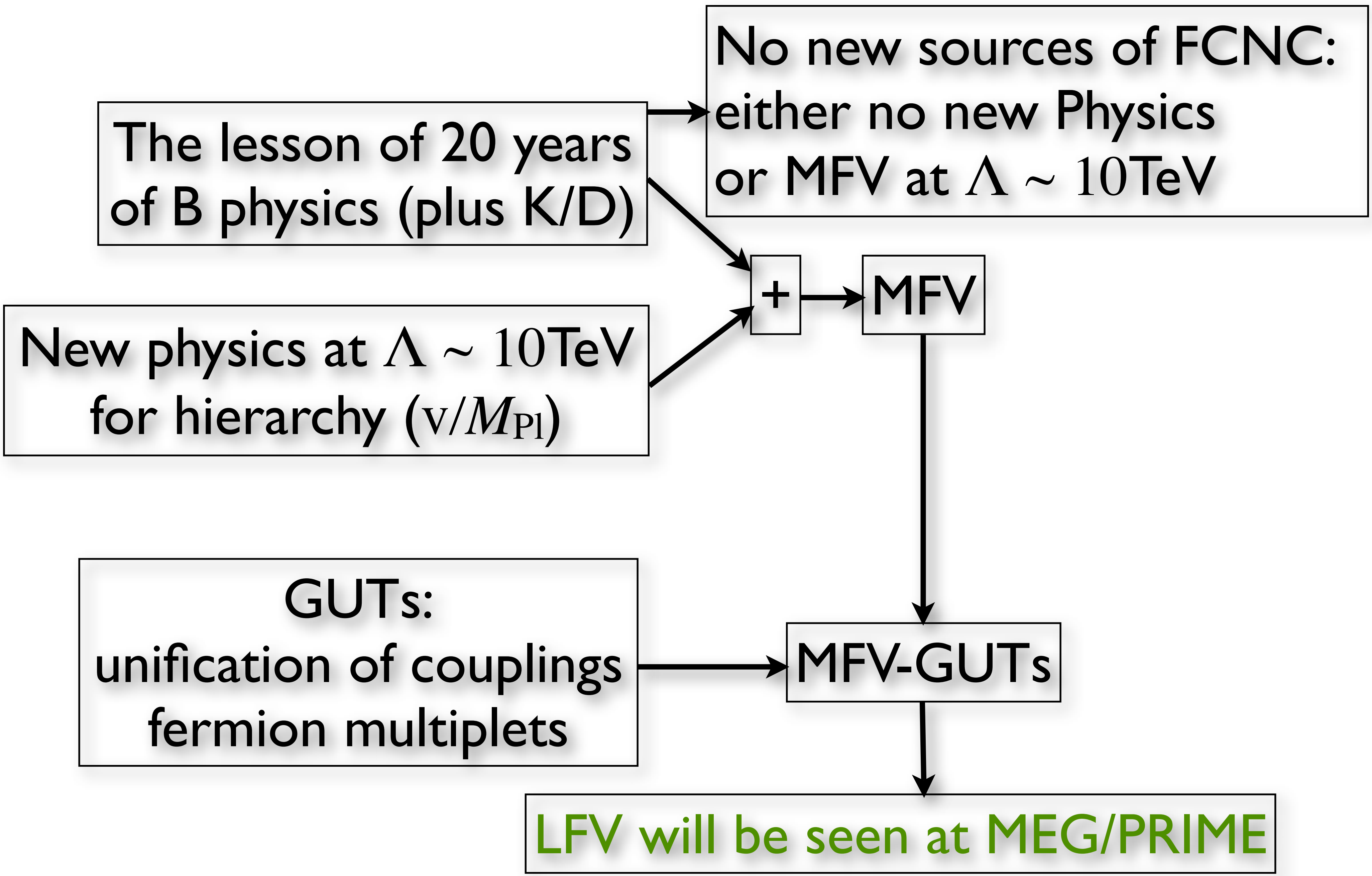
$$\left(\frac{m_t^2}{v^2}\right) \times \begin{cases} \lambda^2(m_\tau/v), & (\tau \to \mu) \\ \lambda^3(m_\tau/v), & (\tau \to e) \\ \lambda^5(m_\mu/v), & (\mu \to e) \end{cases}$$

$(\lambda = 0.22)$

within reach of MEG

COBRA(Constant Bending Radius Spectrometer)

review:


No new sources of FCNC:
either no new Physics
or MFV at $\Lambda \sim 10$TeV
The lesson of 20 years
of B physics (plus K/D)
+
MFV
New physics at $\Lambda \sim 10$TeV
for hierarchy (v/M_{Pl})
GUTs:
unification of couplings
fermion multiplets
MFV-GUTs
LFV will be seen at MEG/PRIME

Conclusions

- FP and CP physics in good shape, but room for improvement
  - Sides: need better V_{ub}, other methods
  - Angles: need better α and a lot better γ (but not clear what you gain)
  - No NP yet
- New Aim: rule out Λ < 10 TeV MFV
  - MFV same type of insight as GIM 35 years ago.
  - Ties FPCP to LHC program
  - Distinct possibility, suggested from FPCP:
    - $\ast$ NP @ LHC (if any) is flavor blind
- Need CKM determination + rare (*i.e.*, SM 1-EW-loop) processes to few %
- MFV with GUT, connects with LFV (which *is* FP) $\rightarrow$ MEG & PRIME

In 20 years:

- the VLHC and NILC will begin to study the new physics at $\Lambda \sim 10$ TeV (maybe sooner, $\Lambda \sim M/g$)

- we will have FPCP meetings, mostly discussing CPV in neutrino interactions
(but we will still have talks on SCET, pQCD and QCD factorization)

- we will be entering the era of precision measurement of LFV processes, establishing patterns, e.g.,

$$\tau \to e\bar{e}e : \tau \to e\bar{\mu}e : \tau \to e\bar{e}\mu : \tau \to \mu\bar{\mu}e : \tau \to \mu\bar{\mu}\mu : \mu \to e\bar{e}e$$

and we will begin to sort out MFV-GUTs

The End

A Confession

Once in a while,
I'm standing here, doing something.
And I think,
"What in the world am I doing here?"
It's a big surprise.

Donald Rumsfeld
—May 16, 2001, interview with the New York Times

The Unknown

As we know,
There are known knowns.
There are things we know we know.
We also know
There are known unknowns.
That is to say
We know there are some things
We do not know.
But there are also unknown unknowns,
The ones we don't know
We don't know.

Donald Rumsfeld
—Feb. 12, 2002, Department of Defense news briefing