invisibles13
neutrinos, dark matter & dark energy physics

Perspectives on the Flavor Problem

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Flavor/CP and New Physics

- Outstanding problems in Particle Physics:
  - Dark Energy
  - Dark Matter
  - Hierarchy
  - Baryogenesis

    Nature of first three may well be solely gravitational
    Baryogenesis requires CPV beyond that in the SM

  - The Flavor Problem

of course, some of us are a bit distracted ...

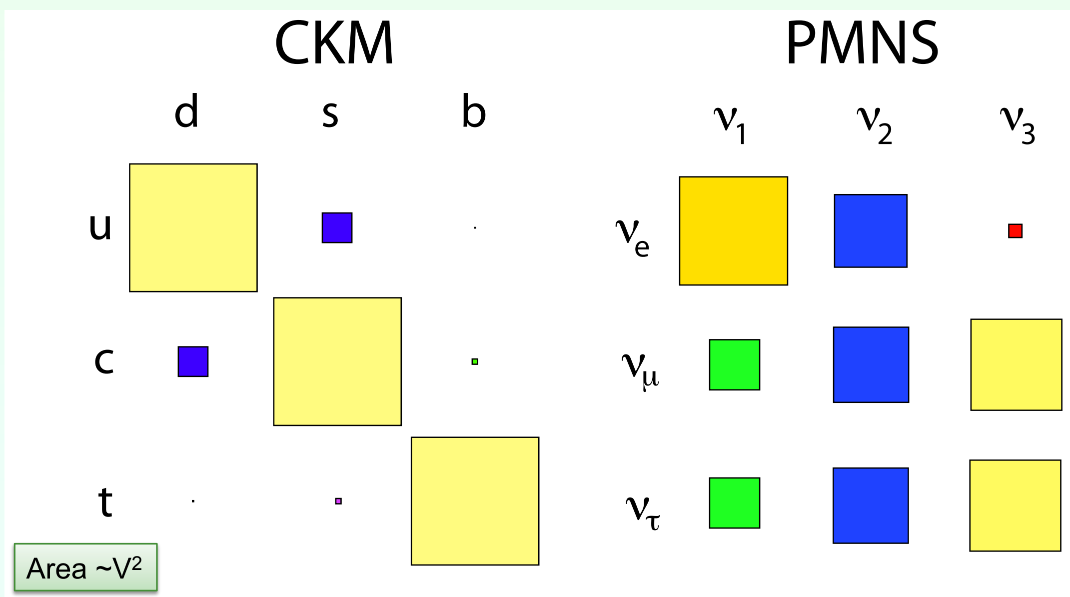
Perspectives on ... which flavor problem?

- Many questions go under “flavor problem”
  I roughly classify them in two camps

- Fundamental or “origin of flavor”
  - Why 3 generations
  - Why the pattern of masses and mixings

- Structural or “coping with flavor”
  - What does flavor physics say about my favorite BSM/NP model

Quarks



Leptons

Origin of flavor

- Very few examples of theories that “explain” the number of generations
  - eg, particular compactifications of superstring theory

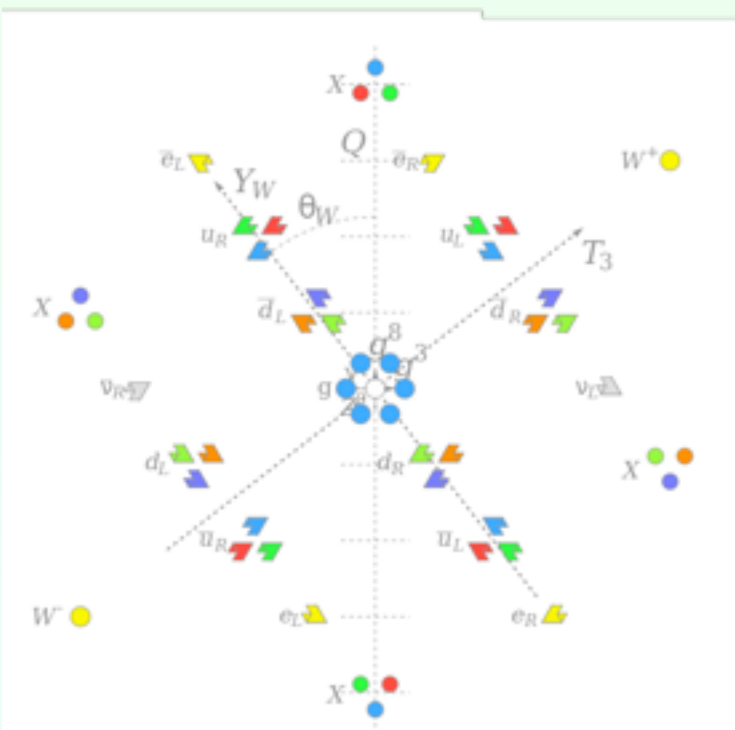
- Abundance of models (“theories of flavor”) addressing mixing and masses, eg
  - Discrete symmetries (A4, S3, ...)
    - Abelian, non-ableian
    - Single higgs, multiple higgs
    - w/wo SUSY
    - ...
  - Froggatt-Nielsen
    - w/wo GUT
    - w/wo SUSY
    - ...
  - Warped extra dimensions
    - Localization along extra dims produces exponential mass ratios
    - Wave function overlaps produce mixing
  - Combinations of the above

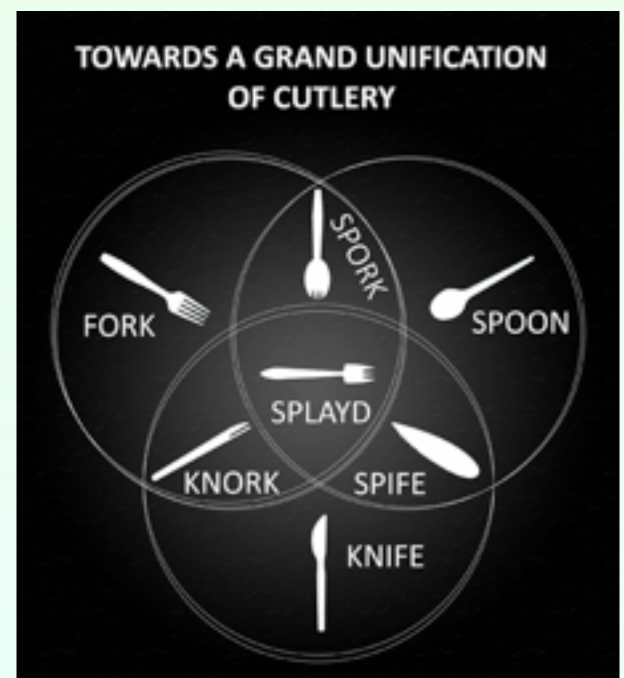
Ross & King to explain all

Quarks vs leptons?

Although not required, it is natural to assume a theory of the origin of flavor will address both, if not combine, the quark-flavor and the lepton-flavor problem:

- Number of generations tied: anomaly cancellation
- Neat fit of each generation into SU(5) (or SO(10)) GUT multiplets





Coping with flavor

- “Flavor physics” often refers only to quark sector
  - Quark mass matrices from EW breaking, and some masses comparable to EW scale
    - -Flavor changing processes abound!!
- SM: built in delicate cancellations (GIM)
- Strong constraints on NP/Diagnostic tool (coroner of models)

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- Lepton Flavor: not necessarily at EW breaking
  - Majorana neutrinos, large masses decouple (eg, see-saw)
  - Dirac neutrinos: all masses small relative to EW
- Lepton Flavor changing processes .. nowhere near as rich

- BTW, Dirac neutrinos: not such a crazy idea
  - An example I like (Arkani-Hamed & Grossman):
    - Dark side is strong interacting (weak at M_{Pl})
    - Gauge invariant operators in SM of dim < 4

$$H\bar{L}, \quad |H|^2, \quad B_{\mu\nu}$$

    - Couple to gauge invariant dark operators, into scalar terms

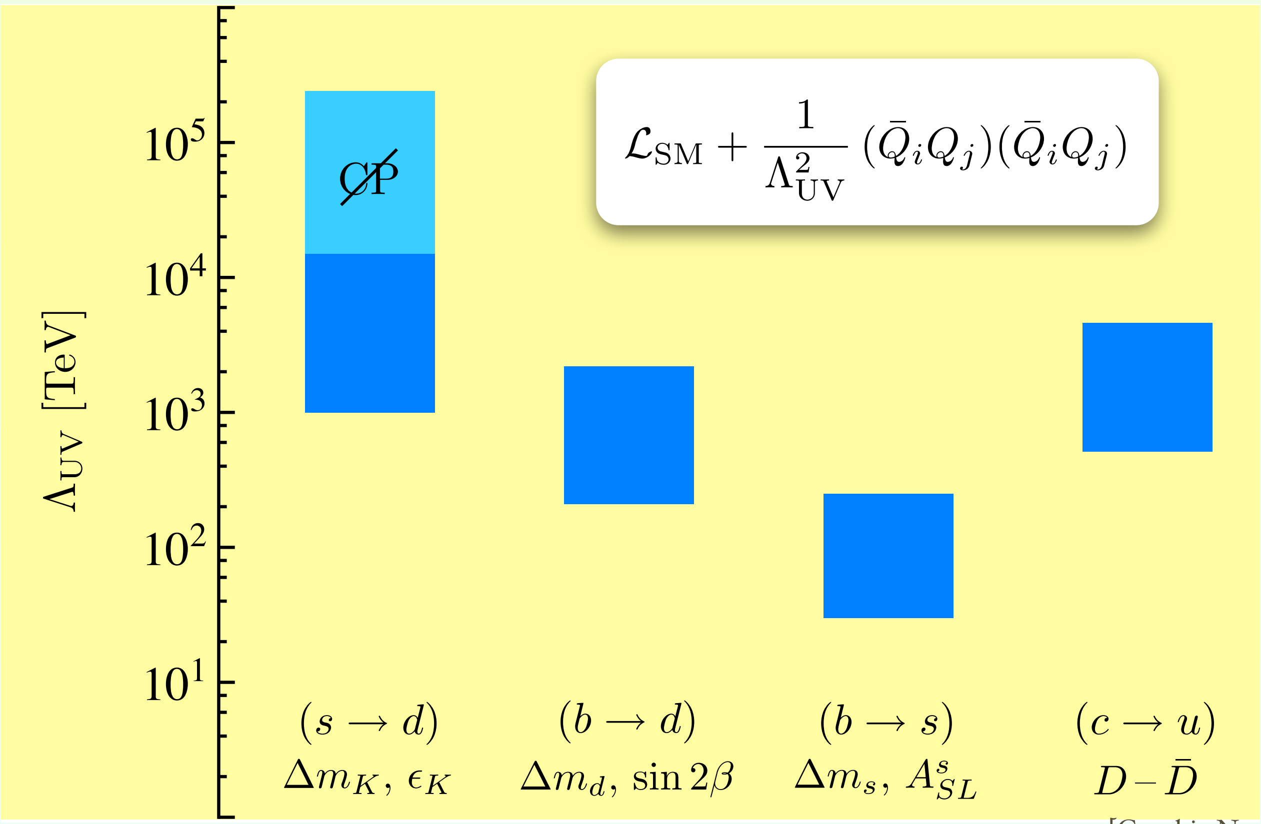
$$H\bar{L}N, \quad |H|^2 S, \quad B_{\mu\nu}Y^{\mu\nu}$$

    - Operators, like *N*, become "fundamental" once dark side goes strong at scale Λ. Dimensionless coefficients naturally of order

$$\left(\frac{\Lambda}{M_{Pl}}\right)^n$$

Generic bounds without a flavor symmetry

- Integrate out NP at UV scale
- Produce local operators
- Assume coupling is order 1 (generic, no flavor suppression)



[Graphic:Neubert, EPS2011]

Alternatively: Specific models

DNA of models (changed from authors' "DNA of flavor physics effects")

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\rm CP}\,(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

AC: Agashe-Carone abliean U(1) susy
RVV2: Ross, Velasco-Sevilla, Vives (non-ab, susy)
AKM: Antusch, King. Malinsky (non-ab, susy)
FBMSSM: flavor blind MSSM
dLL: MFV MSSM with LL mass insertions
LHT: Littlest higgs with T-parity
RS: warped extra-dims model with custodial protection

Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

Altmannshofer, et al Nucl.Phys. B830 (2010) 17-94

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$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
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CPV in interference of mixing/decay

- Decay amplitudes in terms of weak (ϕ_k) and strong (δ_k) phases

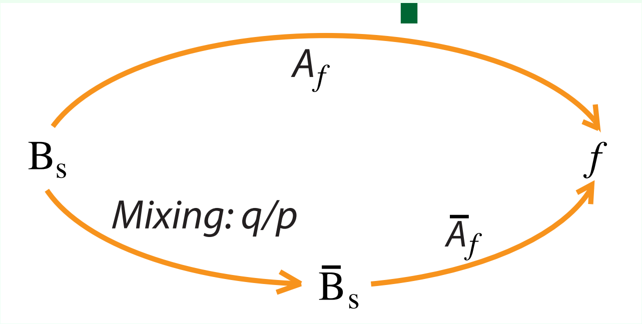
$$A_f = \langle f|H|B\rangle = \sum_k A_k\, e^{i\delta_k}\, e^{i\phi_k}\,, \qquad \overline{A}_{\overline{f}} = \langle \overline{f}|H|\overline{B}\rangle = \sum_k A_k\, e^{i\delta_k}\, e^{-i\phi_k}\,.$$

- CPV in decay if non-vanishing

$$|\overline{A}_{\overline{f}}|^2 - |A_f|^2 \propto \sin(\phi_1 - \phi_2)\sin(\delta_1 - \delta_2)$$

- Theory input: strong phases (usually model dependent)

- Instead CPV in interference of mixing.decay can be theo-clean
  - If amplitudes with a single weak phase dominate

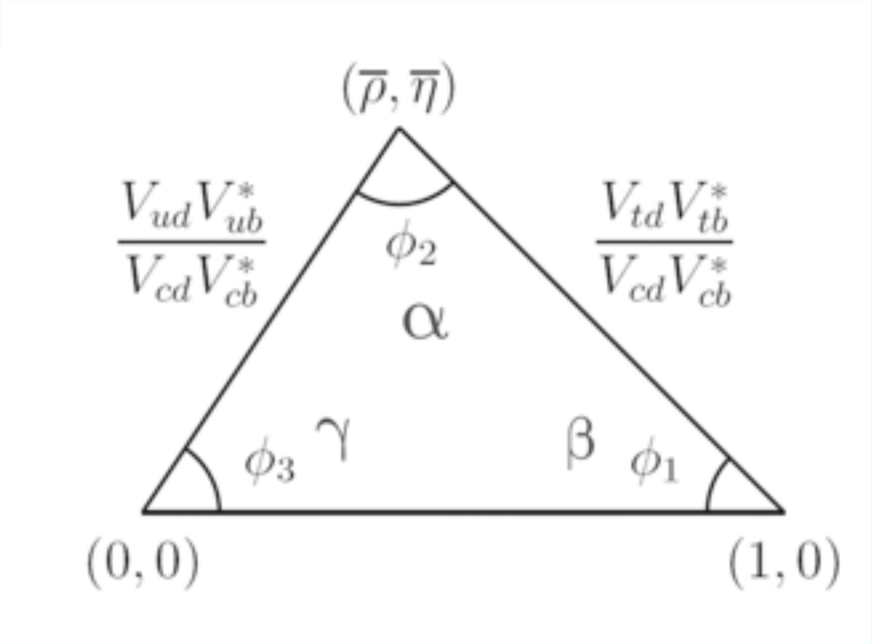


  - Simplest if *f* is a CP eigenstate

$$a(t) = \frac{\Gamma[\overline{B}^0(t) \to f] - \Gamma[B^0(t) \to f]}{\Gamma[\overline{B}^0(t) \to f] + \Gamma[B^0(t) \to f]}$$

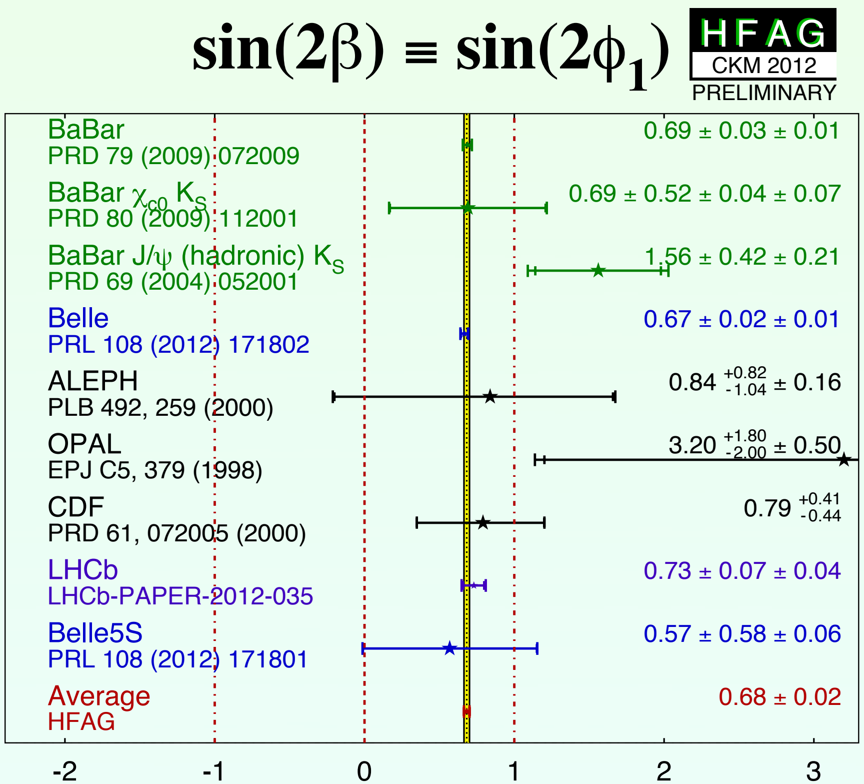
$$= S_f \sin(\Delta m\, t) - C_f \cos(\Delta m\, t)$$

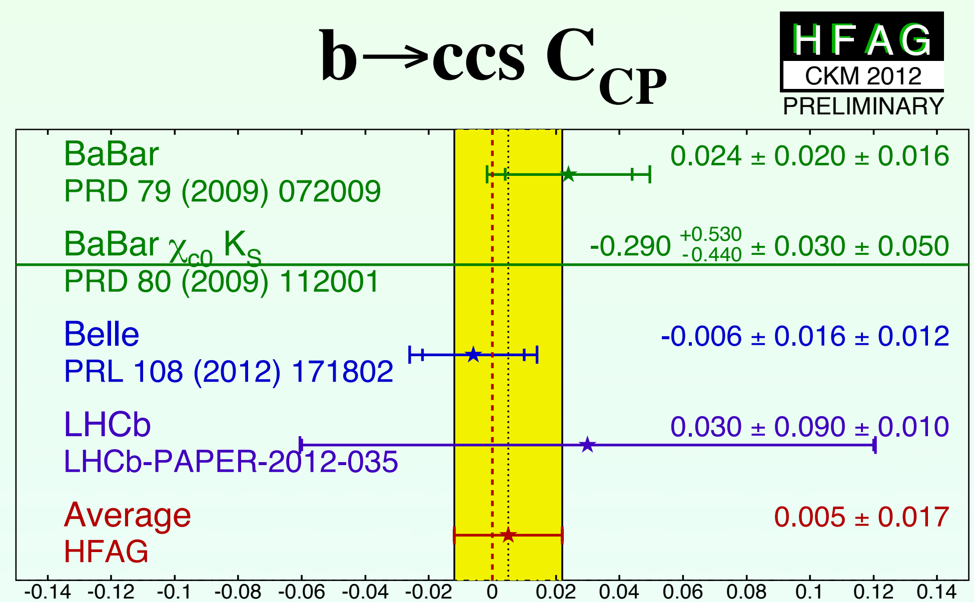
where $S_f = \frac{2\,\mathrm{Im}\,\lambda_f}{1 + |\lambda_f|^2}, \quad C_f = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2}, \quad \lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f}.$



Gold plated examples: $b \longrightarrow c\bar{c}s$

$$B^0 \to \psi K^0_{L,S} \qquad \lambda_{\psi K^0_{S,L}} = \underbrace{\mp}_{-\text{CP of S, L}} \underbrace{\left(\frac{V^*_{tb}V_{td}}{V_{tb}V^*_{td}}\right)}_{\text{q/p}} \underbrace{\left(\frac{V_{cb}V^*_{cs}}{V^*_{cb}V_{cs}}\right)}_{\bar{A}_f/A_f} \underbrace{\left(\frac{V_{cs}V^*_{cd}}{V^*_{cs}V_{cd}}\right)}_{\text{p/q for K}} = \mp e^{-2i\beta}$$

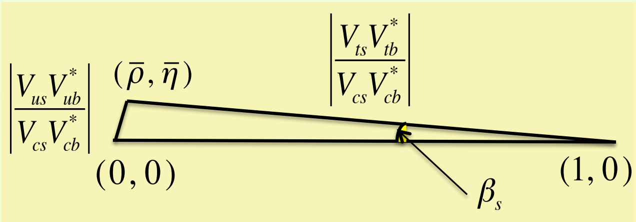




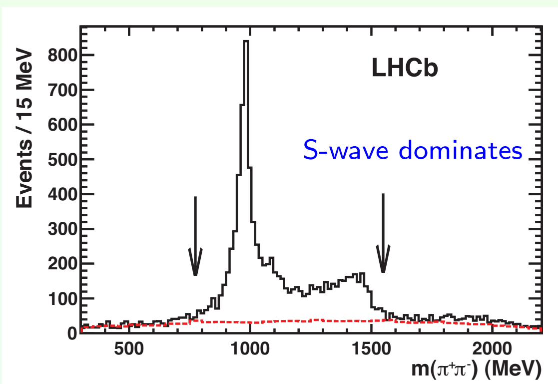
and $B_s \to \psi\phi, \psi\pi^+\pi^-$

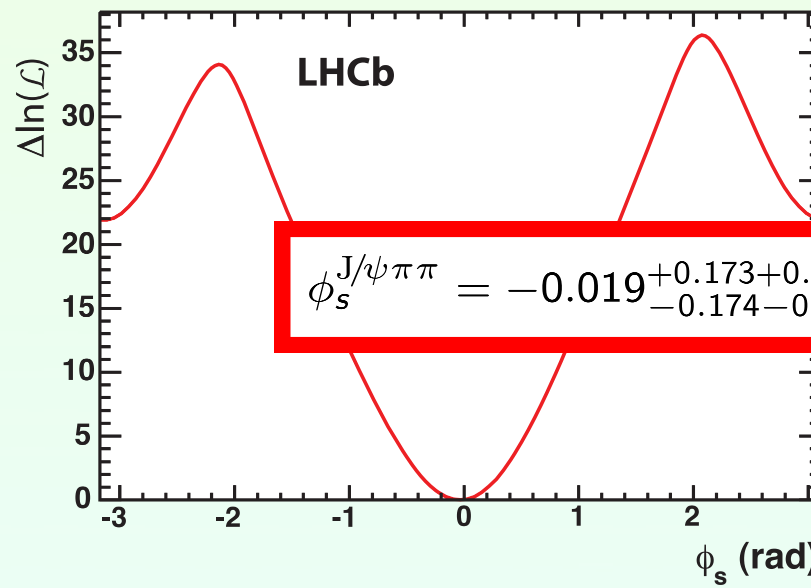
$$\lambda_{\psi\pi^+\pi^-} = -\left(\frac{V_{tb}^* V_{ts}}{V_{tb} V_{ts}^*}\right)\left(\frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}}\right) = -e^{-2i\beta_s}$$

small angle in squashed unitarity triangle ≈ 0 in SM



$$\boxed{\varphi_s^{SM} \equiv -2\beta_s = -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = -0.04 \text{ rad}}$$





$$\boxed{\phi_s^{J/\psi\pi\pi} = -0.019^{+0.173+0.004}_{-0.174-0.003} \text{ rad}}$$

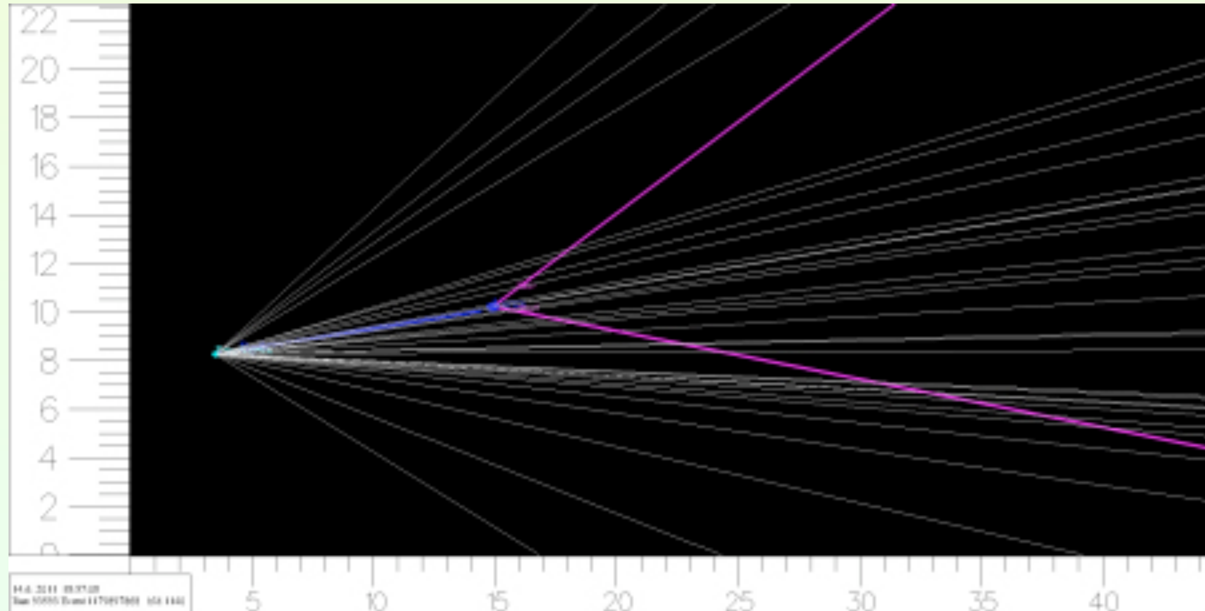
$B \to \psi\phi(K^+K^-)$ requires angular analysis, separate partial waves. Combined analysis:

$$\boxed{\phi_s = -0.002 \pm 0.083 \pm 0.027 \text{ rad}}$$

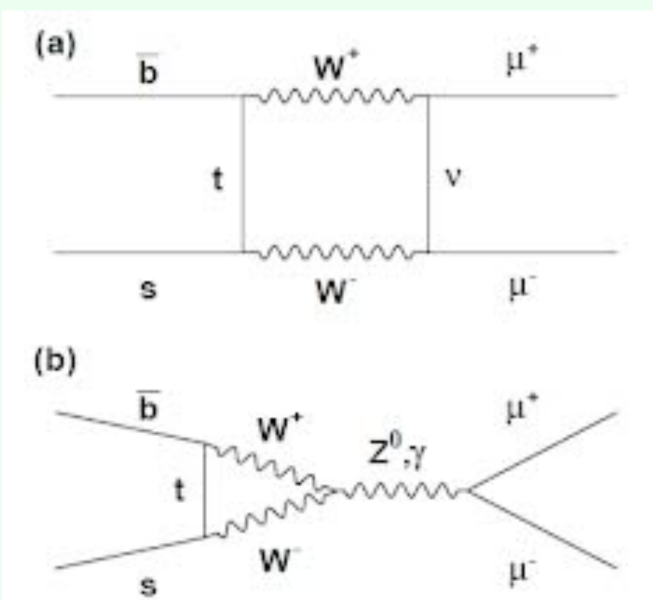
[G Cowan, ICHEP 2012]

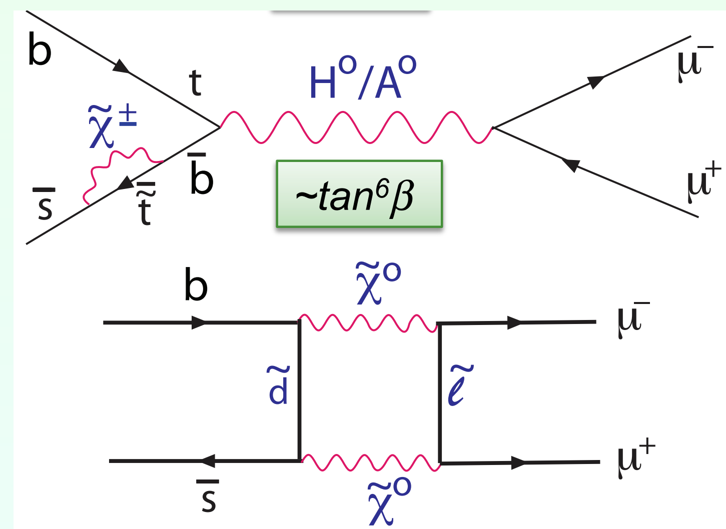
$B \to \mu^+\mu^-$

Reconstructed $B \to \mu^+\mu^-$ event from the LHCb Collaboration
[muon.wordpress.com]



Sensitive to NP:

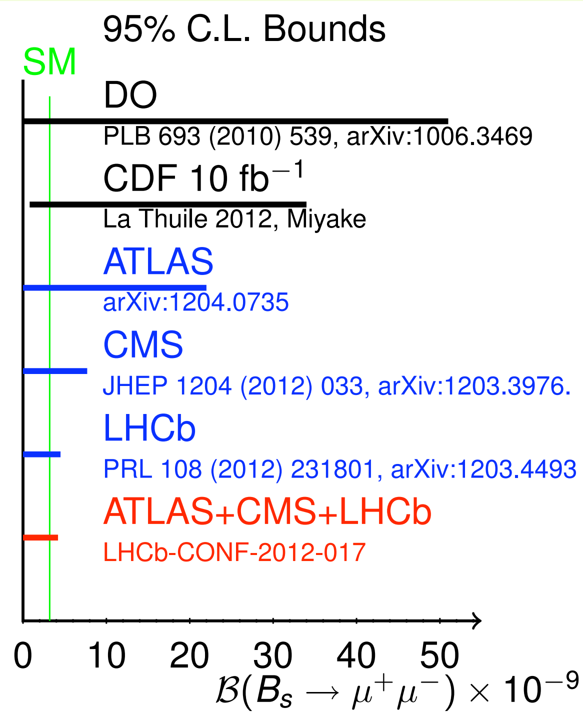




SM

MSSM

As of July 2012 (ICHEP) bounds only



LHCb-CONF-2012-017
Preliminary upper limits (95%C.L.):

$\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 4.2 \times 10^{-9}$

$\mathcal{B}(B^0 \to \mu^+\mu^-) < 8.1 \times 10^{-10}$

LHCb measurement (Nov 2012)

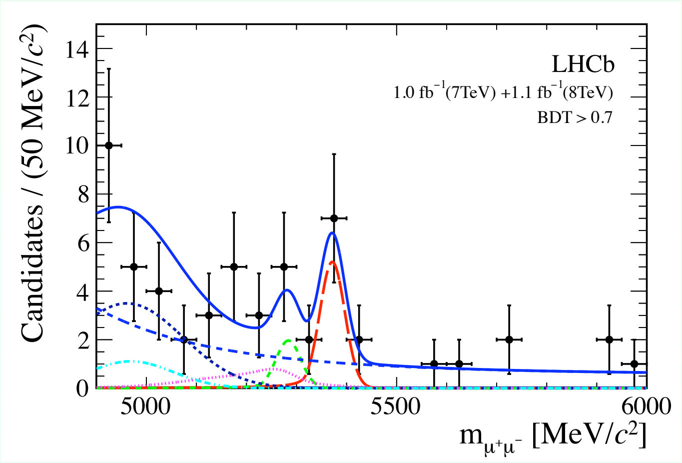
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.2\,^{+1.4}_{-1.2}(\mathrm{stat})\,^{+0.5}_{-0.3}(\mathrm{syst})) \times 10^{-9}$$

recall:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-)^{\mathrm{SM}} = (3.23 \pm 0.27) \times 10^{-9}$$

Also new (best) bound:

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 9.4 \times 10^{-10}$$



[LHCb, Phys.Rev.Lett. 110 (2013) 021801]

Implications for NP searches

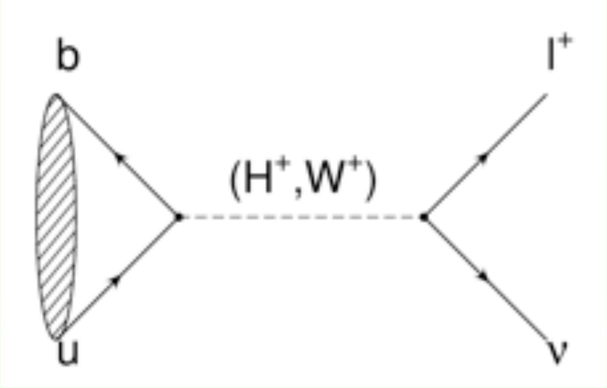
- With few exceptions, no deviations from SM

- Exceptions (some are going away already):
  - $B^{-} \to \tau^{-} \nu$ *(next slide)*, $B^{-} \to D\tau^{-}\nu$, $B^{-} \to D^{*}\tau^{-}\nu$
  - Isospin asymmetry A_I in $B \to K \mu^{+}\mu^{-}$
  - Flavor specific CP asymmetry a_{sl}
  - FB-asymmetry in top production at Tevatron
  - muon $g - 2$

- Tightening bounds on NP require specialized analysis of specific models
  - (infinitely) many variations of SUSY
  - variations on extra-dimensions
  - techni-color (strongly coupled higgs sector with dilaton)
  - ....

Is there still a problem with $B^- \to \tau^- \nu$?

- $B^- \to \tau^- \nu$ in SM is tree level



- Clean SM prediction, lattice gives f_B

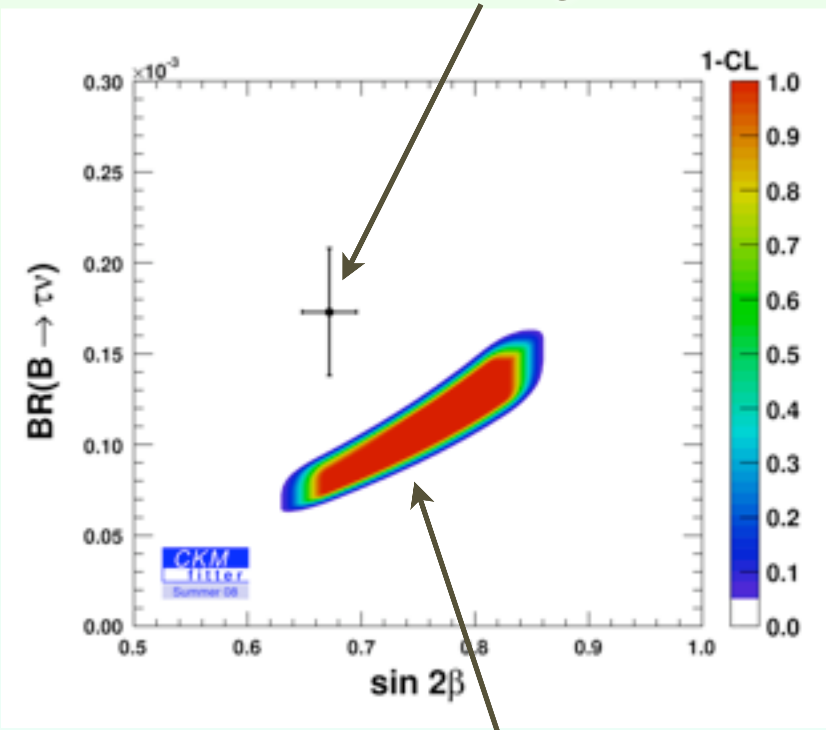
$$\Gamma(B \to \tau\nu) = \frac{G_F^2 m_B}{8\pi} m_\tau^2 \left(1 - m_\tau^2/m_B^2\right)^2 f_B^2 |V_{ub}|^2$$

- Modified for τ, less for e, μ, by charged higgs in 2HDM

- 2HDM modifies box diagram too: cannot use SM extraction of $\sin(2\beta)$ from $B^0 \to \psi K_S$

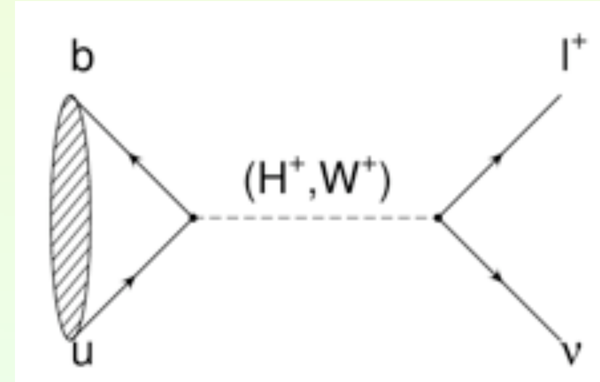
- But NEW Belle result [arXiv:1208.4678]

world avg. summer 2008



Fit excluding $B^- \to \tau^- \nu$ & $B^0 \to \psi K_S$

Is there still a problem with $B^{-} \rightarrow \tau^{-}\nu$?



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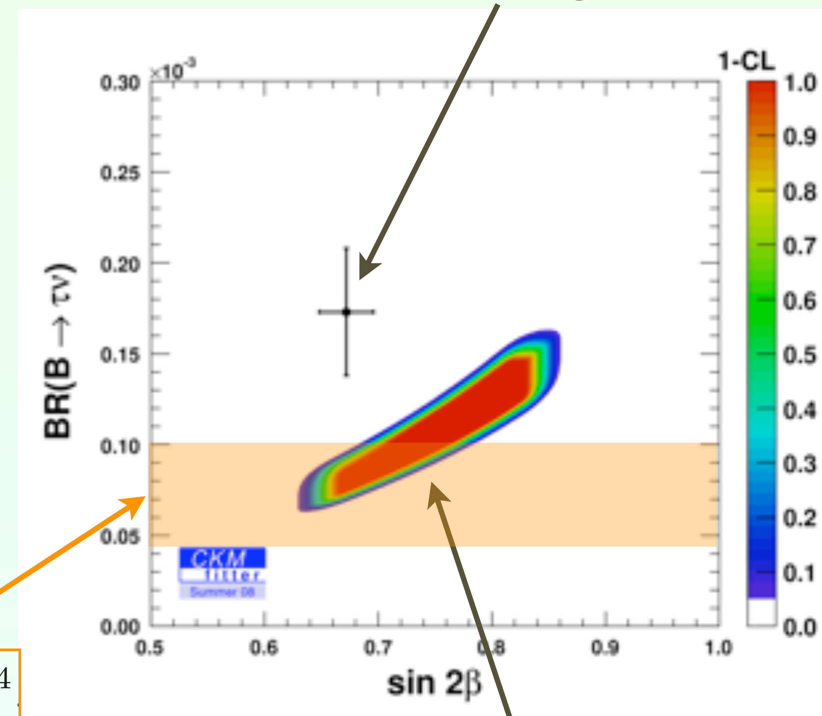
$$\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau) = [0.72^{+0.27}_{-0.25}(\text{stat}) \pm 0.11(\text{syst})] \times 10^{-4}$$

world avg. summer 2008



Fit excluding $B^{-} \rightarrow \tau^{-}\nu$ & $B^0 \rightarrow \psi K_S$

CMSSM

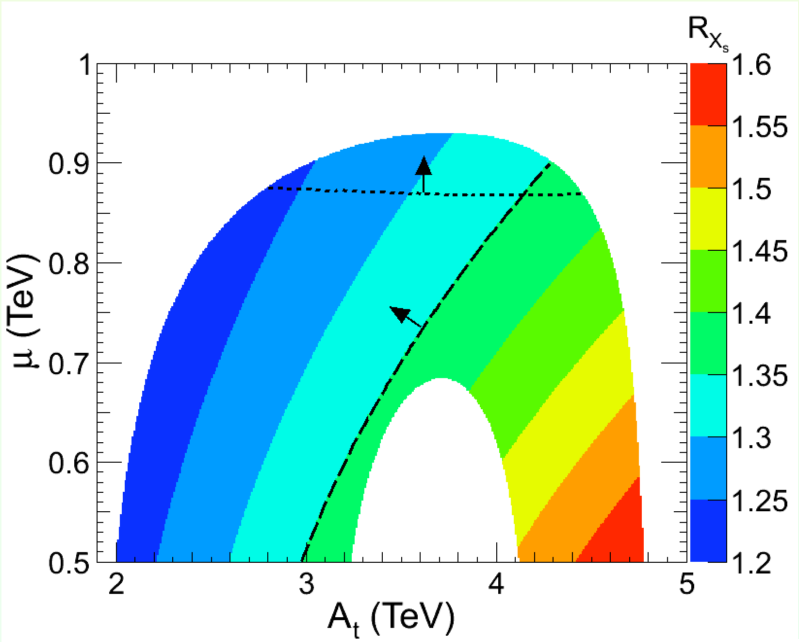
[Haisch & Mahmoudi, arXiv:1210.7806]

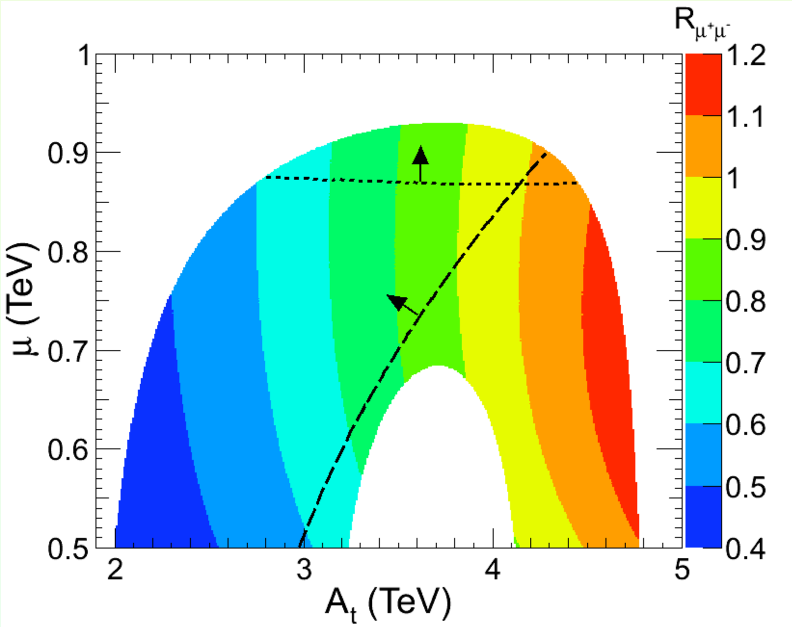
$$\frac{\mathcal{B}(B \to K^*\gamma)^{\rm EXP}}{\mathcal{B}(B \to K^*\gamma)^{\rm SM}} = 1.13 \pm 0.10$$

$$R_{X_s} = \frac{\mathrm{BR}(B \to X_s\gamma)_{\rm MSSM}}{\mathrm{BR}(B \to X_s\gamma)_{\rm SM}}$$

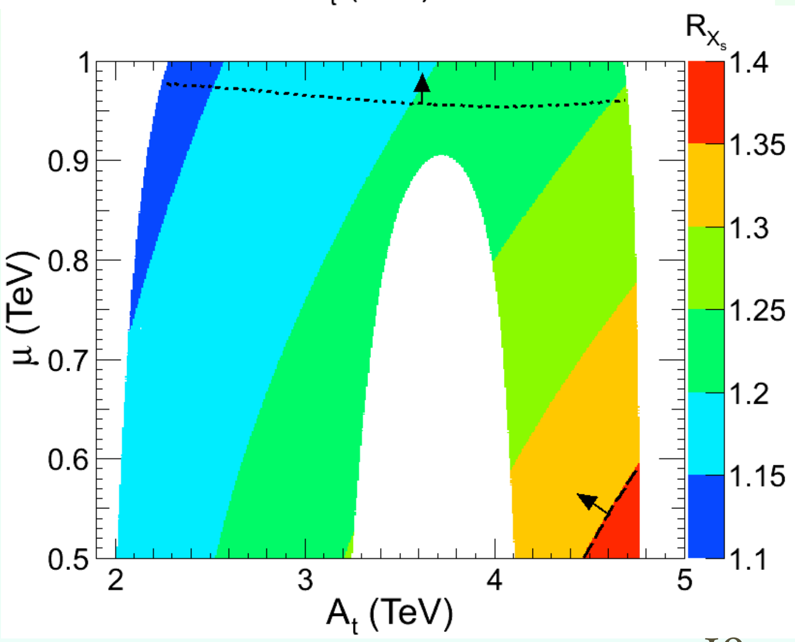
$$R_{\mu^+\mu^-} = \frac{\mathrm{BR}(B_s \to \mu^+\mu^-)_{\rm MSSM}}{\mathrm{BR}(B_s \to \mu^+\mu^-)_{\rm SM}}$$

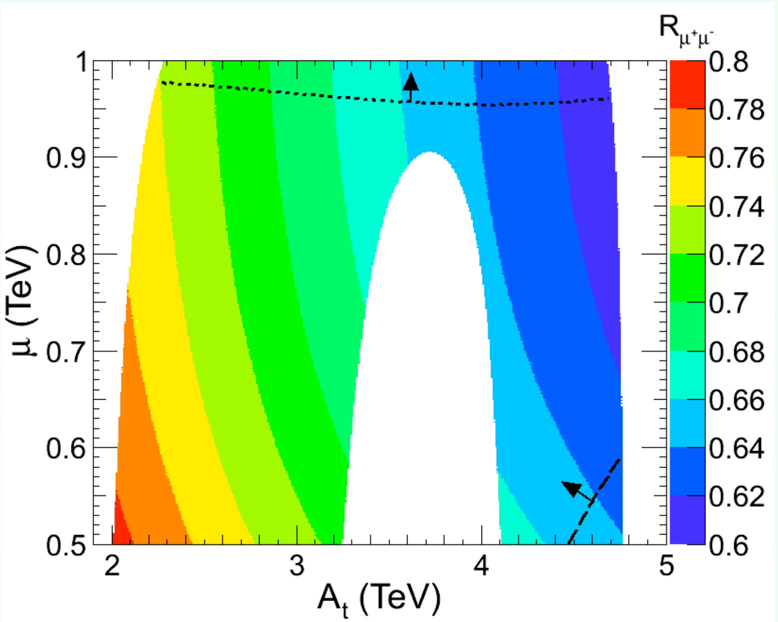
$\tan\beta = 60$





$\tan\beta = 30$



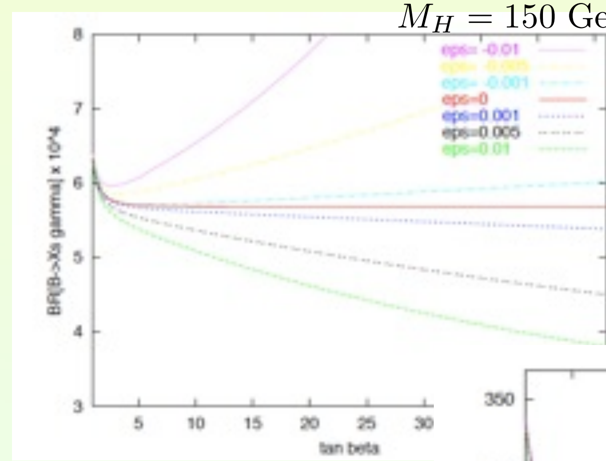


you can't see all parameters here, some have been fixed by higgs flash back, 4 years ago...

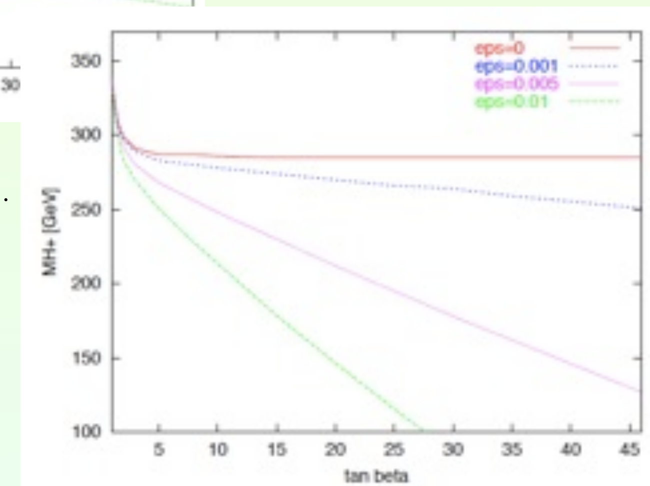
Slide taken from BG FPCP2009

CMSSM (at large $\tan\beta$, possibly)

$M_H = 150$ GeV



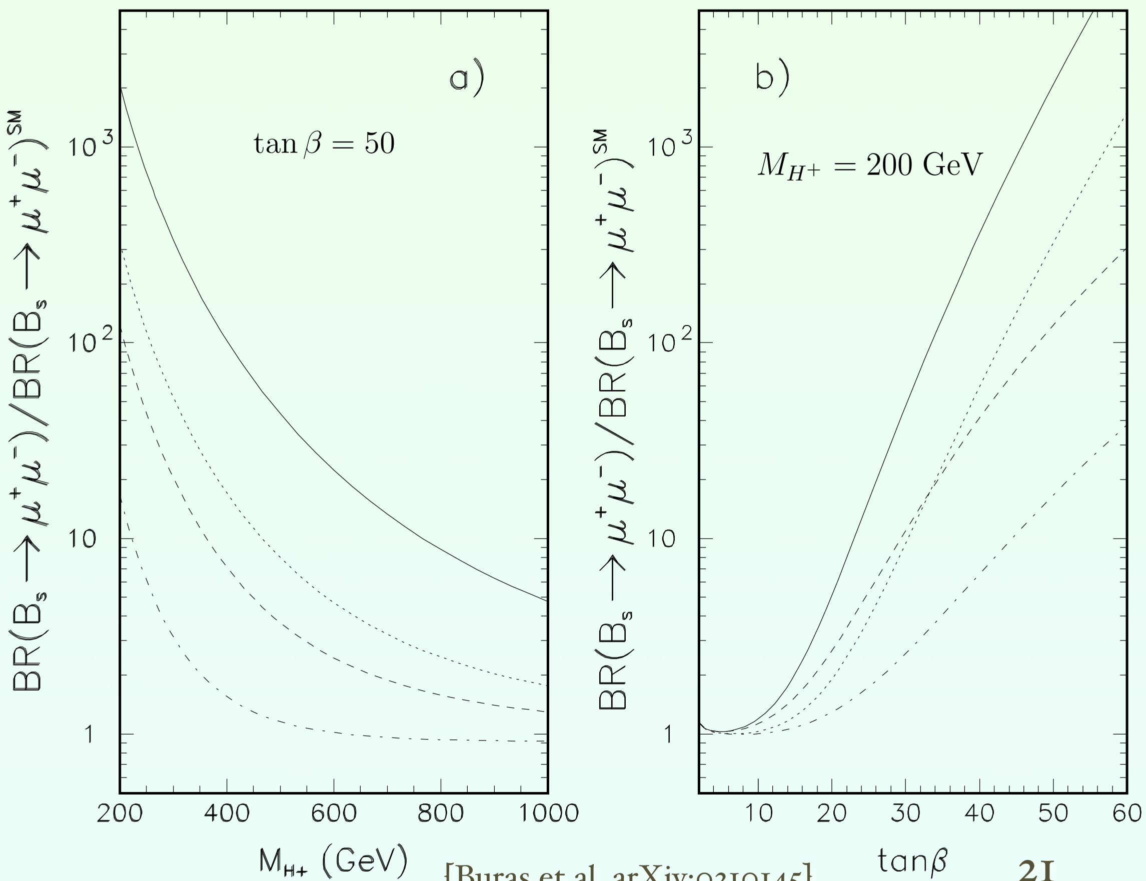
[Degrassi et al, arXiv:0009337]



$\tan\beta \sim 1$	charged Higgs and chargino exchanges dominant
$\tan\beta \gg 1$	Higgs exchange dominant

$$m_b = \sqrt{2} M_W \, \frac{y_b}{g} \, \cos\beta \, (1 + \epsilon_b \tan\beta) \, .$$

five new (beyond SM) parameters



[Buras et al, arXiv:0210145]

solid: $\mu < 0$ $M_{\tilde{t}_1} = 500$ GeV, $M_{\tilde{t}_2} = 850$ GeV

dashed: $\mu > 0$ $M_{\tilde{t}_1} = 500$ GeV, $M_{\tilde{t}_2} = 850$ GeV

dot-dash: $\mu > 0$ $M_{\tilde{t}_1} = 600$ GeV, $M_{\tilde{t}_2} = 750$ GeV

dotted: $\mu < 0$ $M_{\tilde{t}_1} = 600$ GeV, $M_{\tilde{t}_2} = 750$ GeV

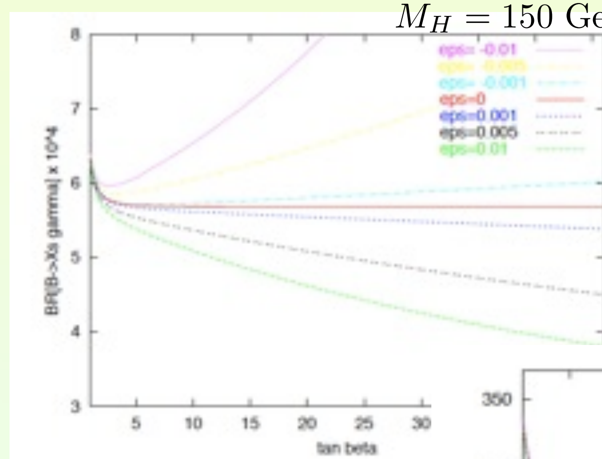
Slide taken from BG FPCP2009

CMSSM (at large tan β, possibly)

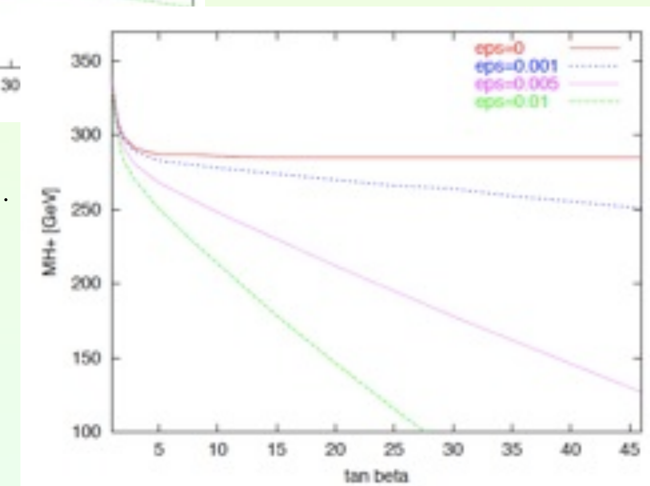
$\tan\beta \sim 1$ charged Higgs and chargino exchanges dominant

$\tan\beta \gg 1$ Higgs exchange dominant

$M_H = 150$ GeV

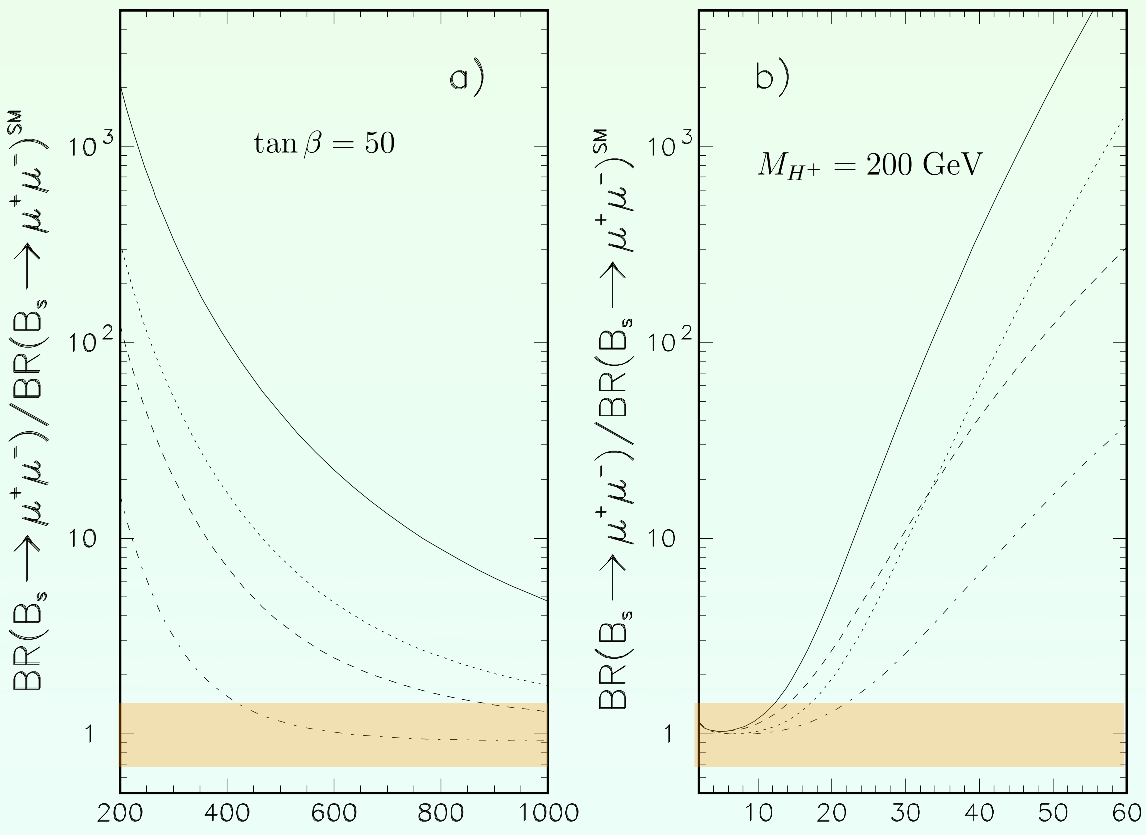


[Degrassi et al, arXiv:0009337]



$$m_b = \sqrt{2} M_W \, \frac{y_b}{g} \, \cos\beta \, (1 + \epsilon_b \tan\beta)\,.$$

five new (beyond SM) parameters



[Buras et al, arXiv:0210145]

solid: $\mu < 0$ $M_{\tilde{t}_1} = 500$ GeV, $M_{\tilde{t}_2} = 850$ GeV

dashed: $\mu > 0$ $M_{\tilde{t}_1} = 500$ GeV, $M_{\tilde{t}_2} = 850$ GeV

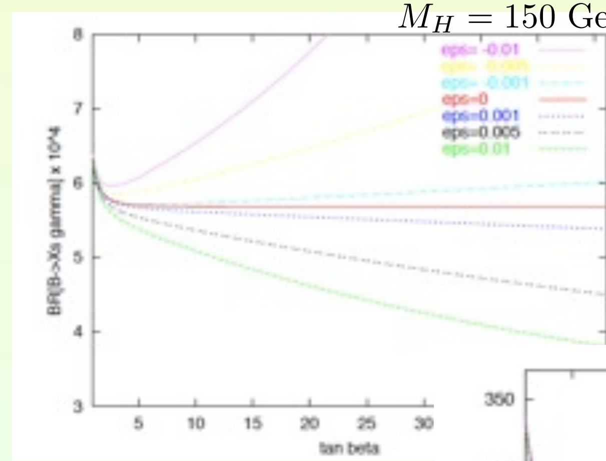
dot-dash: $\mu > 0$ $M_{\tilde{t}_1} = 600$ GeV, $M_{\tilde{t}_2} = 750$ GeV

dotted: $\mu < 0$ $M_{\tilde{t}_1} = 600$ GeV, $M_{\tilde{t}_2} = 750$ GeV

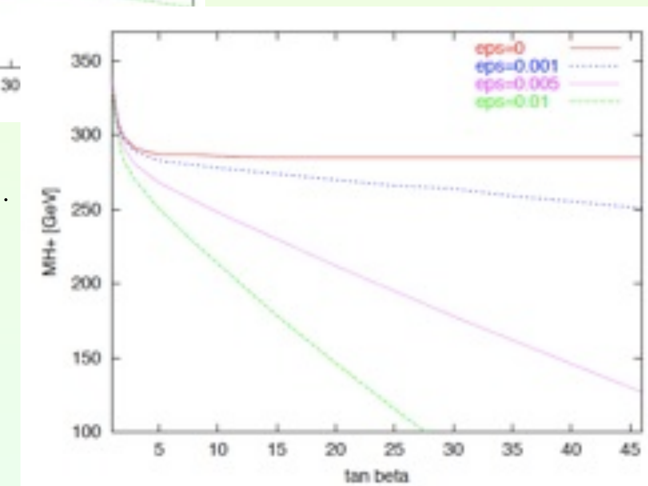
Nov 2012 LHCb

CMSSM (at large $\tan\beta$, possibly)

$M_H = 150$ GeV



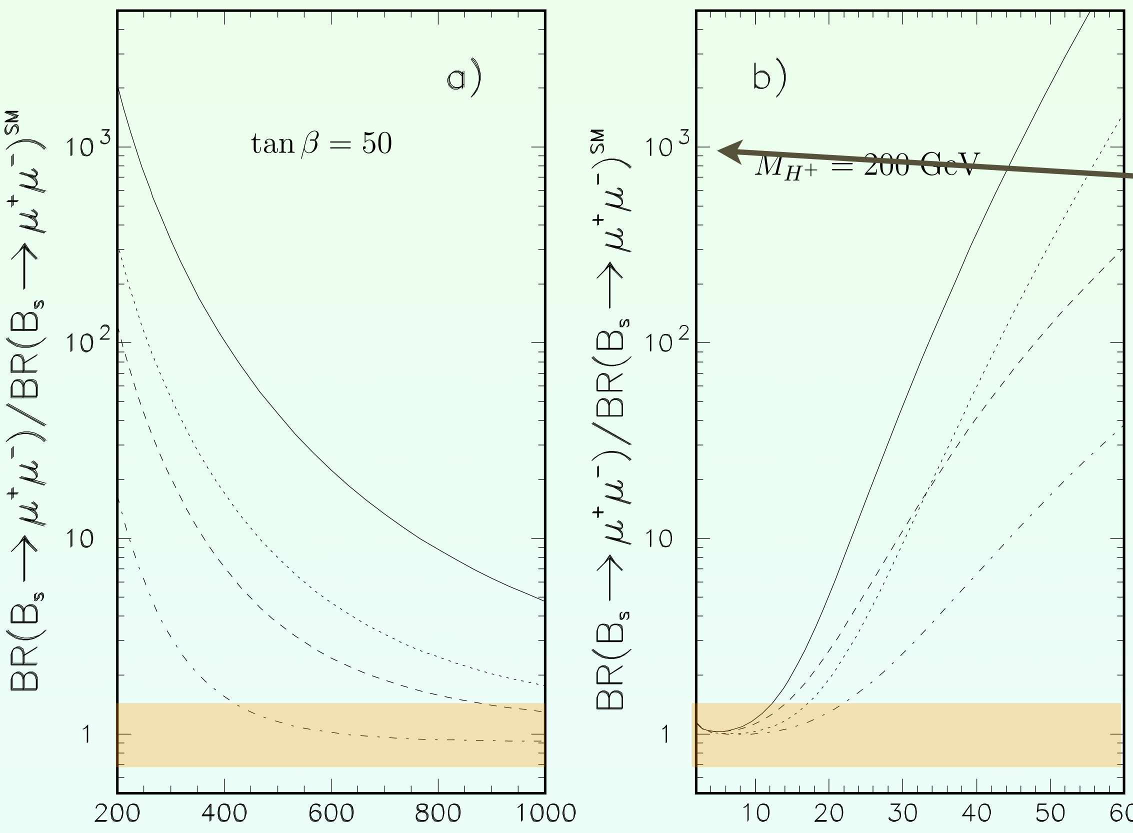
[Degrassi et al, arXiv:0009337]



$\tan\beta \sim 1$	charged Higgs and chargino exchanges dominant
$\tan\beta \gg 1$	Higgs exchange dominant

$$m_b = \sqrt{2} M_W \, \frac{y_b}{g} \, \cos\beta \, (1 + \epsilon_b \tan\beta) \, .$$

five new (beyond SM) parameters



[Buras et al, arXiv:0210145]

Scale! Compare with previous slide!!!

solid: $\mu < 0$ $M_{\tilde{t}_1} = 500$ GeV, $M_{\tilde{t}_2} = 850$ GeV

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Nov 2012 LHCb

At this point I am supposed to show you many more plots of the restricted parameter space in versions of low energy SUSY, extra-dimensions, little higgs.....

Instead, get some “perspective”

Minimal Flavor Violation (MFV)

- Let's take a more generic, less mode dependent, approach
- MFV Premise: Unique source of flavor braking
- Quark sector in SM, in absence of masses has large flavor (global) symmetry G_F:

$$\mathrm{U}(3)_{Q_L} \otimes \mathrm{U}(3)_{U_R} \otimes \mathrm{U}(3)_{D_R}$$

- In SM, symmetry is only broken by Yukawa interactions, parametrized by couplings Y_U and Y_D

For the benefit of the experts, who don't seem to get it:

- NP models must have at least this amount of symmetry breaking ("minimal")
  - They may have more
  - Irrelevant. Here is the story: given new stuff at a given scale Λ, virtual processes will induce corrections to flavor processes (not necessarily perturbatively). Question is: what is the minimum effect in flavor changing processes we have a right to expect?
  - And, yes, it can be avoided by tuning

MFV cont'd

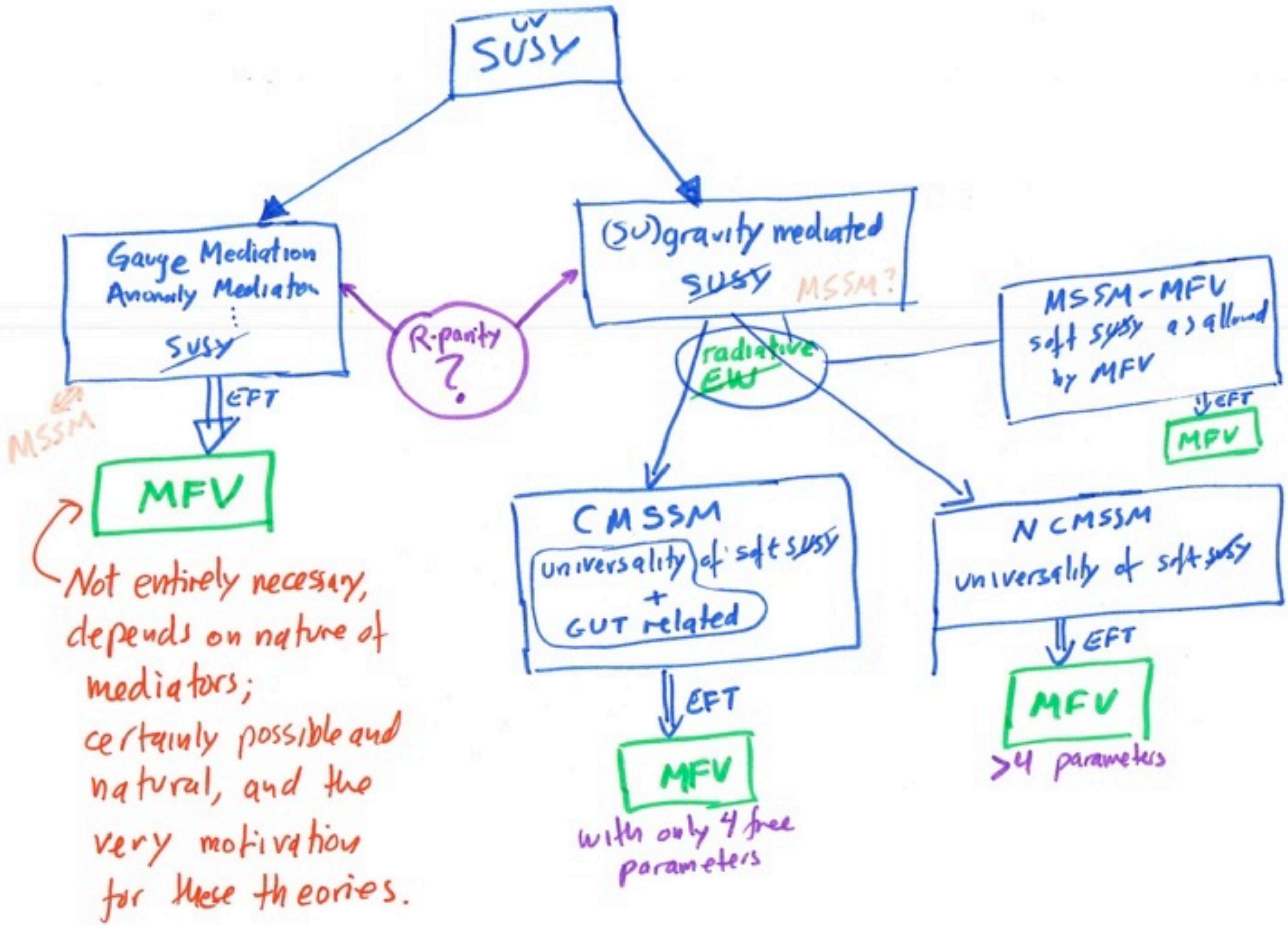
- Recall. Flavor group G_F is

$$\mathrm{U}(3)_{Q_L} \otimes \mathrm{U}(3)_{U_R} \otimes \mathrm{U}(3)_{D_R}$$

- In SM, symmetry is only broken by Yukawa interactions, parametrized by couplings Y_U and Y_D
- MFV: all breaking of G_F must arise from Y_U and Y_D.
- In practice: Build G_F invariants with Y_U and Y_D as constant fields, a.k.a. "spurions"

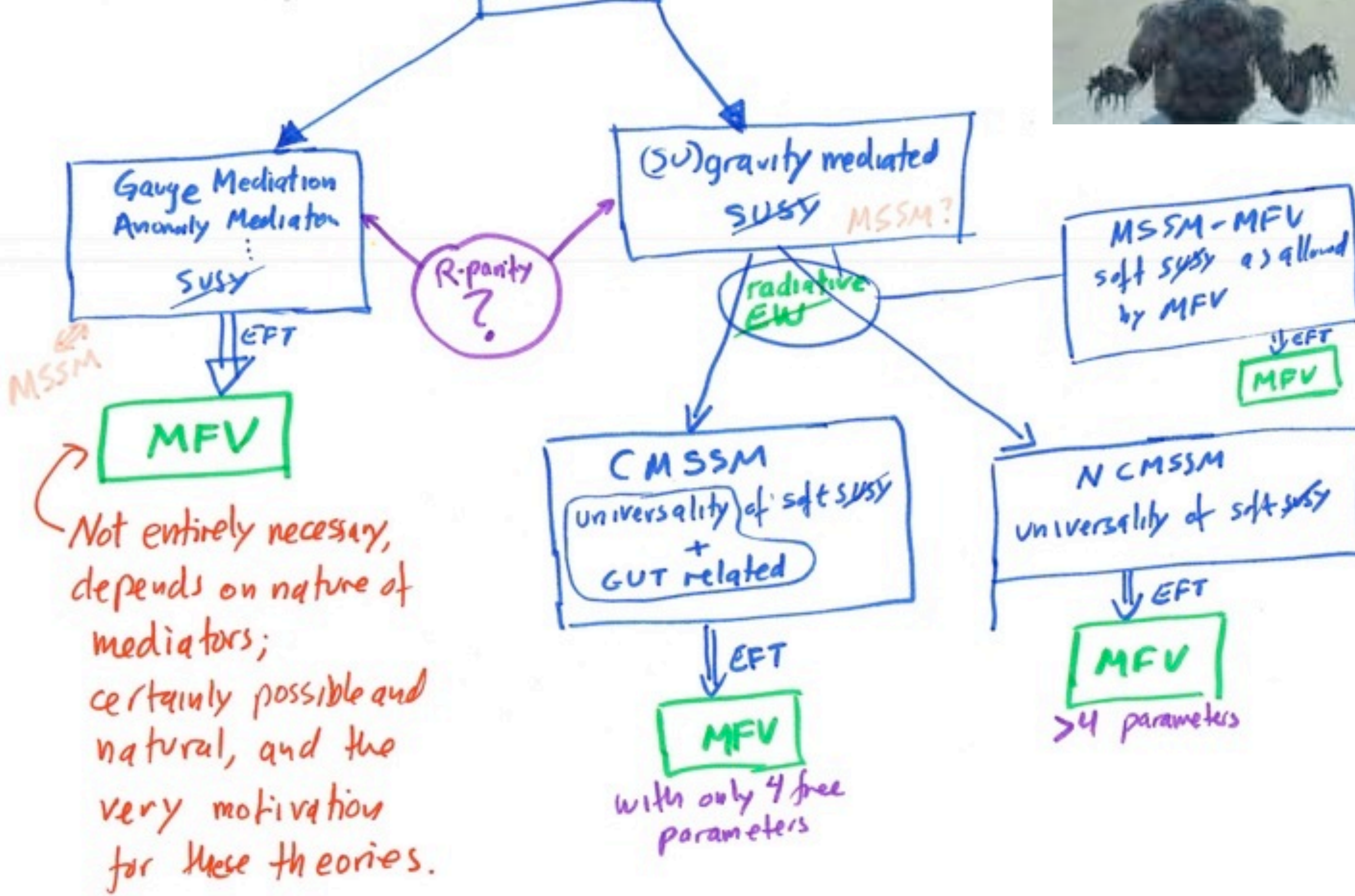
$$Y_u = (\bar{3}, 3, 1)\,,$$
$$Y_d = (\bar{3}, 1, 3)\,.$$

- When going to mass eigenstate basis, all mixing is parametrized by CKM and GIM-like cancellations are automatic
- Result: NP parametrized by high dimension operators: $\Lambda \leq 3\text{–}10$ TeV
  - For perturbative NP $\Lambda = 4\pi$ M



UV SUSY
Gauge Mediation
Anomaly Mediation
SUSY
(SU)gravity mediated
SUSY
MSSM?
R-parity ?
radiative EW
MSSM-MFV
soft susy as allowed by MFV
EFT
MFV
MSSM
EFT
MFV
Not entirely necessary, depends on nature of mediators; certainly possible and natural, and the very motivation for these theories.
CMSSM
universality of soft susy
+
GUT related
EFT
MFV
with only 4 free parameters
NCMSSM
universality of soft susy
EFT
MFV
>4 parameters

[BG, FPCP2009]



UV SUSY
Gauge Mediation
Anomaly Mediation
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Not entirely necessary, depends on nature of mediators; certainly possible and natural, and the very motivation for these theories.
R-parity ?
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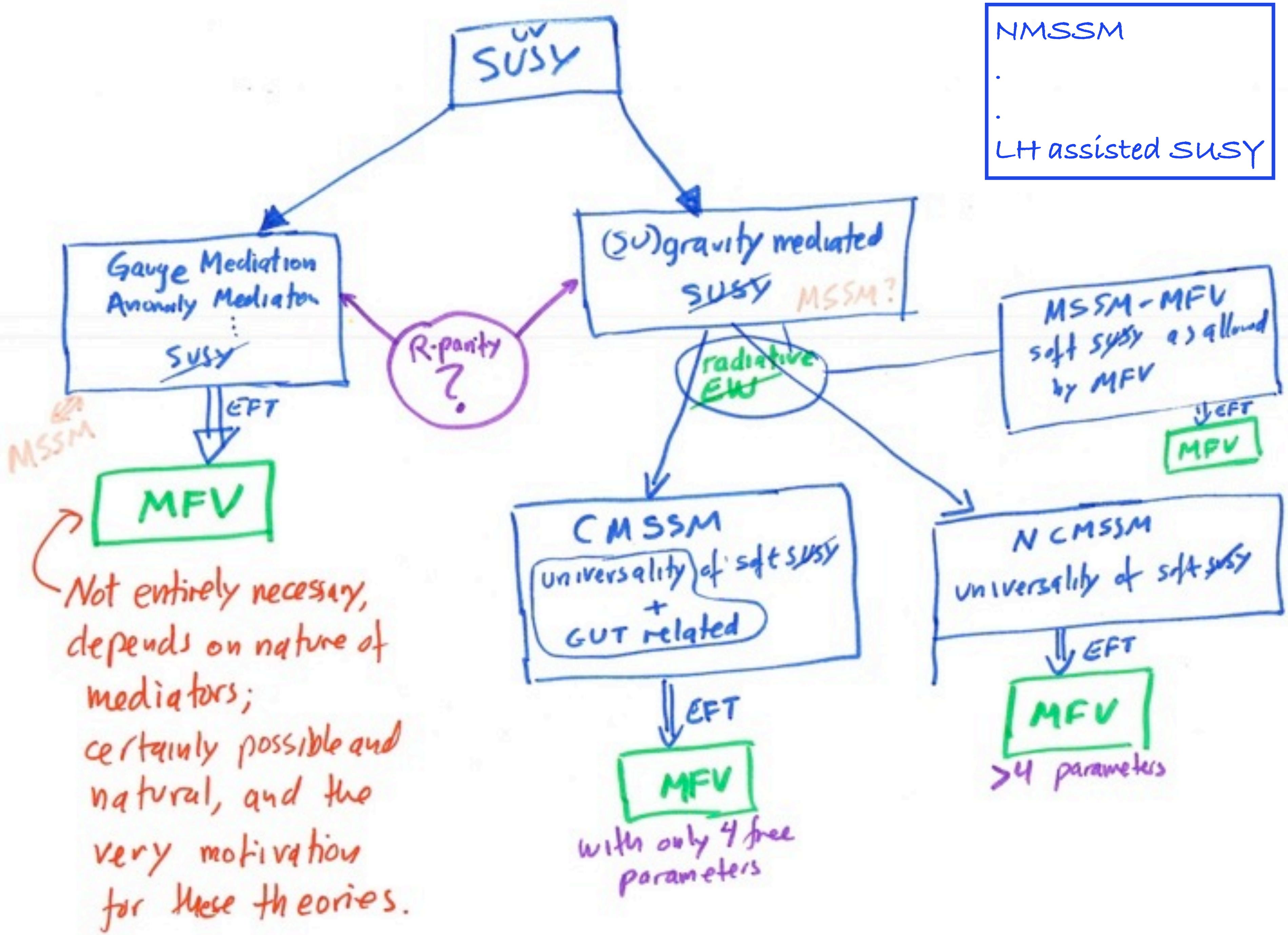
soft susy as allowed by MFV
EFT
MFV
CMSSM
universality of soft susy + GUT related
EFT
MFV
with only 4 free parameters
NCMSSM
universality of soft susy
EFT
MFV
>4 parameters

[BG, FPCP2009]


UV SUSY
NMSSM
.
.
LH assisted SUSY
Gauge Mediation
Anomaly Mediation
SUSY
(SU)gravity mediated
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MSSM?
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?
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EFT
MFV
with only 4 free parameters
MFV
>4 parameters

[BG, FPCP2009]

Digression: can we take spurions seriously?

- Want a model in which spurions are VEVs of scalars
- Want a renormalizable model
- Must gauge G_F (else NGB disaster)
- Desirable (but unnecessary): some chance of LHC physics. But
  - expect $M_V \sim 10^4$ TeV from K^0 physics
  - expect spectrum of vectors roughly like VEVs, i.e., like $Y_{U,D}$
  - so all vectors heavier than 10^4 TeV unless, somehow: inverted hierarchy
- Must: anomaly free
- Desirable: Simplest

- Note: $N = 3$ of generations "explained" (no less than $N_c = 3$ colors explained) (while spectrum and pattern of mixings still engineered).

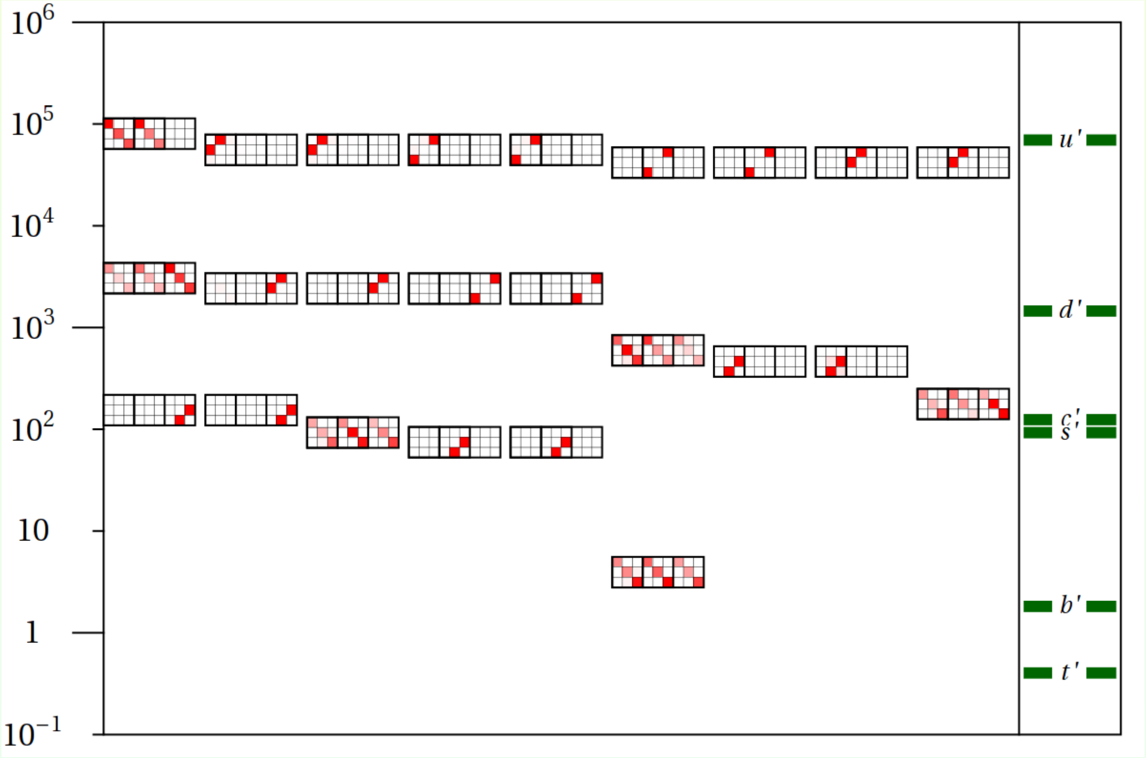
Surprisingly, the simplest renormalizable SM extension with gauged, anomaly free G_F has an inverted hierarchy of vector masses (relative to quark masses)

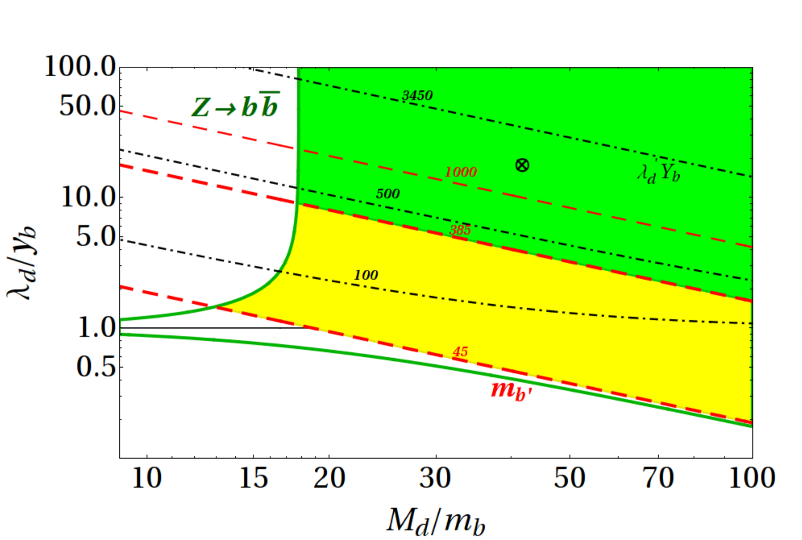
	$SU(3)_{Q_L}$	$SU(3)_{U_R}$	$SU(3)_{D_R}$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
Q_L	3	1	1	3	2	1/6
U_R	1	3	1	3	1	2/3
D_R	1	1	3	3	1	-1/3
Ψ_{uR}	3	1	1	3	1	2/3
Ψ_{dR}	3	1	1	3	1	-1/3
Ψ_u	1	3	1	3	1	2/3
Ψ_d	1	1	3	3	1	-1/3
Y_u	$\overline{3}$	3	1	1	1	0
Y_d	$\overline{3}$	1	3	1	1	0
H	1	1	1	1	2	1/2

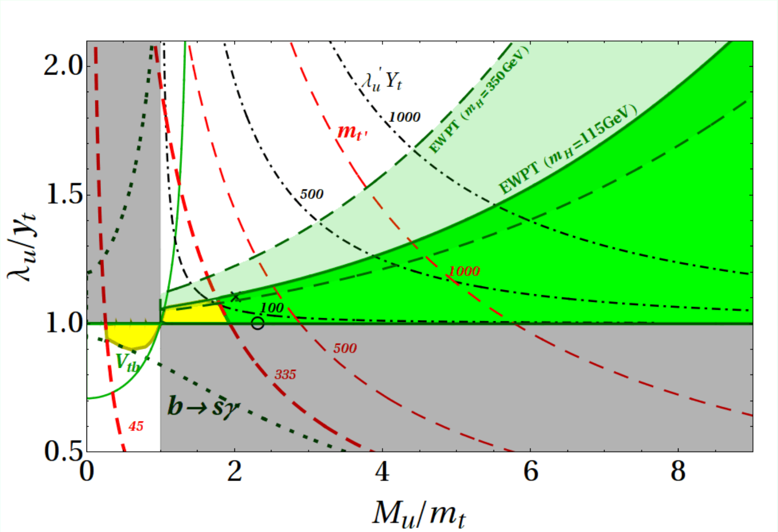
Most general renormalizable lagrangian

$$\begin{aligned}\mathcal{L} =&\mathcal{L}_{kin} - V(Y_u, Y_d, H) + \\ &\big(\lambda_u \overline{Q}_L \tilde{H} \Psi_{uR} + \lambda'_u \overline{\Psi}_u Y_u \Psi_{uR} + M_u \overline{\Psi}_u U_R + \\ &\lambda_d \overline{Q}_L H \Psi_{dR} + \lambda'_d \overline{\Psi}_d Y_d \Psi_{dR} + M_d \overline{\Psi}_d D_R + h.c.\big)\,,\end{aligned}$$

Spectrum (arbitrary overall scale, take it as TeV)







Leptons

- it is easy to accommodate leptons in the gauged-G_F model
- MLFV: MFV for lepton sector
  - Best justified by GUTs, so may as well...
- MFV GUT
  - GUTs connect MFV in quark and lepton sectors
  - New effects (e.g., LFV even for Dirac neutrino)
  - Includes thoroughly studied models
    (e.g., SUSY-GUTs)

MFV-GUTs in a nut-shell

three families of left handed fields: $\psi_i \sim \bar{\mathbf{5}}$ $\quad \chi_i \sim \mathbf{10}$ $\quad N_i \sim \mathbf{1}$ $\quad i = 1, 2, 3$

(d_R^c, L_L) $\quad (Q_L, u_R^c, e_R^c)$

In the absence of masses, symmetric under $SU(3)_{\bar{5}} \times SU(3)_{10} \times SU(3)_1$

Include symmetry breaking (here with one higgs):

$$\lambda_5^{ij}\ \psi_i^T \chi_j H_5^* + \lambda_{10}^{ij}\ \chi_i^T \chi_j H_5$$

gives bad mass relations for light families

$$\lambda_u \propto \lambda_{10}\ , \lambda_d \propto \lambda_e^T \propto \lambda_5$$

$$\frac{1}{M} (\lambda_5')^{ij}\ \psi_i^T \Sigma \chi_j H_{\bar{5}}$$

$\Sigma \sim \mathbf{24}$; M large; freedom to fix mass relations

$$\lambda_u \propto \lambda_{10},\ \lambda_d \propto (\lambda_5 + \epsilon \lambda_5')\ ,\ \lambda_e^T \propto \left(\lambda_5 - \tfrac{3}{2}\epsilon\lambda_5'\right)\ ,\quad \epsilon = M_{\rm GUT}/M$$

$$\lambda_1^{ij}\ N_i^T \psi_j H_5 + M_R^{ij} N_i^T N_j$$

neutrino masses (Dirac+Majorana)

spurion transformation laws:

$$\begin{array}{lcl} Q_L & \to & V_{10}\ Q_L \\ u_R & \to & V_{10}^*\ u_R \\ d_R & \to & V_{\bar{5}}^*\ d_R \\ L_L & \to & V_{\bar{5}}\ L_L \\ e_R & \to & V_{10}^*\ e_R \end{array} \qquad \begin{array}{lcl} \lambda_{10} & \to & V_{10}^*\ \lambda_{10}\ V_{10}^\dagger \\ \lambda_5 & \to & V_{\bar{5}}^*\ \lambda_5\ V_{10}^\dagger \\ \lambda_5' & \to & V_{\bar{5}}^*\ \lambda_5'\ V_{10}^\dagger \\ \lambda_1 & \to & V_1^*\ \lambda_1\ V_{\bar{5}}^\dagger \\ M_R & \to & V_1^*\ M_R\ V_1^\dagger \end{array}$$

connect lepton to quark MFV

get old mixing structures (to be included in composite operators), like

$$\text{quarks:} \qquad \bar{Q}_L \lambda_u^\dagger \lambda_u Q_L \,, \qquad \bar{d}_R \lambda_d \lambda_u^\dagger \lambda_u Q_L$$

$$\text{leptons:} \qquad \bar{L}_L \lambda_1^\dagger \lambda_1 L_L \,, \qquad \bar{e}_R \lambda_e \lambda_1^\dagger \lambda_1 L_L$$

but also get interesting new ones, like

$$\begin{array}{lll}
\text{quarks:} & \bar{Q}_L (\lambda_e \lambda_e^\dagger)^T Q_L \,, & \\
& \bar{d}_R \lambda_e^T (\lambda_e \lambda_e^\dagger)^T Q_L \,, & \bar{d}_R (\lambda_e \lambda_1^\dagger \lambda_1)^T Q_L \,, \\
& \bar{d}_R (\lambda_e^\dagger \lambda_e)^T d_R \,, & \bar{d}_R (\lambda_1^\dagger \lambda_1)^T d_R \,, \\
\text{leptons:} & \bar{L}_L (\lambda_d \lambda_d^\dagger)^T L_L \,, & \\
& \bar{e}_R (\lambda_d \lambda_d^\dagger \lambda_d)^T L_L, & \bar{e}_R \lambda_u \lambda_u^\dagger \lambda_d^T L_L \,, \\
& \bar{e}_R \lambda_u \lambda_u^\dagger e_R \,, & \bar{e}_R (\lambda_d^\dagger \lambda_d)^T e_R \,,
\end{array}$$

going over to quark/lepton mass basis, introduce two new mixing matrices $C = V_{e_R}^T V_{d_L}, \quad G = V_{e_L}^T V_{d_R}$

so get, for example

$$\begin{array}{lcl}
\bar{e}_R \lambda_u \lambda_u^\dagger e_R & & \bar{e}_R \left[C \Delta^{(q)} C^\dagger \right]^* e_R \\
\bar{e}_R \lambda_u \lambda_u^\dagger \lambda_d^T L_L & \longrightarrow & \bar{e}_R \left[C \Delta^{(q)} \bar{\lambda}_d G^\dagger \right]^* e_L \\
\bar{e}_R \lambda_u \lambda_u^\dagger \lambda_e L_L & & \bar{e}_R \left[C \Delta^{(q)} C^\dagger \right]^* \bar{\lambda}_e e_L
\end{array}$$

where $\Delta_{ij}^{(q)} \equiv V_{\text{CKM}}^\dagger \, \bar{\lambda}_u^2 \, V_{\text{CKM}} = \dfrac{m_t^2}{v^2} (V_{\text{CKM}})_{3i}^* (V_{\text{CKM}})_{3j} + \mathcal{O}(m_{c,u}^2/m_t^2)$

quick example (probably out of time by now):

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

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

quick example (probably out of time by now):

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

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

just like pure MLFV

quick example (probably out of time by now):

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

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

just like pure MLFV

Generalizes Barbieri & Hall ($\lambda_5' = 0, C = G = 1$)

New mixing structures

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

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

Independent of M_ν

Hierarchical

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

Large: for Λ=10TeV

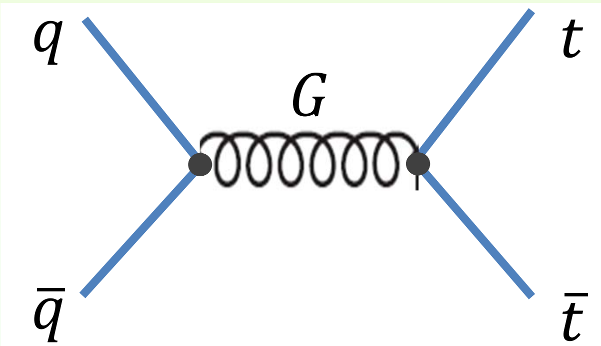
$$\mathrm{Br}(\mu \to e\gamma) \sim 10^{-12}$$

$(\lambda = 0.22)$

(is the Cabibbo angle!)

R. Barbieri, L.J. Hall, Phys. Lett. B 338 (1994) 212
R. Barbieri, L.J. Hall, A. Strumia, Nucl. Phys. B 445 (1995) 219

Flavor Physics and FB asymmetry in top production at Tevatron

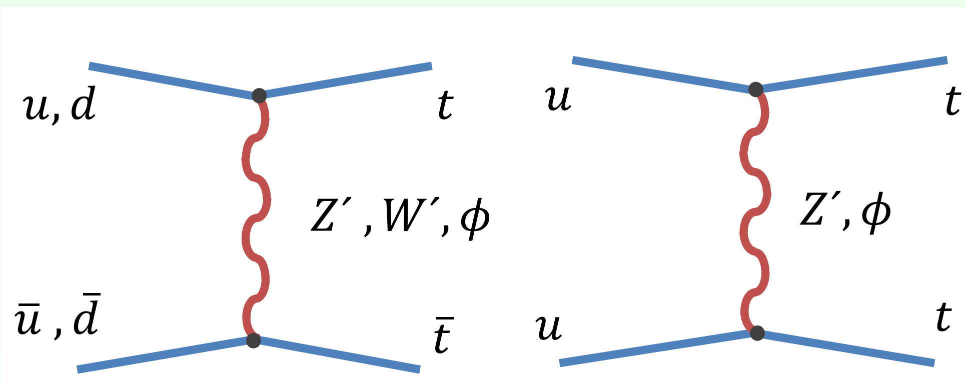


s-channel exchange models

[Marques Tavares, Schmalz / Barcelo, Carmona, Masip, Santiago / Ferrario, Rodrigo / Frampton,Shu,Wang / Djouadi, Richard / Bauer, Goertz, Haisch, Pfoh, Westhoff / Bai, Hewett, Kaplan, Rizzo / Zerwekh /Hewet, Shelton, Spannowsky, Tait, Takeuchi / Haisch, Westhoff / Aguilar-Saavedra, Perez-Victoria, ...]

G is color octet for LO interference with QCD

Need axial coupling; "axigluon." For positive asymmetry and heavy G need $\underline{\mathrm{sign}(g^q\ g^t) = -1}$: vector-axial couplings non-flavor-universal.
Light G: suppressed light-q couplings (from dijets)



t-channel exchange models

[Jung, Murayama, Pierce, Wells / Cheung, Keung, Yuan / Cao, Heng, Wu, Yang / Barger, Keung, Yu / Cao, McKeen, Rosner, Saughnessy, Wagner / Berger, Cao, Chen, Li, Zhang / Bhattacherjee, Biswal, Ghosh/ Zhou, Wang, Zhu / Aguilar-Saavedra, Perez-Victoria / Buckley, Hooper, Kopp, Neil / Rajaraman, Surujon, Tait/ Duraisamy, Rashed, Datta / Shu,Tait,Wang / Cao,Heng,Wu,Yang / Dorsner, Faifer, Kamenik, Kosnik / Jung,Ko,Lee,Nam. Aguilar-Saavedra, Perez-Victoria / Patel, Sharma / Ligeti, Marques Tavares, Schmalz, ...]

- A large FB asymmetry requires large flavor violating couplings
- Like sign tt, di-jets, single top, very constrained at Tevatron and LHC

All models require non-trivial flavor interactions.

Natural implementation: Minimal Flavor Violating Fields, rich phenomenology [BG, Kagan, Trott, Zupan]

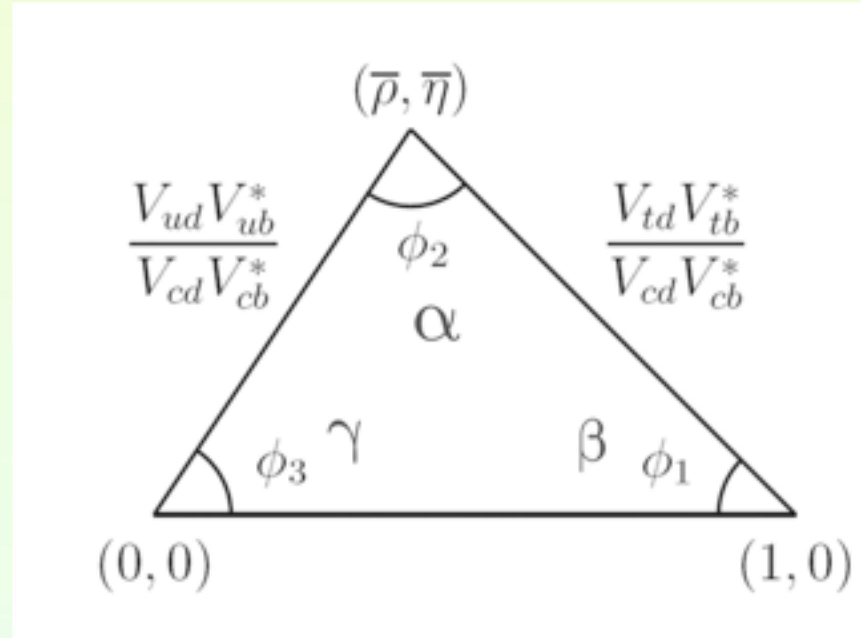
Conclusions

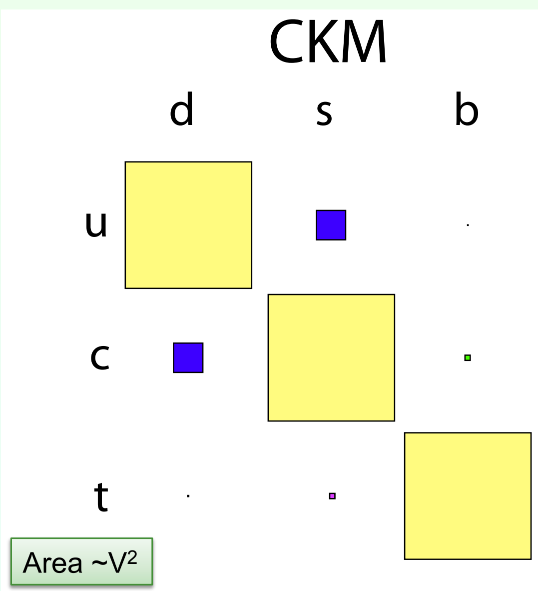
- Flavor physics in quark sector strongly constrains BSM/NP models
- Expect that any complete theory of flavor connects quark and lepton sectors
- In absence of direct evidence for new resonances, generic model independent analysis is valuable
- MFV:
  - Simplest way of relaxing bounds on scale of NP
  - Naturally arising (or to god approximation) in many popular models
  - Extensible to leptons/GUTs
  - Addresses flavor in top-quark-FB-asymmetry
- Gauged flavor models "explain:" number of generations
  - Do not address patterns of masses and mixings
  - MFV? Very nonlinearly
- Plethora of models for patterns of masses and mixings
  - But many only in lepton sector
  - Do not address number of generations (combine with gauged G_F?)
- Still far form a "theory of flavor"

The End

More slides

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

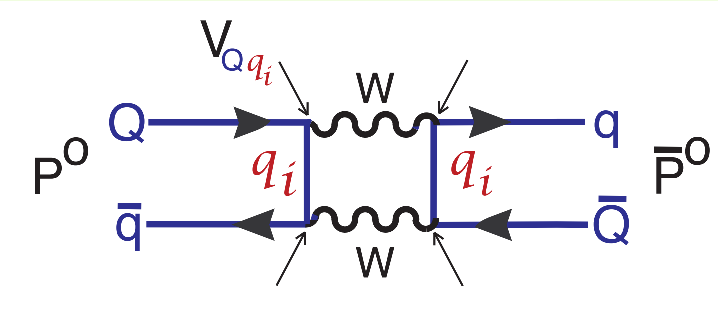




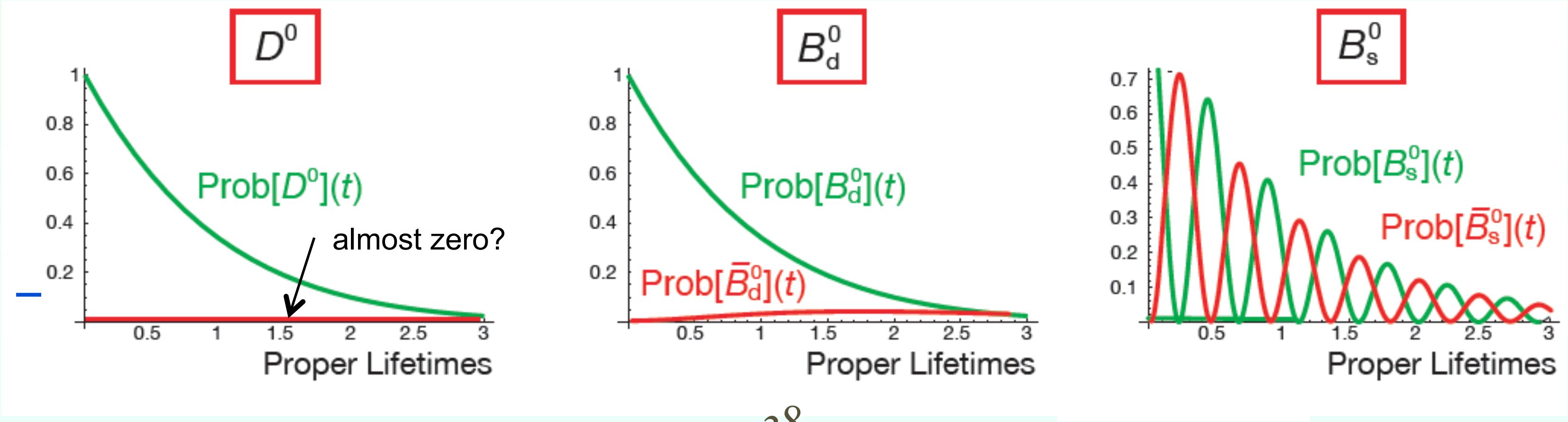
$$= \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}.$$

CPV in Mixing

- In SM neutral pseudoscalar P^0 can mix into antiparticle via box diagram



- Mixing rate depends on
  - Mass of internal quark larger for heavier quark
  - CKM factors V_{ij}
  - Largest for B_s since t-quark is not suppressed by CKM



Mixing Theory

Effective two state system:

$$i\frac{d}{dt}\begin{pmatrix} P^0 \\ \bar{P}^0 \end{pmatrix} = H_{\rm eff}\begin{pmatrix} P^0 \\ \bar{P}^0 \end{pmatrix} \qquad H_{\rm eff} = M - \tfrac{i}{2}\Gamma \qquad M^\dagger = M, \quad \Gamma^\dagger = \Gamma$$

CPT: $H_{\rm eff\,11} = H_{\rm eff\,22}$

diagonalize: $|P_L\rangle = p|P^0\rangle + q|\bar{P}^0\rangle \qquad |P_H\rangle = p|P^0\rangle - q|\bar{P}^0\rangle$

define:
$$\bar{M} = \frac{M_H + M_L}{2} \qquad \Delta M = M_H - M_L \approx 2|M_{12}|\left(1 - \frac{|\Gamma_{12}|^2}{8|M_{12}|^2}\sin^2\phi_{12}\right)$$

$$\bar{\Gamma} = \frac{\Gamma_H + \Gamma_L}{2} \qquad \Delta\Gamma = \Gamma_H - \Gamma_L \approx 2|\Gamma_{12}|\cos\phi_{12}\left(1 + \frac{|\Gamma_{12}|^2}{8|M_{12}|^2}\sin^2\phi_{12}\right)$$

$$\phi_{12} = \arg(-M_{12}/\Gamma_{12})$$

compute, eg:
$$\left(\frac{q}{p}\right) = \frac{\Delta M + \frac{i}{2}\Delta\Gamma}{2(M_{12} - \frac{i}{2}\Gamma_{12})}$$

Flavor Specific: a_{sl}

- Definition $$a_{sl} = \frac{\Gamma(\bar{P} \to f) - \Gamma(P \to \bar{f})}{\Gamma(\bar{P} \to f) + \Gamma(P \to \bar{f})}$$

  where $\Gamma(\bar{P} \to f)(t=0) = 0 = \Gamma(P \to \bar{f})(t=0)$

- Flavor specific means $\bar{f} \neq f$
  - $B_s \to D^+ \mu^- \bar{\nu}_\mu$ vs $\bar{B}_s \to D^- \mu^+ \nu_\mu$
  - Or same sign dileptons: one meson mixes and decays, the other decays without mixing: $\mu^+ \mu^+$ vs $\mu^- \mu^-$

- In SM $$a_{sl} = \frac{|p/q|^2 - |q/p|^2}{|p/q|^2 + |q/p|^2} \approx \frac{\Delta\Gamma}{\Delta M} \tan\phi_{12}$$

  so it is very small in SM,

$$\underset{B^0}{a_{sl}^d} = -4.1 \times 10^{-4}, \quad \underset{B_s}{a_{sl}^s} = 1.9 \times 10^{-5}$$ [A. Lenz, Moriond 2012]

a_{sl}: D0, from di-muons

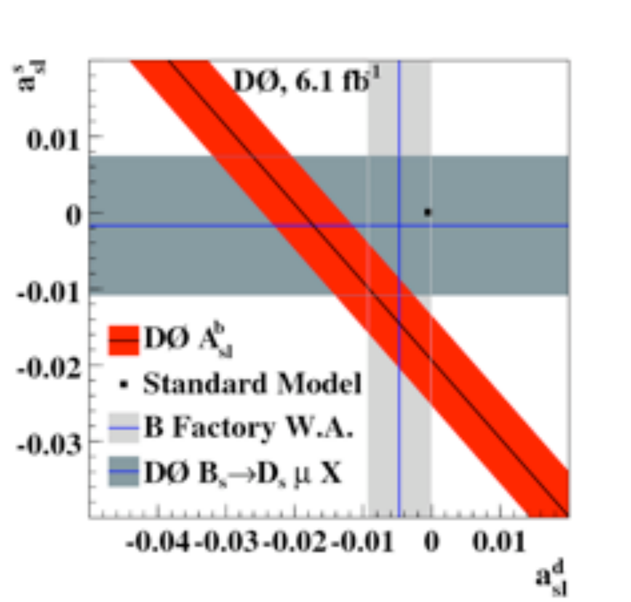
- Dimuons

- $a^b_{sl} = (-0.787 \pm 0.172(\text{stat}) \pm 0.093(\text{syst}))\%$ combined for *d* and *s*

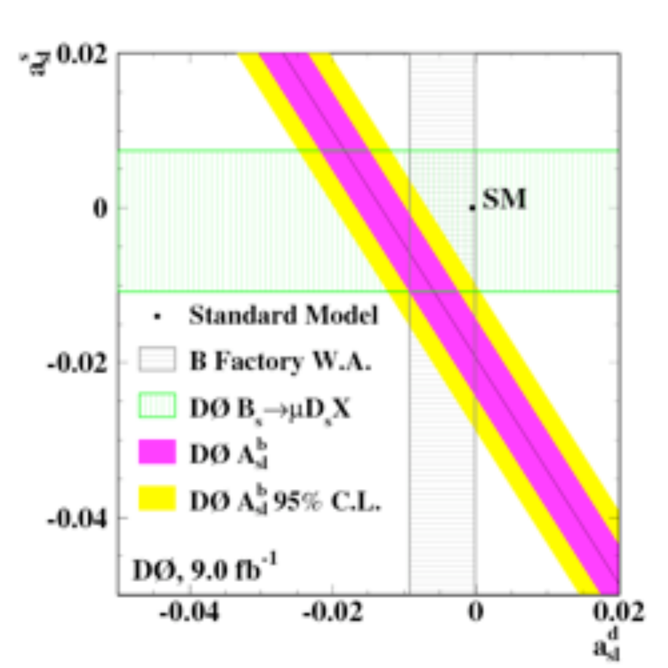
- 3.9σ deviation from SM

- Also use IP (impact parameter) to separate *d* from *s*

$$\begin{aligned} a^d_{\rm sl} &= (-0.12 \pm 0.52)\%, \\ a^s_{\rm sl} &= (-1.81 \pm 1.06)\%. \end{aligned}$$



[Phys.Rev. D82 (2010) 032001]



[Phys.Rev. D84 (2011) 052007]

a_{sl}: D0, from semileptonic

[arXiv:1207.1769]

[Phys. Rev. D86, 072009 (2012)]

- New this year (Jul 7, Aug 29)

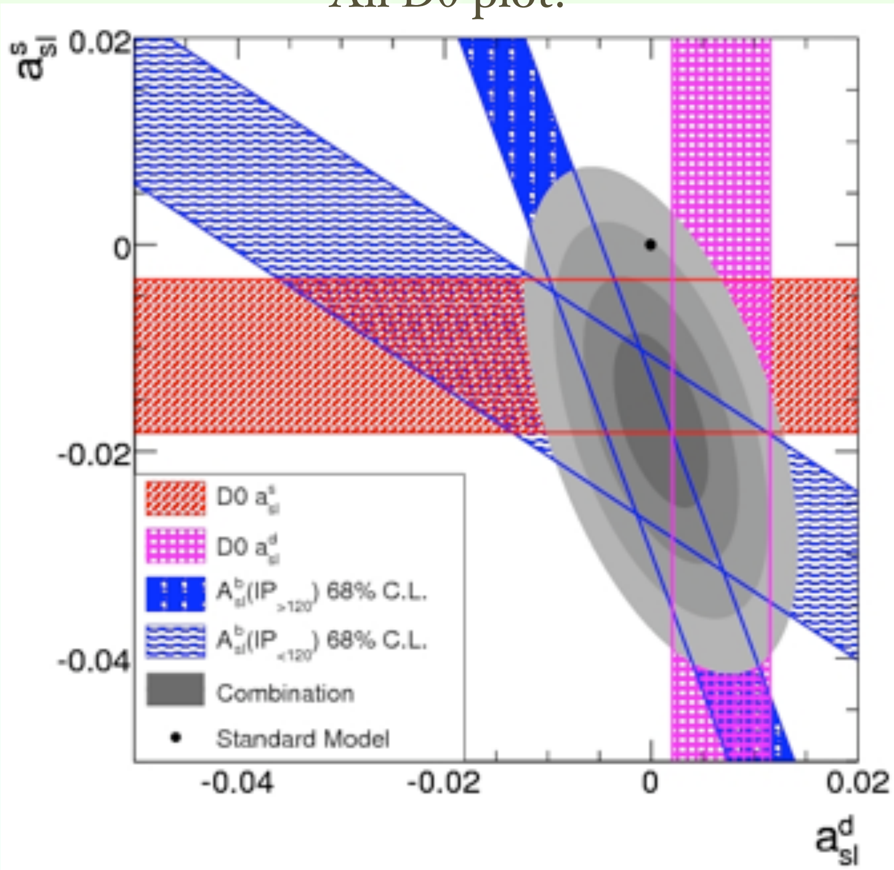
- $$\frac{\Gamma(\bar{B}^0 \to B^0 \to \ell^+ D^{(*)-} X) - \Gamma(B^0 \to \bar{B}^0 \to \ell^- D^{(*)+} X)}{\Gamma(\bar{B}^0 \to B^0 \to \ell^+ D^{(*)-} X) + \Gamma(B^0 \to \bar{B}^0 \to \ell^- D^{(*)+} X)},$$

  with 2 decay channels:

  1. $B^0 \to \mu^+ \nu D^- X$,
     with $D^- \to K^+ \pi^- \pi^-$
     (plus charge conjugate process);
  2. $B^0 \to \mu^+ \nu D^{*-} X$,
     with $D^{*-} \to \bar{D}^0 \pi^-, \bar{D}^0 \to K^+ \pi^-$
     (plus charge conjugate process);

  (idem for B_s)

All D0 plot:



- $a^d_{\rm sl} = [0.68 \pm 0.45\ (\text{stat.}) \pm 0.14\ (\text{syst.})]\%.$

  $a^s_{\rm sl} = [-1.08 \pm 0.72\,(\text{stat}) \pm 0.17\,(\text{syst})]\,\%$

a_{sl}: rest of the world

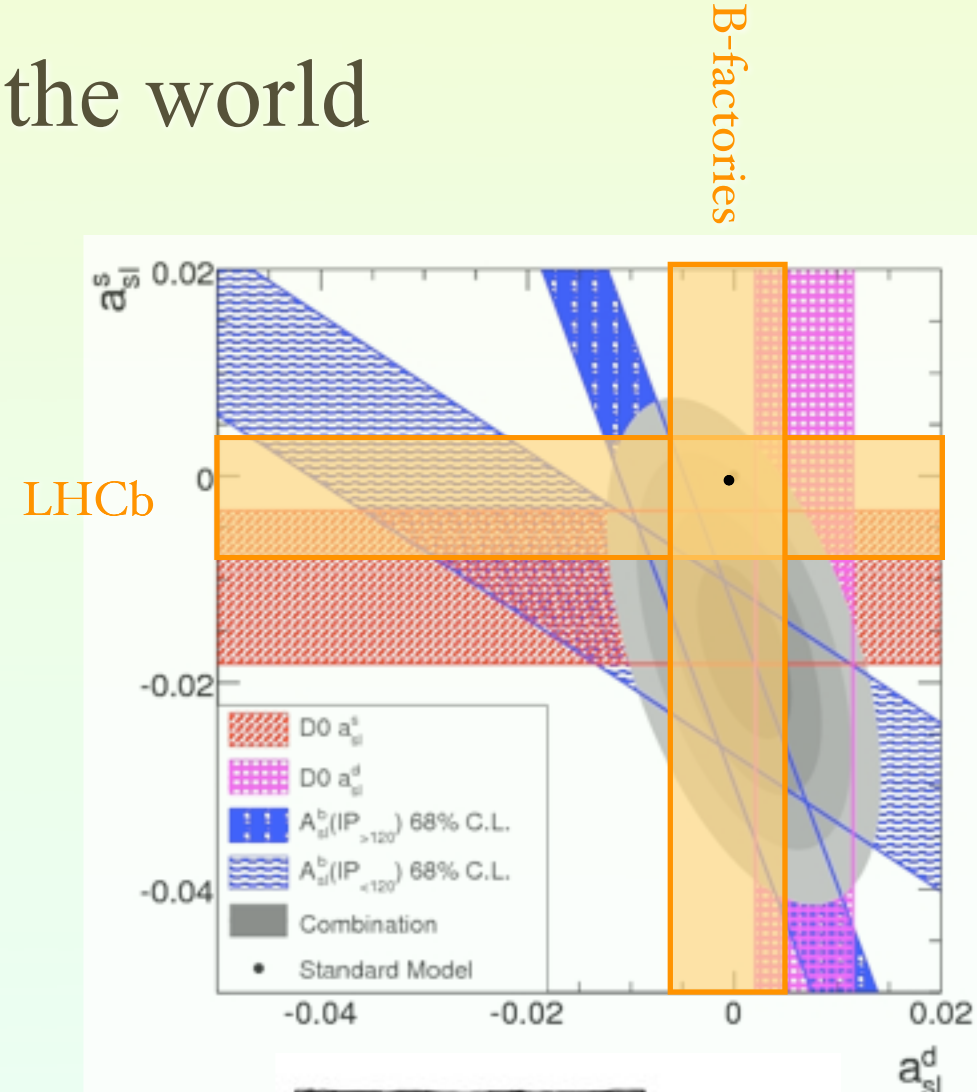
- LHCb [PLB713(2012)186]

$$a_{sl}^{s} = (-0.24 \pm 0. \pm 0.33)\%$$

- B-factories combined

$$a_{sl}^{d} = (-0.05 \pm 0.56)\%$$

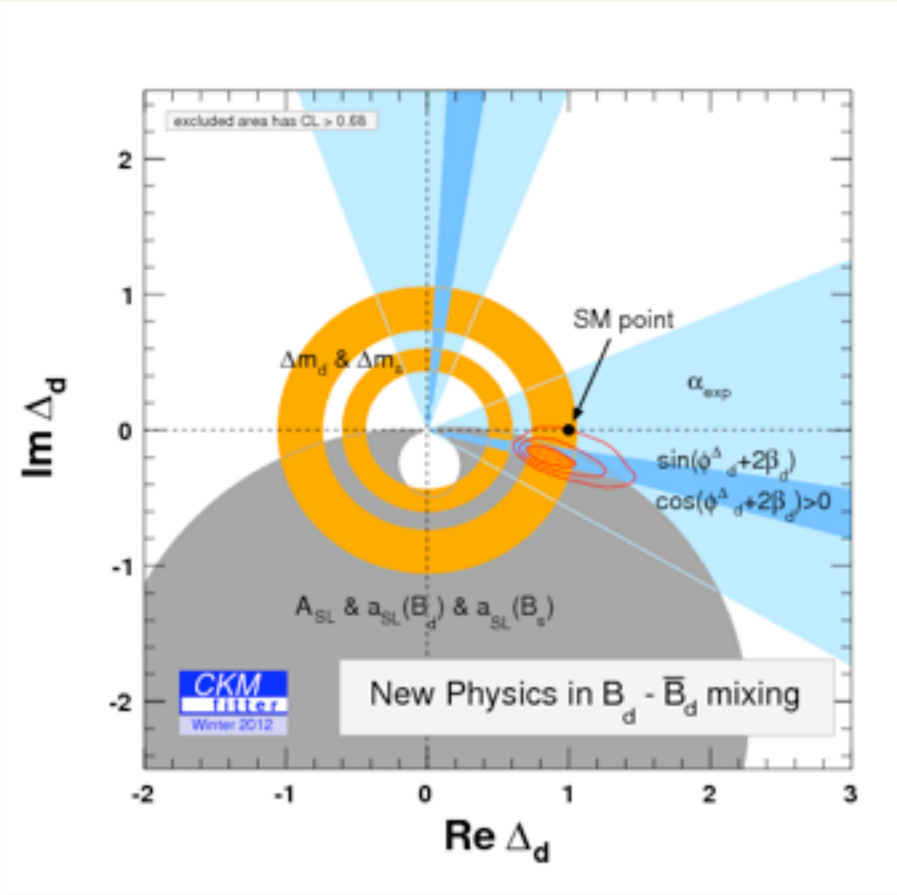
- Superimposed on D0 plot, for comparison
- Consistent with SM
- Will have to wait for more (more precise) data (not Tevatron)

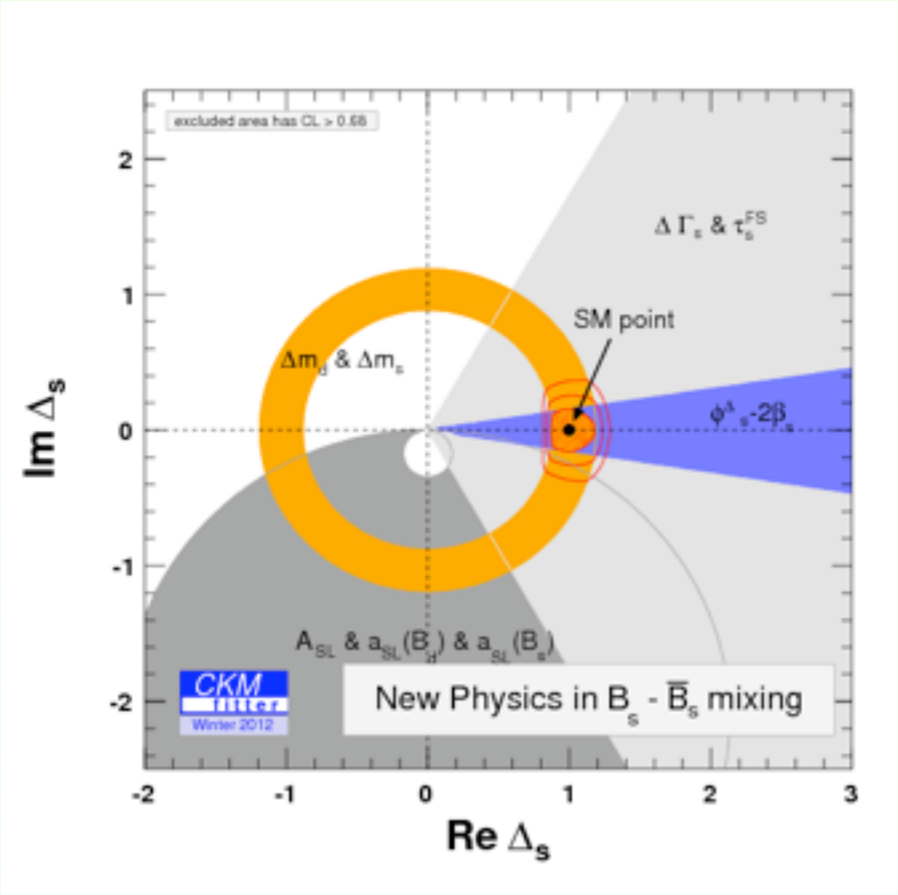


a_{sl}:summary

Characterize NP by

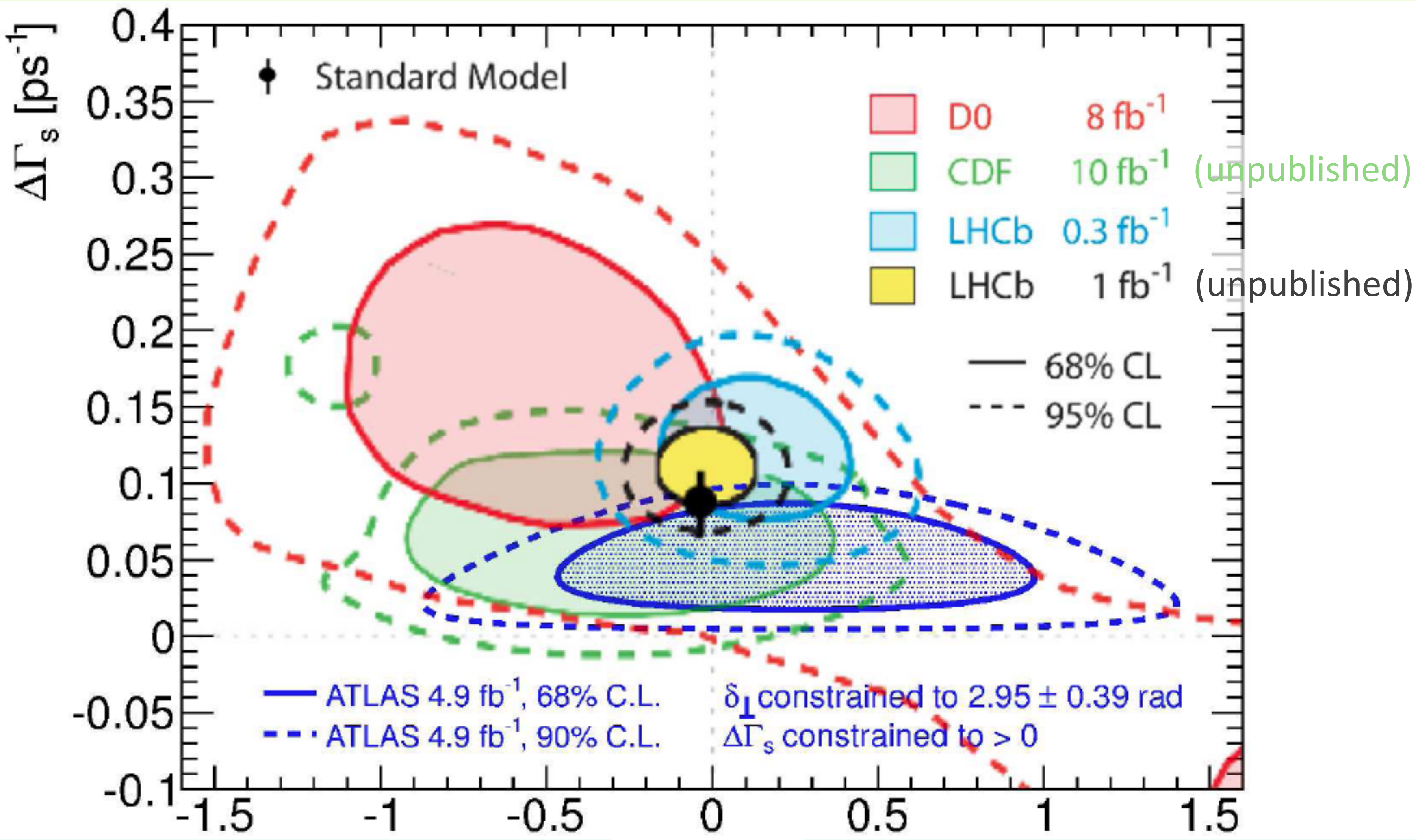
$$M_{12}^q = M_{12}^{q,\mathrm{SM}} \Delta_q$$





(does not include new LHCb result)

Combined fit to polarization, widths and angles in $B \to \psi\phi(K^+K^-)$ gives widths and angles:



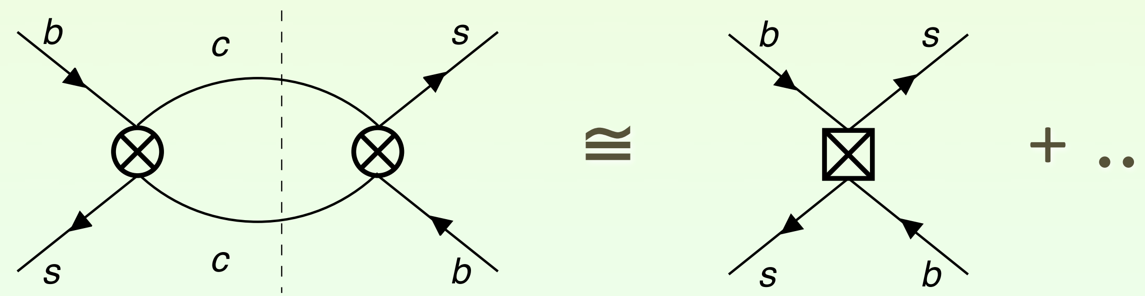
$\varphi_s = -2\beta_s$

[Palestini, ICHEP 2012]

Long Digression

Can we compute Γ (let alone ΔΓ)?

- Standard lore: use OPE
  - OPE: expansion in $1/m_b$



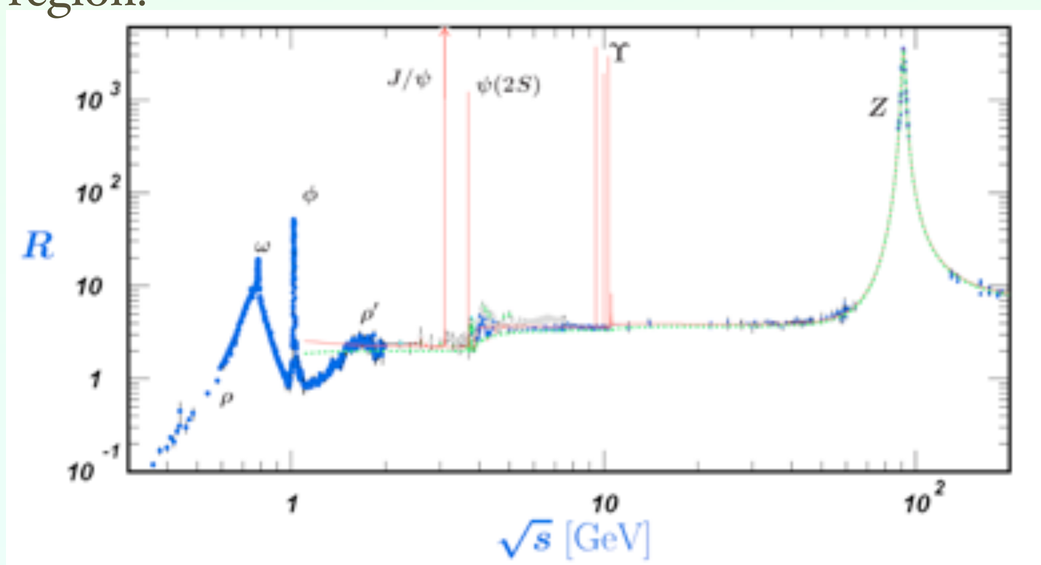
[Lenz & Nierste, eg: JHEP 0706 (2007) 072]

- Normally:
  - OPE valid in “deep Euclidean region”
  - Use dispersion relation to relate to physical region
  - Result in integral over all energies in physical region
  - Duality: replace integral over all energies by smearing over domain
  - Duality works if smearing over large enough region:
    - Include large number of resonances
    - Smooth regions dominate

Poggio-Quinn-Weinberg:

$$\bar{\sigma}(s) = \frac{1}{2i}\Big(\Pi(s+i\Delta) - \Pi(s-i\Delta)\Big)$$

can use OPE for Π if Δ is large enough

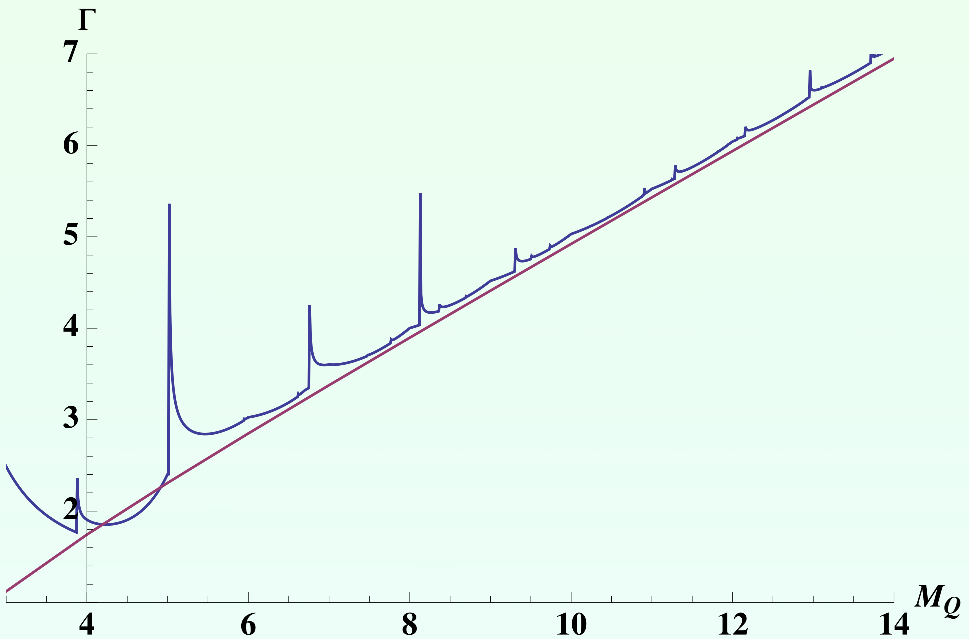


- For B decay we cannot smear (integrate) over quark masses

- Neither can we compute for "deep euclidean" mass

- Maybe duality works if mass is large enough (large number of decay channels)?

- Test the idea by applying it to soluble model: QCD in 2-dims at large N_c (the 't Hooft model)



- Spikes from phase space at thresholds

- Constant difference between "exact" and perturbative: order $(1/M_Q)^0$

$$\Gamma(B) = \Gamma(Q)(1 + 0.14/M_Q)$$

- Smearing will turn the finite difference into one that decreases with $1/M_Q$

- Q: how can this averaging procedure turn a constant difference into one that decreases as $(1/M_Q)^1$?

- Go back to e+e-

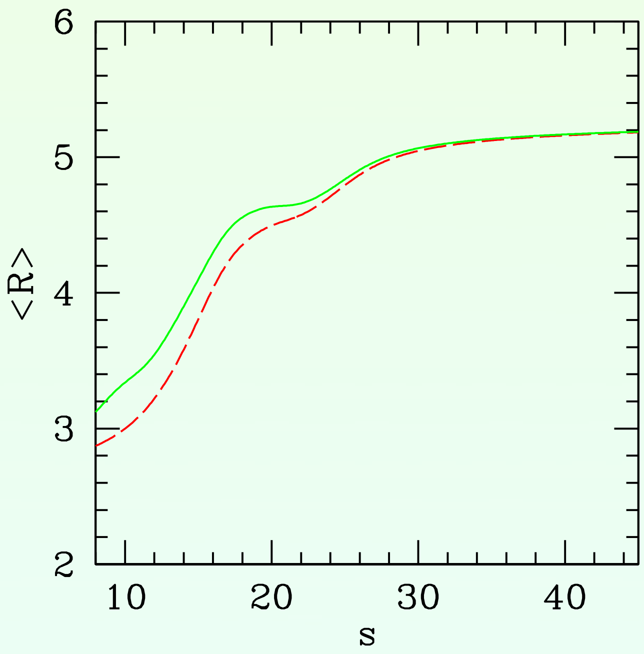
Effect of including narrow resonances in lorentzian smearing:

$$\bar{\sigma}(s) = \frac{\Delta}{\pi} \int_0^\infty ds' \frac{\sigma(s')}{(s'-s)^2 + \Delta^2}$$

red: PQW (exclude resonances)

green: include resonances

NOTE: very slow approach to duality,
effect of resonances significant in resonant region



- Lorentzian smearing

$$\frac{1}{((x-M_Q)^2+1)^n}$$

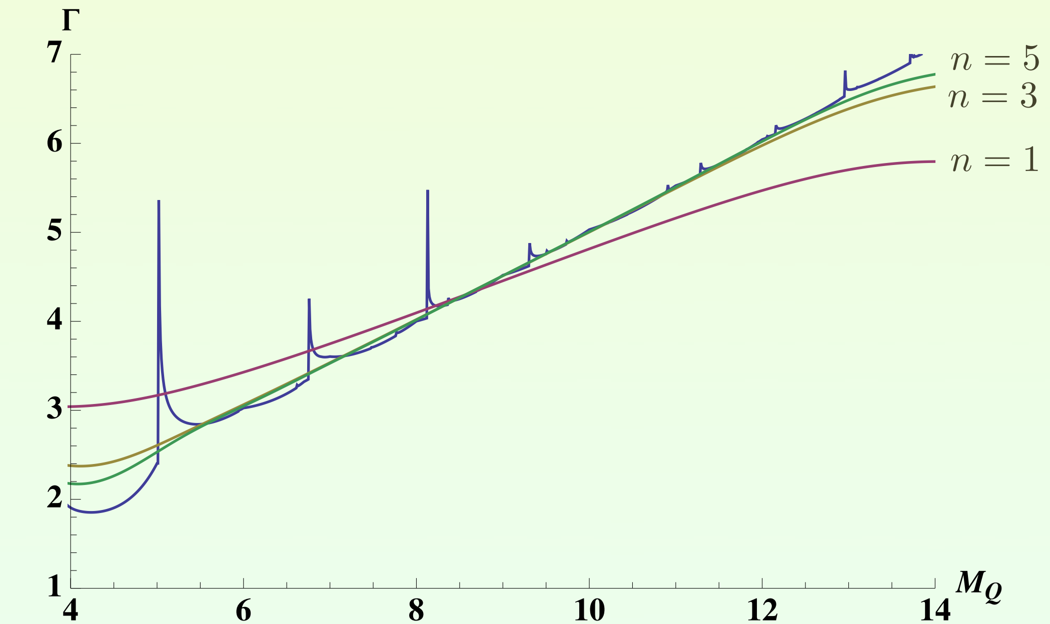
- Justified by OPE provided

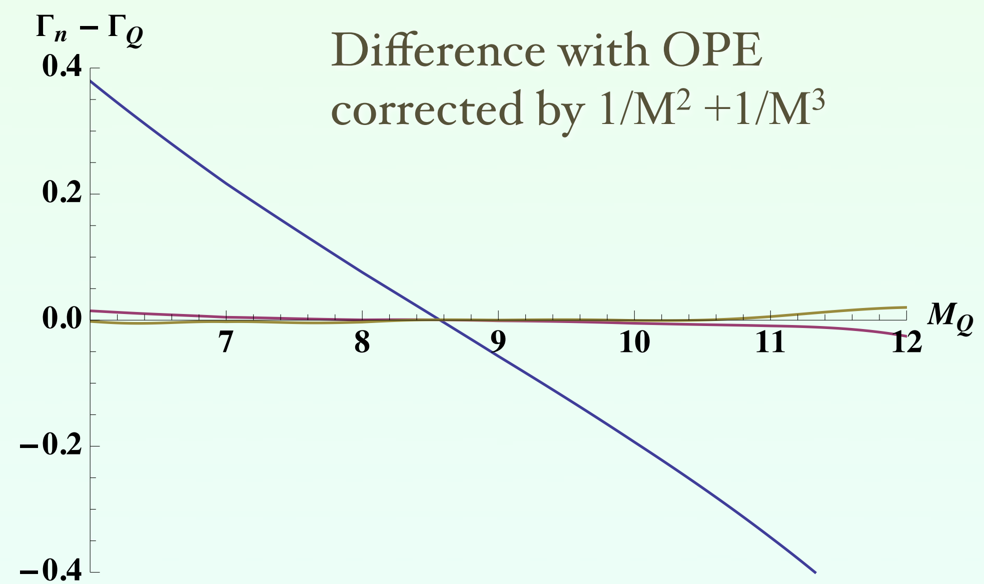
$$n \geq 2$$

- Corrections to OPE:

$$\text{order}\,\frac{1}{M_Q^2}$$

- I conclude:
  Cannot trust OPE for width
  unless asymptotically heavy quark

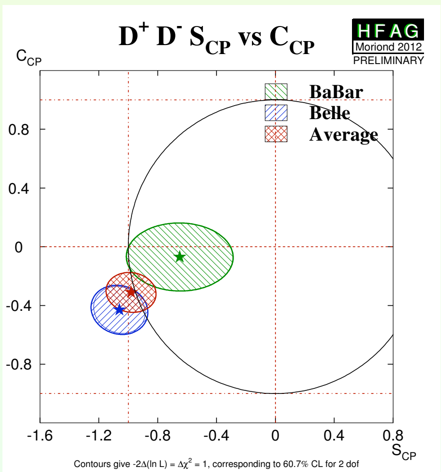


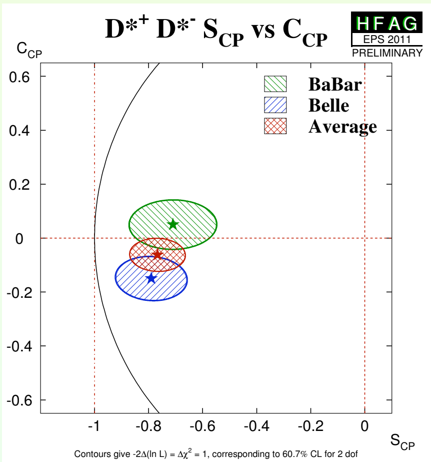


End Long Digression

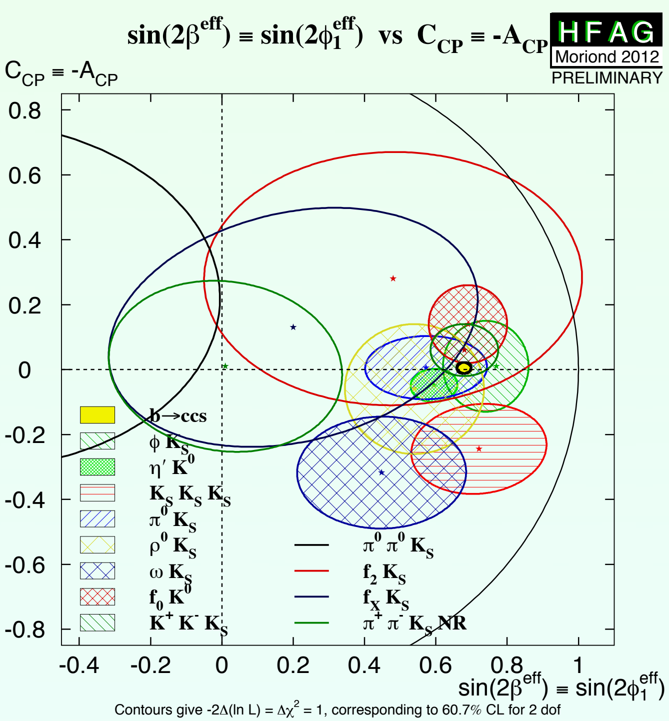
$b \to c\bar{c}d$ modes

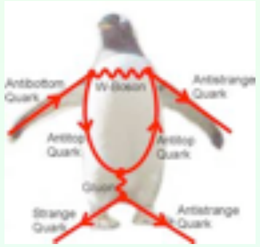
$B^0 \to D^+D^-$	$B^0 \to D^{*+}D^{*-}$	$B^0 \to D^{\pm}D^{*\mp}$
CP-eigenstate	mix of CP-odd/even	Not a CP-eigenstate
$\mathcal{S} = \sin 2\phi_1,\ \mathcal{A} = 0$	$\mathcal{S}$, $\mathcal{A}$ for each of	2 amplitudes × 2 modes
if negligible penguin	longitudinal / transverse	$\Rightarrow C, \mathcal{S}, \mathcal{A}, \Delta\mathcal{S}, \Delta\mathcal{A}$





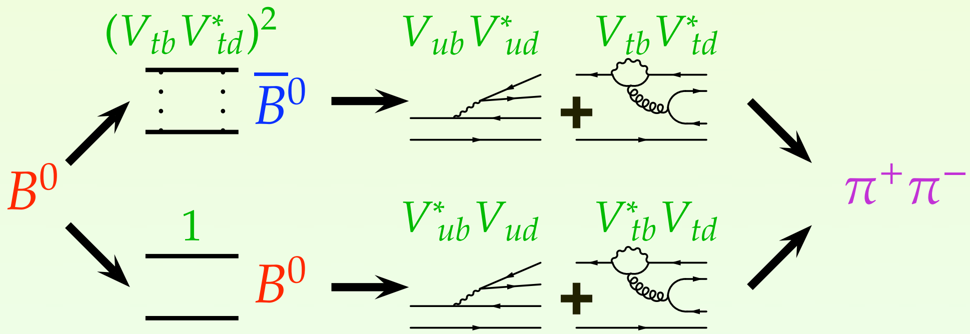
$b \to s$ penguin modes





- No sign of deviations from standard CKM
- Many of these new: expect improvement in next generation

α/φ_2 and Penguin Pollution

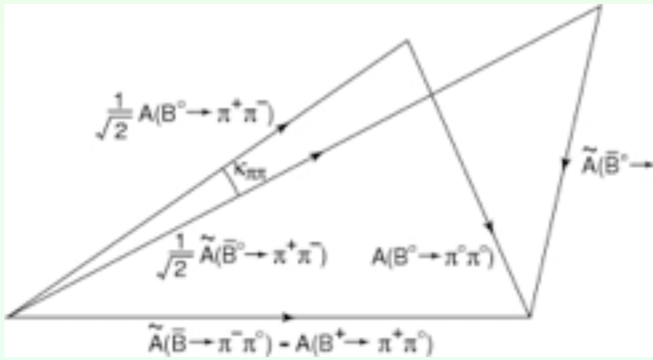


$$\Gamma(B^0) \propto e^{-t/\tau}\,(1+\mathcal{S}_{\pi\pi}\sin\Delta mt + \mathcal{A}_{\pi\pi}\cos\Delta mt)$$

$$\Gamma(\overline{B}^0) \propto e^{-t/\tau}\,(1-\mathcal{S}_{\pi\pi}\sin\Delta mt + \mathcal{A}_{\pi\pi}\cos\Delta mt)$$

$\mathcal{S}_{\pi\pi} = \sqrt{1-\mathcal{A}^2_{\pi\pi}}\sin 2\phi_2^{\rm eff}$, **where** $\phi_2^{\rm eff} = (\phi_2 + \kappa)$ **is not** ϕ_2 [BG Phys.Lett. B229 (1989) 280]

- Isospin analysis [Gronau-London PRL65,3381(1990)]
  - Relations with $B \to \pi^+\pi^0$ and $B^0 \to \pi^0\pi^0$ (same for $B \to \rho\rho$ after resolving polarization)
  - Isospin breaking effects are small

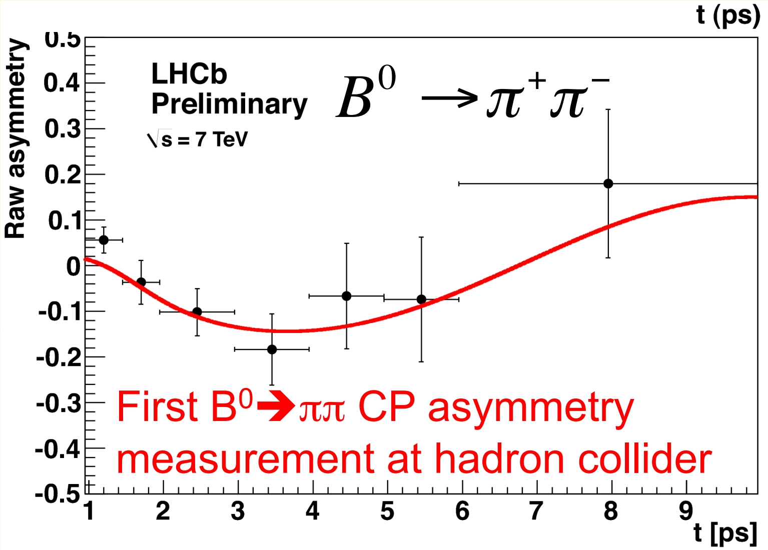


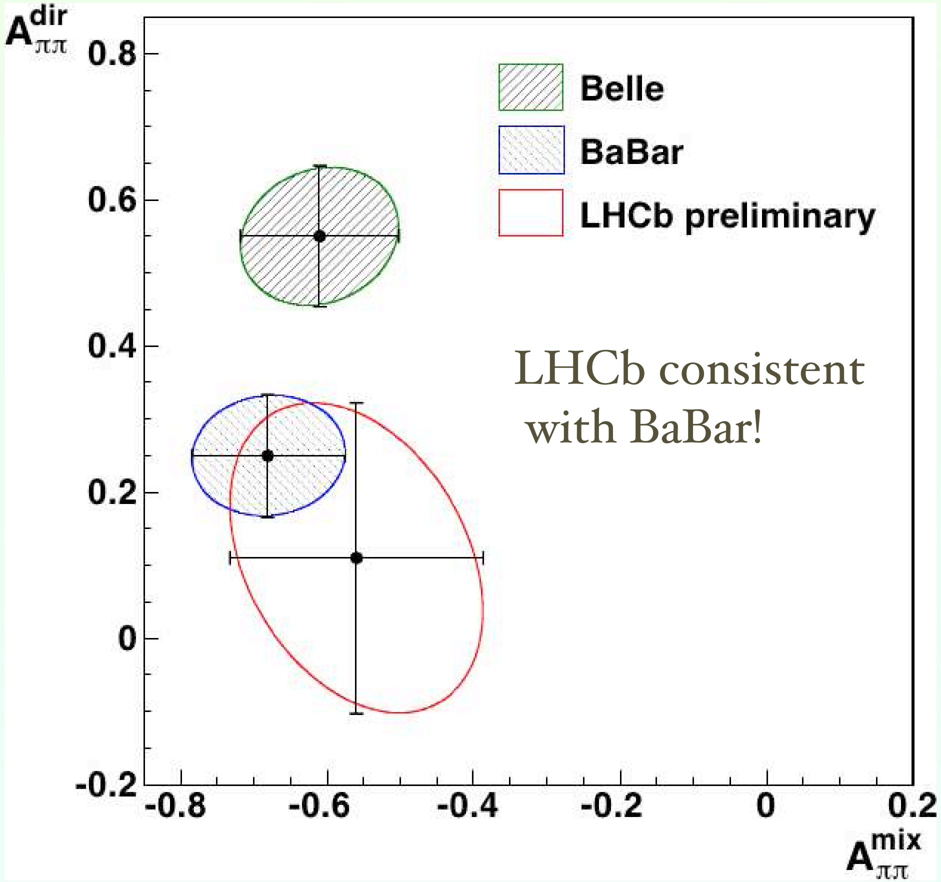
- Time-dependent Dalitz analysis [Snyder-Quinn PRD48,2139(1993)]
  - $B^0 \to \pi^+\pi^-\pi^0$ contains $\rho^+\pi^-$, $\rho^-\pi^+$, $\rho^0\pi^0$ and cross terms (interference)
  - α/φ_2 directly determined, $\rho^\pm\pi^0$ and $\rho^0\pi^\pm$ may improve further (future)

NEW form LHCb

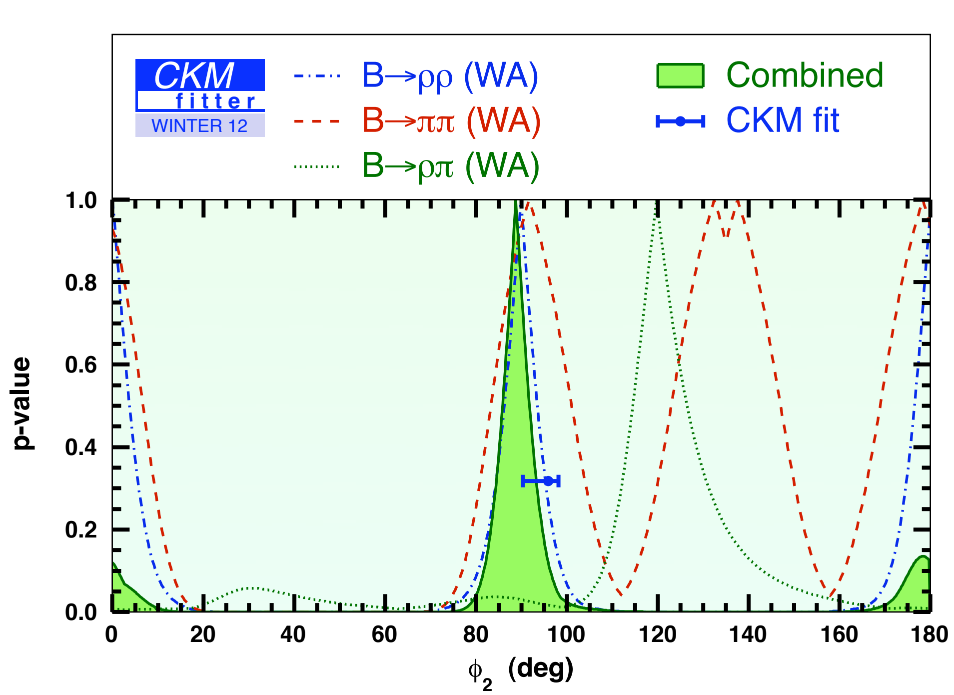
[Paul Soler ICHEP 2012]

$$S_{\pi\pi} = A_{\pi\pi}^{\text{mix}} = 0.56 \pm 0.17 \pm 0.03$$
$$\mathcal{A}_{\pi\pi} = A_{\pi\pi}^{\text{dir}} = 0.11 \pm 0.21 \pm 0.03$$





LHCb consistent with BaBar!



ϕ_2 / $\alpha = (88.7^{+4.6}_{-4.2})^\circ$

[CKMfitter Moriond2012]

Direct CPV

$D^0 \to K^+K^-$ and $\pi^+\pi^-$

[BG & Golden, Phys.Lett. B222 (1989) 501]

$$A \equiv \frac{\Gamma(D^+ \to \mathscr{P}\mathscr{P}) - \Gamma(D^- \to \bar{\mathscr{P}}\bar{\mathscr{P}})}{\Gamma(D^+ \to \mathscr{P}\mathscr{P}) + \Gamma(D^- \to \bar{\mathscr{P}}\bar{\mathscr{P}})} = \frac{2\,\mathrm{Im}\,(a^*b)\,\mathrm{Im}(\Sigma^*\Delta)}{|a|^2\,|\Sigma|^2 + |b|^2\,|\Delta|^2 + 2\,\mathrm{Re}(a^*b)\,\mathrm{Re}(\Sigma^*\Delta)}$$

where $\mathcal{A}(D \to \mathscr{P}\mathscr{P}) = a\Sigma + b\Delta$

$$\Sigma = \tfrac{1}{2}(V^*_{cs}V^{us} - V^*_{cd}V_{ud}), \quad \Delta = \tfrac{1}{2}(V^*_{cs}V_{us} + V^*_{cd}V_{ud})$$

$$|\Sigma| \sim \lambda \gg |\Delta| \sim \lambda^5$$

SU(3) analysis: five invariant amplitudes

$$\langle [8]^i_j | [\bar{6}]_{kl} | D_r \rangle = S\mathscr{T}^i_{jklr}, \quad \langle [8]^i_j | [15_M]^{kl}_m | D_r \rangle = E\mathscr{T}^{ikl}_{jmr}, \quad \langle [27]^{ij}_{kl} | [15_M]^{mn}_p | D_r \rangle = T\mathscr{T}^{ijmn}_{klpr},$$

$$\langle [8]^i_j | [3]^k | D_r \rangle = F\mathscr{T}^{ik}_{jr}, \quad \langle [1] | [3]^i | D_r \rangle = G\mathscr{T}^i_r,$$

Then

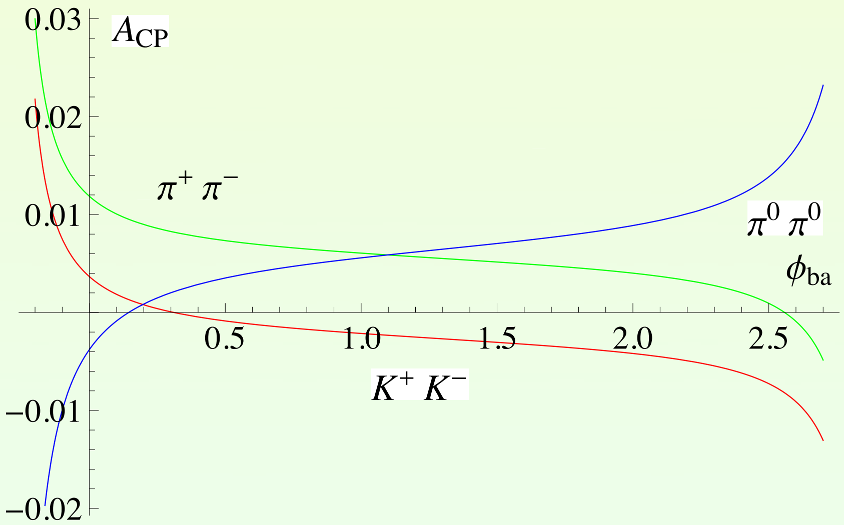
$$\mathcal{A}(D^0 \to K^+K^-) = (2T + E - S)\Sigma + \tfrac{1}{2}(3T + 2G + F - E)\Delta,$$

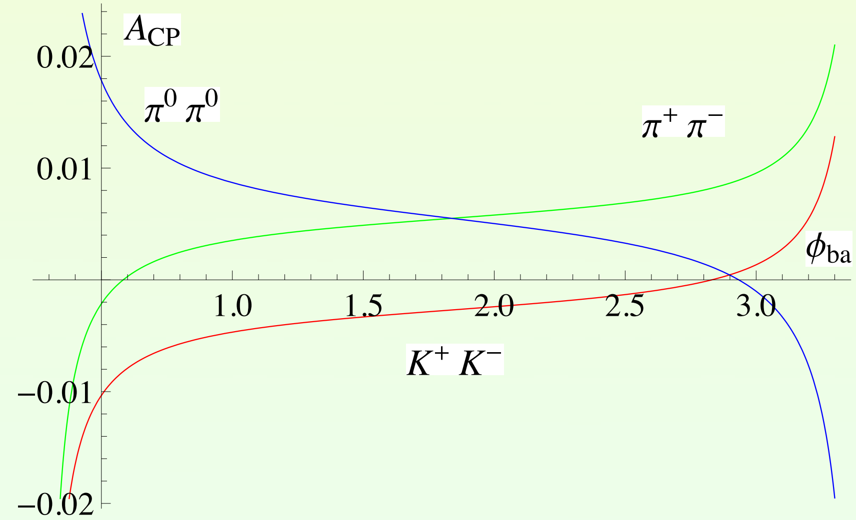
$$\mathcal{A}(D^0 \to \pi^+\pi^-) = -(2T + E - S)\Sigma + \tfrac{1}{2}(3T + 2G + F - E)\Delta.$$

But $\Gamma(D^0 \to K^+K^-)/\Gamma(D^0 \to \pi^+\pi^-) \approx 3$ requires both terms of similar size (enhanced G, F)

$\Rightarrow$ Expect sizable direct CPV in these decays! (predicted in 1989)

Of course, expect large SU(3) breaking effects.





[Pirtskhalava & Uttayarat, Phys.Lett. B712 (2012) 81-86
Bhattacharya, Gronau & Rosner, PRD85 (2012) 054014
Cheng & Chiang, PRD85 (2012) 034036
Brod,Grossman, Kagan & Zupan, JHEP 1210 (2012) 161]

This still requires an enhancement of *F*, *G*, but only of order 10

Or perhaps new physics??

[Rozanov & Vysotsky, arXiv:1111.6949
Altmannshofer, Primulando, Yu & Yu, JHEP 1204 (2012) 049
Cheng, Geng & Wang, PRD85 (2012) 077702
Feldmann, Nandi & Soni, JHEP 1206 (2012) 007
......]

$\Delta A_{cp} = A_{cp}(D^0 \to K^+K^-) - A_{cp}(D^0 \to \pi^+\pi^-)$ [%]

LHCb	$-0.82 \pm 0.21 \pm 0.11$	PRL2012
CDF	$-0.62 \pm 0.21 \pm 0.10$	charm2012
BaBar	(see below)	PRD2011
Belle	$-0.87 \pm 0.41 \pm 0.06$	ICHEP2012
WA	-0.678 ± 0.147 (>4σ)	HFAG2012

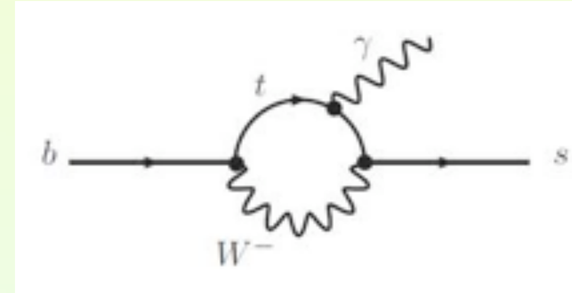
Need to search for A_{CP} in other modes

Individual A_{CP} are not significant

	$A_{cp}(D^0 \to K^+K^-)$ [%]	$A_{cp}(D^0 \to \pi^+\pi^-)$ [%]
CDF	$-0.24 \pm 0.22 \pm 0.09$	$+0.22 \pm 0.24 \pm 0.11$
BaBar	$0.00 \pm 0.34 \pm 0.13$	$-0.24 \pm 0.52 \pm 0.22$
Belle	$-0.32 \pm 0.21 \pm 0.09$	$+0.55 \pm 0.36 \pm 0.09$

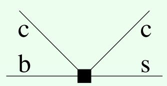
Rare decays

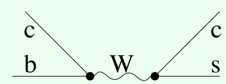
$B \to K^* \gamma$

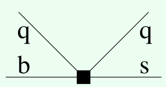


- Sensitive to NP (no tree level SM, new particles in 1-loop)
- 2HDM type II (SUSY-like) always larger than SM
- Effective theorty approach to SM calcualtion:
  - Matching (NNLO)
  - Running (NNLO)
  - Matrix elements (almost complete NNLO)

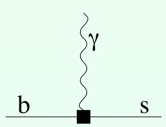
$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{QCD}\times\text{QED}}(u,d,s,c,b) + \frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{8} C_i(\mu)\, Q_i$$

$Q_{1,2} =$ 

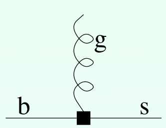
$= (\bar{s}\Gamma_i c)(\bar{c}\Gamma_i' b),$ **from** 

$Q_{3,4,5,6} =$ 

$= (\bar{s}\Gamma_i b)\Sigma_q(\bar{q}\Gamma_i' q),$

$Q_7 =$ 

$= \frac{e m_b}{16\pi^2} \bar{s}_L \sigma^{\mu\nu} b_R F_{\mu\nu},$

$Q_8 =$ 

$= \frac{g m_b}{16\pi^2} \bar{s}_L \sigma^{\mu\nu} T^a b_R G^a_{\mu\nu},$

$|C_i(m_b)| \sim 1$

$|C_i(m_b)| < 0.07$

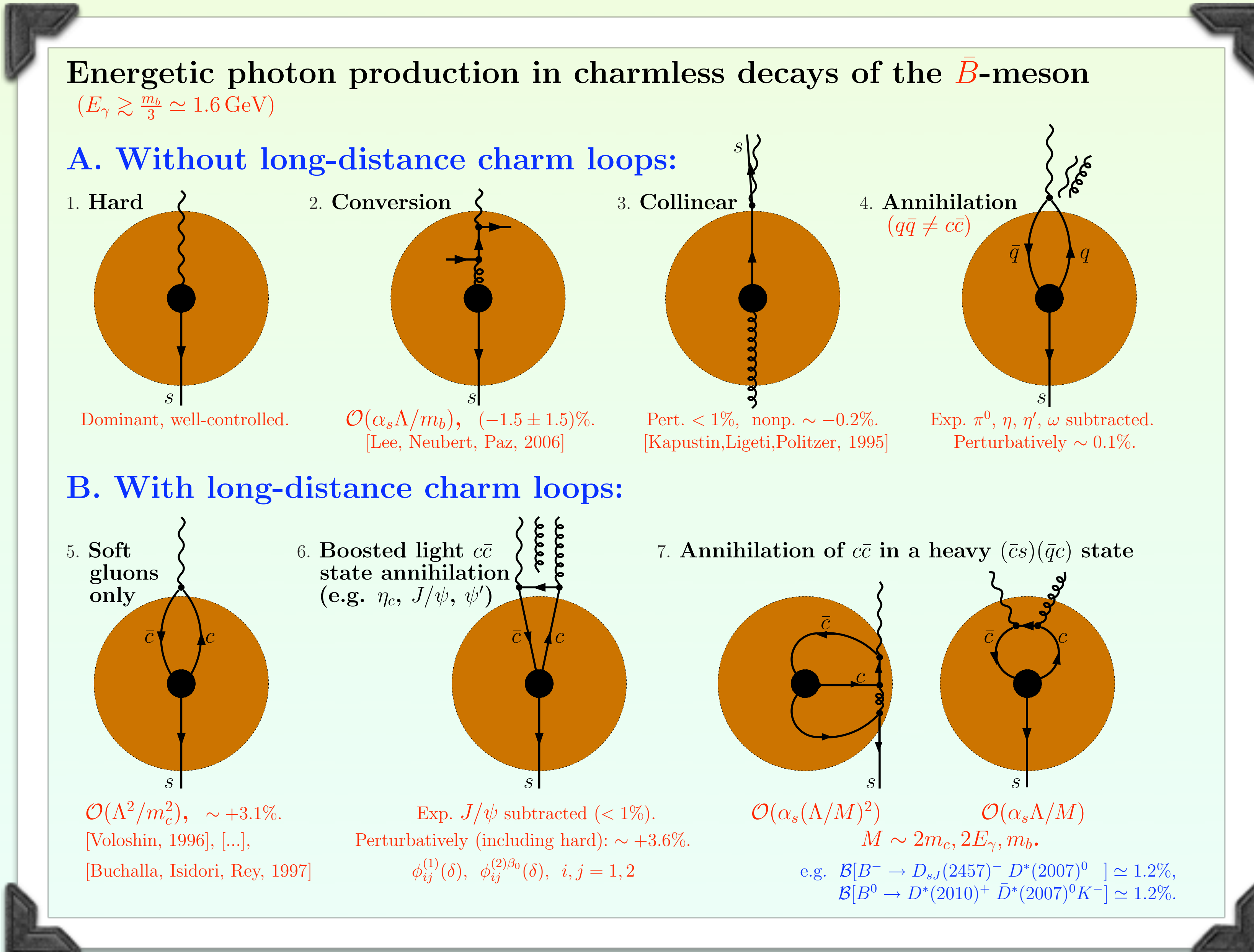
$C_7(m_b) \simeq -0.3$

$C_8(m_b) \simeq -0.15$

Known to NNLO

[Ali, ICHEP 2004]

Relative size of various long distance contributions (“matrix elements”) have been studied

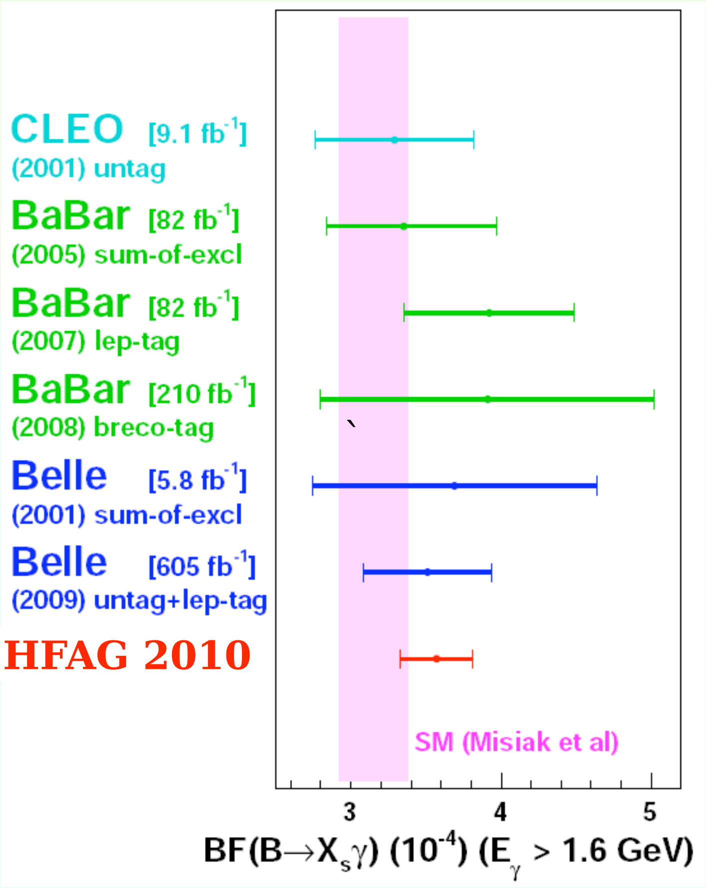


[lifted from Misiak]

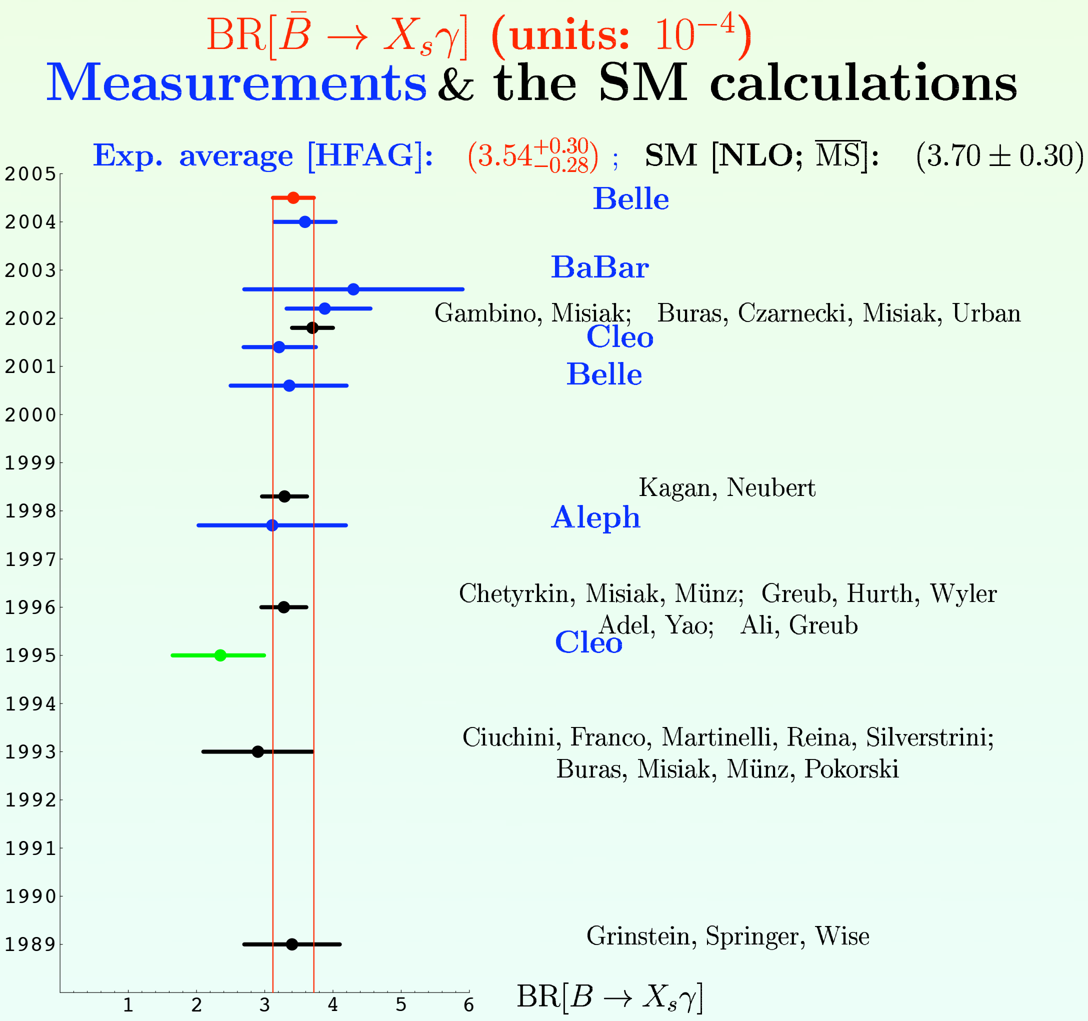
$$\text{HFAG 2010}: \ B(B\to X_s\gamma) = (3.55 \pm 0.26)\times 10^{-4} \ \ (\text{for } E_\gamma > 1.6 \text{ GeV})$$

vs

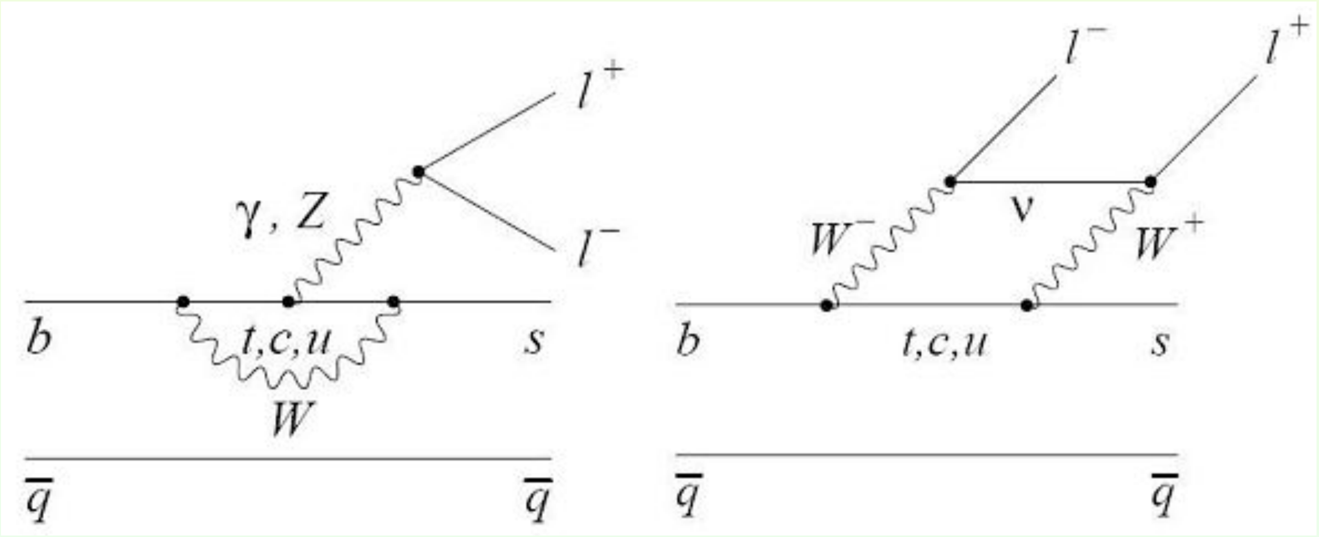
$$\text{SM}: \ B(B\to X_s\gamma) = (3.15 \pm 0.23)\times 10^{-4} \ \ (\text{for } E_\gamma > 1.6 \text{ GeV})$$



A Brief History of Time



$B \to K^{(*)}l^+l^-$



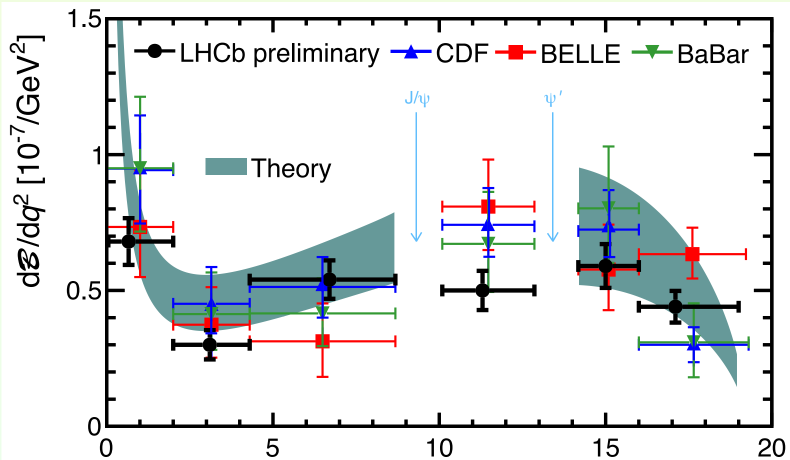
- Sensitive to NP (no tree level SM, new particles in 1-loop)
- Many variables can be studied, e.g., forward-backward asymmetry A_{FB} or Isospin asymmetry:

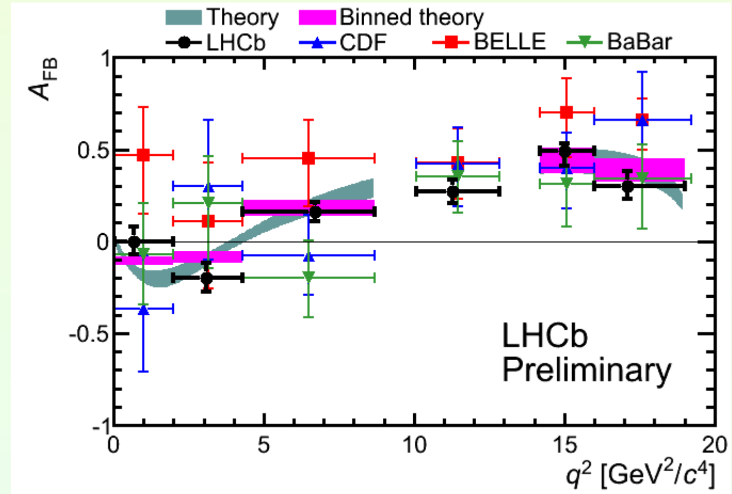
$$A_I = \frac{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) - \frac{\tau_0}{\tau_+}\mathcal{B}(B^\pm \to K^{(*)\pm}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) + \frac{\tau_0}{\tau_+}\mathcal{B}(B^\pm \to K^{(*)\pm}\mu^+\mu^-)}$$

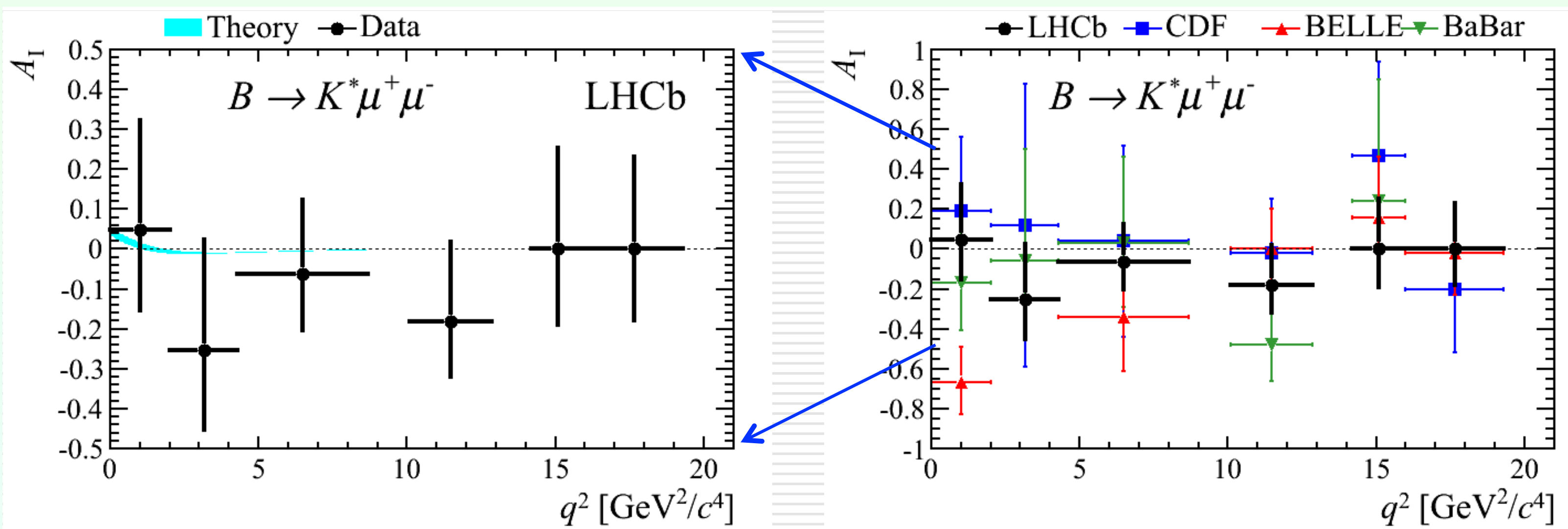
- Charmonium resonance region must be excluded ($B \to K^{(*)}\psi \to K^{(*)}l^+l^-$)
  - Small $q^2 = (p_+ + p_-)^2$, large recoil energy for $K^{(*)}$, use SCET
  - Large q^2, use HQET
  - SM: fairly clean prediction of location of zero in A_{FB}, negligible A_I

$B \to K^* l^+ l^-$

[Gallas, ICHEP 2012]







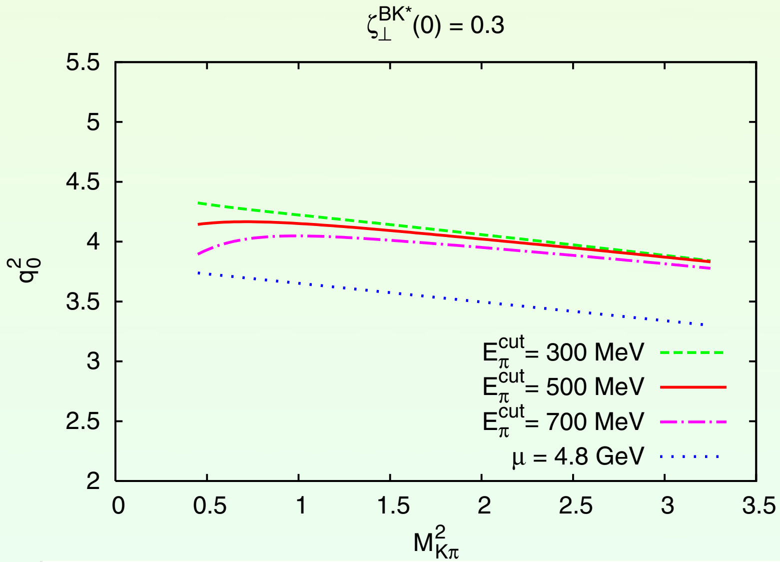
No hint of NP here!

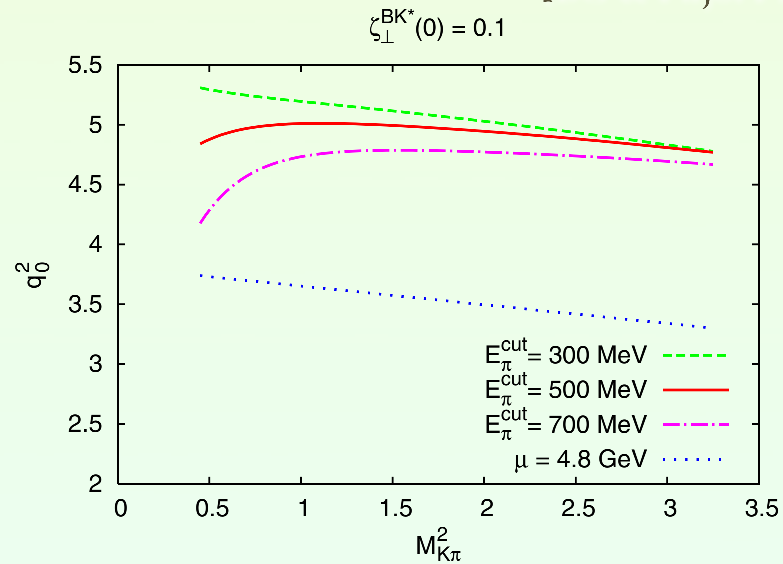
A_{FB} zero

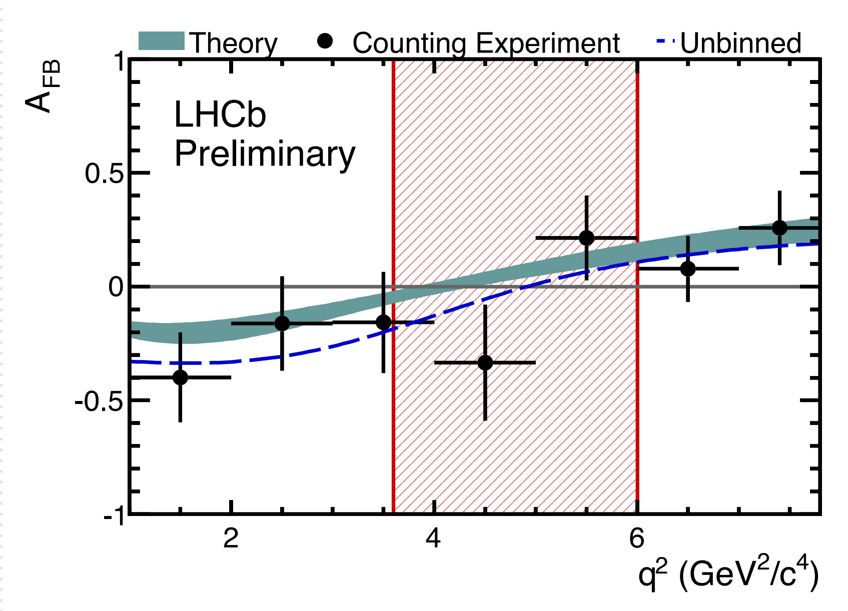
[Burdman]

Theory, including non-resonant $K\pi$, to order Λ/m_b, with maximum π energy cut

[BG & Pirjol PDD 73, 094027 (2006)]

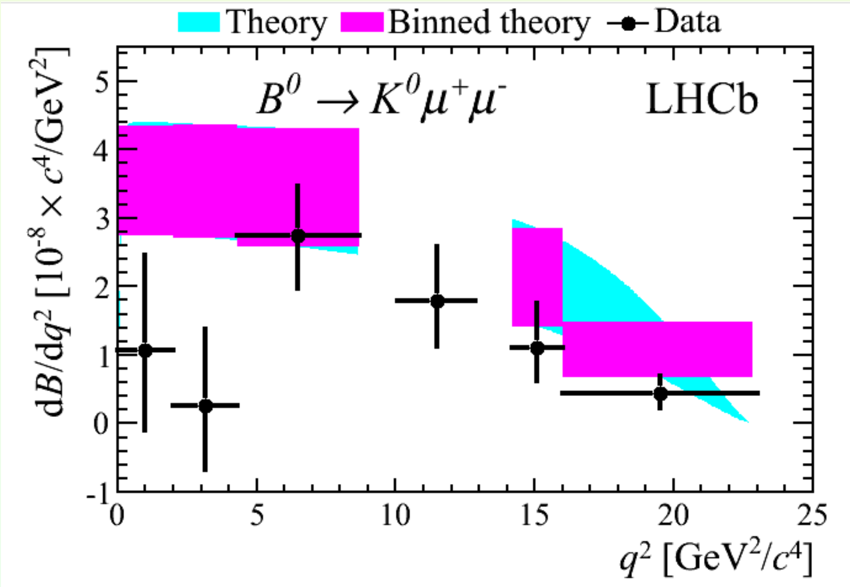






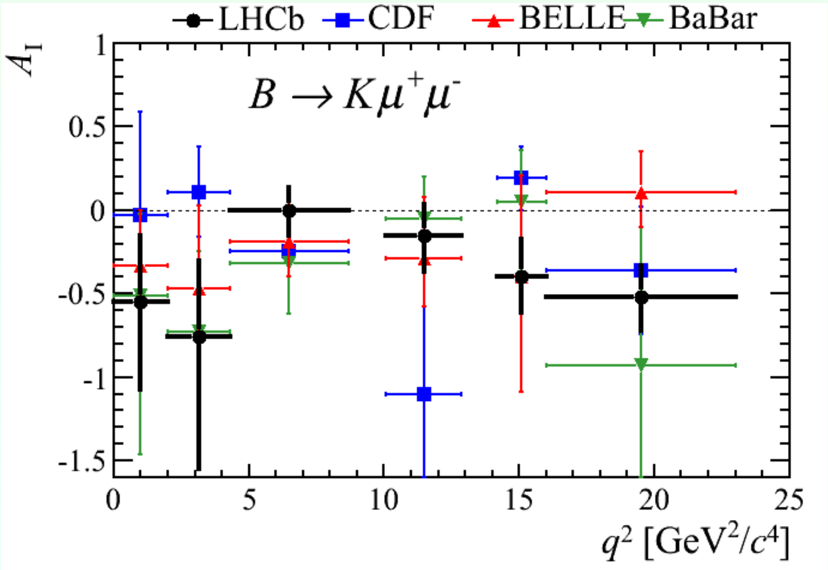
The world's first measurement of q^2_0, at $q^2_0 = 4.9^{+1.1}_{-1.3}$ GeV^2/c^4 [Preliminary]

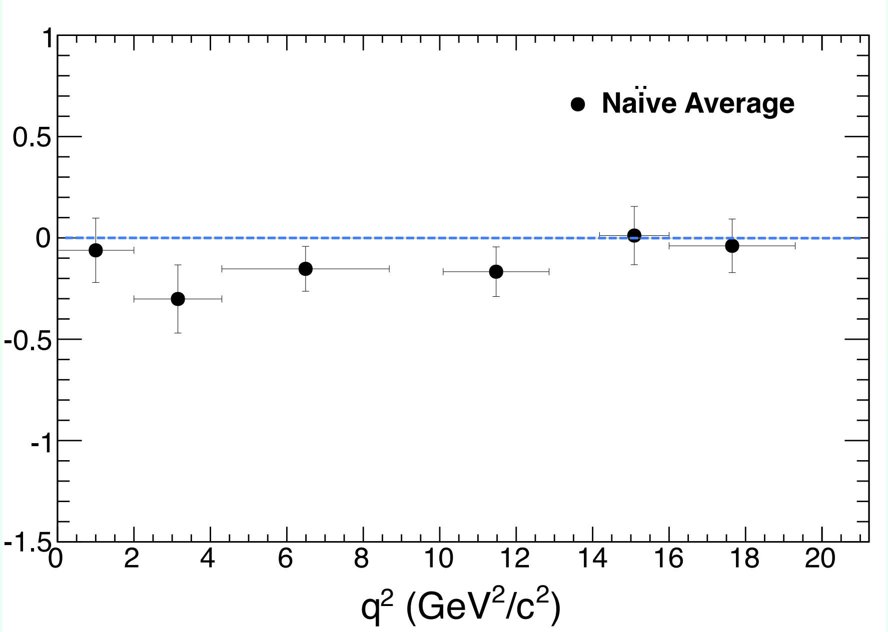
$B \to K l^+ l^-$



Discrepant with SM predictions:

- Low rate at low q^2
- A_I negative throughout
  - LHCb alone: 4.2σ from zero
  - Why in K, but not in K^*?
  - NP models?

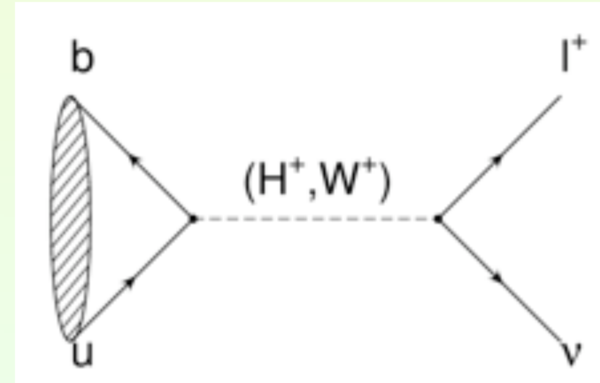




τ

Is there still a problem with $B^- \to \tau^- \nu$?

- $B^- \to \tau^- \nu$ in SM is tree level



- Clean SM prediction, lattice gives f_B

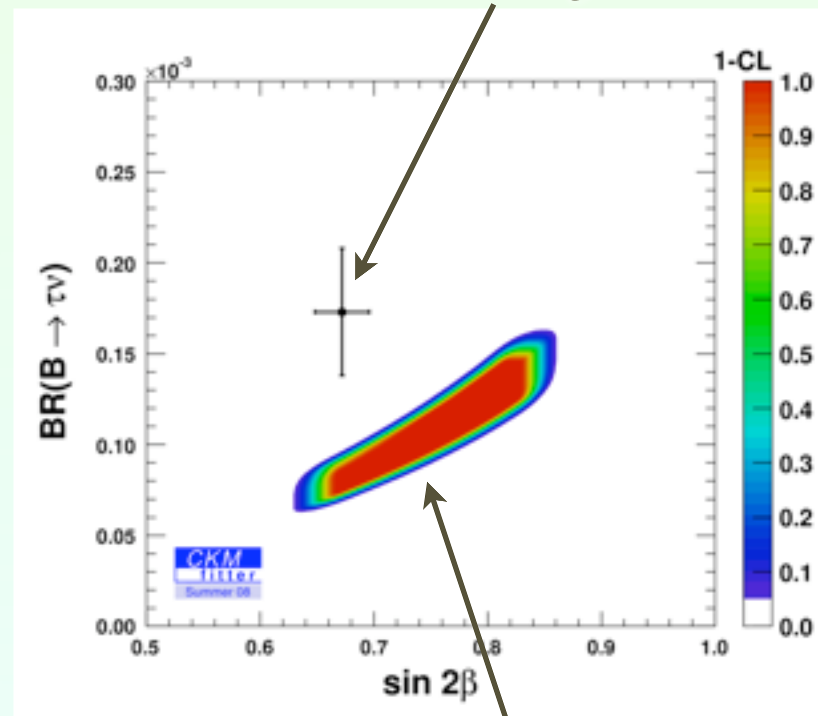
$$\Gamma(B \to \tau\nu) = \frac{G_F^2 m_B}{8\pi} m_\tau^2 \left(1 - m_\tau^2/m_B^2\right)^2 f_B^2 |V_{ub}|^2$$

- Modified for τ, less for e, μ, by charged higgs in 2HDM

- 2HDM modifies box diagram too: cannot use SM extraction of $\sin(2\beta)$ from $B^0 \to \psi K_S$

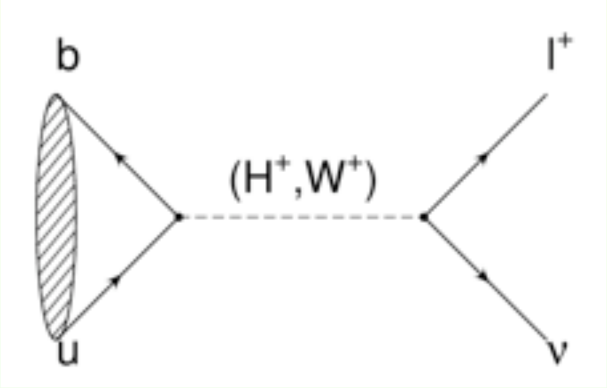
- But NEW Belle result [arXiv:1208.4678]

world avg. summer 2008



Fit excluding $B^- \to \tau^- \nu$ & $B^0 \to \psi K_S$

Is there still a problem with $B^{-} \to \tau^{-} \nu$?



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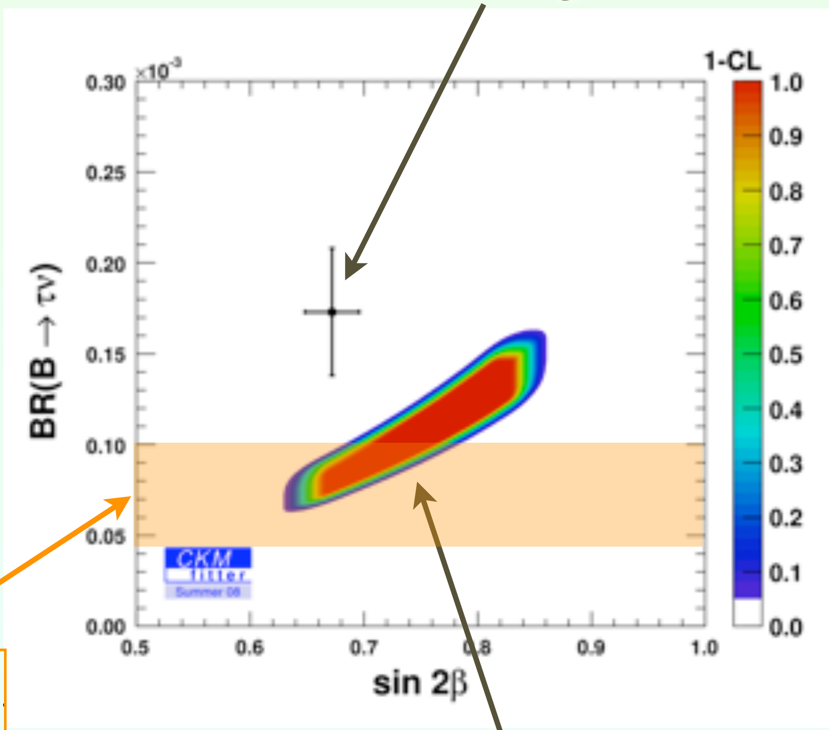
- But NEW Belle result [arXiv:1208.4678]

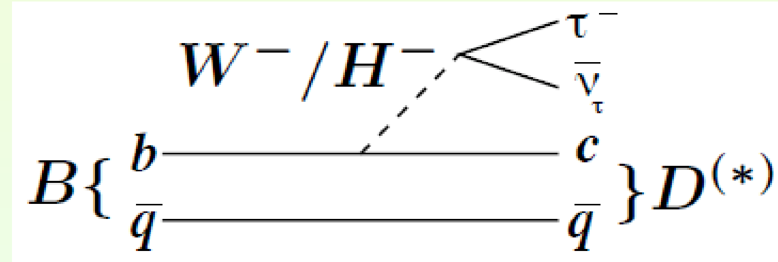
$$\boxed{\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau) = [0.72^{+0.27}_{-0.25}(\text{stat}) \pm 0.11(\text{syst})] \times 10^{-4}}$$

world avg. summer 2008



Fit excluding $B^{-} \to \tau^{-} \nu$ & $B^0 \to \psi K_S$

$B^- \to D\tau^- \nu$ and $B^- \to D^* \tau^- \nu$



- Like $B^- \to \tau^- \nu$, tree level
- Like $B^- \to \tau^- \nu$, enhanced relative to SM
- Sensitive to more form factors, e.g.,

$$\langle D(p_D)|\bar{c}\gamma^\mu b|\bar{B}(p_B)\rangle = F_V(q^2)\left[p_B^\mu + p_D^\mu - m_B^2 \frac{1-r^2}{q^2} q^\mu\right] + F_S(q^2)\, m_B^2 \frac{1-r^2}{q^2} q^\mu ,$$

- 2HDM: tree level

$$\langle D(p_D)|\bar{c}b|\bar{B}(p_B)\rangle = \frac{m_B^2\,(1-r^2)}{\overline{m}_b - \overline{m}_c} F_S(q^2) \qquad r = m_D/m_B$$

- Define R

$$R(D) = \frac{Br(\bar{B} \to D\tau\nu)}{Br(\bar{B} \to D\ell\nu)} \qquad R(D^*) = \frac{Br(\bar{B} \to D^*\tau\nu)}{Br(\bar{B} \to D^*\ell\nu)}$$

	SM Theory	BaBar value	Diff.
R(D)	0.297±0.017	0.440±0.058±0.042	+2.0σ
R(D*)	0.252±0.003	0.332±0.024±0.018	+2.7σ

3.4σ deviation (above) SM in aggregate

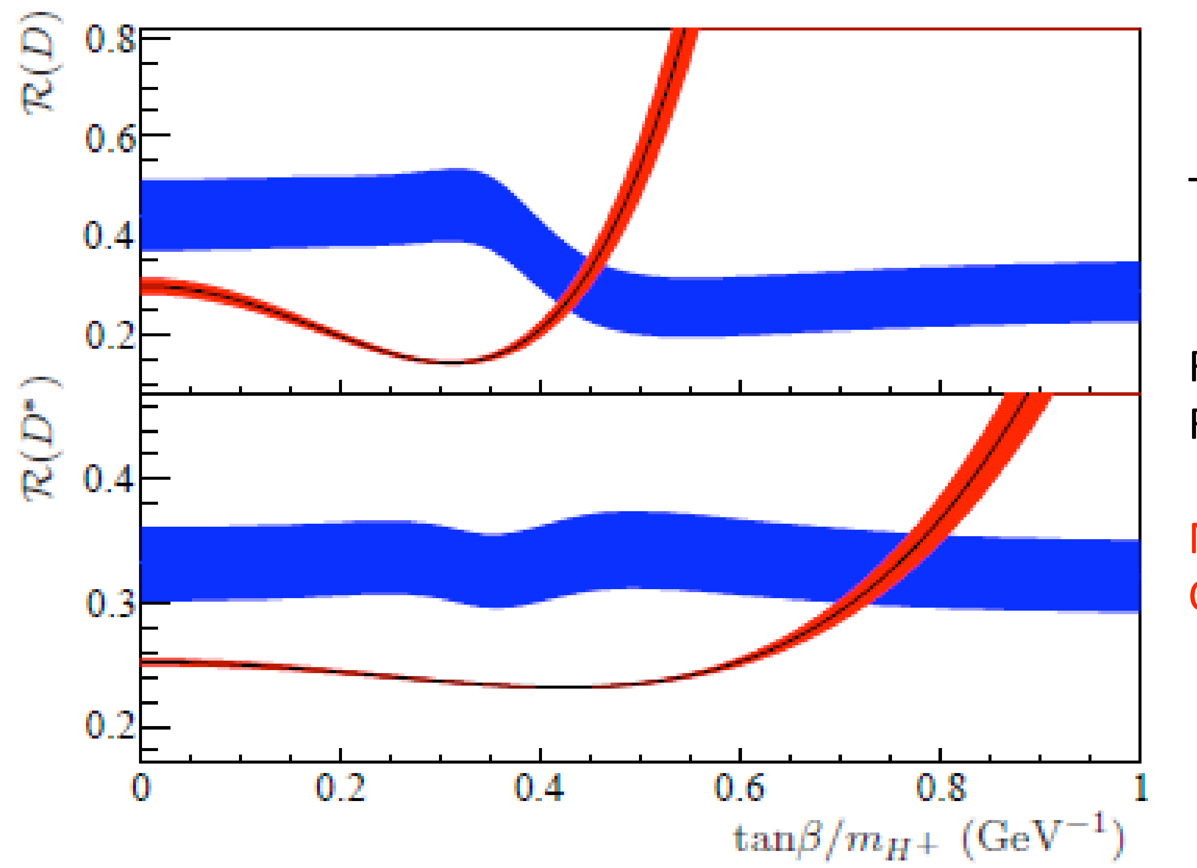
Combination of measurements also inconsistent with 2HDM

SM(D*)

$$\frac{d\Gamma_\tau}{dq^2} = \frac{G_F^2 |V_{cb}|^2 |\mathbf{p}| q^2}{96\pi^3 m_B^2} \left(1 - \frac{m_\tau^2}{q^2}\right)^2 \left[(|H_{++}|^2 + |H_{--}|^2 + |H_{00}|^2) \left(1 + \frac{m_\tau^2}{2q^2}\right) + \frac{3}{2}\frac{m_\tau^2}{q^2} |H_{0t}|^2 \right]$$

$$\boxed{H_t^{2\mathrm{HDM}} = H_t^{\mathrm{SM}} \times \left(1 \mp \frac{\tan^2\beta}{m_{H\pm}^2} \frac{q^2}{1 \mp m_c/m_b}\right)}$$

- for Dτν
+for D*τν

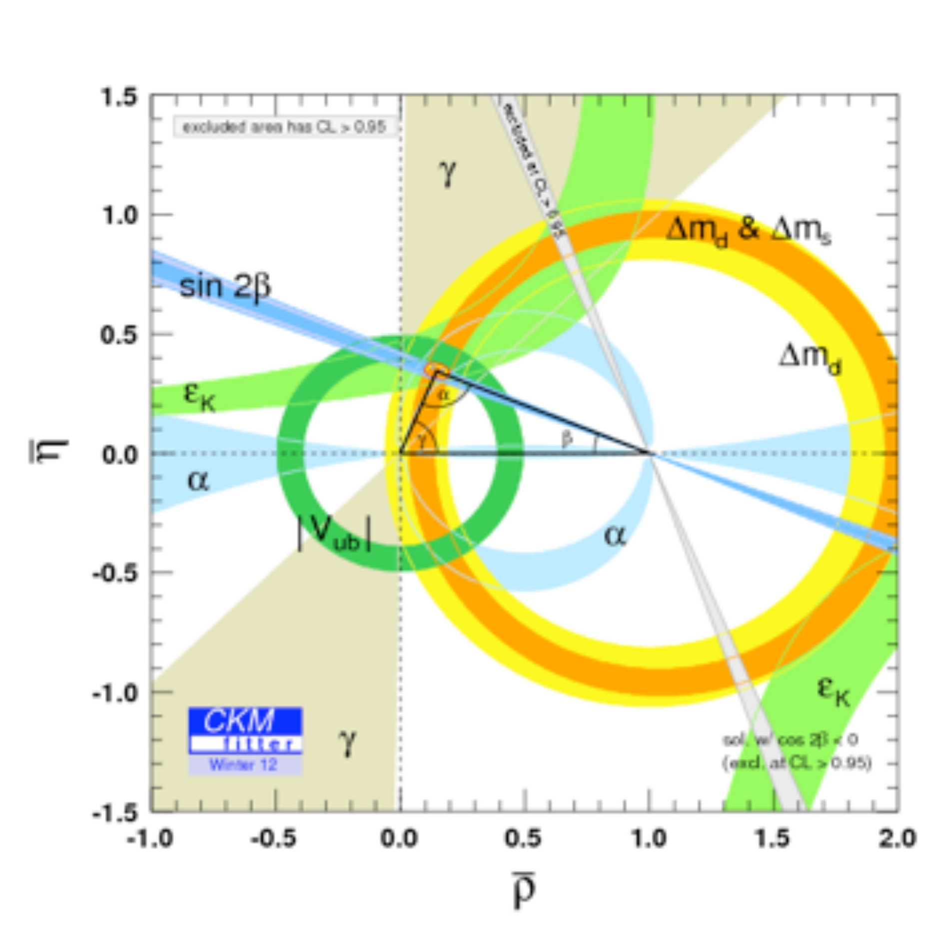


Taking into account the effect of $\tan\beta/m_H$ on efficiency

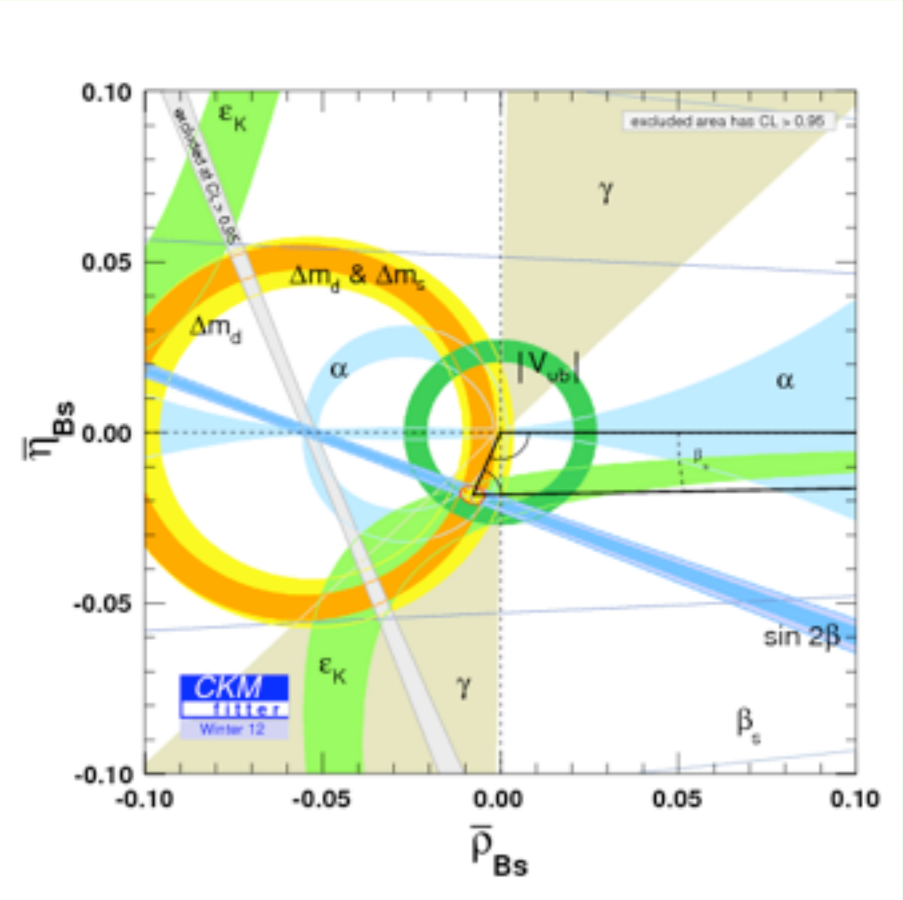
R(D) → $\tan\beta/m_H = 0.44 \pm 0.02$
R(D*) → $\tan\beta/m_H = 0.75 \pm 0.04$

Mutually exclusive with CL >99.8%

NP?



excluded area has CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
|V_ub|
CKM fitter
Winter 12
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
excluded at CL > 0.95
η̄
ρ̄



excluded area has CL > 0.95
ε_K
γ
Δm_d & Δm_s
Δm_d
α
|V_ub|
sin 2β
β_s
CKM fitter
Winter 12
excluded at CL > 0.95
η̄_Bs
ρ̄_Bs

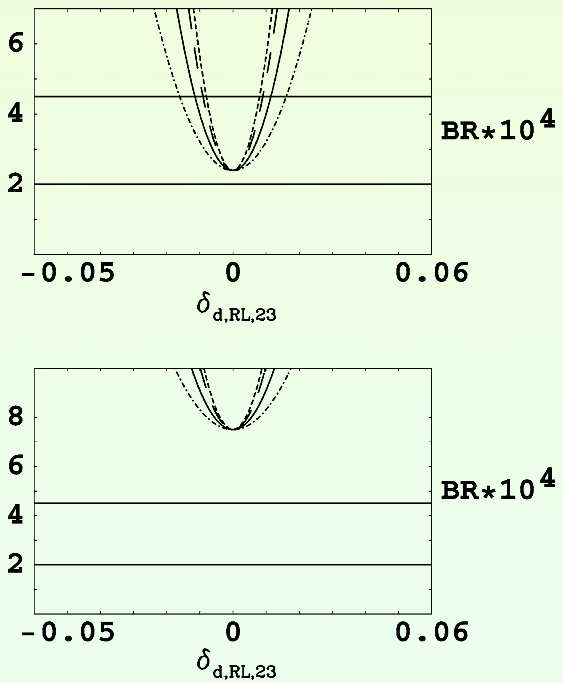
Don’t forget: General MSSM lives in a straightjacket because of flavor

General MSSM

Ruled out unless squarks almost degenerate
Assume small

$$\delta = \frac{\Delta m^2}{\bar{m}^2}$$

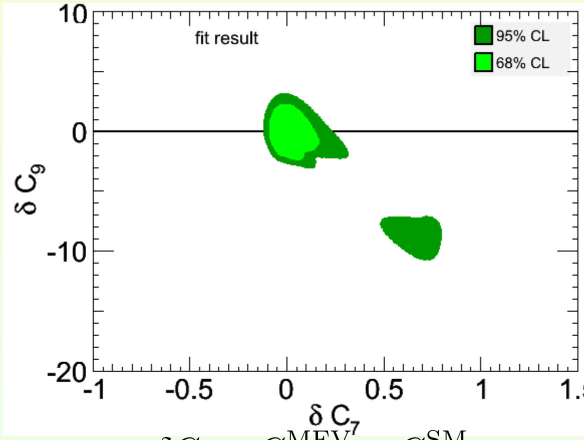
and bound



Besmer et al, NPB609:359,2001

Must introduce (ad-hoc) CMSSM, or NUHM1, or better justified gauge mediation variants

(NUMH1=”non-universal higgs masses”-1 version of MSSM)



- What remains as acceptable NP:
  - Decoupling: Make all new particles ever heavier
  - Flavor Blind: Make all flavor couplings small (MFV)

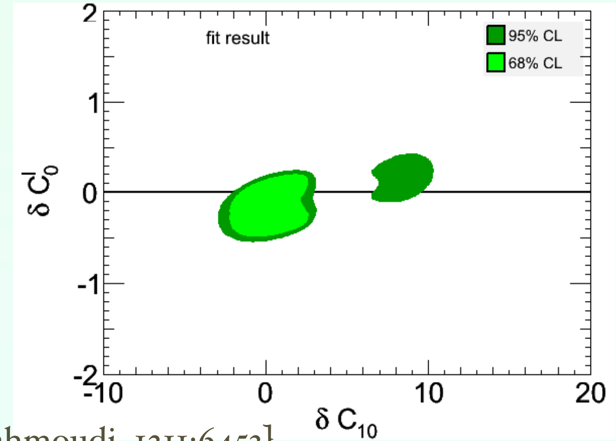
$$\delta C_i = C_i^{\mathrm{MFV}} - C_i^{\mathrm{SM}}$$

- Fabulous for hiding non-existent particles and interactions!

$$\mathcal{H}_{\mathrm{eff}}^{b\to s} = -\frac{4G_F}{\sqrt{2}}\sum_{i=3}^{10}[(V_{us}^* V_{ub} + V_{cs}^* V_{cb})C_i^c + V_{ts}^* V_{tb} C_i^t]P_i + V_{ts}^* V_{tb} C_0^\ell P_0^\ell \; + \; \mathrm{h.c.}$$

- I propose we should be doing something else:
  - We do have deviations form SM
  - Should focus on models that address anomalies
  - Tricky: which anomalies do you focus on?
    - >3σ
    - At least two experiments
    - (No guaranteed persistence, witness B $\to \tau\nu$)
  - Example: top-quark FB asymmetry at Tevatron

$$\begin{aligned}
P_7 &= \tfrac{e}{16\pi^2} m_b (\bar{s}_L \sigma^{\mu\nu} b_R) F_{\mu\nu} \; , \\
P_8 &= \tfrac{g_s}{16\pi^2} m_b (\bar{s}_L \sigma^{\mu\nu} T^a b_R) G_{\mu\nu}^a \; , \\
P_9 &= \tfrac{e^2}{16\pi^2} (\bar{s}_L \gamma_\mu b_L) \textstyle\sum_\ell (\bar{\ell}\gamma^\mu \ell) \; , \\
P_{10} &= \tfrac{e^2}{16\pi^2} (\bar{s}_L \gamma_\mu b_L) \textstyle\sum_\ell (\bar{\ell}\gamma^\mu \gamma_5 \ell) \; , \\
P_0^\ell &= \tfrac{e^2}{16\pi^2} (\bar{s}_L b_R)(\bar{\ell}_R \ell_L) \; .
\end{aligned}$$



[Hurth & Mahmoudi, 1211:6453]

SM Theory ($B_s \to \mu^+\mu^-$)

Reliably compute CP-averaged decay rates in the flavor eigenstate basis

$$\langle\Gamma(B_s(t)\to f)\rangle\big|_{t=0} = \Gamma(B_s^0 \to f) + \Gamma(\bar{B}_s^0 \to f)$$

$$\mathrm{Br}(B_s) = (3.23 \pm 0.27)\times 10^{-9}$$

$$\mathrm{Br}(B_d) = (1.07 \pm 0.27)\times 10^{-10}$$

[Buras et al, Eur.Phys.J. C72 (2012) 2172]

Digression

NEW: De Bruyn et al: This is not what is measured!

[De Bruyn et al, PRD86 (2012) 014027]

Cannot neglect life-time difference:

$$y_s \equiv \frac{\Delta\Gamma_s}{2\,\Gamma_s} \equiv \frac{\Gamma_{\mathrm{L}}^{(s)} - \Gamma_{\mathrm{H}}^{(s)}}{2\,\Gamma_s} = 0.088 \pm 0.014$$

Decay rate is sum of two different exponentials

$$\langle\Gamma(B_s(t)\to f)\rangle \equiv \Gamma(B_s^0(t)\to f) + \Gamma(\bar{B}_s^0(t)\to f) = R_{\mathrm{H}}^f e^{-\Gamma_{\mathrm{H}}^{(s)}t} + R_{\mathrm{L}}^f e^{-\Gamma_{\mathrm{L}}^{(s)}t},$$

Experiment measures total number produced:

$$\mathrm{BR}\,(B_s \to f)_{\mathrm{exp}} \equiv \frac{1}{2}\int_0^\infty \langle\Gamma(B_s(t)\to f)\rangle\,dt$$

where

They obtain:

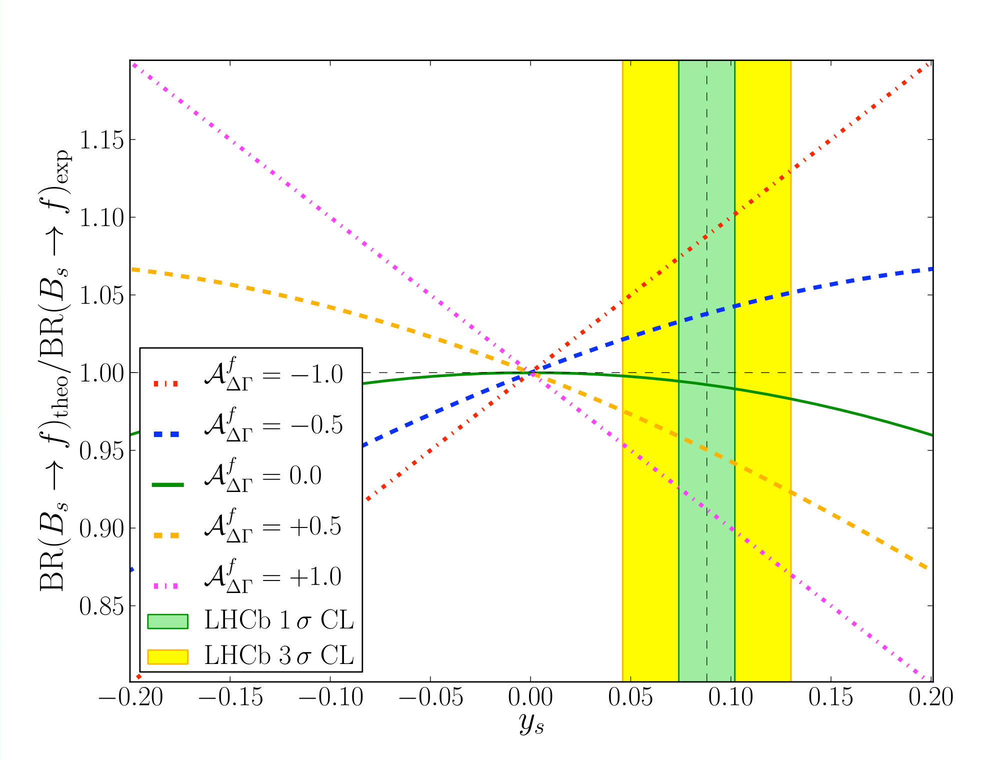
$$\boxed{\mathrm{BR}\,(B_s \to f)_{\mathrm{theo}} = \left[\frac{1-y_s^2}{1+\mathcal{A}_{\Delta\Gamma}^f\, y_s}\right]\mathrm{BR}\,(B_s \to f)_{\mathrm{exp}}}$$

$$\mathcal{A}_{\Delta\Gamma}^f \equiv \frac{R_{\mathrm{H}}^f - R_{\mathrm{L}}^f}{R_{\mathrm{H}}^f + R_{\mathrm{L}}^f}$$

This applies to any final state f (not just $\mu^+\mu^-$)

$B_s \to f$	$\text{BR}(B_s \to f)_{\text{exp}}$ (measured)	$\mathcal{A}^f_{\Delta\Gamma}(\text{SM})$	$\text{BR}(B_s \to f)_{\text{theo}}/\text{BR}(B_s \to f)_{\text{exp}}$ From Eq. (8)	From Eq. (10)
$J/\psi f_0(980)$	$(1.29^{+0.40}_{-0.28}) \times 10^{-4}$ [18]	0.9984 ± 0.0021 [14]	0.912 ± 0.014	0.890 ± 0.082 [6]
$J/\psi K_S$	$(3.5 \pm 0.8) \times 10^{-5}$ [7]	0.84 ± 0.17 [15]	0.924 ± 0.018	N/A
$D_s^- \pi^+$	$(3.01 \pm 0.34) \times 10^{-3}$ [9]	0 (exact)	0.992 ± 0.003	N/A
K^+K^-	$(3.5 \pm 0.7) \times 10^{-5}$ [18]	-0.972 ± 0.012 [13]	1.085 ± 0.014	1.042 ± 0.033 [19]
$D_s^+ D_s^-$	$(1.04^{+0.29}_{-0.26}) \times 10^{-2}$ [18]	-0.995 ± 0.013 [16]	1.088 ± 0.014	N/A

Large corrections!



more generally

End Digression

MLFV

Note: LN vs LF

- Distinguish
  Lepton Number (LN) violating interactions from Lepton Flavor (LF) violating interactions
- LN is a U(1) symmetry, assigning unit charge to all leptons (like baryon number for quarks)
  - Majorana mass breaks LN
- LF is an SU(3) symmetry, mixing different flavors
  - It commutes with $U(1)_{LN}$, *ie*, preserves the LN charge

Desirable to consider LFV at a 'low scale' (few TeV?),
while for see-saw want LNV at an intermediate scale

$$\Lambda_{\rm LF} \ll \Lambda_{\rm LN} \ll M_{\rm planck}$$

- Two approaches. Field content below LFV $\Lambda_{\rm LF}$ scale is three families of L_i and e_{Ri} (plus H and gauge). Then:
    - Minimal: majorana mass is from non-renormalizable interaction
    - Extended: include very heavy ν_{Ri} insofar as it dictates MFV coupling, but then integrate out

MLFV: Minimal Field Content

Assumptions:

1. The breaking of the $U(1)_{LN}$ is independent from the breaking of lepton flavor G_{LF}, with large Λ_{LN} (associated with see-saw)
2. There are only two irreducible sources of G_{LF} breaking, λ_e and g_ν, defined by

$$\mathcal{L}_{\text{Sym.Br.}} = -\lambda_e^{ij}\, \bar{e}_R^i (H^\dagger L_L^j) - \frac{1}{2\Lambda_{LN}}\, g_\nu^{ij} (\bar{L}_L^{ci} \tau_2 H)(H^T \tau_2 L_L^j) + \text{h.c.}$$

Ex: SUSY Triplet Model, A. Rossi, PRD66(2002)075003

Implementation of MLFV in Minimal Field Content Case

- Want to add all possible terms to the lagrangian consistent with assumptions (and usual stuff: Lorentz invariance, gauge symmetry, locality, ...)
- Need characterization of terms that are allowed
- Use spurion method:

$$L_L \to V_L\, L_L \qquad e_R \to V_R\, e_R$$

$$\lambda_e \to V_R\, \lambda_e V_L^\dagger \qquad g_\nu \to V_L^*\, g_\nu V_L^\dagger$$

(recall: $\mathcal{L}_{\text{Sym.Br.}} = -\lambda_e^{ij}\, \bar{e}_R^i (H^\dagger L_L^j) - \frac{1}{2\Lambda_{LN}}\, g_\nu^{ij} (\bar{L}_L^{ci} \tau_2 H)(H^T \tau_2 L_L^j) + \text{h.c.}$)

Then write all operators of dimension 5, 6, ... consistent with assumptions.

For $\mu \to e\gamma, \quad \mu + N \to e + N',$ need two lepton field ops:

Ops with LL

$$O_{LL}^{(1)} = \bar{L}_L \gamma^\mu \Delta L_L \; H^\dagger i D_\mu H$$
$$O_{LL}^{(2)} = \bar{L}_L \gamma^\mu \tau^a \Delta L_L \; H^\dagger \tau^a i D_\mu H$$
$$O_{LL}^{(3)} = \bar{L}_L \gamma^\mu \Delta L_L \; \bar{Q}_L \gamma_\mu Q_L$$
$$O_{LL}^{(4d)} = \bar{L}_L \gamma^\mu \Delta L_L \; \bar{d}_R \gamma_\mu d_R$$
$$O_{LL}^{(4u)} = \bar{L}_L \gamma^\mu \Delta L_L \; \bar{u}_R \gamma_\mu u_R$$
$$O_{LL}^{(5)} = \bar{L}_L \gamma^\mu \tau^a \Delta L_L \; \bar{Q}_L \gamma_\mu \tau^a Q_L$$

Ops with RL

$$O_{RL}^{(1)} = g' H^\dagger \bar{e}_R \sigma^{\mu\nu} \lambda_e \Delta L_L \, B_{\mu\nu}$$
$$O_{RL}^{(2)} = g H^\dagger \bar{e}_R \sigma^{\mu\nu} \tau^a \lambda_e \Delta L_L \, W_{\mu\nu}^a$$
$$O_{RL}^{(3)} = (D_\mu H)^\dagger \bar{e}_R \lambda_e \Delta D_\mu L_L$$
$$O_{RL}^{(4)} = \bar{e}_R \lambda_e \Delta L_L \, \bar{Q}_L \lambda_D d_R$$
$$O_{RL}^{(5)} = \bar{e}_R \sigma^{\mu\nu} \lambda_e \Delta L_L \, \bar{Q}_L \sigma_{\mu\nu} \lambda_D d_R$$
$$O_{RL}^{(6)} = \bar{e}_R \lambda_e \Delta L_L \, \bar{u}_R \lambda_U^\dagger i \tau^2 Q_L$$
$$O_{RL}^{(7)} = \bar{e}_R \sigma^{\mu\nu} \lambda_e \Delta L_L \, \bar{u}_R \sigma_{\mu\nu} \lambda_U^\dagger i \tau^2 Q_L$$

We have used $\Delta \equiv g_\nu^\dagger g_\nu$ with transformation $\Delta \to V_L \Delta V_L^\dagger$

Also neglected Δ^2

We have neglected $\sim (\lambda_e)^2$, hence no RR operators

For $\mu \longrightarrow ee\bar{e}$ need, in addition, four lepton operators

$$O_{4L}^{(1)} = \bar{L}_L \gamma^\mu \Delta L_L \, \bar{L}_L \gamma_\mu L_L$$
$$O_{4L}^{(2)} = \bar{L}_L \gamma^\mu \tau^a \Delta L_L \, \bar{L}_L \gamma_\mu \tau^a L_L$$
$$O_{4L}^{(3)} = \bar{L}_L \gamma^\mu \Delta L_L \, \bar{e}_R \gamma_\mu e_R$$
$$O_{4L}^{(4)} = \delta_{nj} \delta^*_{mi} \bar{L}^i_L \gamma^\mu L^j_L \, \bar{L}^m_L \gamma^\mu L^n_L$$
$$O_{4L}^{(5)} = \delta_{nj} \delta^*_{mi} \bar{L}^i_L \gamma^\mu \tau^a L^j_L \, \bar{L}^m_L \gamma^\mu \tau^a L^n_L$$

where we used $\delta = g_\nu$ (so we can use same expressions for extended field content case)

Up to dimension 6 operators, the new interactions are

$$\mathcal{L}_{\text{eff}} = \frac{1}{\Lambda^2_{\text{LFV}}} \sum_{i=1}^{5} \left(c^{(i)}_{LL} O^{(i)}_{LL} + c^{(i)}_{4L} O^{(i)}_{4L} \right) + \frac{1}{\Lambda^2_{\text{LFV}}} \left(\sum_{j=1}^{2} c^{(j)}_{RL} O^{(j)}_{RL} + \text{h.c.} \right)$$

with coefficients naively $c \sim 1$

We can now study the phenomenology of MLFV
with minimal field content.

Useful to look at parameters first

Also useful to contrast with results of extended field content

Use G_{LF} symmetry to rotate to the mass eigenstate basis (v = Higgs vev)

$$\lambda_e = \frac{m_\ell}{v} = \frac{1}{v}\,\mathrm{diag}(m_e, m_\mu, m_\tau)$$

$$g_\nu = \frac{\Lambda_{LN}}{v^2} U^* m_\nu U^\dagger = \frac{\Lambda_{LN}}{v^2} U^* \mathrm{diag}(m_{\nu_1}, m_{\nu_2}, m_{\nu_3}) U^\dagger$$

U is the PMNS matrix. It is determined from neutrino mixing:

$$U \approx \begin{pmatrix} c e^{i\alpha_1/2} & s e^{i\alpha_2/2} & s_{13} e^{-i\delta} \\ -s e^{i\alpha_1/2}/\sqrt{2} & c e^{i\alpha_2/2}/\sqrt{2} & 1/\sqrt{2} \\ s e^{i\alpha_1/2}/\sqrt{2} & -c e^{i\alpha_2/2}/\sqrt{2} & 1/\sqrt{2} \end{pmatrix}$$

Here $\quad c \equiv \cos\theta_{\rm sol} \quad s \equiv \sin\theta_{\rm sol} \quad \theta_{\rm sol} \simeq 32.5^\circ$

s_{13} is poorly known, $s_{13} < 0.3$

note added

sorry: two different δ

- Hence, amplitudes are given in terms of
    - Λ_{LN} and Λ_{LFV} (actually only ratio $\Lambda_{\text{LN}}/\Lambda_{\text{LFV}}$)
    - Coefficients, C, of order 1
    - Low energy measured (or measurable) masses and mixing angles
- In particular, the following two combinations appear in the operators:

$$\Delta = \frac{\Lambda_{LN}^2}{v^4} U m_\nu^2 U^\dagger \qquad\qquad \delta = \delta^T = \frac{\Lambda_{LN}}{v^2} U^* m_\nu U^\dagger$$

MLFV: Extended Field Content

Recall, now we include RH neutrinos, flavor group has additional $SU(3)_{\nu R}$ factor

Assumptions:

1. The right handed neutrino mass is flavor neutral, ie, it breaks $SU(3)_{\nu R}$ to $O(3)_{\nu R}$. Denote $M_\nu^{ij} = M_\nu \delta^{ij}$
2. The right handed neutrino mass is the only source of LN breaking and $M_\nu \gg \Lambda_{LFV}$
3. Remaining LF-symmetry broken only by λ_e and λ_ν defined by

$$\mathcal{L}_{\text{Sym.Br.}} = -\lambda_e^{ij}\,\bar{e}_R^i(H^\dagger L_L^j) + i\lambda_\nu^{ij}\bar{\nu}_R^i(H^T\tau_2 L_L^j) + \text{h.c.}$$

Ex: SUSY with RH degenerate N's,
J. Hisano et al, Phys. Rev. D 53, 2442–2459 (1996)

Implementation of MLFV in Extended Field Content Case

$$\mathcal{L}_{\text{Sym.Br.}} = -\lambda_e^{ij}\, \bar{e}_R^i (H^\dagger L_L^j) + i\lambda_\nu^{ij} \bar{\nu}_R^i (H^T \tau_2 L_L^j) + \text{h.c.}$$

Same as before, but now transformations are:

$$L_L \to V_L\, L_L \qquad e_R \to V_R\, e_R \qquad \nu_R \to O_\nu\, \nu_R$$

$$\lambda_e \to V_R\, \lambda_e V_L^\dagger \qquad \lambda_\nu \to O_\nu\, \lambda_\nu V_L^\dagger$$

Implementation of MLFV in Extended Field Content Case

$$\mathcal{L}_{\text{Sym.Br.}} = -\lambda_e^{ij}\,\bar{e}_R^i(H^\dagger L_L^j) + i\lambda_\nu^{ij}\bar{\nu}_R^i(H^T\tau_2 L_L^j) + \text{h.c.}$$

Same as before, but now transformations are:

$$L_L \to V_L\, L_L \qquad e_R \to V_R\, e_R \qquad \nu_R \to O_\nu\, \nu_R$$

$$\lambda_e \to V_R\, \lambda_e V_L^\dagger \qquad \lambda_\nu \to O_\nu\, \lambda_\nu V_L^\dagger$$

As before $\quad \Delta = \lambda_\nu^\dagger \lambda_\nu \qquad \Delta \to V_L \Delta V_L^\dagger$

Implementation of MLFV in Extended Field Content Case

$$\mathcal{L}_{\text{Sym.Br.}} = -\lambda_e^{ij}\,\bar{e}_R^i(H^\dagger L_L^j) + i\lambda_\nu^{ij}\bar{\nu}_R^i(H^T\tau_2 L_L^j) + \text{h.c.}$$

Same as before, but now transformations are:

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However $\quad \delta = \lambda_\nu^T \lambda_\nu \qquad \delta \to V_L^*\, \delta\, V_L^\dagger$

In CP limit $\quad \lambda_\nu^* = \lambda_\nu \quad$ and $\quad \Delta = \lambda_\nu^T \lambda_\nu$

- Same operator basis as before (chose Δ and δ by transformation properties)
- Same effective lagrangian, but with $\Lambda_{\mathrm{NL}} \to M_\nu$
- Summary: In mass eigenstate basis

$$\Delta = \begin{cases} \frac{\Lambda_{\mathrm{LN}}^2}{v^4}\; U m_\nu^2 U^\dagger & \text{minimal field content} \\ \frac{M_\nu}{v^2}\; U m_\nu U^\dagger & \text{extended field content, CP limit} \end{cases}$$

$$\delta = \delta^T = \begin{cases} \frac{\Lambda_{\mathrm{LN}}}{v^2}\; U^* m_\nu U^\dagger & \text{minimal field content} \\ \frac{M_\nu}{v^2}\; U^* m_\nu U^\dagger & \text{extended field content} \end{cases}$$

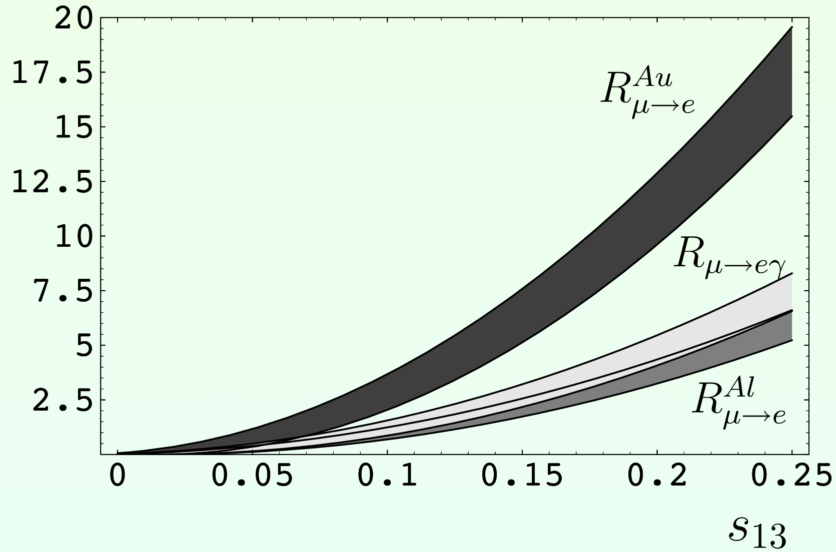
MLFV: Phenomenology

- Future experiments will (continue to) look for flavor changing neutral interactions in the charged lepton sector:
  - MECO … was cancelled, but … mu2e
  - PRIME at the PRISM muon facility at JPARC will measure μ-to-e conversion at 10^{-18} sensitivity
  - MEG at PSI looks for $\mu^+ \rightarrow e^+ \gamma$ at 10^{-13} single event sensitivity

COBRA(Constant Bending Radius Spectrometer)

μ→eγ, μ-to-e conversion and their relatives I: minimal field content

$$B_{\ell_i \to \ell_j(\gamma)} = 10^{-50} \left(\frac{\Lambda_{\rm LN}}{\Lambda_{\rm LFV}} \right)^4 R_{\ell_i \to \ell_j(\gamma)}(s_{13}, \delta; c^{(i)})$$



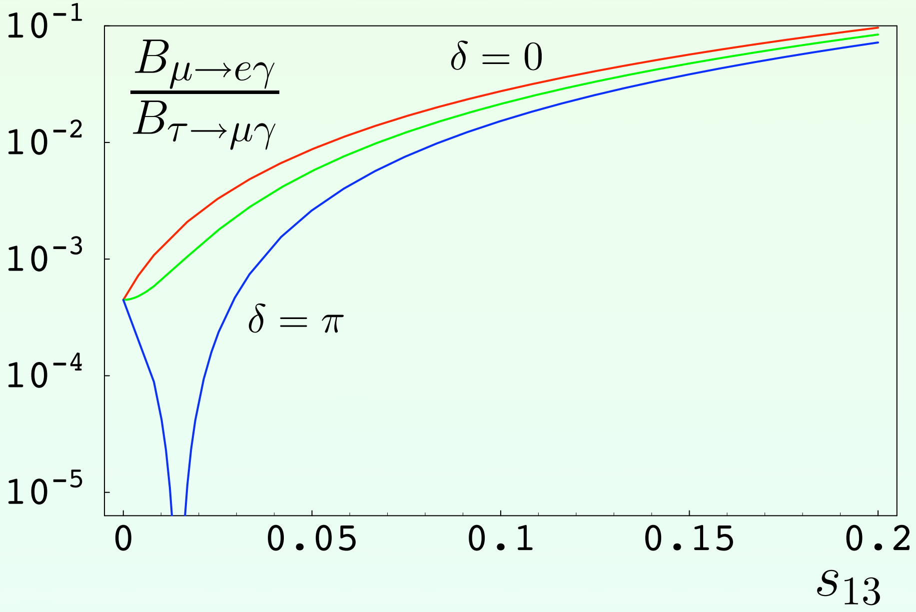
- since $\Delta \propto U(m_\nu)^2 U^\dagger$, only differences of m_ν^2 enter; these are measured!

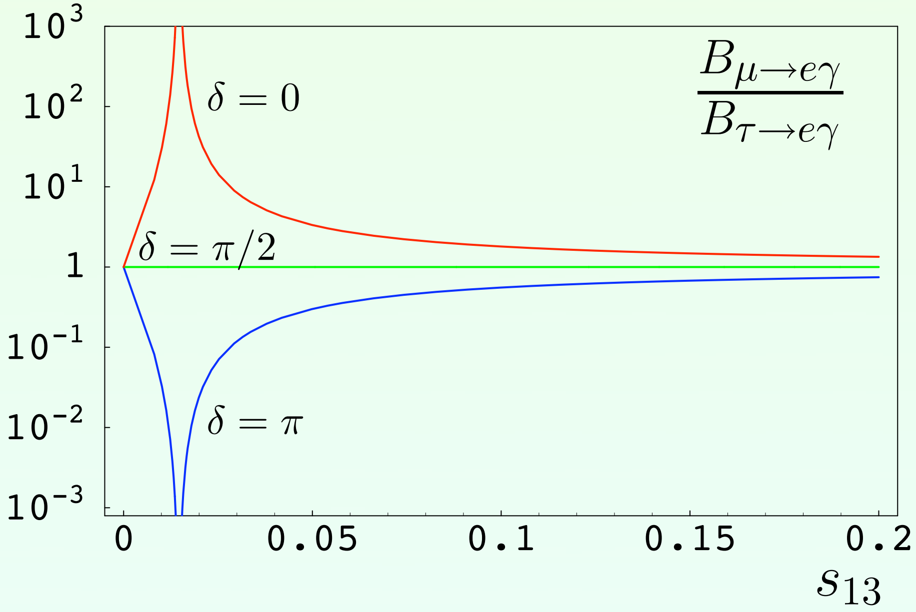
- s_{13} and δ unknown PMNS parameters (scan on δ)
- choose $c^{(i)}$ of order one for the estimate
- ratio of scales can be large:

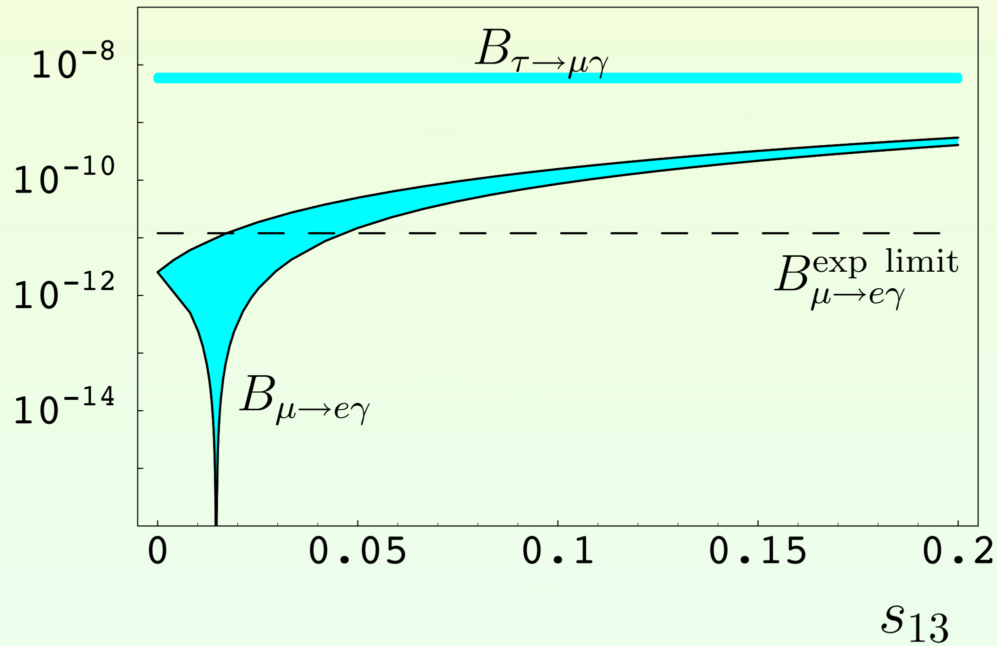
  perturbative $g_\nu \Rightarrow \Lambda_{\rm LN} \lesssim 3 \times 10^{13} (1 \text{ eV}/m_\nu)$ GeV

  so $\Lambda_{\rm LFV} \sim 1$ TeV $\Rightarrow \Lambda_{\rm LN}/\Lambda_{\rm LFV} \lesssim 10^{10}$

Predictive: l→l′γ patterns are independent of unknown input parameters (scales cancel in ratios, in this case $c^{(i)}$'s cancel too, and all other parameters are from long distance)





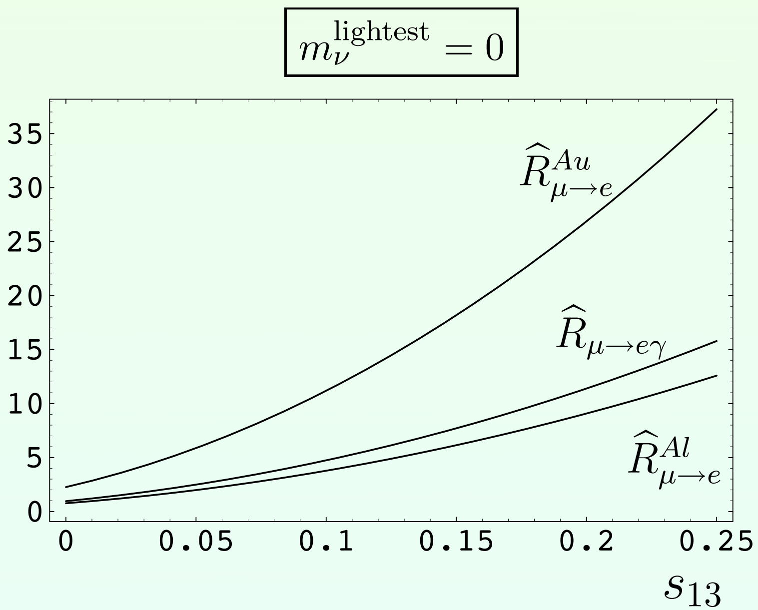


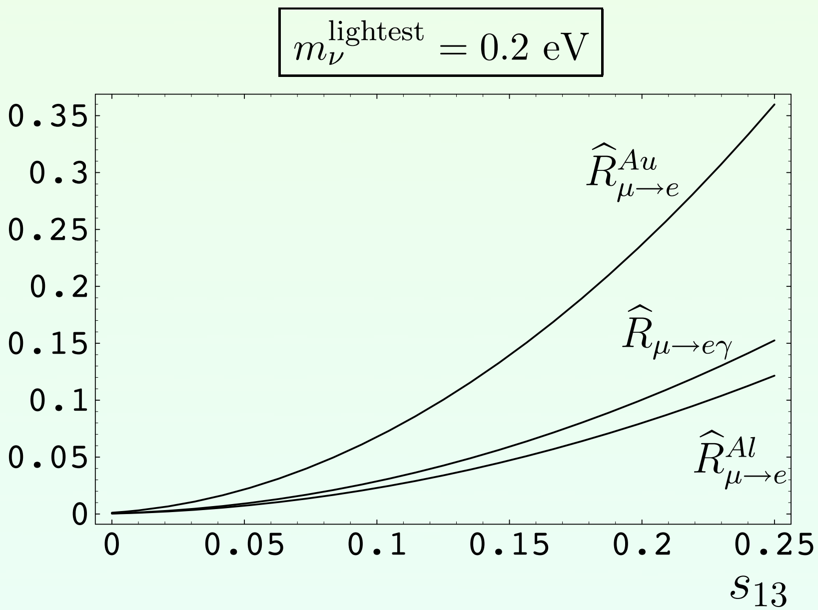
If s_{13} is small, look at tau modes.
Here $\Lambda_{LN}/\Lambda_{LFV} = 10^{10}$ and $c^{(1)}_{RL} - c^{(2)}_{RL} = 1$

Belle and BaBar have recent bounds (summer '05)
of a few × 10^{-7} for Br($\tau\to l\gamma$) and Br($\tau\to lll$)

μ→eγ, μ-to-e conversion and their relatives II: extended field content

- Replace $\Lambda^2_{\rm LN}/\Lambda^2_{\rm LFV}$ by $vM_\nu/\Lambda^2_{\rm LFV}$
- Now $\Delta \propto U\, m_\nu\, U^\dagger$ so amplitudes depend on overall neutrino mass scale (ie, lightest neutrino mass)



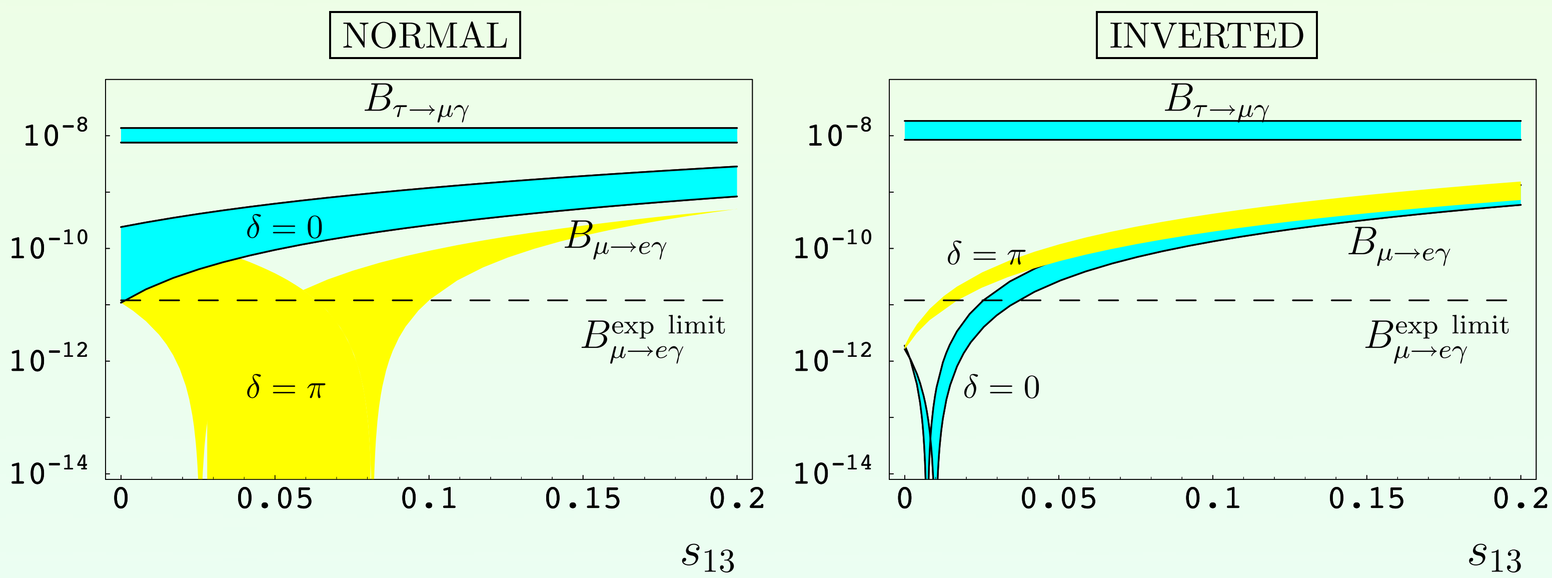


$$B_{\ell_i\to\ell_j(\gamma)} = 10^{-25}\left(\frac{vM_\nu}{\Lambda^2_{\rm LFV}}\right)^2 \widehat{R}_{\ell_i\to\ell_j(\gamma)}(s_{13}, m_\nu^{\rm lightest}; c^{(i)})$$

perturbative $\lambda_\nu \Rightarrow M_\nu \lesssim 10^{13}$ GeV; with $\Lambda_{LFV} \geq 1$ TeV, $\dfrac{vM_\nu}{\Lambda^2_{LFV}} \leq 10^9$

One final note: results depend on hierarchy of neutrino masses,

normal ($m_{\nu 1} \sim m_{\nu 2} \ll m_{\nu 3}$) vs. *inverted* ($m_{\nu 1} \ll m_{\nu 2} \sim m_{\nu 3}$)



$$(vM_\nu)/\Lambda_{\mathrm{LFV}}^2 = 5 \times 10^7$$

$$c_{RL}^{(1)} - c_{RL}^{(2)} = 1$$

shading: $0 \leq m_\nu^{\mathrm{lightest}} \leq 0.02$ eV

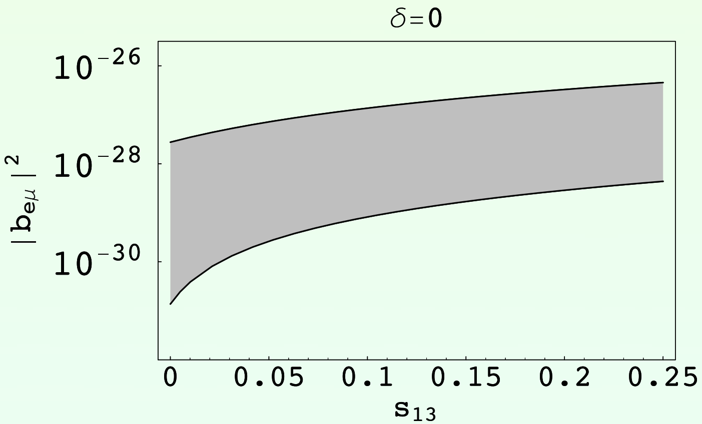
3l Decays: 4L operators

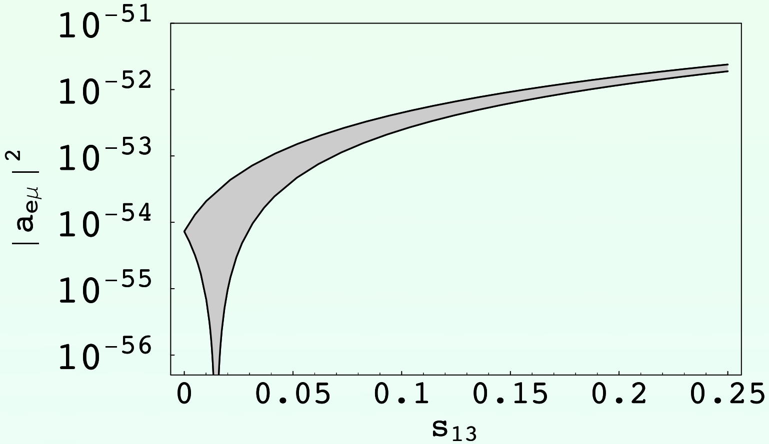
$$\Gamma_{\mu\to 3e}/\Gamma_{\mu\to e\nu\bar{\nu}} = \left[|a_+|^2+2|a_-|^2-8\mathrm{Re}(a_0^* a_-)-4\mathrm{Re}(a_0^* a_+)+6I|a_0|^2\right] \begin{cases} \left(\frac{\Lambda_{\mathrm{LN}}}{\Lambda_{\mathrm{LFV}}}\right)^4 |a_{e\mu}|^2 & \text{minimal} \\ \left(\frac{vM_\nu}{\Lambda_{\mathrm{LFV}}{}^2}\right)^2 |b_{e\mu}|^2 & \text{extended} \end{cases}$$

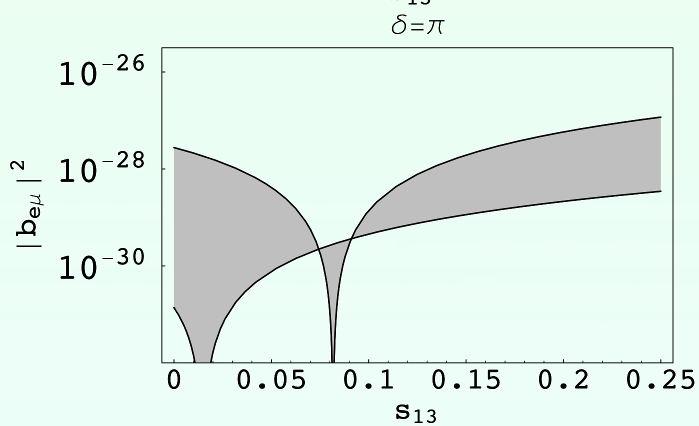
$$a_+ = \sin^2\theta_w (c_{LL}^{(1)} + c_{LL}^{(2)}) + c_{4L}^{(3)}$$

$$a_- = (\sin^2\theta_w - \frac{1}{2})(c_{LL}^{(1)} + c_{LL}^{(2)}) + c_{4L}^{(1)} + c_{4L}^{(2)} + \frac{2\delta_{e\mu}\delta_{ee}^*}{\Delta_{e\mu}}(c_{4L}^{(4)} + c_{4L}^{(5)})$$

$$a_0 = 2e^2(c_{RL}^{(1)} - c_{RL}^{(2)})^*$$

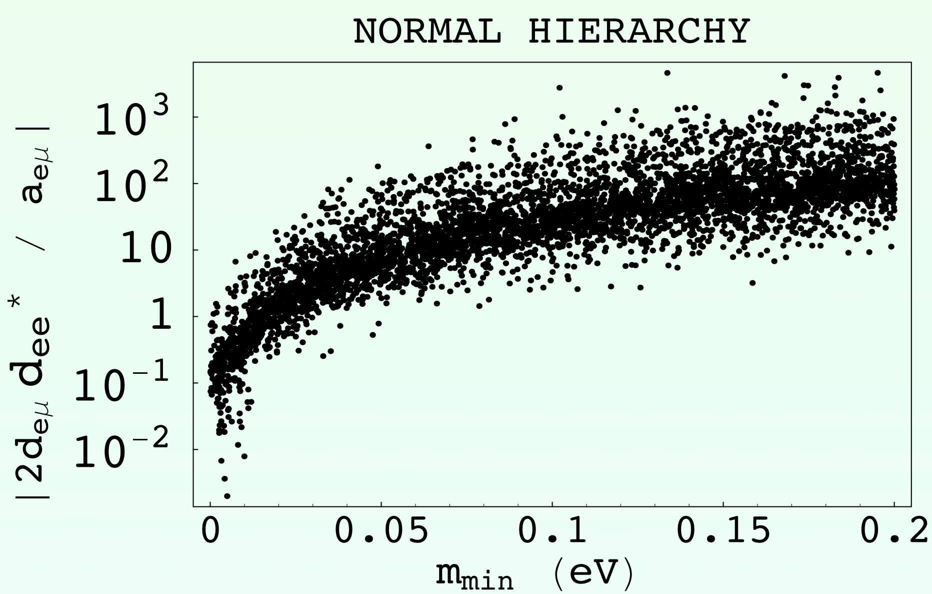


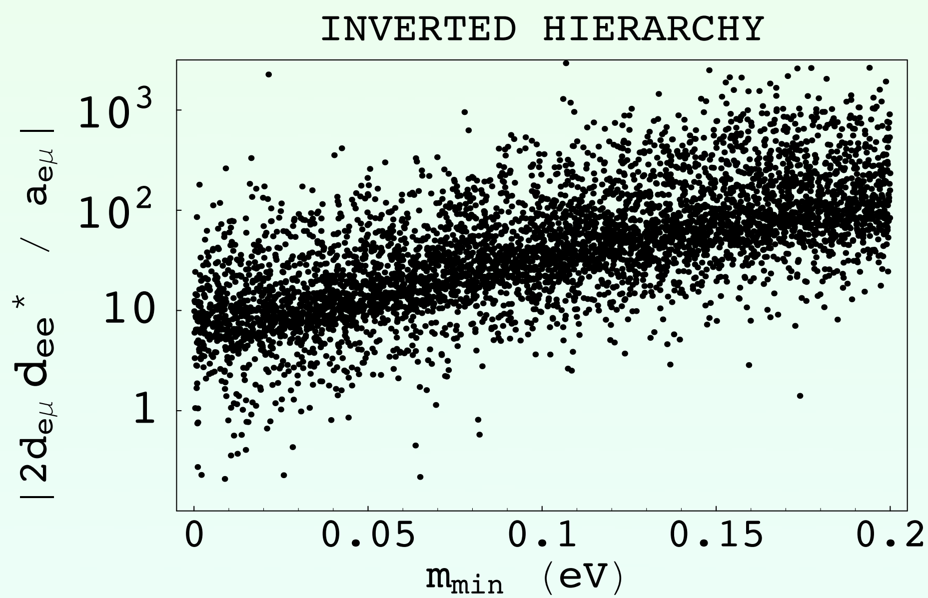




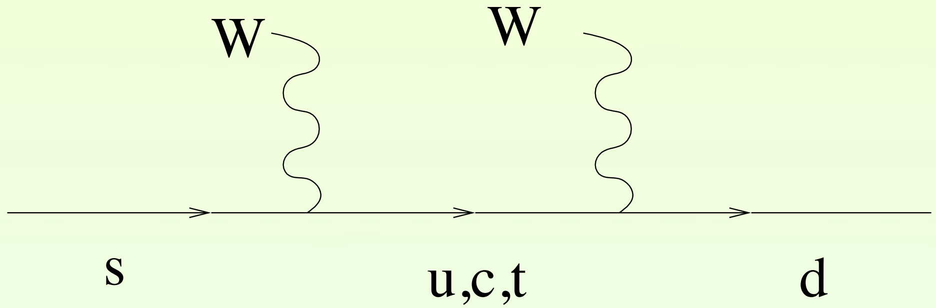
$$\Gamma_{\tau\to e\mu\bar{\mu}} = \Gamma_{\tau\to e\nu\bar{\nu}} \; \frac{v^4|\Delta_{e\tau}|^2}{\Lambda_{\mathrm{LFV}}^4} \; \left[|a_+|^2 + |\tilde{a}_-|^2 - 4\mathrm{Re}[a_0^*(a_+ + \tilde{a}_-)] + 12\tilde{I}|a_0|^2\right]$$

$$\Gamma_{\tau\to\mu\mu\bar{e}} = \Gamma_{\tau\to e\nu\bar{\nu}} \frac{v^4|2\delta_{e\tau}\delta_{\mu\mu}|^2}{\Lambda_{\mathrm{LFV}}^4} |c_L^{(4)} + c_L^{(5)}|^2$$





d_{xx} is δ_{xx}



Part of loop graph (W is virtual).
For any one intermediate quark amplitude is

$$M_W^D F(m_q^2/M_W^2, \mu/M_W)$$

Sum over intermediate quarks and expand

$$\sum_q V_{qd} V_{qs}^* F(m_q^2/M_W^2) \approx \sum_q V_{qd} V_{qs}^* \left[F(0) + \frac{m_q^2}{M_W^2} F'(0) + \cdots \right]$$

For first term use $\sum_q V_{qd} V_{qs}^* = 0$ and for second $\sum_{q \neq u} V_{qd} V_{qs}^* = -V_{ud} V_{us}^*$

$$\Rightarrow \quad \sum_q m_q^2 V_{qd} V_{qs}^* = \sum_{q \neq u} (m_q^2 - m_u^2) V_{qd} V_{qs}^*$$

(jump back)

Decays of/to hadrons

Hopelessly small!

	Br
$\pi^0 \to \mu^+ e^-$	10^{-25}
$\Upsilon \to \tau\mu$	10^{-20}
$\tau \to \pi\mu$	10^{-15}

- We have also explored the effects of deleting a class of operators.
- For example: assume 4L operators are not present
- Can we get 3l decays? Yes, through loops
- Need care in loops of light quarks: chiral lagrangian does the job
- Result: amplitude is ~0.1 of 4L ops (large logs)
- Equivalently, these give a ~20% correction to rate
- Patterns are similar to those from 4L