Flavor Physics and CPV

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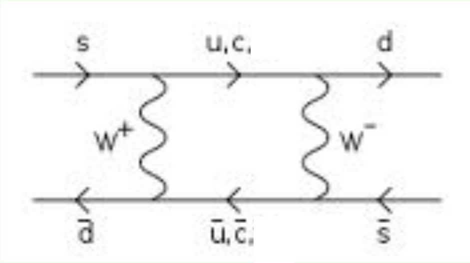
Notables Left Out

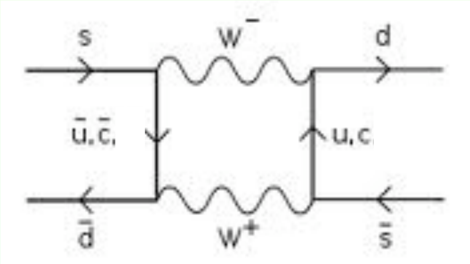
- T violation (BaBar)
- Full determination of UT allowed region, including:
  - semileptonic and current state of excl/incl disparity
  - input from K physics
- Universality and unitarity of CKM
- Combined Higgs/Flavor constraints
- ...

Flavor: The Elegant Probe

Recall:
GIM mechanism and the *prediction* of upper bound on charm mass

$K^0 - \bar{K}^0$ mixing





$$\propto \left(\sum_{q=u,c} V_{qd} V_{qs}^* \times \frac{m_q^2}{M_W^2} \right)^2$$

$$= \sin^2 \theta_C \frac{(m_c^2 - m_u^2)^2}{M_W^4}$$

In view of top and its huge mass, do we still have a prediction?
Is GIM a mirage?

$$\sum_{q=u,c,t,t',\ldots} V_{qd}V^*_{qs} \times F(m_q^2/M_W^2) \sim \text{largest term} = V_{qd}V^*_{qs} \times F(m_q^2/M_W^2)$$

if no accidental cancellation,
i.e., no fine tuning.

Roughly, $V_{qd}V^*_{qs} \times m_q^2 \lesssim 1 \text{ GeV}^2$

that is either

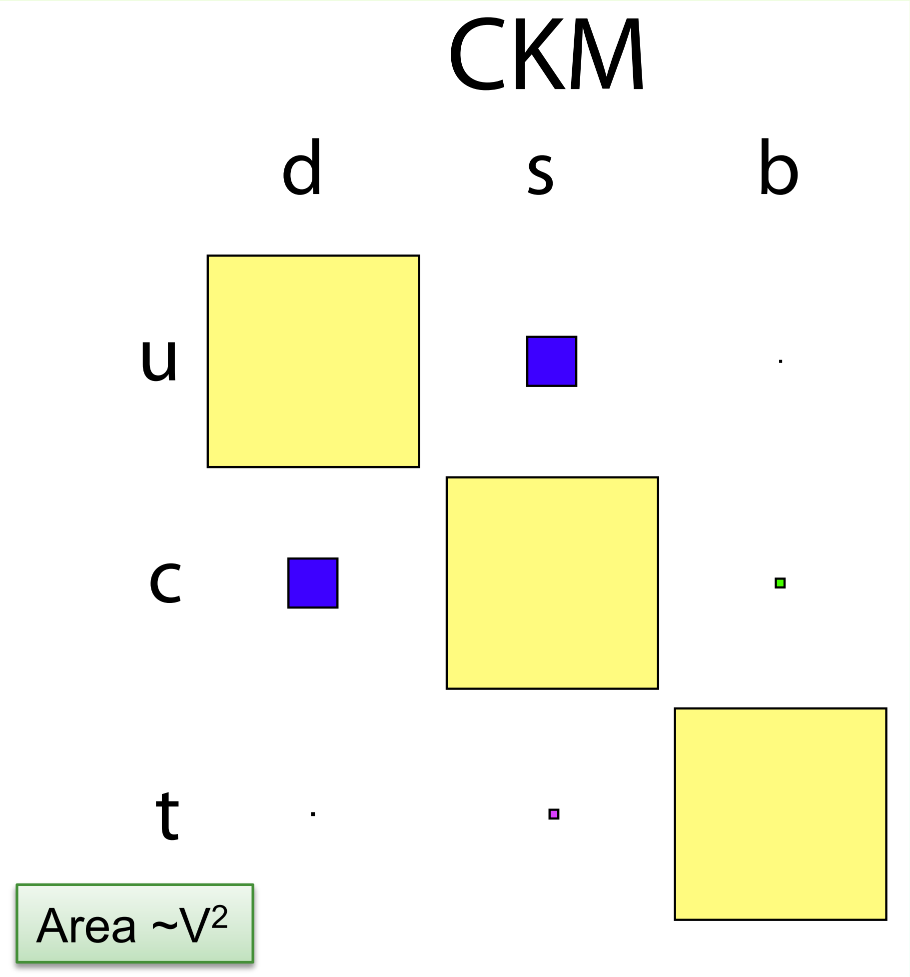
- small mass with large angle (charm) $\sim (0.2)(1.5 \text{ GeV})^2 = 0.5 \text{ GeV}^2$
- large mass with small angle (top) $\sim (0.003)(0.04)(175 \text{ GeV})^2 = 3.7 \text{ GeV}^2$

Both are right ballpark!

Nota bene: Really very rough! Need short distance QCD corrections, full top-dependence form loop, non-perturbative matrix elements, ...

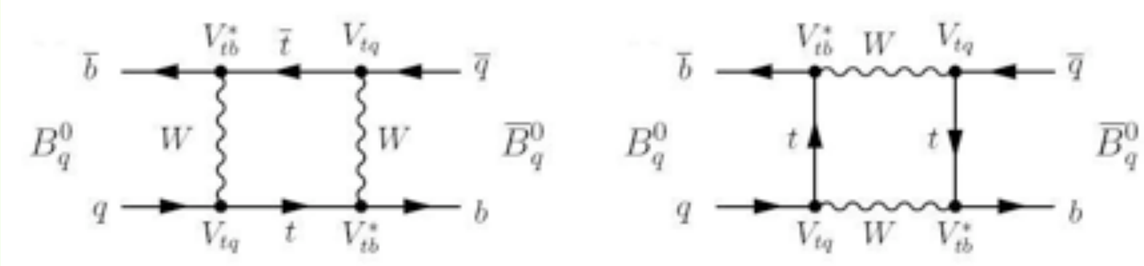
Additional constraints from CP violation in mixing (from complex phases in CKM elements)

CKM texture



More GIM, more predictions

$B^0 - \bar{B}^0$ mixing

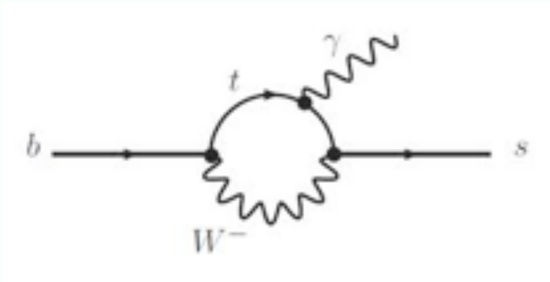


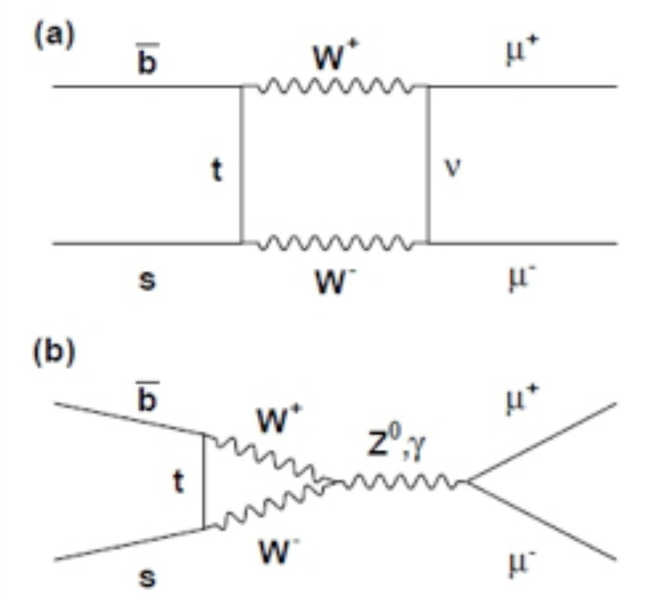
Discovered in 1985

Mixing rate much higher than anticipated:
at the time, thought that $m_t \sim$ few $\times$ 10 GeV

Fast mixing requires much heavier top !!

Similarly





Large top mass make these visible.

All cases above
(mixing, decays)
are sensitive to any kind of stuff
running in the loop

constrains NP

(reigns in speculators)

or,
if you are an optimist

it is a window to
discovery of
NP
(new physics)

(I am too old)

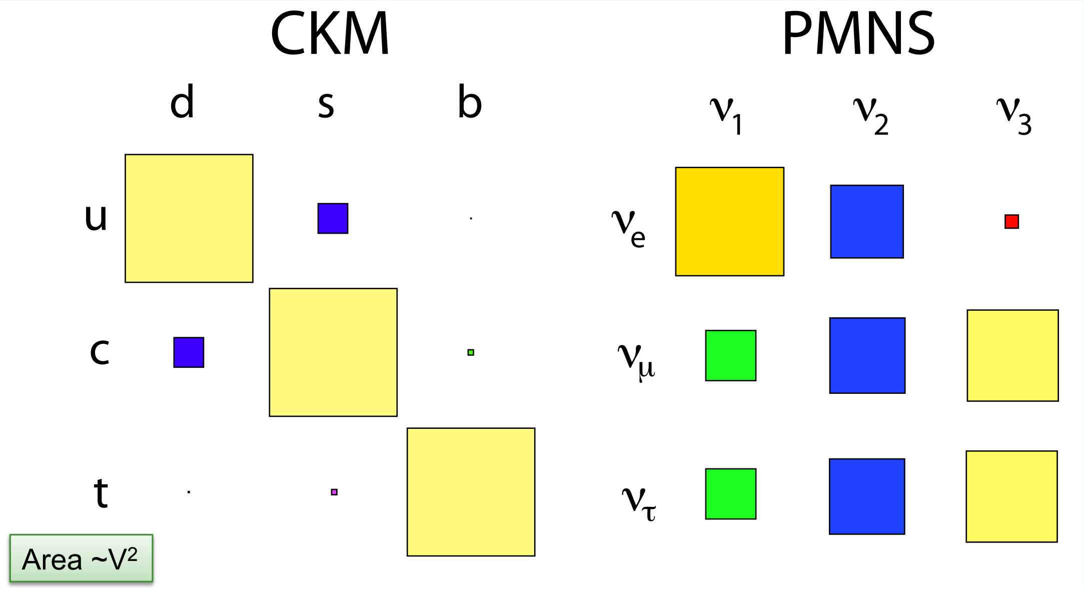
Flavor/CP and New Physics

- 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

- Why 3 generations?
- Why the pattern of masses and mixings?

Quarks



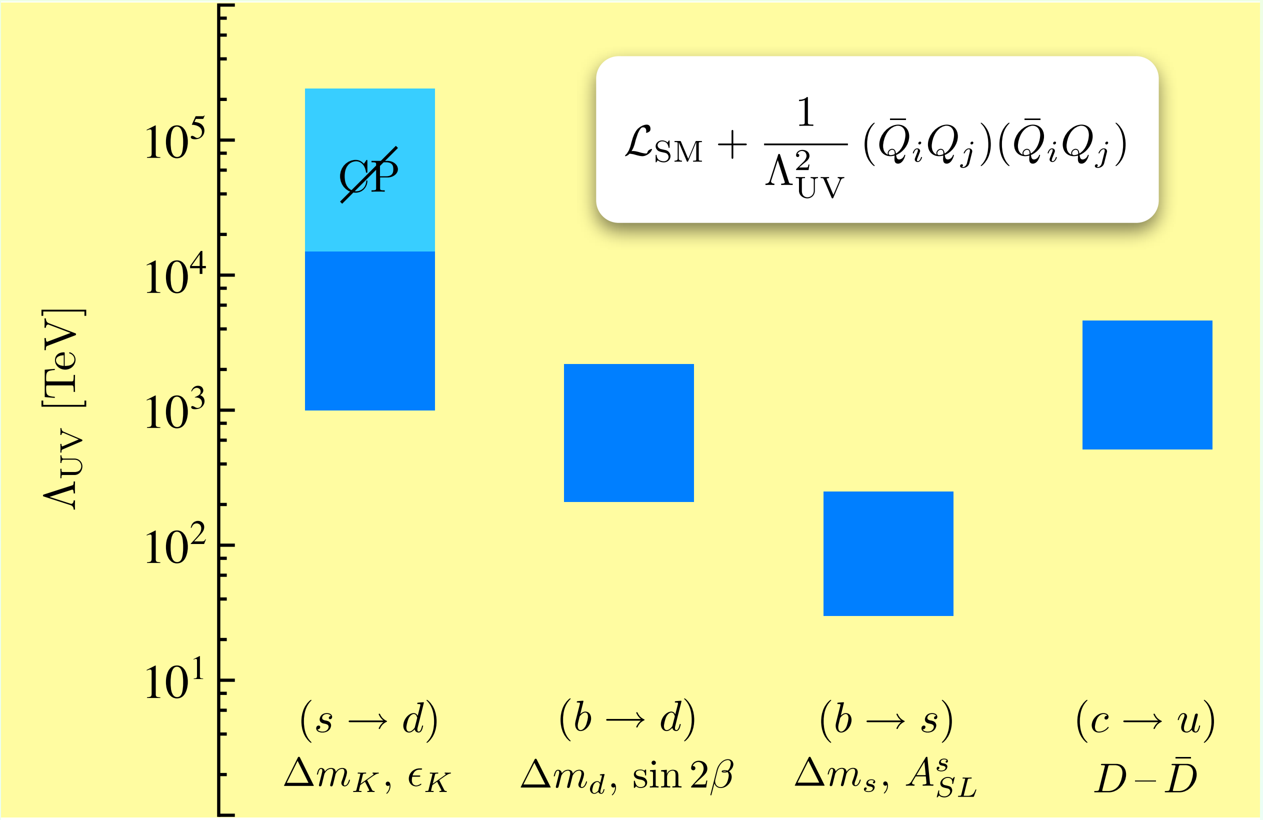
Leptons

Flavor Physics: an important constraint on all new BSM models

[Neubert, EPS2011]

Generic bounds without a flavor symmetry

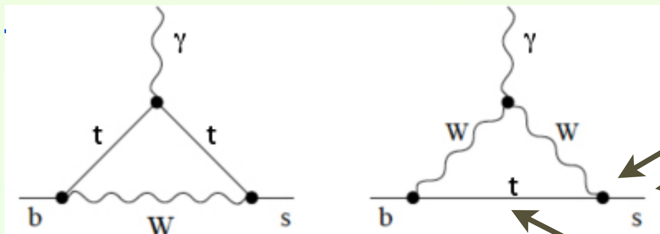
- Integrate out NP at UV scale
- Produce local operators
- Assume coupling is order 1 (generic, no flavor suppression)



Strategy/Philosophy

- Conundrum: distinguish new physics (NP) in loop from SM physics

$B \to X_s \gamma$

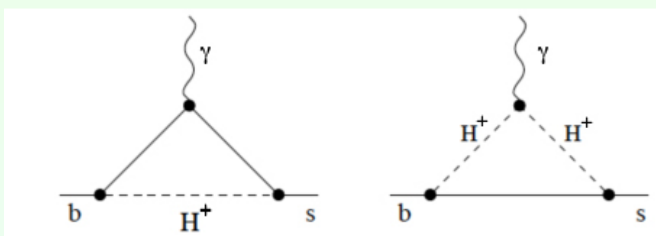


Value of coupling (V_{ts})?

Strong interactions
$B \to X_s \gamma$ vs $b \to s\gamma$

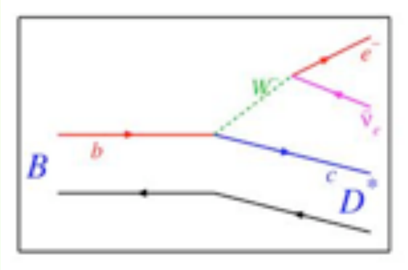
Values of other parameters (m_t, M_W, g_2)?

example
of NP



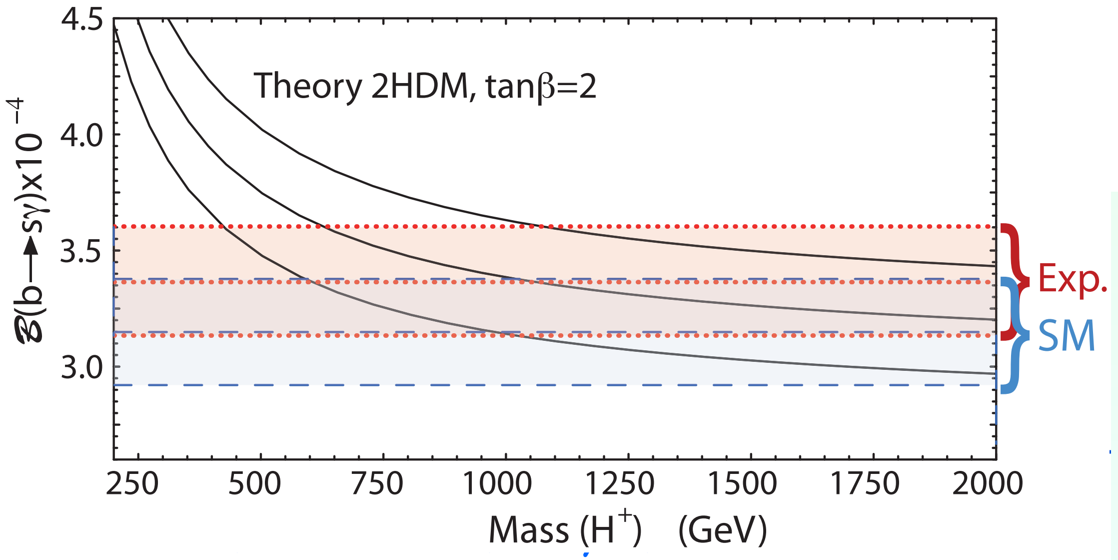
- Must determine parameters using non-flavor physics as well as possible. These include, e.g., m_t, M_W, g_2 in above case.
- Must compute strong interaction effects (but that goes without saying)
- Left with undetermined flavor parameters (e.g., V_{ts}), confused with NP
    - Determine flavor parameter from tree level physics
    - Assume NP is negligible at tree level

In this example: determine V_{ts} using CKM unitarity and tree level semi-leptonic decays



$B \to X_s \gamma$ branching fraction for $E_\gamma > 1.6$ GeV

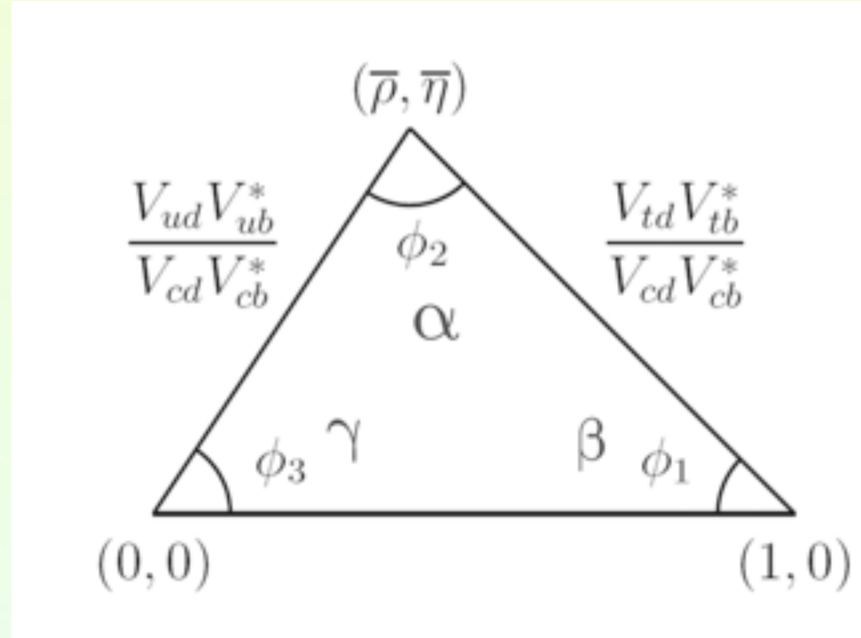
- Measured $(3.37 \pm 0.23) \times 10^{-4}$
- Theory (Misiak, 1010:4896) $(3.15 \pm 0.23) \times 10^{-4}$
- One of toughest constraints on NP

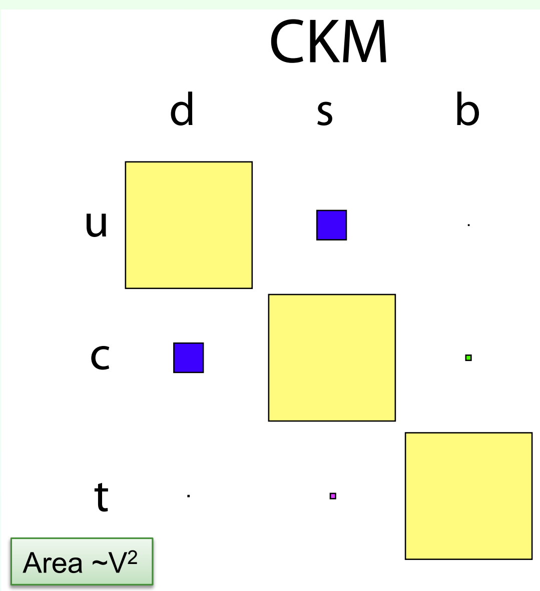


$m(H^+) > 385$ GeV

Unitarity Triangle

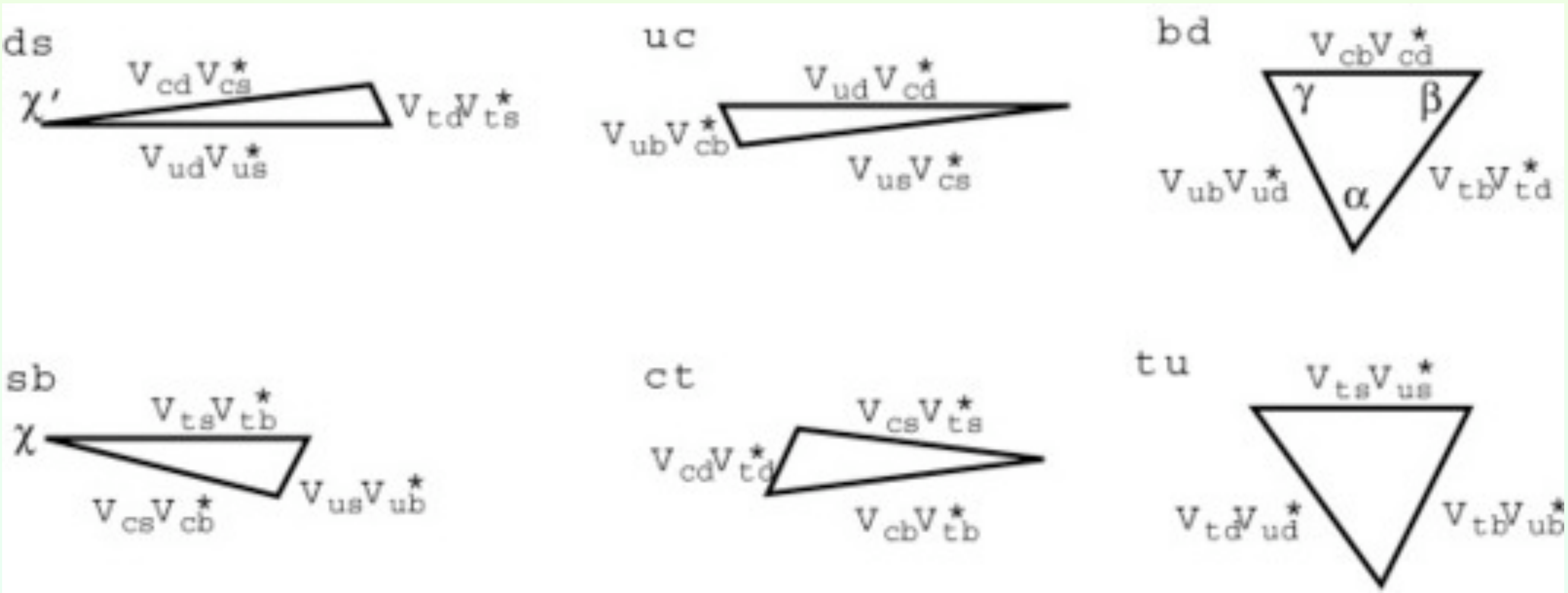
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$





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

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



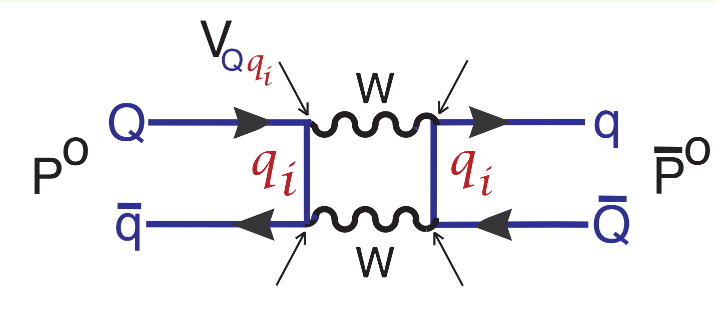
$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$

CPV

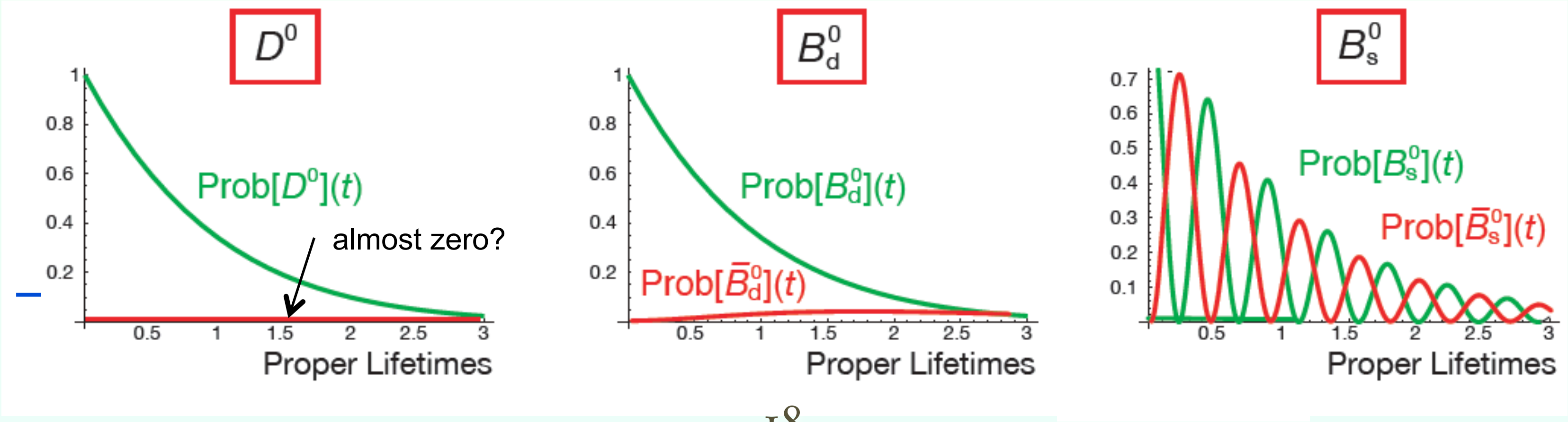
- Distinguish two cases
  - CPV in mixing
  - CPV in decays

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

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

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

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,

$$a^d_{sl} = -4.1 \times 10^{-4}, \quad a^s_{sl} = 1.9 \times 10^{-5}$$ [A. Lenz, Moriond 2012]

B^0 B_s

a_{sl}: D0, from di-muons

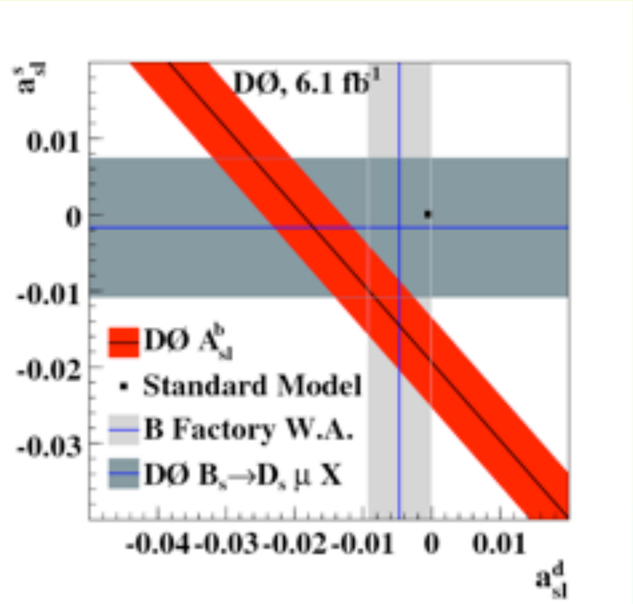
- Dimuons

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

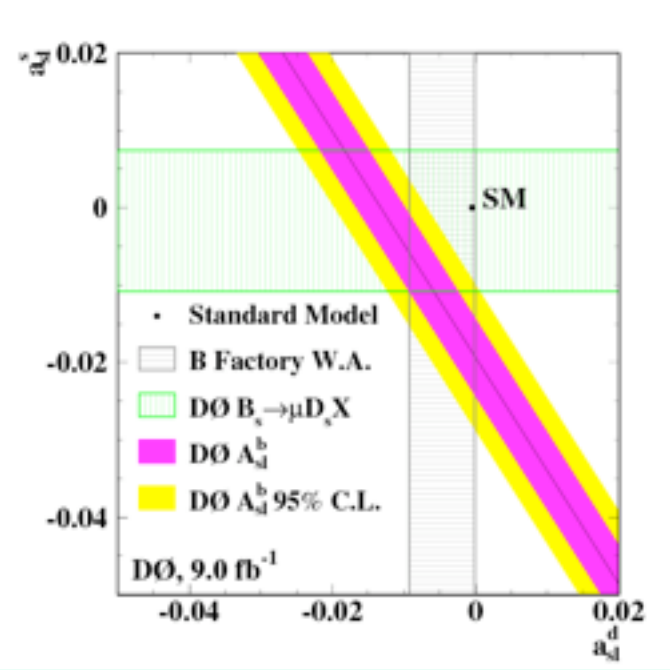
- 3.9σ deviation from SM

- 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)

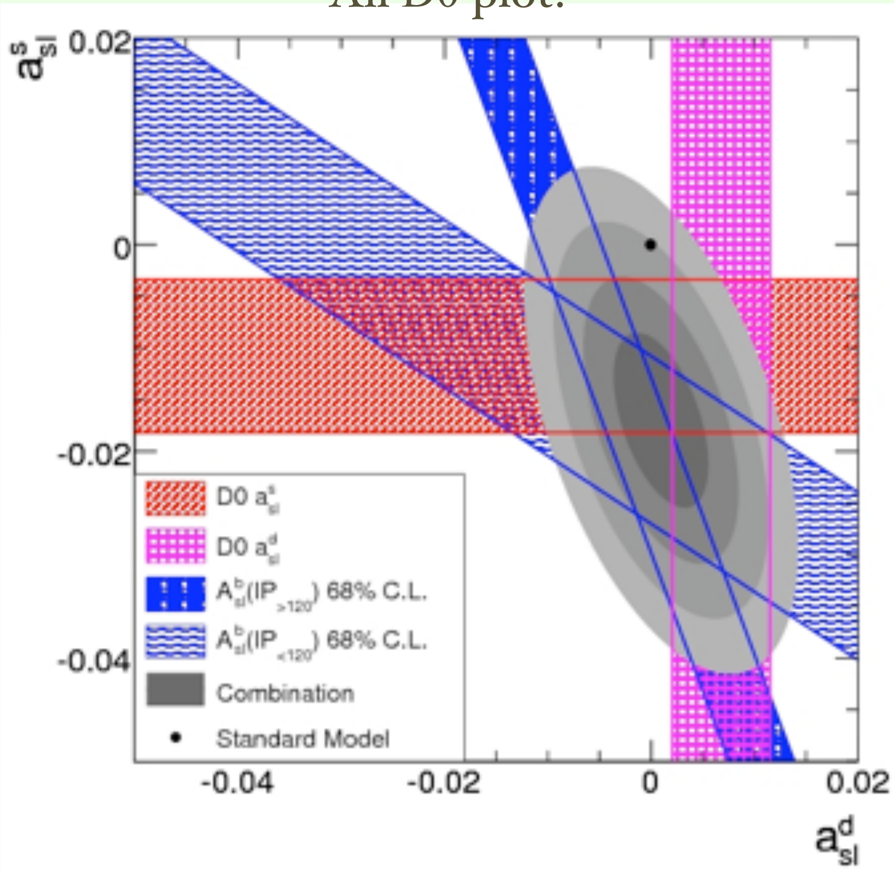
- $$\frac{\Gamma(\bar{B}^0 \to B^0 \to \ell^+ D^{(*)-} X) - \Gamma(B^0 \to \bar{B}^0 \to \ell^- D^{(*)+} X)}{\Gamma(\bar{B}^0 \to B^0 \to \ell^+ D^{(*)-} X) + \Gamma(B^0 \to \bar{B}^0 \to \ell^- D^{(*)+} X)},$$

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]

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

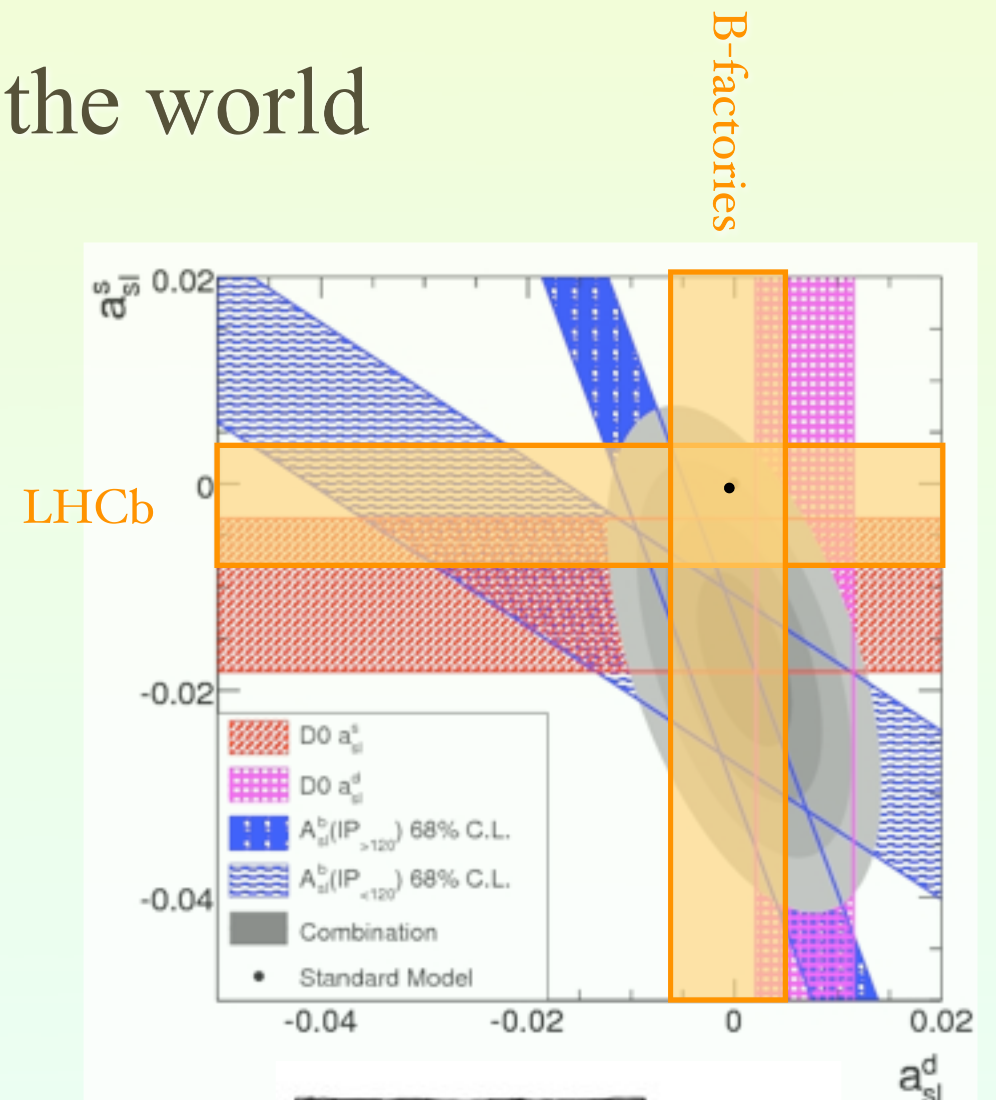
- B-factories combined

$$a^d_{sl} = (-0.05 \pm 0.56)\%$$

- Superimposed on D0 plot, for comparison

- Consistent with SM

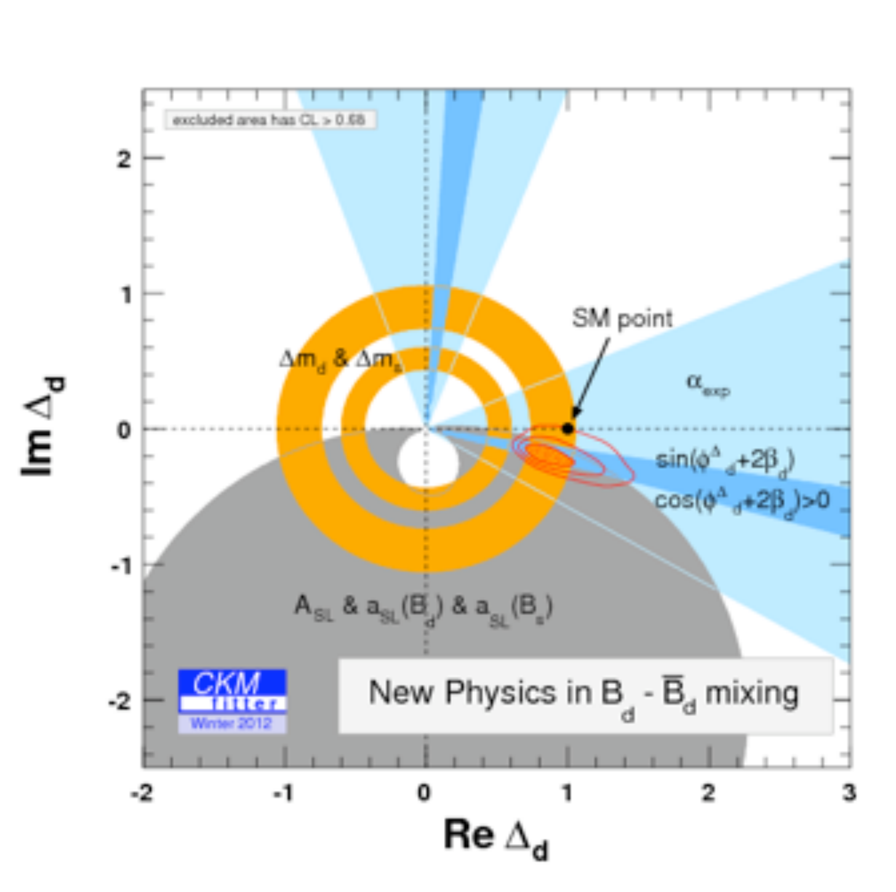
- Will have to wait for more (more precise) data (not Tevatron)

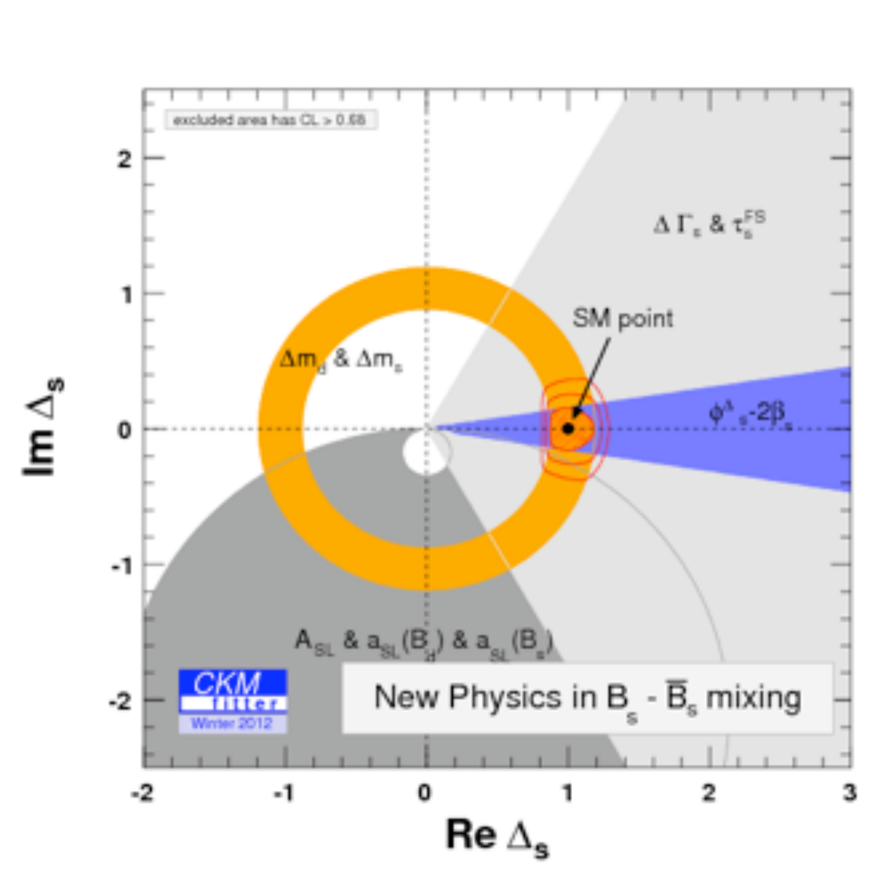


a_{sl}:summary

Characterize NP by

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





(does not include new LHCb result)

CPV in mixing

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

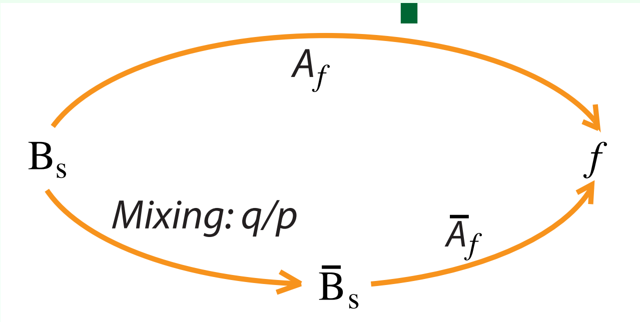
$$A_f = \langle f|H|B\rangle = \sum_k A_k\, e^{i\delta_k}\, e^{i\phi_k}\,, \qquad \overline{A}_{\overline{f}} = \langle\overline{f}|H|\overline{B}\rangle = \sum_k A_k\, e^{i\delta_k}\, e^{-i\phi_k}\,.$$

- 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 mixing can be theory clean
  - If amplitudes with a single weak phase dominate



  - Simplest if *f* is a CP eigenstate

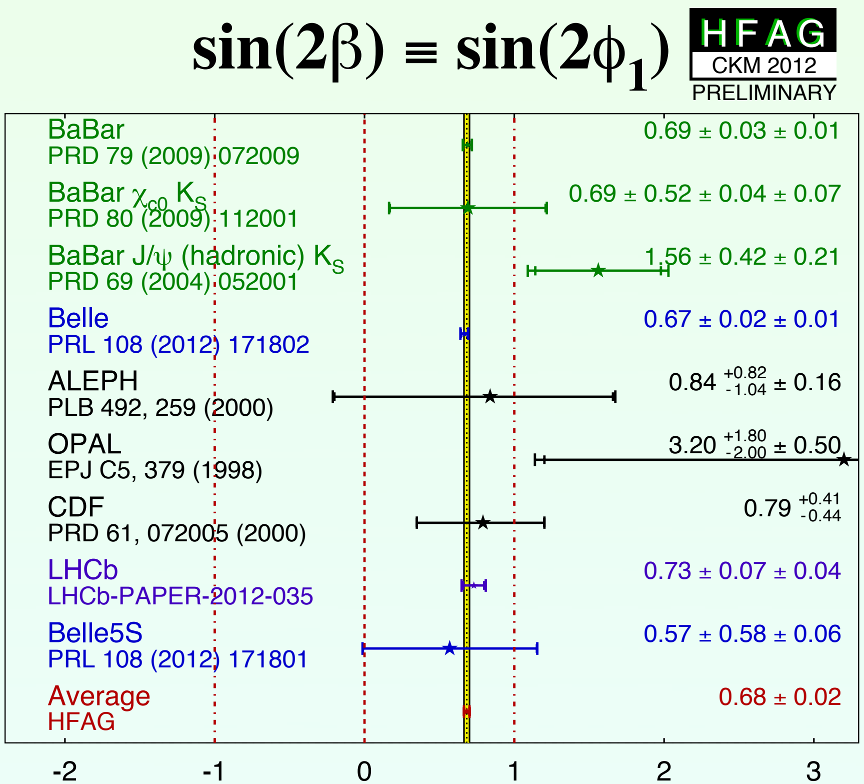
$$a(t) = \frac{\Gamma[\overline{B}^0(t) \to f] - \Gamma[B^0(t) \to f]}{\Gamma[\overline{B}^0(t) \to f] + \Gamma[B^0(t) \to f]}$$

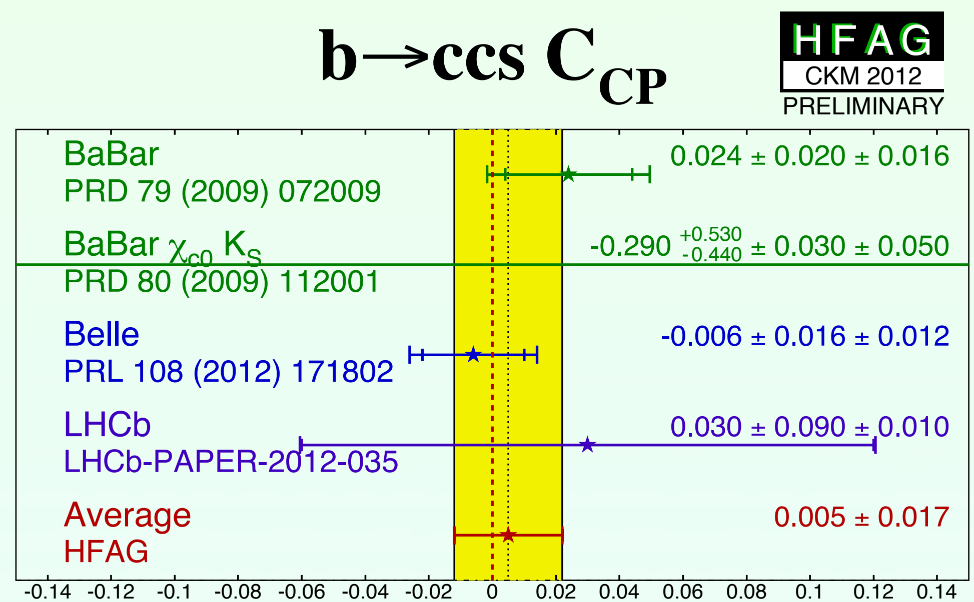
$$= S_f \sin(\Delta m\, t) - C_f \cos(\Delta m\, t)$$

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

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

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

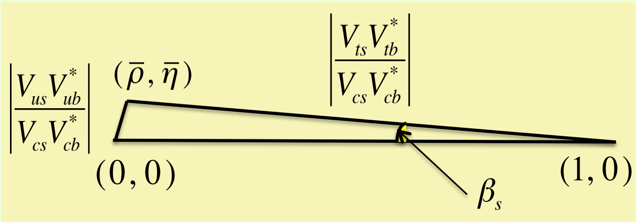




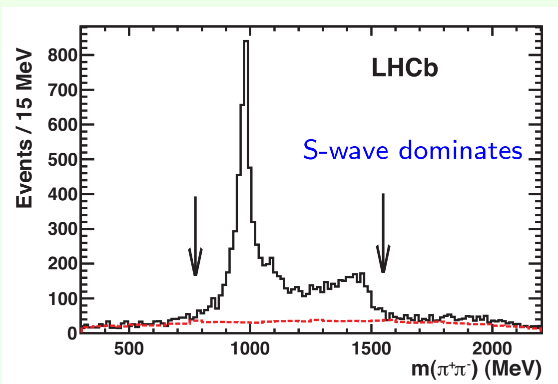
and $B_s \to \psi\phi, \psi\pi^+\pi^-$

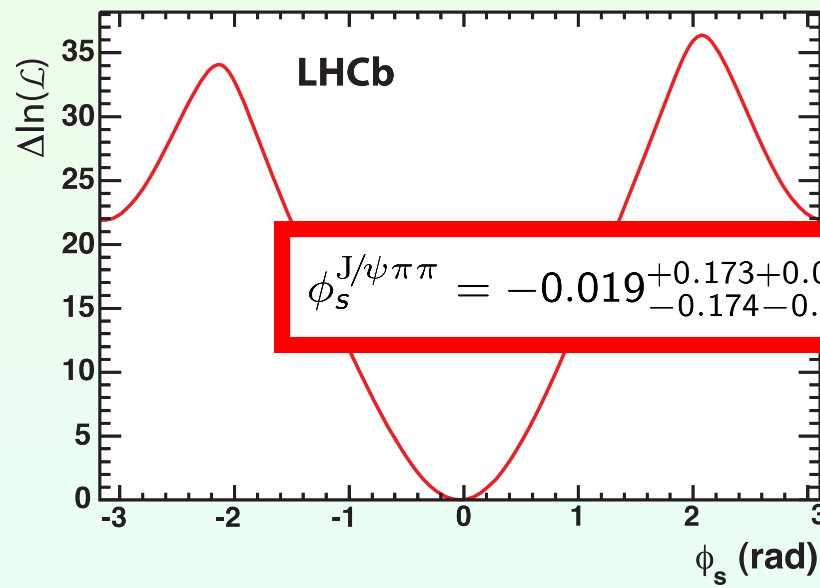
$$\lambda_{\psi\pi^+\pi^-} = -\left(\frac{V_{tb}^* V_{ts}}{V_{tb} V_{ts}^*}\right)\left(\frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}}\right) = -e^{-2i\beta_s}$$

small angle in squashed unitarity triangle ≈ 0 in SM



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





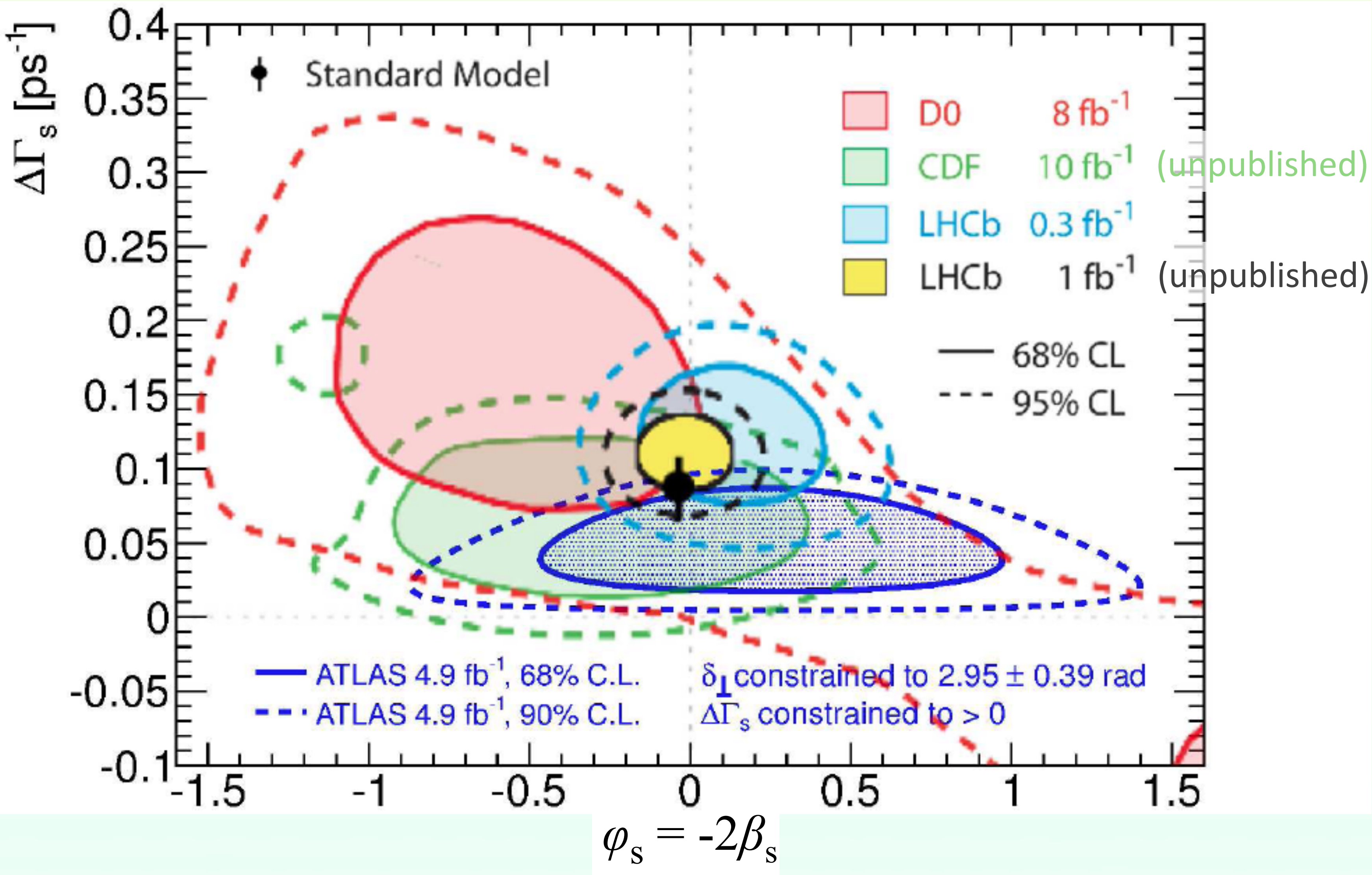
$$\boxed{\phi_s^{J/\psi\pi\pi} = -0.019^{+0.173+0.004}_{-0.174-0.003} \text{ rad}}$$

$B \to \psi\phi(K^+K^-)$ 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]

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

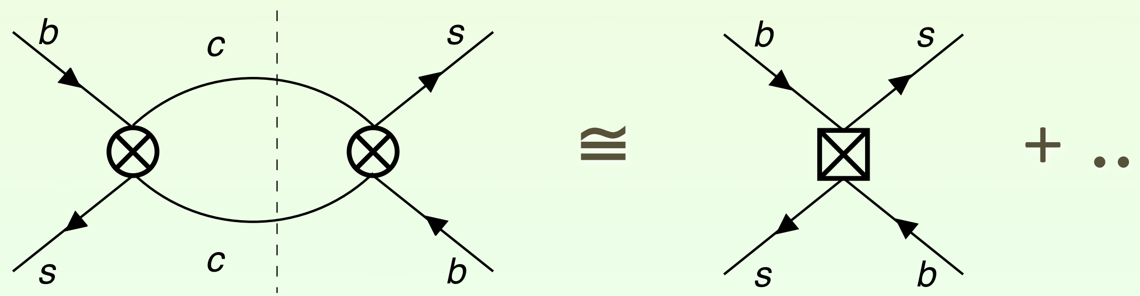


[Palestini, ICHEP 2012]

Long Digression

Can we compute Γ (let alone ΔΓ)?

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



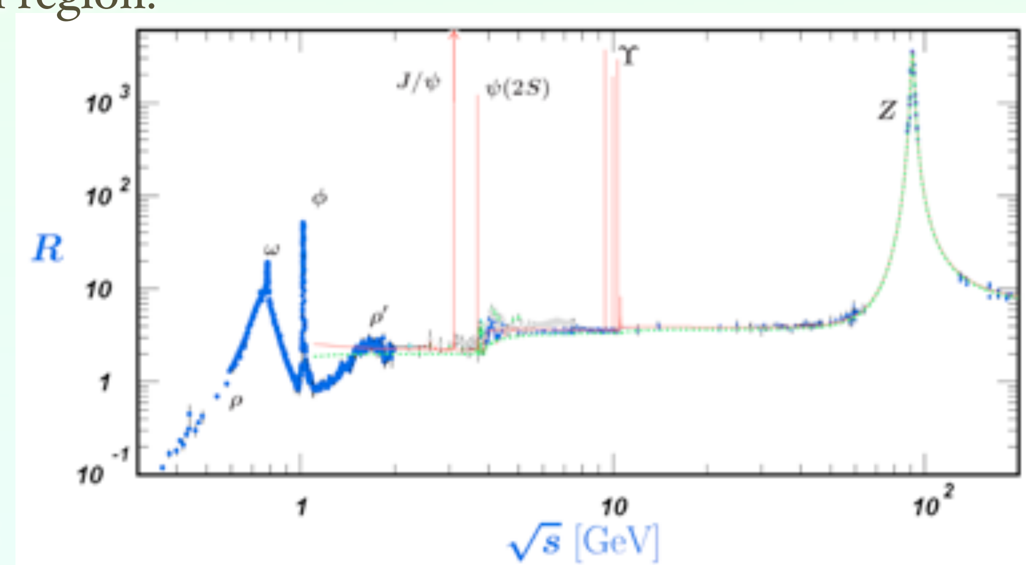
[Lenz & Nierste, eg: JHEP 0706 (2007) 072]

- 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

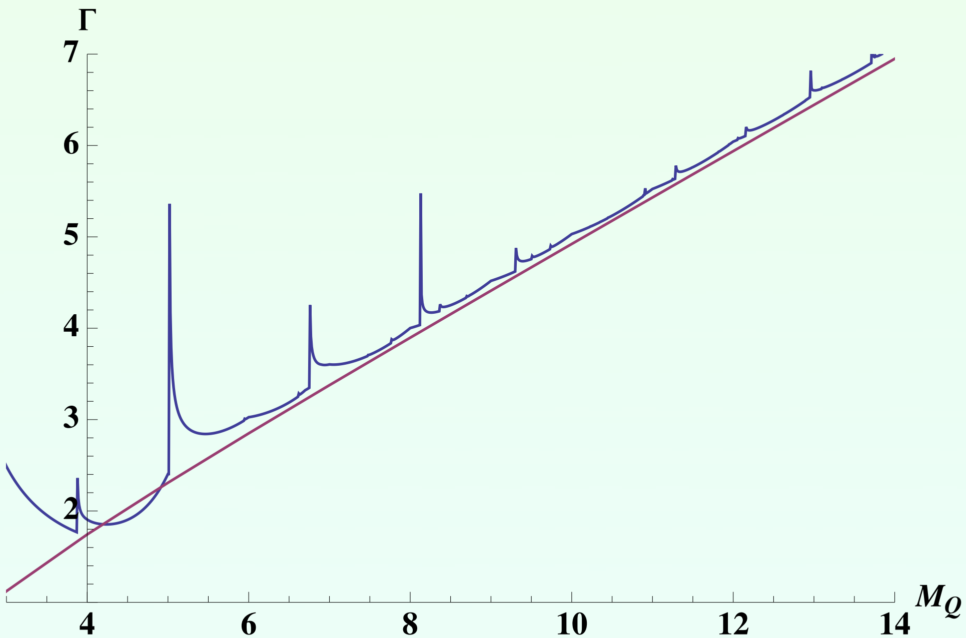
Poggio-Quinn-Weinberg:

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

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-

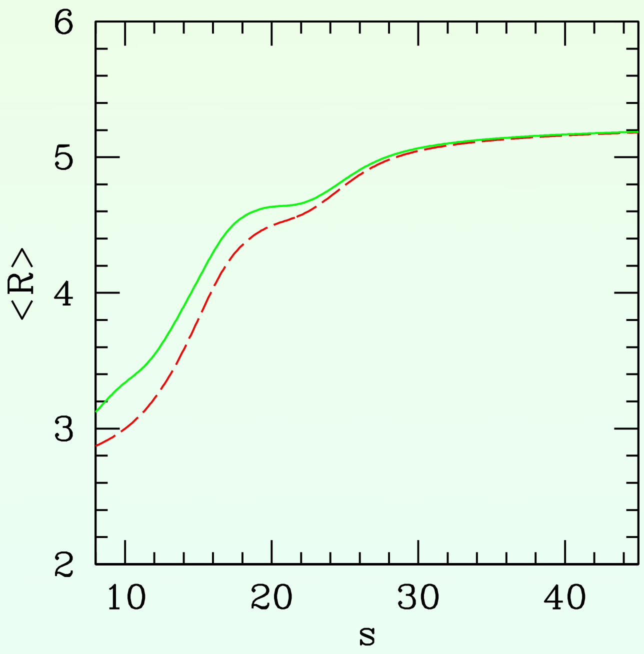
Effect of including narrow resonances in lorentzian smearing:

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

red: PQW (exclude resonances)

green: include resonances

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



- Lorentzian smearing

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

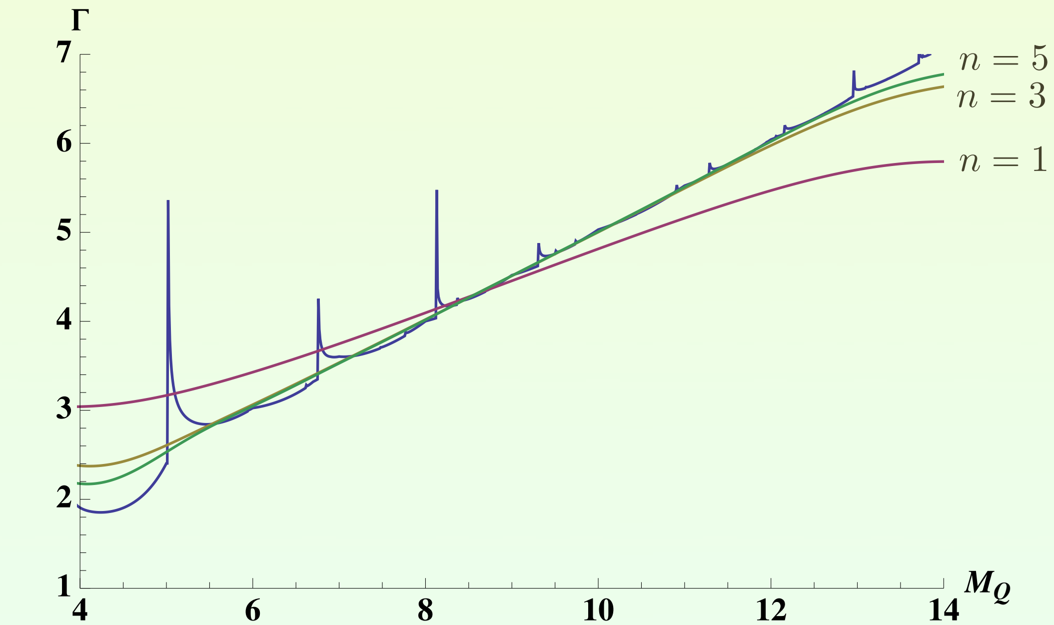
- Justified by OPE provided

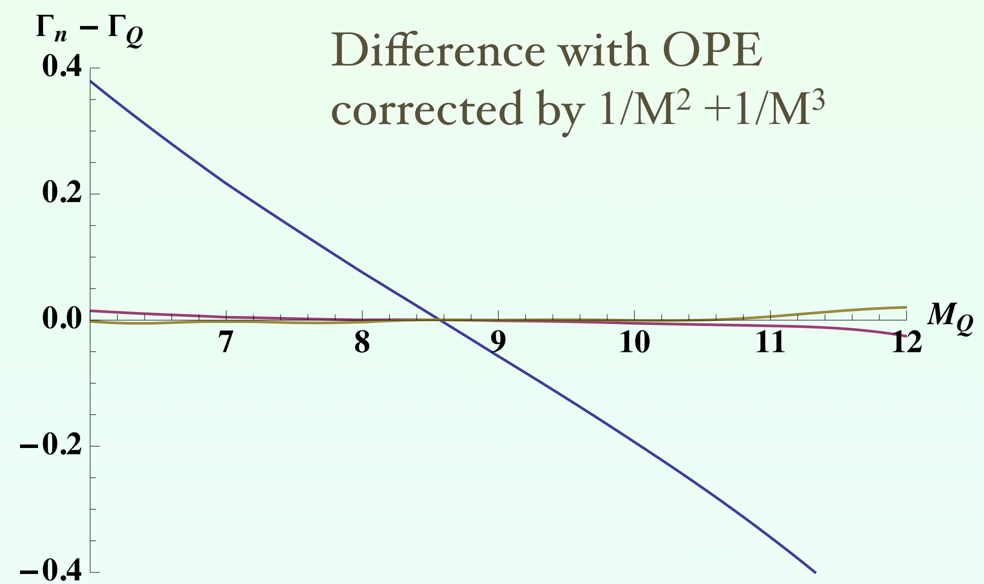
$$n \geq 2$$

- Corrections to OPE:

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

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

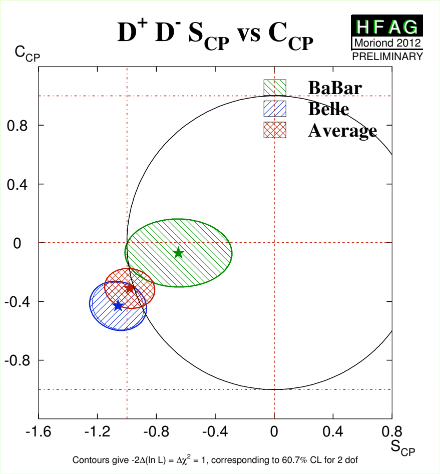


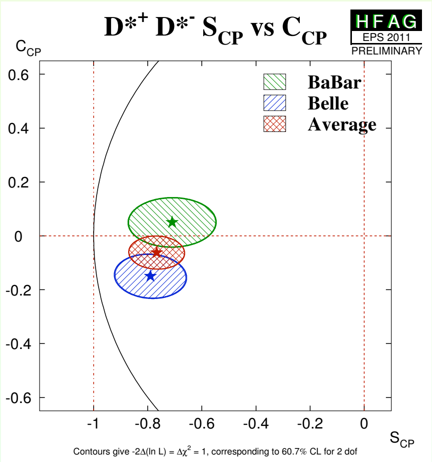


End Long Digression

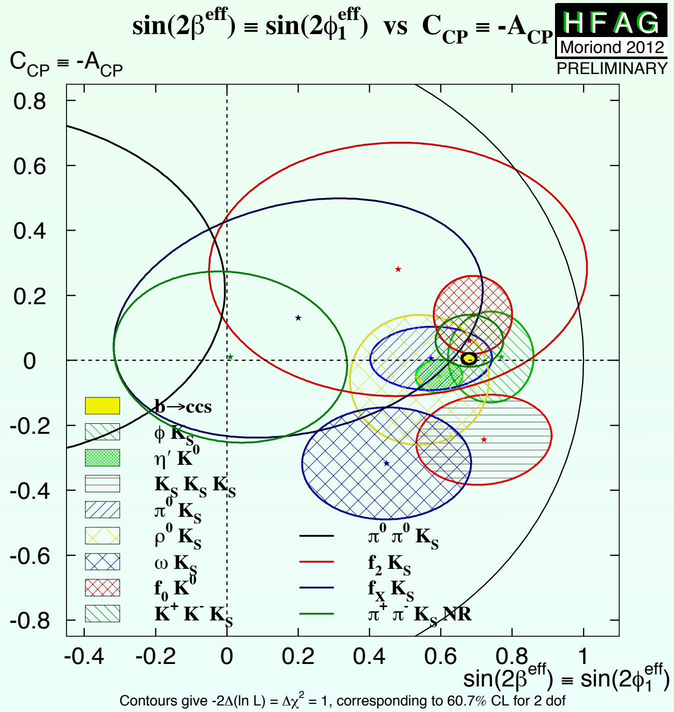
$b \to c\bar{c}d$ modes

$B^0 \to D^+D^-$	$B^0 \to D^{*+}D^{*-}$	$B^0 \to D^{\pm}D^{*\mp}$
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	$\Rightarrow C, \mathcal{S}, \mathcal{A}, \Delta\mathcal{S}, \Delta\mathcal{A}$

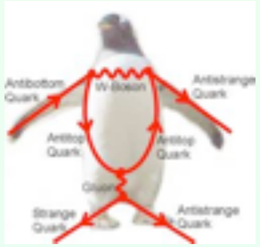




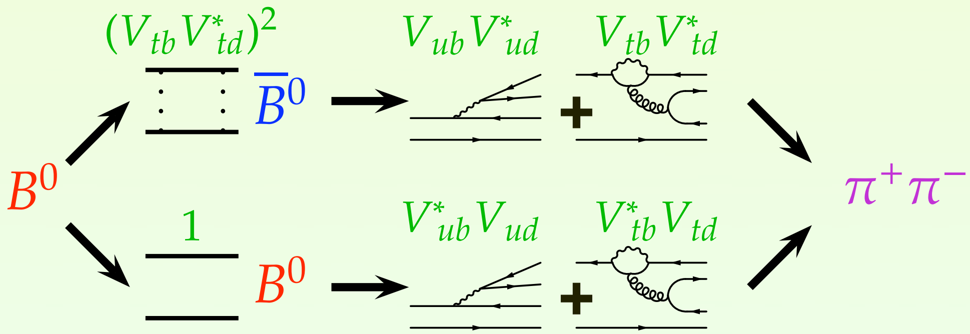
$b \to s$ penguin modes



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



α/φ_2 and Penguin Pollution

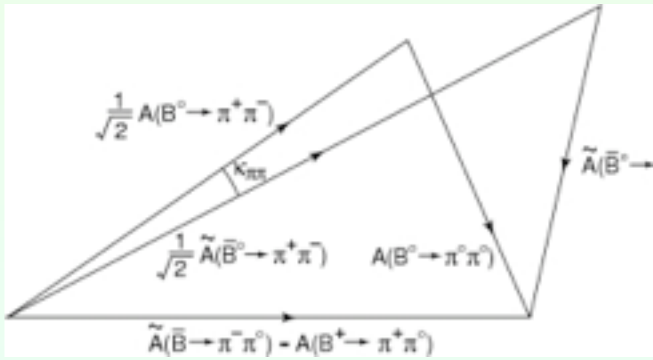


$$\Gamma(B^0) \propto e^{-t/\tau}\,(1+\mathcal{S}_{\pi\pi}\sin\Delta mt + \mathcal{A}_{\pi\pi}\cos\Delta mt)$$

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

$\mathcal{S}_{\pi\pi} = \sqrt{1-\mathcal{A}^2_{\pi\pi}}\sin 2\phi_2^{\rm eff}$, **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

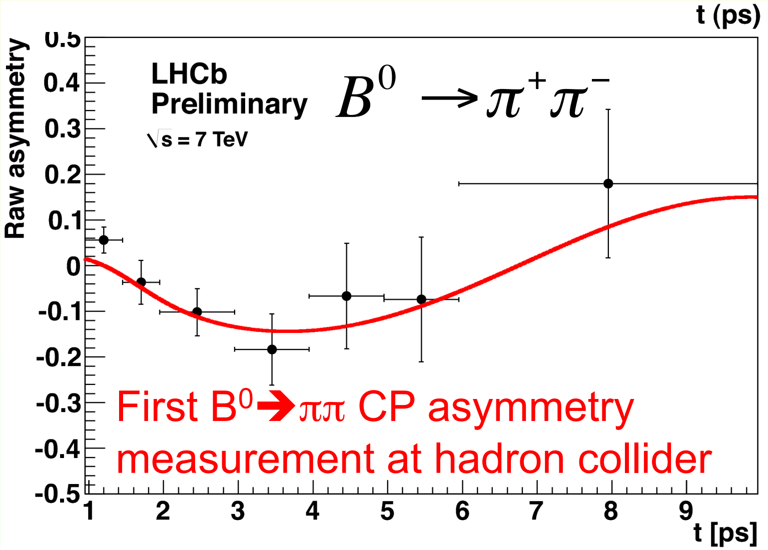


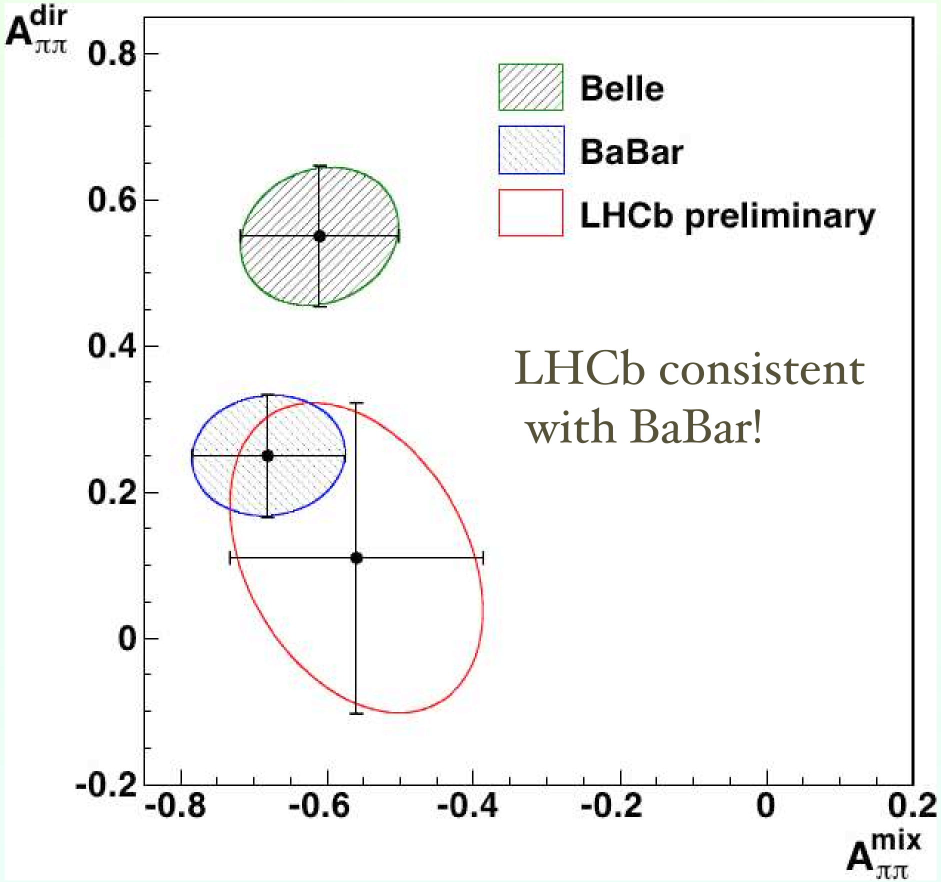
- Time-dependent Dalitz analysis [Snyder-Quinn PRD48,2139(1993)]
  - $B^0 \to \pi^+\pi^-\pi^0$ contains $\rho^+\pi^-$, $\rho^-\pi^+$, $\rho^0\pi^0$ and cross terms (interference)
  - α/φ_2 directly determined, $\rho^\pm\pi^0$ and $\rho^0\pi^\pm$ may improve further (future)

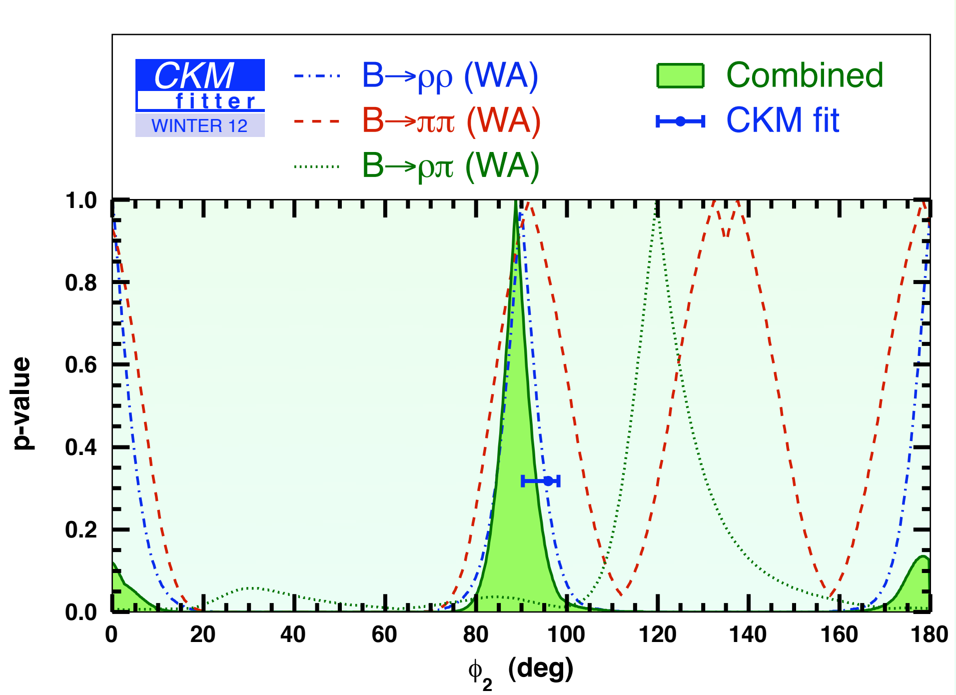
NEW form LHCb

[Paul Soler ICHEP 2012]

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







$\phi_2 / \alpha = (88.7\,^{+4.6}_{-4.2})^\circ$

[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 $\mathcal{A}(D \to \mathscr{P}\mathscr{P}) = a\Sigma + b\Delta$ $\quad \Sigma = \frac{1}{2}(V^*_{cs}V^{us} - V^*_{cd}V_{ud}), \quad \Delta = \frac{1}{2}(V^*_{cs}V_{us} + V^*_{cd}V_{ud})$

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

SU(3) analysis: five invariant amplitudes

$$\langle [8]^i_j | [\bar{6}]_{kl} | D_r \rangle = S\mathscr{T}^i_{jklr}, \quad \langle [8]^i_j | [15_M]^{kl}_m | D_r \rangle = E\mathscr{T}^{ikl}_{jmr}, \quad \langle [27]^{ij}_{kl} | [15_M]^{mn}_p | D_r \rangle = T\mathscr{T}^{ijmn}_{klpr},$$
$$\langle [8]^i_j | [3]^k | D_r \rangle = F\mathscr{T}^{ik}_{jr}, \quad \langle [1] | [3]^i | D_r \rangle = G\mathscr{T}^i_r,$$

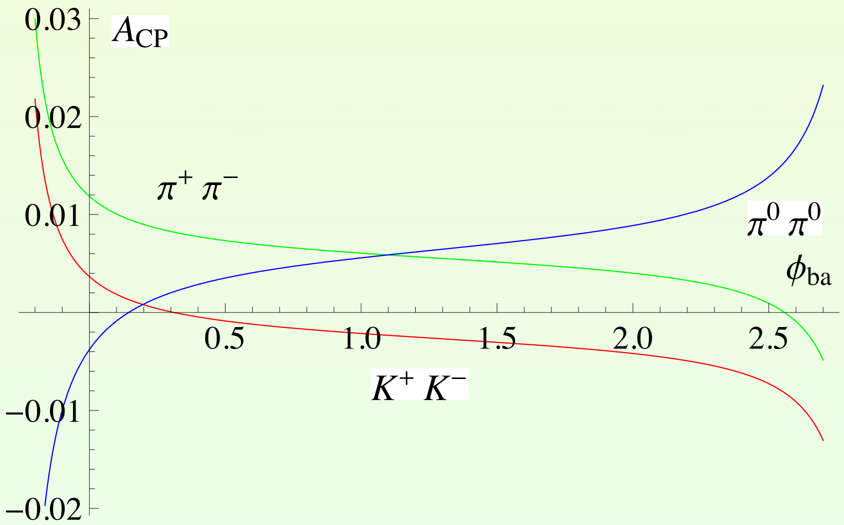
Then

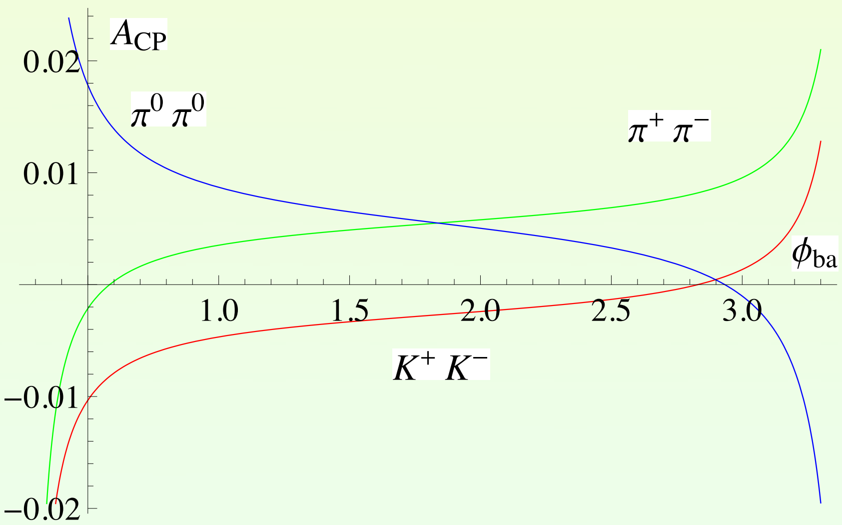
$$\mathcal{A}(D^0 \to K^+K^-) = (2T + E - S)\Sigma + \tfrac{1}{2}(3T + 2G + F - E)\Delta,$$
$$\mathcal{A}(D^0 \to \pi^+\pi^-) = -(2T + E - S)\Sigma + \tfrac{1}{2}(3T + 2G + F - E)\Delta.$$

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 ($>4\sigma$)	HFAG2012

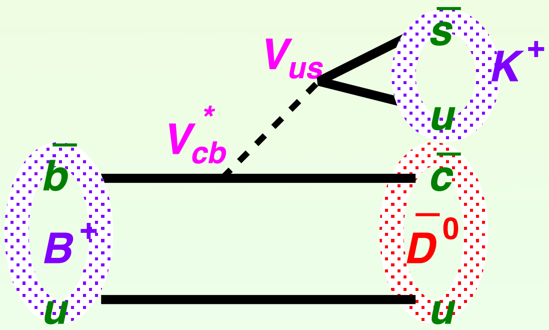
Need to search for A_{CP} in other modes

Individual A_{CP} are not significant

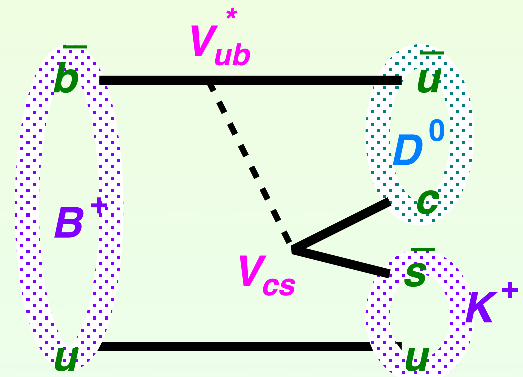
	$A_{cp}(D^0 \to K^+K^-)$ [%]	$A_{cp}(D^0 \to \pi^+\pi^-)$ [%]
CDF	$-0.24 \pm 0.22 \pm 0.09$	$+0.22 \pm 0.24 \pm 0.11$
BaBar	$0.00 \pm 0.34 \pm 0.13$	$-0.24 \pm 0.52 \pm 0.22$
Belle	$-0.32 \pm 0.21 \pm 0.09$	$+0.55 \pm 0.36 \pm 0.09$

γ/φ_3: Tree Level

$A(B^- \to D^0 K^-) \propto \lambda^3$



$A(B^- \to \bar{D}^0 K^-) \propto \lambda^3(\rho + i\eta)$



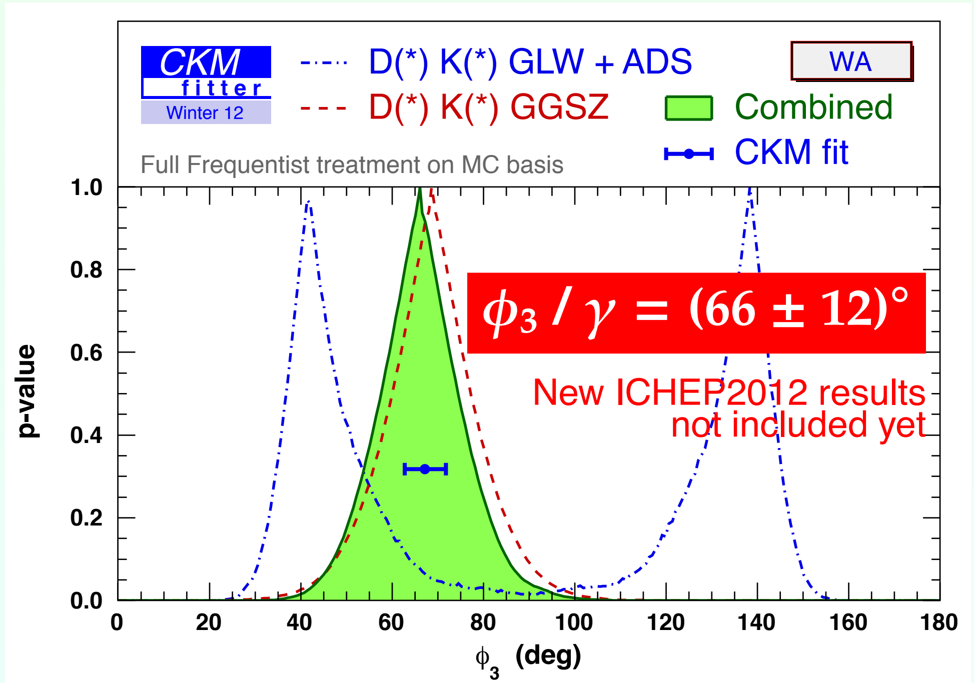
Tree only

D^0 **and** $\bar{D}^0$ **mix**

- **GLW** — $B^- \to D_{cp}K^-$ & $B^+ \to D_{cp}K^+$ ($D_{cp} \to K^+K^-, \pi^+\pi^-, K_S{}^0\,\pi^0, \ldots$)
- **ADS** — $B^- \to D^0\, K^-$ & $B^+ \to D^0\, K^+$ ($D^0 \to K^+\pi^-, K^+\pi^-\pi^0, \ldots$)
- **GGSZ** — $B \to DK$, $D \to K_S{}^0\pi^+\pi^-$, strong phase from Dalitz plot

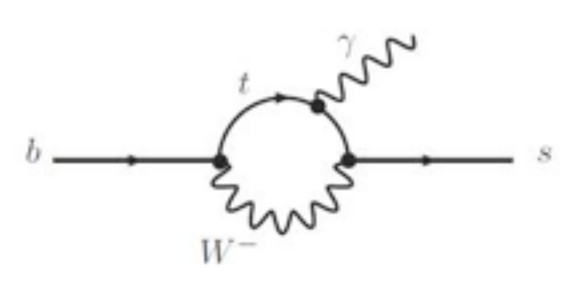
Caution: Standard analysis assumes no CPV in D decay.
CPV in D decay can shift γ/φ_3 by 5^o !
Not included yet.

[Wang, arXiv:1211.4539]



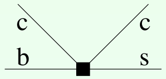
Rare decays

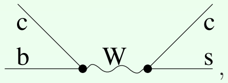
$B \to K^* \gamma$

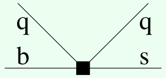


- Sensitive to NP (no tree level SM, new particles in 1-loop)
- 2HDM type II (SUSY-like) always larger than SM
- Effective theorty approach to SM calcualtion:
  - Matching (NNLO)
  - Running (NNLO)
  - Matrix elements (almost complete NNLO)

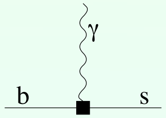
$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{QCD}\times\text{QED}}(u,d,s,c,b) + \frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{8} C_i(\mu)\, Q_i$$

$Q_{1,2} =$ 

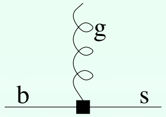
$= (\bar{s}\Gamma_i c)(\bar{c}\Gamma_i' b),$ from 

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

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

$Q_7 =$ 

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

$Q_8 =$ 

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

$|C_i(m_b)| \sim 1$

$|C_i(m_b)| < 0.07$

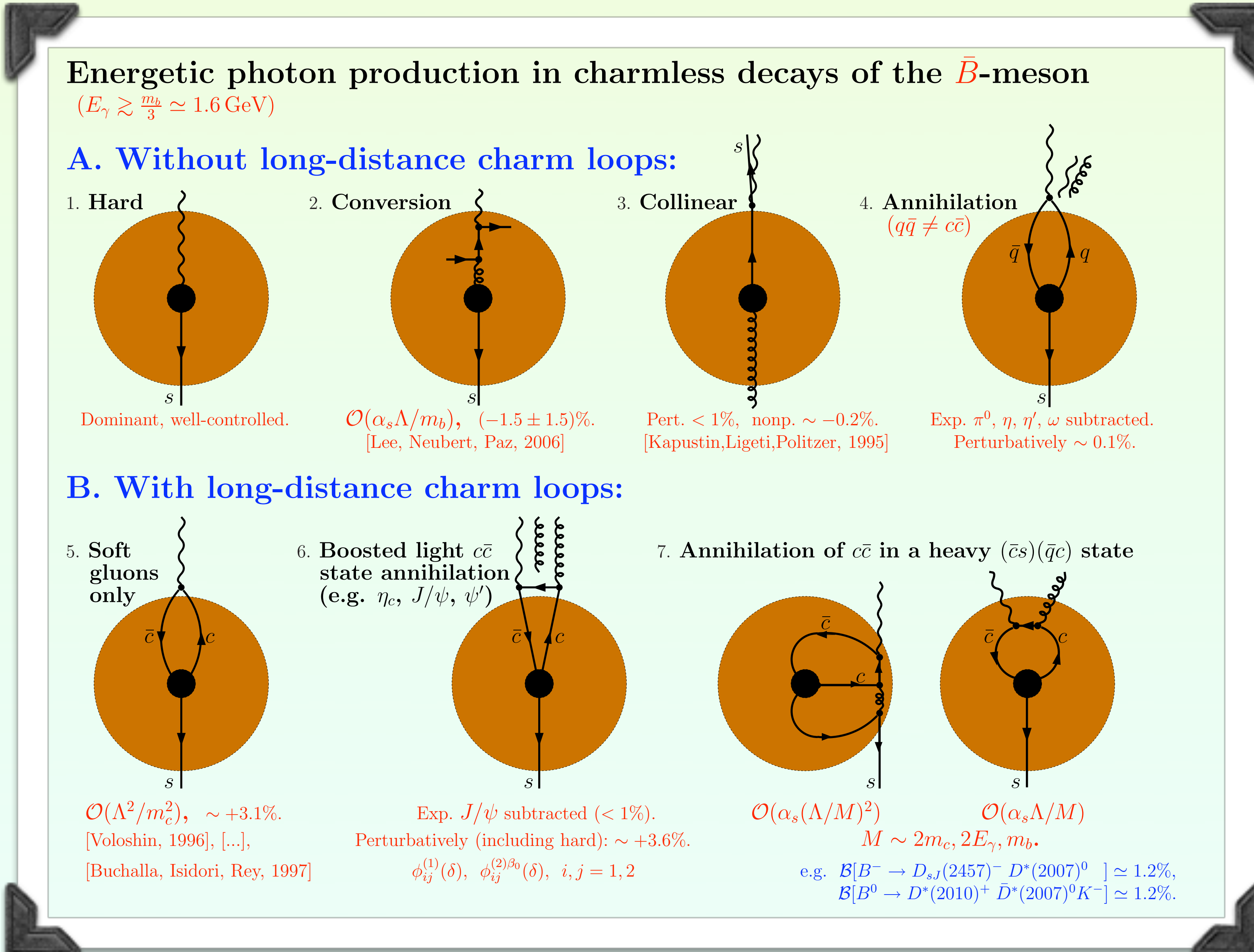
$C_7(m_b) \simeq -0.3$

$C_8(m_b) \simeq -0.15$

Known to NNLO

[Ali, ICHEP 2004]

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

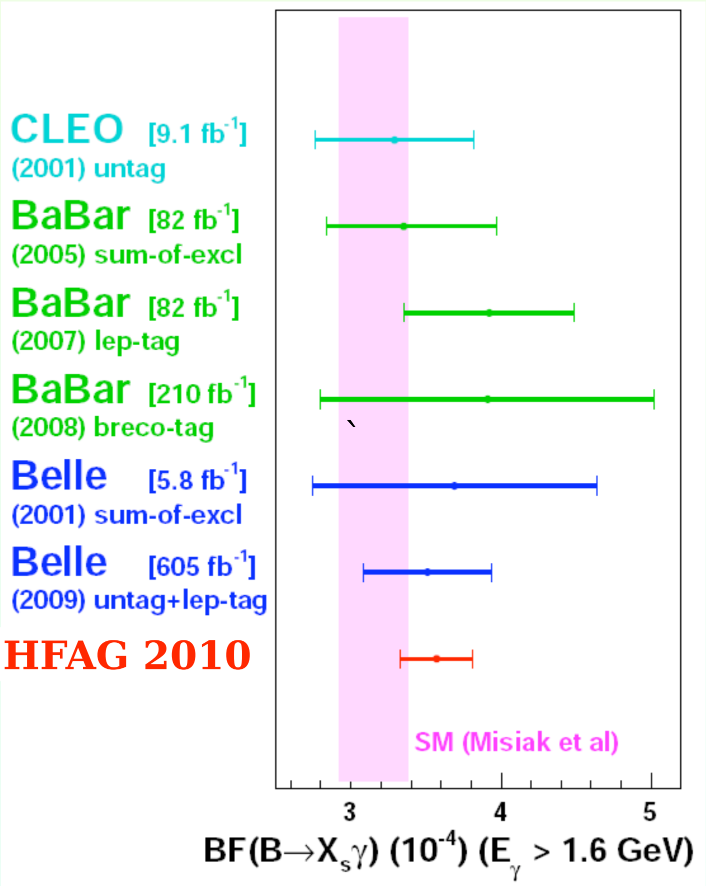


[lifted from Misiak]

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

vs

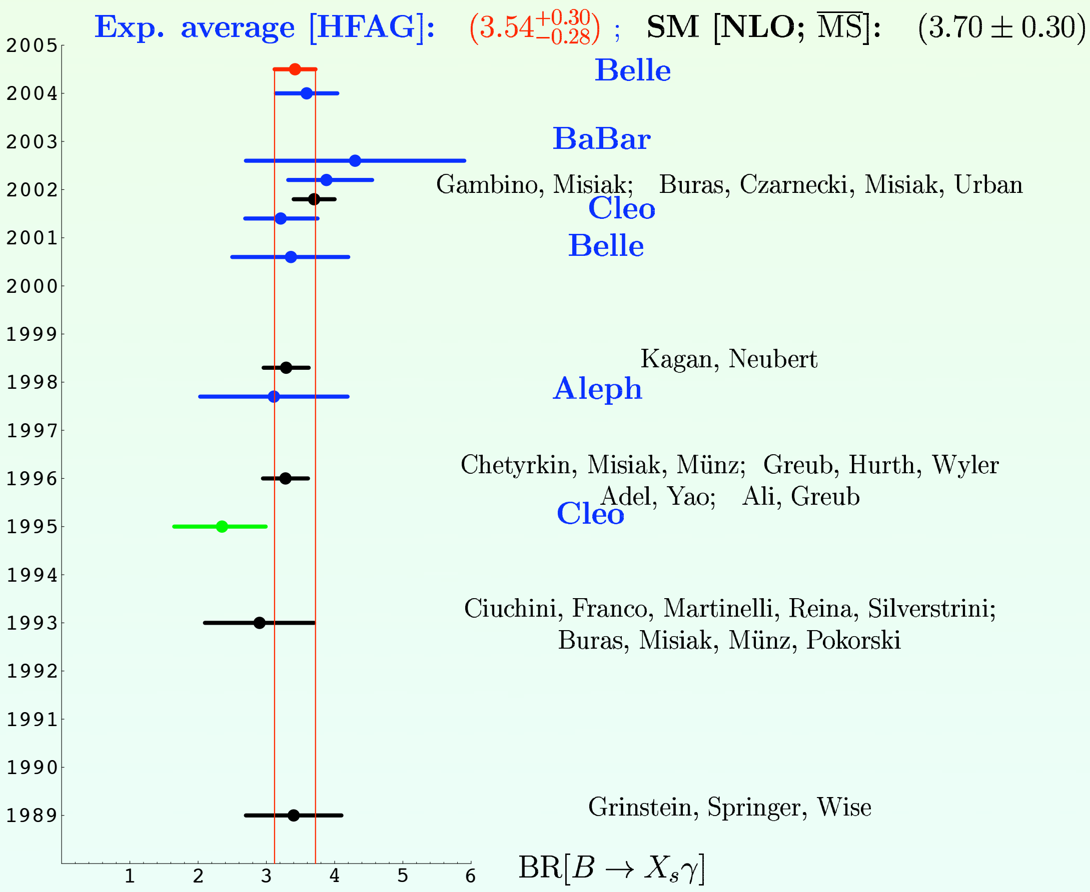
$$\text{SM}: \; B(B \to X_s \gamma) = (3.15 \pm 0.23) \times 10^{-4} \;\; (\text{for } E_\gamma > 1.6 \text{ GeV})$$



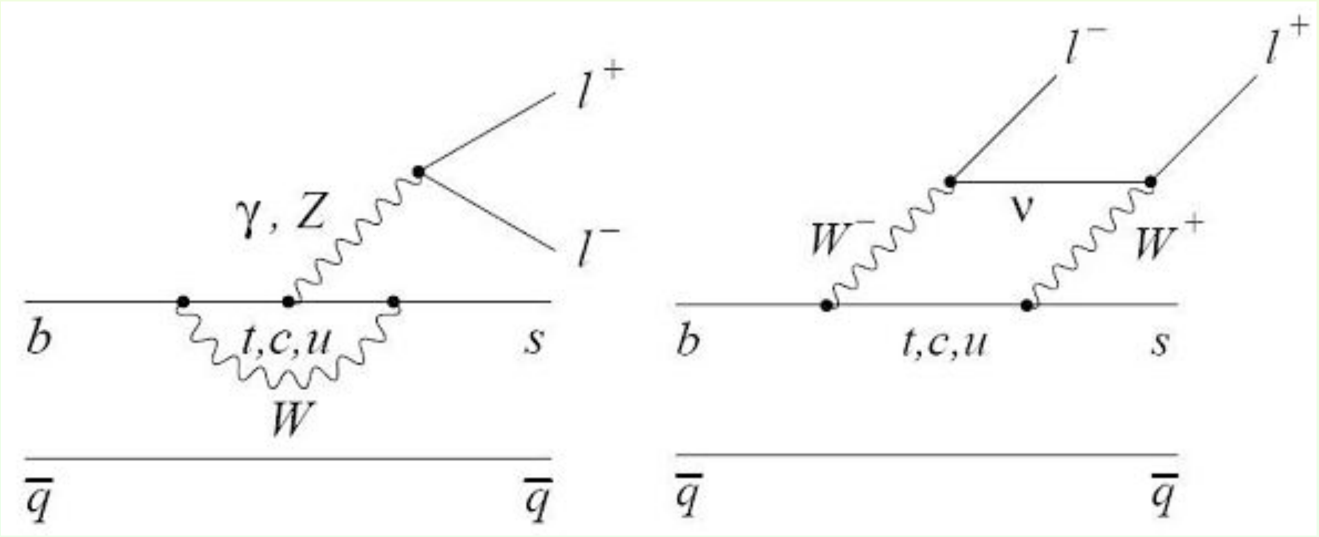
A Brief History of Time

$\mathrm{BR}[\bar{B} \to X_s\gamma]$ **(units: 10^{-4})**

Measurements & the SM calculations



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



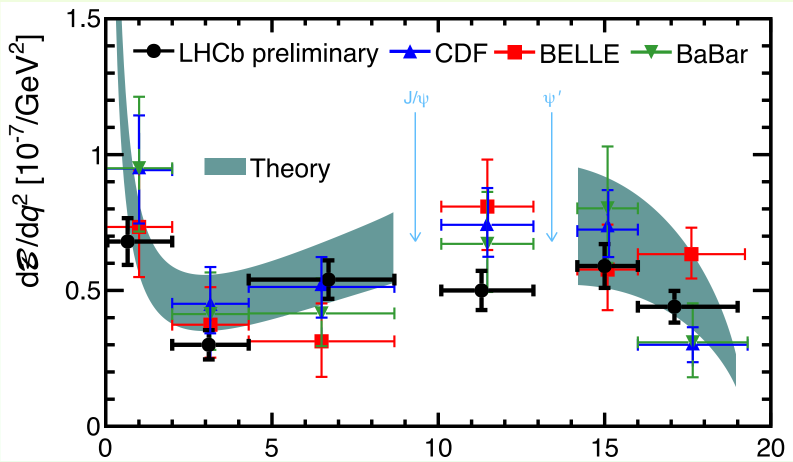
- Sensitive to NP (no tree level SM, new particles in 1-loop)
- Many variables can be studied, e.g., forward-backward asymmetry A_{FB} or Isospin asymmetry:

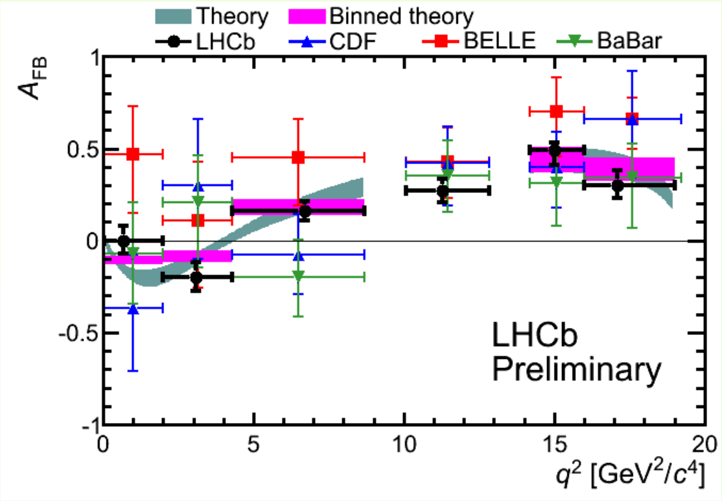
$$A_I = \frac{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) - \frac{\tau_0}{\tau_+}\mathcal{B}(B^\pm \to K^{(*)\pm}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) + \frac{\tau_0}{\tau_+}\mathcal{B}(B^\pm \to K^{(*)\pm}\mu^+\mu^-)}$$

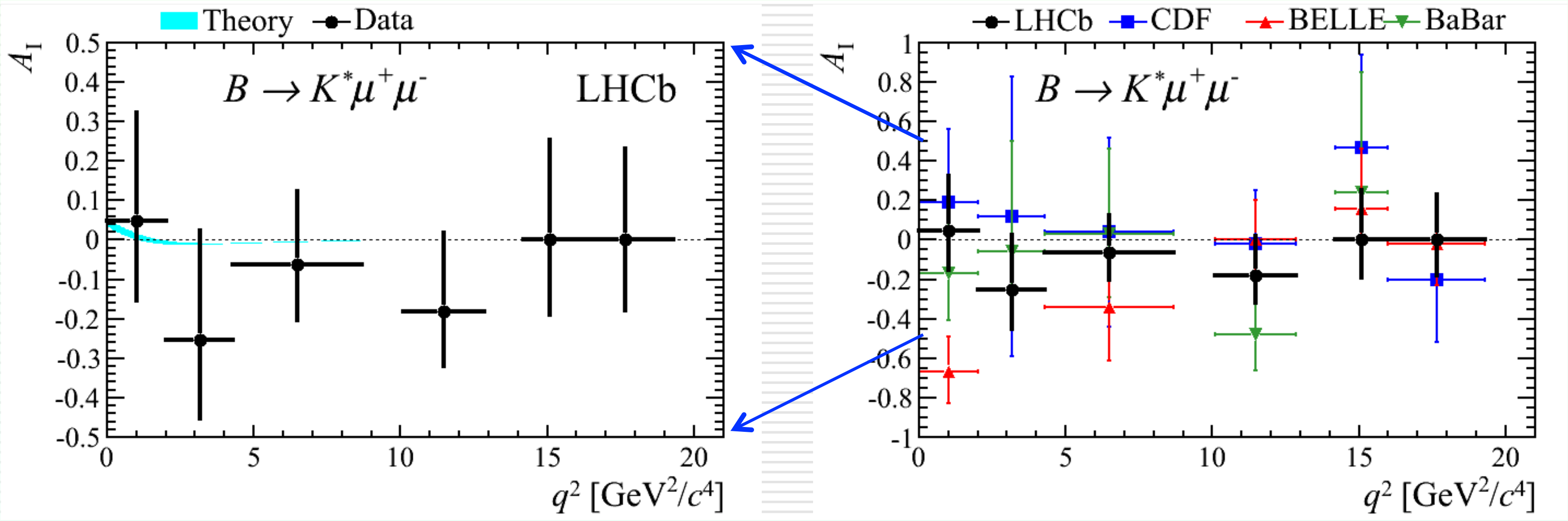
- Charmonium resonance region must be excluded ($B \to K^{(*)}\psi \to K^{(*)}l^+l^-$)
  - Small $q^2 = (p_+ + p_-)^2$, large recoil energy for $K^{(*)}$, use SCET
  - Large q^2, use HQET
  - SM: fairly clean prediction of location of zero in A_{FB}, negligible A_I

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

[Gallas, ICHEP 2012]







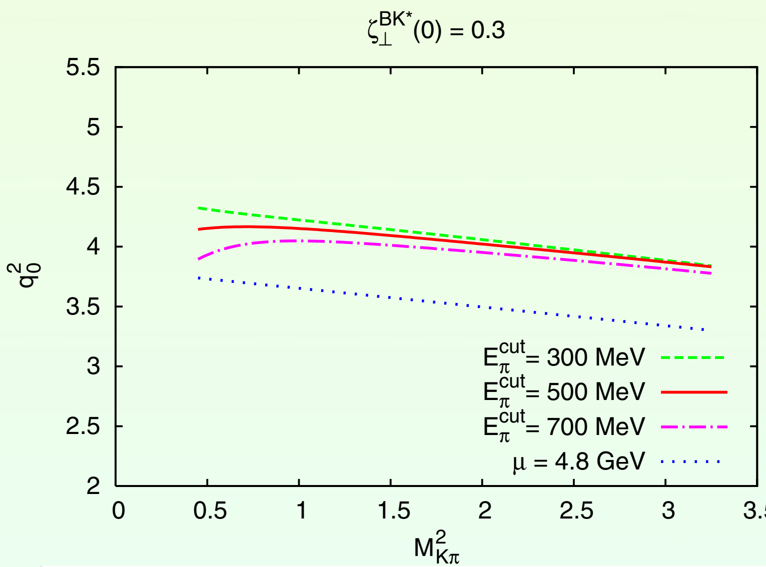
No hint of NP here!

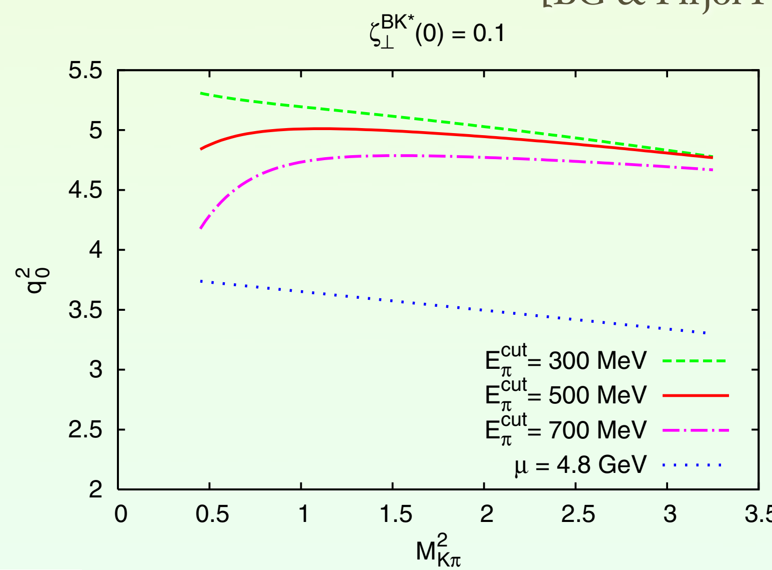
A_{FB} zero

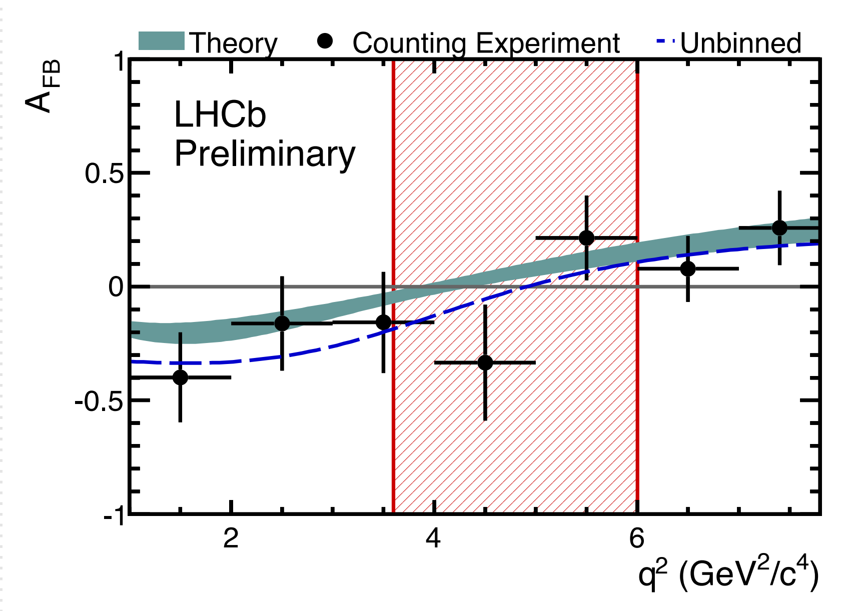
[Burdman]

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

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

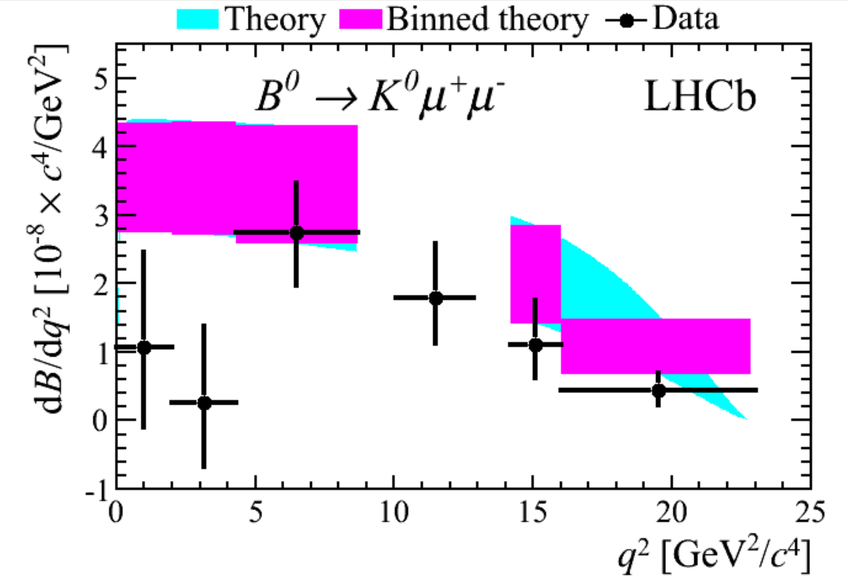






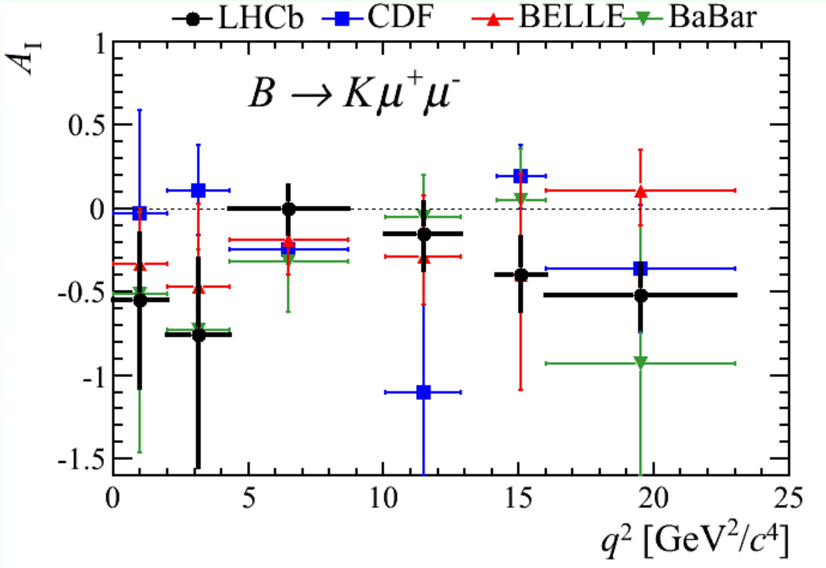
The world's first measurement of q^2_0, at $q^2_0 = 4.9^{+1.1}_{-1.3}$ GeV^2/c^4 [Preliminary]

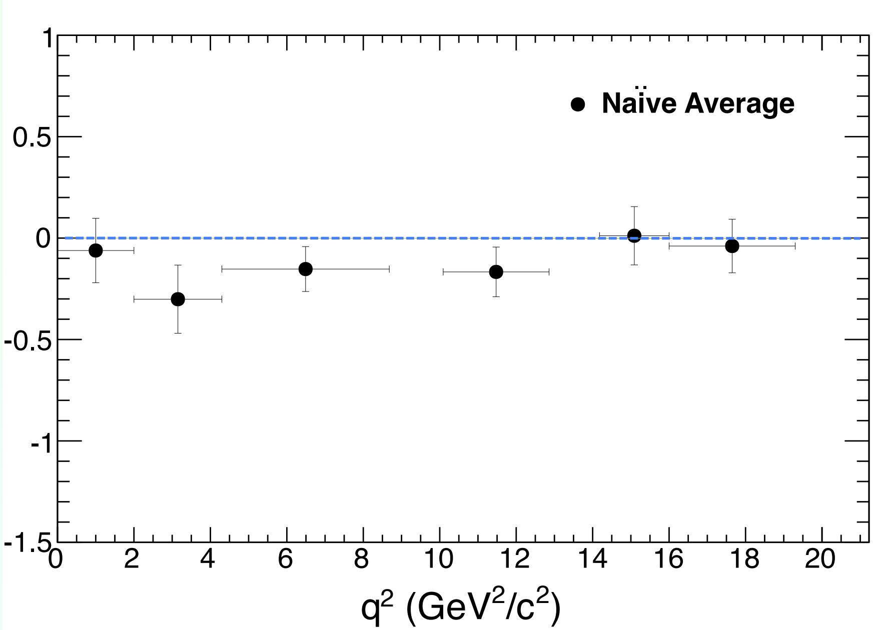
$B \to K l^+ l^-$



Discrepant with SM predictions:

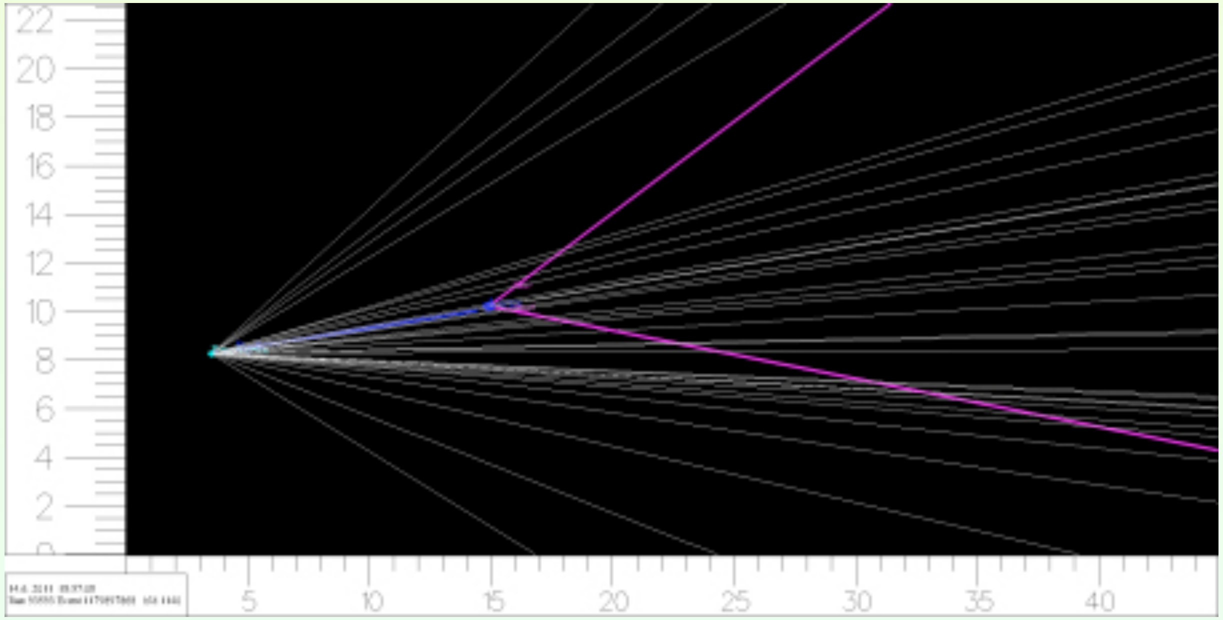
- Low rate at low q^2
- A_I negative throughout
  - LHCb alone: 4.2σ from zero
  - Why in K, but not in K^*?
  - NP models?



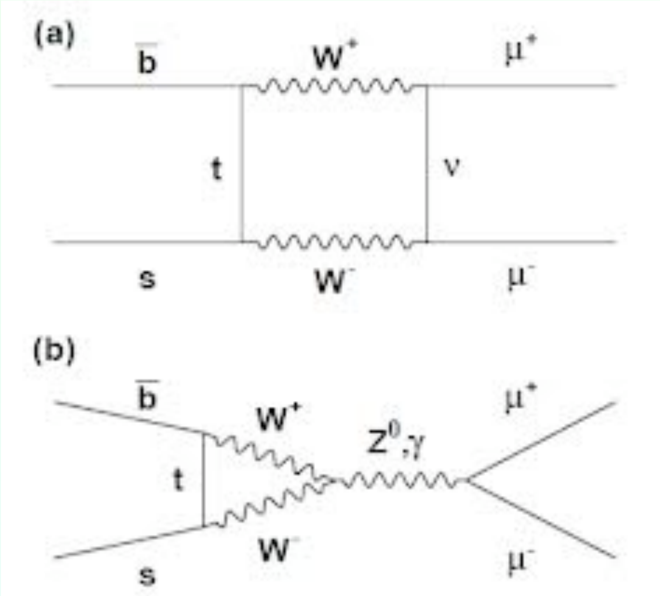


$B \to \mu^+\mu^-$

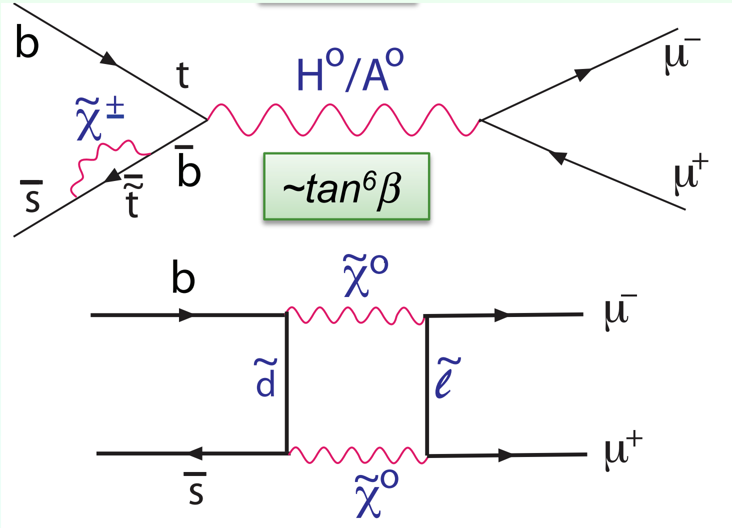
Reconstructed $B \to \mu^+\mu^-$ event from the LHCb Collaboration
[muon.wordpress.com]



Sensitive to NP:



SM



MSSM

SM Theory

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:

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

They obtain:

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

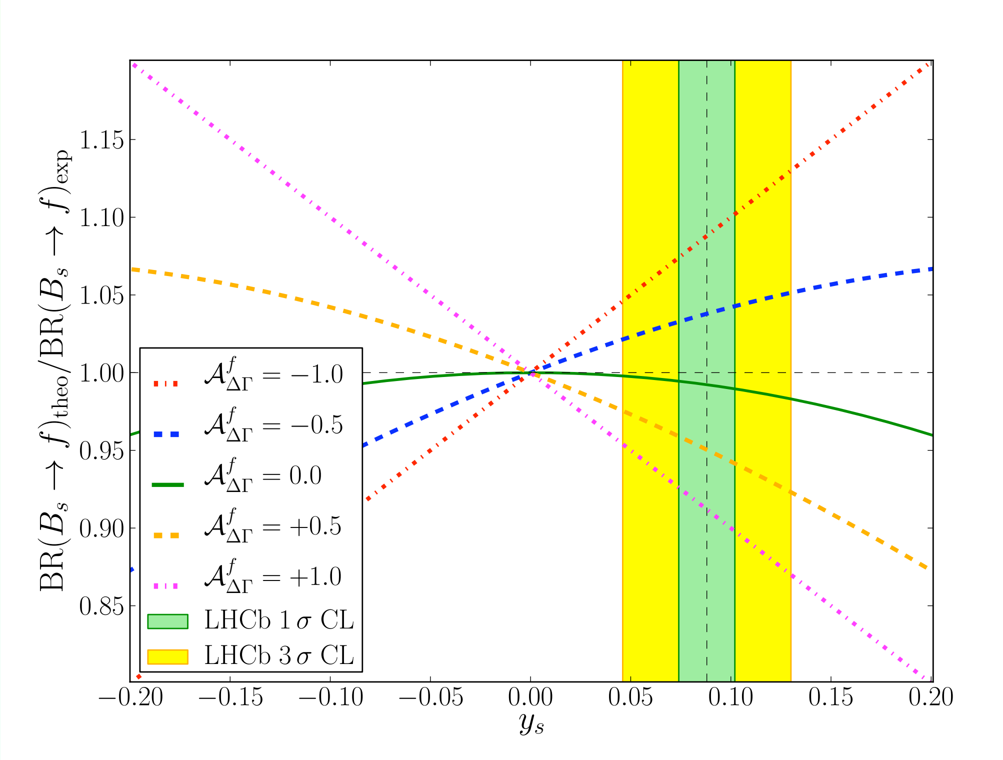
where

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

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

$B_s \to f$	$\mathrm{BR}(B_s \to f)_{\mathrm{exp}}$ (measured)	$\mathcal{A}^f_{\Delta\Gamma}(\mathrm{SM})$	$\mathrm{BR}(B_s \to f)_{\mathrm{theo}}/\mathrm{BR}(B_s \to f)_{\mathrm{exp}}$ 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

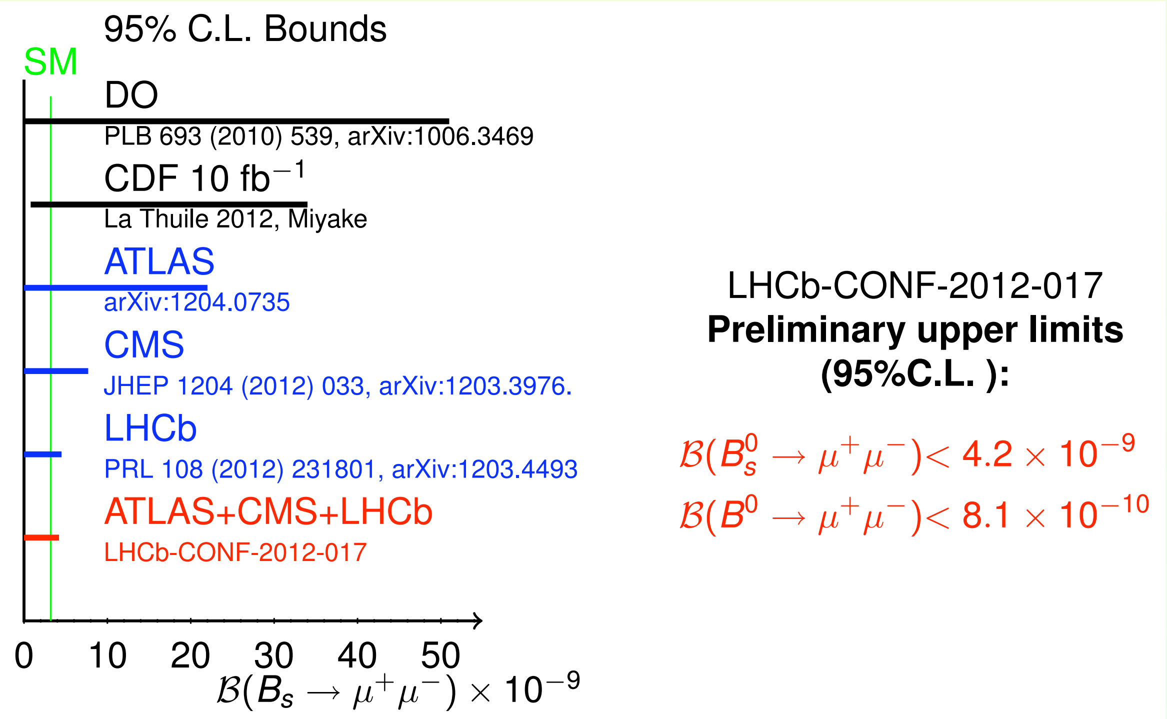
Large corrections!



more generally

End Digression

As of July 2012 (ICHEP) bounds only



LHCb measurement (Nov 2012)

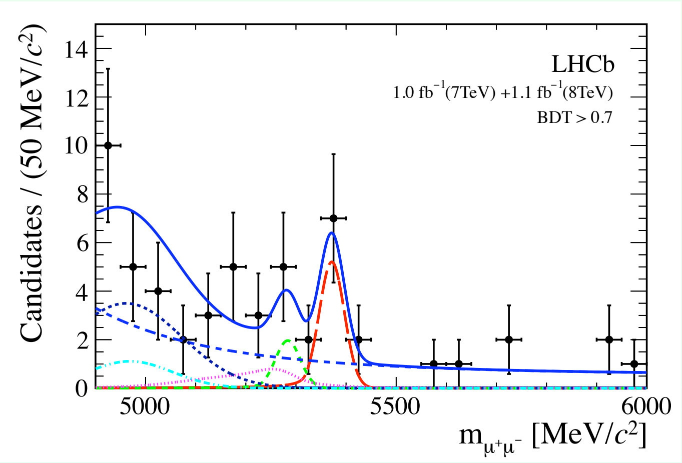
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.2\,^{+1.4}_{-1.2}(\text{stat})\,^{+0.5}_{-0.3}(\text{syst})) \times 10^{-9}$$

recall:

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

Also new (best) bound:

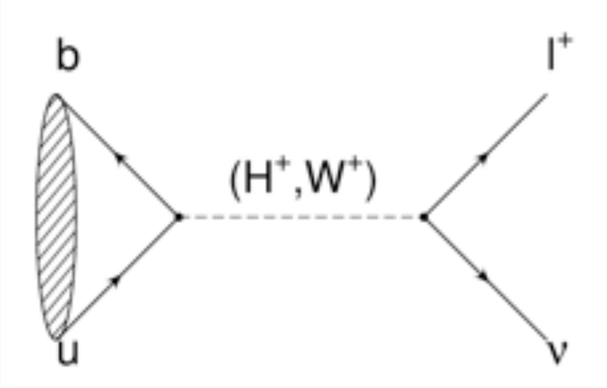
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 9.4 \times 10^{-10}$$



[LHCb, arXiv:1211.6093]

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

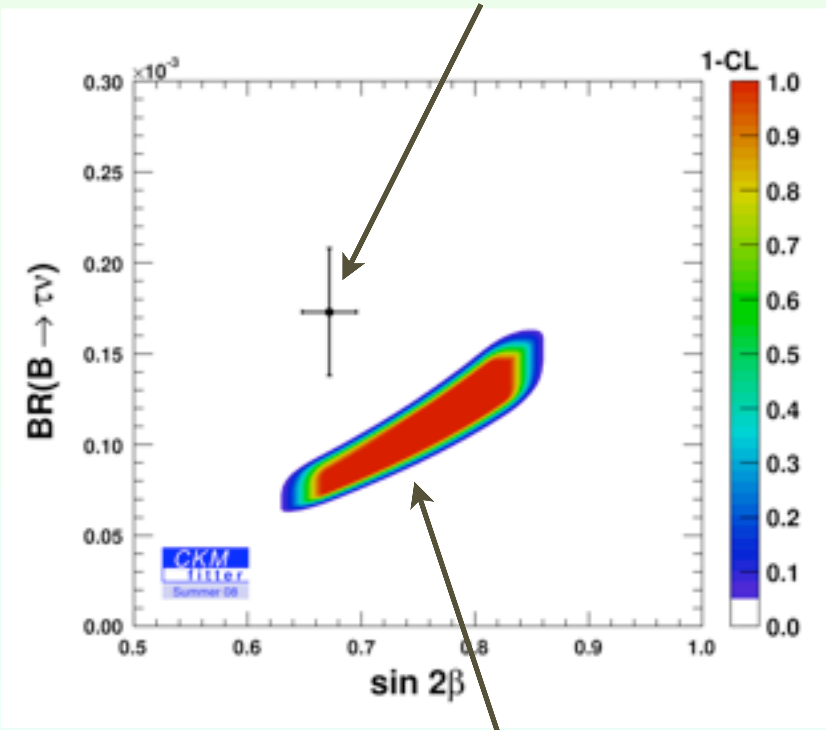
$$\Gamma(B \to \tau\nu) = \frac{G_F^2 m_B}{8\pi} m_\tau^2 \left(1 - m_\tau^2/m_B^2\right)^2 f_B^2 |V_{ub}|^2$$

- 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 $B^0 \to \psi K_S$

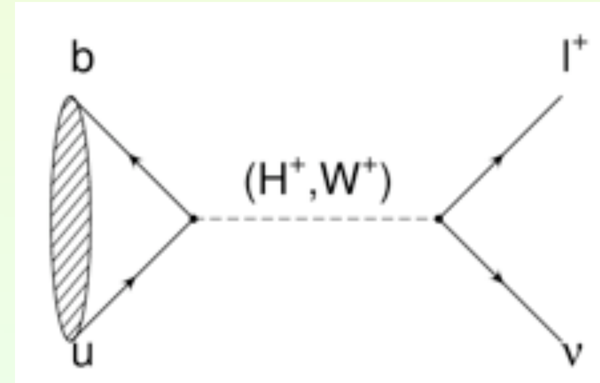
- But NEW Belle result [arXiv:1208.4678]

W.A. summer 2008



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

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



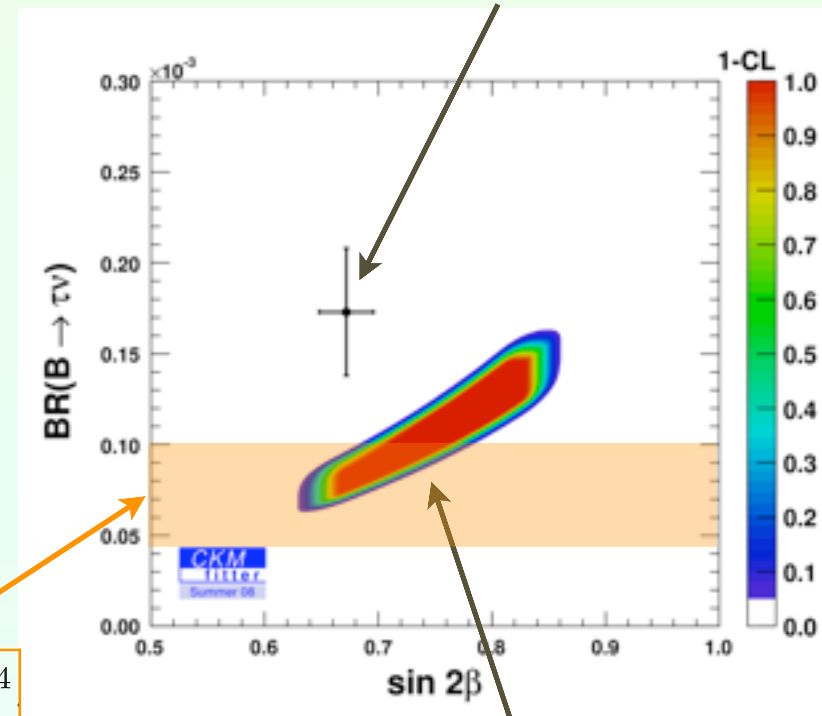
- $B^{-} \to \tau^{-} \nu$ in SM is tree level
- Clean SM prediction, lattice gives f_B

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

- 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]

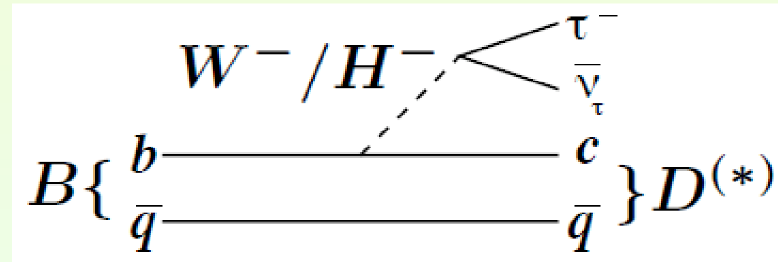
$$\boxed{\mathcal{B}(B^{-} \to \tau^{-} \bar{\nu}_\tau) = [0.72^{+0.27}_{-0.25}(\mathrm{stat}) \pm 0.11(\mathrm{syst})] \times 10^{-4}}$$

W.A. 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

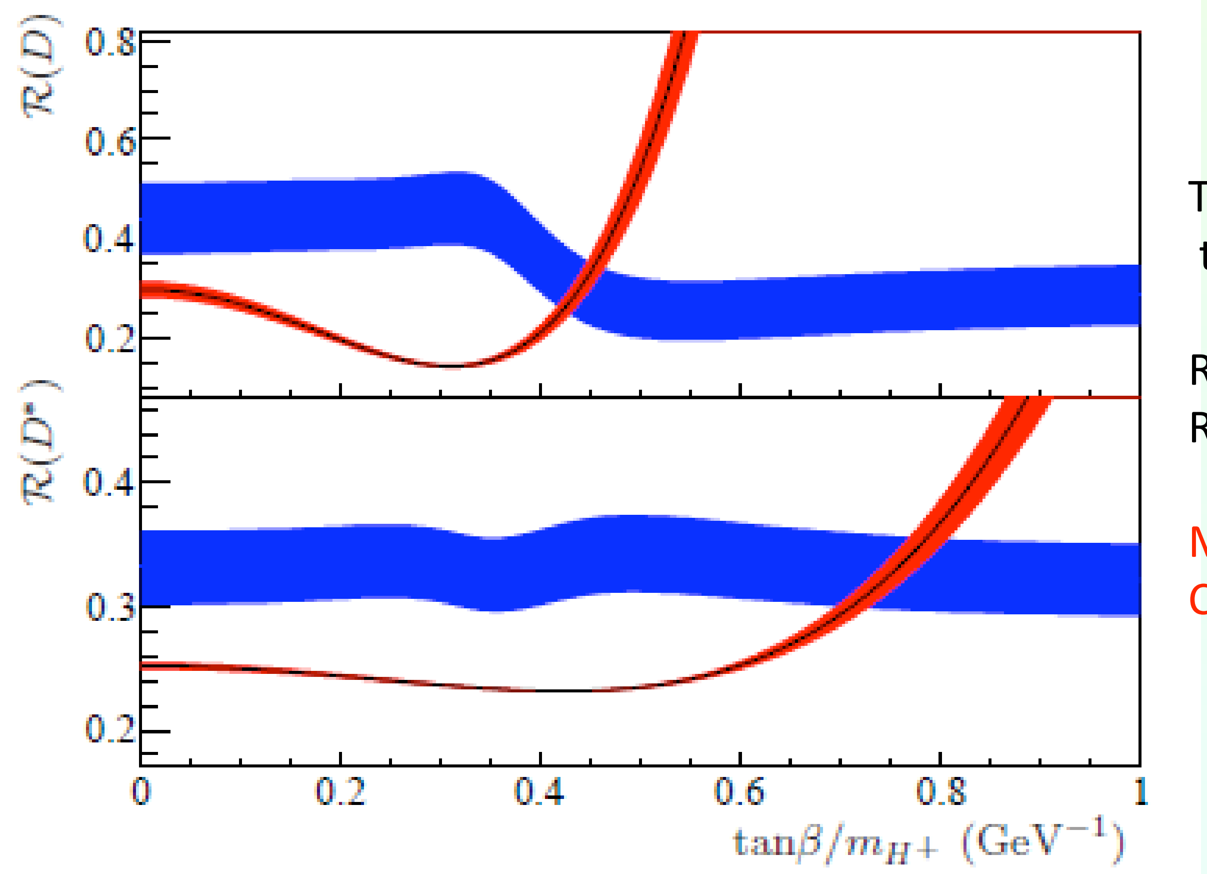
Combination of measurements also inconsistent with 2HDM

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 $D\tau\nu$
+for $D^*\tau\nu$

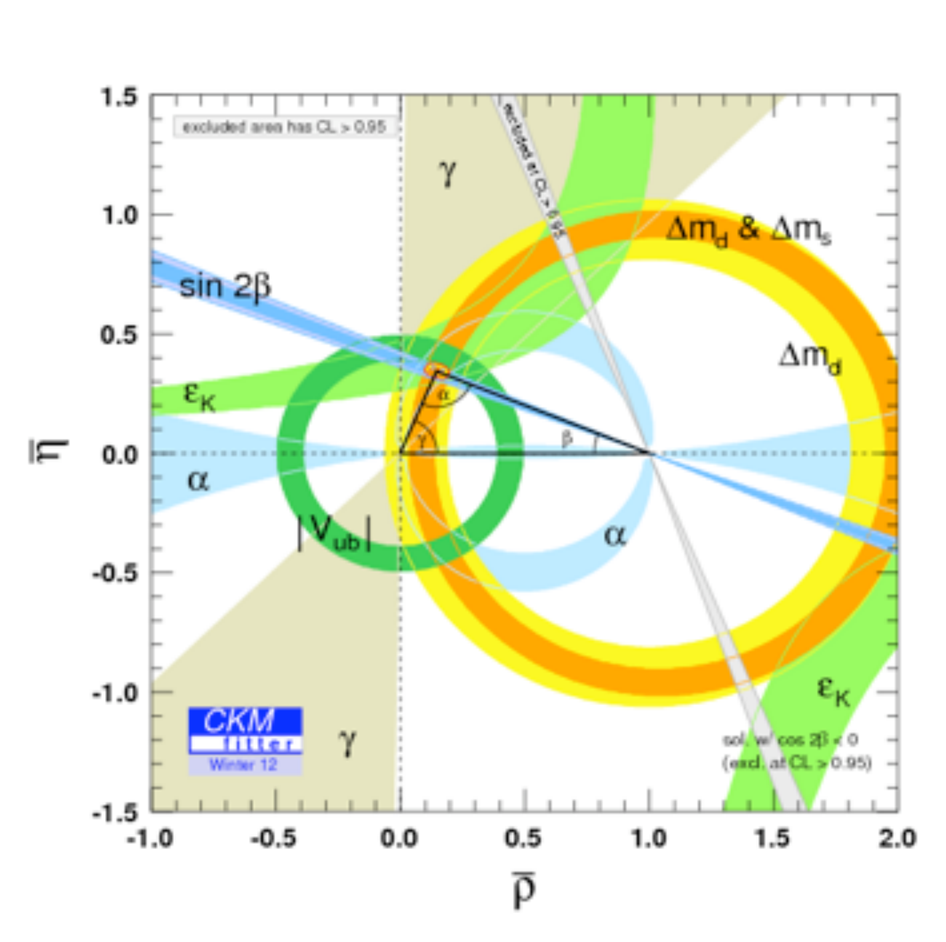


Taking into account the effect of $\tan\beta/m_H$ on efficiency

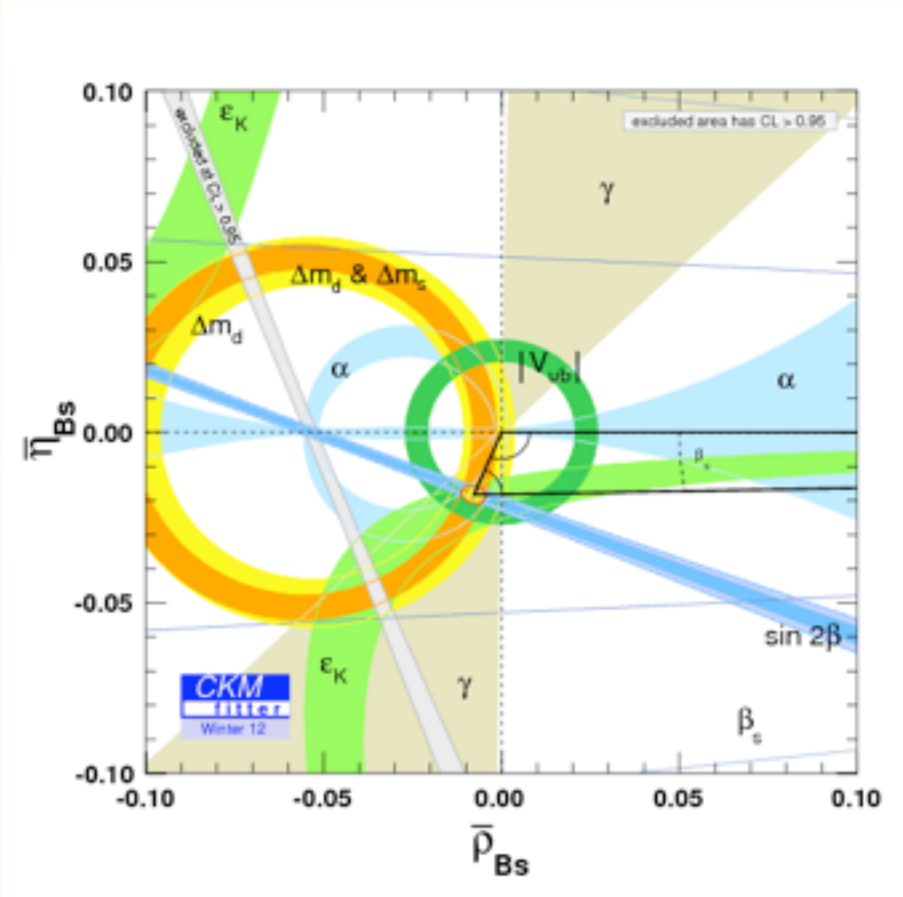
R(D) → $\tan\beta/m_H = 0.44 \pm 0.02$
R(D*) → $\tan\beta/m_H = 0.75 \pm 0.04$

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
$\bar\eta$
$\bar\rho$



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
$\bar\eta_{Bs}$
$\bar\rho_{Bs}$

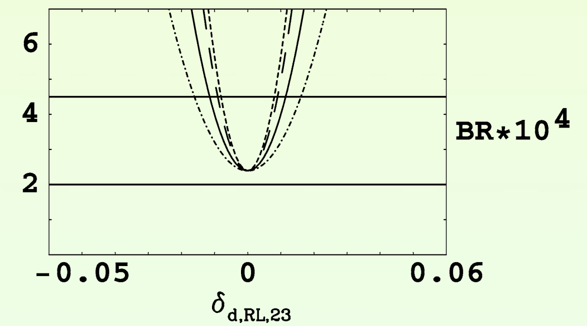
Don’t forget: General MSSM lives in a straightjacket because of flavor

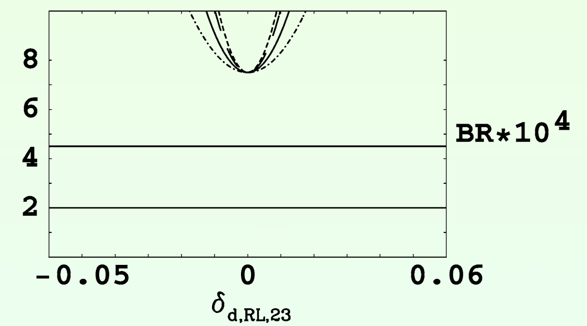
General MSSM

Ruled out unless squarks almost degenerate
Assume small

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

and bound

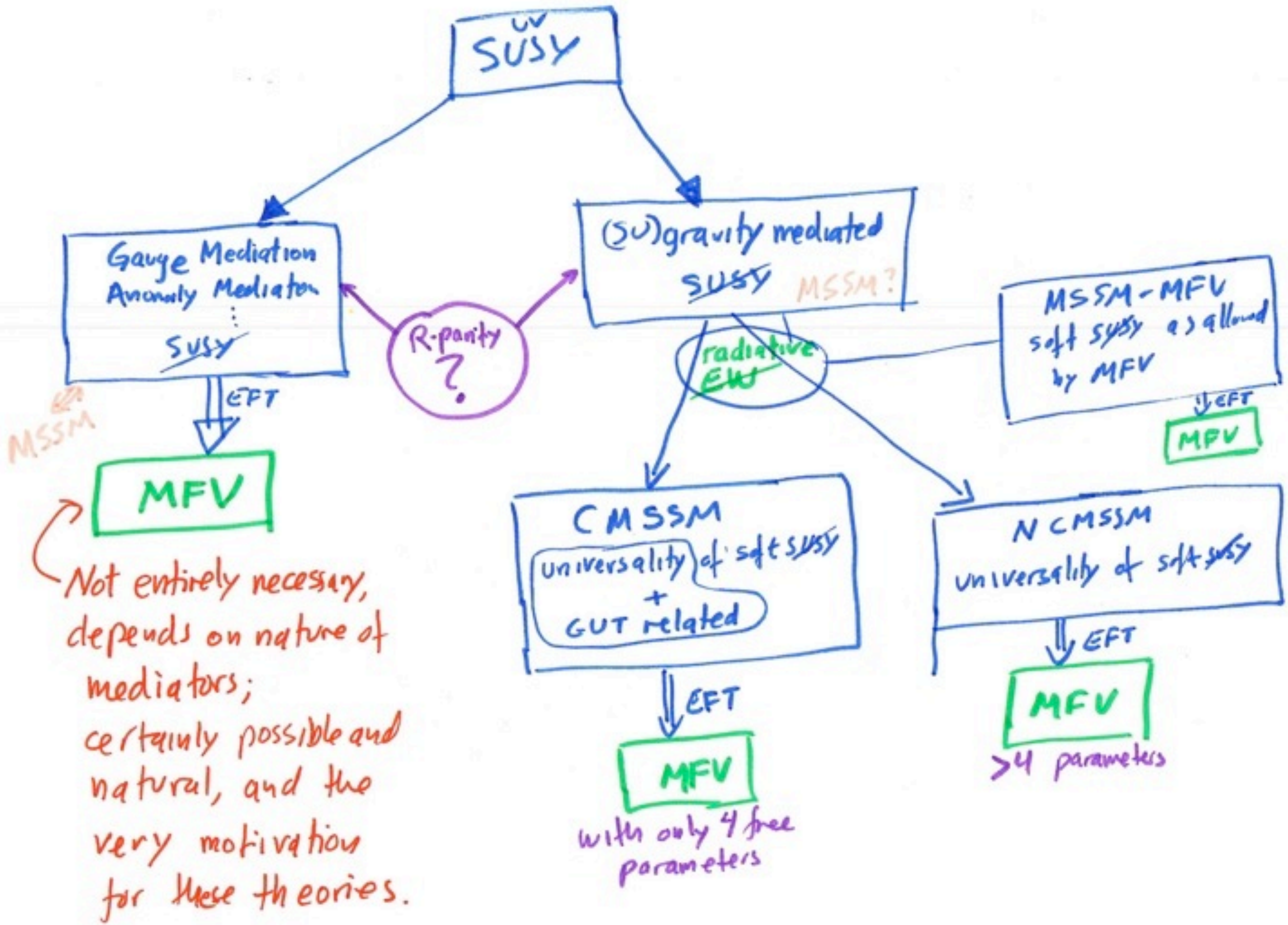




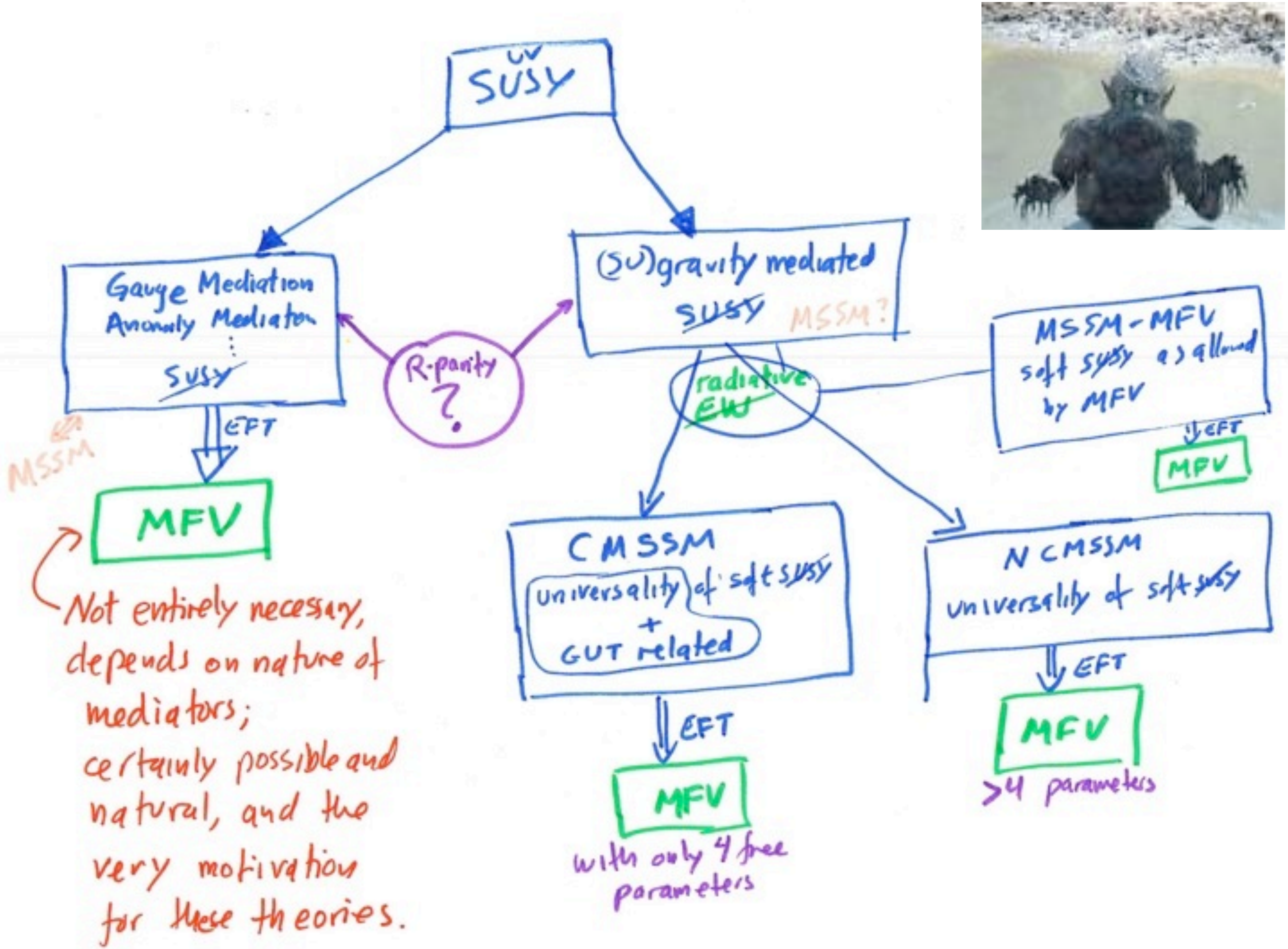
Besmer et al, NPB609:359,2001

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

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


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
CMSSM
universality of soft susy
+
GUT related
NCMSSM
universality of soft susy
with only 4 free parameters
>4 parameters
Not entirely necessary, depends on nature of mediators; certainly possible and natural, and the very motivation for these theories.

[BG, FPCP2009]


UV SUSY
Gauge Mediation
Anomaly Mediation
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MSSM?
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radiative EWSB
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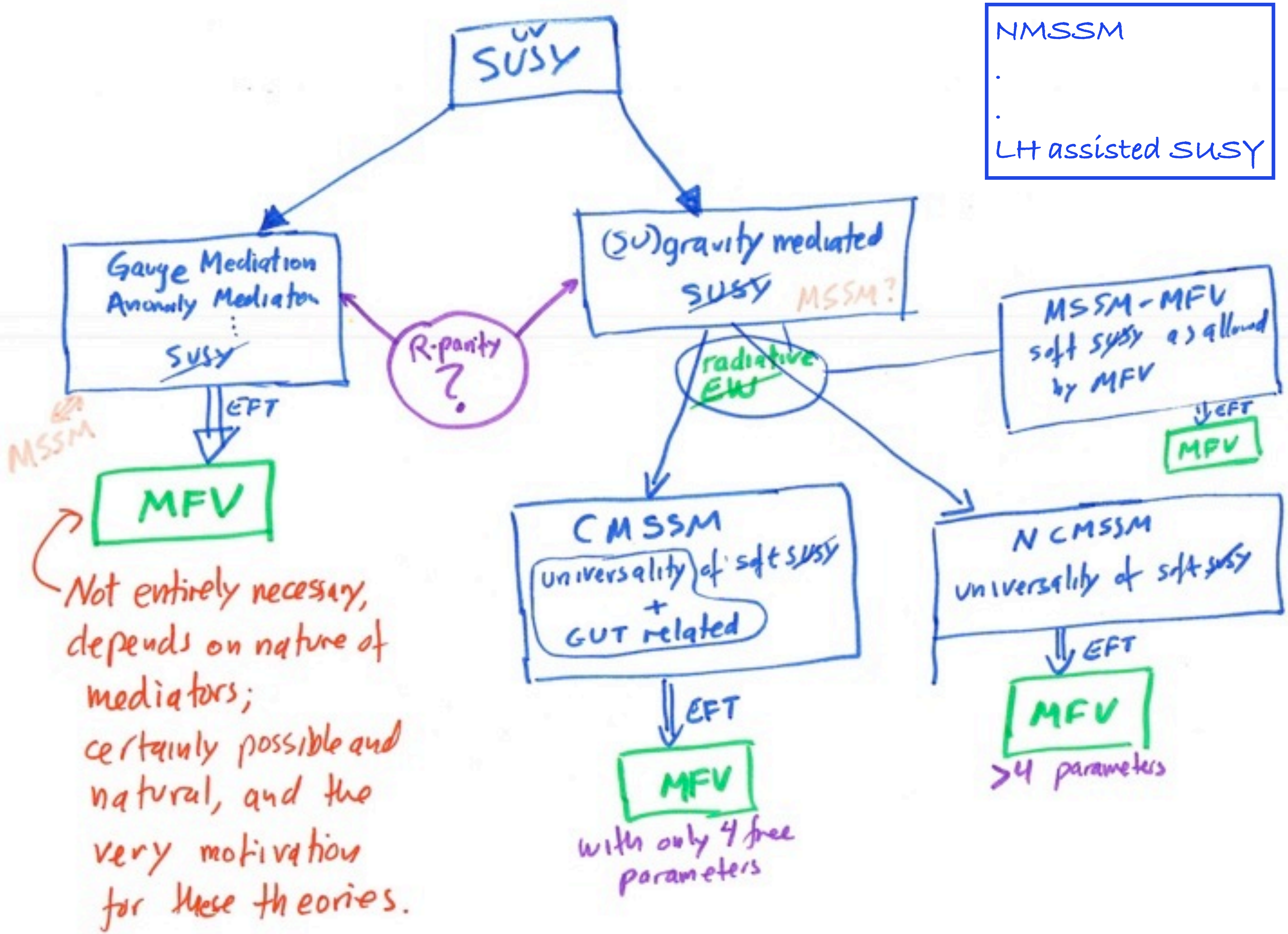
MFV
>4 parameters

[BG, FPCP2009]



UV SUSY
NMSSM
.
.
LH assisted SUSY
Gauge Mediation
Anomaly Mediation
SUSY
R-parity ?
(SU)gravity mediated SUSY
MSSM?
radiative EWSB
MSSM-MFV
soft susy as allowed by MFV
EFT
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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
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MFV
with only 4 free parameters
NCMSSM
universality of soft susy
EFT
MFV
>4 parameters

[BG, FPCP2009]

Implications for NP searches

- With few exceptions, no deviations from SM
- Exceptions (some are going away already):
  - $B^- \to \tau^- \nu$, $B^- \to D\tau^- \nu$, $B^- \to D^* \tau^- \nu$
  - Isospin asymmetry A_I
  - Flavor specific CP asymmetry a_{sl}
- Bounds on NP require specific choices:
  - infinitely many variations of SUSY
  - variations on extra-dimensions
  - techni-color (strongly coupled higgs sector with dilaton)
  - ....
- Standard practice to give updated bounds
  - Interesting to review bounds form the past (perspective)

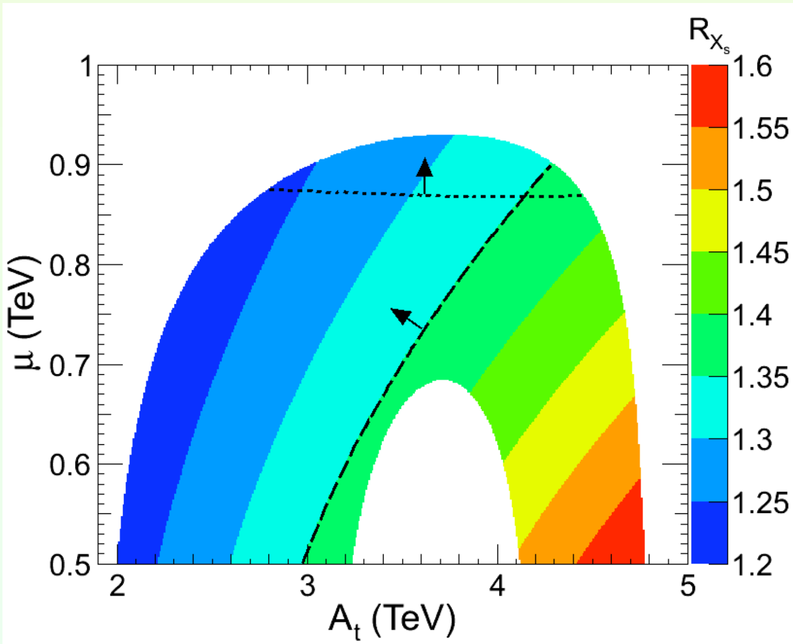
CMSSM

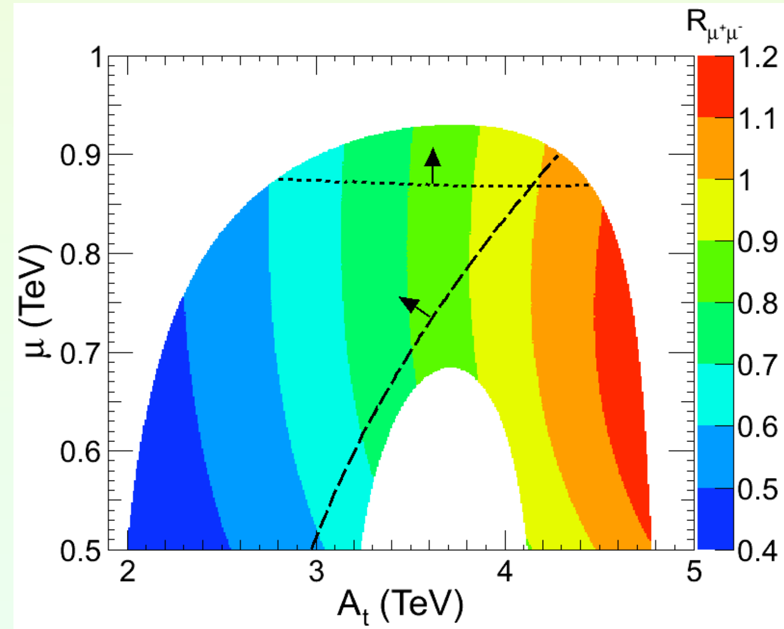
[Haisch & Mahmoudi, arXiv:1210.7806]

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

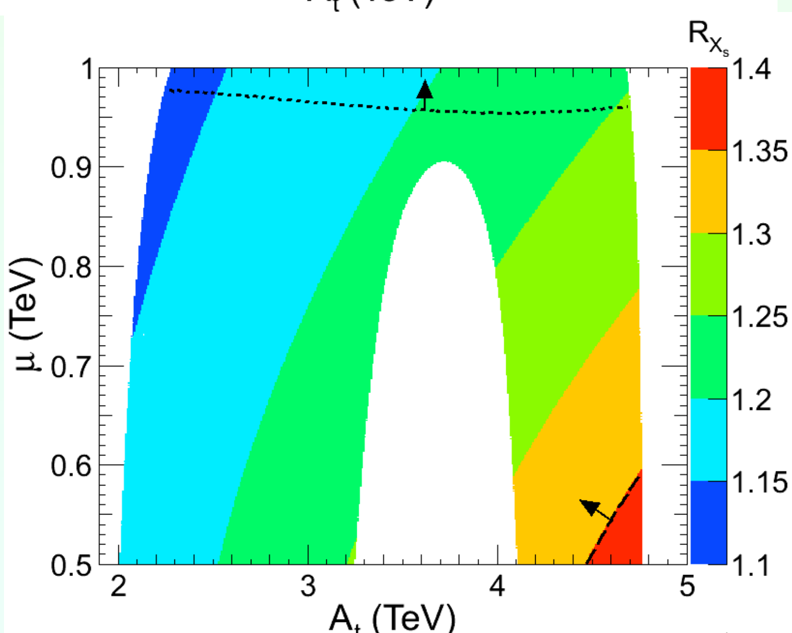
$$R_{X_s} = \frac{\mathrm{BR}(B \to X_s\gamma)_{\rm MSSM}}{\mathrm{BR}(B \to X_s\gamma)_{\rm SM}} \qquad R_{\mu^+\mu^-} = \frac{\mathrm{BR}(B_s \to \mu^+\mu^-)_{\rm MSSM}}{\mathrm{BR}(B_s \to \mu^+\mu^-)_{\rm SM}}$$

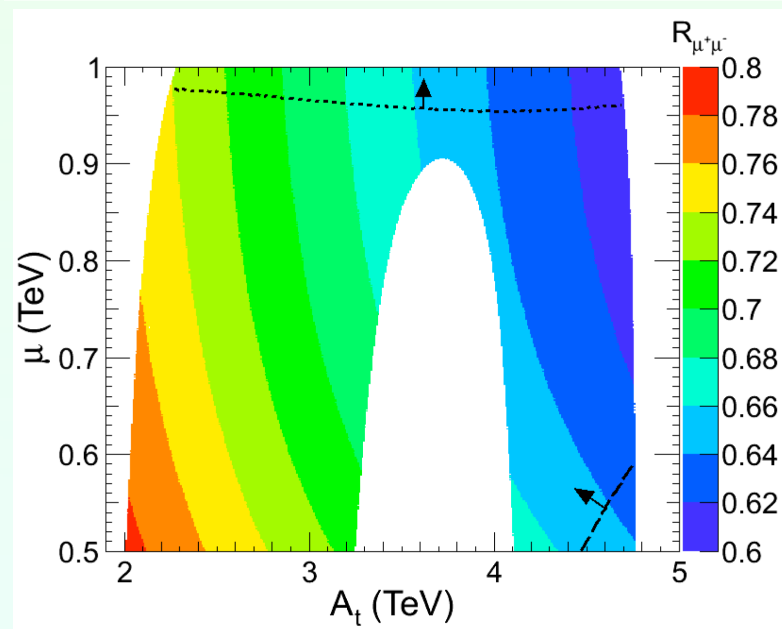
$\tan\beta = 60$





$\tan\beta = 30$



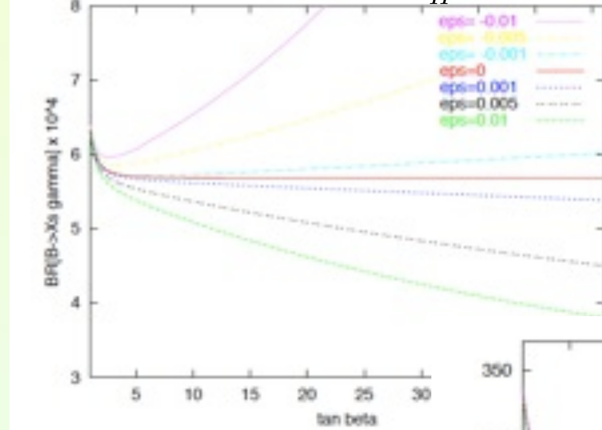


you can't see all parameters here, some have been fixed by higgs flash back, 3 years ago...

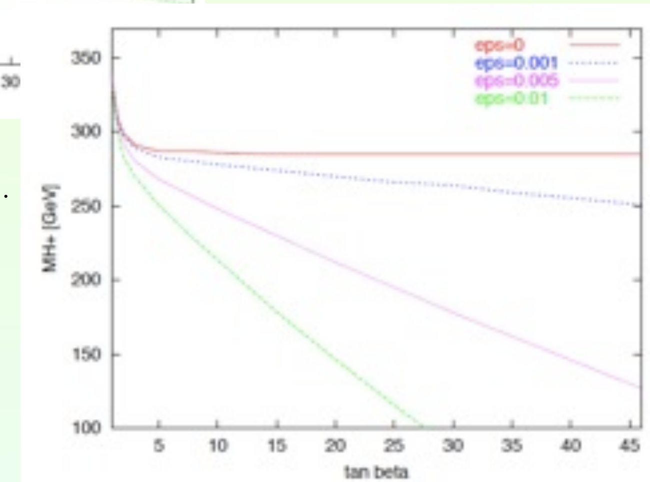
Slide taken again from BG FPCP2009

CMSSM (at large tan β, possibly)

$M_H = 150$ GeV



[Degrassi et al, arXiv:0009337]

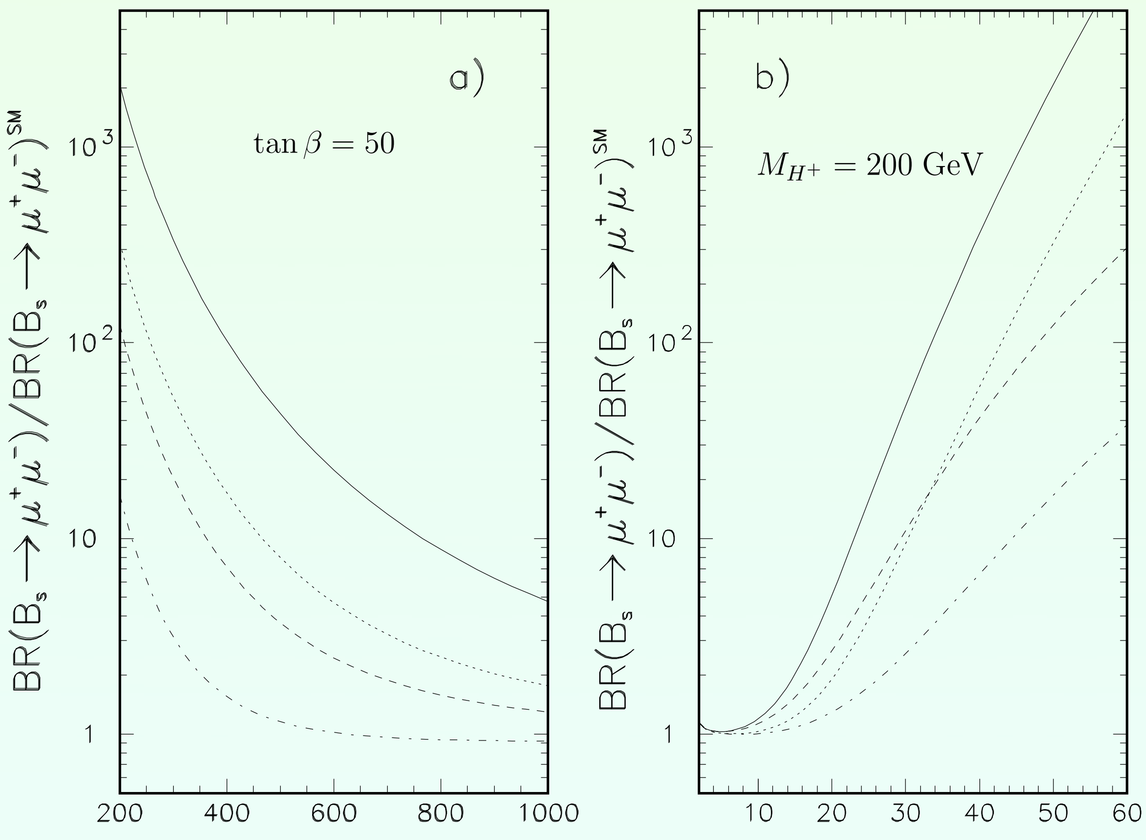


$\tan\beta \sim 1$ charged Higgs and chargino exchanges dominant

$\tan\beta \gg 1$ 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

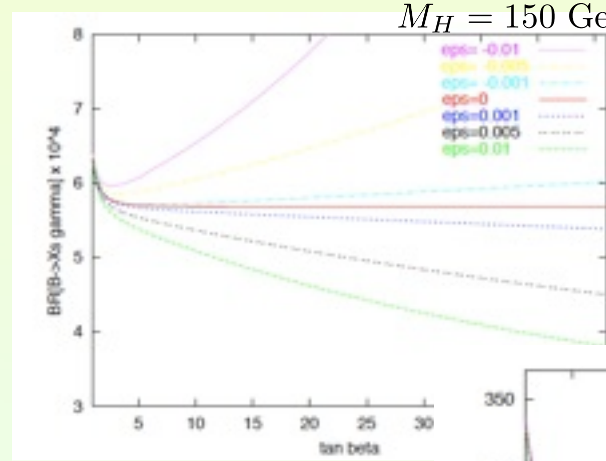
dot-dash: $\mu > 0$ $M_{\tilde{t}_1} = 600$ GeV, $M_{\tilde{t}_2} = 750$ GeV

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

Slide taken again from BG FPCP2009

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

$M_H = 150$ GeV



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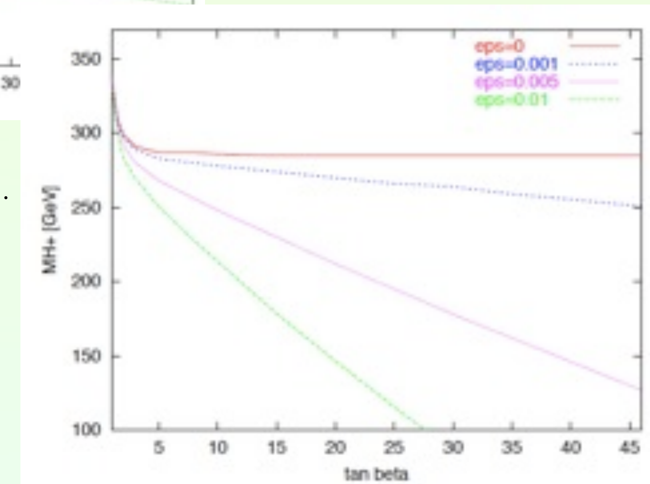

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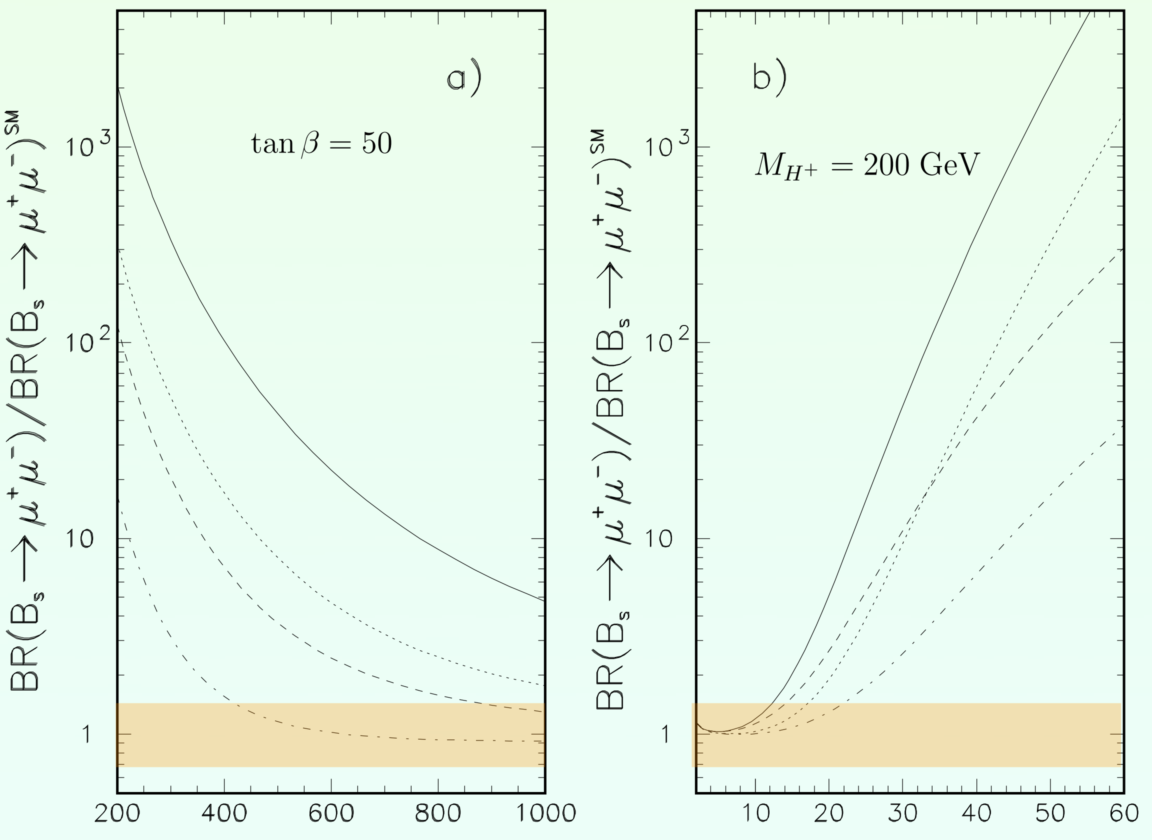

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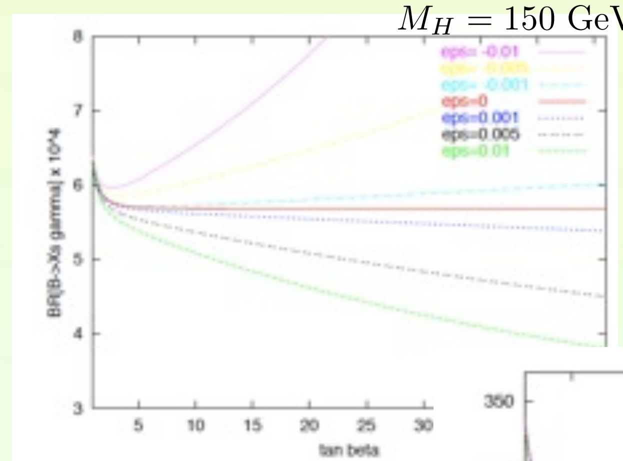
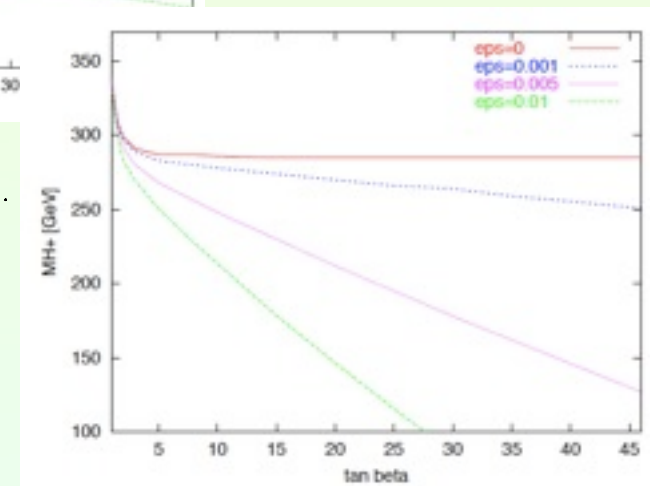
Nov 2012 LHCb

Slide taken again from BG FPCP2009

CMSSM (at large tan β, possibly)



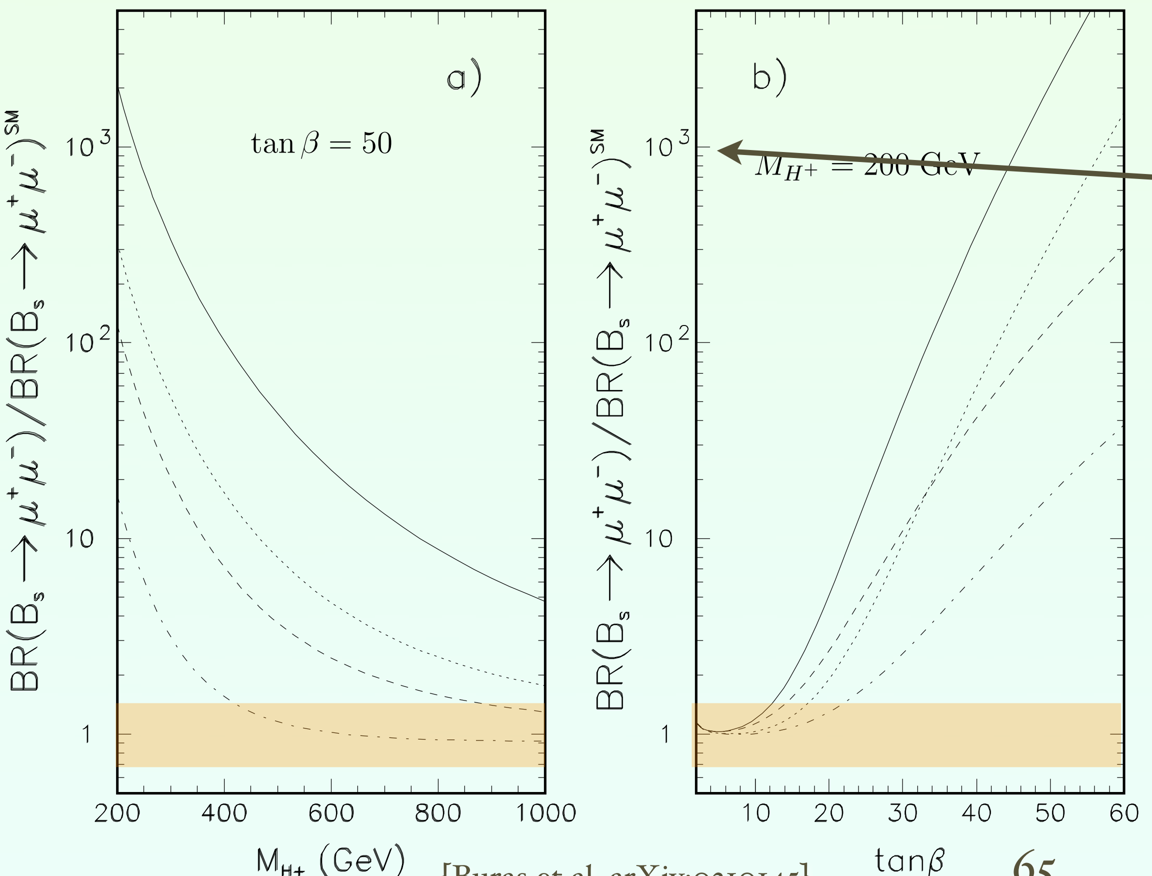
[Degrassi et al, arXiv:0009337]



$\tan\beta \sim 1$	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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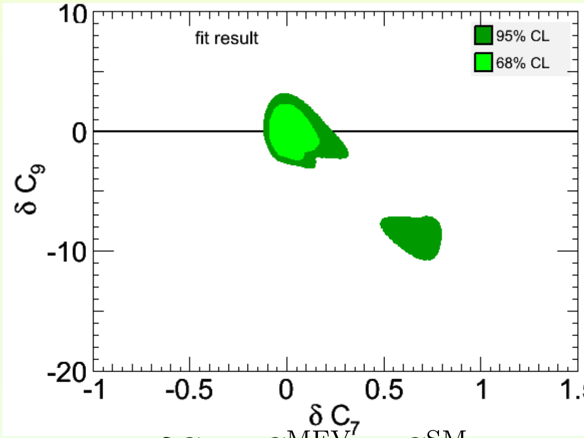
dotted: $\mu < 0$ $M_{\tilde{t}_1} = 600$ GeV, $M_{\tilde{t}_2} = 750$ GeV

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.....

Time to be a philosopher

...



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

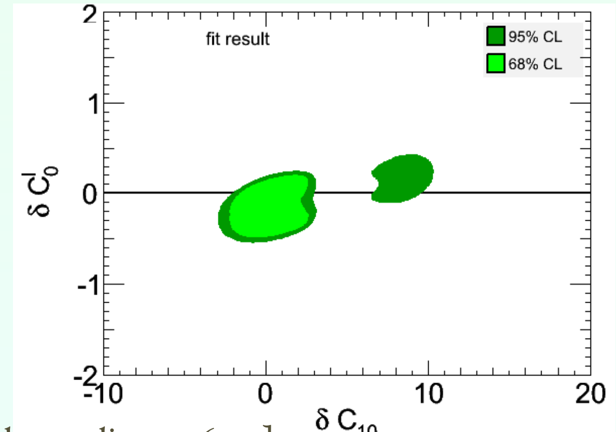
$$\delta C_i = C_i^{\rm MFV} - C_i^{\rm SM}$$

- Fabulous for hiding non-existent particles and interactions!

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

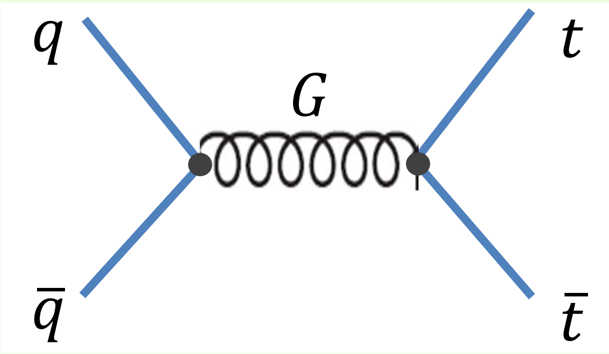
- I propose we should be doing something else:
  - We do have deviations form SM
  - Should focus on models that address anomalies
  - Tricky: which anomalies do you focus on?
    - $>3\sigma$
    - At least two experiments
    - (No guaranteed persistence, witness B $\to \tau\nu$)
  - Example: top-quark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

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



[Hurth & Mahmoudi, 1211:6453]

Flavor Physics and FB asymmetry in top production at Tevatron

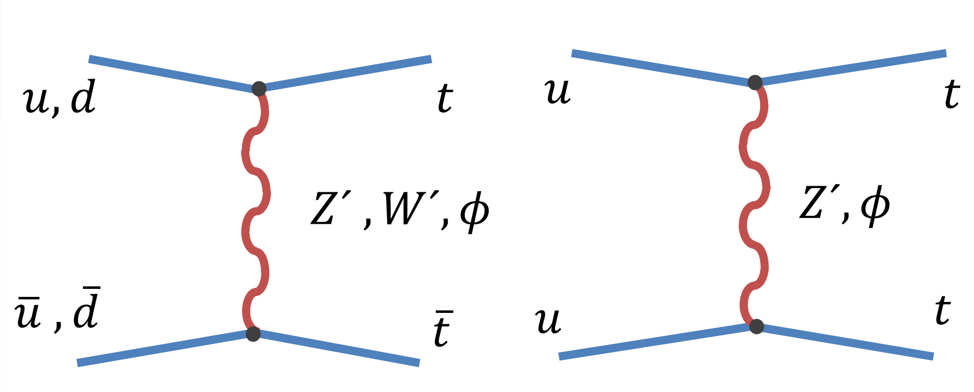


s-channel exchange models

[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

- Physics of Flavor continues to be a rich program in HE:
  - s, c, b and now t
  - CPC/CPV, mixing, semileptonic, rare decays, polarization-amplitudes,...
- Standard Flavor Model (CKM) is incredibly successful
  - Consistent unitarity triangles in all combinations (eg, tree/loop, CPC/CPV)
  - Consistent in rare decays over 6 decades of branching fractions (from radiative decay to purely leptonic decay of B^0)
- Few anomalies
  - B Isospin Asymmetry, decays into tau, ...
  - For some we have no reasonable model (eg, Isospin Asymmetry)
  - Many going away (or gone)
  - Old man: likely to evolve into consistency with SM (with additional data)
- Models of NP pushed (not to a corner but) to
  - Decoupling/high mass
  - Suppressed flavor changing couplings
  - Suppressed CPV phases in couplings

The End