New physics in B_s mixing: Uplifted SUSY

Adam Martin (Fermilab)

based on work with B. Dobrescu and P. Fox (1005.4238)
+ work in progress

Fermilab

CPV from B Factories to Tevatron and LHCb

Sept 2, 2010

Outline

- Motivation: opportunities and anomalies
- New physics in B_s mixing: how? how much?
- Uplifted SUSY!
- consequences of Uplifted SUSY in flavor and at colliders

Motivation

I: Flavor as a second telescope to higher scales

HIGH ENERGY

HIGH PRECISION

generic flavor at TeV scale is totally ruled out! Non-trivial pattern waiting to be unveiled

opportunities at every front -- a very exciting time!

Motivation

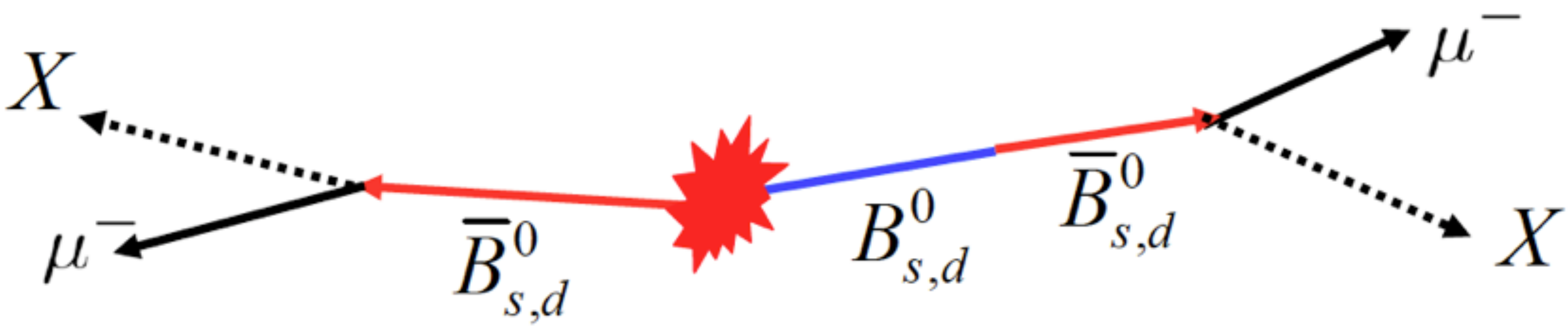
II:

- D0 sees a ~1% asymmetry in the number of $\mu^-\mu^-$ vs. the number of $\mu^+\mu^+$
  (1005.2757)

$$A^b_{SL} = -(9.57 \pm 2.51 \pm 1.46) \times 10^{-3}$$

3.2σ deviation from SM

- like-sign leptons are attributed to B^0_s and B^0_d oscillation



- dimuon asymmetry can be recast in terms of the B_s, B_d "wrong charge" semileptonic asymmetries

$$A^b_{SL} = \frac{N^{++} - N^{--}}{N^{++} + N^{--}} = \frac{N^+_{RS} N^+_{WS} - N^-_{RS} N^+_{WS}}{N^+_{RS} N^+_{WS} + N^-_{RS} N^+_{WS}} \cong 0.5\ a^d_{SL} + 0.5\ a^s_{SL}$$

depend on what fraction of produced b go to B_s, B_d

where:

$$a^q_{SL} = \frac{N(\overline{B^0}_{phys} \to \ell^+ X) - N(B^0_{phys} \to \ell^- X)}{N(\overline{B^0}_{phys} \to \ell^+ X) + N(B^0_{phys} \to \ell^- X)} \simeq \frac{|\Gamma^q_{12}|}{|M^q_{12}|} \sin(\phi^q_M - \phi^q_\Gamma) + \mathcal{O}(|\Gamma^q_{12}|^2)$$

some related quantities

$$a^q_{SL} = \frac{|\Gamma_{12}|}{|M_{12}|} \sin(\phi_M - \phi_\Gamma),\quad \Delta M_s = 2|M_{12}|,\quad \Delta\Gamma = 2|\Gamma_{12}| \cos(\phi_M - \phi_\Gamma)$$

mass difference

lifetime difference

New Physics in a^d_{SL}, a^s_{SL}

$$a^s_{SL} = \frac{|\Gamma_{12}|}{|M_{12}|} \sin\left(\phi_M - \phi_\Gamma\right)$$

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we heard from Christian that this is hard...

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SM theory error is only around 10 - 20%

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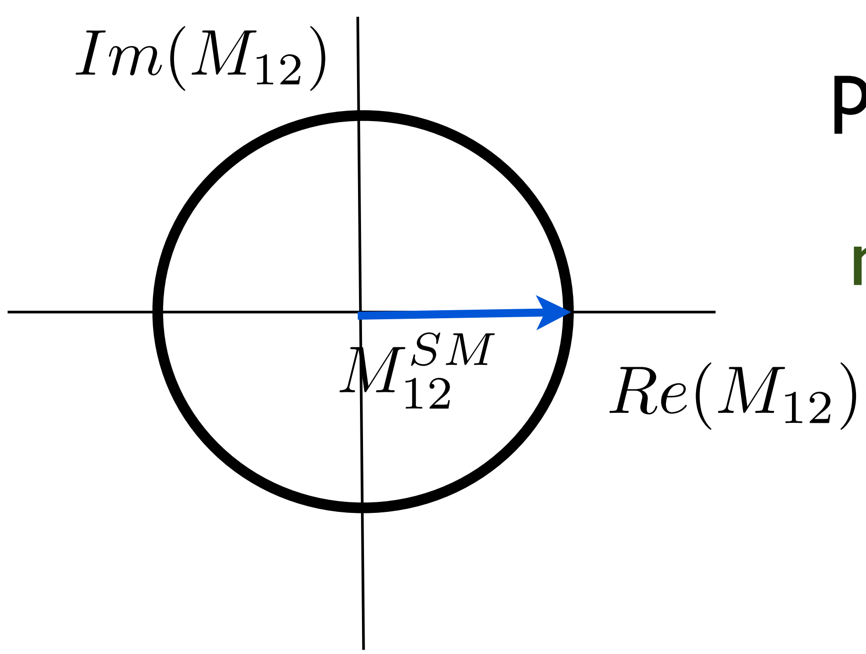
phase is extremely small in the SM $\sim 0.2^\circ$



new contributions can easily change a^s_{SL} by orders of magnitude

Motivation

III:

- different observable: $S_{\psi\phi}$

assuming one decay amplitude, 0^{th} order in Γ_{12}

$$\frac{N(\overline{B^0}_{phys} \to J/\psi\phi) - N(B^0_{phys} \to J/\psi\phi)}{N(\overline{B^0}_{phys} \to J/\psi\phi) + N(B^0_{phys} \to J/\psi\phi)} = -\sin(\Delta m t)\,\underbrace{\sin(\phi_M + 2\phi_f)}_{S_{\psi\Phi}}$$

$2\phi_f$: CKM phase of tree-level $b \to c\bar{c}\bar{s}$ process

strictly speaking, not the same phase as in a^s_{SL} (relative phase of M_{12} and Γ_{12})

in the SM: $\sin(\phi_M - \phi_\Gamma), \sin(\phi_M + 2\phi_f) \simeq 0$

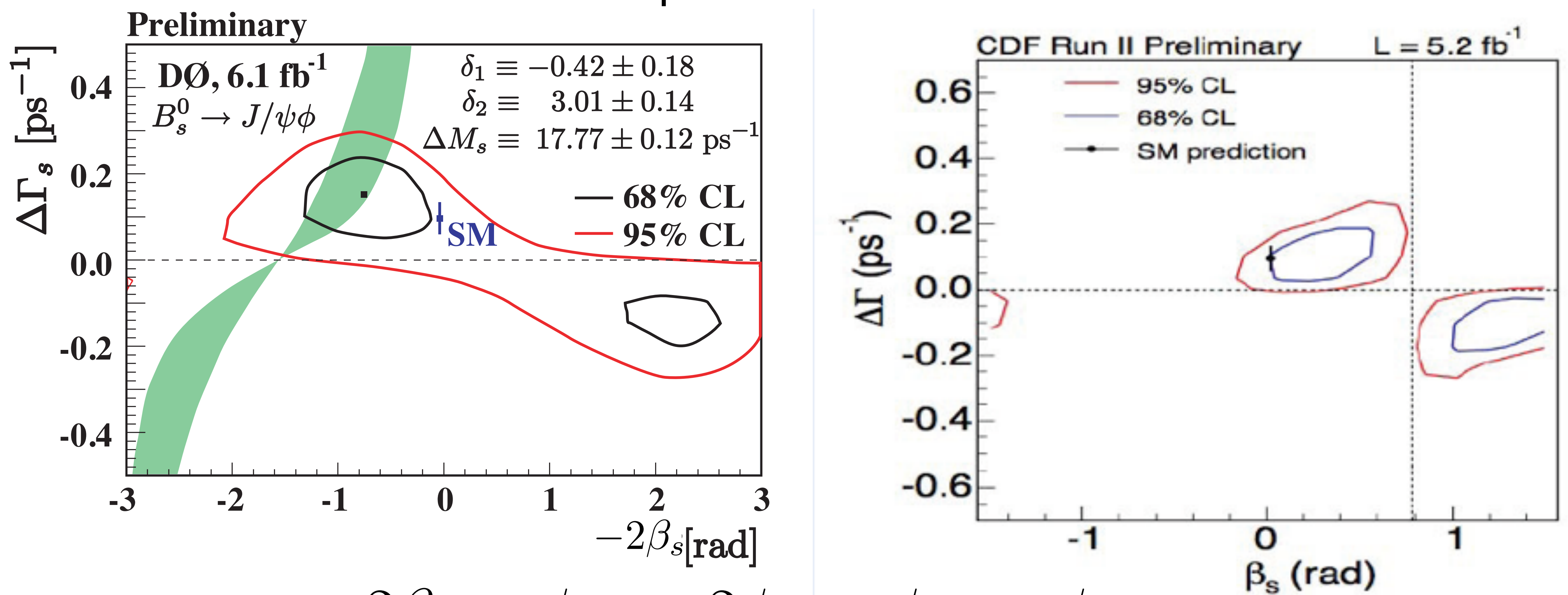
if NP only changes phase in mixing, effect will show up in both

$$\sin(\phi_{NP} + \phi_M - \phi_\Gamma) \simeq \sin(\phi_{NP}) \simeq \sin(\phi_{NP} + \phi_M + 2\phi_f)$$

not the case if there is new physics in the phase of Γ_{12}

What about $S_{\psi\phi}$?

both CDF/D0 measure $S_{\psi\phi}$: extract $\Delta\Gamma$ and $\phi_M + 2\phi_f$



$$-2\beta_s \equiv \phi_M + 2\phi_f \approx \phi_M - \phi_\Gamma$$

- both experiments favor phases >> SM
- $\Delta\Gamma = 2|\Gamma_{12}|\cos(\phi_M - \phi_\Gamma)$ so if new physics only changes the phase, $|\Delta\Gamma|$ can only be smaller than $\Delta\Gamma^{SM} \cong 2|\Gamma_{12}^{SM}|$

In the Standard Model

- For now let's assume $a^d_{SL} = 0$ since the B_d system is tightly constrained by B-factories. Whole asymmetry comes from B_s

from expt.

$$(a^s_{SL})_{comb} \approx -(12.7 \pm 5.0) \times 10^{-3}$$

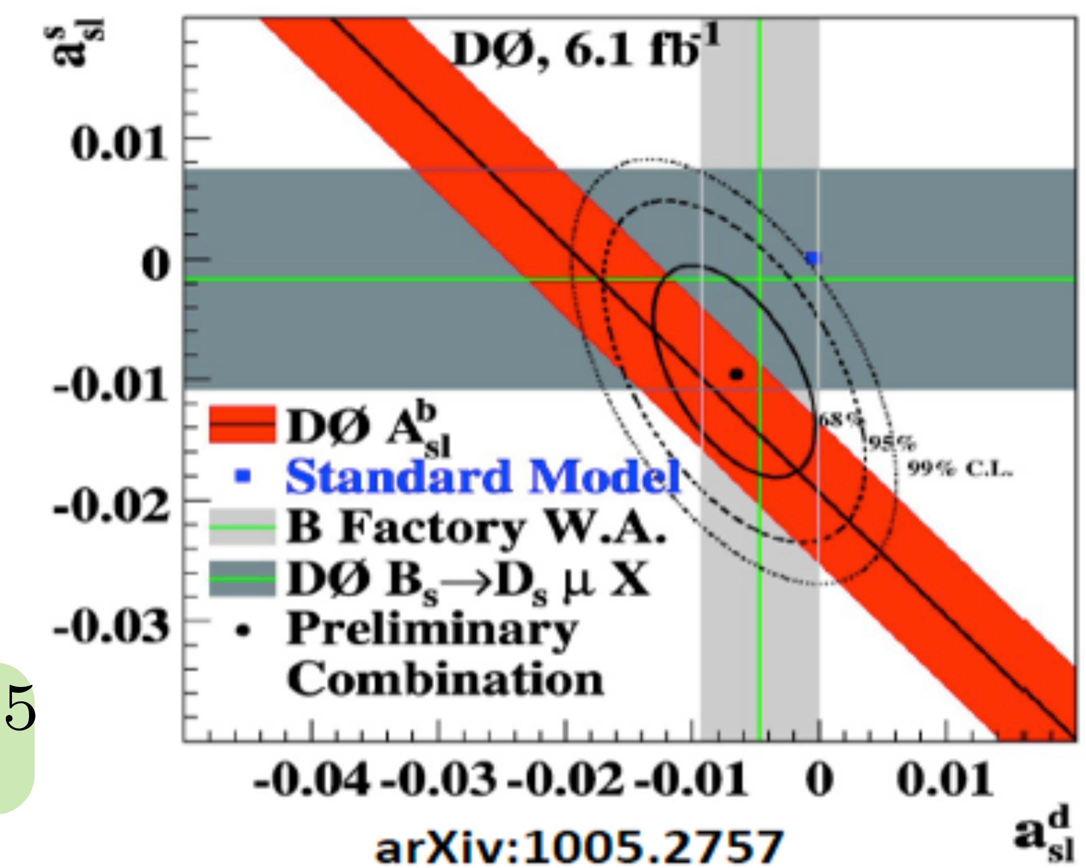
(D0 + older CDF, D0 results)

$$|M^{SM}_{12}| \simeq (9.0 \pm 1.4)\text{ps}^{-1}$$

$$|\Gamma^{SM}_{12}| = 0.045 \pm 0.012 \text{ ps}^{-1}$$

$$\sin{(\phi_M - \phi_\Gamma)}_{SM} \simeq (4.2 \pm 1.4) \times 10^{-3}$$

$$a^s_{SL}(SM) = (2.2 \pm 0.6) \times 10^{-5}$$



arXiv:1005.2757

a first approach

What happens when we try to put new physics only into the phase of M_{12}

$$\Gamma_{12} = \Gamma_{12}^{SM} \qquad M_{12} = M_{12}^{NP} + M_{12}^{SM} \equiv C_{B_s} e^{i\phi_s} |M_{12}^{SM}|$$

(set phase in $M_{12}^{SM}, \Gamma_{12}^{SM}$ to zero)

$$a_{SL}^s = \frac{|\Gamma_{12}^{SM}|}{|M_{12}^{SM}|} \frac{\sin\phi_s}{|C_{B_s}|}$$

plug in $M_{12}^{SM}, \Gamma_{12}^{SM}$, fit to a_{SL}^s and $\Delta M_s = 2|M_{12}| = 2|M_{12}^{SM}| C_{B_s}$

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$$C_{B_s} = 0.98 \pm 0.15 \quad , \quad \sin\phi_s = -2.5 \pm 1.3$$

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??????????????

with the set of assumptions we've made and the current experimental central value, we find an unphysical scenario

So..

- central value will decrease once errors are reduced

Or.. we need to modify our theory assumptions

- put some asymmetry into a^d_{SL}: $a^d_{SL} = (-0.47 \pm 0.46)\%$

has large errors, seems like a easy place to put some (often done in results!)

BUT, not free - central value would imply new physics in B_d mixing!

improved measurement of a^d_{SL} would be great

??????????????

Or.. we need to modify our theory assumptions

- new physics in Γ_{12}^{s} (Christian's talk)
- not a simple 2 state mixing (see Bai, Nelson 1007.0596)
- muons come from some other new physics (rate ~10^{-5} σ_b ?)
- others?

??????????????

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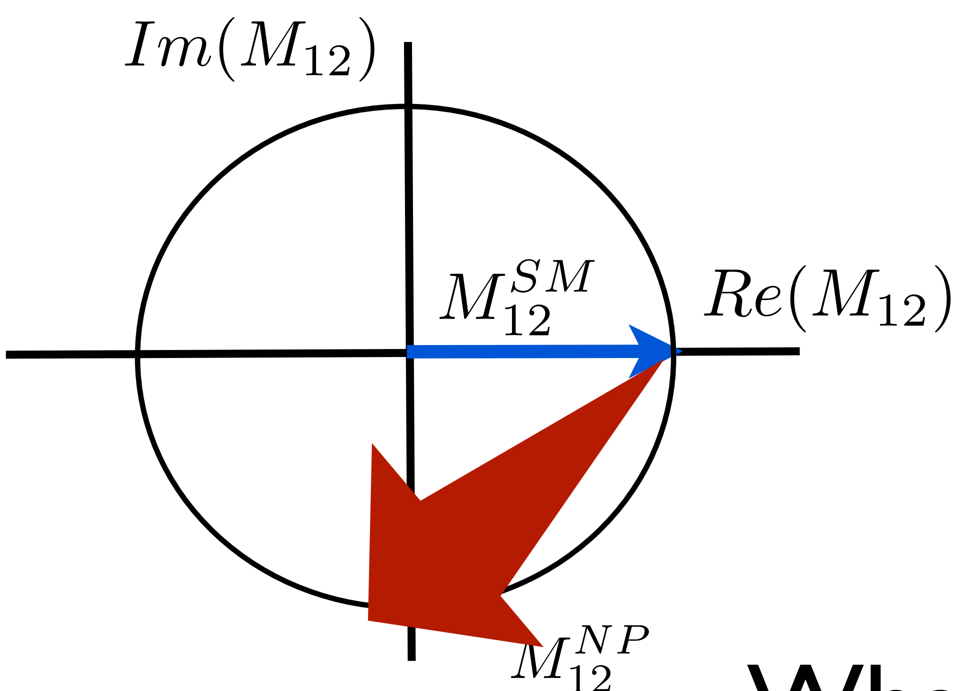
let's keep going with our current strategy

thinking outside the box

Consider the situation where $\sin\phi_s$ settles to a large, but physical value

$$\sin\phi_s \sim -1$$

In this case new physics of this form needs to be large and have a large phase



$$\frac{M_{12}^{NP}}{M_{12}^{SM}} = (C_{B_s} e^{i\phi_s} - 1)$$

$$\frac{|M_{12}^{NP}|}{|M_{12}^{SM}|} \sim \sqrt{2} \qquad arg(M_{12}^{NP}) \sim -3\pi/4$$

What new physics can generate this?

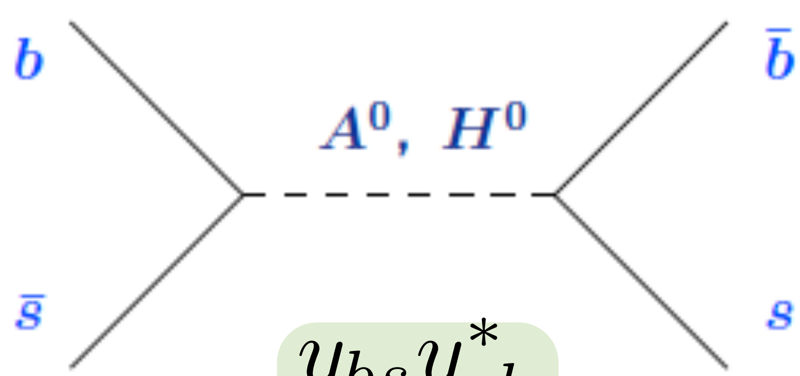
thinking outside the box

what about tree level scalar exchange:

... occurs in general two Higgs doublet models (THDM)
(up-, down-type quarks couple to both Higgses)

$$y_u U^c H_u Q_L + y'_u U^c H_d^* Q_L + y_d D^c H_d Q_L + y'_d D^c H_u^* Q_L$$

can't be simultaneously diagonalized



$$\sim \frac{y_{bs} y_{sb}^*}{M_A^2}$$ complex

most models have a symmetry (discrete, continuous) imposed restrict the couplings

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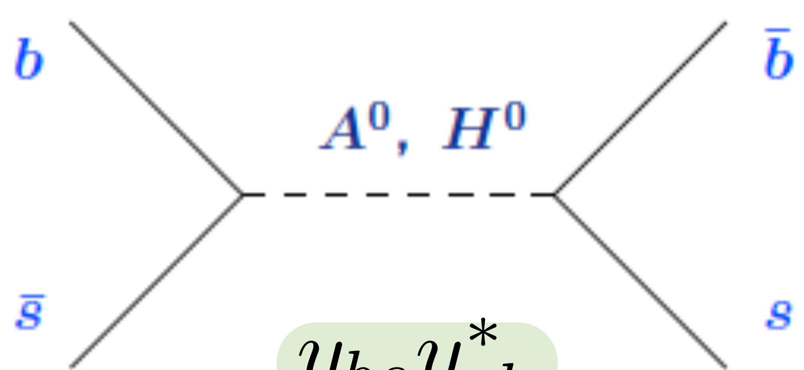

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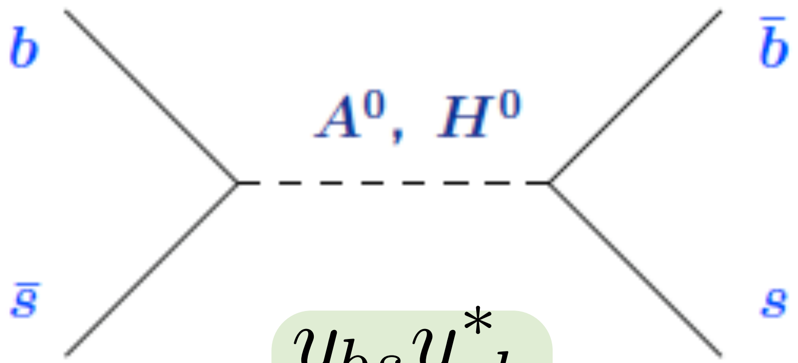

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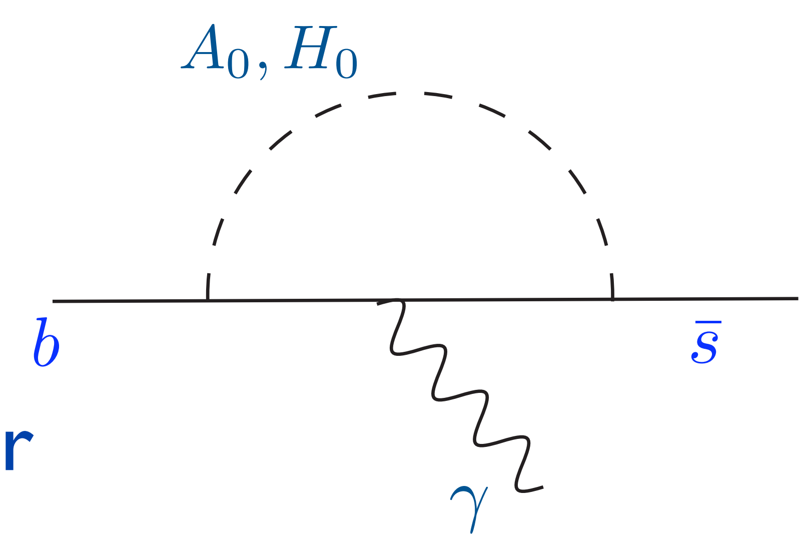
$$(\bar{b}_R s_L)(\bar{b}_L s_R) \quad , \quad (\bar{b}_R s_L)(\bar{b}_R s_L)$$

Advantages of tree-level FCNC:

- Yukawa coupling strength -> $y_b\, y_s > y_b\, y_d >> y_s\, y_d$

  effects in $B_s > B_d >> K$

- $\Delta B = 2$ at tree level, while $\Delta B = 1$ only occurs at loop level -> parametrically smaller



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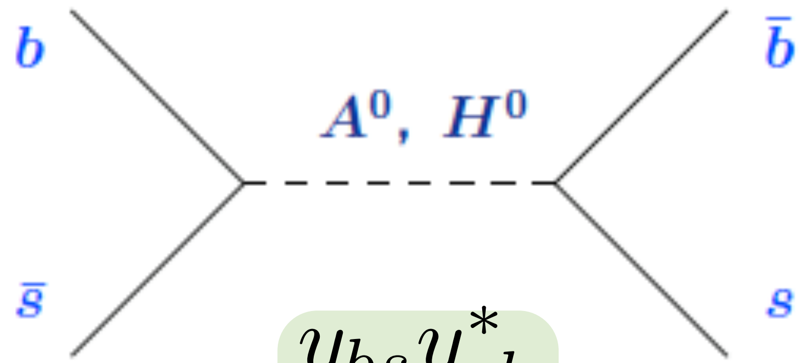

$\sim \frac{y_{bs} y^*_{sb}}{M_A^2}$ complex

$(\bar{b}_R s_L)(\bar{b}_L s_R)$, ~~$(\bar{b}_R s_L)(\bar{b}_R s_L)$~~

vanishes in degenerate A^0/H^0 limit

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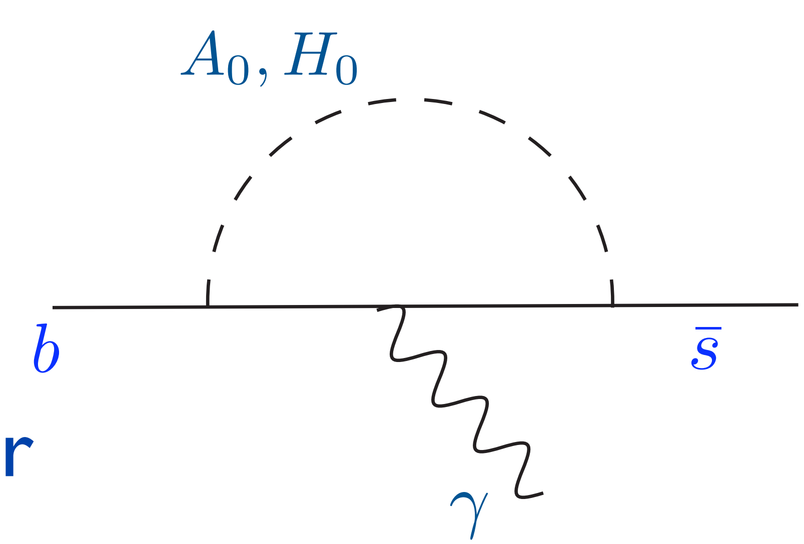


thinking outside the `box'

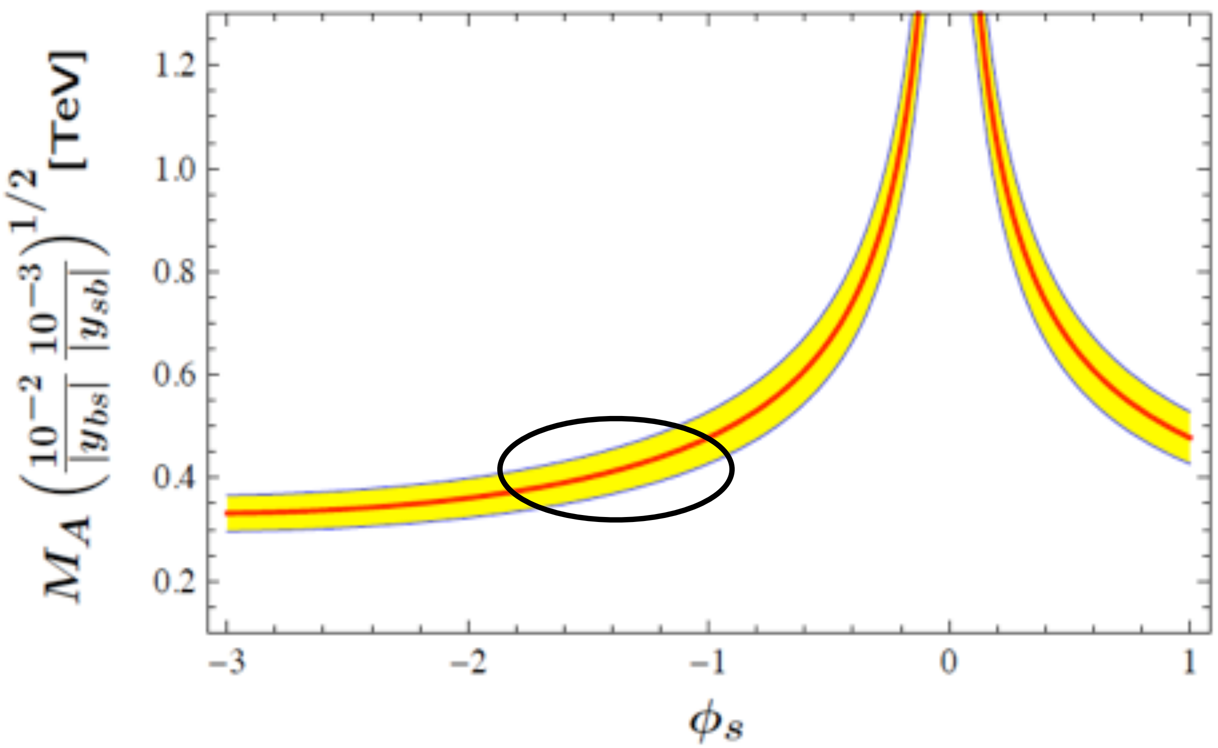
Get the right size effect for

$$M_A \sim 500 \text{ GeV}$$

$$y_{bs} \sim 0.01, |y_{sb}| \sim 0.001$$

'CKM sized'

>> than expected from
Higgs-related FCNC



but how do you get large enough $y_{bs}y_{sb}^*/M_A^2$ without screwing up other flavor observables?

From where? SUSY

the MSSM is a two-Higgs doublet model

Holomorphy constrains the superpotential

⟶ when SUSY is preserved, `type-2' THDM

$$\mathcal{L} \supset -y_u u^c H_u Q_L - y_d d^c H_d Q_L$$

BUT, once SUSY is broken, integrate out superpartners

⟶ generate a completely general THDM

$$\mathcal{L} \supset -y_u u^c H_u Q_L - y_d d^c H_d Q_L - y'_u u^c H_d^\dagger Q_L - y'_d d^c H_u^\dagger Q_L$$

so, therefore $m_d = y_d v_d + y'_d v_u$

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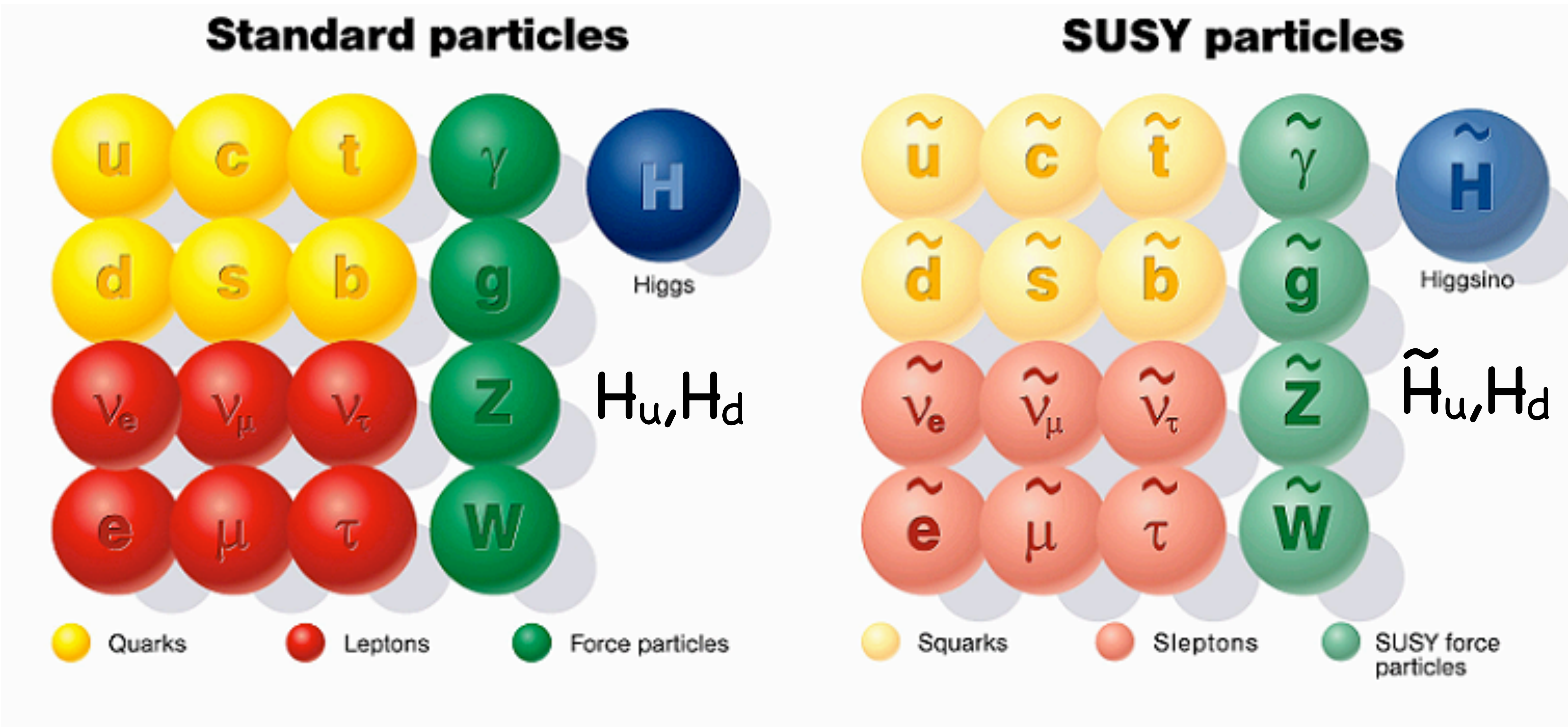

“Minimal Supersymmetric Standard Model (MSSM)”

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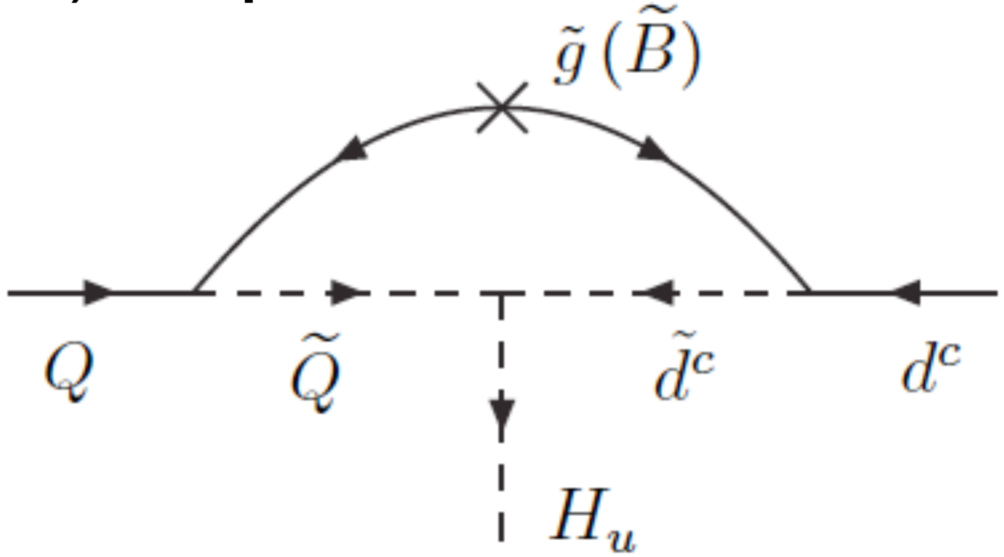
more SUSY

Example: gluino (or bino) loop



$$(y'_d)_F = -\frac{y_d}{3\pi} e^{i(\theta_g - \theta_\mu)} \frac{2|\mu|}{M_{\tilde{d}}} \left[\alpha_s F\left(\frac{M_{\tilde{g}}}{M_{\tilde{Q}}}, \frac{M_{\tilde{d}}}{M_{\tilde{Q}}}\right) + \frac{\alpha e^{i(\theta_B - \theta_g)}}{24 c_W^2} F\left(\frac{M_{\tilde{B}}}{M_{\tilde{Q}}}, \frac{M_{\tilde{d}}}{M_{\tilde{Q}}}\right)\right]$$

$$F(x,y) = \frac{2xy}{x^2 - y^2}\left(\frac{y^2 \ln y}{1 - y^2} - \frac{x^2 \ln x}{1 - x^2}\right)$$

effective coupling y'_d

- proportional to y_d
- knows about superpartner spectrum
- knows about complex SUSY parameters

+ additional diagrams from Higgsino loops or involving A-terms

more SUSY

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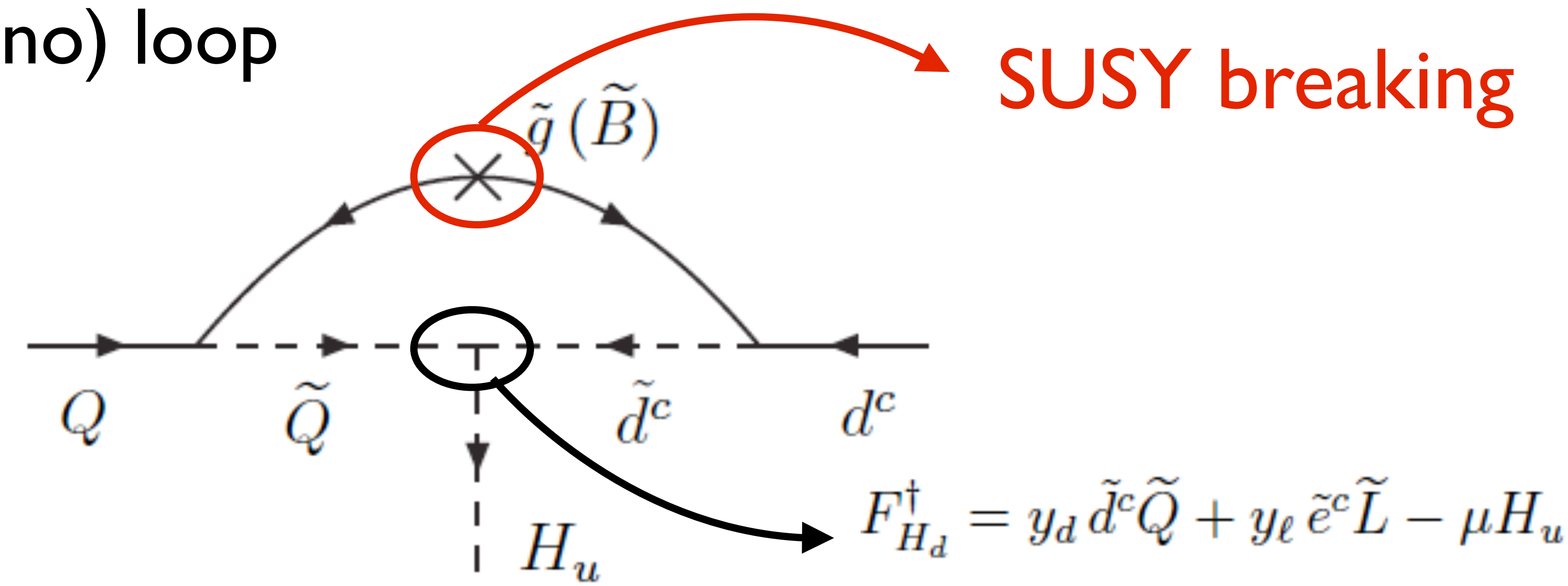

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if the sfermion spectrum is degenerate...

all $F\Big(\frac{M_{\tilde{g}}}{M_{\tilde{Q},j}}, \frac{M_{\tilde{d},i}}{M_{\tilde{Q},j}}\Big)$ are equal: $y_d' = F\, y_d$

c-number

so y_d, y_d' are simultaneously diagonalizable

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if sfermion spectrum is NOT degenerate, ex.) $M_{\tilde{Q},3} \neq M_{\tilde{Q},1}$

$$F\left(\frac{M_{\tilde{g}}}{M_{\tilde{Q},3}}, \frac{M_{\tilde{d},1}}{M_{\tilde{Q},3}}\right) \neq F\left(\frac{M_{\tilde{g}}}{M_{\tilde{Q},1}}, \frac{M_{\tilde{d},1}}{M_{\tilde{Q},1}}\right)$$

each y'_d entry weighted differently

$$\frac{y'_{d,13}}{y_{d,13}} \neq \frac{y'_{d,11}}{y_{d,11}}$$

mass term: $y_d v_d + y'_d v_u$

Yukawa: y_d

→ are not simultaneously diagonalizable: FCNC!

great, but y'_d is loop suppressed, so one expects these effect to be negligible...


UP
-LIFT!

Uplift!

what if : $\frac{v_u}{v_d} \sim 200$??

$$m_b = (y_b\ v_d + y_b'\ v_u)$$

- large $\frac{v_u}{v_d}$ overcomes the loop factor
- $y_d' v_u$ becomes dominant contribution to mass
- big y_b (also y_τ) needed to get right m_b, m_τ

$$y_\tau, y_b \sim \mathcal{O}(1) \qquad y_{d,s} = y_b \frac{m_{d,s}}{m_b}$$, etc.

- misalignment between y_d and y_d' important

This is the `uplifted region' (Dobrescu, Fox 1001.3147)

Uplift! : How did we get here?

look at the Higgs potential:

$$(|\mu|^2 + m_{H_u}^2)|H_u|^2 + (|\mu|^2 + m_{H_d}^2)|H_d|^2 + B_\mu H_u H_d$$
$$+\frac{1}{2}(g^2 + g'^2)(|H_u|^2 - |H_d|^2)^2$$

(see 1001.3147)

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forbid at tree level

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for EWSB: $(|\mu|^2 + m_{H_u}^2)(|\mu|^2 + m_{H_d}^2) < 0$

< 0 $\qquad > 0$

only H_u gets a vev: $v_u/v_d = \infty$ at tree level

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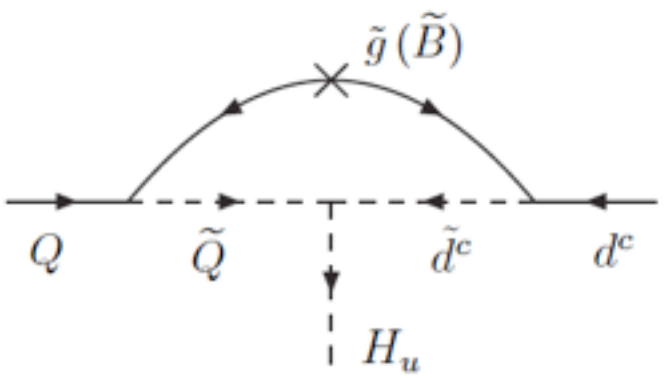
don't worry:

down-type quarks, leptons get mass through loop diagrams: y_d', y_τ'



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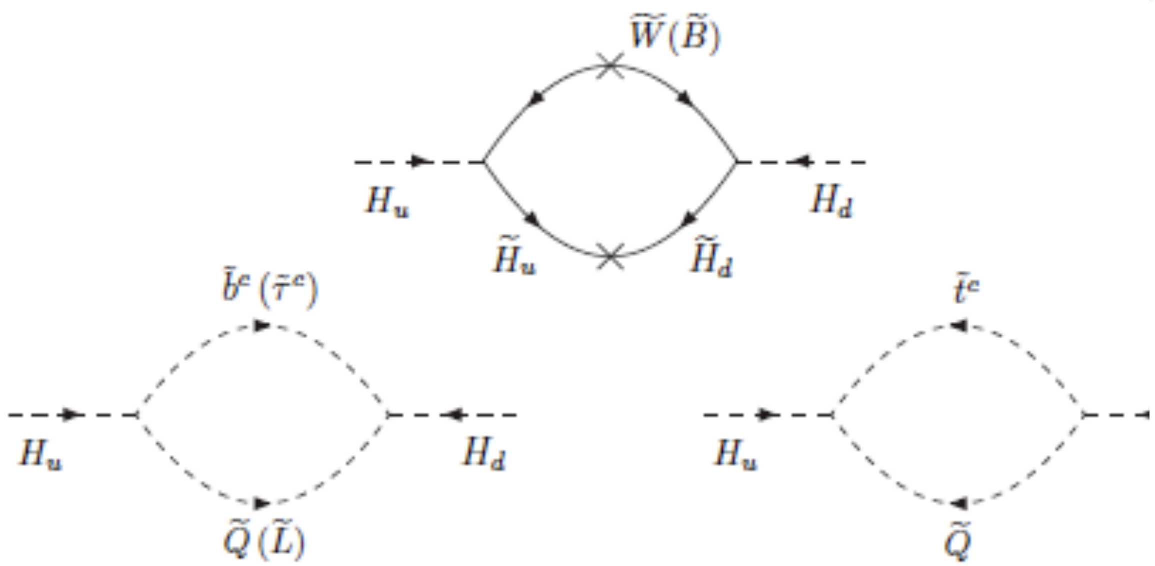
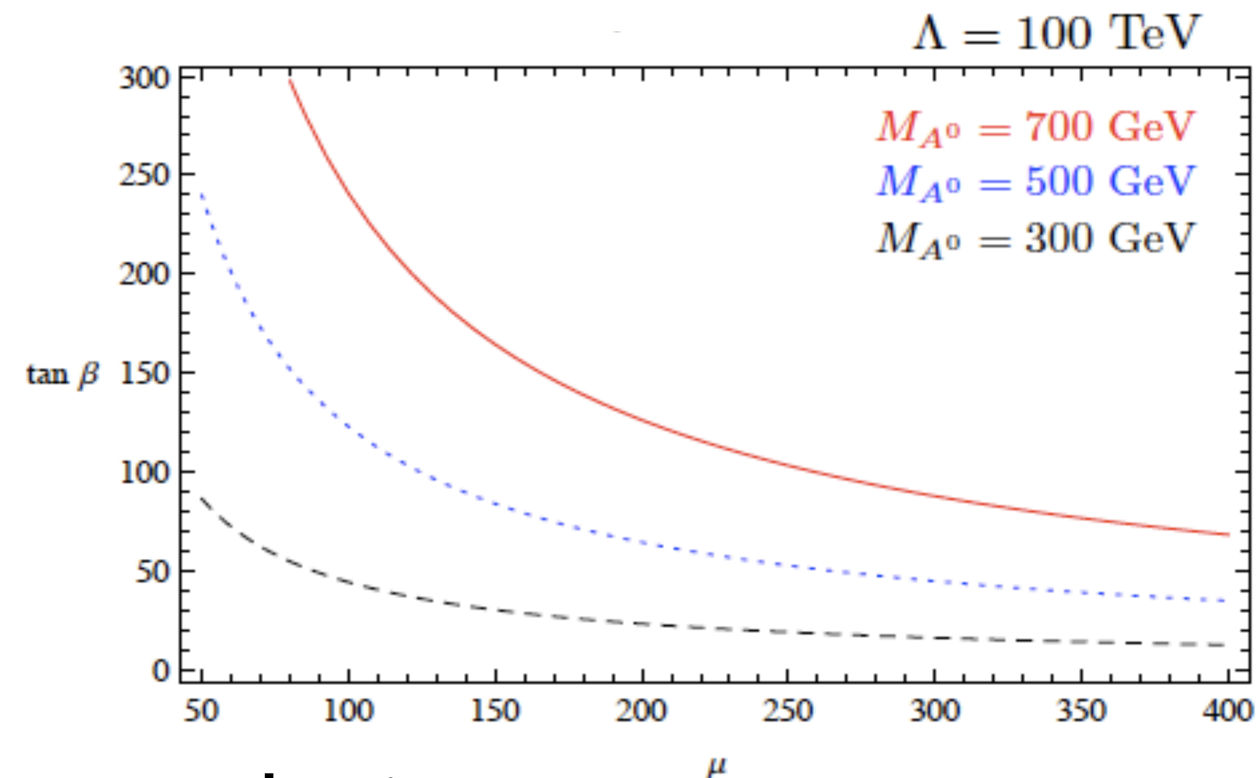
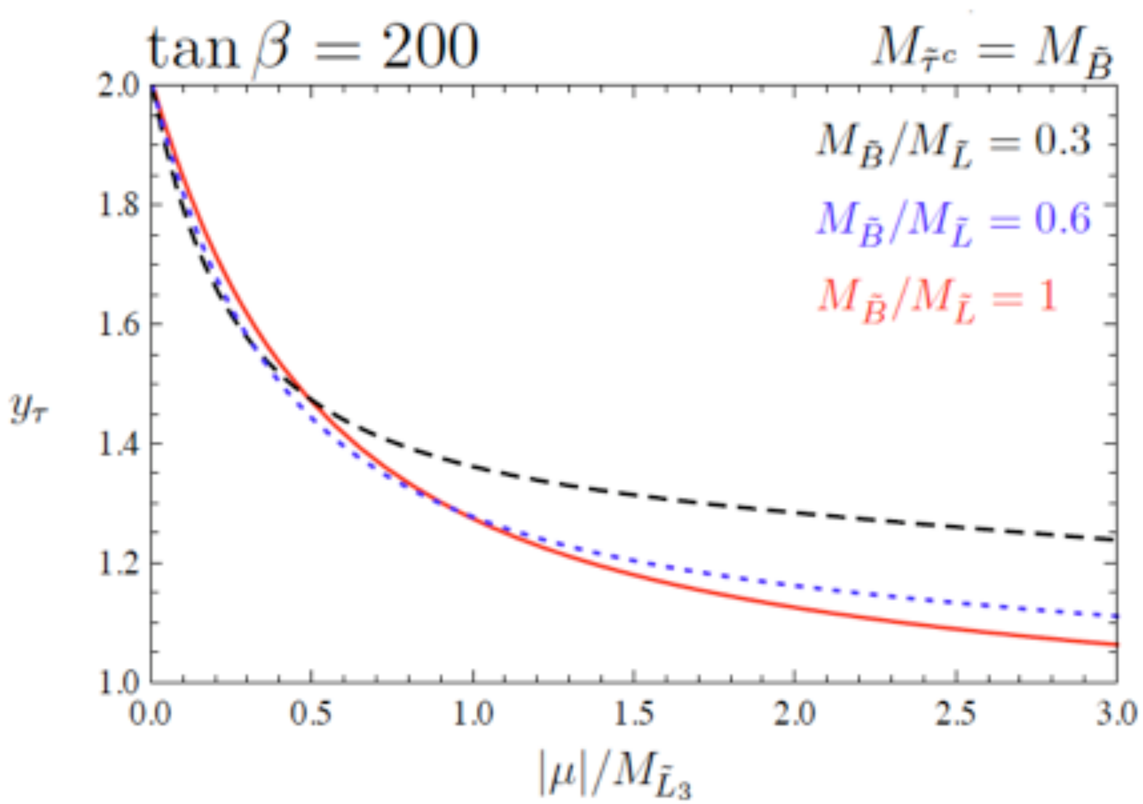
Uplift! : How did we get here?

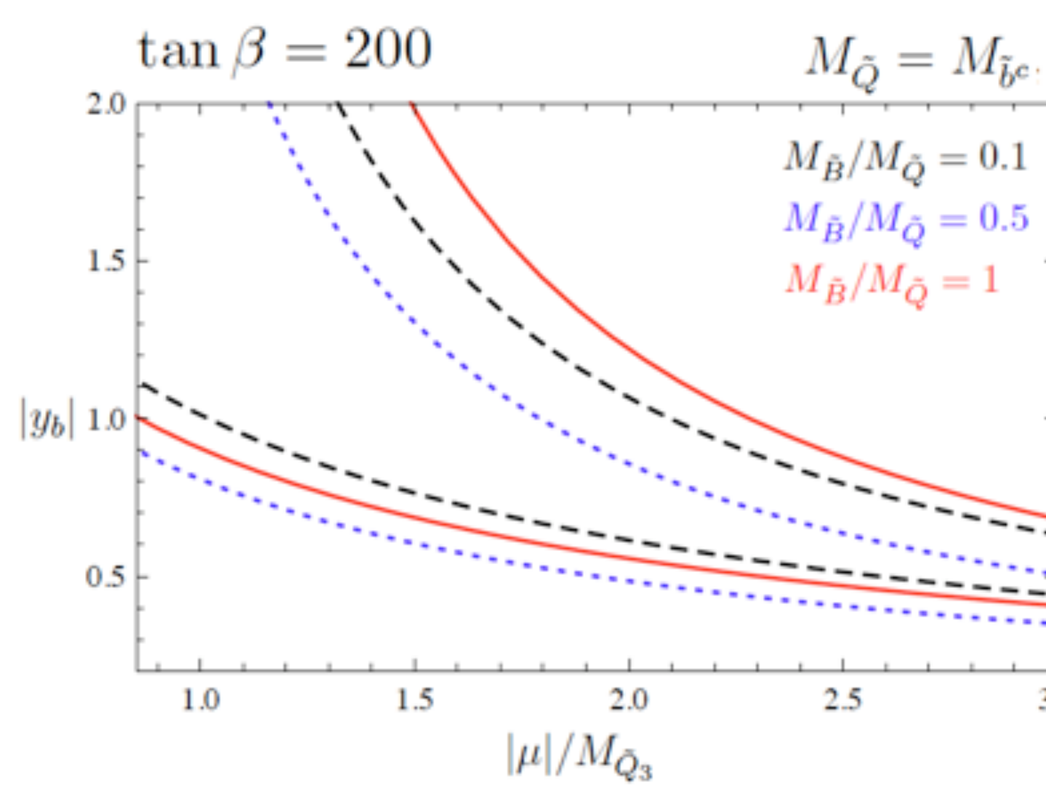
once ~~SUSY~~, loop effects generate $B_\mu,\ v_d \ \rightarrow \tan\beta \gg 1$



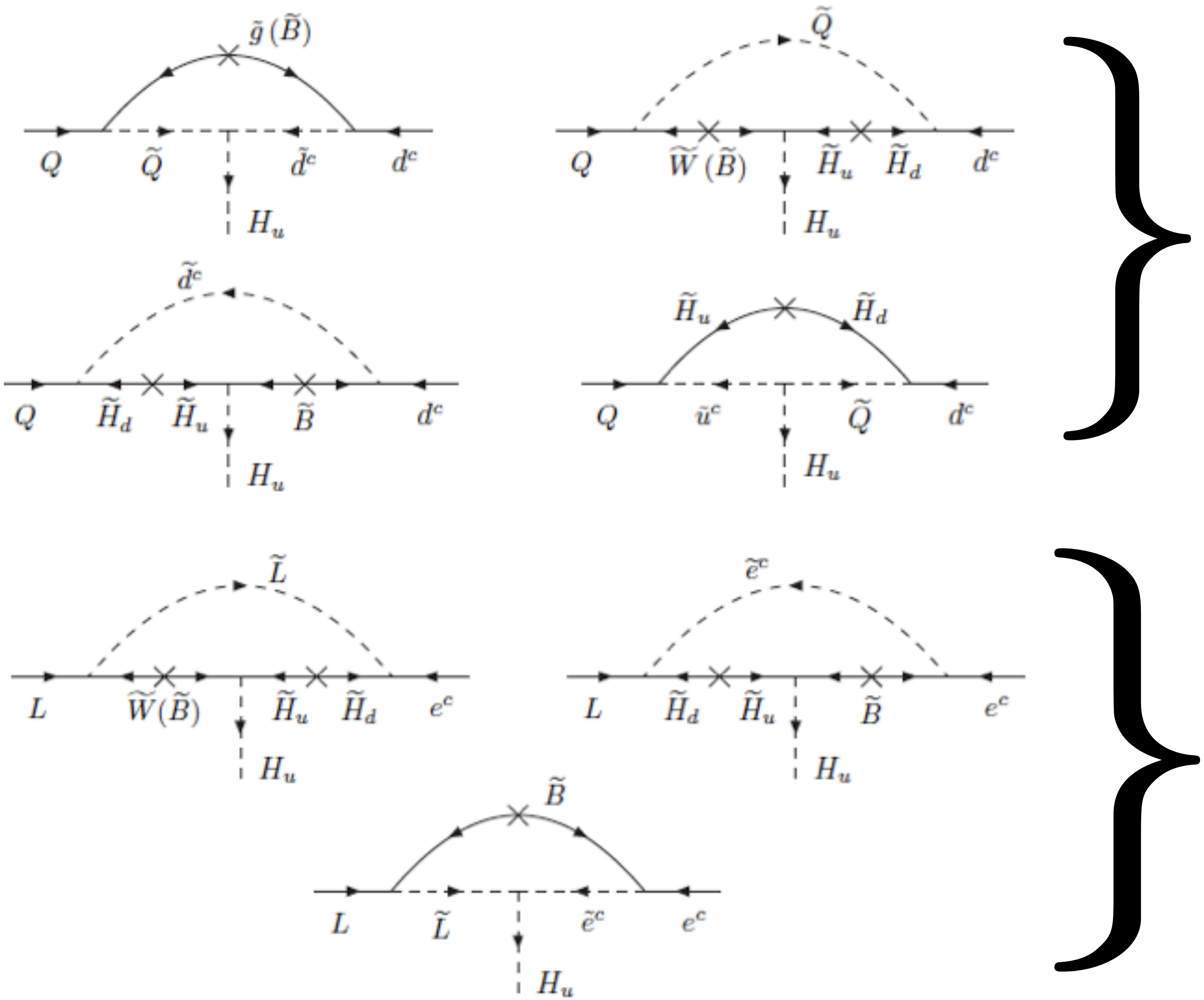


- $y_b\ ,\ \ y_\tau \sim \mathcal{O}(1)$ but certainly perturbative





more Uplifted SUSY



down-type quarks

leptons

different diagrams! gluino diagrams don't contribute to slepton masses... compensate by $y_\tau > y_b$

tan(β)

Be careful, $v_u/v_d = \tan\beta$ is a confusing parameter!

in the 'usual MSSM'

- y_b , y_τ grow with linearly with tan(β) ... reach non-perturbative values for $\mathcal{O}(50)$ or so

- ratio y_b/y_τ is fixed by the ratio of masses, = m_b/m_τ

neither of these is strictly true!

$$\frac{m_b}{m_\tau} = \frac{y_b + y_b' \tan\beta}{y_\tau + y_\tau' \tan\beta}$$

Uplifted SUSY + flavor

for $\frac{v_u}{v_d} \gg 1$ heavy neutral Higgs (H^0/A^0) lie in the H_d doublet

$$-y_d\, d^c\, H_d^0\, d_L$$

Diagonalizing the mass term, you get off-diagonal entries in $y_{d,ij}$

$$y_{bs} = y_b\, V_{ts}\, \xi \qquad y_{sb} = \frac{m_s}{m_b} y_{bs}$$

order 1 (y_b)

order 1, complex, sensitive to splitting of sfermions (ξ)

off-diagonal entries are big $(\mathcal{O}(V_{CKM}))$ and carry new, potentially large phases

right in the range needed to have an effect on B_s for m_A ~ TeV

Uplifted SUSY + flavor

- effects in B_d system suppressed by m_d/m_s

- flavor changing couplings vanish when sfermions are degenerate, so if $M_{\tilde{Q}_1} \cong M_{\tilde{Q}_2} \neq M_{\tilde{Q}_3}$

$$M_{\tilde{d}_1} \cong M_{\tilde{d}_2} \neq M_{\tilde{d}_3}$$

→ no flavor-violation in the Kaon system

Starting from degenerate sfermion masses at a high scale, Yukawa couplings in RGEs will automatically generate the desired splitting

$$y_b \sim 1 \, , y_{s,d} = y_b \frac{m_{s,d}}{m_b} \ll 1 \longrightarrow M_{\tilde{Q},3} < M_{\tilde{Q},1,2}$$

(Dobrescu, Fox, Martin work in progress)

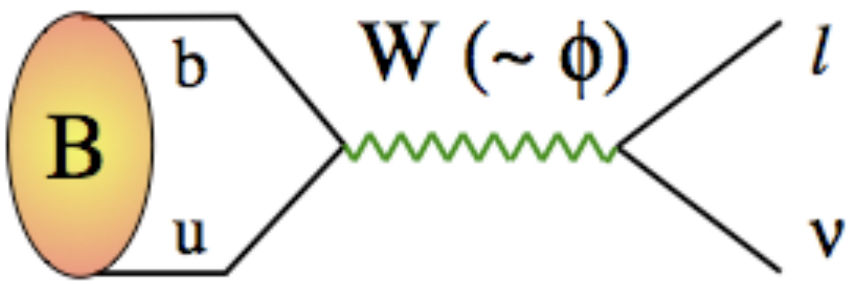
What else can Uplifted SUSY do for you?

- interesting effects in other B-system observables
- distinct collider signals

more Uplifted SUSY + flavor

other interesting effects: $B^{\pm} \to \tau^{\pm}\nu$

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



decay mode is helicity suppressed and CKM suppressed. Susceptible to effects from new physics

$BR(B^+ \to \tau^+\nu)_{SM} = (0.808 \pm 0.071) \times 10^{-4}$ (UTfit: 0908.3470)

more Uplifted SUSY + flavor

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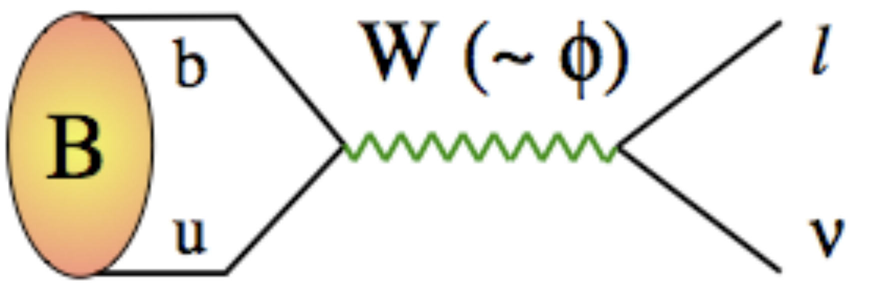

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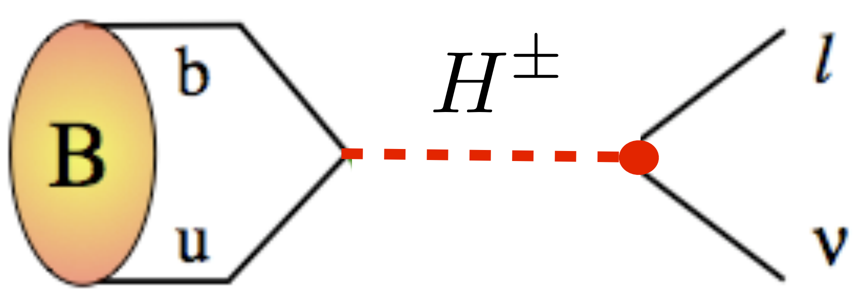
... such as charged Higgs exchange:



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more Uplifted SUSY + flavor

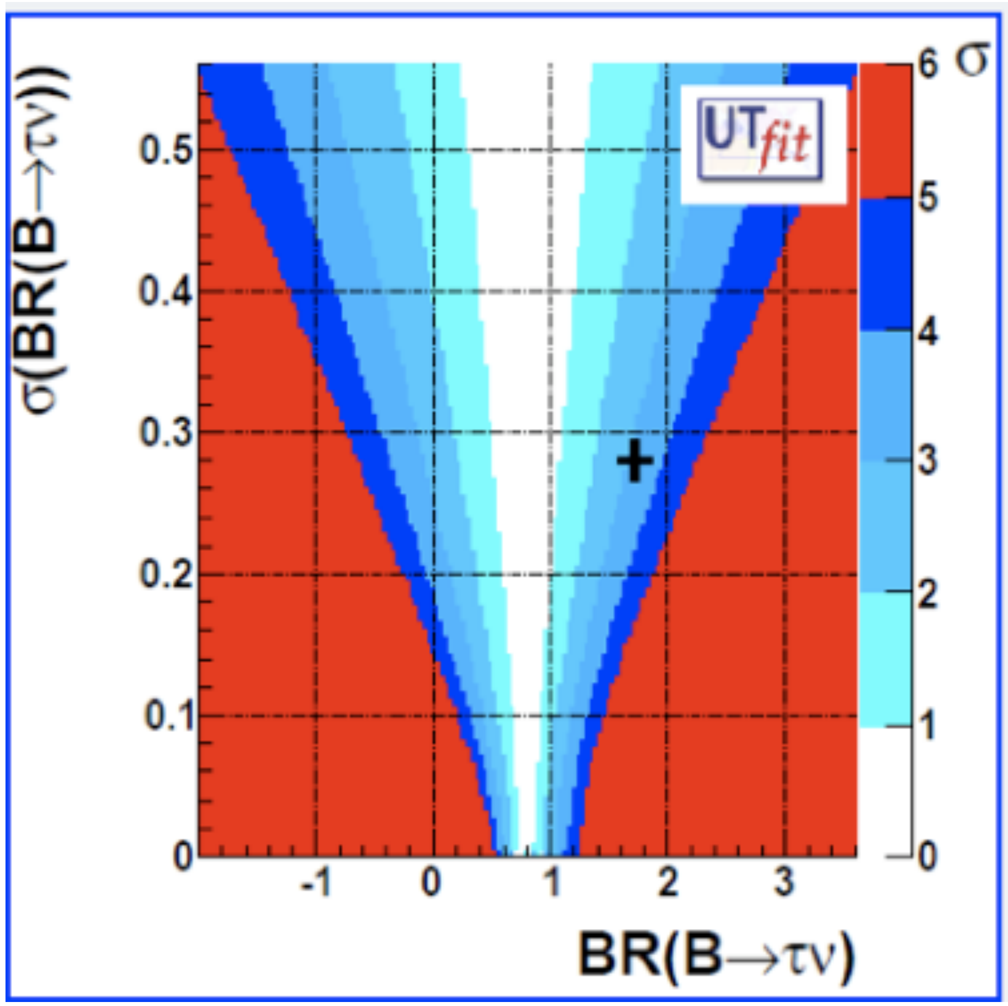
$$BR(B^+ \to \tau^+ \nu)_{SM} = (0.808 \pm 0.071) \times 10^{-4}$$ (UTfit: 0908.3470)

while, comparing with most recent experimental results:

BaBar Semileptonic tag (0912.2453)
BaBar Hadronic tag (0708.2260)

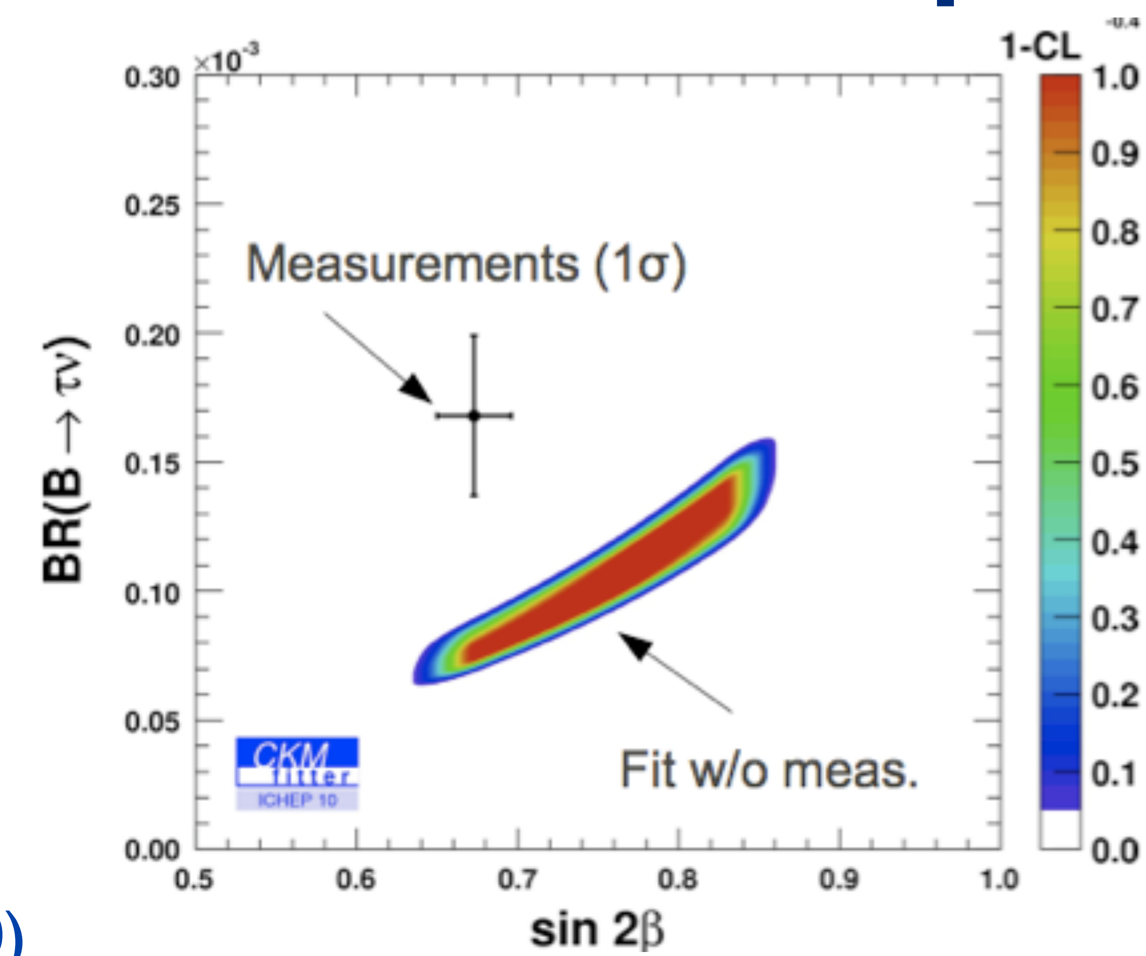
Belle Semileptonic tag (1006.4201)
Belle Hadronic tag (hep-ex/0604018)

$$\text{Belle + BaBar: } BR(B^+ \to \tau^+ \nu) = (1.72 \pm 0.28) \times 10^{-4}$$



(UTfit, CKMfitter talks at ICHEP 2010)

SM is ~3.2 σ discrepant



Uplifted SUSY + flavor

situation looks even worse in the 'conventional' MSSM
(or other `type-2' THDM):

$$\frac{B(B^- \to \tau\nu)}{B(B^- \to \tau\nu)_{SM}} = \left[1 - \tan^2\beta \frac{M_B^2}{M_{H^\pm}^2}\right]^2$$

hard to manage an enhancement without throwing off other observables (ex. $BR(B \to D\tau\nu)$)

BUT in `uplifted SUSY':

$$\frac{BR(B^+ \to \tau^+\nu)}{BR(B^+ \to \tau + \nu)_{SM}} = \left[1 - \left(\frac{y_b}{\underbrace{y_b v_d + y_b' v_u}_{m_b}}\right)\left(\frac{y_\tau}{y_\tau v_d + y_\tau' v_u}\right)\frac{M_B^2}{M_{H_\pm}^2}\right]^2$$

we can have a relative relative phase (even -1) between y_b and y_b' :

enhancing $B^\pm \to \tau^\pm\nu$

(Altmanshofer '10)

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hard to manage an enhancement without throwing off other observables (ex. $BR(B \to D\tau\nu)$)

BUT in `uplifted SUSY': even without new FCNC

$$\frac{BR(B^+ \to \tau^+\nu)}{BR(B^+ \to \tau + \nu)_{SM}} = \left[1 - \left(\frac{y_b}{\underbrace{y_b v_d + y_b' v_u}_{m_b}}\right)\left(\frac{y_\tau}{y_\tau v_d + y_\tau' v_u}\right)\frac{M_B^2}{M_{H_\pm}^2}\right]^2$$

we can have a relative relative phase (even -1) between y_b and y_b' :

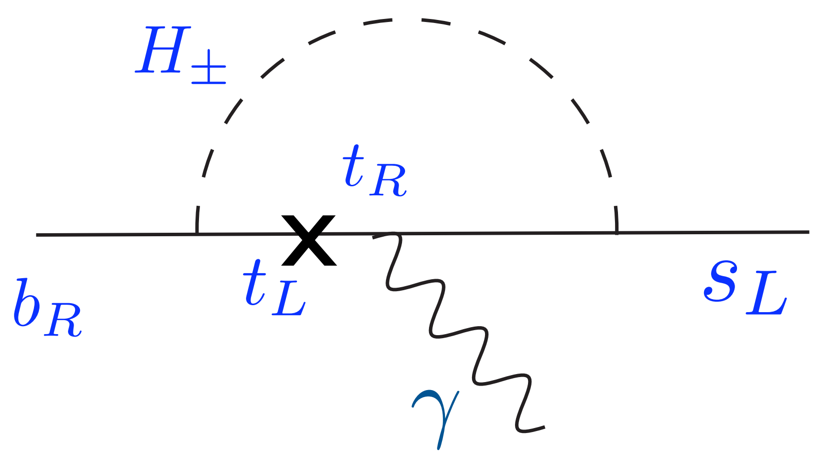
enhancing $B^\pm \to \tau^\pm \nu$

(Altmanshofer '10)

Uplifted flavor effects: some bigger, some smaller

- $b \to s\gamma$: with the usual range of 2HDM parameters, strong, tanβ - independent bound $m_{H_\pm} \gtrsim 300$ GeV

dominant diagram:



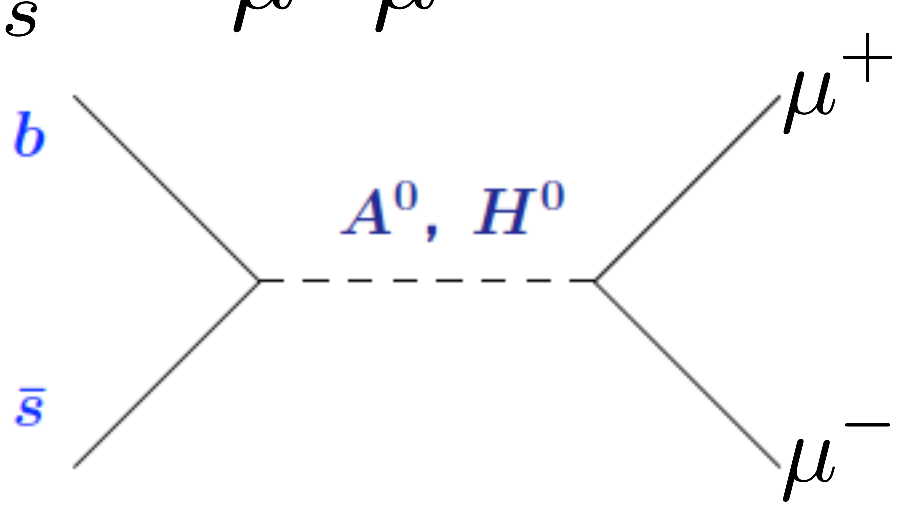
$$\sim \frac{m_t}{M_{H_\pm}^2} y_b\, y_t \cos\beta \sin\beta$$

MSSM: $\dfrac{m_t^2 m_b}{v^2\, M_{H_\pm}^2}$

uplifted: $\dfrac{m_t\, y_b}{M_{H_\pm}^2 \tan\beta}$

contribution in uplifted region smaller by ~ $\dfrac{35\; y_b}{\tan\beta}$

- $B_s^0 \to \mu^+\mu^-$



large y_{bs} enhances these rare decays -- should be right around the corner!

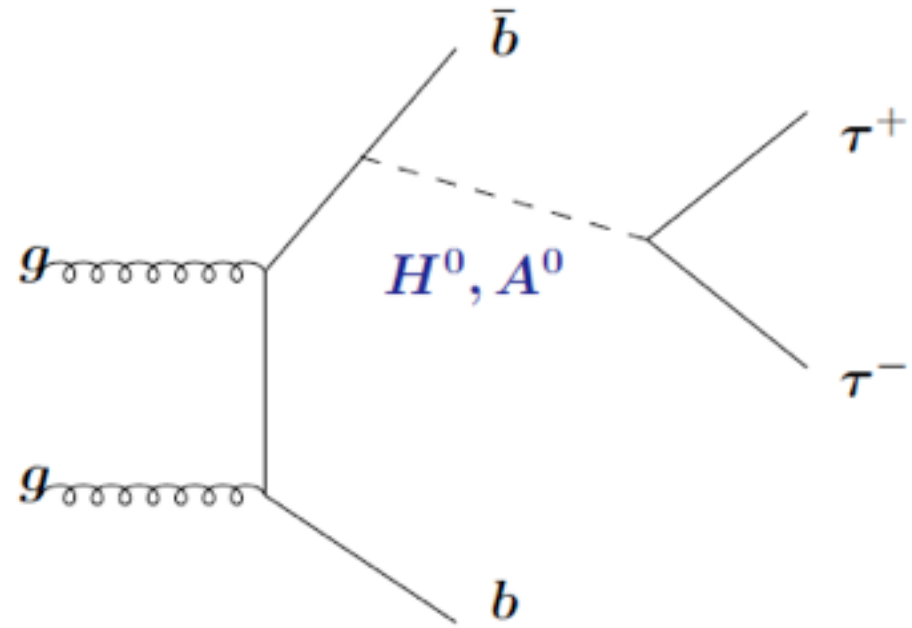
Uplifted SUSY at Tevatron/LHC

- altered collider signatures:

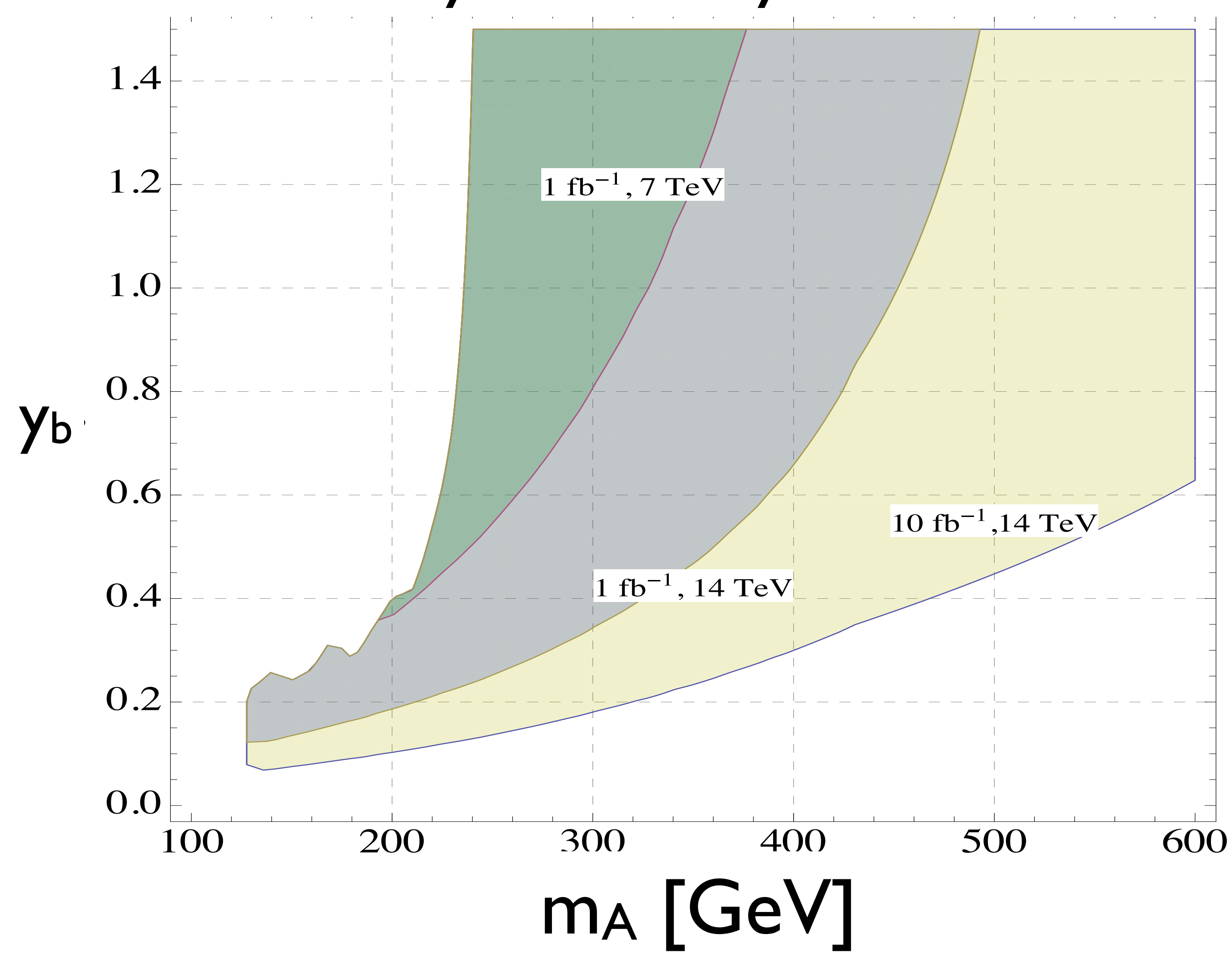
large y_τ ↷

large BR (~30 - 80%) for heavy Higgses (H/A) to $\tau^+\tau^-$

(vs. 10% in usual MSSM)



y_b discovery vs. m_A



Great prospects for early discovery/ limits

(Dobrescu, Fox, AM in preparation)

Conclusions

- D0 like-sign dimuon asymmetry, interpreted as B oscillations means there must be BSM physics

- it's tricky to work in new physics to explain excess without messing up existing flavor constraints

- One possibility: new physics in phase of M^s_{12} -- NP must be large with large phase. In this case, should see an effect in $S_{\psi\varphi}$

'Uplifted SUSY' region is one scenario with the right properties to explain excess

- FCNC through H/A exchange
- couplings sensitive to complex SUSY parameters
- assuming $M_{\tilde{Q}_3} \neq M_{\tilde{Q}_1} \simeq M_{\tilde{Q}_2}$

  effects in $B_s^0 \; > \; B_d^0 \; \gg \; K^0$
- other B-system/collider signatures soon: $B \to \tau\nu, B_s \to \mu^+\mu^-$

input from (super)B-factories essential!

THANKS FOR THE
GREAT WORKSHOP!

EXTRAS

Latest CDF $S_{\psi\phi}$