

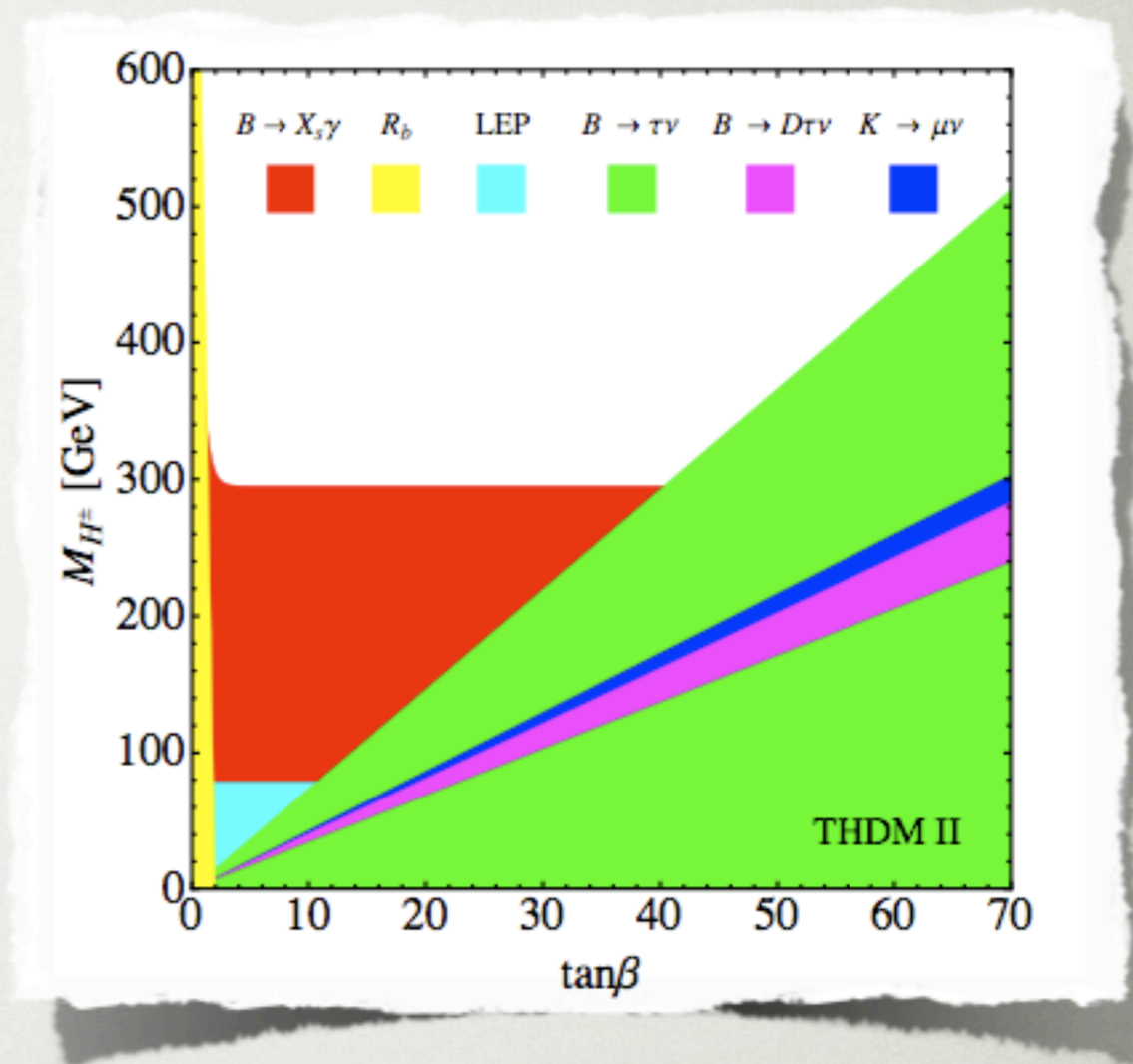
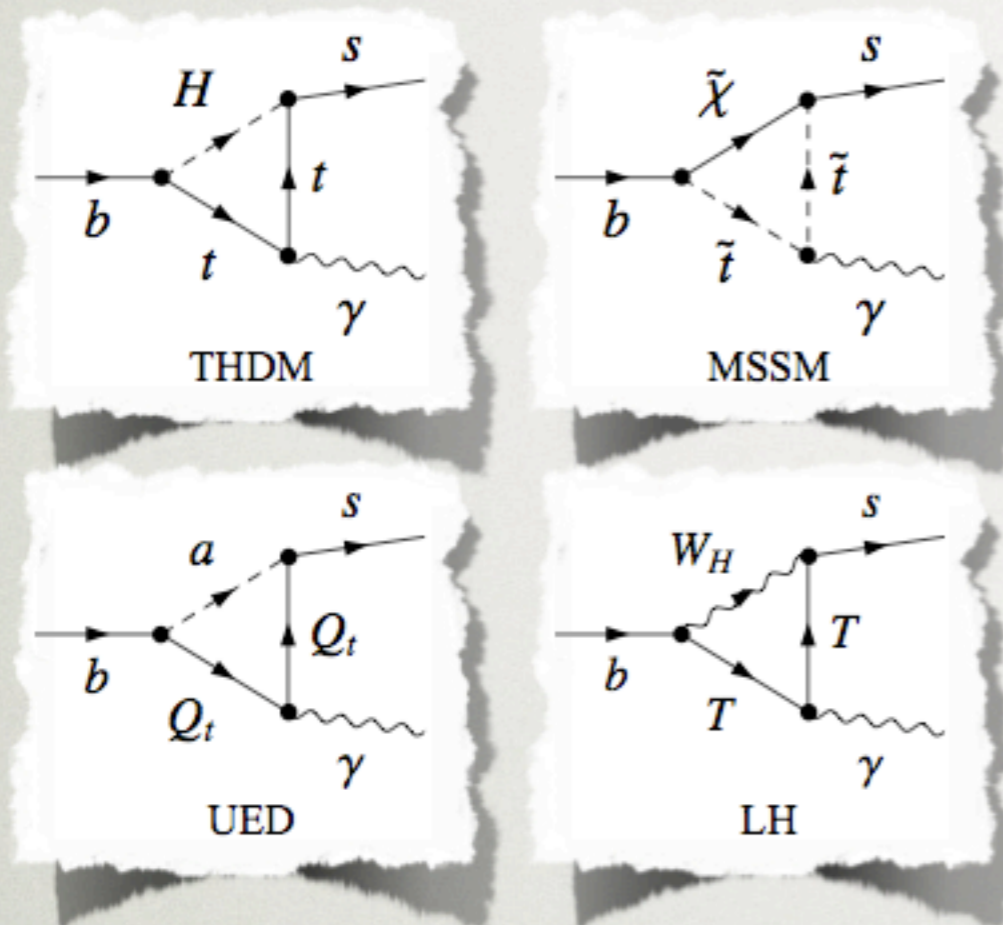


$B \rightarrow X_s \gamma$: SM and Beyond

Ulrich Haisch
University of Mainz (THEP)

Flavor Physics & CP Violation (FPCP),
May 5–9, 2008, National Taiwan University,
Taipei, Taiwan

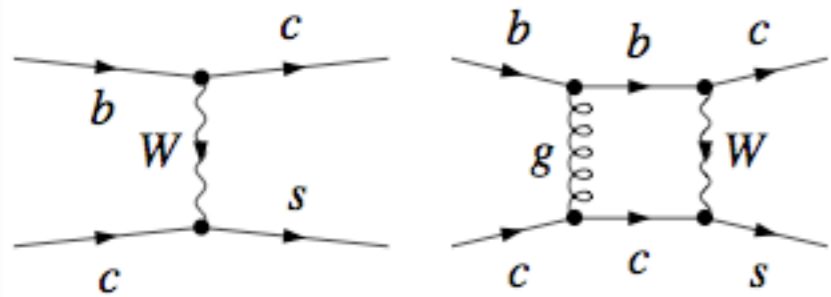
Motivation



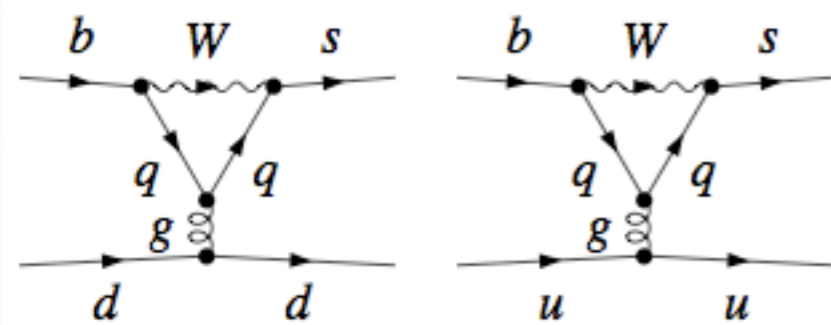
- Inclusive radiative B -meson decay provides stringent constraints on various NP scenarios at EW scale, since it is accurately measured and its theoretical determination is rather precise

- As $\Delta BR_{\text{SUSY}} \sim (0.1 \text{ TeV}/\tilde{m})^2 BR_{\text{SM}}$ and squark masses of at least a few hundred GeV are plausible, SUSY corrections to BR of only a few percent are likely, which calls for precise SM calculations of $b \rightarrow s \gamma$

Effective Theory



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

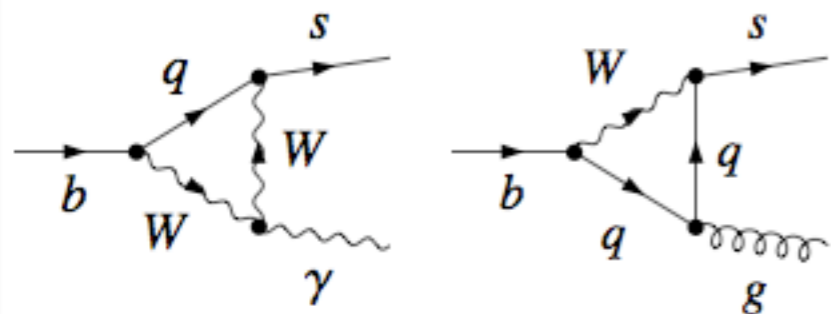


$$Q_{1,2} = (\bar{s}\Gamma_i c) (\bar{c}\Gamma'_i b)$$

$$|C_{1,2}(m_b)| \sim 1$$

$$Q_{3-6} = (\bar{s}\Gamma_i b) \sum_q (\bar{q}\Gamma'_i q)$$

$$|C_{3-6}(m_b)| < 0.07$$



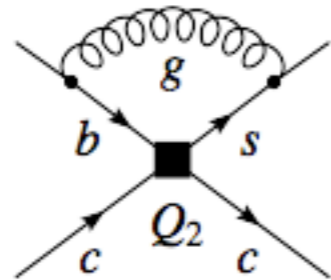
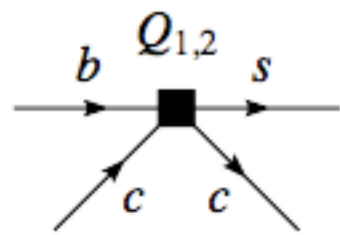
$$Q_7 = \frac{em_b}{16\pi^2} (\bar{s}_L \sigma^{\mu\nu} b_R) F_{\mu\nu}$$

$$C_7(m_b) \sim -0.3$$

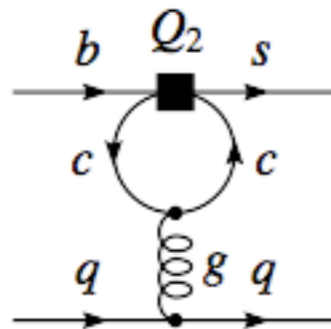
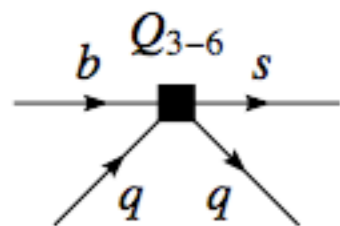
$$Q_8 = \frac{gm_b}{16\pi^2} (\bar{s}_L \sigma^{\mu\nu} T^a b_R) G_{\mu\nu}^a$$

$$C_8(m_b) \sim -0.15$$

Effective Theory



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

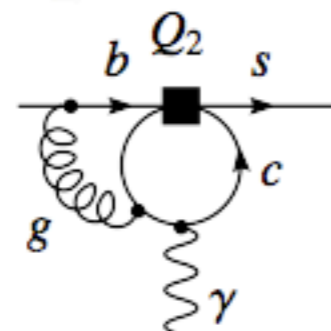
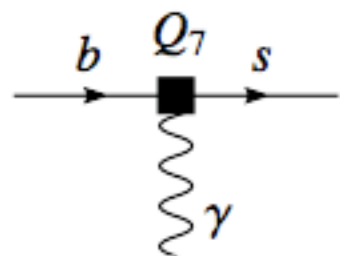


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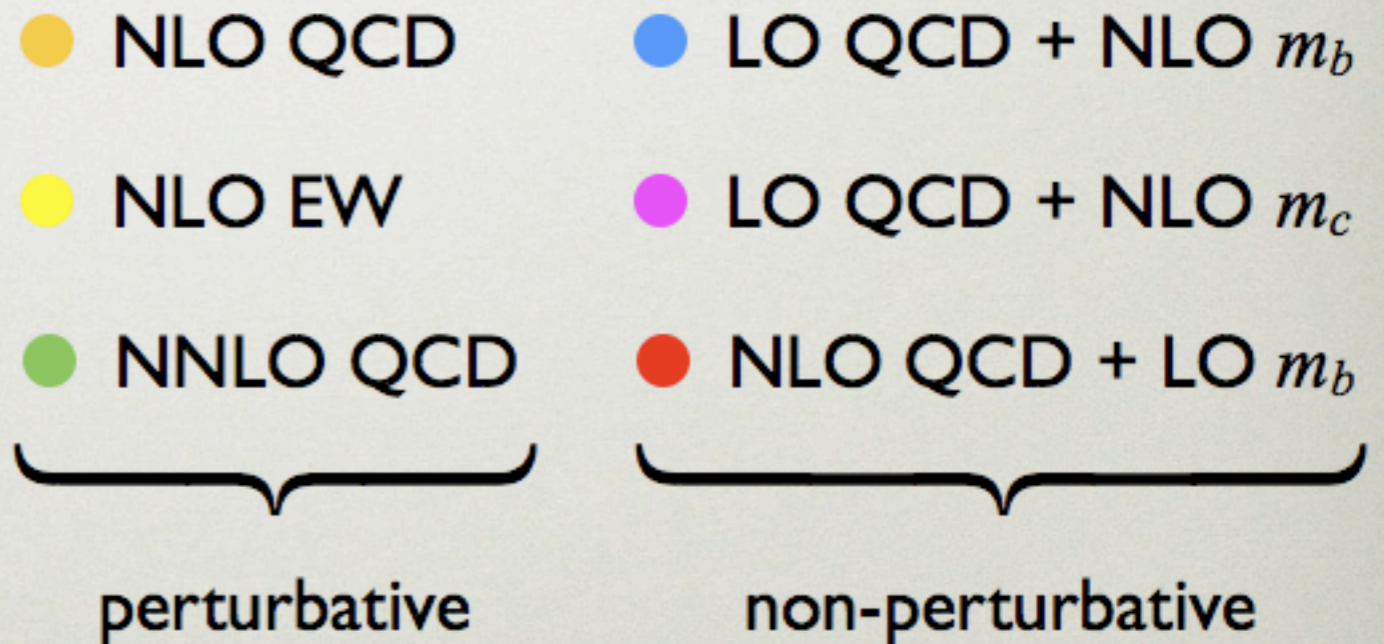
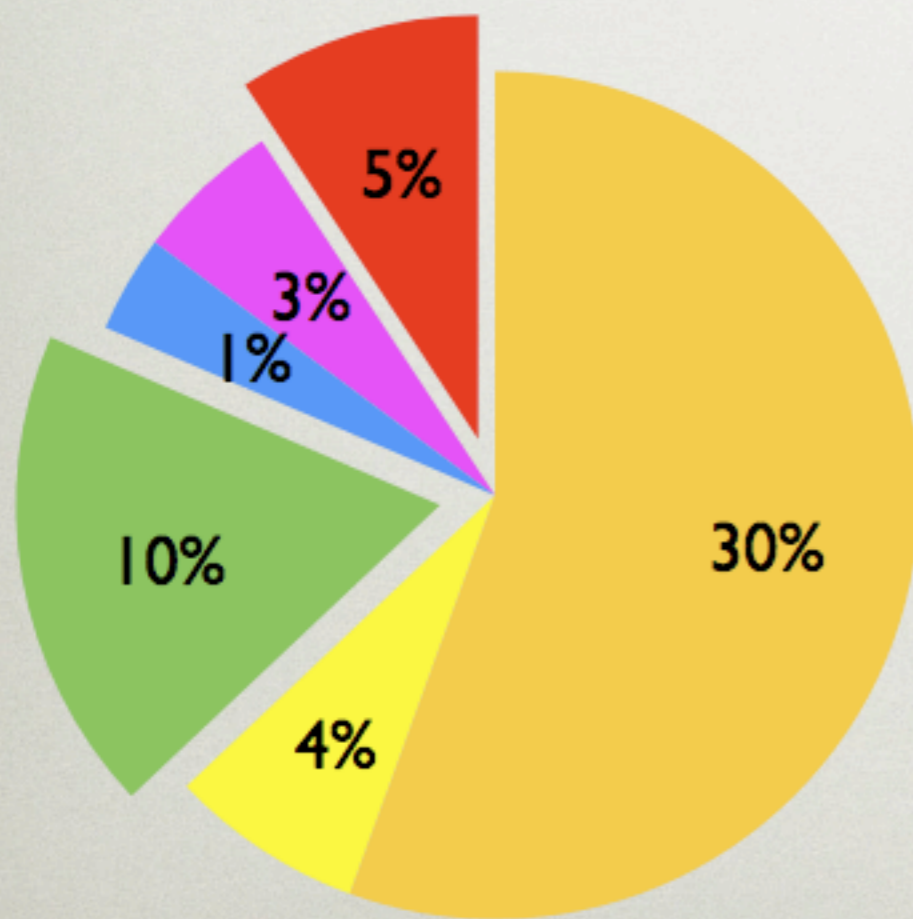
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General Structure

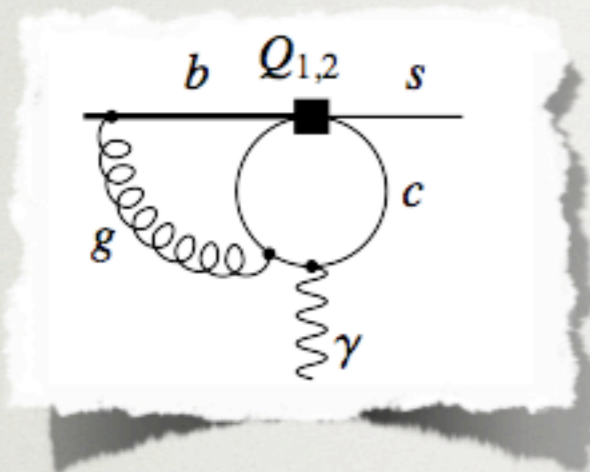
$$\text{BR}(B \rightarrow X_s \gamma)_{\text{SM}}^{E_\gamma > 1.6 \text{ GeV}} = \text{BR}(B \rightarrow X_c e \bar{\nu})_{\text{exp}} \left[\frac{\Gamma(b \rightarrow s \gamma)}{\Gamma(b \rightarrow ce \bar{\nu})} \right]_{\text{LO}}$$

$$\times \left\{ 1 + \mathcal{O}(\alpha_s) + \mathcal{O}(\alpha) + \mathcal{O}(\alpha_s^2) + \mathcal{O}\left(\frac{\Lambda^2}{m_b^2}\right) + \mathcal{O}\left(\frac{\Lambda^2}{m_c^2}\right) + \mathcal{O}\left(\alpha_s \frac{\Lambda}{m_b}\right) \right\}$$

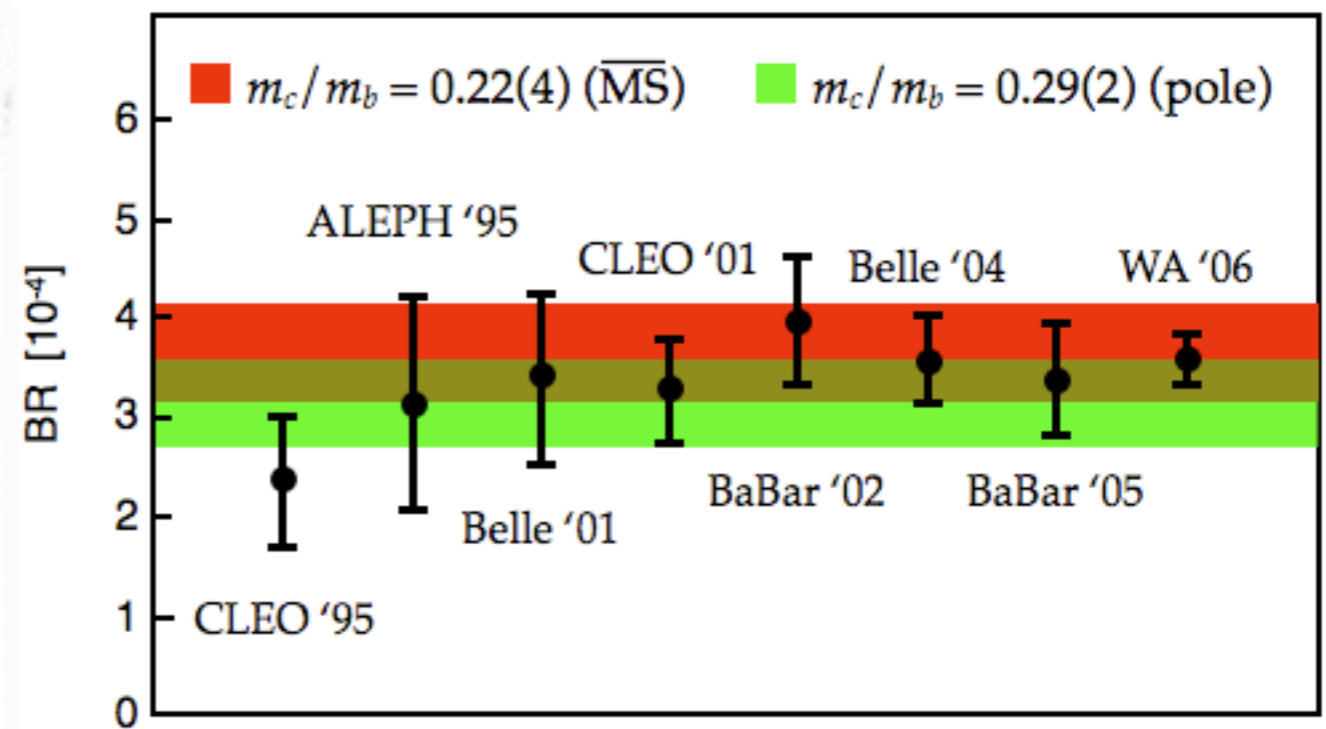


relative size compared to LO

Role of Charm Quark

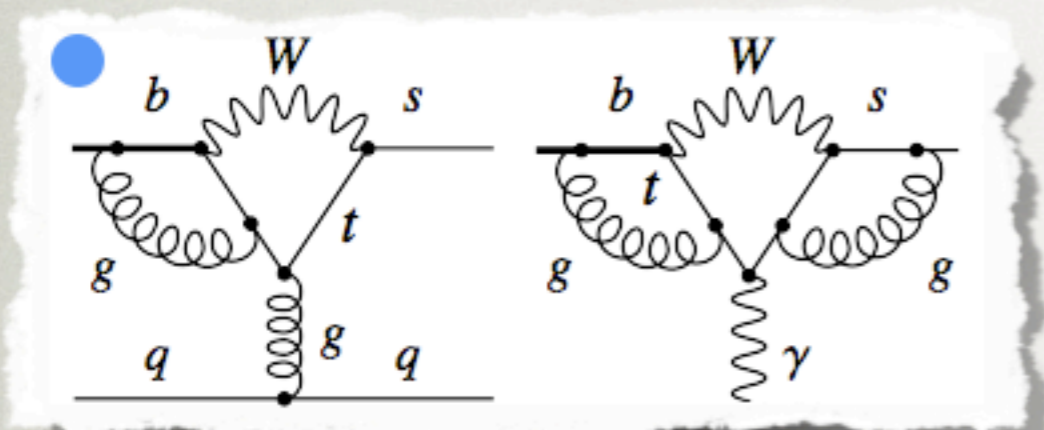


- Changing pole scheme value $m_c/m_b = 0.29(2)$ to \overline{MS} value $0.22(4)$ leads to a shift of SM BR of more than 10% at NLO level
- Charm quark mass dependence of $BR(B \rightarrow X_s \gamma)$ so pronounced because charm quark mass first enters through $b \rightarrow s \gamma$ matrix elements of $Q_{1,2}$ at NLO level

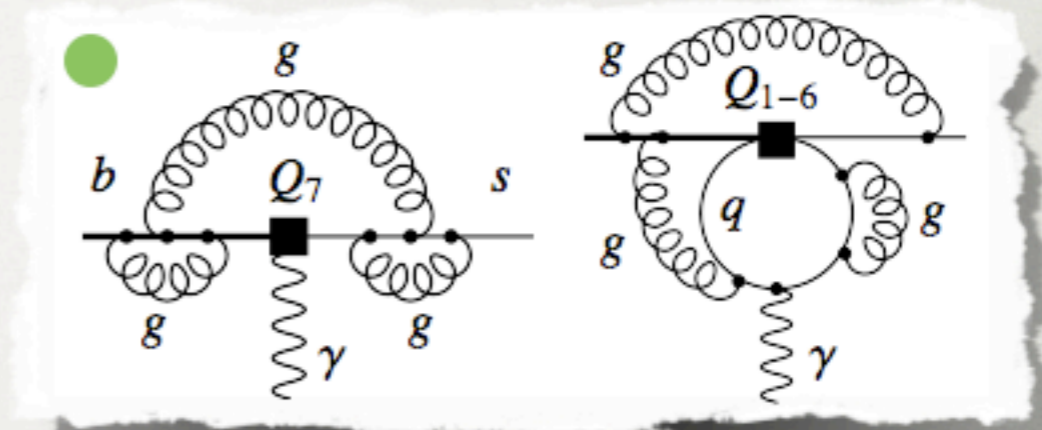


- Natural scale at which charm quark mass should be normalized can thus only be determined by a dedicated calculation of charm quark mass dependence of BR at NNLO

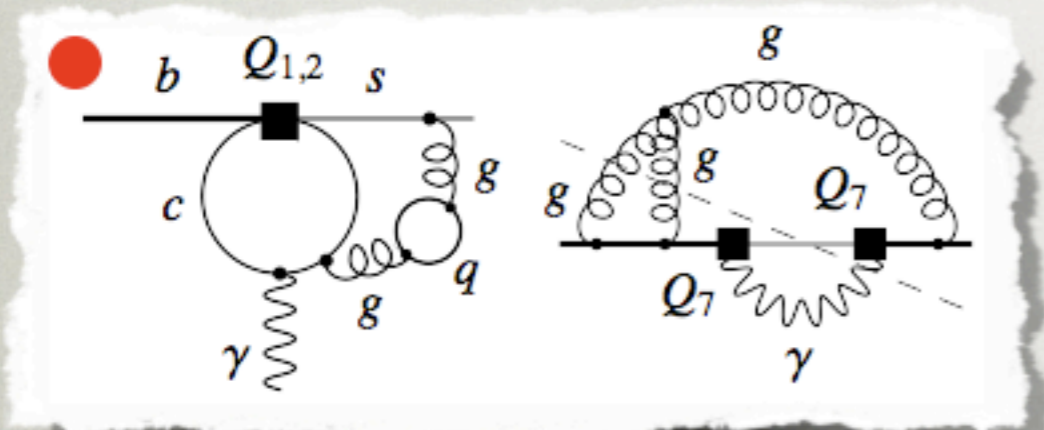
Flavor of NNLO Calculation



Bobeth, Misiak & Urban '00; Misiak & Steinhauser '04



Gorbahn & UH '04; Gorbahn, UH & Misiak '05; Czakon, UH & Misiak '06

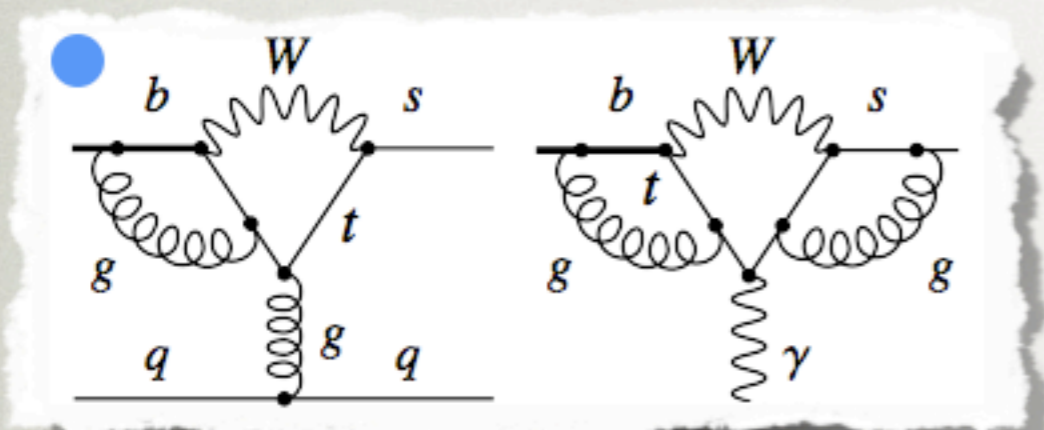


Bieri, Greub & Steinhauser '03; Blokland et al. '05; Melnikov & Mitov '05; Asatrian et al. '05, '06; Misiak & Steinhauser '06

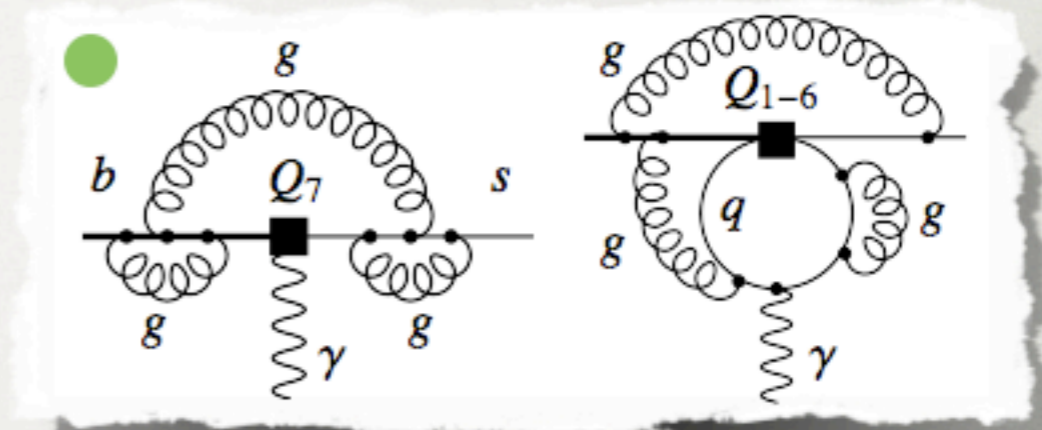
- Matching at high scale $\sim M_W$:
three- for $C_{7,8}$ and two-loop for C_{1-6}
- Running between M_W and m_b :
four- for $b \rightarrow s\gamma(g)$ while three-loop in remaining cases

all Wilson coefficients $C_{1-8}(m_b)$ known at NNLO

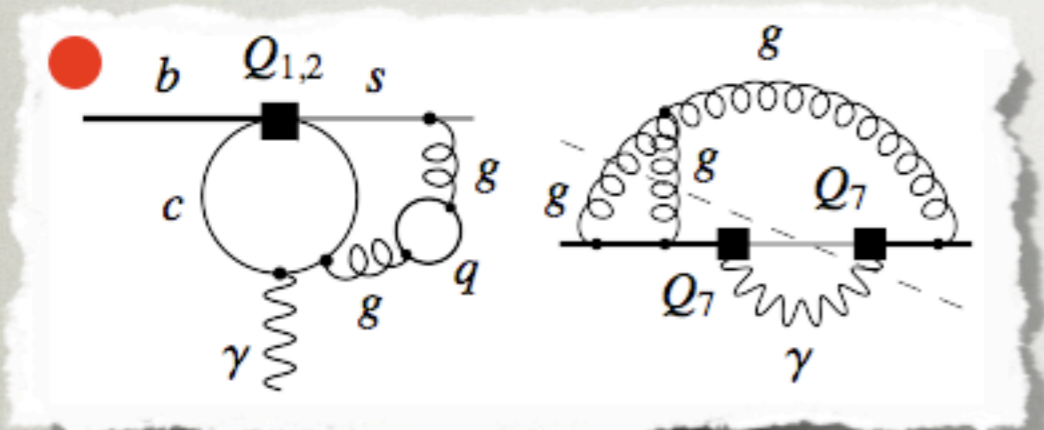
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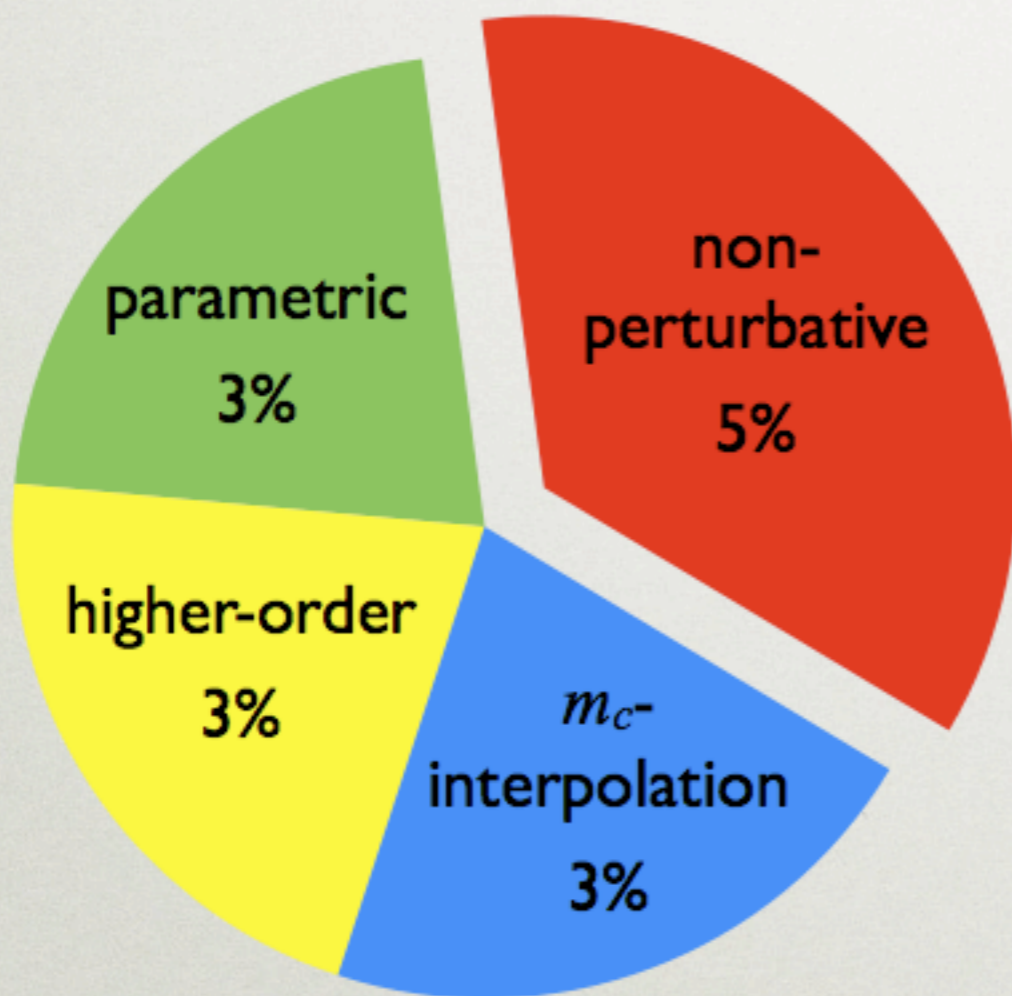
Bieri, Greub & Steinhauser '03; Blokland et al. '05;
Melnikov & Mitov '05; Asatrian et al. '05, '06;
Misiak & Steinhauser '06

- Matrix elements at low scale $\sim m_b$: complete for (Q_7, Q_7) , virtual large- β_0 corrections for $Q_{1,2,7,8}$ and asymptotic form of all matrix elements in heavy charm quark mass limit $m_c \ll m_b/2$

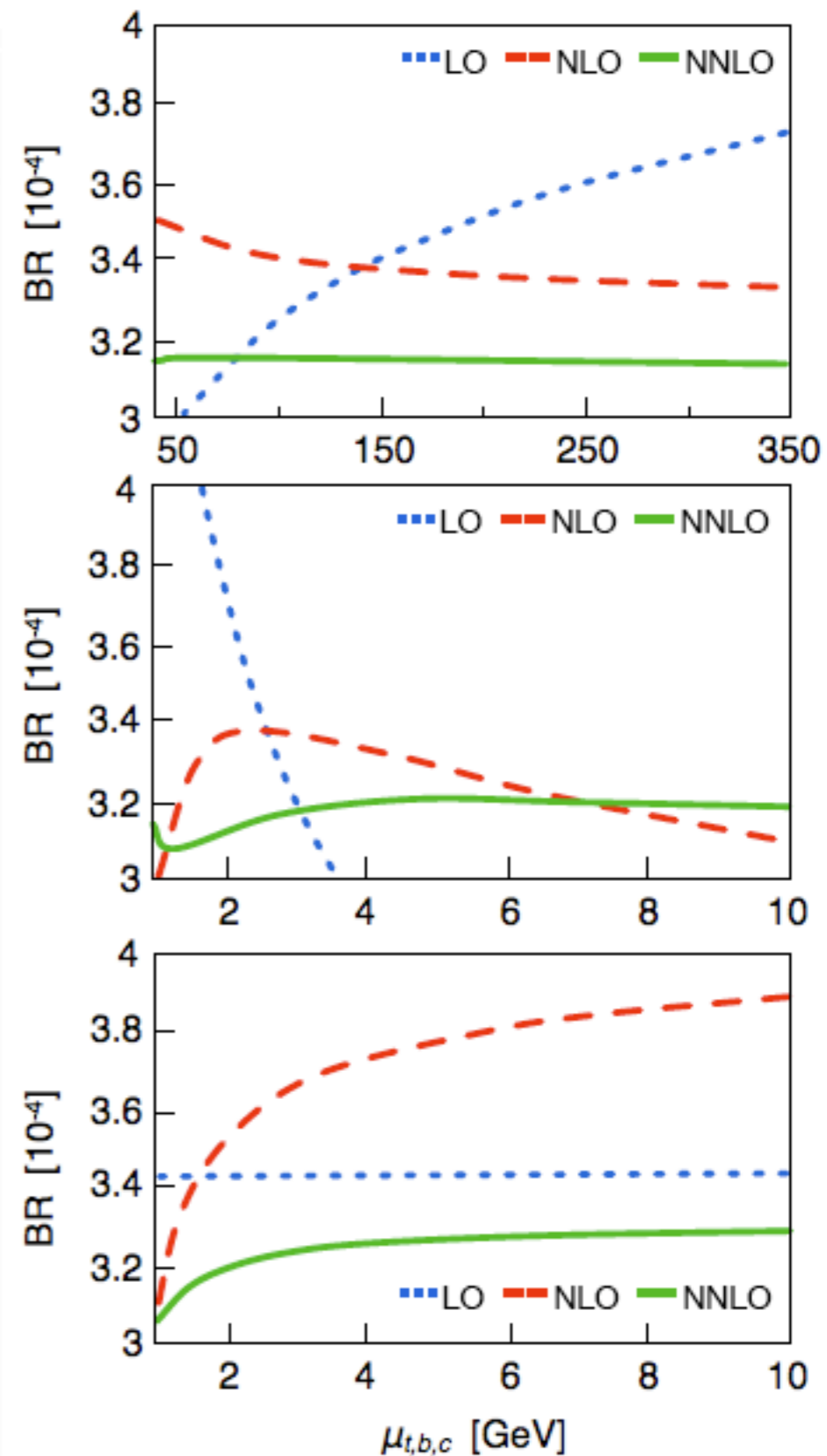
interpolation to $m_c \sim 0.25m_b$ assuming that large- β_0 part describes full result well for $m_c = 0$

First NNLO Estimate

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



individual errors on BR



Photon Energy Cut Effects

Belle '08

- Further problems arise since measurements impose cuts on photon energy $E_\gamma > E_0$ with $E_0 = [1.7, 2.0]$ GeV to suppress backgrounds
- Raises question of how big is fraction of events $1 - T$ in range $E_0 = [1.0, 1.6]$ GeV

● $1 - T = 0.04 \pm 0.01_{\text{pert}}$

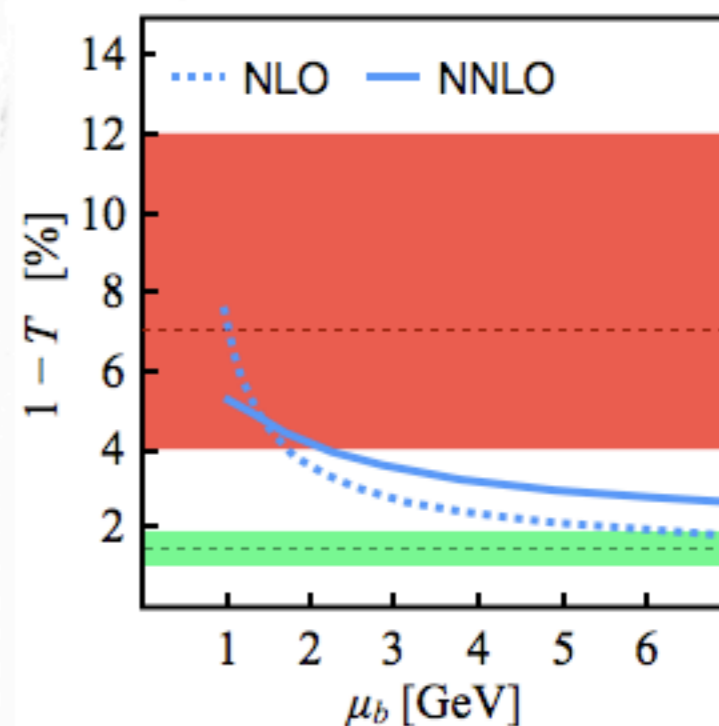
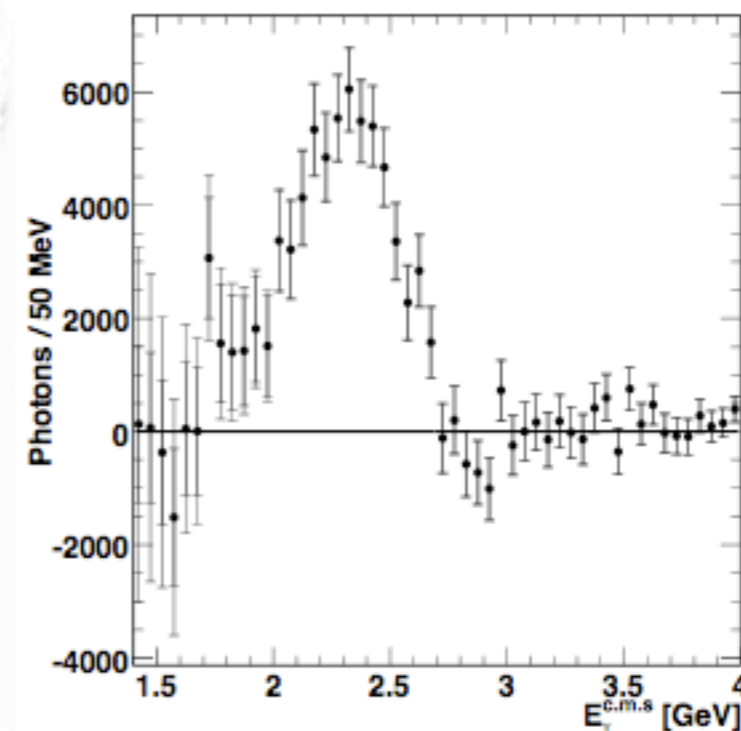
Misiak et al. '06; Misiak & Steinhauser '06

● $1 - T = 0.07^{+0.05}_{-0.03}_{\text{pert}} \pm 0.02_{\text{hadr}} \pm 0.02_{\text{pars}}$

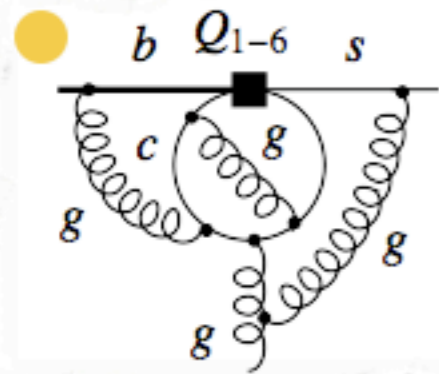
Becher & Neubert '06

● $1 - T = 0.016 \pm 0.003_{\text{pert}}$

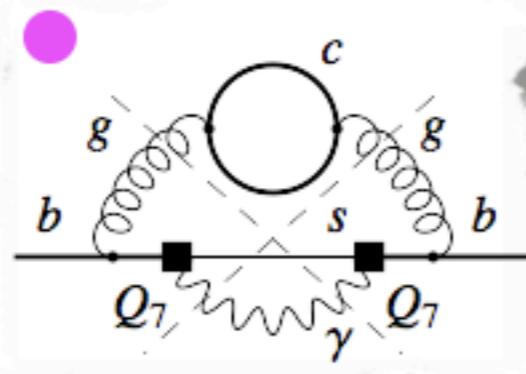
Andersen & Gardi '06



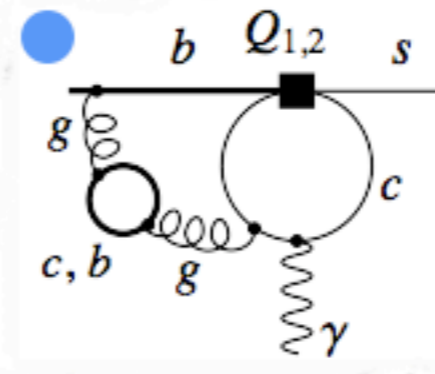
Further Progress



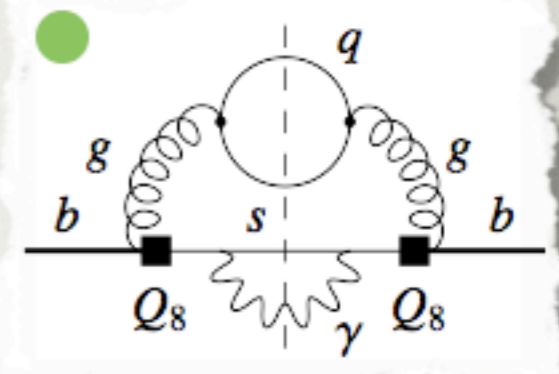
Czakon, UH & Misiak '06



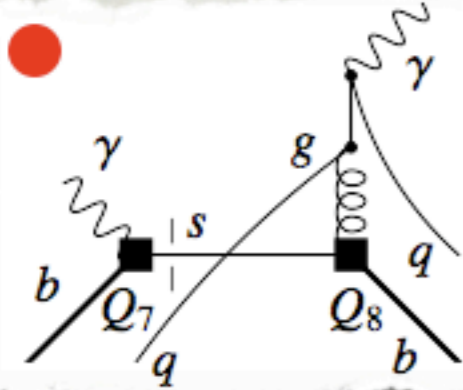
Asatrian et al. '06; Czarnecki & Pak, unpublished



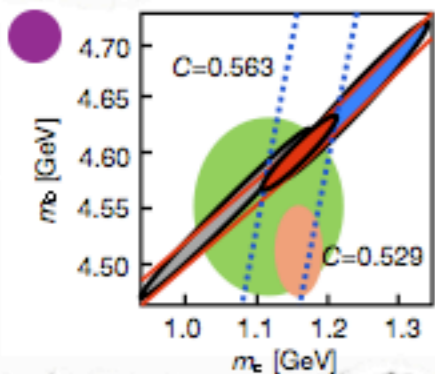
Boughezal, Czakon & Schutzmeier '07



Ligeti et al. '99; Ferroglia, Gambino & UH, unpublished



Lee, Neubert & Paz '06

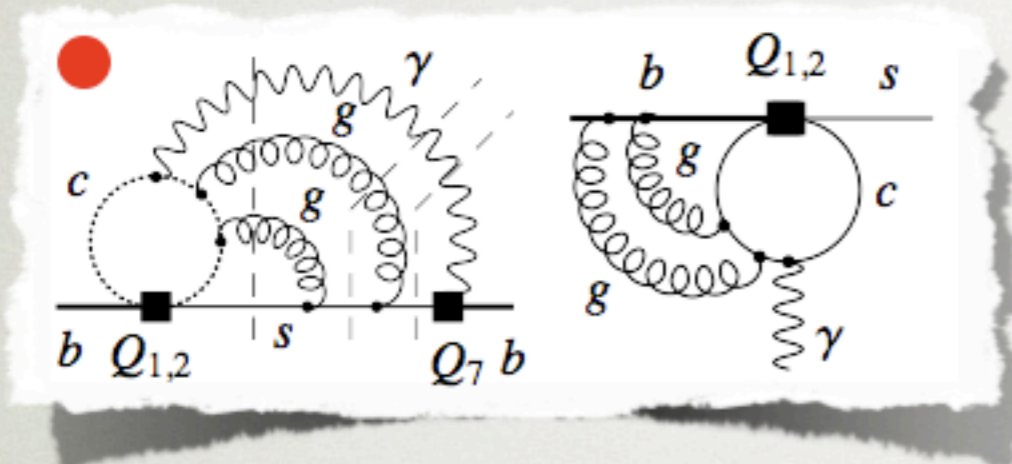


Gambino & Giordano '08

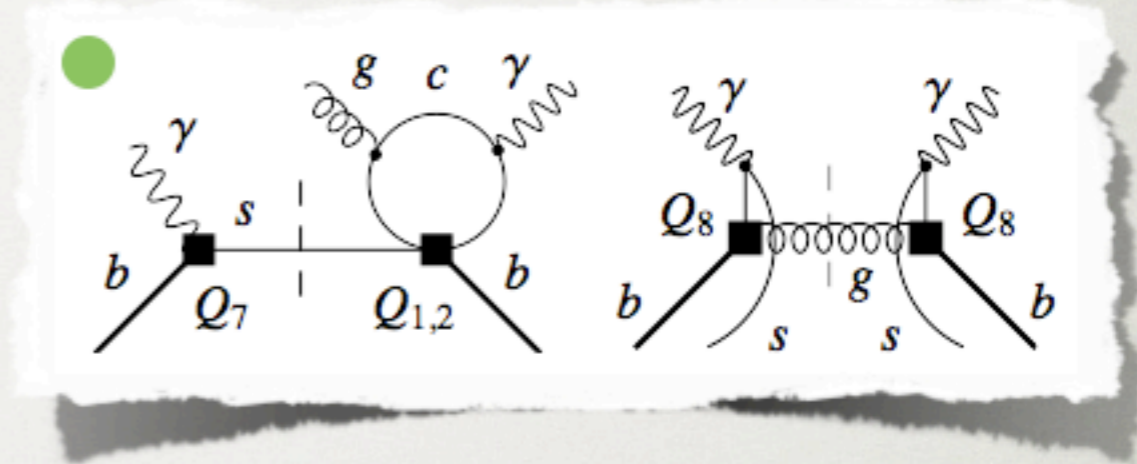
- α_s^2 anomalous dimensions Q_{1-6} into Q_8 : -0.3%
- m_c effects due to gluon lines of (Q_7, Q_7) : $+0.3\%$
- $m_{c,b}$ effects due to gluon lines of $(Q_{1,2}, Q_7)$: $+1.1\%$
- dominant large- β_0 bremsstrahlungs effects: $+2.0\%$
- $\alpha_s \Lambda/m_b$ non-perturbative effects of (Q_7, Q_8) : -1.5%
- updated semileptonic normalization factor: $+4.8\%$

total correction to BR: $+6.4\%$

Ongoing Efforts



Boughezal, Czakon & Schutzmeier, in progress



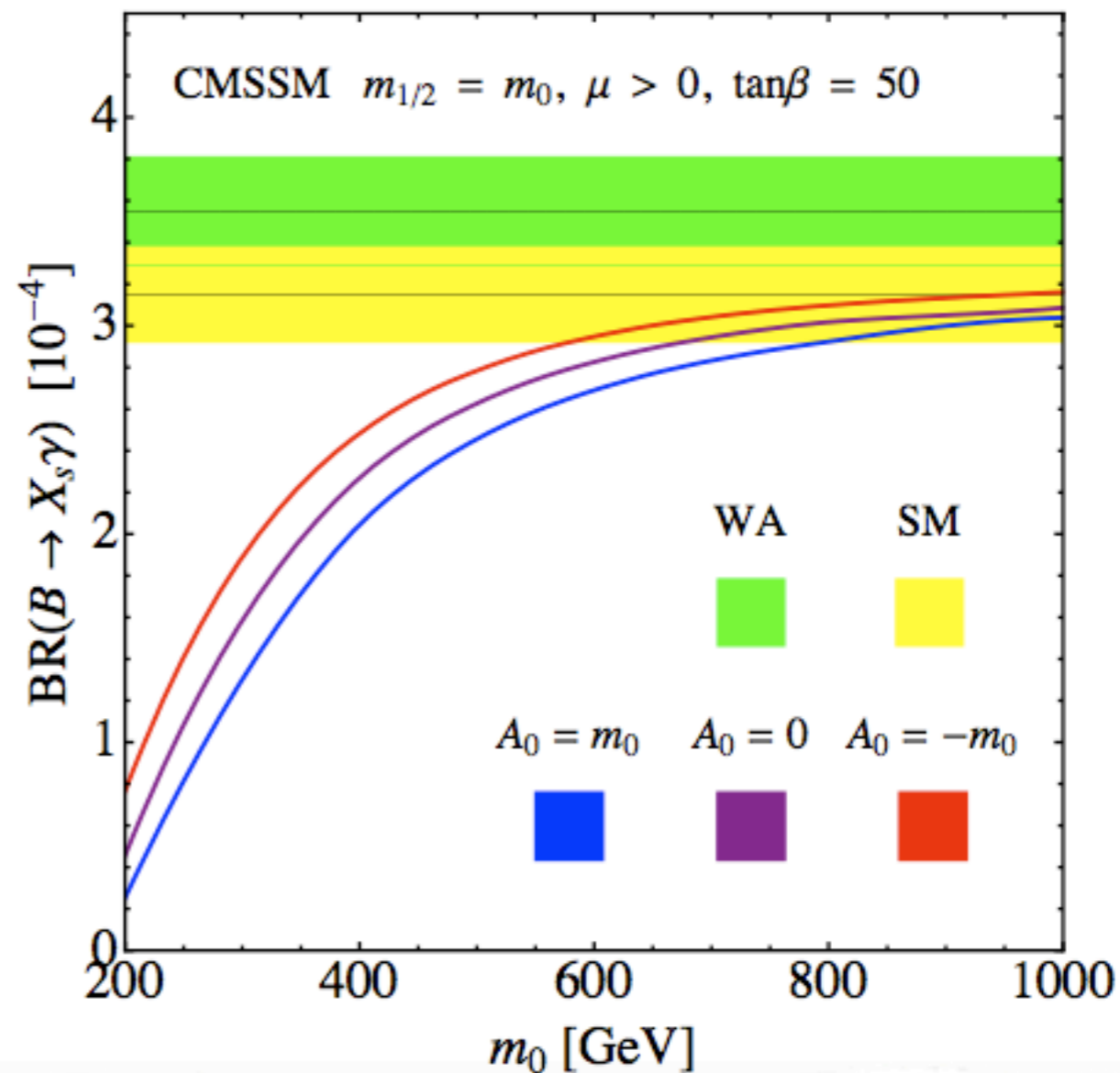
Lee, Neubert & Paz, in progress

- Calculation of α_s^2 corrections to $(Q_{1,2}, Q_7)$ for $m_c = 0$ and of virtual α_s^2 corrections of $Q_{1,2}$ matrix elements for $m_c \sim 0.25m_b$ with aim of significantly reducing or even removing theory uncertainty due to interpolation in charm quark mass

- Dedicated analysis of $\alpha_s \Lambda/m_b$ non-local power-corrections emerging from $(Q_{1,2}, Q_7)$ and (Q_8, Q_8) terms may allow to set rough bound on size of non-perturbative effects, superseding current uncertainty guess-estimate of 5%

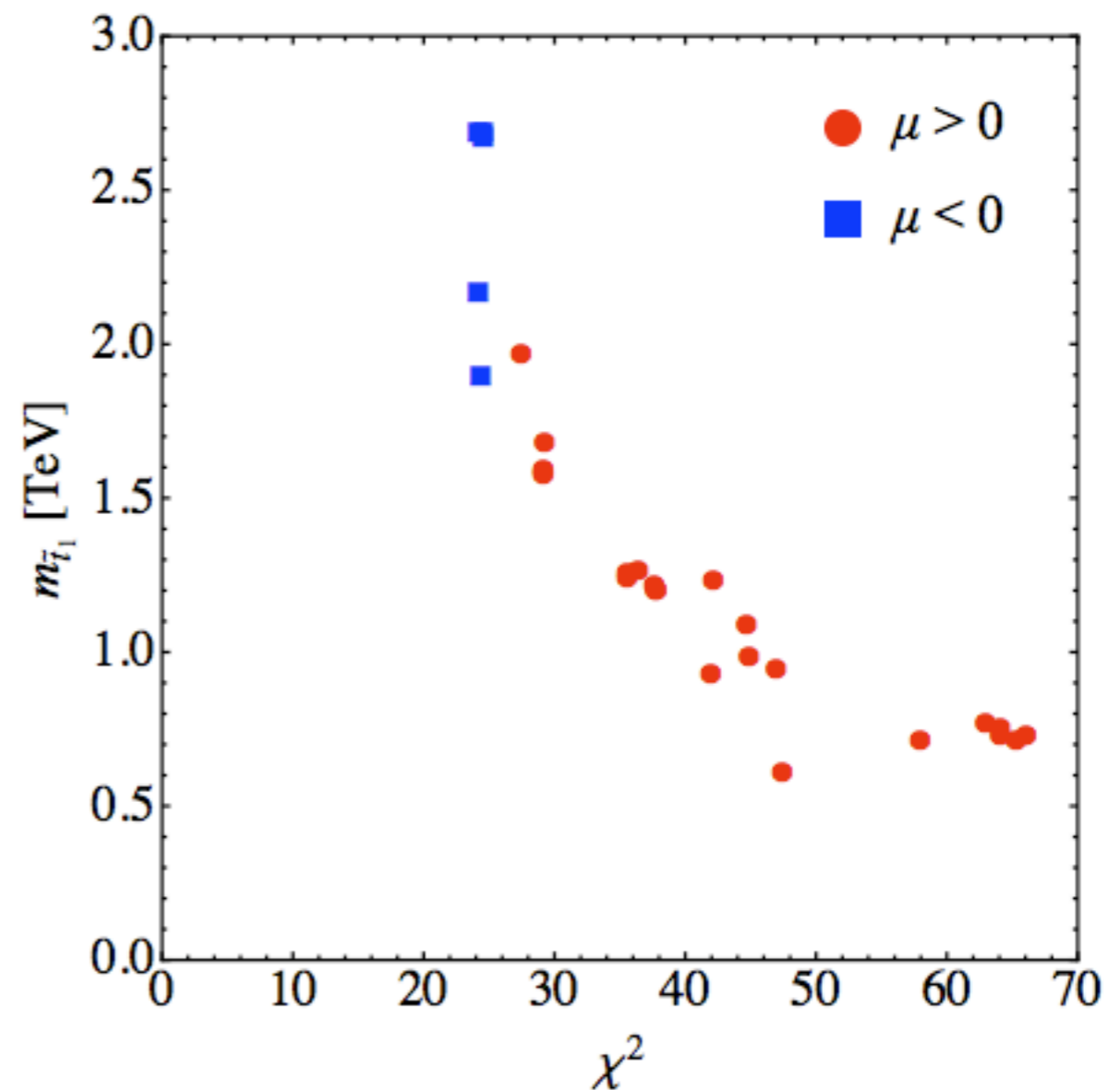
Constrained MSSM

- Minimal flavor-violating SUSY scenarios featuring universal scalar m_0 , gaugino $m_{1/2}$ masses, and trilinear terms A_0 tend to lead for large values of $\tan\beta$ to suppression of $\text{BR}(B \rightarrow X_s \gamma)$ compared to SM prediction
- Departures from minimal flavor-violation induced through third generation off-diagonal elements in Yukawa, sfermion, and trilinear terms allow to bring BR closer to experimental value and thus slightly relax bound on m_0

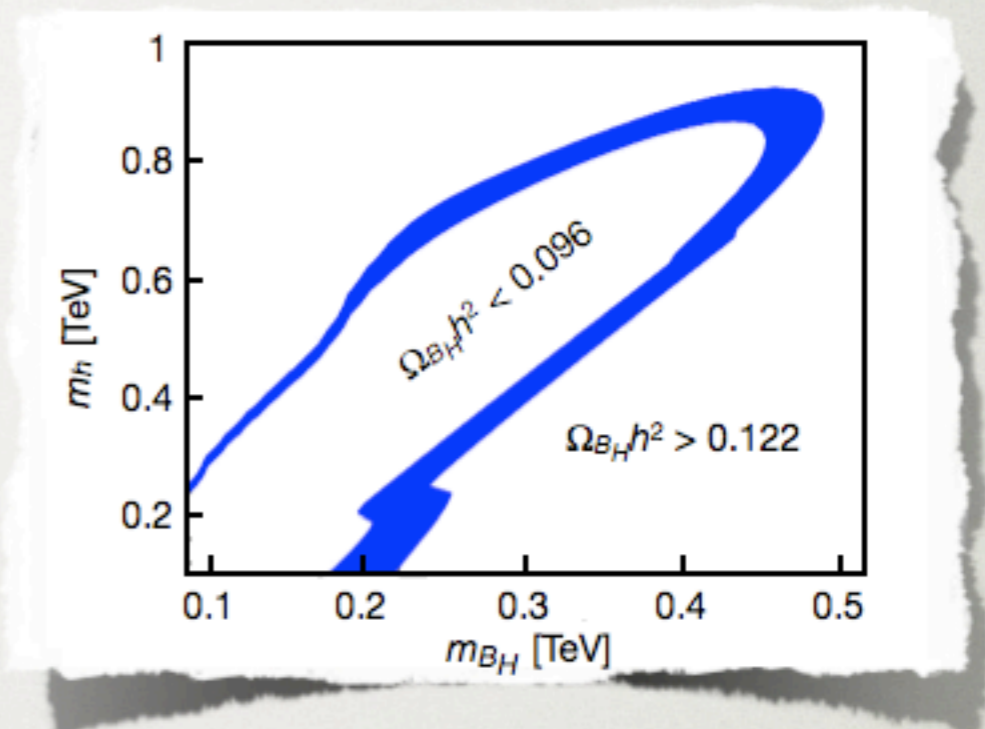
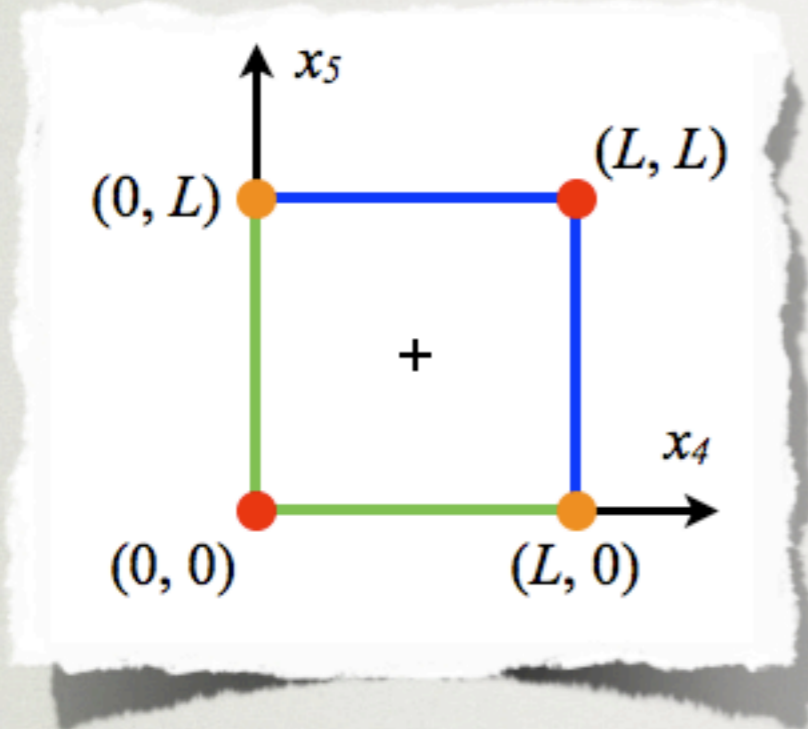


SUSY GUTs

- Minimal $SO(10)$ model with D_3 family symmetry is unable to explain simultaneously bottom quark mass and $BR(B \rightarrow X_s \gamma)$, once stringent Tevatron bound on $B_s \rightarrow \mu^+ \mu^-$ is imposed, unless squarks are unnaturally heavy with masses well above few TeV
- Generic problem of SUSY GUTs with third generation Yukawa unification and universal GUT scale SUSY masses can be cured by relaxing exact Yukawa unification to $b-\tau$ unification



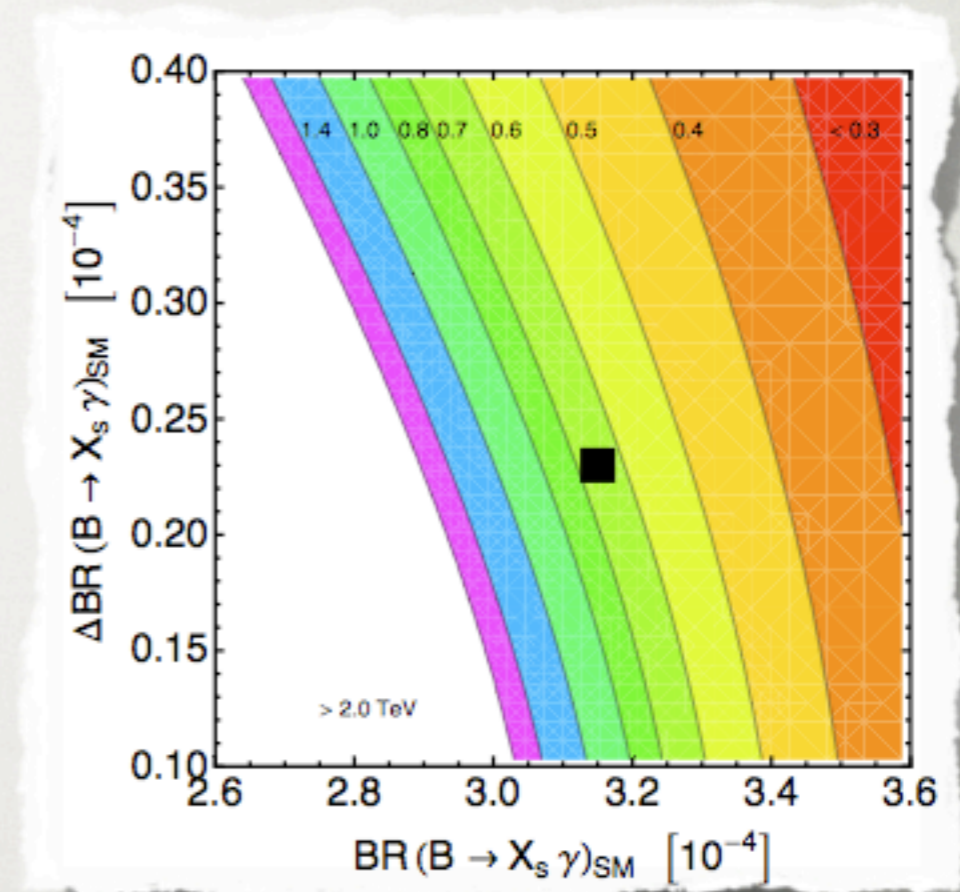
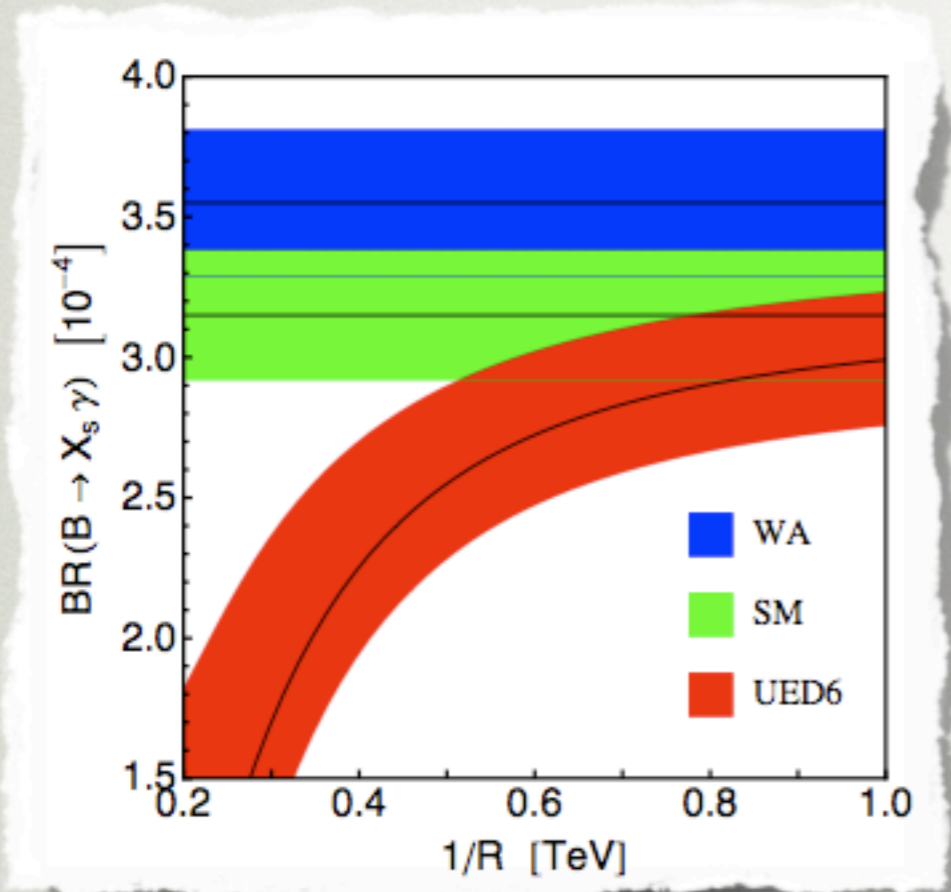
Two Universal Extra Dimensions



- All SM fields propagate in two flat extra dimensions, compactified on a square with side length $L = \pi R$ and adjacent sides being identified. This compactification leads to chiral fermion zero modes, while the higher fermionic KK modes are vector-like as usual

- Since geometry is invariant under rotations by π about the center of square, the model respects an additional Z_2 symmetry. This implies that the lightest KK-odd particle is stable and could provide a viable dark matter candidate for a small KK scale $1/R \lesssim 600 \text{ GeV}$

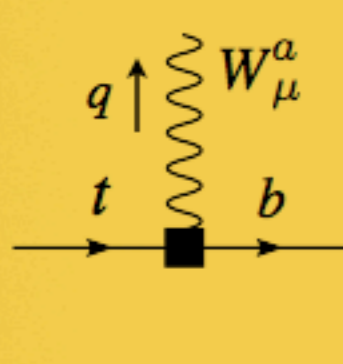
Bound on Compactification Scale



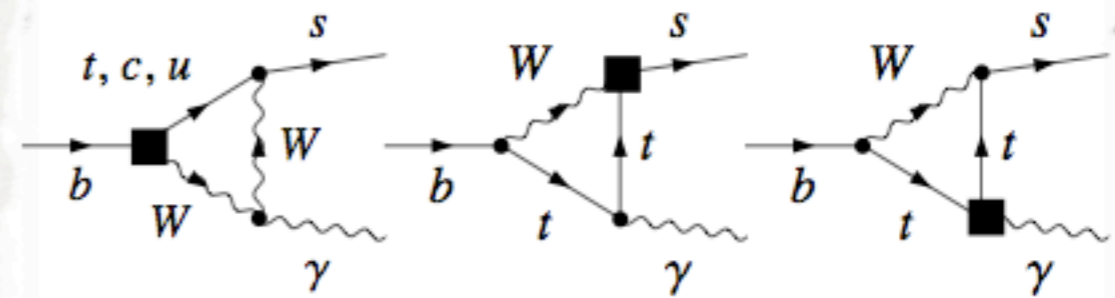
- Inclusion of virtual one-loop KK contributions and quadratic divergent mass corrections to KK scalar masses leads to strong suppression of BR in UED6 compared to SM prediction

- Although cut-off sensitivity weakens constraint on compactification scale, $B \rightarrow X_s \gamma$ leads to strongest direct bound of $1/R > 650 \text{ GeV}$ at 95% CL in variance with dark matter limit

Anomalous Wtb Couplings



$$q \uparrow \begin{array}{c} \text{---} W_{\mu}^a \text{---} \\ \text{---} t \text{---} \\ \text{---} b \text{---} \end{array} = -\frac{ig_W}{\sqrt{2}} \left[\gamma_{\mu} (v_L P_L + v_R P_R) + \frac{i\sigma_{\mu\nu} q^{\nu}}{M_W} (g_L P_L + g_R P_R) \right]$$



95% CL bound	δv_L	v_R	g_L	g_R	$\text{Re } C_7^{(p)}$	$\text{Re } C_8^{(p)}$
upper	0.03	0.0025	0.0004	0.57	0.04	0.15
lower	-0.13	-0.0007	-0.0015	-0.15	-0.14	-0.56

- ATLAS measurements should allow to put stronger bound of few 10^{-2} on g_R , while expected bounds on v_R and g_L are weaker than $B \rightarrow X_s \gamma$ limits by more than order of magnitude due to chiral m_t/m_b enhancement in $b \rightarrow s \gamma$
- Single top production measurement at Tevatron imply $\delta v_L = 0.3 \pm 0.2$. Around order of magnitude better bounds are expected at LHC which would overcome current $B \rightarrow X_s \gamma$ constraint on BSM contribution to v_L

Conclusions

Model	Accuracy	Effect	Bound
THDM type II	NLO	↑	$M_H^\pm > 295 \text{ GeV}$ (95% CL)
MFV MSSM	NLO	↕	—
MFV SUSY GUTs	NLO	↓	—
LR	NLO	↕	—
general MSSM	LO	↕	$ (\delta_{23}^d)_{LL} \lesssim 4 \times 10^{-1}$, $ (\delta_{23}^d)_{RR} \lesssim 8 \times 10^{-1}$, $ (\delta_{23}^d)_{LR} \lesssim 6 \times 10^{-2}$, $ (\delta_{23}^d)_{RL} \lesssim 2 \times 10^{-2}$
UED5	LO	↓	$1/R > 600 \text{ GeV}$ (95% CL)
UED6	LO	↓	$1/R > 650 \text{ GeV}$ (95% CL)
RS	LO	↑	$M_{KK} \gtrsim 2.4 \text{ TeV}$
LH	LO	↑	—
LHT	LO	↕	—

- Inclusion of NNLO corrections has lead to significant reduction of renormalization scale and scheme dependences of $\text{BR}(B \rightarrow X_s \gamma)_{\text{SM}}$ that have been main source of theoretical uncertainty at NLO level
- As new SM prediction is lower than measurements by around 1σ , BSM contributions should be preferably constructive, while NP that leads to suppression of $\text{BR}(B \rightarrow X_s \gamma)$ is more severely constrained than in past

Semileptonic Normalization Factor

$$\text{BR}(B \rightarrow X_s \gamma)_{\text{SM}}^{E_\gamma > E_0} = \frac{\text{BR}(B \rightarrow X_c e \bar{\nu})_{\text{exp}}}{C} \left[\frac{\Gamma(B \rightarrow X_s \gamma)_{\text{SM}}^{E_\gamma > E_0}}{|V_{cb}/V_{ub}|^2 \Gamma(B \rightarrow X_u e \bar{\nu})_{\text{SM}}} \right]$$

$$C = \left| \frac{V_{ub}}{V_{cb}} \right|^2 \frac{\Gamma(B \rightarrow X_c e \bar{\nu})_{\text{SM}}}{\Gamma(B \rightarrow X_u e \bar{\nu})_{\text{SM}}}$$

$$C = 0.580 \pm 0.016$$

Bauer et al. '04

$$C = 0.546^{+0.023}_{-0.033}$$

Gambino & Giordano '08

- New determination of C in kinetic scheme leads to a 5.8% lower value with respect to old fit to semileptonic and radiative moments in $1S$ scheme. This translates into a 4.8% enhancement of $\text{BR}(B \rightarrow X_s \gamma)$ and into an effect of similar size in $\text{BR}(B \rightarrow X_s l^+ l^-)$

