

$B \rightarrow K^* \mu^+ \mu^-$ constraints in CMSSM

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Motivation

Why $B \rightarrow K^* \mu^+ \mu^-$

- In the SM, FCNC processes like $b \rightarrow s$ appear only through loops
- New Physics effects could be comparable to the SM
- Only one hadron in initial and final state
- Good control over long-distance strong interactions (m_b much larger than Λ_{QCD})
- Many observables available
- A lot of data (e.g. Belle, BaBar, CDF, LHCb) & more to come (Belle II, Super B, LHCb upgrade, ...)

Effective Theory

$B \rightarrow K^* l^+ l^-$ is a multi-scale process

- Decaying through weak interactions $\sim O(M_W)$
- Binding through strong interactions $\sim O(1 \text{ GeV})$

Strong hierarchy among external and internal scale

➡ Separation between low and high energies with Operator Product Expansion

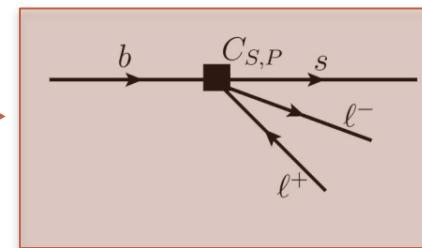
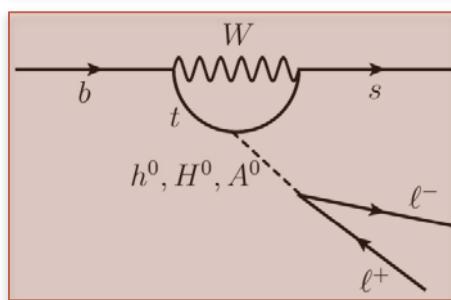
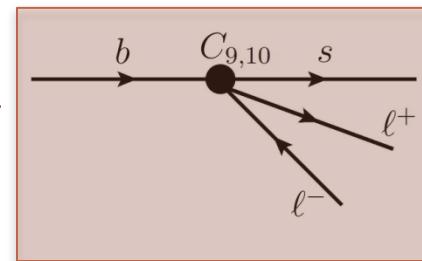
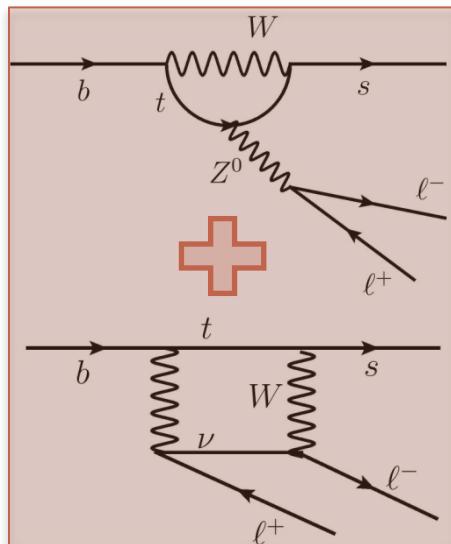
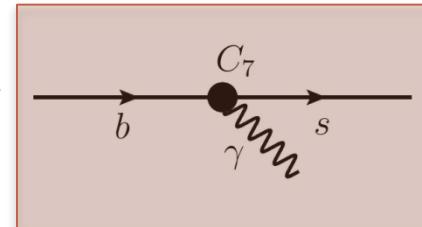
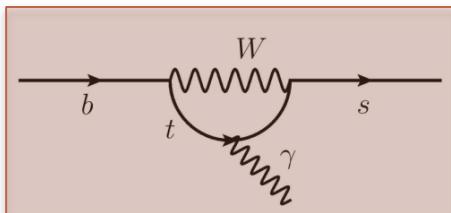
- Long distance: represented by local operators - O_i
- Short distance: Wilson coefficients associated with the operators - C_i

$$H_{\text{eff}} = \frac{-4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=1,\dots,10,S.P} (C_i(\mu) O_i(\mu) + C'_i(\mu) O'_i(\mu))$$

New physics in the effective framework:

- Modified Wilson coefficients: $C_i = C_i^{SM} + C_i^{NP}$
- Addition of NP operators: $\sum_j C_j^{NP} O_j^{NP}$

Operators



$$O_7 = \frac{e}{(4\pi)^2} m_b (\bar{s} \sigma^{\mu\nu} P_R b) F_{\mu\nu}$$

$$O_9 = \frac{e^2}{(4\pi)^2} (\bar{s} \gamma^\mu P_L b) (\bar{\ell} \gamma_\mu \ell)$$

$$O_{10} = \frac{e^2}{(4\pi)^2} (\bar{s} \gamma^\mu P_L b) (\bar{\ell} \gamma_\mu \gamma_5 \ell)$$

$$O_S = \frac{e^2}{(4\pi)^2} m_b (\bar{s} P_R b) (\bar{\ell} \ell)$$

$$O_P = \frac{e^2}{(4\pi)^2} m_b (\bar{s} P_R b) (\bar{\ell} \gamma_5 \ell)$$

Other observables include the chirality flipped counter-parts of the above operators.

Effective Theory

$$\text{Amplitude} \sim \sum_i C_i(\mu_b) \langle K^* ll | O_i(\mu_b) | B \rangle$$

3 steps needed:

- Matching of the full theory and the effective theory at $\mu_0 \sim M_W \longrightarrow C_i(\mu_0)$
- Relevant energy of the decay $\sim m_b \longrightarrow$ Running of C_i from μ_0 to $\mu_b \sim m_b$

Wilson Coefficients:

- Calculated perturbatively (asymptotic freedom) up to NNLO
- Contain all the contributions from scales higher than μ_0
- Process independent

- Evaluation of the matrix elements of operators $\langle O_i \rangle$

Matrix elements

Matrix elements $\langle O_i \rangle$

include non perturbative QCD effects

Form Factors

$$\langle K^* ll | O_7 | B \rangle \rightarrow T_1, T_2, T_3$$

$$\langle K^* ll | O_9 | B \rangle \rightarrow V$$

$$\langle K^* ll | O_{10} | B \rangle \rightarrow A_0, A_1, A_2$$



Different methods: Lattice , LCSR, ...

large uncertainties

QCD factorization applicable when the K^* energy, E_{K^*} is large:

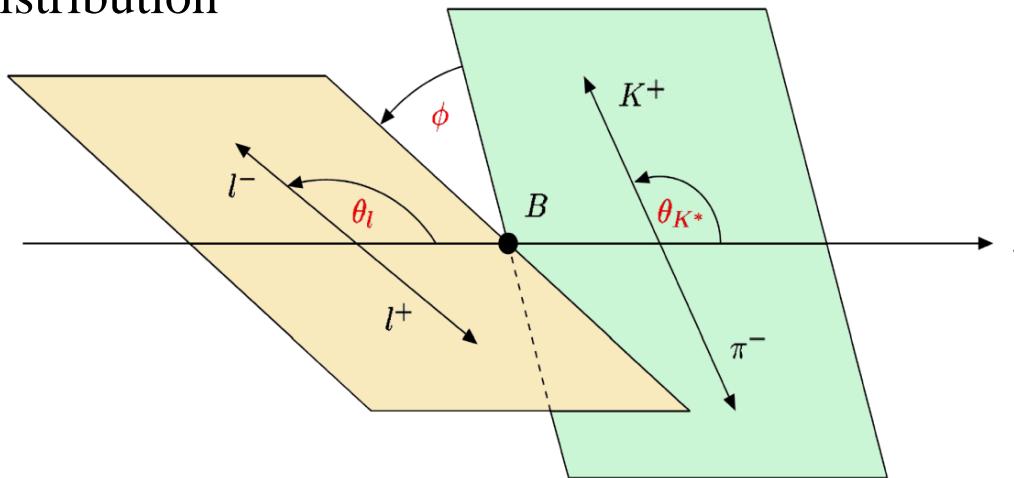
- Expanding in Λ/m_b and Λ/E_{K^*}
- Exploring symmetries



Reduction in Form Factor uncertainties
(which is the main theoretical error)

Angular Distribution

Angular distribution



The full angular distribution of the decay $B^0 \rightarrow K^{*0} l^+ l^-$ with $K^{*0} \rightarrow K^+ \pi^-$ on the mass shell is completely described by four independent kinematic variables:

- q^2 : dilepton invariant mass squared
- θ_l : angle between l^- and the K^* in the dilepton rest frame
- θ_{K^*} : angle between K^+ and B^0 in the K^* rest frame
- ϕ : angle between the normals of the $K^+ \pi^-$ and dilepton plane in the B^0 rest frame

Angular coefficients

Differential decay distribution

$$\frac{d^4\Gamma}{dq^2 d \cos \theta_l d \cos \theta_K d\phi} = \frac{9}{32\pi} J(q^2, \theta_l, \theta_K, \phi)$$

$J = J(\text{dilepton invariant mass, angles})$

$$\begin{aligned} J(q^2, \theta_\ell, \theta_{K^*}, \phi) = & J_1^s \sin^2 \theta_{K^*} + J_1^c \cos^2 \theta_{K^*} + (J_2^s \sin^2 \theta_{K^*} + J_2^c \cos^2 \theta_{K^*}) \cos 2\theta_\ell \\ & + J_3 \sin^2 \theta_{K^*} \sin^2 \theta_\ell \cos 2\phi + J_4 \sin 2\theta_{K^*} \sin 2\theta_\ell \cos \phi + J_5 \sin 2\theta_{K^*} \sin \theta_\ell \cos \phi \\ & + (J_6^s \sin^2 \theta_{K^*} + J_6^c \cos^2 \theta_{K^*}) \cos \theta_\ell + J_7 \sin 2\theta_{K^*} \sin \theta_\ell \sin \phi \\ & + J_8 \sin 2\theta_{K^*} \sin 2\theta_\ell \sin \phi + J_9 \sin^2 \theta_{K^*} \sin^2 \theta_\ell \sin 2\phi \end{aligned}$$

Angular coefficients J_i :

- Function of q^2 only
- Expressed in terms of Wilson Coefficients and Form Factors

Observables

Differential decay rate

$$\frac{d\Gamma}{dq^2} = \frac{3}{4} \left(J_1 - \frac{J_2}{3} \right)$$

Forward Backward Asymmetry

$$A_{FB}(q^2) = \left[\int_0^1 - \int_{-1}^0 \right] d \cos \theta_l \frac{d^2 \Gamma}{dq^2 d \cos \theta_l} \Bigg/ \frac{d\Gamma}{dq^2} = \frac{3}{8} J_6 \Bigg/ \frac{d\Gamma}{dq^2}$$

Forward Backward Asymmetry zero-crossing

$$q_0^2 = -2m_b M_B \frac{C_7^{eff}}{C_9^{eff}} + O(\alpha_s, \Lambda/m_b) \quad \text{At Leading Order independent of Form Factors}$$

Longitudinal Polarization Fraction

$$F_L = -2J_2^c \Big/ \frac{d\Gamma}{dq^2}$$

Many other angular observables $F_T, A_T^{(2)}, A_{Im}, \dots$

Central values and uncertainties

SM values and theoretical errors:

Different sources of errors:

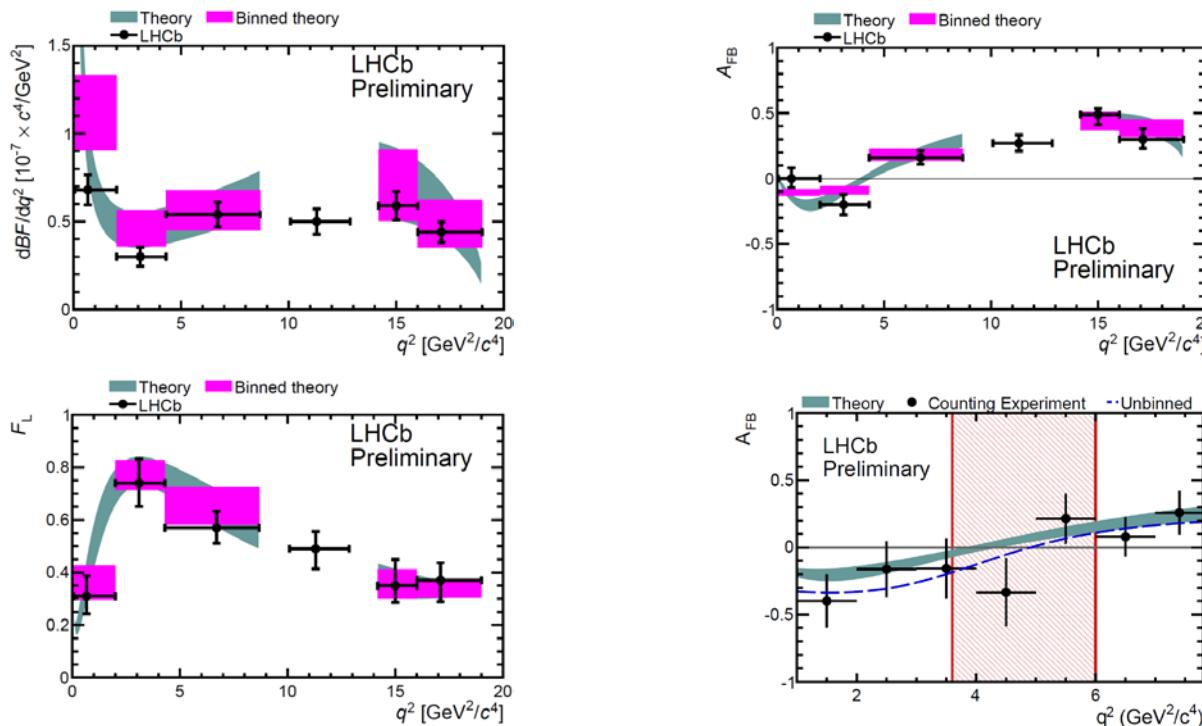
- Form Factor
- Λ/m_b
- Quark masses
- CKM elements
- ...

Observable	SM prediction	Form Factor	Λ/m_b	quark masses	$ V_{tb}V_{ts}^* $	scale
$\langle BR(B \rightarrow K^* \mu^+ \mu^-) \rangle_{[1,6]}$	2.34×10^{-7}	± 1.34	± 0.04	$+0.05$ -0.04	$+0.03$ -0.08	$+0.07$ -0.05
$\langle A_{FB}(B \rightarrow K^* \mu^+ \mu^-) \rangle_{[1,6]}$	0.06	± 0.04	± 0.01	$+0.01$ —	—	—
$\langle F_L(B \rightarrow K^* \mu^+ \mu^-) \rangle_{[1,6]}$	0.71	± 0.12	± 0.01	$+/-$ -0.01	—	—
$q_0^2(B \rightarrow K^* \mu^+ \mu^-)$	4.26	± 0.30	± 0.10	$+0.14$ -0.04	—	$+0.02$ -0.06

Largest source of uncertainty: Form Factor

Experimental results

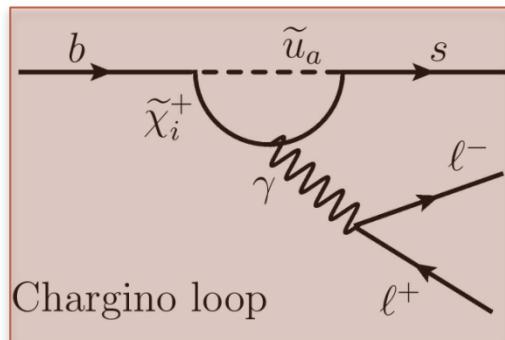
Recent LHCb results



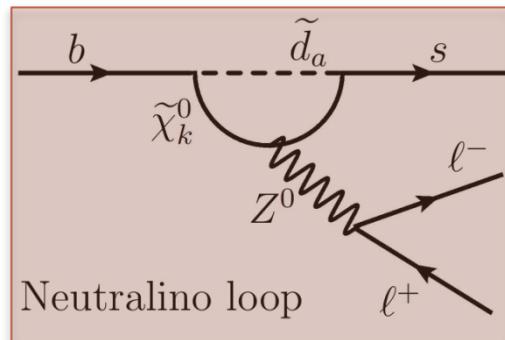
Observable	SM prediction	Experiment
$10^7 \times \langle BR(B \rightarrow K^* \mu^+ \mu^-) \rangle_{[1,6]}$	0.47 ± 0.27	$0.42 \pm 0.04 \pm 0.04$
$\langle A_{FB}(B \rightarrow K^* \mu^+ \mu^-) \rangle_{[1,6]}$	-0.06 ± 0.08	$-0.18^{+0.06}_{-0.06}{}^{+0.01}_{-0.02}$
$\langle F_L(B \rightarrow K^* \mu^+ \mu^-) \rangle_{[1,6]}$	0.71 ± 0.12	$0.66^{+0.06}_{-0.06}{}^{+0.04}_{-0.03}$
$q_0^2(B \rightarrow K^* \mu^+ \mu^-)$	4.26 ± 0.33	$4.9^{+1.1}_{-1.3}$

SUSY contributions

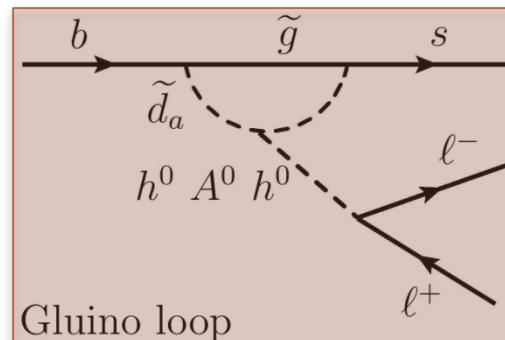
General SUSY contributions to $B \rightarrow K^* l^+ l^-$:



$$+ \dots \rightarrow C_7^{\text{SUSY}}$$



$$+ \dots \rightarrow C_{9,10}^{\text{SUSY}}$$



$$+ \dots \rightarrow C_{S,P}^{\text{SUSY}}$$

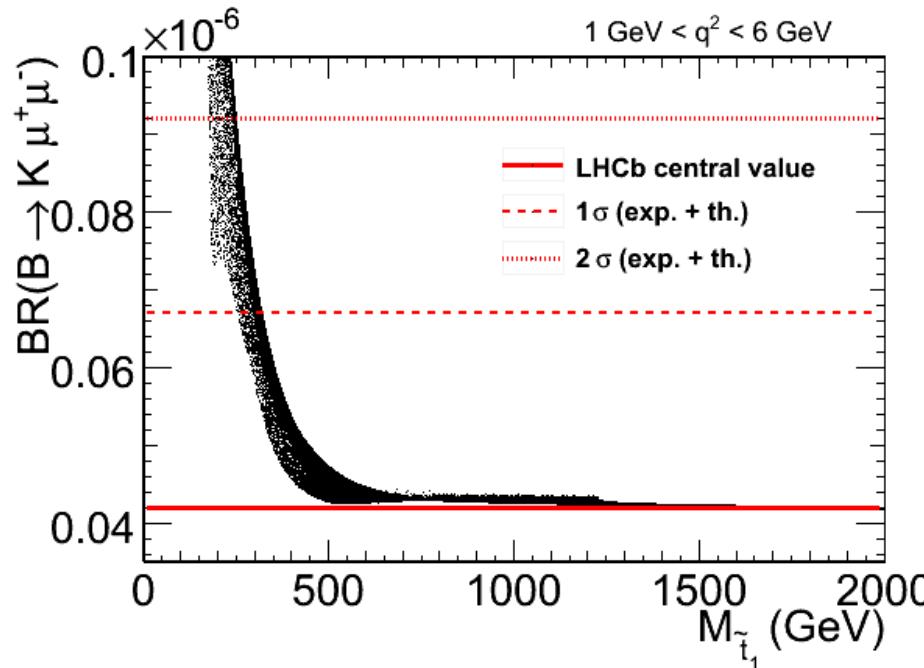
$$C_i = C_i^{\text{SM}} + C_i^{\text{SUSY}}$$

Branching Ratio

CMSSM \longrightarrow five fundamental parameters $\{m_0, m_{1/2}, \tan \beta, A_0, \text{sgn}(\mu)\}$

CMSSM-Branching Ratio vs. lightest stop

$$\tan \beta = 50, A_0 = 0, \mu > 0, m_0 \in [0, 2000] \text{ GeV}, m_{1/2} \in [100, 2000] \text{ GeV}$$



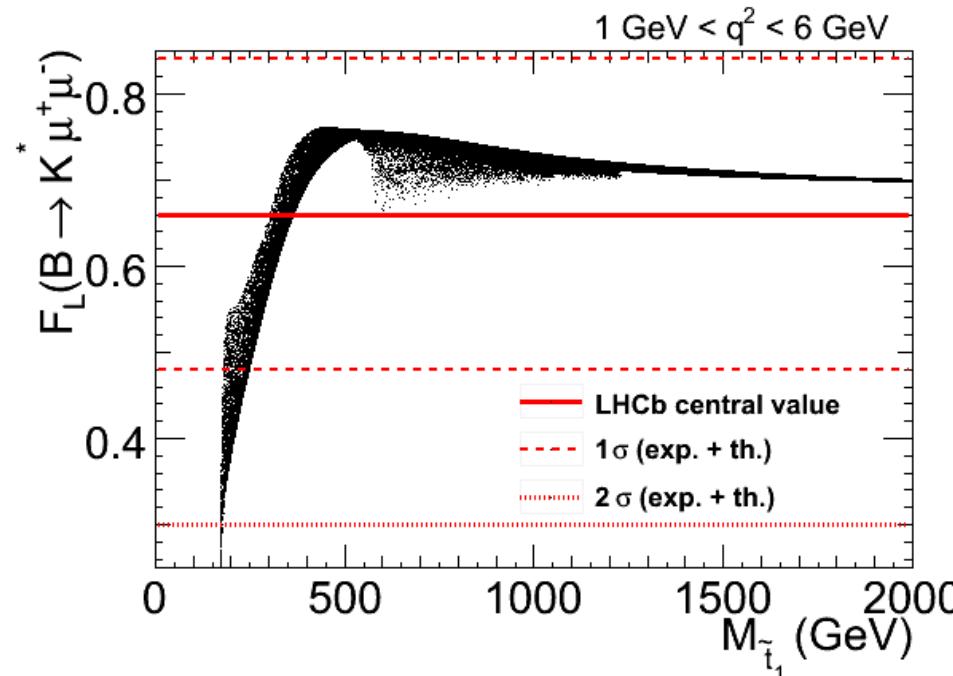
SuperIso v3.3

\longrightarrow Lightest stop > 200 GeV

Longitudinal Polarization Fraction

CMSSM-Longitudinal Polarization Fraction vs. lightest stop

$$\tan \beta = 50, A_0 = 0, \mu > 0, m_0 \in [0, 2000] \text{ GeV}, m_{1/2} \in [100, 2000] \text{ GeV}$$



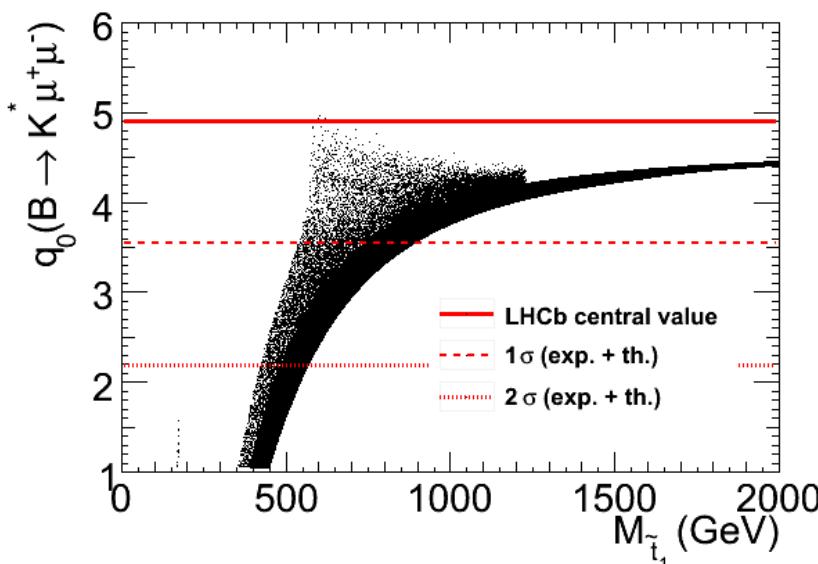
SuperIso v3.3

→ Lightest stop > 170 GeV

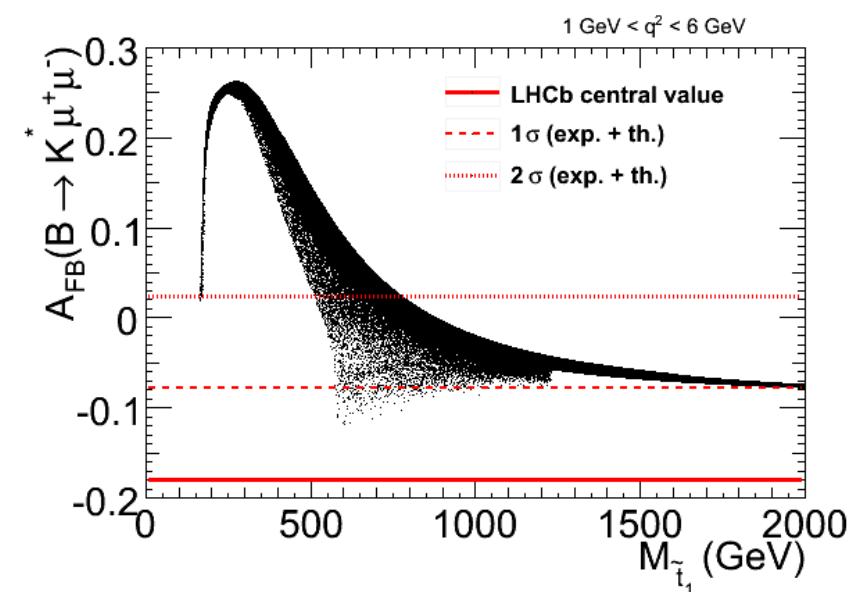
Forward-Backward Asymmetry

CMSSM-Forward-Backward Asymmetry vs. lightest stop

$$\tan \beta = 50, A_0 = 0, \mu > 0, m_0 \in [0, 2000] \text{ GeV}, m_{1/2} \in [100, 2000] \text{ GeV}$$



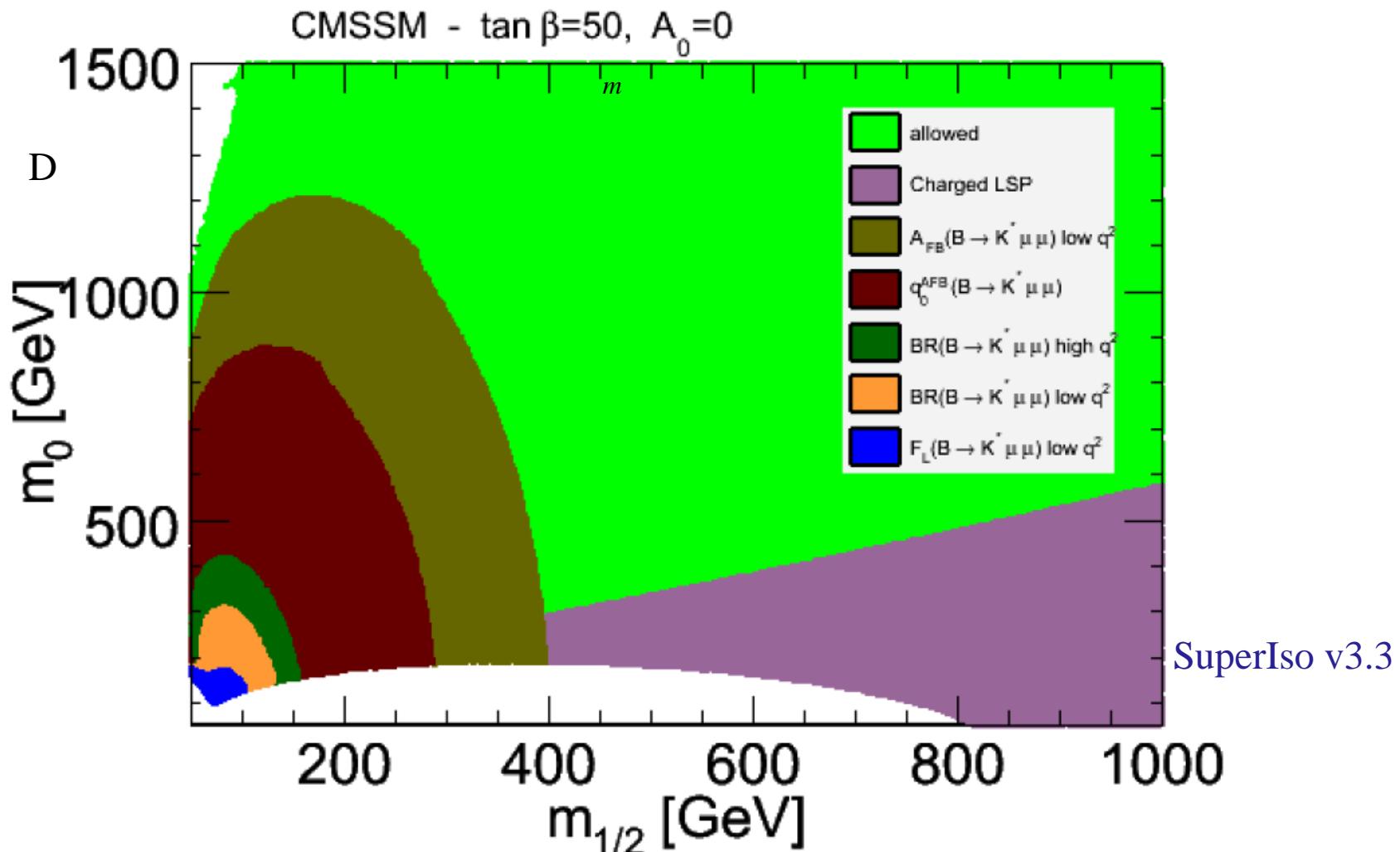
Lightest stop > 350 GeV



Lightest stop > 500 GeV

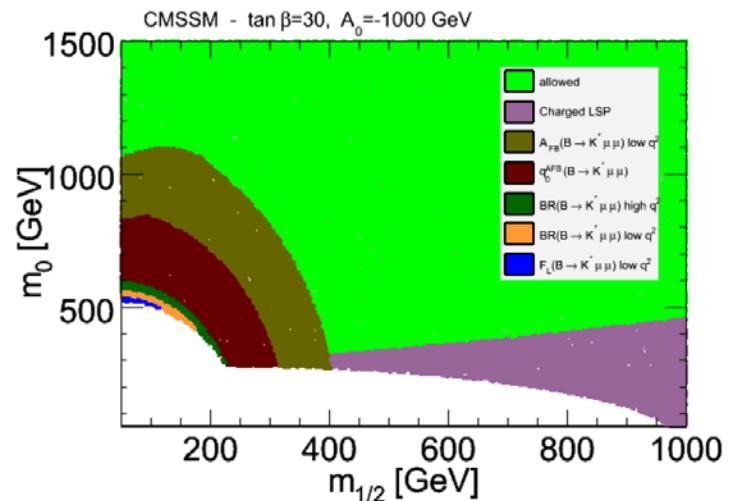
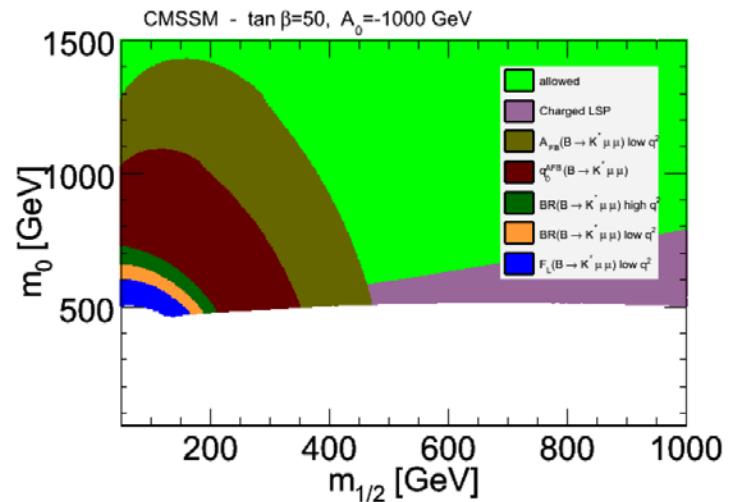
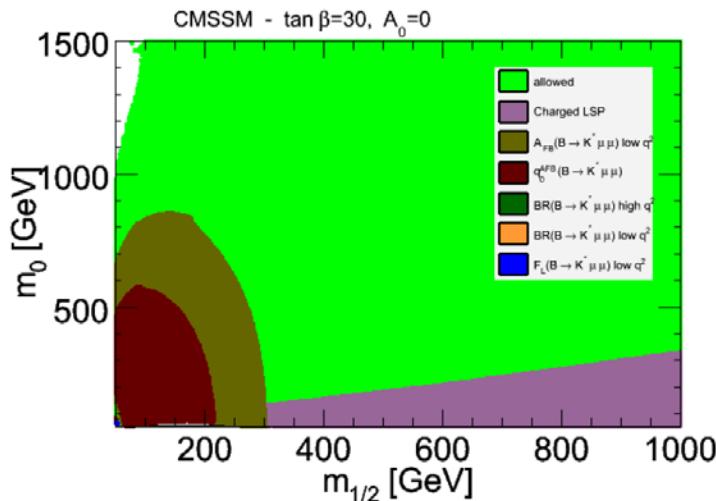
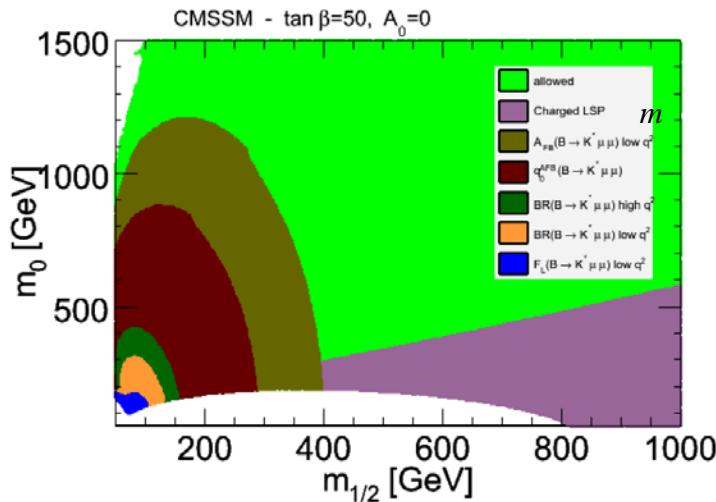
Universal Mass constraints

CMSSM - $m_0 - m_{1/2}$ plane



Universal Mass constraints

CMSSM - $m_0 - m_{1/2}$ plane for two different values of $\tan \beta$ and A_0

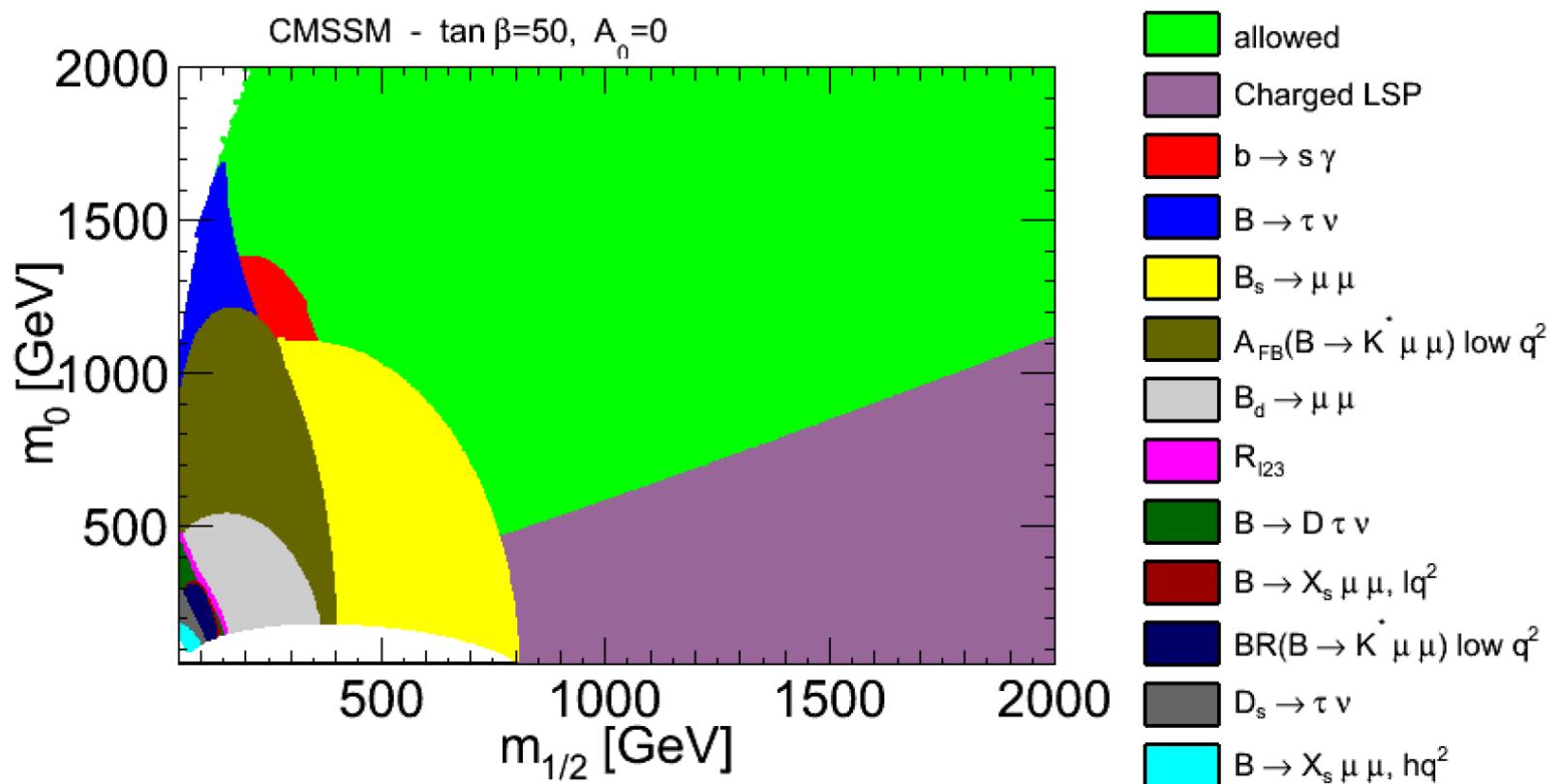


Conclusions:

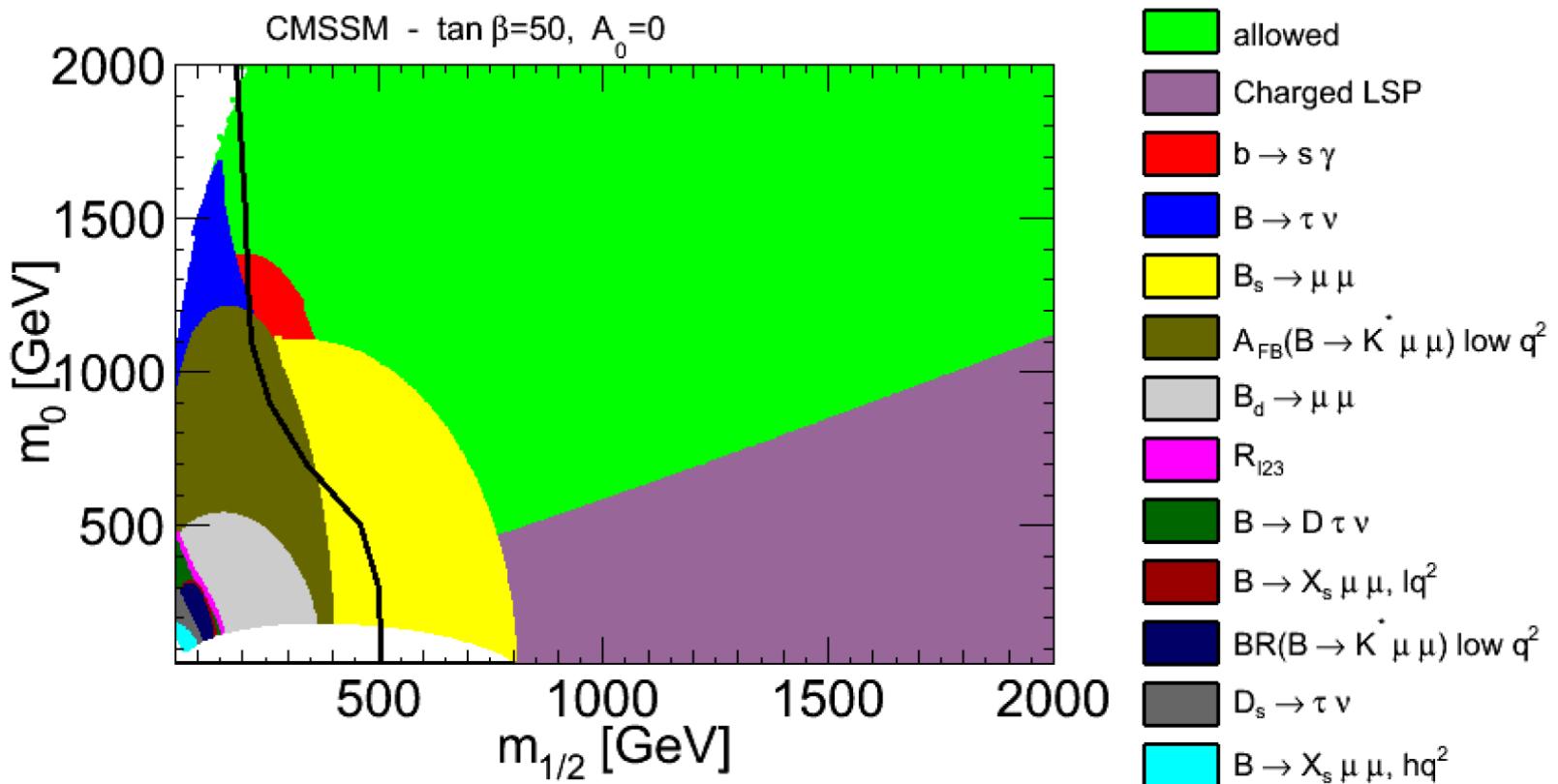
- Many observables available
- Can constrain parameter space in SUSY
- Applicable to other NP models
- Reduction in experimental and theoretical uncertainties necessary to put stronger constraints

Thank you

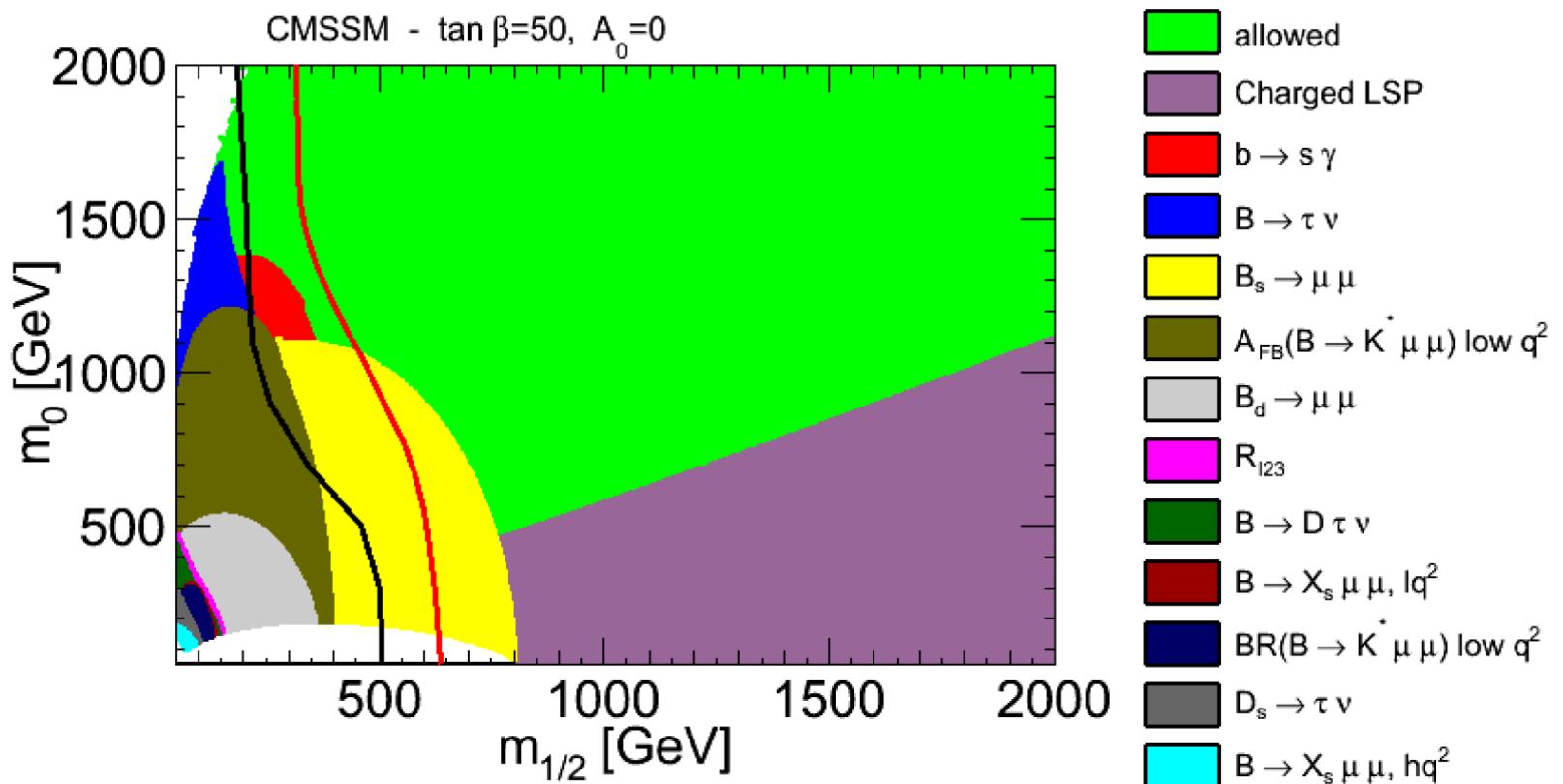
Backup



Backup



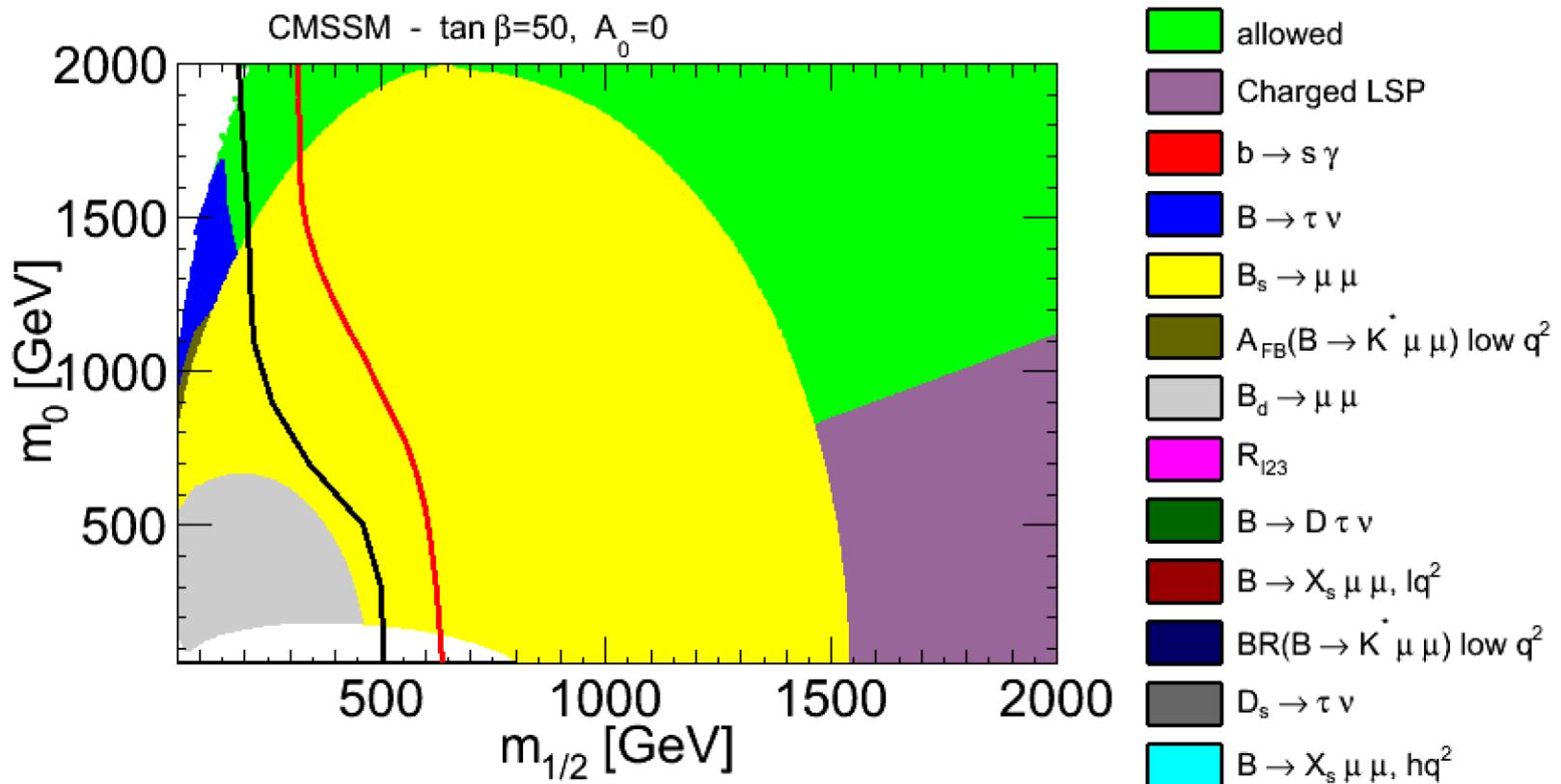
Black line: CMS exclusion limit with 1.1 fb^{-1} data



Black line: CMS exclusion limit with 1.1 fb^{-1} data

Red line: CMS exclusion limit with 4.4 fb^{-1} data

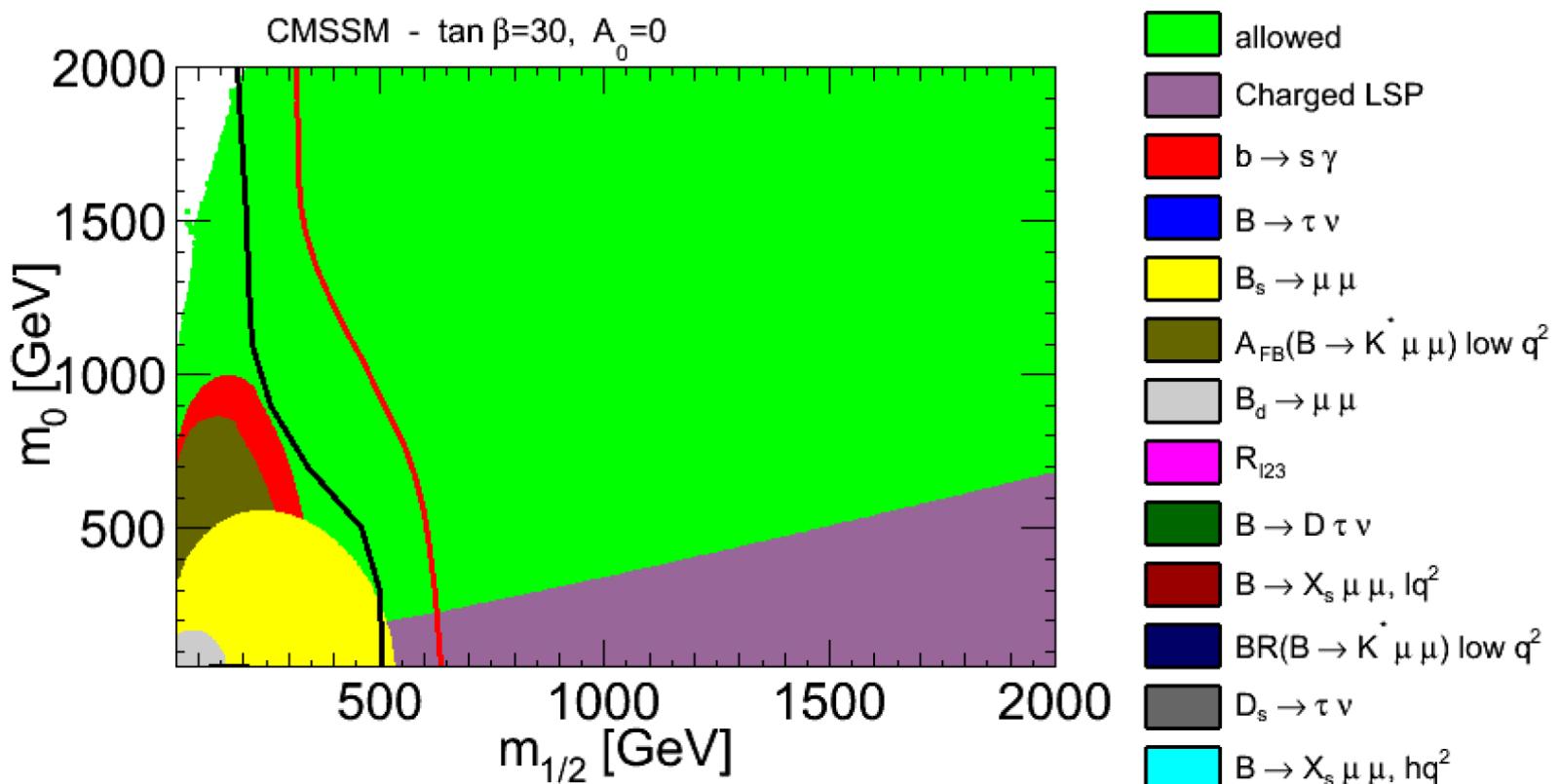
Backup



Black line: CMS exclusion limit with 1.1 fb $^{-1}$ data

Red line: CMS exclusion limit with 4.4 fb $^{-1}$ data

New LHCb limits for $BR(B_s \rightarrow \mu^+ \mu^-)$ and $BR(B_d \rightarrow \mu^+ \mu^-)$



Black line: CMS exclusion limit with 1.1 fb^{-1} data

Red line: CMS exclusion limit with 4.4 fb^{-1} data

New LHCb limits for $BR(B_s \rightarrow \mu^+ \mu^-)$ and $BR(B_d \rightarrow \mu^+ \mu^-)$