# Summer school and workshop on high energy physics at the LHC

## Phenomenology and experimental aspects of SUSY and searches for extradimensions at the LHC

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**Natal, Brazil**

**21-31 October**

# Susy breaking

remember : particles of a ('unbroken') susy multiplet have the same mass

however SUSY particles have not been observed (yet)

this non observation requires them to be heavier than SM particles

**suspersymmetry must be broken to lift mass degeneracy**

**between SM particles and their SUSY partners**

**⇒ several way to do this**

# Susy breaking

taking the vacuum state $|0>$ one can show that *global* supersymmetry is is *spontaneously* broken if:

$$Q \; |0> \neq 0$$

or in other word if the vacuum energy $<0|\, H \,|0>$ is strictly positive

where we remember that $H = P_0 = \frac{1}{4}\sum_r Q_r^2$ (i.e. Hamiltonian)

this can happen in two cases known as:

- type F breaking (O'Raifertaigh)

- type D breaking (Fayet Iliopoulos)

however early incarnations of these were not found to be phenomenologically viable

⇒ look for alternatives

# Susy breaking → Susy models

one can show that *global* supersymmetry can be *explicitely* broken

by adding in a supersymmetry invariant lagrangian new renormalizable,

gauge invariant terms which are not supersymmetry invariant

such terms have been listed and are known as **soft SUSY breaking terms**

**there are as many new parameters as there are soft susy breaking terms**

# **Susy breaking → Susy models**

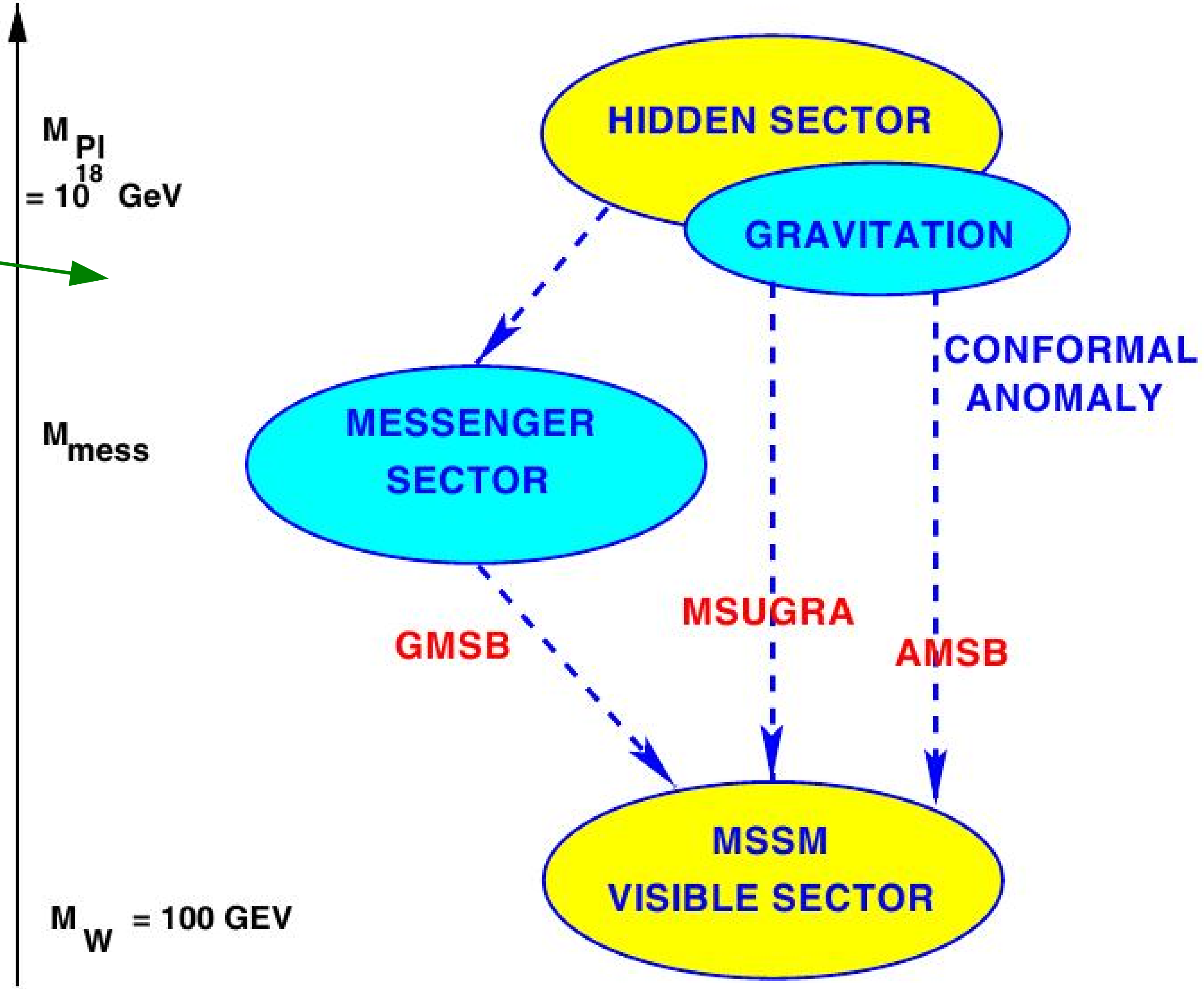
the existence of soft susy breaking terms have been justified in the context of *spontaneously* broken *local* supersymmetry i.e. spontaneouly broken supergravity

the spontaneous breaking occurs in a so called 'hidden sector' at high energy scale and is transmitted to a so called 'visible sector' at lower energy scale (SM particles and susy partners) via some interactions (messengers) :

- gravitational interactions ⇒ e.g. **MSUGRA, AMSB**
- new gauge interactions ⇒ e.g. **Gauge Mediated SUSY Breaking i.e. GMSB**

# Susy breaking → Susy models

**Several SUSY breaking models** (non exhaustive list)



**Customary to introduce a SUSY breaking scale $M_{SB}$ and write gravitino mass**

$$m_{3/2} = \frac{M_{SB}^2}{M_{Pl}\sqrt{3}}$$

# Susy breaking → Susy models

**a large number of new free parameters are introduced**
**i.e. in total 124** including the ones from the SM (which have 19)

**phenomenologically more "viable" models can be defined by making some further assumptions on the parameters and get**

| | |
|---|---|
| $\tan\beta$ | ratio of the vevs of the two Higgs doublet fields |
| $m_{H_u}^2,\ m_{H_d}^2$ | the Higgs mass parameters squared |
| $M_{1,}\ M_2,\ M_3$ | the bino, wino and gluino mass parameters |
| $m_{\tilde{q}},\ m_{\tilde{u}_R},\ m_{\tilde{d}_R},\ m_{\tilde{l}},\ m_{\tilde{e}_R}$ | the 1st / 2nd generation mass parameters |
| $A_u,\ A_d,\ A_e$ | the 1st / 2nd generation trilinear coupling |
| $m_{\tilde{Q}},\ m_{\tilde{t}_R},\ m_{\tilde{b}_R},\ m_{\tilde{L}},\ m_{\tilde{\tau}_R}$ | the 3rd generation sfermion mass parameters |
| $A_t,\ A_b,\ A_\tau$ | the 3rd generation trilinear coupling |

# Susy breaking → Susy models

further reduction of number of parameters is possible if they obey

a set of boundary conditions at high energy scales $M_U \approx 2 \cdot 10^{16}$

$$M_1(M_U) = M_2(M_U) = M_3(M_U) = \boldsymbol{m_{1/2}}$$

**unification of gaugino mass**

$$M_{\tilde{Q}_i}(M_U) = M_{\tilde{u}_R}(M_U) = M_{\tilde{d}_R}(M_U) = M_{\tilde{L}}(M_U) = M_{\tilde{l}_R}(M_U) \\ = m_{H_u}(M_U) = m_{H_d}(M_U) = \boldsymbol{m_o}$$

**universal scalar mass**

$$A_u(M_U) = A_d(M_U) = A_l(M_U) = \boldsymbol{A_o}$$

**universal trilinear coupling**

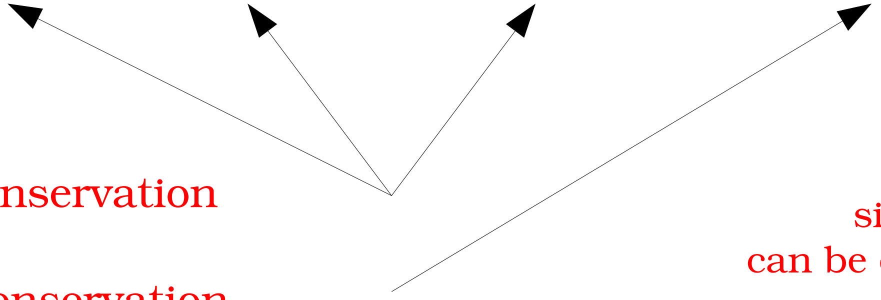
⇒ **five independent parameters**

$$\boldsymbol{M_{1/2},\ m_o,\ A_o,\ \tan\beta\ ,\ \mathrm{sgn}(\mu)}$$

# MSSM lagrangian: a reminder

**additional terms allowed by gauge invariance (and renormalizability)**

$$W_{R_p} = \mu_i H_u L_i + \lambda_{ijk} L_i L_j E_k^C + \lambda'_{ijk} L_i Q_j D_k^C - \lambda''_{ijk} U_i^C U_j^C D_k^C$$



violate Lepton number **L** conservation

violate Baryon number **B** conservation

since B and L
can be carried by boson fields

**violations can be avoided by introducing a discrete symmetry known as R-parity**

i.e. introducing a multiplicatively conserved number

$$R = (-)^{3B+L+2S}$$

$$R_{SM} = +1 \qquad R_{SUSY} = -1$$

| Field | $B$ | $L$ | $S$ | $3B + L + 2S$ |
|---|---|---|---|---|
| quark | 1/3 | 0 | 1/2 | 2 |
| squark | 1/3 | 0 | 0 | 1 |
| lepton | 0 | 1 | 1/2 | 2 |
| slepton | 0 | 1 | 0 | 1 |

# Tentative outline

**LECTURE 2**

- minimal SUSY extensions of the standard model (SM) phenomenology
  Higgs sector, sfermions and gauginos

- direct search examples at the LHC + some indirect constraints

# Minimal SUSY extension of the SM – Higgs sector

consider the potential of the neutral scalars of the Higgs sector of the MSSM

$$V_H = m_1^2 \left|H_d^o\right|^2 + m_2^2 \left|H_u^o\right|^2 + m_3^2 \left(H_d^o H_u^o + h.c.\right) + \frac{g_2^2 + g_1^2}{8}\left(\left|H_d^o\right|^2 - \left|H_u^o\right|^2\right)^2$$

with $m_1^2 = |\mu|^2 + m_{H_d}^2$, $m_2^2 = |\mu|^2 + m_{H_u}^2$, $m_3^2 = B|\mu|^2$ (i.e. soft-SUSY breaking parameters)

**request that its minimum breaks EW symmetry ⇒**

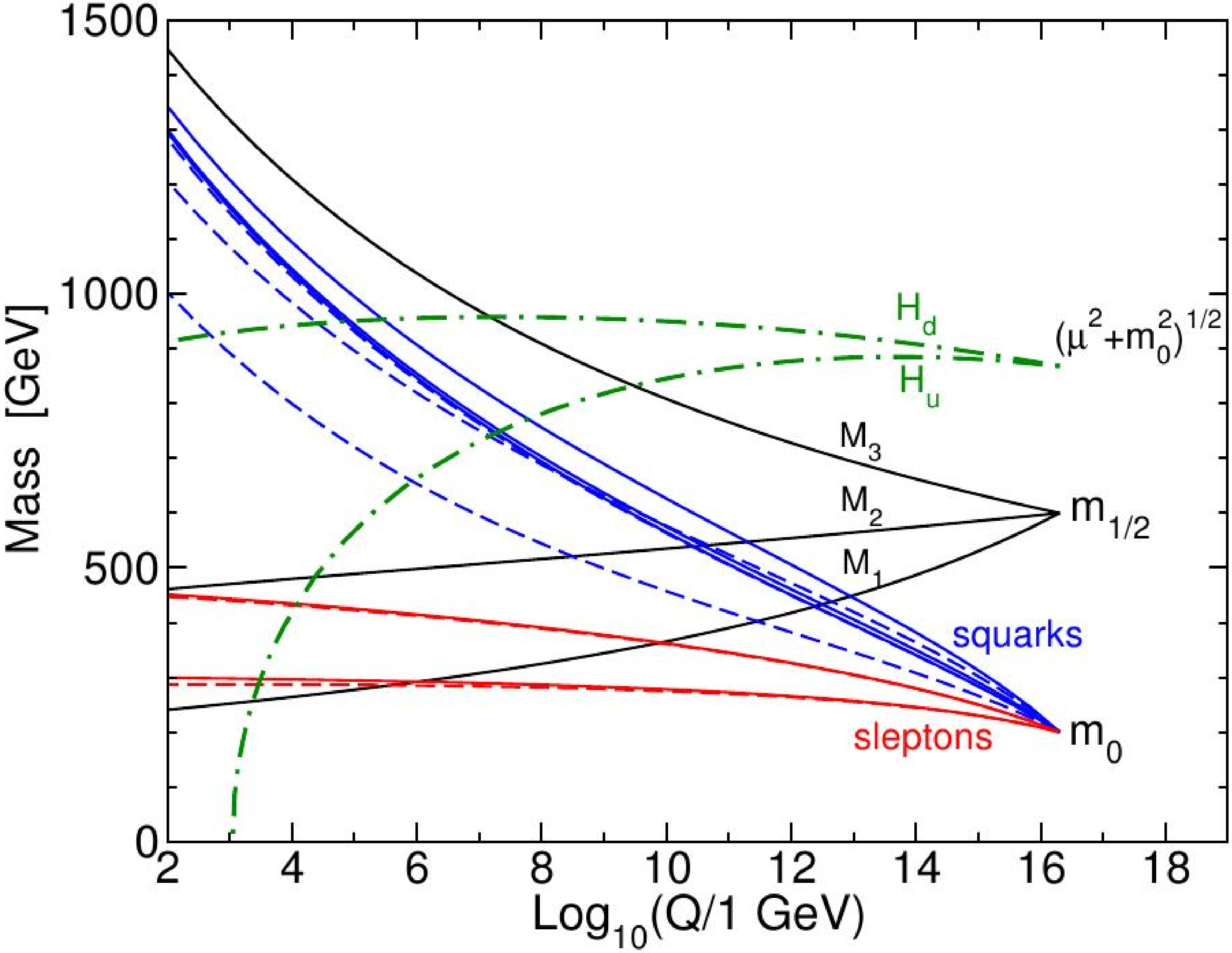
- **need non vanishing soft SUSY-breaking scalar masses $m_{H_u}$, $m_{H_d}$**
- **therefore to break EW we need also to break SUSY**

**from RGE running one can obtain $m_{H_u}^2 < 0$ or $m_{H_u}^2 << m_{H_d}^2$**

**which triggers EW symmetry breaking (EWSB)**

**radiative breaking of the electroweak symmetry**

# MSUGRA



potential minimization condition (radiative ElectroWeak Symmetry Breaking EWSB) :

$$\mu^2 = \frac{m_{H_b}^2 - m_{H_t}^2 \tan^2\beta}{\tan^2\beta - 1} - \frac{m_Z^2}{2}$$

# Minimal SUSY extension of the SM – Higgs sector

thus after EWSB one obtains 5 physical particles in the Higgs sector

- 2 CP-even neutral Higgs bosons : $h$ , $H$
- 1 CP-odd neutral Higgs boson : A
- 2 charged Higgs bosons : $H^{\pm}$

the CP-even Higgs bosons are obtained from the rotation

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H_d^o \\ H_u^o \end{pmatrix} \qquad \cos 2\alpha = -\cos 2\beta \, \frac{M_A^2 - M_Z^2}{M_H^2 - M_h^2}$$

and one obtains the masses (at tree level)

$$M_{h,H}^2 = \frac{1}{2}\left[ M_A^2 + M_Z^2 \mp \sqrt{\left(M_A^2 + M_Z^2\right)^2 - 4\, M_A^2 M_Z^2 \cos^2 2\beta} \right]$$

where out of the 6 parameters $M_h,\ M_H,\ M_A,\ M_{H^{\pm}},\ \beta,\ \alpha$ which decribes the Higgs sector
2 parameters i.e. $\boldsymbol{M_A}$, **tan** $\beta$ can be taken as free independent parameters

# Minimal SUSY extension of the SM – Higgs sector

a strong hierarchy is thus imposed on the mass spectrum at tree level

$$M_H > max\left(M_A, M_Z\right)$$

$$M_h < min\left(M_A, M_Z\right) \cdot |\cos| 2\beta \leqslant M_Z$$

⇒ **at tree level the lighter CP-even Higgs boson should be lighter than the Z boson**

since the h boson is light (and has almost SM like coupling when the A boson is heavy)
is should have been observed at the LEP experiments ...... which was not the case !

**radiative corrections push its mass upward beyond the tree level bound** $M_Z$

**radiative corrections can be large since involving couplings to top quark and stop**

# Minimal SUSY extension of the SM – Higgs sector

**loop corrections raise the lightest Higgs boson mass above the Z boson mass**

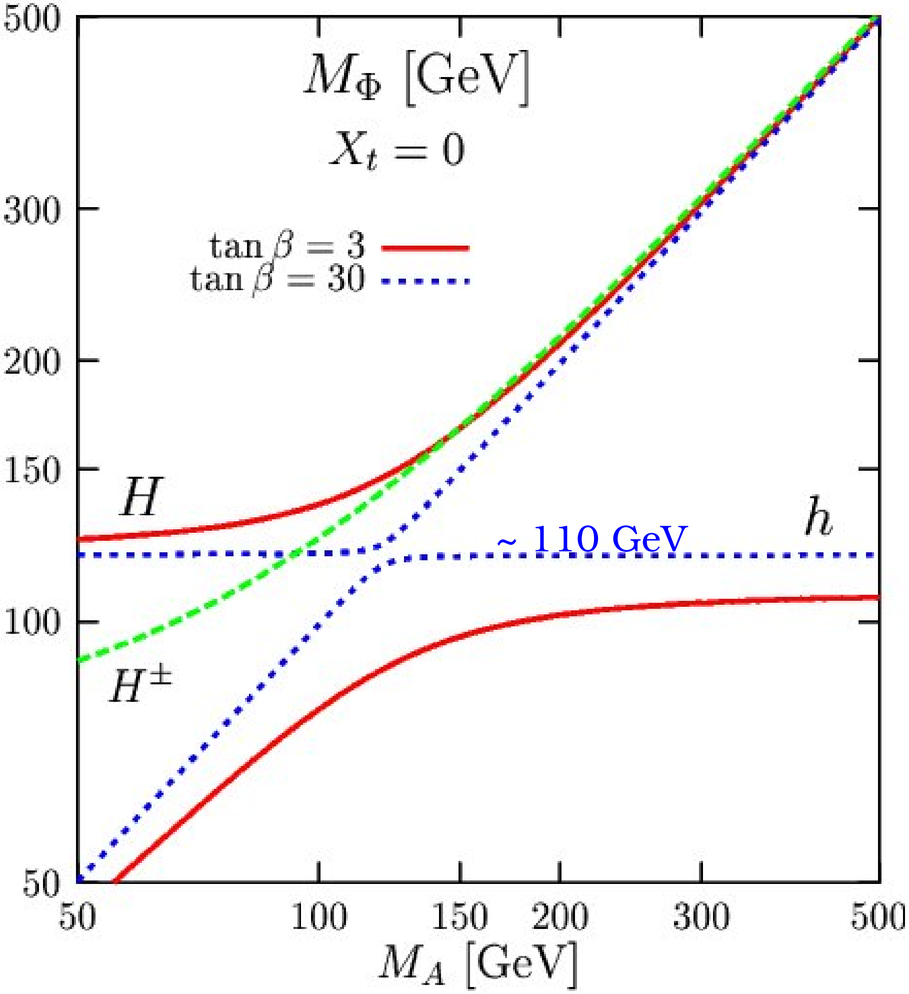
in the limit $M_A \gg M_Z$ , $\tan\beta \gg 1$ and $M_h \ll m_t,\ m_{\tilde{t}}$

$$\boxed{M_h^2 \simeq M_Z^2 \cos^2 2\beta \left[ 1 - \frac{M_Z^2}{M_A^2} \sin^2 2\beta \right] + \frac{3 m_t^4}{2\pi^2 v^2} \left[ \log \frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2} \left( 1 - \frac{X_t^2}{12 M_S^2} \right) \right]}$$

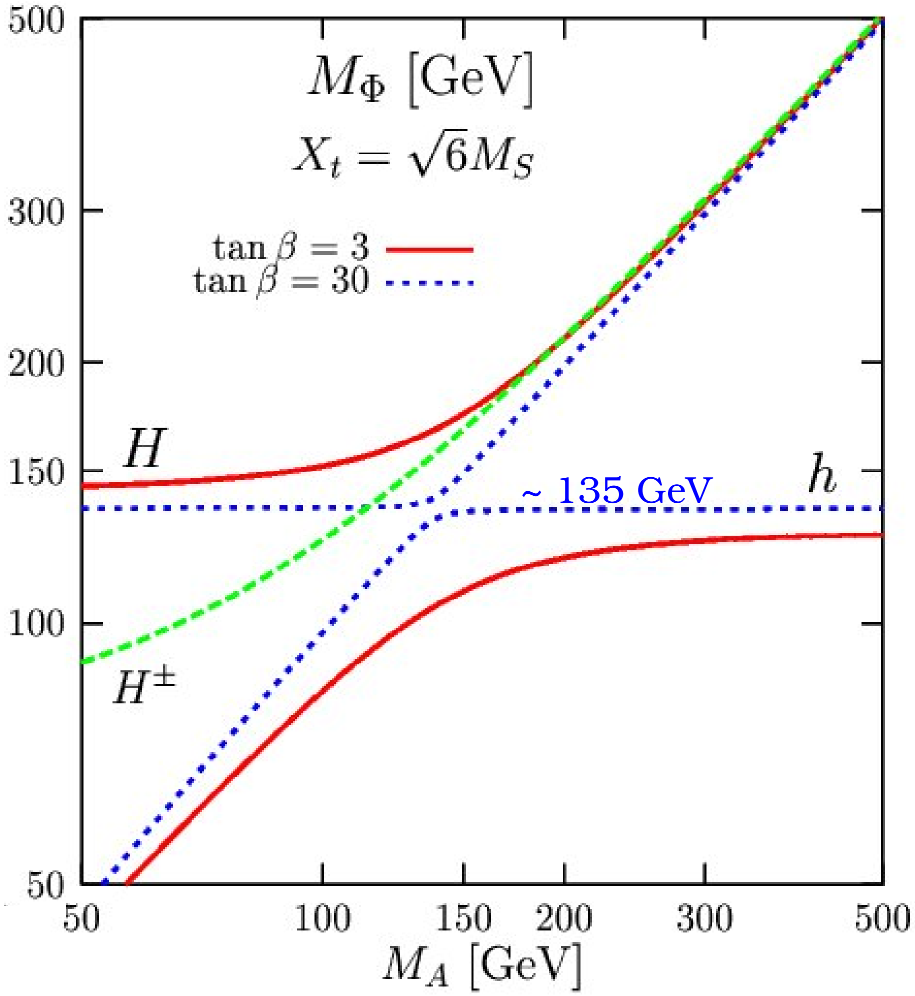
with $X_t = A_t - \mu \cot\beta$ and $m_{\tilde{t}_1} = m_{\tilde{t}_2} = m_{\tilde{t}} \equiv M_S$ (in general $\boldsymbol{M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}}$ )

# Minimal SUSY extension of the SM – Higgs sector

no mixing $X_t = A_t - \mu \cot\beta = 0$



maximal mixing $X_t = A_t - \mu \cot\beta = \sqrt{6}\, M_S$



# Minimal SUSY extension of the SM – Higgs sector

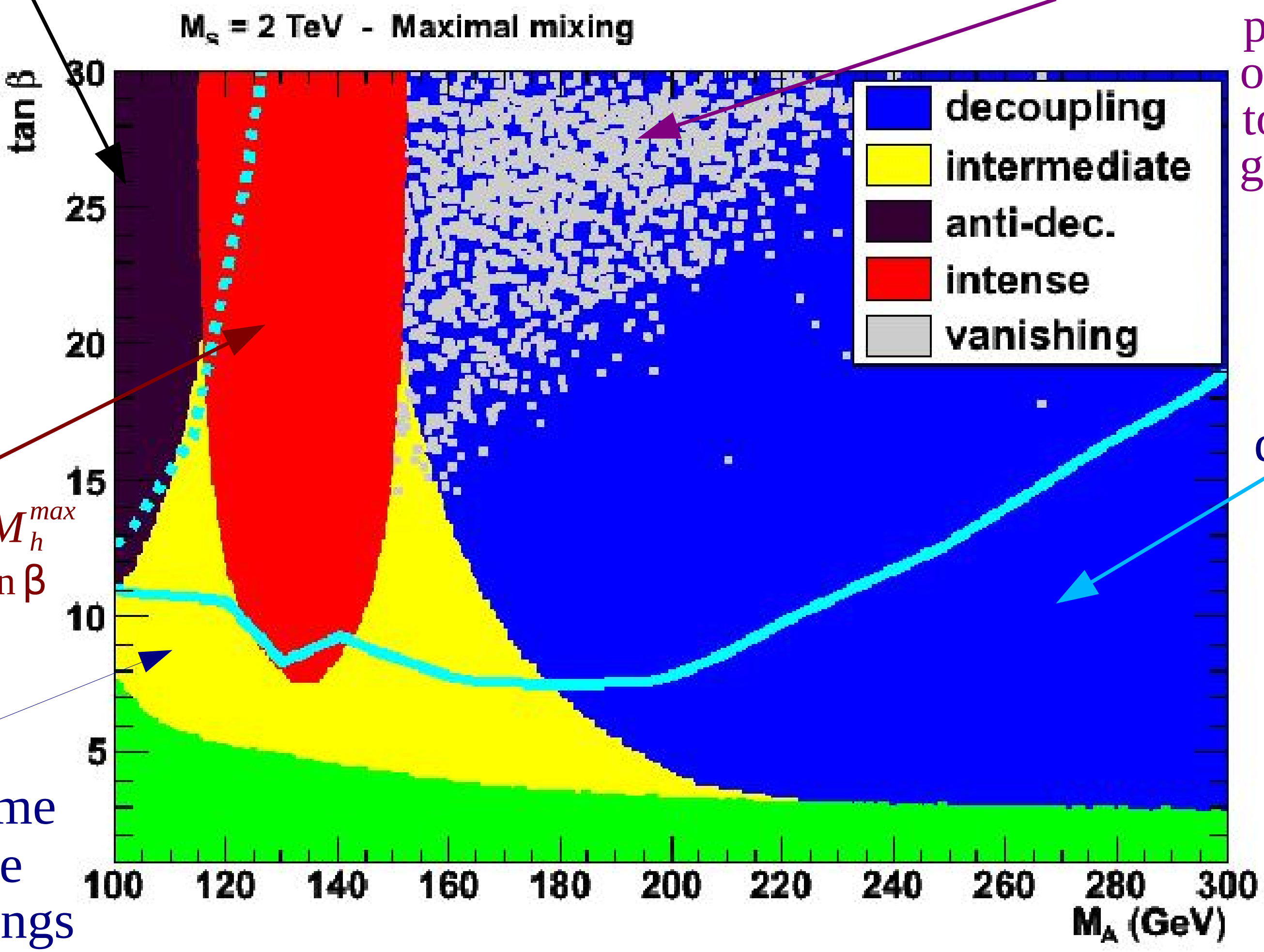
anti-decoupling regime

opposite to dec. regime

role of h and H reversed

vanishing regime

possible suppression of coupling of h or H to fermions or gauge bosons



intense regime

$M_h \sim M_H \sim M_A \sim M_h^{max}$

even more so at high tan β

decoupling regime

$M_A \gg M_Z$

$M_H \sim M_A$

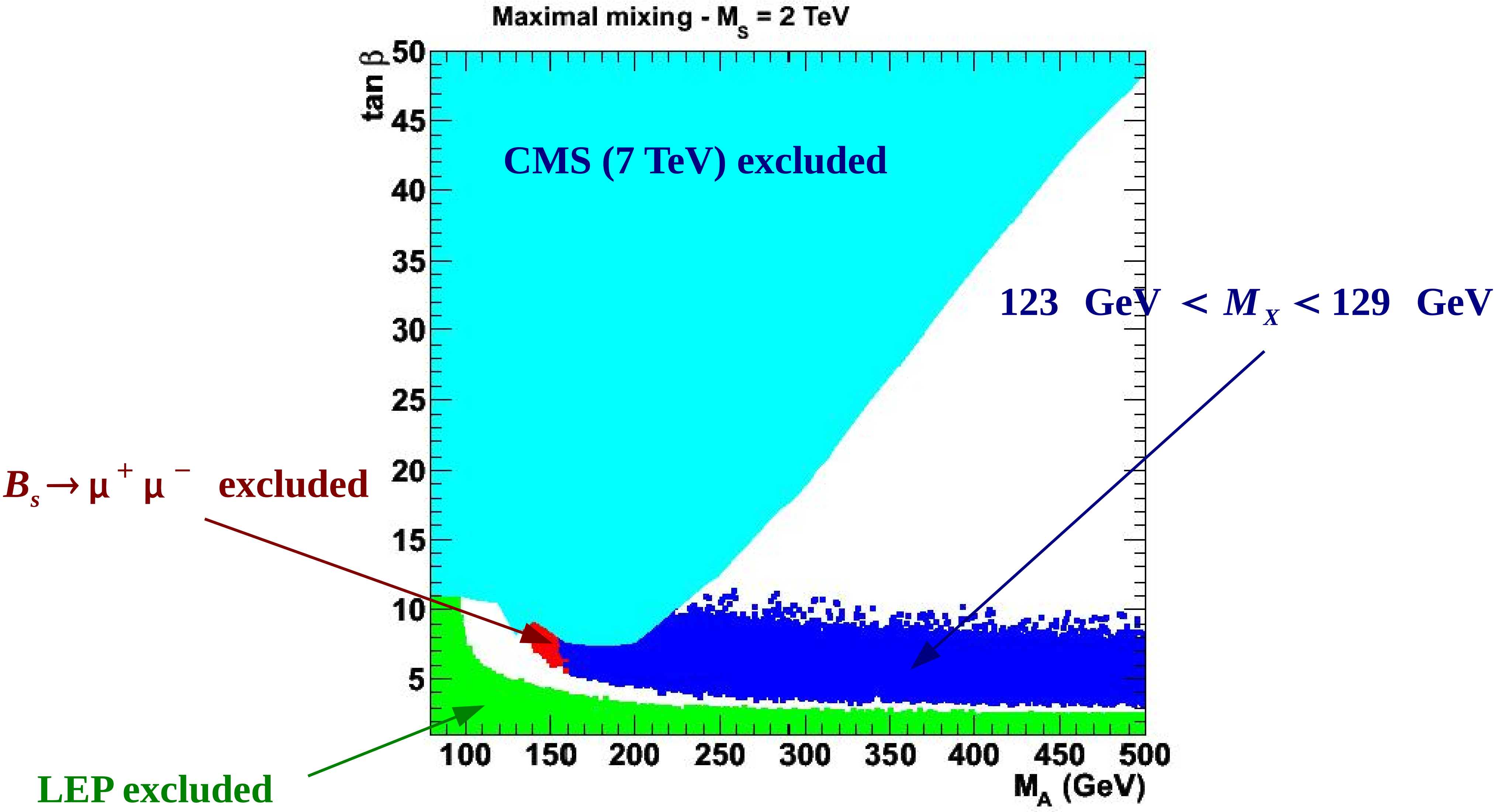
**h is SM like**

$m_h$ close to its maximal value

intermediate regime
both h and H have significant couplings to gauge bosons

Arbey, Battaglia, Djouadi, Mahmoudi, JHEP 1209 (2012) 107

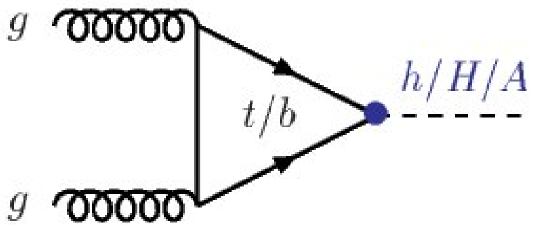
# Minimal SUSY extension of the SM – Higgs sector



Arbey, Battaglia, Djouadi, Mahmoudi, JHEP 1209 (2012) 107

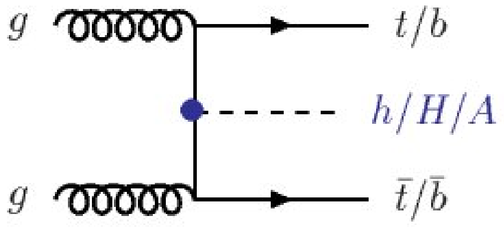
# Minimal SUSY extension of the SM – Higgs sector

**most important production mechanisms of SUSY neutral Higgs bosons similar as production mechanisms of SM Higgs boson**



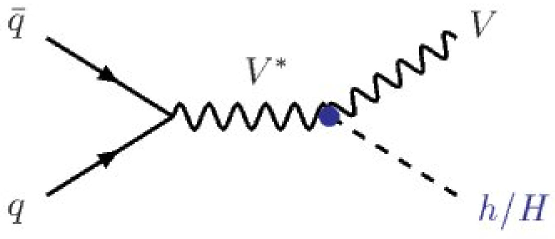
$gg \to h/H/A$

**gluon gluon fusion**
(dominant for small tan β)



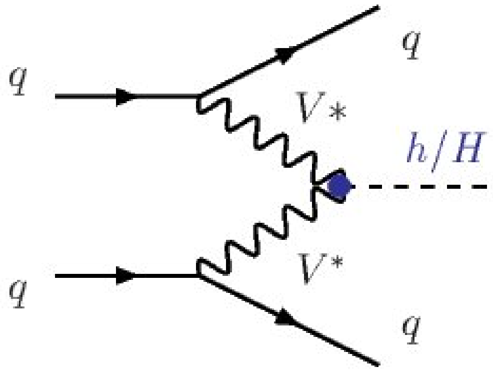
$g g, q\bar{q} \to Q\bar{Q} + h/H/A$

**associated production with heavy quarks**
(dominant for large tan β and at high mass)



$q\bar{q} \to V + h/H$

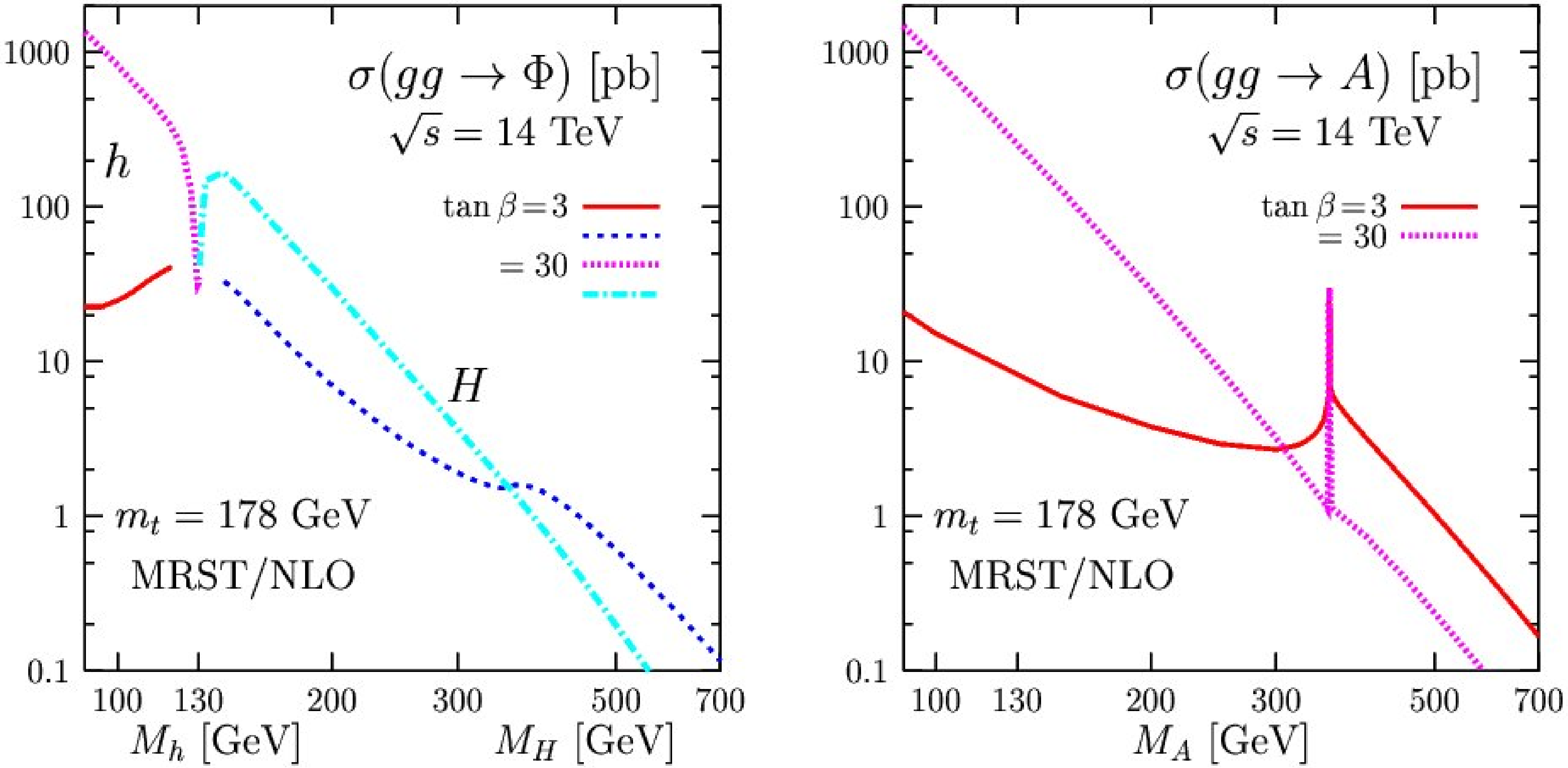
**associated production with W/Z**



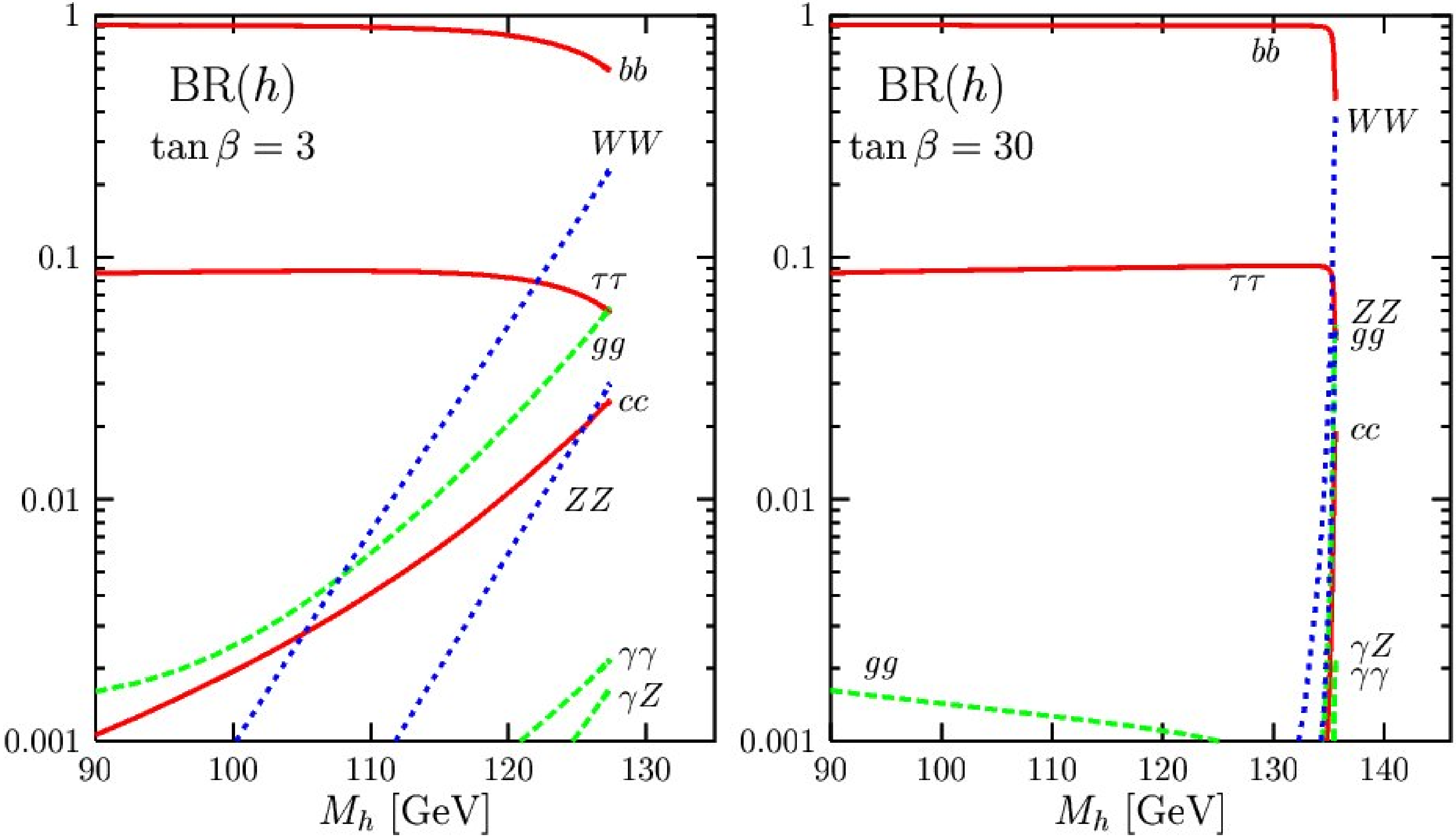
$q q \to V^* V^* \to q q + h/H$

**vector boson fusion for h and H production**

# Minimal SUSY extension of the SM – Higgs sector

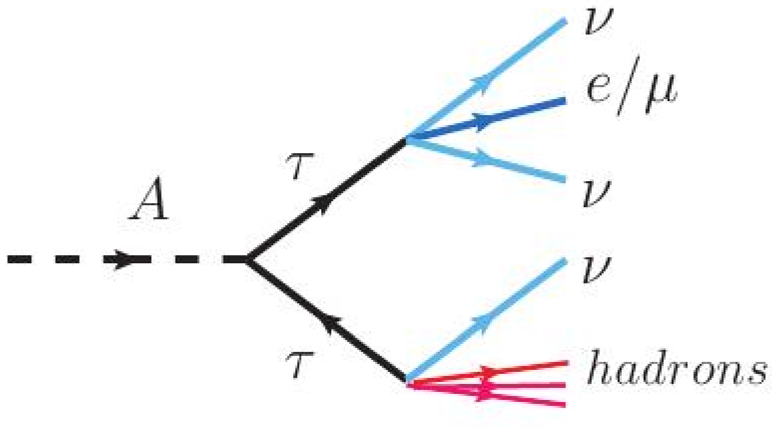


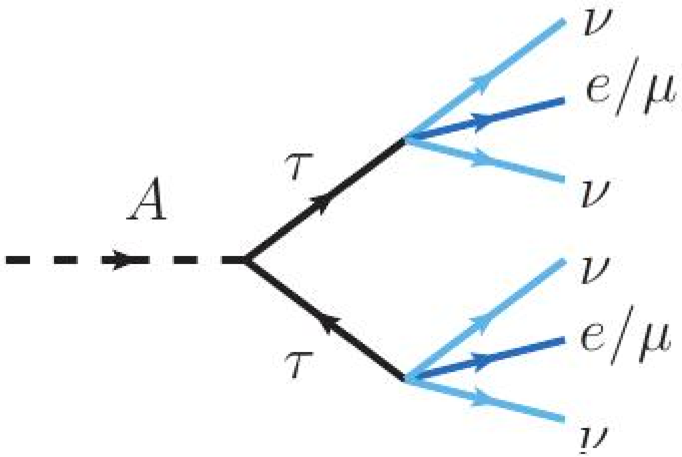
# Minimal SUSY extension of the SM – Higgs sector

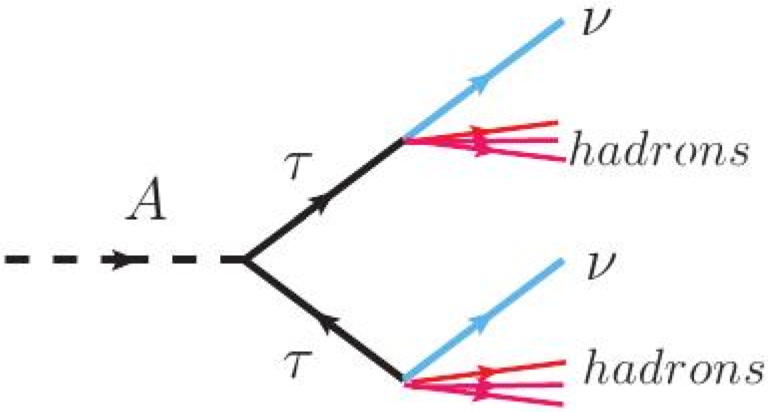


# Minimal SUSY extension of the SM – Higgs sector

assuming various tau lepton decay → giving rise to different type of event signatures

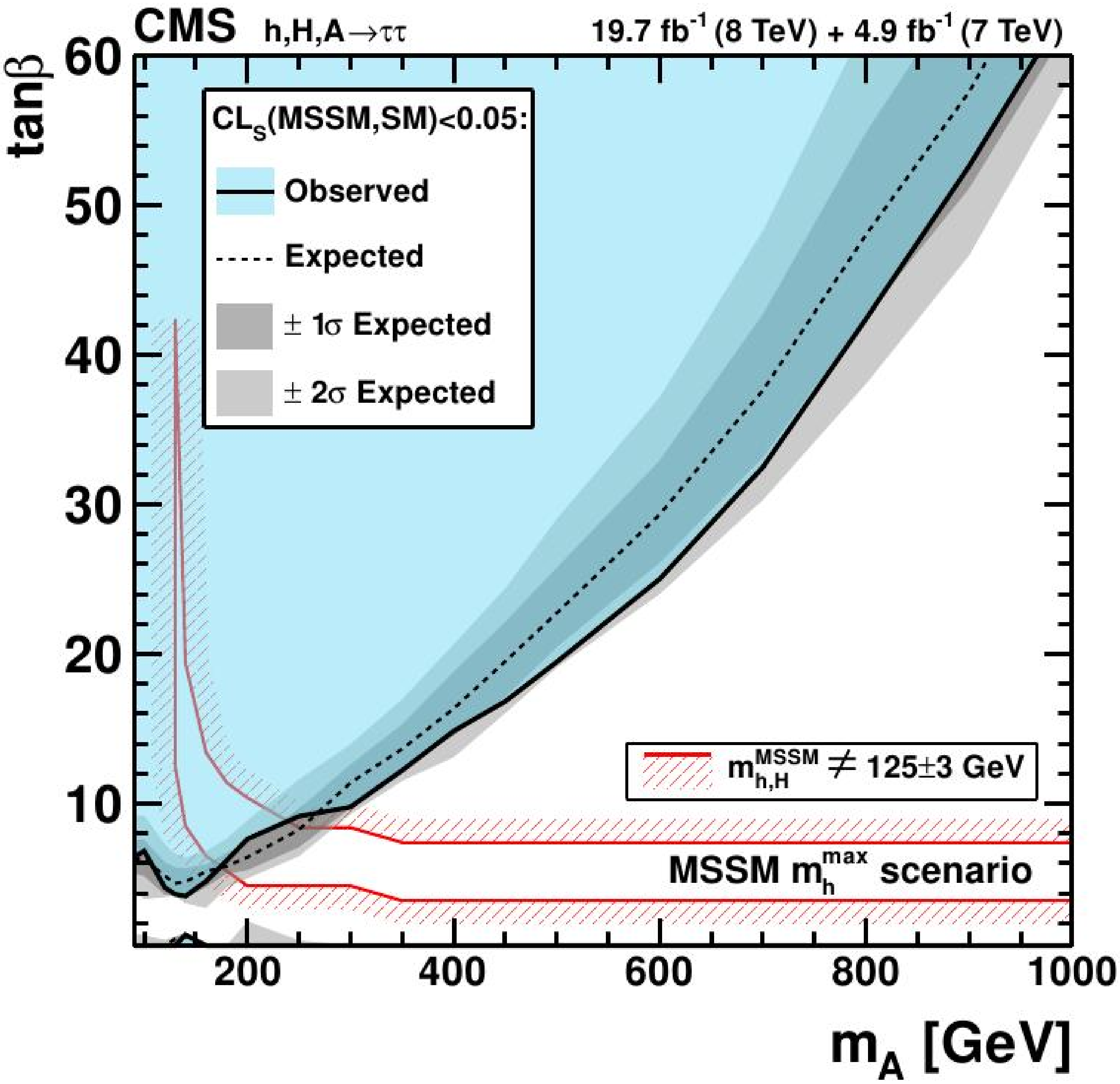






# Minimal SUSY extension of the SM – Higgs sector

| Parameter | $m_{\mathrm{h}}^{\mathrm{max}}$ |
|---|---|
| $m_{\mathrm{A}}$ | 90–1000 GeV |
| $\tan\beta$ | 0.5–60 |
| $M_{\mathrm{SUSY}}$ | 1000 GeV |
| $\mu$ | 200 GeV |
| $M_1$ | $(5/3)\, M_2 \tan^2\theta_W$ |
| $M_2$ | 200 GeV |
| $X_t$ | $2\, M_{\mathrm{SUSY}}$ |
| $A_b, A_t, A_\tau$ | $A_b = A_t = A_\tau$ |
| $m_{\tilde{\mathrm{g}}}$ | 1500 GeV |
| $m_{\tilde{\mathrm{l}}_3}$ | 1000 GeV |



# Minimal SUSY extension of the SM

# Gluino and sfermions

# Squarks and gluinos

stops (sbottoms) are expected to be highly mixed due to large top (bottom) quark mass

→ the mass matrix takes the form

$$M_{\tilde{q}}^2 = \begin{pmatrix} m_{\tilde{q}_L}^2 & a_q m_q \\ a_q m_q & m_{\tilde{q}_R}^2 \end{pmatrix}$$

where $a_q = A_q - \mu \left\{ \cot\beta \; , \; \tan\beta \right\}$ ( $A_q$ are trilinear couplings )

for stops → $\cot\beta$

for sbottoms → $\tan\beta$

we also have $m_{\tilde{q}_L}^2 = M_{\tilde{Q}}^2 + M_Z^2 \cos 2\beta \left( I_{3L}^q - Q_q \sin^2\theta_W \right) + m_q^2$

$m_{\tilde{q}_R}^2 = M_{\{\tilde{U},\tilde{D}\}}^2 + Q_q \; M_Z^2 \cos 2\beta \sin^2\theta_W + m_q^2$

where $M_{\tilde{Q}}, M_{\tilde{U}}, M_{\tilde{D}}$ are soft SUSY breaking masses

the mass eigenvalues are

$$m_{\tilde{q}_{1,2}}^2 = \frac{1}{2} \left( m_{\tilde{q}_L}^2 + m_{\tilde{q}_R}^2 \mp \sqrt{\left( m_{\tilde{q}_L}^2 - m_{\tilde{q}_R}^2 \right)^2 + 4\, a_q^2 m_q^2} \right)$$

**one squark of the 3rd generation (stop sbottom) can be light and lighter than other squarks (lightest stop can be lighter than top quark)**

# Squarks and gluinos

similar story for 3rd generation lepton (tau lepton)

$$M^2_{\tilde{l}} = \begin{pmatrix} m^2_{\tilde{l}_L} & \boxed{a_l m_l} \\ \boxed{a_l m_l} & m^2_{\tilde{l}_R} \end{pmatrix}$$

where $a_l = A_l - \mu \ \tan\beta$ ( $A_l$ are trilinear couplings )

and we have $m^2_{\tilde{l}_L} = M^2_{\tilde{L}} - M^2_Z \cos 2\beta \left( \frac{1}{2} - \sin^2\theta_W \right) + m^2_l$

$m^2_{\tilde{l}_R} = M^2_{\tilde{E}} - M^2_Z \cos 2\beta \ \sin^2\theta_W + m^2_l$

where $M_{\tilde{L}}, M_{\tilde{E}}$ are soft SUSY breaking masses

the mass eigenvalues are

$$m^2_{\tilde{\tau}_{1,2}} = \frac{1}{2} \left( m^2_{\tilde{\tau}_L} + m^2_{\tilde{\tau}_R} \mp \sqrt{\left( m^2_{\tilde{\tau}_L} - m^2_{\tilde{\tau}_R} \right)^2 + 4 a^2_\tau m^2_\tau} \right)$$

**one stau can be light and lighter than other charged sleptons**

# Squarks and gluinos

the weak eigenstates $\tilde{q}_L, \ \tilde{q}_R$ are related to the mass eigenstates $\tilde{q}_{1,} \ \tilde{q}_2$ by

$$\begin{pmatrix} \tilde{q}_1 \\ \tilde{q}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_{\tilde{q}} & \sin\theta_{\tilde{q}} \\ -\sin\theta_{\tilde{q}} & \cos\theta_{\tilde{q}} \end{pmatrix} \begin{pmatrix} \tilde{q}_L \\ \tilde{q}_R \end{pmatrix}$$

with the mixing angle defined by $\cos\theta_{\tilde{q}} = \dfrac{-a_q m_q}{\sqrt{\left(m^2_{\tilde{q}_L} - m^2_{\tilde{q}_1}\right)^2 + 4\, a_q^2 m_q^2}}$

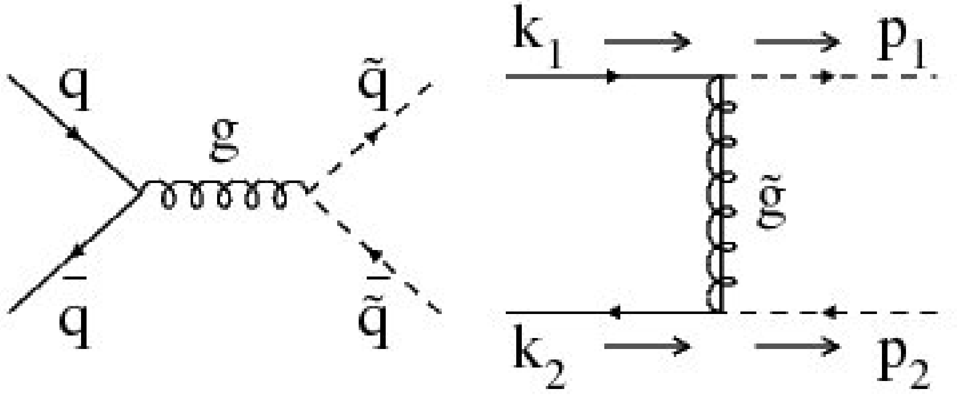
similarly the weak eigenstates $\tilde{\tau}_L, \ \tilde{\tau}_R$ are related to the mass eigenstates $\tilde{\tau}_{1,} \ \tilde{\tau}_2$ by

$$\begin{pmatrix} \tilde{\tau}_1 \\ \tilde{\tau}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_{\tilde{\tau}} & \sin\theta_{\tilde{\tau}} \\ -\sin\theta_{\tilde{\tau}} & \cos\theta_{\tilde{\tau}} \end{pmatrix} \begin{pmatrix} \tilde{\tau}_L \\ \tilde{\tau}_R \end{pmatrix}$$

with the mixing angle $\cos\theta_{\tilde{\tau}} = \dfrac{-a_\tau m_\tau}{\sqrt{\left(m^2_{\tilde{\tau}_L} - m^2_{\tilde{\tau}_1}\right)^2 + 4\, a_\tau^2 m_\tau^2}}$

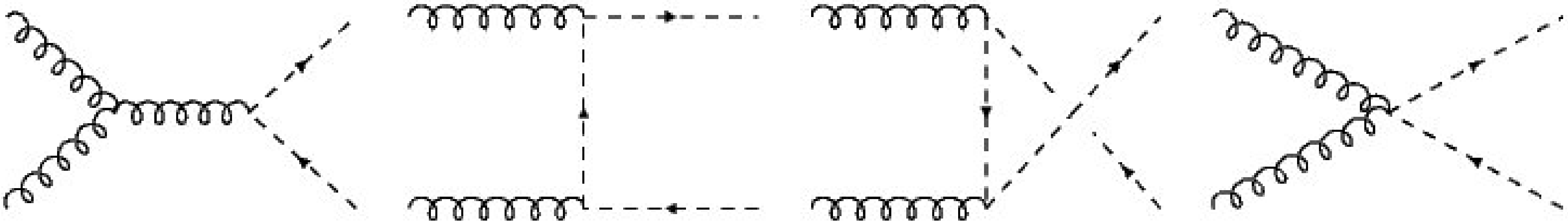
# Squarks and gluinos

## squark pair LO production at hadron colliders



$q\bar{q}\rightarrow\tilde{q}\bar{\tilde{q}}$

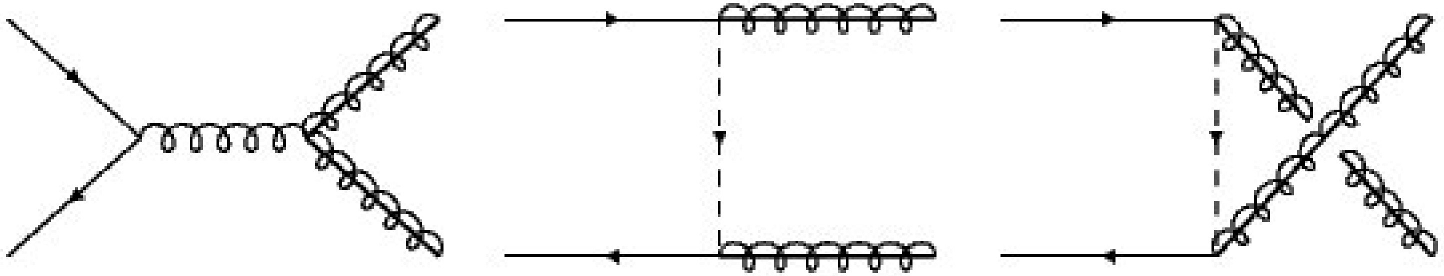
$qq\rightarrow\tilde{q}\tilde{q}$



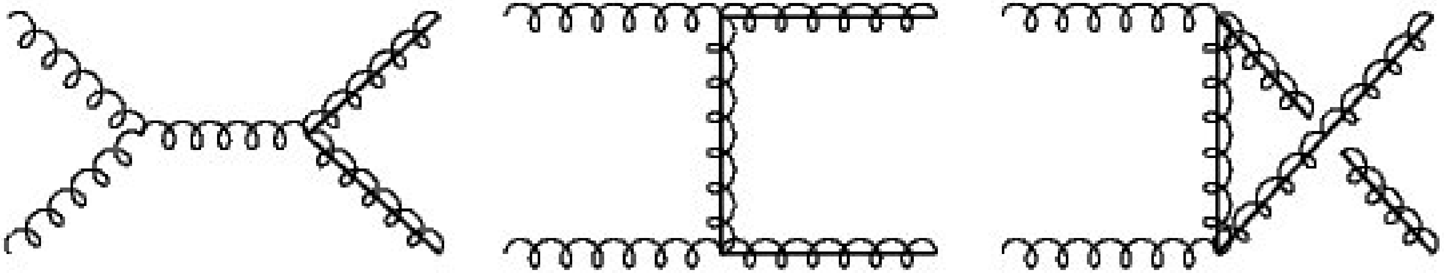
$gg\rightarrow\tilde{q}\bar{\tilde{q}}$

# Squarks and gluinos

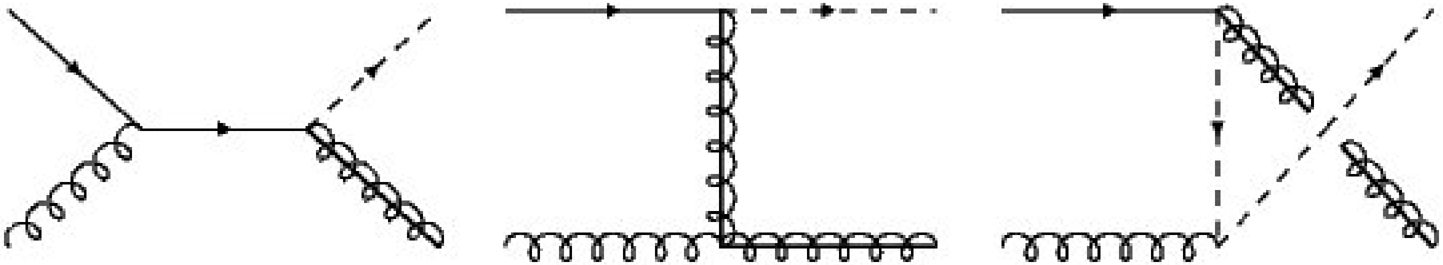
## gluinos pair and gluino-squark LO production at hadron colliders



$q\bar{q}\rightarrow\tilde{g}\tilde{g}$



$gg\rightarrow\tilde{g}\tilde{g}$



$qg\rightarrow\tilde{q}\tilde{g}$

# Squarks and gluinos

- **generically one has** (dropping explicit mentions to flavors and "chiralities") **if kinematically allowed :**

$$\tilde{g} \rightarrow \bar{q}\ \tilde{q}$$

- **together with one of the simplest squark decay, if kinematically allowed**

$$\tilde{q} \rightarrow q\ \tilde{\chi}_1^o$$

giving rise to the simplest cascade decay, $\tilde{g} \rightarrow \bar{q}\ \tilde{q}_L \rightarrow q\ \bar{q}\ \tilde{\chi}_1^0$

**the gluino pair production leads to a final state** $q\ \bar{q}\ q\ \bar{q}\ \tilde{\chi}_1^0\ \tilde{\chi}_1^0$

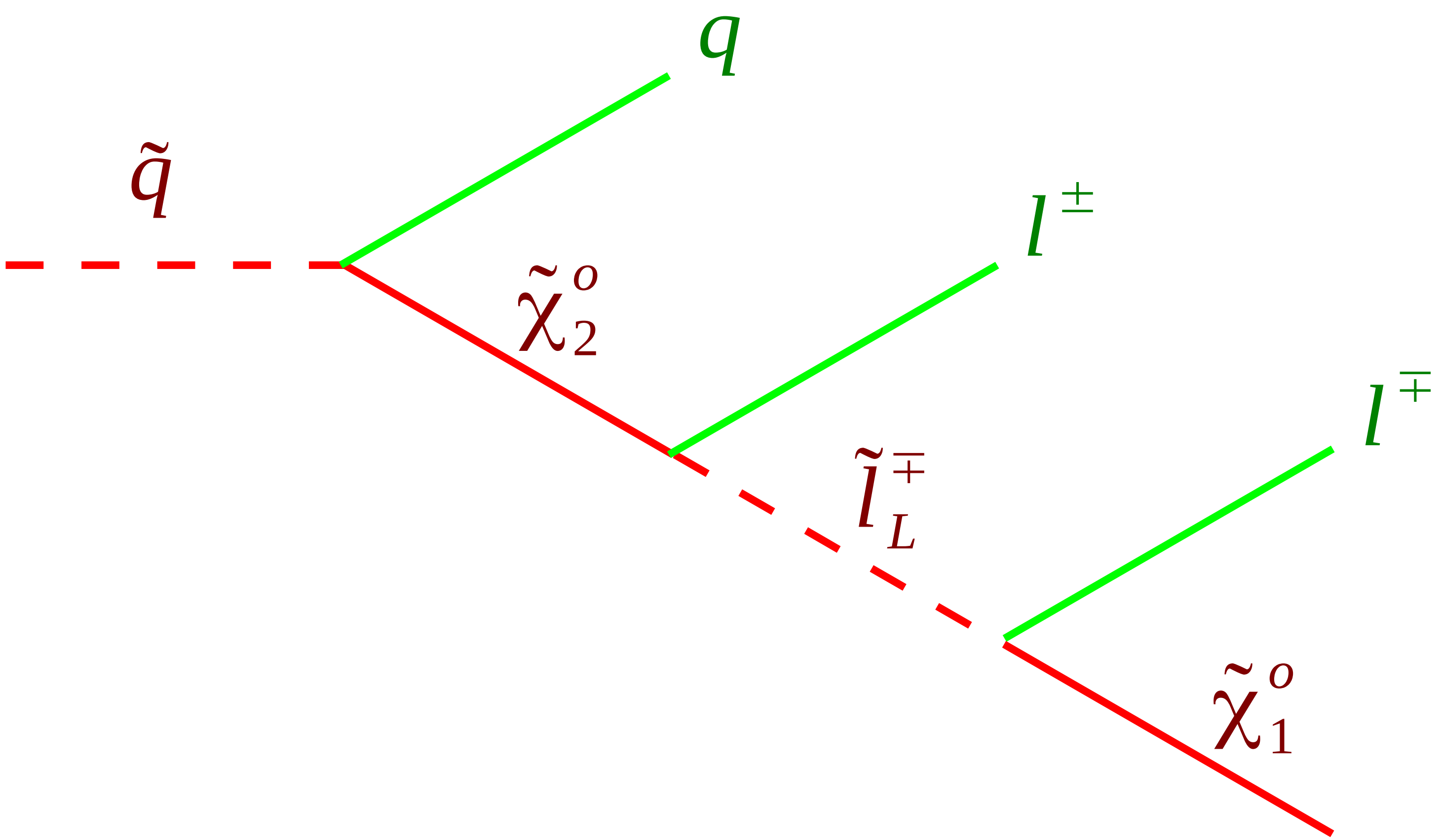
- **the lightest neutralino is often considered to be the Lightest Supersymmetric Particle i.e. the LSP which is stable if one assumes R-parity conservation**

- **final state quarks are giving jets and the stable** $\tilde{\chi}_1^0$ **escapes detection**

**thus giving rise to an event signature with 4 jets and missing transverse energy at hadron colliders**

# Squarks and gluinos

**example**



for a squark pair production with both squarks decaying via this decay cascade

one gets an event signature with **2 jets + 4 leptons and missing transverse energy**

# Squarks and gluinos

## Stops decays

$$\tilde{t}_{1,2} \rightarrow t\ \tilde{\chi}^{o}_{i=1,2,3,4}\ ,\quad \tilde{t}_{1,2} \rightarrow b\ \tilde{\chi}^{+}_{i=1,2}\ ,\quad \tilde{t}_{1,2} \rightarrow t\ \tilde{g}$$

$$\tilde{t}_{1,2} \rightarrow W^{+}\ \tilde{b}_{1,2}\ ,\quad \tilde{t}_{1,2} \rightarrow H^{+}\ \tilde{b}_{1,2}$$

$$\tilde{t}_{2} \rightarrow Z\ \tilde{t}_{1}\ ,\quad \tilde{t}_{2} \rightarrow h\ \tilde{t}_{1}\ ,\quad \tilde{t}_{2} \rightarrow H\ \tilde{t}_{1}\ ,\quad \tilde{t}_{2} \rightarrow A\ \tilde{t}_{1}$$

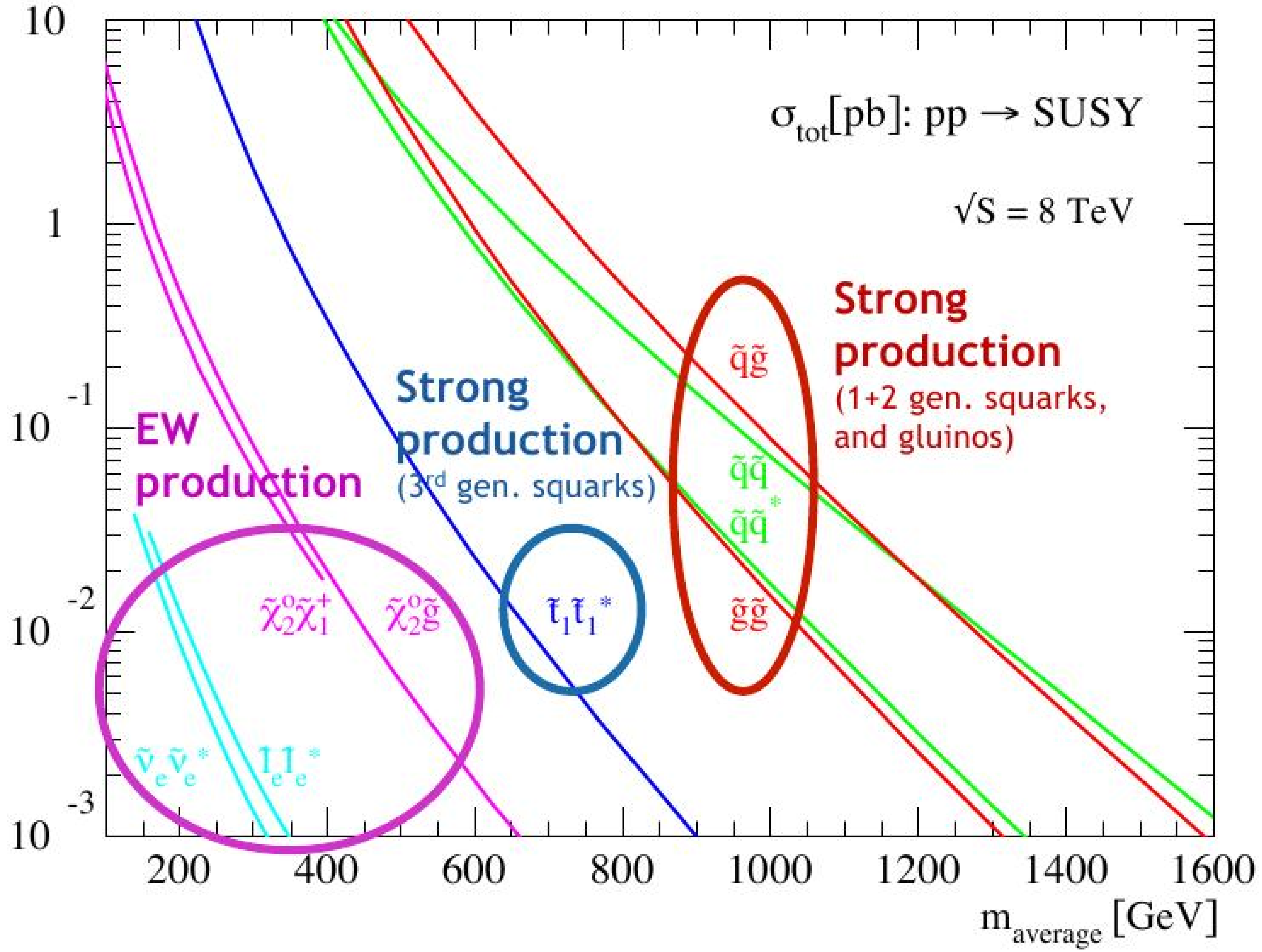
if relatively light they dominantly decay into $\tilde{t}_{1} \rightarrow b\ \tilde{\chi}^{+}_{1}$

and possibly into $\tilde{t}_{1} \rightarrow t\ \tilde{\chi}^{o}_{1}$

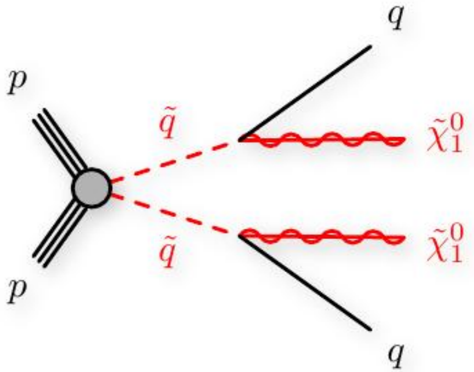
if both kinematically forbidden then the lightest stop can decay via suppressed modes (2-body, 3-body and 4 body decays)

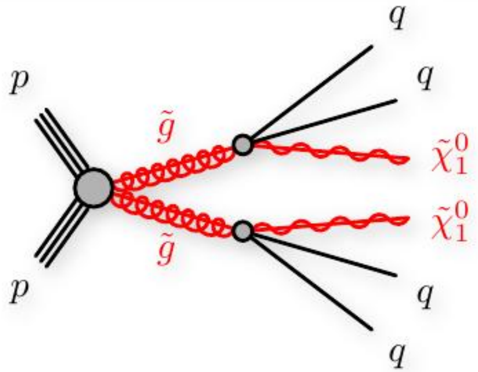
$$\tilde{t}_{1} \rightarrow c\ \tilde{\chi}^{o}_{1}\ ,\quad \tilde{t}_{1} \rightarrow b\ \nu\ \tilde{l}_{L}\ ,\quad \tilde{t}_{1} \rightarrow b\ W \tilde{\chi}^{o}_{1}\ ,\quad \tilde{t}_{1} \rightarrow b\ f\ \bar{f}\,'\tilde{\chi}^{o}_{1}$$

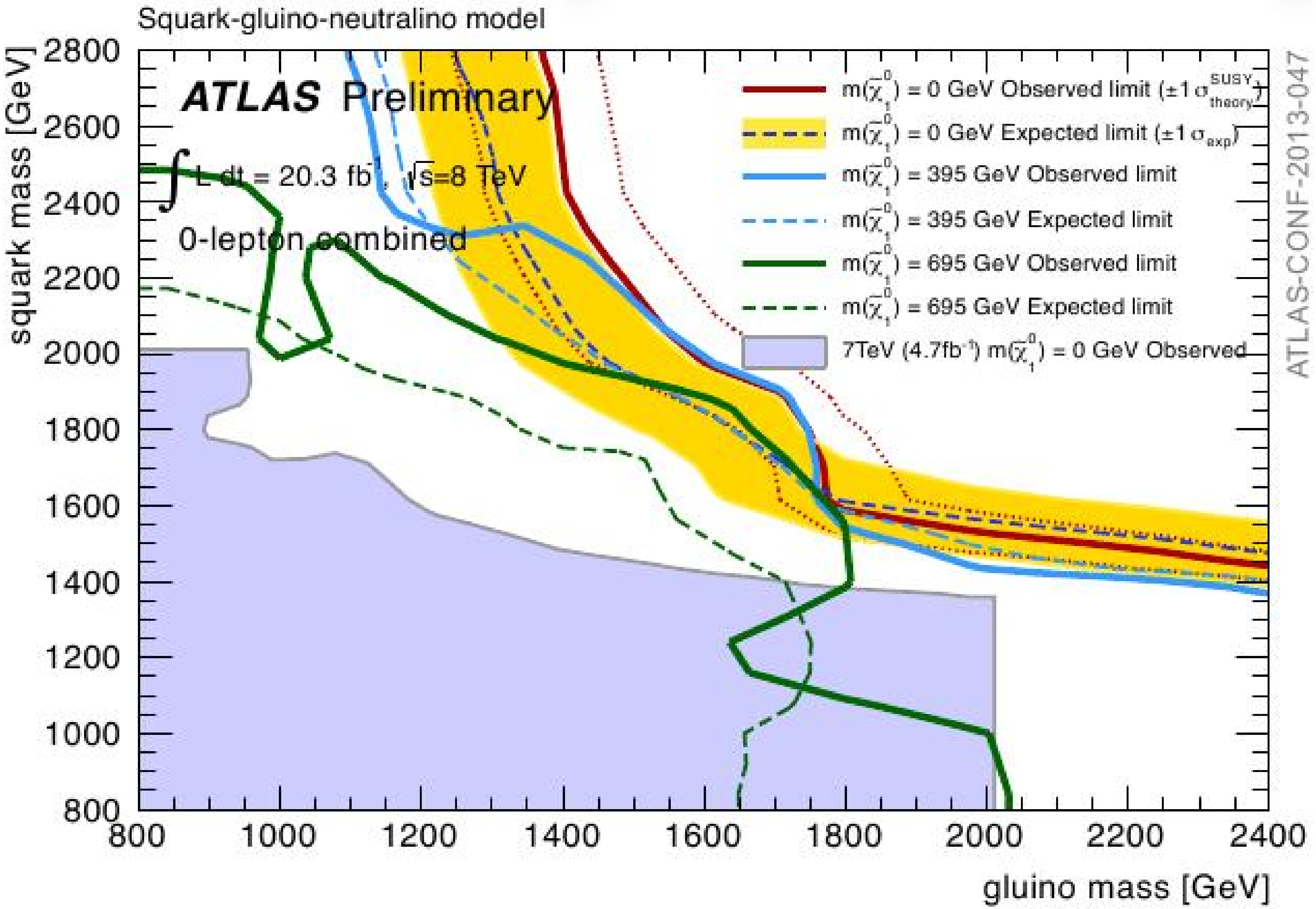
# production cross-sections at the LHC : gross picture



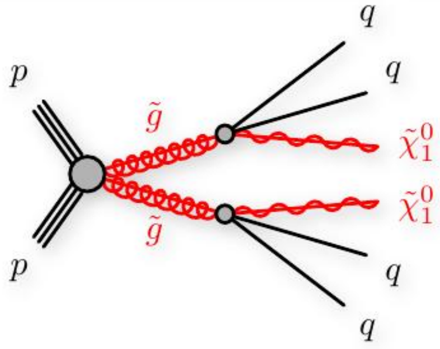
# Squarks and gluinos

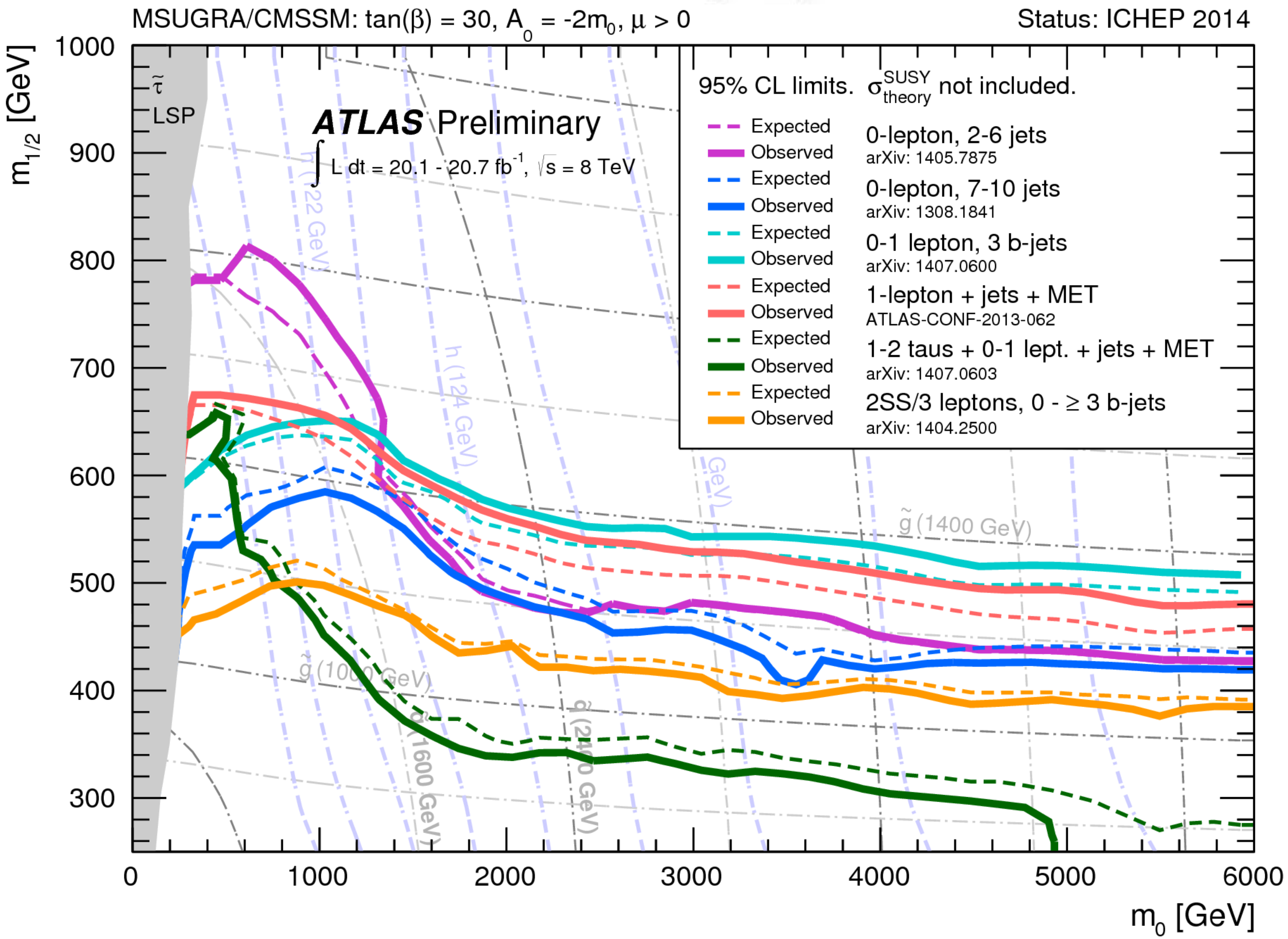




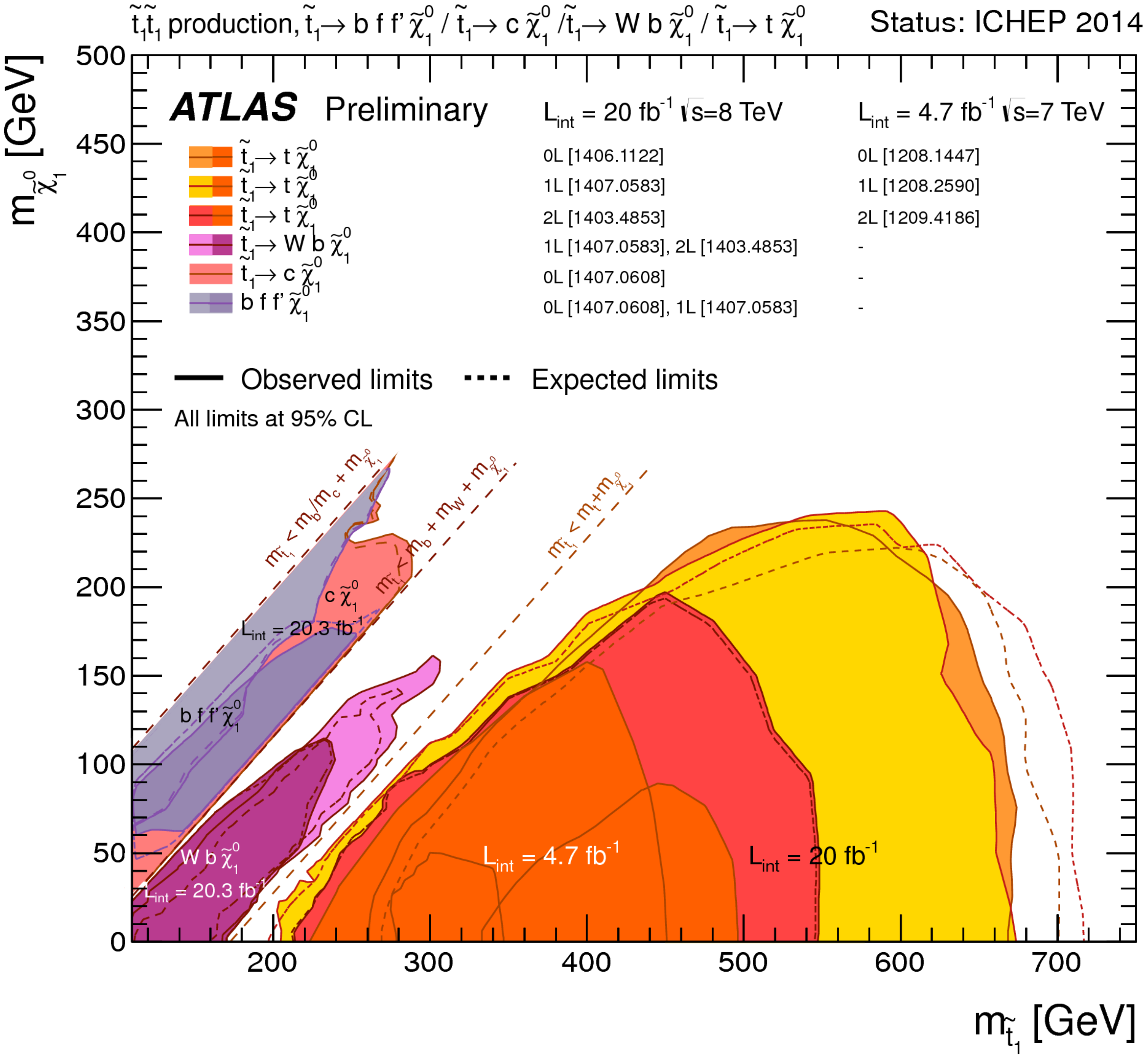


# Squarks and gluinos



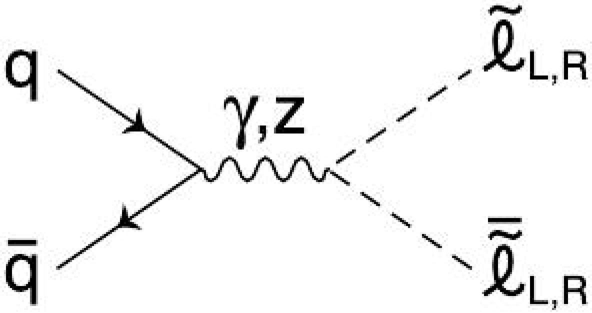


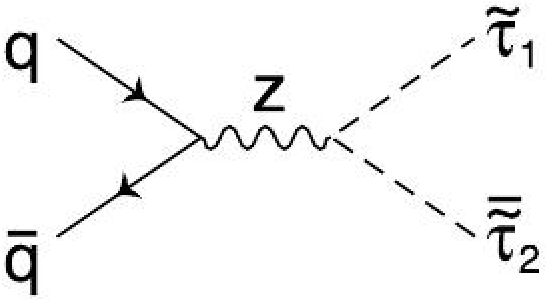
# Squarks and gluinos

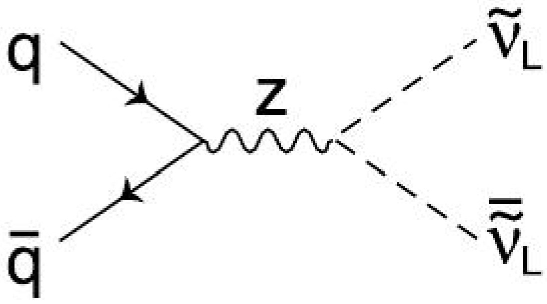


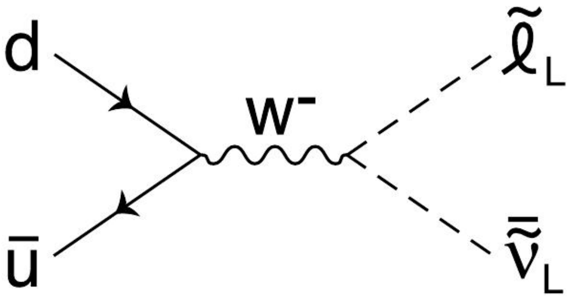
# Sleptons

## slepton pair production at hadron colliders





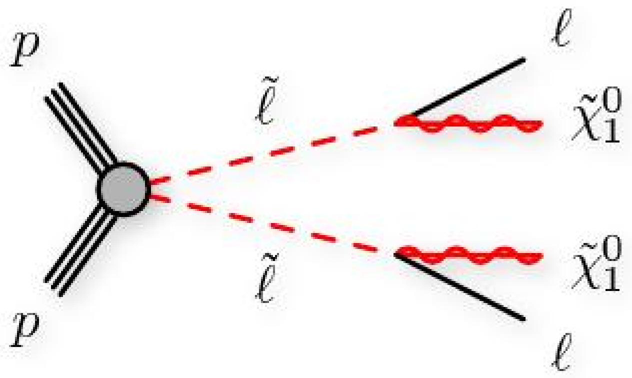




through intermediate W and Drell Yan processes

# sleptons searches at the LHC

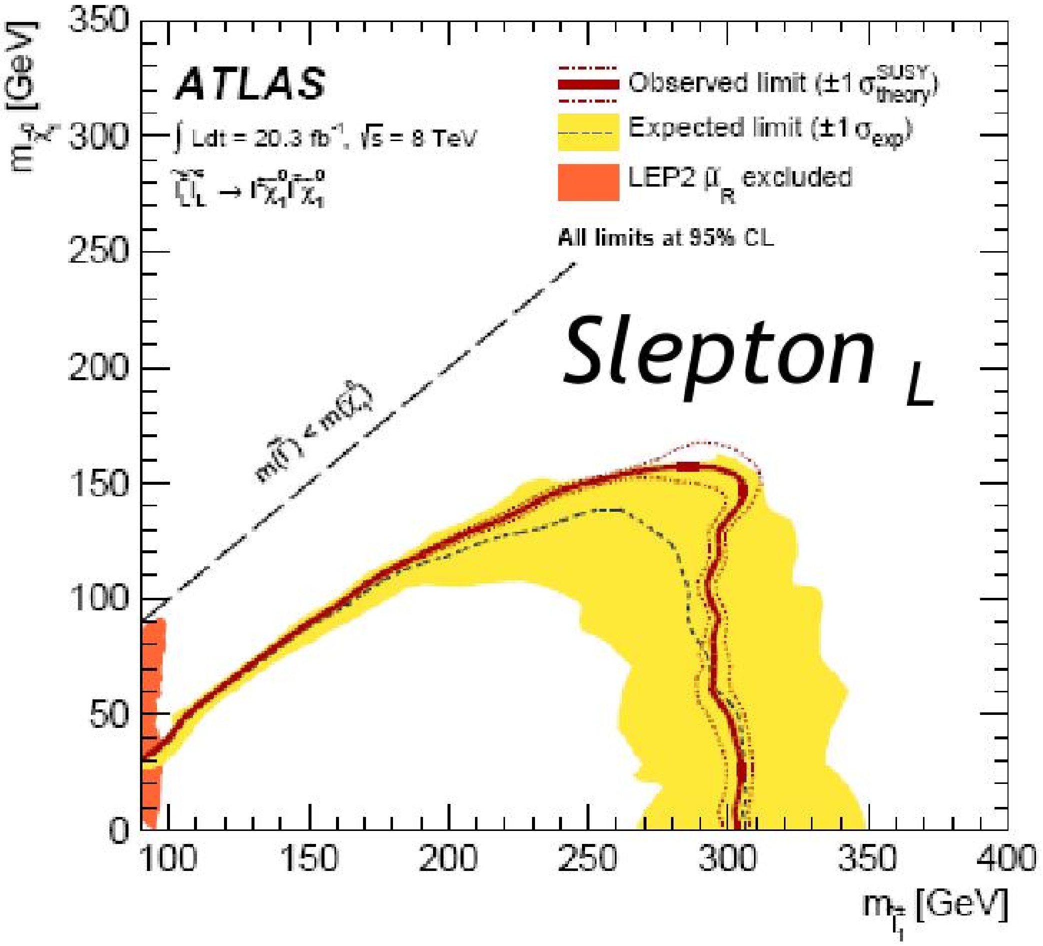
Production through intermediate W and Drell Yan processes

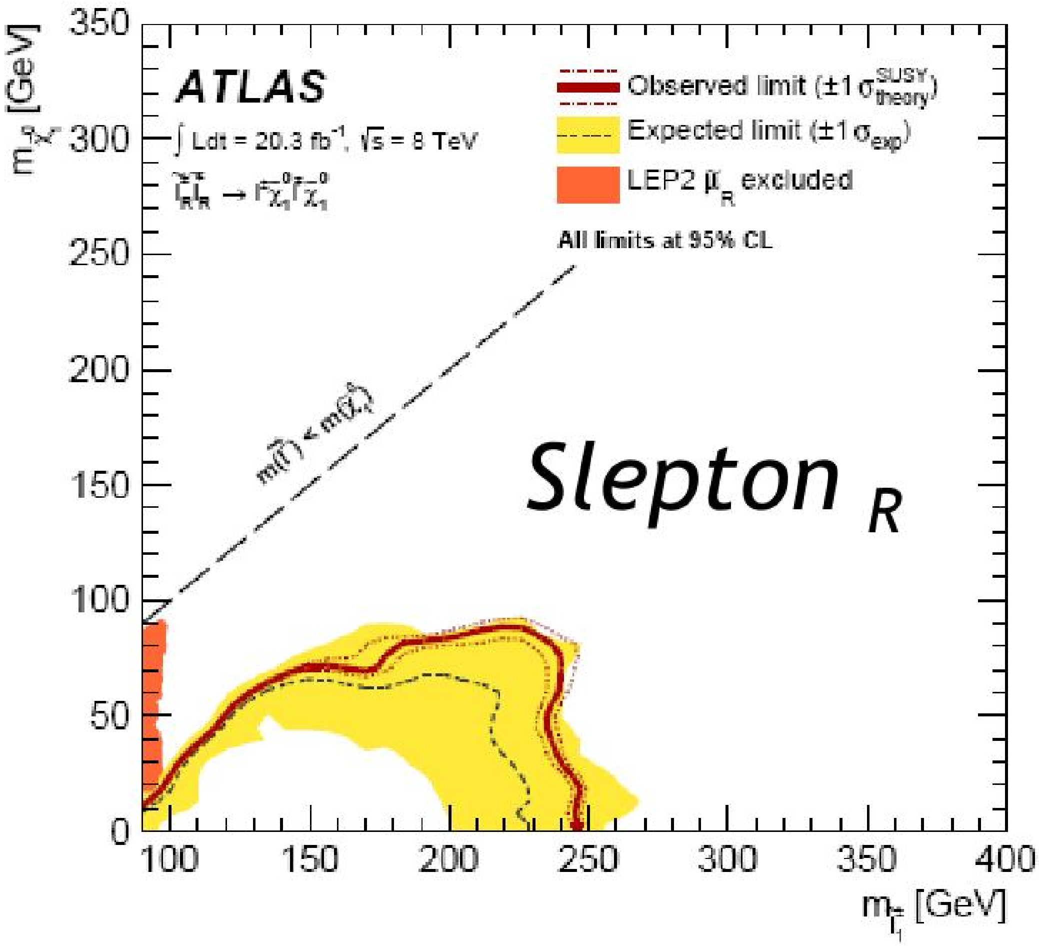


larger cross section for slepton-left

final state with 2 leptons and missing transverse energy

# slepton searches





# Minimal SUSY extension of the SM
## EW gauginos

# EW Gauginos

charginos are charged fermions from $\tilde{W}^+,\ \tilde{W}^-,\ \tilde{H}_d^-,\ \tilde{H}_u^+$ i.e. we combine the gauginos

$$\tilde{W}^+ = \frac{1}{\sqrt{2}}\left(\tilde{W}_1 - i\,\tilde{W}_2\right) \quad \text{and} \quad \tilde{W}^- = \frac{1}{\sqrt{2}}\left(\tilde{W}_1 + i\,\tilde{W}_2\right)$$

and the charged component of the Higgsinos $\tilde{H}_u = \begin{pmatrix} \tilde{H}_u^+ \\ \tilde{H}_u^o \end{pmatrix}$ and $\tilde{H}_d = \begin{pmatrix} \tilde{H}_d^o \\ \tilde{H}_d^- \end{pmatrix}$

intos charged pairs $\chi^+ = \left(\tilde{W}^+,\ \tilde{H}_u^+\right),\quad \chi^- = \left(\tilde{W}^-,\ \tilde{H}_d^-\right)$

the mass term can be written as $\left(\chi^+,\ \chi^-\right)\begin{pmatrix} & X^T \\ X & \end{pmatrix}\begin{pmatrix} \chi^+ \\ \chi^- \end{pmatrix}$

where $X = \begin{pmatrix} M_2 & \sqrt{2}\ M_W\ \sin\beta \\ \sqrt{2}\ M_W\ \cos\beta & \mu \end{pmatrix}$ is the chargino mass matrix

# EW Gauginos

the mass eigenstates can be combined into Dirac spinors and are given by :

$$\tilde{\chi}_1^+ = \begin{pmatrix} \chi_1^+ \\ \bar{\chi}_1^- \end{pmatrix} \qquad \text{and} \qquad \tilde{\chi}_2^+ = \begin{pmatrix} \chi_2^+ \\ \bar{\chi}_2^- \end{pmatrix}$$

which are our charginos and we take $\tilde{\chi}_1^\pm$ to be the lighter chargino by definition

the mass eigenvalue are given by :

$$M^2_{\tilde{\chi}^\pm_{1,2}} = \frac{1}{2}\left(M_2^2 + \mu^2 + 2M_W^2\right) \mp \frac{1}{2}\left[\left(M_2^2 + \mu^2 + 2M_W^2\right)^2 - 4\left(\mu M_2 - M_W^2 \sin 2\beta\right)^2\right]^{1/2}$$

# EW Gauginos

mixing between neutral gaugino and neutral component of Higgsinos give rise to to neutralinos $\tilde{\chi}^o_{i=1,4}$

in the basis $\left(\tilde{B},\ \tilde{W}_{3,}\ \tilde{H}^o_d,\ \tilde{H}^o_u\right)$ the mass matrix takes the form

$$Y = \begin{pmatrix} M_1 & 0 & -M_W \tan\theta_W \cos\beta & M_W \tan\theta_W \sin\beta \\ 0 & M_2 & M_W \cos\beta & -M_W \sin\beta \\ -M_W \tan\theta_W \cos\beta & M_W \cos\beta & 0 & \mu \\ M_W \tan\theta_W \sin\beta & -M_W \sin\beta & \mu & 0 \end{pmatrix}$$

where $M_1$ and $M_2$ are soft SUSY breaking terms

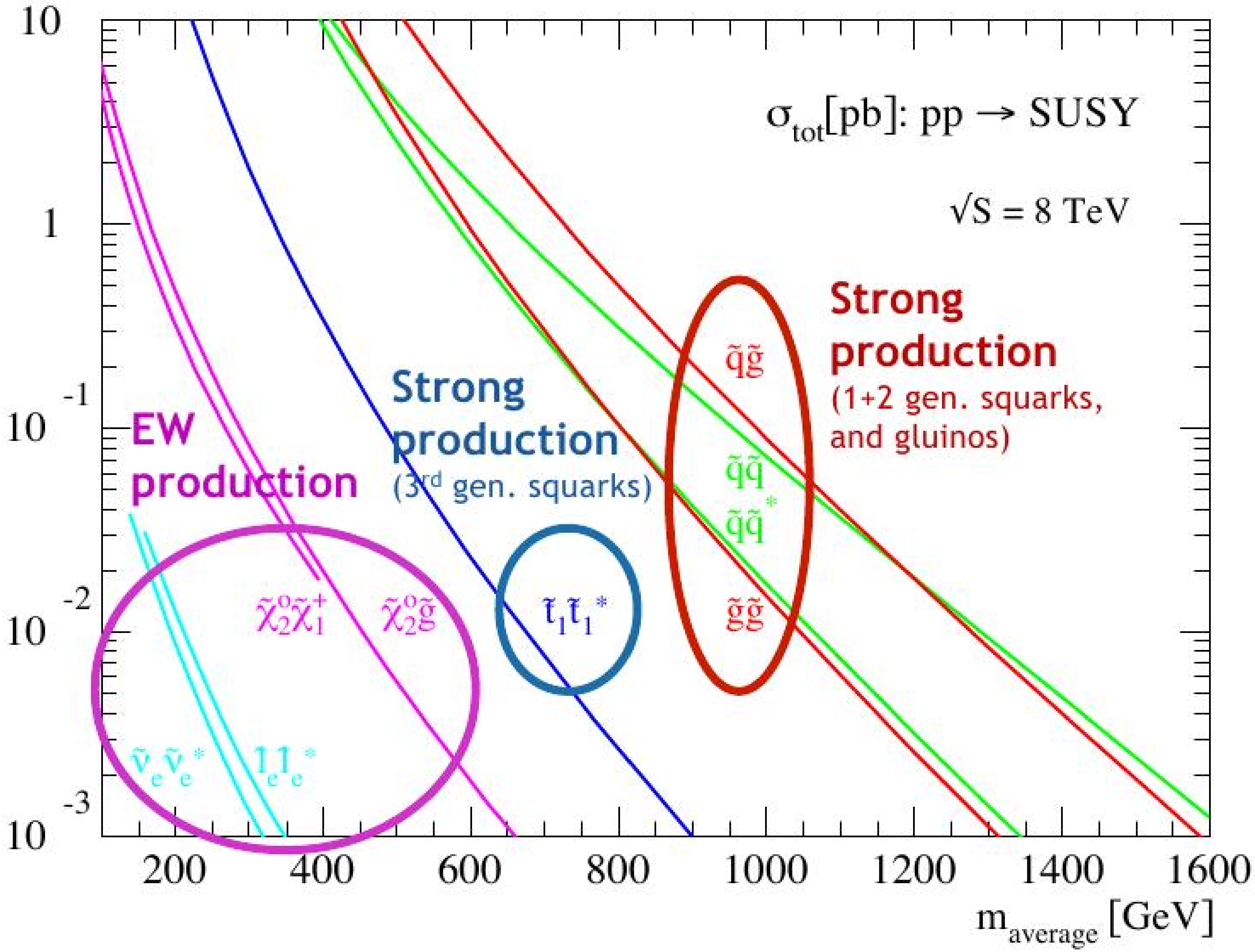
the symmetric neutralino mass matrix can be diagonalized by a single unitary matrix N

$$\tilde{\chi}^o_i = N_{i,1}\ \tilde{B} + N_{i,2}\ \tilde{W}_3 + N_{i,3}\ \tilde{H}^o_d + N_{i,4}\ \tilde{H}^o_u$$

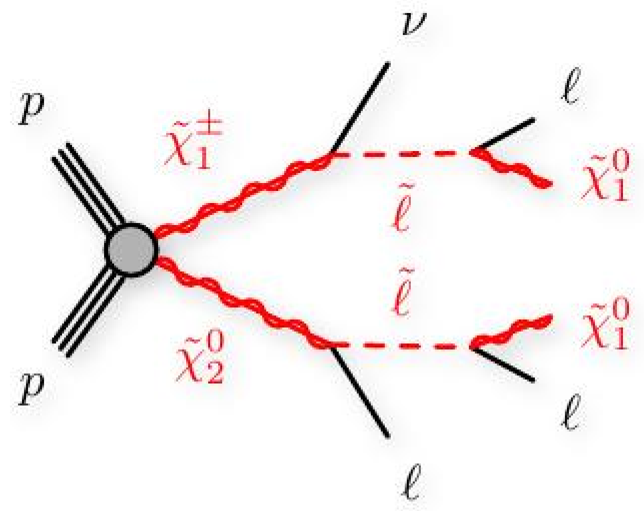
it can be done analytically but resulting formulae are lengthy and not particularly illuminating

eigenstates and eigenvalues are usually calculated numerically

# production cross-sections at the LHC : gross picture



# EW gauginos searches at the LHC

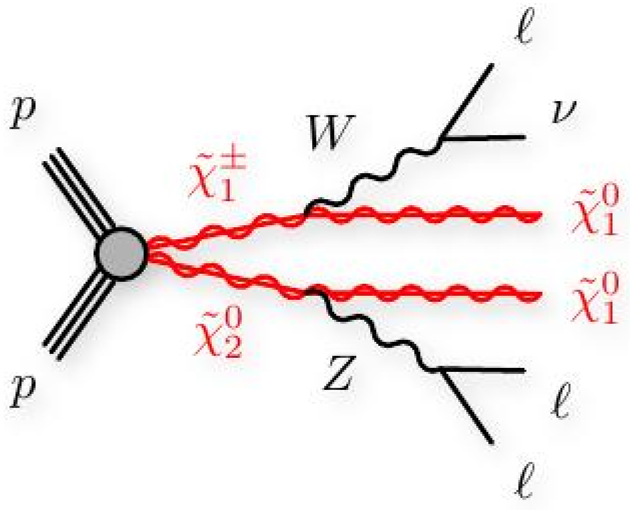


largest cross-section for Wino like $\tilde{\chi}$'s

smaller if Higgsino like

(then also mass degenerate with LSP)

**final states with 3 leptons if light sleptons**



if sleptons are heavy → reduced BR to leptons

**WZ + missing transverse energy final states**

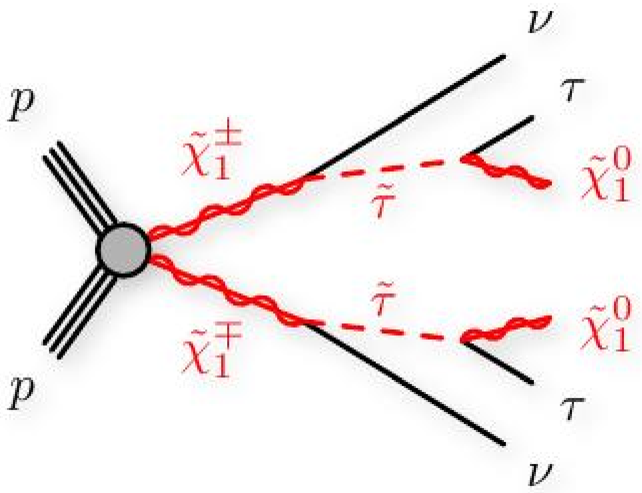
**possible 3-lepton + MET signature**

or WW + missing transverse energy final states

for chargino pairs production and heavy sleptons

# EW gauginos searches at the LHC

Charginos pair production and decay via tau sleptons

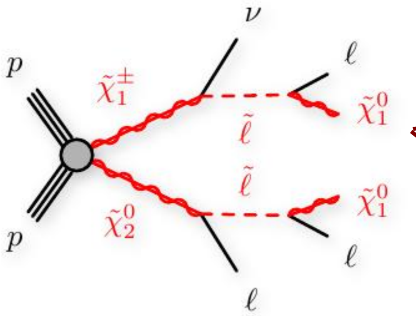


plausible possibility of light tau sleptons

while other sleptons are heavy

final states with 2 tau leptons and missing transverse energy

# EW gauginos searches at the LHC

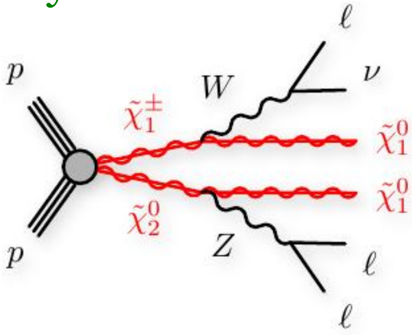


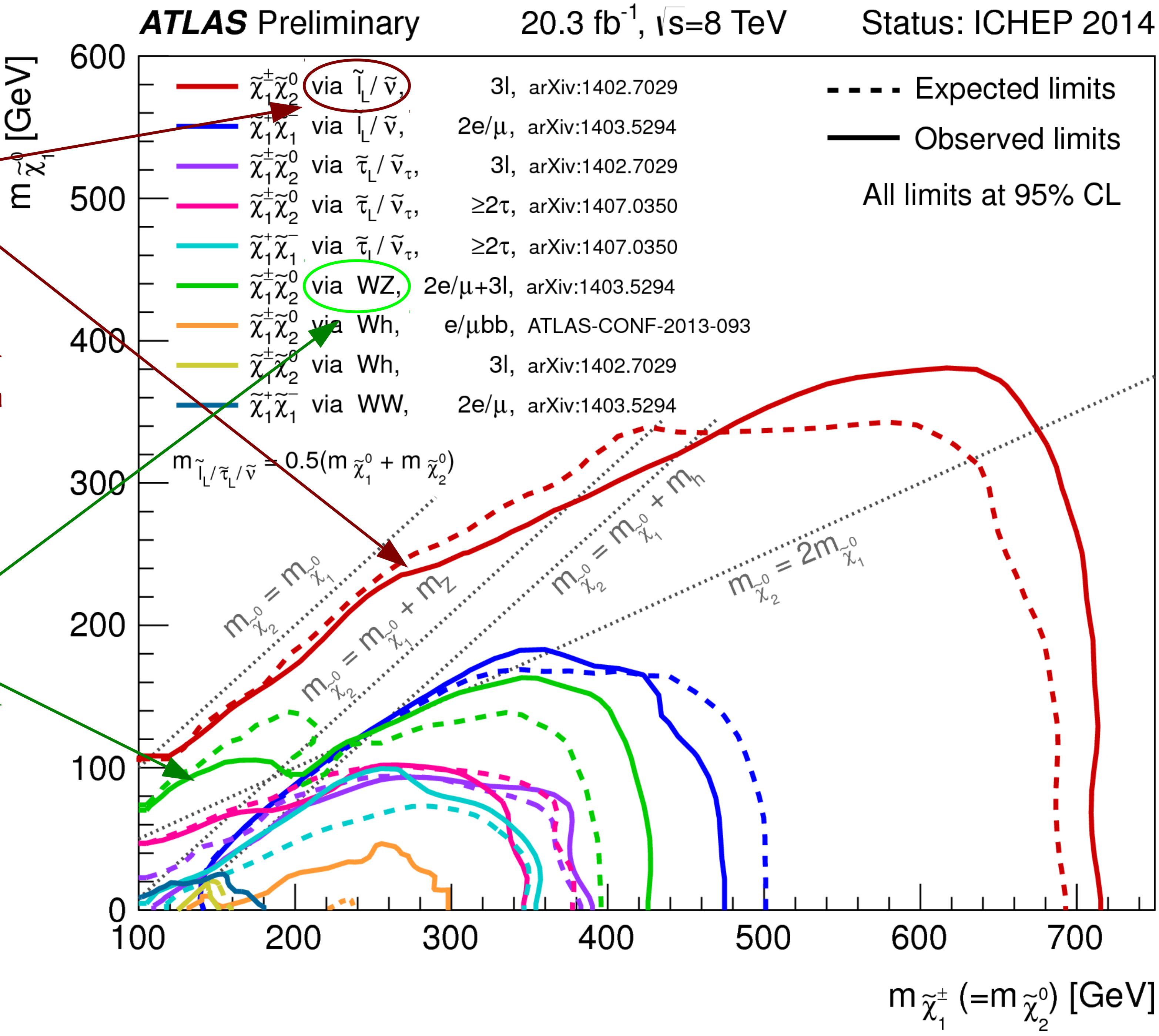
intermediate slepton deca

dominate if slepton is ligh

if slepton is heavy

intermediate gauge boson decay





# Minimal SUSY extension of the SM
# some indirect constraints

# $B_s \rightarrow \mu^+ \mu^-$

- this rare B decays occur at loop level

  → the SM contributions are very small

  → new physics contributions can have a comparable magnitude

- very promising experimental situation

  → Branching ratios start to be measured precisely

- theory ingredients known to a good accuracy

  → in particular QCD corrections are known to a good precision

from N. Mahmoudi, Blois conference 2013

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

## A multi-scale problem

- new physics : $1/\Lambda_{\mathrm{NP}}$
- electroweak interactions : $1/M_{\mathrm{W}}$
- hadronic effects : $1/m_{\mathrm{b}}$
- QCD interactions : $1/\Lambda_{\mathrm{QCD}}$

## ⇒ Effective field theory approach

separation between low and high energies using Operator Product Expansion

$$H_{\mathrm{eff}} = \frac{G_F}{\sqrt{2}} \sum_i V^i_{\mathrm{CKM}} \; C_i \; O_i$$

Wilson coefficients

local operator

- short distance : Wilson coefficents computed perturbatively
- long distance distance : local operators

## New physics:

- correction to the Wilson coefficients: $C_i \to C_i + \Delta C_i^{\mathrm{NP}}$
- additional operators : $\sum_j C_j^{\mathrm{NP}} \; O_j^{\mathrm{NP}}$

from N. Mahmoudi, Blois conference 2013

# $B_s \to \mu^+\mu^-$ predictions

as mentioned previously → use the Operator Product Expansion (OPE) formalism

$$H_{\text{eff}} = \frac{G_F}{\sqrt{2}} \sum_i V^i_{\text{CKM}} \, C_i \, O_i$$

Wilson coefficients → $C_i$

local operator → $O_i$

to calculate the transition amplitude

$$A(\text{Meson} \to \text{Final}) = <\text{Final}|\, H_{\text{eff}} \,|\text{Meson}>$$

$$= \frac{G_F}{\sqrt{2}} \sum_i V^i_{\text{CKM}} \, C_i \; <\text{Final}|\, O_i \,|\text{Meson}>$$

allows to separate the problem of calculating amplitudes A into two distinct parts at some scale $\mu$:

- short distance (pertubative) calculation of the Wilson coefficient $C_i(\mu)$
- long distance (generally non-pertubative) calculation of the matrix element $< O_i(\mu) >$

the scale $\mu$ separates the physics contribution into short distances and long distances contributions

# $B_s \rightarrow \mu^+\mu^-$ predictions

for $B_s \rightarrow \mu^+\mu^-$ one has the effective Hamiltonian

$$H_{\mathrm{eff}} = -\frac{2G_F}{\sqrt{2}}\frac{\alpha}{2\pi\sin^2\theta_W} V_{tb}V_{ts}^{*}\left[C_A O_A + C'_A O'_A + C_S O_S + C'_S O'_S + C_P O_P + C'_P O'_P\right]$$

where

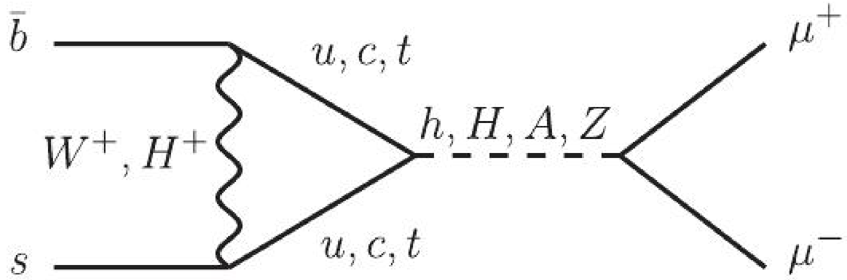
$$O_A = \left(\bar{s}\gamma^{\mu} P_L b\right)\left(\bar{l}\gamma_{\mu}\gamma_5 l\right) \qquad O'_A = \left(\bar{s}\gamma^{\mu} P_R b\right)\left(\bar{l}\gamma_{\mu}\gamma_5 l\right)$$

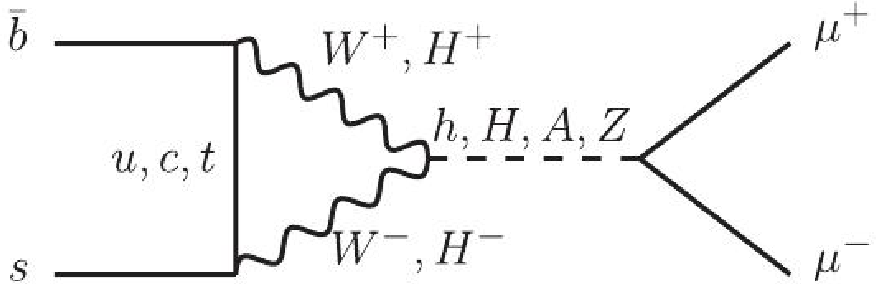
$$O_S = m_b\left(\bar{s} P_R b\right)\left(\bar{l}\, l\right) \qquad O'_S = m_s\left(\bar{s} P_L b\right)\left(\bar{l}\, l\right)$$

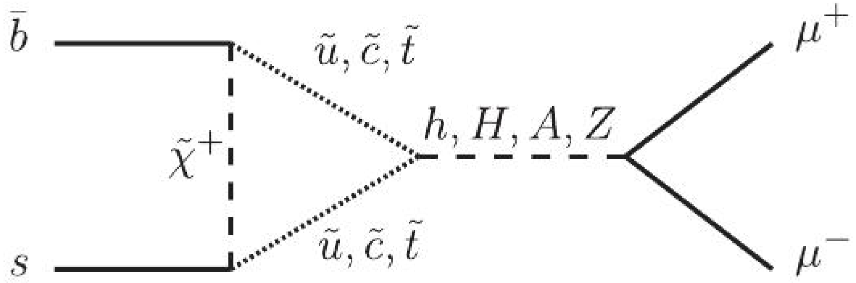
$$O_P = m_b\left(\bar{s} P_R b\right)\left(\bar{l}\gamma_5 l\right) \qquad O'_P = m_s\left(\bar{s} P_L b\right)\left(\bar{l}\gamma_5 l\right)$$

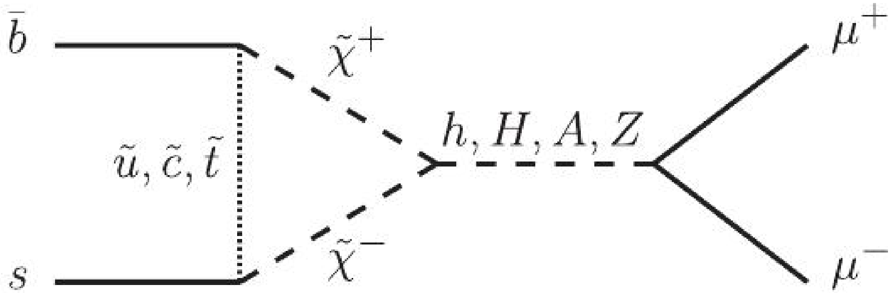
# $B_s \rightarrow \mu^+ \mu^-$ predictions

the Wilson coefficients can be evaluated for 'penguin' contributions

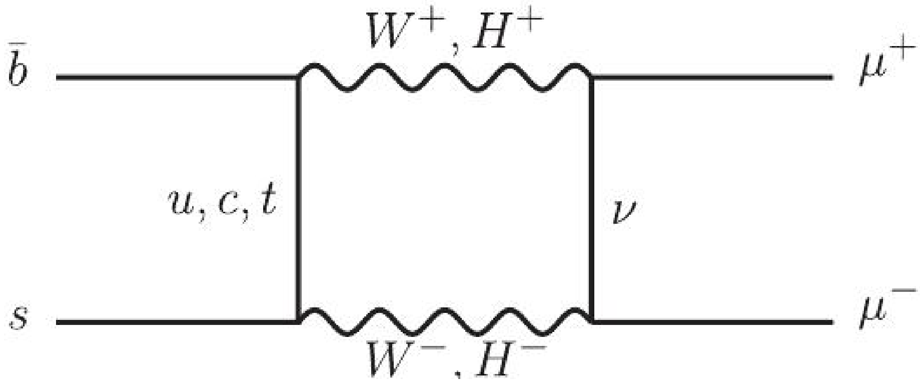


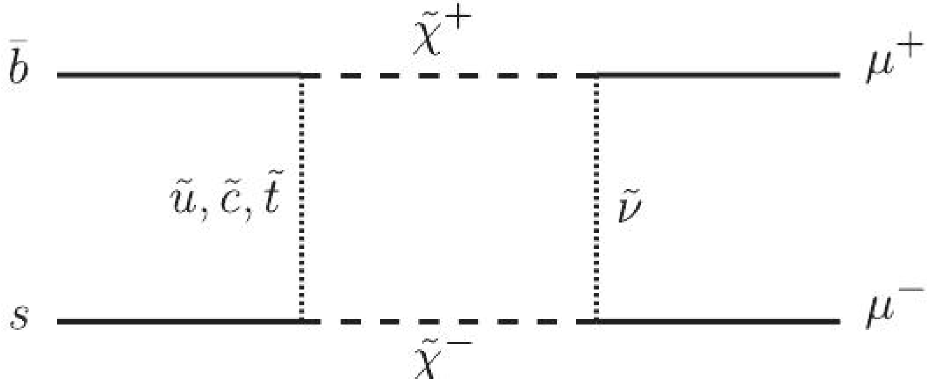






and for 'box' contributions





# $B_s \to \mu^+ \mu^-$ predictions

in the SM $C_A$ is the only non negligible Wilson coefficient

it gets its largest contributions from :

- Z penguin top loop (75%)
- a charmed box diagram (24 %)

one has :

$$\boldsymbol{Br\left(B_s \to \mu^+ \mu^-\right)_{SM} = \left(\; 3.25 \pm 0.17 \;\right) \times 10^{-9}}$$

using :

- $C_A^{SM} = -4.134$ (see arXiv:1303.3820)
- updated values for the $B_s$ decay constant $f_{B_s}$ from lattice QCD
- updated values for the $B_s$ lifetime $\tau_{B_s}$ (averaging experimental inputs)

# $B_s \rightarrow \mu^+ \mu^-$ predictions

in the MSSM we get the following dependencies on $\tan\beta$ and $M_A$

$$Br\left(B_s \rightarrow \mu^+ \mu^-\right)_{\mathrm{MSSM}} \propto \frac{m_b^2 m_\mu^2 \tan^6\beta}{M_A^4}$$

MSSM may have a spectacular impact on the $B_s \rightarrow \mu^+ \mu^-$ process

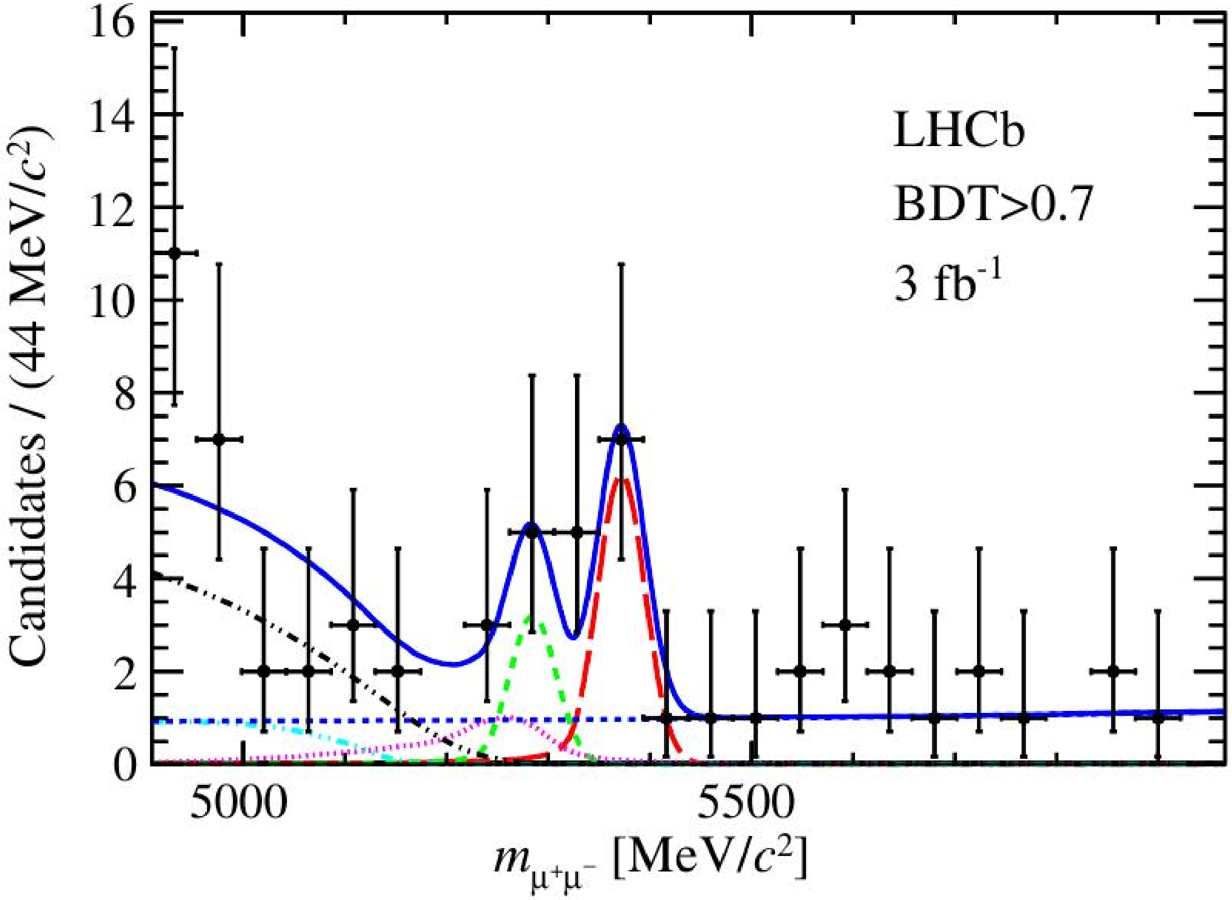
however it is equally possible to effectively suppress the SUSY contribution by

- moving to region of intermediate $\tan\beta$ values
- and/or large masses of the pseudoscalar Higgs boson A

# $B_s \to \mu^+\mu^-$ evidence from the LHCb experiment

from LHCb searches with 1.0 $\mathrm{fb}^{-1}$ at $\sqrt{s} = 7$ TeV and 2 $\mathrm{fb}^{-1}$ at $\sqrt{s} = 8$ TeV

evidence with a statistical significance of 4 $\sigma$



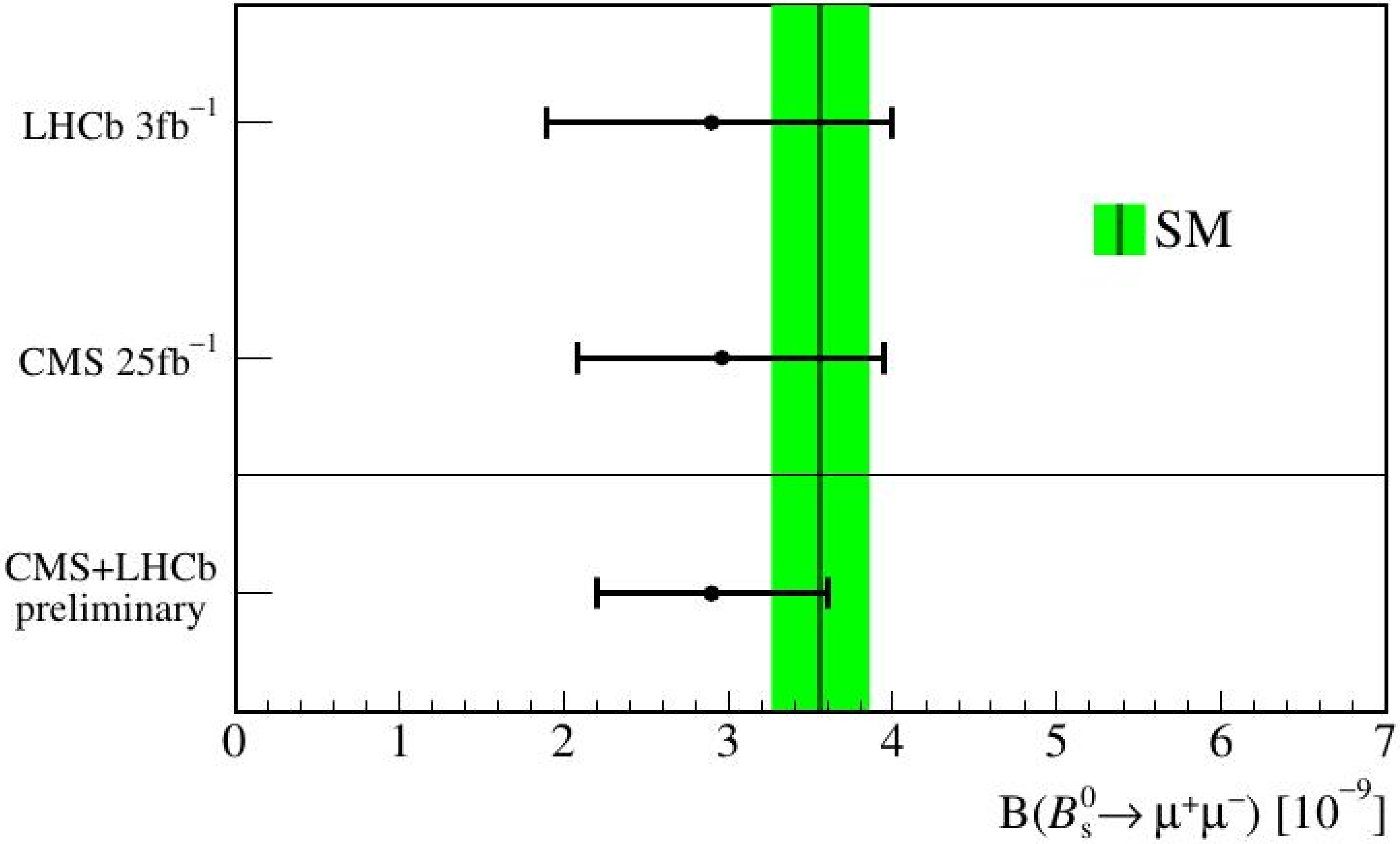
$$\boldsymbol{Br\left(B_s \to \mu^+\mu^-\right)^{\text{time integrated}}_{\text{LHCb}} = \left(2.9^{+1.1}_{-1.0}\right) \times 10^{-9} \in [1.1\ ,\ 6.4] \times 10^{-9}}$$

**in excellent agreement with the SM predictions - still allowing for sizable NP contributions**

# evidence from the CMS and combination with LHCb

from CMS searches with 5.0 $\mathrm{fb}^{-1}$ at $\sqrt{s} = 7$ TeV and 20 $\mathrm{fb}^{-1}$ at $\sqrt{s} = 8$ TeV

evidence with a statistical significance of 4.3 σ



$$Br\left(B_s \to \mu^+\mu^-\right)^{\text{time integrated}}_{\text{CMS}} = \left(3.0^{+1.0}_{-0.9}\right) \times 10^{-9}$$

$$Br\left(B_s \to \mu^+\mu^-\right)^{\text{time integrated}}_{\text{LHCb+CMS}} = \left(2.9 \pm 0.7\right) \times 10^{-9}$$

# $B_s \rightarrow \mu^+ \mu^-$ predictions

- theoretical predictions are CP-averaged quantities in which the effect of $B_s - \bar{B}_s$ oscillations is disregarded (but see arXiv:1303.3820 for time dependent quantities)

- experimental measurement corresponds to an untagged branching fraction which is related to the CP-averaged value by the relation :

$$Br\left(B_s \rightarrow \mu^+ \mu^-\right)_{\text{untag}} = \left(\frac{1 + A_{\Delta\Gamma}\, y_s}{1 - y_s^2}\right) Br\left(B_s \rightarrow \mu^+ \mu^-\right)$$

where :

$$y_s = \frac{1}{2} \tau_{B_s} \Delta\Gamma_s = 0.088 \pm 0.014$$

and :

$$A_{\Delta\Gamma} = \frac{|P|^2 \cos(2\phi_P) - |S|^2 \cos(2\phi_S)}{|P|^2 + |S|^2}$$

# $B_s \to \mu^+\mu^-$ predictions

$S$ and $P$ are related to the Wilson coefficients by :

$$S = \sqrt{1 - 4\frac{m_\mu^2}{M_{B_s}^2}}\,\frac{M_{B_s}^2}{2m_\mu}\,\frac{1}{m_b + m_s}\,\frac{C_S - C'_S}{C_A^{SM}} \qquad\qquad P = \frac{C_A}{C_A^{SM}} + \frac{M_{B_s}^2}{2m_\mu}\,\frac{1}{m_b + m_s}\,\frac{C_P - C'_P}{C_A^{SM}}$$

and :

$$\phi_S = arg(S) \quad , \qquad \phi_P = arg(P)$$

the resulting untagged branching fraction can be directly compared to the experimental measurement

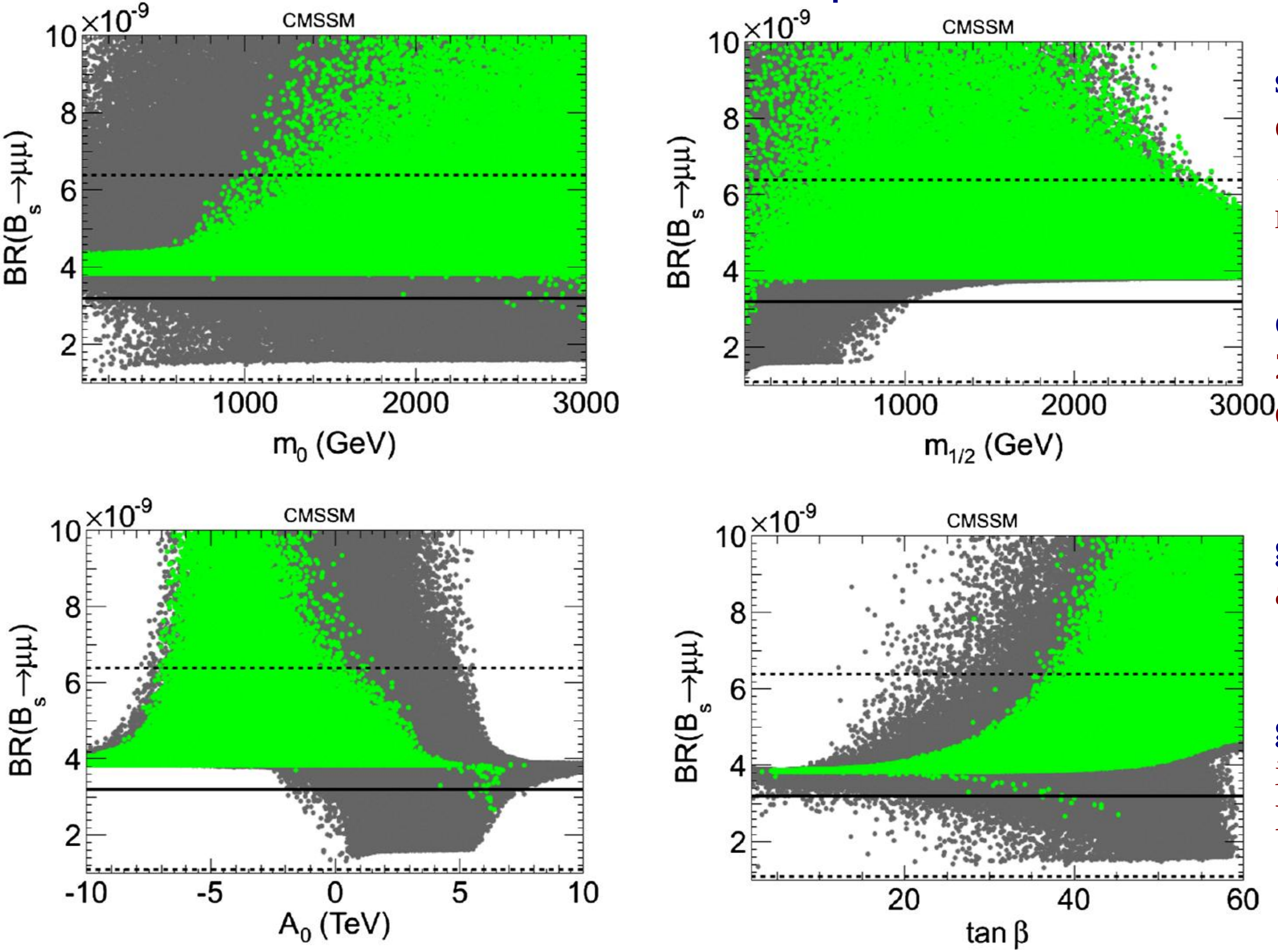
the SM expectation for this corrected branching fraction is:

$$\mathbf{Br\left(B_s \to \mu^+\mu^-\right)_{untag} = (\ 3.87 \pm 0.46\ ) \times 10^{-9}}$$

taken from Arbey, Battaglia, Mahmoudi, Martinez Santos PRD 87 (2013) 035026 (updated value in Buras et al. arXiv:1303.3820)

# constraints on CMSSM from $B_s \to \mu^+ \mu^-$

assume $\mu > 0$



**solid line :**
central value of the $BR(B_s \to \mu^+ \mu^-)$ measurement

**dashed line :**
$2\sigma$ experimental deviation

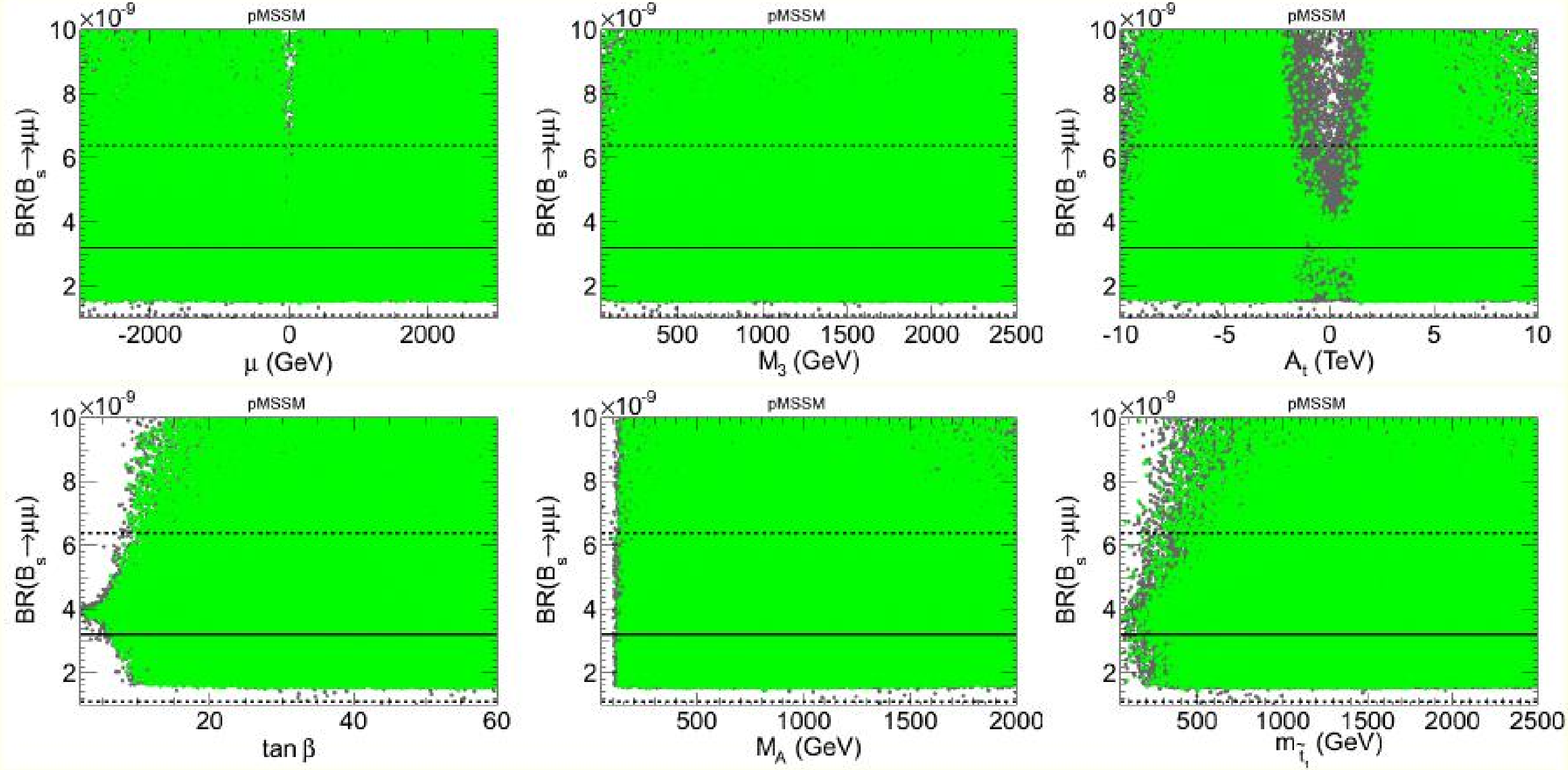
**gray points :**
all valid points

**green points :**
in agreement with the Higgs mass constraints

taken from Arbey, Battaglia, Mahmoudi, Martinez Santos PRD 87 (2013) 035026

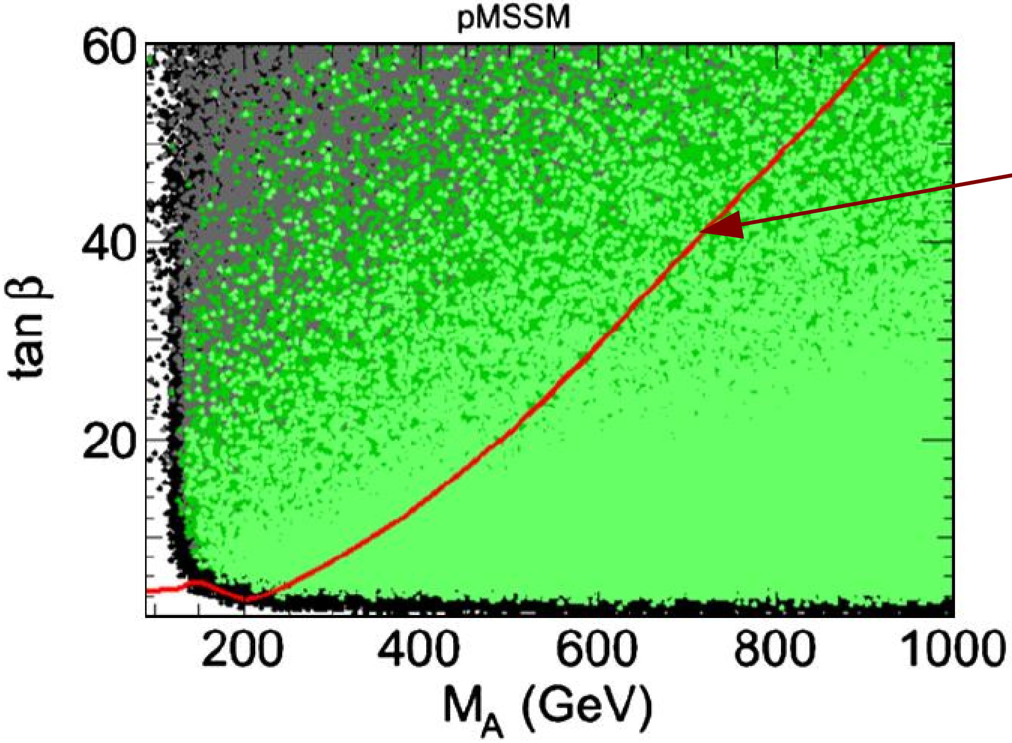
# constraints on pMSSM from $B_s \to \mu^+\mu^-$

same color code as previous slide



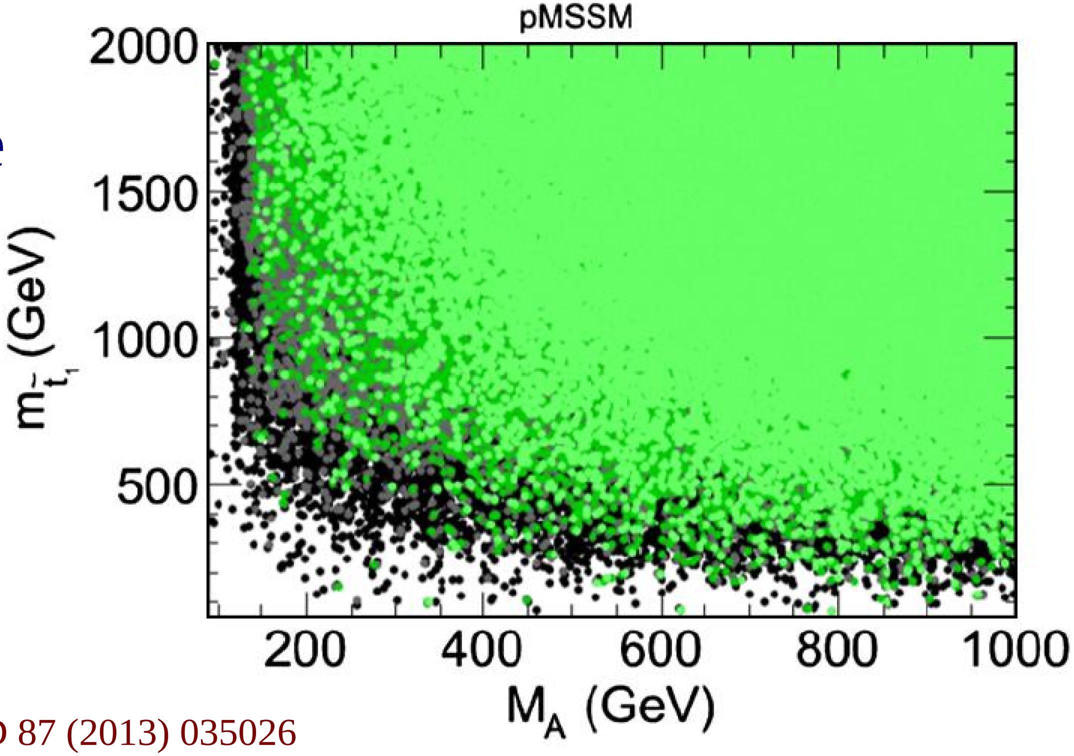
taken from Arbey, Battaglia, Mahmoudi, Martinez Santos PRD 87 (2013) 035026

# constraints on pMSSM from $B_s \rightarrow \mu^+\mu^-$



red line indicated the excluded region from CMS $A/H \rightarrow \tau^+\tau^-$ searches

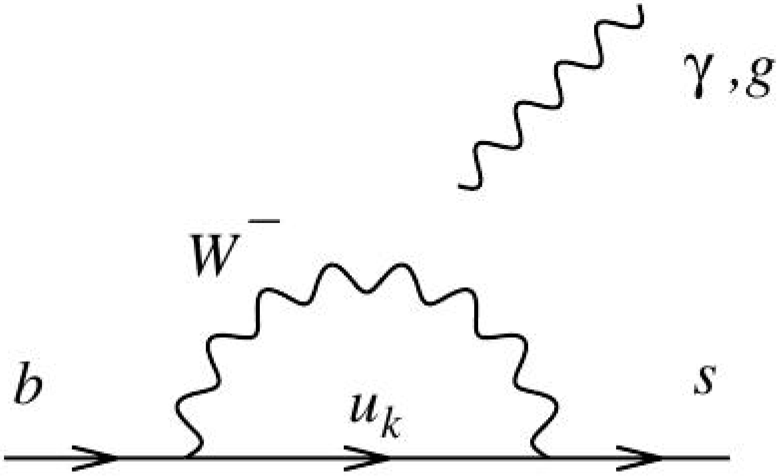
same color code as previous slide

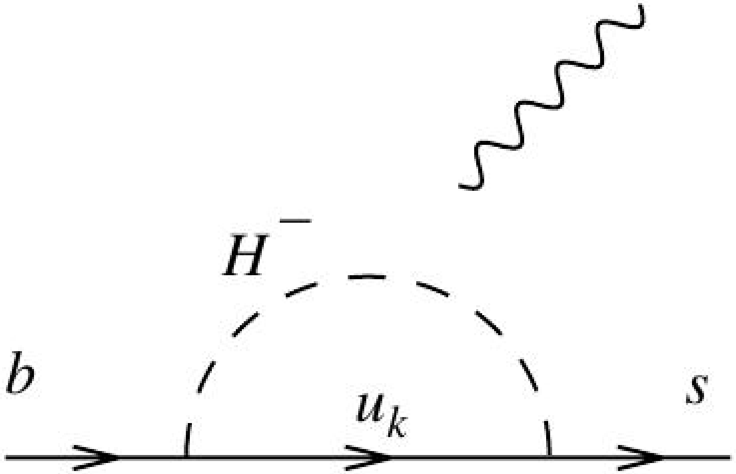


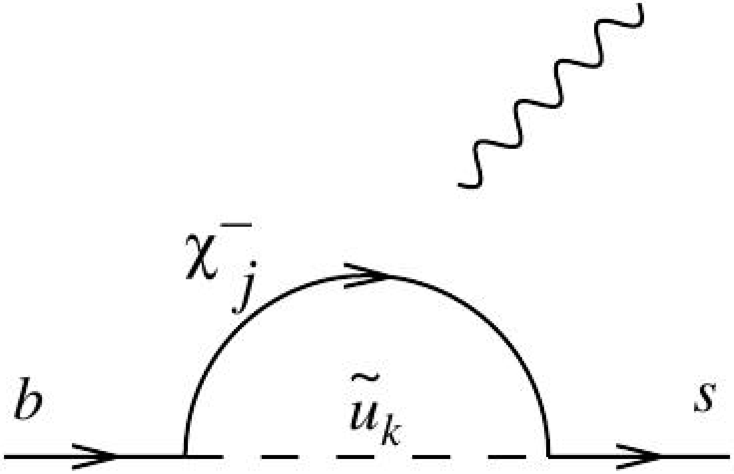
taken from Arbey, Battaglia, Mahmoudi, Martinez Santos PRD 87 (2013) 035026

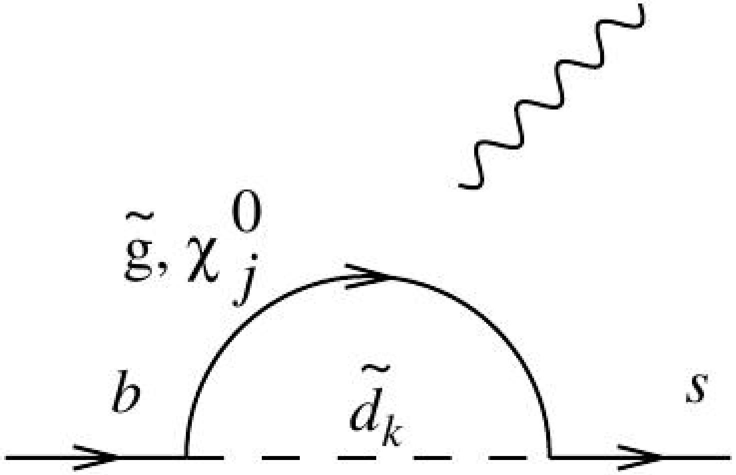
# $B \rightarrow s\ \gamma$

**- this rare B decays occur also at loop level**









the vector line which represents a photon or a gluon is to be attched in all possible way

# $B \to s\ \gamma$

**use also the effective field theory approach**

in the present case with the following relevant operators

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

$$O_8 = \frac{g}{(4\pi)^2}\ m_b\ \left(\ \bar{s}\,\sigma^{\mu\nu}\ T^a\ P_R b\ \right)\ G^a_{\mu\nu}$$

supersymmetry normally prevents any operator of the form $\bar{\Psi}\,\sigma_{\mu\nu}\Psi\ F^{\mu\nu}$

for example in the case susy QED the one loop contribution present in the SM is cancelled by new graphs involving sfermions and gauginos

thus in the supersymmetric limit (unbroken susy) $Br\left[B \to X_s\ \gamma\right]_{\mathrm{SUSY}} = 0$

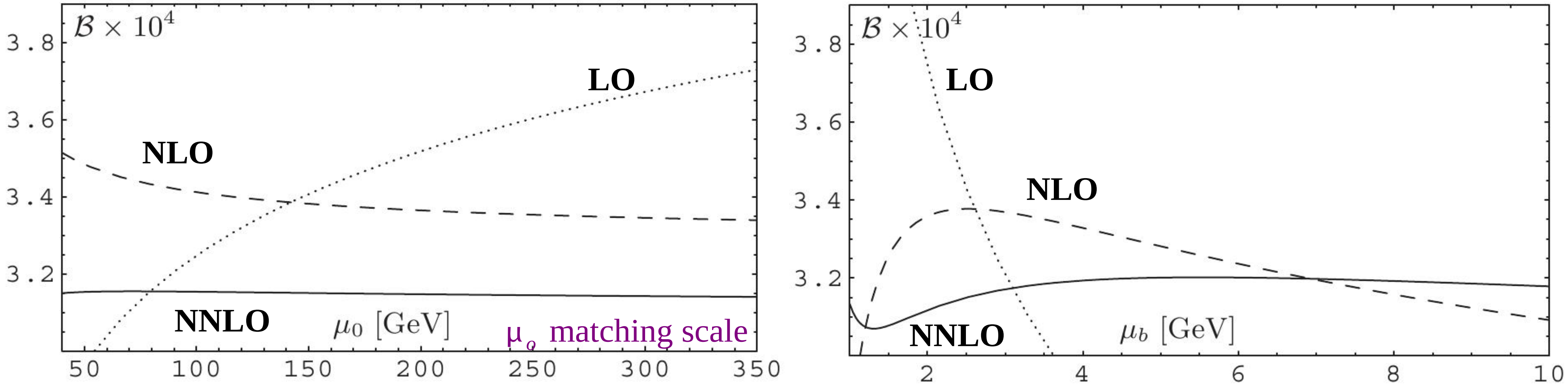
however in the more realistic case of broken supersymmetry this leaves open the possibility of partial (i.e. only and not full) cancellations

# $B \to s\,\gamma$

NNLO calculations have been performed for the SM

Misiak etal. PRL 98 (2007) 022002

helps in reducing scale depence, for example :



$$\text{SM prediction} \;:\quad Br\left(\bar{B} \to X_s \gamma\right) = \left(\, 3.08 \pm 0.23 \,\right) \times 10^{-4}$$

$$\text{experimental value (HFAG 2012)} :\quad Br\left(\bar{B} \to X_s \gamma\right) = \left(\, 3.43 \pm 0.21 \pm 0.07 \,\right) \times 10^{-4}$$

# $B \to s\ \gamma$

susy effects include a significant contribution from charged Higgs exchange :

$$C_{7,8}^{\mathrm{SM}}(M_W) = \frac{1}{\tan^2\beta}\, F_{7,8}^{(1)}\left(\frac{m_t^2(M_W)}{M_H^2}\right) + F_{7,8}^{(2)}\left(\frac{m_t^2(M_W)}{M_H^2}\right)$$

see above (previous slide) for $F_{7,8}^{(1)}$ and we have :

$$F_7^{(2)}(x) = \frac{x\ (3 - 5\mathrm{x})}{12(x-1)^2} + \frac{x\ (3\mathrm{x} - 2)}{6\,(x-1)^3}\ \log x$$

$$F_8^{(2)}(x) = \frac{x\ (3 - x)}{4(x-1)^2} - \frac{x}{2\,(x-1)^2}\ \log x$$

# $B \rightarrow s\ \gamma$

in the susy context, the cancellation observed in the supersymmetric limit (i.e. unbroken susy) leads to expect some amount of cancellation (in the broken susy case) between charged Higgs and susy particle exchange diagram

the heavier the squarks and charginos are → the heavier the charged Higgs must be in order to reproduce the sucesses of the standard model this is one of the reason why the limit on chargino mass is a key experimental result

one also generally assumes **Minimal Flavor Violation**

**i.e the only source of flavor violation at the electroweak scale is the CKM matrix**

**there are two sources that possibly enhance the chargino contribution**

# $B \to s\ \gamma$

## 1) large $\tan\beta$ corrections

the relation between the bottom Yukawa coupling and the bottom mass receives at one loop in this limit a large correction :

$$m_b = -M_W\ \sqrt{2}\ \frac{\lambda_b}{g}\ \cos\beta\ \left(\ 1 + \epsilon_b\ \tan\beta\ \right)$$

where $\epsilon_b$ is obtained from gluino-sbottom and chargino-stop diagrams

such an effect can be taken into account by dividing the expression of $C_{7,8}^{\tilde{\chi}^\pm}$ by $\left(1 + \epsilon_b \tan\beta\right)$

**the leading chargino contribution at two loops is of order $\tan^2\beta$**

# $B \to s \, \gamma$

## 2) large ratio between of susy particles masses $M_{SUSY}$ and EW scale

the higgsinos-stop-bottom supersymmetric coupling $\lambda_{\tilde{t}} \, \bar{b}_L \, \tilde{t}_R \, \tilde{H}^-$
is related to the top quark Yukawa coupling $\lambda_t$ through susy

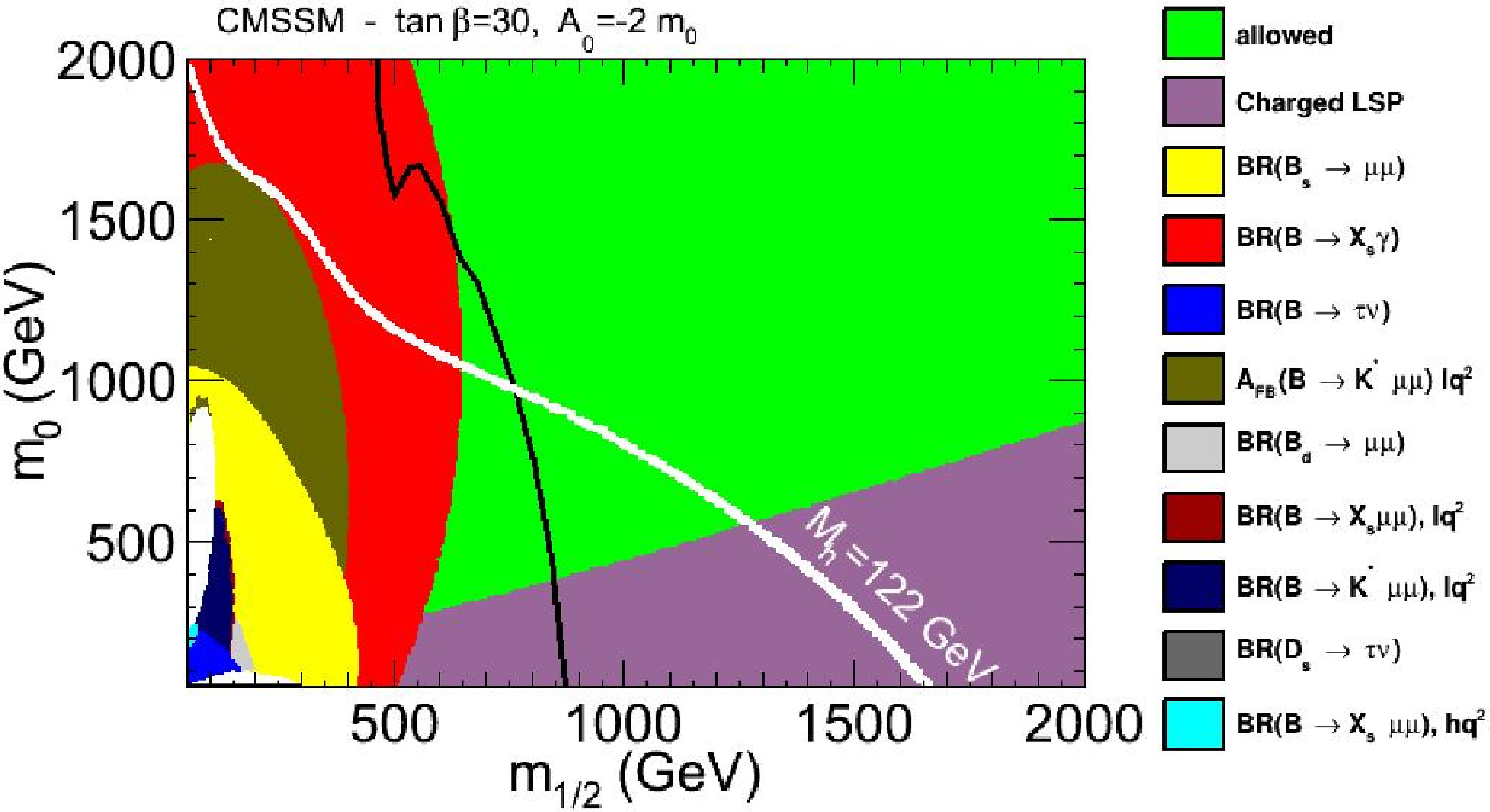
however below the scale $M_{\text{SUSY}}$ this coupling becomes 'frozen'
whereas $\lambda_t$ continues evolving

large log of the ratio $\frac{M_{\text{SUSY}}}{M_W}$ are thus generated when expressing $\lambda_{\tilde{t}}$ in
in term of $\lambda_t$

in practice they can be taken into account by replacing $m_t$
in the chargino contribution by $m_t\left(M_{SUSY}\right)$

similarly the effective operator should be evolved from $M_W$ to $M_{\text{SUSY}}$ but in practice
most of the effect can be taken into account by taking directly the value of $\alpha_3$ at $M_{\text{SUSY}}$

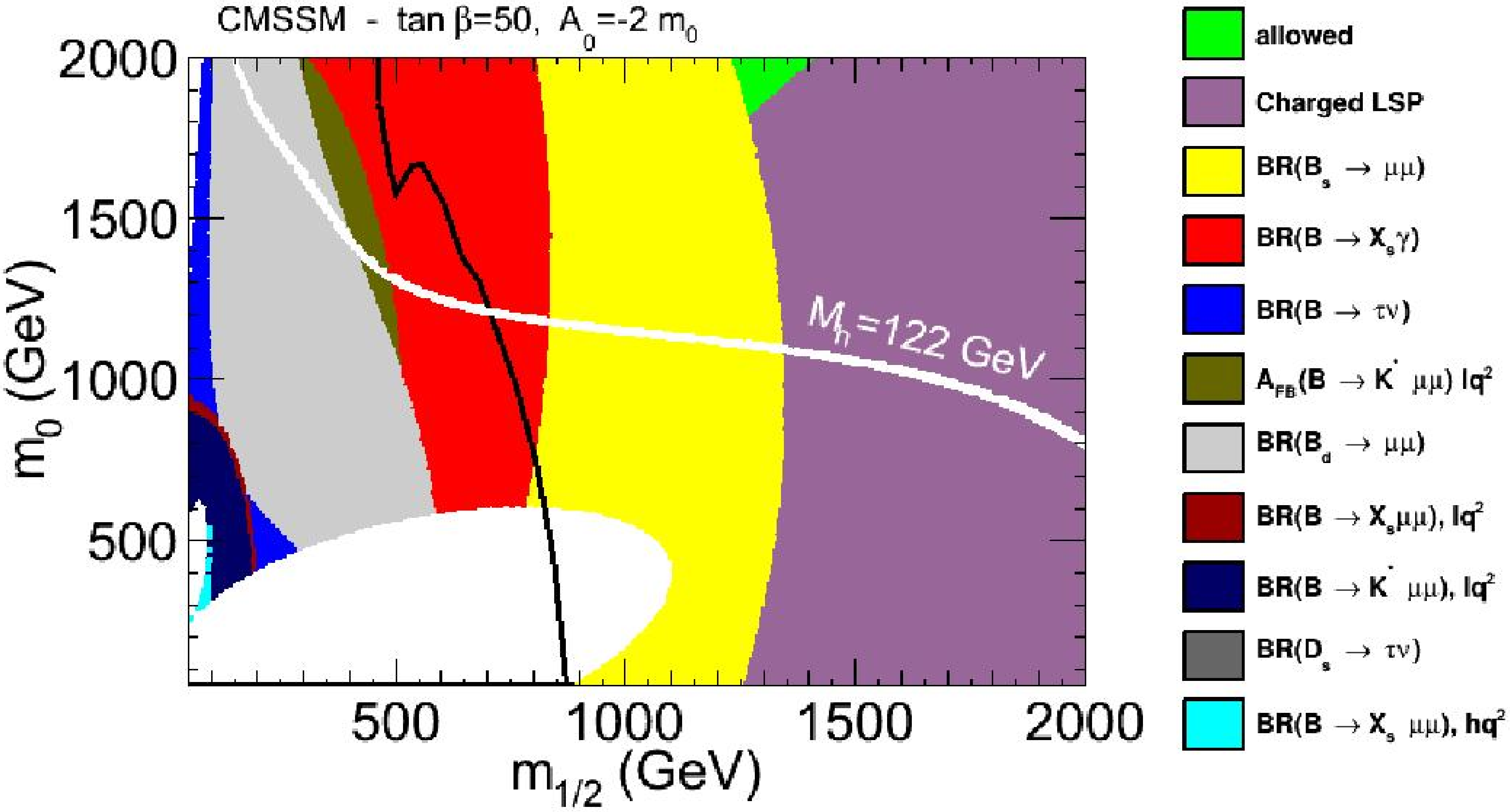
# constraints on CMSSM from rare B decays



black line delimits the ATLAS direct SUSY searches with $20.3\ \mathrm{fb}^{-1}$

Mahmoudi, arXiv:1310.2556

# constraints on CMSSM from rare B decays



black line delimits the ATLAS direct SUSY searches with $20.3\ \mathrm{fb}^{-1}$

Mahmoudi, arXiv:1310.2556

# $\left( g - 2 \right)_\mu$

the muon magnetic moment is related to its spin by the gyromagnetic ratio $g_\mu$ :

$$\vec{\mu}_\mu = g_\mu \left( \frac{q}{2m} \right) \vec{S}$$

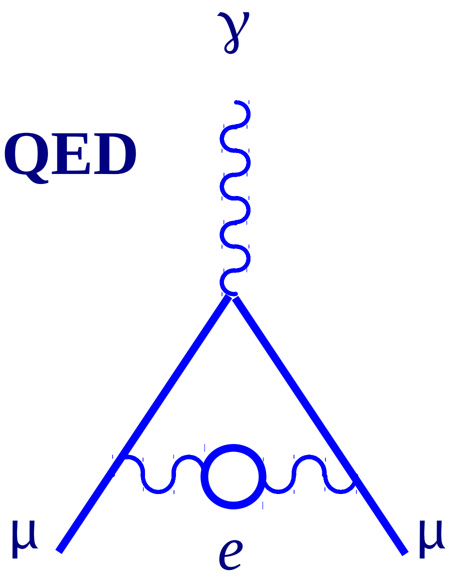
where $g_\mu = 2$ is expected for a structureless spin $\frac{1}{2}$ particle of mass $m$ and charge $q = \pm e$

radiative corrections which couple the muon spin to virtual fields introduce an anomalous magnetic moment defined by :

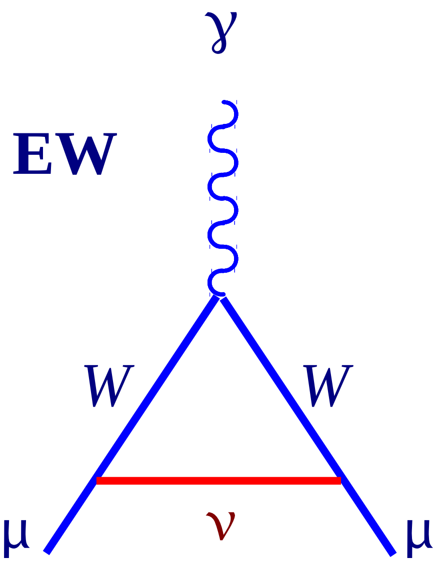
$$a_\mu = \frac{1}{2} \left( g_\mu - 2 \right)$$

# $(g-2)_\mu$

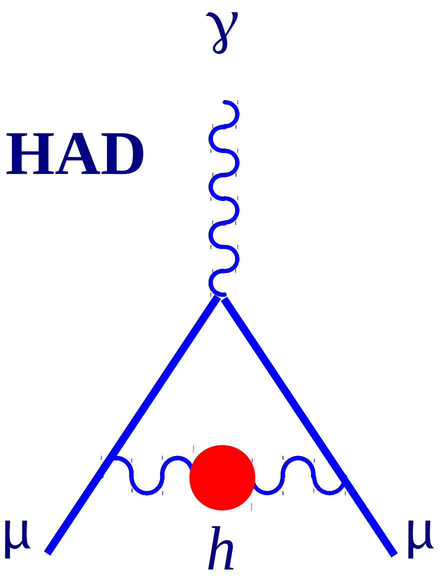
in the standard model → 3 categories of radiative corrections



$a_\mu(QED)$



$a_\mu(EW)$



$a_\mu(HAD)$

$$a_\mu(SM) = a_\mu(QED) + a_\mu(EW) + a_\mu(HAD)$$

# $(\,g-2\,)_\mu$

QED → contributions to $a_\mu(QED)$ known up to 5 loops :

$$a_\mu(QED) = 11658471.958\,(0.002)(0.115\,)(0.085)\times 10^{-10}$$

uncertainties from $\alpha^4$ and $\alpha^5$ terms

uncertainty on α

EW → contributions to $a_\mu(EW)$ known at 1 and 2 loops :

$$a_\mu(EW) = 15.4\,(0.1)(0.2)\times 10^{-10}$$

2-loops hadronic effects in quark
triangle diagrams

from uncertainty on Higgs mass

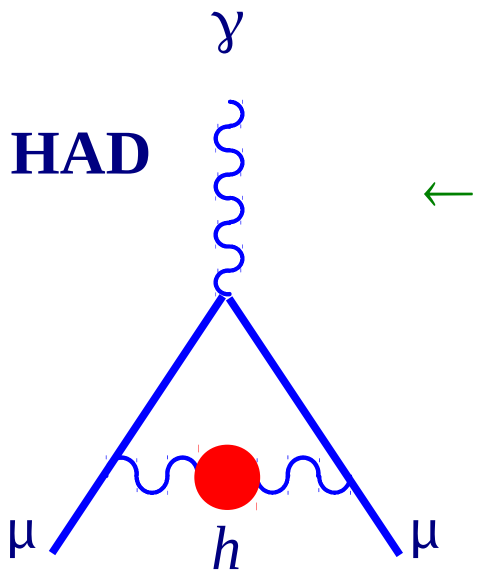
Higgs mass now known → $153.6 \pm 10^{-11}$

(PRD 84 (2013) 053005)

E821 PRD 73 (2006) 072003

# $(\ g - 2\ )_\mu$

HAD → contributions to $a_\mu(HAD)$ source of intense activity

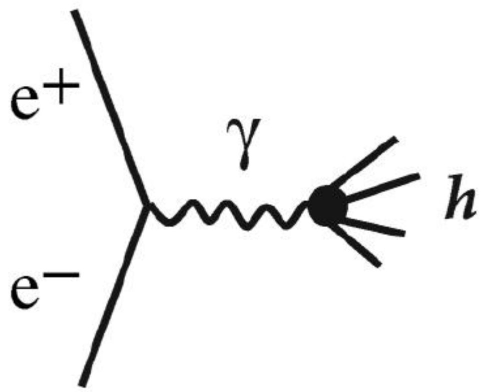


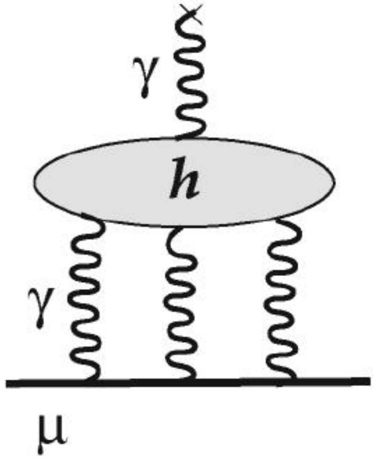
← this lowest order hadronic vacuum polarization loop can be evaluated by using dispersion relation connecting:

the bare cross section for hadrons electroproduction

to

hadronic vacuum polarization contribution to $a_\mu$





E821 PRD 73 (2006) 072003

# $(\, g-2 \,)_{\mu}$

several possible inputs :

- using $e^{+}e^{-} \rightarrow \pi^{+}\pi^{-}$ data

$$a_{\mu}^{(\mathrm{HAD;LO})} = (6963 \pm 62_{\mathrm{exp}} \pm 36_{\mathrm{rad}}) \times 10^{-11}$$

from experimental inputs

from radiative corrections to $e^{+}e^{-}$ data

- using $\tau$ lepton decay

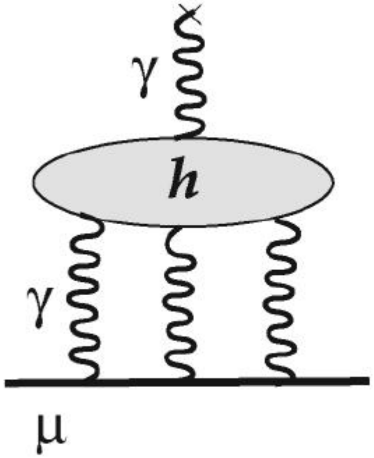
$$a_{\mu}^{(\mathrm{HAD;LO})} = (7170 \pm 50_{\mathrm{exp}} \pm 8_{\mathrm{rad}} \pm 28_{SU(2)}) \times 10^{-11}$$

from isospin corrections when relating $\tau$ to $e^{+}e^{-}$ spectral functions

E821 PRD 73 (2006) 072003

# $(\,g-2\,)_\mu$

effects from hadronic 3-loops  (light by light scattering)



more difficult and controversial to estimate

recommendation of Davier, Marciano
Annu. Rev. Nucl. Part. Sci. 54 (2004) 115
is generally used

$$a_\mu^{(\mathrm{HAD;LBL})} = 120(35) \times 10^{-11}$$

Davier, Marciano, Annu. Rev. Nucl. Part. Sci. 54 (2004) 115

# $\left( \boldsymbol{g-2} \right)_{\mu}$

result from the E821 experiment :

$$a_{\mu}(\mathrm{EXP}) = 11659208.0\,(6.3) \times 10^{-10} \;\; (0.54\ \mathrm{ppm})$$

precision ultimately limited by statistics

the difference :

$$\Delta a_{\mu}(\mathrm{EXP\text{-}SM}) = \left[ \left( 22.4 \pm 10 \right) \;\text{ to }\; \left( 26.1 \pm 9.4 \right) \right] \times 10^{-10}$$

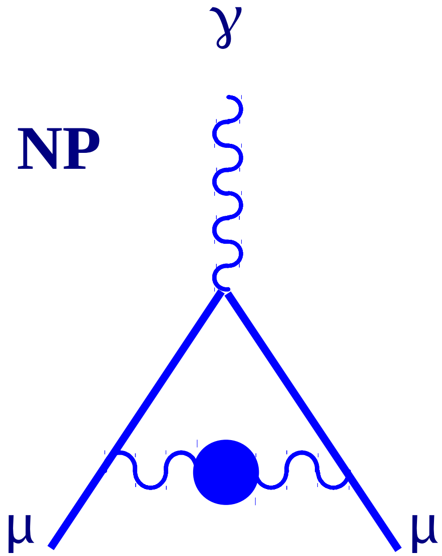
has a significance of 2.2 - 2.7 standard deviations

the use of $\tau$ data gives a smaller discrepancy

E821 PRD 73 (2006) 072003

# $(g-2)_\mu$

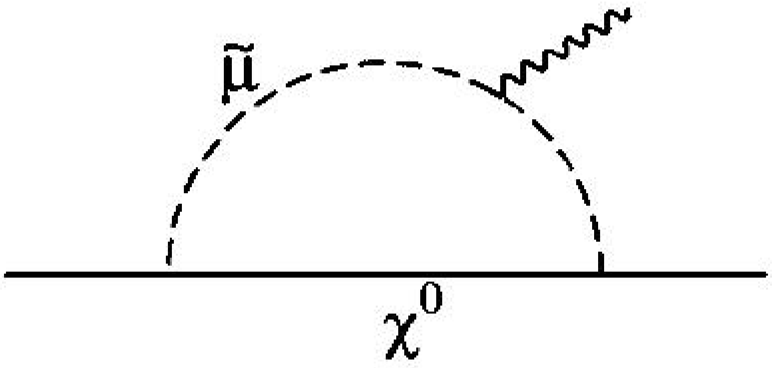
contributions from new physics (NP) may appear from loop corrections



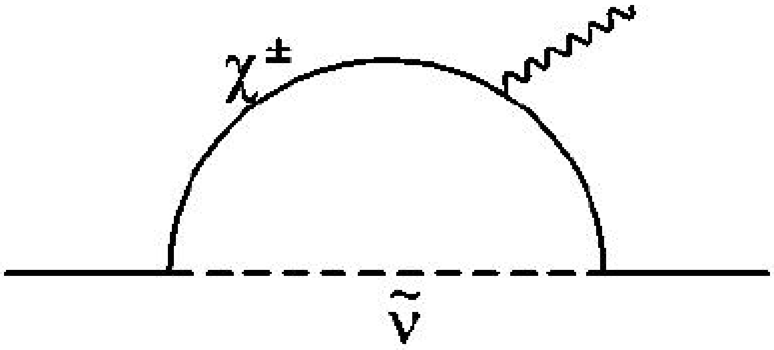
# $(\ g-2\ )_\mu$

in MSSM contributions from :

smuon-neutralino loop $:\Delta\, a_\mu^{\tilde{\chi}^o\,\tilde{\mu}}$



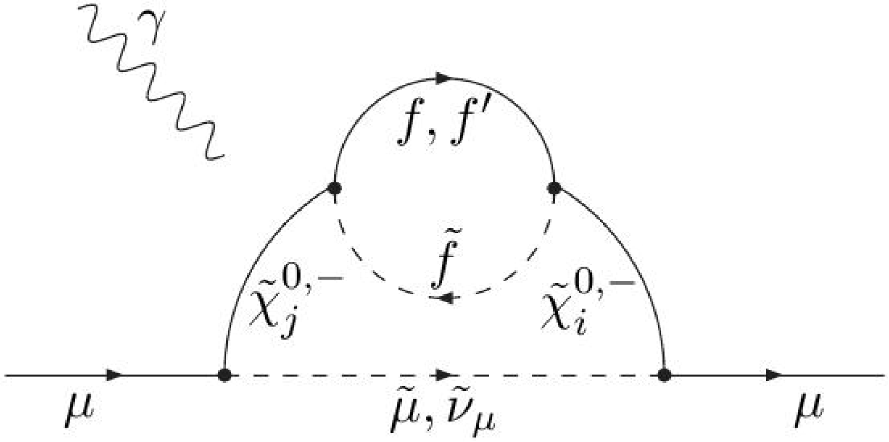
charginos-sneutrino loop $:\Delta\, a_\mu^{\tilde{\chi}^\pm\,\tilde{\nu}}$



Moroi. PRD 53 (1996) 6565

recent calculations made at two loops with fermion/sfermion loop insertion

arXiv:1309.0980



# $\left( \, g - 2 \, \right)_\mu$

Moroi. PRD 53 (1996) 6565

$\Delta a_\mu^{\text{MSSM}}$ is proportional to $\tan\beta$

→ $\left|\Delta a_\mu^{\text{MSSM}}\right|$ becomes larger as $\tan\beta$ increases

sign of $\Delta a_\mu^{\text{MSSM}}$ depends on MSSM parameters

→ dominant contribution proportional to $m_{\text{gaugino}}\ \mu\ \tan\beta$

→ $\Delta a_\mu^{\text{MSSM}}$ becomes positive (negative)

when $m_{\text{gaugino}}\ \mu\ \tan\beta$ is positive (negative)

# $\left(\, g - 2 \,\right)_\mu$

Moroi. PRD 53 (1996) 6565

in the limit where $m_{\text{gauginos}} = \mu = m_{\tilde\mu_L} = m_{\tilde\mu_L} = m_{\tilde\nu} = m_{\text{SUSY}}$

$$\Delta a_\mu^{\tilde\chi^o \tilde\mu} = \frac{1}{192\pi^2} \frac{m_\mu^2}{m_{SUSY}^2} \left( g_1^2 - g_2^2 \right) \tan\beta$$

$$\Delta a_\mu^{\tilde\chi^\pm \tilde\nu} = \frac{1}{32\pi^2} \frac{m_\mu^2}{m_{SUSY}^2} g_2^2 \tan\beta$$

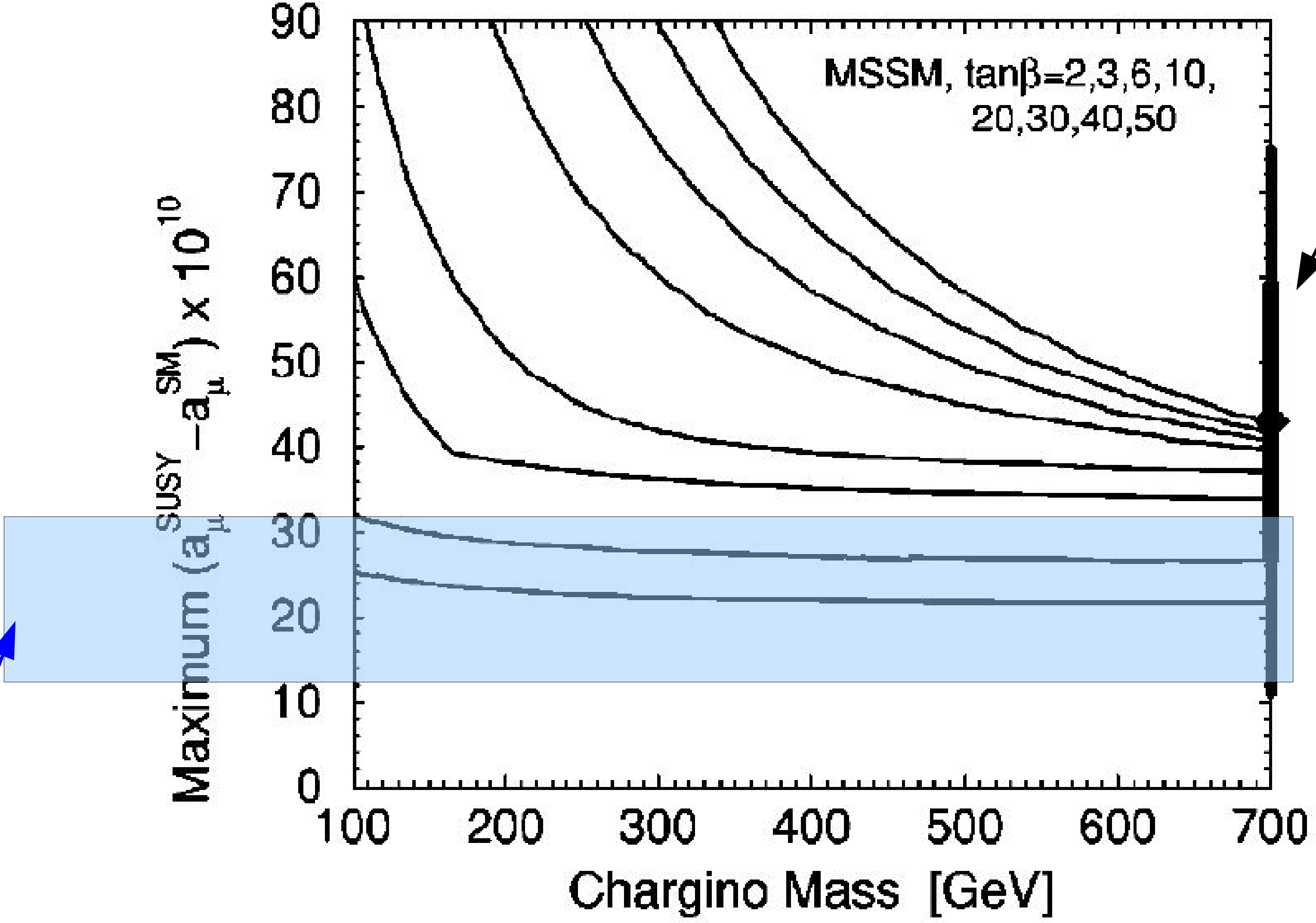
contribution of the $\tilde\chi^\pm \tilde\nu$ loop is substantially larger than that of the $\tilde\chi^o \tilde\mu$ loop

however this dominance does not in general

in some region of the parameter space $m_{\tilde\mu_R}$ plays a significant role

# $(g-2)_\mu$

old $\Delta a_\mu$(EXP-SM) E821 measurement

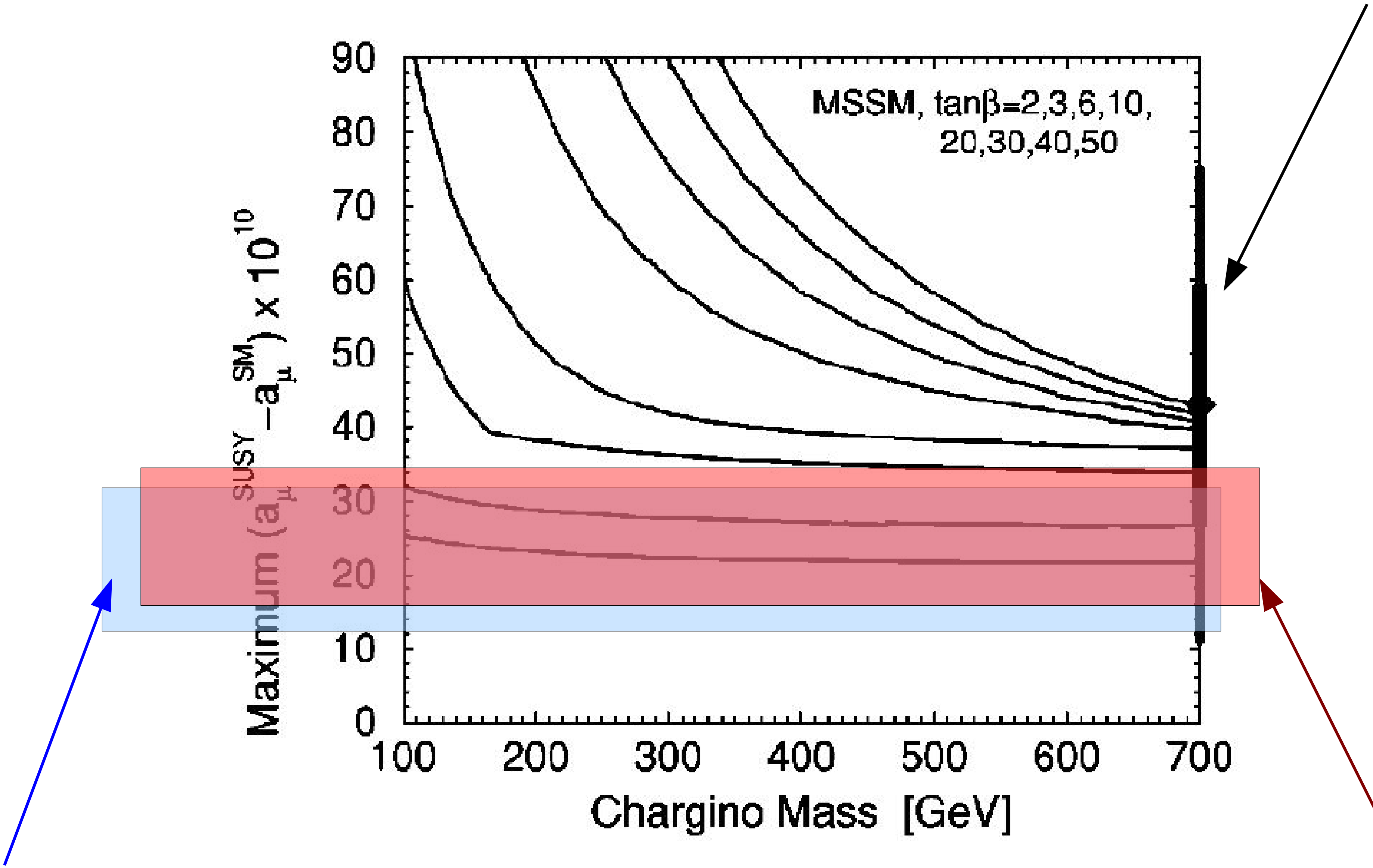


Martin, Wells. PRD 64 (2001) 035003

$\Delta a_\mu(\text{EXP-SM}) = (22.4 \pm 10) \times 10^{-10}$

# $\left( g - 2 \right)_{\mu}$

old $\Delta a_{\mu}$(EXP-SM) E821 measurement



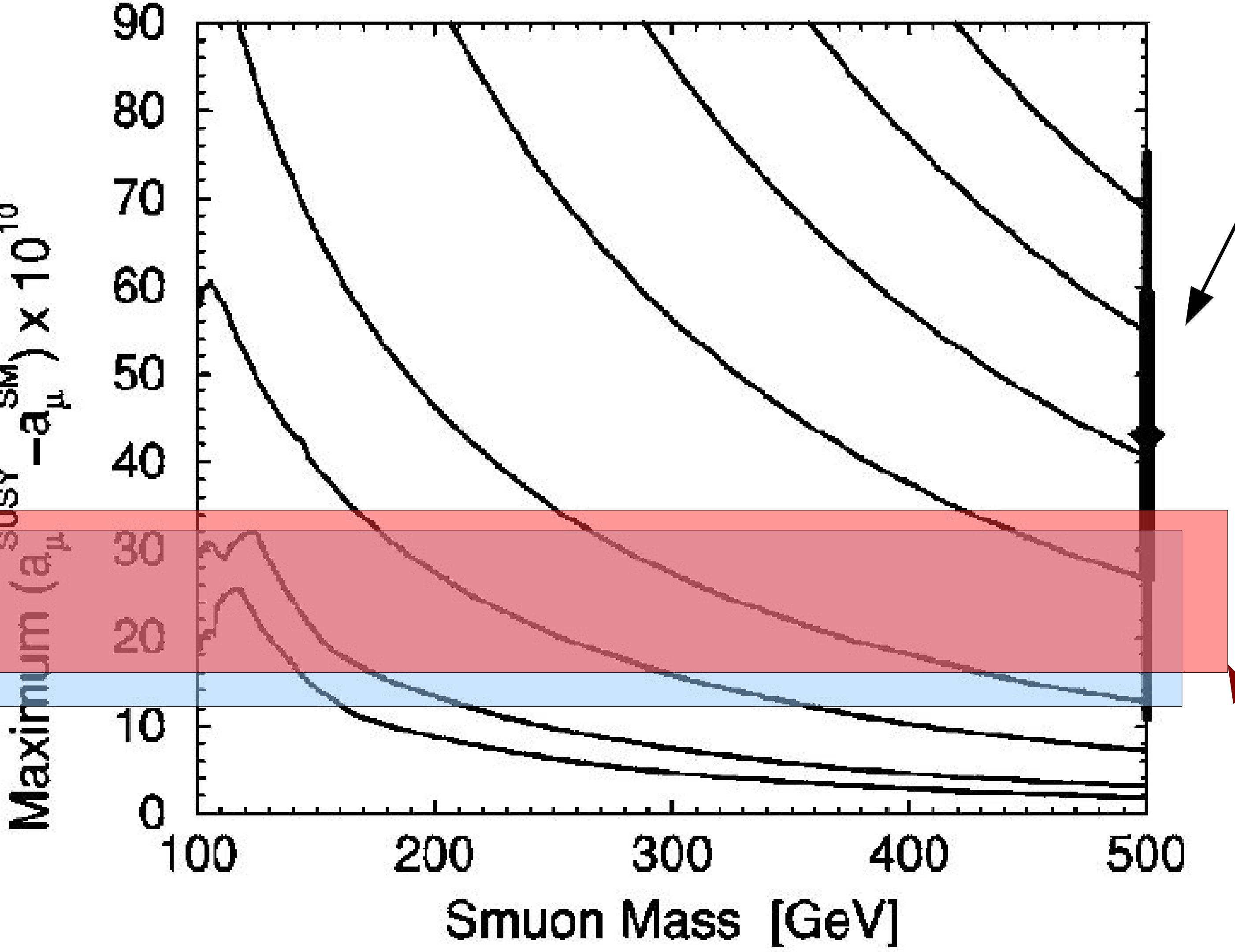
Martin, Wells. PRD 64 (2001) 035003

$\Delta a_{\mu}(\text{EXP-SM}) = \left( 22.4 \pm 10 \right) \times 10^{-10}$

$\Delta a_{\mu}(\text{EXP-SM}) = \left( 26.1 \pm 9.4 \right) \times 10^{-10}$

# $(g-2)_\mu$

old $\Delta a_\mu$(EXP-SM) E821 measurement



Martin, Wells. PRD 64 (2001) 035003

$\Delta a_\mu(\text{EXP-SM}) = (22.4 \pm 10) \times 10^{-10}$

$\Delta a_\mu(\text{EXP-SM}) = (26.1 \pm 9.4) \times 10^{-10}$

# BACKUP

# Minimal SUSY extension of the SM – Higgs sector

Remember (lecture 1) : minimal supersymmetric extension of the standard model needs two Higgs doublets of opposite hypercharge

$$H_d = \begin{pmatrix} H_d^o \\ H_d^- \end{pmatrix} \quad \text{with} \quad Y_{H_d} = -1 \qquad\qquad H_u = \begin{pmatrix} H_u^+ \\ H_u^o \end{pmatrix} \quad \text{with} \quad Y_{H_u} = +1$$

one can show that the potential of the neutral scalars reads

$$V_H = m_1^2 \left|H_d^o\right|^2 + m_2^2 \left|H_u^o\right|^2 + m_3^2 \left(H_d^o H_u^o + h.c.\right) + \frac{g_2^2 + g_1^2}{8} \left( \left|H_d^o\right|^2 - \left|H_u^o\right|^2 \right)^2$$

with $m_1^2 = |\mu|^2 + m_{H_d}^2$ , $m_2^2 = |\mu|^2 + m_{H_u}^2$ , $m_3^2 = B|\mu|^2$

we require that the minimum of the potential breaks the electroweak symmetry $SU(2)_L \times U(1)_Y$ while preserving the electromagnetic symmetry $U(1)_Q$

# Minimal SUSY extension of the SM – Higgs sector

(1) potential should be stable i.e. bounded from below $\Rightarrow$ $m_1^2 + m_2^2 > 2\,|m_3^2|$

(2) for electroweak symmetry breaking one needs a combination of $H_d^o,\ H_u^o$ to have negative squared mass term $\Rightarrow$ $m_3^2 > m_1^2 m_2^2$

if not $<0|H_u^o|0> = <0|H_d^o|0>$ will be a stable minimum and there will be no electroweak symmetry breaking

(3) to have electroweak symmetry breaking and thus have negative squared mass term the potential at the minimum should have a saddle point $\Rightarrow$

$$Det\left(\frac{\partial^2 V_H}{\partial H_i^o \partial H_j^o}\right) < 0 \Rightarrow m_1^2 + m_2^2 < m_3^4$$

# Minimal SUSY extension of the SM – Higgs sector

conditions (2) and (3) are not satisfied if $m_1^2 = m_2^2$ , we then have

$$\bar{m}_1^2 \neq \bar{m}_2^2 \;\Rightarrow\; m_{H_d}^2 \neq m_{H_u}^2$$

thus we must have non vanishing soft SUSY-breaking scalar masse $m_{H_u}$, $m_{H_d}$

**therefore to break electroweak symmetry we need also to break SUSY**

in models such as mSUGRA the soft SUSY breaking scalar Higgs mass are equal at high energy scales (and their square positive)

the RGE running to the lower electroweak energy scale allow to lift this degeneracy

in the RGE running one obtains $m_{H_u}^2 < 0$ or $m_{H_u}^2 << m_{H_d}^2$ which triggers electroweak electroweak symmetry breaking $\Rightarrow$ **radiative breaking of the electroweak symmetry**

# Minimal SUSY extension of the SM – Higgs sector

to obtain the *Higgs physical* fields and their *tree level masses* one develops the 2 complex Higgs doublets around the vacuum into :

- a real (CP-even Higgs bosons) part
- an imaginary (CP-odd Higgs and Goldstone boson) part

and then diagonalizes the mass matrices evaluated at the vacuum

$$M_{ij}^2 = \frac{1}{2} \frac{\partial^2 V_H}{\partial H_i \partial H_j} \Bigg|_{<H_d^o> = v_1/\sqrt{2} \; , \; <H_u^o> = v_2/\sqrt{2} \; , \; <H^\pm> = 0}$$

thus after EWSB one obtains 5 physical particles in the Higgs sector

- 2 CP-even neutral Higgs bosons : $h$ , $H$
- 1 CP-odd neutral Higgs boson : A
- 2 charged Higgs bosons : $H^\pm$

# Minimal SUSY extension of the SM – Higgs sector

a strong hierarchy is thus imposed on the mass spectrum at tree level

$$M_H > max\left(M_A, M_Z\right)$$

$$M_h < min\left(M_A, M_Z\right) \cdot |\cos|2\beta \leqslant M_Z$$

⇒ **at tree level the lighter CP-even Higgs boson should be lighter than the Z boson**

since the h boson is light (and has almost SM like coupling when the A boson is heavy)
is should have been observed at the LEP experiments ...... which was not the case !

**radiative corrections push its mass upward beyond the tree level bound** $M_Z$

**radiative corrections can be large since involving couplings to top quark and stop**

# Minimal SUSY extension of the SM – Higgs sector

the CP-even Higgs bosons are obtained from the rotation

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H_d^o \\ H_u^o \end{pmatrix}$$

where the mixing angle $\alpha$ is given by

$$\cos 2\alpha = -\cos 2\beta \frac{M_A^2 - M_Z^2}{M_H^2 - M_h^2}$$

and one obtains the masses (at tree level)

$$\boxed{M_{h,H}^2 = \frac{1}{2}\left[ M_A^2 + M_Z^2 \mp \sqrt{\left(M_A^2 + M_Z^2\right)^2 - 4 M_A^2 M_Z^2 \cos^2 2\beta} \right]}$$

where out of the 6 parameters $M_h, M_H, M_A, M_{H^\pm}, \beta, \alpha$ which decribes the Higgs sector 2 parameters i.e. $\boldsymbol{M_A}$, **tan** $\beta$ can be taken as free independent parameters

the (tree level) mass of the charged Higgs boson is given by

$$\boxed{M_{H^\pm}^2 = M_A^2 + M_W^2}$$

# Minimal SUSY extension of the SM – Higgs sector

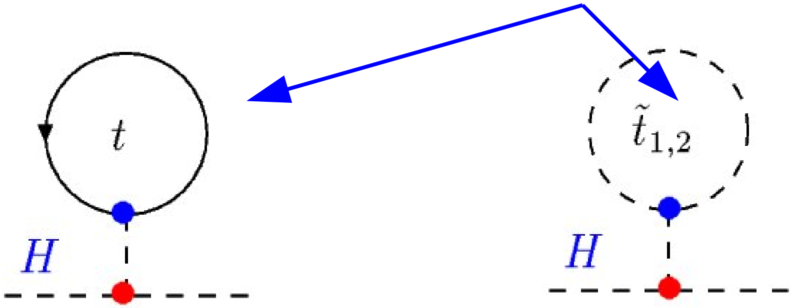
- **for example in the limit** $M_A \gg M_Z \quad \tan\beta \gg 1$ **and assuming :**

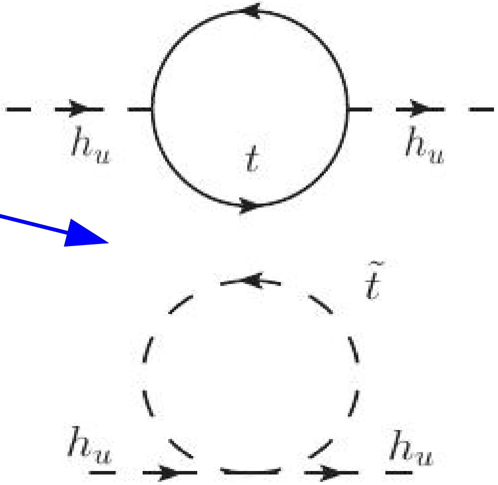
$$m_{\tilde{t}_1} = m_{\tilde{t}_2} = m_{\tilde{t}} \equiv M_S \quad \text{(in general} \quad \boldsymbol{M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}} \;)$$

$$X_t = A_t - \mu \cot\beta \quad \text{(one may assume } X_t \ll M_S \text{ i.e. no stop mixing)}$$

$$M_h \ll m_t,\; m_{\tilde{t}}$$

- dominant contributions from top and stop loop diagrams including so called tadpole diagrams





$$M_h^2 \simeq M_Z^2 \cos^2 2\beta \left[ 1 - \frac{M_Z^2}{M_A^2} \sin^2 2\beta \right] + \frac{3 m_t^4}{2\pi^2 v^2} \left[ \log \frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2} \left( 1 - \frac{X_t^2}{12 M_S^2} \right) \right]$$

correction grows quartically with the top quark mass and logarithmically with the stop masses

correction is very large and increases the **h boson** mass by several tens of GeV i.e. up to about 140 GeV

# Minimal SUSY extension of the SM – Higgs sector

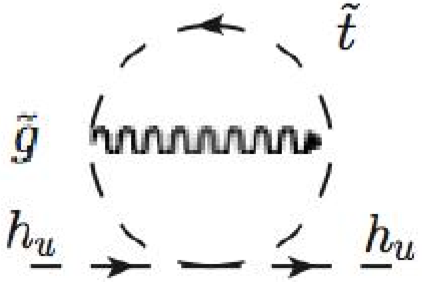
large stop mixing $X_t = A_t - \mu \cot \beta$ can also play a role in raising the light Higgs mass

$$d \frac{A_t}{d \log Q} = \frac{18}{16} \frac{1}{\pi^2} \lambda_t^2 A_t + \frac{32}{3} \frac{\alpha_2}{4\pi} M_3$$

$$\begin{aligned} A_t(M_Z) &\simeq -2.3\ M_3 + 0.2\ A_t \\ m_{\tilde{t}}^2(M_Z) &\simeq \ \ 5.0\ M_3^2 + 0.6\ m_{\tilde{t}}^2 \end{aligned} \qquad \text{for} \quad \tan\beta = 10$$

very large $A_t$ term is needed at GUT scale to make $X_t$ large (>1)

2 loops radiative correction involve stop and gluinos



# Minimal SUSY extension of the SM – Higgs sector

another way to put the CP_even Higgs boson mass matrix in the $\left(H_d, H_u\right)$ basis

introducing the radiative corrections by a $2\times 2$ matrix $\Delta M_{ij}^2$

$$M_S^2 = M_Z^2 \begin{pmatrix} c_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & s_\beta^2 \end{pmatrix} + M_A^2 \begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} + \begin{pmatrix} \Delta M_{11}^2 & \Delta M_{12}^2 \\ \Delta M_{12}^2 & \Delta M_{22}^2 \end{pmatrix}$$

$$M_{h,H}^2 = \frac{1}{2}\left[\; M_A^2 + M_Z^2 + \Delta M_{11}^2 + \Delta M_{22}^2 \mp \sqrt{M_A^4 + M_Z^4 - 2 M_A^2 M_Z^2 \cos_{4\beta} + C}\;\right]$$

$$\tan\alpha = \frac{2\Delta M_{12}^2 - \left(M_A^2 + M_Z^2\right) s_\beta}{\Delta M_{11}^2 - \Delta M_{22}^2 + \left(M_Z^2 - M_A^2\right) c_{2\beta} + \sqrt{M_A^4 + M_Z^4 - 2 M_A^2 M_Z^2 c_{4\beta} + C}}$$

$$C = 4\Delta M_{12}^4 + \left(\Delta M_{11}^2 - \Delta M_{22}^2\right)^2 - 2\left(M_A^2 - M_Z^2\right)\left(\Delta M_{11}^2 - \Delta M_{22}^2\right) c_{2\beta} - 4\left(M^A + M_Z^2\right)\Delta M_{12}^2 s_{2\beta}$$

# Minimal SUSY extension of the SM – Higgs sector

$\Delta M^2_{22}$ involves the dominant stop top corrections

$\Delta M^2_{22} \gg \Delta M^2_{11} \Delta M^2_{12}$

one can trade $\Delta M^2_{22}$ for $M_h$ , which is 'known' by now (i.e. assuming that the discovered Higgs boson can be identified with h) , using :

$$\Delta M^2_{22} = \frac{M^2_H \left(M^2_A + M^2_Z - M^2_h\right) - M^2_A M^2_Z c^2_{2\beta}}{M^2_Z c^2_\beta + M^2_A s^2_\beta - M^2_h}$$

one can then write $M_H$ and $\alpha$ in terms of $M_A$, $\tan\beta$ and $M_h$ :

$$M^2_H = \frac{\left(M^2_A + M^2_Z - M^2_h\right)\left(M^2_Z c^2_\beta + M^2_A s^2_\beta\right) - M^2_A M^2_Z c^2_{2\beta}}{M^2_Z c^2_\beta + M^2_A s^2_\beta - M^2_h}$$

$$\alpha = -\arctan\left(\frac{\left(M^2_A + M^2_Z\right) c_\beta s_\beta}{M^2_Z c^2_\beta + M^2_A s^2_\beta - M^2_h}\right)$$

# Minimal SUSY extension of the SM – Higgs sector

$\Delta M_{22}^2$ involves the dominant stop top corrections

$\Delta M_{22}^2 \gg \Delta M_{11}^2 \Delta M_{12}^2$

one can trade $\Delta M_{22}^2$ for $M_h$ , which is 'known' by now (i.e. assuming that the discovered Higgs boson can be identified with h) , using :

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# Minimal SUSY extension of the SM – Higgs sector

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# Minimal SUSY extension of the SM – Higgs sector

including subleading contributions proportional to $\mu\, A_{t,b}$

$$\Delta M_{11}^2 = -\frac{v^2 s_\beta^2}{32\pi^2}\, \bar{\mu}^2 \left[x_t^2 \lambda_t^4 \left(1 + c_{11}\, l_S\right) + a_b^2 \lambda_b^4 \left(1 + c_{12}\, l_S\right)\right]$$

$$\Delta M_{12}^2 = -\frac{v^2 s_\beta^2}{32\pi^2}\, \bar{\mu} \left[x_t \lambda_t^4 \left(6 - x_t\, a_t\right)\left(1 + c_{31}\, l_S\right) - \bar{\mu}^2 a_b \lambda_b^4 \left(1 + c_{32}\, l_S\right)\right]$$

$$\Delta M_{22}^2 = \frac{v^2 s_\beta^2}{32\,\pi^2} \left[6\,\lambda_t^4\, l_S \left(2 + c_{21}\, l_S\right) + x_t\, a_t \lambda_t^4 \left(12 - x_t\, a_t\right)\left(1 + c_{21}\, l_S\right) \bar{\mu}^4 \lambda_b^4 \left(1 + c_{22}\, l_S\right)\right]$$

with $l_S = \log\left(M_S^2 / m_t^2\right)$, $\bar{\mu} = \mu / M_S$, $a_{t,b} = A_{t,b} / M_S$ and $x_t = X_t / M_S$

the factors $c_{ij}$ take into account the leading 2-loop corrections due to the top and bottom Yukawa couplings and to the strong coupling constant $g_3$

$$c_{ij} = \frac{1}{32\,\pi^2} \left(t_{ij} \lambda_t^2 + b_{ij} \lambda_b^2 - 32\, g_3^2\right)$$

$$\left(t_{11}, t_{12}, t_{21}, t_{22}, t_{31}, t_{32}\right) = \left(12, -4, 6, -10, 9, 7\right)$$

$$\left(b_{11}, b_{12}, b_{21}, b_{22}, b_{31}, b_{32}\right) = \left(-4, 12, 2, 18, -1, 15\right)$$

# Minimal SUSY extension of the SM – Higgs sector

**parameters are renormalized → fine tuning to get the right *Z* boson mass**

$$\frac{M_Z^2}{2} = \frac{m_{H_u}^2 \sin^2\beta - m_{H_d}^2 \cos^2\beta}{\cos 2\beta} - \mu^2$$
$$= \frac{1}{\tan^2\beta - 1} \boxed{m_{H_d}^2} - \frac{\tan^2\beta}{\tan^2\beta - 1} \boxed{m_{H_u}^2} - \boxed{\mu^2}$$

neglecting terms proportional to $g_1^2,\ g_2^2,\ \lambda_b^2$ and $\lambda_\tau^2$, $m_{H_d}^2$ is not renormalized :

whereas we have $\frac{1}{\mu}\frac{d\mu}{dQ} = \frac{3\lambda_t^2}{16\pi^2}$ and $\frac{d\,m_{H_u}^2}{dQ} = \frac{3\lambda_t^2}{8\pi^2} X_t$ with $X_t = A_t - \mu\cot\beta$

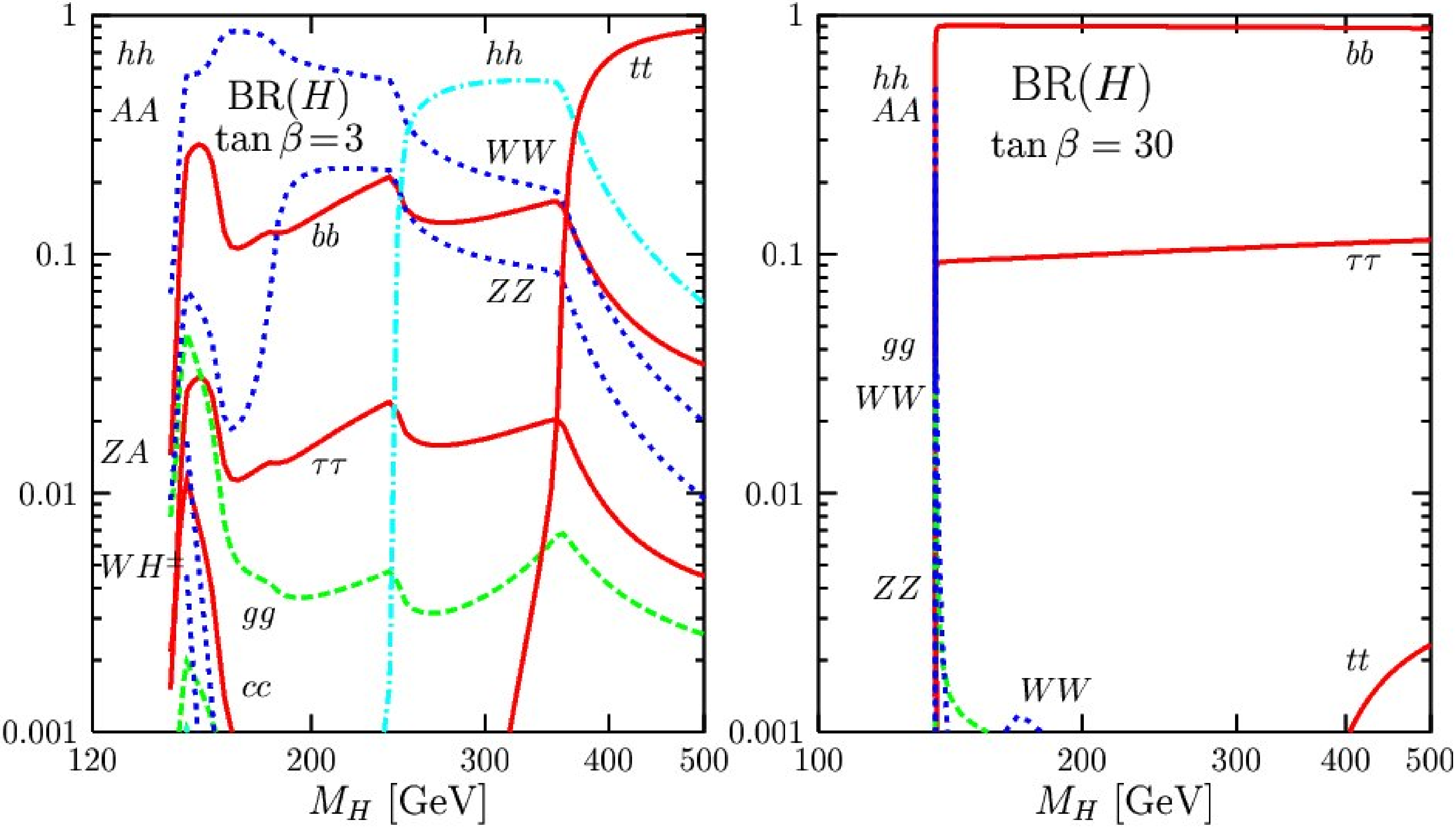
and $8\pi^2 \begin{pmatrix} X_t \\ X_b \end{pmatrix} = \begin{pmatrix} 6\lambda_t^2 & \lambda_b^2 \\ \lambda_t^2 & 6\lambda_b^2 \end{pmatrix} \left[ \begin{pmatrix} X_t \\ X_b \end{pmatrix} + \begin{pmatrix} A_t^2 \\ A_b^2 \end{pmatrix} \right] - \frac{32}{3} \begin{pmatrix} 1 \\ 1 \end{pmatrix} g_3^2 \boxed{M_3^2}$

**gluino mass**

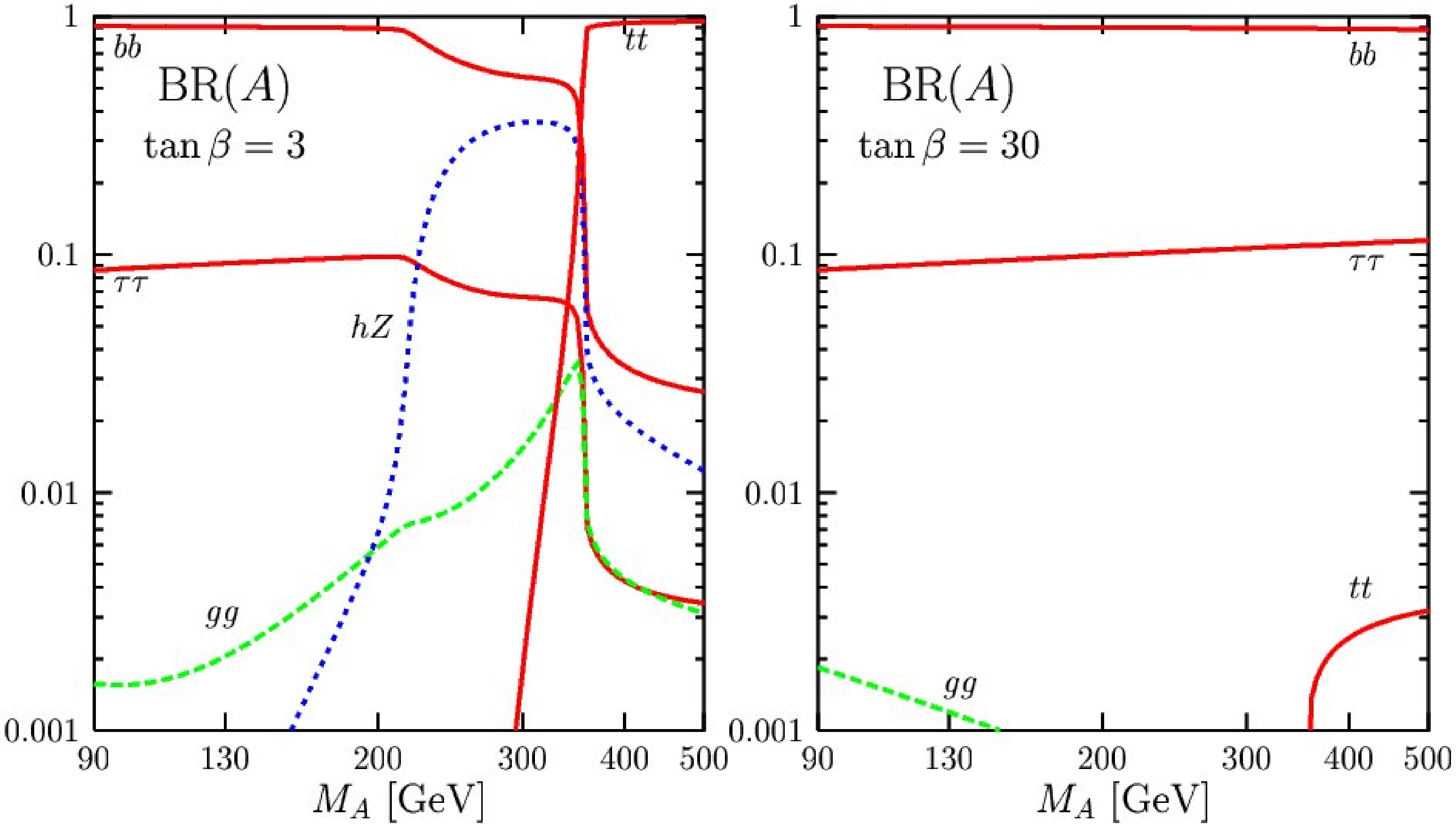
**⇒ at high energy scale (e.g. $M_{GUT}$) :**

$$\frac{M_Z^2}{2} = \frac{1}{\tan^2\beta - 1}\, 2\, m_{H_d}^2 - \frac{\tan^2\beta}{\tan^2\beta - 1}\, m_{H_u}^2 + \frac{\tan^2\beta}{\tan^2\beta - 1} \left(m_Q^2 + m_T^2\right) + \frac{\tan^2\beta}{\tan^2\beta - 1}\, 5.2 \boxed{M_3^2} - 1.1 \frac{g_3}{\lambda_t} \mu^2$$

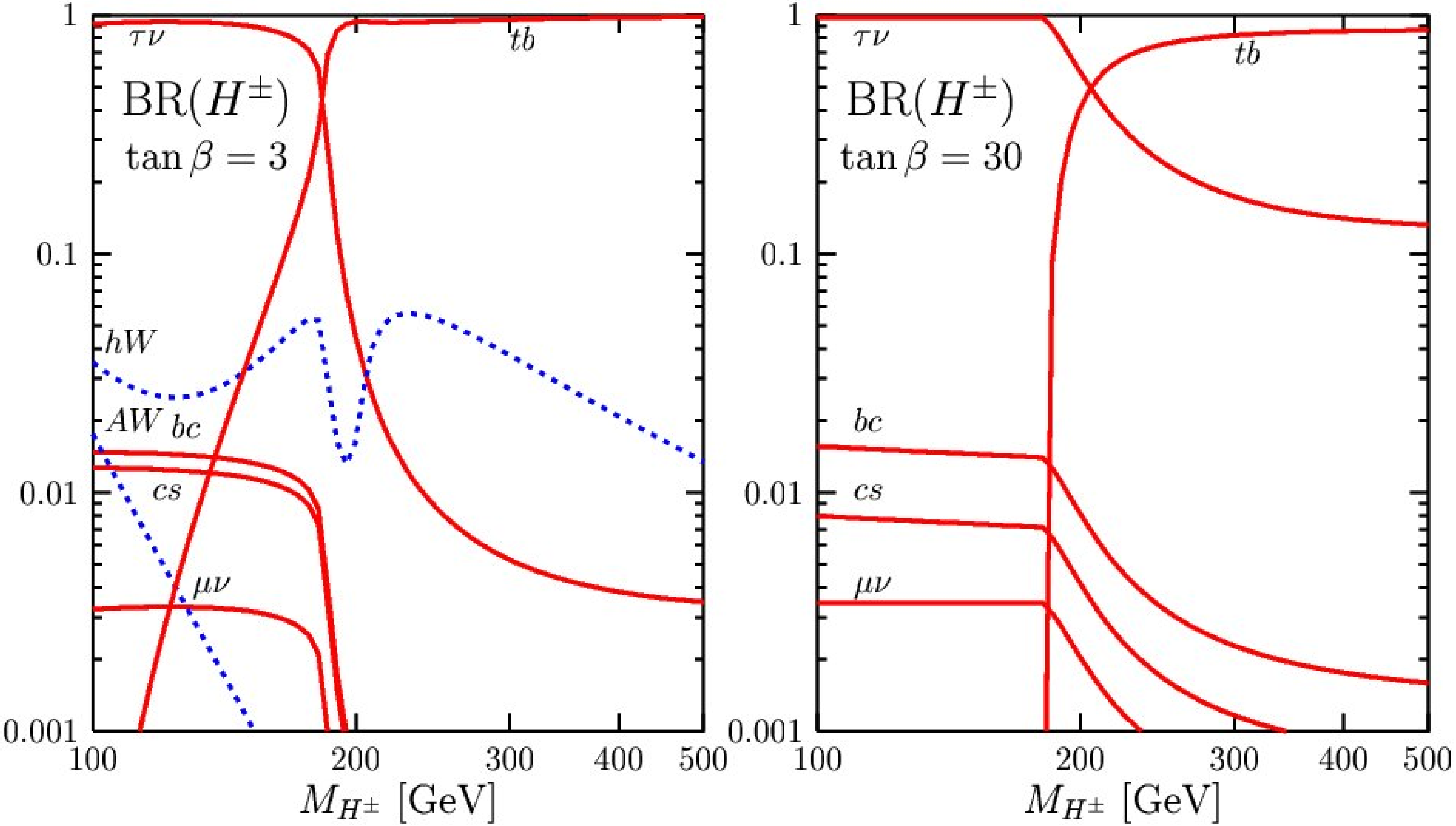
# Minimal SUSY extension of the SM – Higgs sector



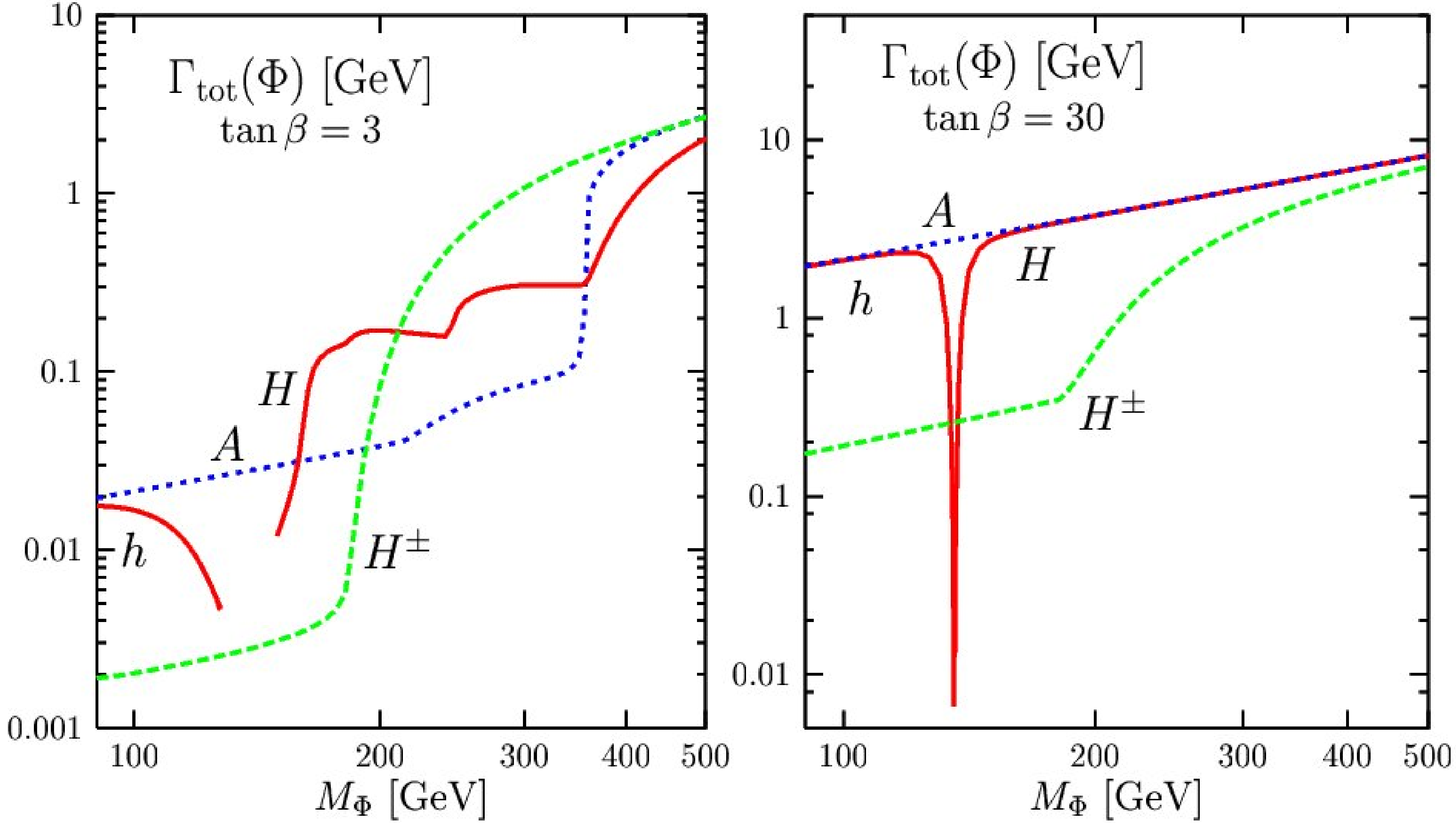
# Minimal SUSY extension of the SM – Higgs sector



# Minimal SUSY extension of the SM – Higgs sector

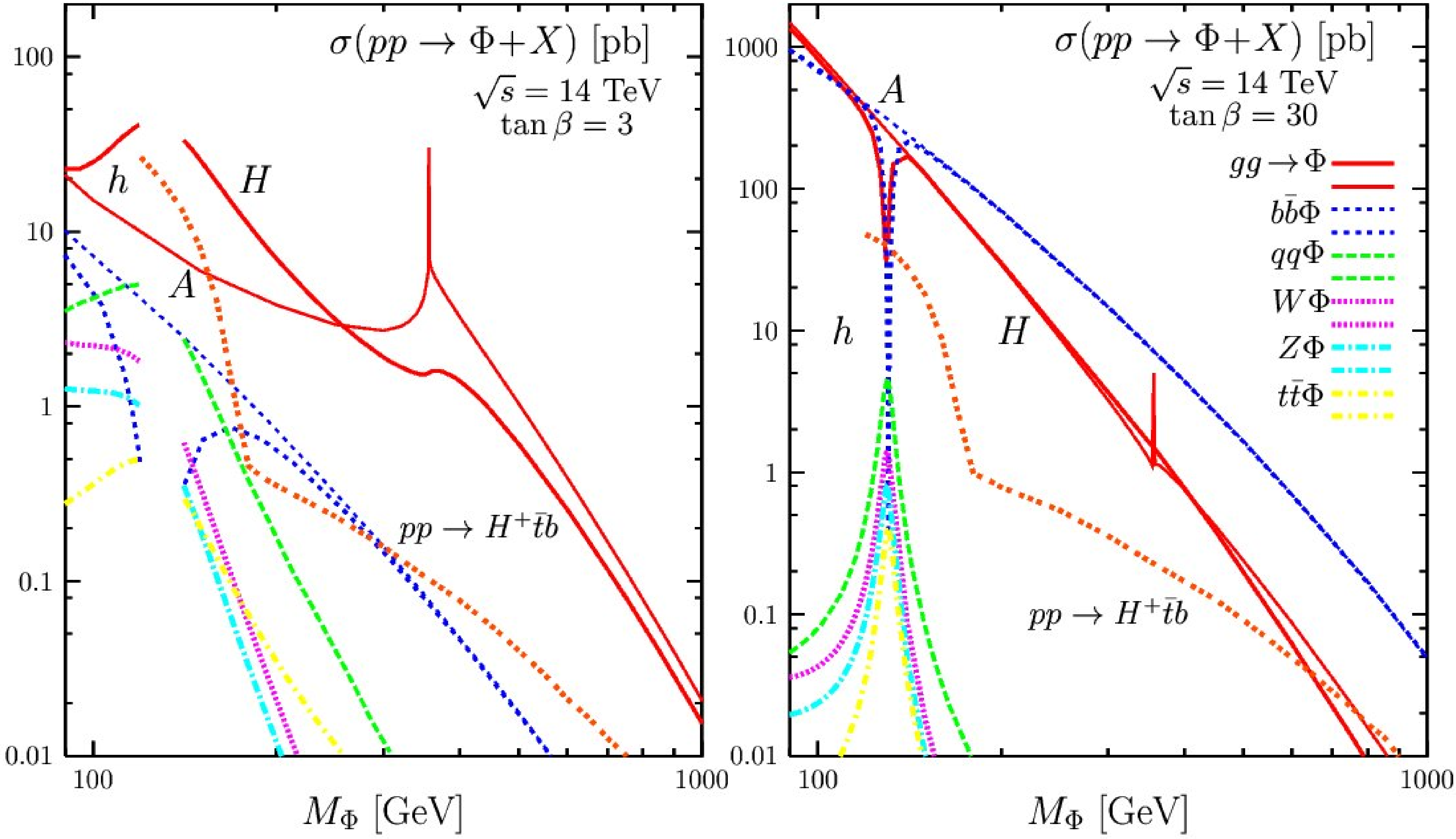


# Minimal SUSY extension of the SM – Higgs sector

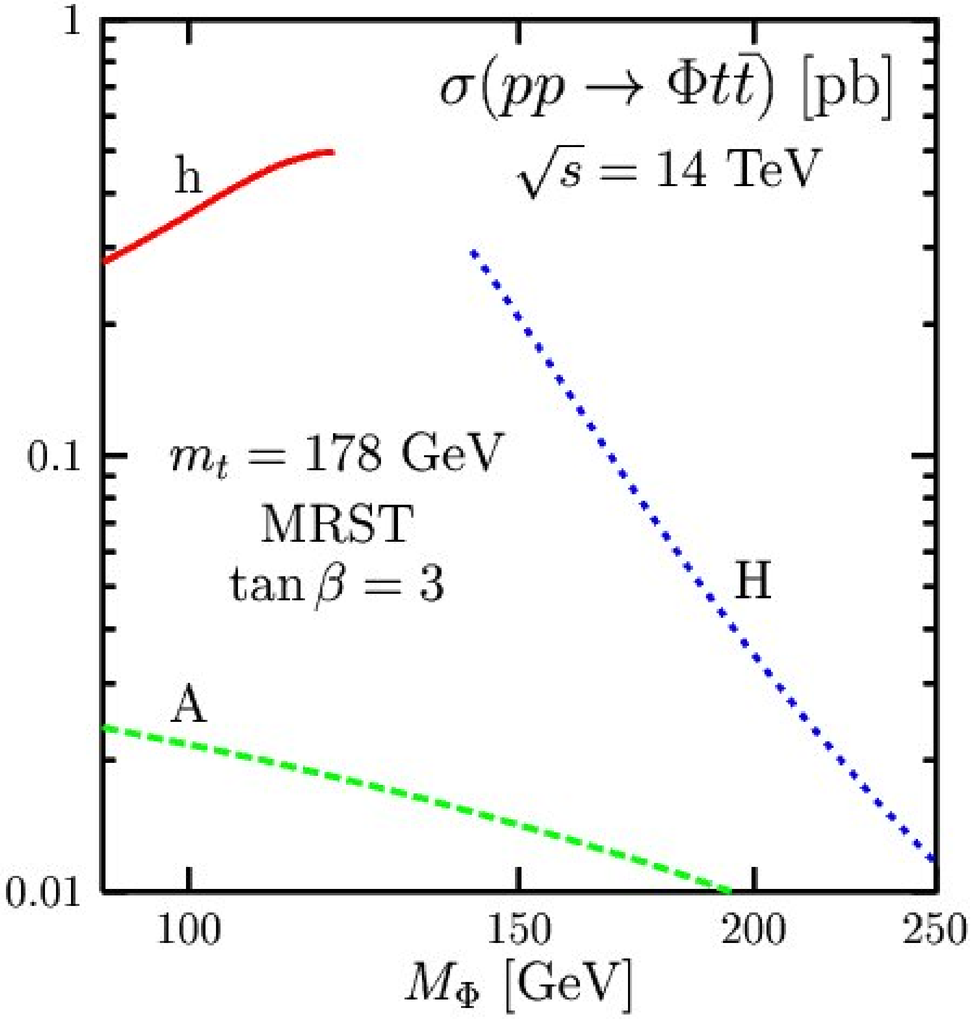


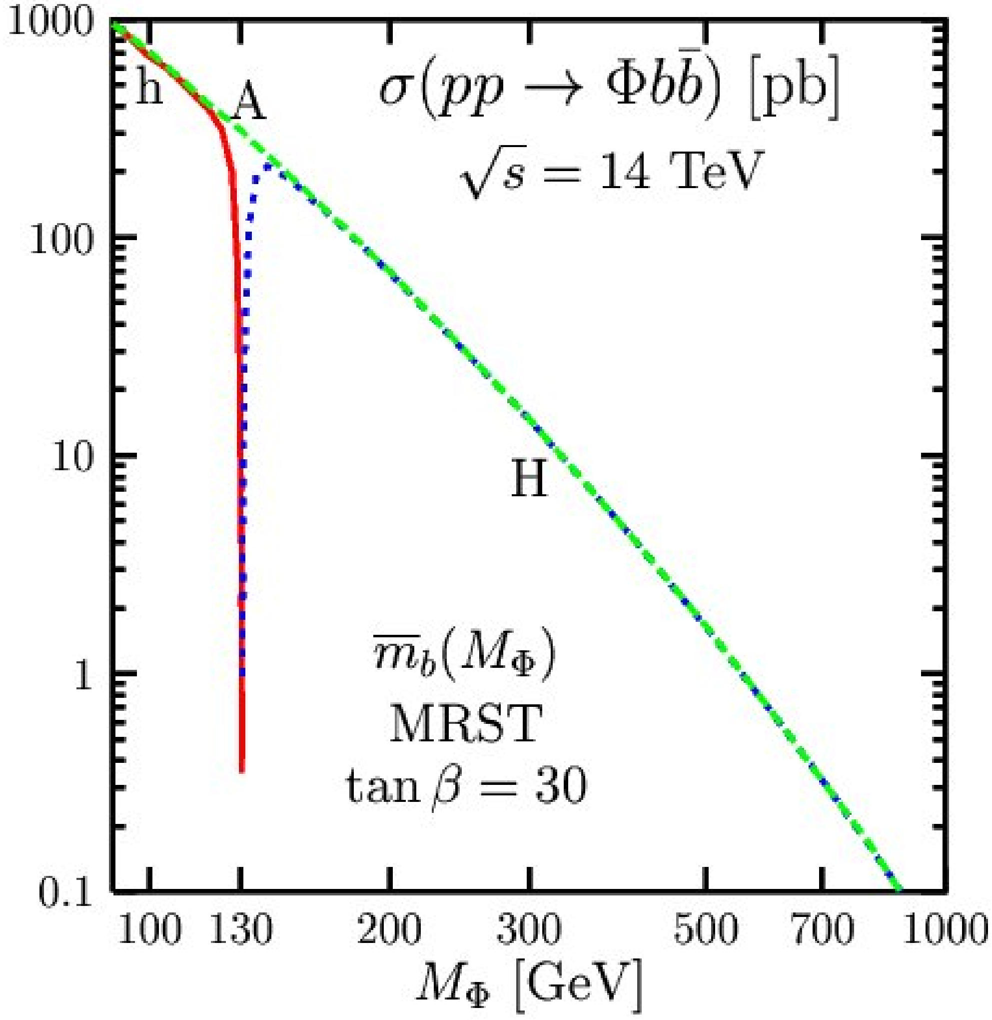
**total width**

# Minimal SUSY extension of the SM – Higgs sector



# Minimal SUSY extension of the SM – Higgs sector





# Minimal SUSY extension of the SM – Higgs sector

## decoupling regime

as mentioned earlier when $M_A \gg M_Z$, **h** approaches its maximal mass value

and the mass of **H** becomes very close to the mass of **A**

- **decoupling regime** of MSSM where there is only one light Higgs boson **h** in the theory and all the other are very heavy and degenerate in mass

- decoupling regime have also an impact on the Higgs boson couplings to SM particles

couplings of **h** and **H** to WW and $ZZ$ are suppressed by mixing angle factors but are complementary

$$g_{HVV} \propto \cos(\beta - \alpha) \xrightarrow{M_A \gg M_Z} \frac{M_Z^2}{2M_A^2}\sin 4\beta \xrightarrow{\tan\beta \gg 1} -\frac{2M_Z^2}{M_A^2 \tan\beta} \longrightarrow 0$$

$$g_{hVV} \propto \sin(\beta - \alpha) \xrightarrow{M_A \gg M_Z} 1 - \frac{M_Z^4}{8M_A^4}\sin^2 4\beta \xrightarrow{\tan\beta \gg 1} 1 - \frac{2M_Z^2}{M_A^4 \tan^2\beta} \longrightarrow 1$$

for $M_A \gg M_Z$, $g_{HVV}$ vanishes while $g_{hVV}$ reaches unity i.e. SM value

especially if $\tan\beta$ is large

# Minimal SUSY extension of the SM – Higgs sector

- coupling to fermion in the decoupling regime

$$g_{huu} \xrightarrow{M_A \gg M_Z} 1 + \frac{M_Z^2}{2M_A^2}\frac{\sin\ 4\beta}{\tan\beta} \xrightarrow{\tan\beta \gg 1} 1 - \frac{2\,M_Z^2}{M_A^2\tan\beta} \xrightarrow{\qquad} 1$$

$$g_{hdd} \xrightarrow{M_A \gg M_Z} 1 - \frac{M_Z^2}{2M_A^2}\sin 4\,\beta\tan\beta \xrightarrow{\tan\beta \gg 1} 1 - \frac{2\,M_Z^2}{M_A^2} \xrightarrow{\qquad} 1$$

$$g_{Huu} \xrightarrow{M_A \gg M_Z} -\cot\beta + \frac{M_Z^2}{2M_A^2}\sin\ 4\,\beta \xrightarrow{\tan\beta \gg 1} -\cot\beta\left(1 + \frac{2\,M_Z^2}{M_A^2}\right) \xrightarrow{\qquad} -\cot\beta$$

$$g_{Hdd} \xrightarrow{M_A \gg M_Z} \tan\beta + \frac{M_Z^2}{2M_A^2}\sin^2\ 4\,\beta \xrightarrow{\tan\beta \gg 1} \tan\beta\left(\frac{2\,M_Z^2}{M_A^4\tan^2\beta}\right) \xrightarrow{\qquad} \tan\beta$$

couplings of the **h** boson approach those of the SM Higgs boson

coupling of the **H** boson to those of the **A** boson (up to a sign)

# Minimal SUSY extension of the SM – Higgs sector

## Other regimes of the MSSM Higgs sector

- anti-decoupling regime : $M_A \ll M_Z$ i.e. situation opposite to the decoupling regime

  roles of **h** and **H** are reversed

  at large $\tan\beta$ the **h** is degenerate in mass with the **A** , **H** degenerate in mass with **Z**

  **h** boson couplings to fermions behaving as **A** , **H** boson couplings to fermions are SM-like

- intense coupling regime : $M_h \sim M_H \sim M_A \sim M_h^{max}$ even more so at high $\tan\beta$

  transition regime where both **A** and **H** have still enhanced couplings to down-type fermions and suppressed couplings to gauge bosons and up-type fermions

- intermediate coupling regime : $\tan\beta \lesssim 3-5,\ \ M_A \lesssim 300-500\ GeV$

  not yet in the decoupling regime and both $\cos^2(\beta-\alpha)$ and $\sin^2(\beta-\alpha)$ are sizeable

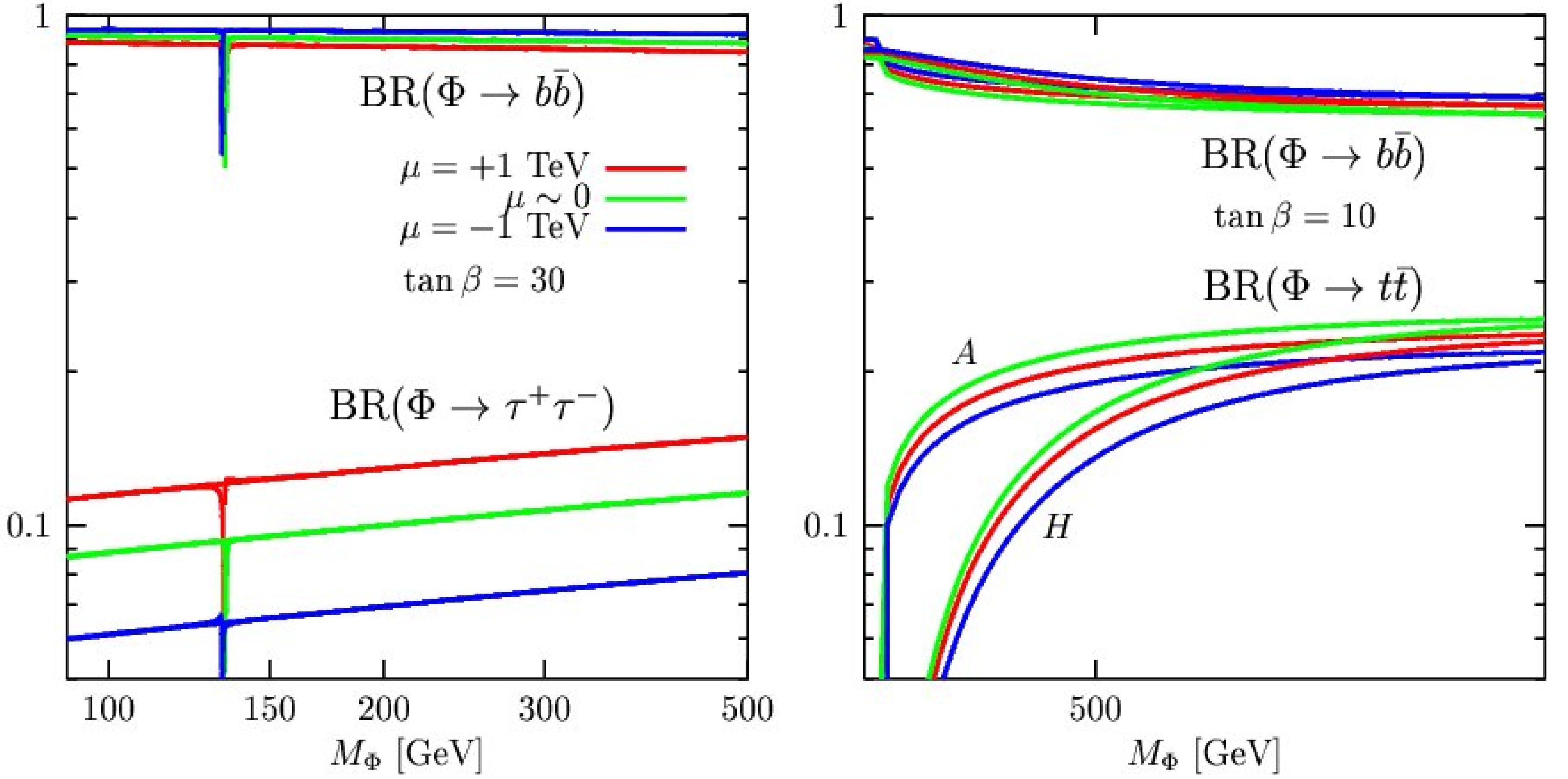
  h and H have significant couplings to the gauge bosons

- vanishing coupling regime : for large values of $\tan\beta$

  and for intermediate to large values of $M_A$ as well as for specific values of the other MSSM parameters which enter the radiative corrections ⟶

  possible suppression of the coupling to one of the CP-even Higgs boson to fermions or gauge bosons (result of cancellation between tree-level terms and radiative corrections)

# Minimal SUSY extension of the SM – Higgs sector



BR for the decay of the 3 neutral Higgs bosons into $b\bar{b}$ , $\tau\tau$ for $\tan\beta=30$ (left) and of the heavier H/A bosons into $b\bar{b}$ , $t\bar{t}$ for $\tan\beta=10$ (right) in the maximal mixing scenario with $M_S=m_{\tilde{g}}=1$ TeV including SUSY-QCD corrections for $\mu=\pm1$ TeV and without the SUSY-QCD correction $(\mu\sim0)$

# Minimal SUSY extension of the SM – Higgs sector

**decoupling regime** $M_A > 150\ GeV$ **for** $\tan\beta = 30$

$M_A > 400 - 500\ GeV$ **for** $\tan\beta = 3$

the lighter **h** boson reaches its maximal mass value $M_h^{max} < 140\ GeV$

has SM-like coupling and decays as the SM Higgs boson

dominant modes : $b\bar{b}\,,\ WW^*$

decays into $\tau^+\tau^-,\ gg,\ ,c\bar{c},\ ZZ^*$ at the level of a few percent

loop induced decays into $\gamma\gamma,\ Z\gamma$ at the level of a few per mille

total decay width of the **h** boson is small : $\Gamma(h) < O(10\ MeV)$

for the heavier Higgs bosons decay pattern depends on $\tan\beta$

for $\tan\beta >> 1$ : strong enhancement of the Higgs coupling to down type fermions

the neutral Higgs bosons **H** and **A** decay almost exclusively into : $b\bar{b}$ (~90 %)

$\tau^+\tau^-$ (~10 %)

total decay width from O(1 GeV) to O(10 GeV) for small to large $\tan\beta$

# Minimal SUSY extension of the SM – Higgs sector

**anti-decoupling regime :** $M_A < 130\ GeV$ **and** $\tan\beta = 30$

the neutral Higgs bosons **h** and **A** decay dominantly into : $b\bar{b}$ (~90 %)

$\tau^+\tau^-$ (~10 %)

all other modes below the per mille level except for the gluonic decay

total widths O(1 GeV)

the heavier CP-even Higgs boson will have a mass $M_H \sim M_h^{max}$

plays the the role of the SM Higgs boson with one difference: in the low $M_A$ range

the h and H Higgs bosons would be light enough for $H \to hh$ and $H \to AA$

which would have been dominant but are in fact closed due to LEP2 bound

$$M_A \sim M_h > M_Z$$

$H \to hh^* \to h\, b\bar{b}$ and $H \to AA^* \to A\, b\bar{b}$ do not compete with the dominant decay modes $H \to b\bar{b}$ and $H \to WW^*$

**H is SM-like in this regime**

# Minimal SUSY extension of the SM – Higgs sector

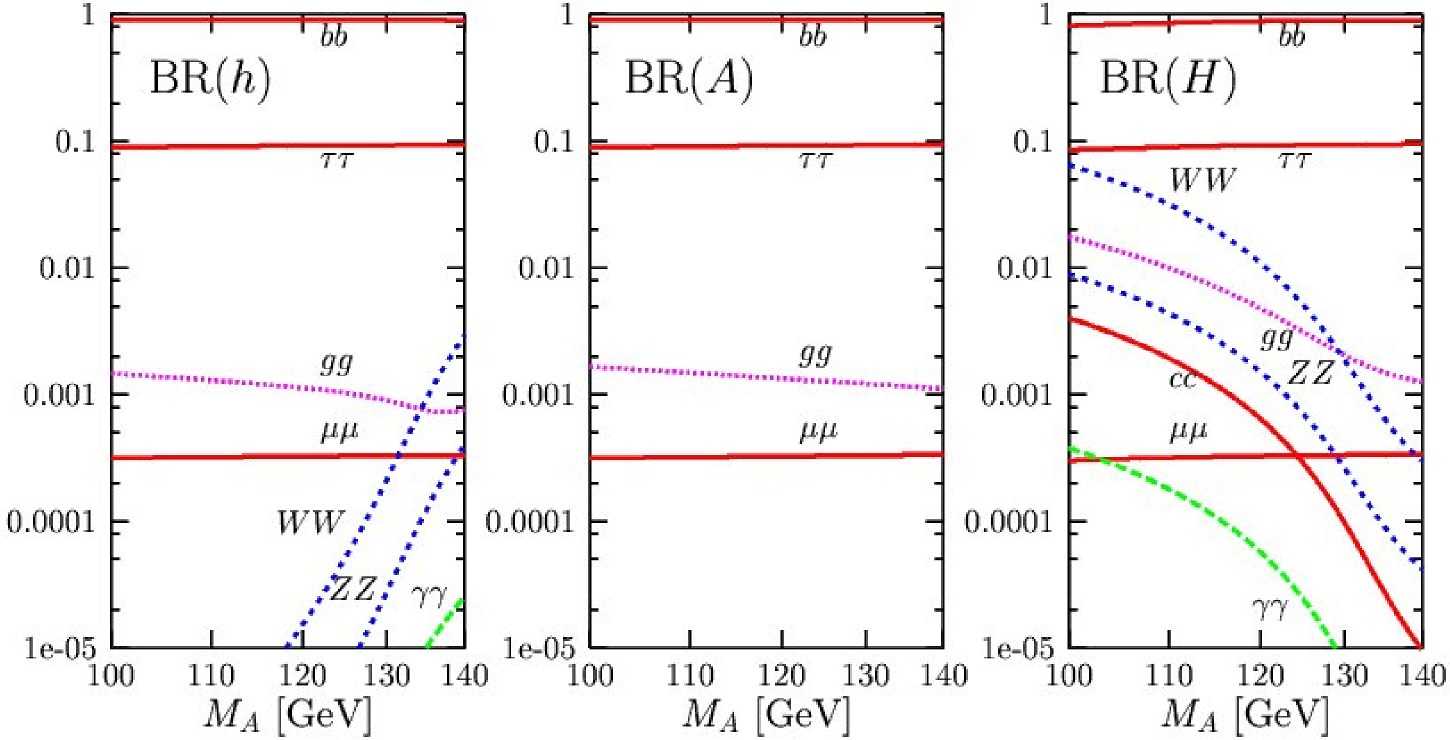
**intense coupling regime :** $M_A \sim 120-140\ GeV$ **and** $\tan\beta=30$

couplings of the h and H to gauge boson and up-type fermions are suppressed

couplings to down-type fermions (b quarks and tau leptons) are enhanced

the neutral Higgs bosons **h** and **H** decay dominantly into : $b\bar{b}$ (~90 %)

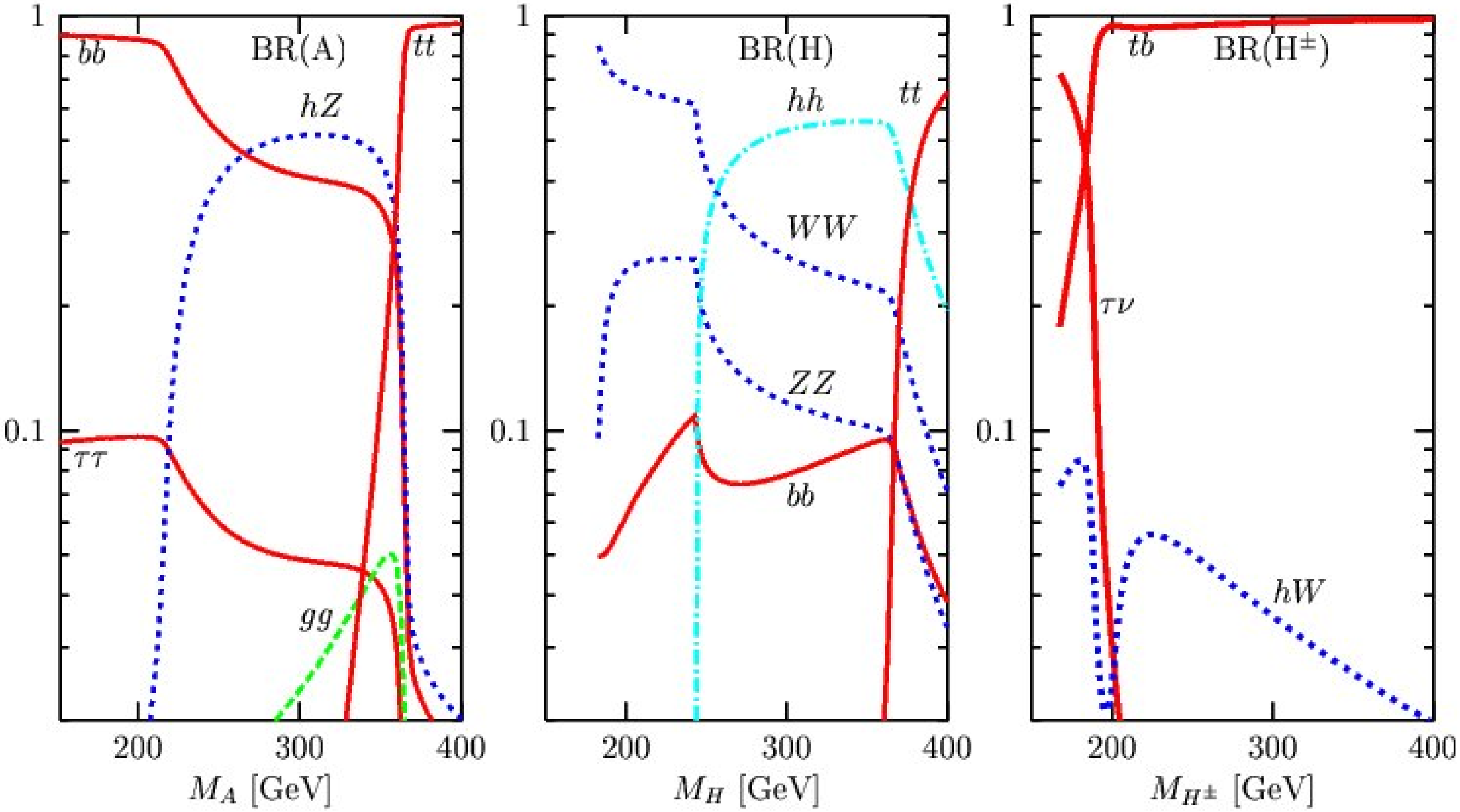
$\tau^+\tau^-$ (~10 %)



*The decay branching ratios of the neutral MSSM h, H and A bosons as a function of $M_A$ in the intense–coupling regime with* $\tan\beta = 30$.

# Minimal SUSY extension of the SM – Higgs sector

**intermediate coupling regime :** small values of $\tan\beta$ when the couplings to b quarks and tau leptons are not strongly enhanced and for **H/A** masses below top quark pairs threshold



*The decay branching ratios of the heavier MSSM Higgs particles A, H and* $H^\pm$ *as a function of their masses in the intermediate–coupling regime with* $\tan\beta = 2.5$. *The top mass is set to* $m_t = 182$ *GeV and only the branching ratios larger than 2% are displayed.*

# Minimal SUSY extension of the SM – Higgs sector

**vanishing coupling regime :** moderate to large values of $M_A$ i.e. 150 – 300 GeV

and for large values of $\tan\beta \sim 30$

lighter CP-even Higgs **h** coupling to b quarks and tau leptons vanish

for the **H** decays : few differences w.r.t the decoupling regime

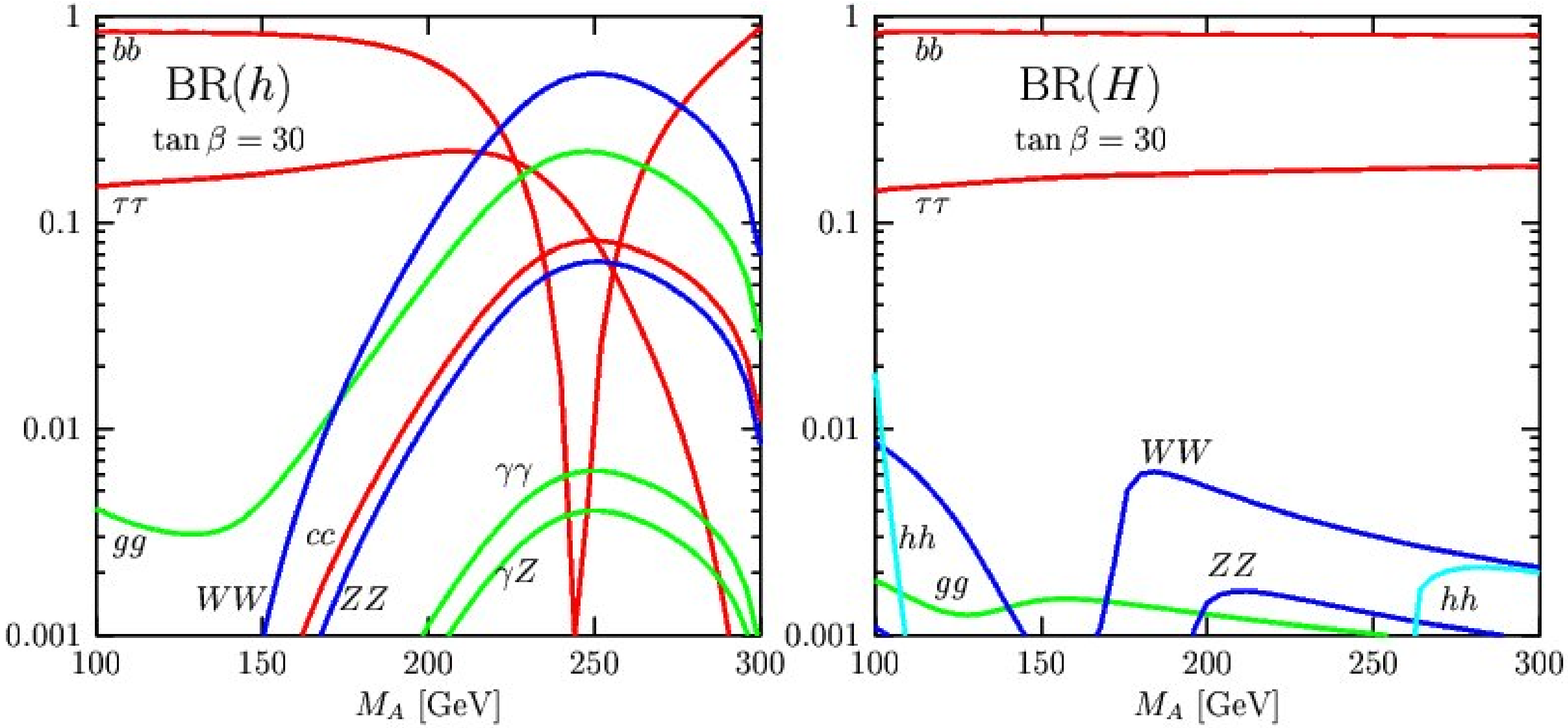
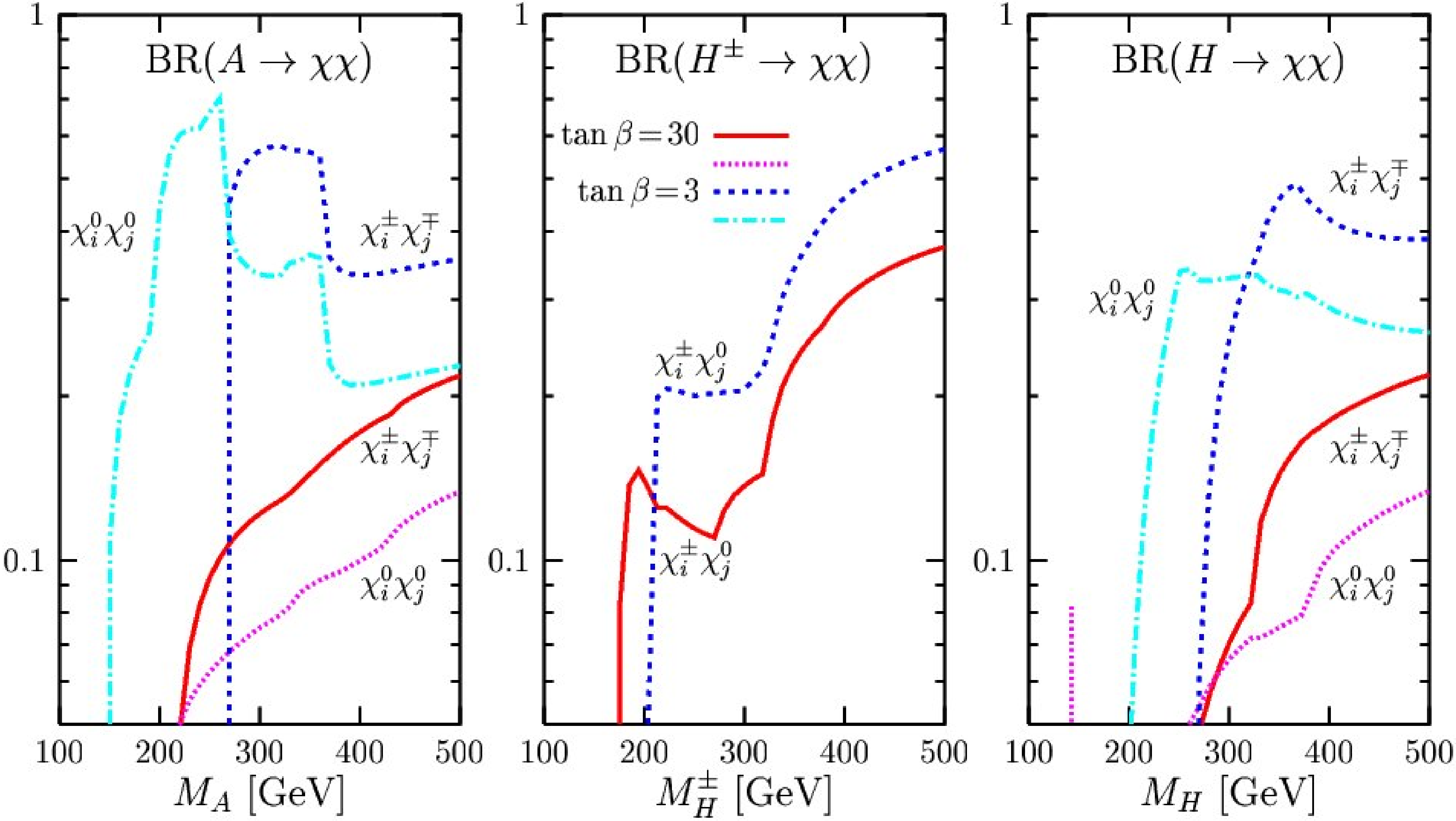


*Figure 2.24: The decay branching ratios of the CP–even h and H bosons as a function of* $M_A$ *for* $\tan\beta = 30$ *in the small* $\alpha$ *scenario. The other MSSM parameters are:* $M_S = 0.7$ *TeV,* $M_2 = M_3 = \frac{1}{5}\mu = 0.5$ *TeV,* $X_t = 1.1$ *TeV and* $A_b = A_t$.

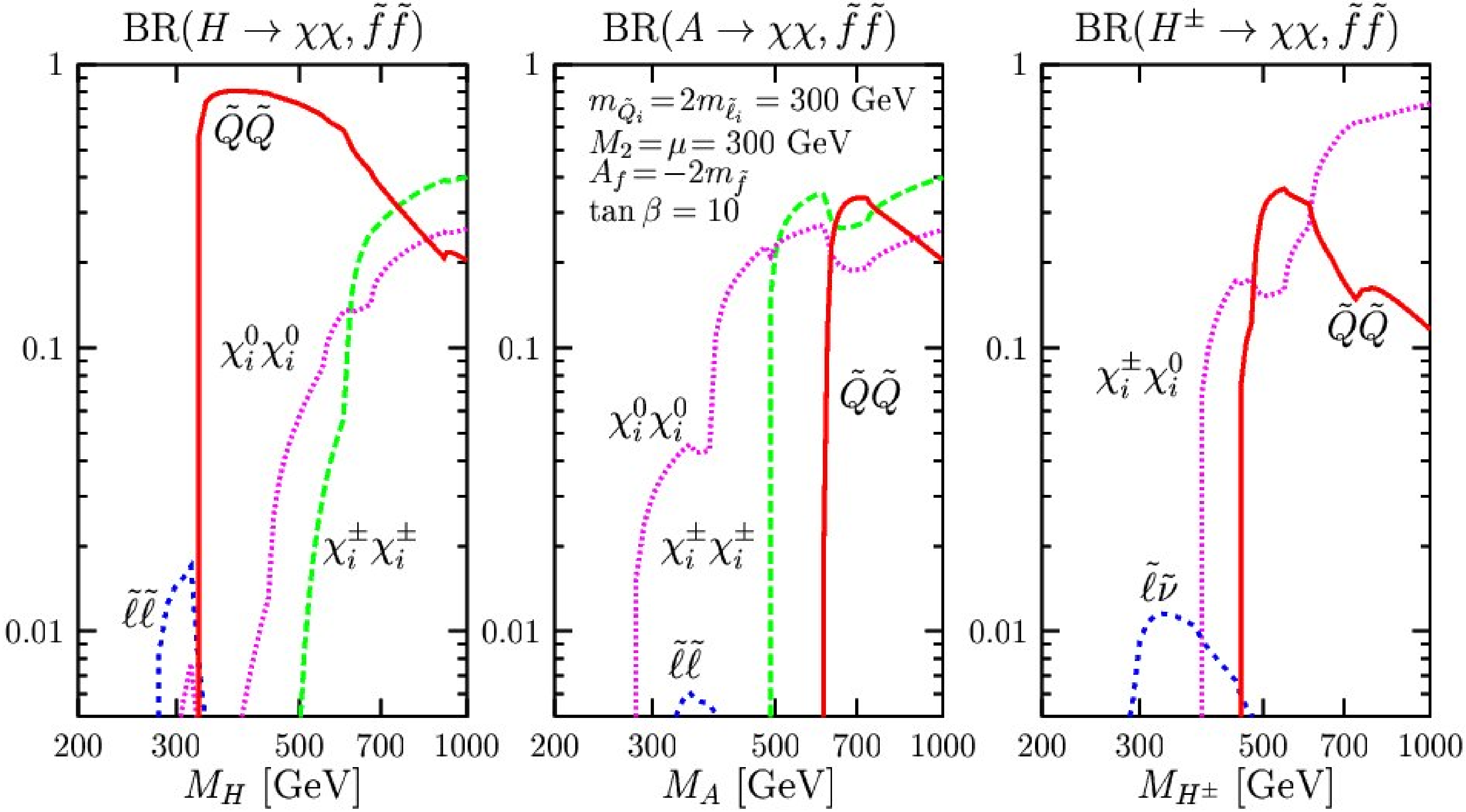
# Minimal SUSY extension of the SM – Higgs sector

**Example of decays into susy particles**



# Minimal SUSY extension of the SM – Higgs sector

**Example of decays into susy particles**



# Squarks and gluinos

one can calculate the underlying soft breaking parameters from the the physical squark masses and mixing angles

- for the stop sector:

$$m_{\tilde{Q}}^2 \;=\; m_{\tilde{t}_1}^2 \cos^2\theta_{\tilde{t}} + m_{\tilde{t}_2}^2 \sin^2\theta_{\tilde{t}} - M_Z^2 \cos 2\beta \left(\frac{1}{2} - \frac{2}{3}\sin^2\theta_W\right) - m_t^2$$

$$m_{\tilde{U}}^2 \;=\; m_{\tilde{t}_1}^2 \sin^2\theta_{\tilde{t}} + m_{\tilde{t}_2}^2 \cos^2\theta_{\tilde{t}} - \frac{2}{3} M_Z^2 \cos 2\beta \sin^2\theta_W - m_t^2$$

- for the sbottom sector:

$$m_{\tilde{Q}}^2 \;=\; m_{\tilde{b}_1}^2 \cos^2\theta_{\tilde{b}} + m_{\tilde{b}_2}^2 \sin^2\theta_{\tilde{b}} + M_Z^2 \cos 2\beta \left(\frac{1}{2} - \frac{1}{3}\sin^2\theta_W\right) - m_b^2$$

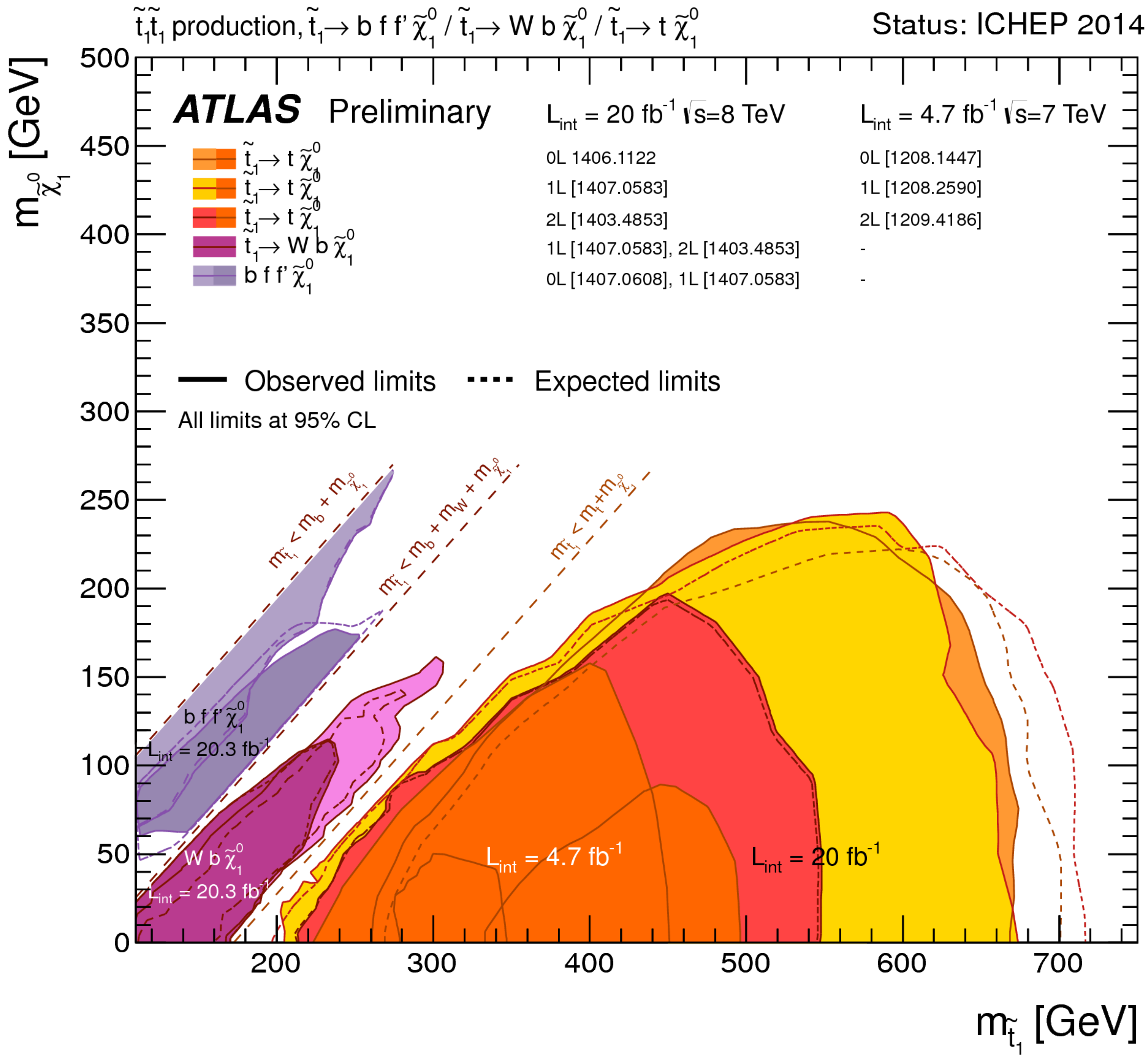
$$m_{\tilde{D}}^2 \;=\; m_{\tilde{b}_1}^2 \sin^2\theta_{\tilde{b}} + m_{\tilde{b}_2}^2 \cos^2\theta_{\tilde{b}} + \frac{1}{3} M_Z^2 \cos 2\beta \sin^2\theta_W - m_b^2$$

off diagonal element of the squark mass matrix $a_q m_q \;=\; \frac{1}{2}\left(m_{\tilde{q}_1}^2 - m_{\tilde{q}_2}^2\right) \sin 2\theta_{\tilde{q}}$

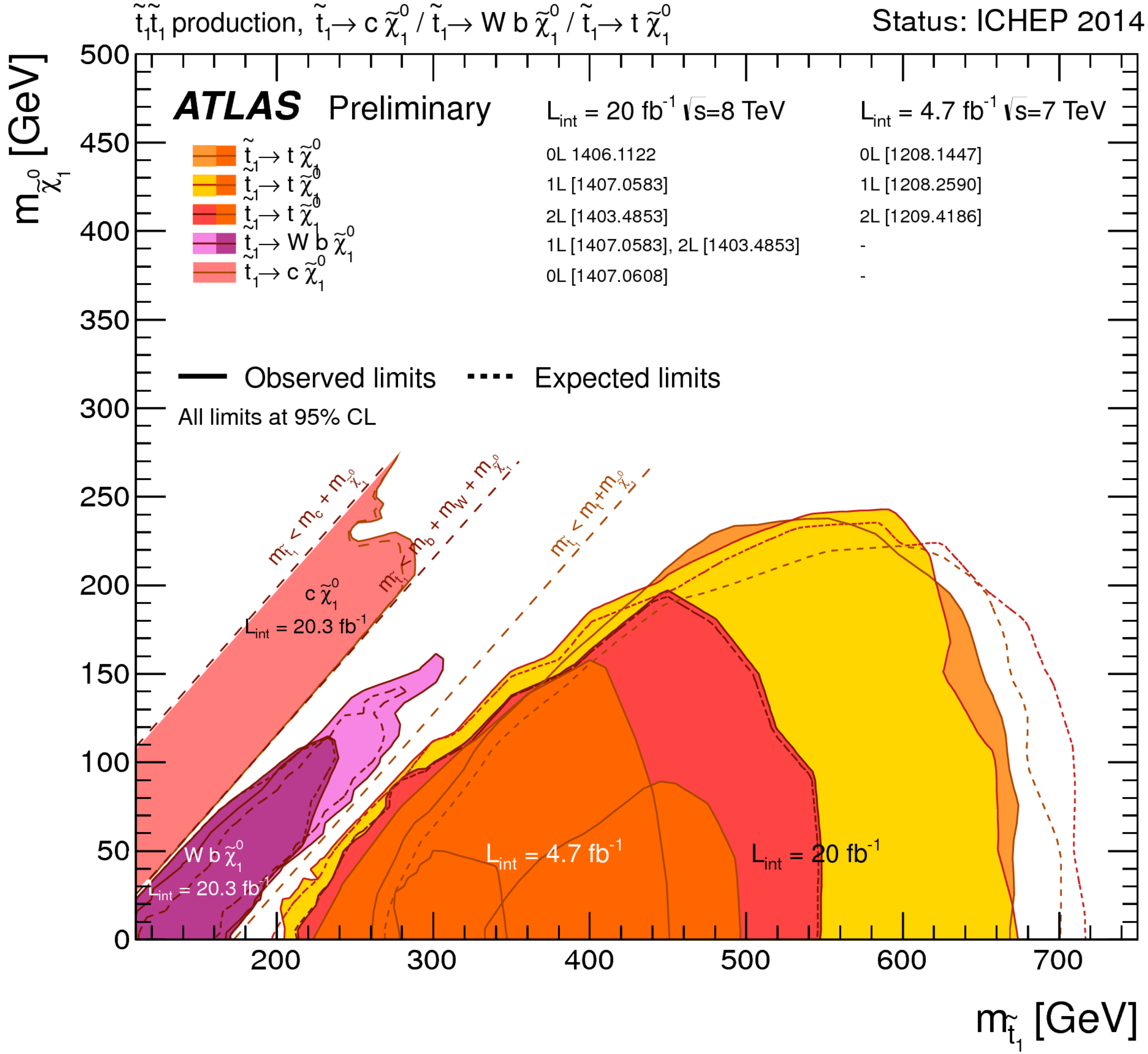
parameter $m_{\tilde{Q}}$ enters both in $\tilde{t}$ and $\tilde{b}$ → one can deduce a sum rule at tree level :

$$m_W^2 \cos 2\beta \;=\; m_{\tilde{t}_1}^2 \cos^2\theta_{\tilde{t}} + m_{\tilde{t}_2}^2 \sin^2\theta_{\tilde{t}} - m_{\tilde{b}_1}^2 \cos^2\theta_{\tilde{b}} - m_{\tilde{b}_2}^2 \sin^2\theta_{\tilde{b}} - m_t^2 + m_b^2$$

# Squarks and gluinos



# Squarks and gluinos



# Gauginos and Sleptons

useful approximation is obtained in the limit where $M_Z \ll |\mu + M_2|$

$$M^2_{\tilde{\chi}_1^\pm} \simeq M_2 - \frac{M_W^2 \left(M_2 + \mu \sin 2\beta\right)}{\mu^2 - M_2^2}$$

$$M^2_{\tilde{\chi}_2^\pm} \simeq |\mu| + \frac{M_W^2 \left( |\mu| + sign(\mu) \; M_2 \; \sin 2\beta\right)}{\mu^2 - M_2^2}$$

if $M_2 \ll |\mu|$ the chargino is gaugino-like (Wino-like) with mass $M_{\tilde{\chi}^\pm} \simeq M_2$

and the heavier chargino is higgsino like with mass $M_{\tilde{\chi}^\pm} \simeq |\mu|$

if $M_2 \gg |\mu|$ the situation is reversed

when $\mu \simeq -M_2$ then the charginos masses are

$$M^2_{\tilde{\chi}^\pm_{1,2}} = \left(M_2^2 + M_W^2\right) \mp \left[\left(M_2^2 + M_W^2\right)^2 - 4 \; \left(M_2^2 + M_W^2 \sin 2\,\beta\right)^2\right]^{1/2}$$

for $\tan\beta \simeq 1$ both charginos become degenerate with $M^2_{\tilde{\chi}_1^\pm} \simeq M^2_{\tilde{\chi}_2^\pm} \simeq M_2^2 + M_W^2$

and nearly degenerate with the W if $M_2$ is small

# Gauginos and Sleptons

in the limit where $M_Z \ll \left|\mu \pm M_1\right|, \left|\mu \pm M_2\right|$ approximate values of the neutralinos masses can be found ;

$$M_{\tilde{\chi}_1^o} \simeq M_1 - \frac{M_Z^2 \sin^2\theta_W \left(M_1 + \mu \sin 2\beta\right)}{\mu^2 - M_2^2}$$

$$M_{\tilde{\chi}_2^o} \simeq M_2 - \frac{M_Z^2 \cos^2\theta_W \left(M_2 + \mu \sin 2\beta\right)}{\mu^2 - M_2^2}$$

$$M_{\tilde{\chi}_3^o} \simeq |\mu| + \frac{M_Z^2 \left(1 - \epsilon \sin 2\beta\right) \left(|\mu| + M_1 \cos^2\theta_W + M_2 \sin^2\theta_W\right)}{2\left(|\mu| + M_1\right) \left(|\mu| + M_2\right)}$$

$$M_{\tilde{\chi}_4^o} \simeq |\mu| + \frac{M_Z^2 \left(1 + \epsilon \sin 2\beta\right) \left(|\mu| - M_1 \cos^2\theta_W - M_2 \sin^2\theta_W\right)}{2\left(|\mu| - M_1\right) \left(|\mu| - M_2\right)}$$

where $\epsilon$ is the sign of $\mu$

# Gauginos and Sleptons

furthermore if universality of gauginos masses one has $M_1 \simeq 0.5\ M_2$ at the weak scale then one has :

- if $M_2 \ll |\mu|$ i.e. the gaugino-like region, the LSP $\tilde{\chi}_1^o$ is bino-like

  the lightest chargino and second lightest neutralino are gaugino-like
  and $2M_{\tilde{\chi}_1^o} \simeq M_{\tilde{\chi}_2^o} \simeq M_{\tilde{\chi}_1^\pm} \simeq M_2$

  the heavier chargino and neutralinos are higgsino-like
  and $M_{\tilde{\chi}_3^o} \simeq M_{\tilde{\chi}_4^o} \simeq M_{\tilde{\chi}_2^\pm} \simeq \mu$

- if $M_2 \gg |\mu|$ i.e. the higgsino-like region ,
  the LSP $\tilde{\chi}_1^o$ is higgsino-like and nearly degenerate with the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^o$
  the heavier chargino and neutralinos are gaugino-like and $2M_{\tilde{\chi}_3^o} \simeq M_{\tilde{\chi}_4^o} \simeq M_{\tilde{\chi}_2^\pm} \simeq M_2$

- the mixed region : obviously no *pure* gaugino- ot higgsino-like states
  and for not too small $M_2$ i.e. $M_2 \geqslant 100$ GeV the region $M_1 \leqslant \mu \leqslant M_2$ is characterized by
  - dominant bino LSP $\tilde{\chi}_1^o$
  - nearly degenerate higgsino-like $\tilde{\chi}_1^\pm$ , $\tilde{\chi}_{2,}^o$ and $\tilde{\chi}_3^o$
  - nearly degenerate gaugino-like $\tilde{\chi}_2^\pm$ and $\tilde{\chi}_4^o$

# EW Gauginos

concentrating on the next lightest neutralino $\tilde{\chi}_2^o$

for small $M_{\tilde{\chi}_2^o}$ 2-body decay modes are inaccessible and $\tilde{\chi}_2^o$ mainly decays via 3-body modes

while branching fraction for charginos 3-body decays were close to those for the W boson

the branching fraction for the neutralino decay $\tilde{\chi}_2^o \rightarrow \tilde{\chi}_1^o f \bar{f}$

differ considerable from those of $Z \rightarrow f \bar{f}$

even for sfermions considerable heavier than the Z boson (Z exchange does not dominate)

this is because the coupling of the Z boson to neutralinos are very sensitive to model parameter

and can be considerably suppressed

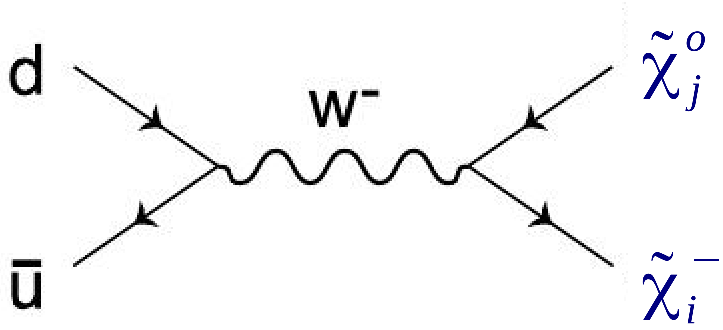
neutralino decay pattern (and resulting signature) are much more sensitive to model parameter than those for chargino decays

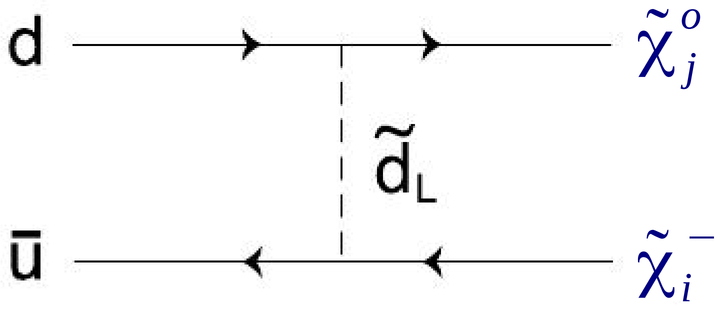
# Gauginos

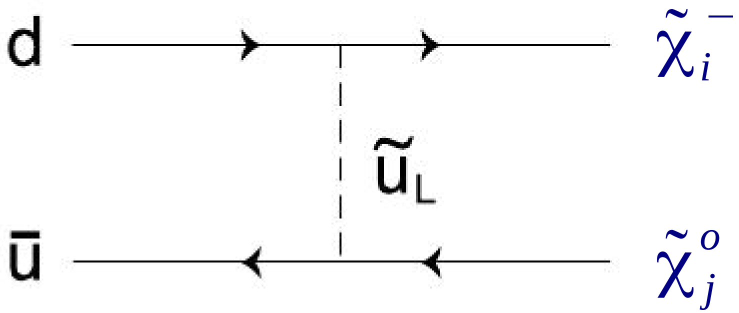
**chargino neutralino** associated **production** at hadron collider dominantly through

$$d\,\bar{u} \;\rightarrow\; \tilde{\chi}_i^{\pm}\;\tilde{\chi}_j^{o}$$

contribution from other flavor are subdominant

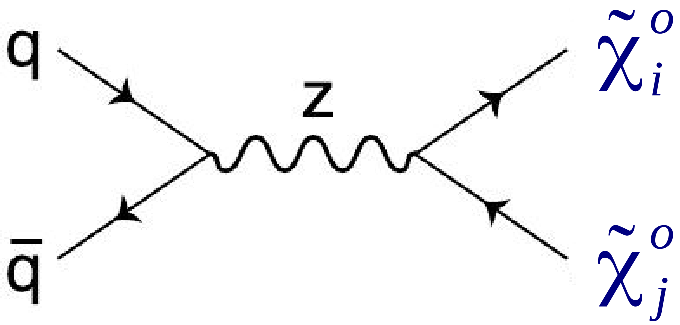


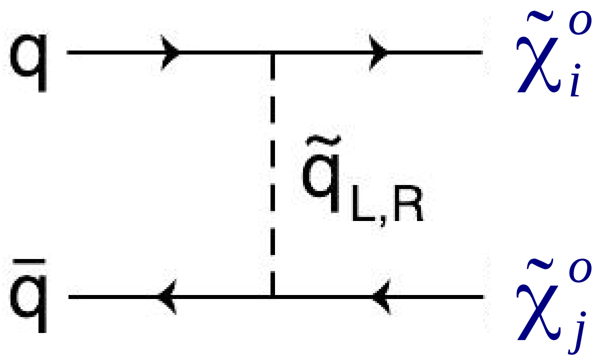


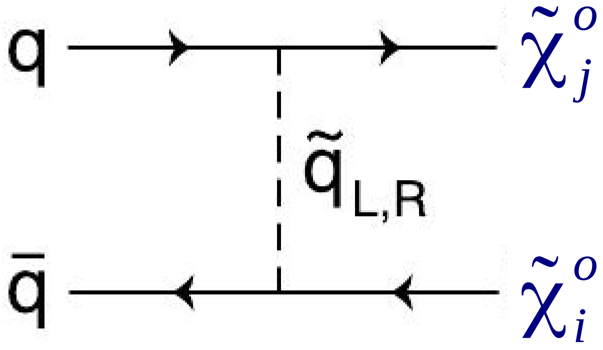


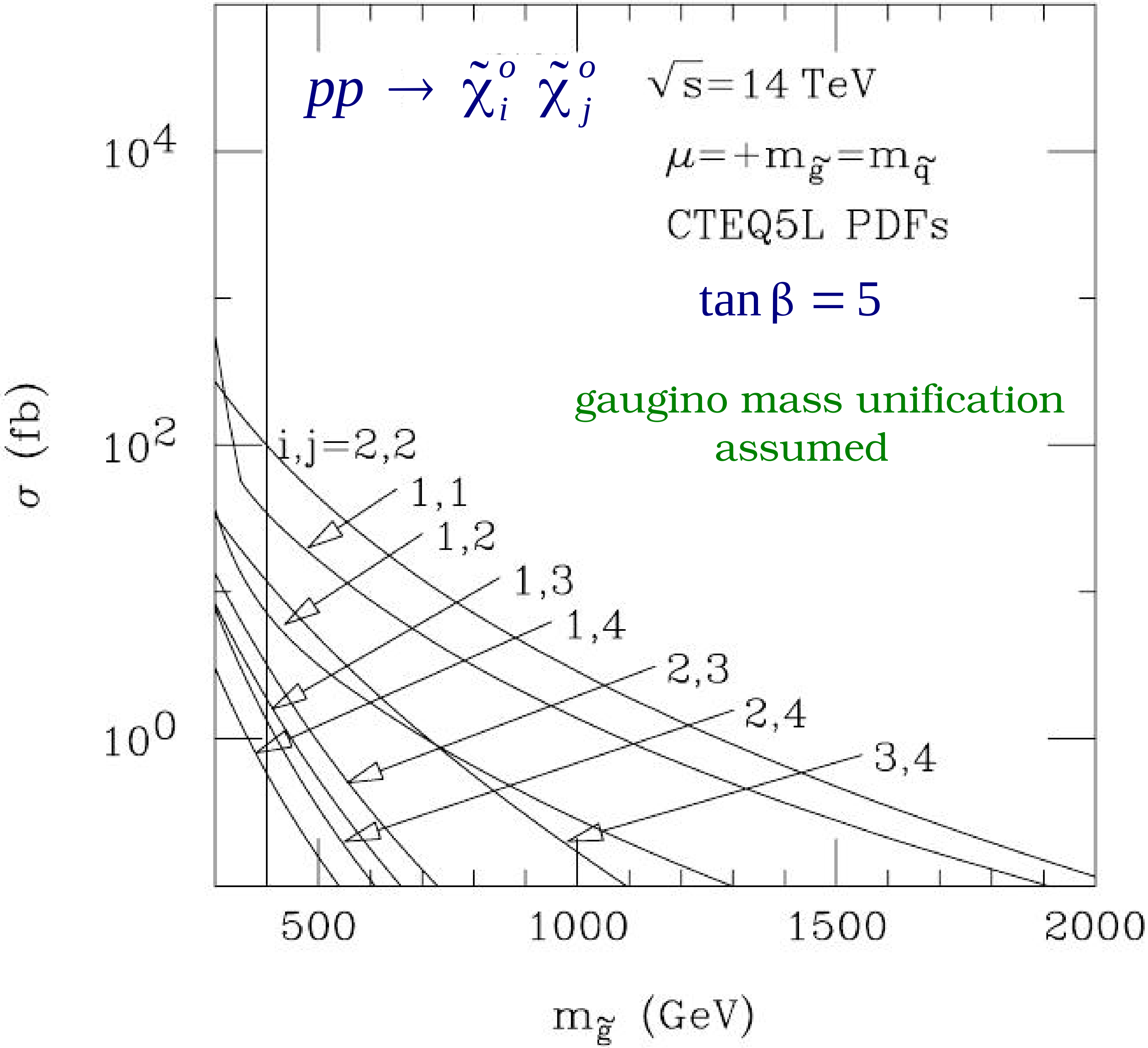
# Gauginos and Sleptons

neutralino pair production



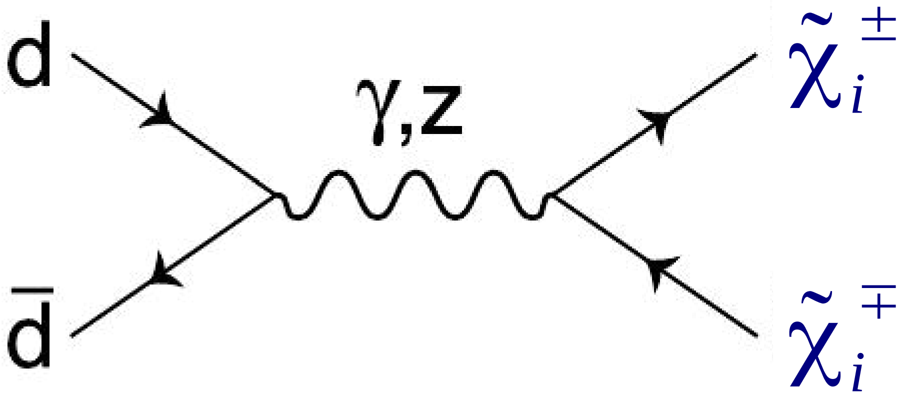


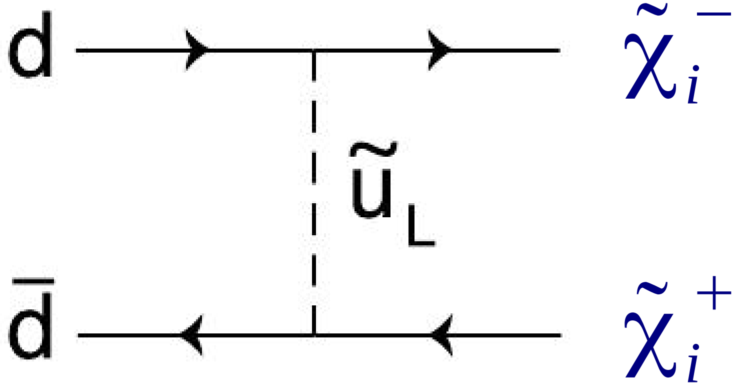




# Gauginos

at leading order charginos pair production occurs via $d\bar{d}$ , $u\bar{u}$ (etc ...) annihilations





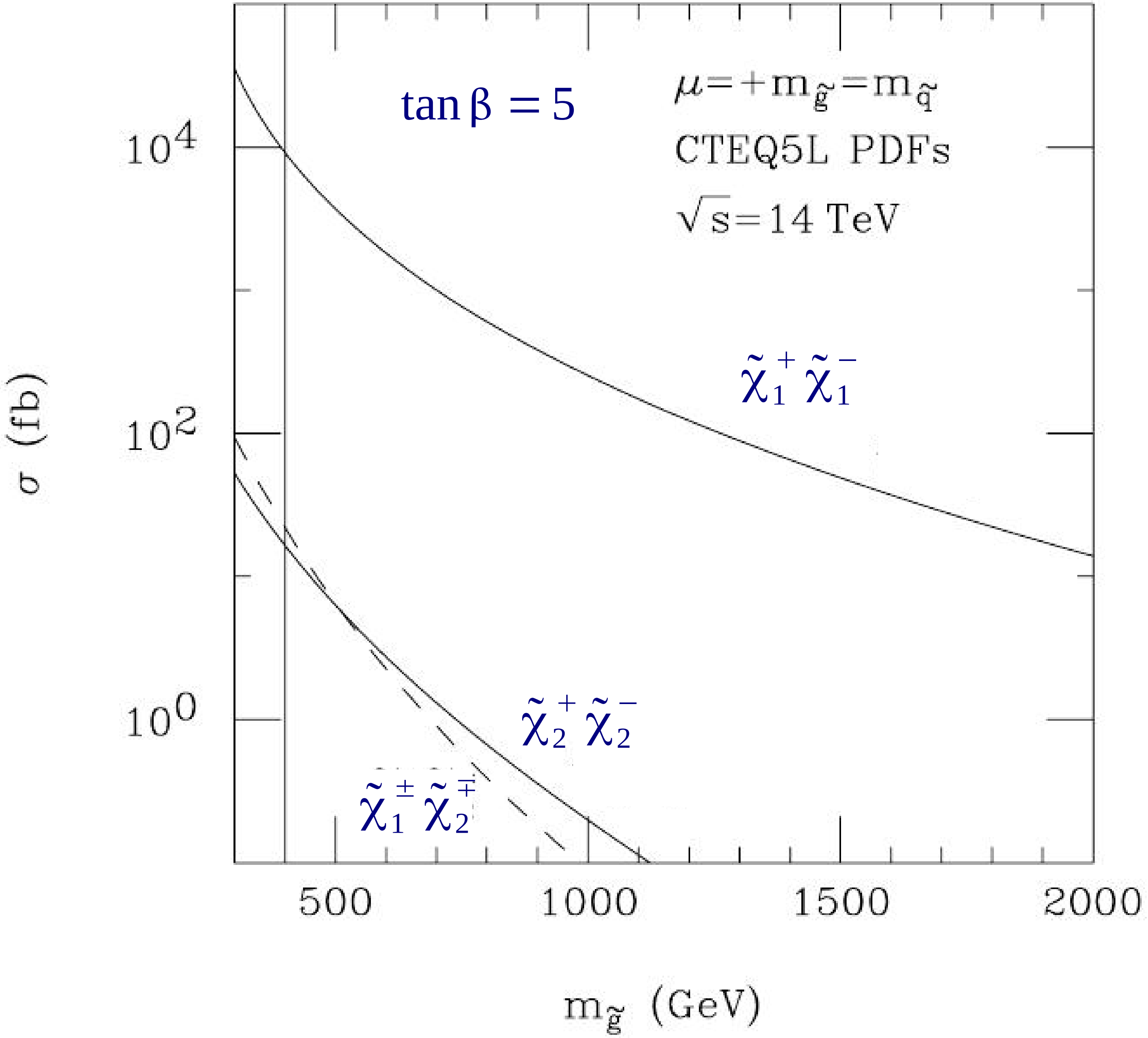
the possible final states consist of $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ , $\tilde{\chi}_2^+ \tilde{\chi}_2^-$ and $\tilde{\chi}_1^- \tilde{\chi}_2^+ + \tilde{\chi}_1^+ \tilde{\chi}_2^-$

1st two occur via $\gamma$ or $Z$ exchange in the s-channel and t-channel squark exchange

$\tilde{\chi}_1^- \tilde{\chi}_2^+ + \tilde{\chi}_1^+ \tilde{\chi}_2^-$ only via Z exchange in the s-channel and t channel squark exchange

( conservation of e.m. current forbids photon coupling to particles of unequal mass )

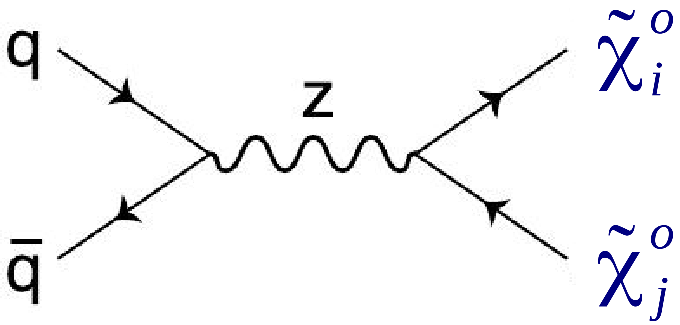
# Gauginos and Sleptons

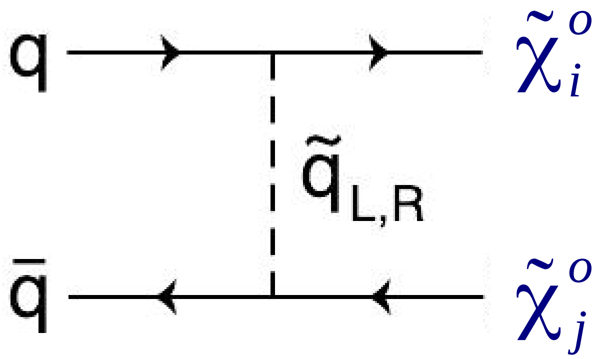


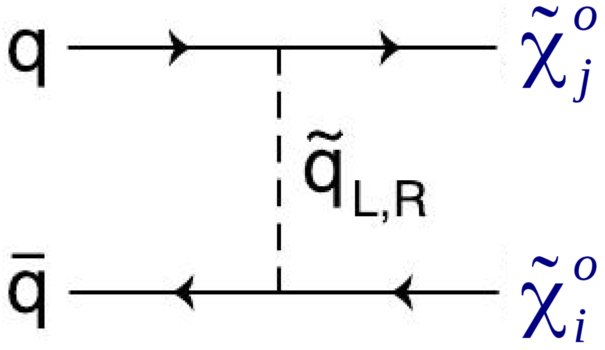
gaugino mass
unification
assumed

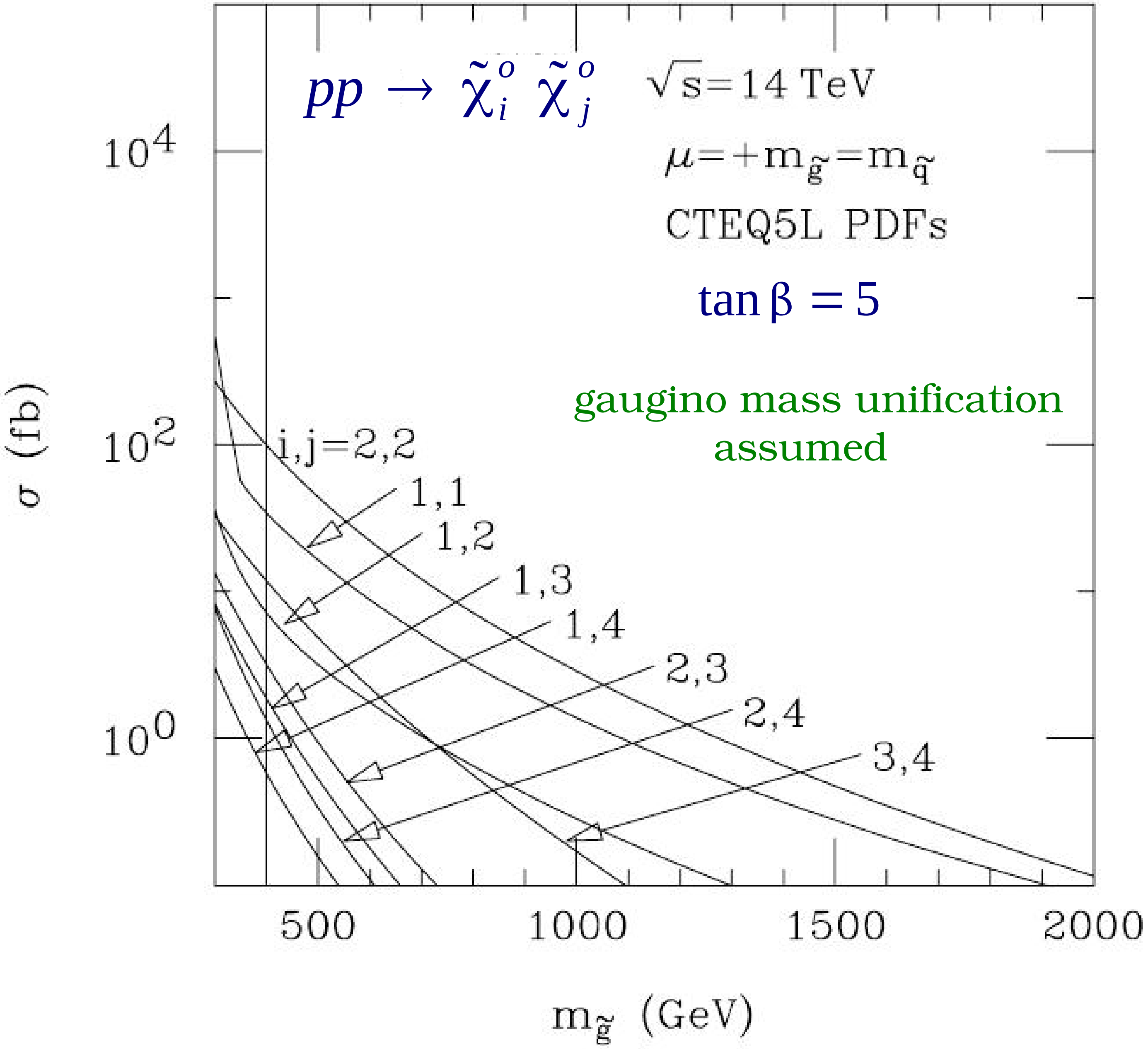
# Gauginos and Sleptons

neutralino pair production









# $B_s \to \mu^+\mu^-$ predictions

**two main steps :**

1) calculating $C_i^{\rm eff}(\mu)$ at scale $\mu \sim M_W$ by requiring matching between the effective and full theories

$$C_i^{\rm eff}(\mu) = C_i^{(0)\,\rm eff}(\mu) + \frac{\alpha_s}{4\pi}\, C_i^{(1)\,\rm eff}(\mu) + \ldots$$

2) evolving the $C_i^{\rm eff}(\mu)$ to scale $\mu \sim m_b$ using RGE :

$$\mu \frac{d}{d\mu} C_i^{\rm eff}(\mu) = C_j^{\rm eff}(\mu)\, \gamma_{ji}^{\rm eff}(\mu)$$

driven by the anomalous dimension matrix $\hat{\gamma}^{\rm eff}(\mu)$ :

$$\hat{\gamma}^{\rm eff}(\mu) = \frac{\alpha_s(\mu)}{4\pi}\, \hat{\gamma}^{(0)\,\rm eff} + \frac{\alpha_s^2(\mu)}{(4\pi)^2}\, \hat{\gamma}^{(1)\,\rm eff} + \ldots$$

from N. Mahmoudi, Blois conference 2013

# $B_s \to \mu^+\mu^-$ predictions

**to calculate the transition amplitude :**

$$A(\text{Meson} \to \text{Final}) = \langle \text{Final} | H_{\text{eff}} | \text{Meson} \rangle$$
$$= \frac{G_F}{\sqrt{2}} \sum_i V^i_{\text{CKM}} C_i(\mu) \quad \langle \text{Final} | O_i | \text{Meson} \rangle (\mu)$$

**one needs the hadronic matrix elements** $\langle \text{Final} | O_i | \text{Meson} \rangle$

## how to calculate the hadronic matrix elements ?

→ model building, Lattice simulation, light flavor symmetries, heavy flavour symmetries, ...

→ describe hadronic matrix elements in terms of **hadronic quantities**

**two types of hadronic quantities :**

- **decay constants:** probability amplitude of hadronizing quark pair into a given hadron
- **form factors:** transition from a meson to another through flavor change

from N. Mahmoudi, Blois conference 2013

# $B_s \rightarrow \mu^+ \mu^-$ predictions

Since we are considering $B_s$ the matrix element of $H_{\text{eff}}$ is to be taken between vacuum and $B_s$ state i.e. $< 0 | \, H_{\text{eff}} \, | B_s >$

taking $< 0 | \, H_{\text{eff}} \, | B_s >$ allows to find vanishing (vector and tensor) operators :

$$< 0 | \, \left( \bar{s} \gamma^{\mu} P_{L,R} b \right) \left( \bar{l} \gamma_{\mu} l \right) \, | B_s > \; = \; 0$$

$$< 0 | \, \left( \bar{s} \sigma^{\mu\nu} P_{L,R} b \right) \left( \bar{l} \sigma_{\mu\nu} P_{L,R} l \right) \, | B_s > \; = \; 0$$

and non vanishing ones which can be expressed in terms of the $B_s$ decay constant $f_{B_s}$

$$< 0 | \; \bar{s} \gamma^{\mu} \gamma_5 b \; | B_s > \; = \; i f_{B_s} \; p_B^{\mu}$$

$$< 0 | \; \bar{s} \gamma_5 b \; | B_s > \; = \; -i f_{B_s} \frac{m_{B_s}^2}{m_b + m_s}$$

# $B_s \rightarrow \mu^+\mu^-$ predictions

squaring the matrix element and summing over the final lepton spins
the branching ratio can be written

$$Br\left(B_s \rightarrow \mu^+\mu^-\right) = \frac{G_F^2 \alpha^2 M_{B_s} f_{B_s}^2 \tau_{B_s}}{16\pi^3 \sin^4\theta_W} \left|V_{tb} V_{ts}^*\right|^2$$

$$\times \sqrt{1-\frac{4m_\mu^2}{M_{B_s}^2}} \left\{ \left(1-\frac{4m_\mu^2}{M_{B_s}^2}\right) \left|F_S\right|^2 + \left|F_P + 2\ m_\mu F_A\right|^2 \right\}$$

where $\tau_{B_s}$ is the lifetime of the $B_s$ meson and

$$F_S = \frac{1}{2} M_{B_s}^2 \left[ \frac{C_S - C'_S \hat{m}_s}{1+\hat{m}_s} \right] \qquad F_P = \frac{1}{2} M_{B_s}^2 \left[ \frac{C_P - C'_P \hat{m}_s}{1+\hat{m}_s} \right]$$

$$F_A = \frac{1}{2}\left(C_A - C'_A\right)$$

with $\hat{m}_s = m_s / m_b$

note that one can compute time dependent rate $\Gamma\left(B_s(t) \rightarrow \mu^+\mu^-\right)$ see arXiv:1303.3820

# $B_s \to \mu^+\mu^-$ predictions

in the MSSM the largest contribution to $C_S$ and $C_P$ in the large $\tan\beta$ region reads

$$C_S \approx -C_P$$

$$\approx -\mu A_t \frac{\tan^3\beta}{\left(1+\epsilon_b \tan\beta\right)^2} \frac{m_t^2}{m_{\tilde{t}}^2} \frac{m_b m_\mu}{4\sin^2\theta_W M_W^2 M_A^2} f\left(x_{\tilde{t}\mu}\right)$$

where $x_{\tilde{t}\mu} = m_{\tilde{t}}^2/\mu^2$ with $m_{\tilde{t}}$ the geometric average of the two stop masses and :

$$f(x) = -\frac{x}{1-x} - \frac{x}{1-x^2}\log x$$

the $\epsilon_b$ correction parameterizes loop-induced terms that receive their main contribution from Higgsino and gluino exchange

# $B \to s\, \gamma$

**use also the effective field theory approach**

in the present case with the following relevant operators

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

$$O_8 = \frac{g}{(4\pi)^2}\; m_b \left( \bar{s}\, \sigma^{\mu\nu}\; T^a\; P_R b \right) G^a_{\mu\nu}$$

supersymmetry normally prevents any operator of the form $\bar{\Psi}\, \sigma_{\mu\nu} \Psi\, F^{\mu\nu}$

for example in the case susy QED the one loop contribution present in the SM is cancelled by new graphs involving sfermions and gauginos

thus in the supersymmetric limit (unbroken susy) $Br\left[B \to X_s\, \gamma\right]_{\mathrm{SUSY}} = 0$

however in the more realistic case of broken supersymmetry this leaves open the possibility of partial (i.e. only and not full) cancellations

# $B \rightarrow s\ \gamma$

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however in the more realistic case of broken supersymmetry this leaves open the possibility of partial (i.e. only and not full) cancellations

# $B \rightarrow s\ \gamma$

the decay rate $\Gamma\left[b \rightarrow s\,\gamma\right]$ suffers from large uncertainties because of the $m_b^5$ factor

one way to improve this is to normalize it to the $b \rightarrow c\,e\,\bar{\nu}_e$ decay rate

$$\Gamma\left[b \rightarrow c\,e\,\bar{\nu}_e\right] = \frac{G_F^2\, m_b^5}{\left(192\,\pi^3\right)} \left|V_{cb}\right|^2 g\left(\frac{m_c}{m_b}\right) \left[1 - \frac{2}{3\,\pi}\,\alpha_3(m_b)\, f\left(\frac{m_c}{m_b}\right)\right]$$

where $g(x) = 1 - 8\mathrm{x}^2 + 8\mathrm{x}^6 - 24\,x^4 \log x$ is the phase space factor and

the last factor $f(x)$ is the NLO QCD correction to the semileptonic decay

we have to a good approximation

$$\frac{Br\left[b \rightarrow X_s\,\gamma\right]}{Br\left[b \rightarrow X_c\,e\,\bar{\nu}_e\right]} \sim \frac{\Gamma\left[b \rightarrow s\,\gamma\right]}{\Gamma\left[b \rightarrow c\,e\,\bar{\nu}_e\right]}$$

where the corrections can be computed

# $B \to s\ \gamma$

one obtains :

$$\frac{Br\left[b \to X_s \gamma\right]}{Br\left[b \to X_c e \bar{\nu}_e\right]} = \left|\frac{V_{ts}^* V_{tb}}{V_{cb}}\right|^2 \frac{6\alpha}{\pi g\left(m_c/m_b\right)} \frac{\left(\frac{\bar{m}_b(m_b)}{m_b}\right)^2}{1-\frac{2}{3\pi}\alpha_3(m_b) f\left(m_c/m_b\right)}$$

$$\times \left| \eta^{16/23}\ C_7(M_W)\ +\ \frac{8}{3}\left(\eta^{14/23} - \eta^{16/23}\right)\ C_8(M_W)\ +\ \sum_{i=1}^{8} h_i \eta_i^a \right|^2$$

with $\eta \equiv \alpha_3(M_W)/\alpha_3(m_b) \sim 0.548$ and :

$$C_{7,8}^{\mathrm{SM}}(M_W) = F_{7,8}^{(1)}\left(\frac{m_t^2(M_W)}{M_W^2}\right)$$

and :

$$F_7^{(1)}(x) = \frac{x\ \left(7 - 5\mathrm{x} - 8\mathrm{x}^2\right)}{24\left(x-1\right)^3} + \frac{x^2\ \left(3\mathrm{x} - 2\right)}{4\left(x-1\right)^4}\ \log x$$

$$F_8^{(1)}(x) = \frac{x\ \left(2 + 5\mathrm{x} - x^2\right)}{8\left(x-1\right)^3} - \frac{3x^2}{4\left(x-1\right)^4}\ \log x$$

# $(g-2)_\mu$

this relation reads :

$$a_\mu^{(\mathrm{HAD;LO})} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} \frac{ds}{s^2} K(s) R(s)$$

where $R(s) \equiv \dfrac{\sigma_{\mathrm{tot}}(e^+e^- \to \text{hadrons})}{\sigma_{\mathrm{tot}}(e^+e^- \to \mu^+\mu^-)}$ and $K(s)$ is a kinematical factor

$R(s)$ is the critical input to the evaluation and the $s^{-2}$ dependence of the kernel weights preferentially the values of $R(s)$ at low energies

⇒ the low energy region (e.g. near the ρ resonance) dominates the determination of $a_\mu^{(\mathrm{HAD})}$

⇒ the high energy region is less critical

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