The Role of Precision Studies in the Quest for New Physics

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Fermilab

OUTLINE

- The Standard Model
- Open questions and possible solutions
- How to establish new physics
- Status of New Physics searches
- A journey in supersymmetry

THE STANDARD MODEL

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- The SM is a Quantum Field Theory: fusion of Special Relativity and Quantum Mechanics

- There are three main ingredients:
  - ***Forces:*** $SU(3)_c \times SU(2)_W \times U(1)_Y$
  - ***Matter:*** quarks, leptons, gauge bosons
  - ***Spontaneous Symmetry Breaking:*** mass generation

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where the problems begin

FERMION MASSES

- Transformation properties under SU(3) x SU(2) x U(1)

$$\begin{aligned} \begin{pmatrix} u_L^a \\ d_L^a \end{pmatrix} &= (\mathbf{3},\ \mathbf{2},\ \mathbf{+1/3}) \\ u_R^a &= (\mathbf{3},\ \mathbf{1},\ \mathbf{+4/3}) \\ d_R^a &= (\mathbf{3},\ \mathbf{1},\ \mathbf{-2/3}) \\ \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} &= (\mathbf{1},\ \mathbf{2},\ \mathbf{+1}) \end{aligned}$$

- Fermion mass terms are forbidden?

(u_L,d_L) are a SU(2) doublet
u_R and d_R are SU(2) singlets

→ $\cancel{m_u \bar{u}_L u_R}$

THE HIGGS MECHANISM

- We have a problem with Weak Interactions

  Exact SU(2) gauge invariance requires ***massless*** *fermions and vector bosons (W and Z)*

- Spontaneous Symmetry Breaking:

  $SU(3)_S \times SU(2)_W \times U(1)_Y \rightarrow SU(3)_S \times U(1)_{em}$

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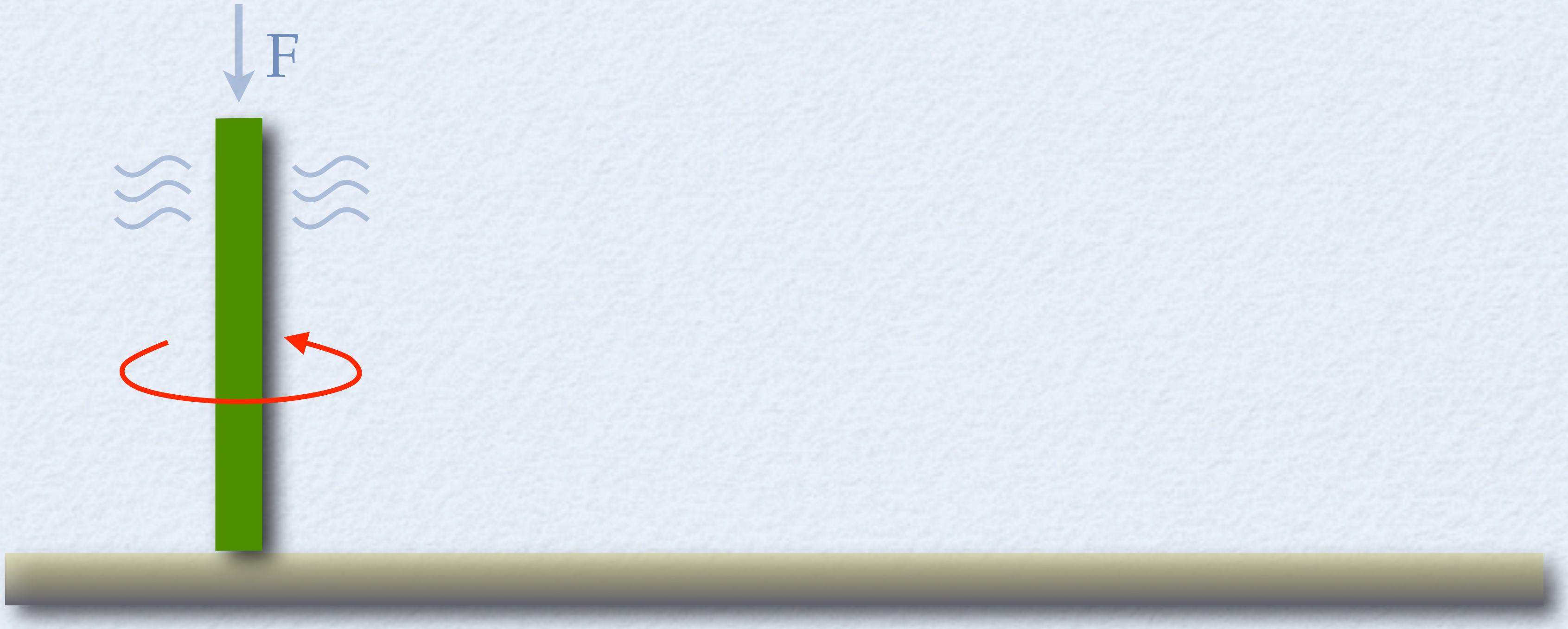

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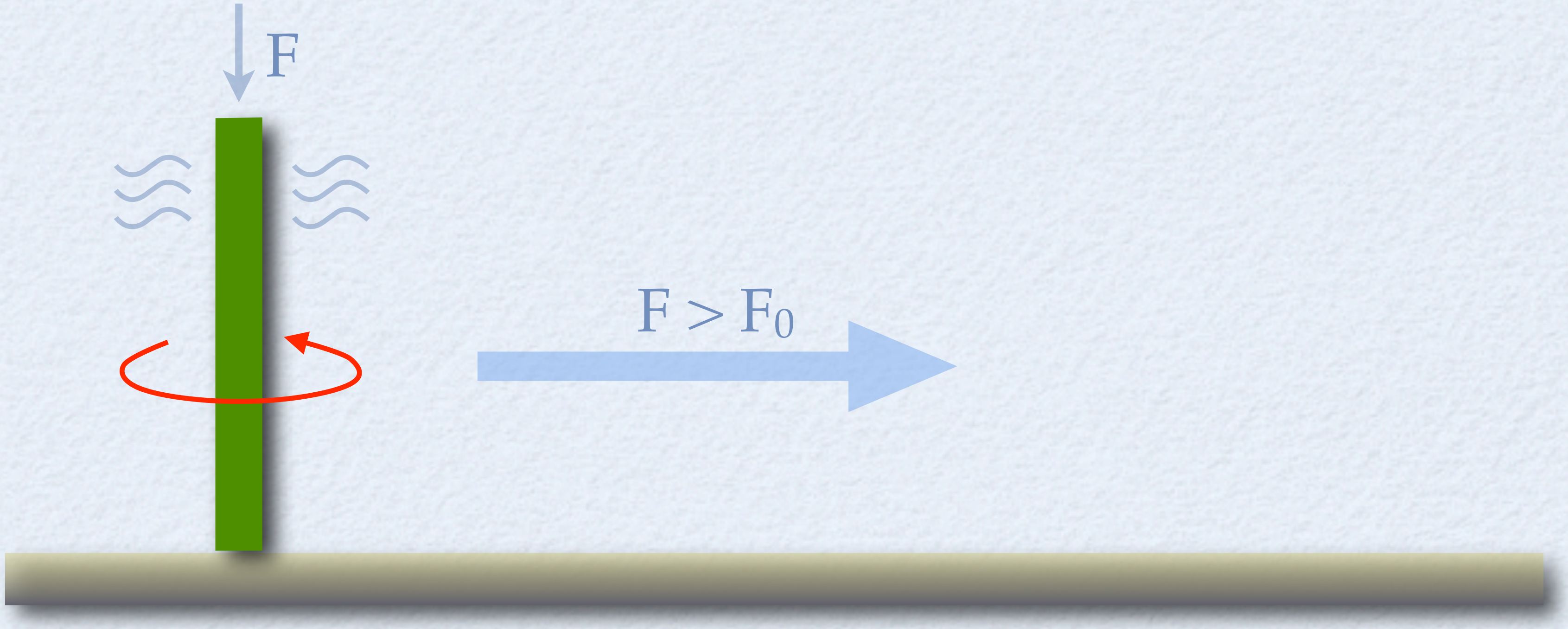

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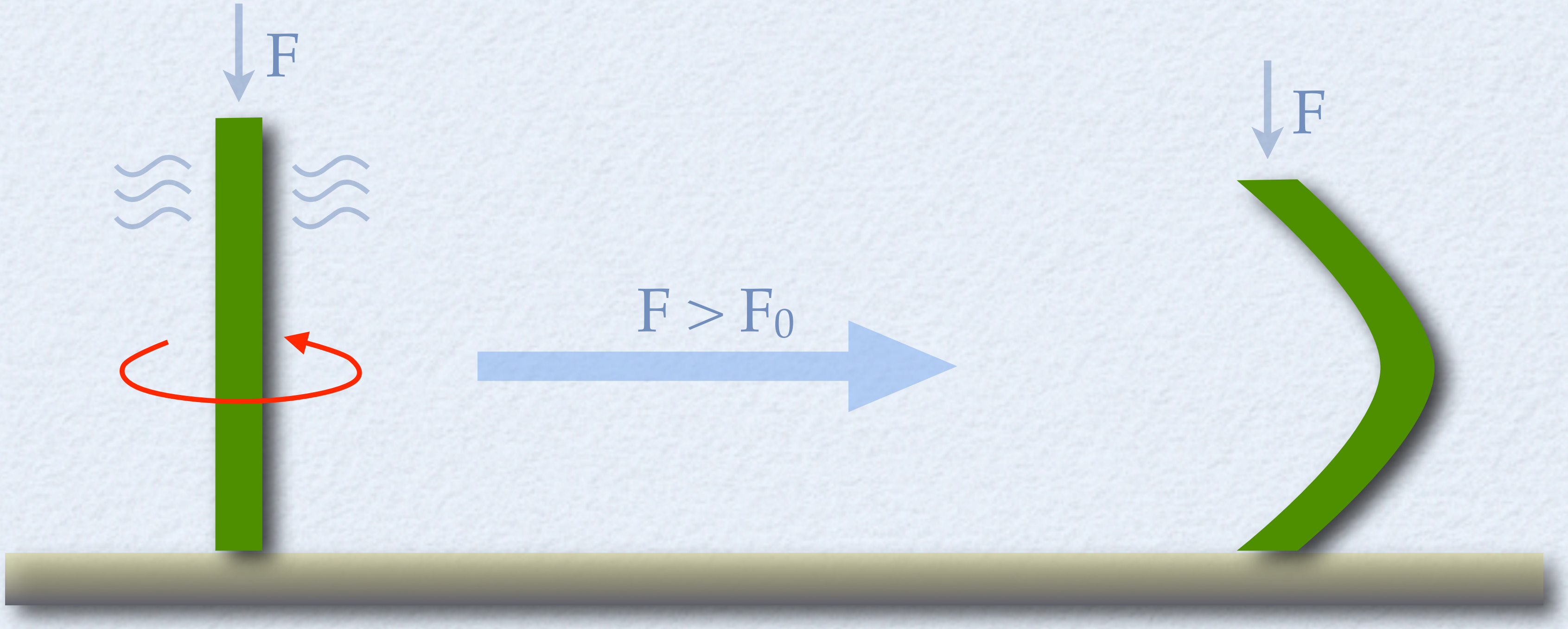

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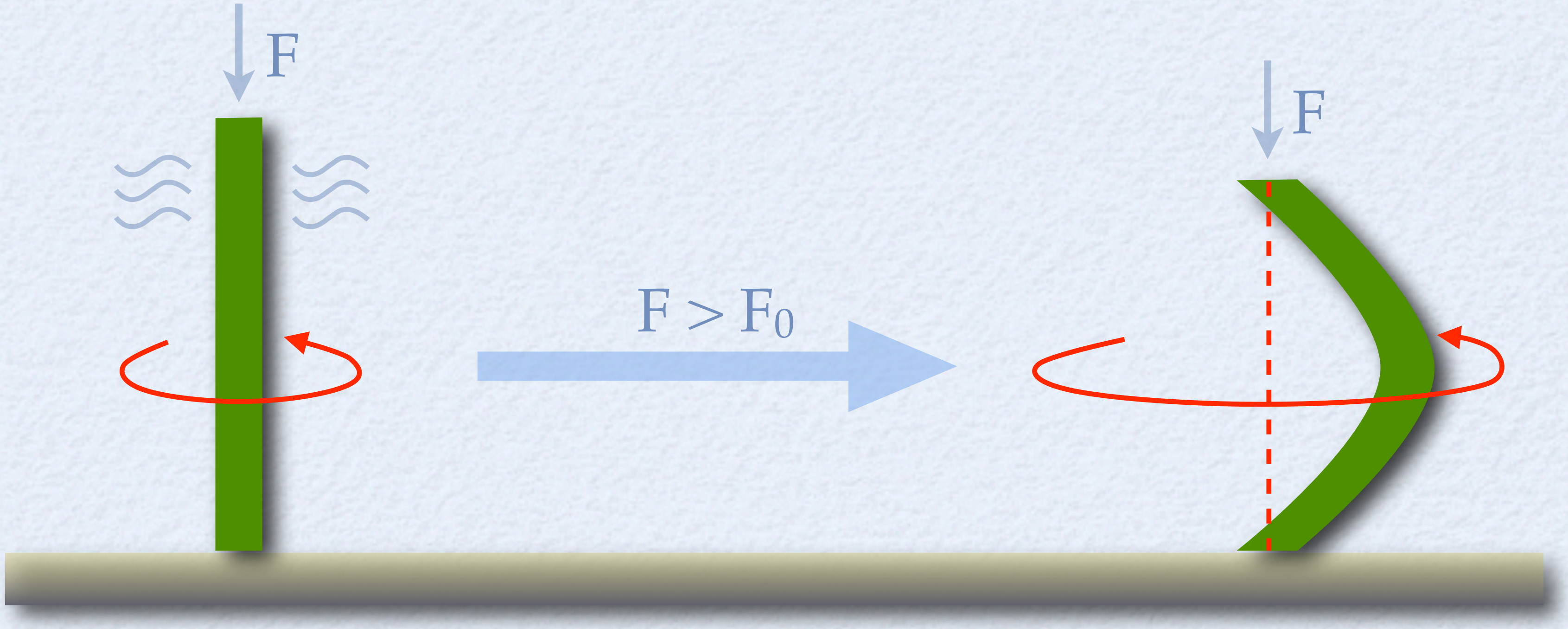

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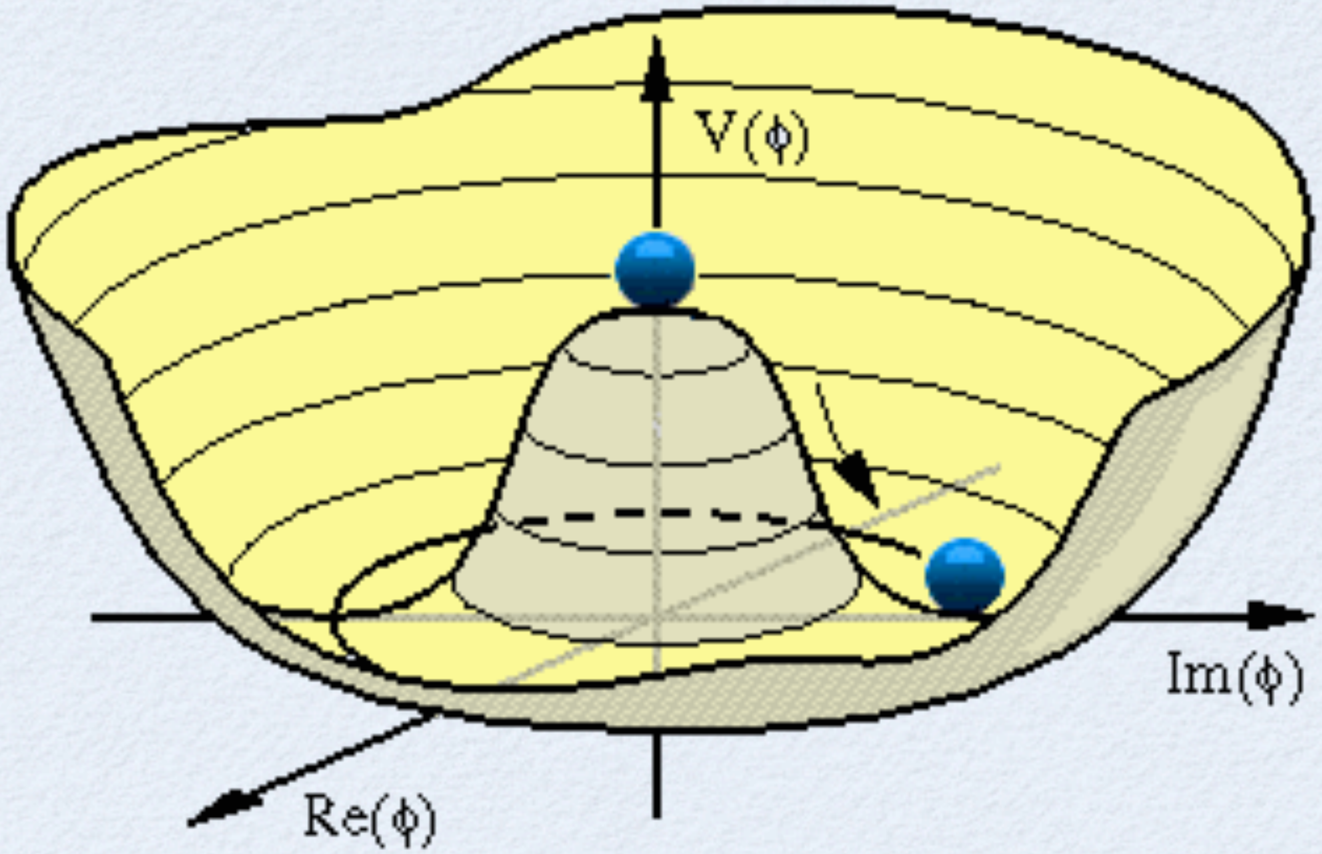


- A scalar SU(2) doublet (Φ) acquires a non-vanishing constant value over the whole space (v.e.v.)
- The W and Z become massive
- A neutral scalar particle of unknown mass emerges (h)

THE HIGGS MECHANISM

- The Higgs is a SU(2) doublet with a vev:

$$\mathcal{L}_Y = \bar{Q}_L Y_d H d_R + \bar{Q}_L Y_u H^\dagger u_R + \text{h.c.}$$

after EWSB

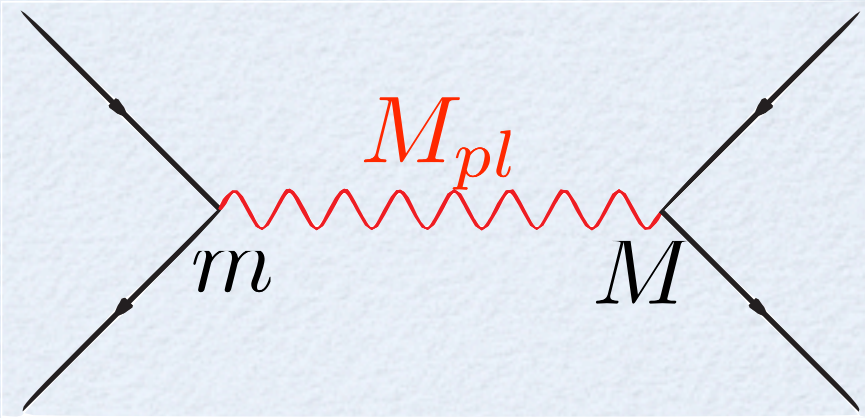
$$\mathcal{L}_m = \bar{d}_L (v Y_d) d_R + \bar{u}_L (v Y_u) u_R + \text{h.c.}$$

OPEN QUESTIONS

GRAVITY

- General Relativity is hard to quantize:
  - naive approaches fail
  - loop gravity, superstrings theories
- Typical scale associated with gravity:

$$V = G_N\frac{mM}{r}$$

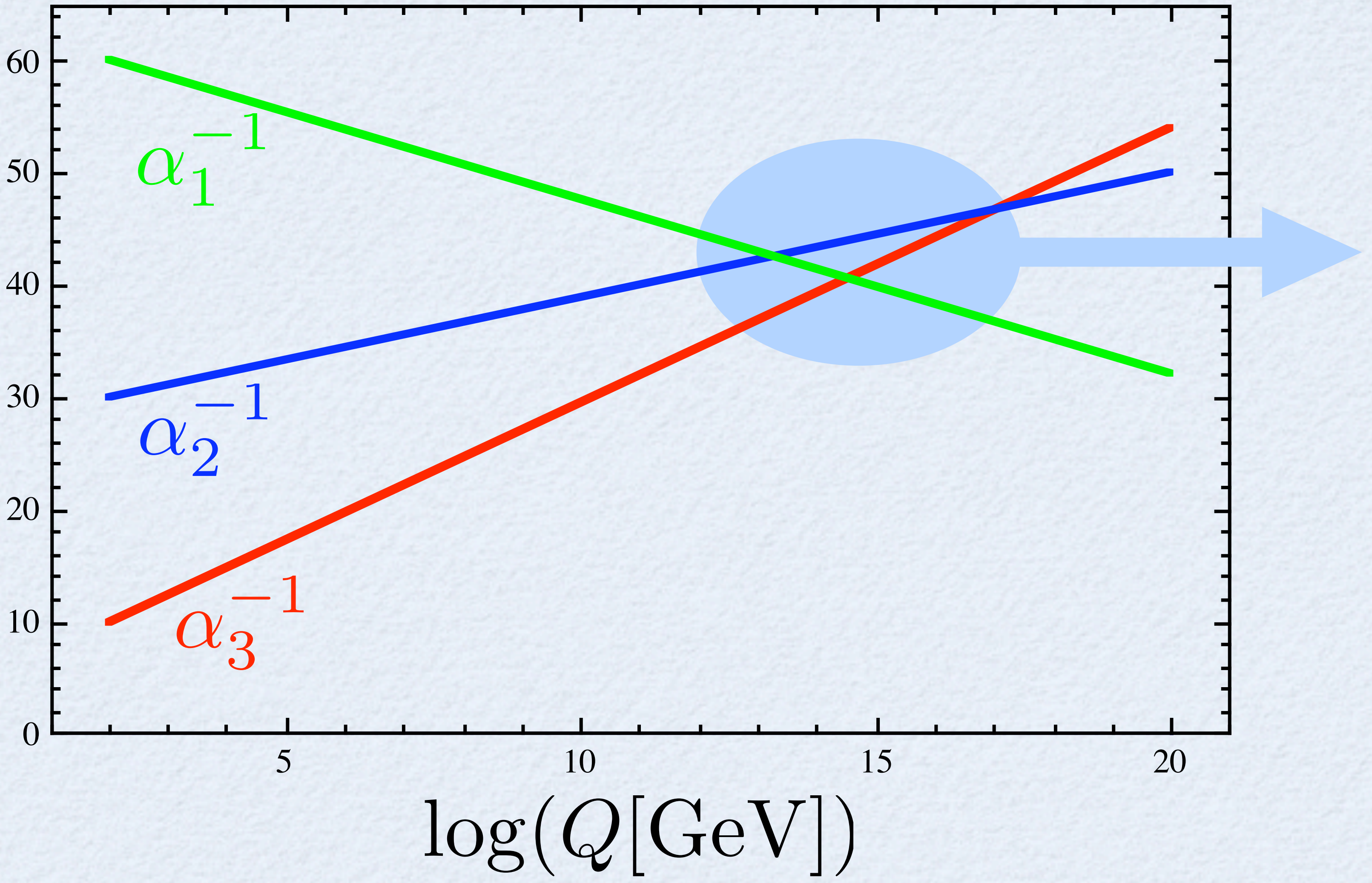


$$\sim \frac{mM}{M_{pl}^2}\cdot\frac{1}{r}$$

$$M_{pl} = G_N^{-1/2} = 1.22\times 10^{19}\ \mathrm{GeV}$$

GRAND UNIFICATION

- The strength of the SM interactions depend strongly on the energies (Q) of the interacting particles



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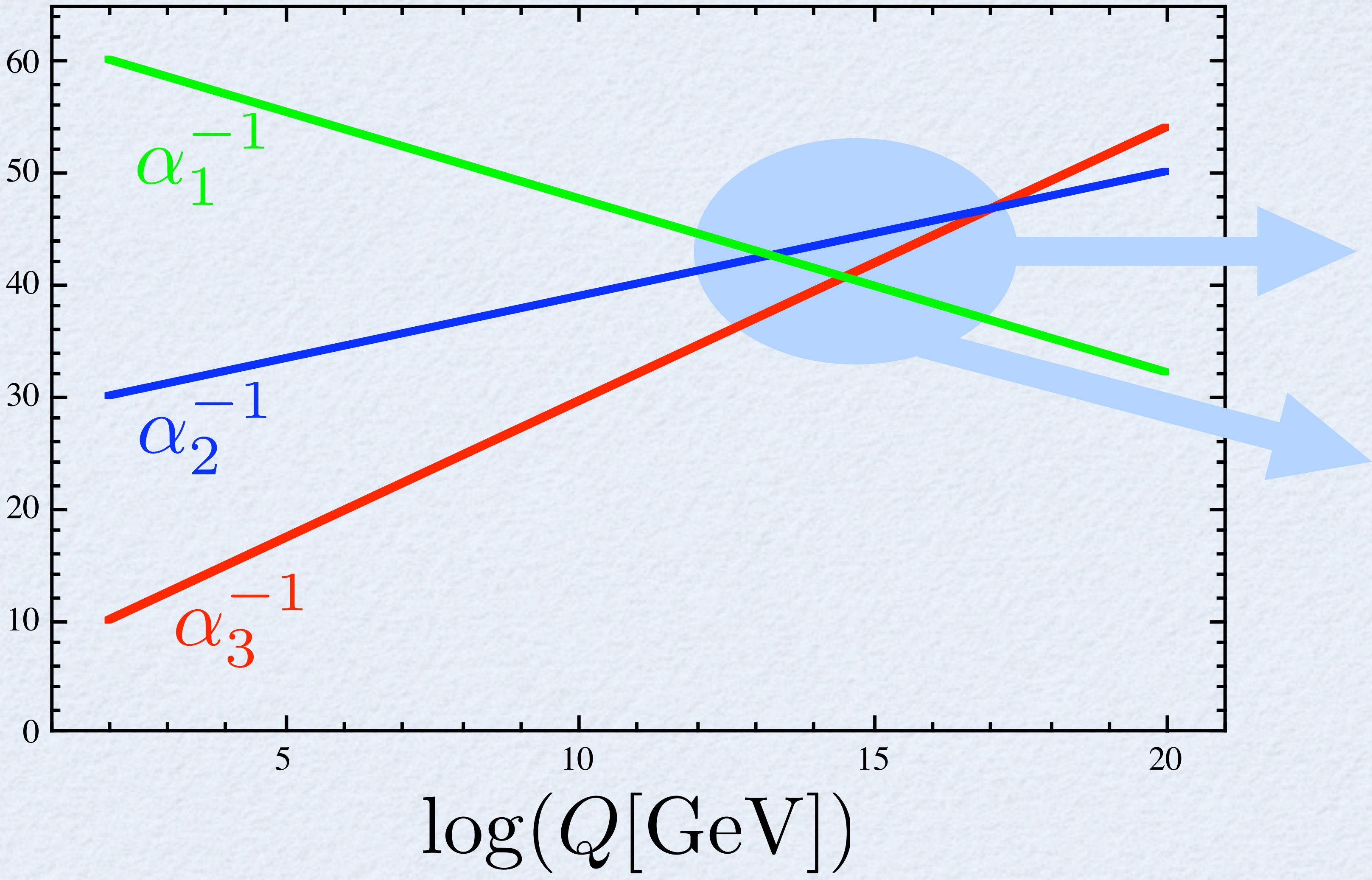
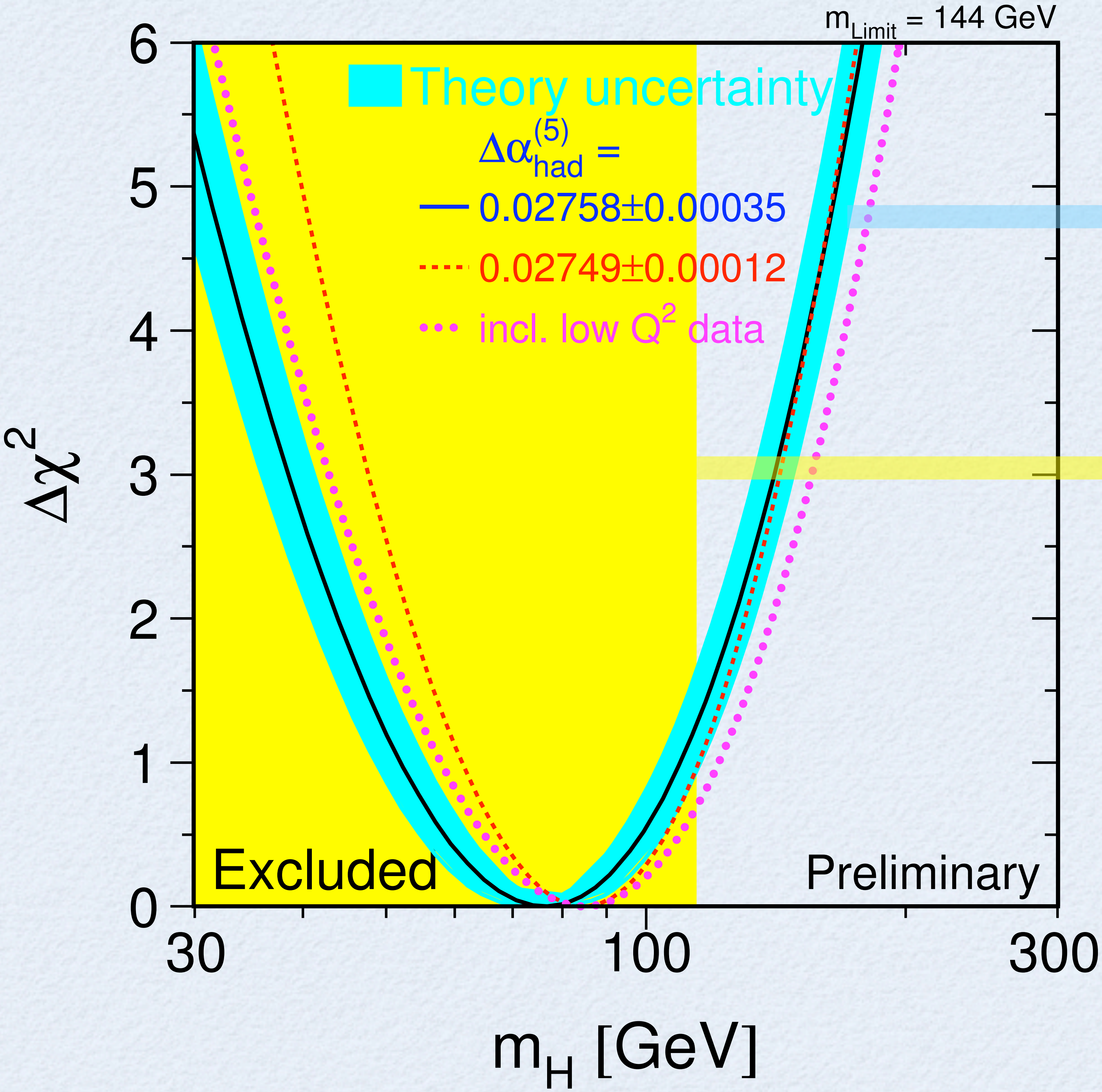


$M_{GUT} \sim 10^{16}$ GeV

Not quite unified

HIGGS ?



Indirect

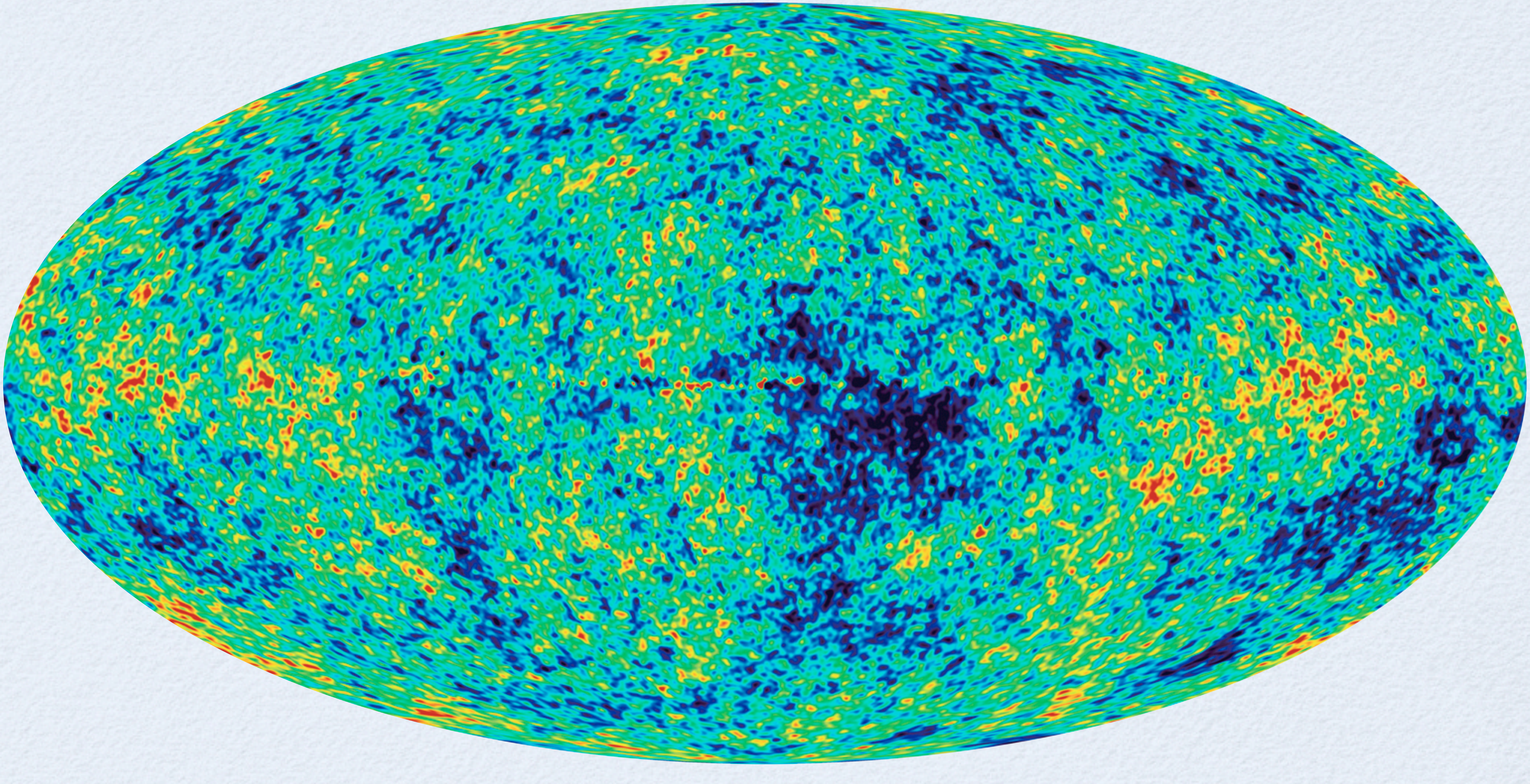
Direct

HIERARCHY PROBLEM

- Embed the SM into a theory that contains very large scales (M_{pl}, M_{GUT})
- Quantum fluctuations produce enormous masses for all particles not protected by a symmetry
- Fermions are protected by chirality, Gauge bosons receive masses close to the Higgs vev, the Higgs boson is unprotected:

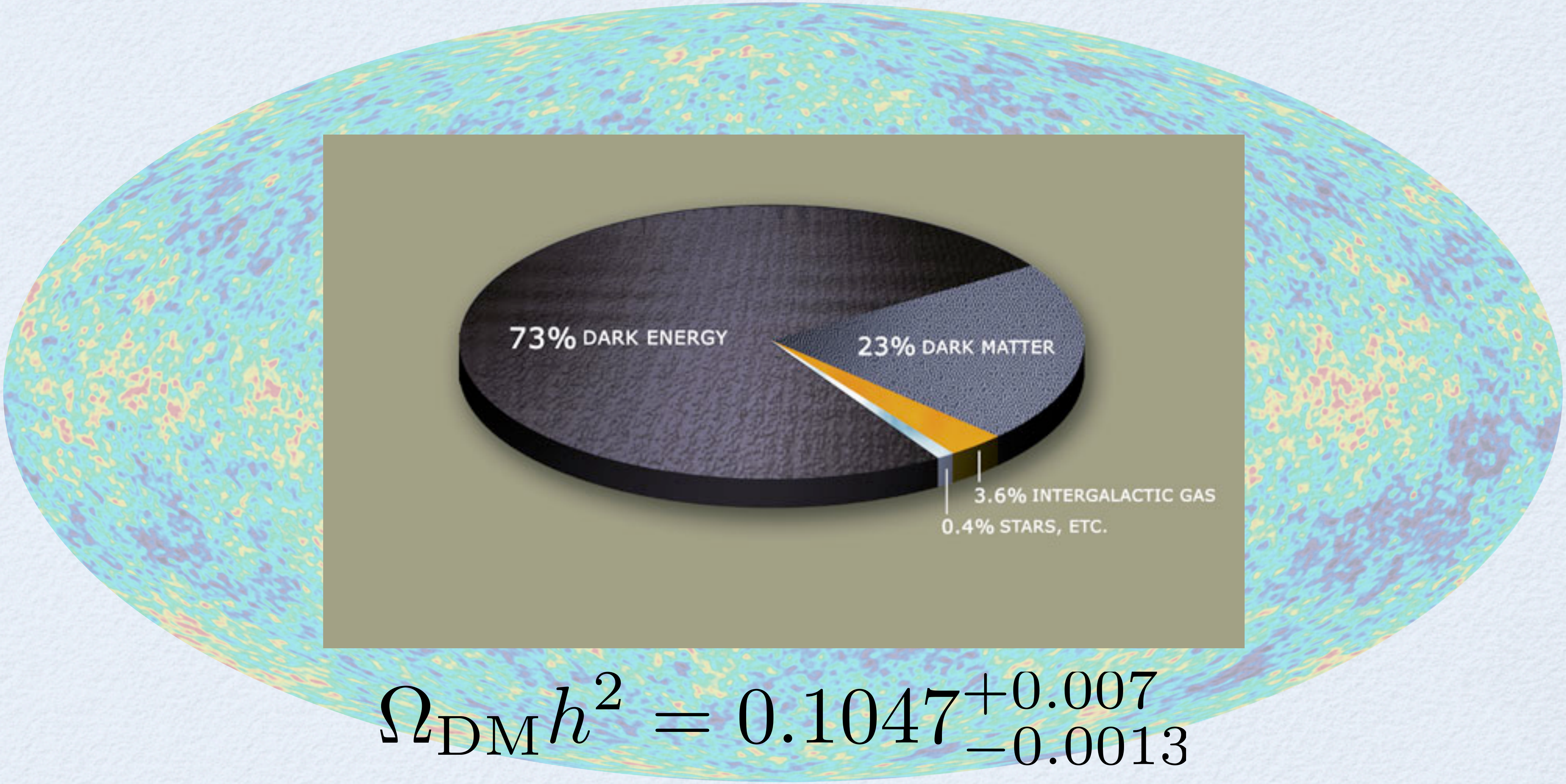
$$\begin{aligned} \delta m_H &\sim M_{GUT} \sim 10^{16}\ \mathrm{GeV} \\ (m_H)_{\mathrm{fit}} &\sim 10^2\ \mathrm{GeV} \end{aligned}$$

DARK MATTER



WMAP

DARK MATTER



$$\Omega_{\mathrm{DM}} h^2 = 0.1047^{+0.007}_{-0.0013}$$

PARAMETERS

- The Gauge part of the SM depends on 4 parameters:

$$\alpha_1,\ \alpha_2,\ \alpha_3,\ \theta_{\rm QCD}$$

- Electroweak Symmetry Breaking introduces other 15 parameters:

$$m_e,\ m_\mu,\ m_\tau,\ m_u,\ m_d,\ m_s,\ m_c,\ m_b,\ m_t$$

$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$$m_H,\ \langle H \rangle$$

FLAVOR VIOLATION

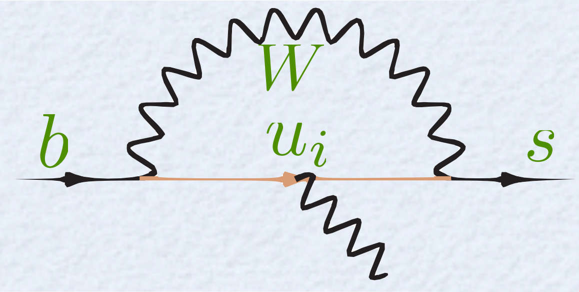
- Yukawa Lagrangian: $\mathcal{L}_Y = \bar{Q}^0_L Y_d H d^0_R + \bar{Q}^0_L Y_u H^\dagger u^0_R + \text{h.c.}$
- Gauge interactions: $\mathcal{L}_{\text{gauge}} \sim \bar{u}^0_L \not{W} d^0_L + \bar{u}^0 \not{Z} u^0 + \bar{d}^0 \not{Z} d^0$
- Quark Mass Eigenstate Basis:

  $u_A = U_A u^0_A$ and $d_A = D_A d^0_A$ (A=L,R)

  $\mathcal{L}_{\text{gauge}} \sim \bar{u}_L V_{\text{CKM}} \not{W} d_L + \bar{u} \not{Z} u + \bar{d} \not{Z} d$ with $V_{\text{CKM}} = U_L D_L^\dagger$
- Of the four initial unitary matrices ($U_{L,R}$ and $D_{L,R}$), only one is observable (V_{CKM})

FLAVOR VIOLATION

- No Flavor Changing Neutral Currents at tree level
- FCNC suppressed also at the loop level (GIM):



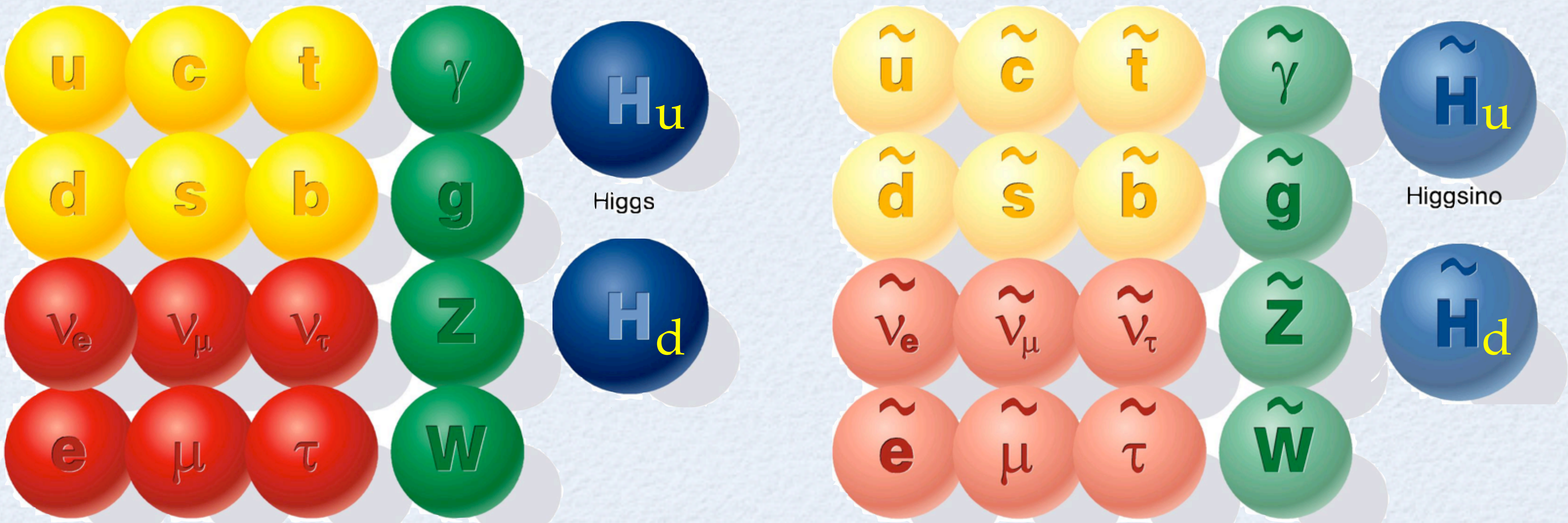
$$\propto V_{ib}V_{is}^{*}\, f\left(\frac{m_{u_i}^2}{m_W^2}\right) \sim V_{tb}V_{ts}^{*}\left[f\left(\frac{m_t^2}{m_W^2}\right) - f(0)\right]$$

- These features have fantastic experimental implications and are a consequence of the (arbitrary) decision of introducing only one Higgs doublet

POSSIBLE SOLUTIONS

SUPERSYMMETRY

- Double number of particles (degrees of freedom)
- New symmetry at the TeV scale protects the Higgs mass
- Lightest sparticle provides a dark matter candidate
- Exact unification of em, weak and strong interactions
- Relieves the tension between direct and indirect Higgs bounds



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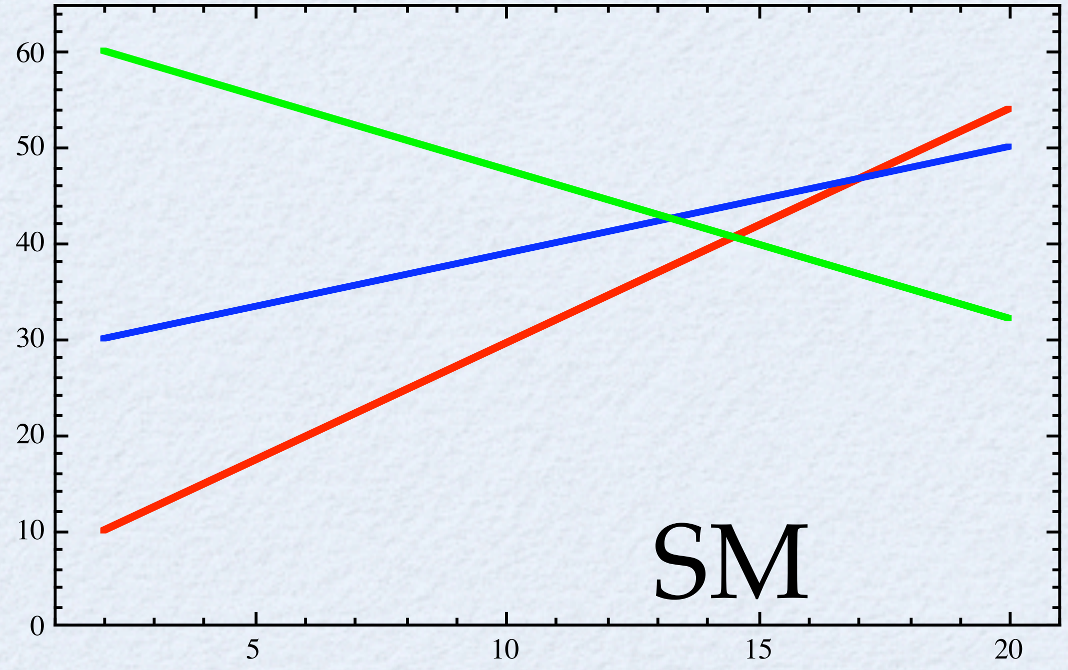

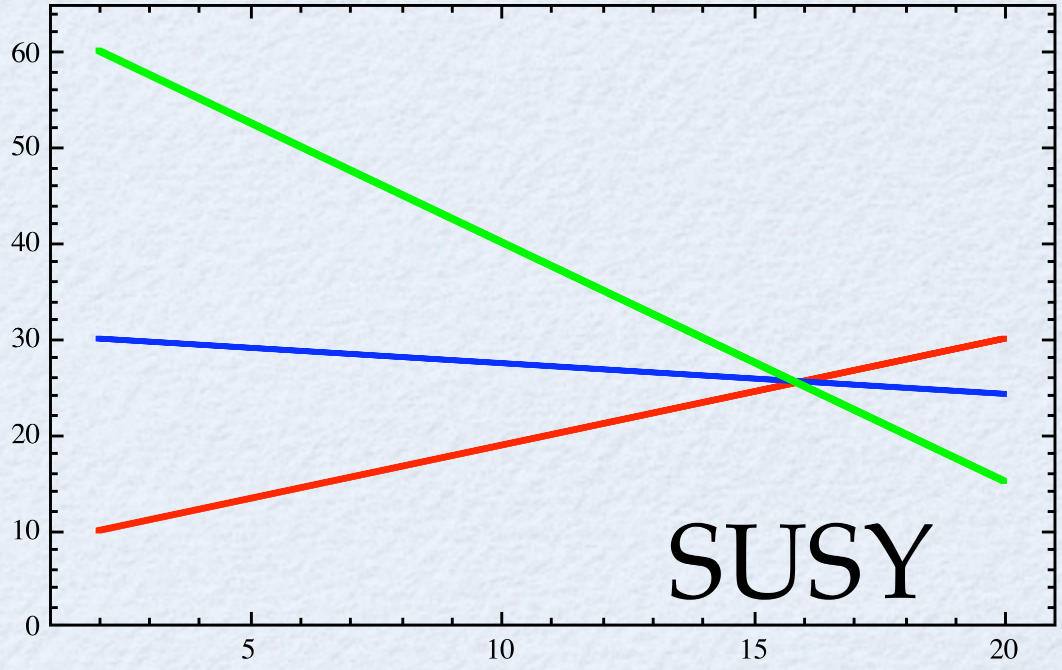

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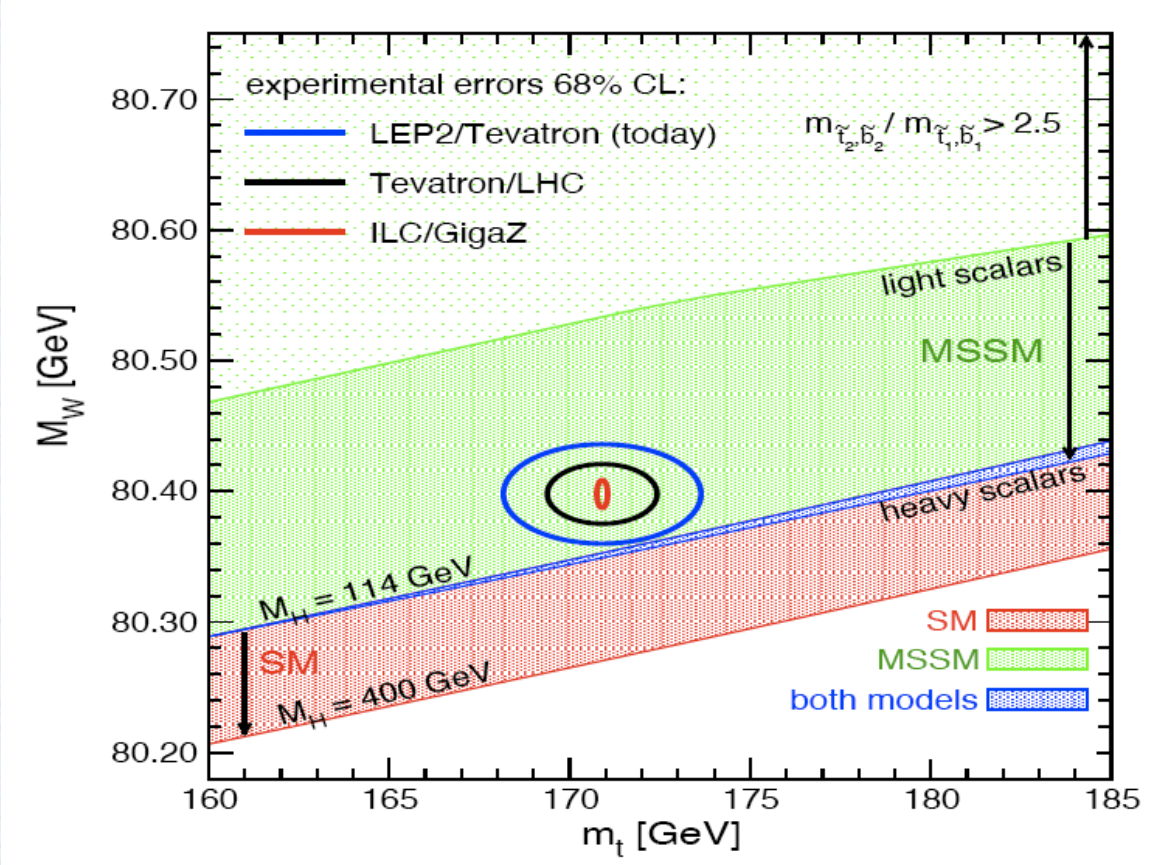
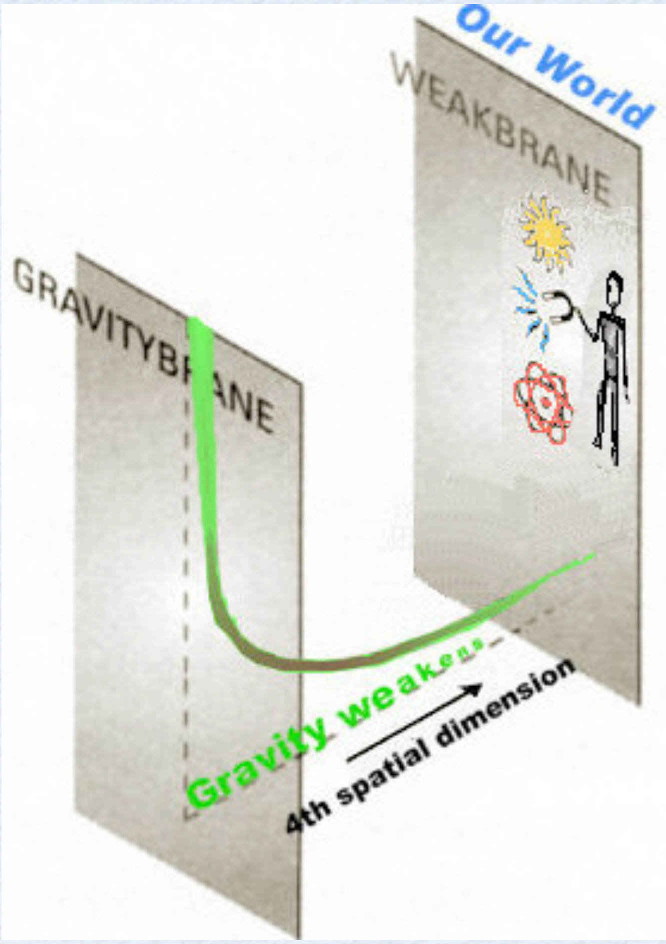


- indirect
- direct SM
- direct MSSM

OTHER OPTIONS



- Extra Dimensions
  - Elimination of the Planck scale
  - Some of the other problems can be tackled

$$M_{pl} = M_{EW}\ e^{kr_c\pi}$$

- Technicolor

  Higgs as a bound state of a strong force at the TeV scale

- Little Higgs

  Higgs as a pseudo-Goldstone boson
  "Modern incarnation of technicolor"

COMPLEMENTARITY

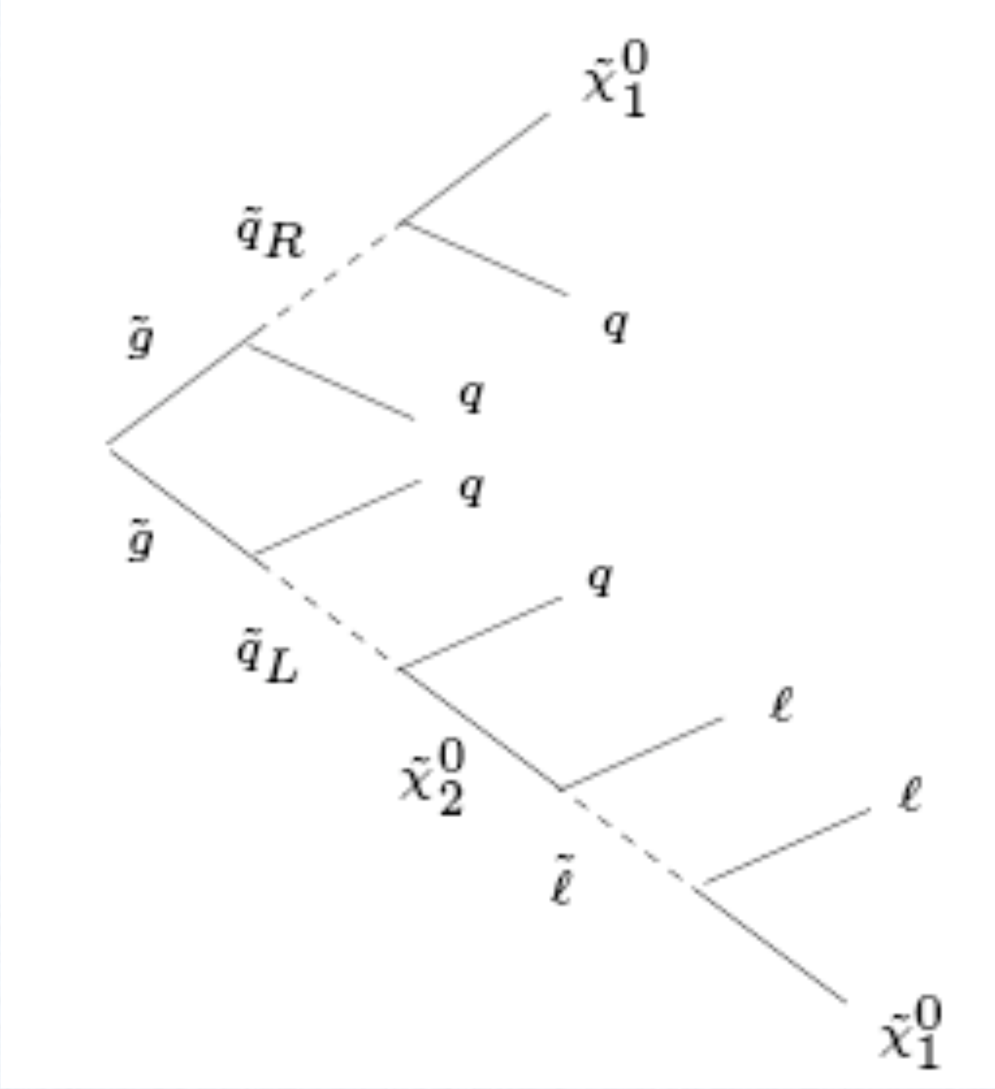
- ***Direct detection*** at Colliders (Tevatron, LHC)

- ***Indirect detection*** at *B* factories (BaBar, Belle), LHCb, super-*B* factories, rare *K* decays, Project-X, CLEO-c, LFV experiments (MEG),...

- ***Cosmology***: dark matter relic density, direct dark matter detection (CDMS,...)

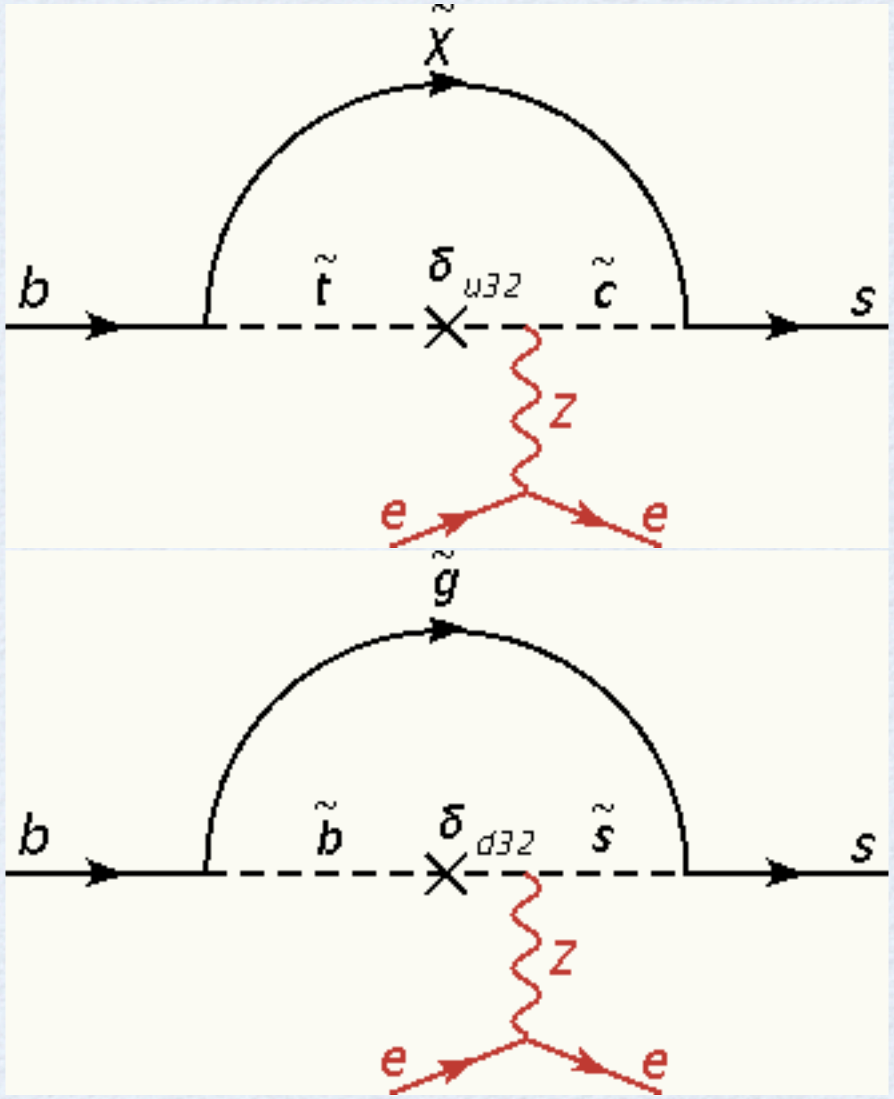
COMPLEMENTARITY

Direct detection



Establish new particles

Indirect detection



Quantum structure

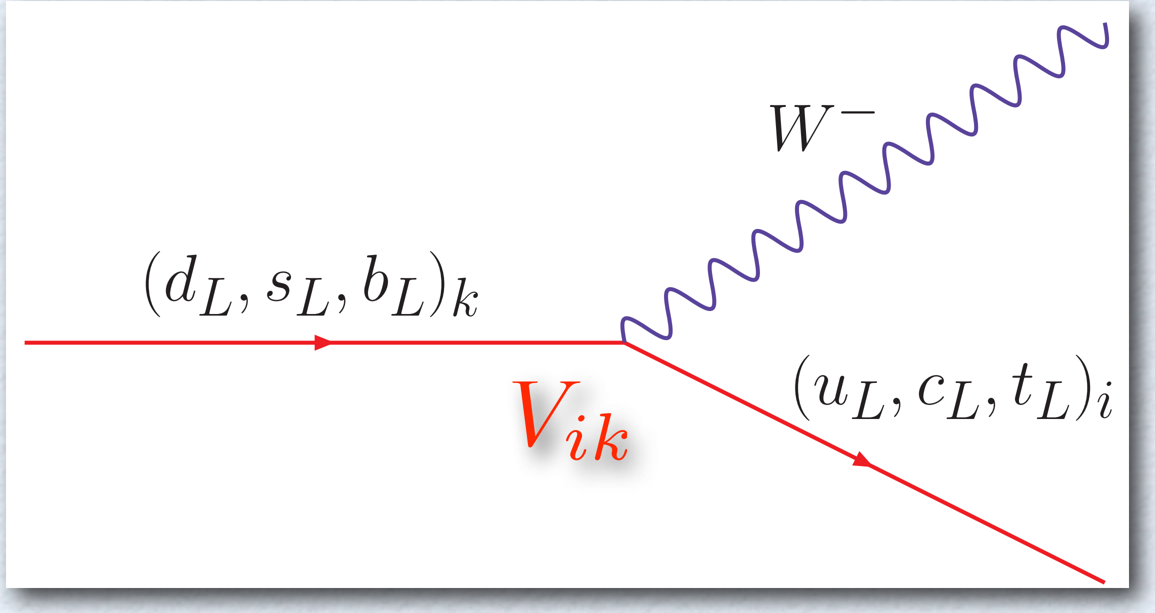
STATUS OF NEW PHYSICS SEARCHES

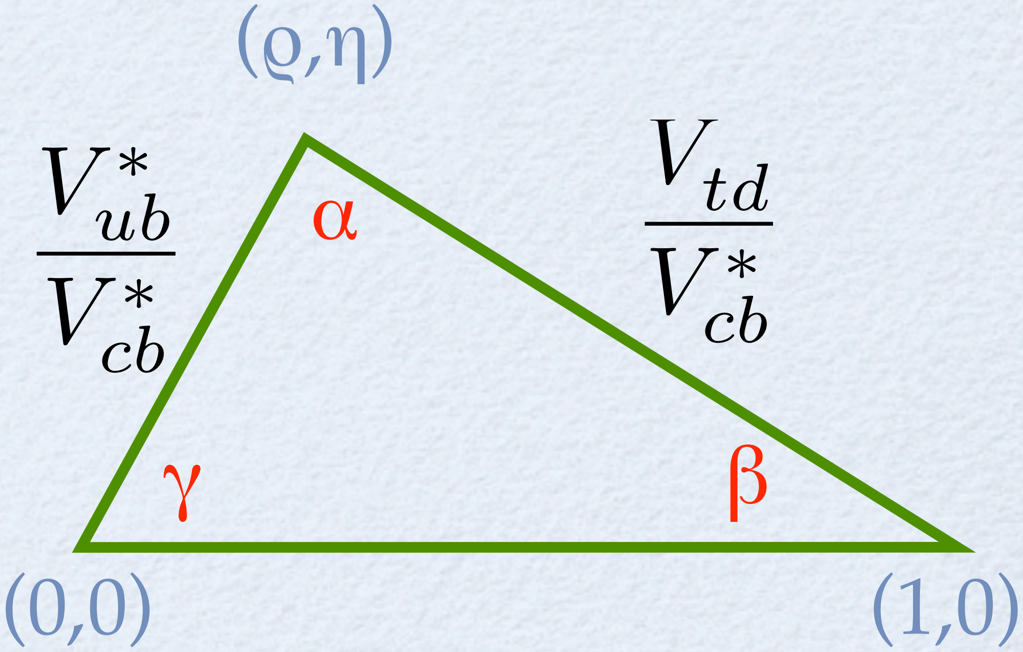
Electroweak Fits

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ^0_{had} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21586
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.374
Γ_W [GeV]	2.140 ± 0.060	2.091
m_t [GeV]	170.9 ± 1.8	171.3

UNITARITY TRIANGLE

- Unitarity of the CKM matrix implies relations between the various elements
- Focus on the smallest elements
- $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$





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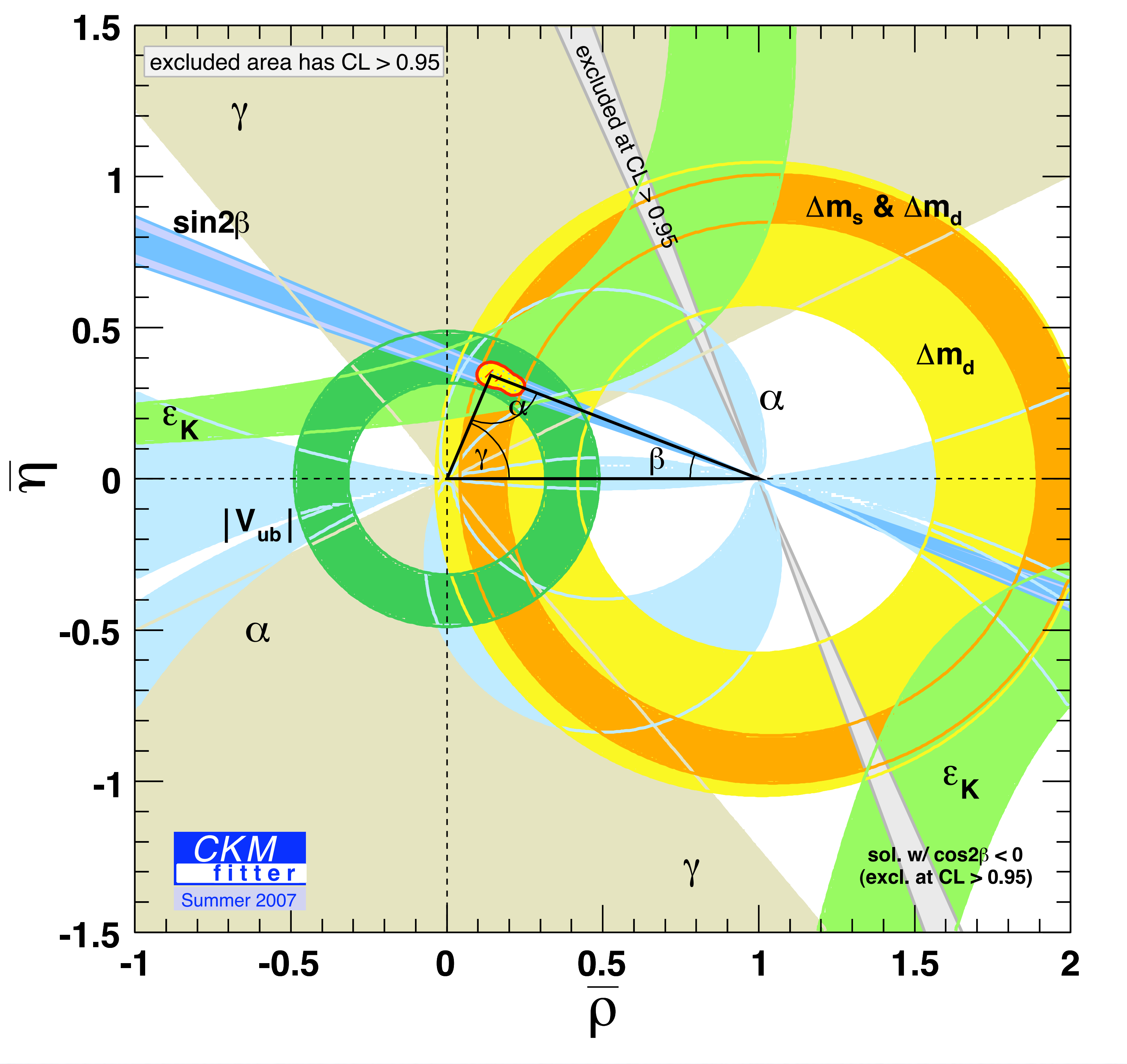

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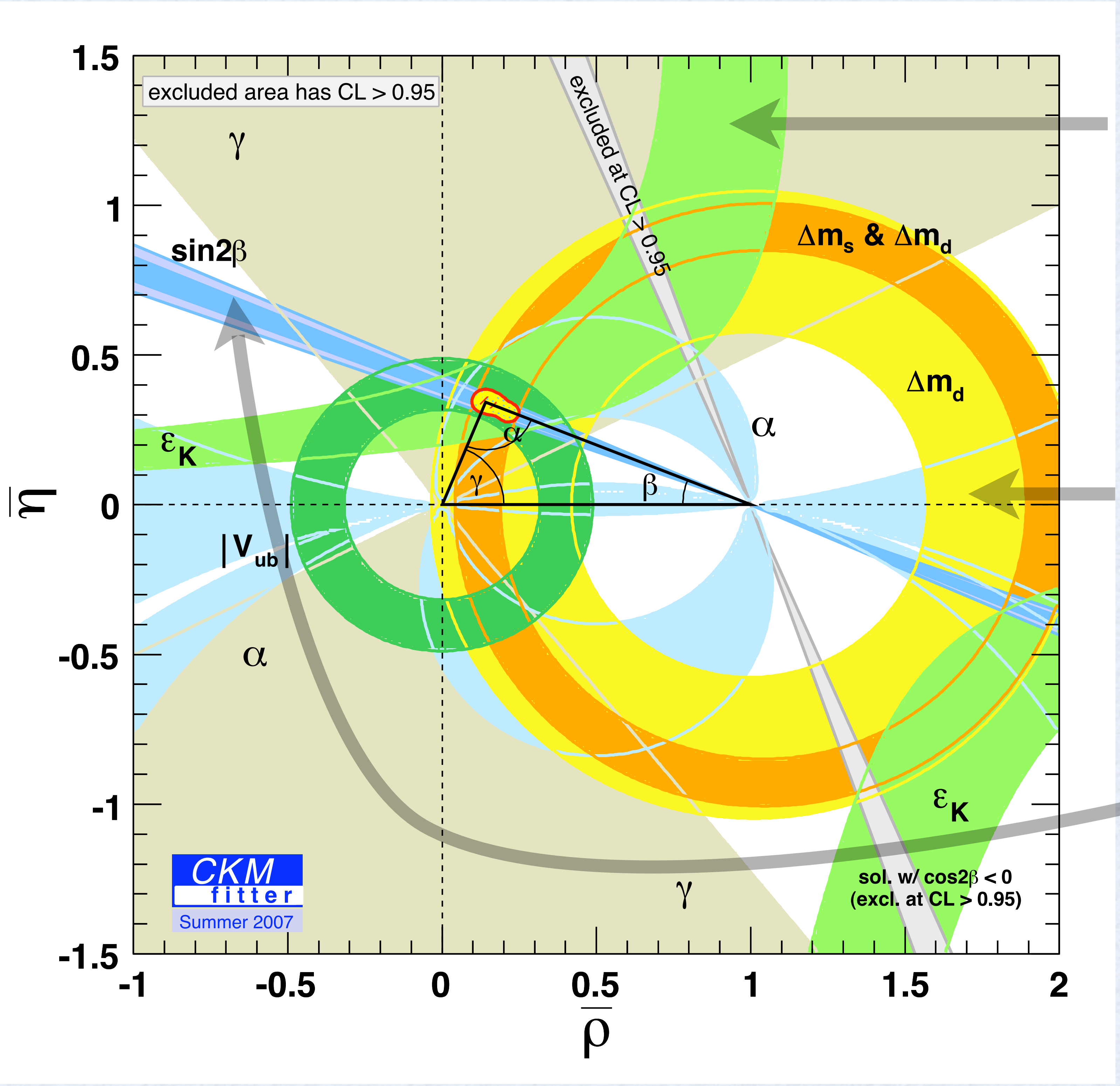
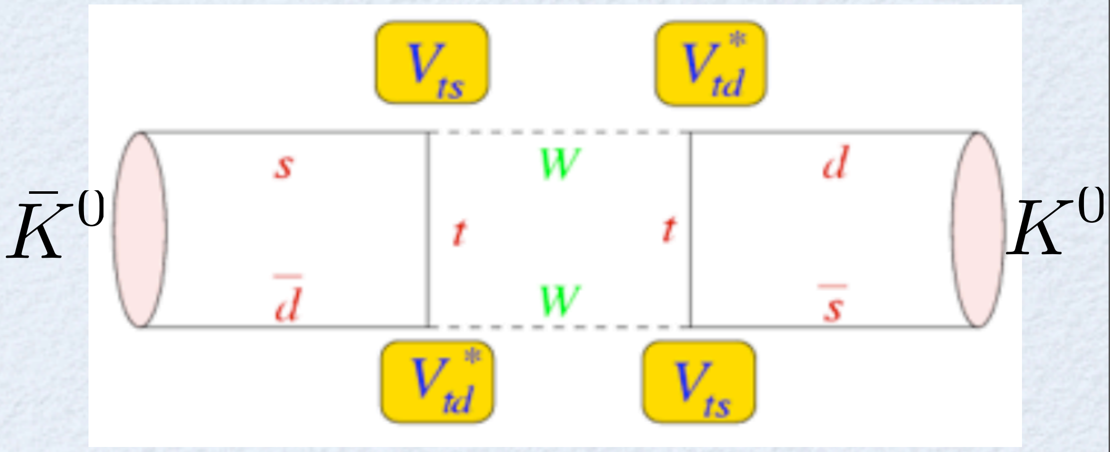
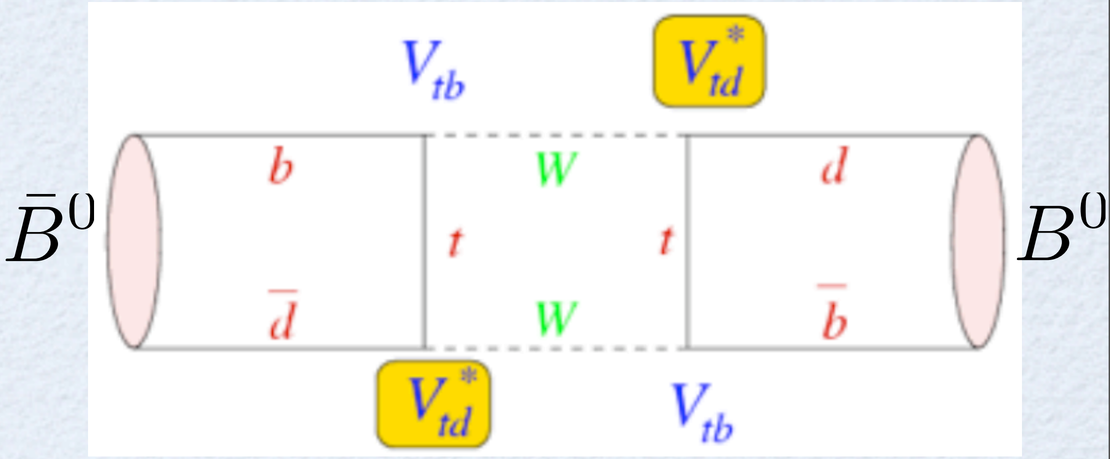
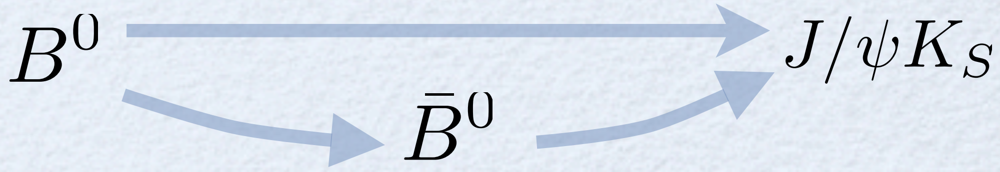








$$\begin{tikzcd}
B^0 \arrow[rr] \arrow[dr, bend right] & & J/\psi K_S \\
& \bar{B}^0 \arrow[ur, bend right] &
\end{tikzcd}$$

HINTS FOR NEW PHYSICS!

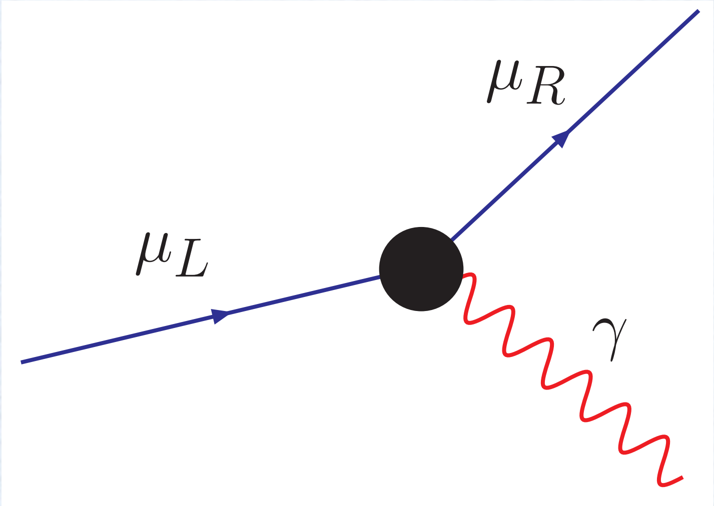
- Dark Matter relic density:

$$\Omega h^2 = 0.1047^{+0.007}_{-0.0013}$$ → 80 σ

- Muon anomalous magnetic moment

$$\begin{aligned} a_\mu^{\rm exp} &= 11659208(6) \times 10^{-10} \\ a_\mu^{\rm SM}(ee) &= 11659178(6) \times 10^{-10} \\ a_\mu^{\rm SM}(\tau) &= 11659179(7) \times 10^{-10} \end{aligned}$$

problem solved?



$$\delta a_\mu = (29.3 \pm 8.2) \times 10^{-10}$$ → 3.6 σ

LATEST FROM CLEO

- The width for $D_s \to \ell\nu$ is

$$\Gamma(D_s \to \ell\nu) = \frac{m_{D_s}}{8\pi} \left|G_F V_{cs}^* m_\ell\right| f_{D_s}^2 \left(1 - \frac{m_\ell^2}{m_{D_s}^2}\right)^2$$

- f_{Ds} is *extracted from data* and *lattice-QCD*:

$$\begin{aligned} (f_{D_s})_{\rm exp} &= (277 \pm 9)\mathrm{MeV} \quad \text{[CLEO]} \\ (f_{D_s})_{\rm QCD} &= (241 \pm 3)\mathrm{MeV} \quad \text{[HPQCD]} \end{aligned}$$

- The discrepancy is at the 3.8σ level

- Requires ***non-MFV*** new physics! leptoquarks,...

- Independent cross check of the lattice result needed

WHAT DOES THIS MEAN?

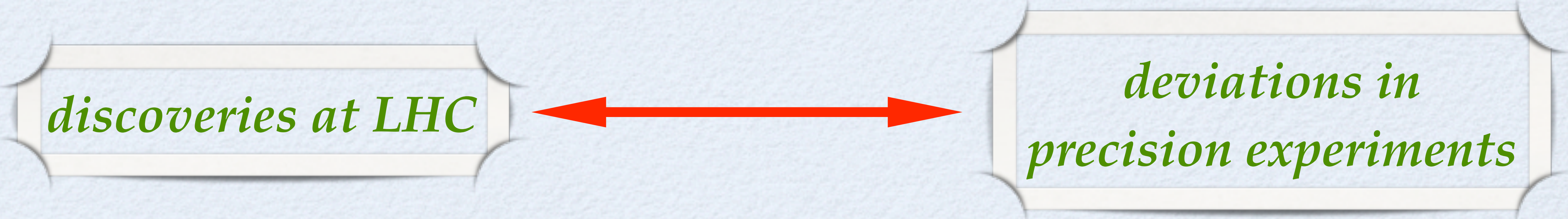
TWO SCENARIOS

TWO SCENARIOS

- *Decoupling*
  - New Physics is very heavy (>> TeV)
  - Arbitrary Flavor Changing couplings

Two Scenarios

- *Decoupling*
  - New Physics is very heavy (>> TeV)
  - Arbitrary Flavor Changing couplings
- *Minimal Flavor Violation*
  - The amazing agreement of *B* factories measurements with the SM predictions is a ***powerful test of the CKM mechanism***
  - Relatively light new particles with CKM-like couplings
  - Correlation between Tevatron/LHC results and low-energy data



discoveries at LHC ↔ ***deviations in precision experiments***

MINIMAL FLAVOR VIOLATION

- We adopt the definition of D'Ambrosio, Giudice, Isidori and Strumia: ***the only relevant information contained in the quark Yukawa's are the eigenvalues and the CKM matrix***:

  $$Y_U = D_L \, V^\dagger_{\mathrm{CKM}} \, \lambda_u^{diag} \, U_R \quad , \quad Y_D = D_L \, \lambda_d^{diag} \, D_R$$

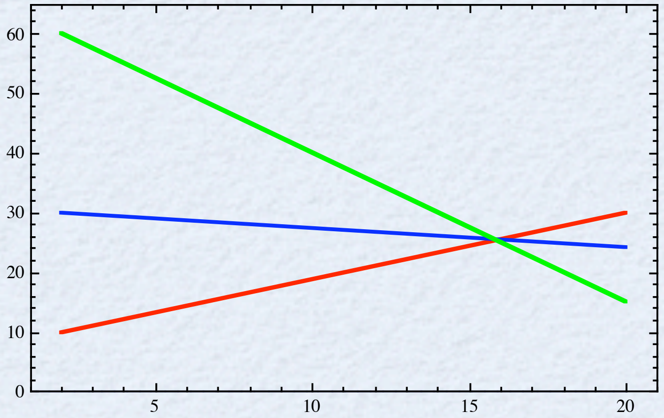
  where the matrices U_R, D_L and D_R are unphysical.

- Can be implemented as an *exact symmetry* of the theory (!)
- The structure of Flavor Changing Neutral Currents usually follows the CKM pattern
- If new physics is fairly light (< 1 TeV) deviations are unavoidable

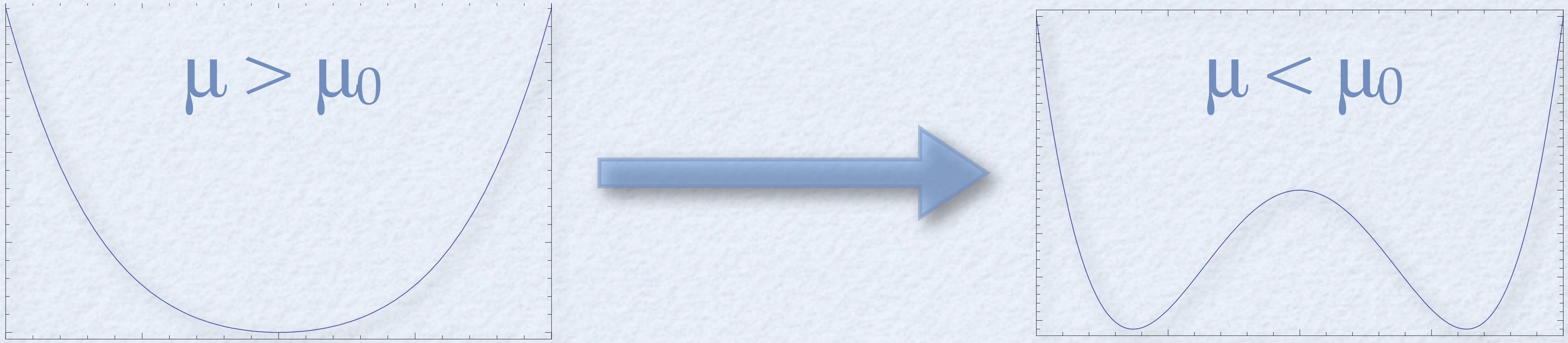
A JOURNEY IN SUSY:
HOW LIGHT CAN THE HIGGS SPECTRUM BE?

REALISTIC MODELS

- R-parity (dark matter candidate)
- Grand Unification



- Radiative ElectroWeak Symmetry Breaking



- Minimal Flavor Violation

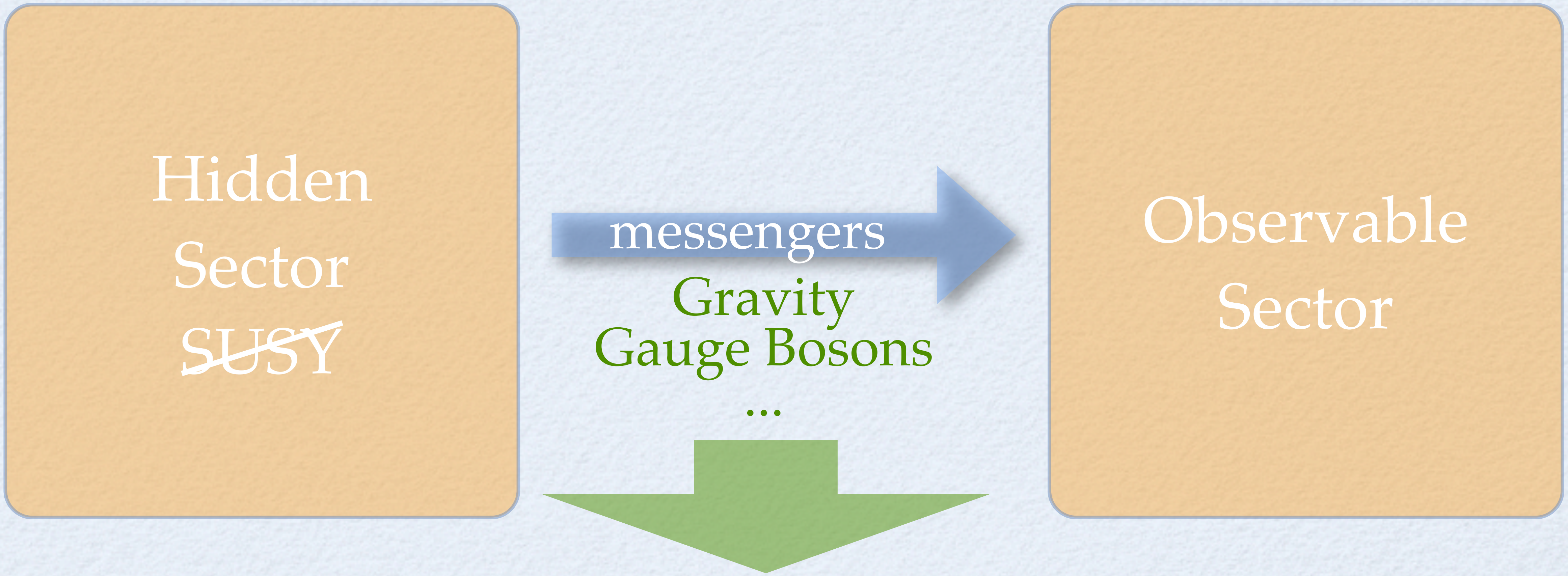
TWO HIGGS DOUBLETS

- Any supersymmetric model requires two Higgs doublets (**H_u,H_d**)
- The Higgs spectrum is much richer: three neutral Higgses (**h,H,A**) and one charged Higgs (**H^+**)
- There are two vev's: one for each doublet

$$\frac{\langle H_u^0 \rangle}{\langle H_d^0 \rangle} = \tan\beta$$

SUSY BREAKING

- Absence of super-partners degenerate in mass with the SM particles implies that SUSY must be spontaneously broken



Hidden
Sector
~~SUSY~~

messengers

Gravity
Gauge Bosons
...

Observable
Sector

Supergravity inspired MSSM (SUGRA)
Gauge Mediation (GM)
...

SOFT BREAKING TERMS

- Squark mass terms:

$$\mathcal{L}_{\text{soft}}^{squarks} = \tilde{Q}^{\dagger} M_{Q}^{2} \tilde{Q} + \tilde{U}^{\dagger} M_{U}^{2} \tilde{U} + \tilde{D}^{\dagger} M_{D}^{2} \tilde{D} + \tilde{Q} Y_{U}^{A} H_u \tilde{U} + \tilde{Q} Y_{D}^{A} H_d \tilde{D}$$

- Sleptons mass terms:

$$\mathcal{L}_{\text{soft}}^{sleptons} = \tilde{L}^{\dagger} M_{L}^{2} \tilde{L} + \tilde{E}^{\dagger} M_{E}^{2} \tilde{E} + \tilde{L} Y_{D}^{E} H_d \tilde{E}$$

- Gauginos mass terms:

$$\mathcal{L}_{\text{soft}}^{gauginos} = \frac{1}{2}\left(M_1 \tilde{B} B + M_2 \tilde{W} W + M_3 \tilde{g} g \right)$$

- Higgs mass terms:

$$\mathcal{L}_{\text{soft}}^{higgs} = \mu B H_1 H_2 + M_1^2 H_1^2 + M_2^2 H_2^2$$

MSSM WITH MFV

- General soft-breaking terms:

$$\begin{aligned}
\mathcal{L}^{squarks}_{\text{soft}} &= \tilde{Q}^\dagger M_Q^2 \tilde{Q} + \tilde{U}^\dagger M_U^2 \tilde{U} + \tilde{D}^\dagger M_D^2 \tilde{D} + \tilde{Q} Y_U^A H_u \tilde{U} + \tilde{Q} Y_D^A H_d \tilde{D} \\
\mathcal{L}^{sleptons}_{\text{soft}} &= \tilde{L}^\dagger M_L^2 \tilde{L} + \tilde{E}^\dagger M_E^2 \tilde{E} + \tilde{L} Y_D^E H_d \tilde{E} \\
\mathcal{L}^{gauginos}_{\text{soft}} &= \frac{1}{2}\left(M_1 \tilde{B} B + M_2 \tilde{W} W + M_3 \tilde{g} g \right) \\
\mathcal{L}^{higgs}_{\text{soft}} &= \mu B H_1 H_2 + M_1^2 H_1^2 + M_2^2 H_2^2
\end{aligned}$$

- MFV soft-breaking terms:

$$\begin{aligned}
M_Q^2 &= m_Q^2 \left(1 + b_1\, Y_U Y_U^\dagger + b_2\, Y_D Y_D^\dagger \right. \\
&\qquad \left. + b_3\, Y_D Y_D^\dagger\, Y_U Y_U^\dagger + b_4\, Y_U Y_U^\dagger\, Y_D Y_D^\dagger \right) \\
M_U^2 &= m_U^2\, (1 + b_5\, Y_U^\dagger Y_U) \\
M_D^2 &= m_D^2\, (1 + b_6\, Y_D^\dagger Y_D) \\
A_U &= a_U\, (1 + b_7\, Y_D Y_D^\dagger)\, Y_U \\
A_D &= a_D\, (1 + b_8\, Y_U Y_U^\dagger)\, Y_D
\end{aligned}$$

MSSM WITH MFV

- mSugra:

$$M_{1/2},\ M_0,\ A_0,\ \tan\beta,\ \mathrm{sign}(\mu)$$

- Non Universal Higgs Mass (NUHM) MSSM:

$$M_{1/2},\ M_0,\ M_{H_1},\ M_{H_2},\ A_0,\ \tan\beta,\ \mathrm{sign}(\mu)$$

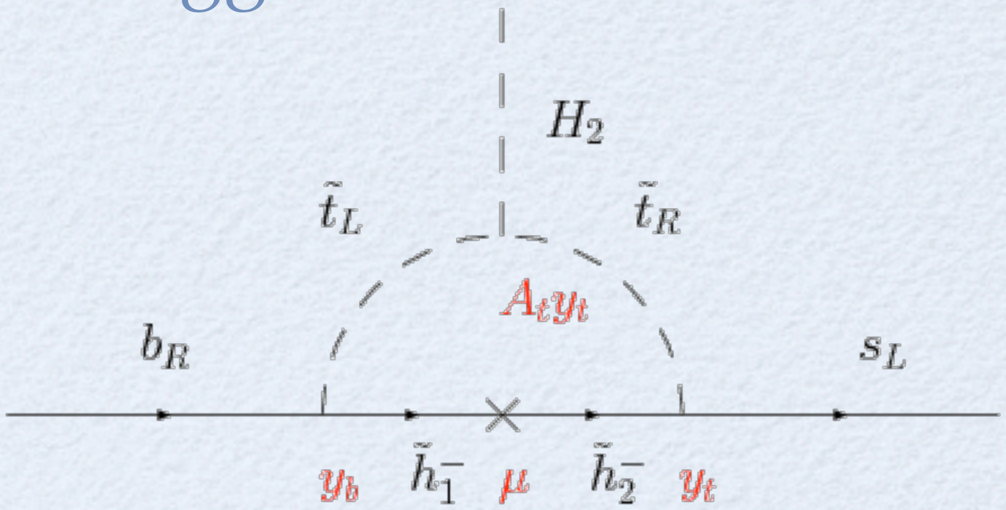
- Most general MFV MSSM:

$$(M_Q^2)_{ij} = M_Q^2\ \delta_{ij}, \quad (M_U^2)_{ij} = M_U^2\ \delta_{ij}, \quad (M_D^2)_{ij} = M_D^2\ \delta_{ij},$$
$$(M_L^2)_{ij} = M_L^2\ \delta_{ij}, \quad (M_E^2)_{ij} = M_E^2\ \delta_{ij}, \quad M_{H_1}^2, \quad M_{H_2}^2,$$
$$(Y_U^A)_{ij} = A_U e^{i\phi_{A_U}} (Y_U)_{ij}, \quad (Y_D^A)_{ij} = A_D e^{i\phi_{A_D}} (Y_D)_{ij},$$
$$(Y_E^A)_{ij} = A_E e^{i\phi_{A_E}} (Y_E)_{ij},$$

HIGGS-MEDIATED FCNC

- In the MSSM at large tanβ there are tree-level Higgs-mediated FCNC's:

$$\mathcal{L}_{\mathsf{Y}} \;=\; -\bar{d}_{\mathsf{L}} Y^{d} d_{\mathsf{R}} H_1 + \bar{d}_{\mathsf{L}} \left(\Delta Y^{d}\right) d_{\mathsf{R}} H_2^{*} \\ \qquad\quad +\bar{u}_{\mathsf{L}} Y^{u} u_{\mathsf{R}} H_2 + \bar{u}_{\mathsf{L}} \left(\Delta Y^{u}\right) u_{\mathsf{R}} H_1^{*}$$



- For instance the bR-sL-Higgs coupling reads:

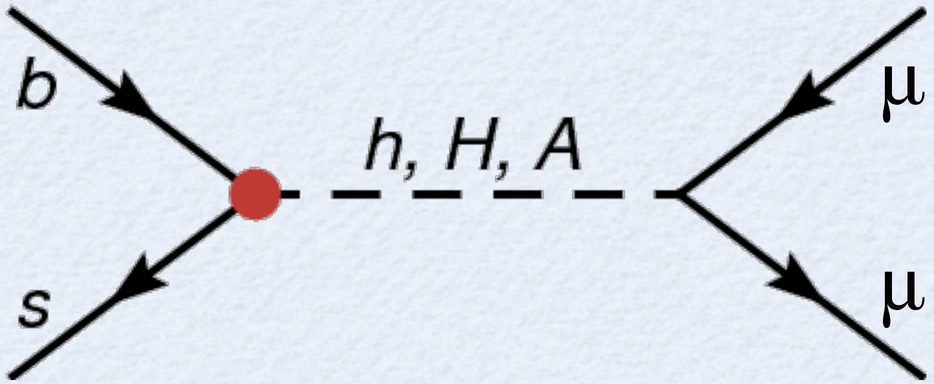
$$\mathcal{L}_S = \frac{i g_2}{2 M_W}\, m_b\, \frac{(\epsilon_Y^{\tilde{\chi}^-} + \epsilon_Y^{\tilde{g}}) V_{ts} \tan^2\beta}{(1+\epsilon_0 \tan\beta)^2}\, \bar{b}_R s_L S + h.c.$$

induced from RG running

- In SUSY models with Grand Unification and Minimal Flavor Violation:

$$\mathrm{sign}\left(\epsilon_Y^{\tilde{\chi}^-} / \epsilon_Y^{\tilde{g}}\right) < 0$$

$B_s \to \mu\mu$



$$\sim \tan^3 \beta / M_A^2$$

- The experimental bound and the SM predictions are:

$$BR(B_s \to \mu\mu)_{\rm exp} < 5.8 \times 10^{-8} \text{ at } 90\% \; C.L. \quad [CDF\&D0]$$

$$BR(B_s \to \mu\mu)_{\rm SM} = (3.8 \pm 1.0) \times 10^{-9}$$

- In GUT MFV SUSY models the branching ratio reads

$$\mathrm{BR}(B_s \to \mu^+\mu^-) \simeq \frac{4 \times 10^{-8}}{[1 + 0.5 \times \frac{\tan\beta}{50}]^4} \left[\frac{\tan\beta}{50}\right]^6 \left(\frac{160 \text{ GeV}}{M_A}\right)^4 \left(\frac{\epsilon_Y^{\tilde{\chi}^-} + \epsilon_Y^{\tilde{g}}}{4 \times 10^{-4}}\right)^4$$

- In our models the chargino contribution can easily be ~ 3 x 10^{-3}. The sum of chargino and gluino is naturally in the few x 10^{-4} range

OTHER OBSERVABLES

- Muon Anomalous Magnetic Moment:

$$\delta a^{\chi\tilde{\nu}}_{\mu^+} \simeq \frac{g_2^2}{32\pi^2}\frac{m_\mu^2}{m_{\tilde{\nu}}^2}\frac{\mathrm{Re}(\mu M_2)\tan\beta}{m_{\tilde{\nu}}^2}$$

$$\delta a_\mu = (29.3 \pm 8.2) \times 10^{-10}$$

3.6σ deviation

- B → τ ν

$$R(B \to \tau\nu) = \frac{\mathrm{BR}(B \to \tau\nu)^{\mathrm{SUSY}}}{\mathrm{BR}(B \to \tau\nu)^{\mathrm{SM}}} = \left(1 - \frac{m_B^2}{m_{H^\pm}^2}\frac{\tan^2\beta}{1+\epsilon_0\tan\beta}\right)^2$$

$$R(B \to \tau\nu)^{\mathrm{exp}} = 1.02 \pm 0.40$$

complete agreement

OTHER OBSERVABLES

- B → X_s γ

$$\mathcal{B}(B \to X_s\gamma)_{\rm exp} = (3.55 \pm 0.26) \times 10^{-4}$$

$$\mathcal{B}(B \to X_s\gamma)_{\rm SM} = (2.98 \pm 0.26) \times 10^{-4}$$

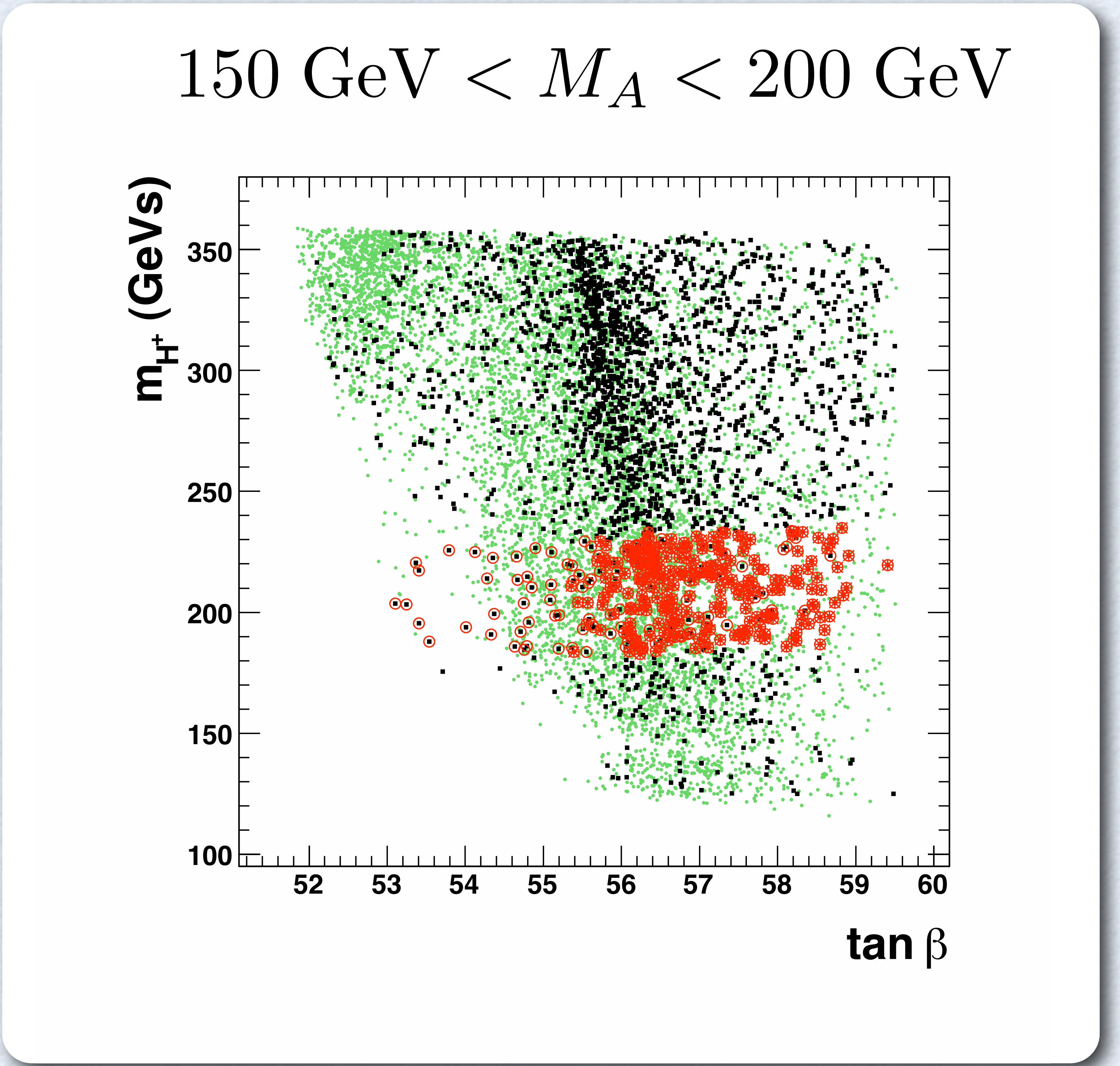
- Dark Matter relic density

$$\Omega h^2 < 0.13 \ (99\% \ \mathrm{C.L.})$$

- B_s mass difference

  Not a constraint in these models

MINIMAL SUPERGRAVITY

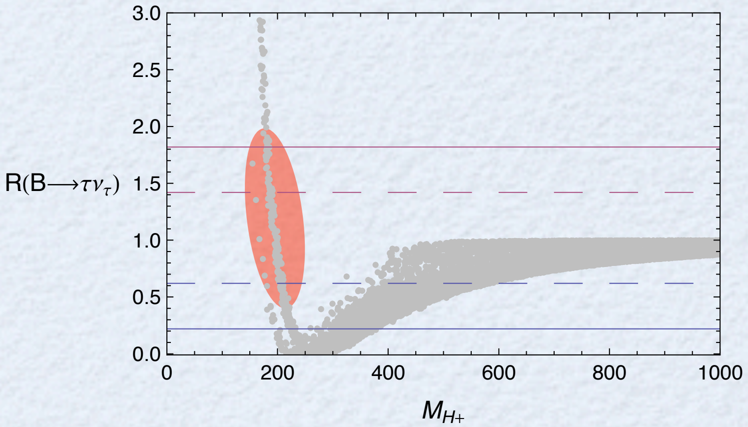


green: direct bounds

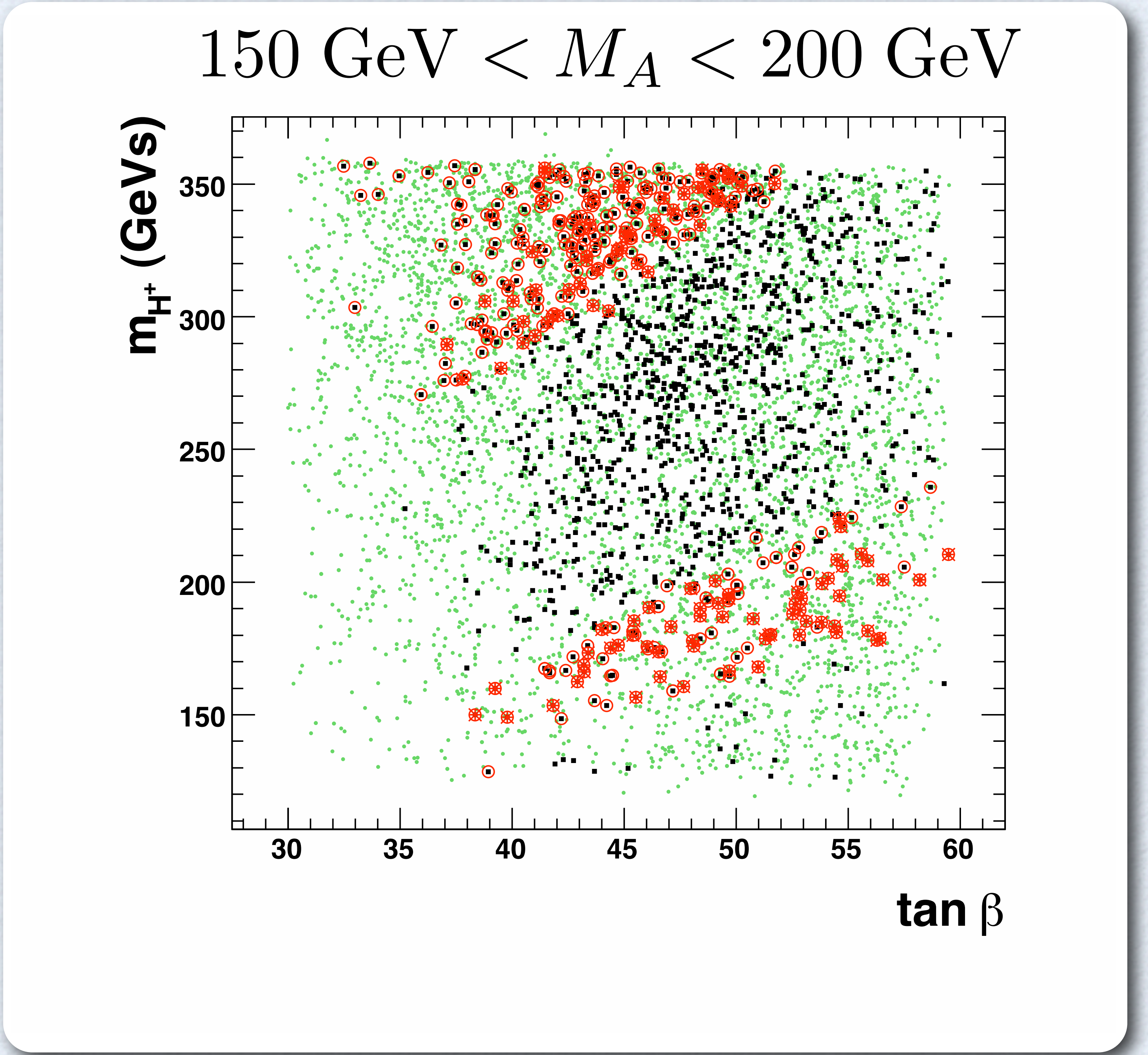
black: direct constraints
upper bound on Ωh^2

red: direct constraints
upper bound on Ωh^2
$B \to \tau\nu$

In the surviving region the $B \to \tau\nu$ amplitude is negative:



NON-UNIVERSAL HIGGS MASS



green: direct bounds

black: direct constraints
upper bound on Ωh²

red: direct constraints
upper bound on Ωh²
B→τν

We can have light Higgses with smaller tanβ
The B→τν amplitude can have both signs

COLLIDER IMPLICATIONS

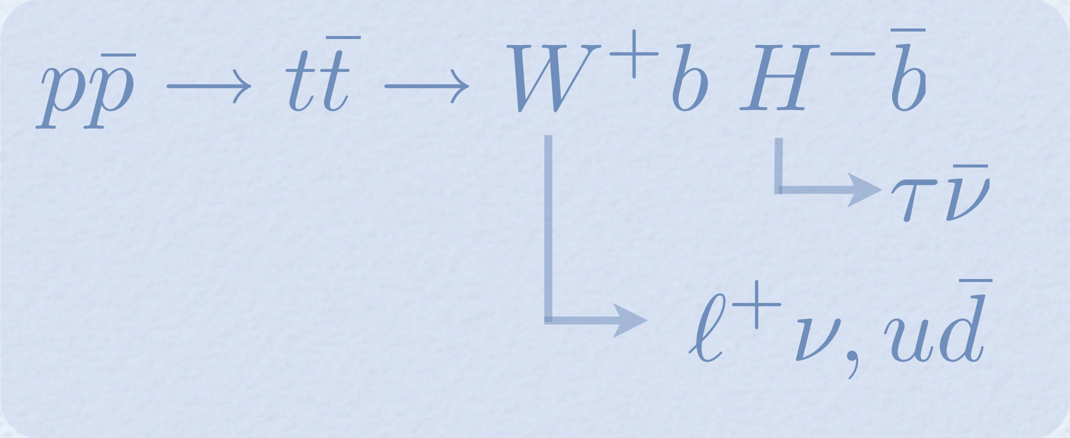
DIRECT SEARCHES AT COLLIDERS

	mass (GeV)		mass (GeV)
χ_1	130 – 180	χ_2	250 – 330
χ_3	430 – 540	χ_4	450 – 550
$\chi_1^\pm$	250 – 330	$\chi_2^\pm$	450 – 550
$\tilde g$	820 – 1050		
$\tilde t_1$	780 – 1050	$\tilde t_2$	890 – 1170
$\tilde b_1$	850 – 1150	$\tilde b_2$	930 – 1200
$\tilde u_R$	1160 – 1550	$\tilde u_L$	1180 – 1560
$\tilde d_R$	1150 – 1550	$\tilde d_L$	1170 – 1570
$\tilde \tau_1$	320 – 860	$\tilde \tau_2$	720 – 1160
$\tilde e_R$	900 – 1360	$\tilde e_L$	920 – 1380
$\tilde \nu_1$	700 – 1160	$\tilde \nu_3$	920 – 1380
h	112.4 – 115.6	H	165 – 200
A	165 – 200	$H^\pm$	150 – 210

- Light Higgs spectrum
- Light gauginos: in particular $m_{\tilde g} < m_{\tilde q}$ implies that we can have interesting signatures in 3-body ($\tilde g \to t\bar t\chi^0$) or loop induced 2-body decays ($\tilde g \to g\chi^0$)

CHARGED HIGGS PRODUCTION

- $M_{H^\pm} < M_t:$



$$p\bar{p} \longrightarrow t\bar{t} \longrightarrow W^+ b\, H^- \bar{b}$$

$$H^- \longrightarrow \tau\bar{\nu}$$

$$W^+ \longrightarrow \ell^+\nu,\, u\bar{d}$$

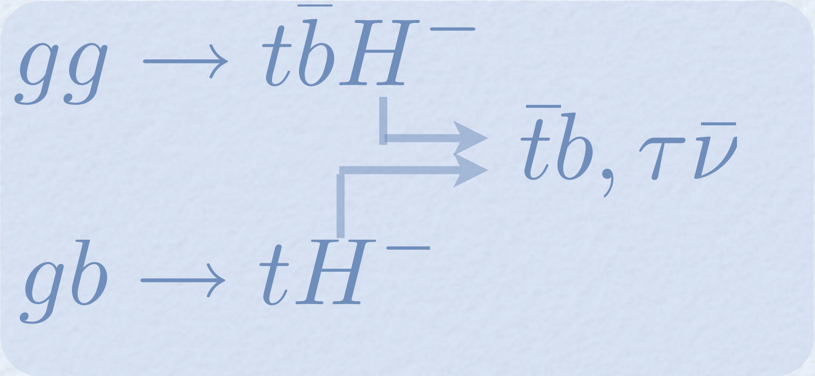
$$\sigma_{t\bar{t}}(\text{Tevatron}) \sim 7 \text{ pb}$$

$$\sigma_{t\bar{t}}(\text{LHC}) \sim 800 \text{ pb}$$

↓

$8\text{x}10^6$ tt per year (10 fb^{-1})

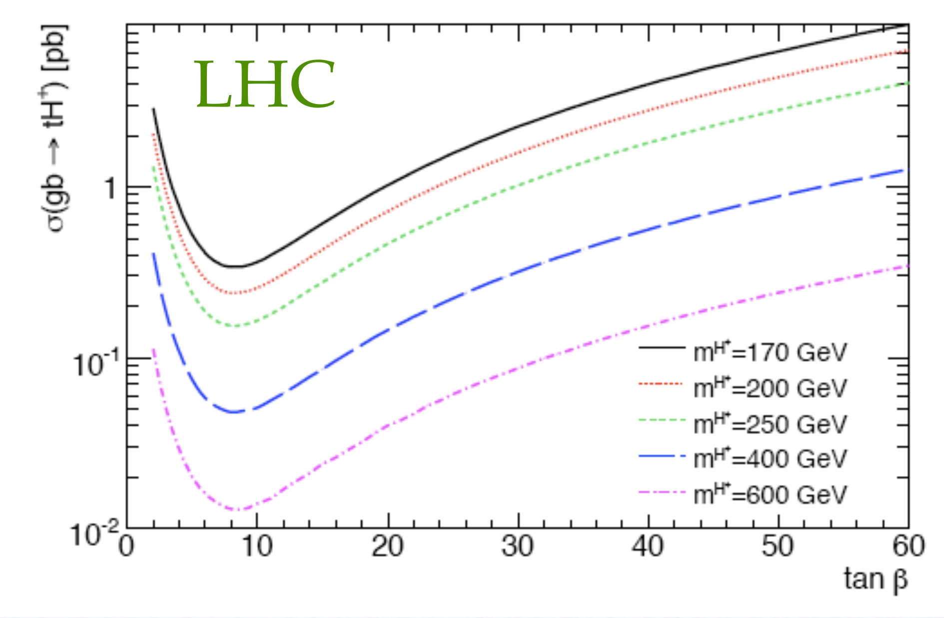
- $M_{H^\pm} > M_t:$



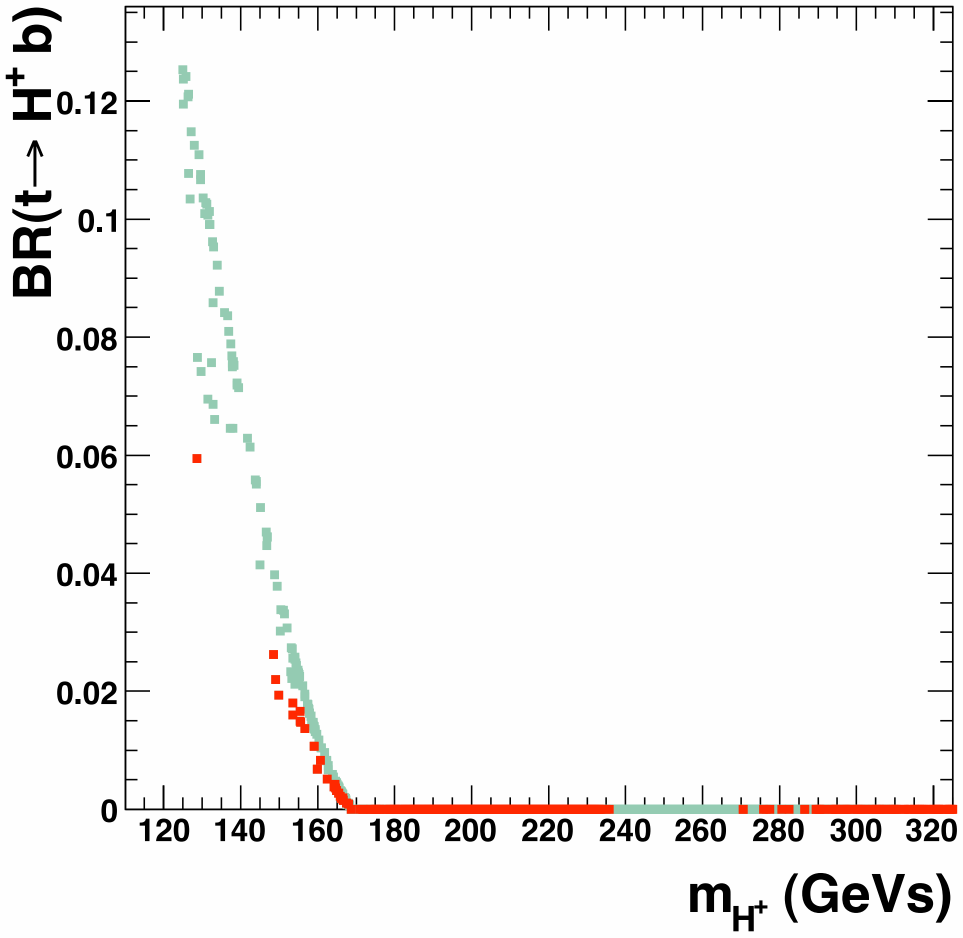
$$gg \longrightarrow t\bar{b}H^-$$

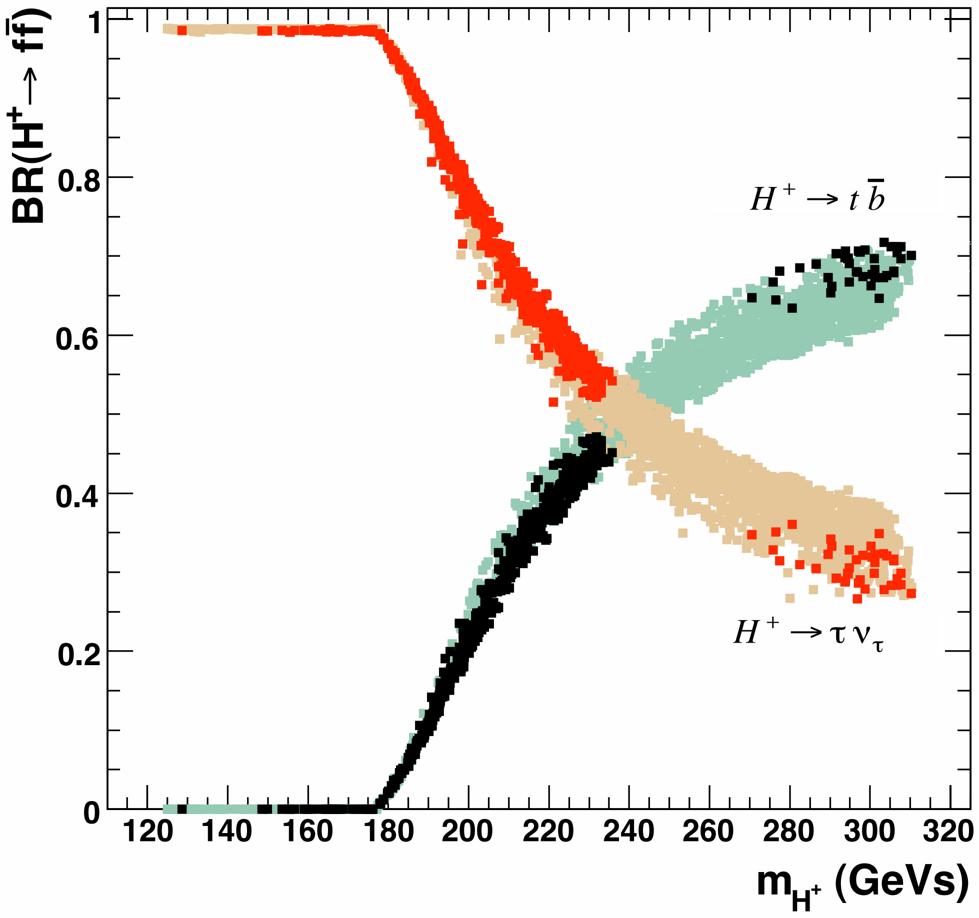
$$gb \longrightarrow tH^-$$

$$H^- \longrightarrow \bar{t}b,\, \tau\bar{\nu}$$



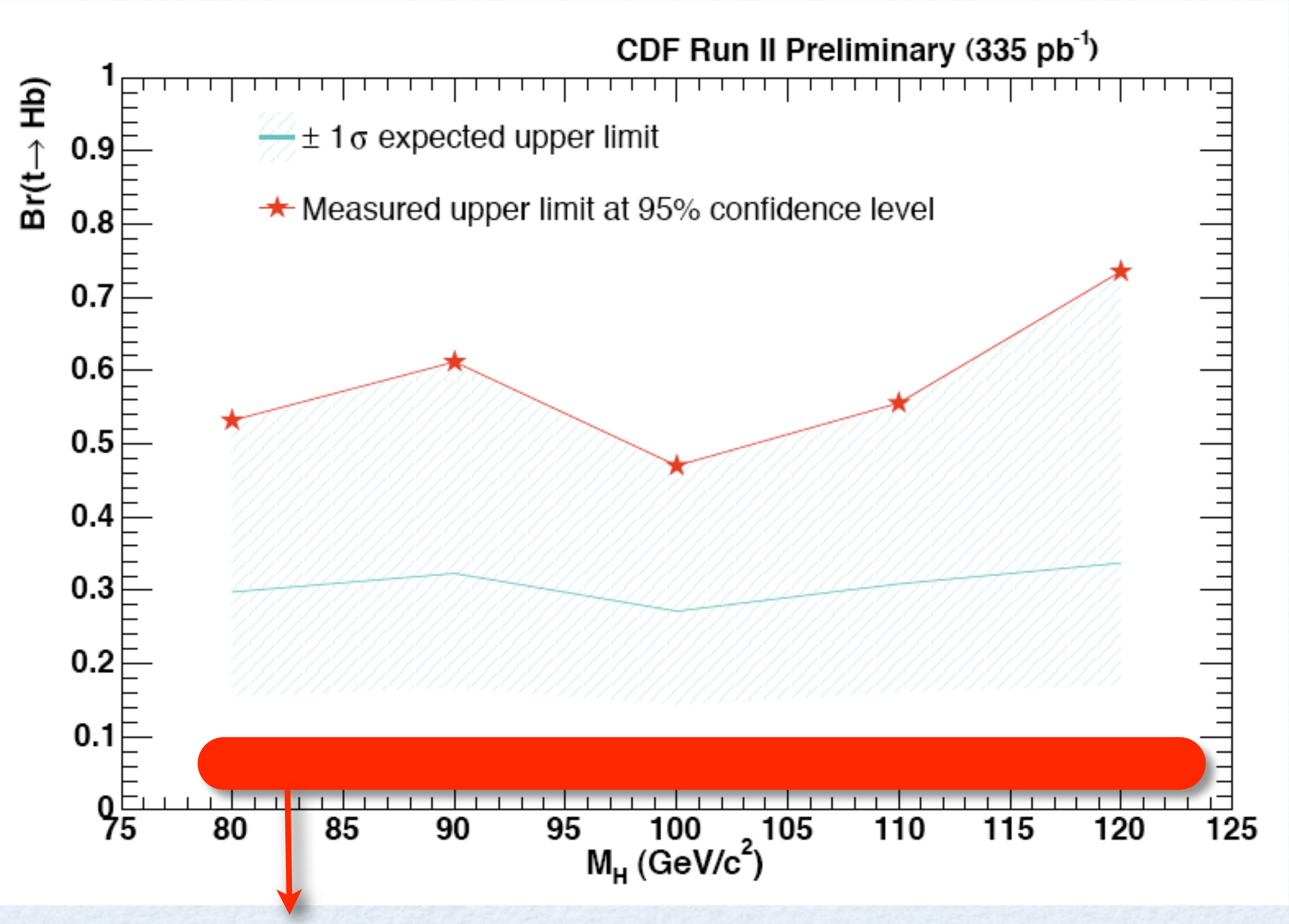
BRANCHING RATIOS





DIRECT SEARCHES AT CDF

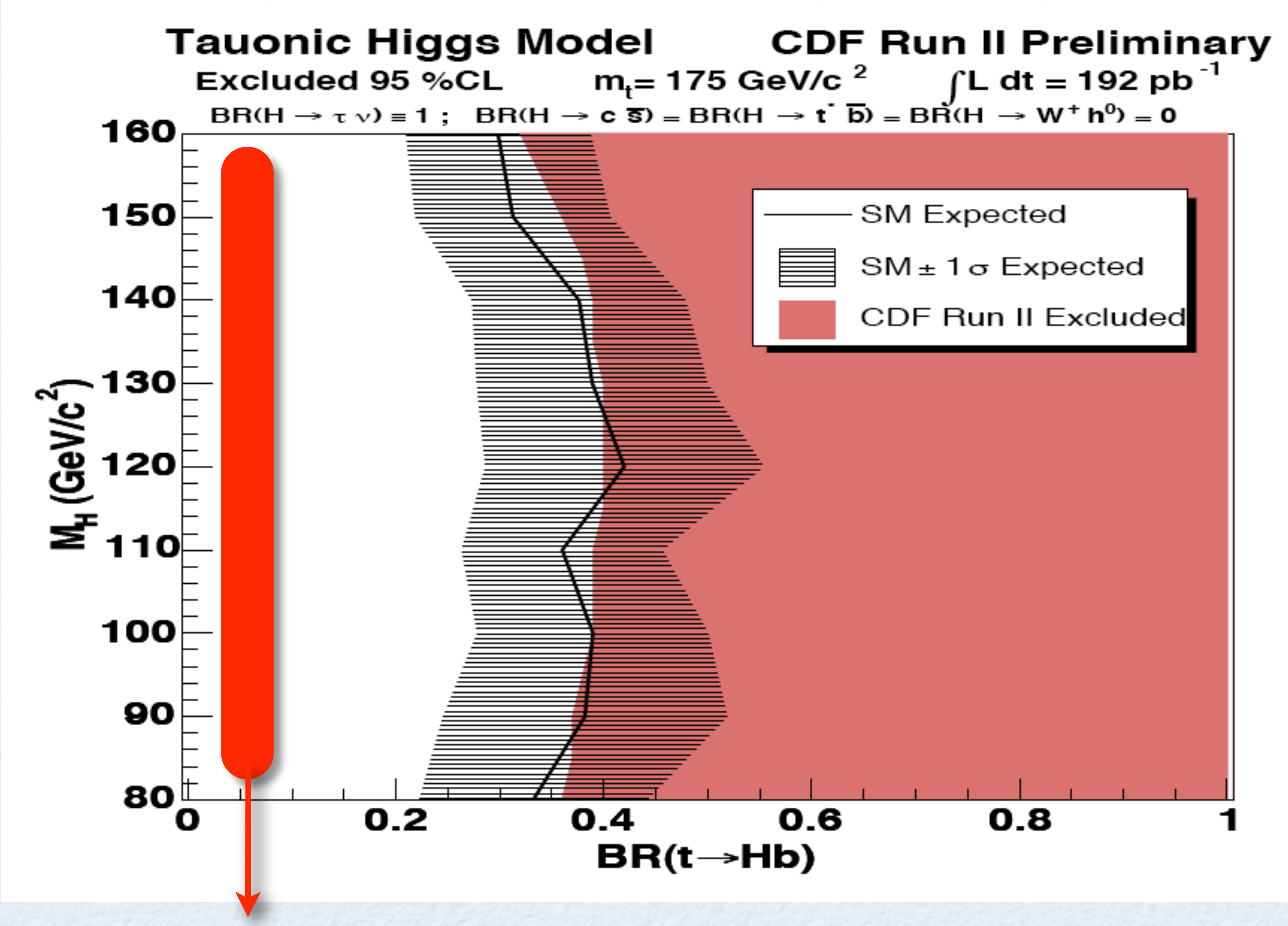
Dedicated search: $\ell + \tau_h + \not{E}_T + j_b + j$



Interesting region

DIRECT SEARCHES AT CDF

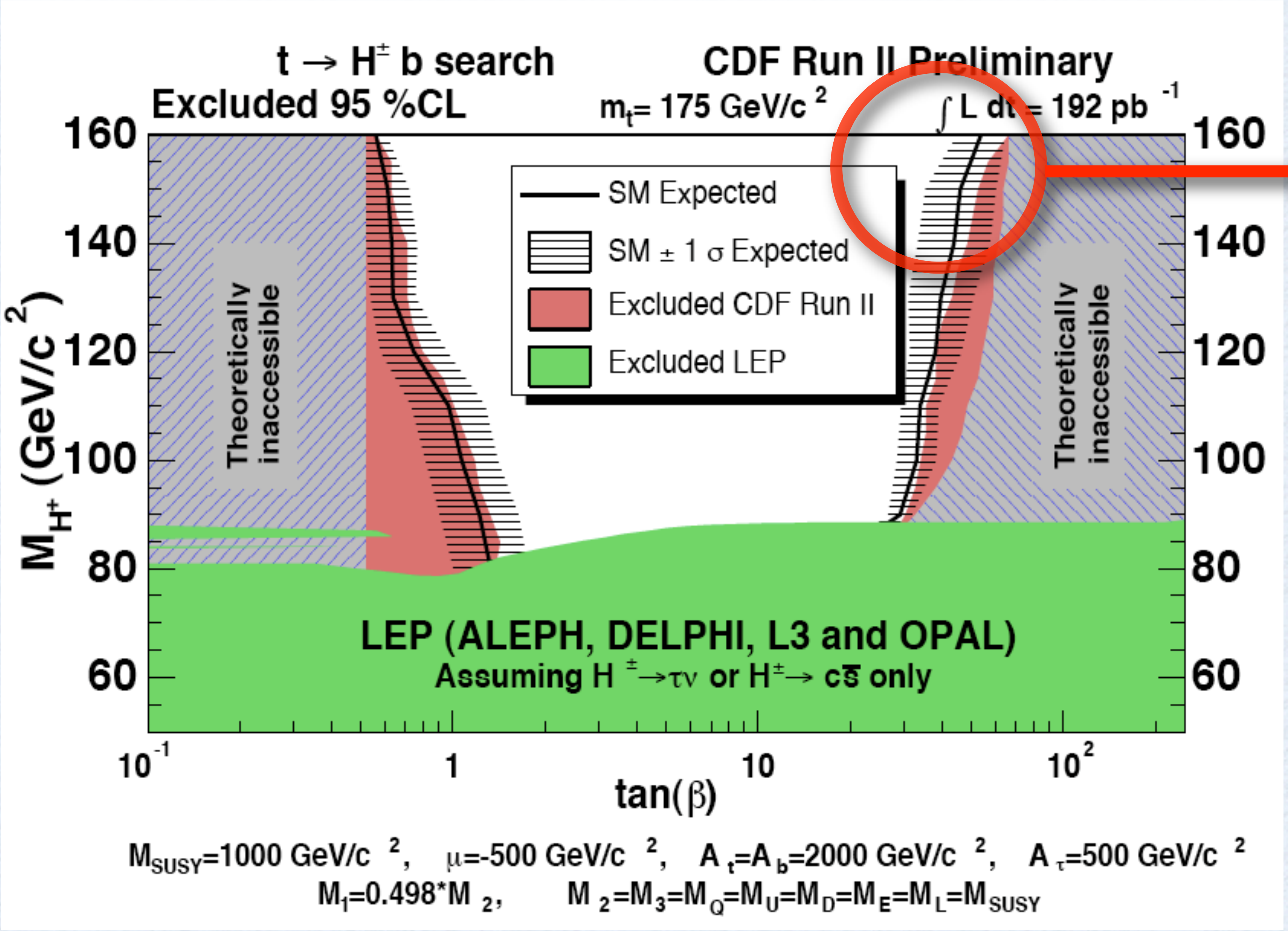
Di-top analysis reinterpretation



Interesting region

DIRECT SEARCHES AT CDF

Di-top analysis reinterpretation: ***SUSY analysis***

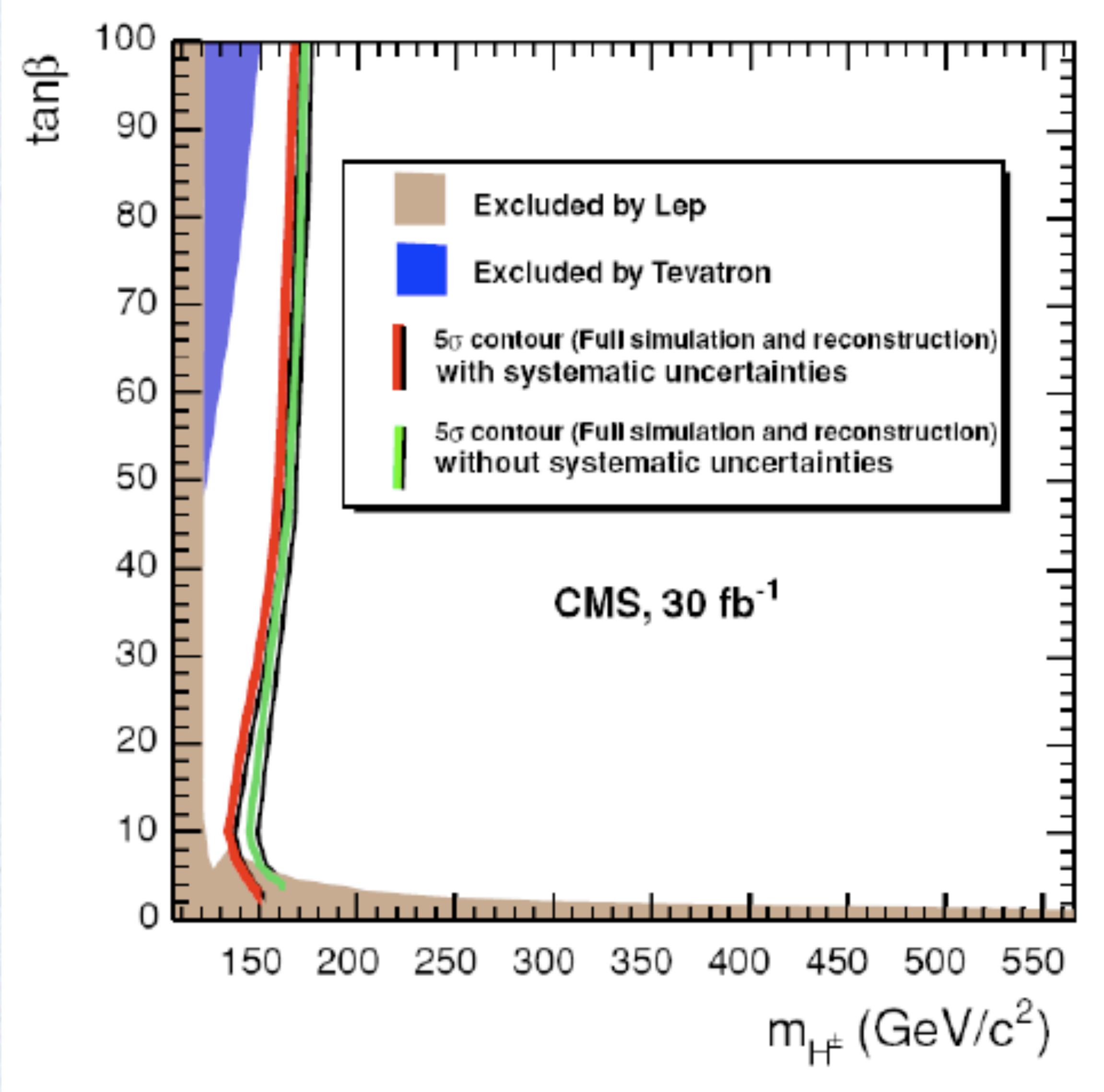


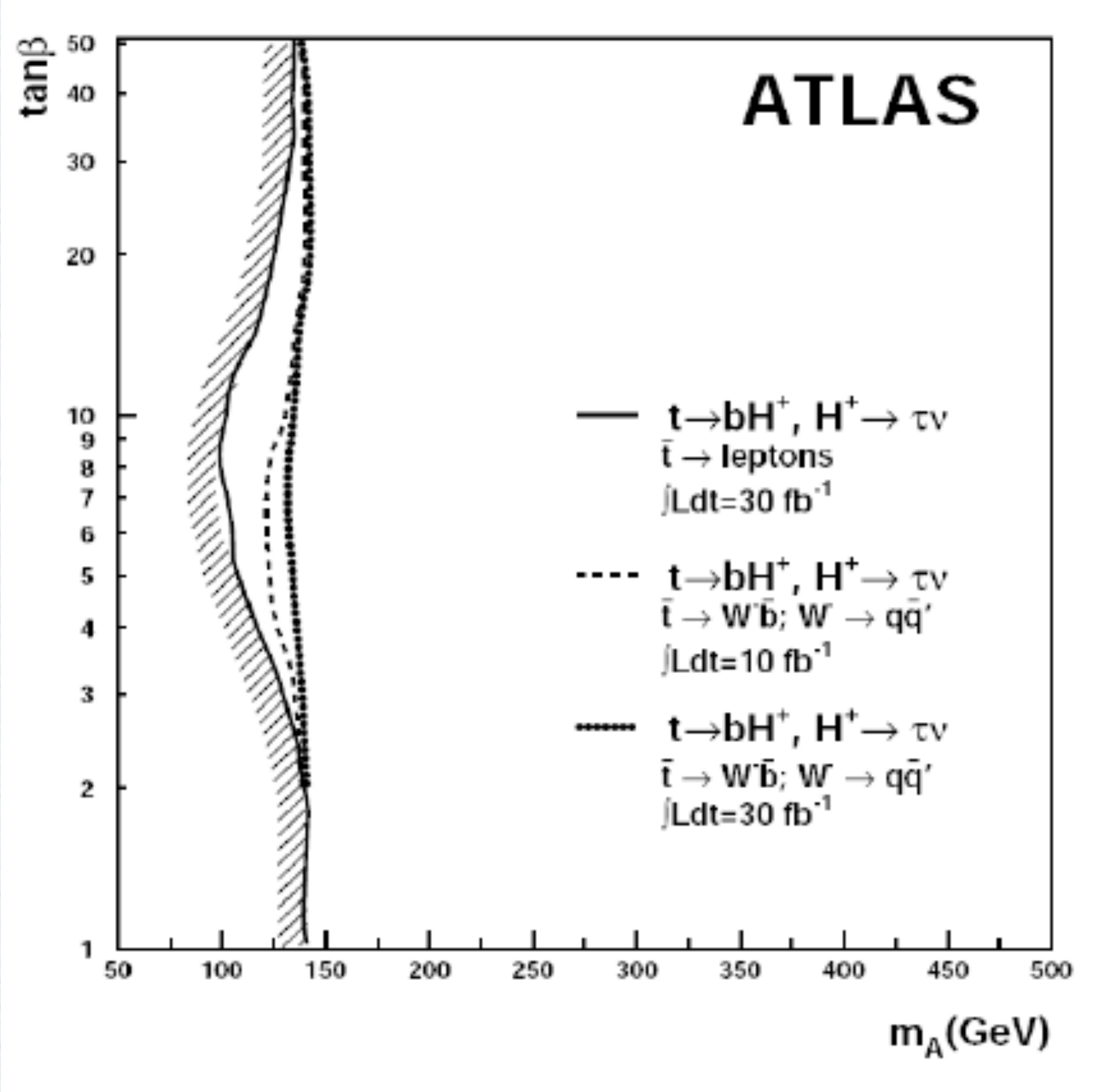
Interesting region

DIRECT SEARCHES AT THE LHC

$p\bar{p} \to t\bar{t} \to b\bar{b}W(\ell\nu)H(\tau\nu)$

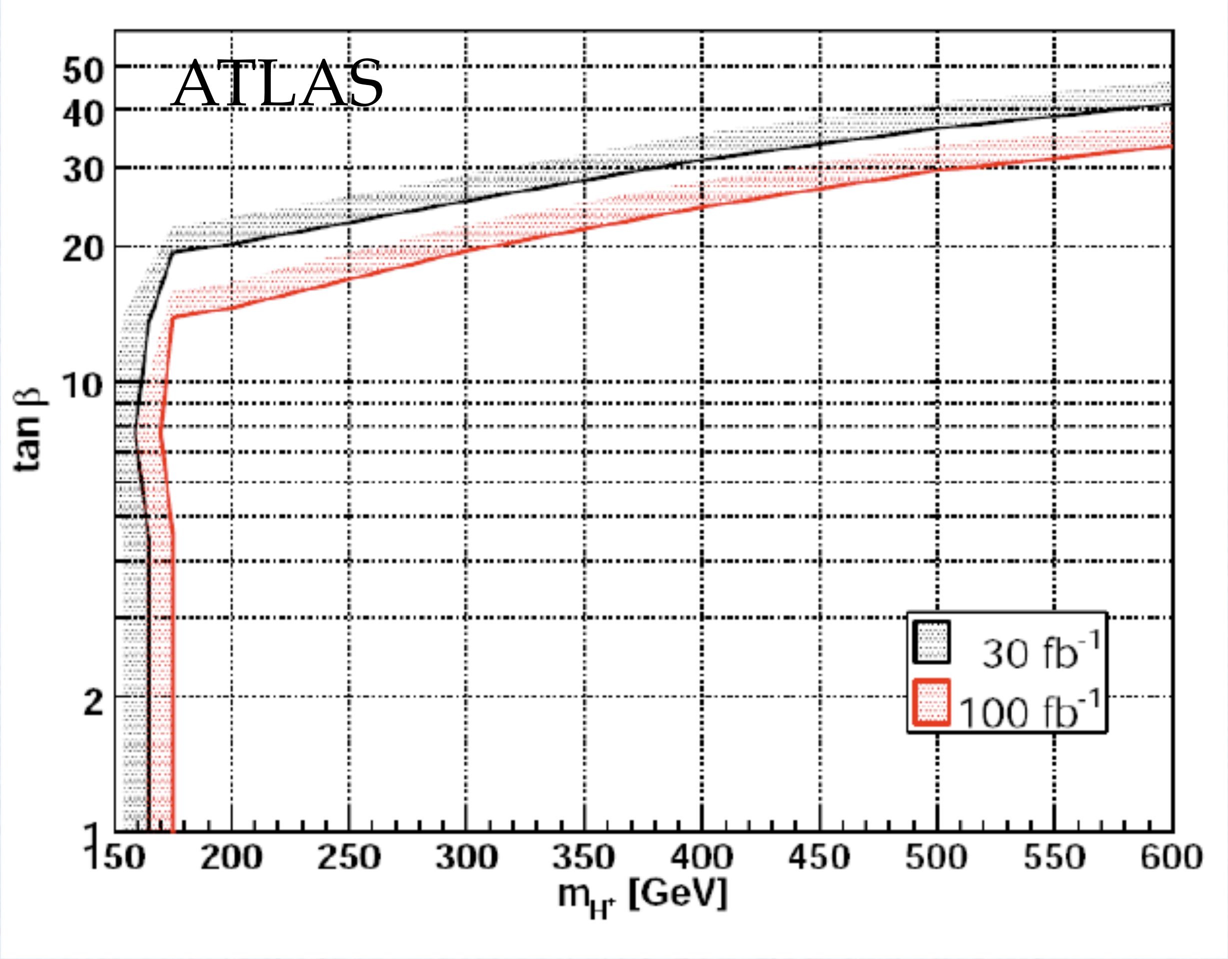
$p\bar{p} \to t\bar{t} \to b\bar{b}W(q\bar{q})H(\tau\nu)$

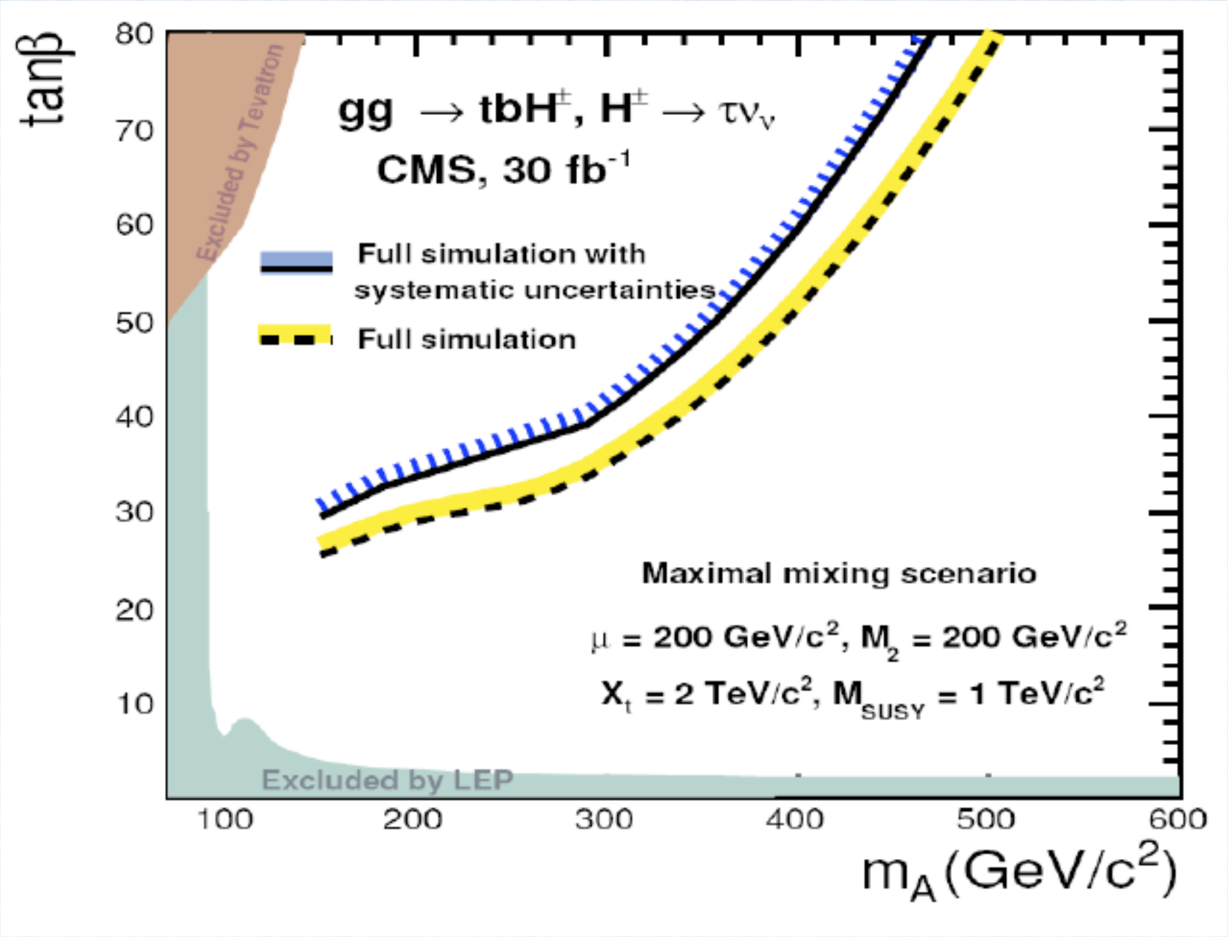




DIRECT SEARCHES AT THE LHC

$$gg \to tbH(\tau\nu)$$





The interesting part of the parameter space is covered

INDIRECT SEARCHES

- The most promising indirect channels to look for a light charged Higgs scenario are $B_s \rightarrow \mu\mu$ and $B \rightarrow \tau\nu$
- Another possibility is to look for ***Lepton Flavor Violation***
  - $\ell_i \rightarrow \ell_j \gamma$
  - A supersymmetric see-saw generates lepton flavor violating terms in the slepton sector:

$$\delta_{LL}^{ij} \approx -\frac{(3+a_0^2)}{8\pi^2} \log\left(\frac{M_X}{M_R}\right) (Y_\nu^\dagger Y_\nu)_{ij}$$

  - There is some degree of freedom in the choice of Yukawas of the neutrinos

LEPTON FLAVOR VIOLATION

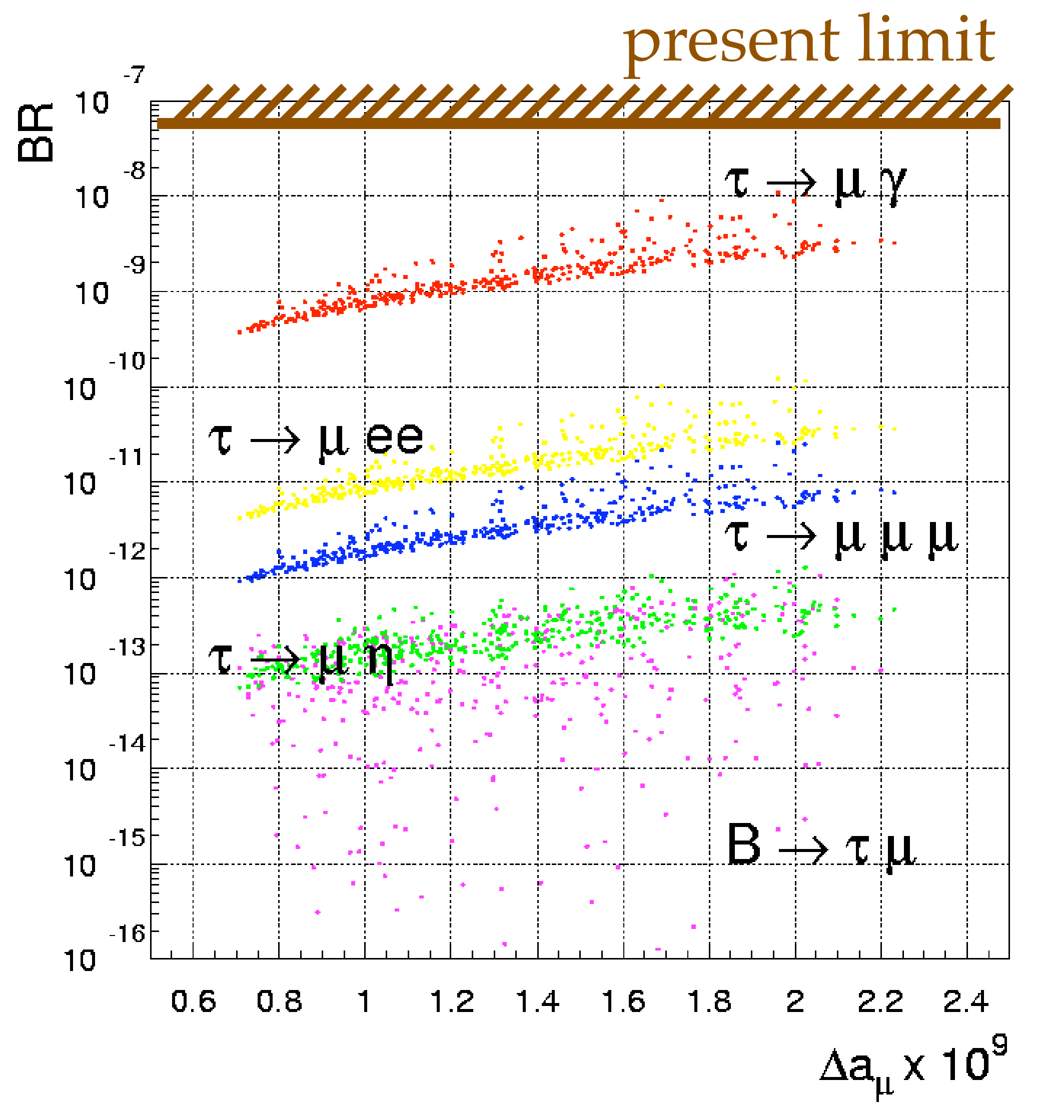
- We adopt a conservative approach and take $y_{\nu_3} \sim 1$ and assume that the ***mixing is CKM-like***

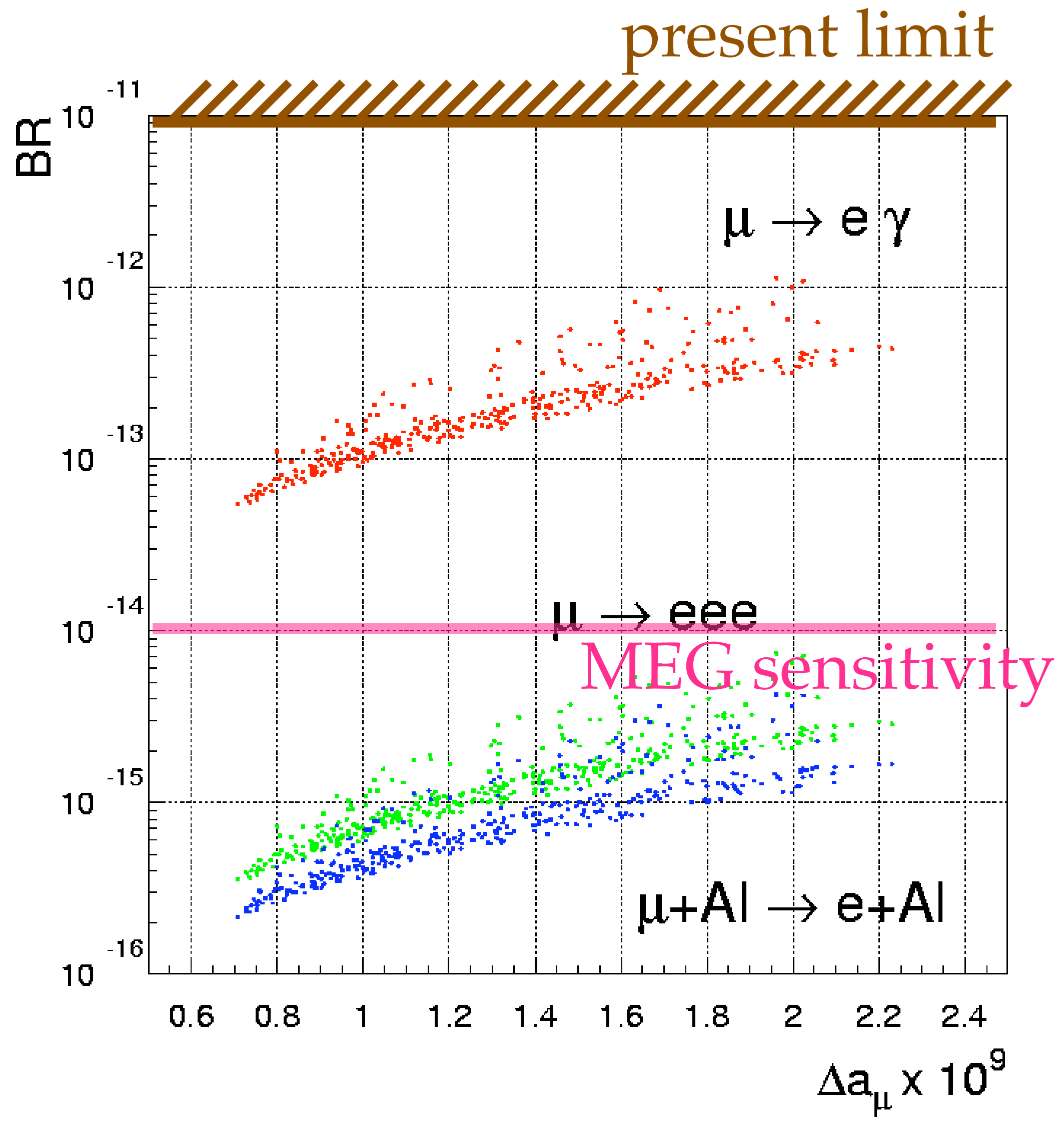
- ***There is a strong correlation with the muon g-2:***

$$\mathcal{B}(\ell_i \to \ell_j \gamma) \approx \left[\frac{\Delta a_\mu}{20 \times 10^{-10}}\right]^2 \times \begin{cases} 1 \times 10^{-13} \left|\frac{\delta_{LL}^{12}}{3\times10^{-5}}\right|^2 & [\mu \to e]\ , \\ 1 \times 10^{-9} \left|\frac{\delta_{LL}^{23}}{6\times10^{-3}}\right|^2 & [\tau \to \mu]\ . \end{cases}$$

- $\mu \longrightarrow e\gamma$ can easily reach the sensitivities of MEG

INDIRECT SEARCHES: LFV





A very light Higgs and large tanβ, usually generate too large LFV couplings. In our case, they are under control because of the large gaugino-sfermion mass splitting

CONCLUSIONS

- The Standard Model provides an excellent description of Nature

- Nevertheless, there are some chinks in its armor:
  - ***Dark Matter**, **Muon g-2***
  - several theoretical biases (***Grand Unification**, **hierarchies**, ...*)

- New Physics at the Terascale has to be ***Minimal Flavor Violating***

- The interplay between ***precision searches*** and ***direct detection*** at colliders will play a critical role in identifying new physics

- ***In two years the world we know will be shattered and the exploration of the unknown will begin..... stay tuned!***

BACKUP SLIDES

MINIMAL FLAVOR VIOLATION

- Restore the flavor symmetry group of the SM:

$$SU(3)^3_q = SU(3)_{Q_L} \otimes SU(3)_{U_R} \otimes SU(3)_{D_R}$$

- The Yukawas are replaced by auxiliary fields with a constant background value and with the following transformation properties:

$$Y_U \sim (3, \bar{3}, 1)_{SU(3)^3_q} \quad , \quad Y_D \sim (3, 1, \bar{3})_{SU(3)^3_q}$$

- Yukawa interactions are now invariant under SU(3)^3:

$$\mathcal{L}_Y = \bar{Q}_L Y_D D_R H + \bar{Q}_L Y_U U_R H_c + h.c.$$

- Using the SU(3) symmetry we can rotate the background values of the auxiliary fields Y$_{U,D}$:

$$Y_U = V^\dagger_{\mathrm{CKM}} \, \lambda_u^{diag} \quad , \quad Y_D = \lambda_d^{diag}$$

MINIMAL FLAVOR VIOLATION

- The only flavor changing structure is:

$$\lambda_{\rm FC} = \begin{cases} \left(Y_U\, Y_U^\dagger\right)_{ij} \simeq \lambda_t^2 V_{3i}^* V_{3j} & i \neq j \\ 0 & i = j \end{cases}$$

- Generic flavor changing currents:

$$\bar{Q}_L Y_U Y_U^\dagger Q_L \;\;,\;\; \bar{D}_R Y_D^\dagger Y_U Y_U^\dagger Q_L \;\;,\;\; \bar{D}_R Y_D^\dagger Y_U Y_U^\dagger Y_D D_R$$

⬇

$$\bar{Q}_L \lambda_{\rm FC} Q_L \;\;,\;\; \bar{D}_R \lambda_d \lambda_{\rm FC} Q_L \;\;,\;\; \bar{D}_R \lambda_d \lambda_{\rm FC} \lambda_d D_R$$

MINIMAL FLAVOR VIOLATION

- If there are more Higgs doublets:
  - λ_b can be large
  - there is a new source of SU(3) breaking

$$\lambda^d_{\mathrm{FC}} = \left(Y_D\, Y_D^\dagger\right)_{ij} \simeq \frac{2m_b^2}{v^2}\tan^2\beta \begin{pmatrix} 0 & & \\ & 0 & \\ & & 1 \end{pmatrix}$$

  - In principle we have non-holomorphic Higgs interactions

$$\epsilon_0\, \bar{Q}_L \lambda_d D_R H_U^c \quad \Longrightarrow \quad \delta m_b = m_b\, \epsilon_0 \tan\beta$$

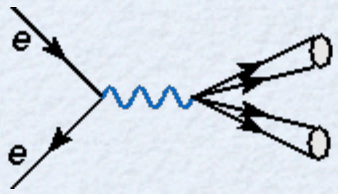
(G-2) μ

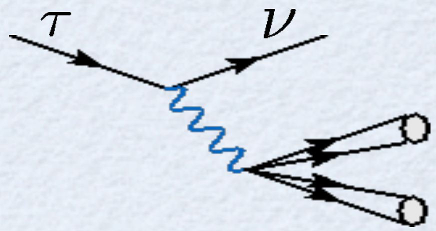
- Dominated by the chargino-sneutrino diagram:

$$\delta a^{\chi\tilde{\nu}}_{\mu^+} \simeq \frac{g_2^2}{32\pi^2}\frac{m_\mu^2}{m_{\tilde{\nu}}^2}\frac{\mathrm{Re}(\mu M_2)\tan\beta}{m_{\tilde{\nu}}^2}$$

the sign of the SUSY contribution is *sign(μ)*

- Theoretical predictions are complicated by non-perturbative effects:
    - ✓ light-by-light scattering
    - ✓ hadronic contribution - can be extracted from e^+e^- and τ data (the latter up to isospin corrections)





- Experimental and theoretical results read:

$$\begin{aligned} a_\mu^{\mathrm{exp}} &= 11659208(6)\times 10^{-10} \\ a_\mu^{\mathrm{SM}}(ee) &= 11659178(6)\times 10^{-10} \\ a_\mu^{\mathrm{SM}}(\tau) &= 11659179(7)\times 10^{-10} \end{aligned}$$

$$\Rightarrow \boxed{\delta a_\mu = (29.3 \pm 8.2)10^{-10}}$$

3.6σ effect

$B \longrightarrow \tau\ \ \nu$

- The experimental measurement is:

$$\mathrm{BR}(B \to \tau\nu) = \begin{cases} (1.79^{+0.56}_{-0.49}(\mathrm{stat})^{+0.46}_{-0.51}(\mathrm{syst})) \times 10^{-4} & \textit{Belle} \\ (1.2 \pm 0.4(\mathrm{stat}) \pm 0.3(\mathrm{bckg}) \pm 0.2(\mathrm{syst})) \times 10^{-4} & \textit{BaBar} \end{cases}$$

$$\mathrm{BR}(B \to \tau\nu)^{\mathrm{WA}} = (1.42 \pm 0.43) \times 10^{-4}$$

- The SM expectation is (tree-level W exchange):

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

- The supersymmetric corrections interfere destructively with the SM amplitude and are given by

$$\frac{\mathsf{BR}(B \to \tau\nu_\tau)^{\mathsf{SUSY}}}{\mathsf{BR}(B \to \tau\nu_\tau)^{\mathsf{SM}}} = \left(1 - \frac{m_B^2}{m_{H^\pm}^2}\frac{\tan^2\beta}{1+\epsilon_0\tan\beta}\right)^2$$

$B \rightarrow \tau\ \nu$

- f_B and V_{ub} are the dominant source of error:

$$\begin{aligned} f_B &= (0.216 \pm 0.022)\ \text{GeV} \\ |V_{ub}| &= (4.09 \pm 0.26) \times 10^{-3} \qquad \text{[HFAG]} \end{aligned}$$

- The ratio experiment/SM is, therefore:

$$\boxed{R(B \to \tau\nu) = 1.02 \pm 0.40}$$

$B \to X_s\, \gamma$

- The dipole operators are:

$$H^{b\to s\gamma}_{\mathrm{Dipole}} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \left[C_7(\mu)\cdot \frac{e m_b}{16\pi^2}\bar{s}_{\mathrm{L}}\sigma_{\mu\nu}b_{\mathrm{R}}F^{\mu\nu} \;+\; C_8(\mu)\cdot\frac{g_s m_b}{16\pi^2}\bar{s}_{\mathrm{L}\alpha}T^a_{\alpha\beta}\sigma_{\mu\nu}b_{\mathrm{R}\beta}G^{a\mu\nu}\right]$$

- W^+ and H^+ contributions have the same sign (both negative)

- The sign of the chargino contribution is *-sign*($A_t\mu$).
At the EW scale we have $A_t \sim -2\, M_{1/2}$, hence we have destructive and constructive interference for $\mu > 0$ and $\mu < 0$, respectively.

- World average: $\mathcal{B}(B \to X_s\gamma)_{\mathrm{exp}} = (3.55 \pm 0.26) \times 10^{-4}$

- SM prediction: $\mathcal{B}(B \to X_s\gamma)_{\mathrm{SM}} = (2.98 \pm 0.26) \times 10^{-4}$

$B \to X_s \gamma$

- The SM prediction includes NNLO effects

  The charm mass dependence is calculated in the $m_c >> m_b/2$ limit and an extrapolation is used. The exact calculation of the 3-loop matrix element of O_2 using Mellin-Barnes techniques is being pursued [Boughezal, Czakon, Schutzmeier]

- Becher & Neubert showed that the standard OPE is valid only for cuts on the photon energy of about *1 GeV*.

- In order to get a reliable prediction for a more realistic cut of *1.6 GeV*, effective theory techniques (SCET RGE) have to be used:

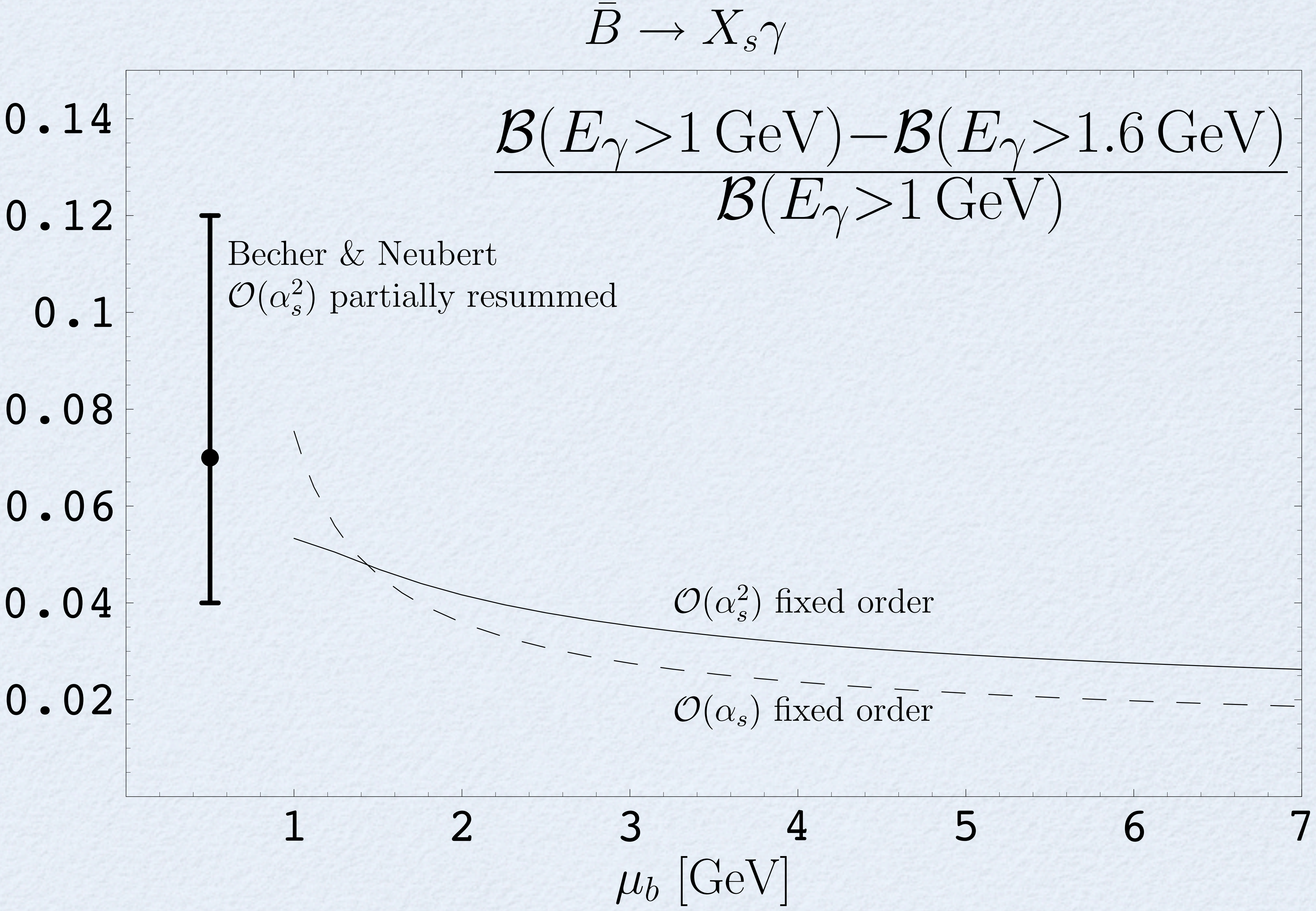
$$BR(B \to X_s\gamma)_{E_\gamma > 1.6\text{GeV}} = 3.15 \times 10^{-4}$$

[normal OPE]

$$BR(B \to X_s\gamma)_{E_\gamma > 1.6\text{GeV}} = 2.98 \times 10^{-4}$$

[SCET approach]

$B \to X_s\,\gamma$

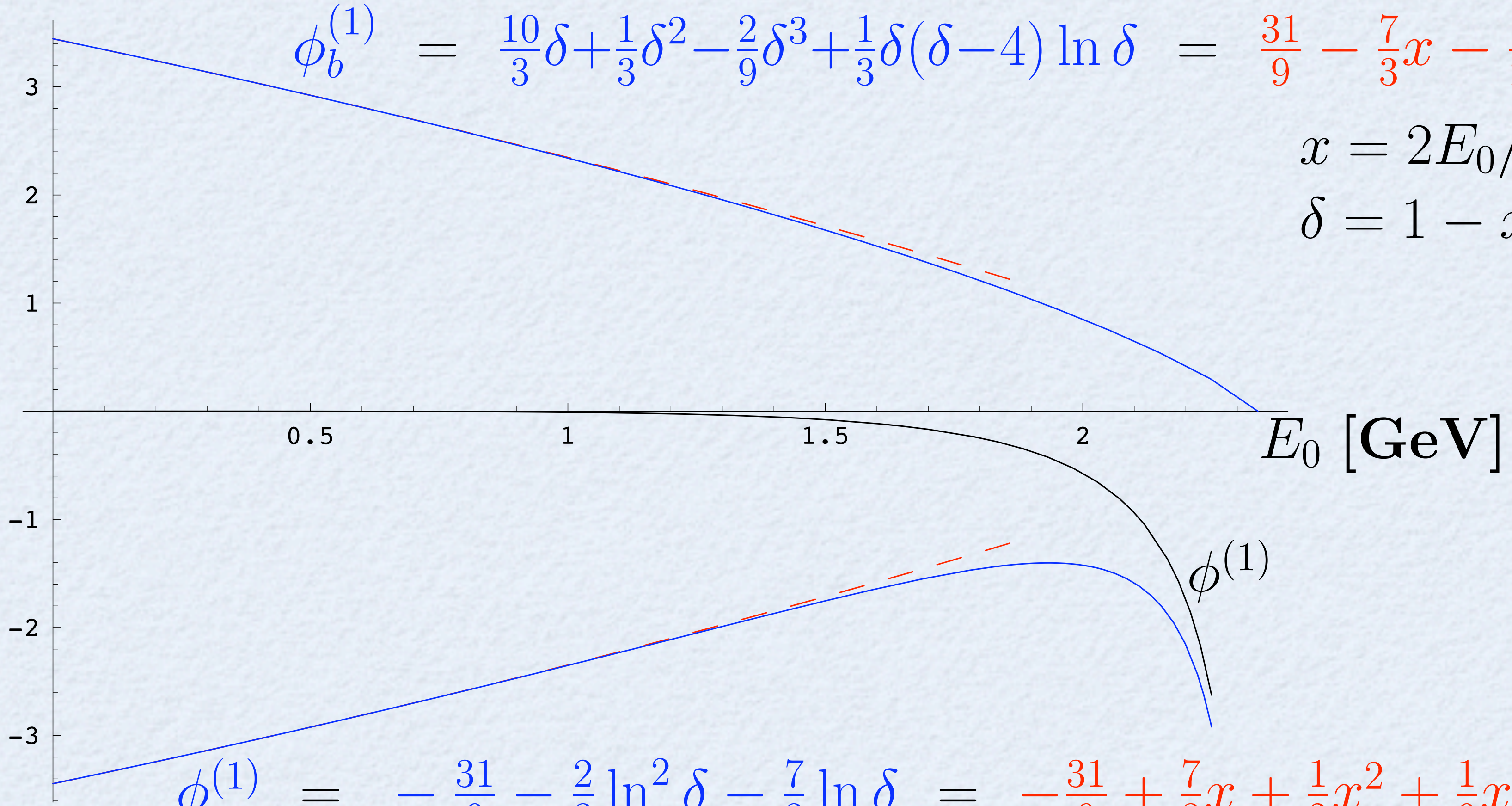

$\bar{B} \to X_s\gamma$
$\frac{\mathcal{B}(E_\gamma > 1\,\mathrm{GeV}) - \mathcal{B}(E_\gamma > 1.6\,\mathrm{GeV})}{\mathcal{B}(E_\gamma > 1\,\mathrm{GeV})}$
Becher & Neubert
$\mathcal{O}(\alpha_s^2)$ partially resummed
$\mathcal{O}(\alpha_s^2)$ fixed order
$\mathcal{O}(\alpha_s)$ fixed order
0.14
0.12
0.1
0.08
0.06
0.04
0.02
1
2
3
4
5
6
7
μ_b [GeV]

$B \to X_s \gamma$

For simplicity, let us set $C_i(\mu_b) \to 0$ for $i \neq 7$. Then, in the "fixed order":

$$\mathcal{B}(E_\gamma > E_0)/\mathcal{B}_{\text{total}} = 1 + \frac{\alpha_s(\mu_b)}{\pi}\phi^{(1)}(E_0) + \left(\frac{\alpha_s(\mu_b)}{\pi}\right)^2 \phi^{(2)}(E_0) + \dots$$

$$\phi^{(1)}(E_0) = \phi_a^{(1)}(E_0) + \phi_b^{(1)}(E_0)$$



$$\phi_b^{(1)} = \frac{10}{3}\delta + \frac{1}{3}\delta^2 - \frac{2}{9}\delta^3 + \frac{1}{3}\delta(\delta-4)\ln\delta = \frac{31}{9} - \frac{7}{3}x - \frac{1}{2}x^2 - \frac{1}{9}x^3 - \frac{5}{36}x^4 + \mathcal{O}(x^5)$$

$x = 2E_0/m_b$

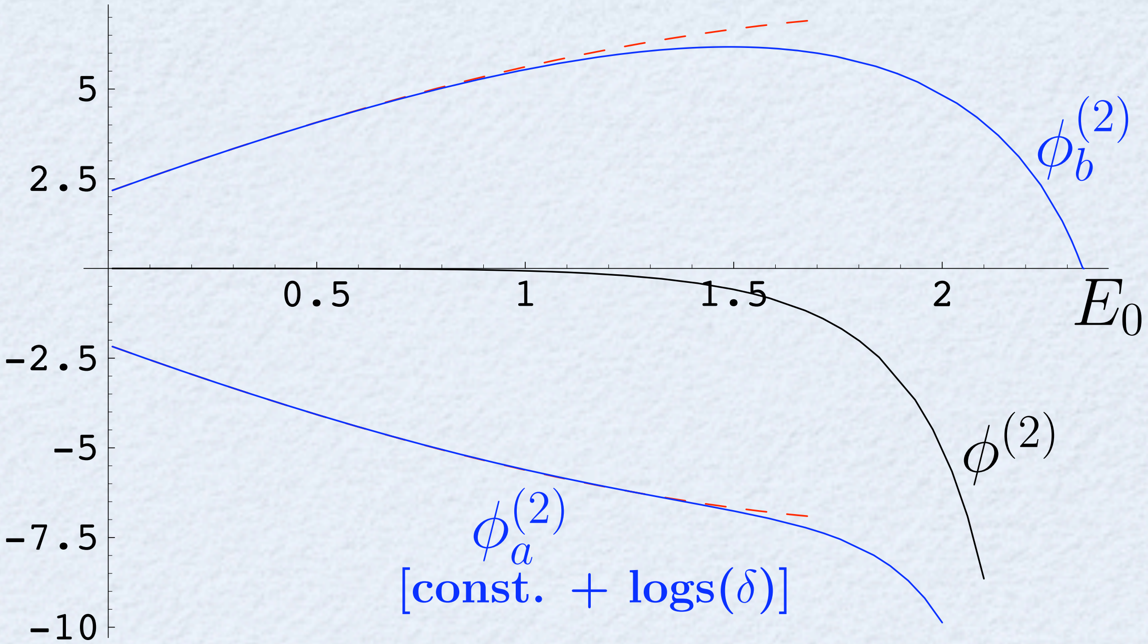
$\delta = 1 - x$

$$\phi_a^{(1)} = -\frac{31}{9} - \frac{2}{3}\ln^2\delta - \frac{7}{3}\ln\delta = -\frac{31}{9} + \frac{7}{3}x + \frac{1}{2}x^2 + \frac{1}{9}x^3 - \frac{1}{36}x^4 + \mathcal{O}(x^5)$$

Terms up to $\mathcal{O}(x^3)$ must cancel out.

$B \rightarrow X_s \gamma$

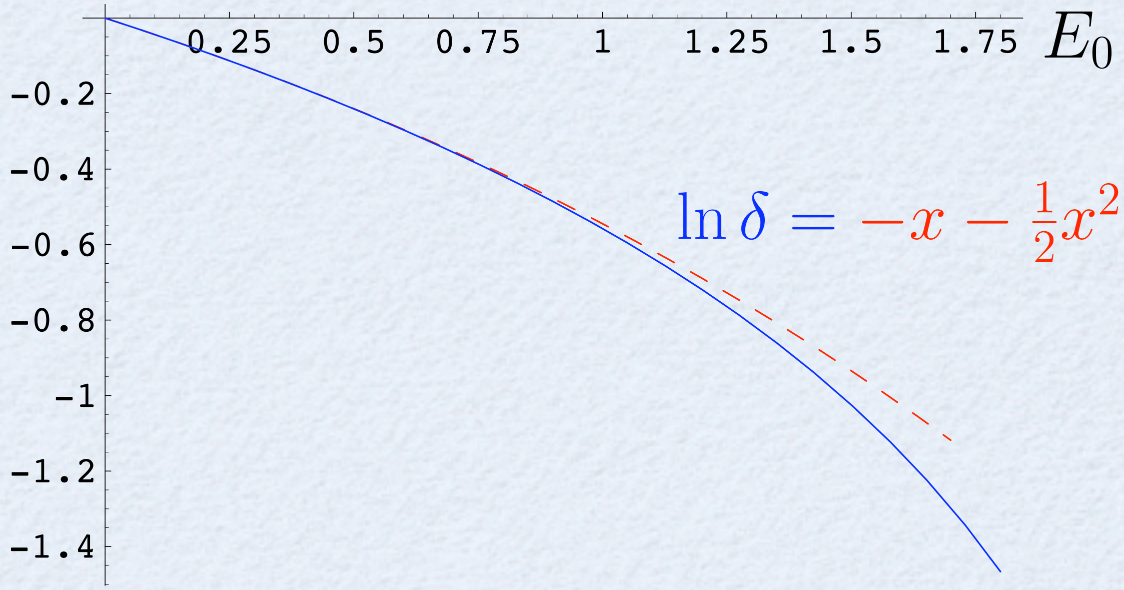
The same pattern arises at $\mathcal{O}(\alpha_s^2)$:



$x = 2E_0/m_b$

$\delta = 1 - x$

It must be the case also at higher orders because:



$\ln \delta = -x - \frac{1}{2}x^2 - \frac{1}{3}x^3 + \mathcal{O}(x^4)$

However, only "const + logs(δ)" have been included at orders $\mathcal{O}(\alpha_s^3)$ and higher in hep-ph/0610067.

OTHER OBSERVABLES

- B_s mass difference (ΔM_{Bs})
  - Proportional to $(\tan\beta)^4$
  - Cancellation m_H - m_A implies m_s/m_b suppression

- Dark matter relic density (Ωh^2)
  - Experimental errors are tiny (4%)
  - Theory uncertainties are much larger
    - ✓ parametric errors (e.g. M_t) and uncertainties in the RGE running from the GUT to the EW scales (especially in the large tanβ region) impact strongly the calculation of Ωh^2
    - ✓ points for which Ωh^2 is too small can be recovered by some other dark matter candidate
  - We impose only a loose upper bound: $\Omega h^2 < 0.13$ (99% C.L.)

LIGHT HIGGS PARAMETER SPACE

$$m_A^2 = M_{H_d}^2(m_t) - M_{H_u}^2(m_t) - m_Z^2$$

- The running of M_{H_u} is driven by the large Yukawa of the top. Hence we always have $m_{H_u}^2(m_t) < 0$:

$$m_{H_u}^2(m_t) \simeq -0.12 M_0^2 - 2.7 M_{1/2}^2 + 0.4 A_0 M_{1/2} - 0.1 A_0^2$$

- The running of M_{H_d} depends strongly on tanβ
    - For moderate tanβ (< 10): $m_{H_d}^2(m_t) > 0$
    - For large tanβ, the bottom Yukawa plays a more important role until the limiting case $m_{H_d}^2(m_t) \simeq m_{H_u}^2(m_t) < 0$

- Low m_A can only be achieved at large tanβ

LIGHT HIGGS PARAMETER SPACE

- The LSP condition $m_{\tilde{\tau}} > m_{\tilde{\chi}^0}$ implies a lower bound on M_0
- The absence of charge and color breaking minima implies $|A_0| < 3\,M_0$
- Both $B \rightarrow X_s\gamma$ and $B_s \rightarrow \mu\mu$, require a small A_t
  - An approximate formula is: $A_t = 0.25\,A_0 - 2\,M_{1/2}$
  - We need large A_0 and small $M_{1/2}$
  - Under these conditions ***the chargino contribution to ε_Υ decreases and the gluino one is increased*** (i.e. more efficient cancellation)
- We need large tanβ, large A_0, large M_0 and small $M_{1/2}$

GAUGE MEDIATION

- The soft breaking terms are:

$$\begin{aligned} M_i &= N\Lambda\, \tilde{\alpha}_i\, g(x) \equiv \hat{M}_i g(x) \\ M_A^2 &= 2N\Lambda^2 \left[C_3\tilde{\alpha}_3 + C_2\tilde{\alpha}_2 + 3/5\, Y^2\tilde{\alpha}_1\right] f(x) \end{aligned}$$

- The Higgs mass squared are controlled by RGE effects and are essentially proportional to M_3; hence:

$$M_A^2 \simeq M_{H_d}^2 - M_{H_u}^2 \simeq (C_d - C_u) M_3^2$$

- The lower limit on the stau mass, sets a lower limit on M_1 and hence a stronger lower limit on M_3:

$$m_{\tilde{\tau}_1}^2 \sim m_{\tilde{\tau}_R}^2 \sim 6/5 M_1^2 > (100\ \mathrm{GeV})^2 \Longrightarrow M_3 > 1350\ \mathrm{GeV}$$

■ $M_A < 200$ GeV implies, therefore, the strong fine-tuning C_d-$C_u \sim 10^{-2}$

ANOMALY MEDIATION

- The soft breaking terms are:

$$
\begin{aligned}
M_i &= \frac{1}{g_i}\beta_i m_{3/2} \\
M_A^2 &= 1/2\,\dot{\gamma}_A m_{3/2}^2 + m_0^2\,Y_A \\
A_A &= \beta_{Y_A} m_{3/2}
\end{aligned}
$$

- ***The squared scalar masses tend to be tachyonic and Fayet-Iliopoulos D-terms were added*** (strong model dependence)

- As a consequence it is extremely ***easy to obtain a light M_A***

- A correct EWSB is obtained only for moderate tanβ, therefore the ***phenomenology of these models (for light M_A) is less interesting***