The Quest for Physics at the Weak Scale

(A short and incomplete mid 2011overview)

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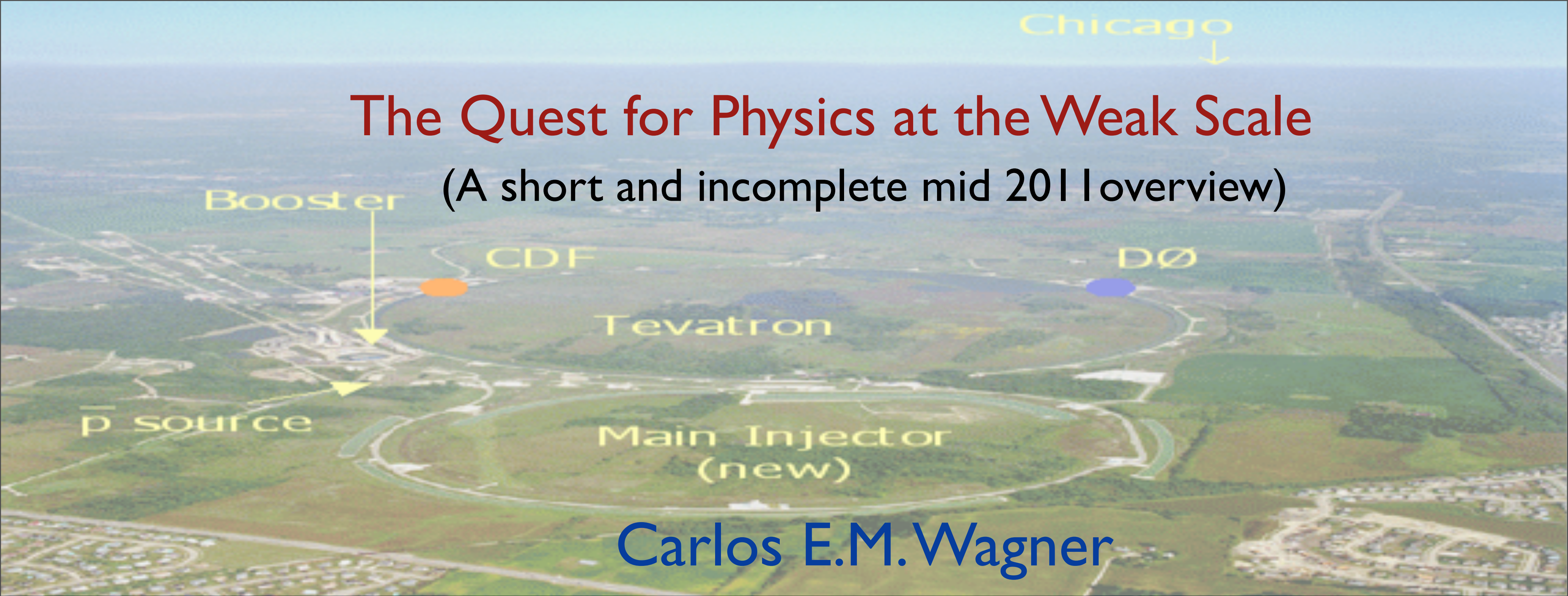


PLHC Conference
Perugia, Italy, June 10, 2011

Physics at the Weak Scale : Motivation

- Electroweak Symmetry Breaking and the Hierarchy Problem.
- Low Energy Supersymmetry, Technicolor, Extra Dimensions...

- Origin of Matter
- Dark Matter (Weak scale annihilation cross section)
- Electroweak Baryogenesis (New states and CP-violation)

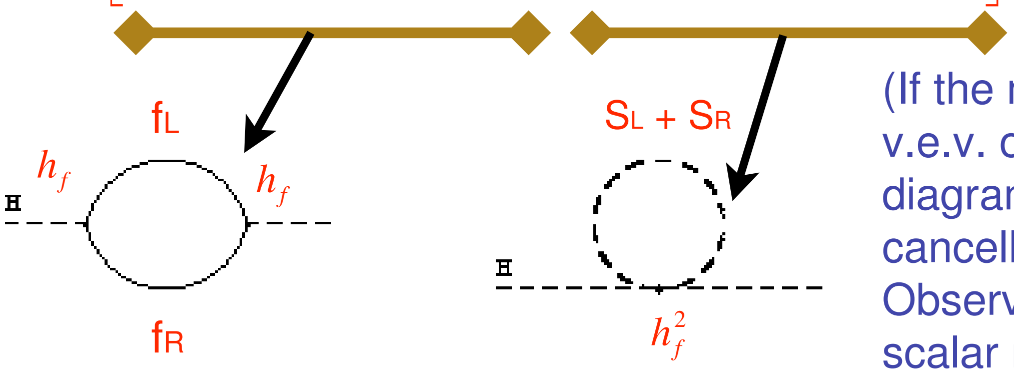
- Explanation of Observed Experimental Anomalies

Higgs Mass Parameter Corrections

Quadratic Divergent contributions:

One loop corrections to the Higgs mass parameter cancel if the couplings of scalars and fermions are equal to each other

$$\delta m_H^2 = \frac{N_C h_f^2}{16\pi^2}\left[-2\Lambda^2 + 3m_f^2\log\left(\frac{\Lambda^2}{m_f^2}\right) + 2\Lambda^2 - 2m_s^2\log\left(\frac{\Lambda^2}{m_s^2}\right)\right]$$

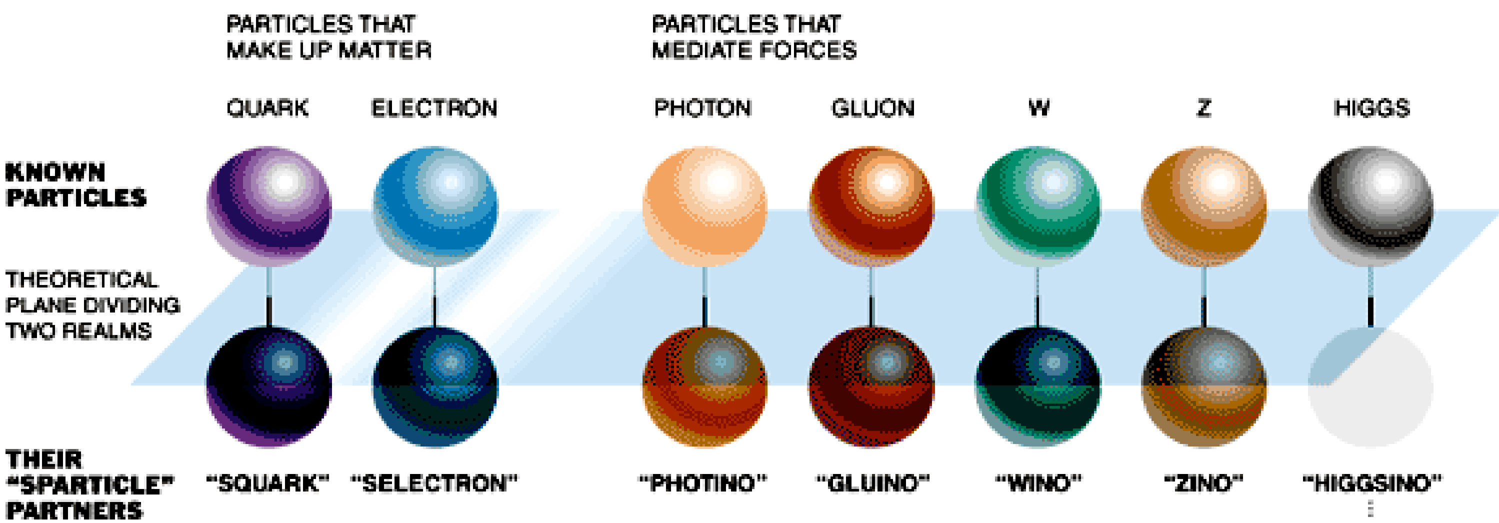


(If the masses proceed from the v.e.v. of H, there is another diagram that ensures also the cancellation of the log term. Observe that the fermion and scalar masses are the same in this case, equal to h_f v.)

Supersymmetry is a symmetry that ensures the equality of these couplings

Physics Beyond the SM: Supersymmetry

fermions ⟷ **bosons**



Photino, Zino and Neutral Higgsino: Neutralinos

Charged Wino, charged Higgsino: Charginos

No new dimensionless couplings. Couplings of supersymmetric particles equal to couplings of Standard Model ones.
Two Higgs doublets necessary. Ratio of vacuum expectation values denoted by $\tan\beta$

Soft Supersymmetry Breaking Terms

$$\mathcal{L}_{soft} = -\frac{1}{2}(M_3 \tilde{g}\tilde{g} + M_2 \tilde{W}\tilde{W} + M_1 \tilde{B}\tilde{B})$$
$$-m_Q^2 \tilde{Q}^\dagger \tilde{Q} - m_U^2 \tilde{U}^\dagger \tilde{U} - m_D^2 \tilde{D}^\dagger \tilde{D} - m_L^2 \tilde{L}^\dagger \tilde{L} - m_E^2 \tilde{E}^\dagger \tilde{E}$$
$$-m_{H_1}^2 H_1^* H_1 - m_{H_2}^2 H_2^* H_2 - (\mu B H_1 H_2 + cc.)$$
$$-(A_u h_u \tilde{U}\tilde{Q} H_2 + A_d h_d \tilde{D}\tilde{Q} H_1 + A_l h_l \tilde{E}\tilde{L} H_1) + c.c.$$

All gauge invariant mass terms allowed in the theory. These terms do not affect the condition of cancellation of quadratic divergences, which depend on equality of couplings and not masses.

All terms can be, in principle, matrices in flavor space, inducing mixing between squarks and sleptons of different flavors : Plenty of new, free parameters. Preference towards flavor independent SUSY breaking schemes.

G. Perez and W. Altmannshofer's talks

Renormalization Group Evolution

- One interesting thing is that the gaugino masses evolve in the same way as the gauge couplings:

  $d(M_i/\alpha_i)/dt = 0, \qquad \frac{dM_i}{dt} = -b_i \alpha_i M_i / 4\pi, \qquad d\alpha_i/dt = -b_i \alpha_i^2 / 4\pi$

  $t \equiv \ln(M_{GUT}^2/Q^2)$

- The scalar fields masses evolve in a more complicated way.

  $4\pi dm_i^2/dt = +C_a^i 4M_a^2 \alpha_a - |Y_{ijk}|^2[(m_i^2 + m_j^2 + m_k^2 + A_{ijk}^2)]/4\pi + \frac{3}{5} Y_i \alpha_1 D_Y$

- Colored particles are affected by positive, strongly coupled corrections and tend to be the heaviest ones.

- Weakly interacting particles tend to be lighter, particular those affected by large Yukawas.

- There scalar field H_2 is both weakly interacting and couples with the top quark Yukawa. Its mass naturally becomes negative.

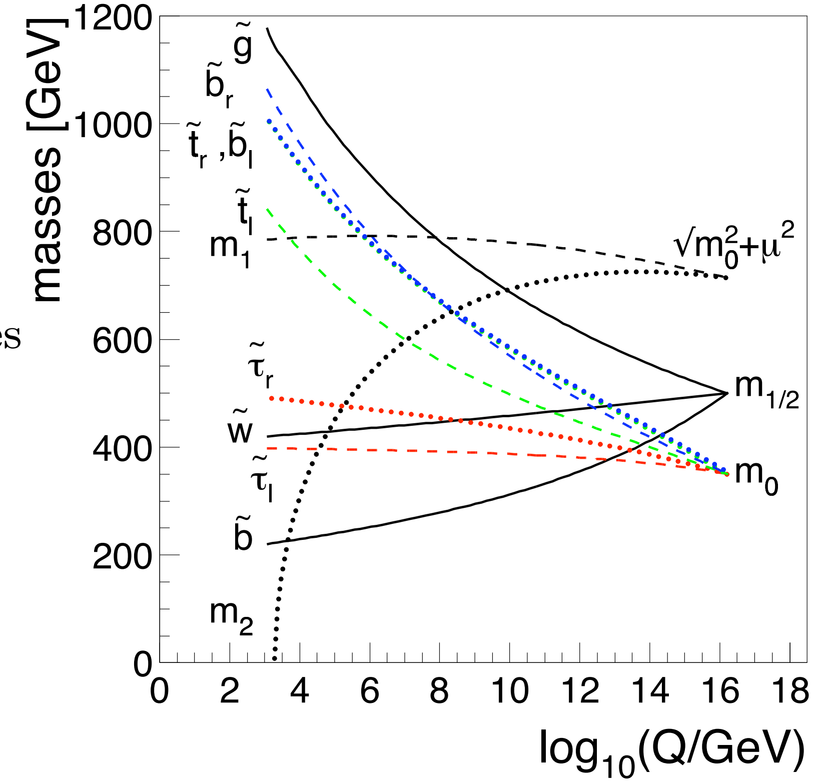
⋆ Solve hierarchy/naturalness problem by having $\Delta m^2 \simeq \mathcal{O}(v^2)$

SUSY breaking scale must be at or below 1 TeV if SUSY is associated with EWSB scale !

⋆ EWSB is radiatively generated

In the evolution of masses from high energy scales
⟶ a negative Higgs mass parameter is induced
via radiative corrections

⟹ *important top quark effects!*



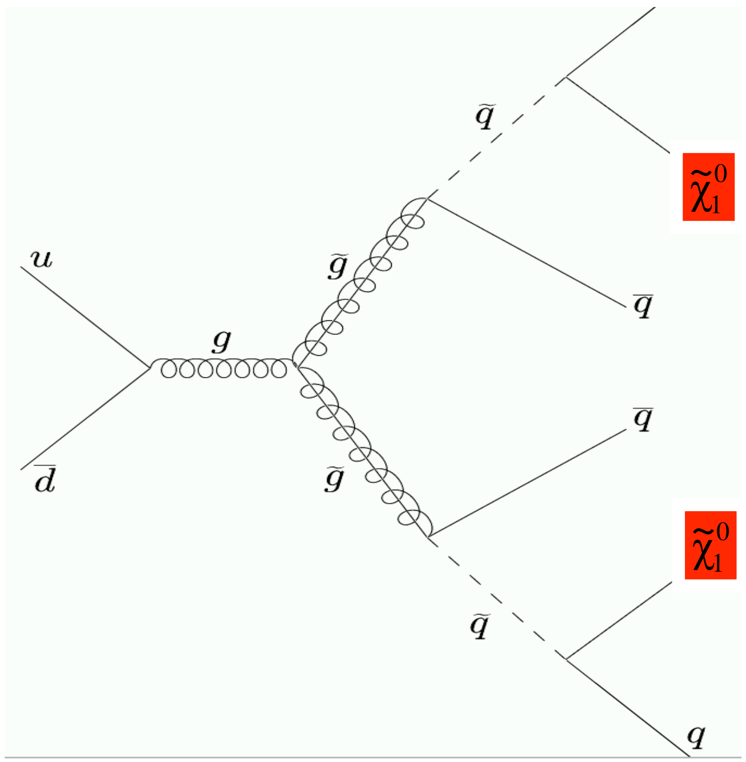
Preservation of R-Parity:

Supersymmetry at colliders

Gluino production and decay: Missing Energy Signature

Supersymmetric Particles tend to be heavier if they carry color charges.

Charge-less particles tend to be the lightest ones.



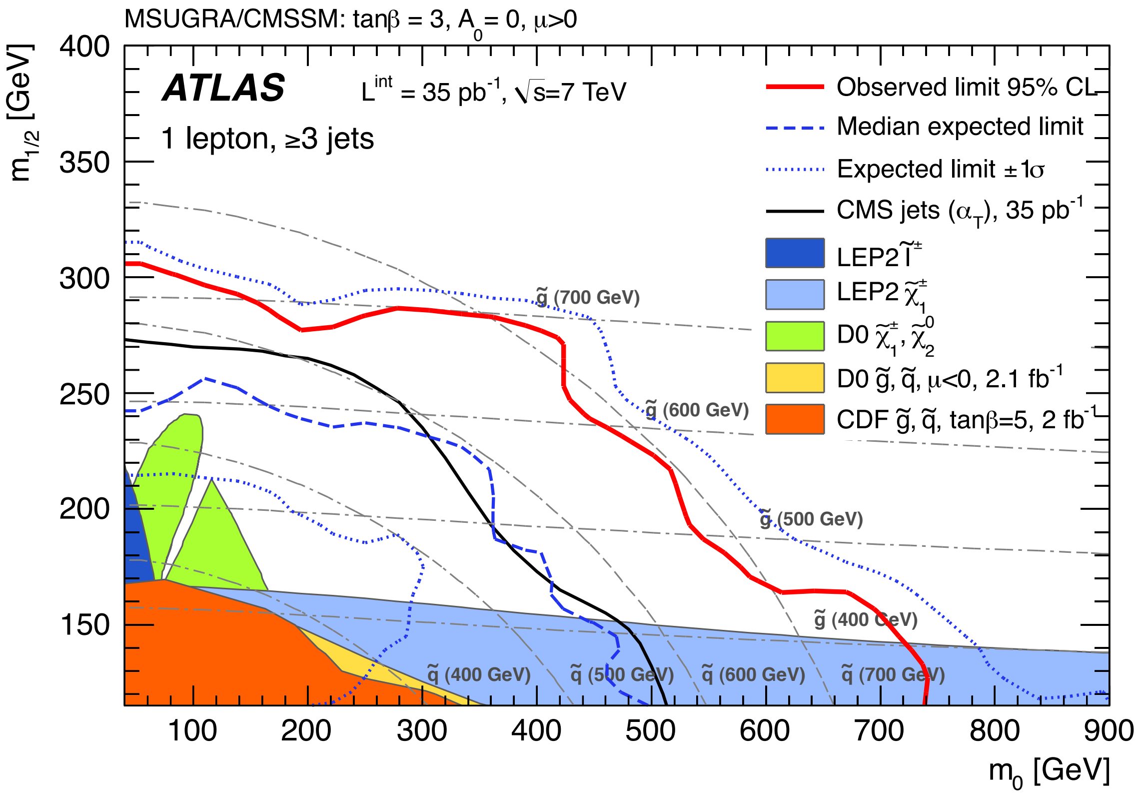
Possibility of observing DM candidate due to presence of color particles.

If just weakly interacting particles, DM observation at LHC would be difficult.

➢ **Lightest supersymmetric particle = Excellent Cold dark matter candidate.**

Results of Searches for Supersymmetry at the LHC

Masses of squarks and gluinos below about 700 GeV seem to be in conflict with data in simple supersymmetry models. But Higgs mass already pointing to masses of order 1 TeV...



So far, no evidence of new physics at the LHC.
But more data is coming...

Low Energy Supersymmetry Breaking: Light Gravitino

$$m_{\tilde{G}} \sim \frac{F}{M_{Pl}} \qquad m_{\rm SUSY} \simeq \frac{\alpha}{4\pi}\frac{F}{M}$$ (gauge mediated models)

If R-parity conserved, heavy particles cascade to lighter ones and

NLSP $\longrightarrow$ SM partner + $\tilde{G}$

- Signatures: The NLSP (Standard SUSY particle) decays

decay length $$L \sim 10^{-2}{\rm cm}\left(\frac{m_{\tilde{G}}}{10^{-9}{\rm GeV}}\right)^2 \times \left(\frac{100{\rm GeV}}{M_{\rm NLSP}}\right)^5$$

⋆ NLSP can have prompt decays:

Signature of SUSY pair: 2 hard photons, (H's, Z's) + $\not{E}_T$ from $\tilde{G}$

⋆ macroscopic decay length but within the detector:

Displaced decay vertices

★ Quasistable particles : binos (missing energy) or sleptons (heavy muons)

Renormalization Group Invariants

They allow a direct connection between low and high energy quantities.

Interestingly enough, there are 14 RGIs in the MSSM

Invariant	Symmetry	Dependence on Soft Masses
$D_{B_{13}}$	$B_1 - B_3$	$2(m^2_{\tilde{Q}_1} - m^2_{\tilde{Q}_3}) - m^2_{\tilde{u}_1} + m^2_{\tilde{u}_3} - m^2_{\tilde{d}_1} + m^2_{\tilde{d}_3}$
$D_{L_{13}}$	$L_1 - L_3$	$2(m^2_{\tilde{L}_1} - m^2_{\tilde{L}_3}) - m^2_{\tilde{e}_1} + m^2_{\tilde{e}_3}$
D_{χ_1}	χ_1	$3(3m^2_{\tilde{d}_1} - 2(m^2_{\tilde{Q}_1} - m^2_{\tilde{L}_1}) - m^2_{\tilde{u}_1}) - m^2_{\tilde{e}_1}$
$D_{Y_{13H}}$	$Y_1 - \frac{10}{13} Y_{3H}$	$m^2_{\tilde{Q}_1} - 2m^2_{\tilde{u}_1} + m^2_{\tilde{d}_1} - m^2_{\tilde{L}_1} + m^2_{\tilde{e}_1} - \frac{10}{13}$ (1<->3+H)
D_Z	Z	$3(m^2_{\tilde{d}_3} - m^2_{\tilde{d}_1}) + 2(m^2_{\tilde{L}_3} - m^2_{H_d})$
$I_{Y\alpha}$	Y	$(m^2_{H_u} - m^2_{H_d} + \sum_{gen}(m^2_{\tilde{Q}} - 2m^2_{\tilde{u}} + m^2_{\tilde{d}} - m^2_{\tilde{L}} + m^2_{\tilde{e}}))/g_1^2$
I_{B_r}		M_r/g_r^2
I_{M_1}		$M_1^2 - \frac{33}{8}(m^2_{\tilde{d}_1} - m^2_{\tilde{u}_1} - m^2_{\tilde{e}_1})$
I_{M_2}		$M_2^2 + \frac{1}{24}(9(m^2_{\tilde{d}_1} - m^2_{\tilde{u}_1}) + 16m^2_{\tilde{L}_1} - m^2_{\tilde{e}_1})$
I_{M_3}		$M_3^2 - \frac{3}{16}(5m^2_{\tilde{d}_1} + m^2_{\tilde{u}_1} - m^2_{\tilde{e}_1})$
I_{g_2}		$1/g_1^2 - 33/(5g_2^2)$
I_{g_3}		$1/g_1^2 + 33/(15g_3^2)$

M. Carena, PD, N. Shah, C. Wagner 2010

Applications of RGI's

RGI sum rules have been considered by many authors :

Martin & Ramond 1993; Kawamura, Kobayashi, Kubo 1997; Kazakov 1997; Hisano & Shifman 1997 Jack, Jones, Pickering 1997; Arkani-Hamed, Giudice, Luty, Rattazzi 1997; Carena, Huiti, Kobayashi 2000 Kobayashi & Yoshioka 2000; Ananthanarayan & Pandita 2005; Demir 2005; Kane, Kumar, Morrissey, Toharia 2007; Meade, Seiberg, Shih 2009; Balazs, Li, Nanopoulos, Wang 2010; etc...

- For most general flavor independent models, establish two sum rules and a one to one relationship between RGIs and parameters of the model, apart from the messenger scale

- For minimal models, several rum rules are established, that lead to spectrum predictions from a limited number of observables.

- Two loop effects, which break the rules, can be taken into account in a simple way. Efficiency of method strongly dependent on experimental uncertainties.

M. Carena, P. Draper, N. Shah, C.W. '10 & '11

Generic Flavor Blind Models

$D_{B_{13}} = 0$ and $D_{L_{13}} = 0$ → direct tests of the flavor-blind hypothesis

★ 5 sfermion masses, 3 gauginos, 2 Higgs mass parameters, 3 gauge couplings

13 d.o.f at the scale M and 12 RGIs

==> can reconstruct everything as an algebraic function of one unknown M

all couplings and soft masses at scale M

$$M_1 = g_1^2 I_{B_1}, \qquad M_2 = g_2^2 I_{B_2}, \qquad M_3 = g_3^2 I_{B_3}$$

$$m_{\tilde{L}}^2 = -\frac{1}{440}(26D_{Y_{13H}} + 11D_{\chi_1} + 20((g_1^4 I_{B_1}^2 + 33 g_2^4 I_{B_2}^2) - (I_{M_1} + 33 I_{M_2}) + g_1^2 I_{Y\alpha})),$$

$$m_{H_d}^2 = m_{\tilde{L}}^2 - \frac{1}{2}D_Z, \quad m_{H_u}^2 = m_{\tilde{L}}^2 - \frac{1}{2}D_Z - \frac{13}{11}D_{Y_{13H}} + \frac{g_1^2}{11}I_{Y\alpha}, \quad m_{\tilde{e}}^2 = \frac{1}{220}(26D_{Y_{13H}} + 11D_{\chi_1} - 20(2(g_1^4 I_{B_1}^2 - I_{M_1}) - g_1^2 I_{Y\alpha})),$$

$$m_{\tilde{u}}^2 = -\frac{1}{990}(78D_{Y_{13H}} + 33D_{\chi_1} + 20(4((g_1^4 I_{B_1}^2 - 11 g_3^4 I_{B_3}^2) - (I_{M_1} - 11 I_{M_3})) + 3 g_1^2 I_{Y\alpha})),$$

$$m_{\tilde{d}}^2 = \frac{1}{1980}(78D_{Y_{13H}} + 33D_{\chi_1} - 20(2((g_1^4 I_{B_1}^2 - 44 g_3^4 I_{B_3}^2) - (I_{M_1} - 44 I_{M_3})) - 3 g_1^2 I_{Y\alpha})),$$

$$m_{\tilde{Q}_1}^2 = \frac{1}{3960}(78D_{Y_{13H}} - 627D_{\chi_1} - 20((g_1^4 I_{B_1}^2 + 297 g_2^4 I_{B_2}^2 - 176 g_3^4 I_{B_3}^2) - (I_{M_1} + 297 I_{M_2} - 176 I_{M_3}) - 3 g_1^2 I_{Y\alpha})).$$

$$g_a(t_M) = [g_a(t_0)^{-2} - B_a(t_M - t_0)/8\pi^2]^{-\frac{1}{2}}$$ → only t_M remains unknown

Bound all parameters by requiring 5 < log(M/GeV) <16 => extra uncertainty

Predicting an MGM Spectrum

Measuring one gaugino and 2 sfermion masses [$M_3 \quad m_{\tilde{e}_1} \quad m_{\tilde{Q}_1}$]

==> reconstruct the rest from constraint equations, including M

Example: $A = 2B^2 = 0.3\ \mathrm{TeV}^2$, M=10^7 GeV (Input)

5% error assumed

	Calculated	Data
M_3 (GeV)		446.8
$m_{\tilde{Q}_1}$ (GeV)		641.6
$m_{\tilde{e}_1}$ (GeV)		114.0
$g_1(M)$	0.5153 ± 0.0465	0.5159
$g_2(M)$	0.6647 ± 0.0400	0.6679
$g_3(M)$	0.9093 ± 0.1090	0.9144
M_1 (GeV)	84.4 ± 12.5	84.2
M_2 (GeV)	158.5 ± 24.0	159.4
$m_{\tilde{L}_1}$ (GeV)	221.3 ± 52.0	227.2
$m_{\tilde{u}_1}$ (GeV)	611.6 ± 36.5	608.4
$m_{\tilde{d}_1}$ (GeV)	607.5 ± 41.0	604.7

$\mathrm{Log}_{10}(M/\mathrm{GeV}) \approx 7 \pm 3$ (Calc)

★ Also, using D_{Y1} obtain relationships among the 3rd generation and Higgs soft masses

$$D_{Y_{13H}} \equiv D_{Y_1} - \frac{10}{13} D_{Y_{3H}} = -\frac{10}{13}(\delta_u - \delta_d)$$

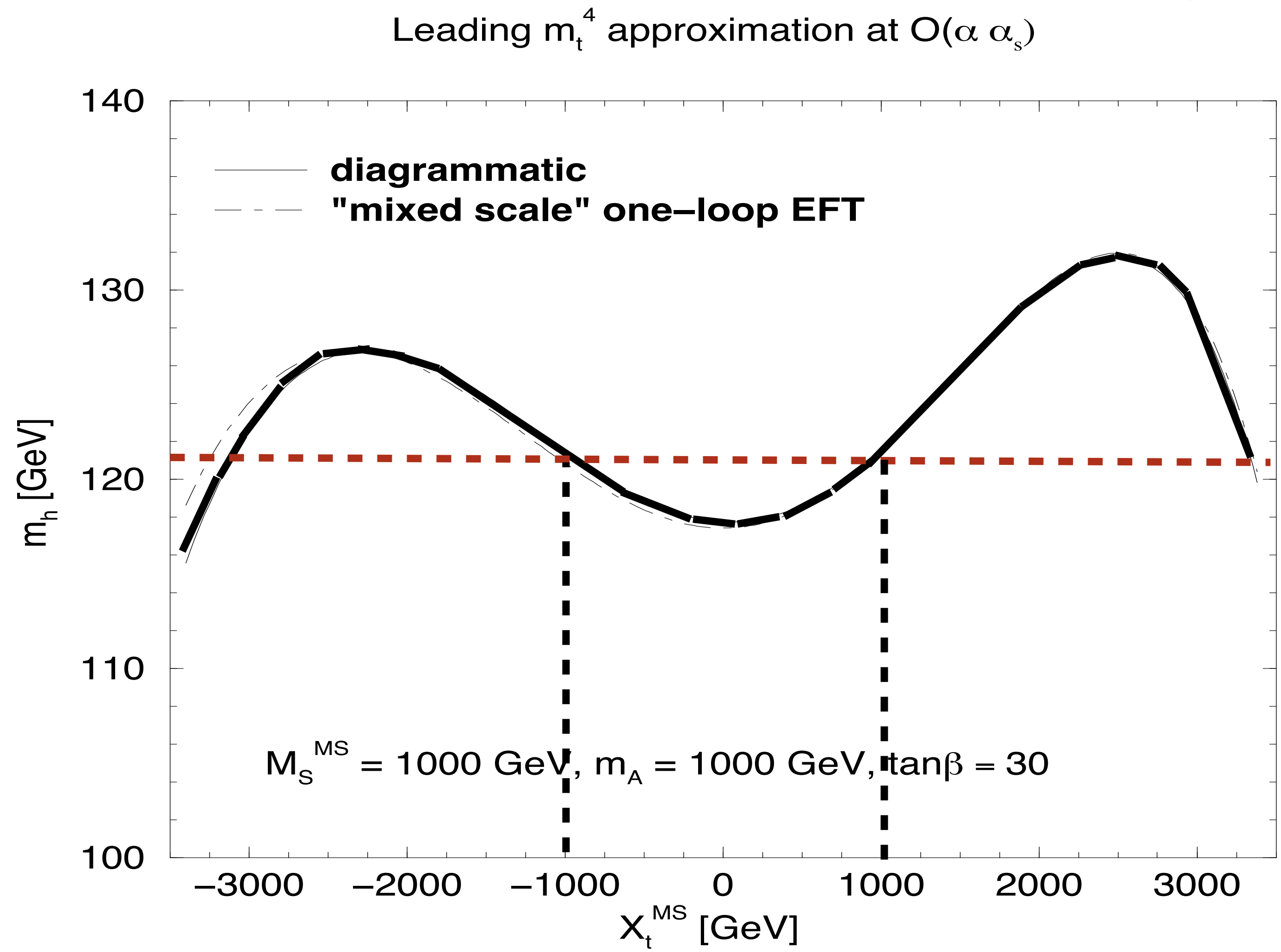
$$I_{Y_\alpha} \equiv \frac{2D_{Y_1} + D_{Y_{3H}}}{g_1^2(M)} = \frac{1}{g_1^2(M)}(\delta_u - \delta_d)$$

M. Carena, P. Draper, N. Shah, C.W. '10 & '11

Standard Model-like Higgs Mass in the MSSM

Long list of two-loop computations: Carena, Degrassi, Ellis, Espinosa, Haber, Harlander, Heinemeyer, Hempfling, Hoang, Hollik, Hahn, Martin, Pilaftsis, Quiros, Ridolfi, Rzehak, Slavich, C.W., Weiglein, Zhang, Zwirner

Carena, Haber, Heinemeyer, Hollik, Weiglein, C.W.'00

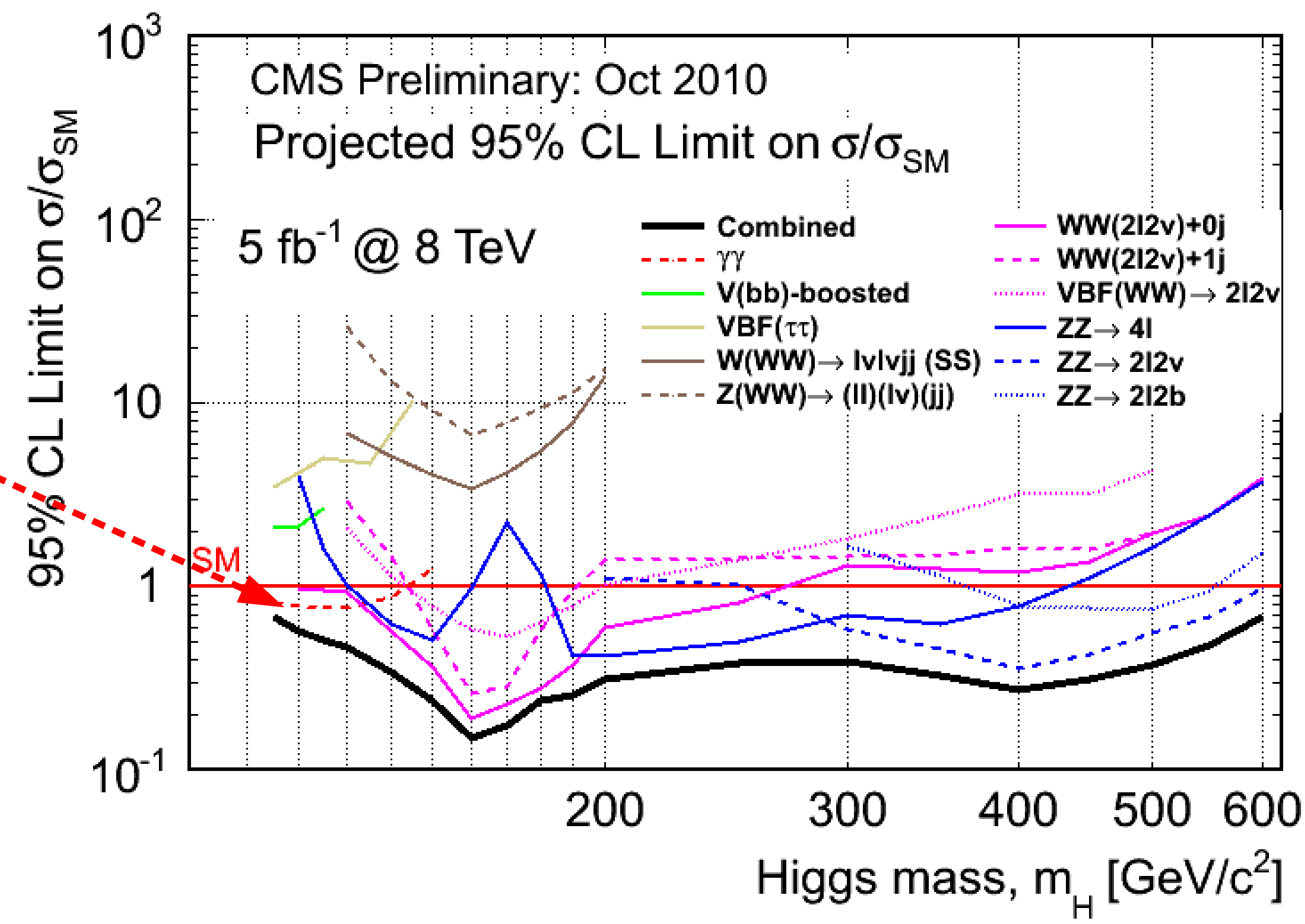


For natural values of the stop mixing, the Higgs remains lighter than 120 GeV

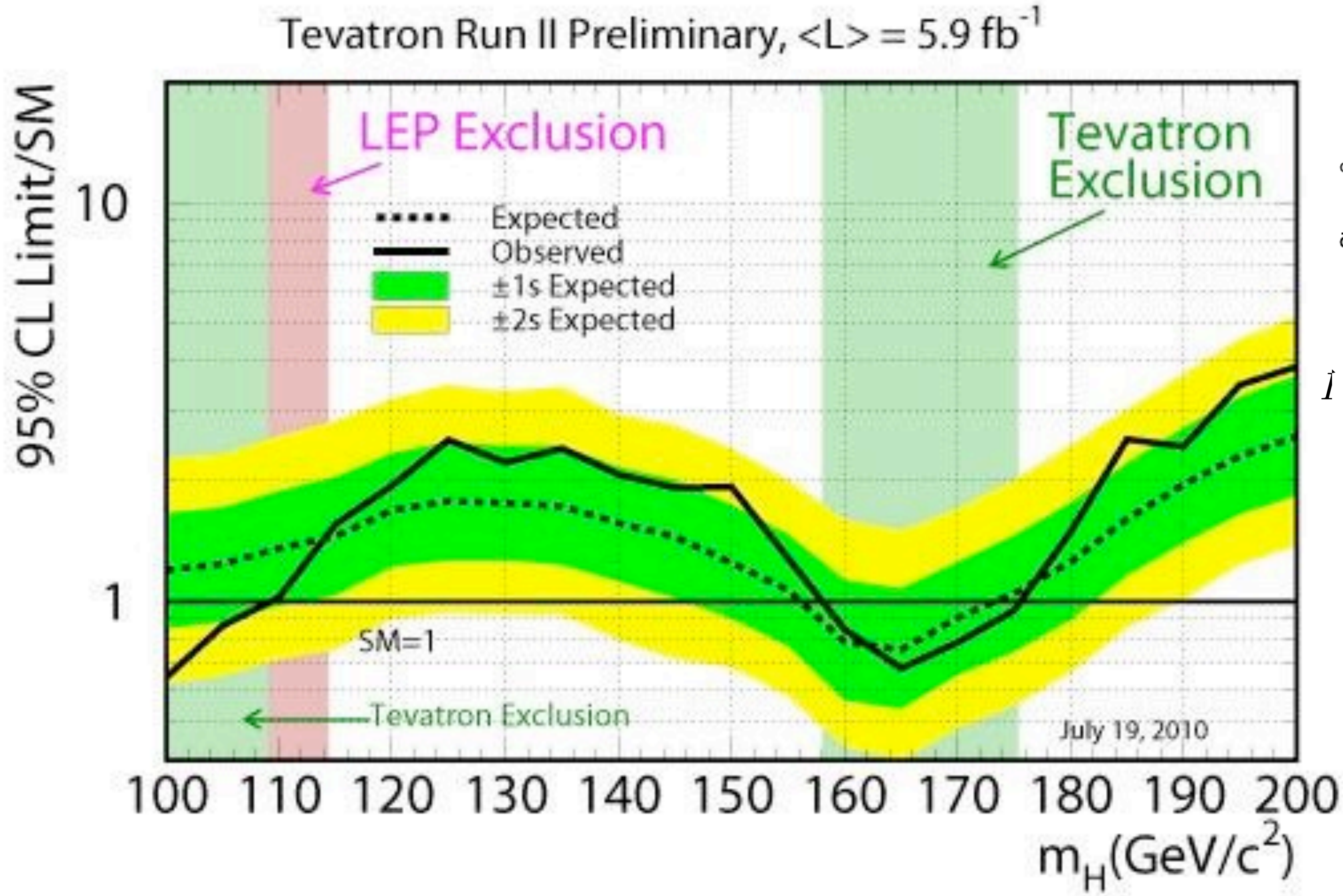
$$X_t = A_t - \mu/\tan\beta, \qquad X_t = 0\,:\ \text{No mixing;} \qquad X_t = \sqrt{6}M_S\,:\ \text{Max. Mixing}$$

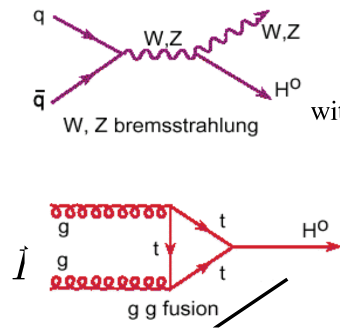
Contributions by channel

- Hardest point is lowest mass
- 5 channels at 120GeV
- H→γγ best



The Tevatron is providing bounds on the Higgs mass





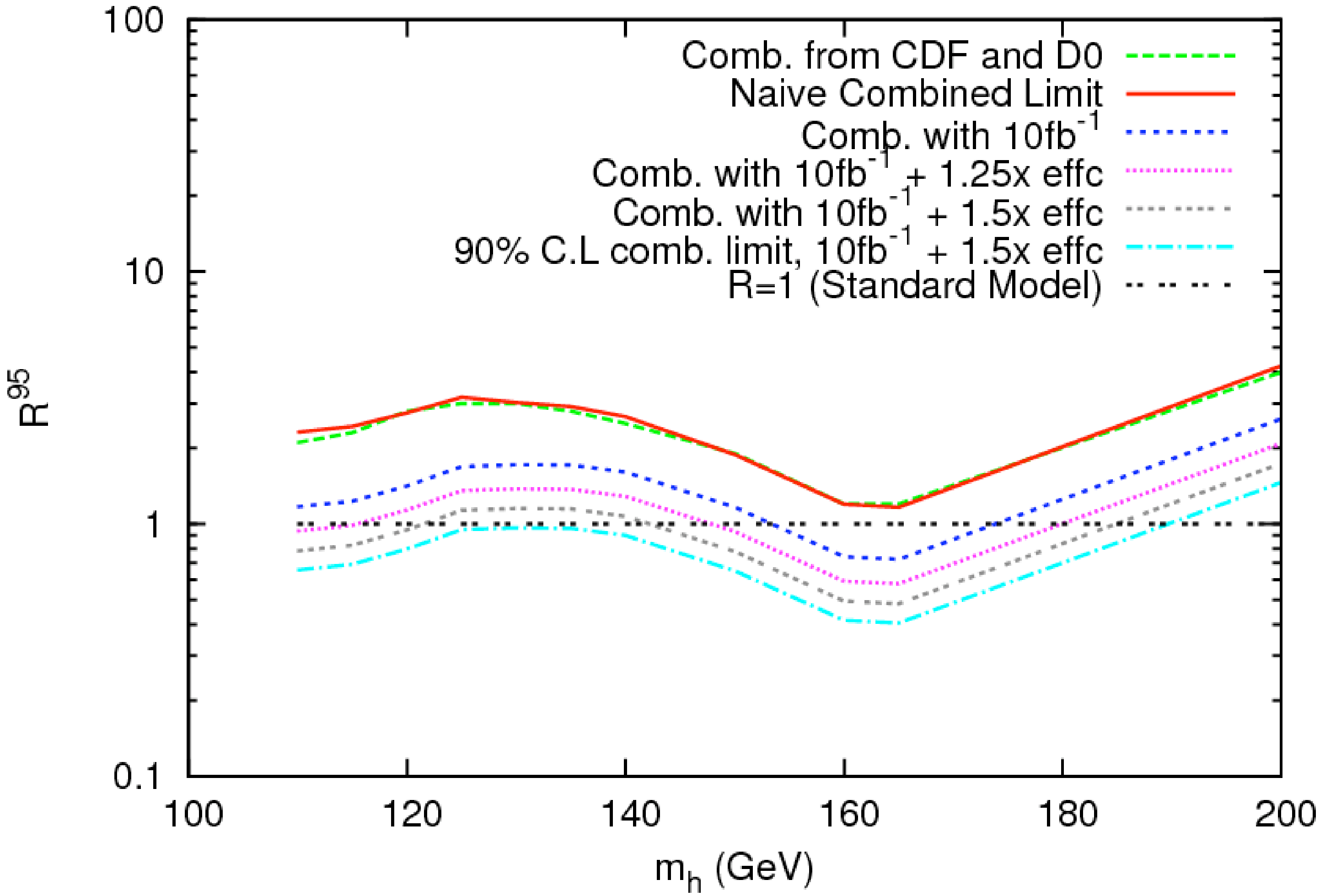
with $H \to b\bar{b}$, WW

with $H \to WW$

Interesting enough, if a Higgs were there, one would expect, in average $R_{\rm obs} = R_{\rm exp} + 1$.
The excess statistical significance is, however, $2/R_{\rm exp}$

Prospects for Higgs Searches at the Tevatron

P. Draper, T. Liu and C. Wagner'09



Improvements with respect to Winter'09 10 percent already achieved

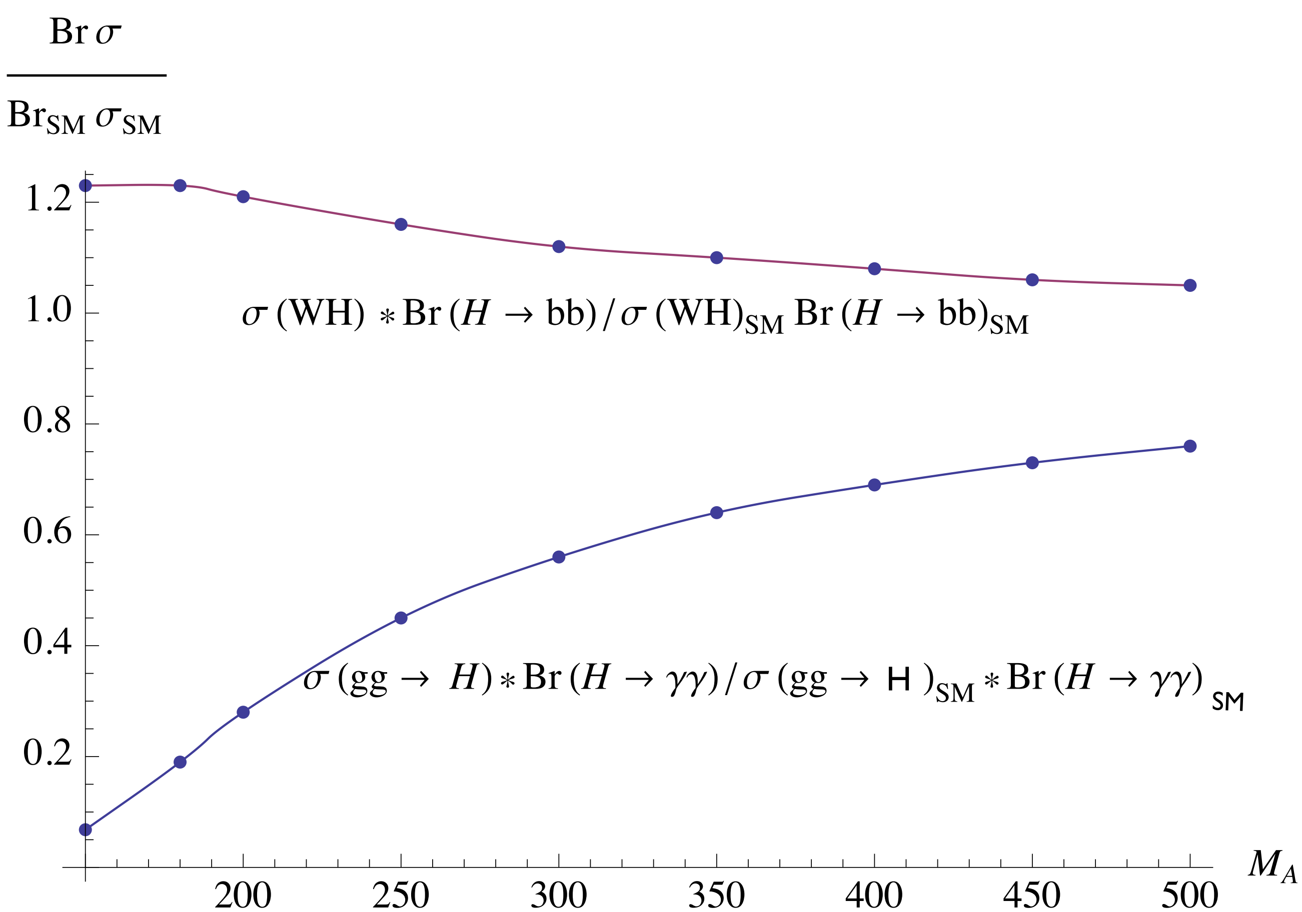
Tevatron shutdown expected this fall, with about $10\ \mathrm{fb}^{-1}$ of luminosity

With the current run, and expected improvements, the Tevatron should probe the Higgs mass region up to 190 GeV

MSSM SM Higgs Searches at the LHC

- In the MSSM, one of the Higgs bosons has standard model like couplings to the top and gauge bosons
- The main SM-like channels of production and/or decay are induced by loops, which are affected by new physics (mainly stops)
- Moreover, the dominant width of Higgs decay into bottom quarks may be enhanced due to mixing with non-standard Higgs bosons. Top Yukawa tend to be somewhat reduced by same effect.

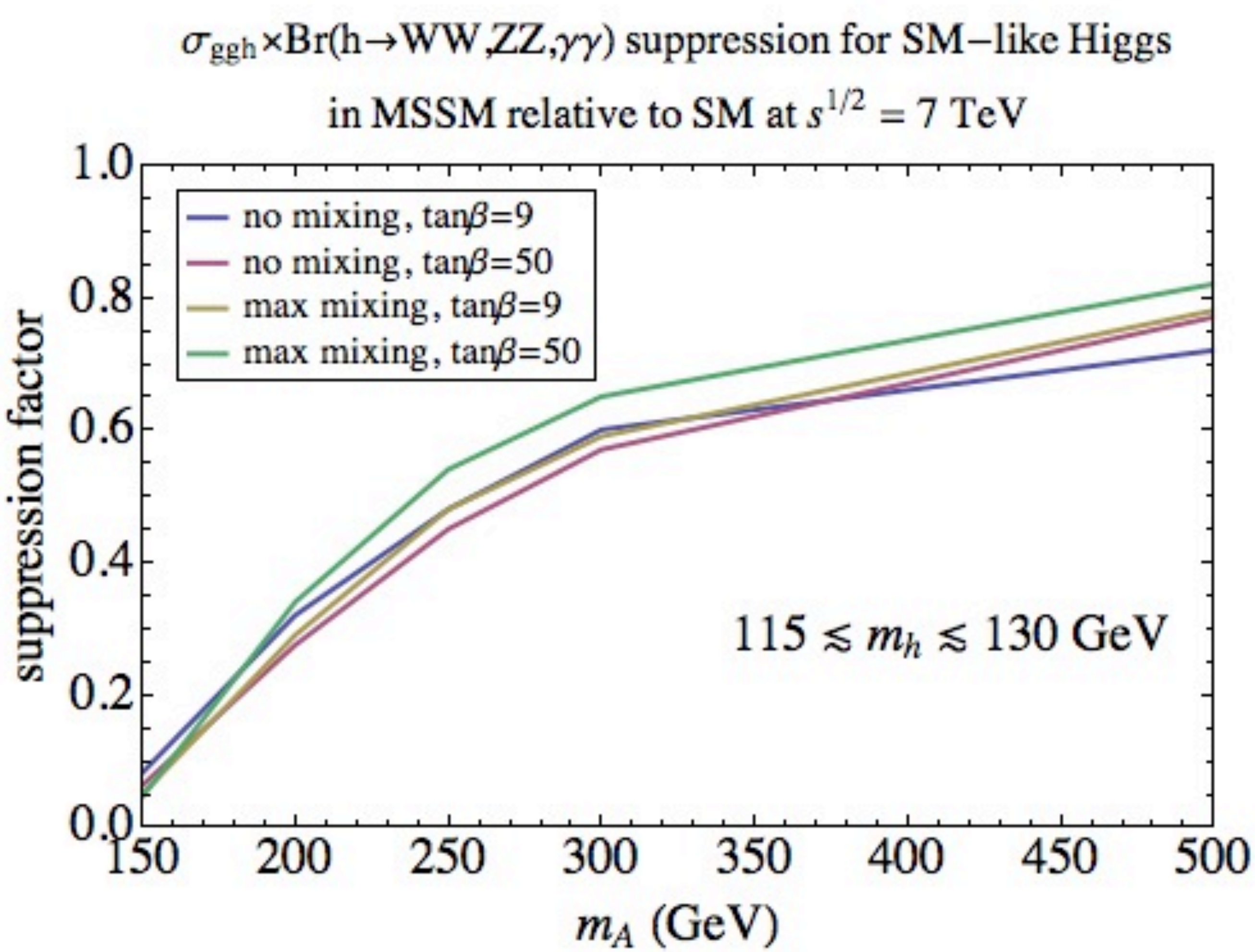
Suppression factor in the LHC channels at the 2012--2013 run



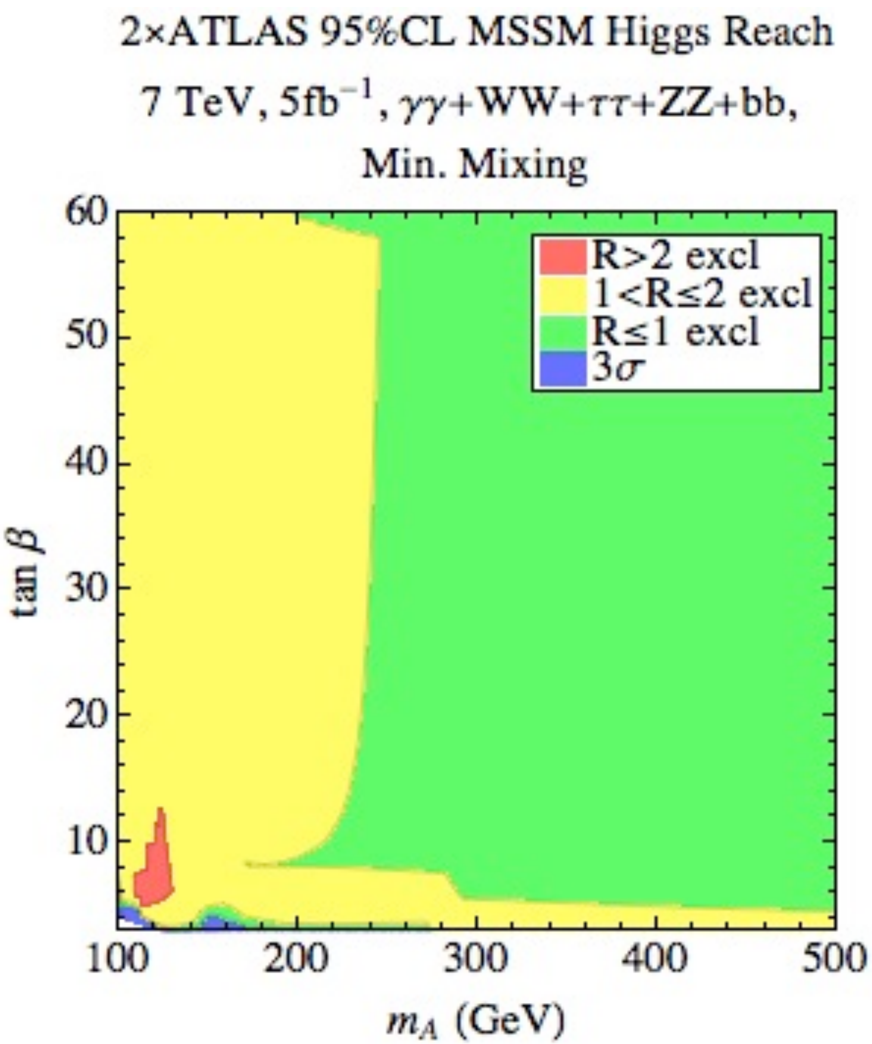
$\tan\beta = 10$
Minimal Mixing

Even for a CP-odd Higgs mass of 500 GeV, suppression is quite relevant.

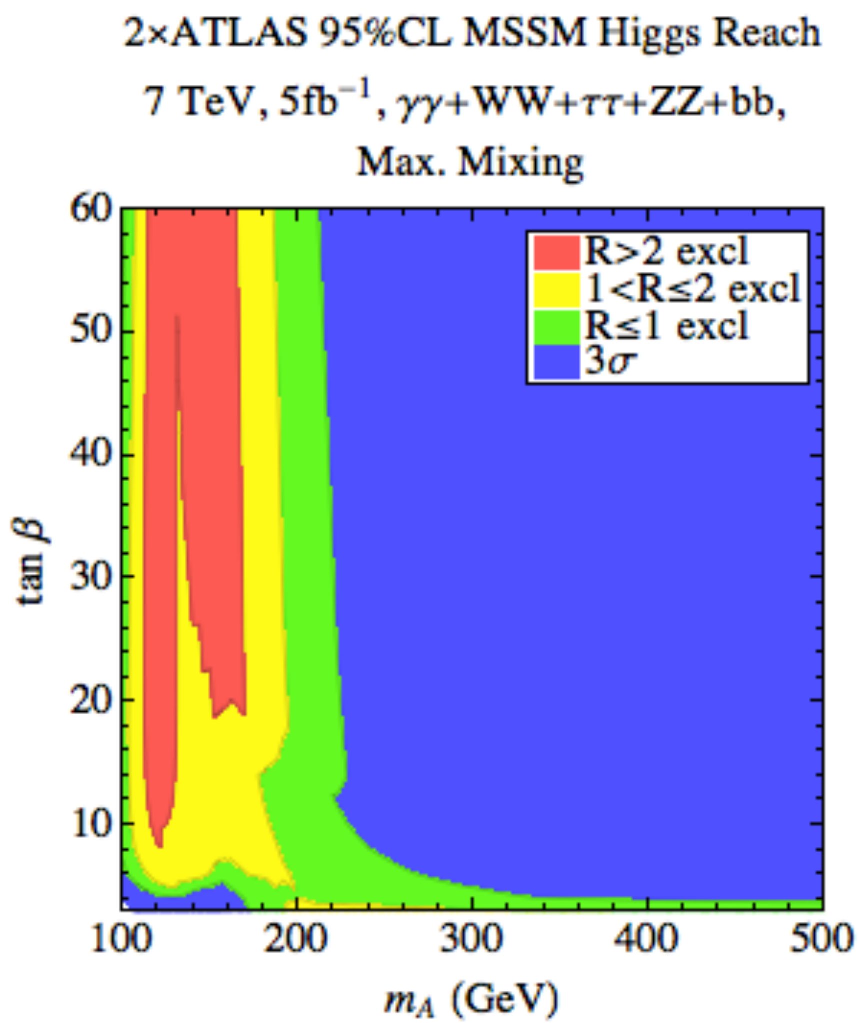
Suppression factor in the LHC channels at the 2012--2013 run



The SM-like Higgs reach is worse than the one at small luminosity at the 14 TeV LHC (P. Draper, T. Liu, C.W. '10)



$m_h \simeq 115\text{GeV}$

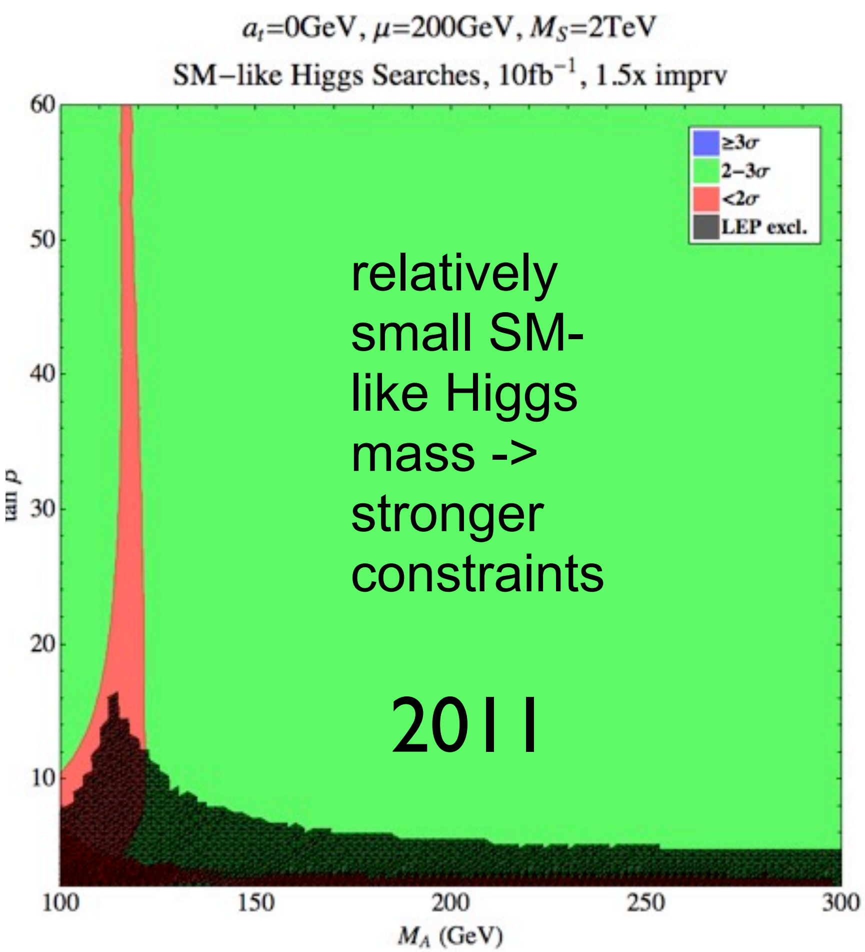


$m_h \simeq 130$ GeV

P. Draper, T. Liu and C.W. '09

Standard Higgs search channels at the Tevatron.

$m_h \simeq 115\text{GeV}$



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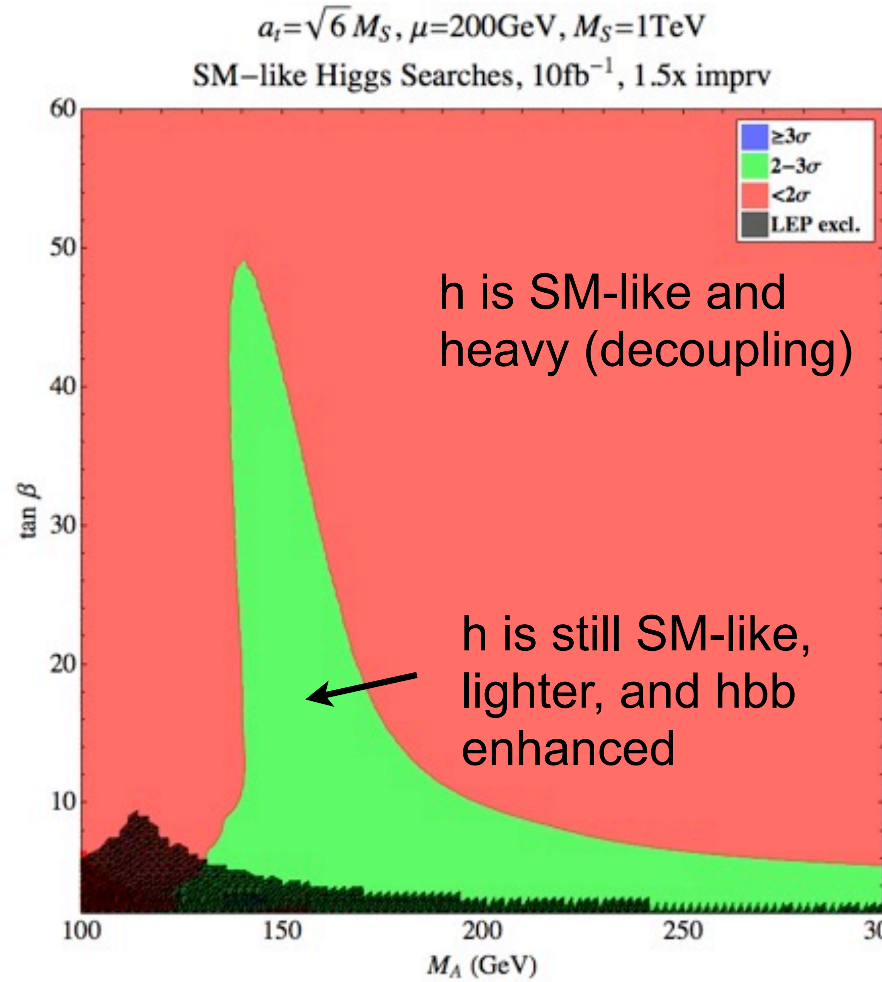
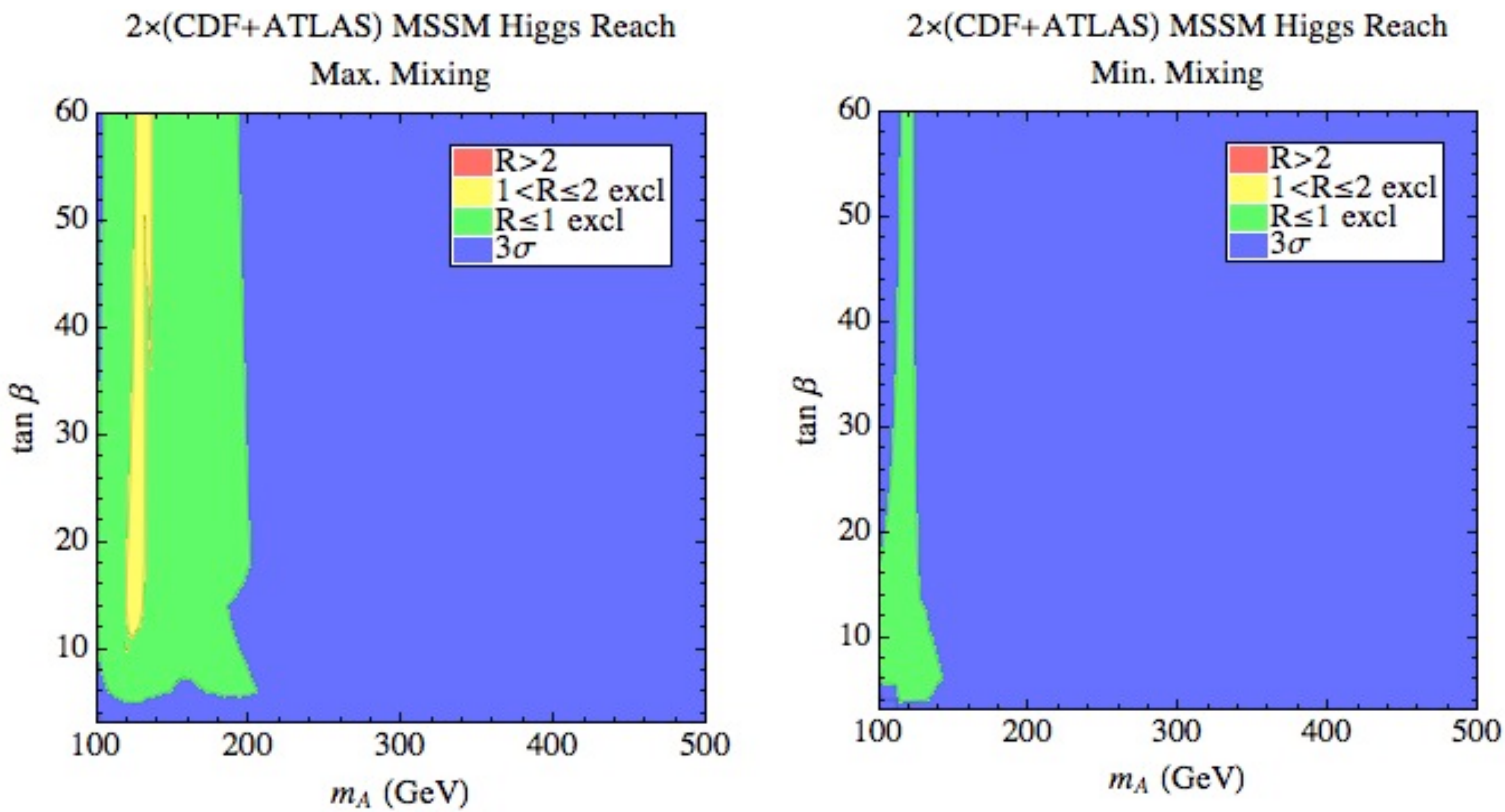


At the end of the Tevatron run, more than 2 sigma sensitivity is achieved in most parameter space in minimal mixing, while weaker reach in maximal mixing scenario.

Since sensitivity is somewhat complementary to that of the Tevatron, combination of data from all experiments at the end of 2012 may be useful



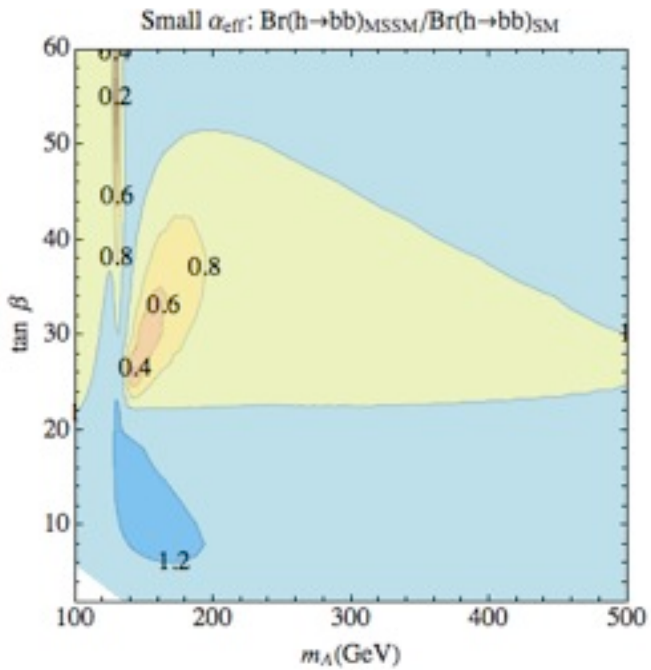
Evidence or Discovery in almost all parameter space

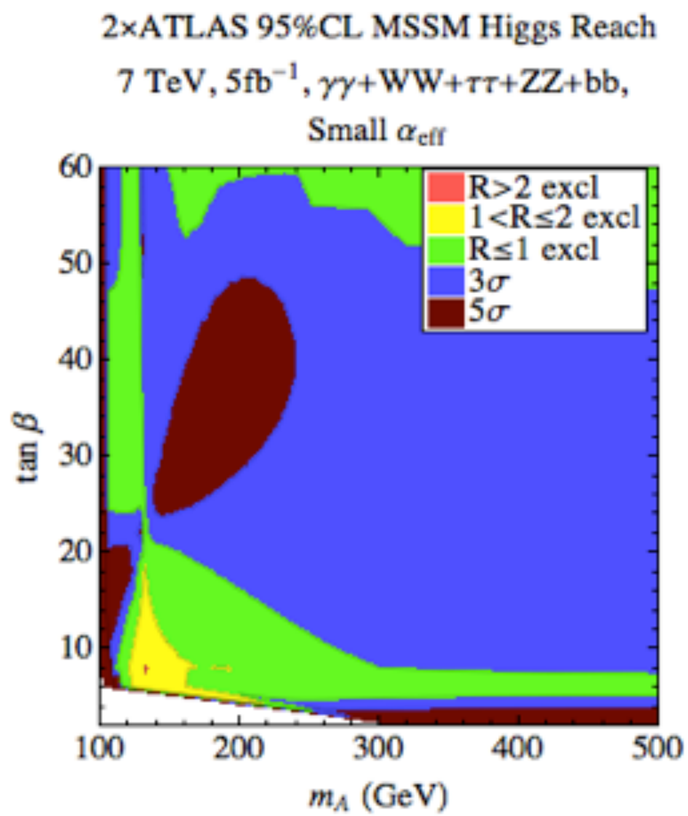
Limited regions of parameter space with suppression of bottom coupling : Enhancement of photon branching ratio

It can occur for large values of both the Higgsino mass and the stop mixing parameter (away, however, from maximal mixing)

Carena, Mrenna, C.W. '99
Carena, Haber, Logan, Mrenna '00
Carena, Heinemeyer, Weiglein, C.W. '03

$$\left[\frac{m_A^2}{m_Z^2} - \frac{1}{2\pi^2}(3\bar{\mu}^2 - \bar{\mu}^2 \bar{A}_t{}^2) + 1\right] \simeq \frac{\tan\beta}{150}\left[\bar{\mu}\bar{A}_t(2\bar{A}_t{}^2 - 11)\right].$$





$$\bar{\mu} = \frac{\mu}{M_{\rm SUSY}} = 2$$

$$\bar{A}_t = \frac{A_t}{M_{\rm SUSY}} = -1.5$$

Carena, Draper, Liu, C.W. , to appear

Constrained by non-standard Higgs boson searches

Higgs Bosons Decaying to Bottom pairs at the LHC

- In the past the decay of Higgs into bottom quarks have been ignored due to overwhelming backgrounds
- However, the study of jet substructure has revealed new possibilities
- In particular, boosted Higgs bosons decaying to bottom pairs might be easily separated from the QCD background by the use of these techniques
- This is true in the SM model, for a light Higgs produced in association with W bosons, where the proportion of boosted Higgs is small

Butterworth, Davison, Rubin, Salam'08

Plehn, Salam, Spannowsky'09 (ttbar+H)

- In the MSSM, there are new possibilities for boosted Higgs, namely induced by the decay of heavy supersymmetric particles

Kribs, Martin, Roy, Sapnnowsky'10

Gori, Schwaller, C.W.'11

Good prospects of observing Higgs in the14 TeV run and, perhaps, even in the 7 TeV run (Gori's talk today)

Searches for non-standard Higgs bosons

QCD: S. Dawson, C.B. Jackson, L. Reina, D. Wackeroth '06
M. Carena, S. Heinemeyer, G. Weiglein, C.W, EJPC'06

- Searches at the Tevatron and the LHC are induced by production channels associated with the large bottom Yukawa coupling.

$$\sigma(b\bar{b}A) \times BR(A \to b\bar{b}) \simeq \sigma(b\bar{b}A)_{\rm SM} \frac{\tan^2\beta}{(1+\Delta_b)^2} \times \frac{9}{(1+\Delta_b)^2+9}$$

$$\sigma(b\bar{b}, gg \to A) \times BR(A \to \tau\tau) \simeq \sigma(b\bar{b}, gg \to A)_{\rm SM} \frac{\tan^2\beta}{(1+\Delta_b)^2+9}$$

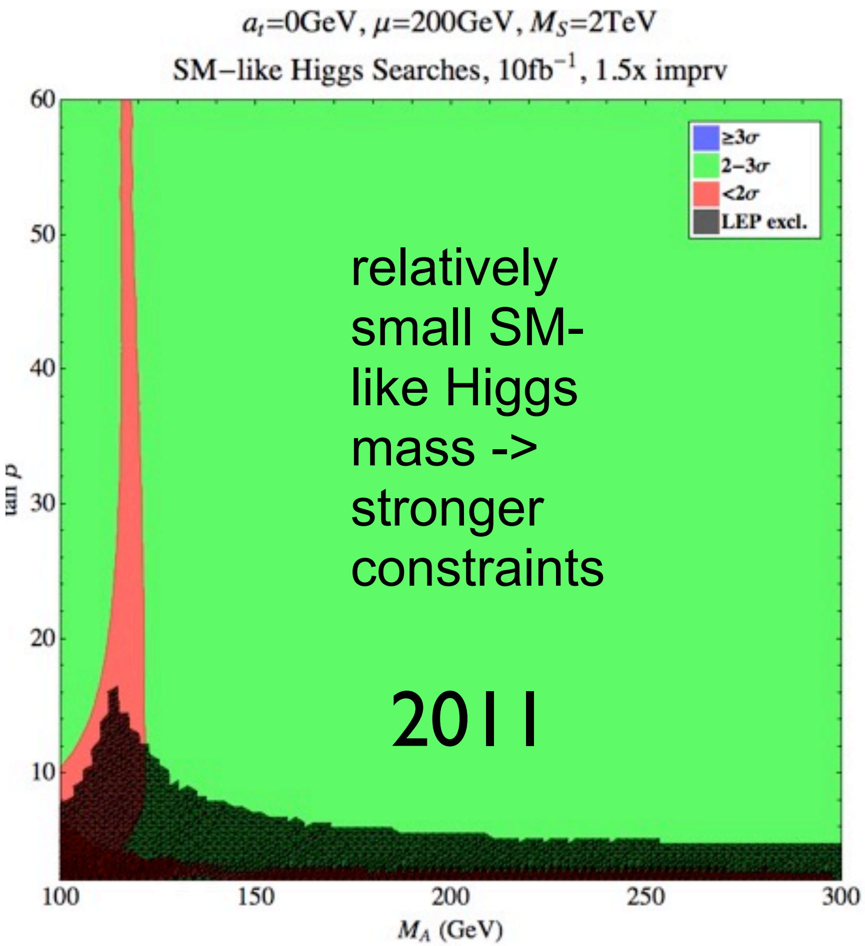
- There may be a strong dependence on the parameters in the bb search channel, which is strongly reduced in the tau tau mode.

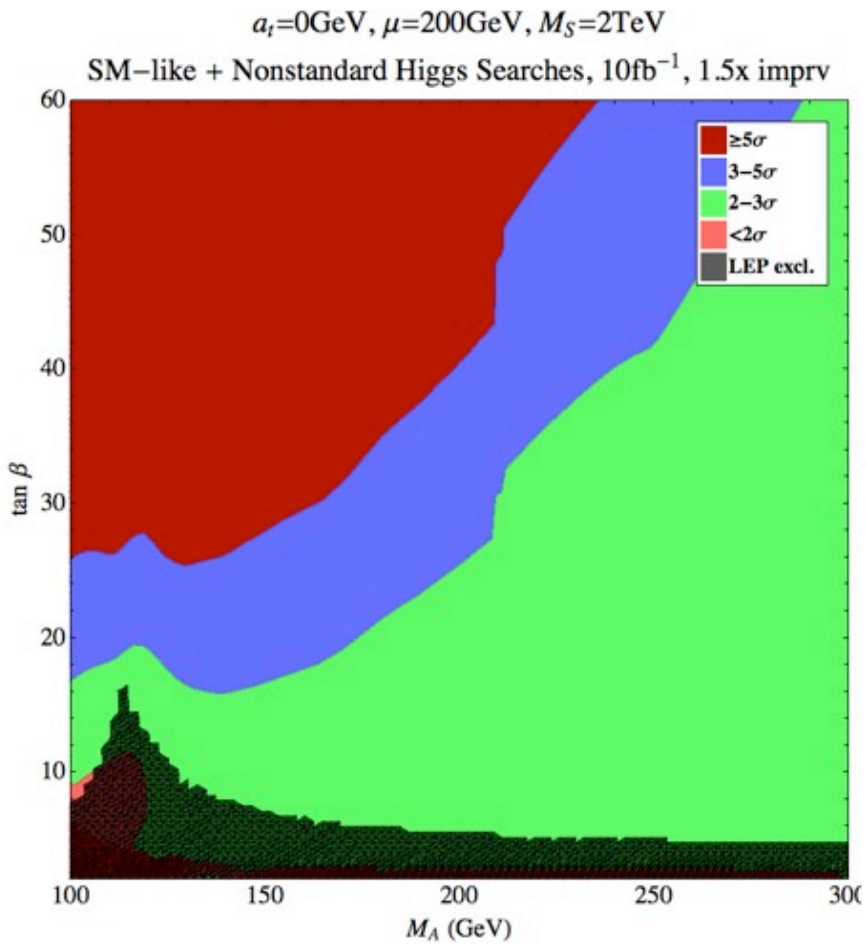
Validity of this approximation confirmed by NLO computation by D. North and M. Spira, arXiv:0808.0087
Further work by Mhulleitner, Rzehak and Spira, 0812.3815, Dawson et al '10, Djouadi et al'11

Minimal Mixing Scenario : Standard and non-standard Higgs search channels.

$m_h \simeq 115\text{GeV}$

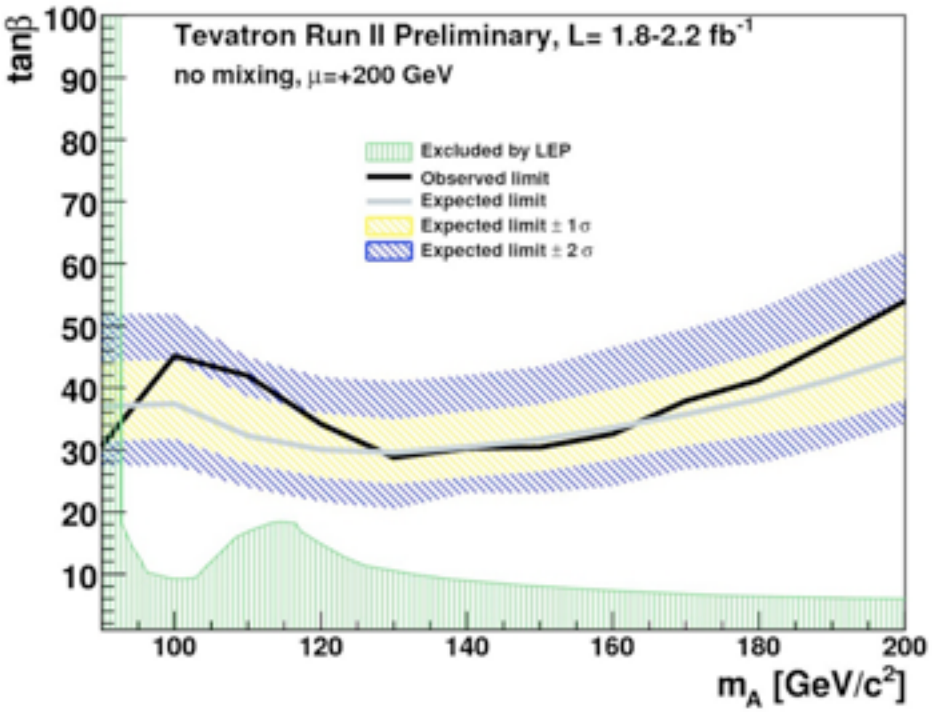
P. Draper, T. Liu and C.W. '09

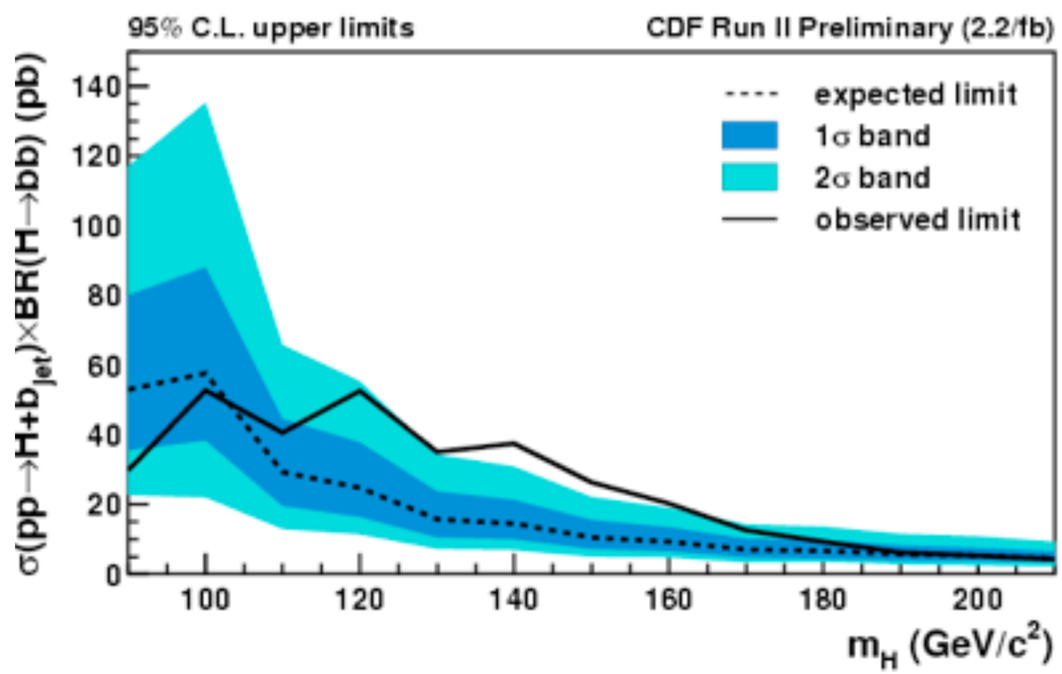




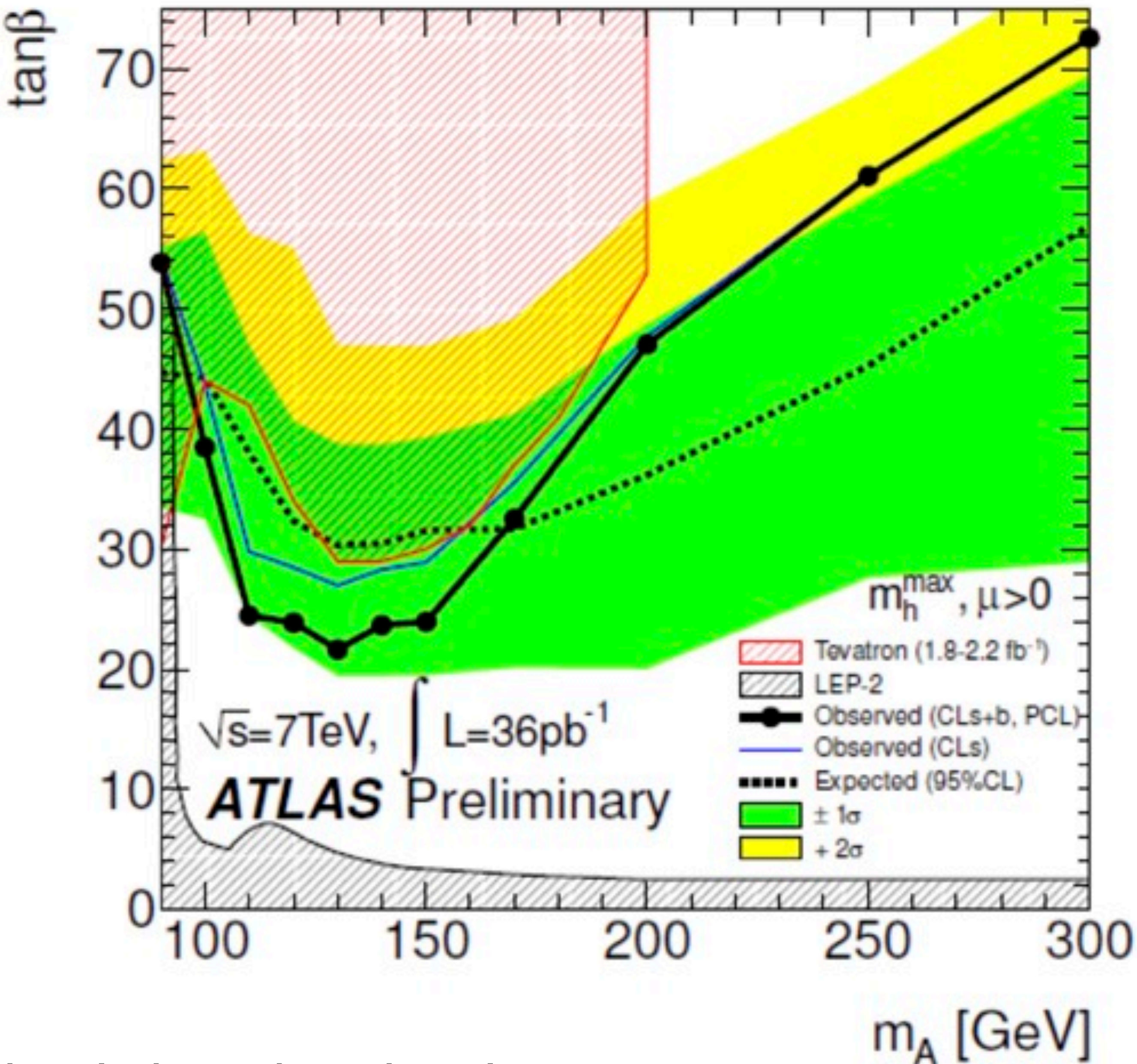
Even with only SM channels and 2011 run, more than 2 sigma sensitivity is achieved in most parameter space. Combination with non standard channels enhances sensitivity considerably.

Searches for non-standard Higgs bosons at the Tevatron





And they are already providing meaningful limits



A detailed combined analysis is in progress

Singlet Extensions of the MSSM

- Models in which the mu-term is forbidden by some symmetry but include singlets with couplings

$$P[\Phi] = \lambda S H_1 H_2$$

may lead to a natural explanation of the origin of mu.

Since S is a singlet, its mass is driven naturally to small values by Yukawa interactions, leading to a v.e.v. that generates the mu-term.

They don't spoil unification and they can lead to an increase of the SM-like Higgs boson mass

$$m_h^2 = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \text{loop corr.}$$

They also include an additional CP-even and CP-odd Higgs bosons. The CP-odd component may become light in models in which trilinear soft breaking terms of the singlet are suppressed (Dobrescu et al., Dermisek et al)

Such light scalars would couple to the SM-like Higgs boson and may induce additional, exotic decays. Neutralinos are also light in certain examples (nMSSM) inducing invisible decays of the SM-like Higgs (Menon, Morrissey, C.W.)

More general MSSM Higgs extensions: EFT approach

- The non-minimal part of the Higgs sector is parametrically heavier than the weak scale (understood as v = 174 GeV)

- SUSY breaking is of order v, hence heavy masses nearly supersymmetric

M : overall ``heavy'' scale   SUSY breaking mass splittings $\Delta m \sim \mathrm{v} \ll M$

In practice: formalism applies for e.g. $M \sim 1\ \mathrm{TeV}$

Low energy superpotential: at leading order in 1/M

$$W = \mu H_u H_d + \frac{\omega_1}{2M}(H_u H_d)^2$$

- can include SUSY breaking via a spurion X= $m_S\, \theta^2$ $W_X \supset \alpha_1 \frac{\omega_1}{2M} X (H_u H_d)^2$

Only two new parameters: ω_1 and X

Carena, Kong, Ponton, Zurita'10

see also Dine, Seiberg, Thomas; Antoniadis, Dudas, Ghilencea, Tziveloglou

- At NLO, Kähler potential only:

$$K = H_d^\dagger e^{2V} H_d + H_u^\dagger e^{2V} H_u + \Delta K^{\rm CV} + \Delta K^{\rm Cust}$$

Custodially violating (treel level) :

$$\Delta K^{\rm CV} = \frac{c_1}{2|M|^2}(H_d^\dagger e^{2V} H_d)^2 + \frac{c_2}{2|M|^2}(H_u^\dagger e^{2V} H_u)^2 + \frac{c_3}{|M|^2}(H_u^\dagger e^{2V} H_u)(H_d^\dagger e^{2V} H_d)$$

Custodially preserving (tree level) :

$$\Delta K^{\rm Cust} = \frac{c_4}{|M|^2}|H_u H_d|^2 + \left[\frac{c_6}{|M|^2} H_d^\dagger e^{2V} H_d + \frac{c_7}{|M|^2} H_u^\dagger e^{2V} H_u\right](H_u H_d) + {\rm h.c.}$$

Plus SUSY breaking terms obtained by multiplication by spurion, with new coefficients

$$X \to \gamma_i \ , \qquad X^\dagger X \to \beta_i$$

- EFT coefficients can be essentially arbitrary, if UV theory complicated enough

Some Examples

Carena, Kong, Ponton, Zurita'10

m_A (GeV)	m_h (GeV)	m_H (GeV)	$m_{H^\pm}$ (GeV)
184	204	234	203
g^2_{hWW}	g^2_{HWW}	g^2_{hgg}	g^2_{Hgg}
0.3	0.7	1.39	0.36
channel	BMSSM (SM)	channel	BMSSM (SM)
$h \to WW$	0.73 (0.72)	$h \to ZZ$	0.25 (0.27)
$H \to WW$	0.70 (0.71)	$H \to ZZ$	0.29 (0.29)
$A \to b\bar{b}$	0.87	$H^+ \to t\bar{b}$	0.99

Two neutral Higgs boson decaying into gauge bosons

m_A (GeV)	m_h (GeV)	m_H (GeV)	$m_{H^\pm}$ (GeV)
210	111.3	215	225
g^2_{hWW}	g^2_{HWW}	g^2_{hgg}	g^2_{Hgg}
0.98	0.02	1.39	0.84
channel	BMSSM (SM)	channel	BMSSM (SM)
$h \to b\bar{b}$	0.03 (0.79)	$h \to \gamma\gamma/10^{-3}$	12.1 (2.1)
$h \to$ jets	0.56 (0.07)	$h \to WW$	0.36 (0.05)
$H \to b\bar{b}$	0.86	$H \to \tau\bar{\tau}$	0.14
$A \to b\bar{b}$	0.86	$A \to \tau\bar{\tau}$	0.14
$H^\pm \to \tau\nu_\tau$	0.35	$H^\pm \to t\bar{b}$	0.64

Model with enhanced SM-like Higgs decay into photons

Extra Dimensions

- Some possible implementations:
- Large extra dimensions: Only gravity propagate into them. They solve the hierarchy problem by lowering the fundamental Planck scale.
- Universal Extra Dimensions: All fields propagate into them. The compactification radius should be at least of the order of the (inverse) TeV scale, in order to avoid phenomenological problems
- Warped extra dimensions: Non-trivial extra dimensional metric. All fundamental parameters are of the order of the Planck scale. Weak scale is obtained by exponentially small warp factor.

Universal Extra Dimensions

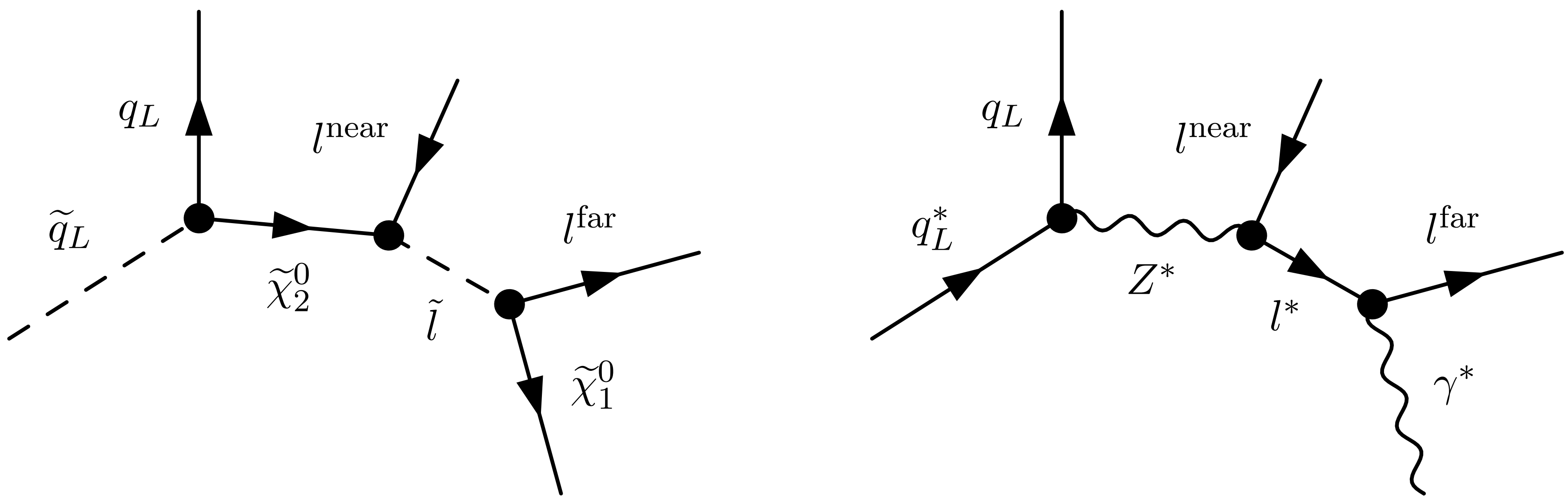
Appelquist, Cheng, Dobrescu'01

Most natural extension of four dimensional description:

- All particles live in all dimensions, including quarks, leptons, Higgs bosons, gauge bosons and gravitons.
- Universality implies a translational invariance along the extra dimension, and thus conservation of the component of momentum in the that direction.
- This implies that a KK state with $n \neq 0$, carrying non-zero momentum in the extra dimension, cannot decay into standard, zero modes. (replaced by KK-parity)
- The lightest KK particle is stable, being a good dark matter candidate.

Decay Chains are similar to the ones in SUSY

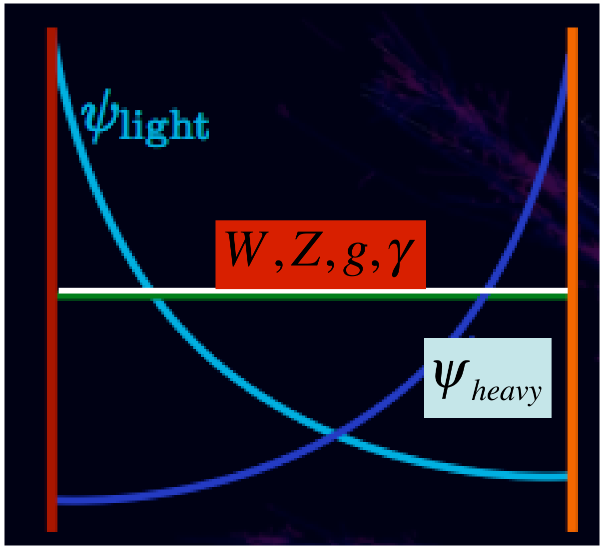
Difficult to differentiate between the two. Cross sections are larger for UED, but this can be compensated by a somewhat larger mass spectrum.



$$\text{Masses}: \; n/R + \text{rad. corr.}$$

(a) (b)

Warped Extra Dimensions



UV brane

IR brane

Higgs + KK modes

Hierarchical fermion masses from localization

FCNC and higher dimensional operators suppressed for the light fermion families

Many KK excitations of bulk SM fields ==> rich phenomenology

All KK mode masses are quantized in units of $\pi\, k\, \exp(-kL)$,

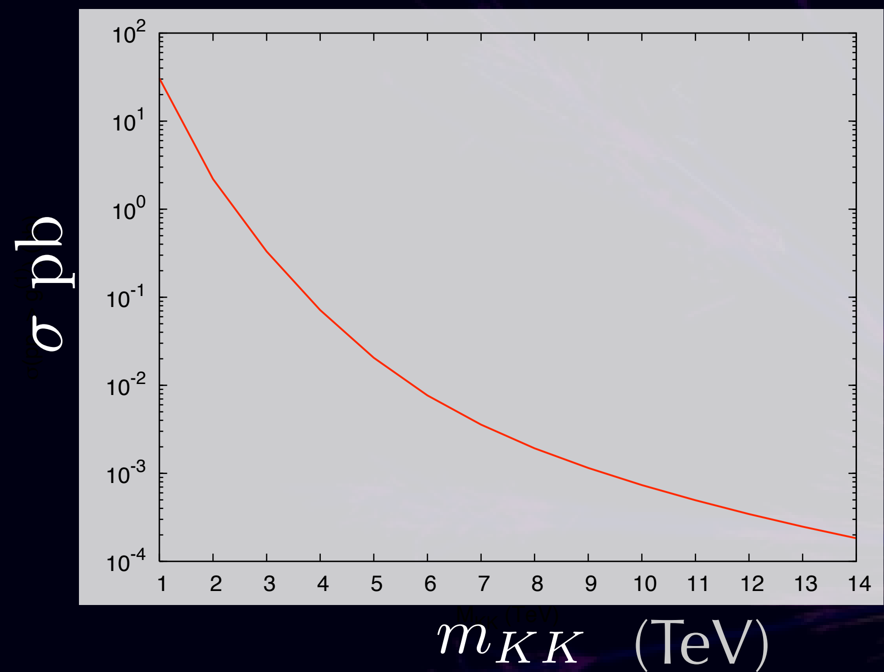
$$m_n = (x_1 + (n-1)\pi) k \exp(-kL)$$

where $x_1 \simeq 2.5$ for gauge bosons and 3.8 for gravitons. For even fermions, it depends on the localization, but it is similar to gauge bosons. In general, it depends on localization and on brane terms.

- Since all KK modes tend to be localized towards the IR brane, and the heavy SM fermions should also be localized towards this brane, KK glons couple strongly to top quarks.

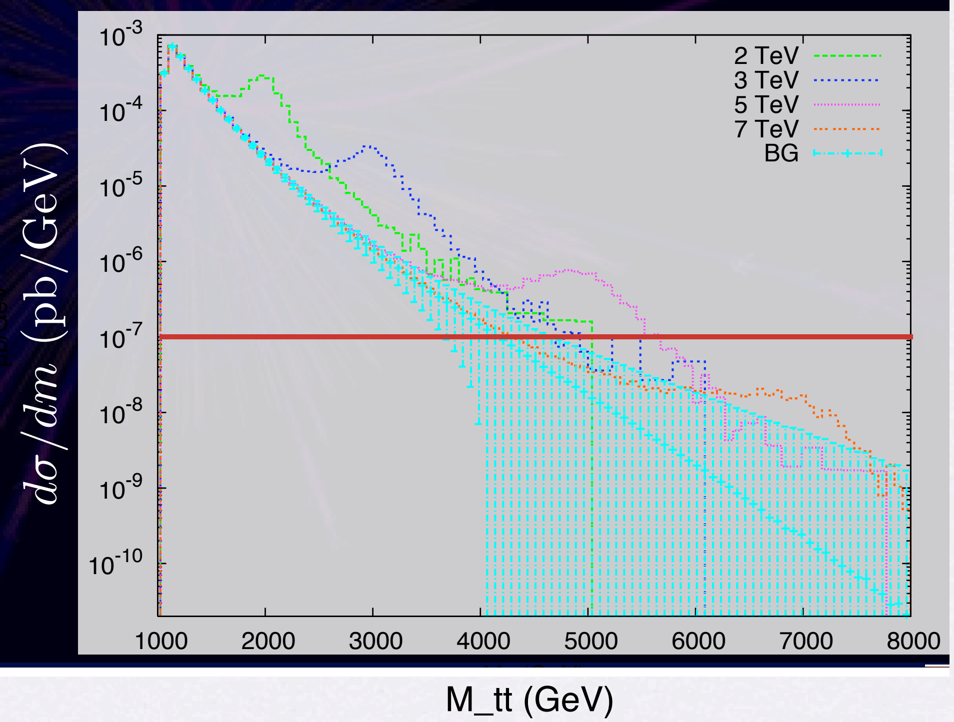
Agashe et al; B. Lillie, L. Randall, L. Wang hep-ph/0701166

Top pairs from KK gluons



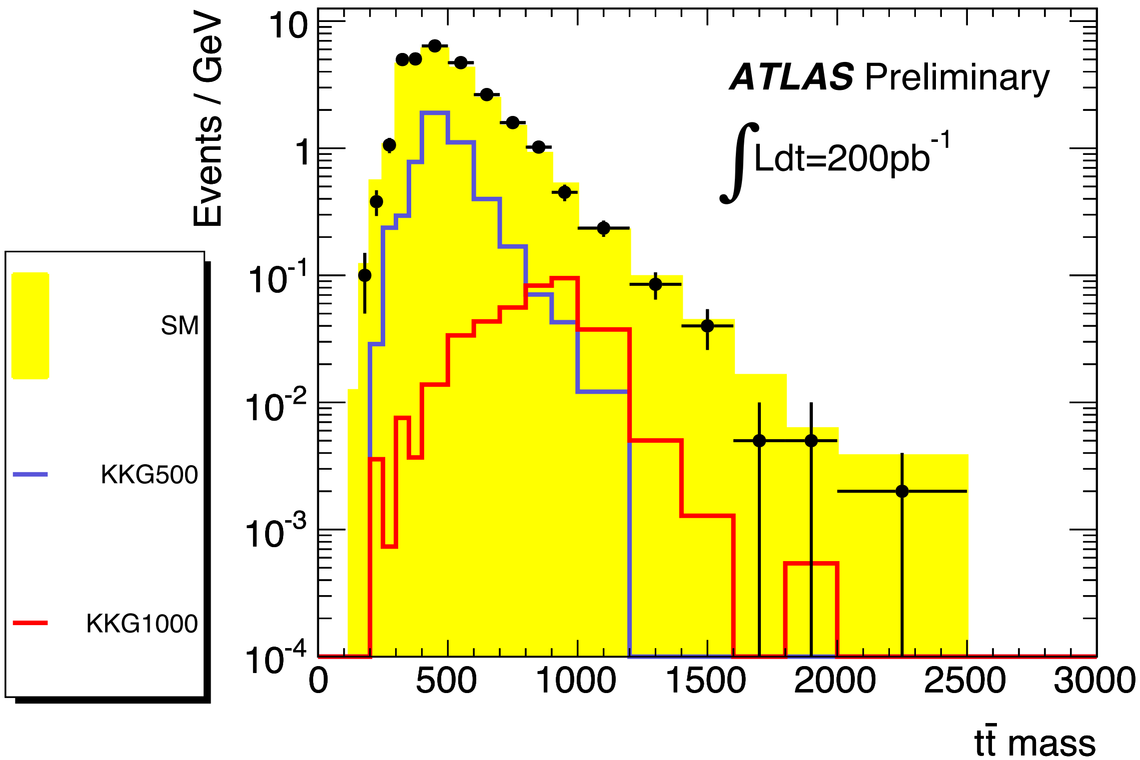
Cross-section at LHC reasonable, limited by small coupling to light fermions, and lack of glue-glue coupling

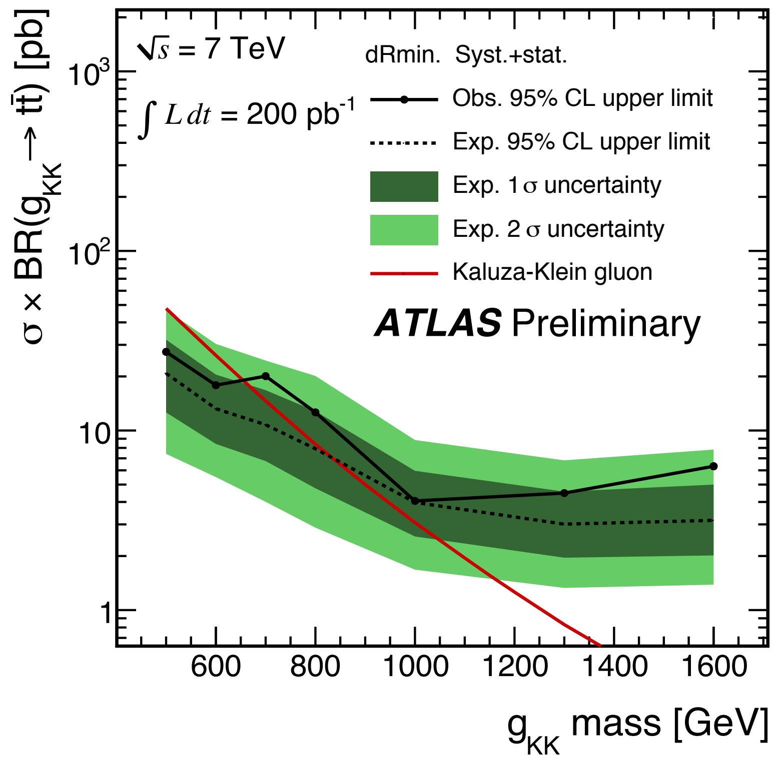
- Nice signal above SM top production
  - PDF and stat. errors shown, assuming $100 fb^{-1}$
- Width/Mass ~17%



More realistic reach estimates

- When heavy gluon KK modes decay into top-quarks, tops are heavily boosted
- Reach depends on proper top quark identification and control of backgrounds.
- KK gluons decaying dominantly into right-handed top quarks may be discovered up to masses of 4 TeV. (Agashe et al'07, U. Baur, L. Ohr'08)
- Measurement of the inclusive top cross section may provide information on the particular RS model, and, in particular of the size of the IR brane kinetic terms. (Lillie, Tait, Shu'07).


SM
KKG500
KKG1000
Events / GeV
ATLAS Preliminary
∫Ldt=200pb-1
tt̄ mass

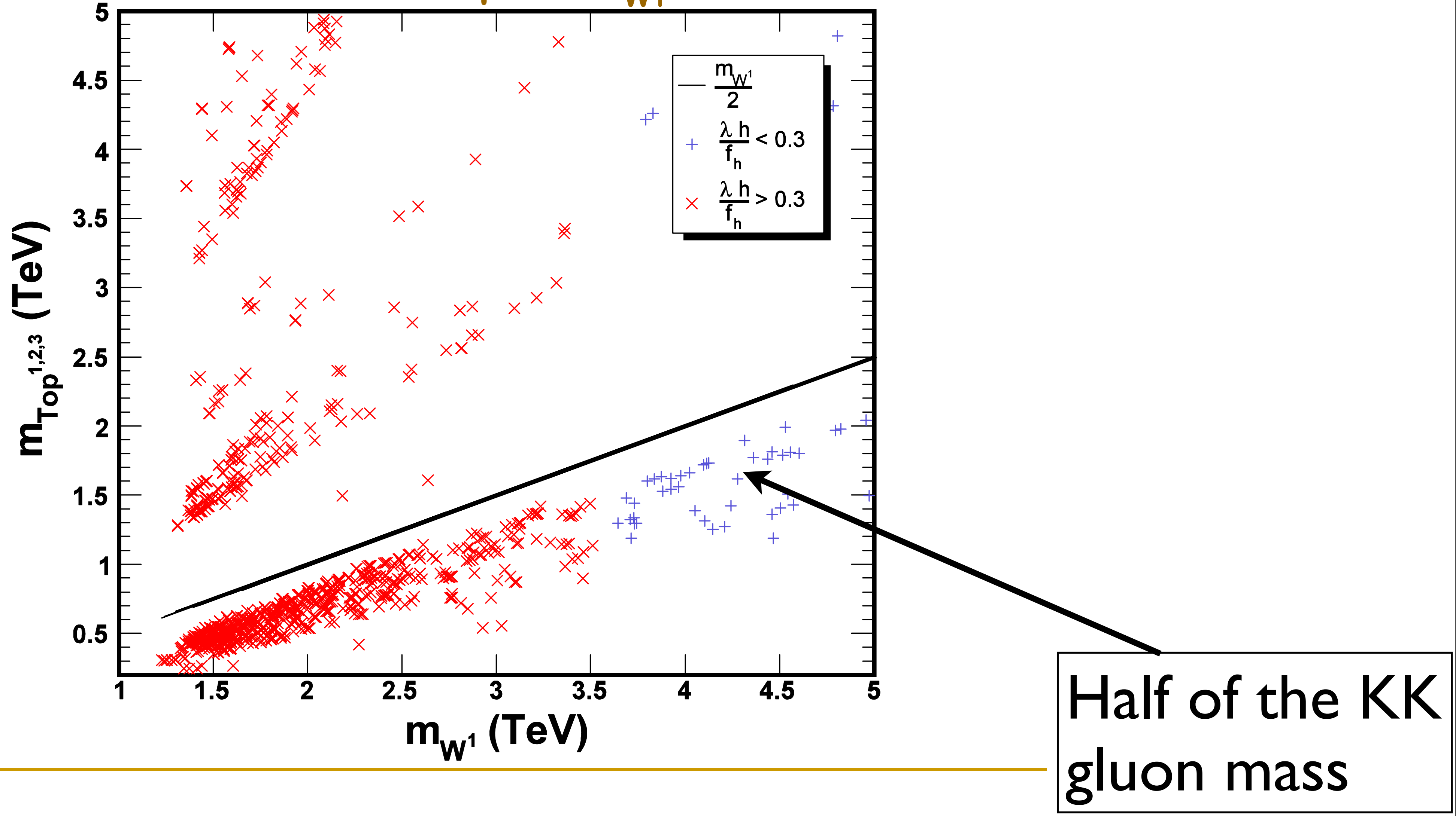

√s = 7 TeV
∫ L dt = 200 pb-1
dRmin. Syst.+stat.
Obs. 95% CL upper limit
Exp. 95% CL upper limit
Exp. 1 σ uncertainty
Exp. 2 σ uncertainty
Kaluza-Klein gluon
ATLAS Preliminary
σ × BR(gKK → tt̄) [pb]
gKK mass [GeV]

GHU models with Custodial Symmetry :

Agashe, Delgado, May, Sundrum'03
Contino, Da Rold, Pomarol'06

First few KK mode of the Top vs. m_{W1}

Medina, Shah, Wagner '07



In these models KK gluons are strongly coupled to KK tops and KK tops provide their dominant decay branching ratio

Gauge-Higgs Unification: Collider Phenomenology

- t^1 production cross section through QCD alone and through QCD+G^1 for M_{G1}=4 TeV.

M. Carena, A. Medina, B. Panes, N. Shah, C.W. '08

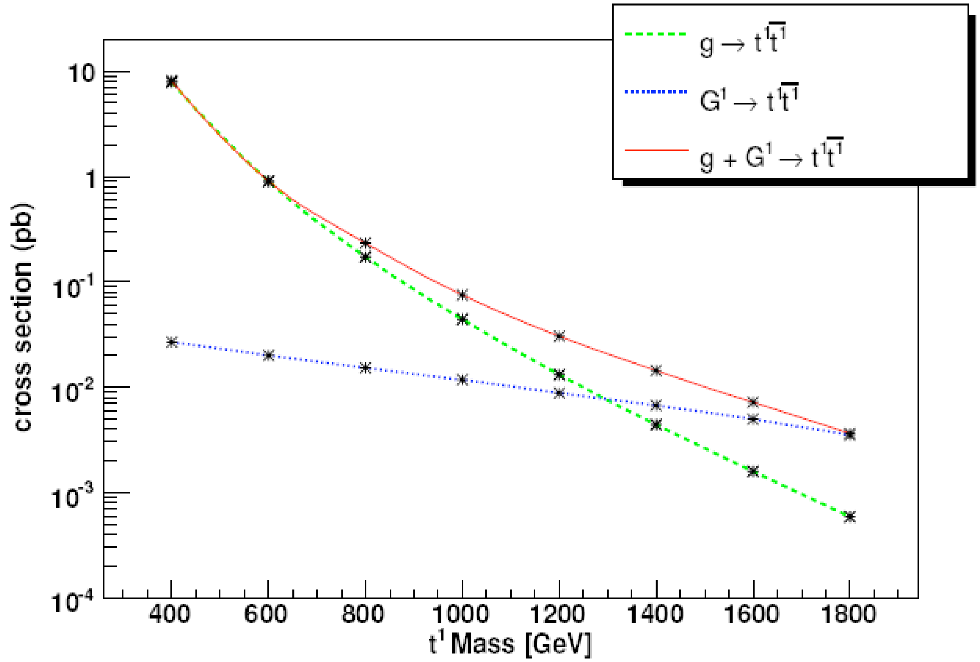


Figure 5: Cross section for $M_{G^1} = 4.0$ TeV with couplings $g_{G^1\bar{t}^1{}_L t^1_L}/g_s(\tilde{k}) = -5.18$ and $g_{G^1\bar{t}^1{}_R t^1_R}/g_s(\tilde{k}) = -2.77$.

Notice that for $M_{t1} \approx$ 1.5 TeV, G^1-induced production contributes in a significant amount to the t^1 production cross section.

Heavy quark reach increased to about 1.5 TeV from the QCD production reach of about 1.1 TeV

Are there any Hints of New Physics

Beyond the ones coming from Astrophysics and Cosmology ?

(N. Weiner's talk for complementary view)

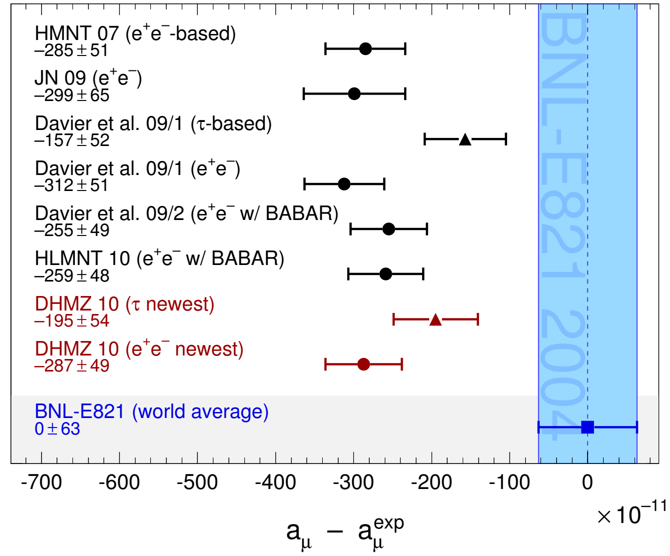
Observed HEP Anomalies

Signals which are two to three standard deviations away from the expected SM predictions.

- 100 GeV Higgs signal excess. Rate about one tenth of the corresponding SM Higgs one.
- 115 GeV Higgs signal, seen only by Aleph experiment at LEP.
- DAMA/LIBRA annual modulation signal, direct DM detection searches (sodium iodide NaI scintillation crystal). COGENT experiment sees a compatible signal, disputed by XENON
- Anomalous magnetic moment of the muon.
- Forward-backward asymmetry of the bottom quark at LEP.
- Forward-backward asymmetry of the top quark at the Tevatron.
- Apparent anomalous neutrino results, in MiniBoone, MINOS, LSND and reactor fluxes.
- CP-violation in the Bs mixing seen by D0 and CDF. Related dimuon charge asymmetry at D0
- Anomalies observed in $B \to K\pi$, $B \to \tau\nu$ and $B \to K l^+ l^-$ transitions
- Apparent 214 MeV muon pair resonance in the decay $\Sigma \to p\, \mu^+ \mu^-$
- Anomalous W + 2 jets events with invariant mass of the 2 jets peaking at 150 GeV at CDF
- Proton radius difference measured in electron or muon hydrogen atoms ? (R. Hill, G. Paz'11)

Muon Anomalous Magnetic Moment

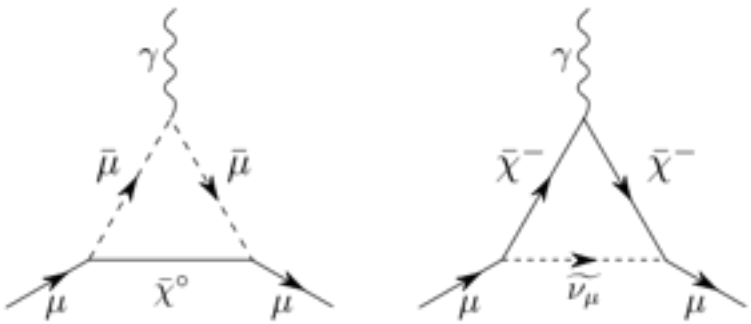
Present status: Discrepancy between Theory and Experiment at more than three Standard Deviation level



$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = 287\ (63)(49) \times 10^{-11}$$

3.6σ Discrepancy A. Hoecker'11; Boughezal, Melnikov'11

New Physics at the Weak scale can fix this discrepancy. Relevant example : Supersymmetry



$$\delta a_\mu \simeq \frac{\alpha}{8\pi \sin^2\theta_W} \frac{m_\mu^2}{\tilde{m}^2} \tan\beta \simeq 15 \times 10^{-10} \left(\frac{100\ {\rm GeV}}{\tilde{m}}\right)^2 \tan\beta$$

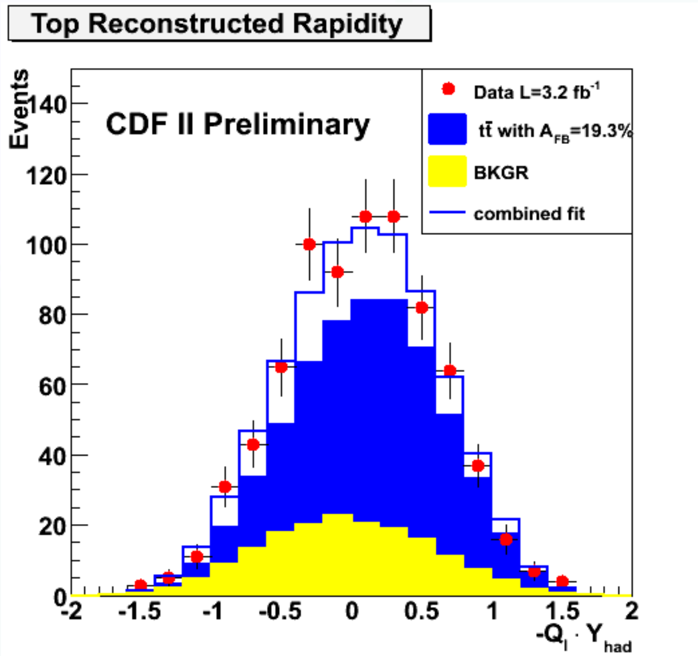
M. Carena, G. Giudice, C. E.M. Wagner '96

Here $\tilde{m}$ represents the weakly interacting supersymmetric particle masses.

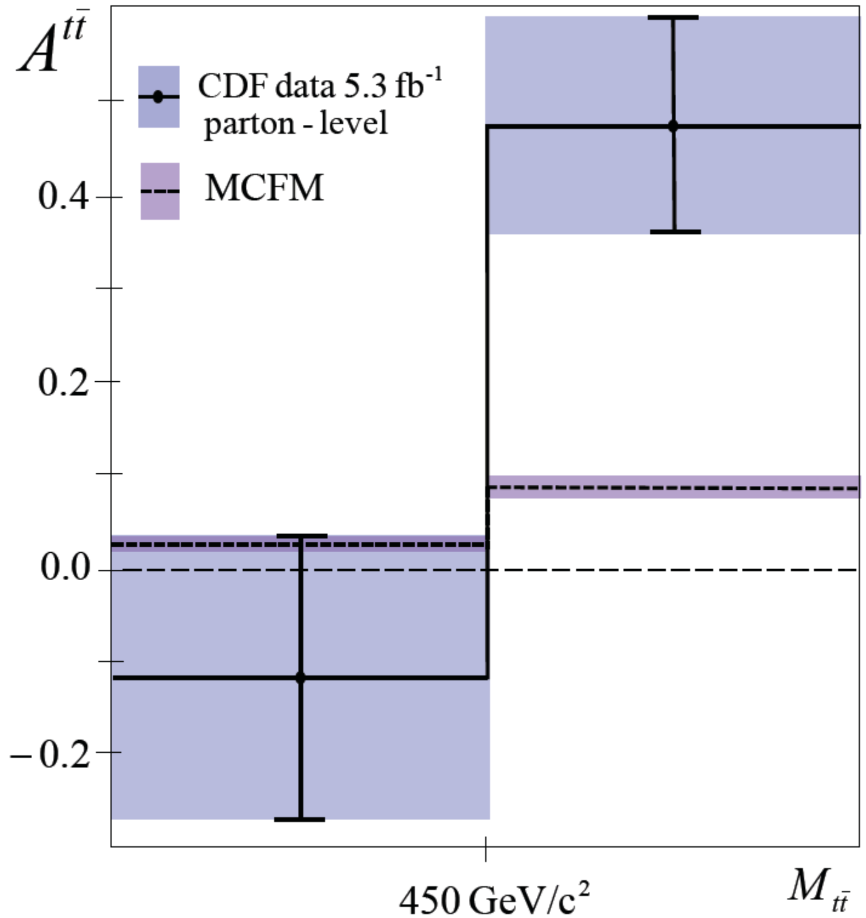
For $\tan\beta \simeq 10$ (50), values of $\tilde{m} \simeq 230$ (510) GeV would be preferred.

Masses of the order of the weak scale lead to a natural explanation of the observed anomaly !

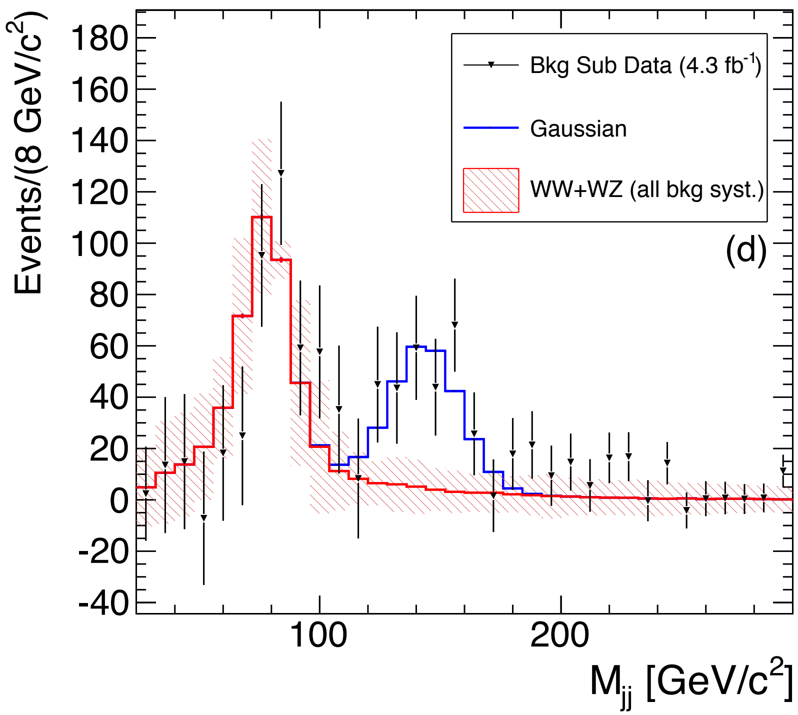
Top Forward Backward Asymmetry and Direct Dark Matter detection



A_{fb} = 19.3% +/- 6.5% (stat) +/- 2.4% (syst)



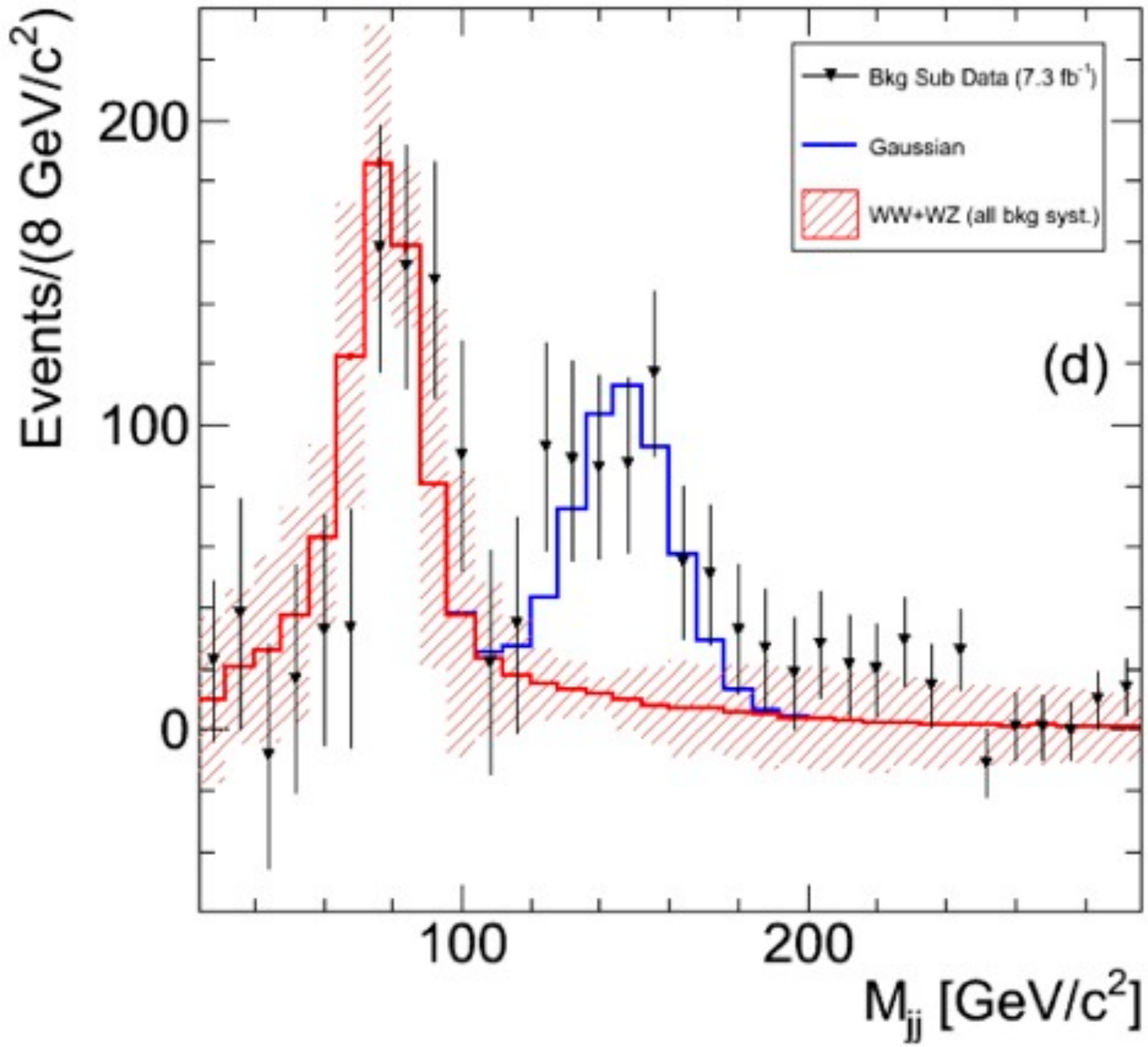
Regarding the CDF W + 2 jets anomaly announced two months ago at Fermilab



- Data fitted with SM templates plus a gaussian.
- $\Delta\chi^2$ observed 20.31 that corresponds to a statistical significance of 3.7σ (including trial factor)

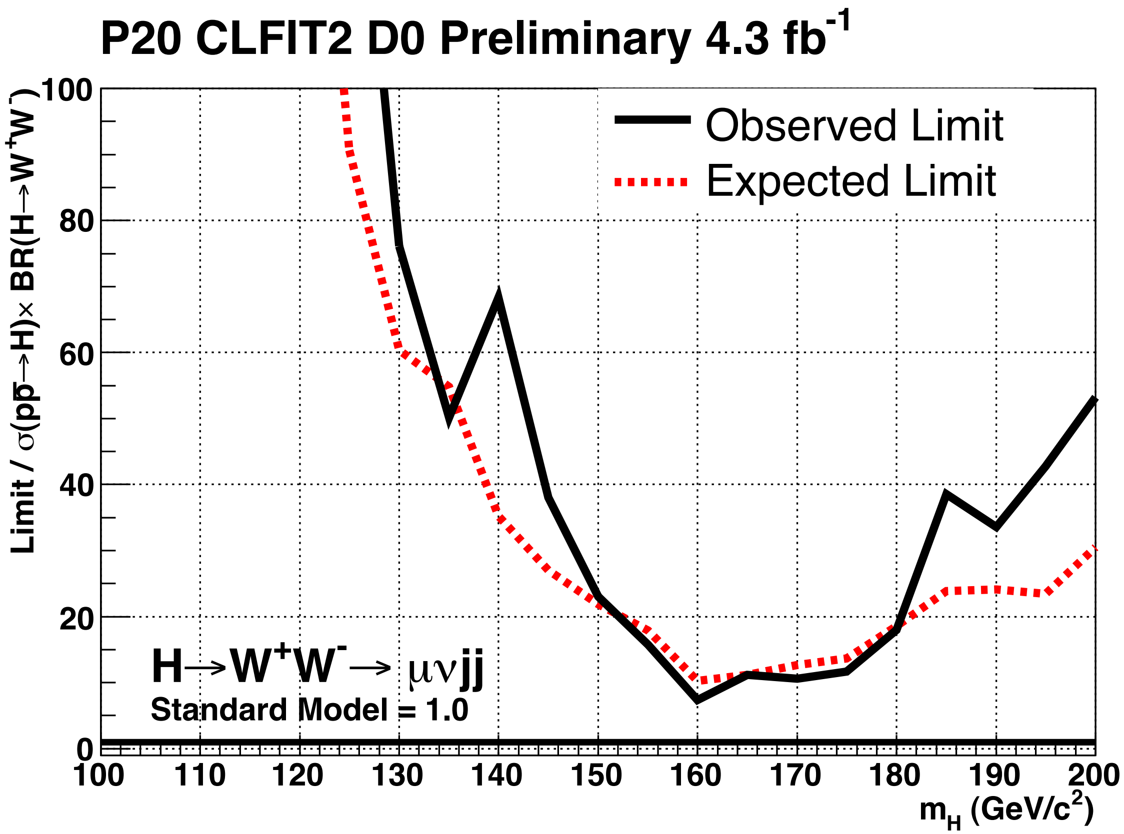
	Electrons	Muons
Excess events	156 ± 42	97 ± 38
Excess events / expected diboson	0.60 ± 0.18	0.44 ± 0.18
Mean of the Gaussian component	144 ± 5 GeV/c^2	

Significance increased to 4.7 S.D. after recent update



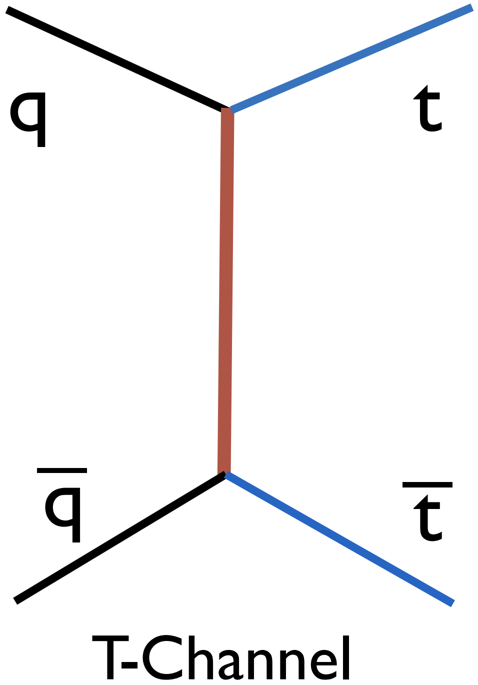
D0 is going to report on their results soon, may be today (J. Zhu's talk)

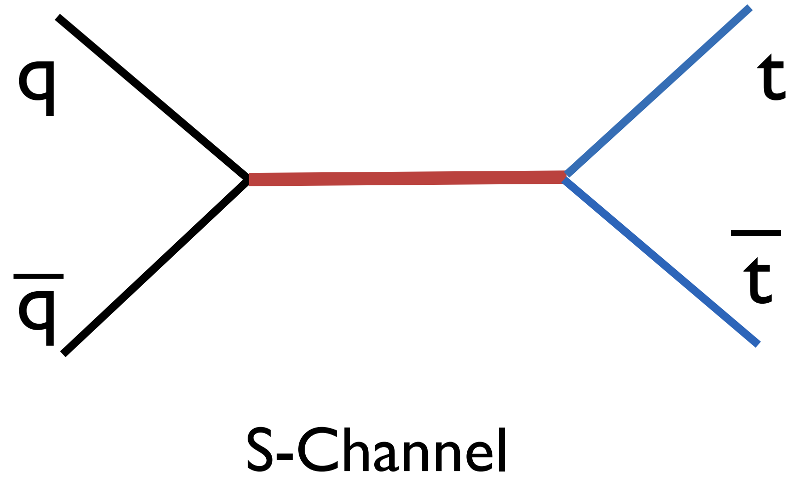
D0 Thesis on Higgs WW limits



S.M. Zelitch'10

Possible Explanations of Tevatron Anomalies
Top Forward Backward Asymmetry





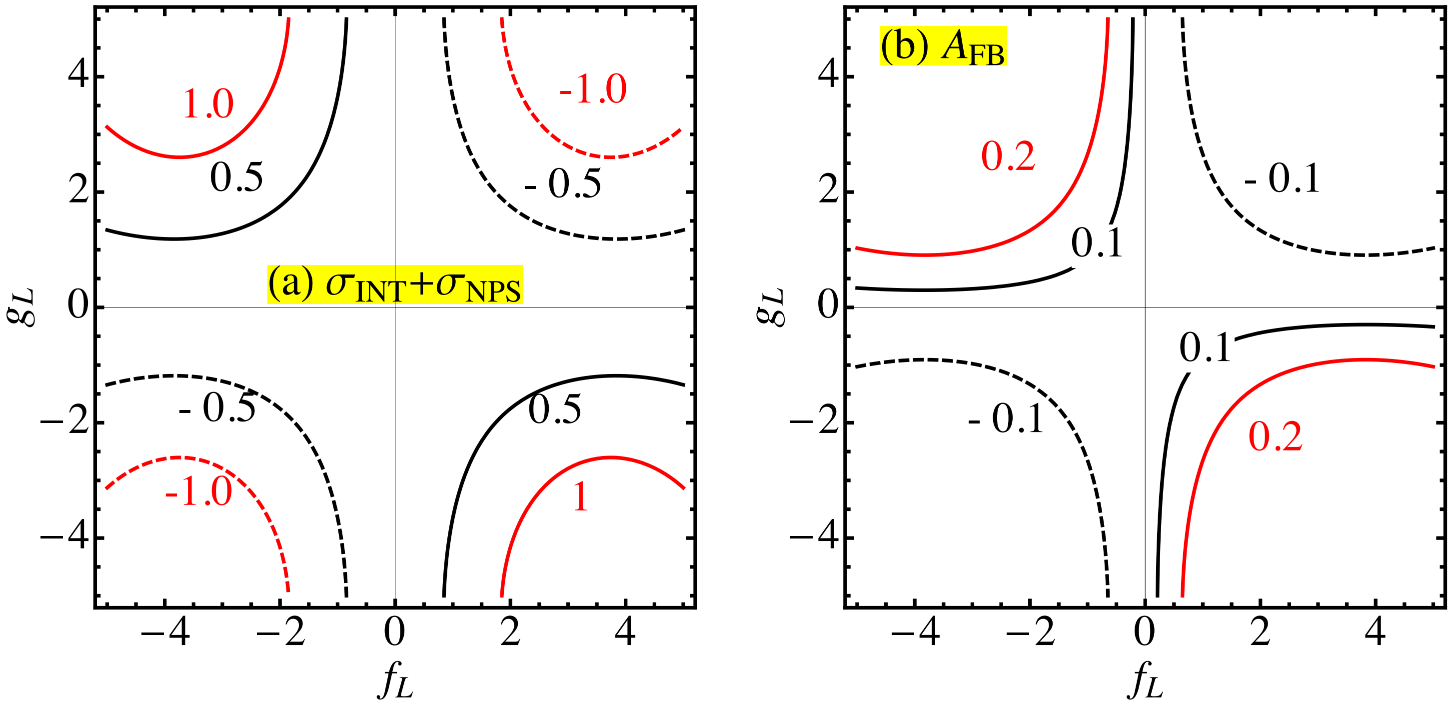
Red line : New Physics

S-Channel : Heavy (Axi-)Gluon Resonance. (Ferrario, Rodrigo; Shu, Tait, Wang; Perez et al, Djouadi et al) Already constrained by LHC.

T-Channel : New Flavor violating, Charged or neutral, scalar or vector resonances (Jung, Murayama, Pierce, Wells; Cheung, Keung, Yuan; Barger, Berger, Shaughnessy....)

Global fit in different models, including cross section and invariant mass distribution constraints : Cao, McKeen, Shaughnessy, Rosner, C.W. '10

Heavy, 2 TeV Gluon Resonance

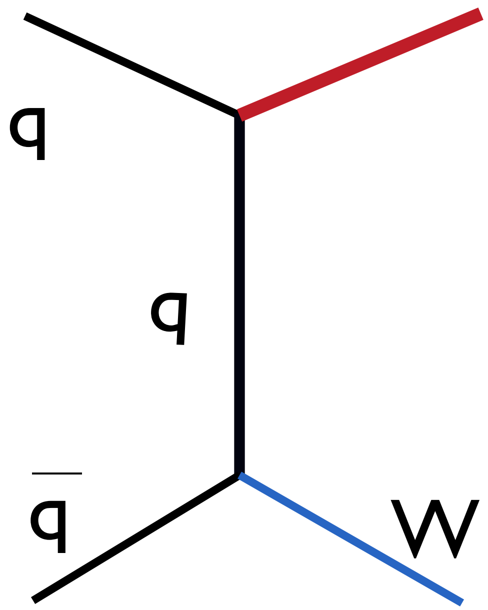


Opposite charges to light and heavy generations.

Cao, McKeen, Shaughnessy, Rosner, C.W. '10

Due to large couplings and heavy gluon width, LHC dijet searches already put strong constraints on this scenario

Possible Explanations of Tevatron Anomalies
W + 2 jets Anomaly



T-Channel

S-Channel

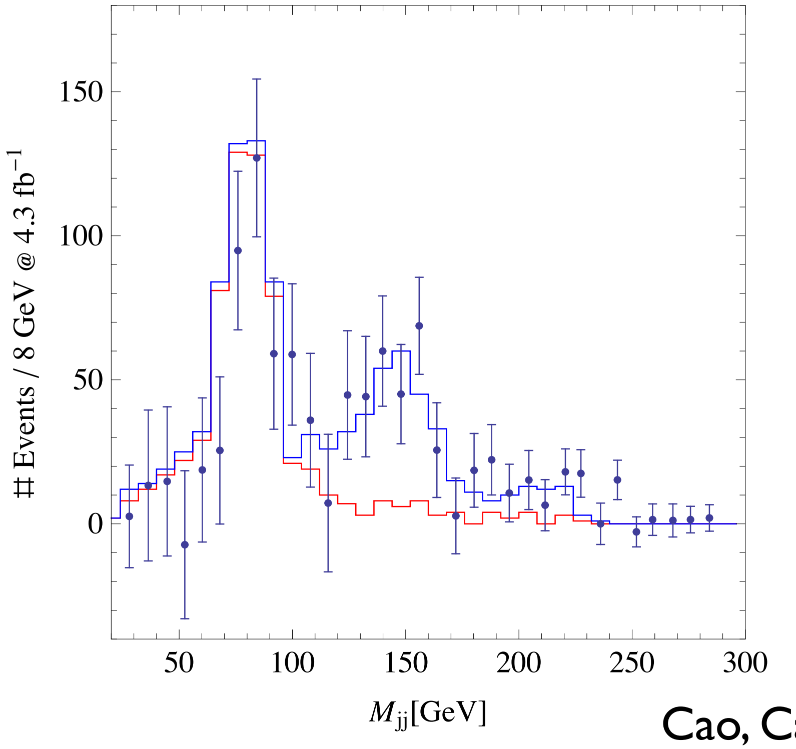
Red lines : New Physics. External one decays into two jets

S-Channel : Scalar or Vector Resonances (Eichten, Lane, Martin; Cilic and Thomas; Cao, Carena, Gori, Menon, Schwaller, Wang, C.W. ...)

T-Channel : New Charged or neutral, scalar or vector resonances (Hooper, Buckley, Kopp, Perez, Neil; Fox, Liu, Tucker Smith, Weiner, Yu...)

Two Higgs Doublet Model Explanations

- 250 to 300 GeV charged Higgs boson, decaying to neutral one
- Neutral Higgs boson has CP-even and CP-odd components which may be split, providing one or two close-by resonances. Flavor Physics constraints.
- Real Higgs mass enhanced w.r.t. SM prediction, in order to regain agreement with precision electroweak measurements



Cao, Carena, Gori, Menon, Schwaller, Wang, C.W. '11

Technicolor ? Eichten, Lane and Martin suggest a technirho decaying into a technipion ! arXiv:1104.0976

Kinematic Distributions

Kinematic distributions can rule out some of these models, but still both s-channel explanations, as well as flavor universal Z' models seem to be consistent with data.

Z' models lead to new photon and Z plus 2 jets signals and are easily constrained at the LHC (Hewett, Rizzo'11)

Common Origin of Anomalies ?

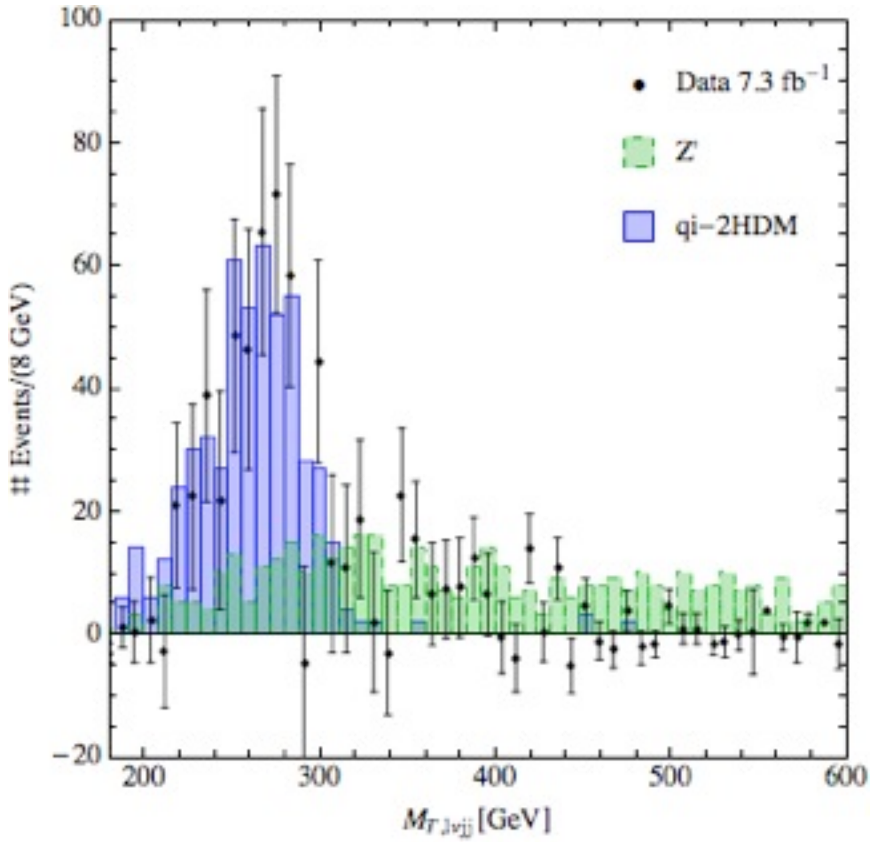
Several proposals to do that, one particularly interesting based on Z' proposed by Hooper, Buckley, Koop and Neil '11

Another based on two Higgs doublets, proposed by Ann Nelson, T. Okui and T. Roy'11 Constrained by Flavor Physics

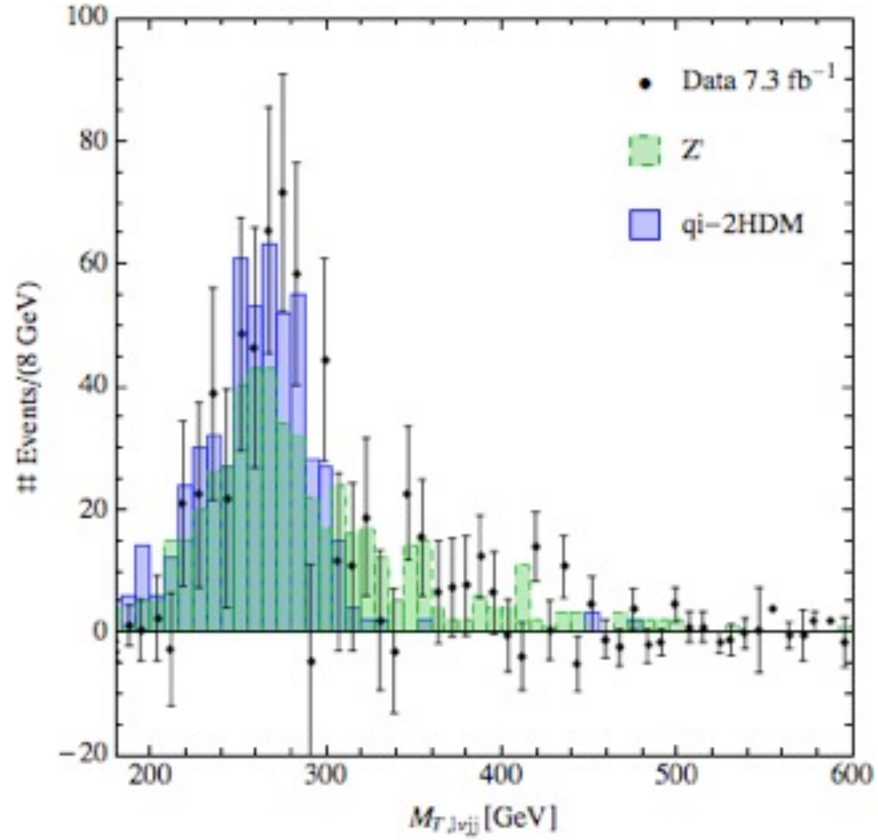
Somewhat different implementation of this idea, Q.H. Cao, M. Carena, S. Gori, A. Menon, P. Schwaller, L.T. Wang, C.W. '11

Total invariant mass distribution

Only up-quark Z'coupling



Universal Z' coupling



Cao, Carena, Gori, Menon, Schwaller, Wang, C.W. to appear

Reasons for Proposal and Later Solutions to 4 Puzzles (1932)

- 1) Klein Paradox --apparent violation of unitarity (solution:positron existence- pair production possible)
- 2) Wrong Statistics in Nuclei--N-14 nucleus appeared to be bosonic--(solution: neutron not a proton-electron bound state)
- 3) Beta Ray Emission-apparent Energy non conservation (solution:neutrino)
- 4) Energy Generation in Stars (solution: nuclear forces, pep chain, carbon cycle etc.----pion)

G. Segre'10

Stay Tuned

Backup Slides

Regions of parameter space consistent with Neutralino relic density: Heavy CP-odd boson and heavy Sleptons

Green : $\tan\beta = 50$

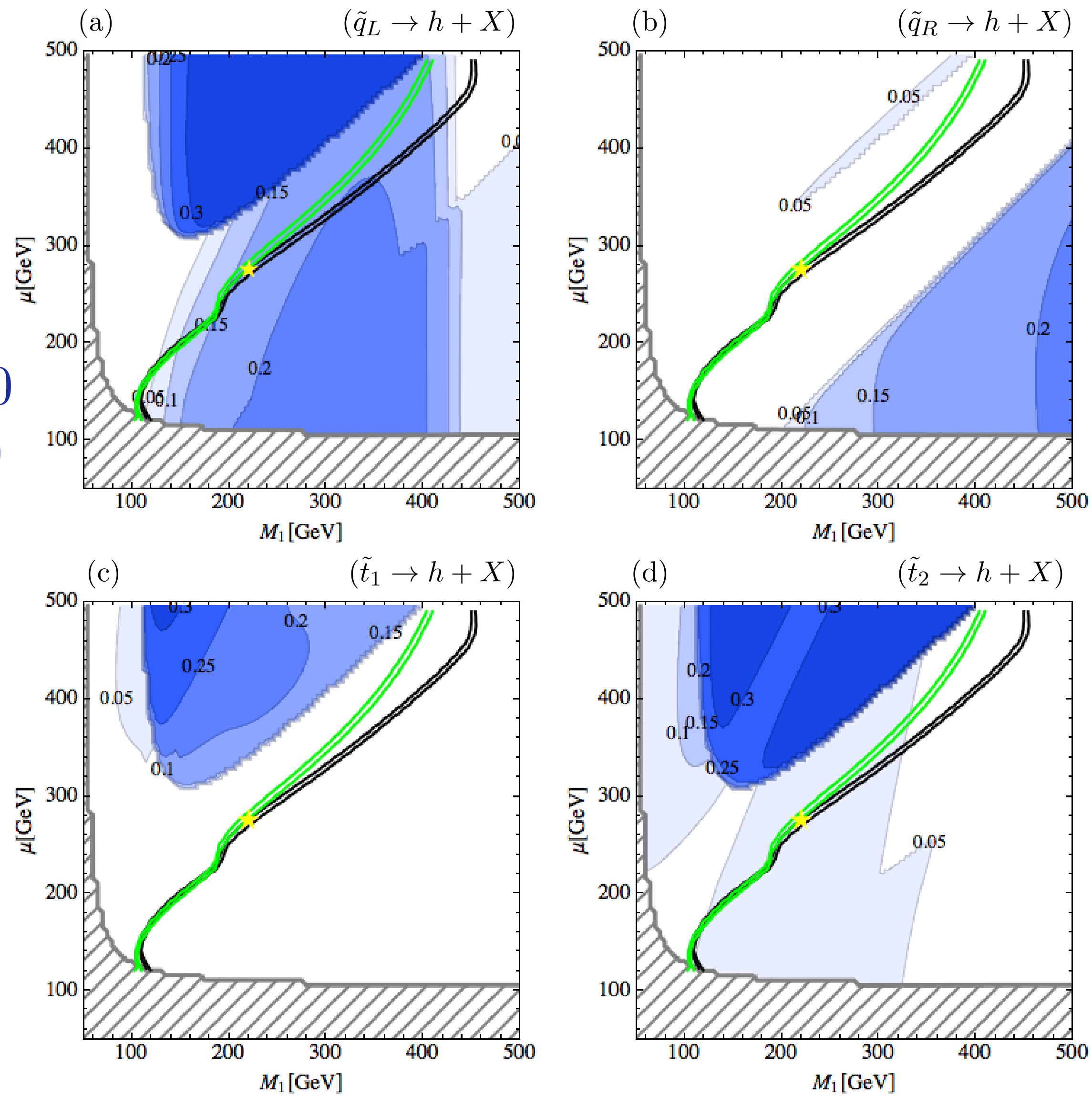
Black : $\tan\beta = 10$

$m_A = 1TeV$

$m_{\tilde{q}} \simeq 1$ TeV

$M_{\tilde{g}} \simeq 6M_1$

$M_2 = 2M_1$



Gori, Schwaller, C.W.'11

Regions of parameter space consistent with Neutralino relic density: Heavy Sleptons and Light CP-odd boson

Countours of proper relic density

Green : $\tan\beta = 50$

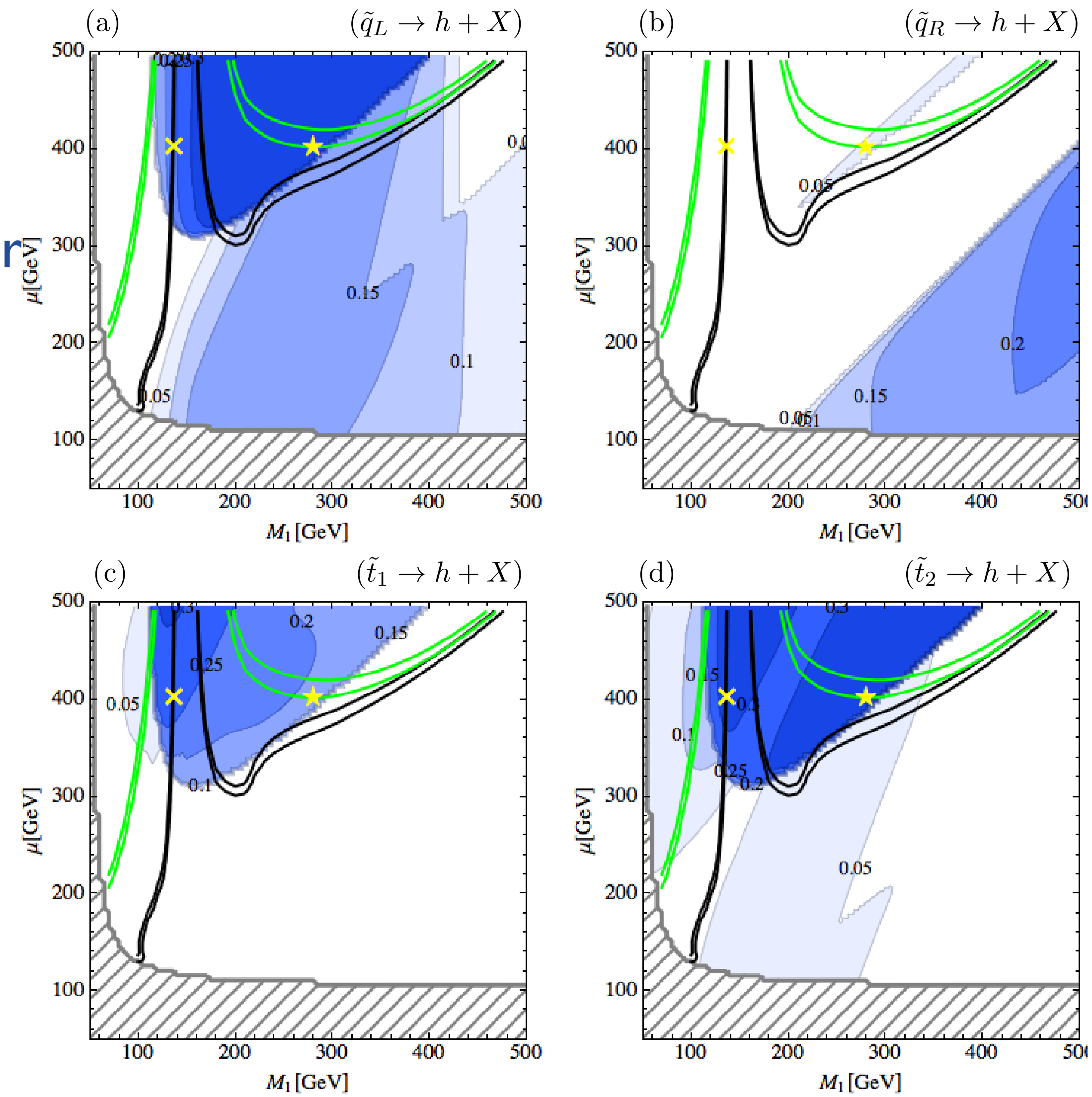
Black : $\tan\beta = 10$

$m_A = 300$ GeV

$m_{\tilde q} \simeq 1$ TeV

$M_{\tilde g} \simeq 6 M_1$

$M_2 = 2 M_1$



Blue regions :

Appreciable Branching Decay Fraction.

Darker means larger branching decay fraction.

X : energetic quarks, leptons and missing energy

Gori, Schwaller, C.W., arXiv:1103.4138

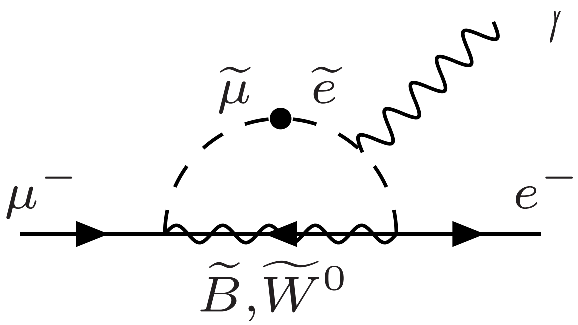
Good prospects of observing Higgs in the14 TeV run and, perhaps, even in the 7 TeV run (Gori's talk today)

SUSY Breaking and Flavour Changing Neutral Currents

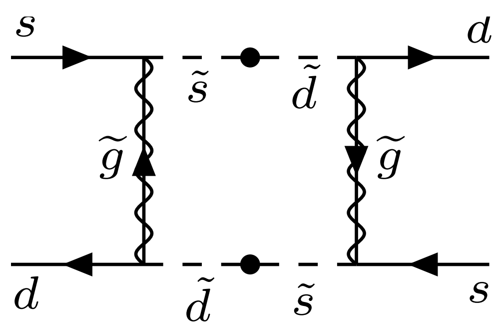
- Two particularly constraining examples of flavor changing neutral currents induced by off-diagonal soft supersymmetry breaking parameters

- Contribution to the mixing in the Kaon sector, as well as to the rate of decay of a muon into an electron and a photon.

Demand masses larger than 10 TeV, unless flavor violation is small.



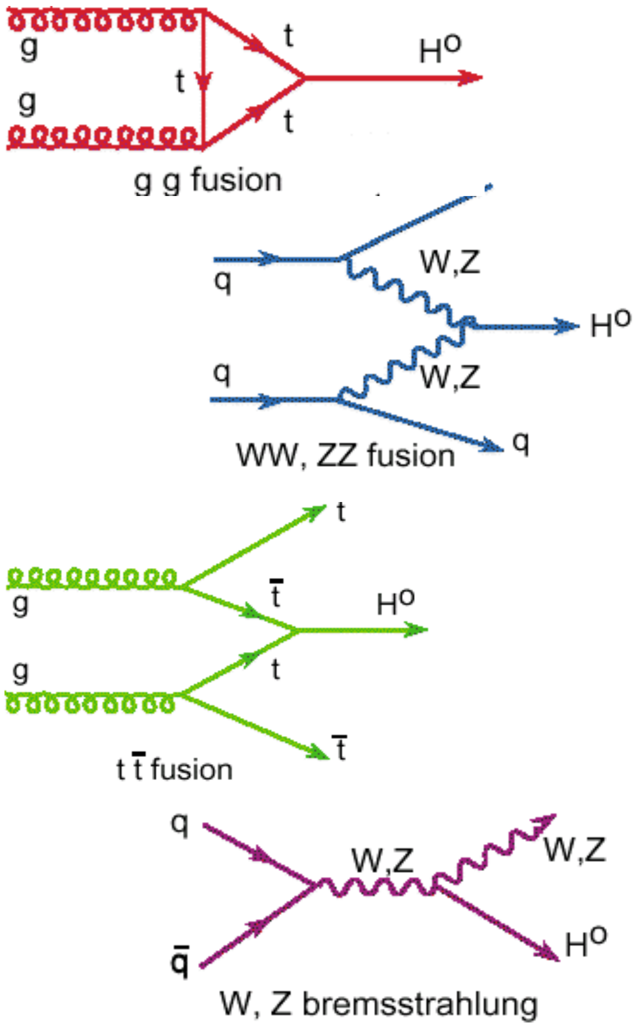
$\mu^- \rightarrow e^- \gamma$



$K^0 \leftrightarrow \overline{K^0}$

Low Energy Supersymmetry requires reduced flavor dependence.
Preference towards flavor independent SUSY breaking schemes.

The search for the Standard Model Higgs at the LHC

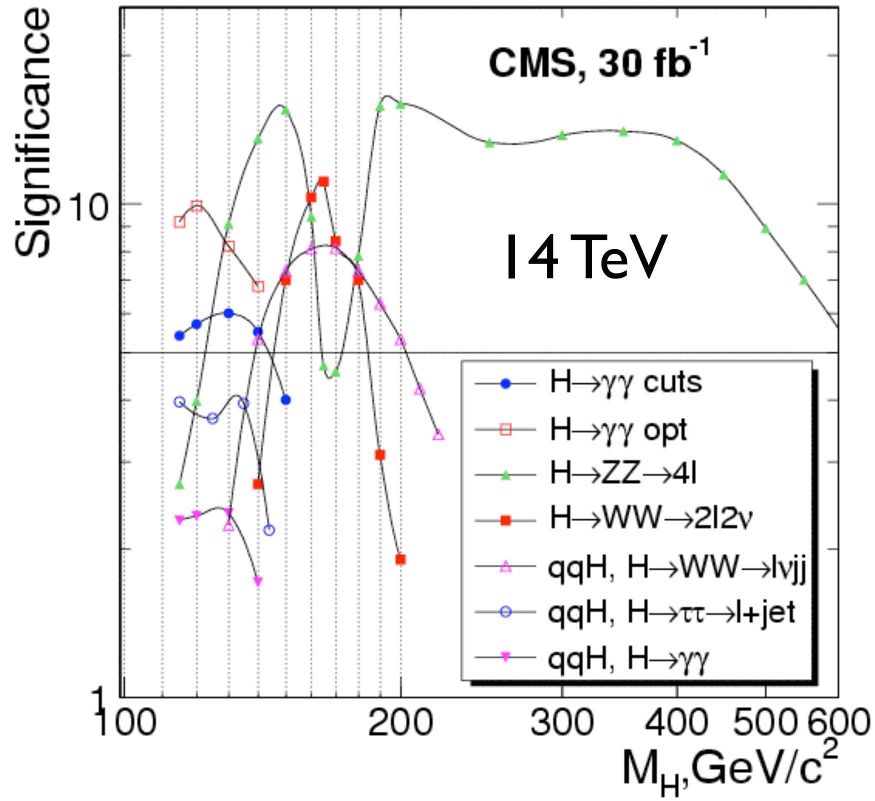


- **Low mass range** $m_{H_{SM}} < 200$ GeV

$$H \to \gamma\gamma, \tau\tau, bb, WW, ZZ$$

- **High mass range** $m_{H_{SM}} > 200$ GeV

$$H \to WW,\ ZZ$$

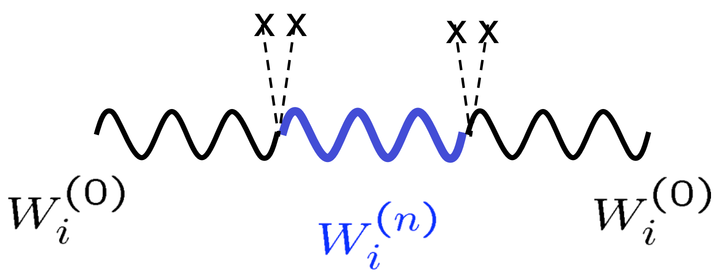


If there is a Higgs boson, with properties similar to those predicted in the Standard Model, the high energy/luminosity LHC will find it.

Effects of KK modes of the gauge bosons on Z pole observables

SM in the bulk

- Large mixing with Z and W zero modes through Higgs



Large corrections to the M_z/M_w ratio (T parameter)

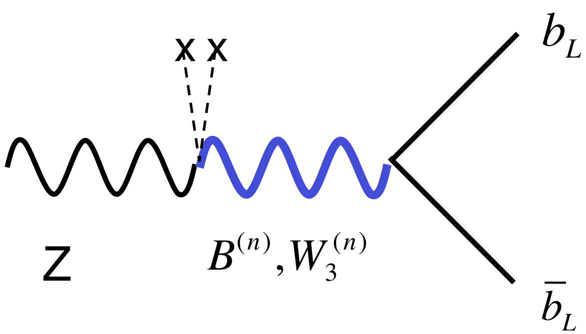
$$\Downarrow$$

$$M_{KK} \geq 5-10 \ \text{TeV}$$

- Top and bottom zero modes localized closer to the IR brane

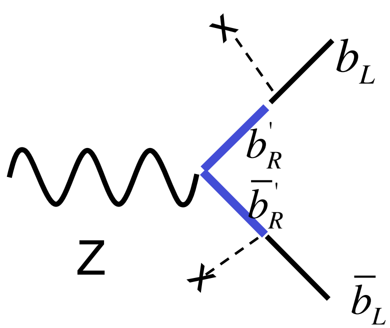
Large gauge and Yukawa couplings to Gauge Bosons and fermion KK modes

Large corrections to the Zbb coupling



$$\Downarrow$$

$$M_{KK} \gtrsim 7-8 \, \text{TeV}$$



Csaki et al'02; Hewett et al'02, Pomarol et al'02

How to obtain a phenomenologically interesting theory?

1) Extend SM bulk gauge symmetry to a custodial symmetry

$SU(2)_L \times SU(2)_R$

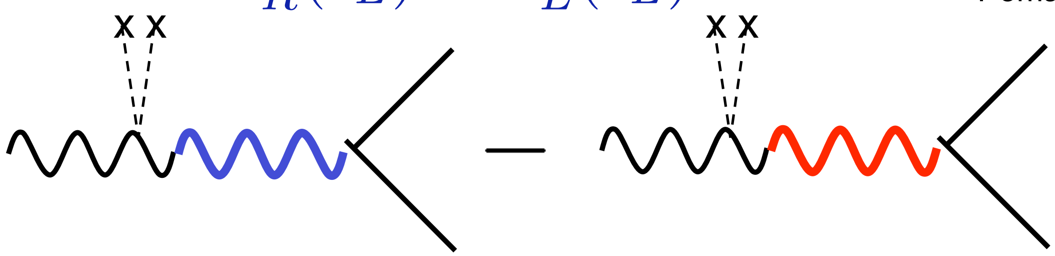
Agashe, Delgado, May, Sundrum '03

$T \propto$  ~ 0

2) The custodial symmetry together with a discrete L $\leftrightarrow$ R symmetry and a specific bidoublet structure of the fermions under $SU(2)_L \times SU(2)_R$

$$T^3_R(b_L) = T^3_L(b_L)$$

Agashe, Contino, DaRold, Pomarol '06

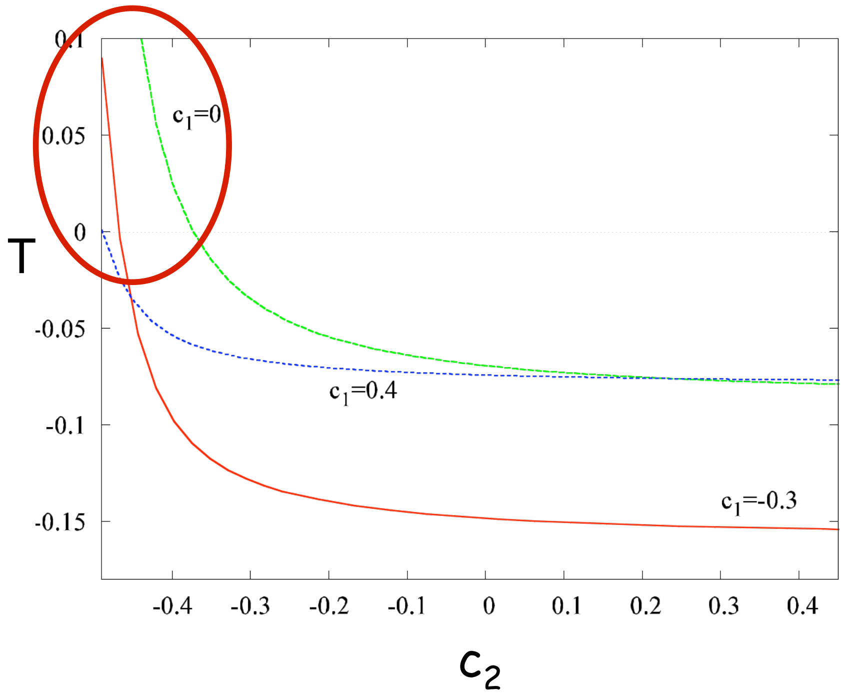
$\delta g_{b_L} \propto$  ~ 0

==> reduce tree level contributions to the T parameter and the Zbb coupling that allow for lightest KK gauge bosons with $M_{KK} \sim 3$ TeV

Correlation between corrections to T and Zbb

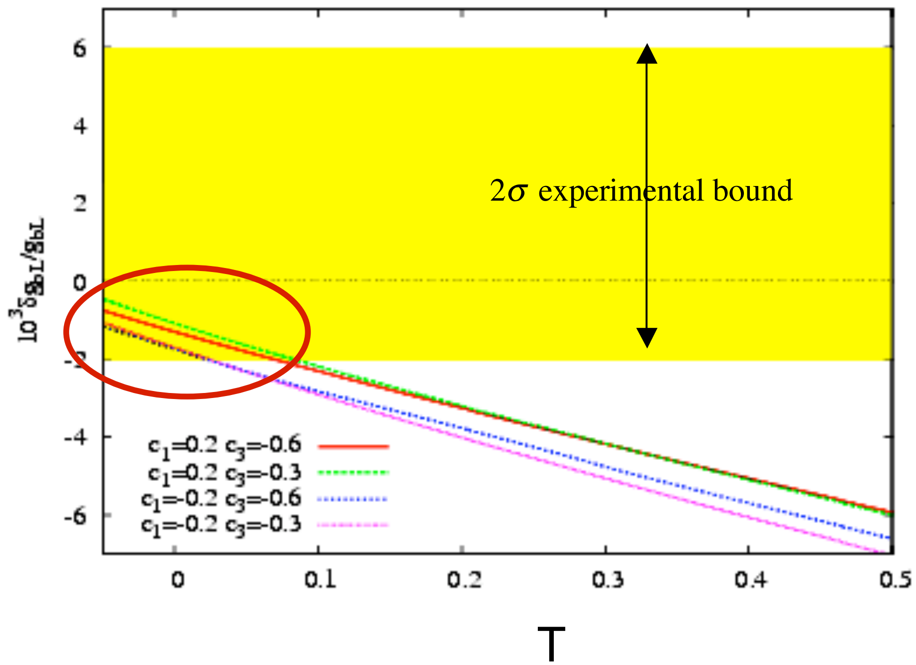
T has negative values in most of the parameter space. Positive values require: RH top "almost flat" and LH top/bottom near the IR

M.~Carena, E.~Ponton, J.~Santiago and C.~E.~M.~Wagner, **Nucl.Phys.B759:202-227,2006 and hep-ph/0701055**



UV (singlet localization) IR

c_2 : Right-handed top bulk mass



Positive T leads to deviations from allowed experimental values of Zbb

Warped Extra Dimensions

Randall, Sundrum'99

Solution to the Hierarchy Problem

- Space is compact, of size 2 L, with orbifold conditions x, y → x,-y
- Brane at y = 0 (Ultraviolet or Planck Brane)

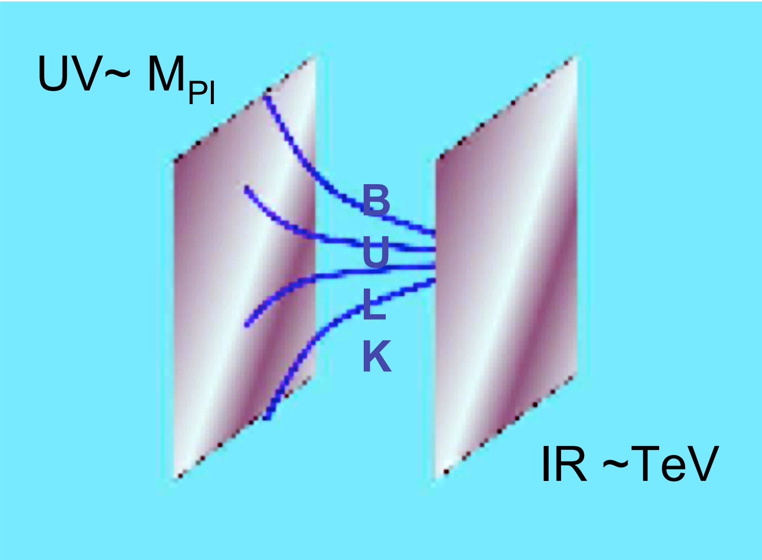
  Brane at y = L (Infrared or TeV Brane)

- Non-factorizable metric: $ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$ solution to 5d Einstein equations
- Newton's law modified: 5d Planck mass relates to M_{Pl}: $M_{Pl}^2 = \frac{(M_{Pl}^{fund.})^3}{2k}(1 - e^{-2kL})$

➔ Natural energy scale at the UV brane: Fundamental Planck scale $\Rightarrow M_{Pl}^{fund.}$

At the TeV brane, all masses are affected by an exponential warp factor: $e^{-kL} << 1$

.



Assuming fundamental scales all of same order:

$$M_{Pl} \approx M_{Pl}^{fund.} \approx \mathrm{k}$$

Solution to Hierarchy problem :

Higgs field lives on the TeV brane

$$\mathrm{v} \sim \tilde{\mathrm{k}} \equiv \mathrm{k}\, \mathrm{e}^{-\mathrm{kL}} \approx M_{Pl}\, \mathrm{e}^{-\mathrm{kL}} \sim \mathrm{TeV}$$

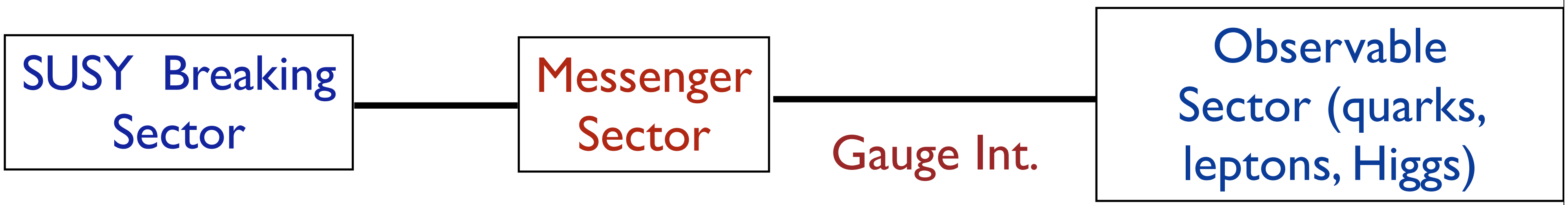
with kL ~30

Physics Beyond the Standard Model : The LHC ERA

- The current decade will see the completion of the Tevatron and the full development of the LHC program, which will provide detailed information of physics at the TeV scale.
- Origin of fermion and gauge boson masses (electroweak symmetry breaking dynamics) expected to be revealed by these experiments.
- Missing energy signatures at the LHC may reveal the presence of one or more dark matter candidates which may be the first evidence of a world of new particles. Direct and indirect detection experiments will reach maturity.
- Tevatron, LHCb and super B-factories will provide accurate information on flavor physics, leading possibly to complementary information on new physics.
- Search for charged lepton number violation and neutrino double beta decay experiments could reveal nature of neutrinos, and new dynamics at the TeV scale. Neutrino oscillation experiments may lead to the observation of CP-violation or other surprises.
- The next years can mark the termination of the Standard Model Dictatorship and the beginning of a genuine new era in physics, similar to the one that led to the successful SMs of particle physics and cosmology, which arguably started about 100 years ago.

Gauge Mediated SUSY Breaking

- Supersymmetry breaking is transmitted to the observable sector via (flavor blind) gauge interactions



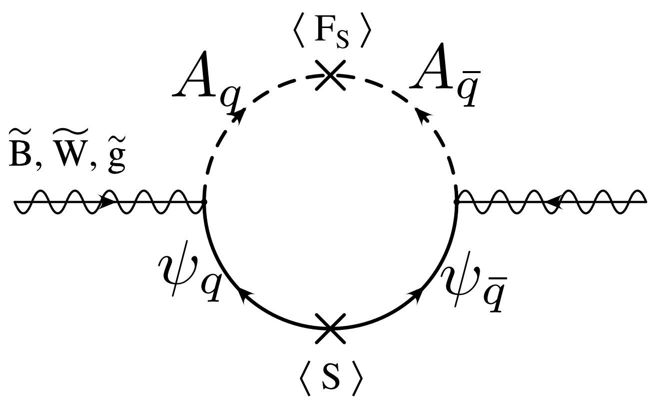
- Messenger sector in complete representations of SU(5) and vector-like.

- Minimal model: One $(5,\bar{5}) \equiv (3,2) + (\bar{3},\bar{2})$

$$W = \lambda\, S\, 3\, \bar{3} + \gamma\, S\, 2\, \bar{2}, \qquad < S >= S + F_S \theta^2,$$

with S a singlet field parametrizing SUSY breaking and the messenger mass

Integrating the messenger sector gives mass to gauginos at one-loop



$$M_a = \frac{\alpha_a}{4\pi}\Lambda, \qquad \text{where} \qquad \Lambda \equiv \frac{\langle F_S \rangle}{\langle S \rangle}.$$

Gauge bosons do not get contributions since they are protected by gauge invariance
==> successful SUSY breakdown

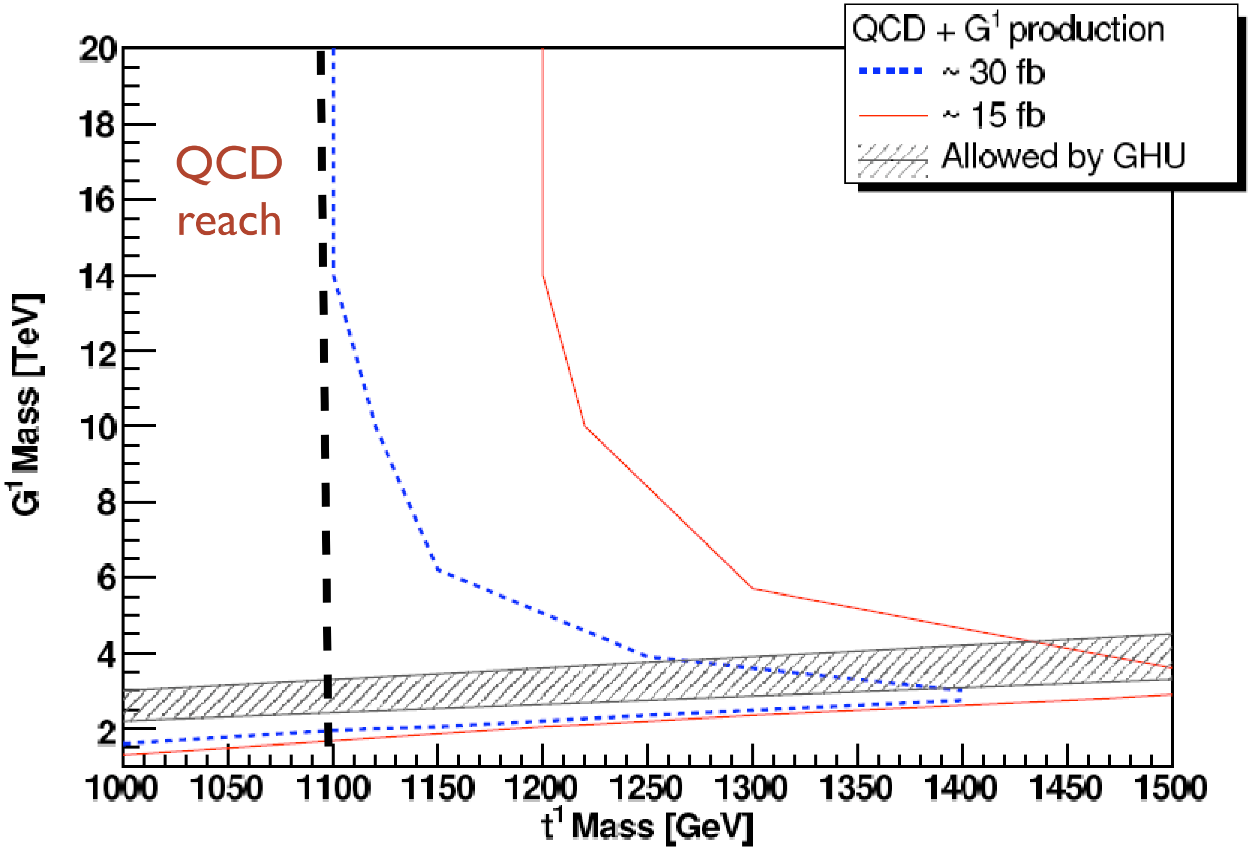
Scalar superpartner masses are generated at two-loops

$$m^2_{A_i} = 2\Lambda^2 \left[\left(\frac{\alpha_3}{4\pi}\right)^2 C_3^{A_i} + \left(\frac{\alpha_2}{4\pi}\right)^2 C_2^{A_i} + \left(\frac{\alpha_1}{4\pi}\right)^2 C_1^{A_i} \right]$$

Minimal GMSB model can be generalized by putting N copies of the messenger sector. All expressions above multiplied by N

LHC Discovery Reach

- First KK mode of the top decays mostly into W and bottom-quarks
- Two points were explored, on the blue and red lines. In the first the KK top may be discovered with 100 inverse fb, in the second with 300 inverse fb.



M. Carena, A. Medina, B. Panes, N. Shah, C.W. '08

Figure 20: Curves of constant cross section for QCD in addition of G^1 decay, in (m_{G^1}, m_{t^1}) plane.

KK Gravitons at the LHC

- Graviton KK modes have 1/TeV coupling strength to SM fields and masses starting with a few hundred GeV.
- KK graviton states produced as resonances.
- One can rewrite the warp factor and the massive graviton couplings in terms of mass parameters as:

Graviton Coupling strength

E/Λ_π

$$\exp(-kL) = \frac{m_n}{kx_n}$$

$$\Lambda_\pi \simeq \frac{\bar{M}_{Pl} m_1}{kx_1}$$

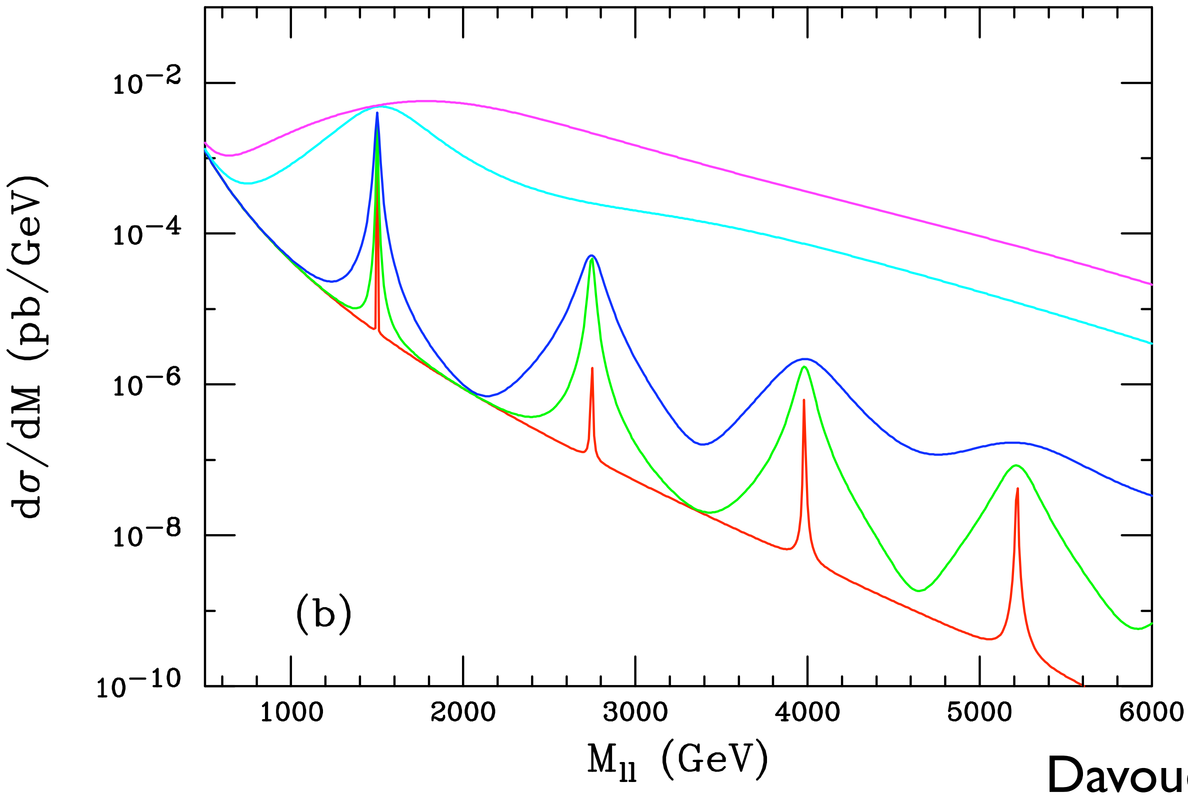
with $x_1 \simeq 3.8$, $x_n \simeq x_1 + (n-1)\pi$.

- Calling $\eta = k/\bar{M}_{Pl}$, one gets that the graviton width is

$$\Gamma(G^n) \simeq m_1 \eta^2 \frac{x_n^3}{x_1}$$

• Warped Extra Dimensions

Narrow graviton resonances: $pp \to G_N \to e^+e^-$



Davoudiasl, Hewett, Rizzo, '00

From top to bottom: $k/M_{Pl} = 1, 0.5, 0.1, 0.05, 0.01$

Higgs From Gauge Fields in Warped Extra Dimensions

Contino, Da Rold, Pomarol'06

Bulk gauge symm: $SU(3)_c \times SO(5) \times U(1)_X \longrightarrow SO(5) \supset SU(2)_L \times SU(2)_R$

UV: $SU(2)_L \times U(1)_Y$ IR: $SO(4) \times U(1)_X \simeq SU(2)_L \times SU(2)_R \times U(1)_X$

Extra gauge bosons have the quantum numbers of the Higgs

$$SO(5)/SO(4) \longrightarrow A_\mu^{\hat{a}}(-,-) \quad A_5^{\hat{a}}(+,+)$$

Identify with H

No tree-level Higgs potential $\longrightarrow$ induced at one-loop (calculable)

Coleman-Weinberg potential has been computed for the model considered here by A. Medina, N. Shah, C.W. , Phys. Rev. D 76: 095010 (2007)

- EWSB minima in large regions of parameter space
- Can be consistent with Z, W, top masses and Higgs LEP bound

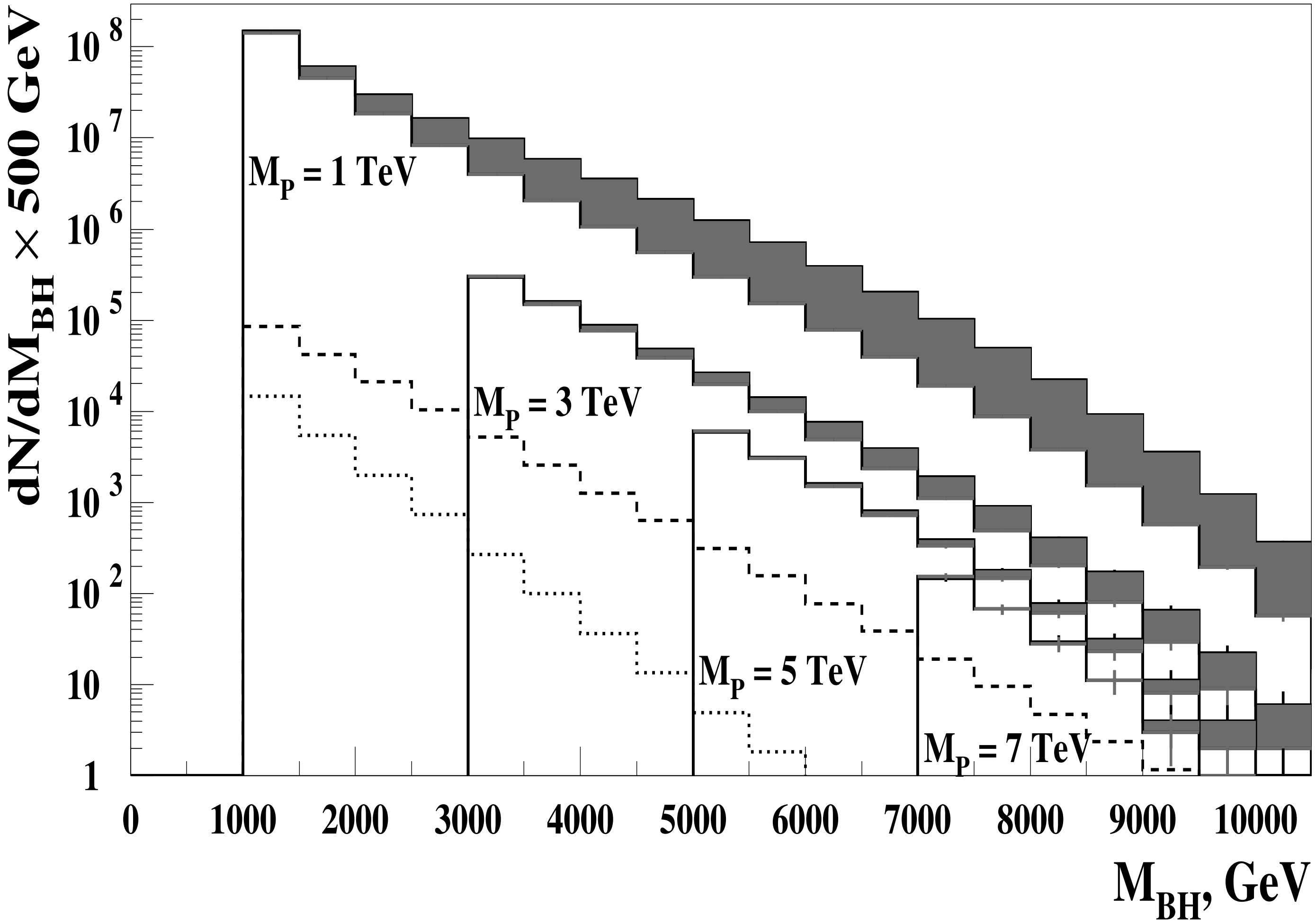
Black Hole Production ?

- Two partons with center of mass energy $\sqrt{s} = M_{BH}$, with $M_{BH} > M_{Pl}^{fund}$ collide with a impact parameter that may be smaller than the Schwarzschild radius.

  $$R_S \simeq \frac{1}{M_{Pl}^{fund}} \left(\frac{M_{BH}}{M_{Pl}^{fund}} \right)^{\frac{1}{d+1}}$$

- Under these conditions, a blackhole may form
- If $M_{Pl}^{fund} \simeq 1$ TeV $\rightarrow$ more than 10^7 BH per year at the LHC (assuming that a black hole will be formed whenever two partons have energies above M_{Pl}^{fund}).
- Decay dictaded by blackhole radiation, with a temperature of order $1/R_S$. Signal is a spray of SM particles in equal abundances: hard leptons and photons.
- At LHC, limited space for trans-Planckian region and quantum gravity.

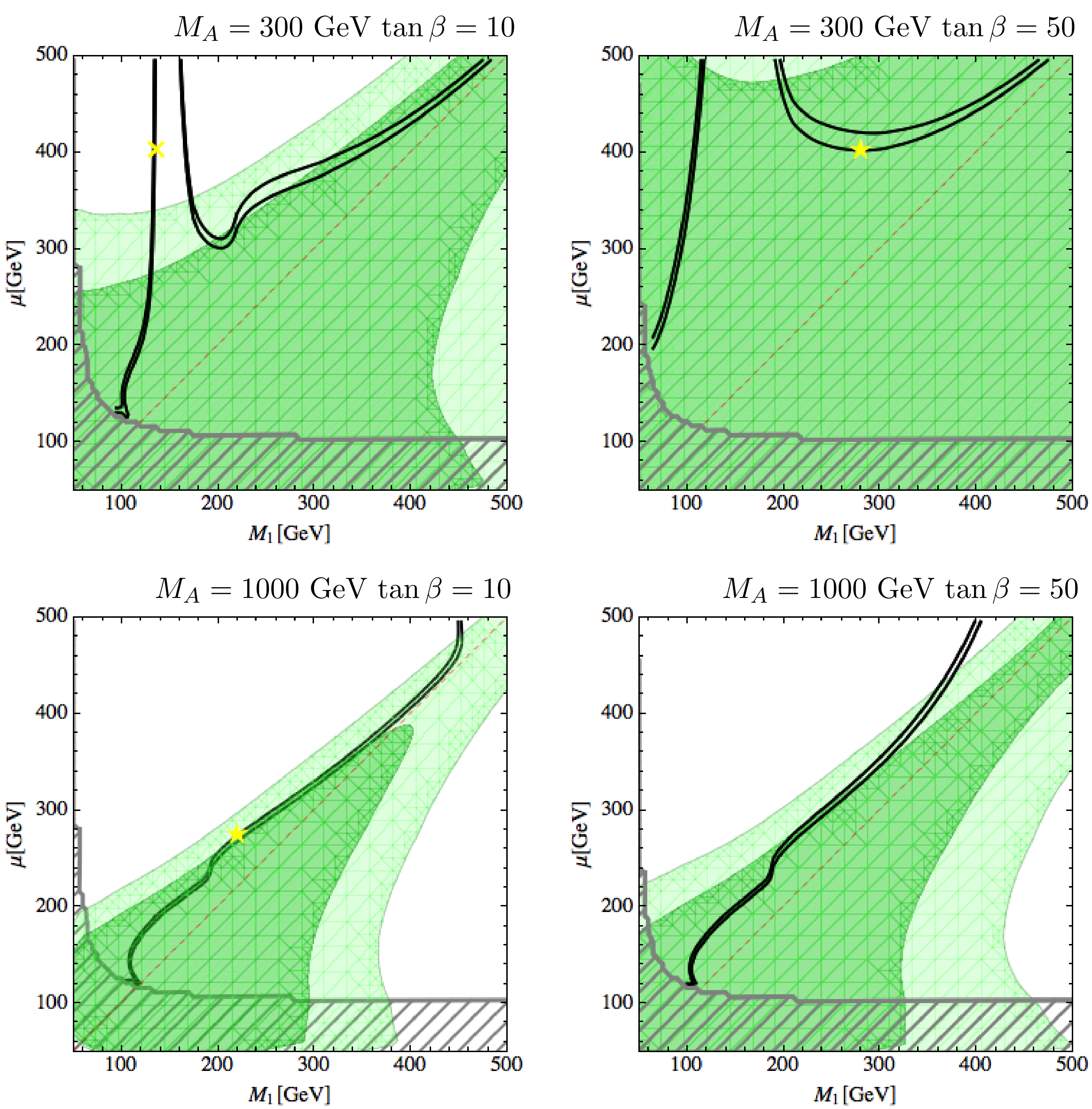
Black Hole production at the LHC



Dimopoulos and Lansberg; Thomas and Giddings '01

Sensitivity up to $M_{Pl}^{\mathrm{fund}} \simeq 5 - 10$ TeV for 100 fb^{-1}.

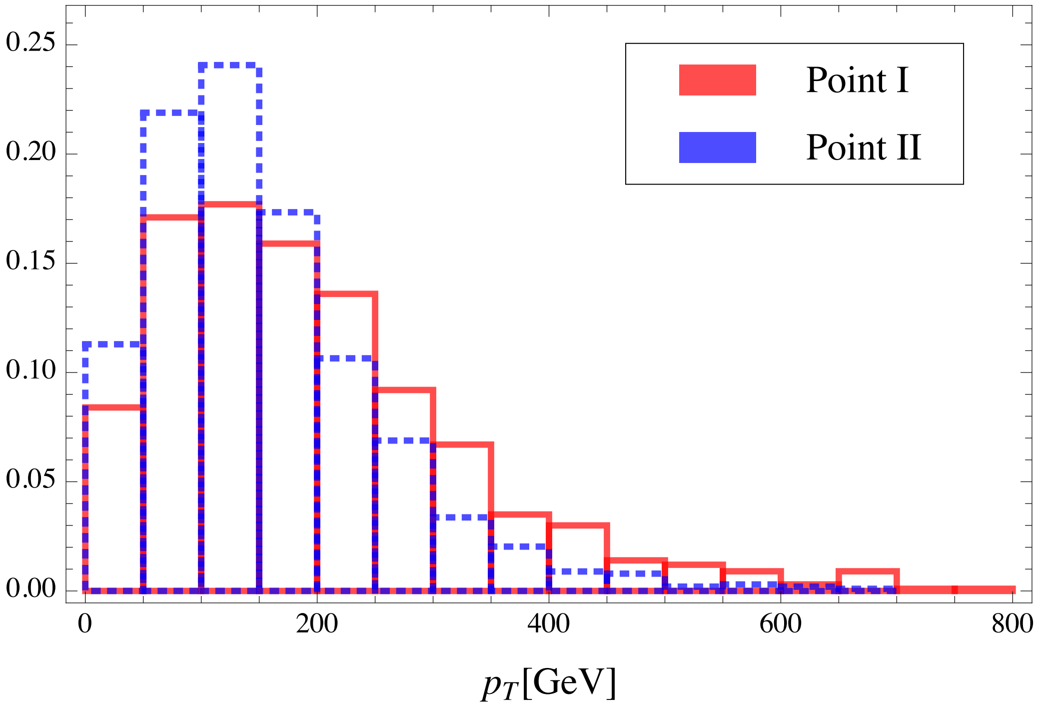
Direct Dark Matter Cross Section Constraints (post Xenon)



Gori, Schwaller, C.W. '11

Heavy sleptons : The presence of (boosted) Higgs bosons is quite generic in the high p_T sample (14 TeV analysis)

(I) $M_A = 1000$ GeV $M_1 = 220$ GeV $\mu = 280$ GeV $\tan\beta = 10$,
(II) $M_A = 300$ GeV $M_1 = 280$ GeV $\mu = 400$ GeV $\tan\beta = 50$,
(III) $M_A = 300$ GeV $M_1 = 135$ GeV $\mu = 400$ GeV $\tan\beta = 10$.
(IV) $M_A = 300$ GeV $M_1 = 49$ GeV $M_2 = 400$ GeV $\mu = 300$ GeV $\tan\beta = 10$



- $\not{E}_T > 200$ GeV,
- at least two jets, with $p_{T1} > 300$ GeV and $p_{T2} > 200$ GeV,
- no isolated leptons.

Boosted Higgs : $p_T > 200$ GeV

	σ[pb]	$\sigma_{\rm cut}$[pb]	σ_h[fb]	$\sigma_{\rm boosted}$[fb]
(I)	1.11	0.52	78	31
(II)	0.73	0.34	116	31
(III)	2.59	0.90	360	135
(IV)	1.60	0.83	231	101

Good prospects of observing Higgs in the 14 TeV run and, perhaps, even in the 7 TeV run.

Gori, Schwaller, C.W., arXiv:1103.4138

Boosted Higgs at the 7 TeV Run

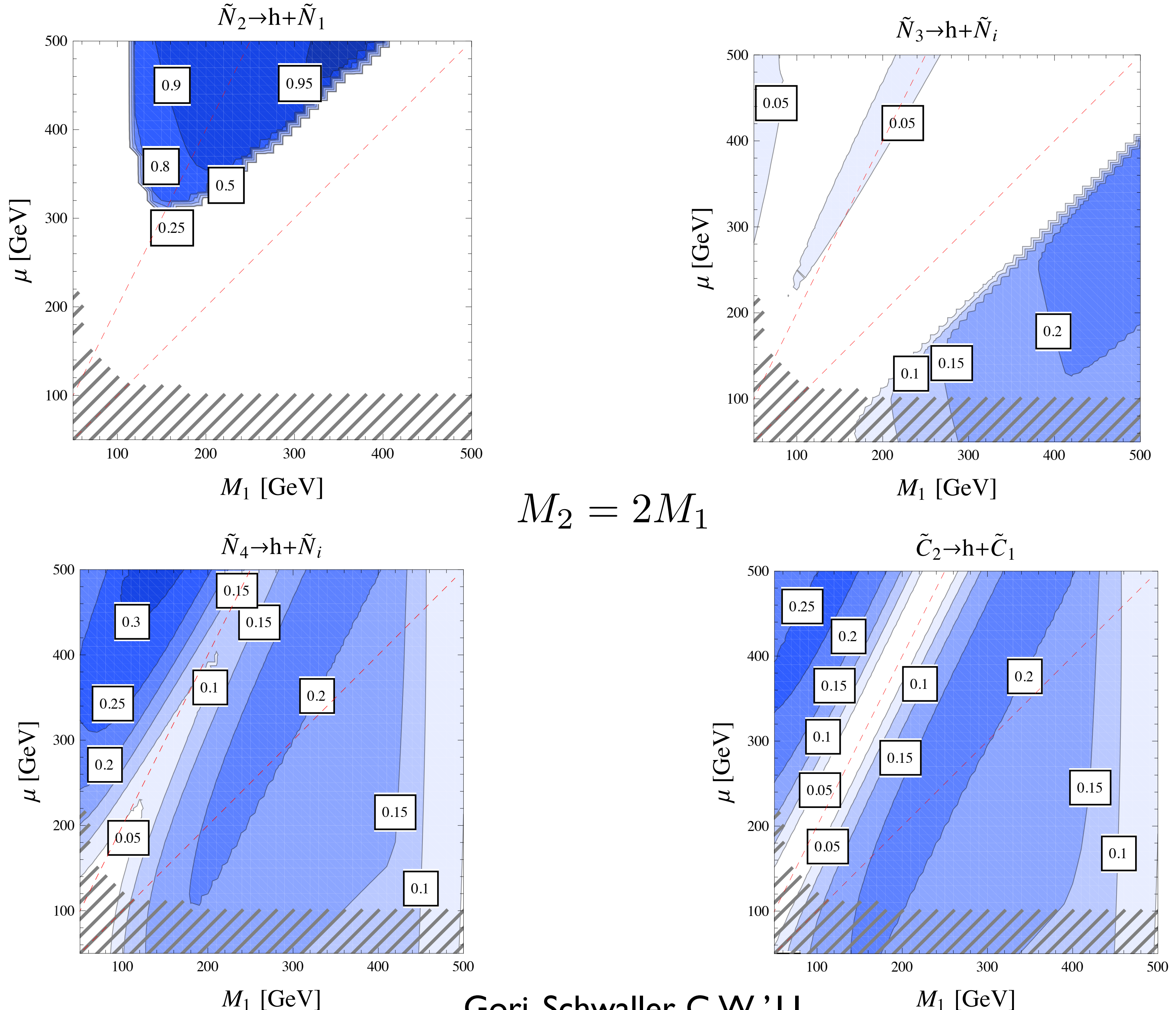
	σ [pb]	σ_{cut} [pb]	σ_h [fb]	$\sigma_{\mathrm{boosted}}$ [fb]
(I)	0.092	0.019	2.7	1.1
(II)	0.042	0.015	5.1	1.1
(III)	0.113	0.030	10	3.6
(IV)	0.106	0.029	8.2	3.3

Squark Masses 1 TeV

	σ [pb]	σ_{cut} [pb]	σ_h [fb]	$\sigma_{\mathrm{boosted}}$ [fb]
(I)	0.23	0.086	11	3.0
(II)	0.18	0.063	17	2.0
(III)	0.31	0.142	36	11
(IV)	0.36	0.169	45	14

Squark Masses 800 GeV

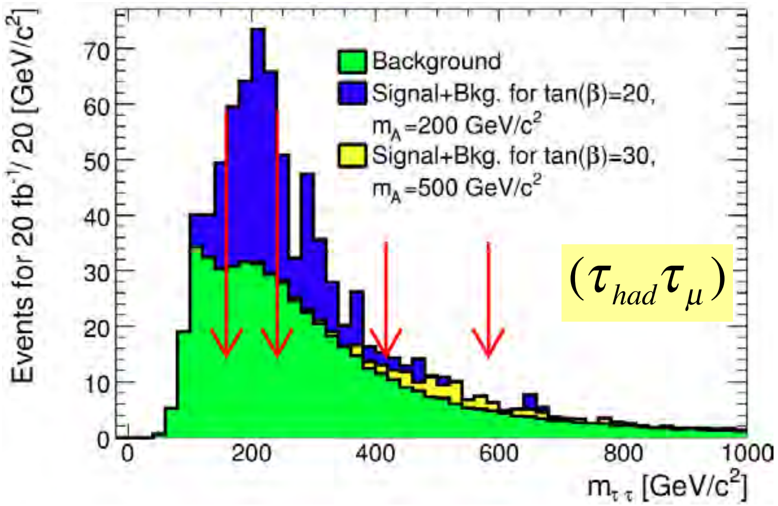
Chargino and Neutralino Decays into Higgs



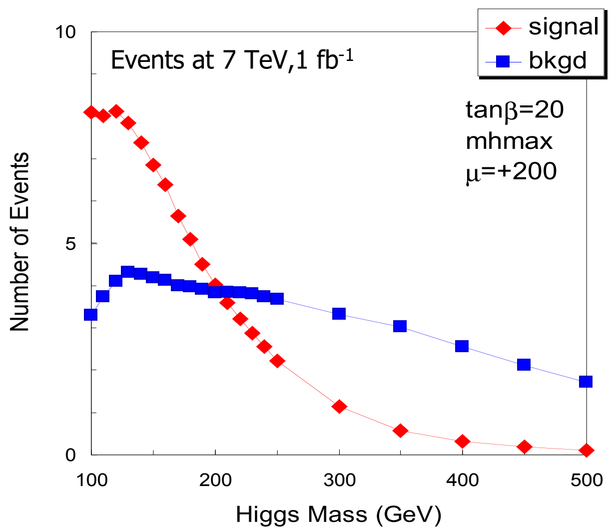
Gori, Schwaller, C.W. '11

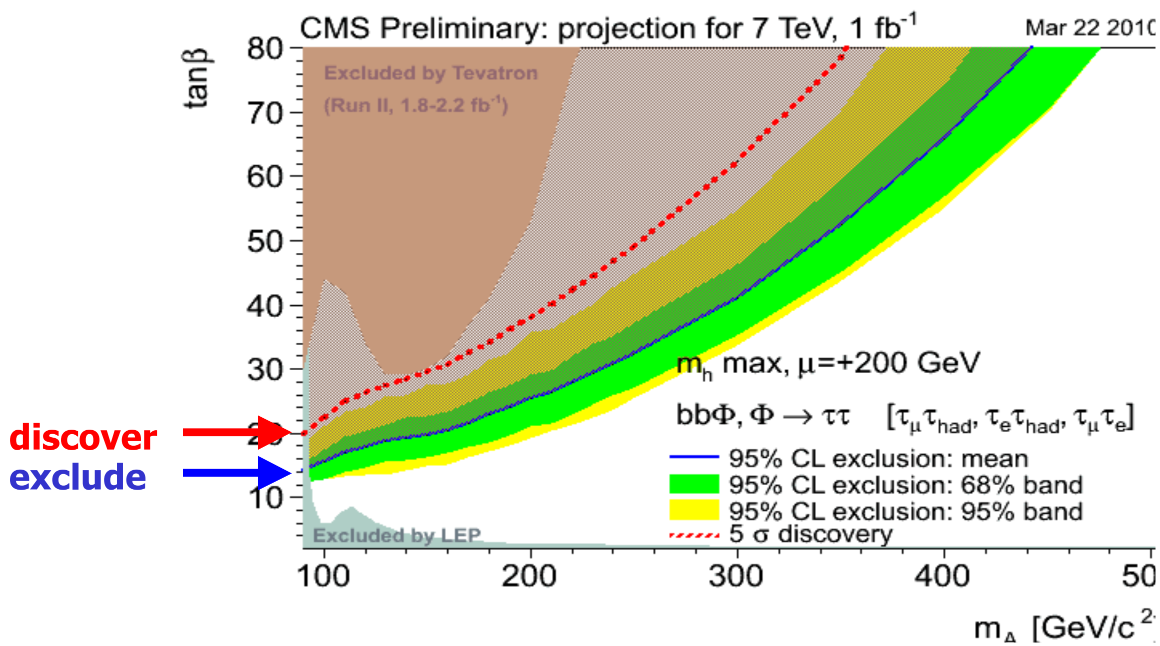
Non-Standard LHC Channels may also help

MSSM Higgs In $pp \to bb\Phi;\ \Phi \to \tau^+ \tau^-$



- – – Isolated pairs of $(\tau_{had}\tau_\mu),(\tau_{had}\tau_e),(\tau_\mu\tau_e)$
- – – With MET, 1 tagged bjet, veto extra jets
- – – Build $\tau\tau$-mass using collinear approx
- – – Count events in sliding $\tau\tau$-mass window
- – – Dominant backgrounds: $t\bar{t}$, $Z+b\bar{b}$ & $Z+c\bar{c}$
  - -- assessed from data

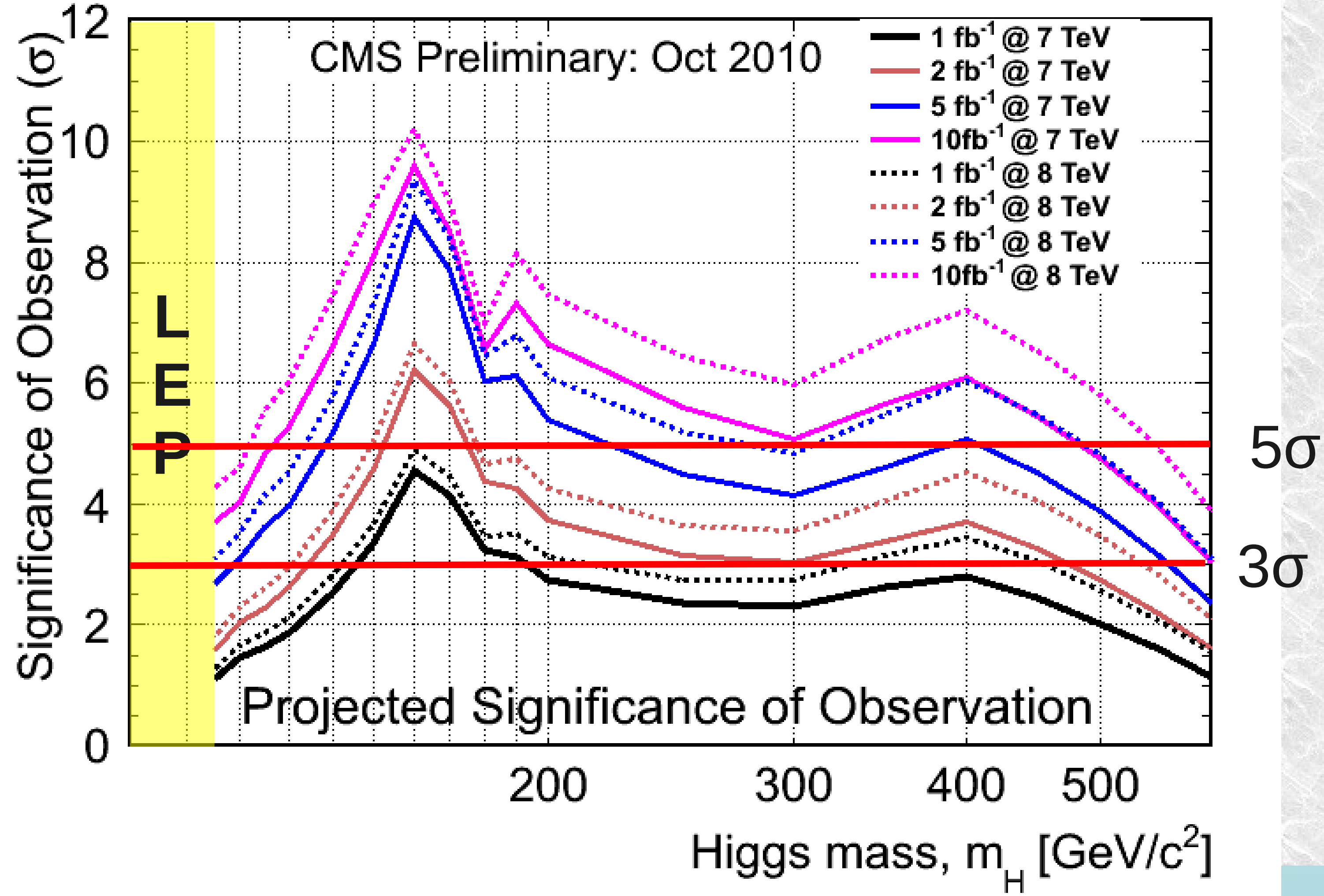




V. Sharma '10

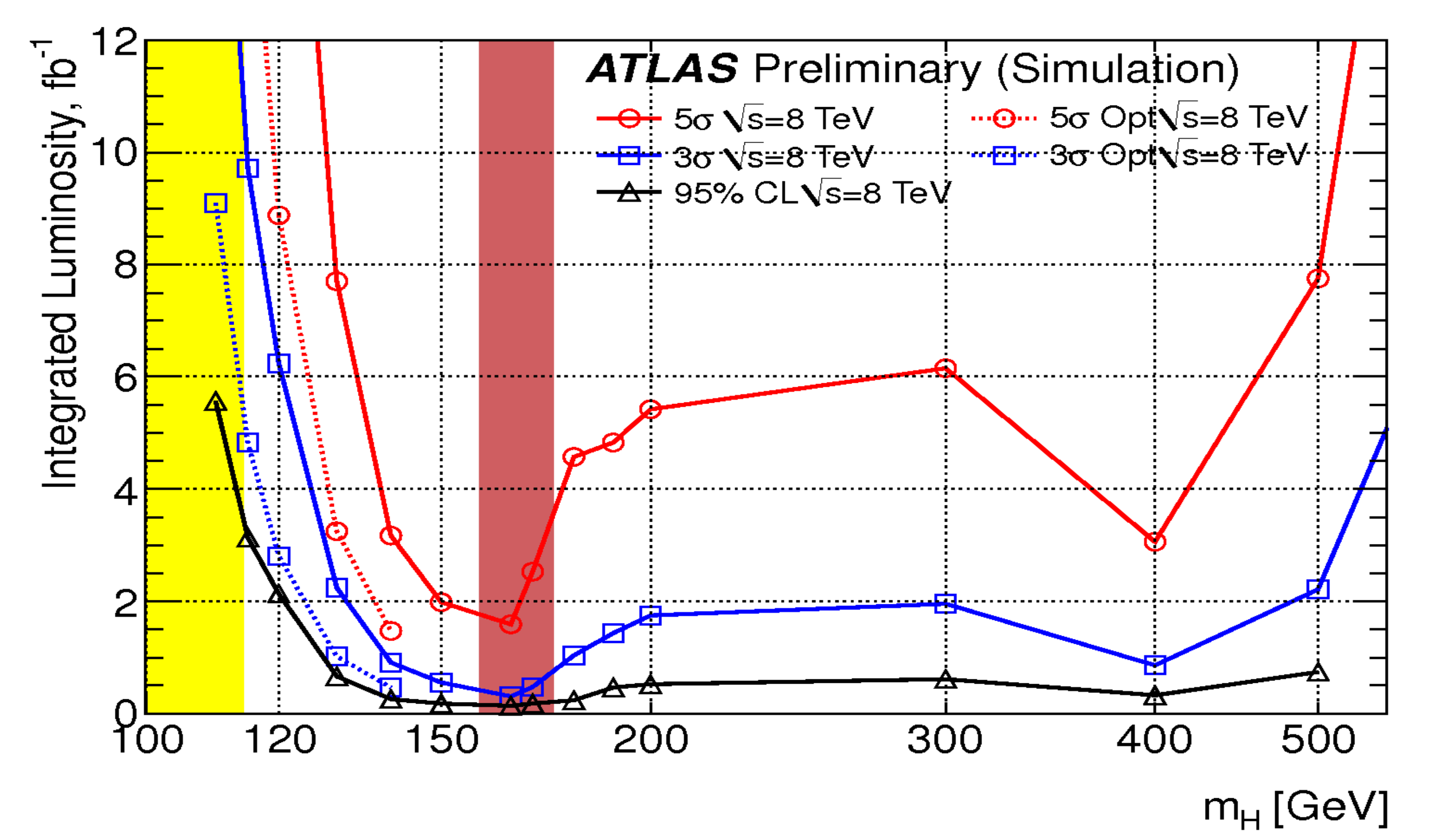
Current 7 TeV LHC Run

Sensitivity to SM Higgs



Current 7 TeV LHC Run

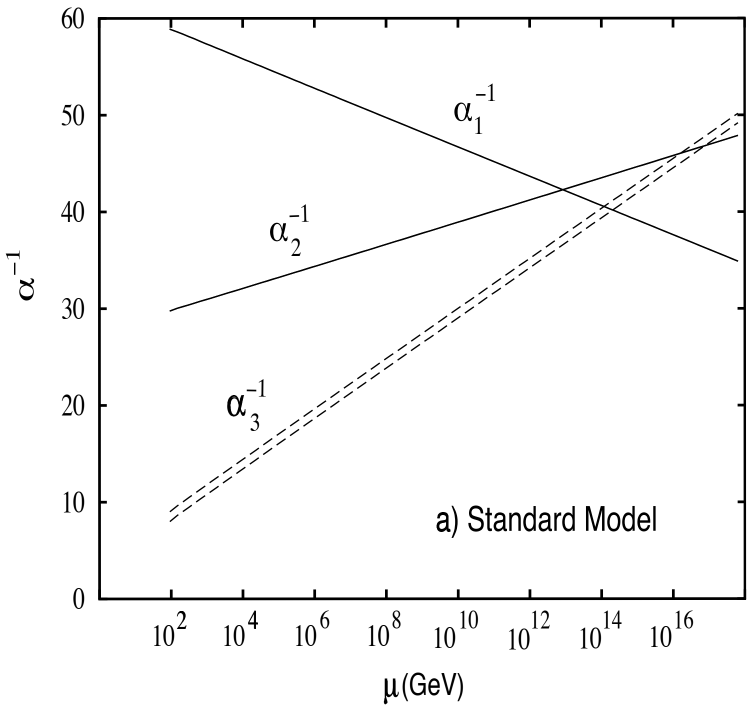
Sensitivity of Higgs search



$5 fb^{-1}$ at 8TeV gives 3σ for 114 to >500GeV

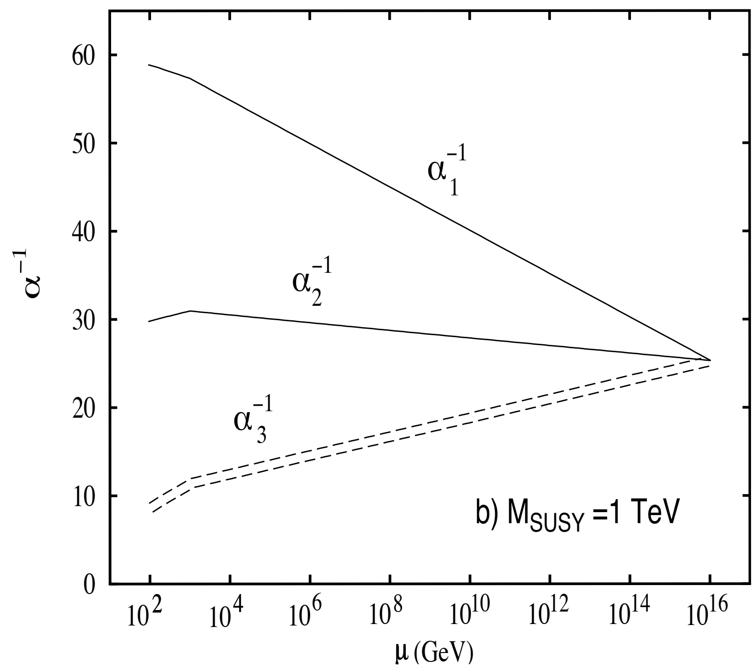
SM:

Couplings tend to converge at high energies, but unification is quantitatively ruled out.



MSSM:

Unification at $\alpha_{GUT} \simeq 0.04$ and $M_{GUT} \simeq 10^{16}$ GeV.



Experimentally, $\alpha_3(M_Z) \simeq 0.118 \pm 0.004$

Bardeen, Carena, Pokorski & C.W.

in the MSSM: $\alpha_3(M_Z) = 0.127 - 4(\sin^2\theta_W - 0.2315) \pm 0.008$

Remarkable agreement between Theory and Experiment!!

Threshold Corrections

- The unification prediction depends strongly on the supersymmetry particle mass spectrum,

$$\alpha_3(M_Z) \simeq 0.127 - \alpha_3^2(M_Z) \ln \left(\frac{T_{SUSY}}{M_Z} \right)$$

- The threshold scale does not correspond to any particular particle scale but it may be approximated by

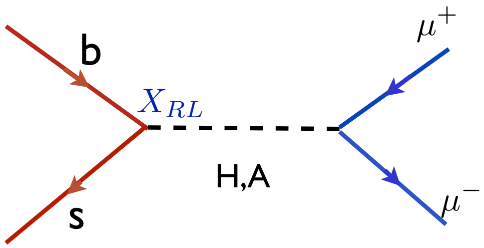
$$T_{SUSY} \simeq |\mu| \left(\frac{M_2}{M_3} \right)^{3/2}$$

where Mi are the SU(2) and SU(3) gaugino masses.

- Naive unification may be obtained for threshold scales of the order of 1 TeV, which are easier to obtain for a smaller ratio of the wino and gluino masses than what the simplest models predict.

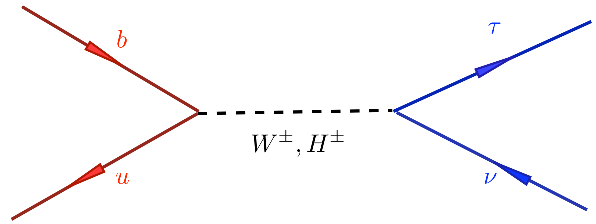
Flavor Higgs induced effects

- The same corrections to the couplings induced FCNC in the neutral Higgs sector, which combined with charged Higgs induced contributions, lead to important flavor effects induced by the Higgs sector at large values of $\tan\beta$



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

$$\left(g_{A\mu\mu} = \frac{m_\mu \tan\beta}{v} \right)$$



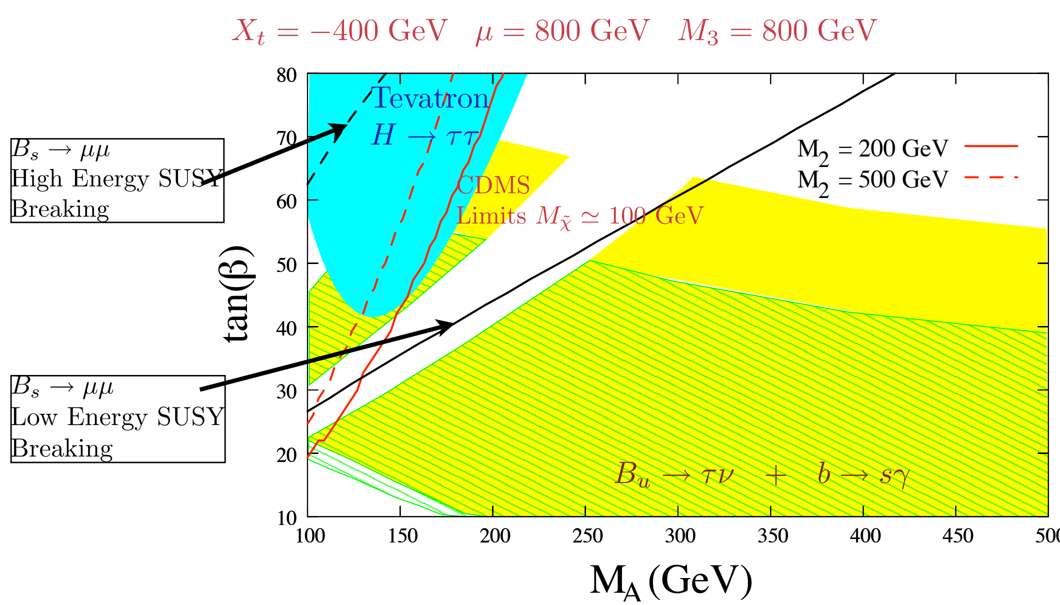
$$X_{RL} \propto \frac{\left(E_t h_t^2 + E_{g,3} - E_{g,(1,2)}\right)\tan^2\beta}{\left(1 + E_{g,(1,2)}\tan\beta\right)\left(1+\Delta_b\right)}$$

Babu, Kolda'00, Buras et al'02, Dedes, Pilaftsis'03...

In models with flavor independent high energy supersymmetry breaking, flavor violating gluino couplings are induced at low energies and cannot be ignored.

Very relevant constraints come also from b to s gamma, which receives SUSY contributions from charged Higgs, chargino and gluino loops.

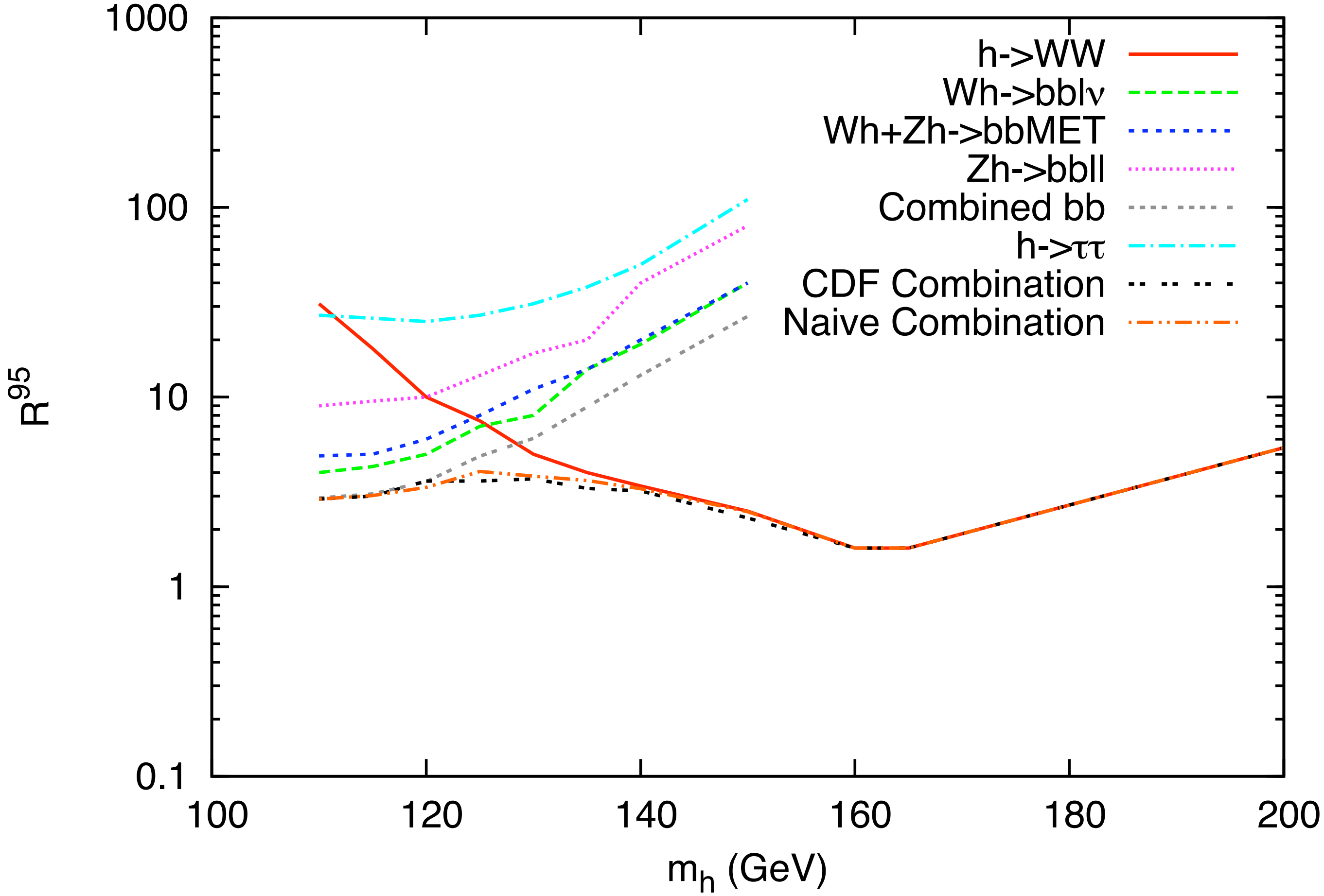
Direct dark matter detection may also become relevant.



M. Carena, A. Menon, C.W.

Comparison of Simple Combination of Channels with CDF Results. Ratio R for exclusion

P. Draper, T. Liu and C. Wagner'09



Applicable to new model in which all channels rescale in the same way.
In the MSSM, channels should be considered separately and recombined.