Argonne National Laboratory
HEP Theory Group

Overview of the Group and Higgs and BSM Activities

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July 26, 2011

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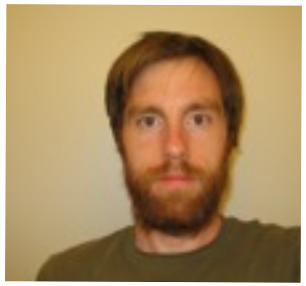

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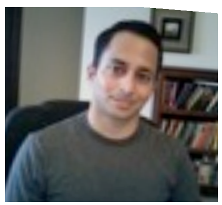

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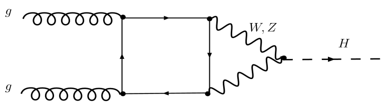
Higgs Physics

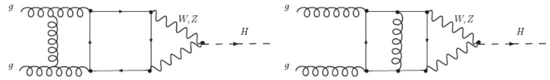
- As a whole, the most noteworthy contributions of the group are on Higgs physics.
- The cross sections and uncertainty estimates for Higgs production used by both the Tevatron and the LHC collaborations in their searches were derived by Argonne personnel.
- We examine the discovery and exclusion reach of the Tevatron and LHC colliders in different production and decay channels in the SM and beyond.
- We also study new methods for looking for the Higgs in beyond the SM scenarios, as well as for the determination of the Higgs boson properties and the possible differentiation of Higgs from other look-alike particles.

Higgs Production at Hadron Colliders

- Large corrections to $gg \to H$ from EW effects due to light quarks; parametrically scale like $y_{W,Z} N_F$. No mF suppression for light fermions



- what is the effect of QCD corrections to this contribution?
- No one knew! Requires 3loop multiscale calculation



- a K-factor between 1-3.5 was assumed in the literature
- Tevatron assumed a K-factor of 3.5 in their very first exclusion of SM mH= 170GeV
- Devised an EFT approach to estimate the K-factor; confirmed that 3.5 is correct

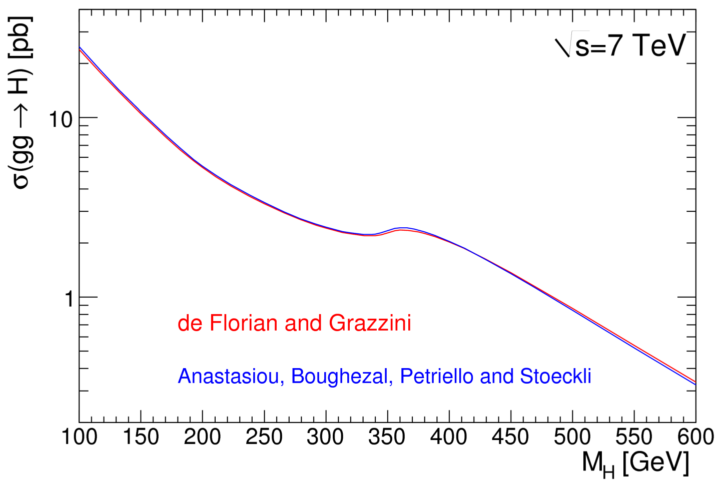
Boughezal, Petriello et al, JHEP 0904 (2009) 003

- **Higgs Physics at the LHC: Argonne influence**

- Provided the prediction for $gg \to H$ cross section at the Tevatron and the LHC
- Our predictions are the official cross sections used by both colliders

CERN Yellow Report 2011

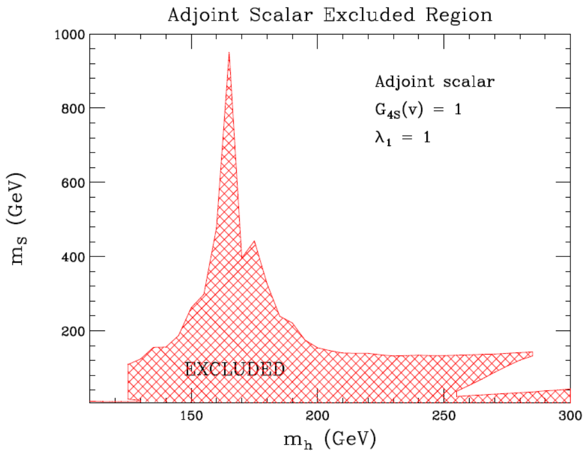
CERN-2011-002



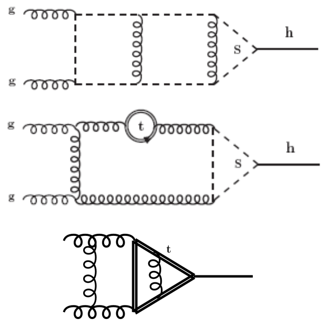
Higgs Production : Bounds on New Physics

- Realized that the Tevatron Higgs exclusion limits stringently constrain the parameter space of colored scalars appearing in theories beyond the SM

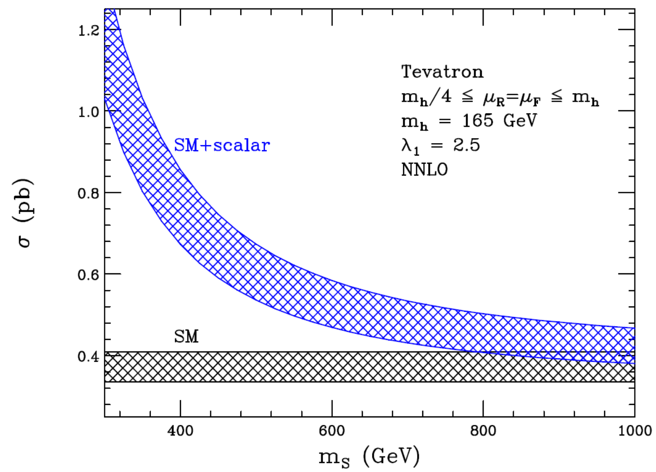
Boughezal 2011



Phys.Rev. D83 (2011) 093003



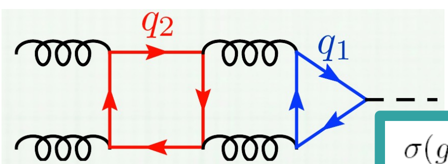
Adjoint scalars Boughezal, Petriello (2010)



Phys.Rev. D81 (2010) 114033

- Quantified the effect of a fourth generation of heavy quarks on the Higgs production cross section. Result used by the Tevatron collaborations in setting exclusion limits

Boughezal et al, JHEP 1006 (2010) 101



$$\frac{\sigma(gg\to H)^{(n_h)}}{\sigma(gg\to H)^{(SM)}} = \frac{\Gamma(H\to gg)^{(n_h)}}{\Gamma(H\to gg)^{(SM)}} =$$

$$n_h^2 - \left(\frac{\alpha_s'(\mu)}{\pi}\right)^2 n_h \left[\frac{77}{288} n_h(n_h-1) + \left(\frac{4}{3}n_l + \frac{19}{4}\right)\sum_q \log\left(\frac{m_q(\mu)}{m_t(\mu)}\right)\right] + \mathcal{O}(\alpha_s'^3)$$

Higgs Identity

UV identity:

- is the higgs fundamental or composite?
- is the higgs mass fine-tuned? (is the higgs supersymmetric or a goldstone boson??)
- does the new physics at the TeV scale, if any, solve the gauge hierarchy problem?

IR identity:

- if we observe a scalar resonance, how do we know it has a VEV that breaks the electroweak symmetry?
- what are its quantum numbers and electroweak properties?

some partial answers to the above questions, by looking into :

- gluon-fusion (ggh) production channel: compositeness and naturalness
- decay into ZZ final states: spin, CP, and origin of electroweak symmetry breaking
- decay branching fractions into pairs of electroweak vector bosons: electroweak quantum numbers

compositeness and naturalness (0901.0266, Low and Shalgar; 0907.5413, Rattazzi, Low, and Vichi; 1010.2753, Low and Vichi)

- ggh is the dominant production channel at the LHC.
- it is a loop-induced process!
- three operators could modify the rate at dim-6:

$$\frac{c_y y_t}{f^2}(H^\dagger H)\bar{f}_L H f_R$$

$$\frac{c_H}{2f^2}\partial_\mu(H^\dagger H)\partial^\mu(H^\dagger H)$$

$$\frac{\alpha_s}{2\pi}\frac{c_g y_t}{m_\rho^2}H^\dagger H G^a_{\mu\nu}G^{a\mu\nu}$$

$$\Gamma(h \to gg) = \Gamma(h \to gg)_{SM}\left[1 - \xi\,\mathrm{Re}\left(c_H + 2c_y + \frac{4y_t^2 c_g}{g_\rho^2 I_g}\right)\right]$$

if the higgs is realized in nature as a goldstone boson, ggh rate is reduced!

in addition, the interference between SM top and a heavy top-like fermion is *destructive* if the higgs quadratic divergence is *cancelled*, and *constructive* if it is *not cancelled*.

(in SUSY the trend is reversed, unless the stop mixing is large.)

if the higgs scalar is fundamental and its mass fine-tuned, the rate is enhanced over the SM!

One example is ggh rate in universal extra-dimensional models:

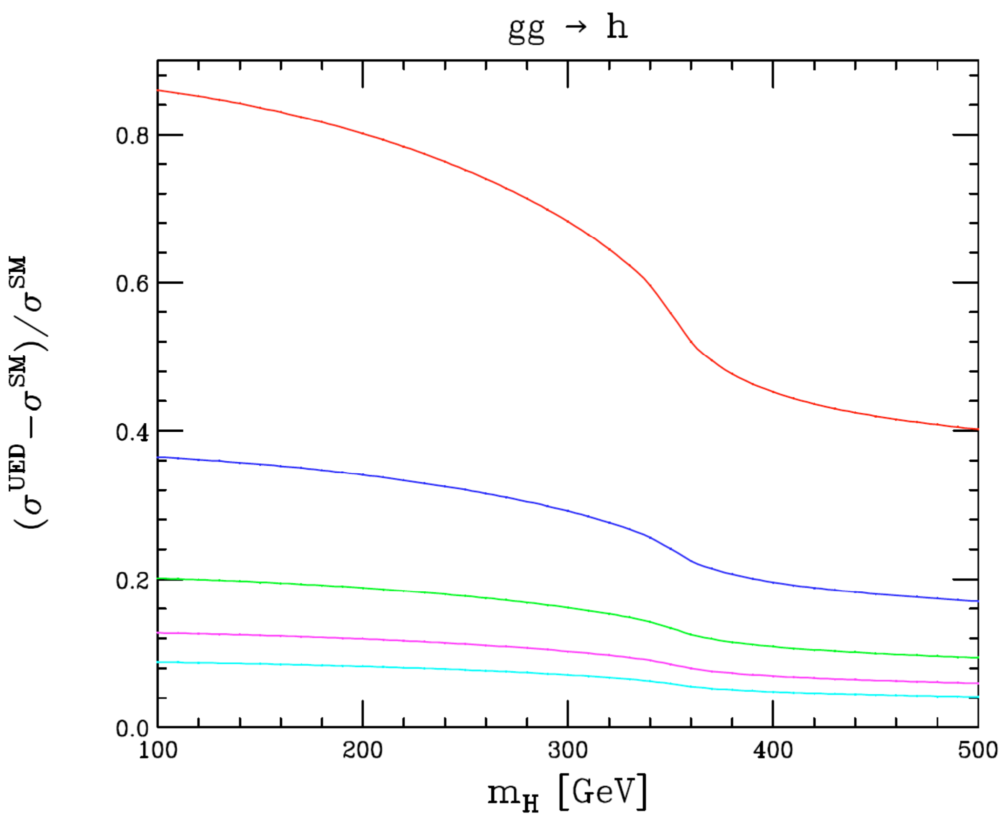
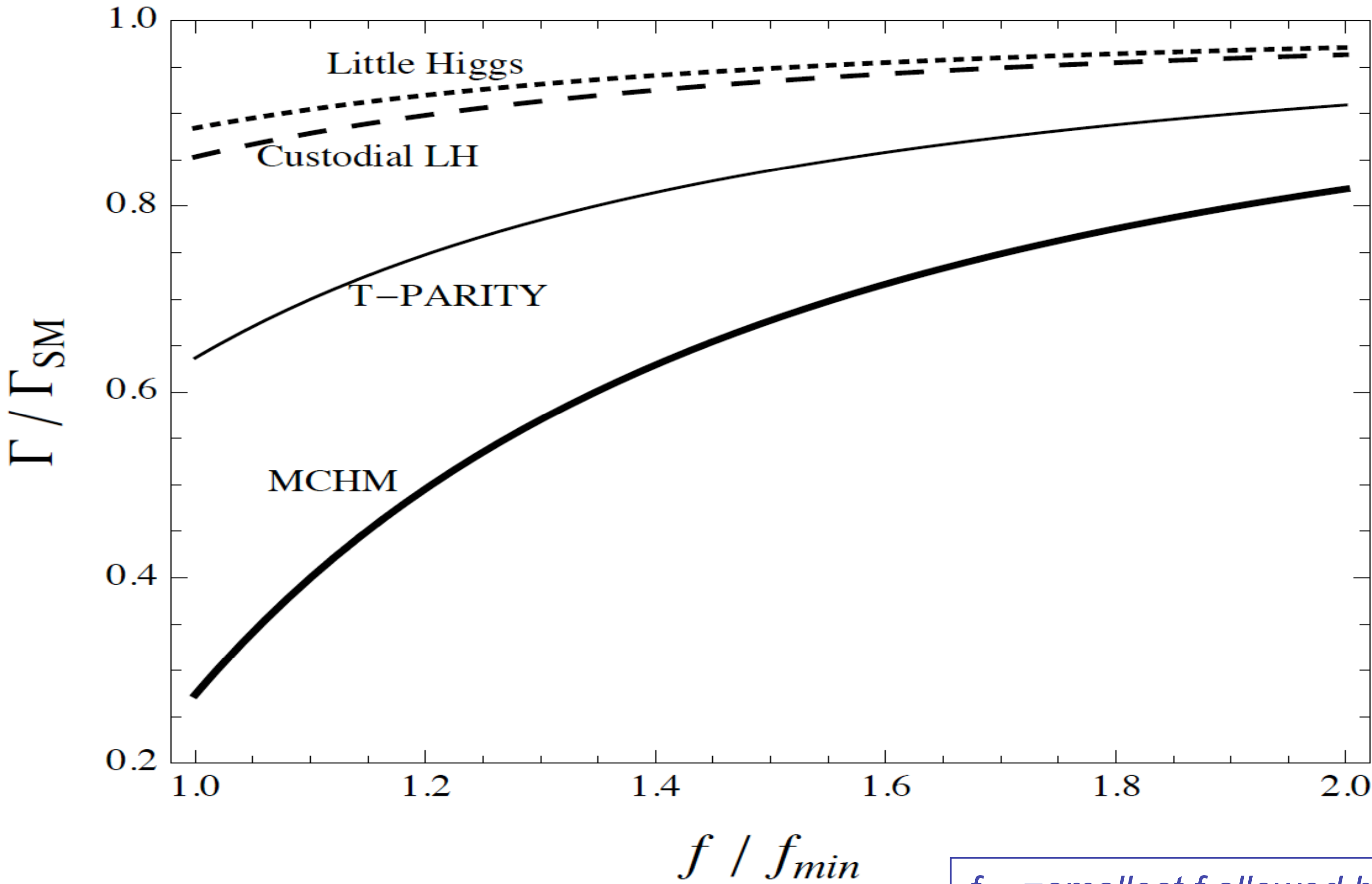


Figure 1: The fractional deviation of the $gg \to h$ production rate in the UED model as a function of m_H; from top to bottom, the results are for $m_1 = 500, 750, 1000, 1250, 1500$ GeV.

F. Petriello, hep-ph/0204067

a survey of existing composite higgs models, where the higgs is a pseudo-goldstone boson, confirms our general results:

1010.2753, Low and Vichi



f_{min}=smallest f allowed by pEW.

electroweak quantum number (1005.0872, Low and Lykken; 1105.4587, Low, Lykken, and Shaughnessy)

- electroweak quantum numbers determine its couplings to pairs of electroweak vector bosons: WW, ZZ, Zγ, and γ γ.

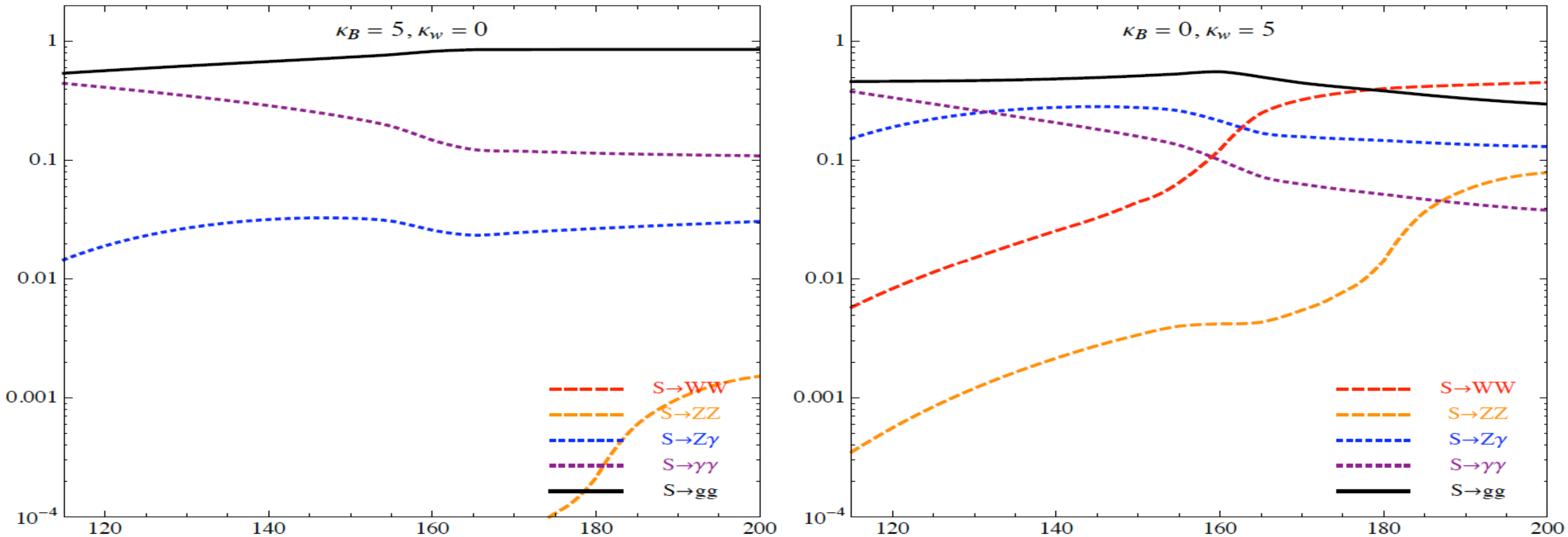
for a Higgs doublet: Br(WW) > Br(ZZ) >>> Br(γ γ) >~ Br(Zγ)

⇧ tree level couplings

⇧ loop-induced couplings

this pattern does not hold for an electroweak singlet scalar!

In fact, a higgs imposter (eg a singlet scalar) is likely to show up first in the γ γ and Z γ channels, while the search in the WW and ZZ channels might turn up empty! this is the case even if the mass is above WW threshold!



spin, CP, and higgs mechanism (0806.2864, Keung, Low, and Shu; 0911.3398, Cao, Jackson, Keung, Low, and Shu)

higgs -> ZZ ->4l is the gold-plated mode for higgs mass above 130 GeV ---- the kinematics could be fully reconstructed!!

the other two terms are higgs imposters!!

$$\mathcal{L}_{eff} = \frac{1}{2} m_S\, S \left(c_1 Z^\nu Z_\nu + \frac{1}{2}\frac{c_2}{m_S^2} Z^{\mu\nu} Z_{\mu\nu} + \frac{1}{4}\frac{c_3}{m_S^2} \epsilon_{\mu\nu\rho\sigma} Z^{\mu\nu} Z^{\rho\sigma} \right)$$

higgs mechanism predicts only this term!

one observable is particularly useful: ϕ, the azimuthal angle between the two decay planes of the Z.

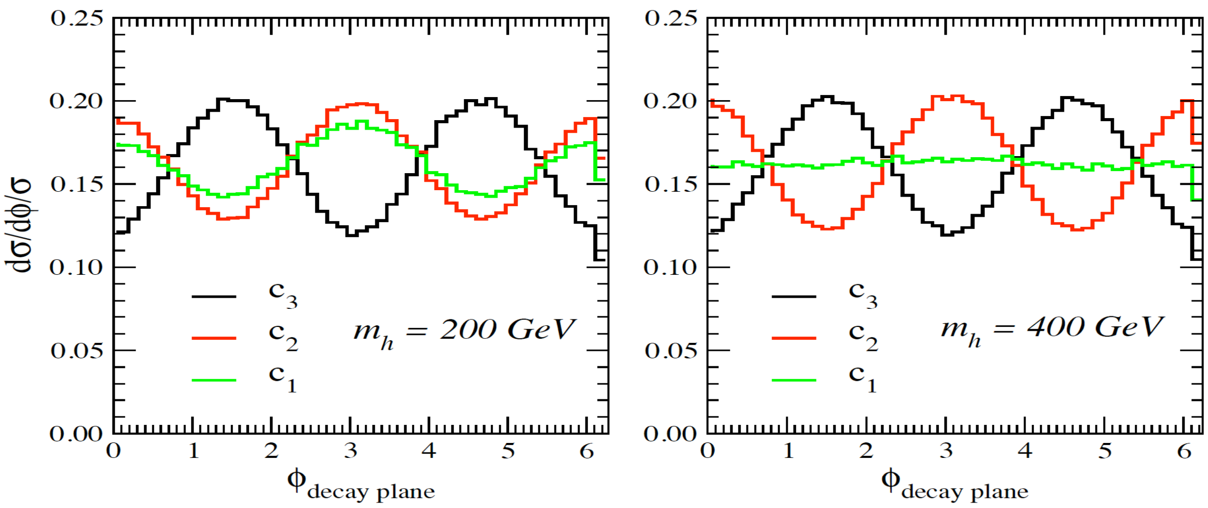


FIG. 4: *The normalized azimuthal angular distributions for 200 and 400 GeV scalar masses, turning on one operator at a time.*

Higgs Discovery/Exclusion in $H \to W^+W^-$

Study began right after decision to operate LHC at $\sqrt{s} = 7$ TeV. Goal: evaluate impact of reduced energy on LHC sensitivity with 1 fb^{-1} integrated luminosity

LHC expectations have grown; 20 - 25 fb^{-1} by end of 2012!

Berger, Q-H Cao, C Jackson, G Shaughnessy axXiv:1003.3875

Phys Rev D **82**, 053003 (2010)

- Used ATLAS and CMS cuts from TDR's
- energy dependent parton level analysis of signal and backgrounds, including showering, plus detector simulations
- verified agreement with ATLAS and CMS expectations at 14 TeV

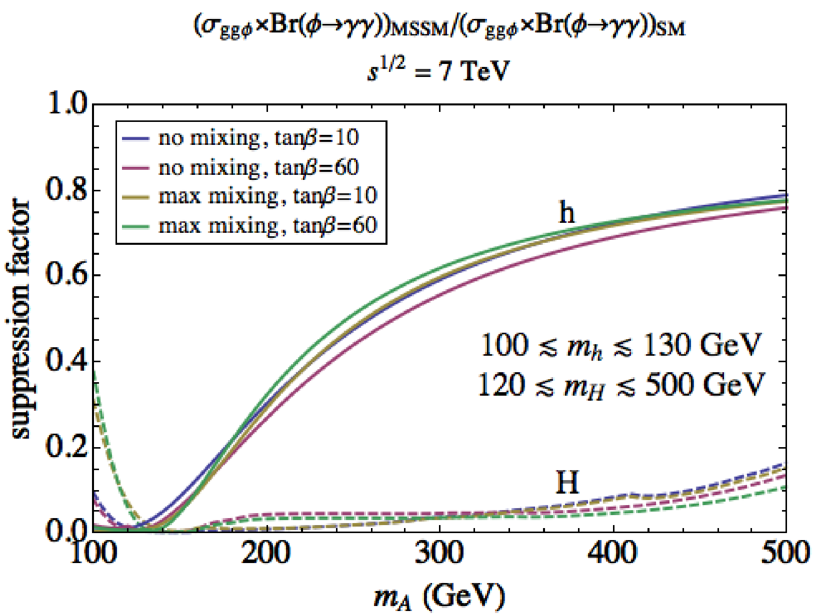
$\sqrt{s} = 7$ TeV "predictions" for $m_H = 140, 160, 180, 200$ GeV

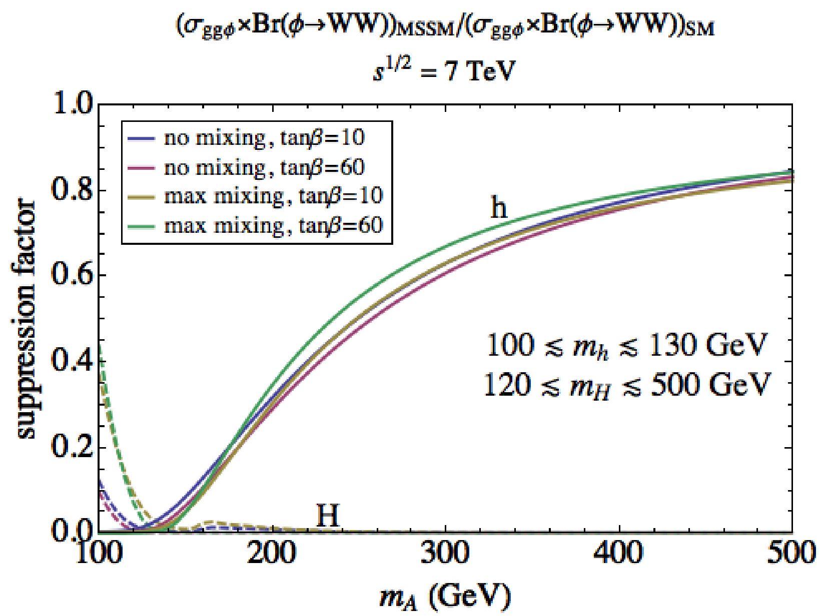
- at least 2 fb^{-1} required for 5σ discovery in $H \to W^+W^-$ channel
- exclusion possible at 160 GeV with 1 fb $^{-1}$
- improved cuts suggested

MSSM Higgs Searches at the LHC

P. Draper, T. Liu, C. Wagner, **Phys.Rev.D81:015014,2010**; M. Carena, P. Draper, T. Liu, C. Wagner, arXiv:1107.4354

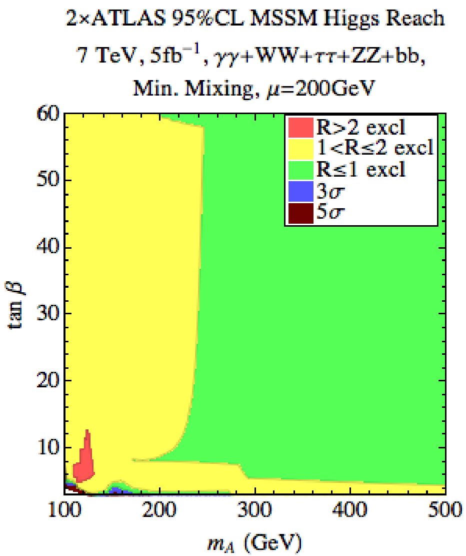
- In the MSSM, one of the Higgs bosons has standard model like couplings to the top and gauge bosons
- The main SM-like channels of production and/or decay are induced by loops, which are affected by new physics (mainly stops)
- Moreover, the dominant width of Higgs decay into bottom quarks may be enhanced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

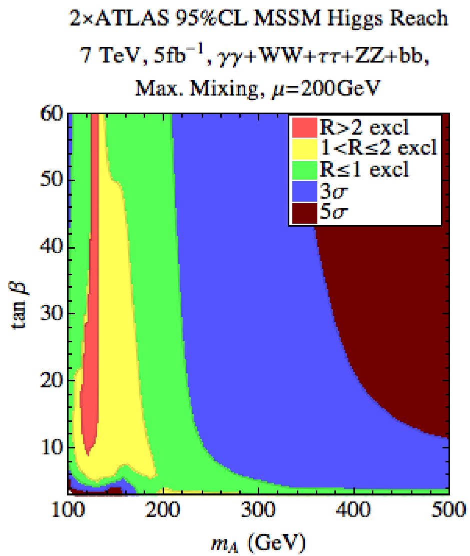




7 TeV LHC MSSM Higgs Reach

P. Draper, T. Liu, C. Wagner, **Phys.Rev.D81:015014,2010**; M. Carena, P. Draper, T. Liu, C. Wagner, arXiv:1107.4354

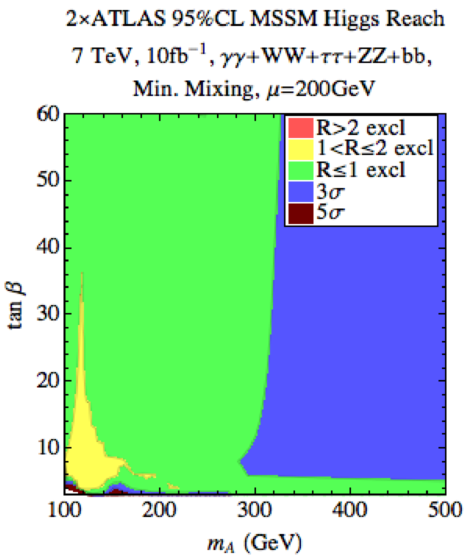


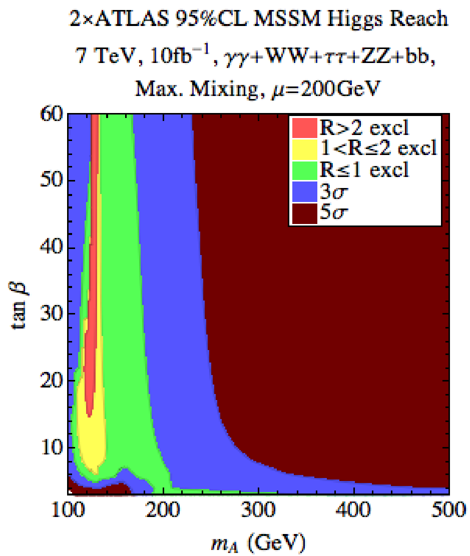


Suppression of

$$BR(h \to \gamma\gamma)$$

leads to reduced reach at low values of the CP-odd Higgs mass





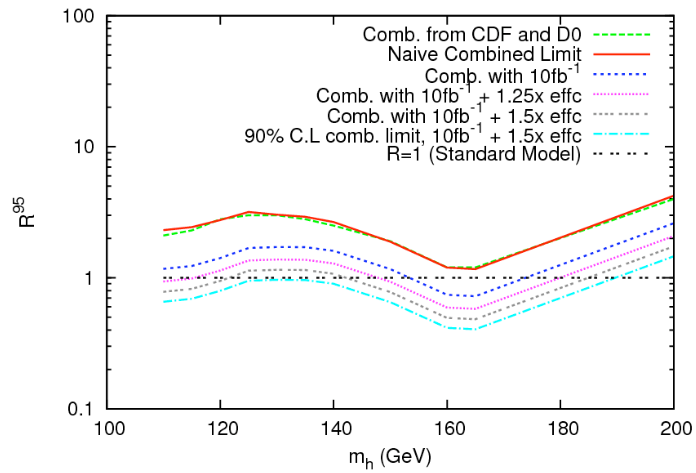
At sufficiently large luminosity

$$Vh, h \to bb$$

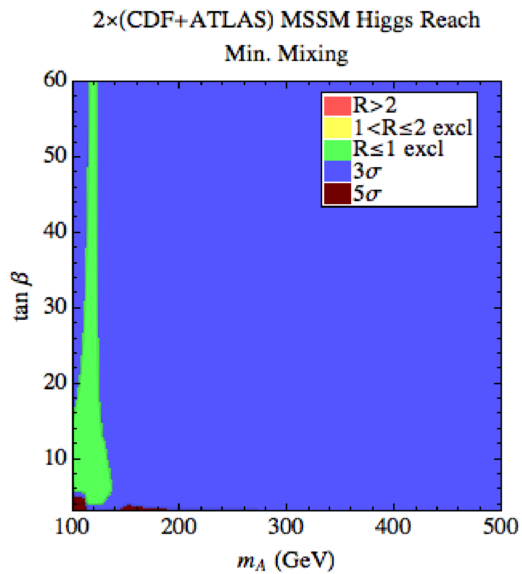
$$\mathrm{WBF}, h \to \tau\tau$$

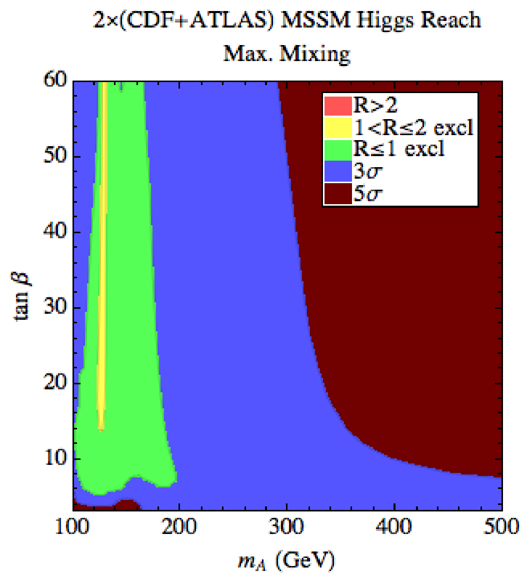
are helpful in partially reducing the reach suppression

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



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

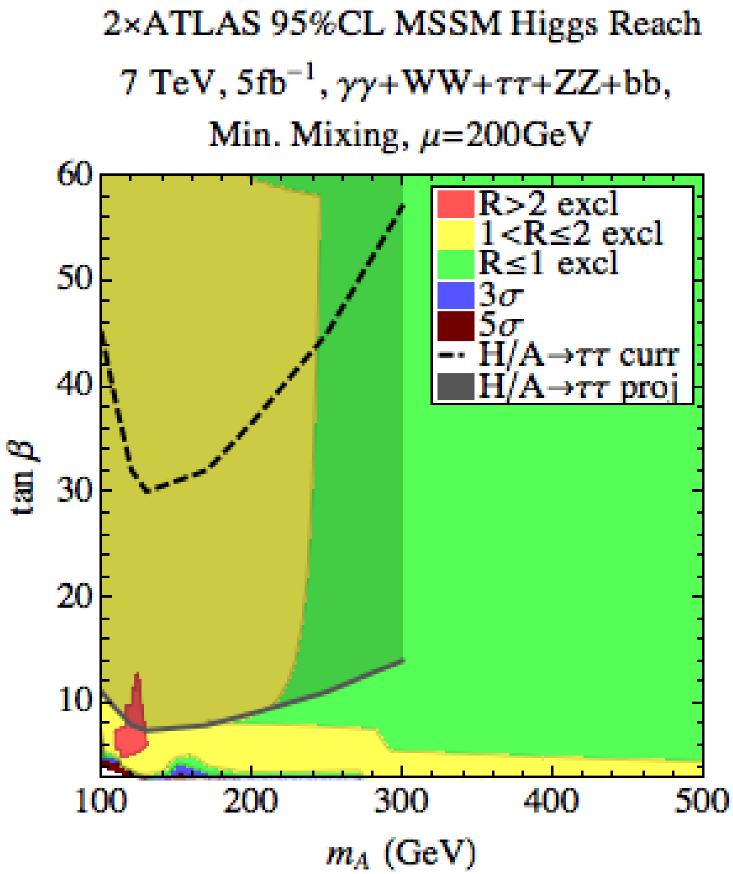


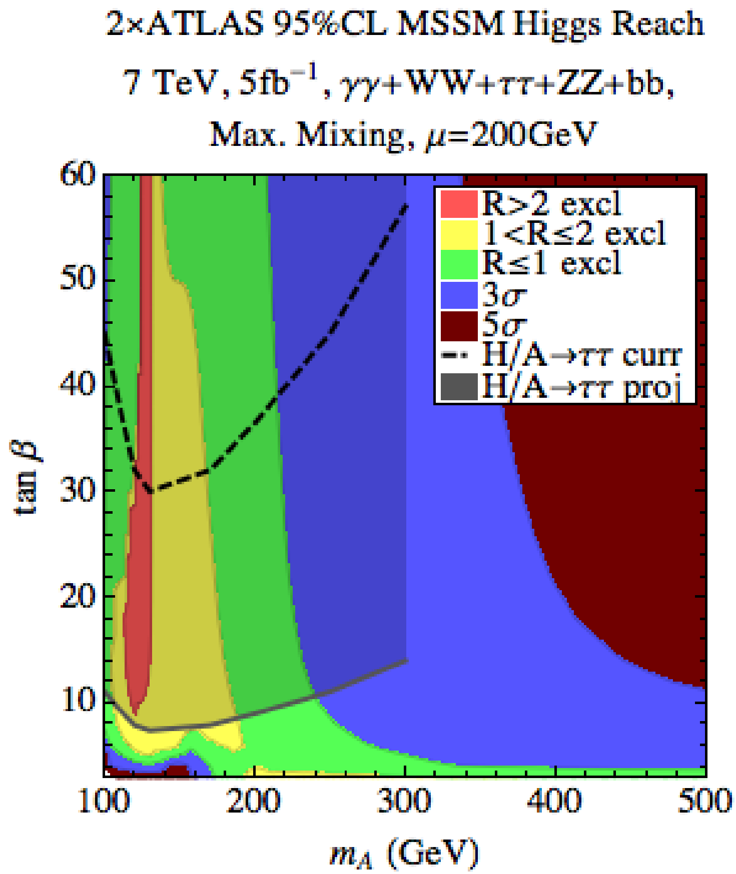


Combination of 5 inverse fb LHC with 10 inverse fb Tevatron data : Evidence of SM-like Higgs presence in almost all parameter space

M. Carena, P. Draper, T. Liu, C.W.'11

Complementarity with LHC non-standard Higgs searches





M. Carena, P. Draper, T. Liu, C.W.'11

Non-standard Higgs searches allow to probe most of the parameter space for which standard reach is suppressed

Search for SM-like Higgs Boson from SUSY Particle Decays
Parameter space consistent with Neutralino Relic Density: Heavy Sleptons

Look for boosted SM-like Higgs bosons, decaying to bottom quarks

Butterworth, Davison, Rubin, Salam'08

Higgs from heavy sparticle decays tend to be boosted

Kribs, Martin, Roy, Spannowsky'10

Countours of proper relic density

Green : $\tan\beta = 50$

Black : $\tan\beta = 10$

$m_A = 300$ GeV

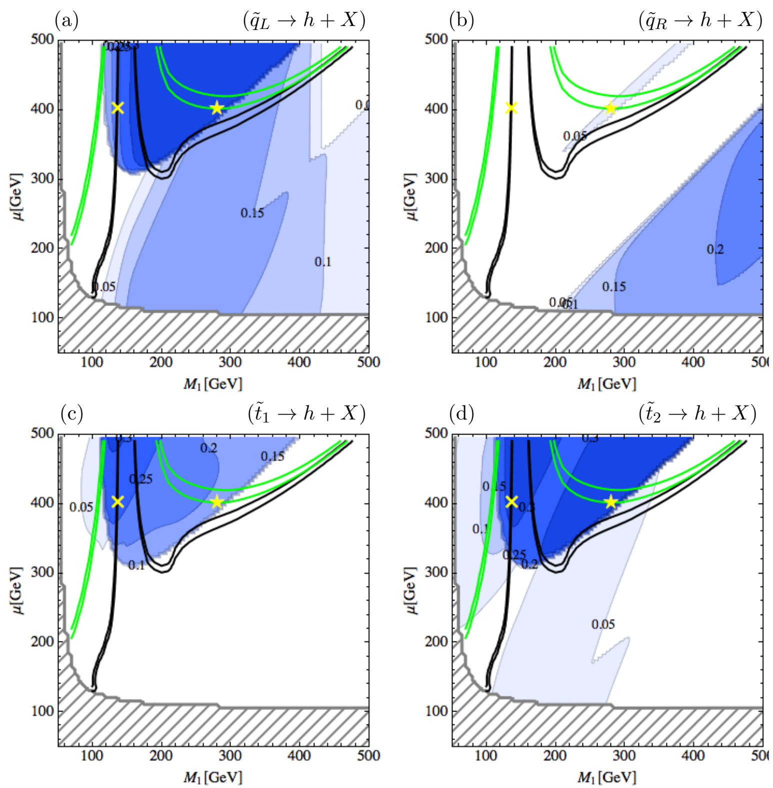
$m_{\tilde{q}} \simeq 1$ TeV

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

$M_2 = 2M_1$

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



Blue regions :

Appreciable Branching Decay Fraction.

Darker means larger branching decay fraction.

X : energetic quarks, leptons and missing energy

Gori, Schwaller, Wagner, **Phys.Rev.D83:115022,2011**

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

Beyond the Standard Model

- Group made non-trivial progress in model-building, motivated either by new theoretical ideas or by attempts to provide interpretations of unexpected experimental results.
- These include CP-violation in the Bs meson system, the forward-backward asymmetry of the top quark, and the recently reported dijet excess in the production of a W plus two jets.
- We analyzed the possibility of explaining anomalies in direct and indirect dark matter detection, and studied ways of identifying the properties of a dark matter particle.
- Group also analyzed models that could lead to the understanding of baryogenesis, the origin of the matter-antimatter asymmetry in the Universe.

Top Quark Physics

Different models leading to its explanation to the observed Forward-Backward asymmetry were analyzed by
Q.H. Cao, D. McKeen, J. Rosner, G. Shaughnessy and C. E.M. Wagner,
Phys.Rev.D81:114004,2010
Axigluon and flavor violating charged vector bosons preferred by fit to the FB asymmetry, production cross section and tt invariant mass.

Implications for Same-sign Top Quark Production was analyzed by
E. Berger, Q.H. Cao, C.R. Chen, C.S. Li and H. Zhang,
Phys. Rev. Lett 106, 201801 (2011)

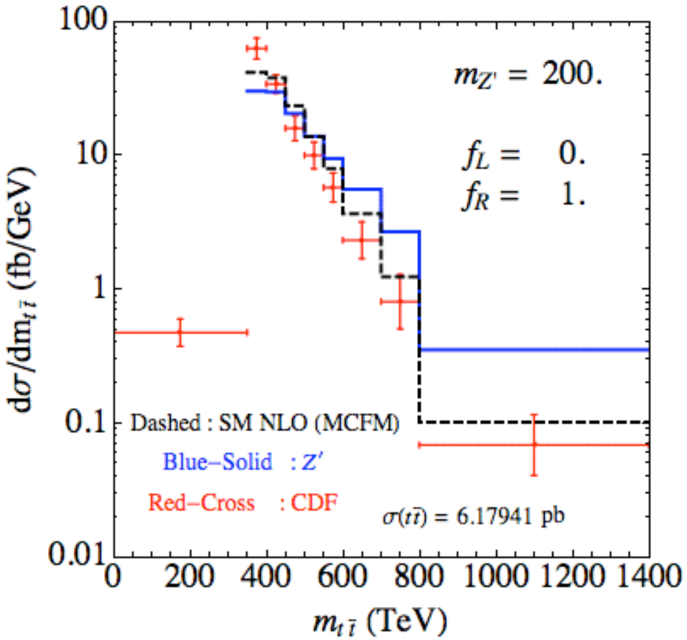
Further work on color sextet vector bosons and same-sign top quark pairs at the LHC performed by E. Berger, Q.H. Cao, C.R. Chen and H. Zhang,
Phys. Rev. Lett. 105, 181802 (2010) and Phys. Lett B696, 68 (2011)

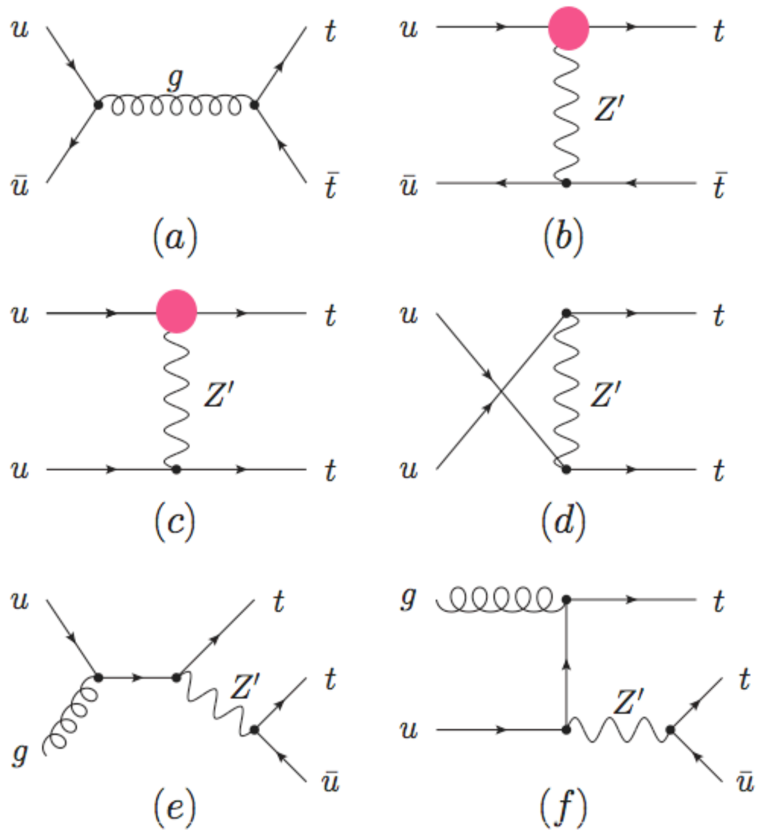
Top Quark Polarization as a Probe of Models with Extra Gauge Bosons was studied by E. Berger, Q.H. Cao, C.R. Chen and H. Zhang,
Phys. Rev. D83, 114026 (2011).

Non-universal FCNC Z-prime model

$$\mathcal{L} = g_W \bar{u}\gamma^\mu (f_L P_L + f_R P_R) t Z'_\mu + h.c.$$

Left-handed coupling is highly constrained by $B_d - \bar{B}_d$ mixing.





Use Tevatron A_{FB} data to determine right-handed FCNC coupling f_R (Berger et al)

Tevatron Constraints

★ Fit to the Tevatron data includes SM, New Physics (NP), and Interference terms (Berger et al).

★ The inclusive cross section for $t\bar{t}$ pair production has been measured accurately. Its agreement within errors with SM expectations limits f_R from above.

$$\sigma(t\bar{t}) = 7.50 \pm 0.48 \text{ pb}$$

★ The $t\bar{t}$ invariant mass spectrum, both normalization and shape, also imposes an upper bound on NP models.

★ Large A_{FB} observed for $m_{t\bar{t}} \geq 450 \text{ GeV}$ limits f_R from below.

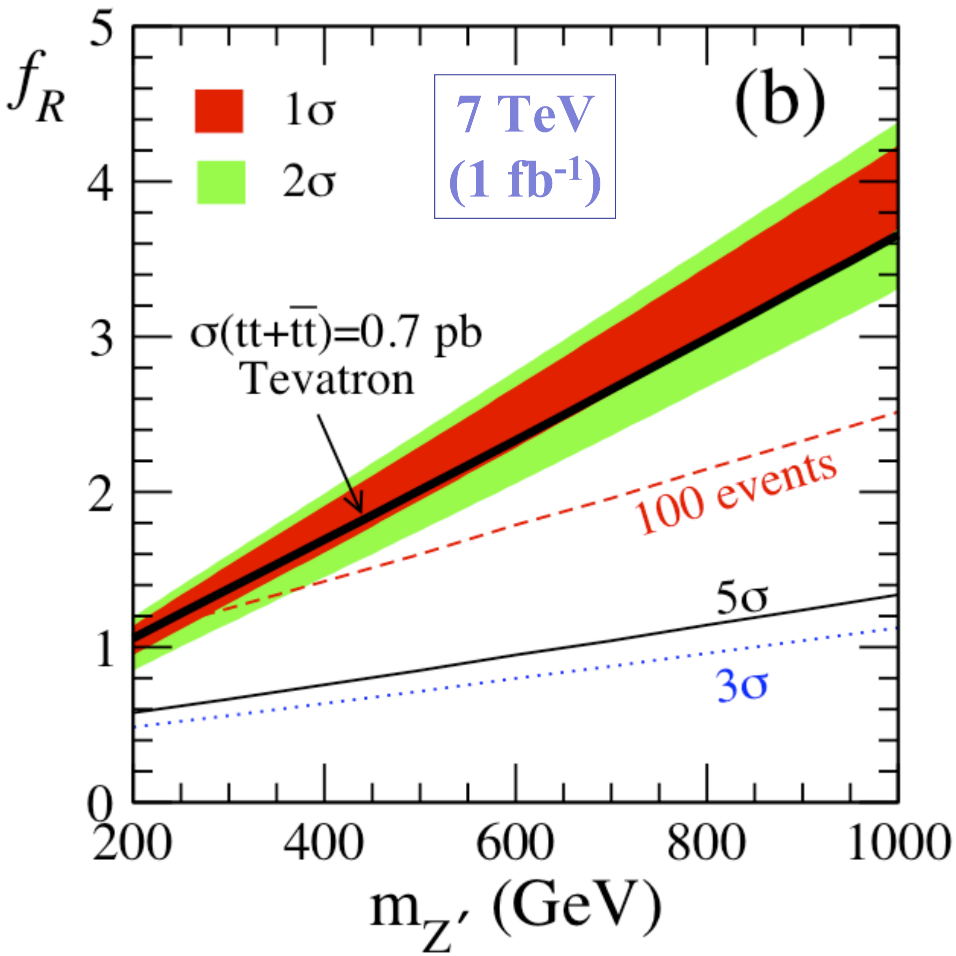
$$A_{\rm FB} = 0.475 \pm 0.114$$

★ The negative search for same-sign top quark pair at Tevatron also limits the NP parameter space -- eliminates part of the otherwise allowed region.

$$\sigma(tt + \overline{tt}) < 0.7 \text{ pb}$$

Same-sign top pair production

Flavor Changing Z' Model -- LHC Predictions *(Berger et al)*



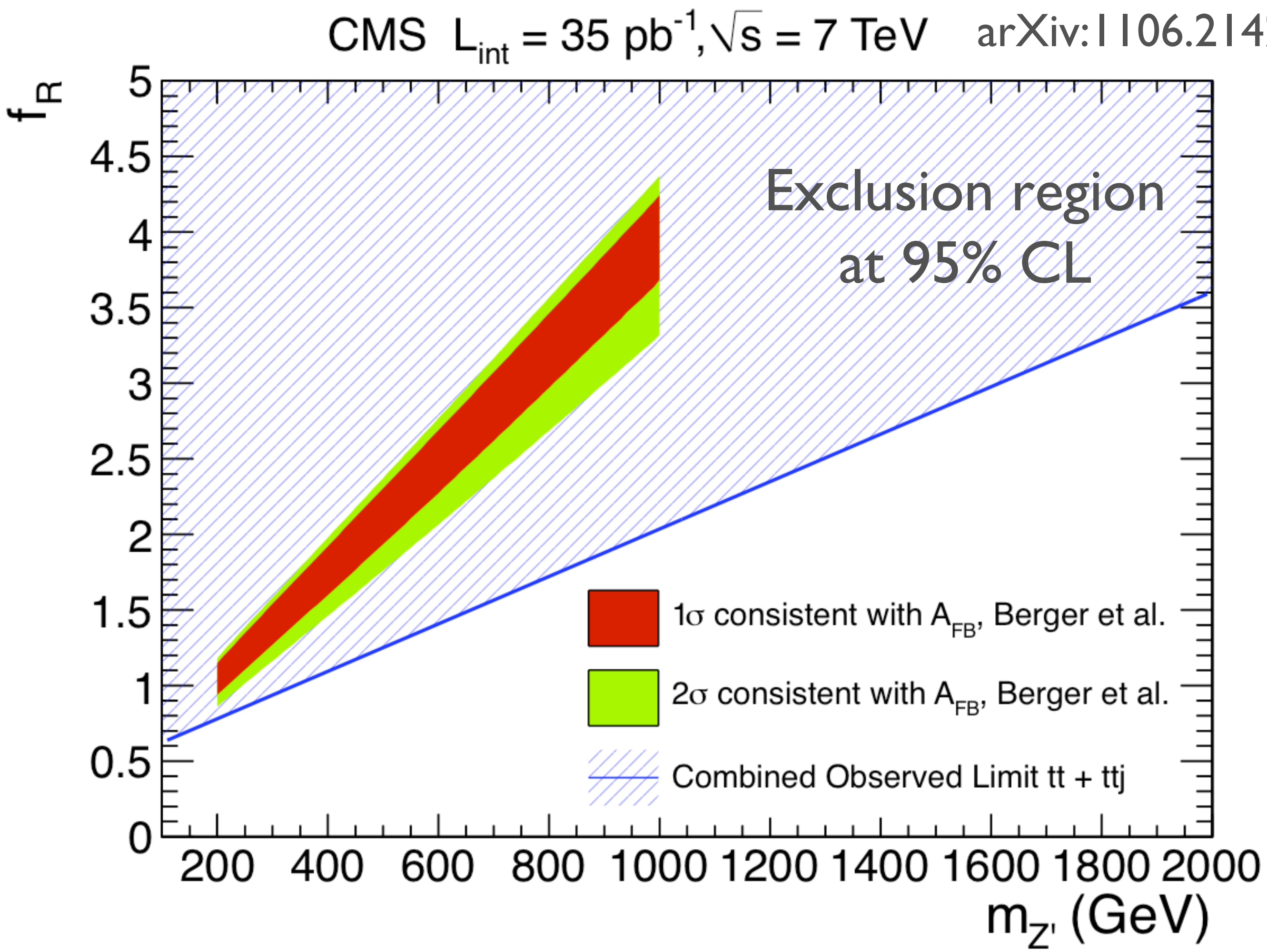
Bands show the 1 σ and 2 σ fits to the Tevatron $t\bar{t}$ inclusive cross section and A_{FB} .

Parameter region of right-handed coupling f_R and Z' mass to fit Tevatron A_{FB} is above the LHC 5σ discovery curve.

LHC 7 TeV measurements would impose hard constraints on f_R . Search for same-sign top quark pairs is interesting in other model contexts also.

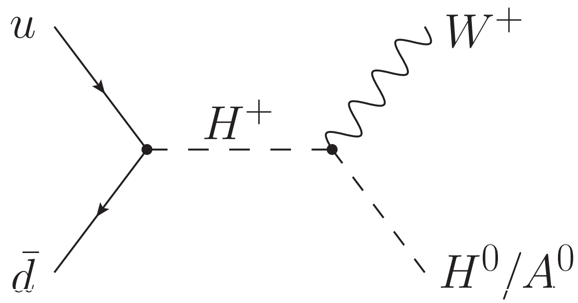
CMS Search for Same-sign top pairs

arXiv:1106.2142, June '11

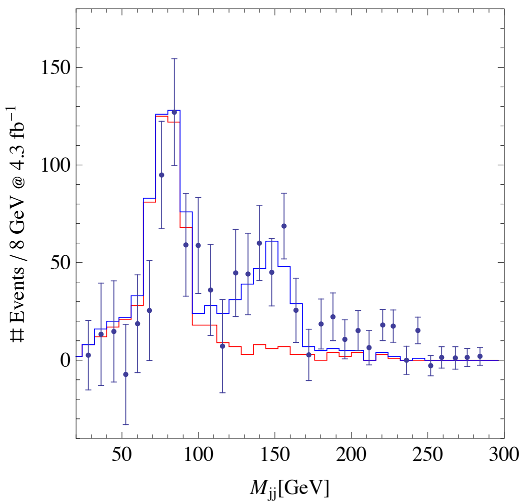


Z-prime exchange alone cannot explain Tevatron A_{FB}

W+ 2jets from a quasi-inert Higgs doublet



Production of Charged Higgs, decaying into neutral Higgs and W.



Consistent with precision measurements and flavor physics, as well as with photon/Z + 2jets constraints. Model consistent with D0 data at the 95 % C.L.

Q.H. Cao, M. Carena, S. Gori, A. Menon, P. Schwaller, L.T. Wang and C. Wagner,
arXiv:1104.4776, Phys. Rev. D in press.

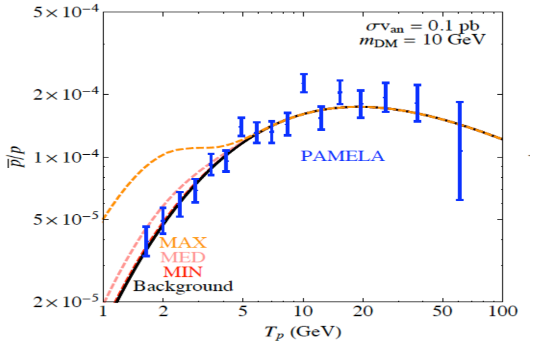
Dark Matter Identity

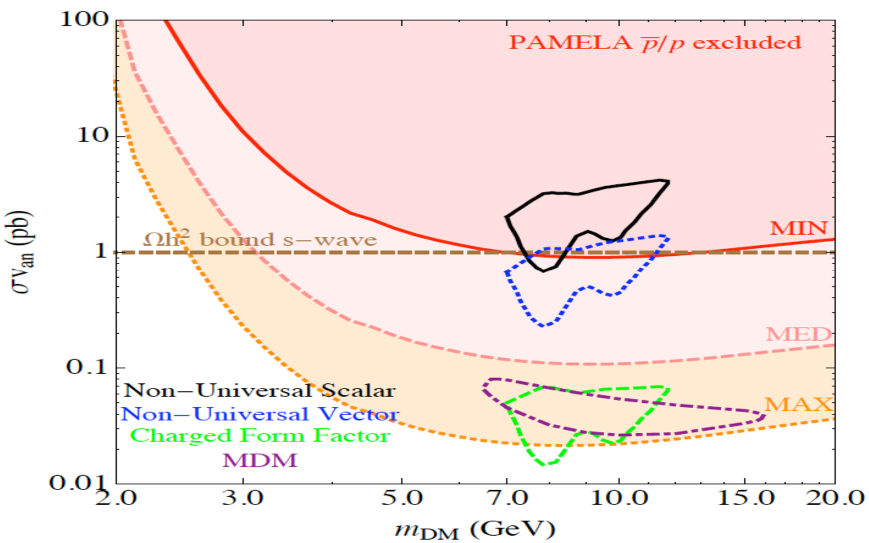
<u>what is the identity of the dark matter?</u> ---- a model independent study

- Direct detection relies on DM scattering off nuclei.

Crossing symmetry ---> DM annihilates into quarks, which is constrained by PAMELA measurements of anti-protons!

- Using effective operators, we study pbar/p constraints on DM interpretations of CoGeNT signals.





A light scalar DM interacting with SM through a Higgs portal is strongly disfavored by pbar/p measurement to be the source of CoGeNT signals!

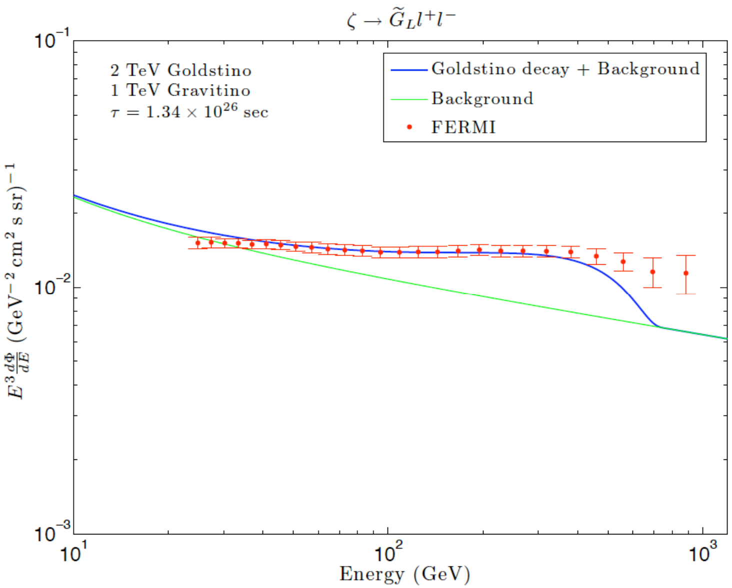
0912.4510, Cao, Low, and Shaughnessy;
1010.1774, Keung, Low, and Shaughnessy

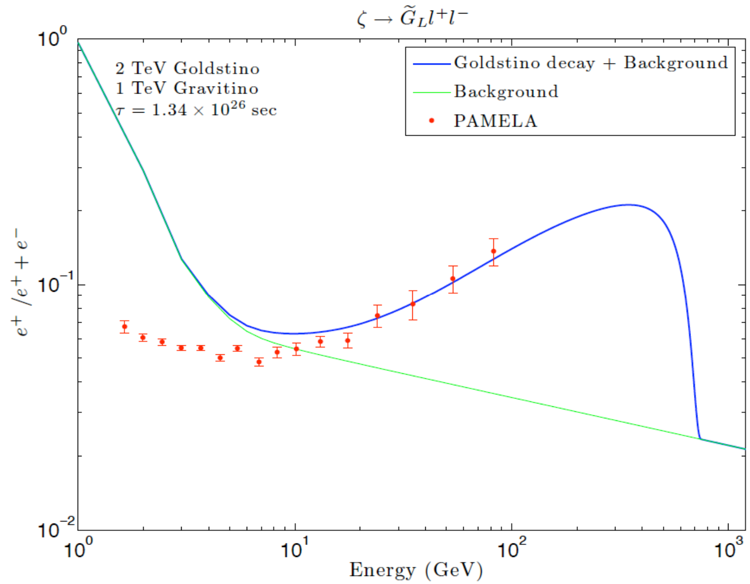
A model leading to an explanation of CoGeNT may be obtained in the NMSSM, with a mostly singlino dark matter, annihilating resonantly with mainly singlet CP-odd scalars,
Q.H. Cao, P. Draper, L.T. Wang, T. Liu, C.E.M. Wagner and H. Zhang, Phys.Rev.Lett.106:121805,2011

The identity of the dark matter: could it be decaying?

1012.5300:Cheng, Huang, Low, and Menon

- If the DM decays, we could be seeing its decay products!
- PAMELA sees excess in positron fraction while Fermi-LAT sees more e+e-.





It's difficult to reconcile both anomalies in conventional two-body decaying DM:

$$\mathrm{DM} \to \ell^+ \ell^- \quad \text{or} \quad \mathrm{DM} \to 2\phi \to (\ell^+\ell^-)(\ell^+\ell^-)$$

We proposed a new scenario for supersymmetric decaying DM, without R-parity violation, where the decay is three-body with a missing particle (LSP)

$$\zeta \to \widetilde{G}_L + \ell^+ + \ell^-$$

It turned out much easier to fit both PAMELA and Fermi in this scenario!

Renormalization Group allows the obtention of couplings and masses at high energies.
RG Invariants 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, P. Draper, N. Shah and C. Wagner, **Phys.Rev. D82 (2010) 075005**

Applications of RGI's

- 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 General Gauge Mediation, additional sum rules are established, plus a possibility of determining the messenger scale.

- For minimal models, several sum rules are established, that allow to establish 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 and C. Wagner,
Phys.Rev. D82 (2010) 075005, Phys. Rev. D83 (2011) 035014

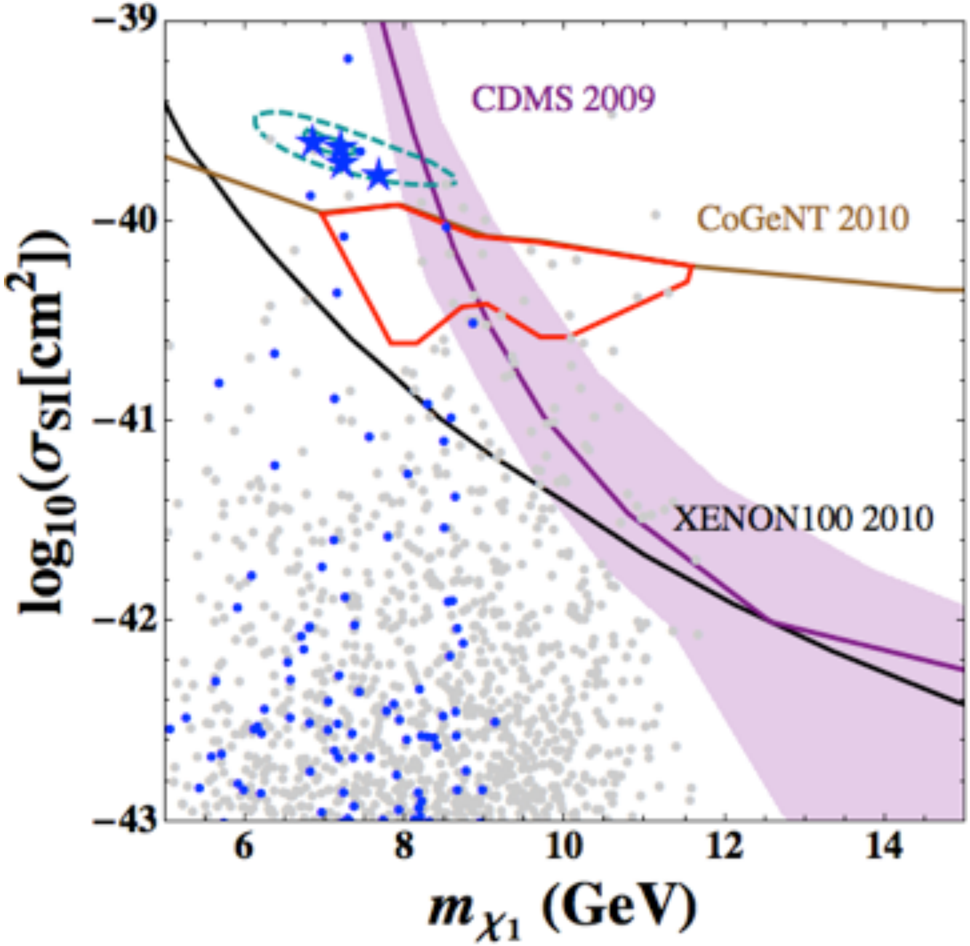
Summary

- Theory Group carries a Broad Research Program.
- Successful supervision of postdocs and students.
- Emphasis on the connection of Theory with Experiment.
- Group develops programs which are being used by the Tevatron and LHC experimental collaborations.
- Work on all aspects of Higgs and BSM physics, from QCD corrections, to properties, flavor physics, model building and collider phenomenology.

Postdocs

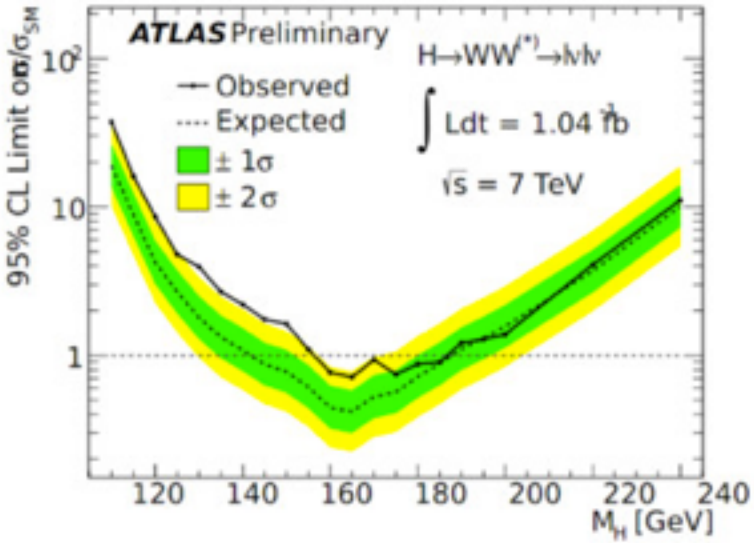
- The HEP Theory Group has been very successful in the supervision of postdocs.
- Most of the recent Argonne postdocs have found excellent positions and carried on successful careers after their stay at Argonne.
- Notable recent cases in last few years are Csaba Balazs, Ayres Freitas, Xavier Garcia i Tormo, Jay Hubisz, Chris Jackson, Pavel Nadolsky and Alexander Velytsky.
- Current postdocs, Q.H. Cao and G. Shaughnessy, departing this year, have already secured faculty and postdoc positions at Peking University and the Univ. of Wisconsin, Madison, to continue their high quality research activities.

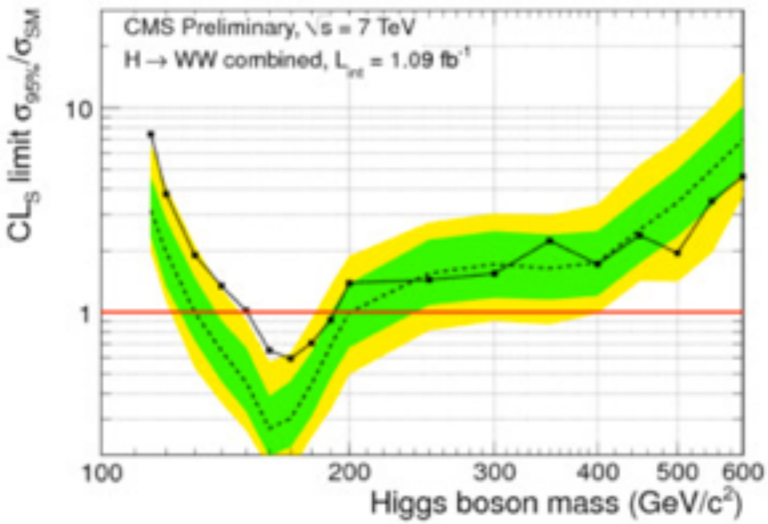
NMSSM near the PQ limit

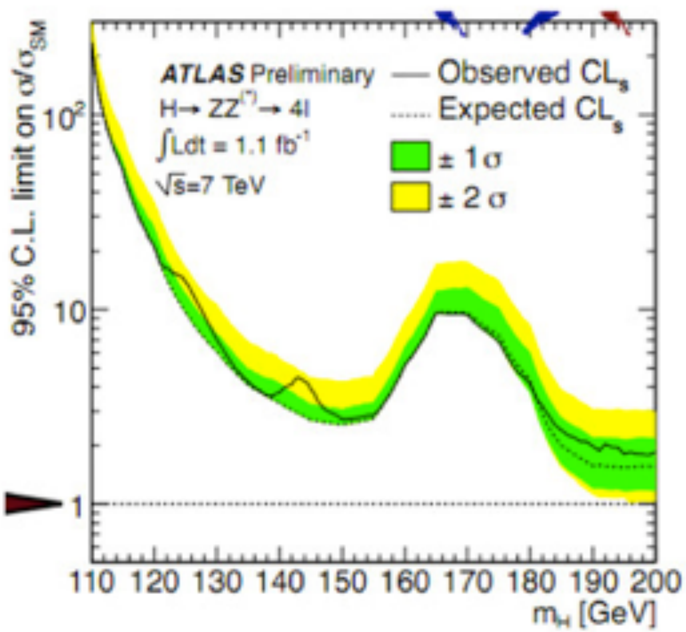


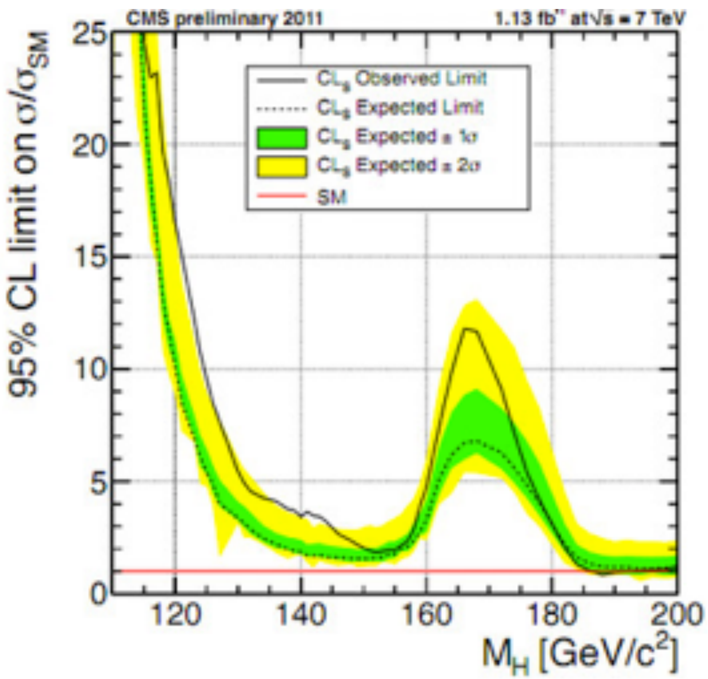
Direct dark matter detection cross section increases with lower values of the lightest CP-even Higgs mass

Q.H. Cao, P. Draper, T. Liu, C. Wagner, L.T. Wang'11


ATLAS Preliminary
H→WW(*)→lνlν
Observed
Expected
± 1σ
± 2σ
√s = 7 TeV
95% CL Limit σ/σSM
MH [GeV]


CMS Preliminary, √s = 7 TeV
H → WW combined, Lint = 1.09 fb-1
CLS limit σ95%/σSM
Higgs boson mass (GeV/c2)


ATLAS Preliminary
H→ ZZ(*)→ 4l
∫Ldt = 1.1 fb-1
√s=7 TeV
Observed CLs
Expected CLs
± 1σ
± 2 σ
95% C.L. limit on σ/σSM
mH [GeV]


CMS preliminary 2011
1.13 fb-1 at √s = 7 TeV
CLs Observed Limit
CLs Expected Limit
CLs Expected ± 1σ
CLs Expected ± 2σ
SM
95% CL limit on σ/σSM
MH [GeV/c2]