New Electroweak Physics at the LHC

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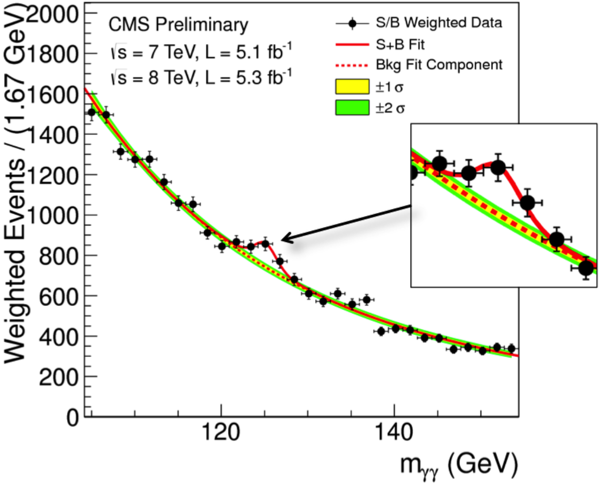
arXiv: 1203.2932, 1206.6888

STONY BROOK UNIVERSITY

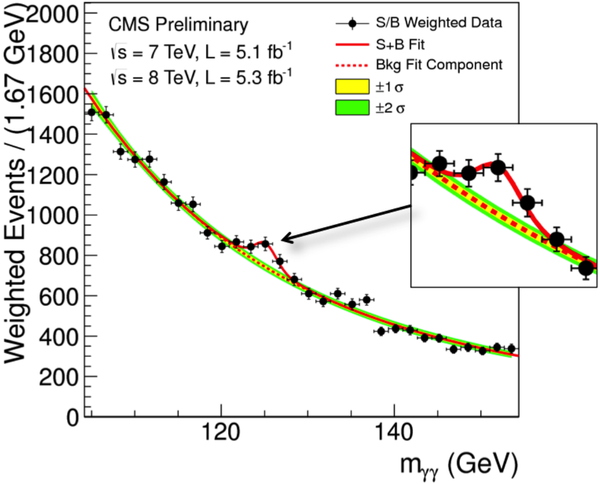
DESY Theory Seminar

July 10, 2012

Woot!


CMS Preliminary
√s = 7 TeV, L = 5.1 fb-1
√s = 8 TeV, L = 5.3 fb-1
S/B Weighted Data
S+B Fit
Bkg Fit Component
±1 σ
±2 σ
Weighted Events / (1.67 GeV)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
120
140
mγγ (GeV)

Woot!



Where's the rest?

Where is the New Physics?

- The 125 GeV Higgs is the only sign of “new” physics at the LHC so far.
- The LHC is very good at producing strong particles.
  - $\Rightarrow$ limits rising to TeV & beyond on strong BSM physics.
  - $\Rightarrow$ maybe bad news for "natural" explanations of weak scale like SUSY (though not a killing blow yet).
- Limits on new electroweak physics much lower.
  - $\rightarrow$ could still expect to find new $\mathcal{O}(100\,\mathrm{GeV})$ particles!

$\Rightarrow$ **What can we say about the BSM EW sector?**

1. Higgs physics already constrains **Electroweak Baryogenesis**.
2. **Charginos** could be hiding in plain sight!

Excluding
Electroweak Baryogenesis
in the MSSM

Electroweak Baryogenesis

$$\eta \;=\; \frac{n_B - n_{\bar{B}}}{n_\gamma} \;\approx\; 6 \times 10^{-10} \qquad \neq \qquad 0$$

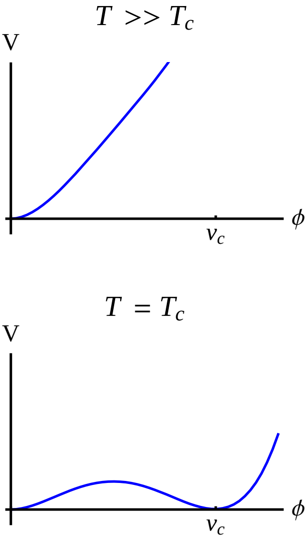
- Have to satisfy *Sakharov conditions* to generate Baryon Asymmety in the early universe (BAU):

  1. $\not{B}$ 2. $\not{C}$, $\not{CP}$ 3. $\not{T}$

- Electroweak Baryogenesis (EWBG) uses weak-scale physics to fulfill these conditions. → **We can test this at the LHC.**
  - Sphelaron transitions violate Baryon number
  - The electroweak phase transition could provide departure from thermal equilibrium.
  - The MSSM contains fermions [EWinos] with $\not{CP}$ higgs couplings.

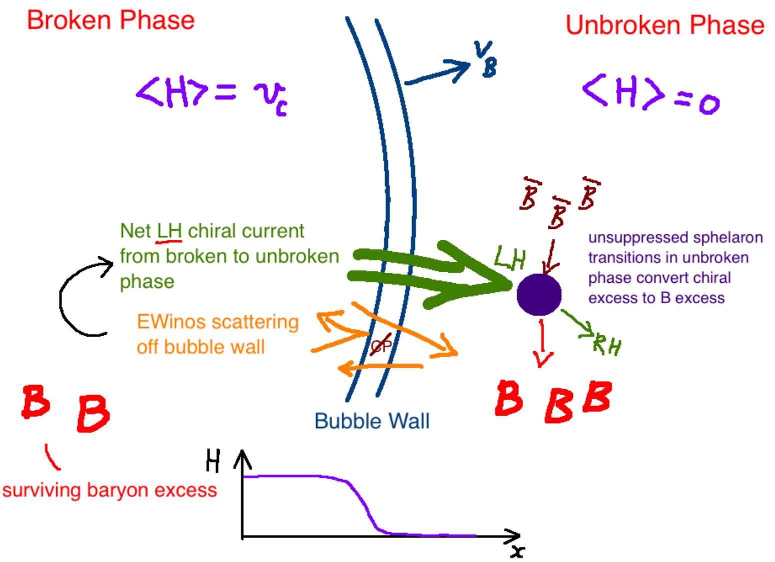
Huge literature: see paper for many references.

Thermal Higgs Potential



$T_c \sim 100\,\mathrm{GeV}$

Generating Baryon Number



Calculating BAU

The calculation of the generated BAU approximately factorizes:

1. Generating BAU during the (presumed strong) phase transition.
   - Extremely complicated tunneling, quantum transport and hydrodynamics calculation.
   - The theoretical uncertainties are still $\mathcal{O}(100\%)$, but it looks like sufficient BAU can be generated for appropriate choices of $(M_1, M_2, \mu, \tan\beta, m_A)$.
2. Ensuring a sufficiently strong first order phase transition . Suppression of sphelaron effects in broken phase requires

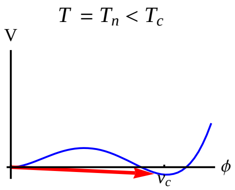
$$v_c/T_c \gtrsim 1.$$

   - Depends mostly on **bosons coupled to higgs** (e.g. stops).
   - Difficult but possible in MSSM. **Strongest constraint.**

How to get a strong phase transition?

One-loop picture gives good intiution:

- Need a cubic term H^3 in higgs potential to get an energy barrier.



→ Purely thermal contribution from bosons: $\delta V \propto T\, m_i(H)^3$

- SM: W, Z contributions not strong enough.
- MSSM: stops can enhance phase transition!
  - $m^2_{U_3} \approx -\Pi_{\tilde{t}_R}$ to get $\delta V \sim T(y_t H)^3 \Rightarrow$ light RH stop.
  - LH stop heavy (higgs mass, ρ parameter)

"Light Stop Scenario" [LSS] can give EWBG in MSSM!

(Two-loop and non-perturbative effects are sizable and enhance the PT.)

LSS before 125 GeV Higgs

Constraints on stop sector:

- Strong phase transition without color breaking requires light mostly RH stop: $m_{\tilde{t}_R} < m_t$, $A_t \lesssim m_Q/2$.
- Avoiding large ρ-corrections and LEP higgs mass bound requires mostly LH stop heavier than $\sim$ TeV.

Other constraints:

- Gluino heavier than $\sim 500\,\mathrm{GeV}$ to decouple from plasma.
- M_1 or $M_2 \sim \mu \sim \mathcal{O}(100\,\mathrm{GeV})$ with sufficiently large $\not{C}\not{P}$ phases in the EWino sector. $\tan\beta \lesssim 15$. [BAU creation]
- 1^{st}, 2^{nd} generation sfermions $\gtrsim 10\,\mathrm{TeV}$. [1-loop EDMs]
- $m_A \gtrsim$ TeV [2-loop EDMs] unless $\not{C}\not{P}$-phases pushed into M_1 (*Bino-Driven EWBG*: Li, Profumo, Ramsey-Musolf)

LSS with 125 GeV Higgs

- Higgs above LEP bound is difficult within MSSM EWBG.
- Carena, Nardini, Quiros, Wagner (0809.3760) extensively investigated the EWBG window of the MSSM.
  - Require strong phase transition, no color breaking.
  - LSS EFT includes most important 1- and 2-loop effects.

  $\Rightarrow$ *Optimistically*, $m_h \approx 125\,\mathrm{GeV}$ requires

  $m_{\tilde{t}_R} = 80 - 115\,\mathrm{GeV}$, $m_{\tilde{t}_L} \gtrsim 10^3\,\mathrm{TeV}$, $\tan\beta \approx 5 - 15$

- Very strange! Conflict with naturalness. How to get such a spectrum?
- $\sim 100\,\mathrm{GeV}$ stop is an interesting prediction of MSSM EWBG, but could be hidden somehow (e.g. displaced vertex decay).

Can we exclude the LSS using higgs data only?

Fingerprint of EWBG

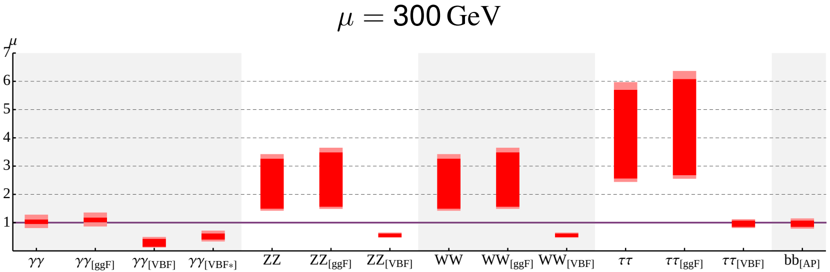
- Compared to SM, non-decoupling effects can change higgs couplings (in Bino-mediated EWBG).
- Additional particles can change loop-induced couplings to gluons and photons.
- Most important effects are from light RH stop:
  - hgg coupling can be enhanced $\gtrsim 3\times$ due to constructive interference between stop and top.
  - $h\gamma\gamma$ coupling suppressed $\sim \frac{1}{2}\times$ due to destructive stop interference with dominant W contribution.

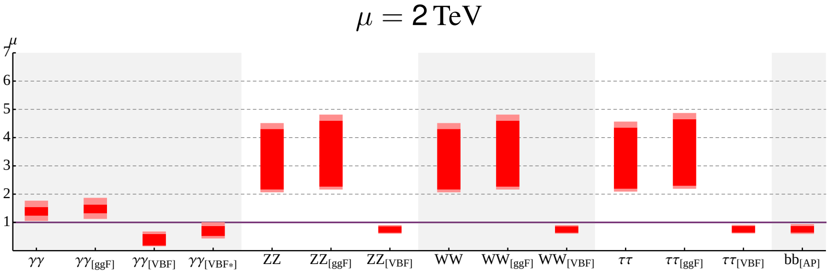
$\Rightarrow$ Hence expect

- $h \to \gamma\gamma$ via VBF suppressed.
- Inclusive $h \to \gamma\gamma$ moderately enhanced.
- All other inclusive signal strengths strongly enhanced.

(See e.g. Djouadi hep-ph/0503173)

Fingerprint of EWBG

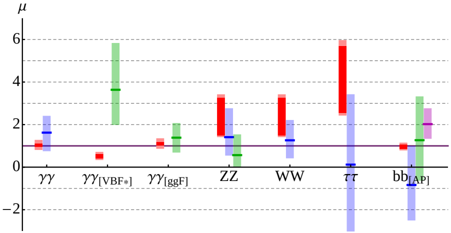




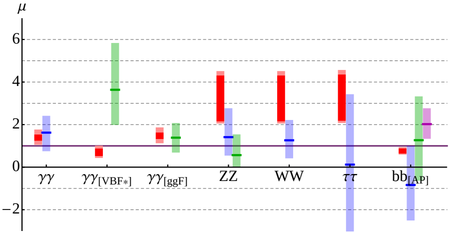
Compare to 2011 Higgs Data

Compare EWBG prediction to ATLAS, CMS and Tevatron data:

$\mu = 300\,\mathrm{GeV}$



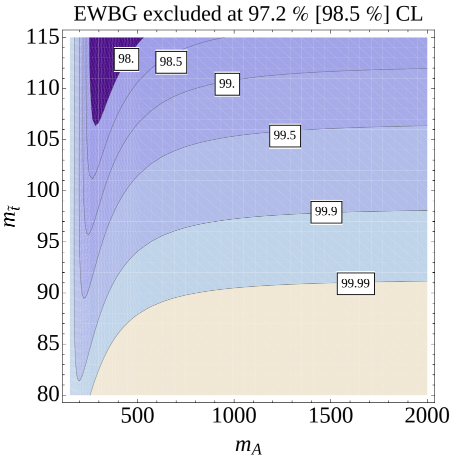
$\mu = 2\,\mathrm{TeV}$



Significant tension, especially in diphoton VBF channel.

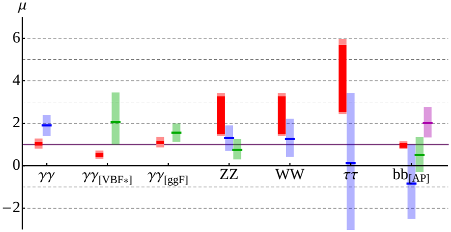
Compare to 2011 Higgs Data

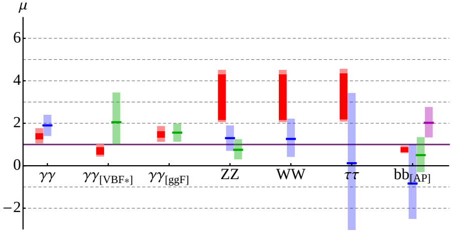
$m_h = 125\,\text{GeV}$



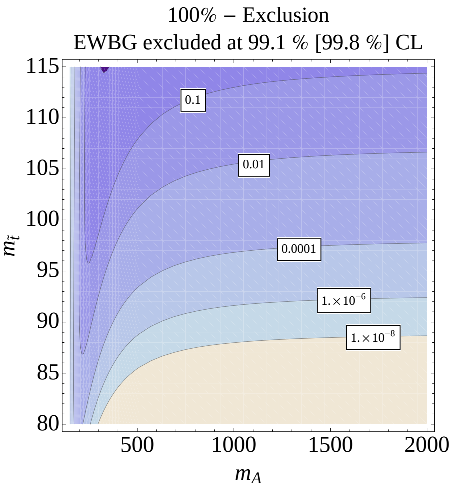
EWBG in MSSM excluded at 90%+ CL in $m_h \in (123, 128)\,\text{GeV}$ range.

Jul 4 2012 Update





Jul 4 2012 Update



EWBG in MSSM is now excluded at 99+% CL

Upshot

- **EWBG in MSSM is thoroughly excluded!**
- Higgs results are likely to exclude EWBG in many other BSM models (e.g. Cohen, Morrissey, Pierce ’12).
- One could imagine “stealth-EWBG” scenarios using singlets (e.g. Ashoorioon, Konstandin ’09), but testability was one of the nicest things about EWBG. . .

Let’s look at something that’s more likely to exist…

W-partners (Charginos?) Hiding in *WW*

Let's look at something that's more likely to exist…

W-partners (Charginos?) Hiding in WW

Please forgive chronological order,

experimental updates almost too fast to keep up…

WW Cross Section Measurement

ATLAS and CMS [1] measured *WW* production cross section $\sigma_{WW}^{\mathrm{tot}}$ with $\approx 5\ \mathrm{fb}^{-1}$ of data in the fully leptonic final state.

	measured (pb)	SM expectation
ATLAS	$53.4 \pm 2.1(\mathrm{stat}) \pm 4.5(\mathrm{syst}) \pm 2.1(\mathrm{lumi})$	45.1 ± 2.8
CMS	$52.4 \pm 2.0(\mathrm{stat}) \pm 4.5(\mathrm{syst}) \pm 1.2(\mathrm{lumi})$	47.0 ± 2.0

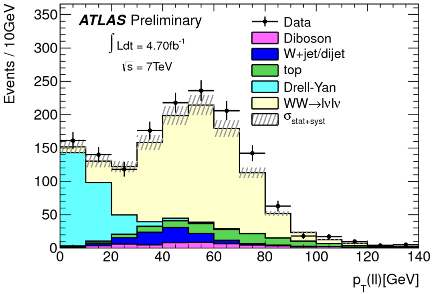
These measurements are extremely consistent with each other, and they are higher than SM prediction by $\sim 1.5\sigma$.

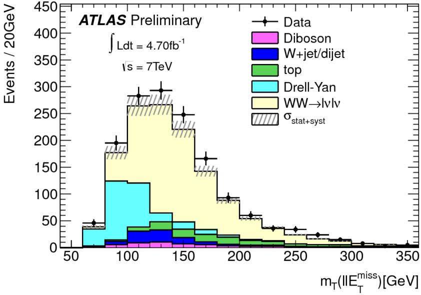
The shape of differential distributions seems slightly off as well.

[1] ATLAS-CONF-2012-025, CMS PAS SMP-12-005

WW Cross Section Measurement

ATLAS (CMS is similar):





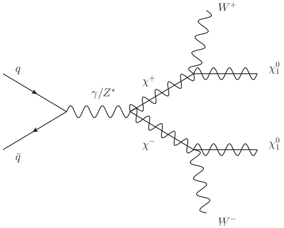
Most likely (conservative) explanation:
some issue with NLO BG calculation.

But it could be an early sign of new EW physics!
Indeed, something like this is expected in many scenarios

Wino-like Charginos?

- $\sigma(pp \to \tilde{\chi}_1^+ \chi_1^-)$ roughly right if $\tilde{\chi}_1^\pm$ is not much heavier than W.

- Decay & kinematics should be W-like since we do *not* want hard tails in the distributions, just some enhancement at moderate $\not{E}_T, p_T$.
  - $\rightarrow$ mass gap should be $\sim 100\,\mathrm{GeV}$.
  - $\rightarrow$ no sleptons with $m_{\tilde{\ell}} < m_{\tilde{\chi}_1^\pm}$



- Hence has to decay into something light: bino-like neutralino (gravity mediation) or gravitino (GMSB).

- This is obviously not a new idea...

Is this trivially excluded?

- Solid chargino mass bound from LEP: $m_{\tilde{\chi}_1^\pm} \gtrsim 100\,\mathrm{GeV}$. OK!
- ATLAS & CMS multi-lepton searches: possible constraints, but bounds still weak.
- What about the light particle $\tilde{\chi}_1^\pm$ decays to?

  $\rightarrow$ gravity mediation: even massless neutralinos are still **OK!** [Dreiner et. al '09]. Prior bounds assume gaugino mass unification.

  We are more interested in this scenario as a simplified model.

  $\rightarrow$ GMSB: Have to be careful to avoid **photon constraints.**

Photon Constraints on GMSB Scenarios

In gauge mediation, the NLSP decays to its superpartner and a (practically massless) gravitino.

- **Bino NLSP:** $\tilde{\chi}_1^0 \to \gamma \tilde{G}$ gives striking photon signals.

  CMS $\gamma\gamma$ + MET + jet search rules out chargino pair production* and decay to neutralinos for $m_{\tilde{\chi}_1^\pm} \lesssim 450\,\mathrm{GeV}$. **NOPE!**

- **Wino co-NLSP:** for $M_1 > M_2 > m_{\tilde{G}}$, the chargino $\tilde{\chi}_1^\pm$ decays directly to $W + \tilde{G}$, since an accidental cancellation makes the mass gap to χ_0^1 very small.

  The Wino NLSP $\tilde{\chi}_1^0$ decays to $Z/\gamma + \tilde{G}$, so $\chi_1^0 \chi_1^\pm$ associated production yields at most one photon.

  Tevatron $\gamma + \ell + \not{E}_T$ search rules* out $m_{\tilde{\chi}_1^\pm} < 135\,\mathrm{GeV}$. **OK!**

- **Chargino NLSP**†**:** narrow region of parameter space where charged higgsino is NLSP, and Higgsino-rich $\tilde{\chi}_1^0$ decays to $\chi_1^\pm$ via off-shell $W^\pm$, so $\chi_1^0 \chi_1^\pm$ production yields no photons but enriches $\chi_1^\pm \chi^+$ final state: **No additional $m_{\tilde{\chi}_1^\pm}$ constraints from photons, but interesting leptonic signatures.**

*Kats, Meade, Reece, Shih ’11 †Kribs, Martin, Roy ’09

Example Scenario

- Simplified model from pMSSM (gravity mediation):
  - $m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_2^0} \approx 115\,\mathrm{GeV}$
  - $m_{\tilde{\chi}_1^0} \approx 20\,\mathrm{GeV}$.
  - $m_{\tilde{f}}, \ \mu > 1\,\mathrm{TeV}$
- **MC Info:**
  - Calculate spectrum & NLO production cross section in `SuSpect` & `Prospino`.
  - Generate & shower $pp \to \tilde{\chi}_1^+ \chi_1^- \to W^+ W^- \tilde{\chi}_1^0 \tilde{\chi}_1^0 \to \ell\ell + \mathrm{MET}$ events in Pythia 8, interfaced with Pythia 6.4 for hard process.
  - Perform toy-version of ATLAS & CMS *WW*-analyses in `FastJet`-based program with simple detector simulation.

Add chargino contribution to ATLAS & CMS background predictions and see whether agreement with data improves.

$m_{\tilde{\chi}_1^\pm} = 115\,\mathrm{GeV} \qquad m_{\tilde{\chi}_1^0} = 20\,\mathrm{GeV}$

$\sigma(pp \to \chi_1^+\chi_1^- \to \chi_1^0\chi_1^0\ W^+W^-)$ = 2430. fb,
$\sigma \times \mathrm{Br}(W \to e/\mu/\tau + \nu)^2$ = 257.776 fb (K-factor = 1.29255).
With 4.7 fb^{-1} of data we expect ~1212 events.

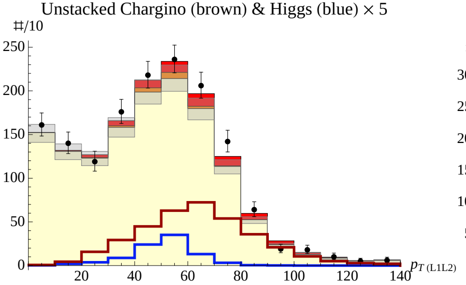
Cut Efficiencies (ATLAS_WW_5ifb)

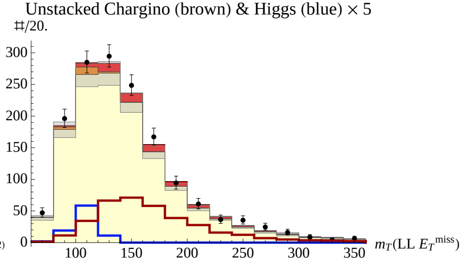
Cut Description	N_{SIM}	%	N_{exp}
before any cuts	60 000	100.	1211.55
PASSING ANY OF THE LEPTON TRIGGERS	39 494	65.8233	797.479
exactly two leptons	13 309	22.1817	268.741
pass jet veto	9010	15.0167	181.934
opposite sign leptons	9010	15.0167	181.934
pass pT_LL > 25, 20 cut	6877	11.4617	138.863
pass mLL cut (mLL > 15 && |mLL - mZ| > 15 for ee/mumu, mLL > 10 for emu)	5990	9.98333	120.953
pass ETmissREL > 50 GeV cut (25 for emu)	3622	6.03667	73.1369

- $\sigma_{\tilde{\chi}_1^+\tilde{\chi}_1^-} = 2.4$ pb.
- About 6% of leptonic decays ($\sim$ 70 events) pass cuts of the ATLAS /CMS *WW* cross section measurement analyses.

$m_{\tilde{\chi}_1^\pm} = 115\,\text{GeV} \qquad m_{\tilde{\chi}_1^0} = 20\,\text{GeV}$

Using ATLAS analysis (CMS is similar):





- In all 6 kinematic distributions, $\chi^2/N_{dof} \approx 1$ for SM alone and $\chi^2/N_{dof} \approx 0.5$ for SM + charginos.
- By eye we can see that bins that were deficient are preferentially filled by the chargino contribution, while bins that worked well aren't changed much.

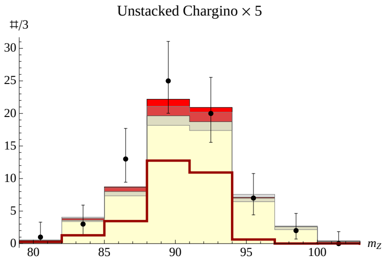
Would this signal appear elsewhere?

- WZ cross section measurement.
- $h \to WW$ searches use data-driven WW BG estimation. Charginos could contaminate both signal and control regions, with different results. [see Feigl, Rzehak, Zeppenfeld '12]
- ATLAS/CMS multi-lepton searches

We have to understand the effect on each channel, and make sure our scenario is not already excluded.

WZ Cross Section Measurement

- Done by ATLAS and CMS for 1 fb^{-1} datasets.
- New contributions can help here as well, but there is not enough statistics for it to really matter yet.
- Example using ATLAS analysis:



- GMSB scenarios would have smaller contributions in this channel than the gravity-mediated example shown here.

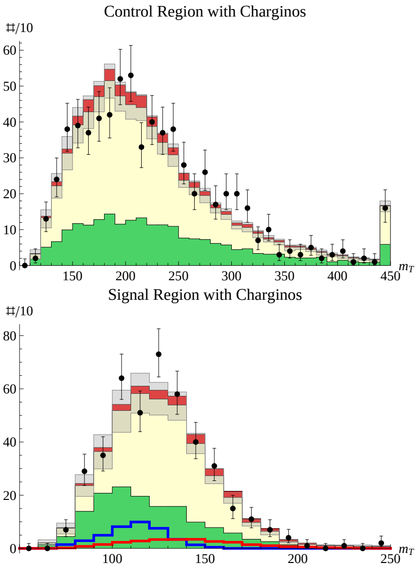
$h \to WW$ Searches

- It is known that Charginos can show up in Higgs searches. For example:
  - Lisanti, Weiner ('11) explored the ability of such searches to find charginos in their signal region.
  - Feigl, Rzehak, Zeppenfeld ('11, '12) demonstrate that these searches might miss a higgs in the signal region if charginos contaminate the *WW* control region.
- We examined the effects of our scenario in detail using the ATLAS $h \to WW$ analysis.

$\to$ Contamination is not as big an issue for us, but it might reduce signal sensitivity. Under Investigation.

  - charginos decay via *W*'s, no sleptons to boost leptonic decay fraction. $\to$ smaller contamination.
  - Both signal and control regions get roughly equal contributions that are $\sim$ 10% of and similar in shape to the *WW* contribution.

Example: ATLAS $h \to WW$ 0j channel



Trilepton Searches

- The most constraining LHC bound on charginos comes from CMS 5 fb^{-1} multi-lepton search[2] which is sensitive to $pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \to 3\ell + \mathrm{MET}$
- They define many signal regions differentiated by $\not{E}_T$, H_T and character of the lepton triplet (no OSSF, OSSF w/o Z, OSSF Z).

For $m_{\tilde{\chi}_1^\pm} = 115\,\mathrm{GeV}$, $m_{\tilde{\chi}_1^0} = 20\,\mathrm{GeV}$ Scenario:

Signal Region	$N_{\chi_2^0 \chi_1^\pm}$	N_{data}	N_{BG}
$\not{E}_T > 50, H_T > 200,\ \ Z$	1.4	20	18.9 ± 6.4
$\not{E}_T > 50, H_T < 200,\ \mathrm{no}\ Z$	**5.3**	**30**	**27.0 ± 7.6**
$\not{E}_T > 50, H_T < 200,\ \ Z$	**44**	**141**	**134 ± 50**
$\not{E}_T < 50, H_T < 200,\ \mathrm{no}\ Z$	5.4	123	144 ± 36
$\not{E}_T < 50, H_T < 200,\ \ Z$	52.	657	764 ± 183

Not excluded, but might be visible soon!

[2] arXiv:1204.5341

Other Constraints

Dark Matter

- Gauge mediation doesn't have a natural DM candidate.
  ⇒ needs extensions or non-standard cosmologies.
- Light Bino LSP in gravity-mediated case would overclose the universe if we want on-shell W, Z in EWino decay to avoid CMS trilepton bounds.
  - Light sleptons can increase annihilation, but not enough.
  - Increasing higgsino fraction also increases annihilation, but reduced production cross section means charginos no longer explain WW-excess

  ⇒ needs non-thermal production, or RPV.

Other Constraints

Higs Phenomenology

- Charginos can in principle increase $h\gamma\gamma$ effective coupling by $\sim 30\%$.
  - This only works for low $\tan\beta$ and maximal chargino mixing. $\rightarrow$ chargino production cross section too small to explain *WW*-excess.
  - $\mathrm{Br}(h \rightarrow \chi_1^0 \chi_1^0)$ is enhanced, *reducing* $h \rightarrow \gamma\gamma$ rate.
- In our scenario, effect of charginos in higgs couplings is small.
- In the MSSM, non-decoupling effects or light stops would have to increase $h\gamma\gamma$.

Maybe consider vector-like W/Z-partners?

(Under investigation)

NEW DATA!

PRELIMINARY

Updates

- New ATLAS 5/fb trilepton search[1]
  - m_T^W cut makes it much more sensitive to $\chi_1^{\pm}\chi_i^0 \to W^{\pm}Z + \mathrm{MET}$
  - Excludes our previous example scenario!
  - Have to suppress trilepton signature.
  - → **GMSB with chargino NLSP!**
  - → Maybe: increase mass gap so $\chi_0^2 \to h\chi_0^1$ ($h \to b\bar{b}$ search?)
- New ATLAS 5/fb dilepton search[2]
  - SS lepton category is sensitive to $\chi_1^0\chi_1^+ \to W^{-\star}\chi_1^+\chi_1^+$
  - → **Constrains GMSB chargino NLSP scenario!**

[1] ATLAS-CONF-2012-077 [July 3]

[2] ATLAS-CONF-2012-076 [June 30]

GMSB with Chargino NLSP

- Can have a higgsino-rich chargino NLSP with few-GeV splitting to neutralino if $\tan\beta \sim 2$ and $M_2 \sim -\mu$.

$\Rightarrow$ $\chi^0_{1,2} \to \chi^\pm_1 W^\star$

  - No photon signal, since $\chi^\pm_1 \to W^\pm \tilde{G}$
  - Off-shell W produces extremely soft leptons or quarks, basically invisible.

  $\to$ **Invisible to trilepton searches!**

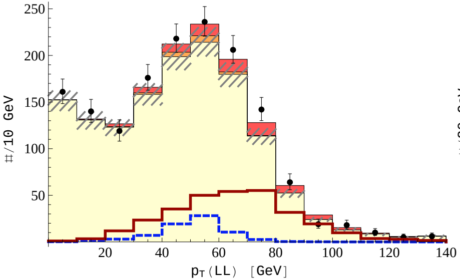
$\Rightarrow$ $\chi^0_{1,2}\chi^\pm_1$ contributes both to $\chi^\pm_1\chi^\pm_1$ and $\chi^\mp_1\chi^\pm_1$ final state.

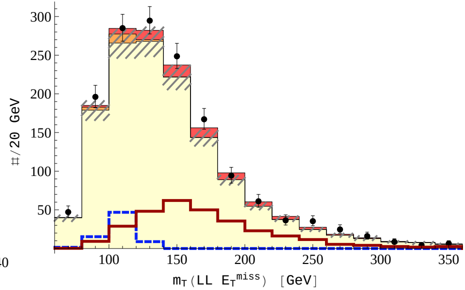
  - Effectively enhances OS chargino pair production cross section, mitigating reduction due to higgsino fraction.
  - Sensitive to some same-sign dilepton searches.

- Enhances $h \to \gamma\gamma$ by $\sim 25\%$.

GMSB with Chargino NLSP

Using ATLAS analysis (CMS is similar):





$$m_{\chi_1^\pm} \approx 110\,\text{GeV}, \qquad m_{\chi_1^0} \approx 113\,\text{GeV}, \qquad m_{\chi_2^0} \approx 131\,\text{GeV}$$

- $\chi_1^\pm \chi_1^\mp$, $\chi_{1,2}^0 \chi^\pm$ together contribute about 80 events to *WW* search. Even better than gravity-mediated example scenario!
- SS-dilepton search: Obs 9, Exp $11 \pm 1.5 \pm 3.9$, EWinos 2. **OK**

Conclusion

- With bounds on strongly produced BSM physics approaching TeV, New Physics might show up in EW sector first.
- **EWBG in the MSSM is dead!**
- *“You look but you do not see."*
  $\mathcal{O}(100\,\mathrm{GeV})$ Charginos might be right under our noses.
- Could be a background issue! Needs to be clarified.
- If the “excesses" in WW analyses are BSM physics, then it is already strongly constrained. **Will show up in other searches soon!**
- Vector-like W/Z partners are another intriguing possibility...