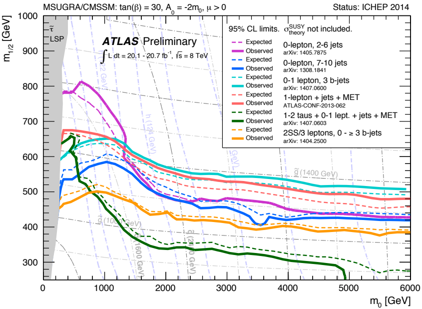
Towards explaining WW excess at the LHC

Krzysztof Rolbiecki
IFT UAM/CSIC Madrid

J.S. Kim, KR, K. Sakurai, J. Tattersall arXiv:1406.0858
KR and K. Sakurai, JHEP 1309 (2013) 004

Tons of exclusion limits from LHC



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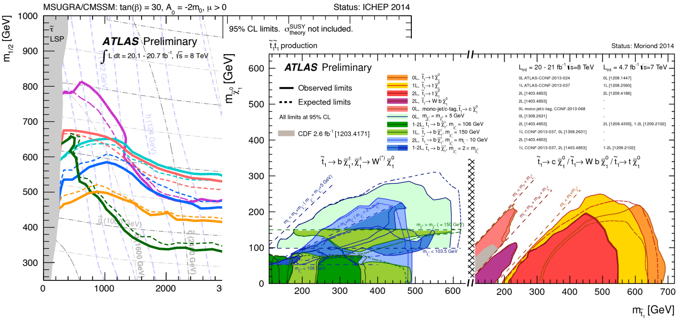

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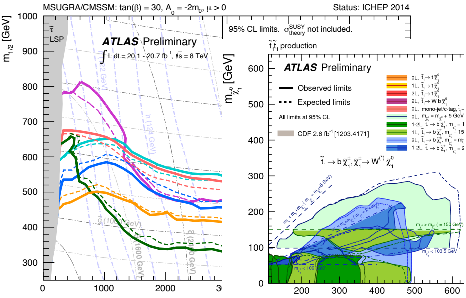

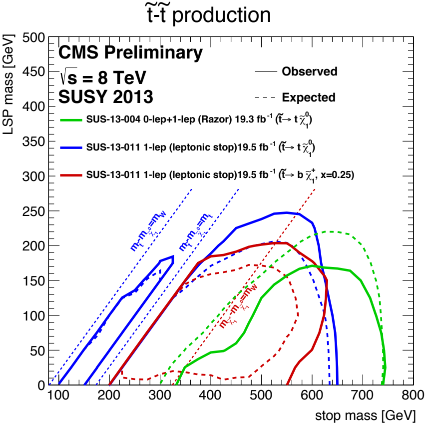

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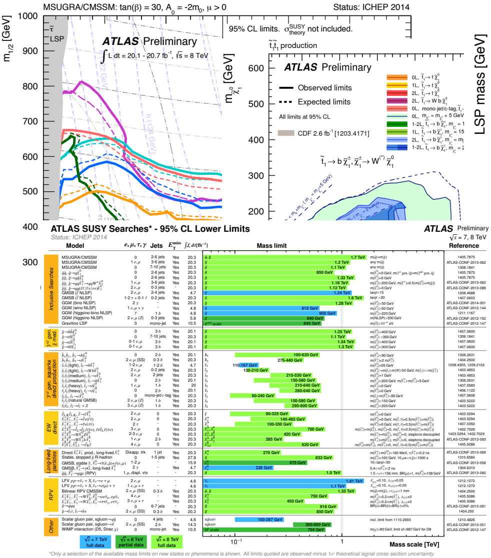

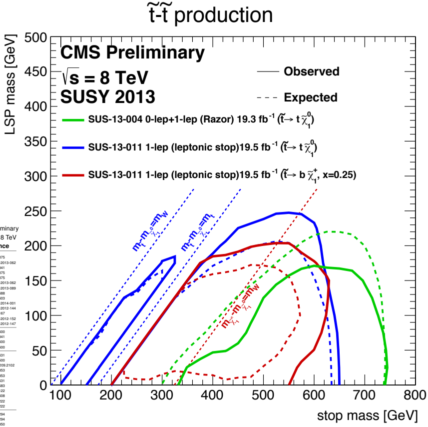

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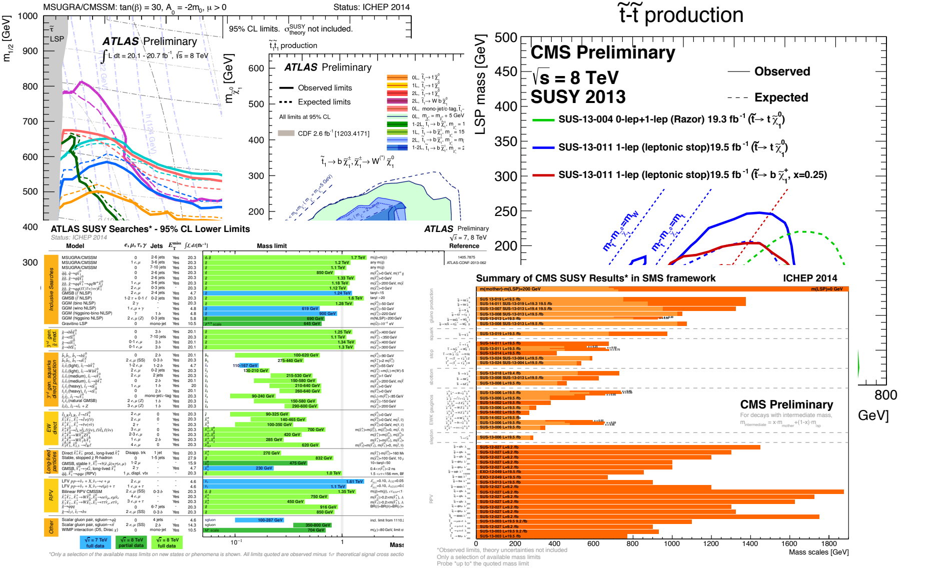
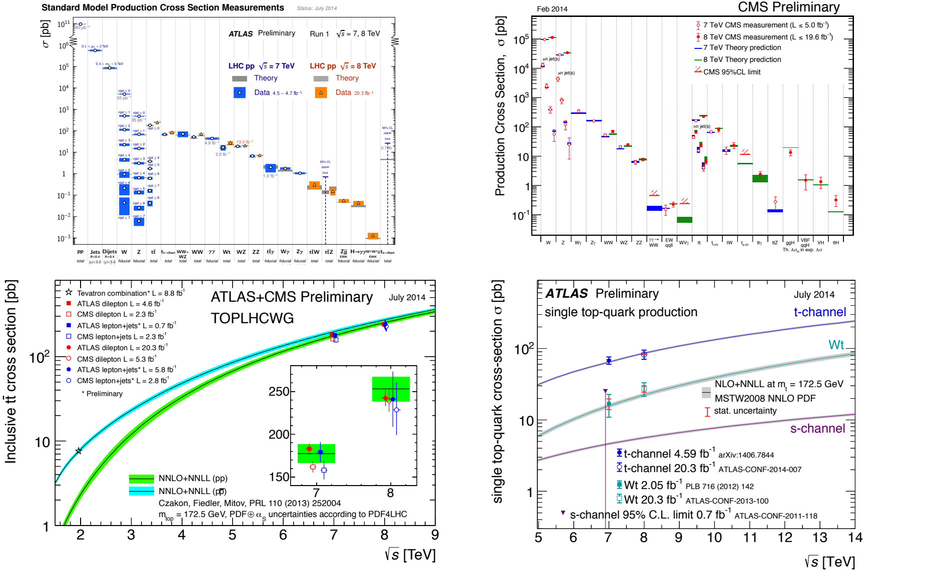
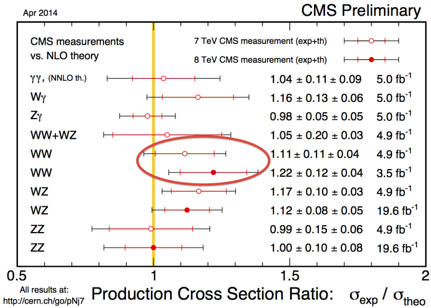


Good overall agreement of SM measurements



WW cross section at the LHC

- SM NLO prediction:
  $\sigma = {\color{red}46} \pm 2\ \text{pb}$ @ 7 TeV
  $\sigma = {\color{blue}57.3}^{+2.4}_{-1.6}\ \text{pb}$ @ 8 TeV
- ATLAS and CMS reported an excess in SM WW cross section measurements

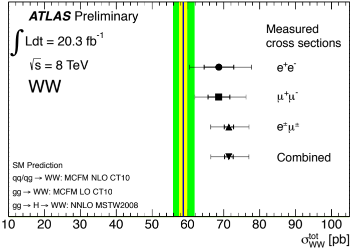


- 7 TeV, full data set:
  $\sigma = {\color{red}51.9} \pm 2.0\ (\text{stat}) \pm 3.9\ (\text{syst}) \pm 2.0\ (\text{lumi})\ \text{pb}$ ATL-2012-242
  $\sigma = {\color{red}52.4} \pm 2.0\ (\text{stat}) \pm 4.5\ (\text{syst}) \pm 1.2\ (\text{lumi})\ \text{pb}$ CMS-12-005
- 8 TeV, $\mathcal{L} = 3.54\ \text{fb}^{-1}$:
  $\sigma = {\color{blue}69.9} \pm 2.8\ (\text{stat}) \pm 5.6\ (\text{syst}) \pm 3.1\ (\text{lumi})\ \text{pb}$ arXiv:1301.4698

New from ICHEP

- full 8 TeV data set from ATLAS gives:
  $\sigma = 71.4 \pm 1.2\ (\mathrm{stat})^{+5.0}_{-4.4}\ (\mathrm{syst})^{+2.2}_{-2.1}\ (\mathrm{lumi})\ \mathrm{pb}$ ATL-2014-033
- theory prediction:
  $\sigma = 58.7^{+3.0}_{-2.7}\ \mathrm{pb}$
- with different contribution calculated at:
  $q\bar{q} \to WW$ NLO MCFM; $gg \to WW$ LO MCFM;
  $gg \to H \to WW$ NNLO+NNLL

- statistical error negligible
- consistent excess in all lepton channels
- the main systematic uncertainty originating from jet veto efficiency

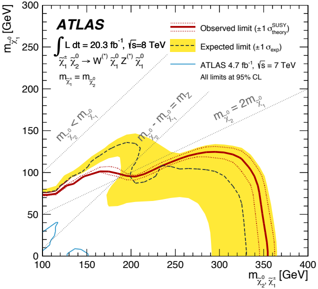


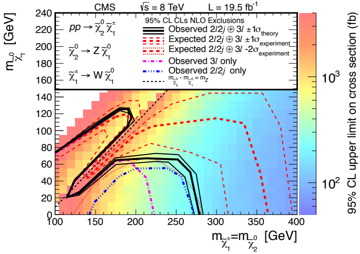
Slight excess in 3-lepton electroweakinos?

- constraints on chargino/neutralino parameter space are also becoming serious
- typically tri-lepton channel most constraining

$$pp \to \tilde{\chi}_1^{\pm}\,\tilde{\chi}_2^0 \to \ell'^{\pm}\tilde{\chi}_1^0 \ell^+\ell^-\tilde{\chi}_1^0$$

- still some parameter space allowed around $m_{\tilde{\chi}_1^{\pm}} \sim 200\ \mathrm{GeV}$
- the final word at $\sqrt{s} = 8\ \mathrm{TeV}$ but will be significantly improved at $14\ \mathrm{TeV}$
- the bounds can be relaxed if e.g. BR$(\tilde{\chi}_2^0 \to h^{(*)}\tilde{\chi}_1^0)$ significant





Outline

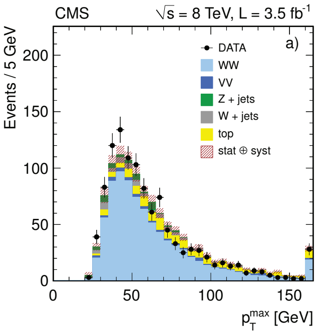
Outline

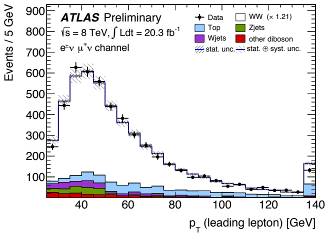
WW cross section measurements

- looking for

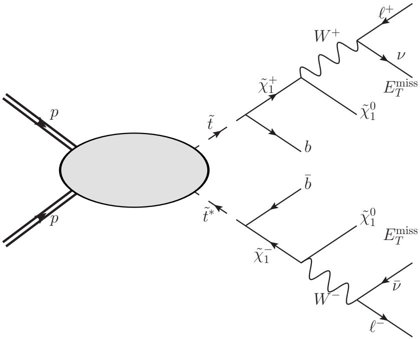
$$pp \to W^+W^- \to \ell^+\nu\ell'^-\nu$$

- final state: two opposite-sign leptons and missing energy
- basic selection:
  - $\Rightarrow$ jet veto to suppress $t\bar{t}$
  - $\Rightarrow$ lepton $p_T \gtrsim 20$ GeV
  - $\Rightarrow$ projected $E_T^{\text{miss}} \gtrsim 40$ GeV (depends on channel) to suppress Drell-Yan
  - $\Rightarrow$ Z veto for same flavor states
- main backgrounds:
  - $\Rightarrow$ top
  - $\Rightarrow$ Drell-Yan
  - $\Rightarrow$ W+jets
  - $\Rightarrow$ diboson





Di-lepton signal from $\tilde{t}_1\tilde{t}_1^*$



- large QCD cross section $\mathcal{O}(20~\mathrm{pb})$ for $m_{\tilde{t}_1} \sim 200~\mathrm{GeV}$
- for small mass difference, $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^\pm}$, b-jets are soft, $p_T^b \lesssim 20~\mathrm{GeV}$
- jet veto would not have effect
- observed final state similar to WW: $\ell^+\ell'^- + E_T^{\rm miss}$

KR, Sakurai arXiv:1303.5696

Kim, KR, Sakurai, Tattersall arXiv:1406.0858

- another possibility with stops and sbottoms, see:

Curtin, Meade, Tien arXiv:1406.0848

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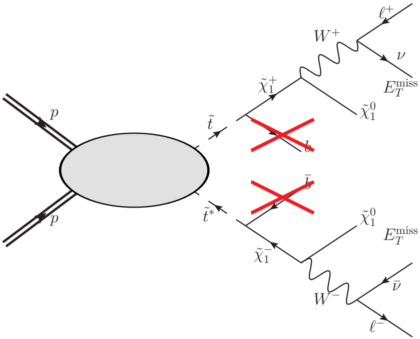

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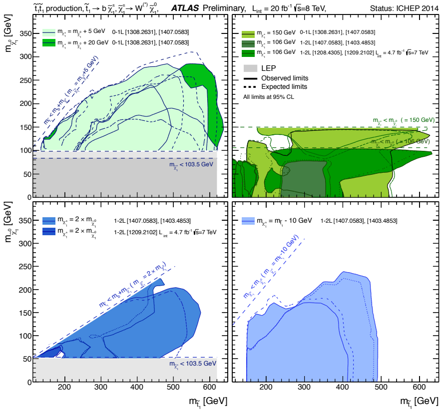
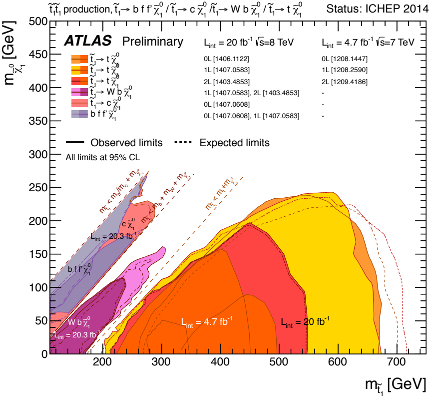
LHC vs stops


ATLAS Preliminary, L_int = 20 fb^-1 √s=8 TeV,
Status: ICHEP 2014
LEP
Observed limits
Expected limits
All limits at 95% CL
m_χ̃1^0 [GeV]
m_t̃1 [GeV]


Status: ICHEP 2014
ATLAS Preliminary
L_int = 20 fb^-1 √s=8 TeV
L_int = 4.7 fb^-1 √s=7 TeV
0L [1406.1122]
1L [1407.0583]
2L [1403.4853]
1L [1407.0583], 2L [1403.4853]
0L [1407.0608]
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0L [1208.1447]
1L [1208.2590]
2L [1209.4186]
Observed limits
Expected limits
All limits at 95% CL
m_χ̃1^0 [GeV]
m_t̃1 [GeV]

Outline

Simulation

- simplified model assumes a decay chain

$$\tilde{t}_1 \to \tilde{\chi}_1^{\pm}\, b \to \tilde{\chi}_1^0\, W^{(*)}\, b \to \tilde{\chi}_1^0\, \ell\, \nu\, b$$

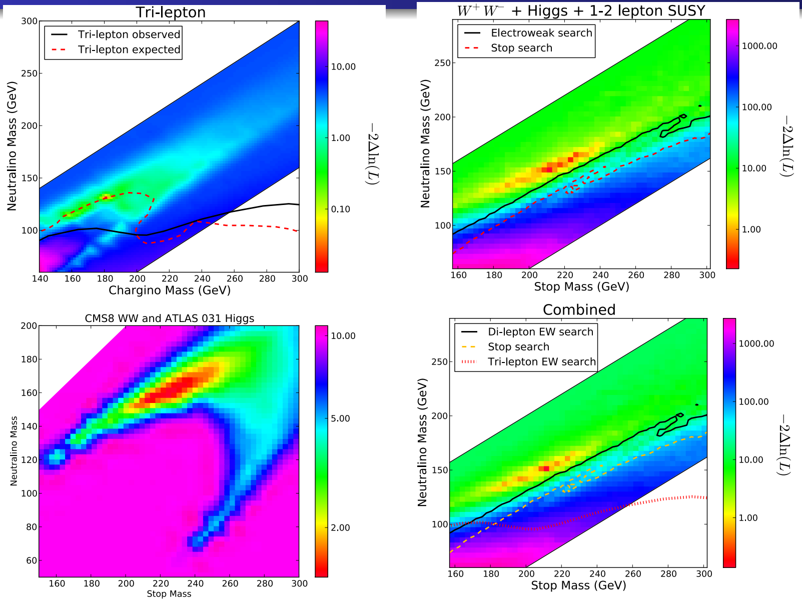
- fix $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^{\pm}} = 7\ \mathrm{GeV}$ or $15\ \mathrm{GeV}$ to ensure “invisible” b
- at this point everything is fixed by $m_{\tilde{t}_1}$ and $m_{\tilde{\chi}_1^0}$
- simulation using `Herwig++ 2.7.0` and `CheckMATE/ATOM`

  see a talk by Jong Soo Kim tomorrow
- includes production of $pp \to \tilde{t}_1 \tilde{t}_1^*$, $pp \to \tilde{\chi}_1^{\pm} \tilde{\chi}_2^0$, $pp \to \tilde{\chi}_1^{+} \tilde{\chi}_1^{-}$
- experimental studies covered: SM measurements (WW, WZ), Higgs, SUSY-EW searches (di-lepton, tri-lepton), stop searches (1-2 leptons), squark and gluino searches (1-2 leptons)
- at each point of the $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0})$ grid, likelihood ratio statistic is calculated

Searches included in the scan

Description	$\sqrt{s}$ [TeV]	Luminosity [fb^{-1}]	Number of SR	Refs.
ATLAS W^+W^-	7	4.6	1	[arXiv:1210.2979]
CMS W^+W^-	7	4.9	1	[arXiv:1306.1126]
CMS W^+W^-	8	3.5	1	[arXiv:1301.4698]
ATLAS Higgs	8	20.7	2	[ATLAS-CONF-2013-031]
ATLAS Electroweak (2 ℓ)	8	20.3	13	[arXiv:1403.5294]
ATLAS $\tilde{q}$ and $\tilde{g}$ (1-2 ℓ)	8	20.1	19	[ATLAS-CONF-2013-062]
ATLAS $\tilde{q}$ and $\tilde{g}$ razor (2 ℓ)	8	20.3	6	[ATLAS-CONF-2013-089]
ATLAS Electroweak (3 ℓ)	8	20.3	20	[arXiv:1402.7029]
ATLAS $\tilde{t}$ (1 ℓ)	8	20.7	8	[ATLAS-CONF-2013-037]
ATLAS $\tilde{t}$ (2 ℓ)	8	20.3	12	[arXiv:1403.4853]
CMS $W^\pm Z^0$	8	19.6	4	[CMS-PAS-12-006]
ATLAS $W^\pm Z^0$	8	13.0	4	[ATLAS-CONF-2013-021]
ATLAS $\tilde{t} \to b\nu_\tau\tilde{\tau}_1$	8	20.3	1	[ATLAS-CONF-2014-014]

Scan results



Best fit compared to SM

Study	SR	Obs	Exp	SM s.d.	Best fit exp	Best fit s.d
ATLAS W^+W^- (7 TeV) [arXiv:1210.2979]	Combined	1325	1219 ± 87	1.1-σ	95	0.1-σ
CMS W^+W^- (7 TeV) [arXiv:1306.1126]	Combined	1134	1076 ± 62	0.8-σ	77	0.3-σ
CMS W^+W^- (8 TeV) [arXiv:1301.4698]	Combined	1111	986 ± 60	1.8-σ	65	0.9-σ
ATLAS Higgs [ATLAS-CONF-2013-031]	WW CR	3297	3110 ± 186	0.9-σ	293	0.5-σ
	Higgs SR	3615	3288 ± 220	1.4-σ	376	0.2-σ
ATLAS $\tilde{q}$ and $\tilde{g}$ (1-2 ℓ) [ATLAS-CONF-2013-062]	Di-muon	7	1.7 ± 1	2.5-σ	0.8	2.1-σ
ATLAS Electroweak (3 ℓ) [arXiv:1402.7029]	SR0τa01	36	23 ± 4	2.1-σ	4.1	1.4-σ
	SR0τa06	13	6.6 ± 1.9	1.9-σ	2.2	1.3-σ
	SR0τa10	24	16.4 ± 2.4	1.6-σ	0.4	1.5-σ

$\Rightarrow$ overall reduction of 12.3 in log-likelihood compared to SM at minimum

$\Rightarrow$ best fit point:

$$m_{\tilde{t}_1} = 212^{+35}_{-35}\ \text{GeV}$$
$$m_{\tilde{\chi}^0_1} = 150^{+30}_{-20}\ \text{GeV}$$

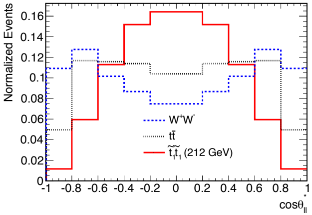
Outline

Probing production polar angle

- observable using pseudorapidities of the final state leptons

$$\cos\theta^*_{\ell\ell} = \tanh\left(\frac{\Delta\eta_{\ell\ell}}{2}\right) \qquad \Delta\eta_{\ell\ell} = \eta_{\ell_1} - \eta_{\ell}$$

Moortgat-Pick, KR, Tattersall, arXiv:1102.0293



- for stop and WW production,

$$\begin{aligned} pp &\rightarrow \tilde{t}_1\,\tilde{t}_1^* \rightarrow \tilde{\chi}_1^0\,\ell^+\,\nu\,b\,\tilde{\chi}_1^0\,\ell'^-\,\bar{\nu}\,\bar{b} \\ pp &\rightarrow W^+\,W^- \rightarrow \ell^+\,\nu\,\ell'^-\,\bar{\nu} \end{aligned}$$

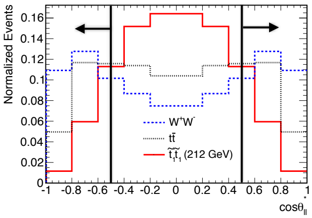
- $\cos\theta^*_{\ell\ell}$ is sensitive to the angular distributions of the initial state W's and $\tilde{t}_1$'s

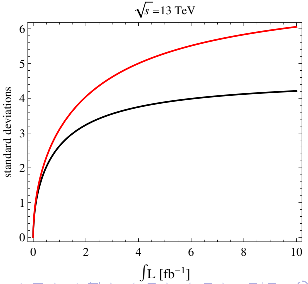
Asymmetry of $\cos\theta^*_{\ell\ell}$

- define an asymmetry using $\cos\theta^*_{\ell\ell}$

$$\mathcal{A} = \frac{N(|\cos\theta^*_{\ell\ell}| > 0.5) - N(|\cos\theta^*_{\ell\ell}| < 0.5)}{N_{\mathrm{tot}}}$$

- forward vs central region
- stops asymmetry: $\mathcal{A}_{\tilde{t}_1} = -0.52$,
  SM only: $\mathcal{A}_{\mathrm{SM}} = 0.12$,
  stops and SM: $\mathcal{A}_{\mathrm{SM}+\tilde{t}_1} = -0.04$
- after $5\ \mathrm{fb}^{-1}$ a 5-σ discrimination achievable at $\sqrt{s} = 13\ \mathrm{TeV}$
- at $\sqrt{s} = 8\ \mathrm{TeV}$ a 3-σ difference with full data sample
- less prone to systematic errors than cross section alone



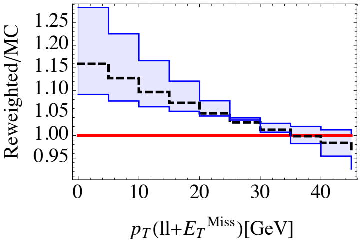


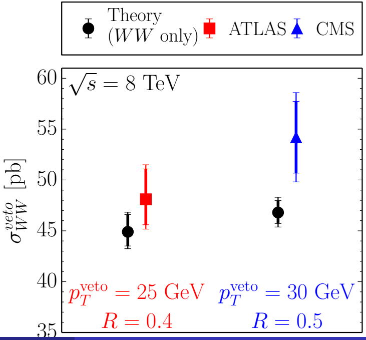
Missing higer orders?

- jet veto efficiency crucial for understanding WW measurement
- other di-boson cross sections do not suffer from this problem
- including NNLL transverse momentum resummation could decrease discrepancy by 3-7% but cannot account for the whole excess

  Meade, Ramani, Zeng arXiv:1407.4481
- employing soft collinear effective theory reduces scale variation and renders theory prediction compatible with experiment

  Jaiswal, Okui arXiv:1407.4537



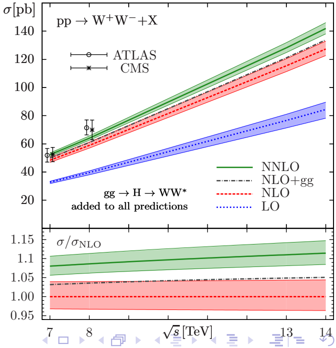


The NNLO story

T. Gehrmann ea arXiv:1408.5243

$\frac{\sqrt{s}}{\mathrm{TeV}}$	σ_{LO}	σ_{NLO}	σ_{NNLO}	$\sigma_{gg\to H\to WW^*}$
7	$29.52^{+1.6\%}_{-2.5\%}$	$45.16^{+3.7\%}_{-2.9\%}$	$49.04^{+2.1\%}_{-1.8\%}$	$3.25^{+7.1\%}_{-7.8\%}$
8	$35.50^{+2.4\%}_{-3.5\%}$	$54.77^{+3.7\%}_{-2.9\%}$	$59.84^{+2.2\%}_{-1.9\%}$	$4.14^{+7.2\%}_{-7.8\%}$
13	$67.16^{+5.5\%}_{-6.7\%}$	$106.0^{+4.1\%}_{-3.2\%}$	$118.7^{+2.5\%}_{-2.2\%}$	$9.44^{+7.4\%}_{-7.9\%}$
14	$73.74^{+5.9\%}_{-7.2\%}$	$116.7^{+4.1\%}_{-3.3\%}$	$131.3^{+2.6\%}_{-2.2\%}$	$10.64^{+7.5\%}_{-8.0\%}$

- fully inclusive $pp \to WW + X$
- NNLO account for $\sim 10\%$ increase in cross section
- note that formally NNLO $gg \to WW$ was included in previous estimates
- apparent improvement in explaining exp results
- 8 TeV still slightly high



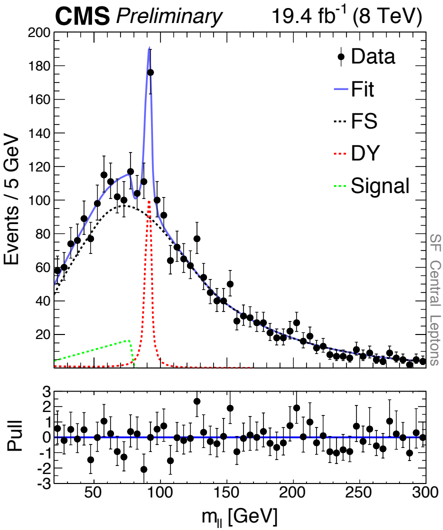
The NNLO story

	$VV_{\rm th}$	ATLAS WZ	CMS WZ	ATLAS ZZ	CMS ZZ	ATLAS WW	CMS WW
$\frac{\sigma(8\mathrm{TeV})}{\sigma(7\mathrm{TeV})}$	~ 1.22	1.07 ± 0.09	1.19 ± 0.08	1.06 ± 0.13	1.23 ± 0.18	1.38 ± 0.06	1.33 ± 0.07

- the ratio of cross sections stable across the channels and orders in perturbation theory
- WW systematically higher than prediction
- NNLO calculation of $pp \to ZZ + X$ overshoots measured cross-sections, in particular for ATLAS8
- the experiments measure fiducial cross sections rather than the fully inclusive cross sections
- especially true for WW: efficiency $< 10\%$ ($\sim 50\%$ for ZZ)
- differential calculation should settle the issue

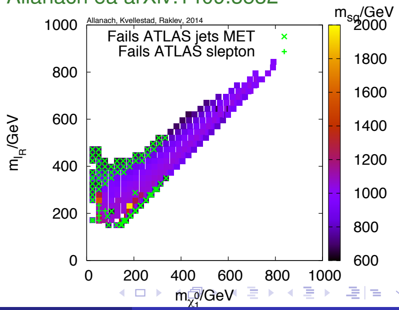
One more hint

CMS PAS-SUS-12-109



- 2.6-sigma excess in SF
- consistent with light gauginos/sleptons
- light states preferred by $g-2$ and DM

B. Allanach ea arXiv:1409.3532



Outline

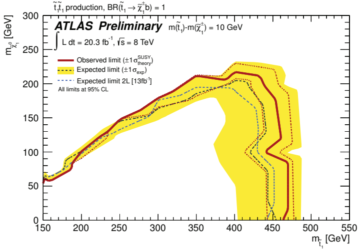
Summary

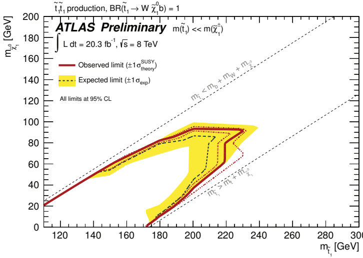
- ⇒ ATLAS and CMS observed consistent excesses in WW production
  - certainly not a statistical fluctuation
  - systematics cannot be ruled out yet, missing NNLL?
- ⇒ another hint from tri-lepton search and Higgs measurements
- ⇒ can be attributed to new physics, e.g. supersymmetric stops
- ⇒ light stops markedly improve agreement with data
- ⇒ different searches point to the same region in parameter space
- ⇒ distinction from the SM possible using angular distributions
- ⇒ outlook:
  - study of other simplified models, decay chains, etc.
  - including additional constraints: dark matter, low energy, EWPT

BACKUP

LHC vs light stops

- LHC started constraining light stops
- for us the channel with intermediate chargino is interesting
- m_{T2} used to suppress $t\bar{t}$ background
- this limits sensitivity of the search in region with (almost) off-shell W
- more constraints on 3-body, 4-body, FV stop decays also from non-stop searches e.g. Yu ea, arXiv:1211.2997; Krizka ea, arXiv:1212.4856





Rapidity and pseudorapidity

- Rapidity

$$y = \frac{1}{2}\log\left(\frac{E+p_L}{E-p_L}\right) = \log\left(\frac{E+p_L}{\sqrt{m^2+p_T^2}}\right)$$

- Rapidity is additive under Lorentz boosts along the beam direction
- The difference in rapidity of two particles is invariant under boosts along the beam axis
- For massless particles we have

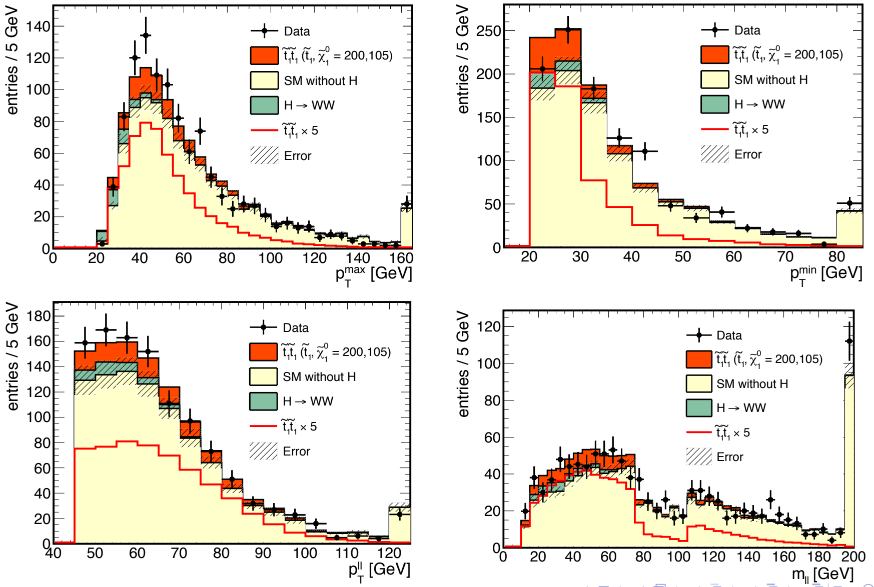
$$y = \frac{1}{2}\log\left(\frac{1+\cos\theta}{1-\cos\theta}\right) = -\log\tan\frac{\theta}{2}$$

- Define pseudorapidity as

$$\eta = -\log\tan\frac{\theta}{2}$$

Back to talk

Modified distributions



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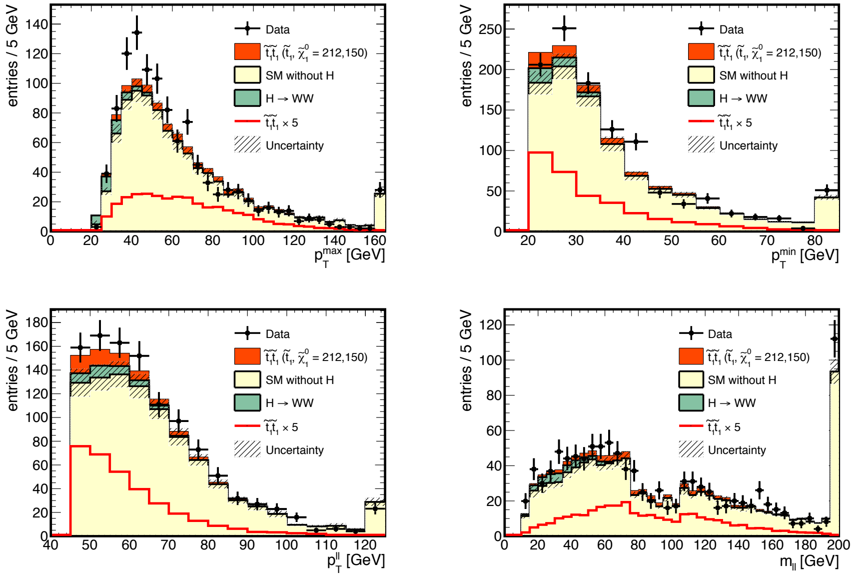

Other constraints

- the heavy Higgs boson requires large stop contribution
  - $\Rightarrow$ can be achieved if the stops are split:
  - $\Rightarrow$ $m_{\tilde{t}_R} = 195$ GeV, $m_{\tilde{t}_L} = 2000$ GeV, $A_t = 2000$ GeV
  - $\Rightarrow$ $m_h = 125.6$ GeV, bonus: $R_{\gamma\gamma} = 1.05 \cdot R_{\gamma\gamma}^{\mathrm{SM}}$
- gaugino parameters for correct chargino and LSP
  - $\Rightarrow$ $M_1 = 105$ GeV, $M_2 = 190$ GeV, $\mu = 2500$ GeV and $\tan\beta = 15$
- light stuff having the following masses:
  - $\Rightarrow$ $m_{\tilde{t}_1} = 203.7$ GeV, $m_{\tilde{\chi}_1^0} = 104.9$ GeV and $m_{\tilde{\chi}_1^\pm} = 189.5$ GeV
- low energy observables evaluated as
  - $\Rightarrow$ $\mathrm{BR}(B \to X_s\gamma) = 3.7 \times 10^{-4}$ and $\mathrm{BR}(B_s \to \mu\mu) = 3.45 \times 10^{-9}$
  - $\Rightarrow$ needs $m_{\tilde{b}_R} = 1000$ GeV
- basic consistency can be ensured
- dark matter relic density could be regulated by light right-handed sleptons

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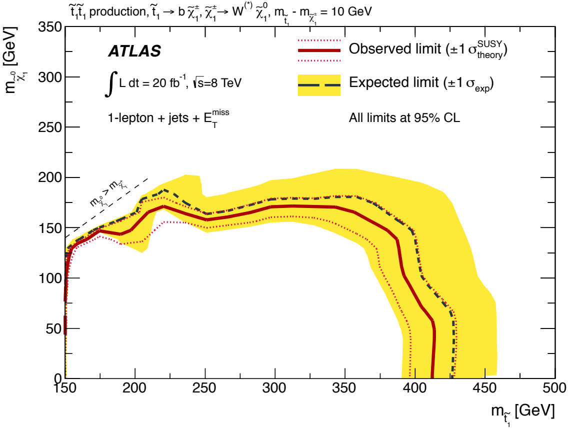

$\tilde{t}_1\tilde{t}_1$ production, $\tilde{t}_1 \to b\,\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^\pm \to W^{(*)}\,\tilde{\chi}_1^0$, $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^\pm} = 10$ GeV
ATLAS
$\int L\,dt = 20\ \mathrm{fb}^{-1}$, $\sqrt{s}$=8 TeV
1-lepton + jets + E_T^{miss}
Observed limit ($\pm 1\ \sigma^{SUSY}_{theory}$)
Expected limit ($\pm 1\ \sigma_{exp}$)
All limits at 95% CL
$m_{\tilde{\chi}_1^0} > m_{\tilde{\chi}_1^\pm}$
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{t}_1}$ [GeV]
0
50
100
150
200
250
300
350
400
450
500