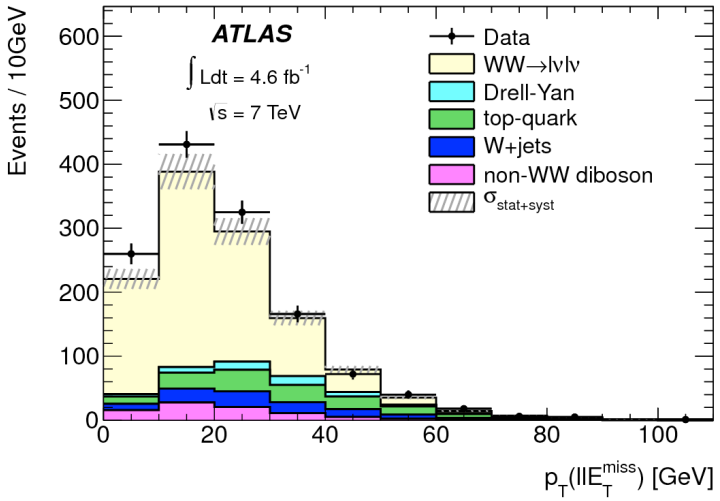
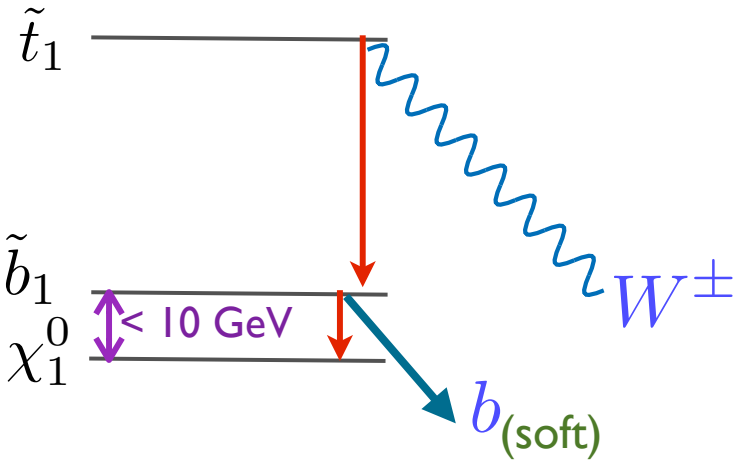
SUSY in Standard Model Standard Candles





Fermilab LPC Seminar
Batavia, Illinois

30 April 2014

David Curtin
Yang Institute for Theoretical Physics
Stony Brook

Based on

1206.6888 DC, Prerit Jaiswal, Patrick Meade

1304.7011 DC, Prerit Jaiswal, Patrick Meade, Pin-Ju Tien

1405.XXXX DC, Patrick Meade, Pin-Ju Tien

Introduction

Introduction

- What are the big motivations for new physics? There are many, but three stand out for their supposed `accessibility':

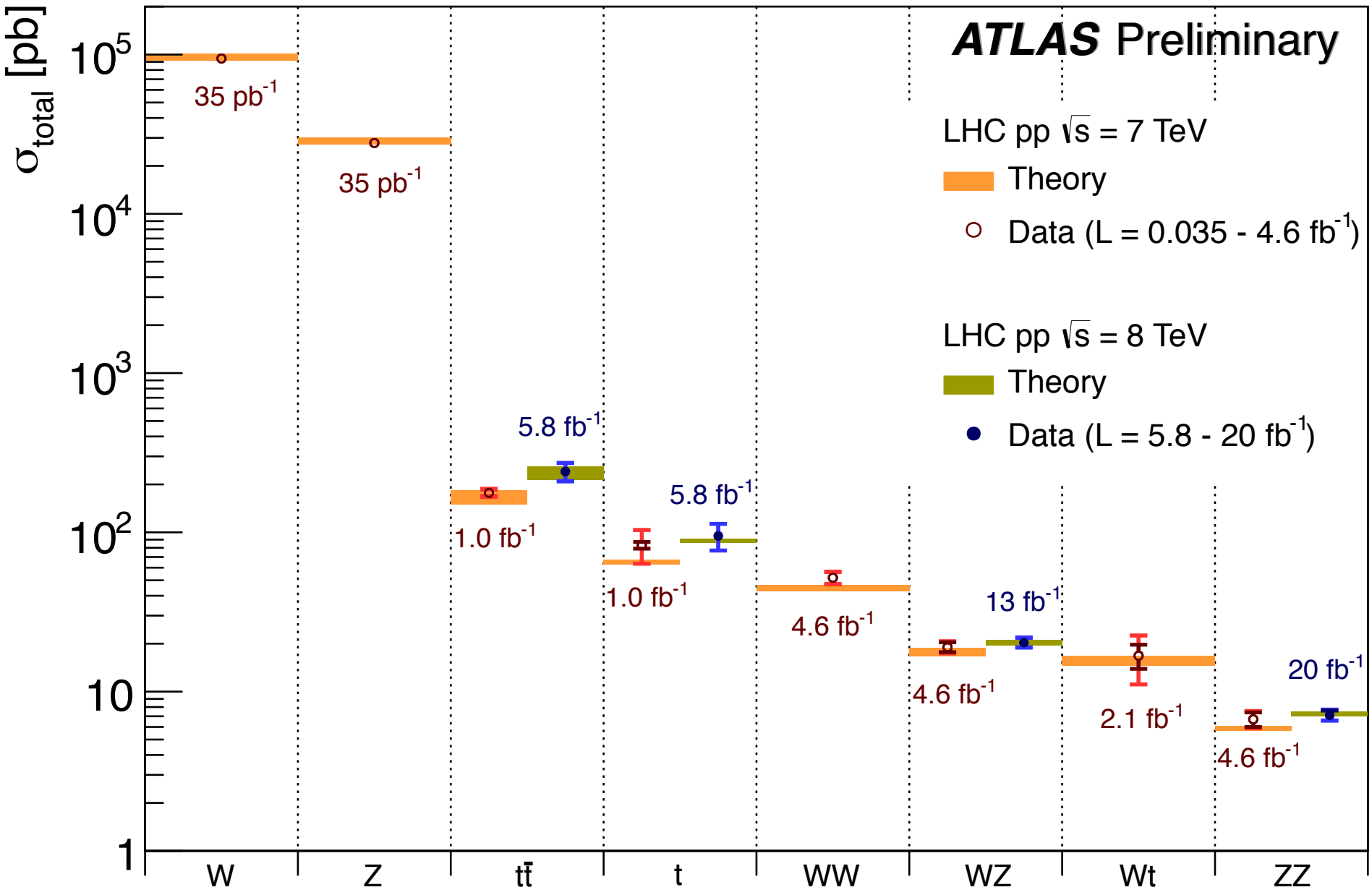
  1. Hierarchy Problem
  2. Dark Matter
  3. Muon (g-2)

- The first problem caused us to look for distinctive QCD signals (jets + MET, stops etc) but so far, no luck.
  - The "Hierarchy Problem ⇛ jets + MET" prediction is relatively easily circumvented. Maybe pursue another angle?
- All of these problems have a connection to O(100 GeV) new electroweak physics. Where could such signals be hiding?

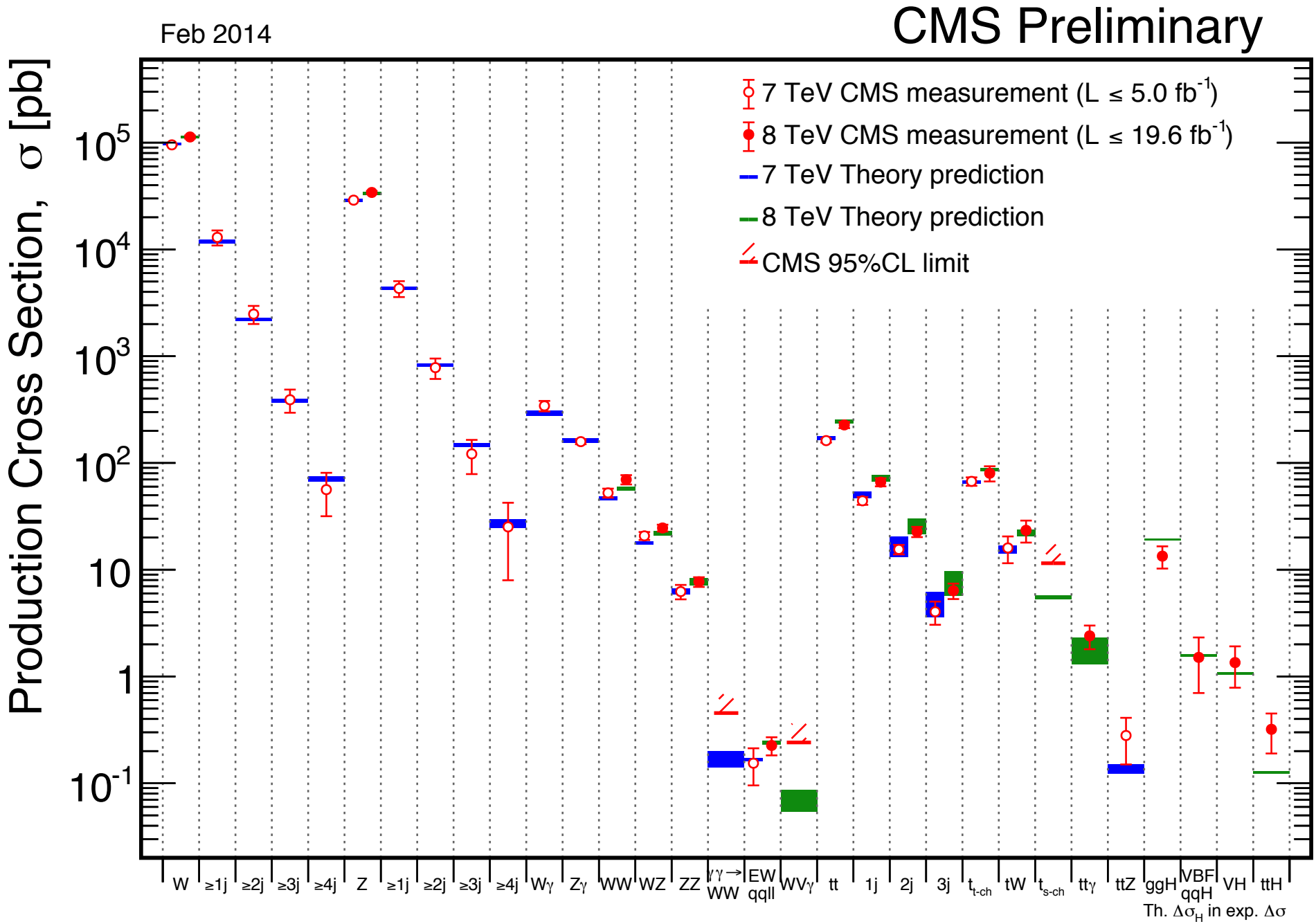
➡ W, Z `precision' measurements.

Standard Model Standard Candles

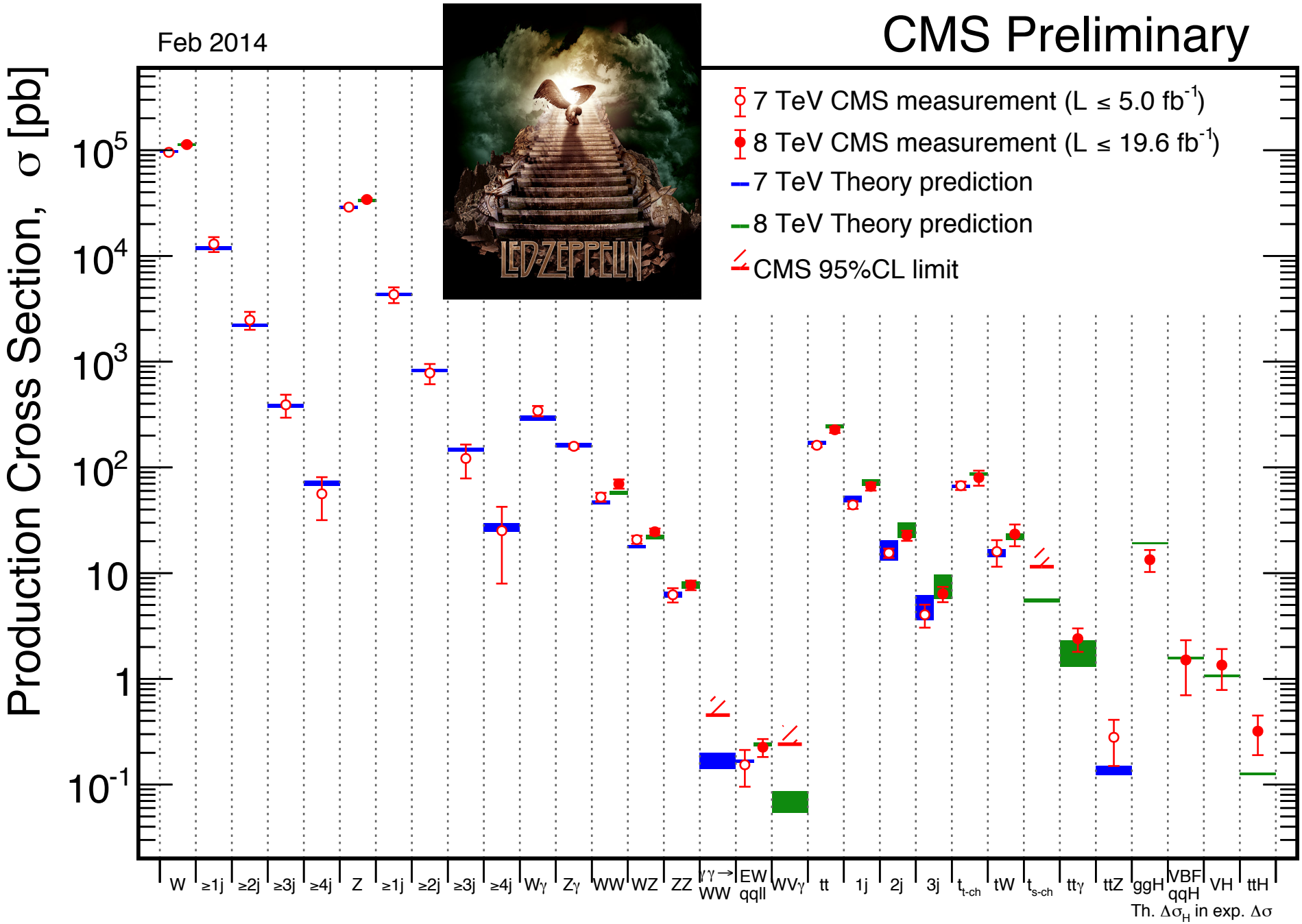
SM Standard Candles



SM Standard Candles



SM Standard Candles



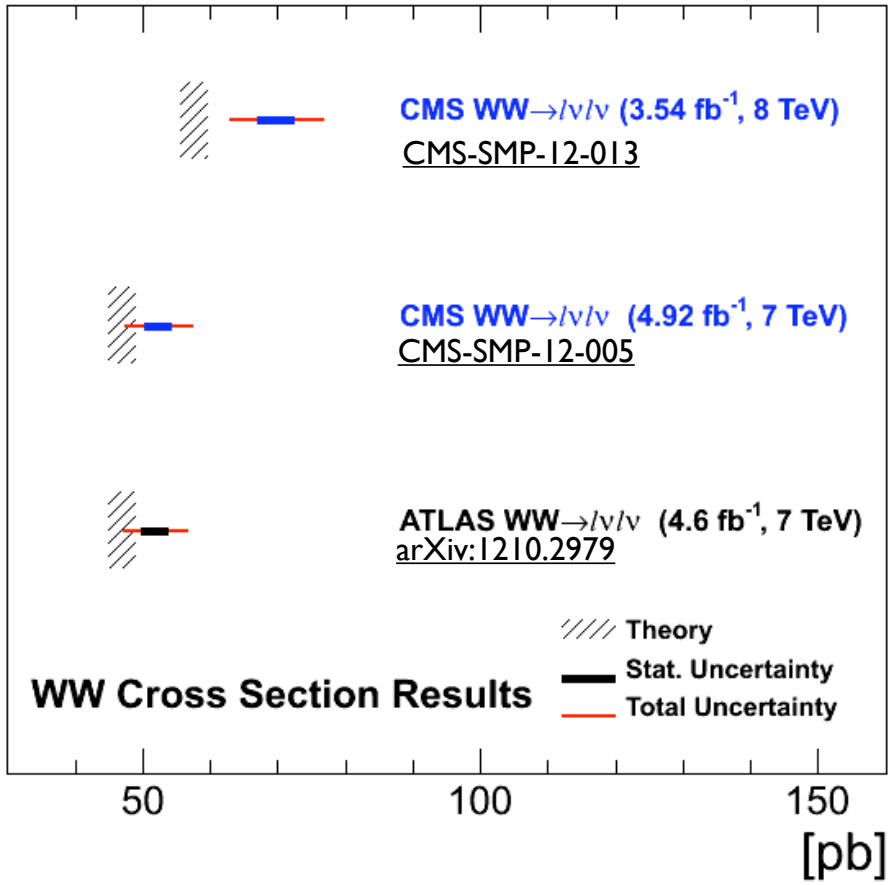
A Tantalizing Anomaly

- All three measurements of **WW cross section** measurement are HIGH by ~ 15 - 20%
  ⇛ ~ 3σ combined significance

- WW is important background for h→WW* analysis. Data-driven BG estimates up-scaled their MC by ~20% as well.

  ➡ This excess shows up in 7 out of 7 public WW "measurements"!
  CMS/ATLAS h→WW @ 7, 8 TeV
  CMS WW @ 7, 8 TeV,
  ATLAS WW @ 7 TeV

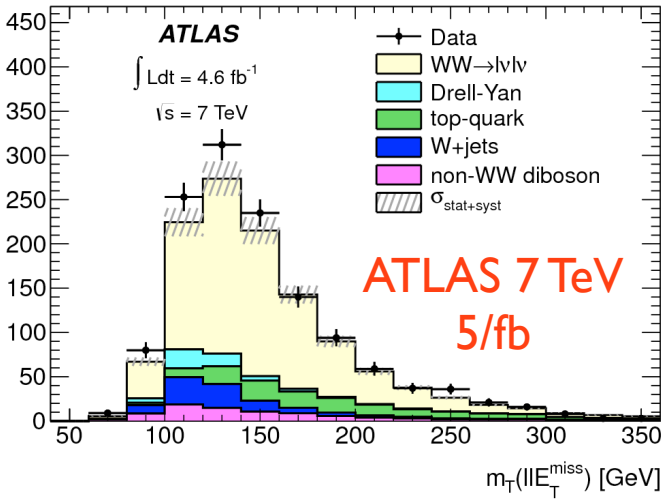
- The excess grows with $\sqrt{s}$ faster than PDF luminosity → slightly higher mass scale than m_W?



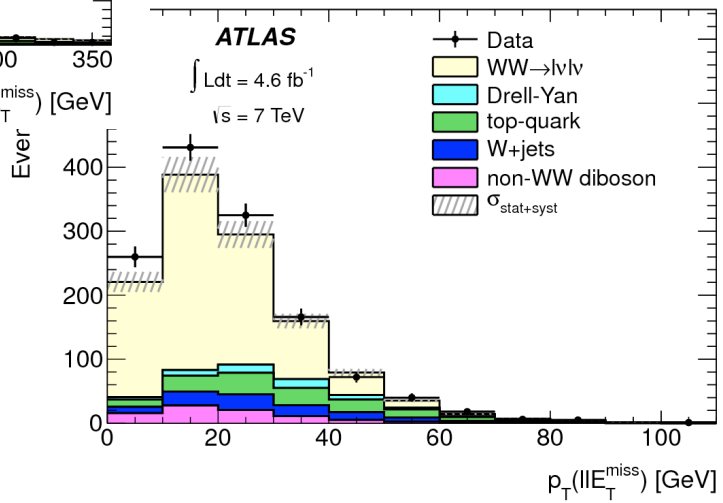
$$\left.\frac{\sigma(8)}{\sigma(7)}\right|_{\text{th}} = 1.21 \qquad \left.\frac{\sigma(8)}{\sigma(7)}\right|_{\text{exp}} = 1.33$$

A Tantalizing Anomaly

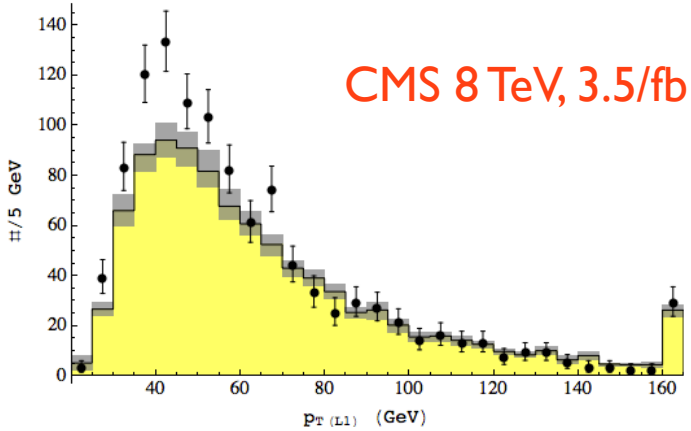
In all three measurements the excess looks more like a **shape discrepancy** than just a uniform cross section excess.

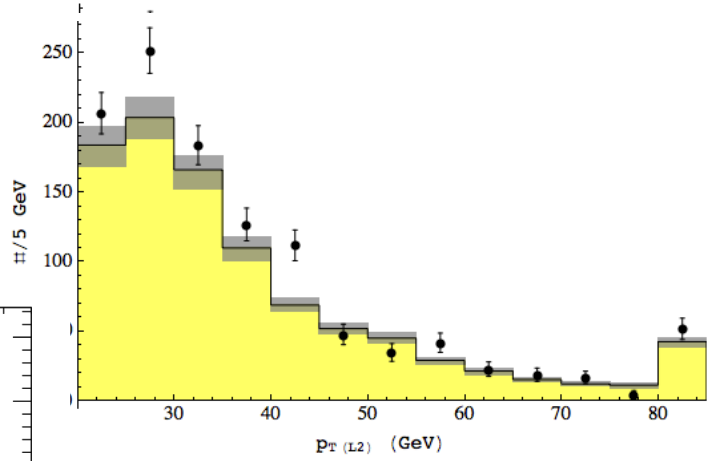


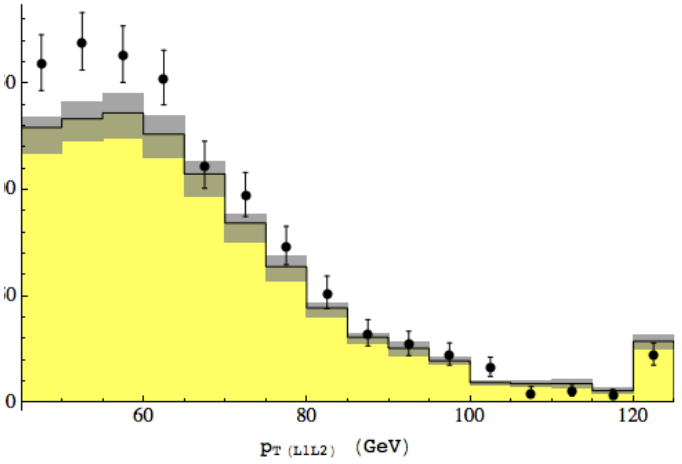
ATLAS 7 TeV 5/fb



Doesn't seem to line up with any obvious backgrounds...







Where to go from here?

- The LHC8 20/fb WW cross section measurements are > 1 year overdue.. Silence is telling...
- What about SM explanations:
  - No BG jumps out as being a possible source of deviation
  - Un-accounted for higher-order corrections to σ(WW)?

QCD NNLO would have to be ~20% effect.....
NNLL+approx NNLO is ~ 3% (1307.3249 Dawson, Lewis, Zeng)

σ(ZZ) agrees perfectly with SM!
If QCD, why no deviation here?

Doesn't seem very likely... jet veto dependency also not strong enough.

- Obviously further work on SM predictions of WW are needed.
- Reducing systematic error of WW measurement also vital! (better understanding of jet acceptance, fake leptons)

Upcoming Result

- A pT-rapidity resummation of NNLO+NLL WW production cross section would allow more accurate prediction of lepton cuts and jet veto efficiency.
- Preliminary results by Harikrishnan Ramani, Patrick Meade, Mao Zeng, paper out soon.
- Reweigh LL events from different generators and observe change in WW signal acceptance due to resummation effects.
  - **MadGraph** (CMS WW): **reduce** WW prediction by 7-13%.
  - **MC@NLO** (ATLAS WW): **increase** WW prediction by 0 - 9%
  - **POWHEG**: very little change, ± 3%. (Some resummation included.)
- Future WW measurements should/will use POWHEG for prediction.
- Resummation effects INCREASE the size of the WW cross section discrepancy for CMS (greatest effect) and somewhat decrease it for ATLAS.

But: ATLAS h→WW* control region already uses POWHEG and is 20% high.

Where to go from here?

It could be new physics!

SUSY provides several possible explanations
(though one can look at them as simplified models that occur in other frameworks as well)

W/Z Partners

Lepton Partners

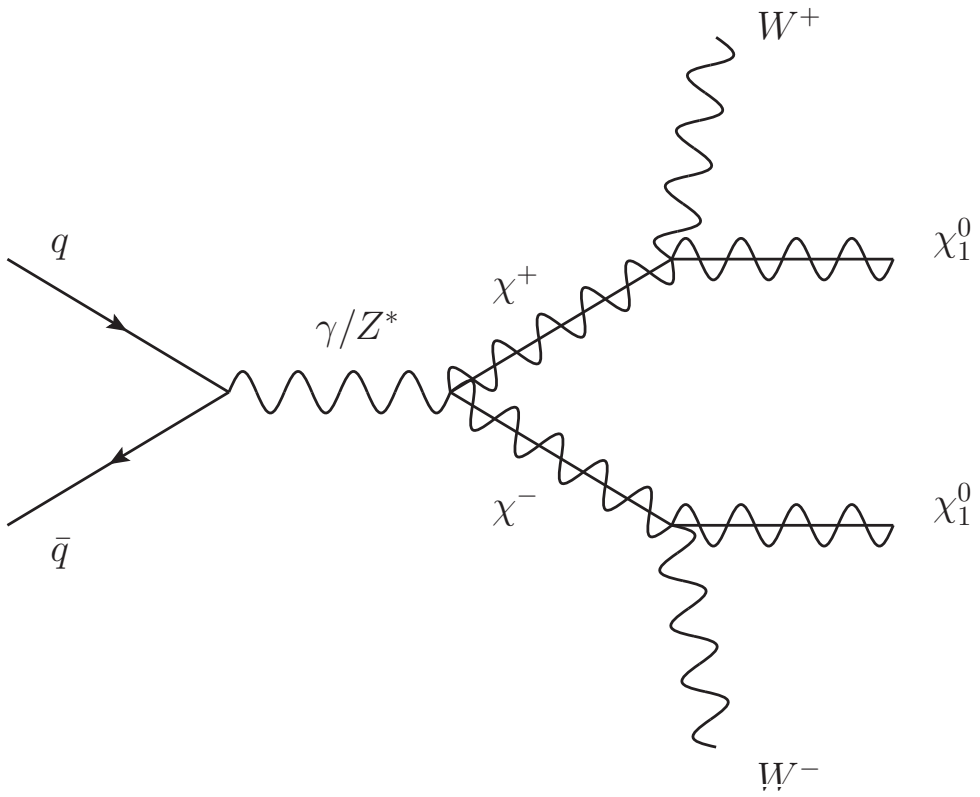
"mimic leptonic W decay"

Top Partners

"supersymmetrize top decay"

Corollary: we should use WW (and other standard candles) to constrain SUSY, independent of any anomalies!

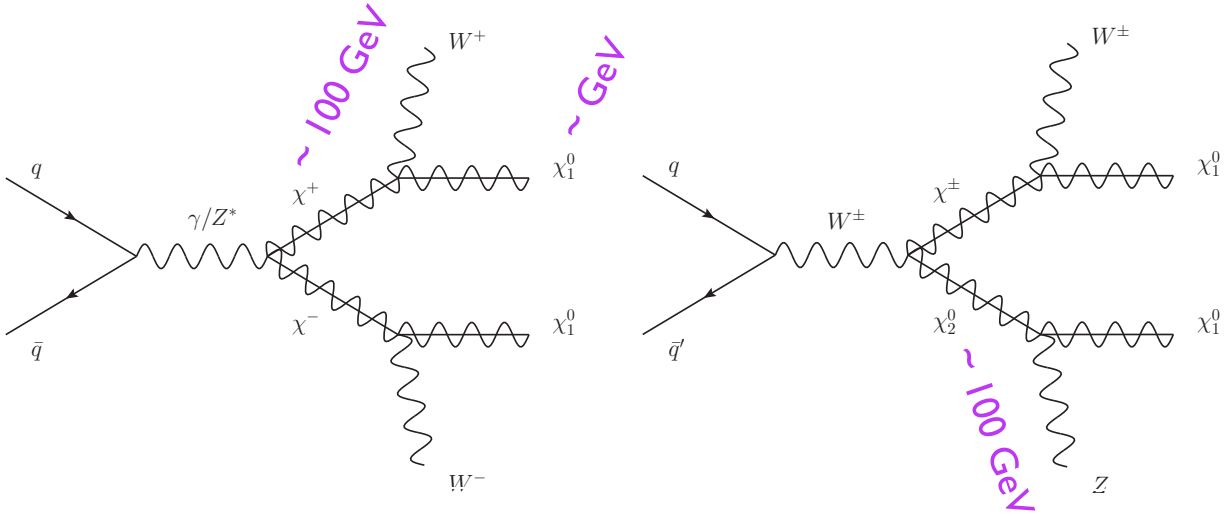
W/Z - Partners



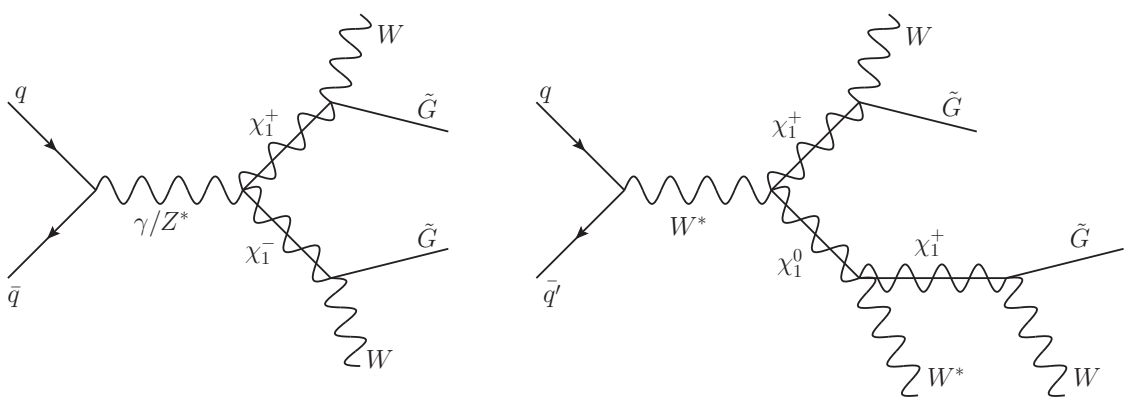
Charginos

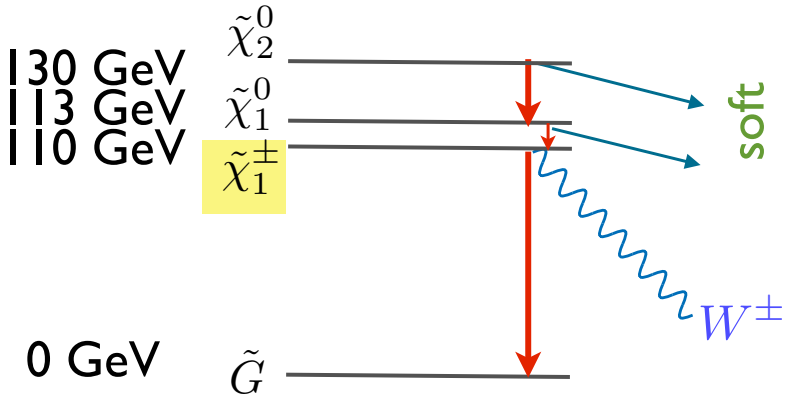
CMS SUS-13-017-pas
ATLAS CONF-2013-035

- ~100 GeV Charginos can give enough WW signal, but usually comes with WZ or Wh signals: RULED OUT

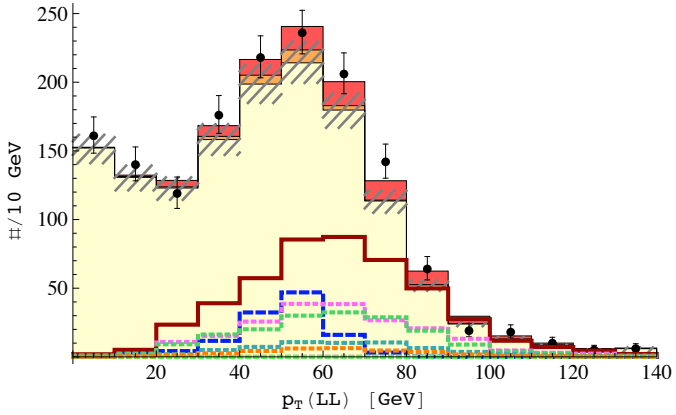


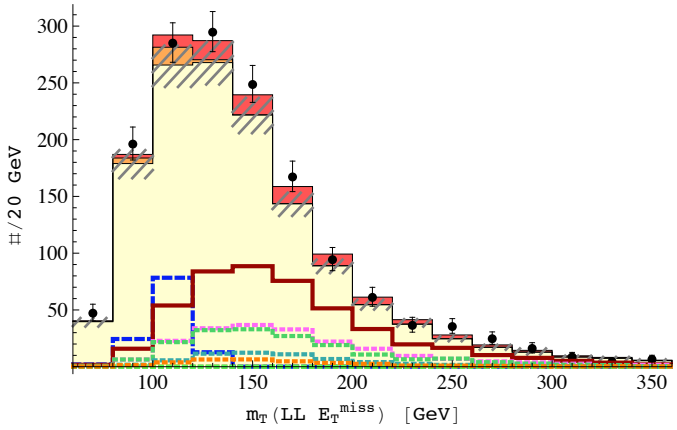
- Solution: **Chargino-NLSP** in GMSB [0807.4926 Kribs, Martin, Roy: low tanβ, large Wino-Higgsino mixing]



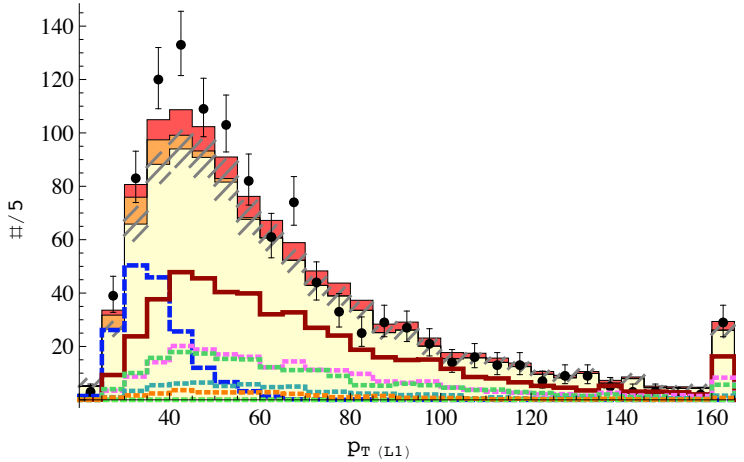


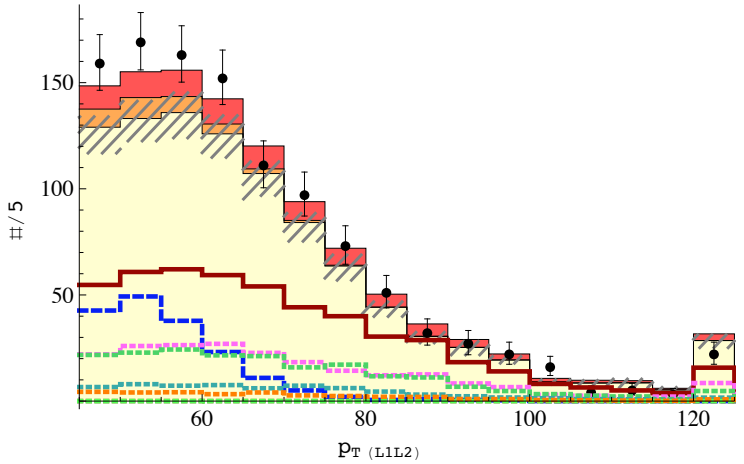
ATLAS7 5/fb

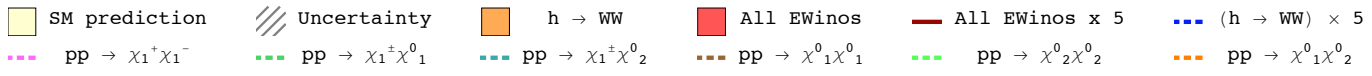




CMS8 3.5/fb







All fits greatly improved compared to SM

Chargino-NLSP Signatures

- Amusing: only region of MSSM where charginos give 15% enhancement to $h \to \gamma\gamma$
- **OS Dilepton** signature: explicitly NOT excluded yet with 20/fb

> **GMSB model point** The CL_s value is also calculated for the GMSB model point where the chargino is the NLSP [$m(\tilde{\chi}_1^{\pm}) = 110$ GeV, $m(\tilde{\chi}_1^0) = 113$ GeV and $m(\tilde{\chi}_2^0) = 130$ GeV] [40]. The observed CL_s value is found to be 0.52 using the SR-WWa region, which the most sensitive signal region for this point. The expected and observed 95% CL limit on σ/σ_{SUSY} are 2.6 and 2.9, respectively.

ATLAS-CONF-2013-049

- **Trilepton signature**: no sensitivity to our model at 20/fb

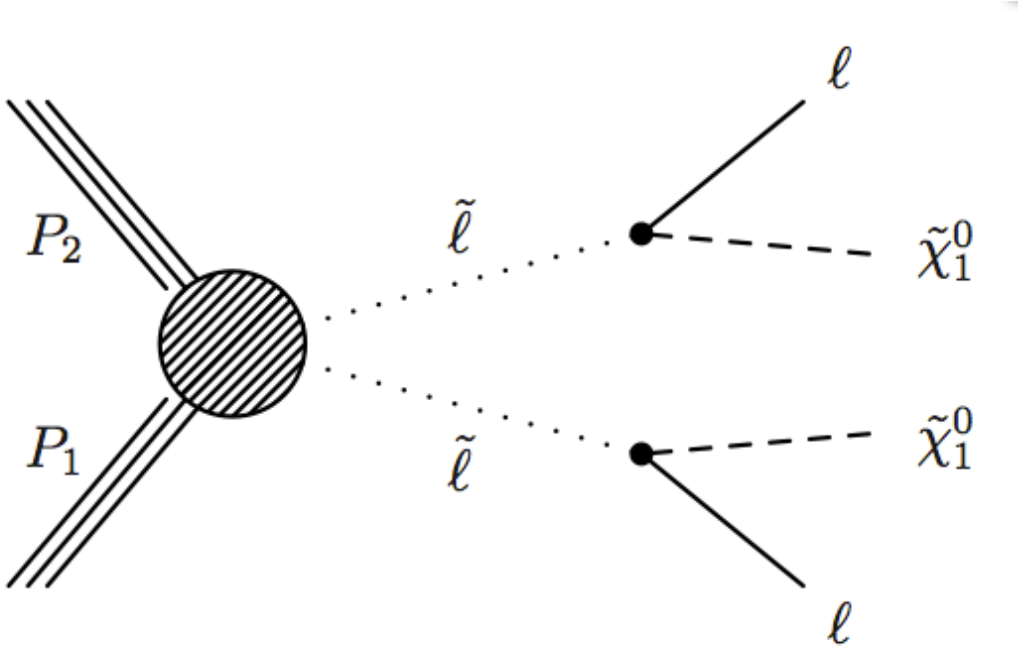
CMS SUS-13-006-PAS ATLAS-CONF-2013-035

"Smoking Gun"

- **SS Dileptons**: CMS SUS-13-006-pas with 20/fb has sensitivity, naively 2σ conflict, BUT all signal bins are much below SM, so maybe some issues with search, or just downward fluctuation?....

⇛ Some tension, but interpretation unclear?

Lepton Partners

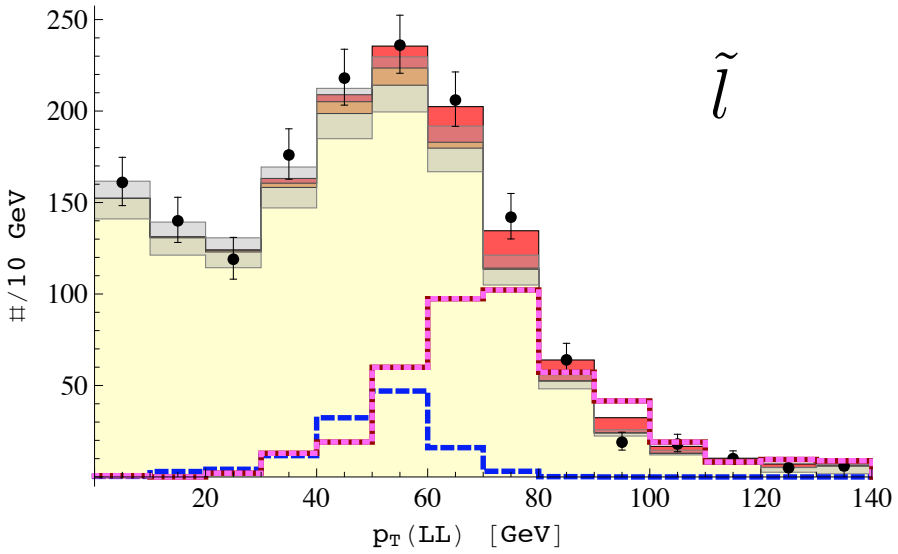


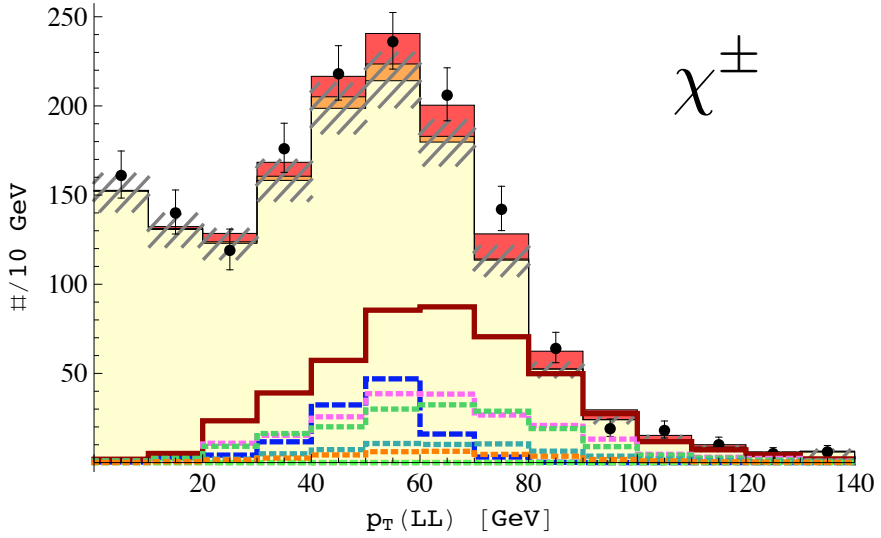
Sleptons

$\tilde{e}_{L,R}$, $\tilde{\mu}_{L,R}$ ~ 110 GeV

χ_1^0 ~ 60 GeV

- Lower production cross section, but 100% Br to ll + MET
- Only get SFOS dileptons → safe from SS dilepton, trilepton bounds!
- Naively has more MET, but can **fit just as well as charginos!**





Sleptons + Binos can do all kinds of nifty things for you...

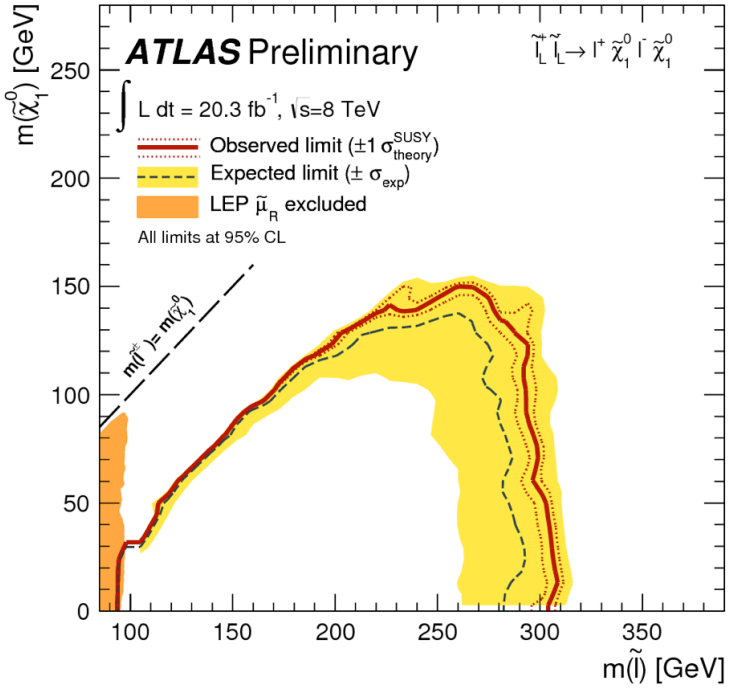
but let's take a step back first...

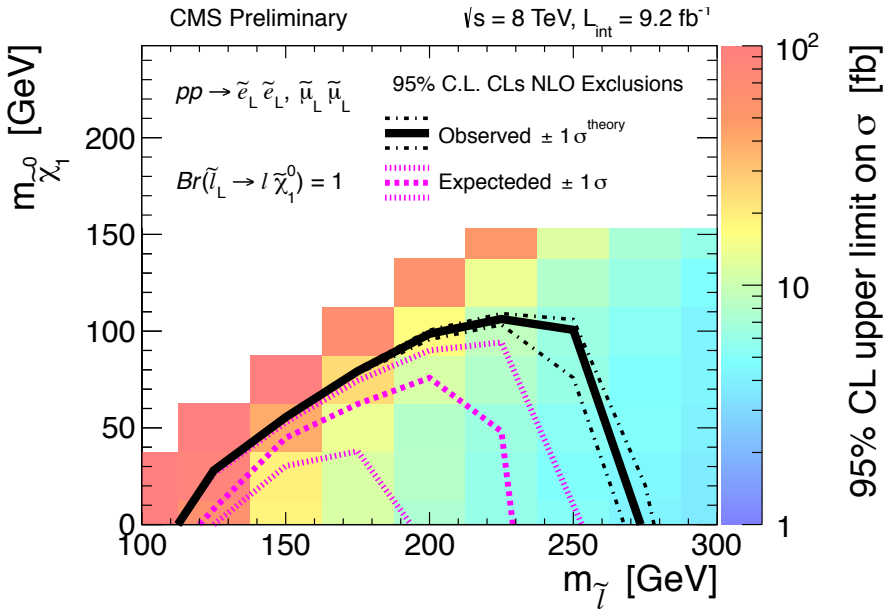
and talk about something (possibly) more archival:

Setting new bounds on EW physics with Standard Model Standard Candles

Standard Candles have Exclusion Power!

- We learned from examining the Chargino and Slepton scenarios that the WW measurement can be the harbinger of new physics!
- We should exploit that sensitivity not just for **discoveries** but also for **setting bounds** ⇛ **treat WW like a slepton search!**
- These bounds will be **entirely complementary** to LHC bounds (heavy states with lots of MET) and LEP bounds (light states below 100 GeV)





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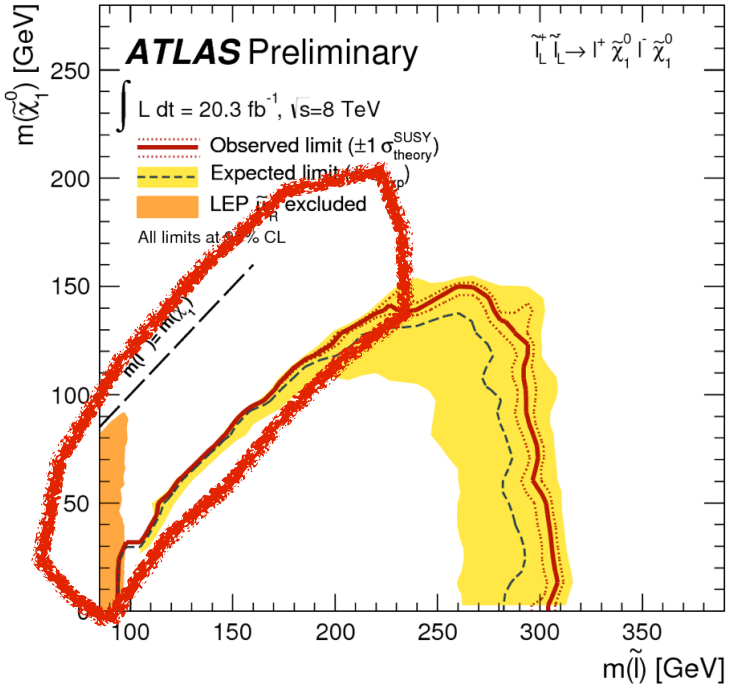
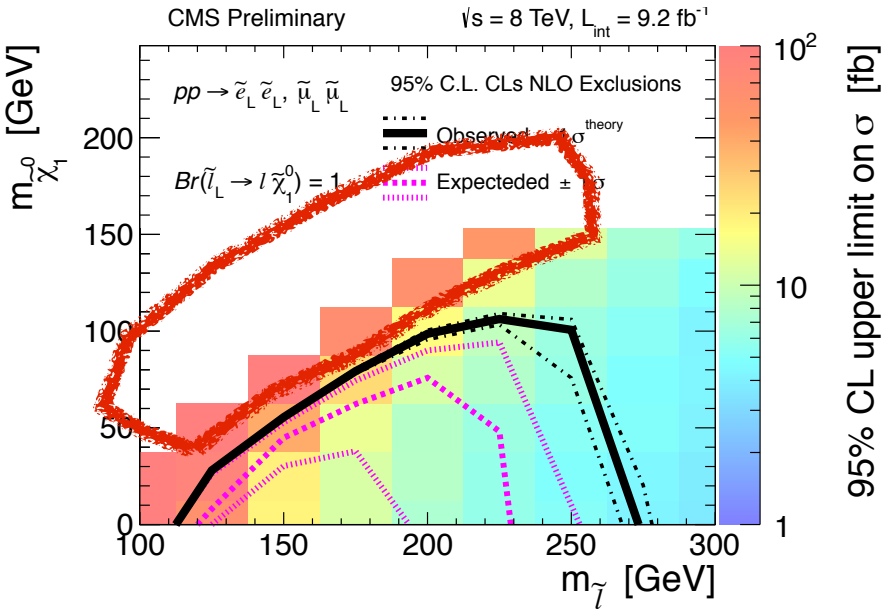
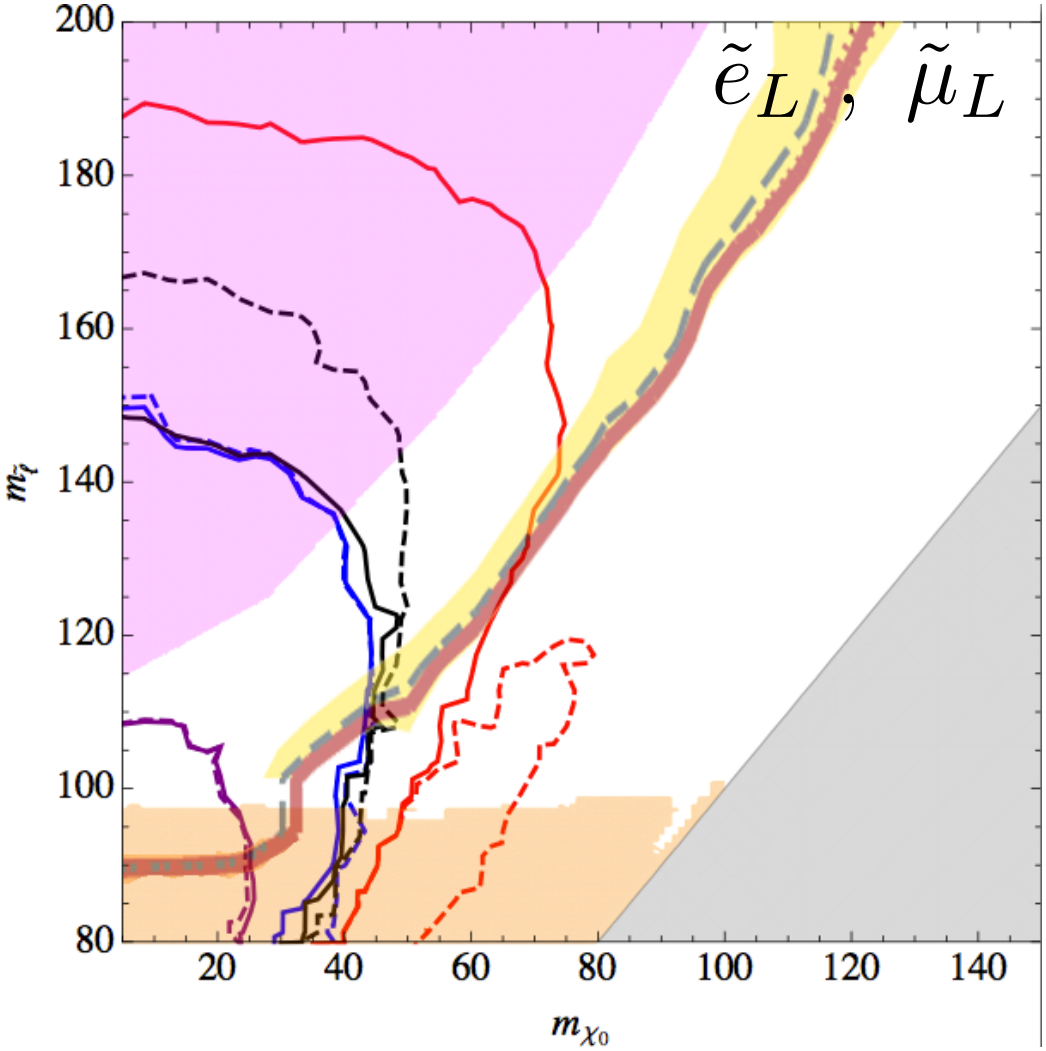


→ Exclude New Physics along the "WW-like Funnel"



LH Slepton Exclusions from WW Measurement

UPDATE: ATLAS 20/fb Direct Search



LEP

CMS 9/fb LHC8 slepton search

ATLAS7

CMS7

CMS8

combined

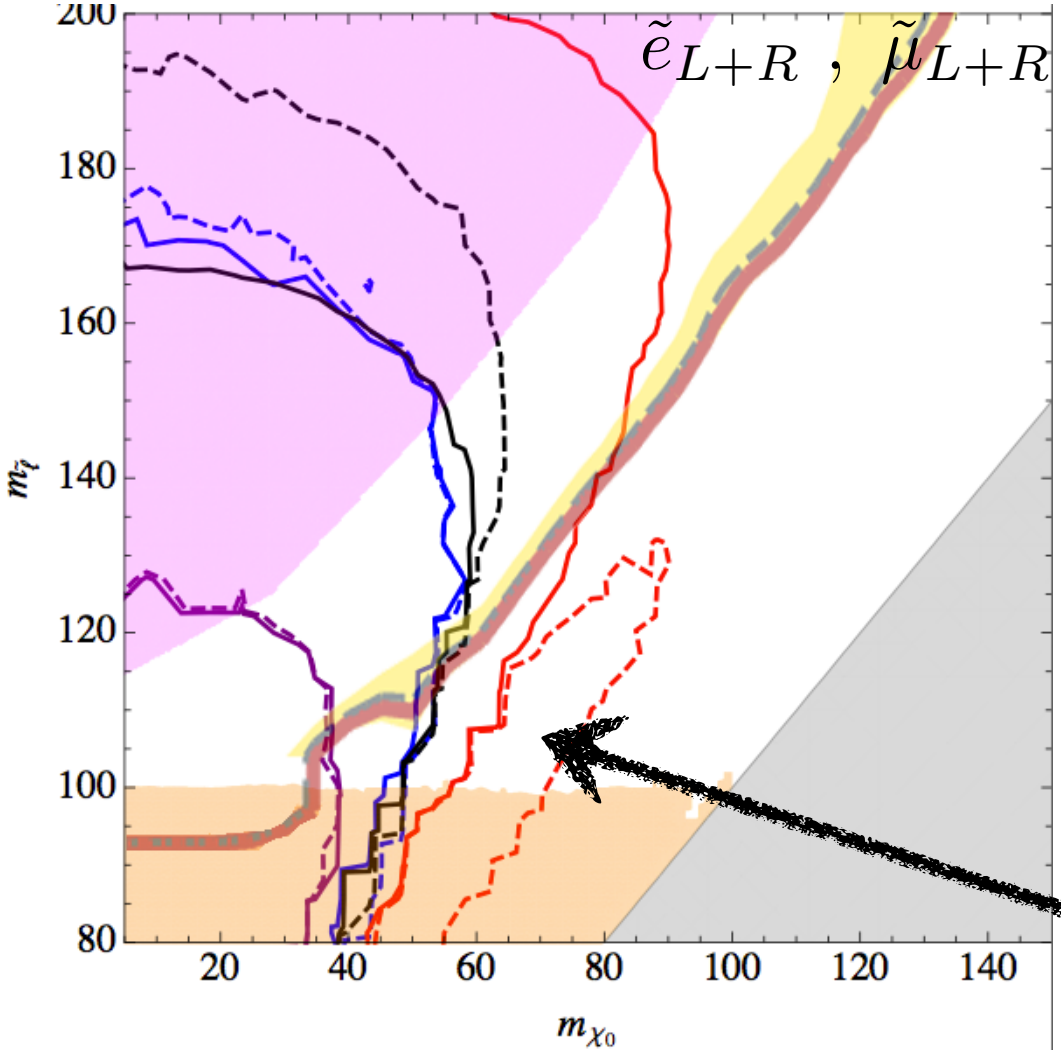
——— shape only

-------- shape + normalization

New EW constraints, complementary to other search strategies!

LH + RH Slepton Exclusions from WW Measurement

UPDATE: ATLAS 20/fb Direct Search



LEP

CMS 9/fb LHC8 slepton search

ATLAS7

CMS7

CMS8

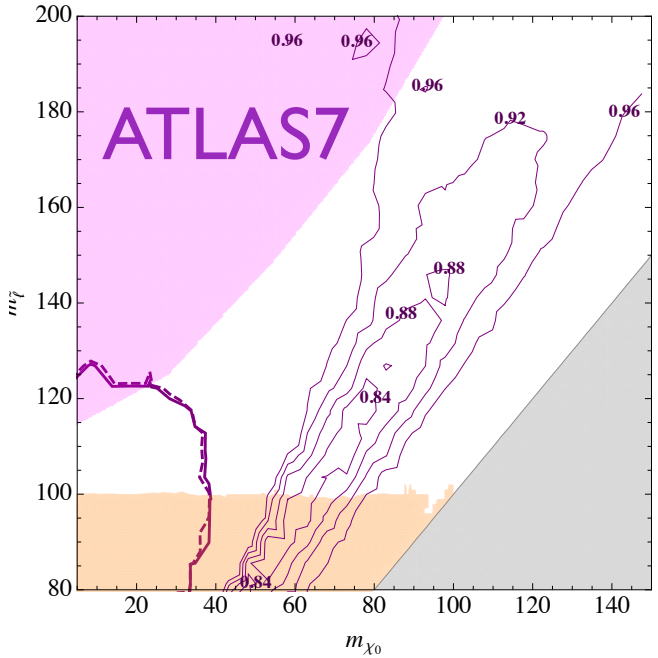
combined

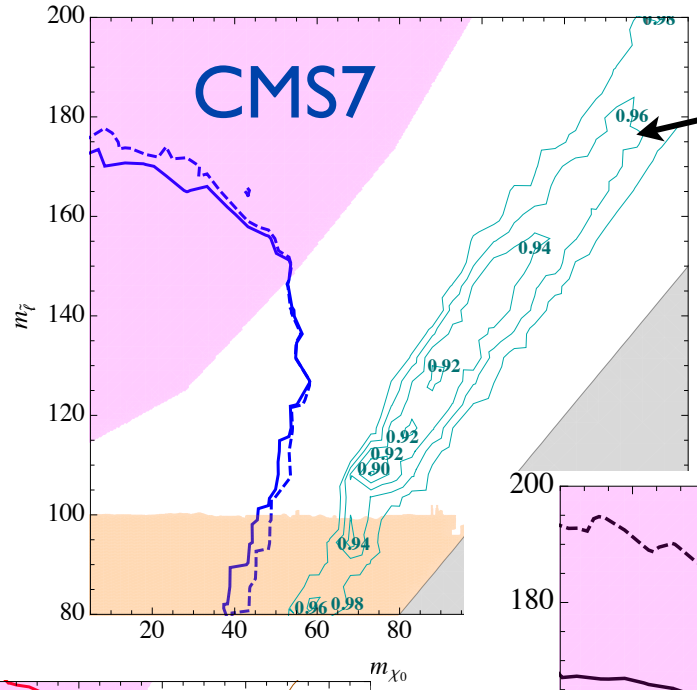
——— shape only

-------- shape + normalization

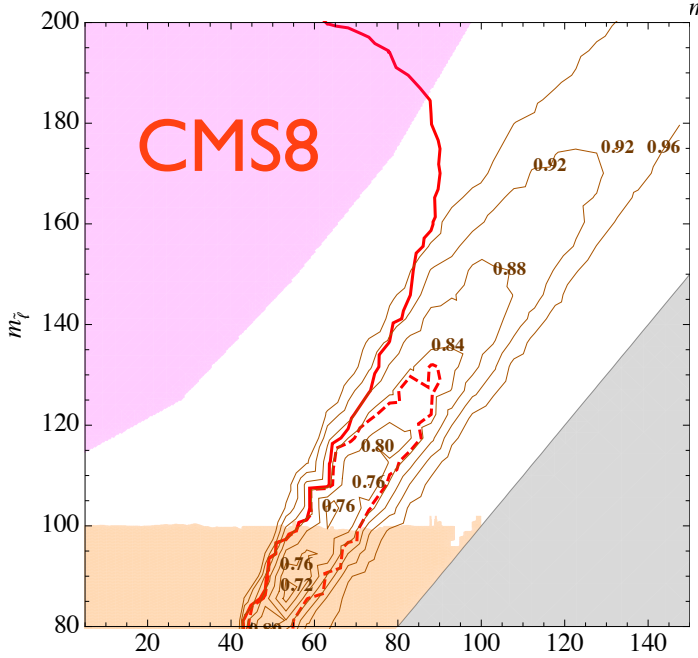
CMS8:
Amusing "SM Exclusion" everywhere except here
~ 115 GeV Sleptons ~ 75 GeV Binos

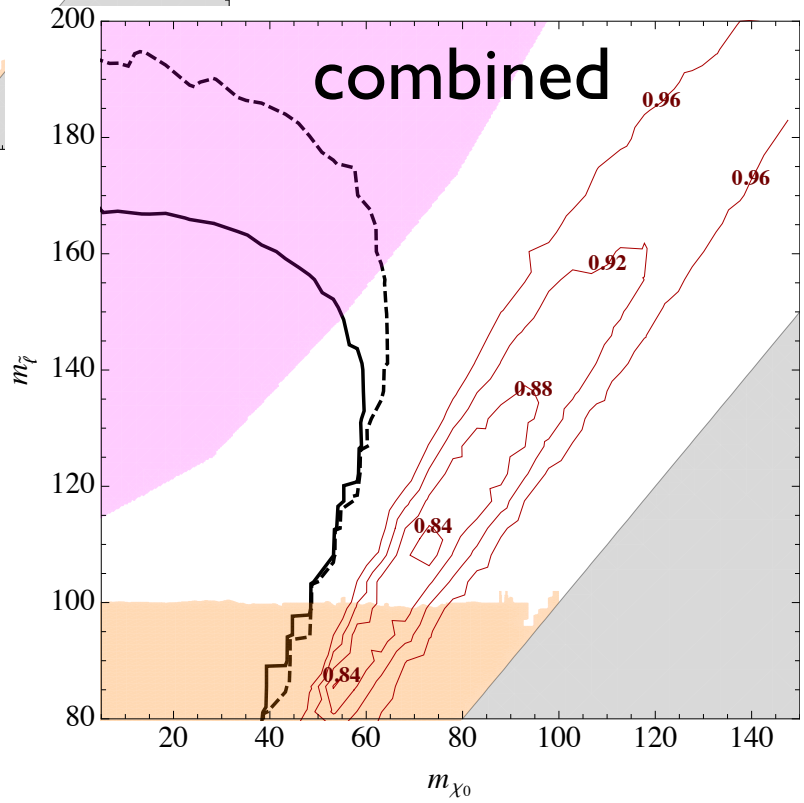
Sleptons can improve WW fit

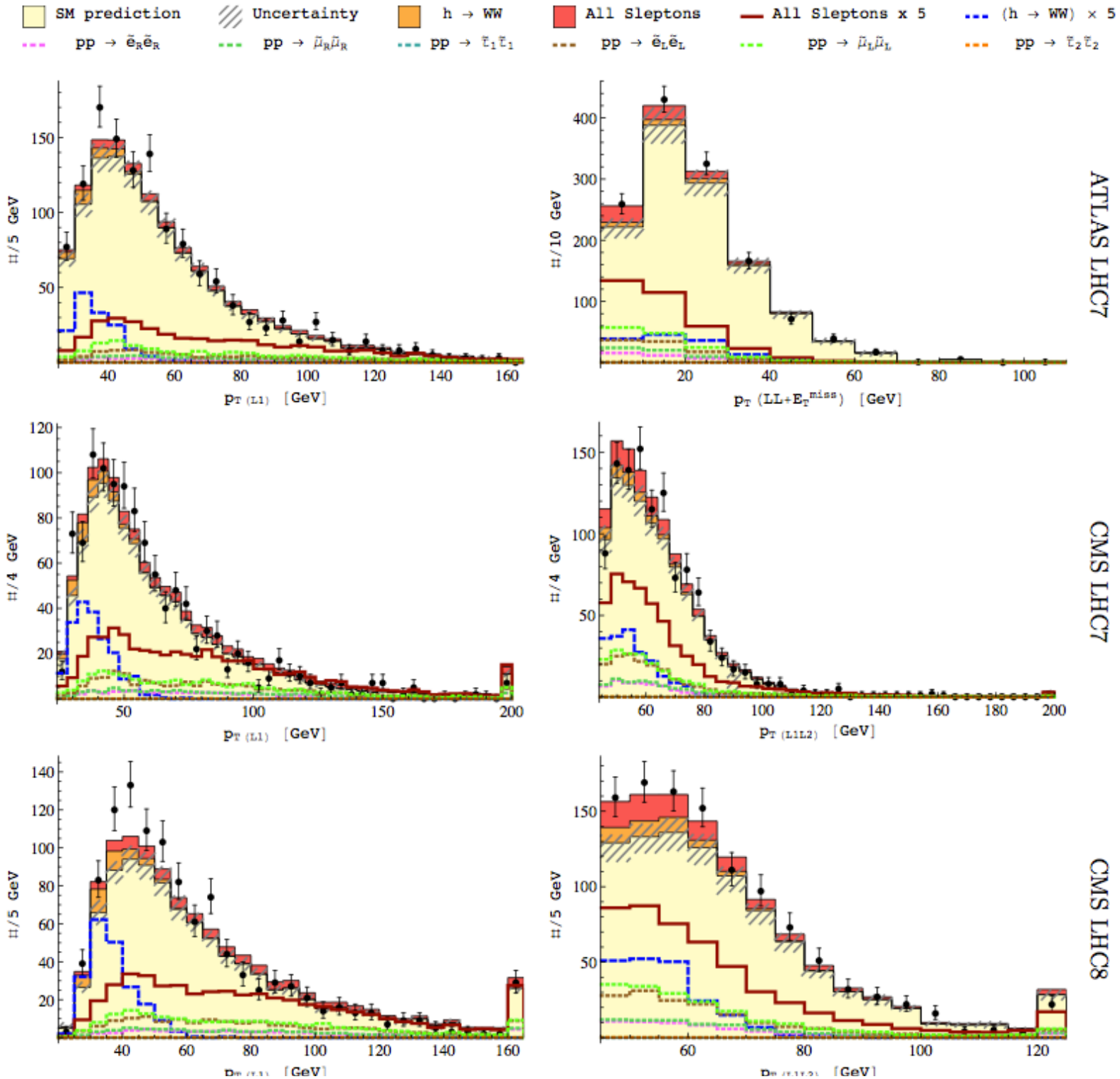




$$r_{\chi^2} = \chi^2_{\mathrm{SM+sleptons}} / \chi^2_{SM}$$






SM prediction
Uncertainty
h → WW
All Sleptons
All Sleptons x 5
(h → WW) × 5
pp → $\tilde{e}_R\tilde{e}_R$
pp → $\tilde{\mu}_R\tilde{\mu}_R$
pp → $\tilde{\tau}_1\tilde{\tau}_1$
pp → $\tilde{e}_L\tilde{e}_L$
pp → $\tilde{\mu}_L\tilde{\mu}_L$
pp → $\tilde{\tau}_2\tilde{\tau}_2$
#/5 GeV
$p_{T\ (L1)}$ [GeV]
#/10 GeV
$p_{T\ (LL+E_T^{miss})}$ [GeV]
ATLAS LHC7
#/4 GeV
$p_{T\ (L1)}$ [GeV]
#/4 GeV
$p_{T\ (L1L2)}$ [GeV]
CMS LHC7
#/5 GeV
#/5 GeV
CMS LHC8

Are there any dangerous processes?

No!

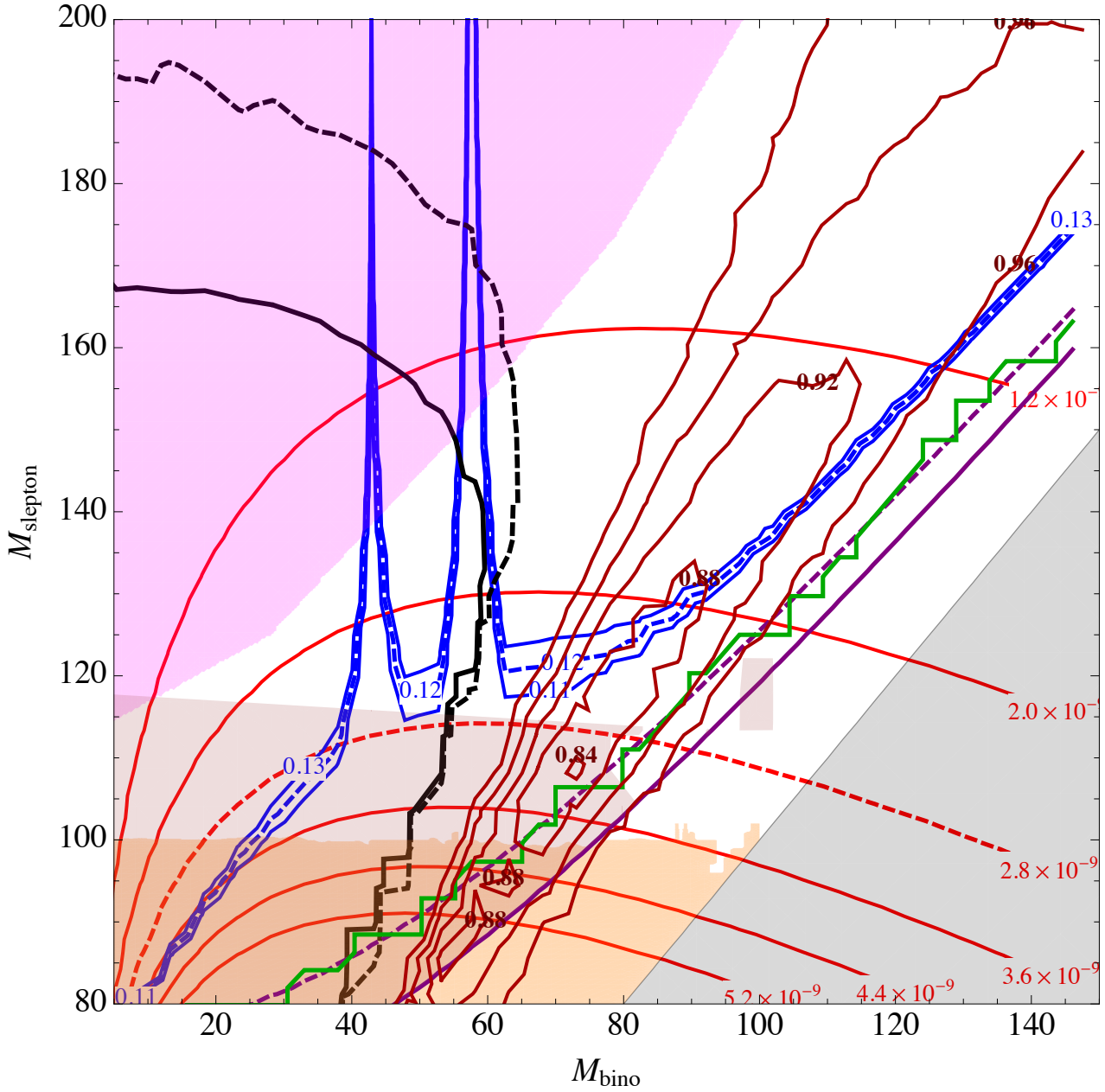
However, WW excess should be concentrated in Same-Flavor channels.

→ **That's our smoking gun!**

We sure would love to see more **flavor-resolved** kinematic distributions for WW. Also, 20/fb?

Interesting pollution of h→WW* signal vs background region would lead to UNDERestimation of signal strength.

Bino-DM, WW, g-2 all work simultaneously!



$\tilde{e}, \tilde{\mu}, \tilde{\tau}$ universal
soft mass ~ 100 GeV

μ ~ 500 GeV
tan β ~ 5

CMS slepton

LEP

combined WW bounds

g-2

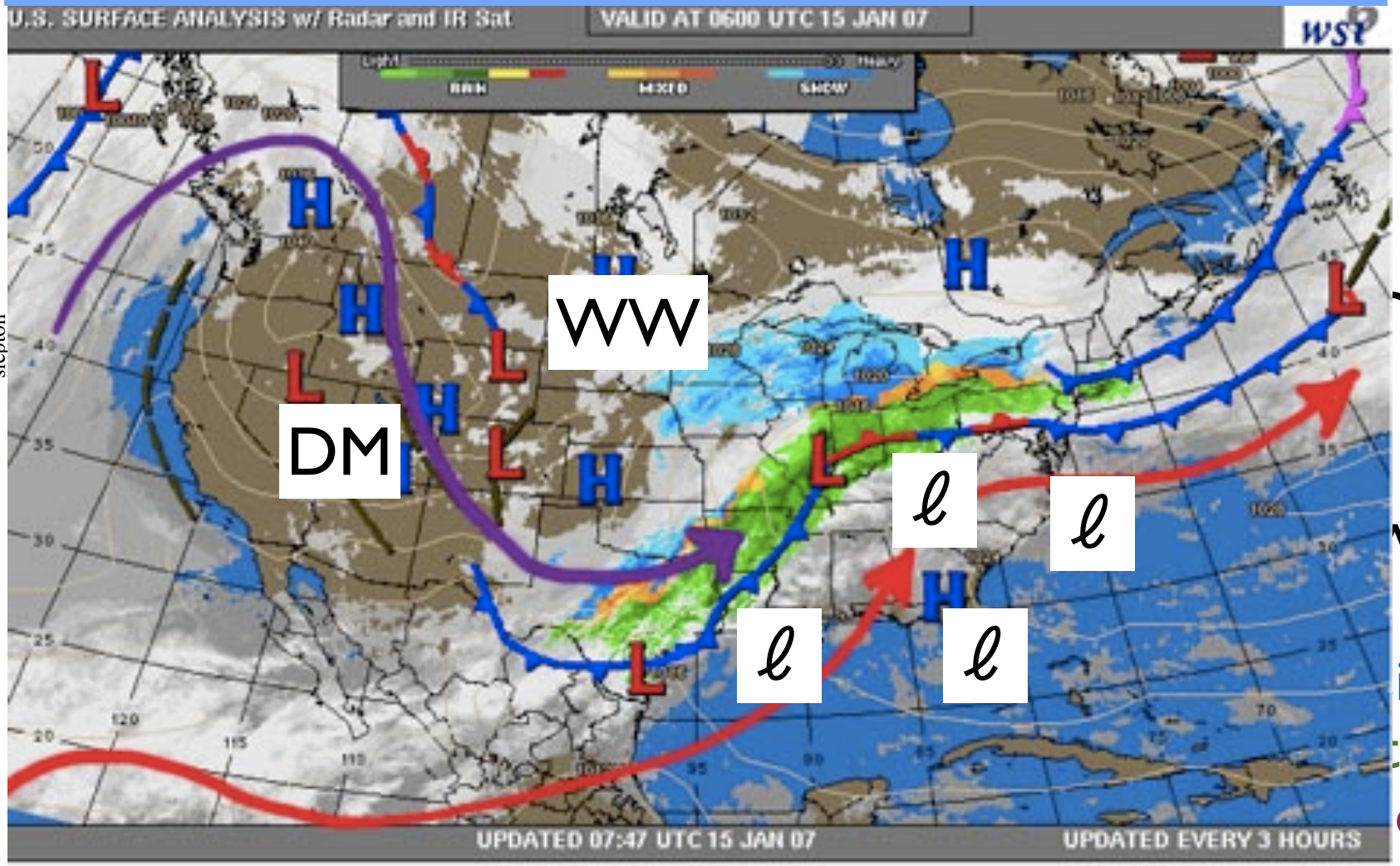
DM relic density

DM direct detection

WW preferred region

Bino-DM, WW, g-2 all work simultaneously!

Forecast for tomorrow:
SUSY, with a chance of sleptons?



M_{slepton}

M_{bino}

universal

100 GeV

GeV

~ 5

LEP

V bounds

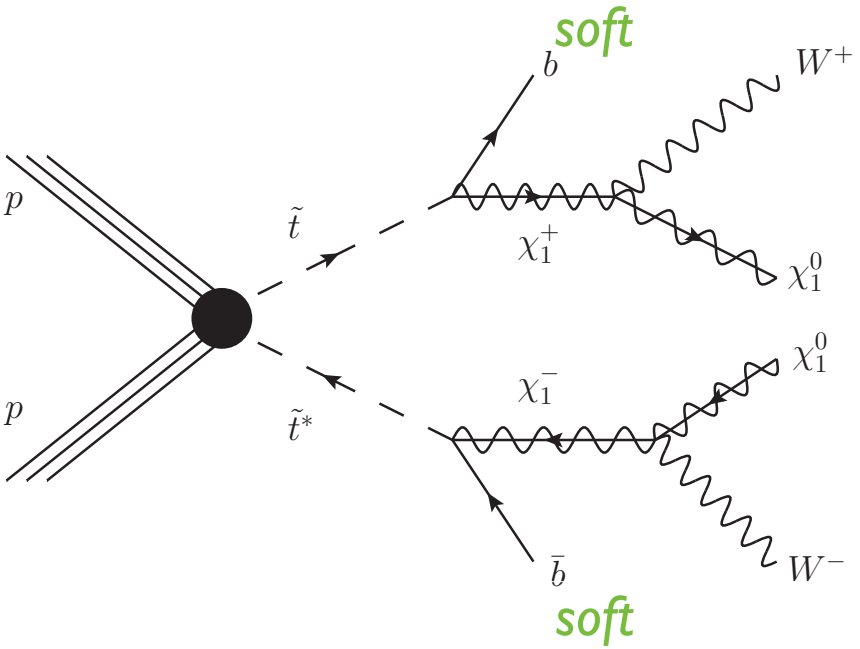
ity

ection

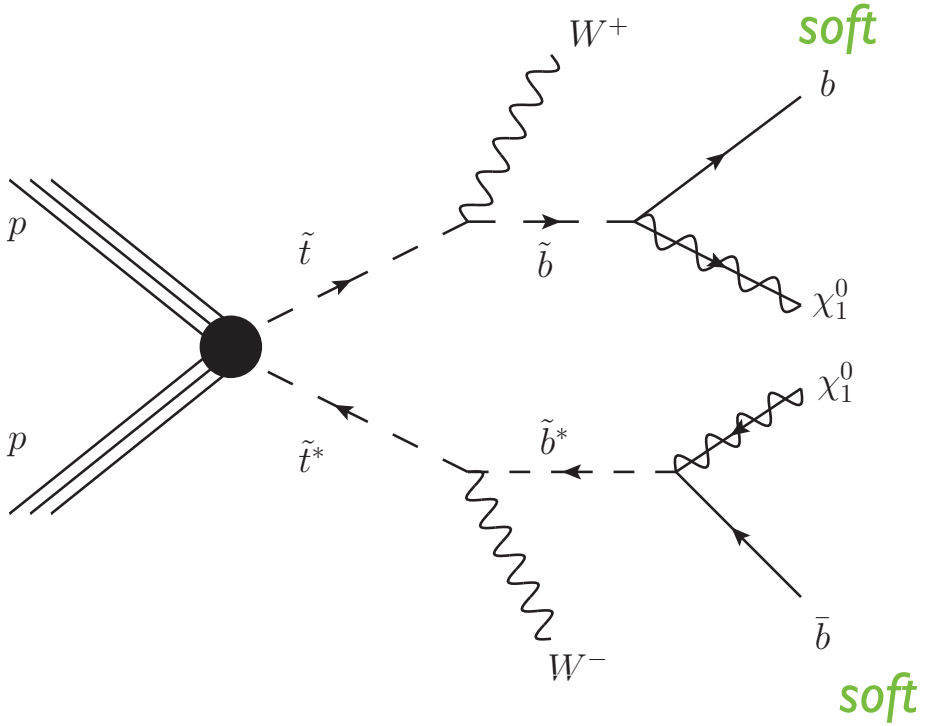
d region

Top Partners

$\tilde{t}_1 \to \chi^+ b$

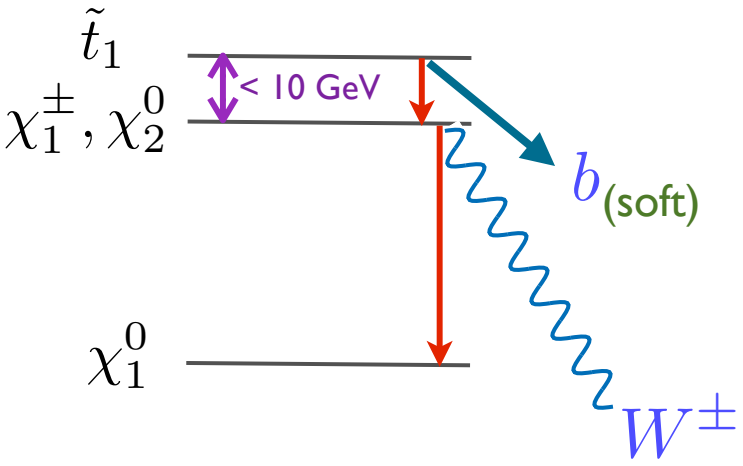


$\tilde{t}_1 \to W^+ \tilde{b}$



Hiding Top Partners in WW

Squeezed Stops

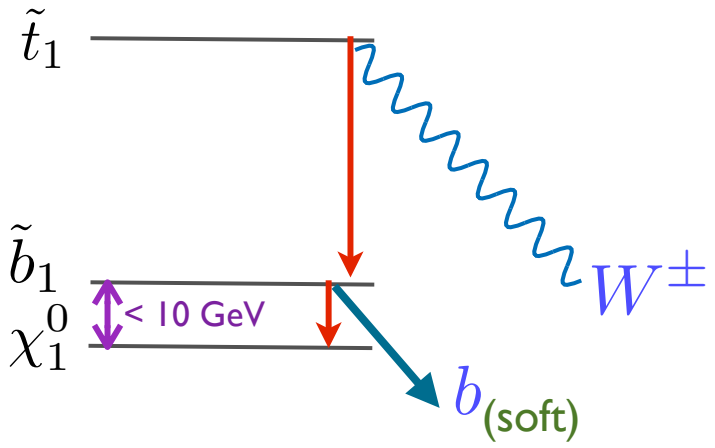


~ 200 GeV

~ 100 GeV

1303.5696 Rolbiecki, Sakurai

Squeezed Sbottoms

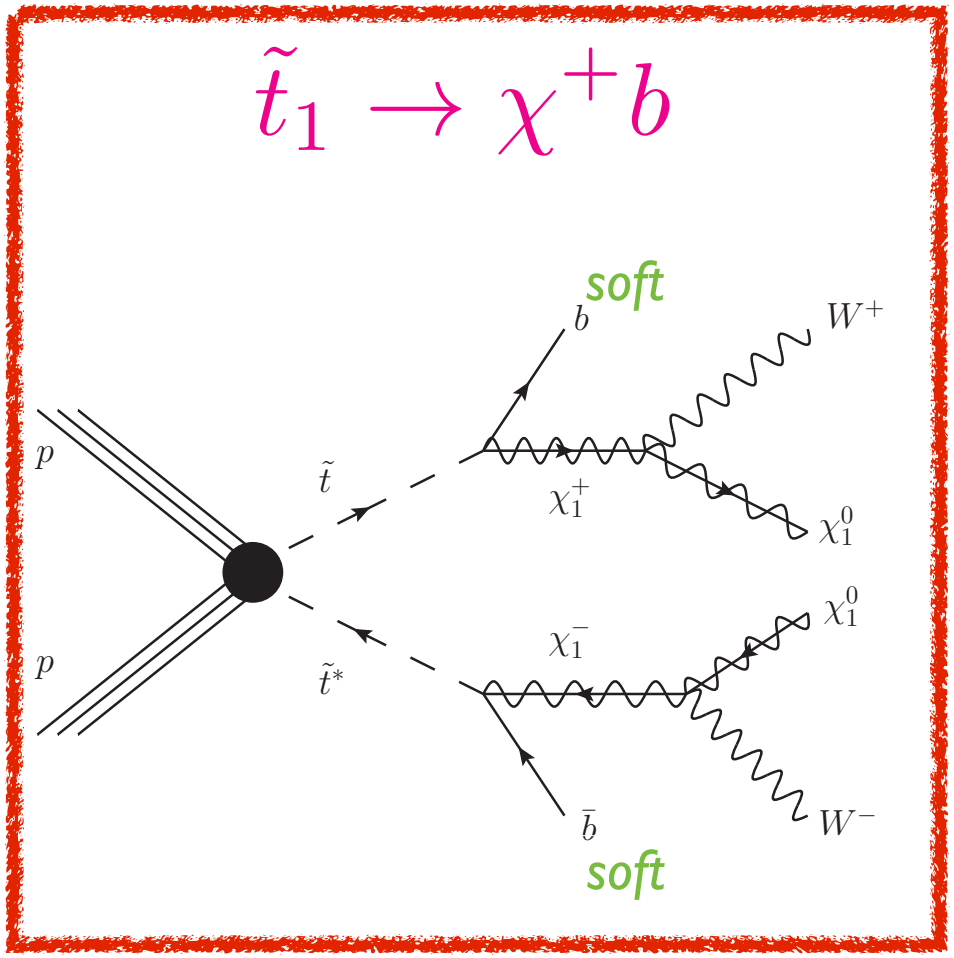


1404.XXXX DC, Patrick Meade, Pin-Ju Tien

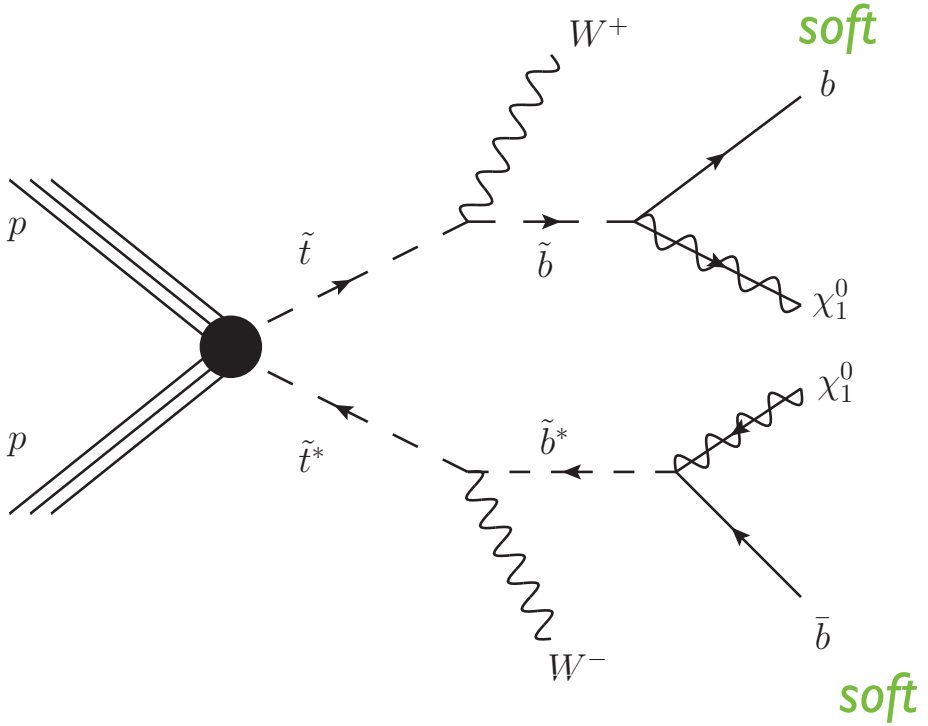
- Light stops decay to W + MET + (soft b)
- Strong stop production cross section O(10pb) allows initial mass scale to be higher (200 GeV) than direct EW production.
- Avoids SS dilepton signal or strong flavor correlatoins in WW, and hides a light stop!
- Sbottom constraints?
- Could even get natural spectrum? Let's see...

Squeezed Stops

$\tilde{t}_1 \to \chi^+ b$



$\tilde{t}_1 \to W^+ \tilde{b}$



Preliminary!

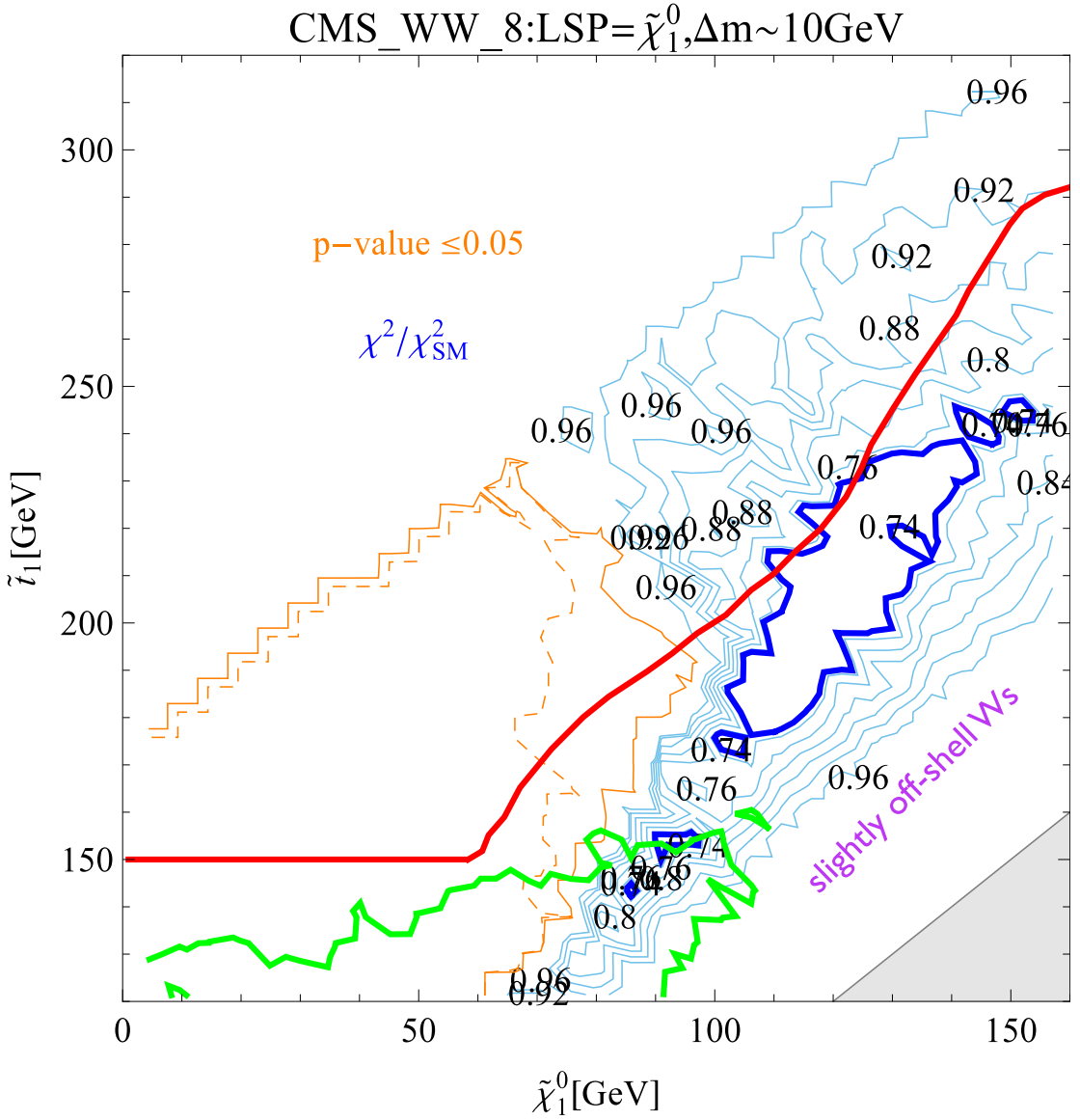
1404.XXXX
(DC, Patrick Meade, Pin-Ju Tien)

Squeezed Stops

Systematically explore squeezed stop parameter space, *including shape analysis*

$$m_{\tilde{t}_1} - m_{\tilde{\chi}_1^\pm} \approx 10 \text{ GeV}$$

Assume other stop is *heavy* enough to evade bounds from top + X decays



ATLAS8 13/fb search for $\tilde{t}_1 \to b + \chi_1^+$
ATLAS-CONF-2012-167

ATLAS7 5/fb search for LIGHT stop
1208.4305

WW χ^2 improvement

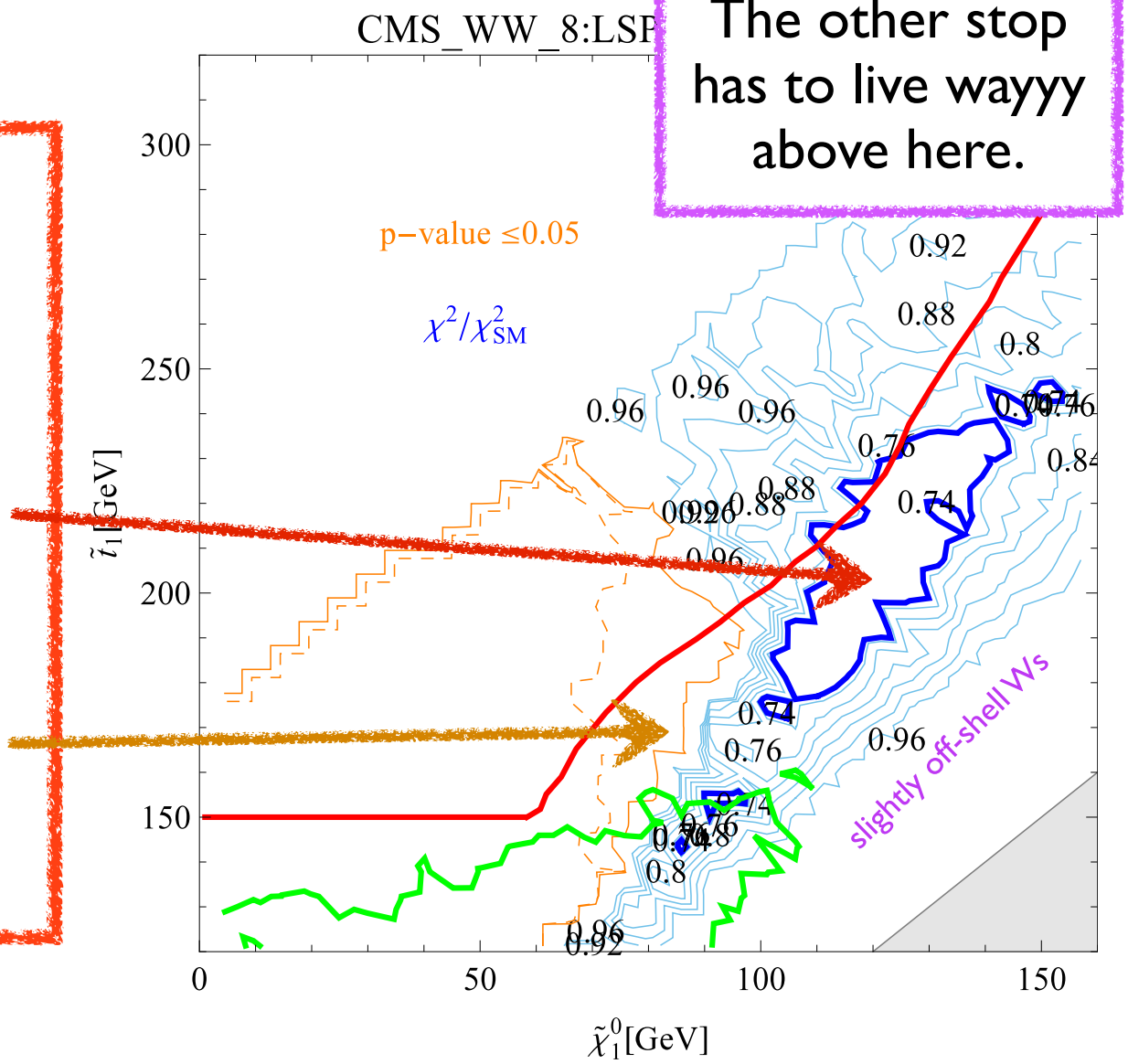
WW bounds

Preliminary!

1404.XXXX
(DC, Patrick Meade, Pin-Ju Tien)

Squeezed Stops

- "WW-funnel", where high-MET searches loose sensitivity, is probed by WW
- Stops could live in that funnel and improve fit of WW data
- new bounds from WW fill in gap between two direct searches



Prediction:
~ 200 GeV Chargino!

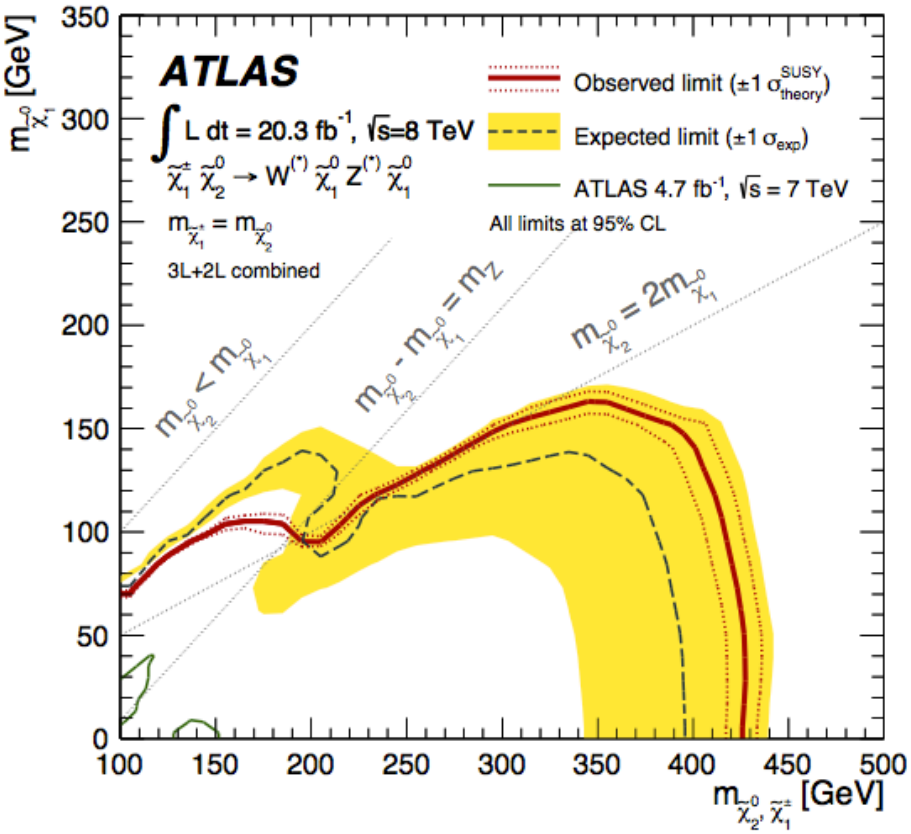
Preliminary!

1404.XXXX
(DC, Patrick Meade, Pin-Ju Tien)

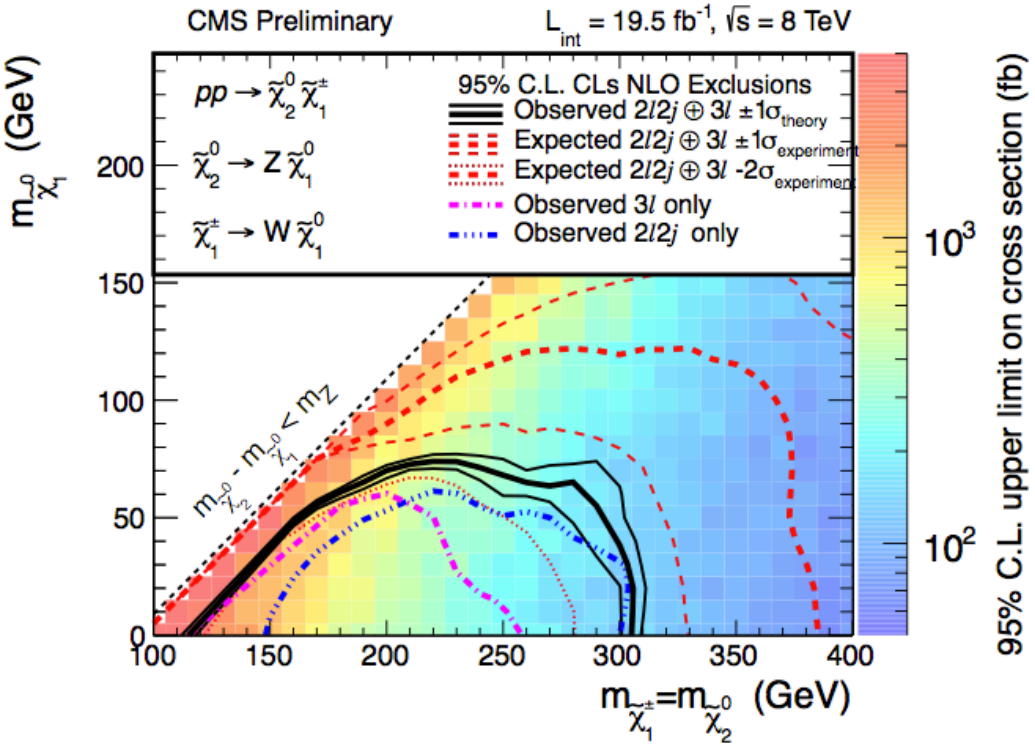
Squeezed Stops

Prediction: ~ 200 GeV Chargino!

1402.7029



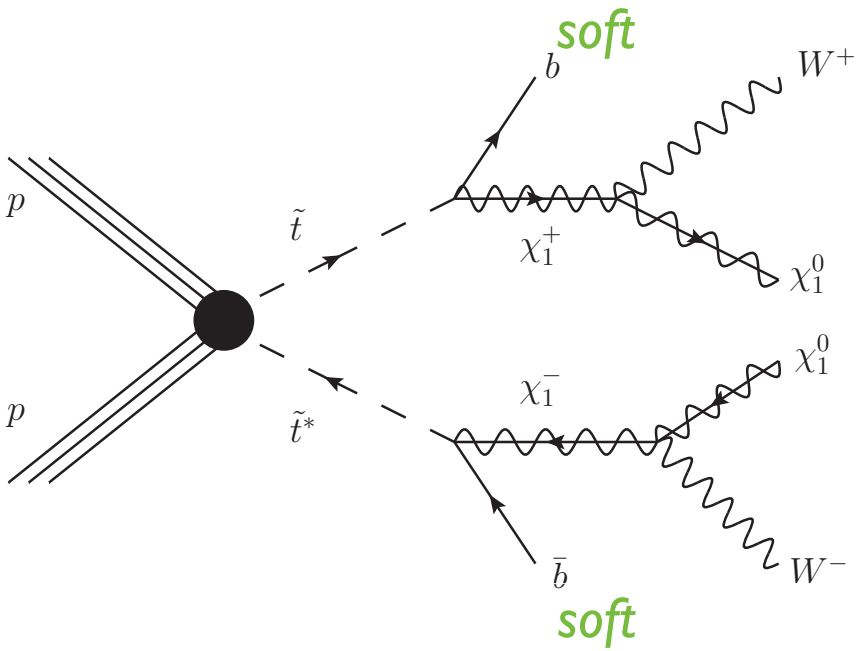
SUS-13-006-pas



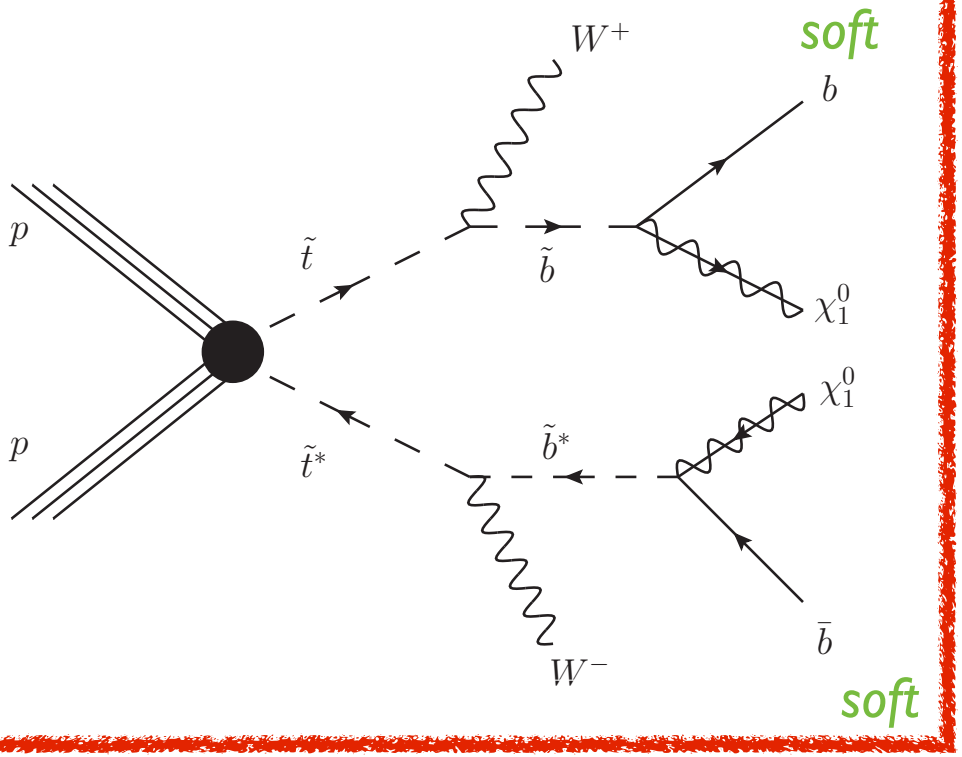
Both ATLAS and CMS chargino exclusion bounds are lower than expected in that region!

Squeezed Sbottoms

$\tilde{t}_1 \to \chi^+ b$



$\tilde{t}_1 \to W^+ \tilde{b}$

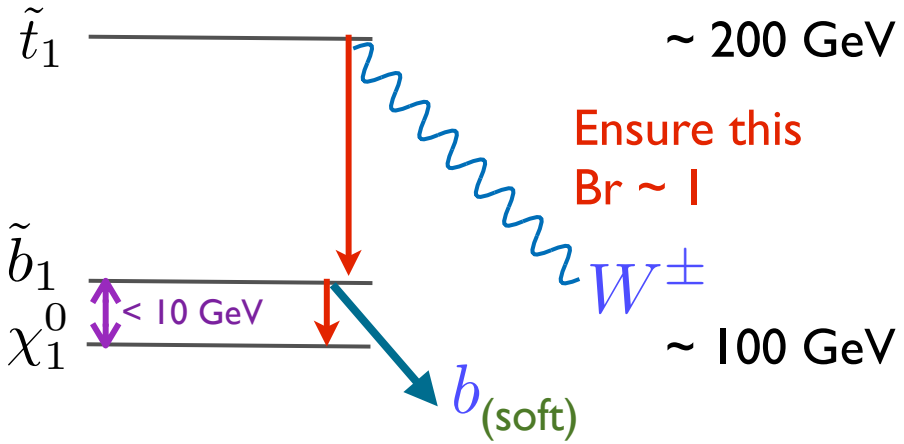


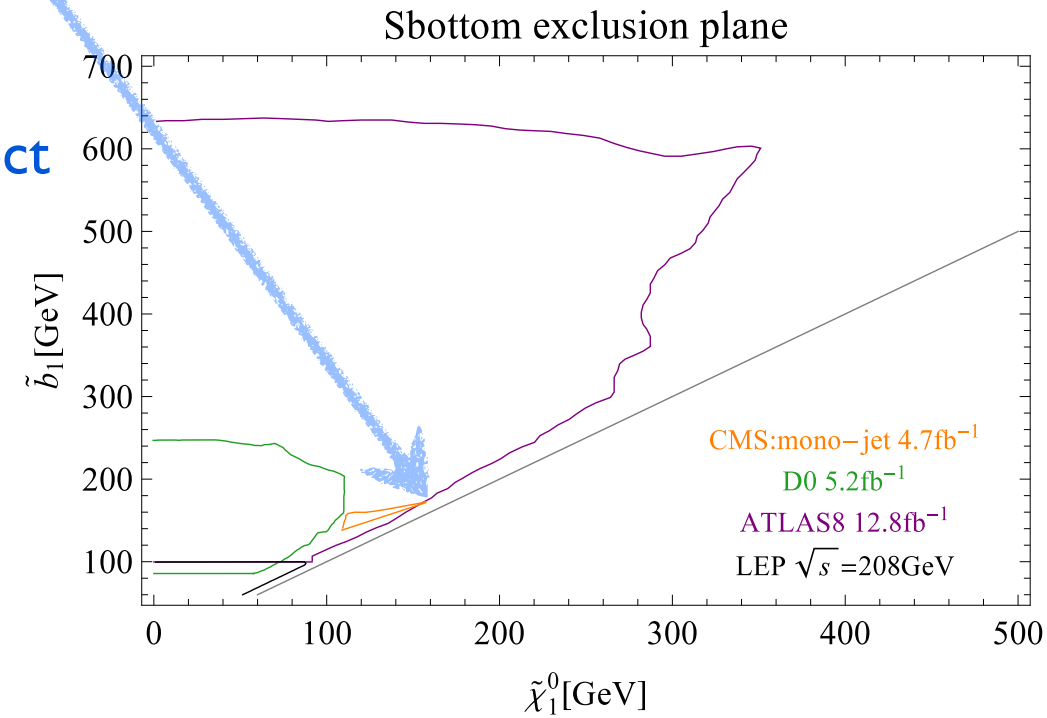
Preliminary!

Squeezed Sbottoms

1404.XXXX
(DC, Patrick Meade, Pin-Ju Tien)

- New way to hide stops in WW.
- In Stop-LSP mass plane, same region preferred by WW as for squeezed stop case previously.
- Sbottom searches give stringent constraints, but those could be weaker for m_{b1} - mX0 < 10 GeV
- Sbottoms could provide t-channel annihilation for bino DM → correct relic density possible!
- Heavy(er) charginos ⇛ could also insert sleptons into spectrum for muon (g-2) or thermal Bino DM.





Preliminary!

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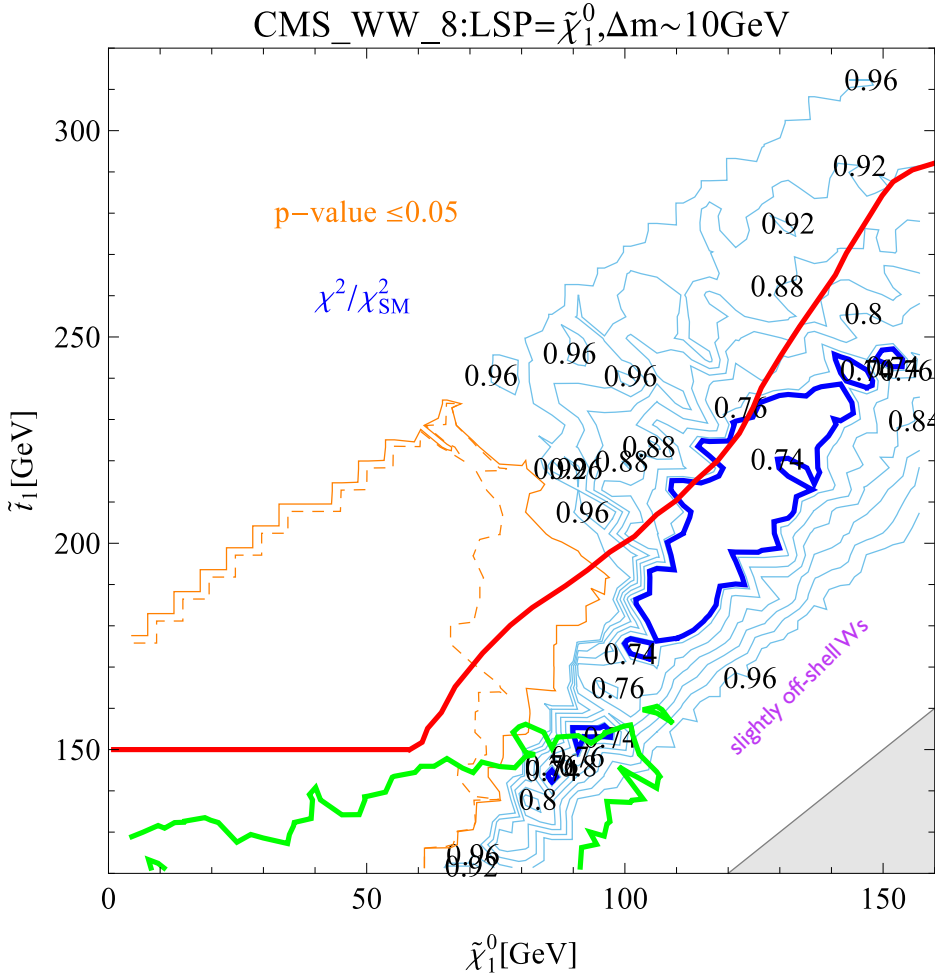
(DC, Patrick Meade, Pin-Ju Tien)

(Plots from squeezed stop case)

Same kinematic region preferred as for squeezed stop case.



Could a *fully natural* stop spectrum be hiding in WW??

Preliminary!

Natural Squeezed Stops

Let's not worry where m_h = 125 GeV comes from (NMSSM, D-terms, ...).

Minimize quadratic corrections to higgs mass (minimal/no tuning)
⇛ want as light a stop spectrum as possible

What if both stops were light and nearly **degenerate**?

1404.XXXX (DC, Patrick Meade, Pin-Ju Tien)

Preliminary!

1404.XXXX
(DC, Patrick Meade, Pin-Ju Tien)

Squeezed Stops

Degenerate stops means no top + X decays

$m_{t1} = m_{t2}$ also preferred kinematically from WW

ATLAS8 13/fb search for $\tilde{t}_1 \to b + \chi_1^+$
ATLAS-CONF-2012-167

ATLAS7 5/fb search for LIGHT stop
1208.4305

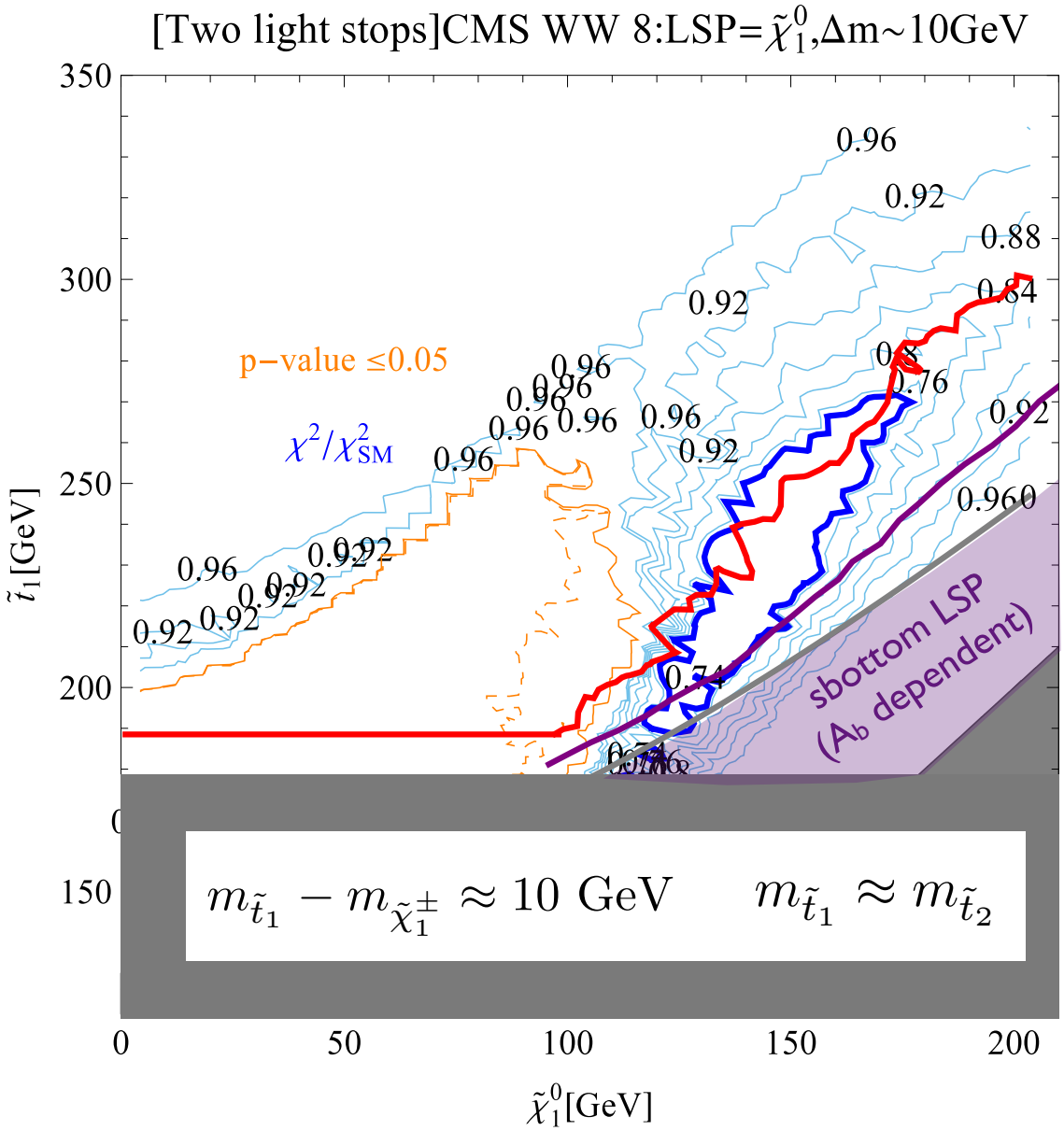
WW χ^2 improvement

WW bounds

ATLAS7 13/fb sbottom search
ATLAS-CONF-2012-165

$$\tilde{b}_L \to b + \tilde{\chi}_1^0$$

$$m_{\tilde{b}_L} \approx m_{\tilde{t}_1} - (30 \text{ to } 60 \text{ GeV})$$



Preliminary!

1404.XXXX
(DC, Patrick Meade, Pin-Ju Tien)

Squeezed Stops

Degenerate stops means no top + X decays

$m_{\tilde{t}_1} = m_{\tilde{t}_2}$ also preferred

Prediction:

if a natural squeezed stop spectrum hides in WW it looks like this:

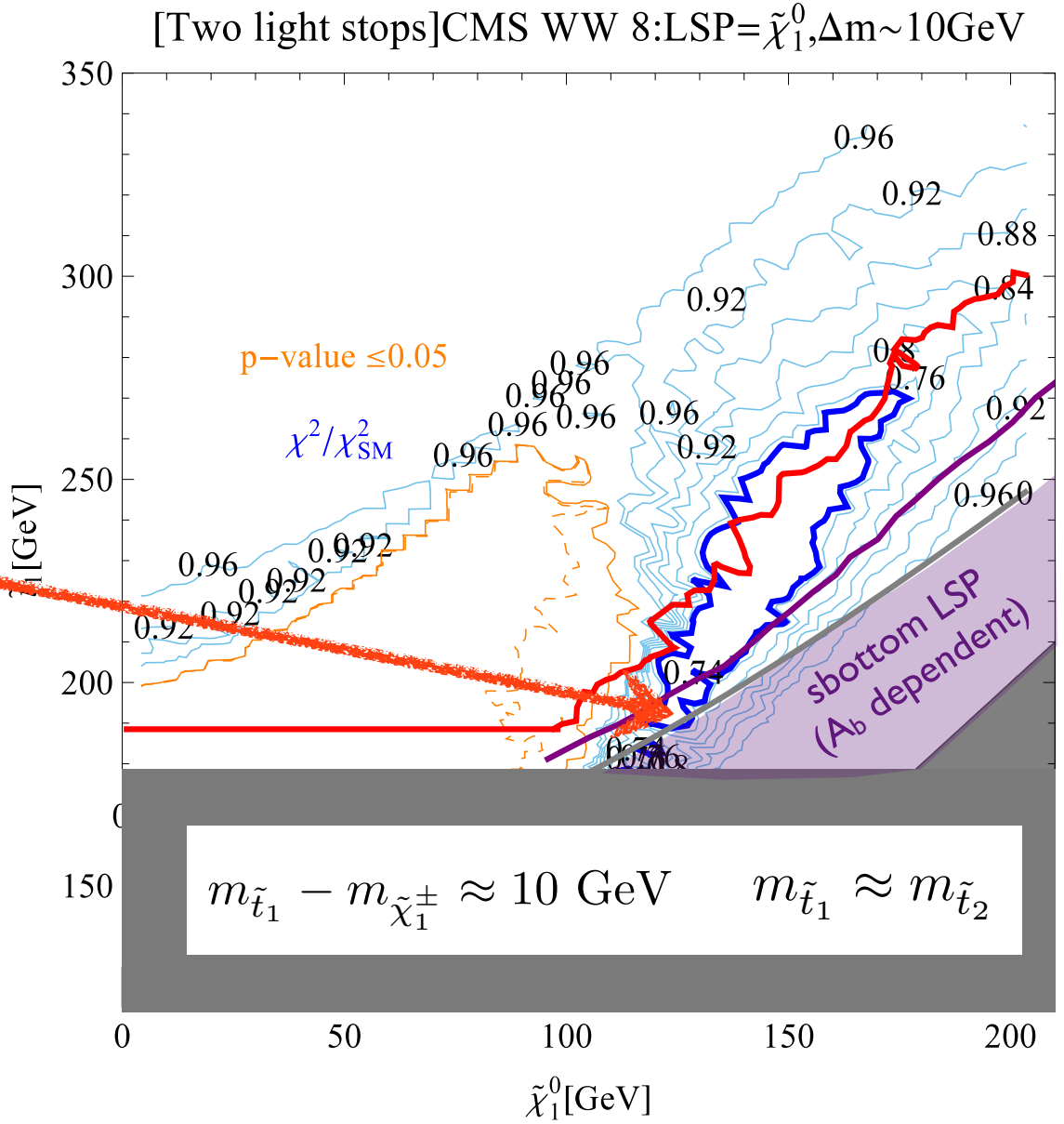
stops ~ 200 GeV

chargino ~ 190 GeV

LSP ~ 130 GeV

$$\tilde{b}_L \to b + \tilde{\chi}_1^0$$

$$m_{\tilde{b}_L} \approx m_{\tilde{t}_1} - (30 \text{ to } 60 \text{ GeV})$$

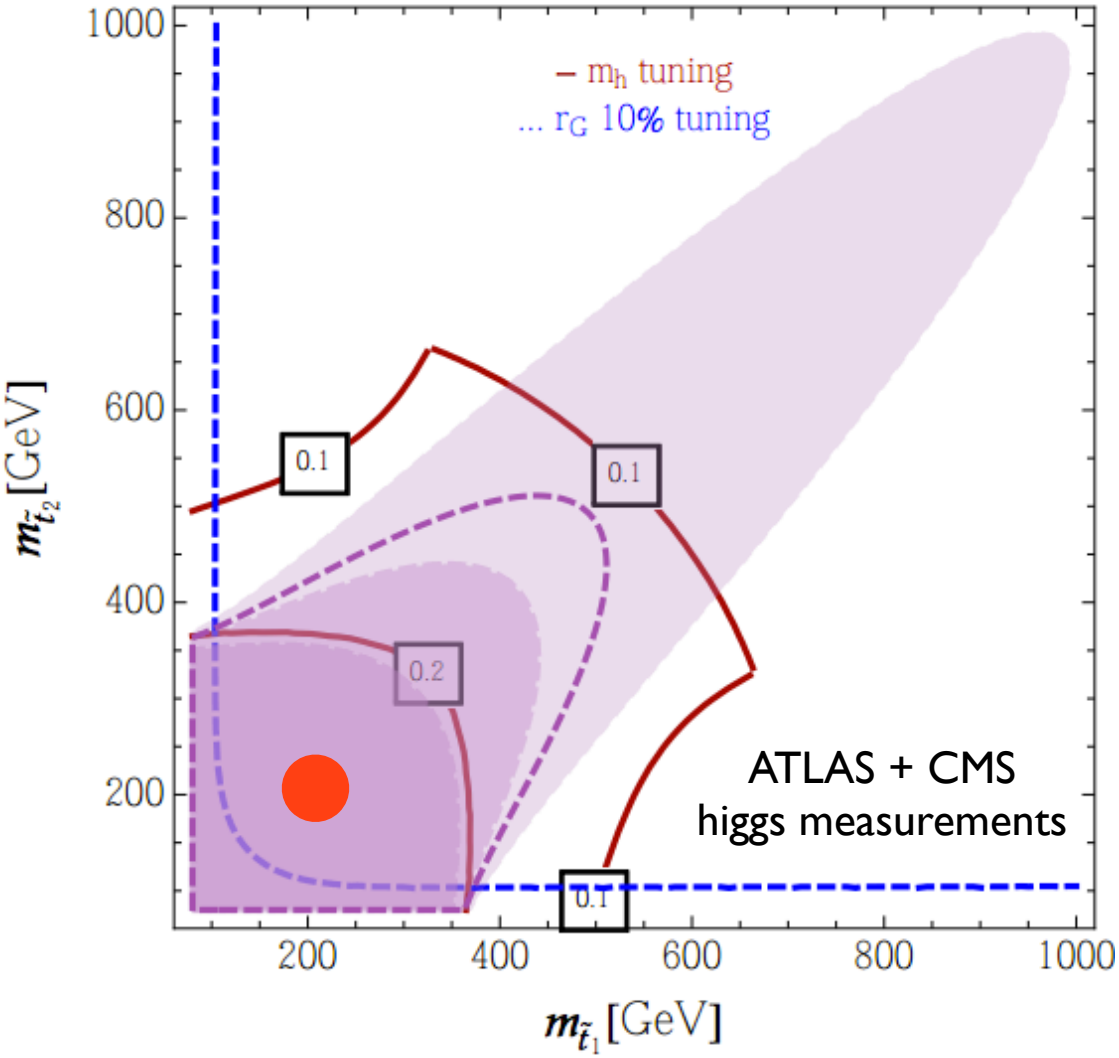


What about higgs constraints on such light stops?

Higgs Constraints

1401.7671 (Fan, Reece)

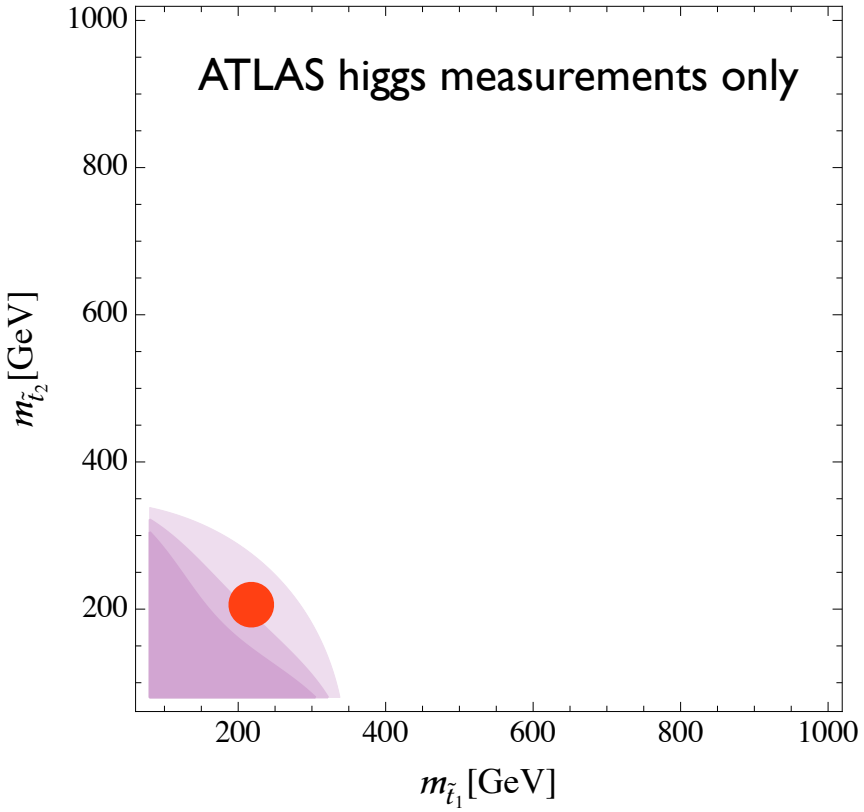
- For each choice of stop1,2 masses there is a MAXIMUM allowed mixing to get masses, but a MINIMUM required mixing to have those stops not spoil measured higgs couplings.
- When these two mixing requirements are in conflict you can get constraints.
- Assumes nothing else modifying higgs coupling.

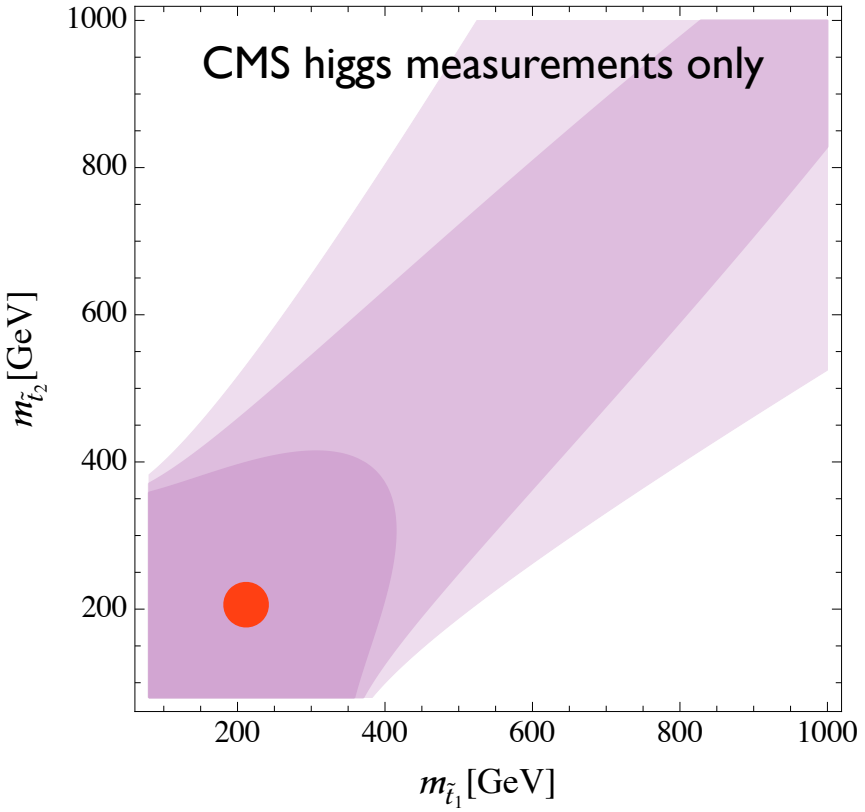


Our natural spectrum is excluded at > 3σ?

Higgs Constraints

Figures provided by Fan & Reece





ATLAS and CMS disagree strongly on h → γγ

ATLAS says our spectrum is OK!

What's the upshot? (upstop?)

1. If there are 1 or 2 stops hiding in WW, they have mass ~ 200 GeV, and come with ~100 GeV LSP &
   EITHER ~190 GeV chargino OR ~110 GeV Sbottom

2. stop2 is either very heavy to escape t + MET searches, or it is degenerate with stop1

3. If stop2 is degenerate with stop1, then either CMS $h \to \gamma\gamma$ is off, or there are additional particles in loops (sbottoms?) ⇛ MORE NEW PHYSICS! (not to mention how to generate the higgs mass...)

4. Squeezed sbottom scenario can also accommodate light sleptons
   ⇛ thermal Bino DM and muon (g-2)!

5. Any scenario with sbottoms could be excluded by refining predictions for sbottom signal in highly squeezed regions.

6. There are kinematic discriminants to find stops in WW directly with LHC8 data at 3σ level! (1303.5696)

Conclusion

Conclusions

- Diboson measurements should be used to set constraints on new physics, since they are sensitive to mass regions missed by high-MET searches.
- No obvious SM sources for excess. WW cross section prediction should be improved, and **systematic errors** need to be reduced. Some partial progress already!
- We could have already seen SUSY hiding in SM Standard Candles! WW anomaly offers tantilizing hints of possible new physics:
  - Charginos can work, but maybe under tension with SSDL.
  - Sleptons give **WW, DM, (g-2)$_\mu$**. Predict flavor-diagonal excess.
  - **Stops** can hide in **WW**, maybe even have a **natural SUSY spectrum**. Squeezed sbottom can also include **DM, (g-2)$_\mu$**

General rule:
You can fit **a lot** of sub-300-GeV BSM into the leptonic WW final state!