Sniffing out new physics with Standard Model Standard Candles

Theory Seminar
Rutgers University

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Yang Institute for Theoretical Physics
Stony Brook

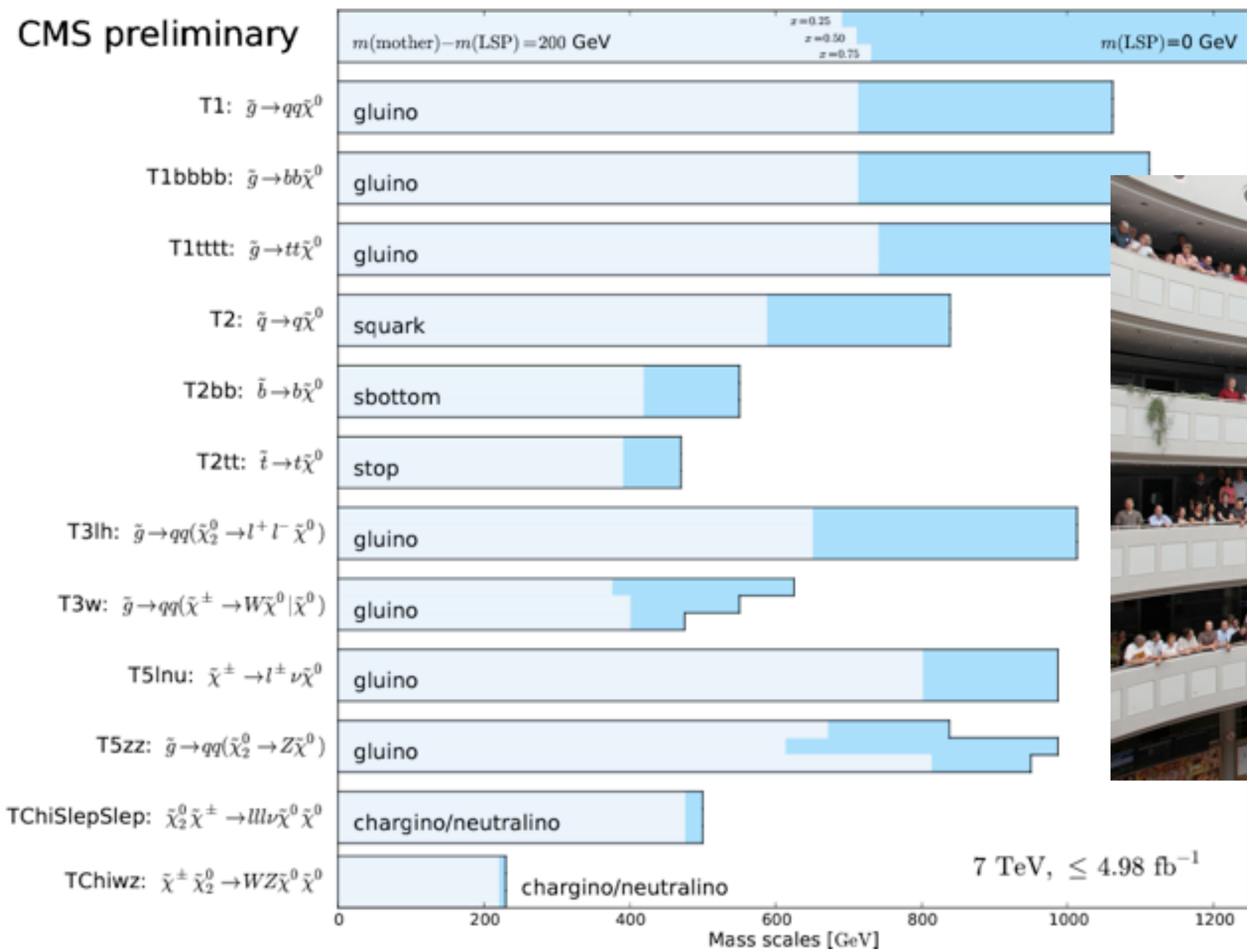
Based on

1206.6888 (DC, Prerit Jaiswal, Patrick Meade)
1304.7011 (DC, Prerit Jaiswal, Patrick Meade, Pin-Ju Tien)

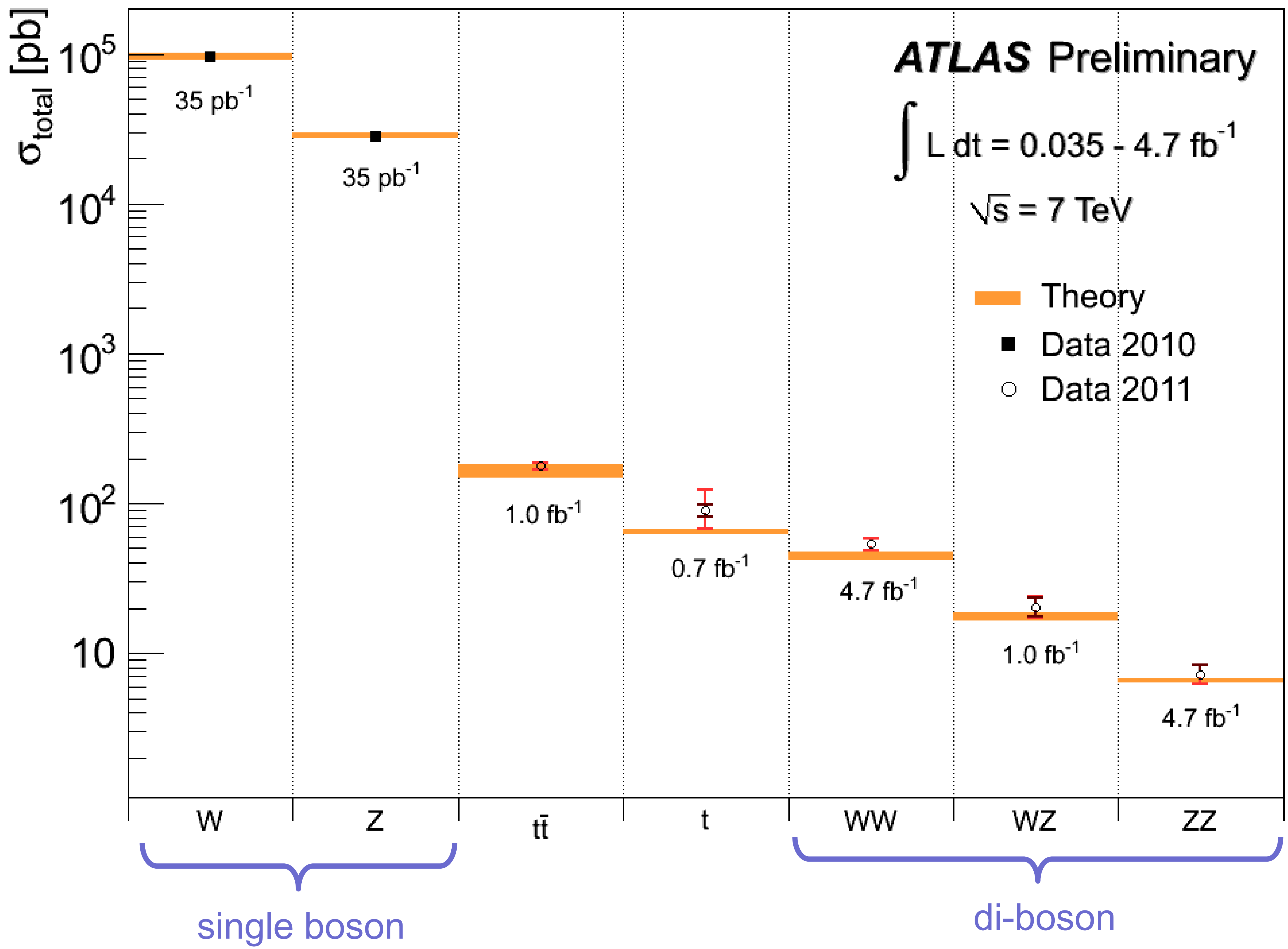
Outline

- *Something's afoot in WW...*
- Something Fancyful:
  Dreaming about new electroweak states to explain the discrepancies
- Something Archival:
  "Boring" SM measurements have BSM exclusion power! (Don't need LEP-like precision)
  → **Produce qualitatively new limits**
- Being responsible citizens: what else could it be?

Oh SUSY, where art thou?

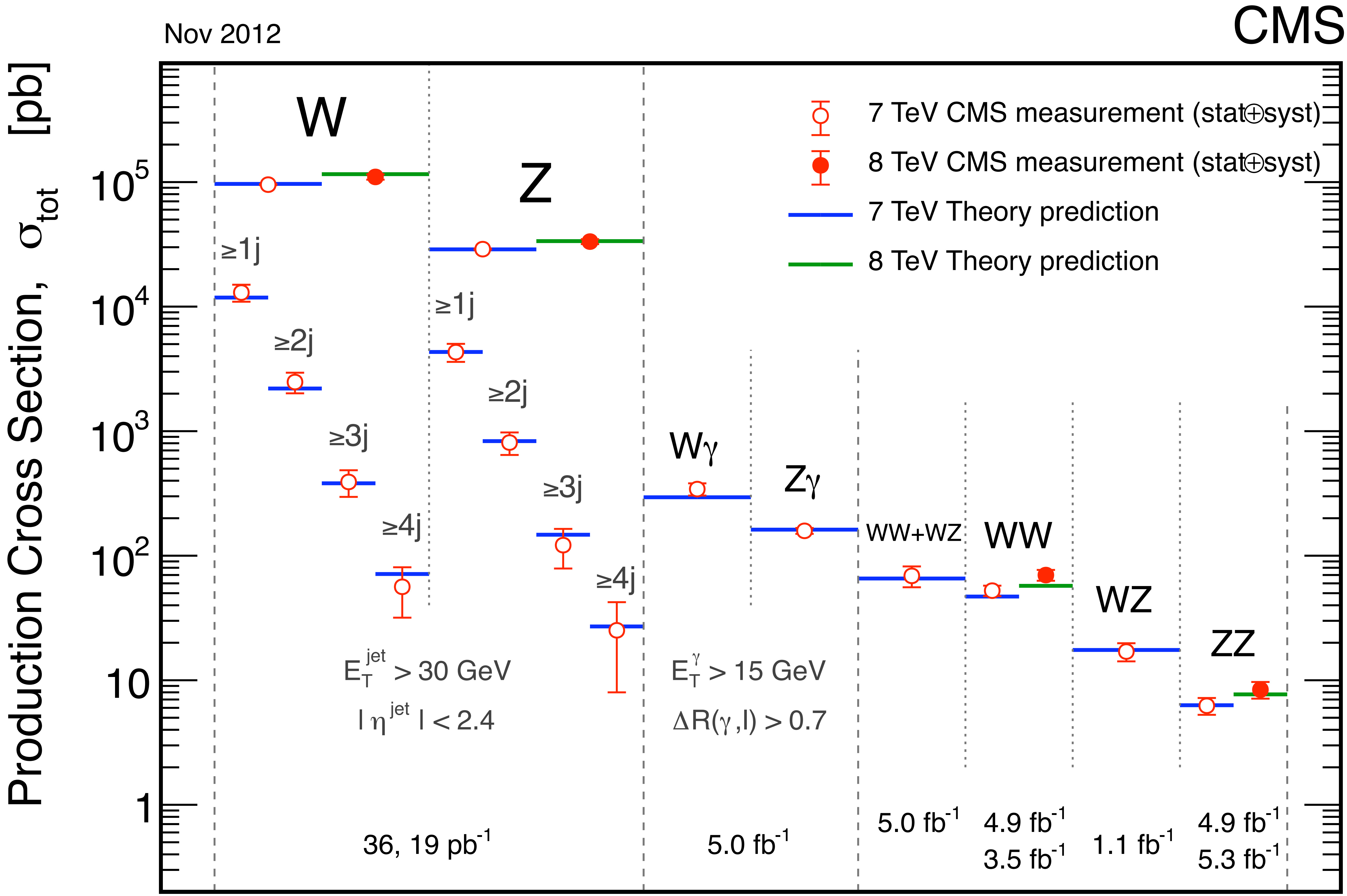


Let's use Standard Candles to look under the lamppost...

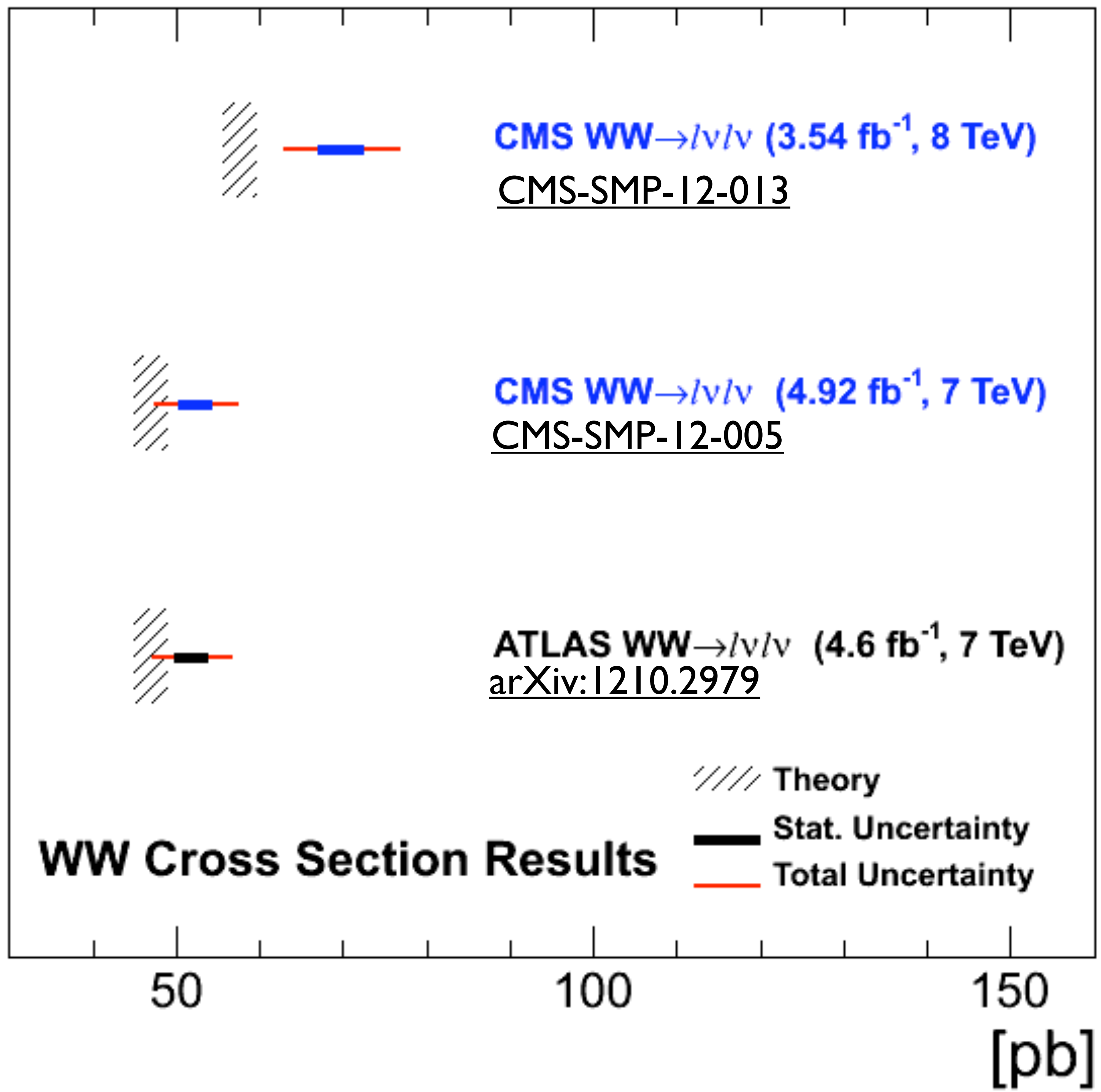


- Very similar agreement with (N)NLO predictions is observed by CMS

CMS EW HCP ZOOM IN



Some visual "evidence"



WW cross section

- In principle the LHC makes 8 measurements highly sensitive to the WW cross section
  - SM WW at CMS7, ATLAS7, CMS8, ATLAS8
  - $h \longrightarrow WW$ at CMS7, ATLAS7, C
- What's the status?

ww measurement:
OS dilepton + jetveto
min lepton pT, Z veto
MET > about 50, pTLL > about 50

h->ww measurement (0j)
OS dilepton + jet veto
min lepton pT, Z veto
MET > about 50, pTLL > about 50
mLL < 50
delta_phi_ll < 1.8

h->ww control region (0j)
as above, except
mLL > about 100
no delta_phi_ll requirement

SO BASICALLY h->WW and WW have same cuts, except for and additional mLL and phiLL requirement for h->WW

WW cross section

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Every reported* measurement is higher than the SM

WW cross section

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- What's the status?

Every reported* measurement is higher than the SM

NOT Fermi line high...

No neutron stars or earth's limb either.....

WW cross sec measurements

ATLAS 7

$$\sigma(pp \to W^+W^-) = 53.4 \pm 2.1(\text{stat}) \pm 4.5(\text{sys}) \pm 2.1(\text{lum})\ \text{pb}$$

CMS 7

$$\sigma(pp \to W^+W^-) = 52.4 \pm 2(\text{stat}) \pm 4.5(\text{sys}) \pm 1.2(\text{lum})\ \text{pb}$$

NLO theory at 7 TeV:

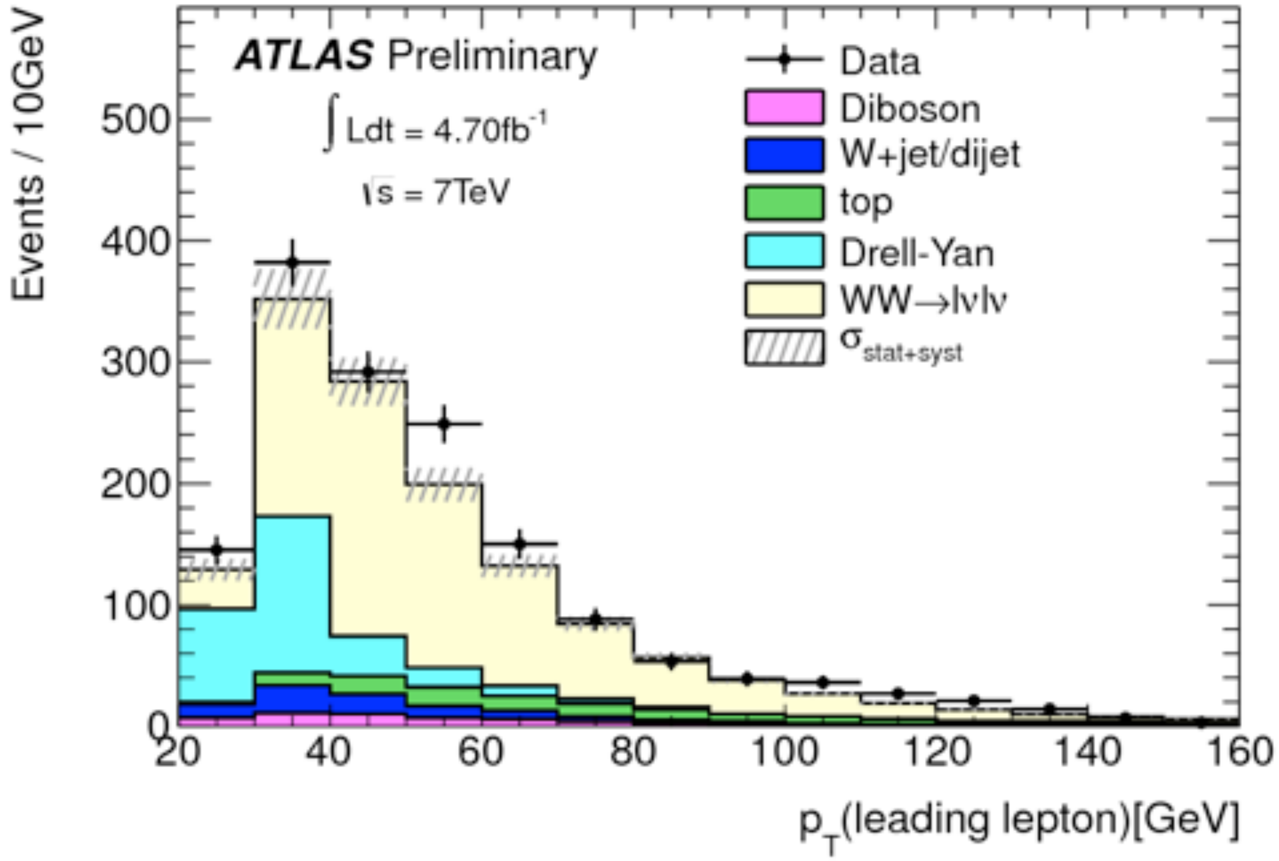
$$\sigma(pp \to W^+W^-) = 45.1 \pm 2.8\,\text{pb}$$ ATLAS MC@NLO

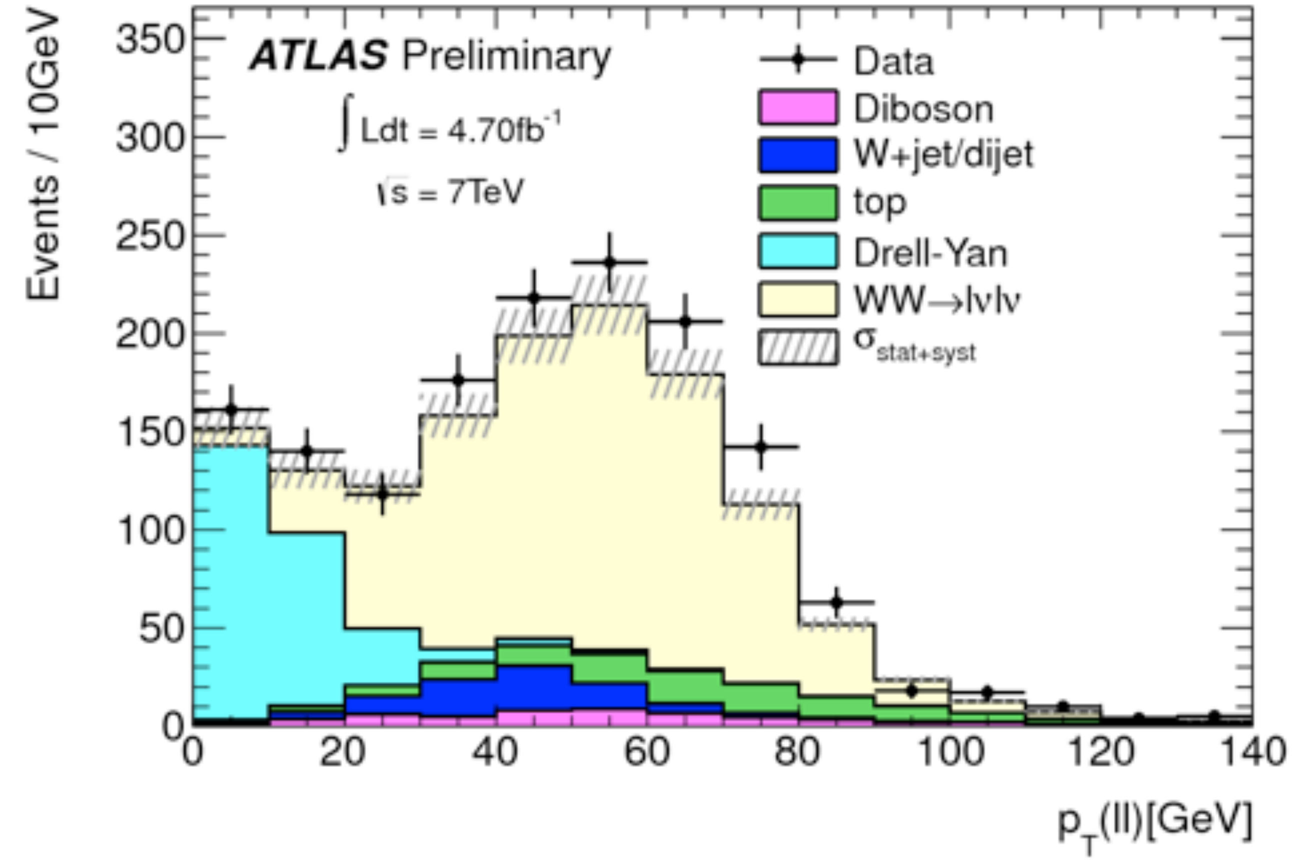
$$\sigma(pp \to W^+W^-) = 47 \pm 2\,\text{pb}$$ MCFM

Campbell, Ellis, Williams

1.4σ and 1σ is an "anomaly"?

- ATLAS and CMS are more consistent with each other than the SM...
- NOT just a "rate" anomaly


ATLAS Preliminary
∫ Ldt = 4.70fb-1
√s = 7TeV
Data
Diboson
W+jet/dijet
top
Drell-Yan
WW→lνlν
σstat+syst
Events / 10GeV
pT(leading lepton)[GeV]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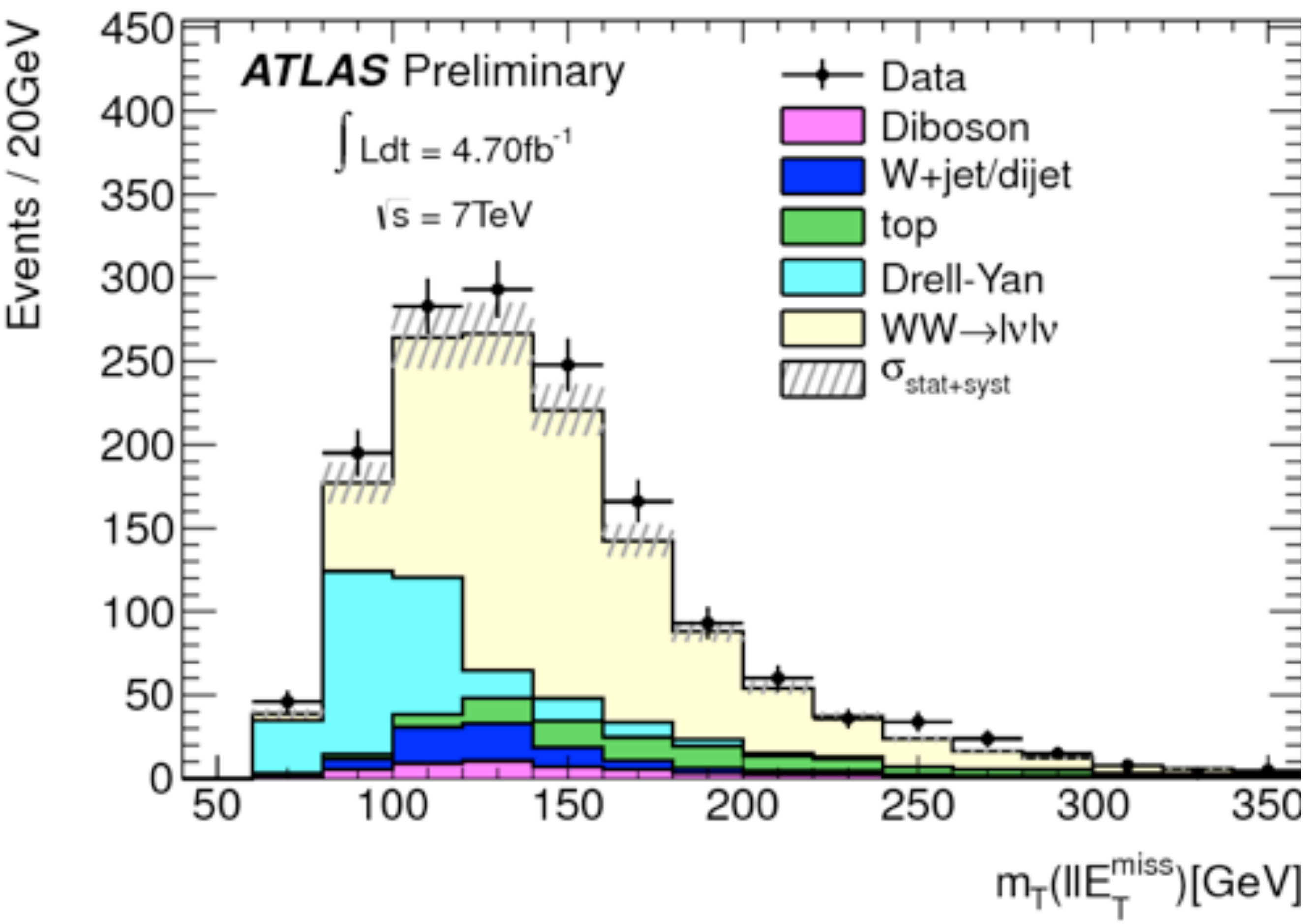
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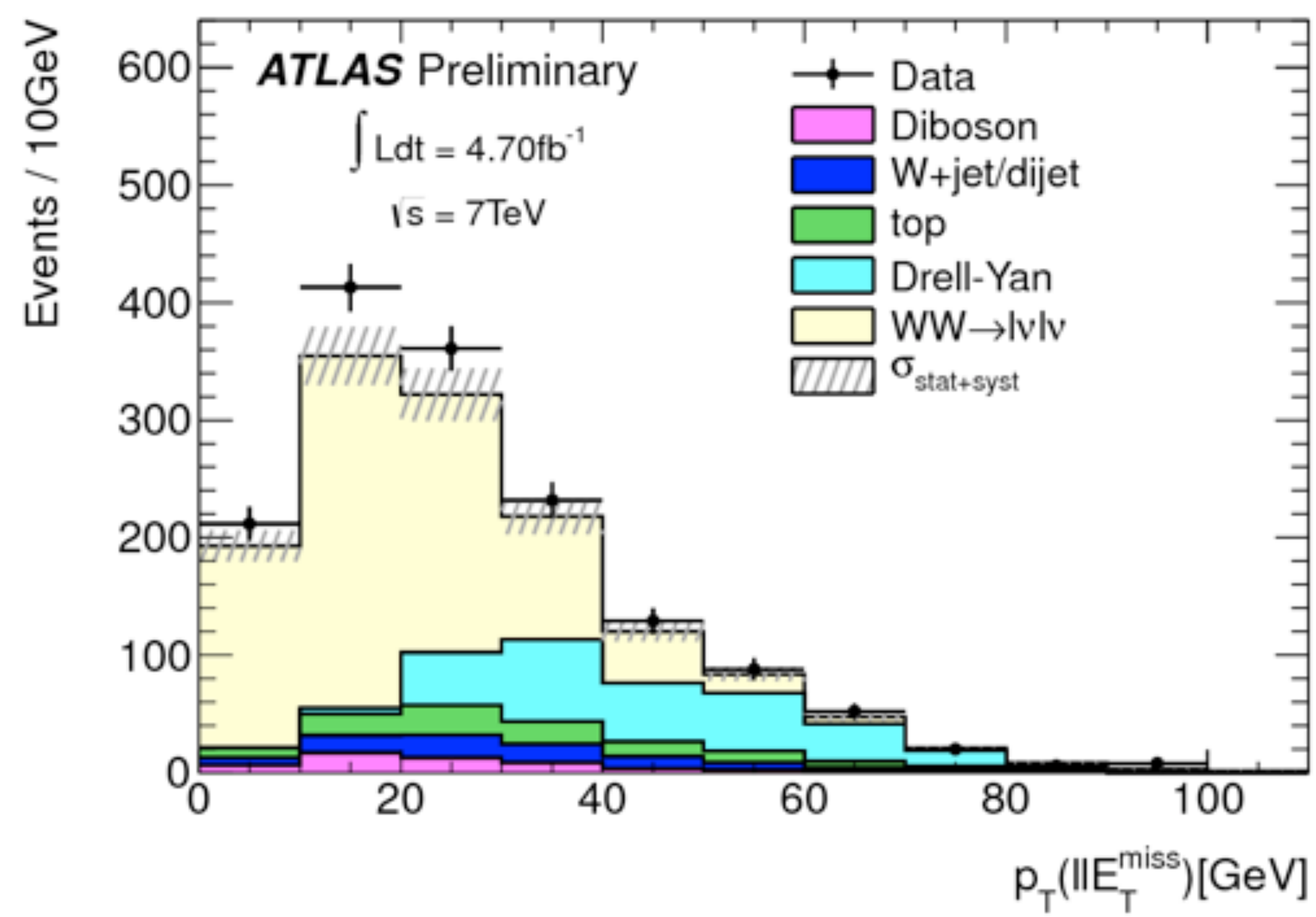
Events / 20GeV
mT(llETmiss)[GeV]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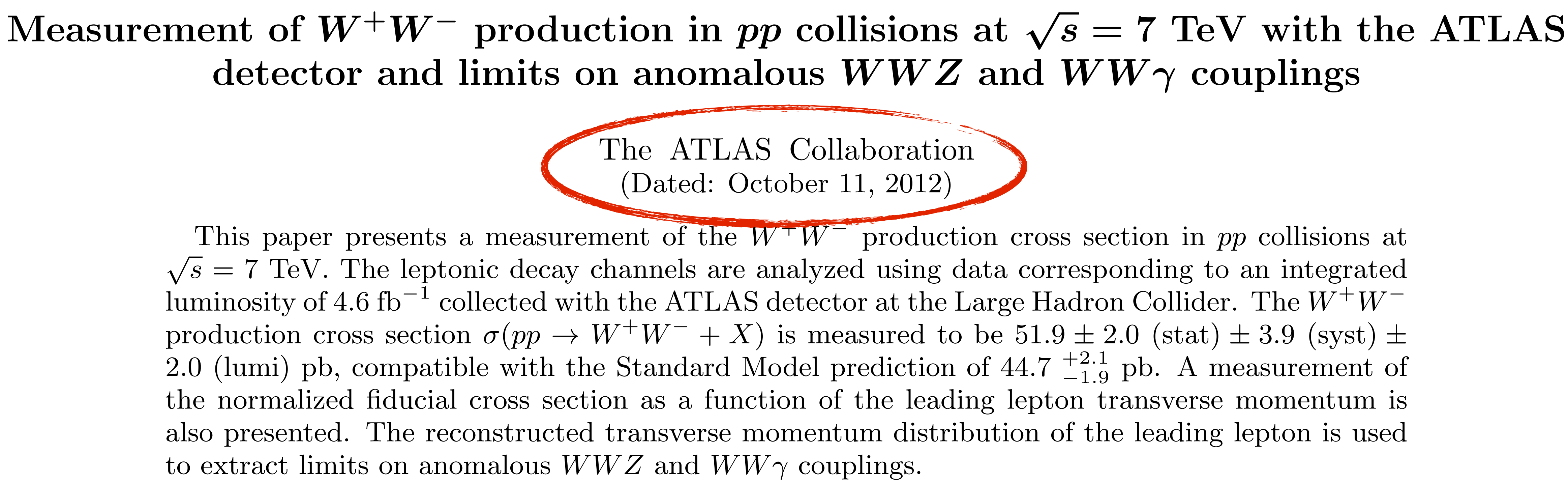
Updated LHC-7



Significance about the same as before

Additional pt(ll) cut

Updated LHC-7

Measurement of W^+W^- production in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector and limits on anomalous WWZ and $WW\gamma$ couplings

The ATLAS Collaboration
(Dated: October 11, 2012)

This paper presents a measurement of the W^+W^- production cross section in pp collisions at $\sqrt{s} = 7$ TeV. The leptonic decay channels are analyzed using data corresponding to an integrated luminosity of 4.6 fb^{-1} collected with the ATLAS detector at the Large Hadron Collider. The W^+W^- production cross section $\sigma(pp \to W^+W^- + X)$ is measured to be 51.9 $\pm$ 2.0 (stat) $\pm$ 3.9 (syst) $\pm$ 2.0 (lumi) pb, compatible with the Standard Model prediction of $44.7\,^{+2.1}_{-1.9}$ pb. A measurement of the normalized fiducial cross section as a function of the leading lepton transverse momentum is also presented. The reconstructed transverse momentum distribution of the leading lepton is used to extract limits on anomalous WWZ and $WW\gamma$ couplings.

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Three different SM cross sections @ 7 TeV have been given: 45.1, 47, 44.7

Experiments need consensus outside of Higgs on cross sections...

CMS 8 Tev 3.5/fb

WW→2ℓ2ν at 8 TeV: systematics & results

σ = 69.9 ± 2.8 (stat) ± 5.6 (sys) ± 3.1 (lum) pb

NLO prediction (MCFM): 57.25 ($^{+2.35}_{-1.60}$) pb

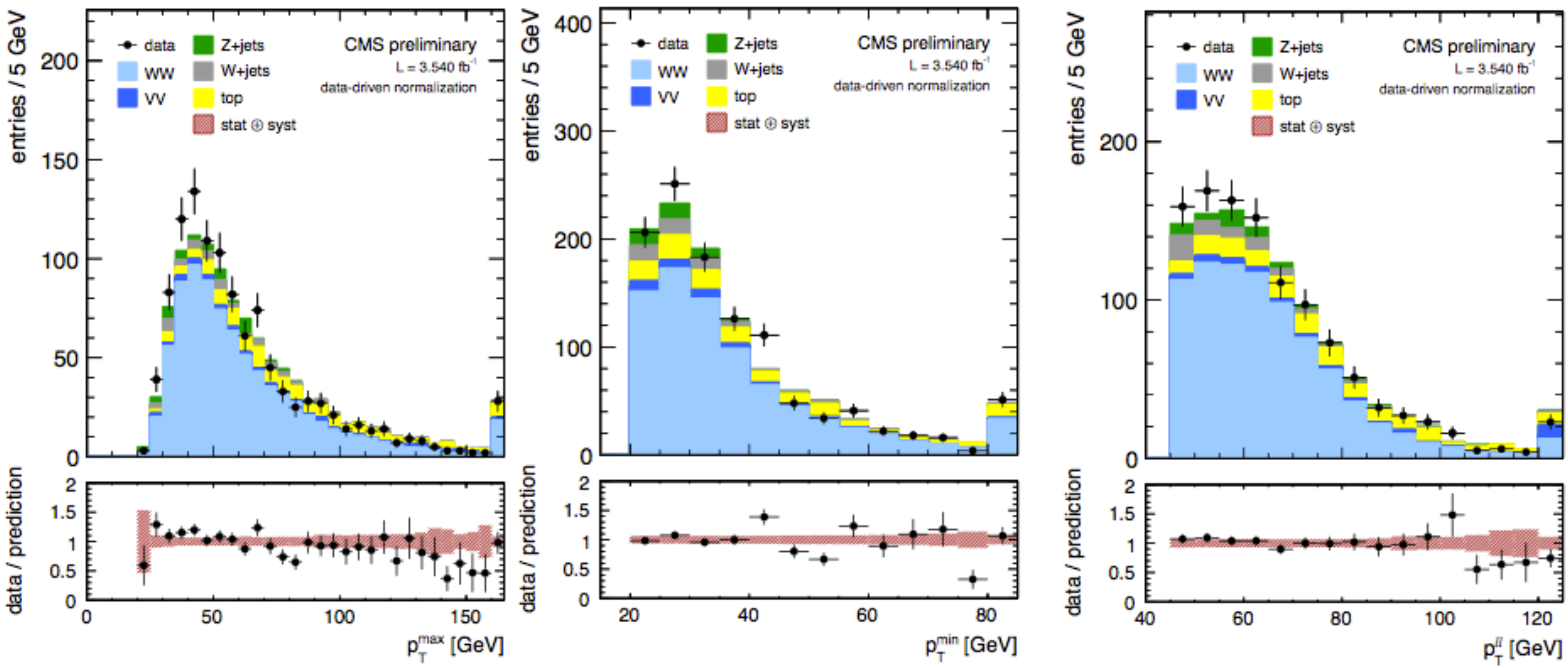
- **Already 4% statistical precision**
- **About 1.8σ higher than the NLO prediction**

It grows at 8 TeV even faster!

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

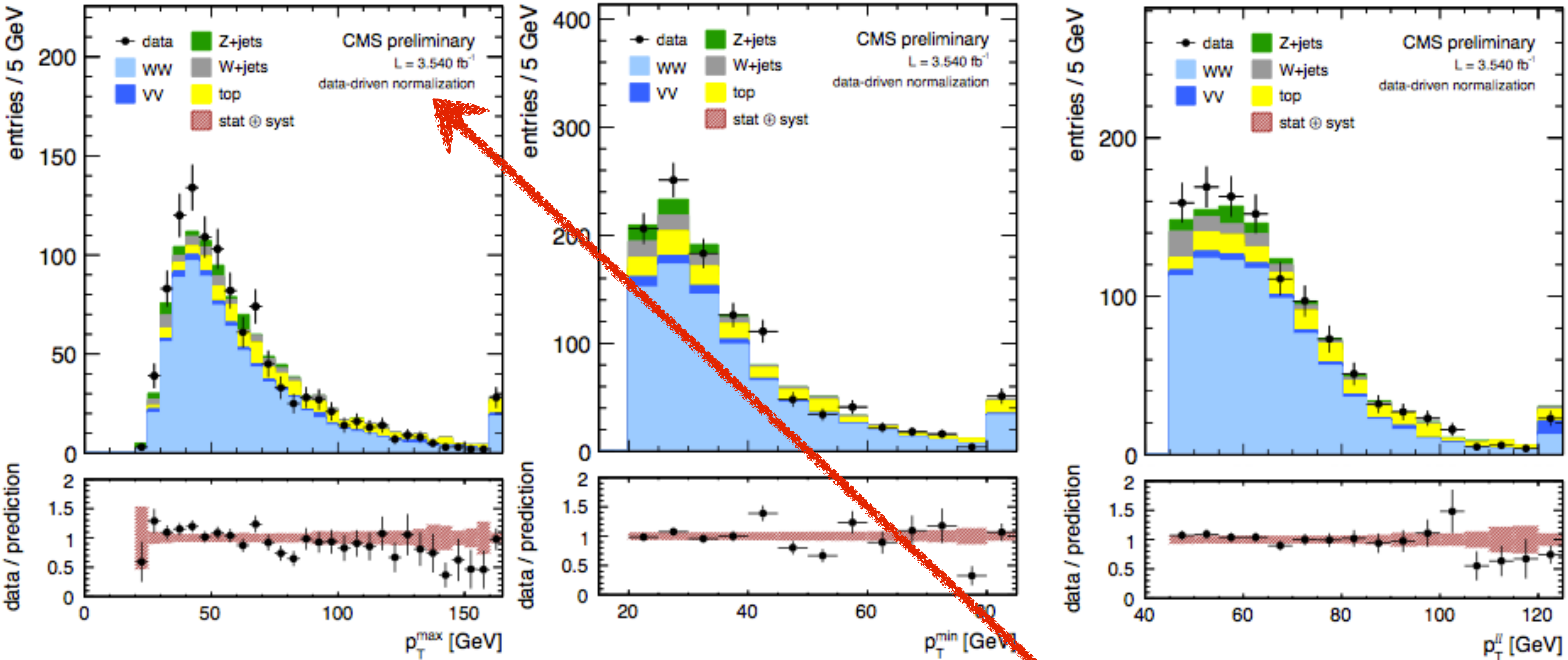
almost 3σ when combined with LHC7

CMS8



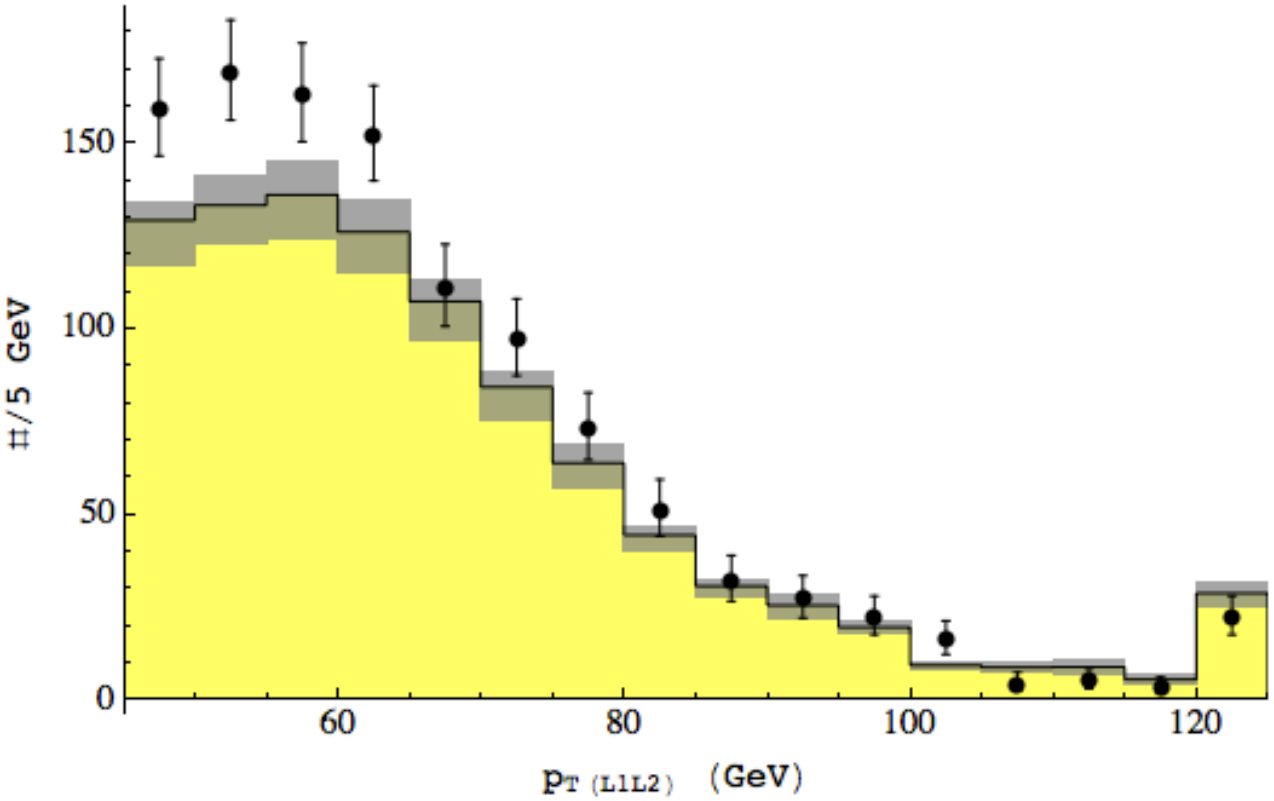
Looks pretty good...

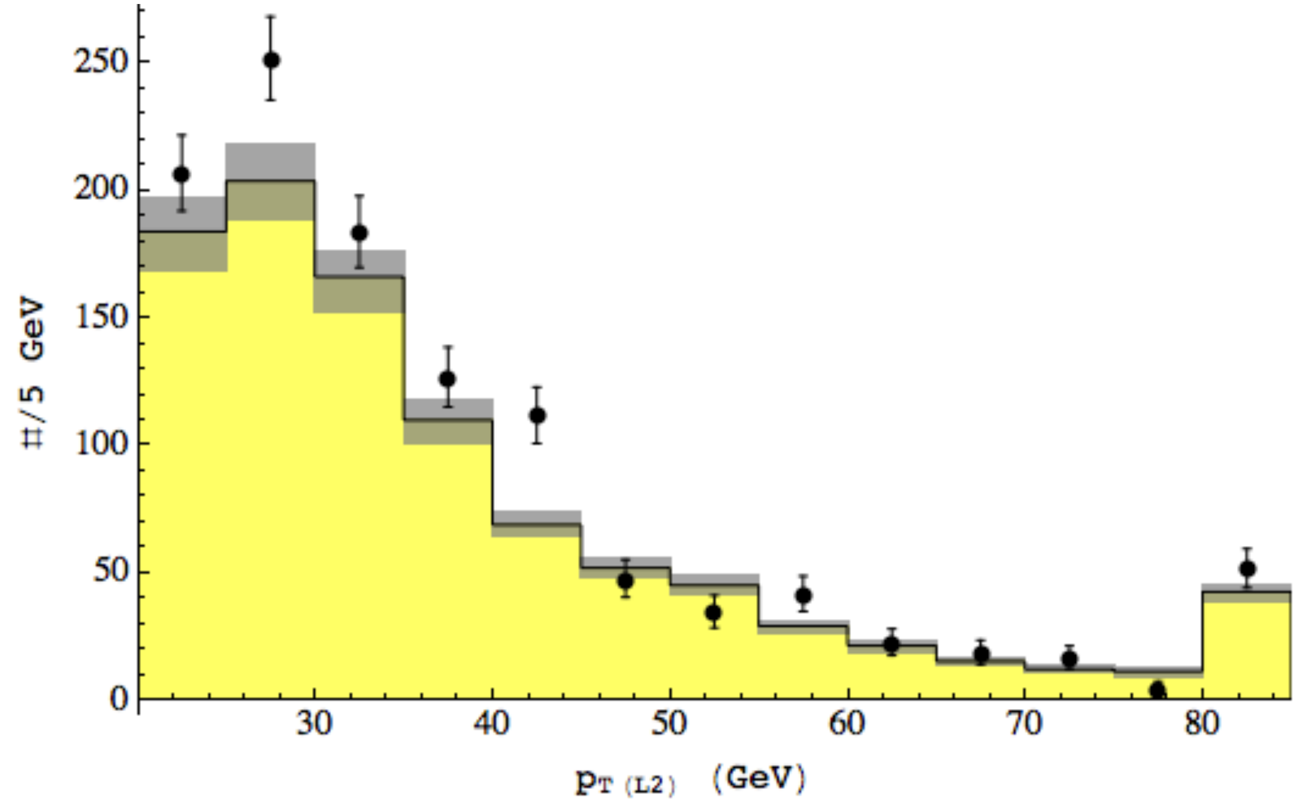
CMS8

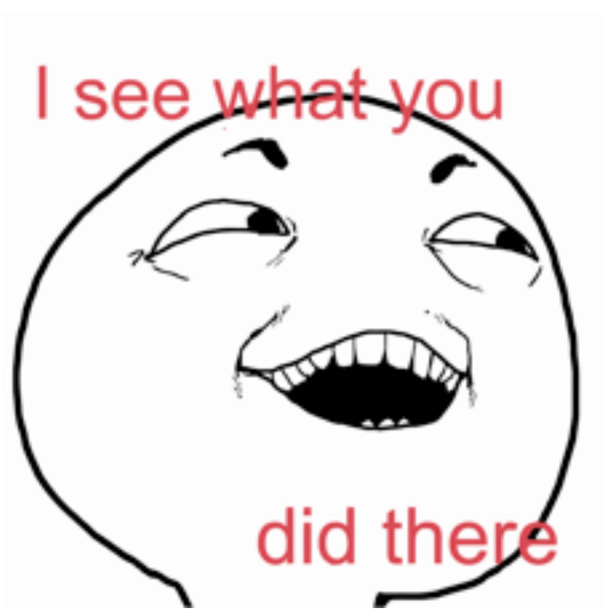


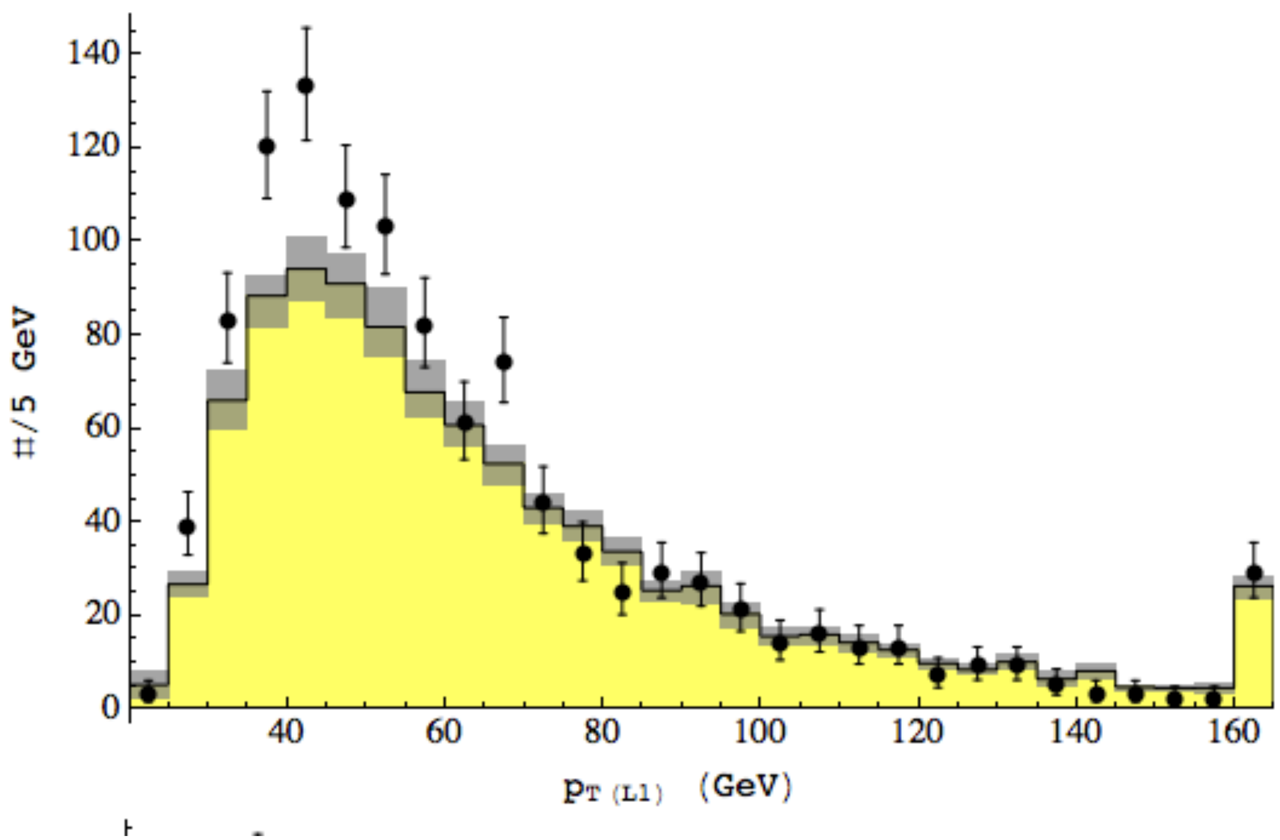
Looks pretty good...

Let's get rid of that renormalization









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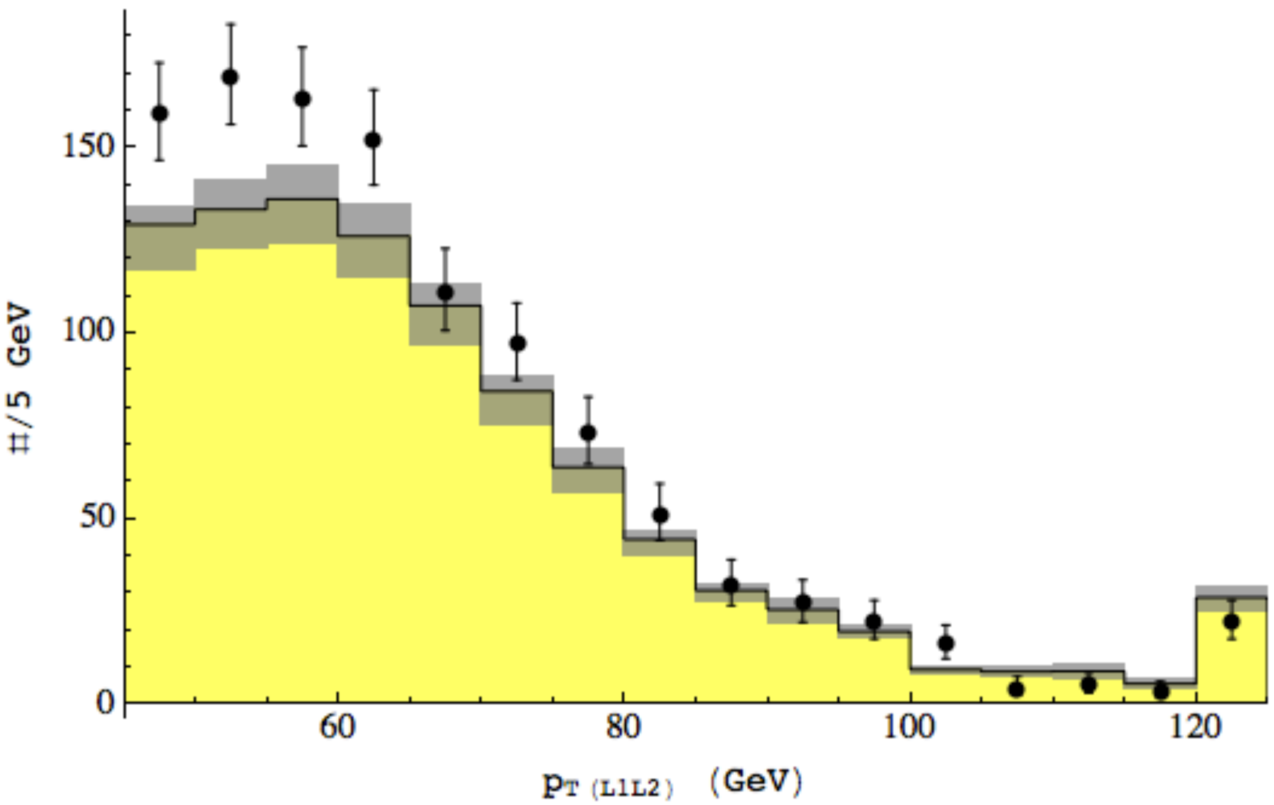
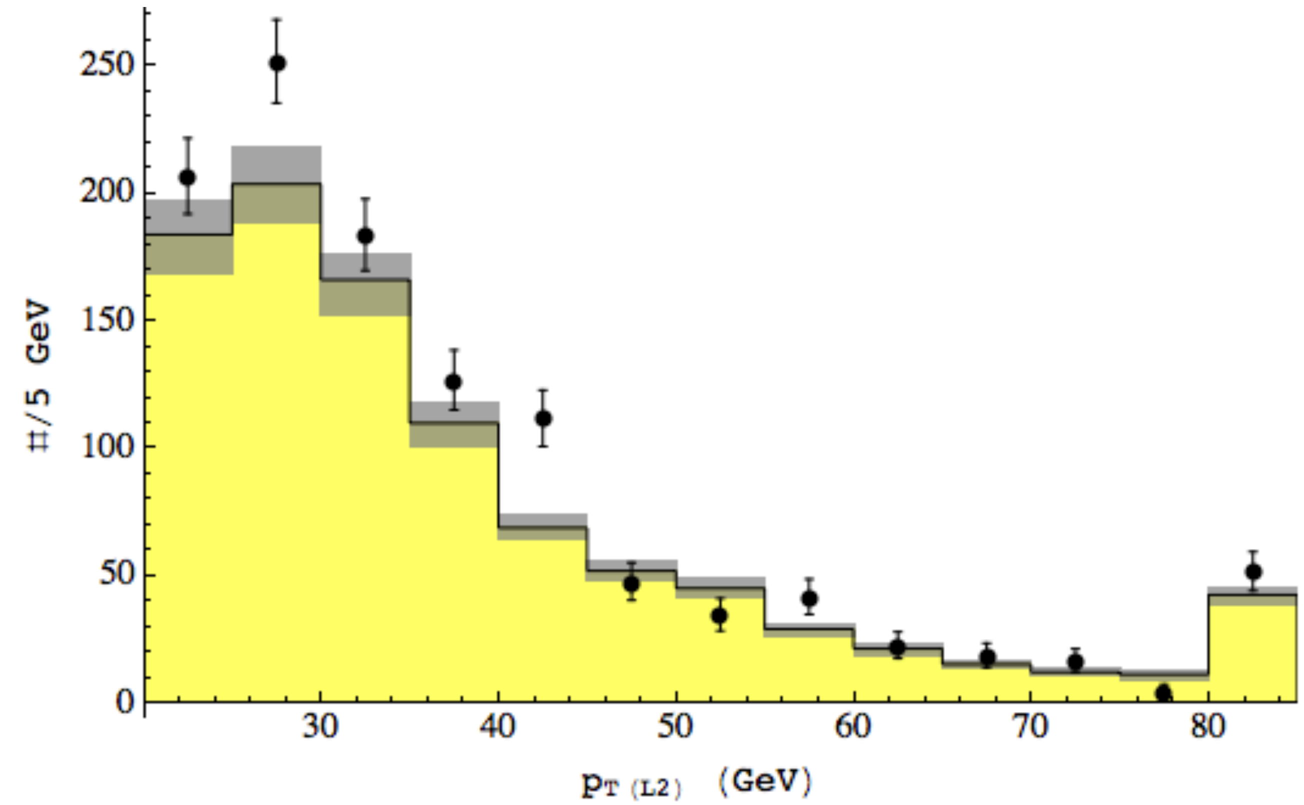
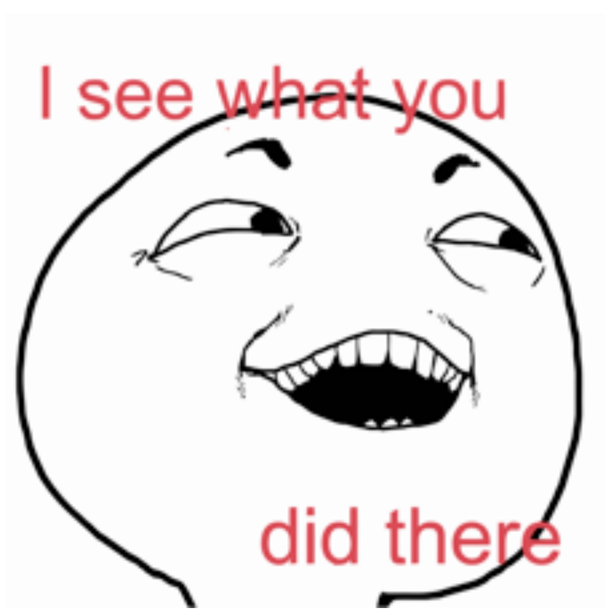
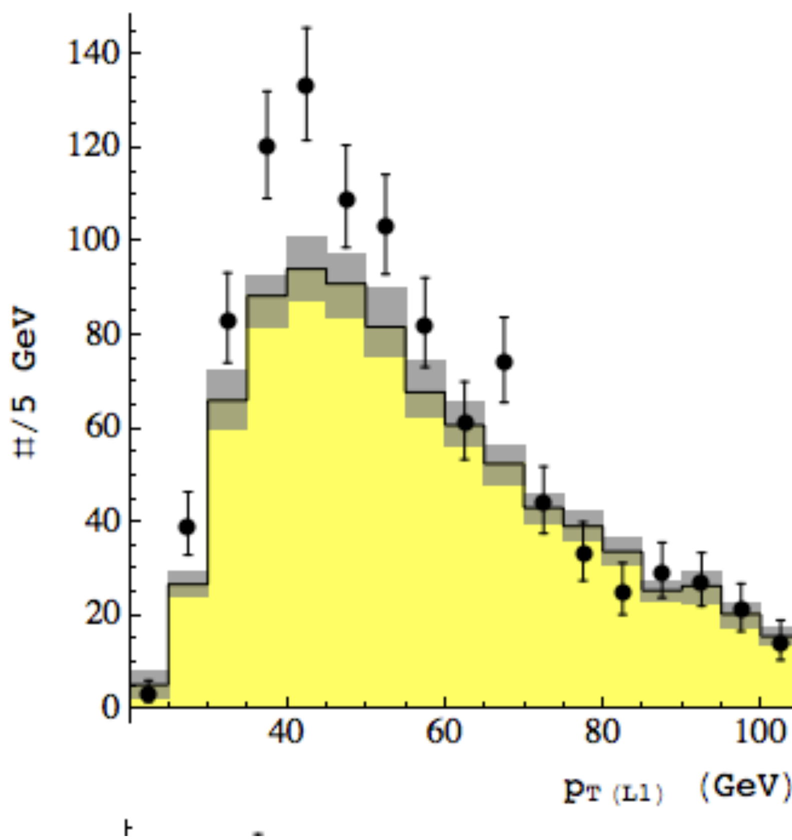


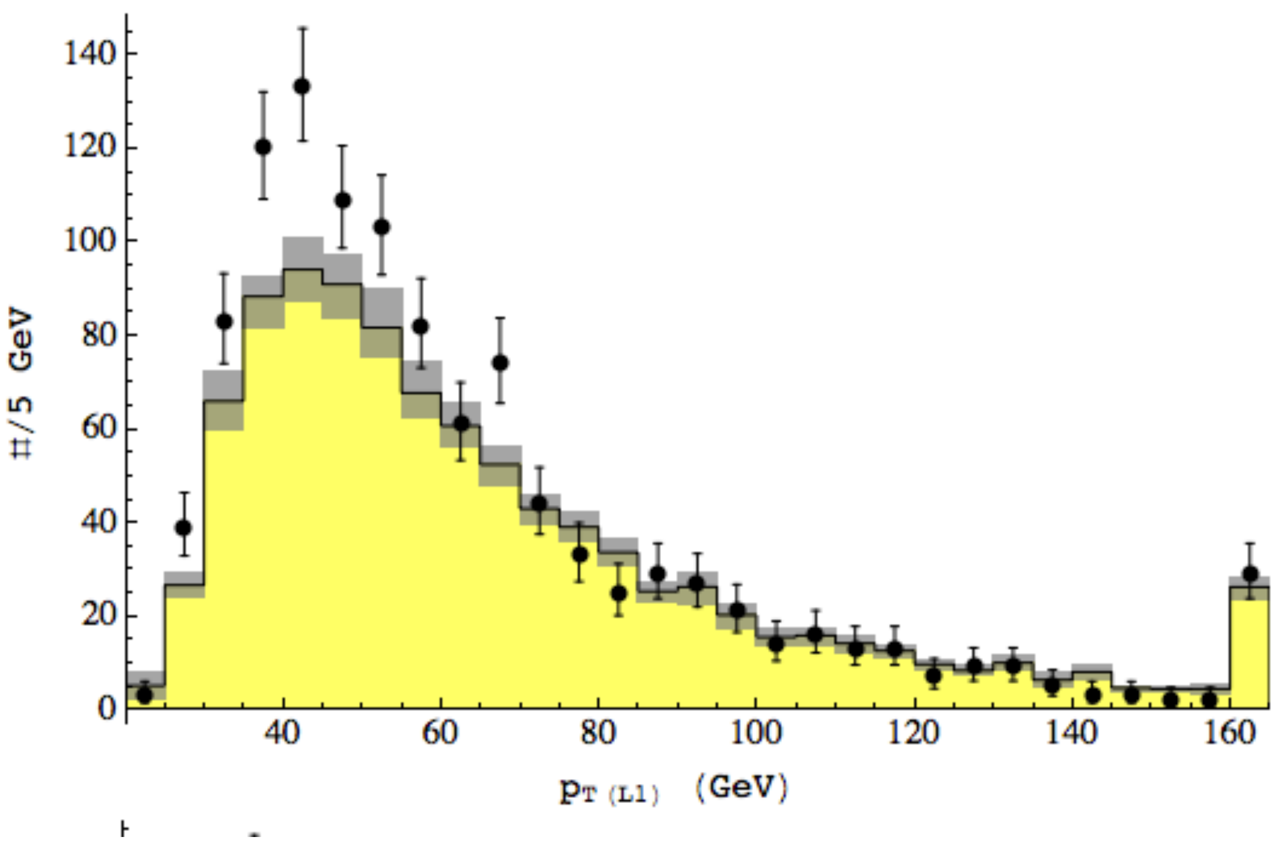




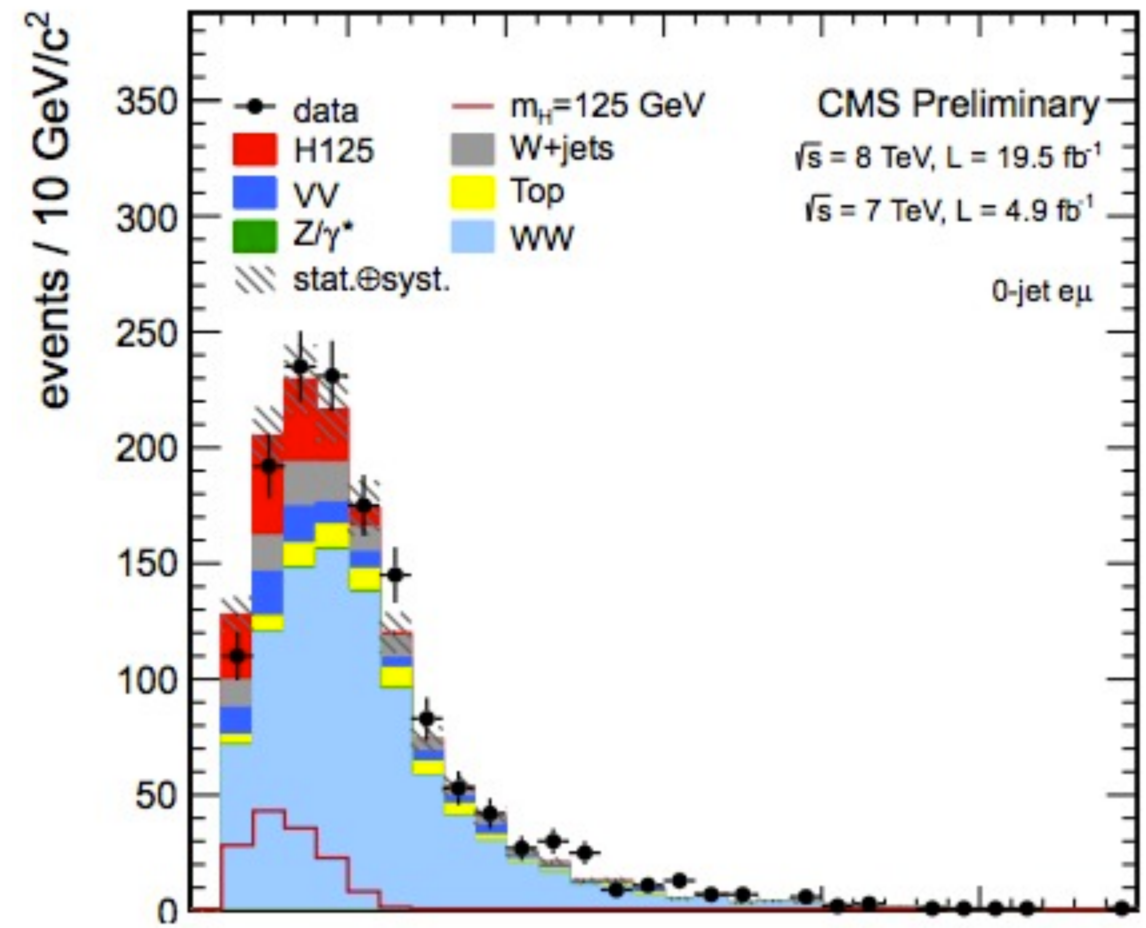


(Apologies to SEARCH workshop attendees.)

This is serious business....



CMS8 WW



CMS8 H $\longrightarrow$ WW

Upward fluctuations in all measurements or a trend?

Two roads diverged in a yellow wood,
and sorry I could not travel both...

SM calculation wrong

New Physics

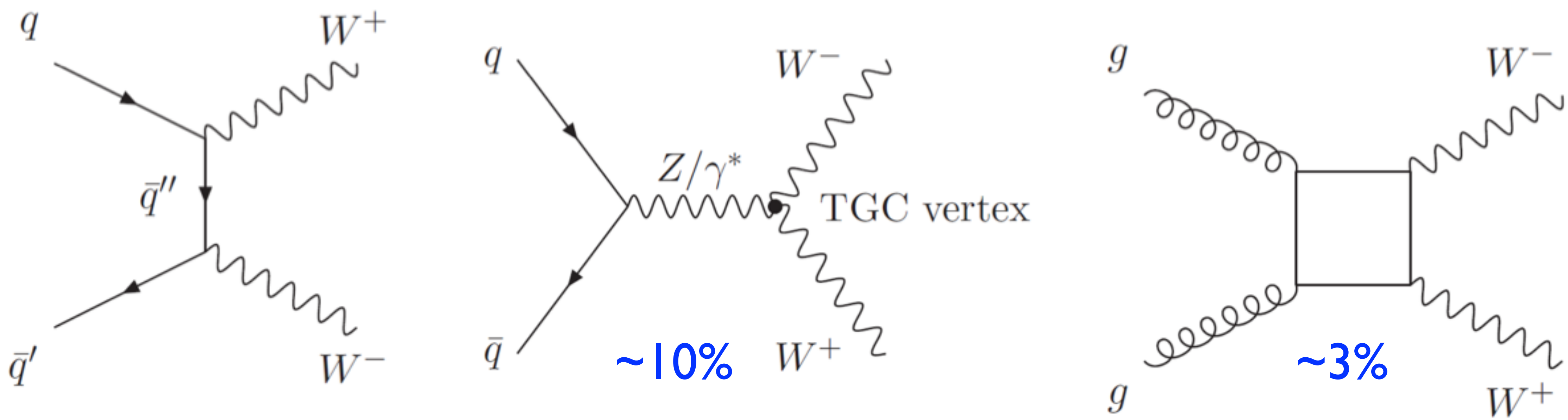
Will come back to the less traveled one
and that of course may make all the difference...

Let’s be hopeful.

Possible BSM Explanations for WW Excess

Ingredients for a BSM explanation

When you're measuring the WW cross section...

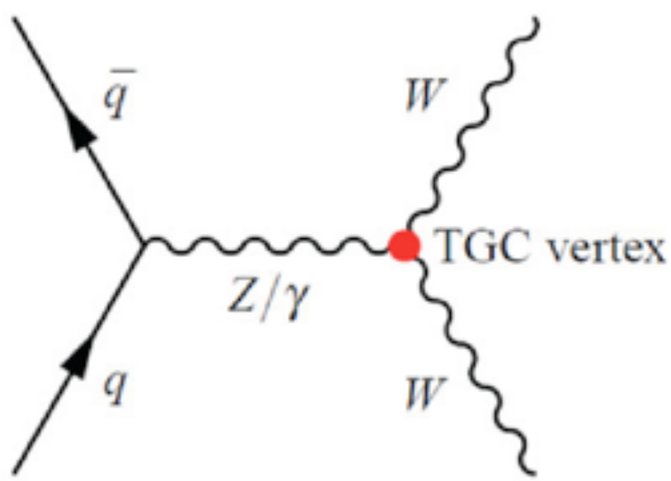


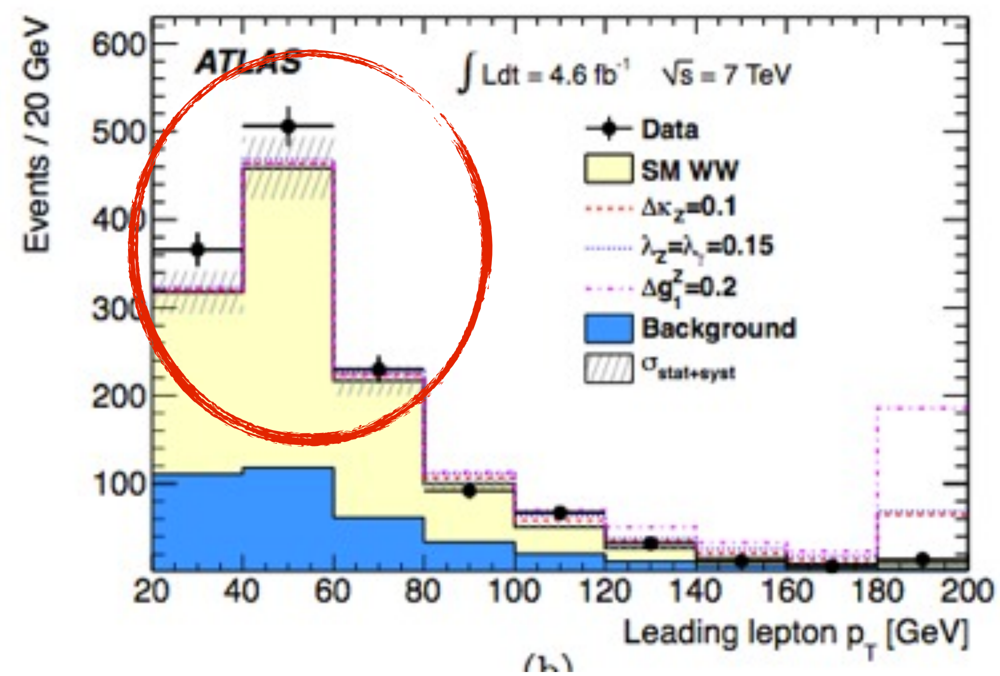
.. you're really counting the number of dilepton + MET events in fiducial region with jet veto

$$\sigma_{WW} = \frac{N_{\text{data}} - N_{\text{bkg}}}{C_{WW} \times A_{WW} \times \text{BR} \times \mathcal{L}}$$

Ingredients for a BSM explanation

- Need to produce dileptons + MET and NOTHING ELSE (jet veto)
- These new events do **not** have to contain real Ws (but that could help)
- The experimentalists do use WW to look for certain kinds of new physics...





.. but this modifies the TAILS of the distributions. We need to modify the BULK.

We need **a few pb** of WW-like events from BSM!

Ingredients for a BSM explanation

- It could be something decaying to WW + MET

  → **Charginos** or something like it.

- It could be something decaying directly to dileptons + MET

  → **Sleptons** or something like it

- Isn't SUSY dead?
  - NOPE.

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RPC SUSY pre-LHC:

——————— ~300 GeV colored States (Tevatron limits)

——————— ~100 GeV EW States (LEP limits)

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RPC SUSY post-LHC:

~**1 TeV** colored States (LHC run1 limits)

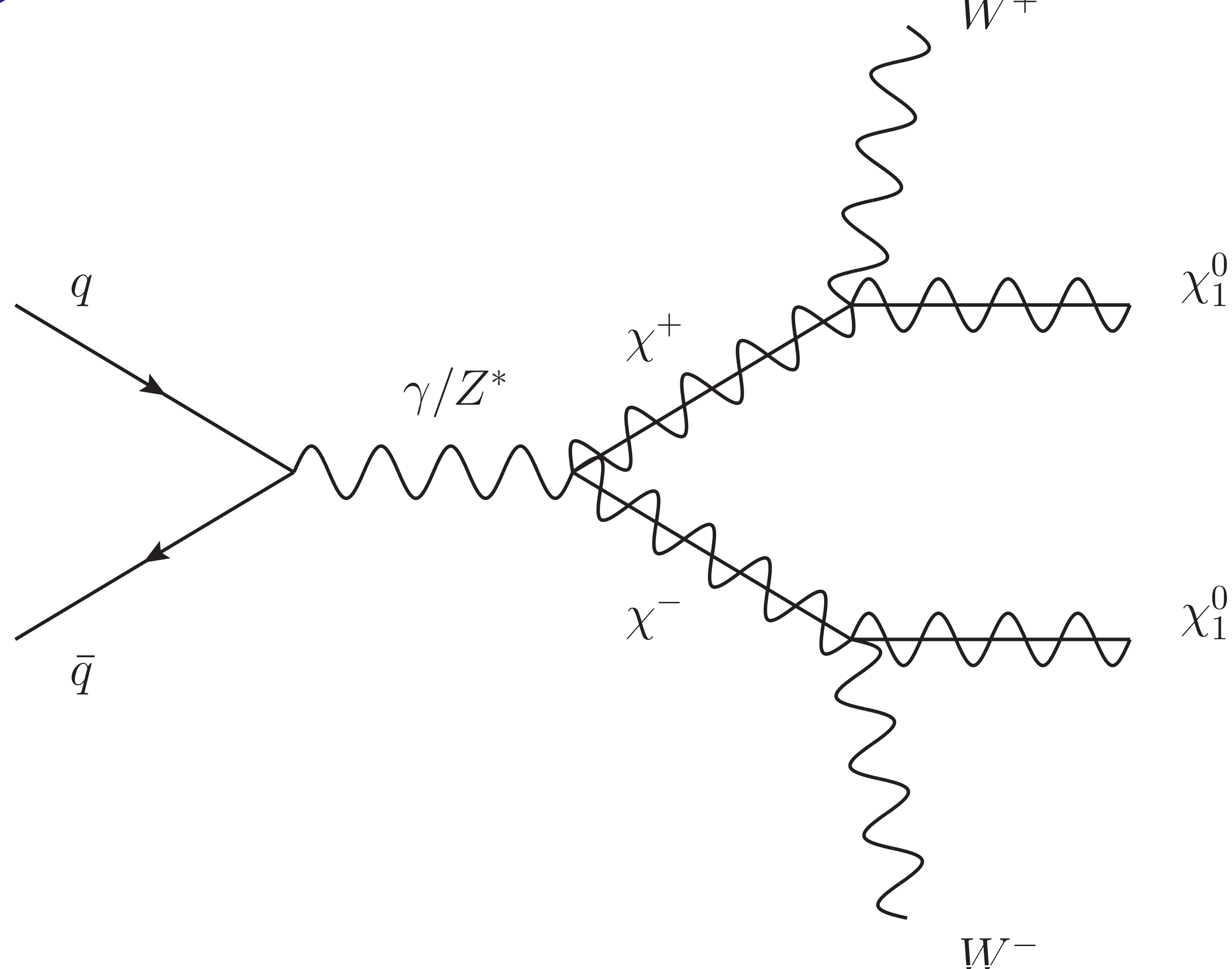
~**100 GeV** EW States (LEP limits)

Hadron Colliders relatively insensitive to EW NP.

EW NP game is just beginning!

Example Topology for WW + MET:

Chargino Pair Production



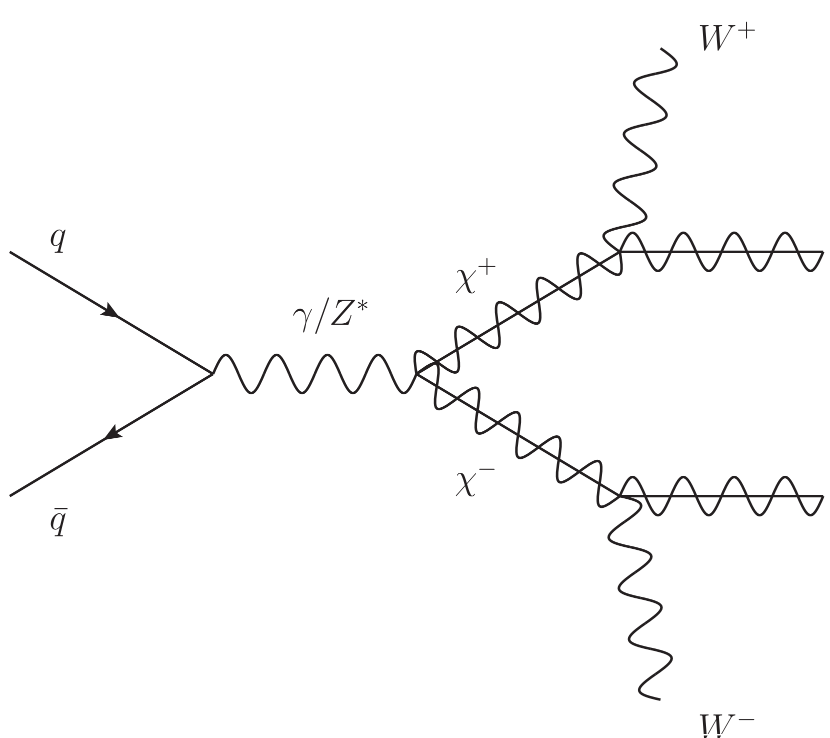
Charginos

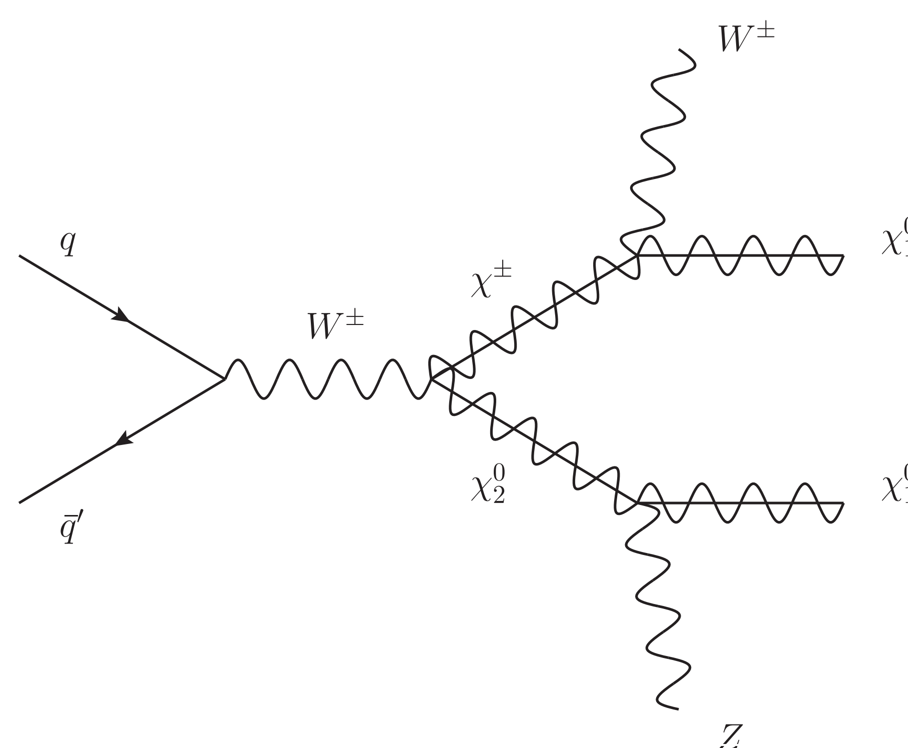
- Consider Gravity-Mediated scenario right above the LEP bound

$\chi_1^{\pm}, \chi_2^0$ ~ 100 GeV

χ_1^0 ~ GeV

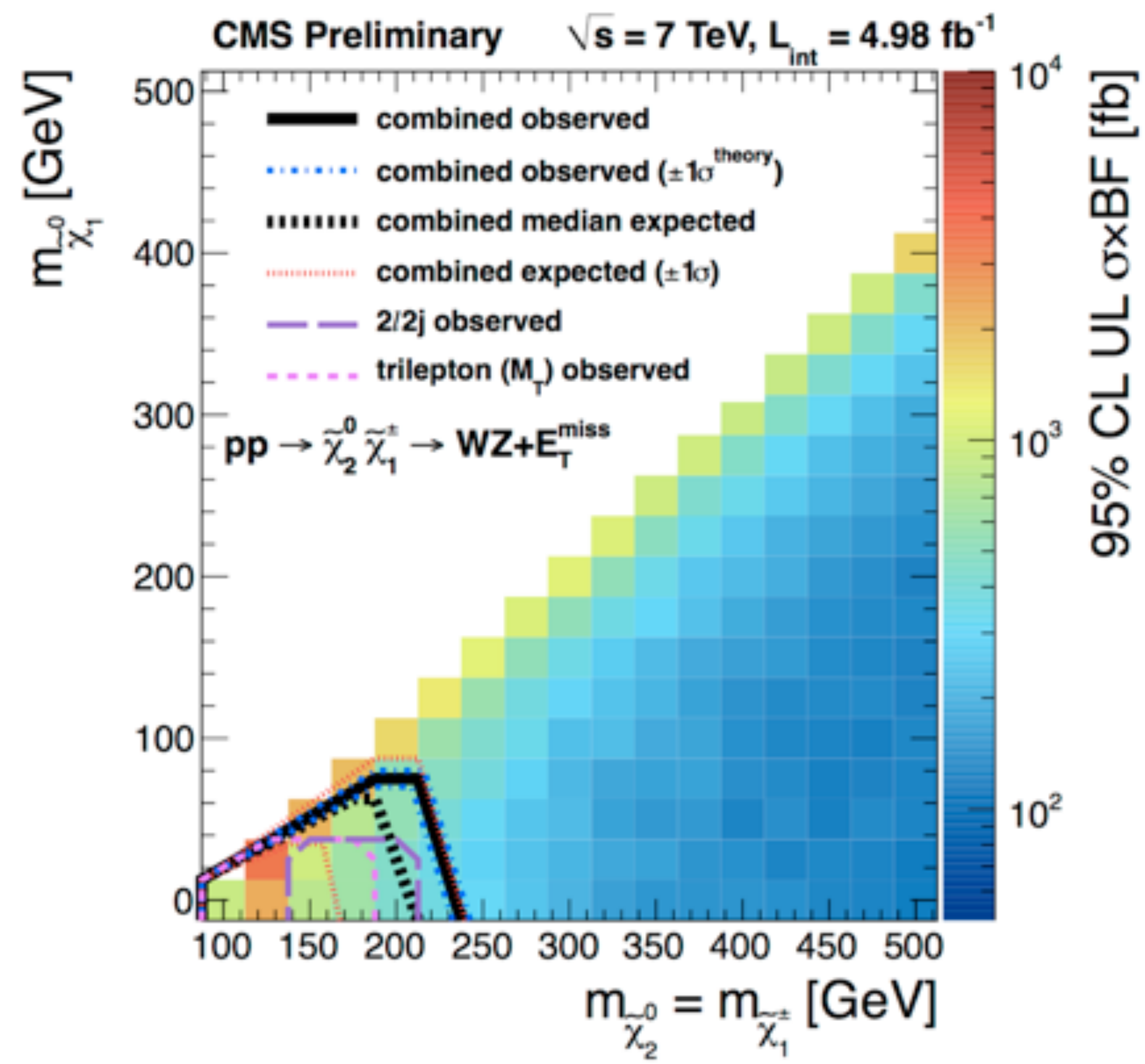
- Get plenty of **WW**, but also **WZ** or **Wh** production (wino or higgsinos)





LHC has produced some EW constraints!

WZ final state ruled out far above LEP limit.



Wh also ruled out by ATLAS 7 TeV Wh search for up to ~160 GeV Higgsinos

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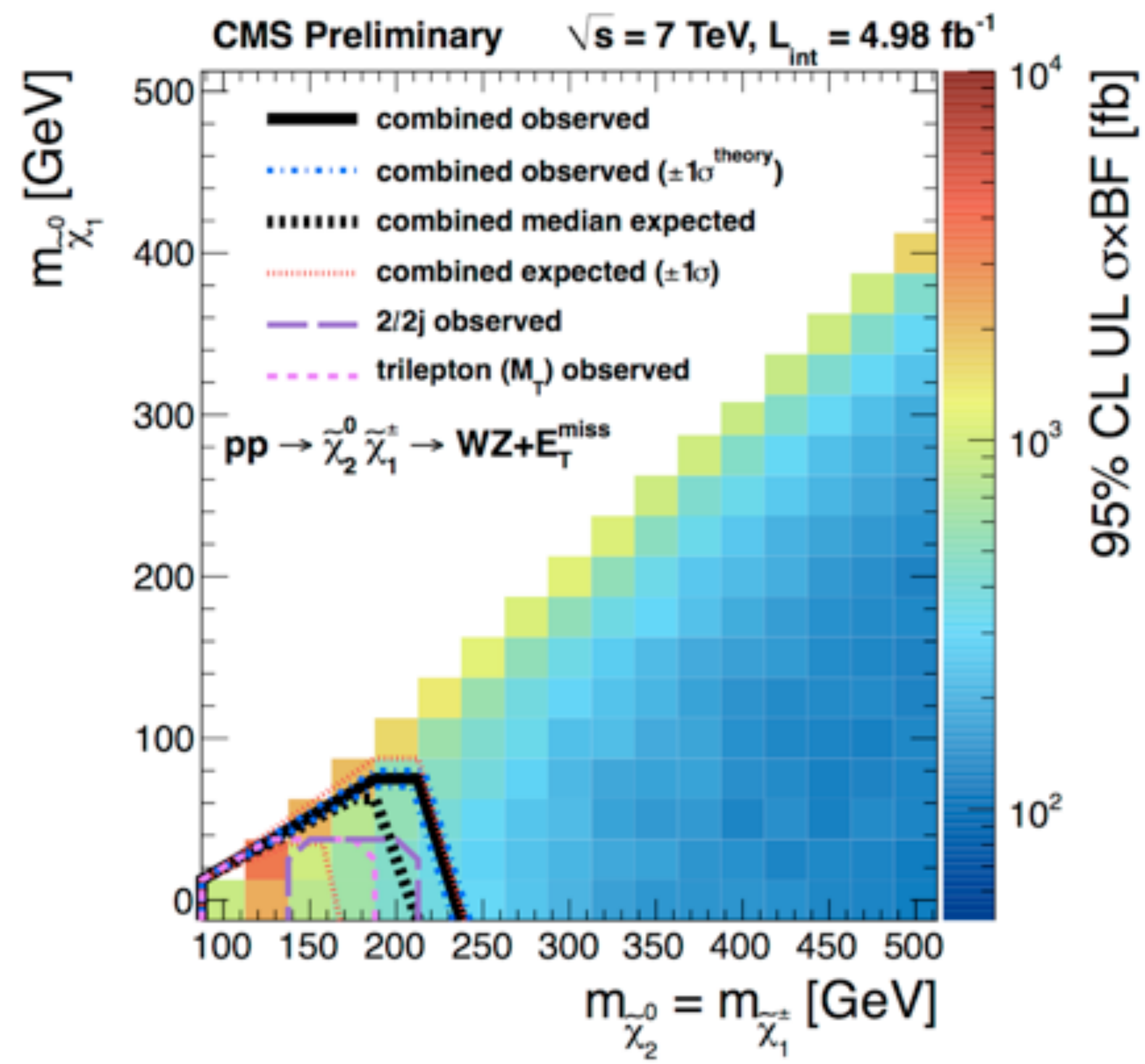

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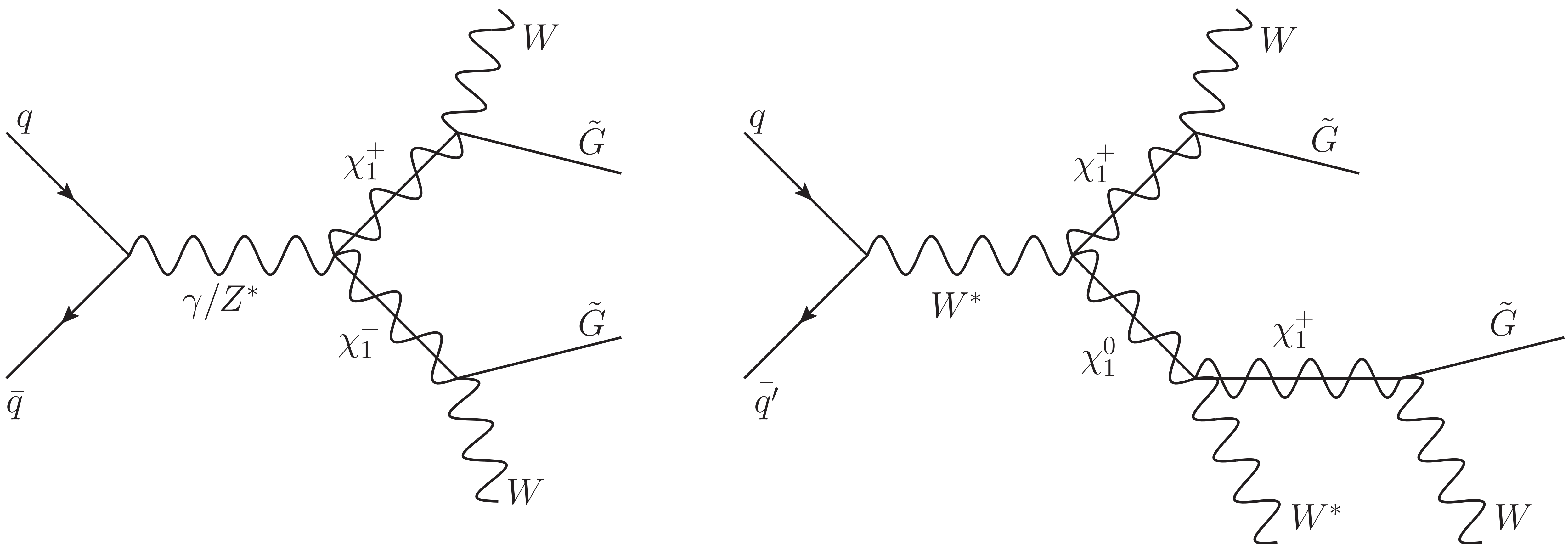
We set this limit in 1206.6888, not ATLAS.

Can you have charginos without WZ/Wh?

- Consider **Chargino-NLSP** in gauge-mediated SUSY breaking.
  - low tanβ, large Wino-Higgsino mixing



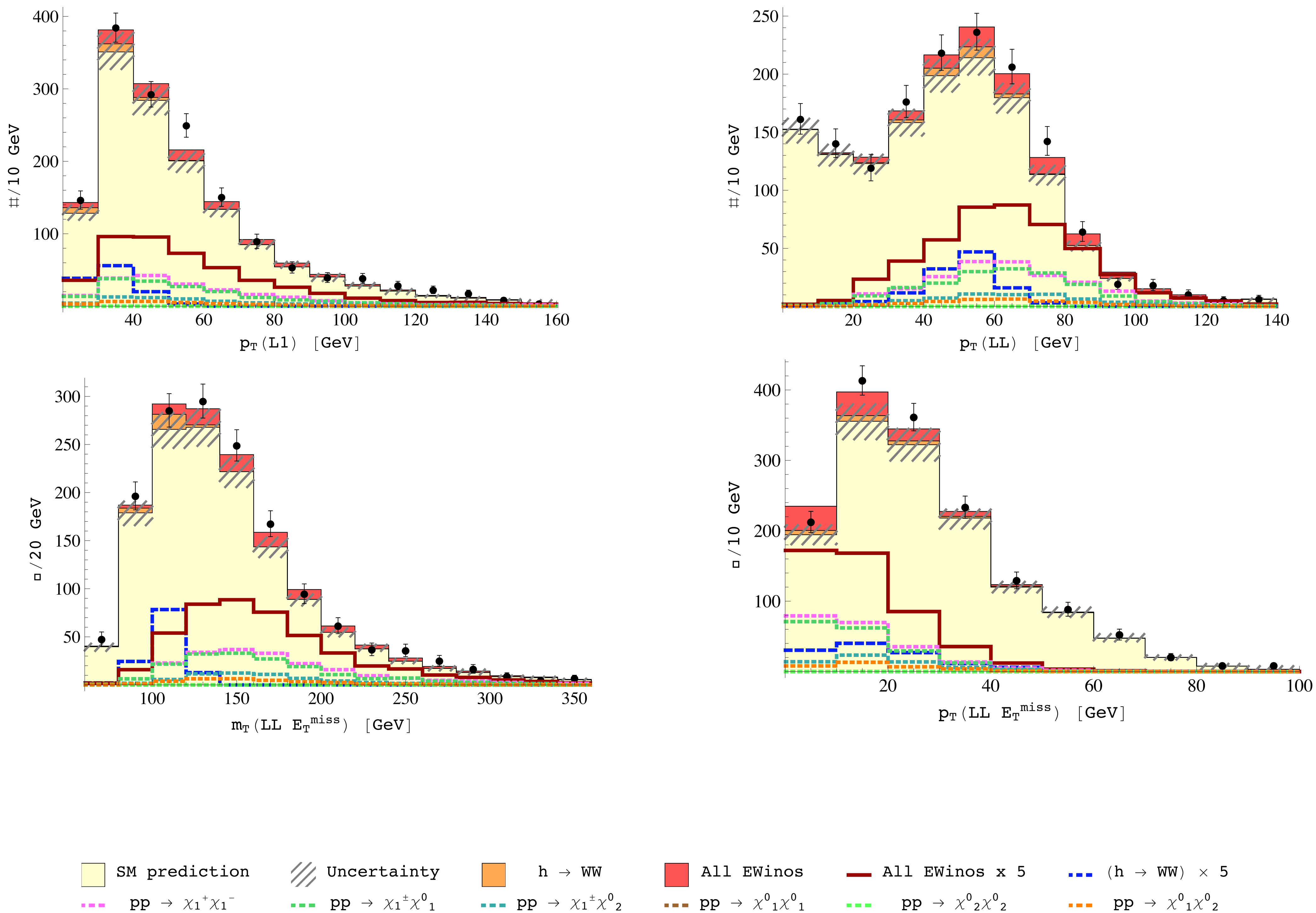
$m_{\chi_1^\pm} \approx 110\,\mathrm{GeV}$

$m_{\chi_1^0} \approx 113\,\mathrm{GeV}$

$m_{\chi_2^0} \approx 130\,\mathrm{GeV}$

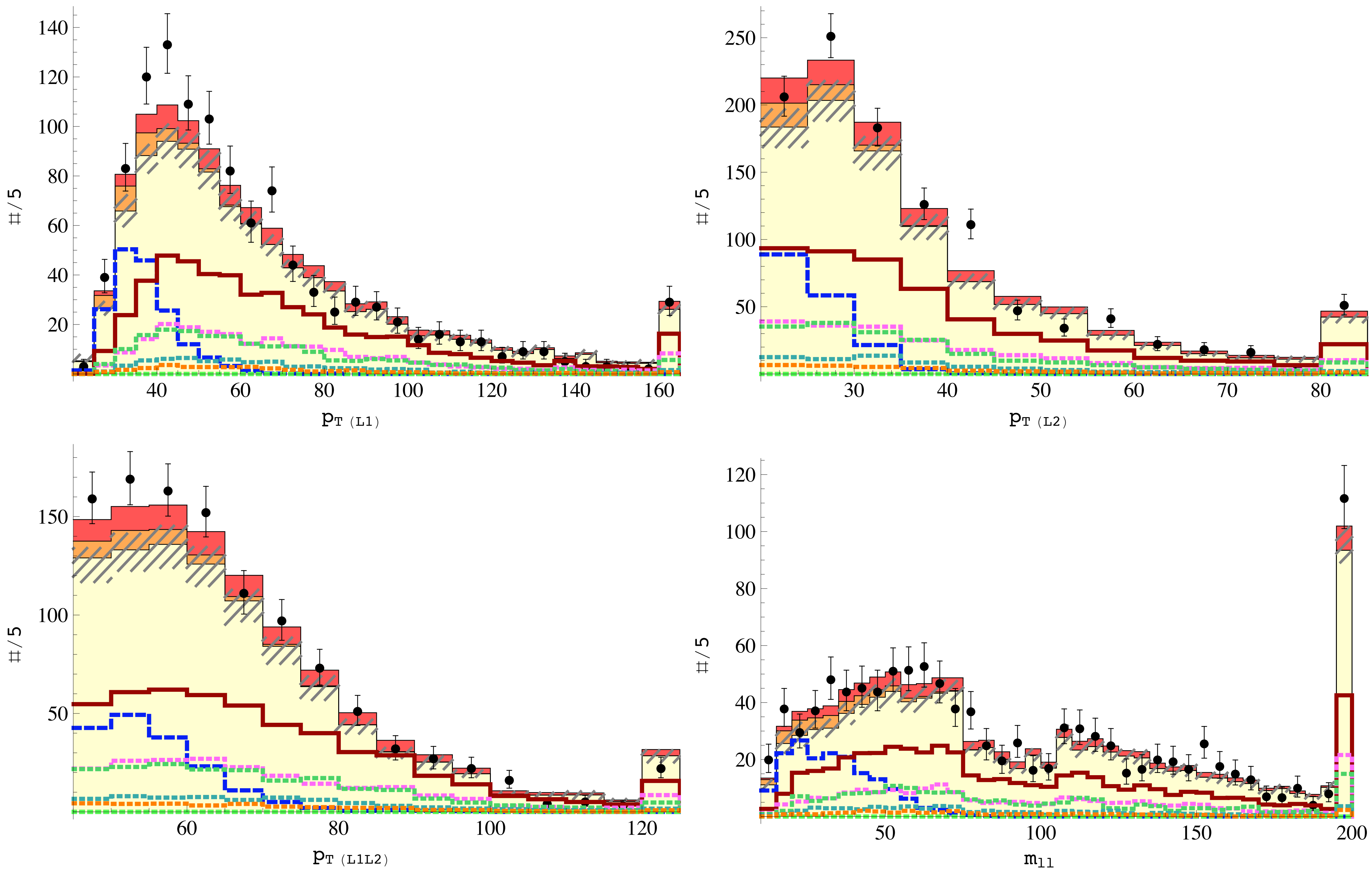
$\sigma_{NLO} \sim 4.3\,\mathrm{pb}$

ATLAS7



χ^2 cut in half compared to SM

CMS8



SM p-value 0.001

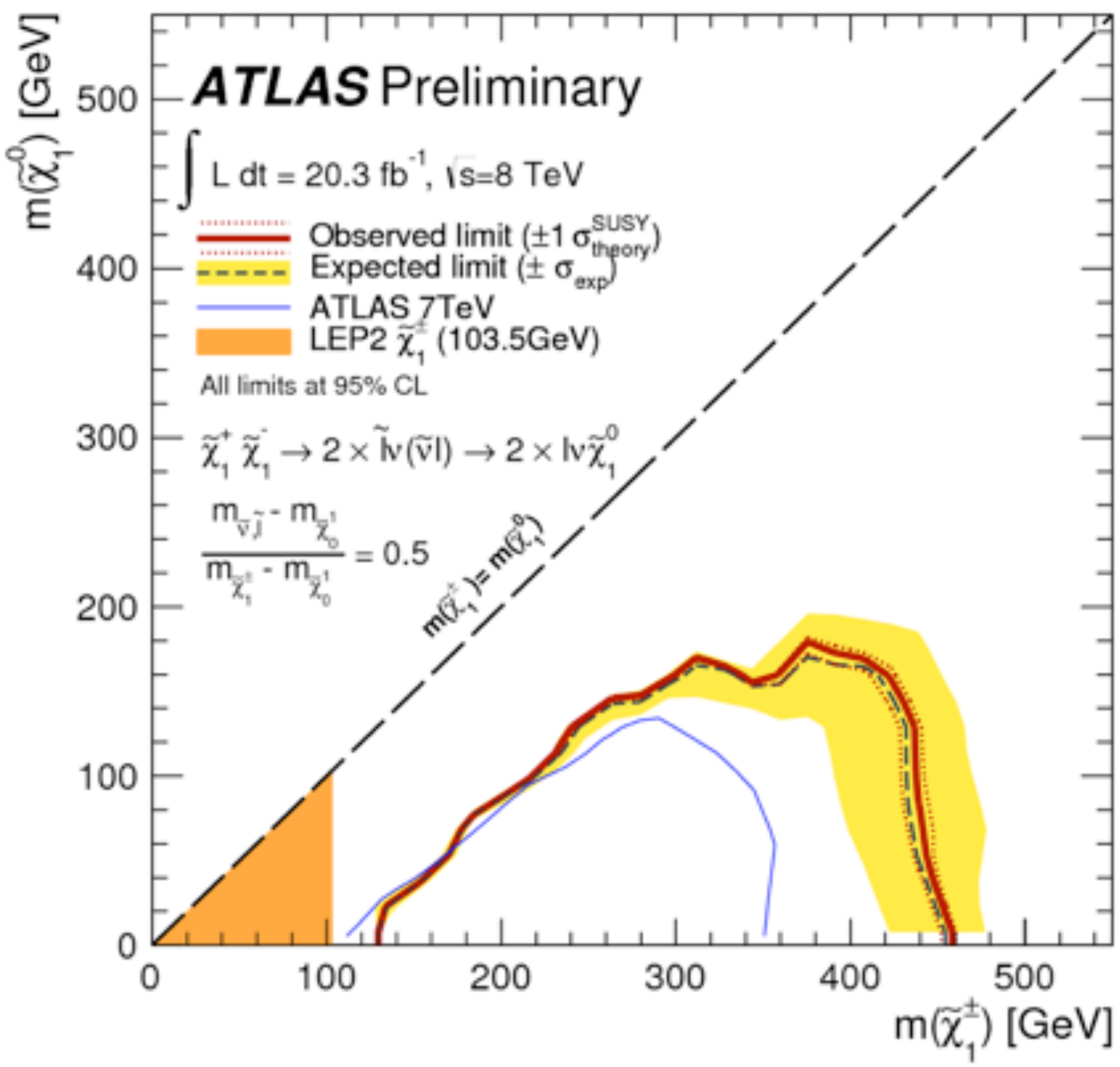
SM+charginos 0.3

SM+h 0.1

SM+h+charginos 0.75

ATLAS 20/fb Chargino Search [Dilepton]

ATLAS-CONF-2013-049



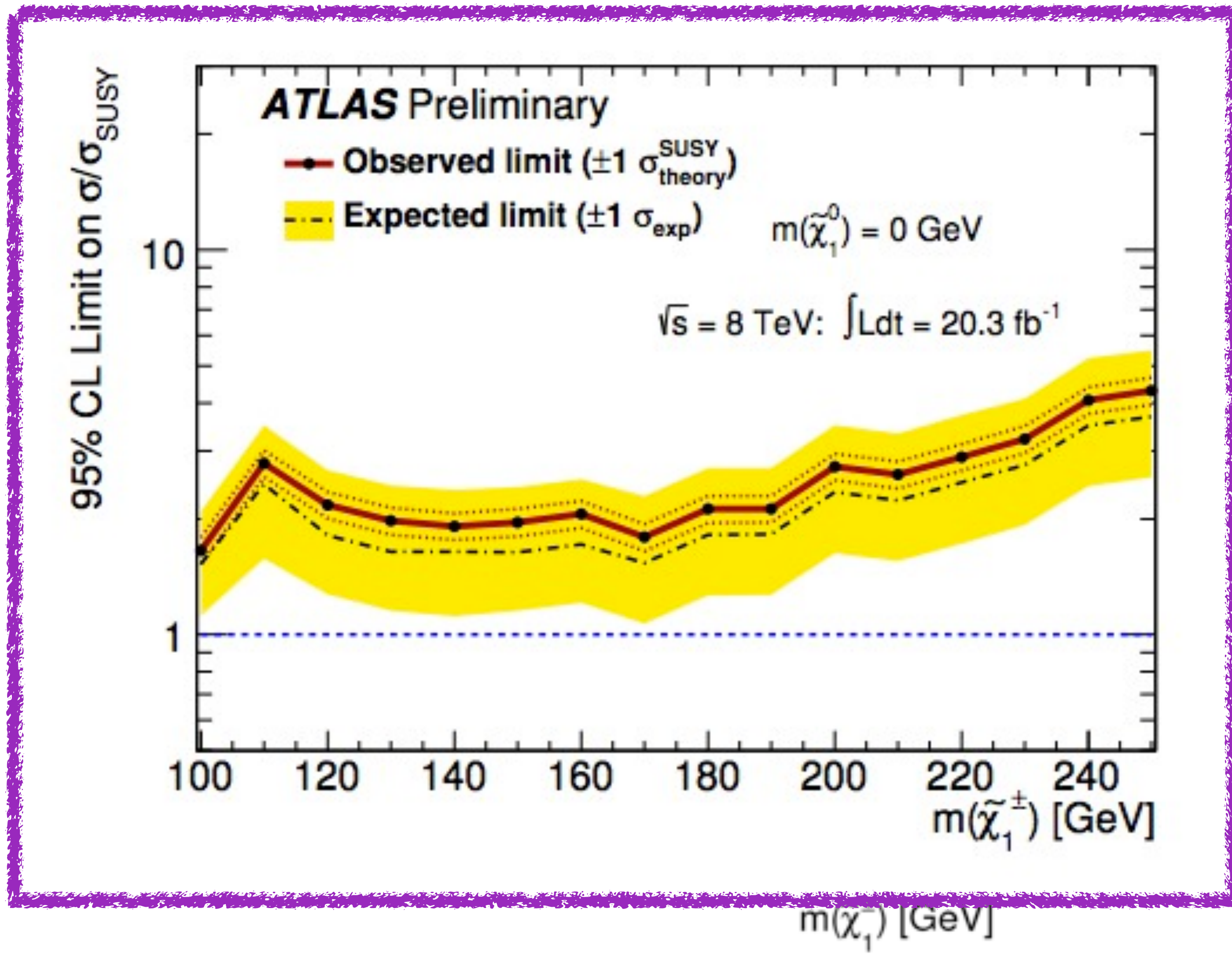
$m_{\chi+}$ limit 130 GeV.

The collaboration explicitly tested our chargino scenario, and it is **not excluded.**

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 20/fb Chargino Search [Dilepton]

ATLAS-CONF-2013-049



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ATLAS 20/fb Chargino Search [Trilepton]

ATLAS-CONF-2013-035

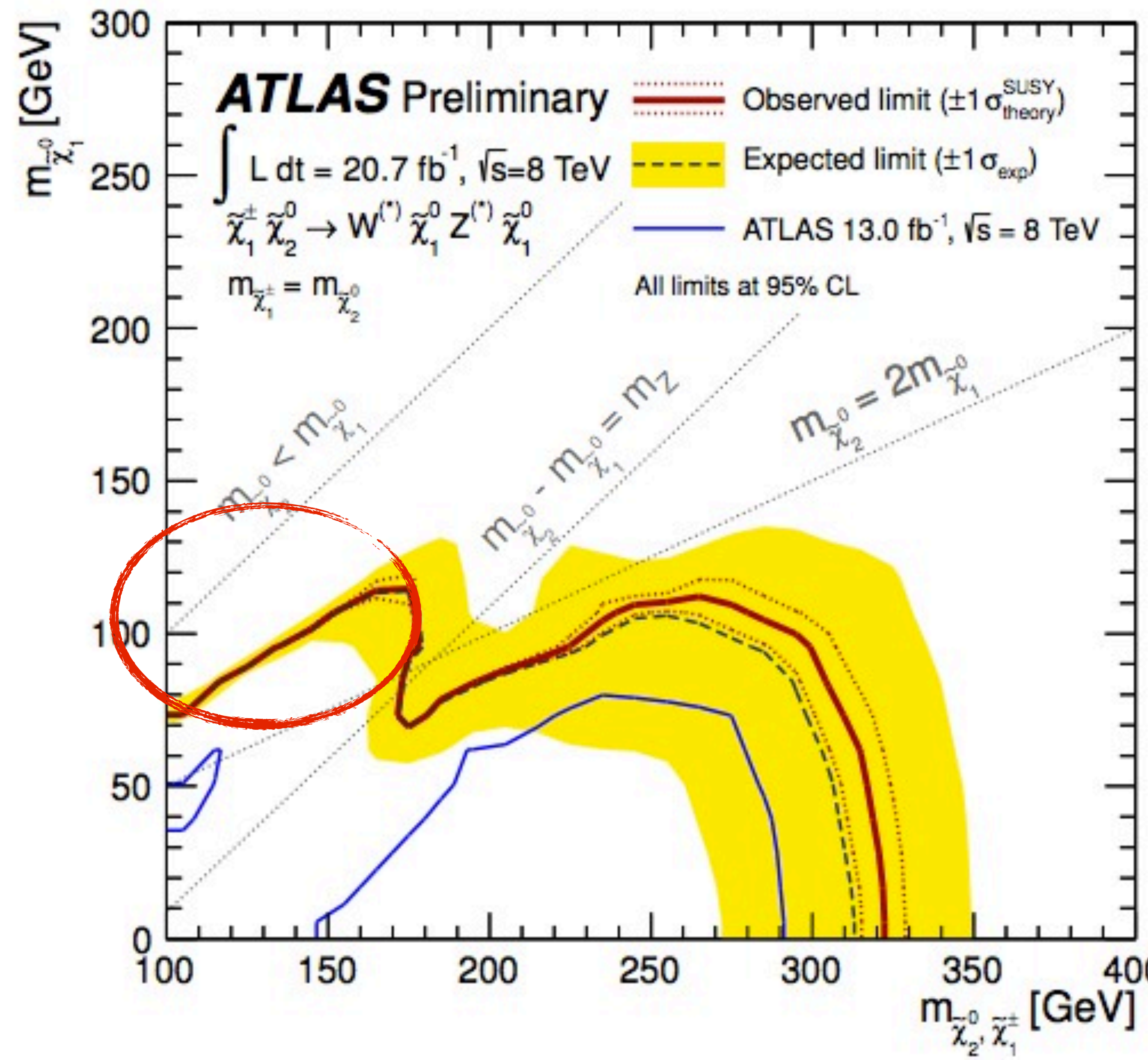
Not exactly our model,

$m_{\chi_1^\pm} \approx 110\,\mathrm{GeV}$

$m_{\chi_1^0} \approx 113\,\mathrm{GeV}$

$m_{\chi_2^0} \approx 130\,\mathrm{GeV}$

but it looks like we're still OK.

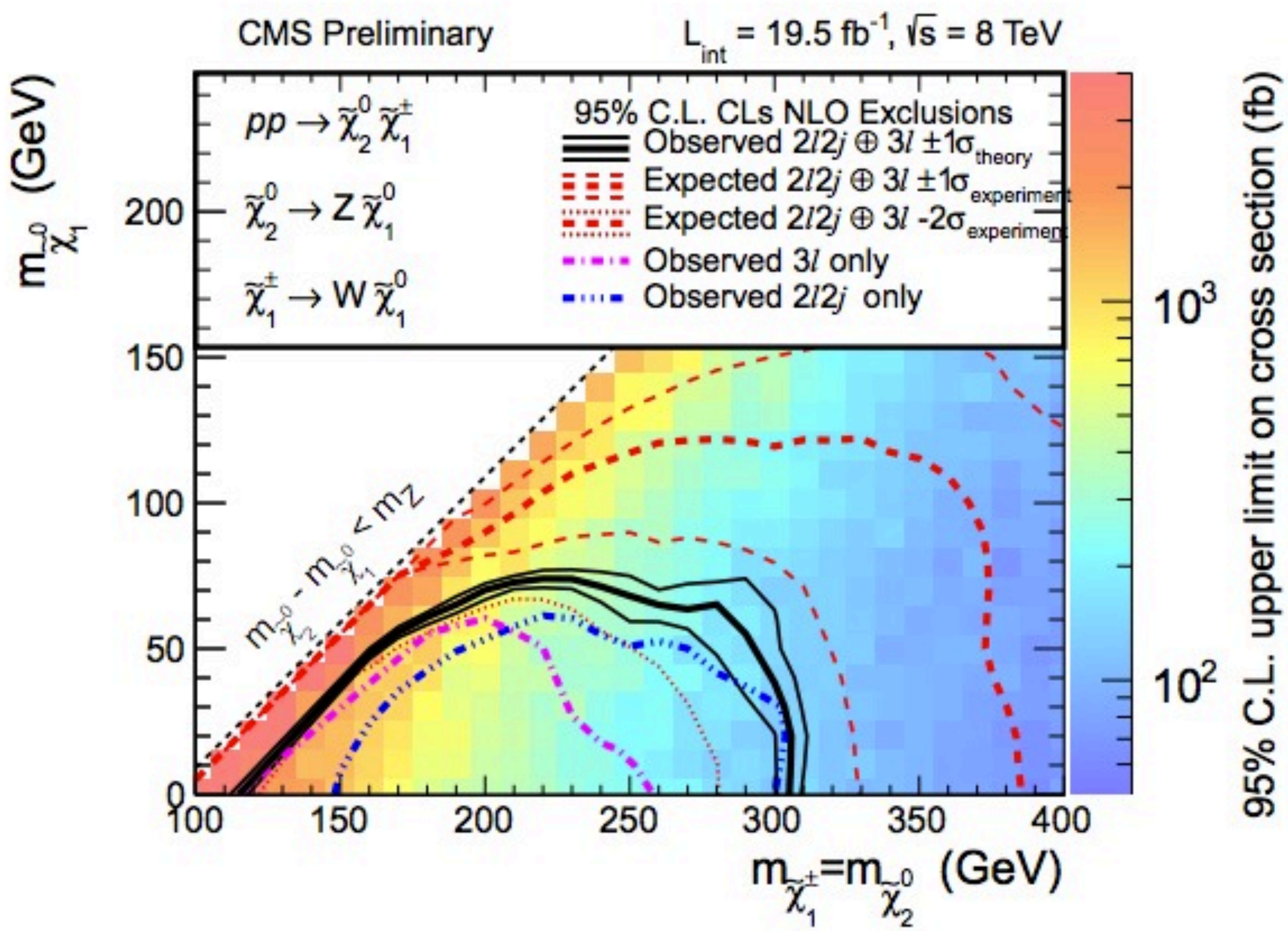


(b) Decay via gauge bosons

CMS 20/fb Chargino Search [Trilepton]

SUS-13-006-PAS

does not look sensitive to our model.



Other consequences of this Scenario

- Smoking Gun: **SS Dileptons**, some OS dileptons
    - **Can discover/exclude with 20/fb!**
- Amusingly, this is the only scenario in which charginos can increase $h \to \gamma\gamma$, by about 15%

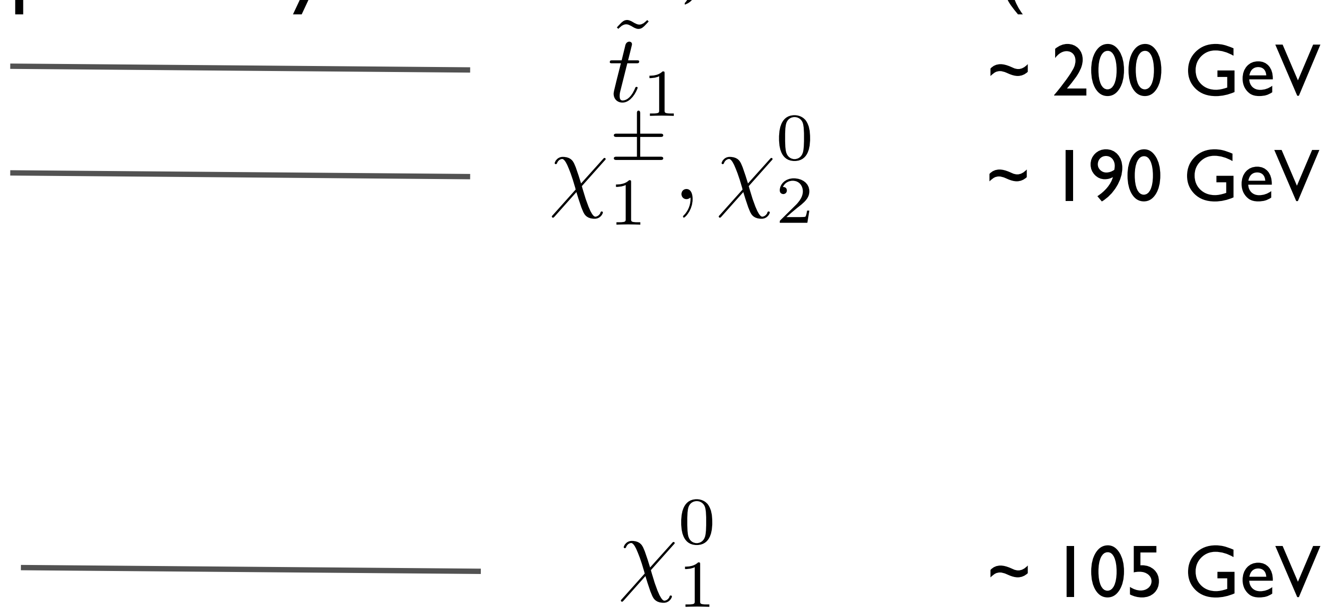
Other consequences of this Scenario

- $h \to WW$ measurement:
    - control region (m_{ll} > 100 GeV)* used to scale WW MC prediction in signal region (m_{ll} < 50 GeV)*
    - Our charginos look so much like WW that they pollute signal and control region in proportion to WW
    - ➡ charginos do NOT significantly affect $h \to WW$ sensitivity

*ATLAS 7 TeV

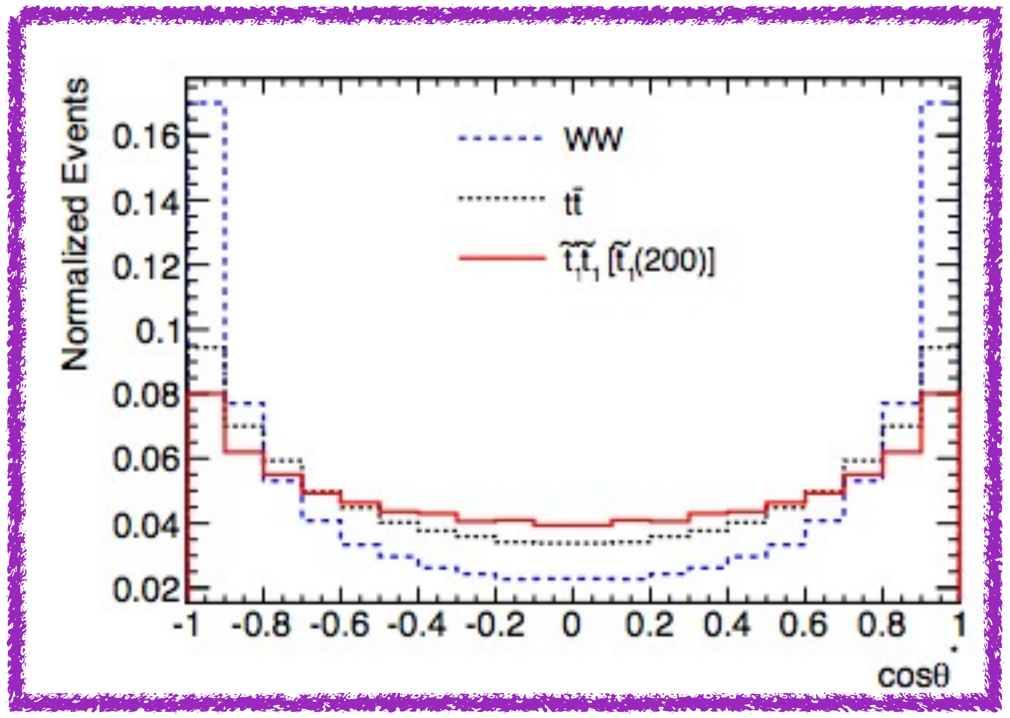
Another possibility: squeezed stops.

- Recently proposed by Rolbiecki, Sakurai (1303.5696)

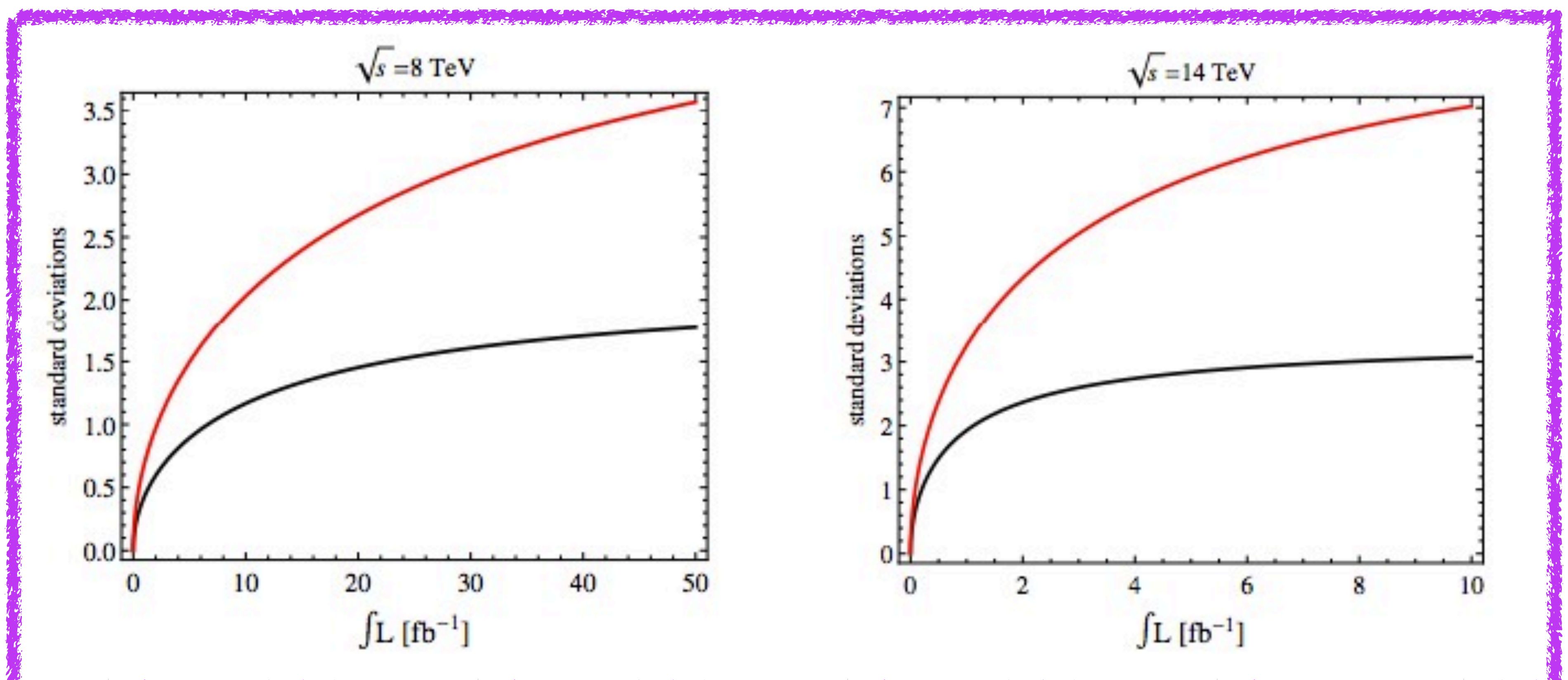


- Light stops decay via $\tilde{t}_1 \to \bar{b}\ \tilde{\chi}_1^+$ where b is soft (undetected)
- Effectively allows relatively heavy charginos to be produced with the (relatively light) stop pair production cross section O(10 pb)
- Avoids SS dilepton signal and hides a light stop!

Another possibility: squeezed stops.

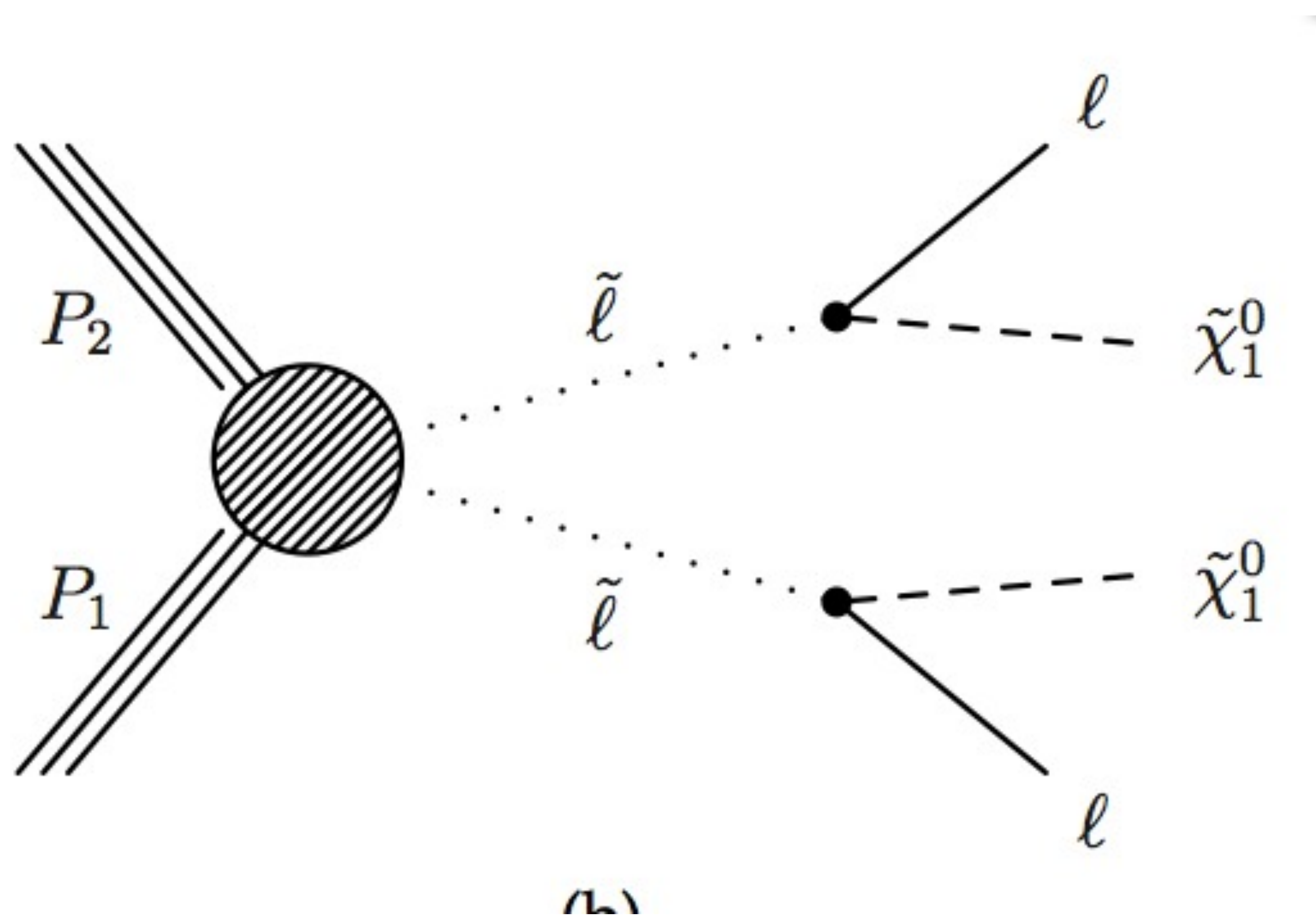


There are kinematic discriminants
that may enable 3 sigma discovery with full LHC8 data.

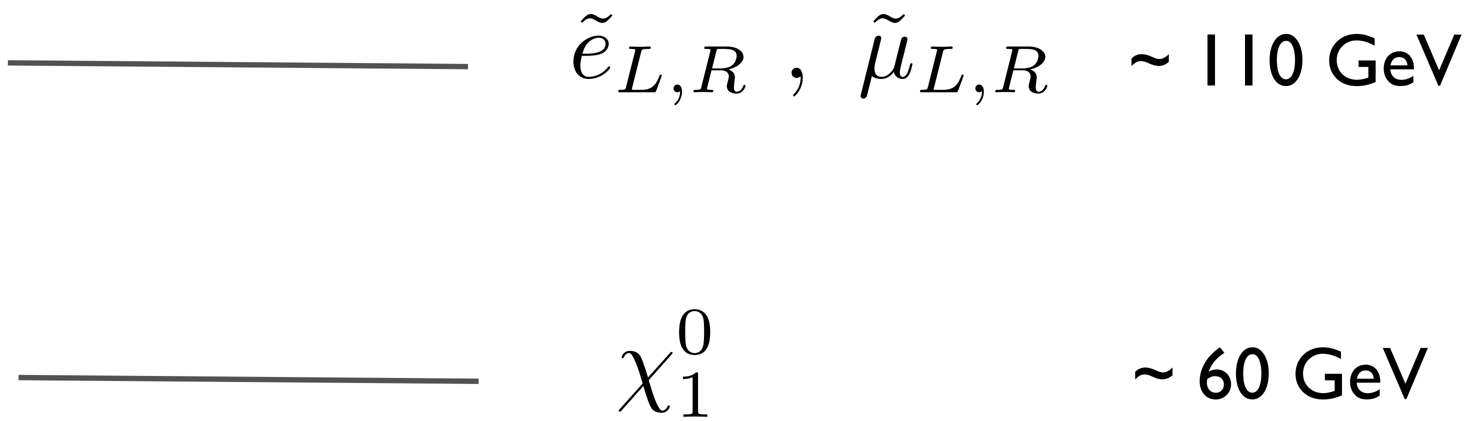


Example Topology for ll + MET:

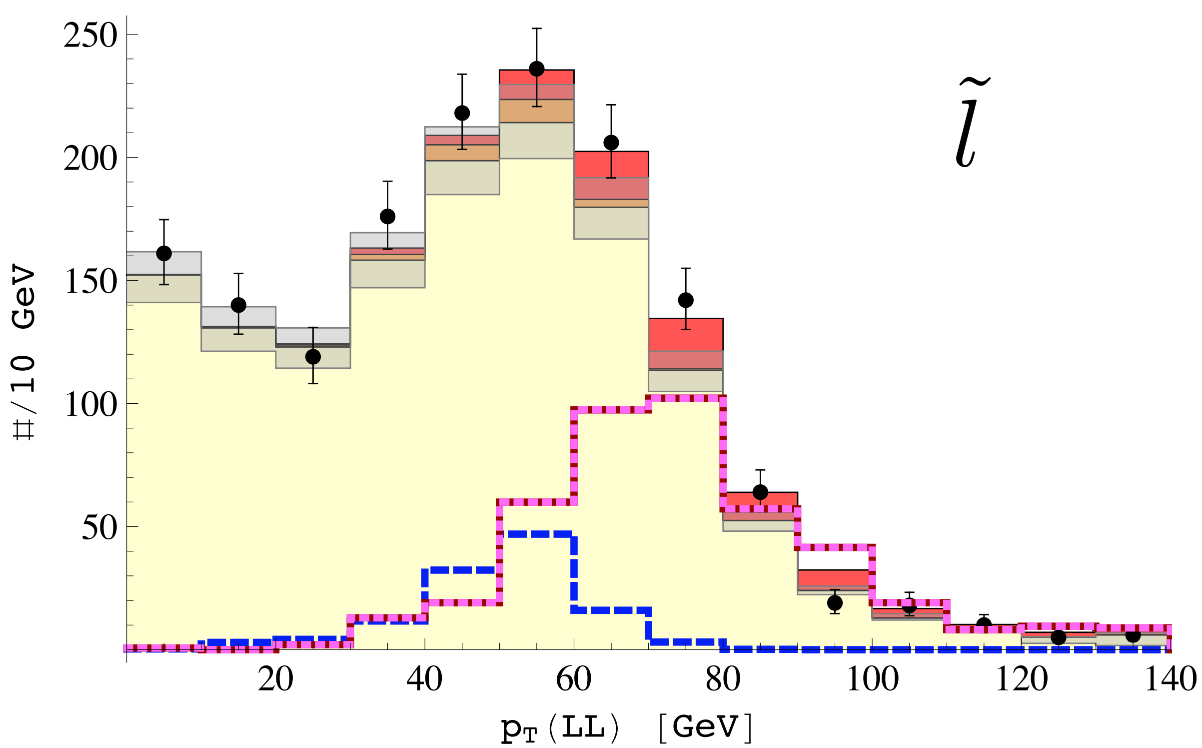
Slepton Pair Production

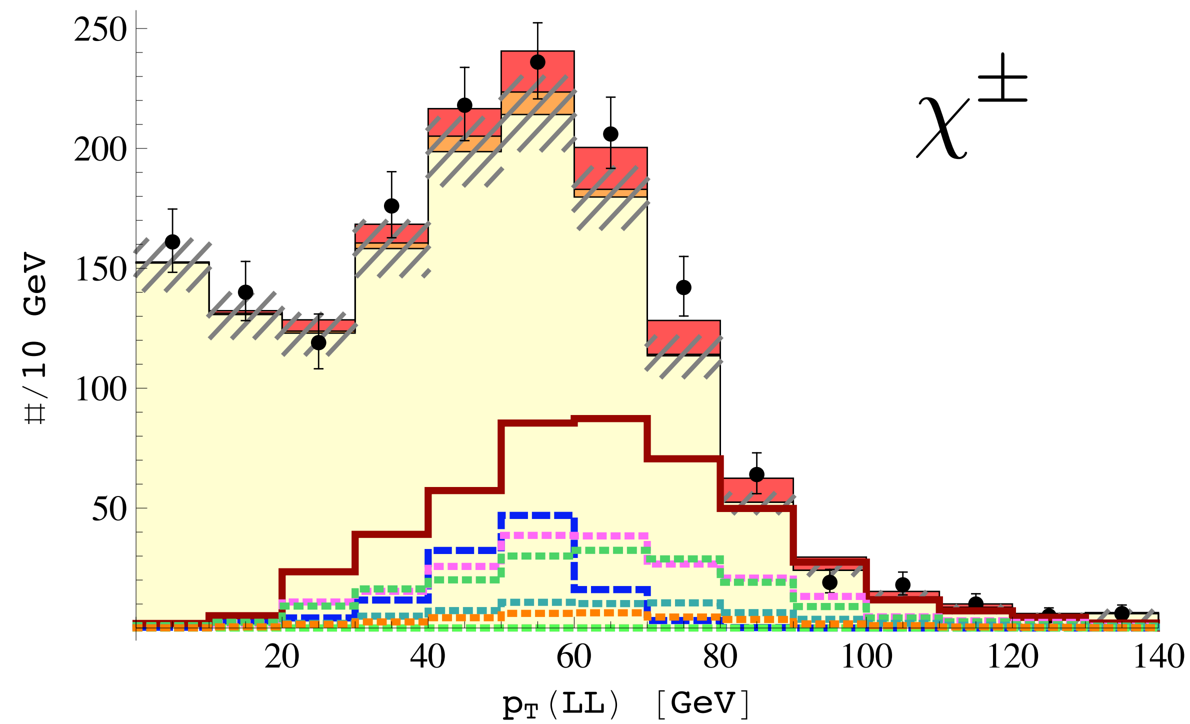


Sleptons



- 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...

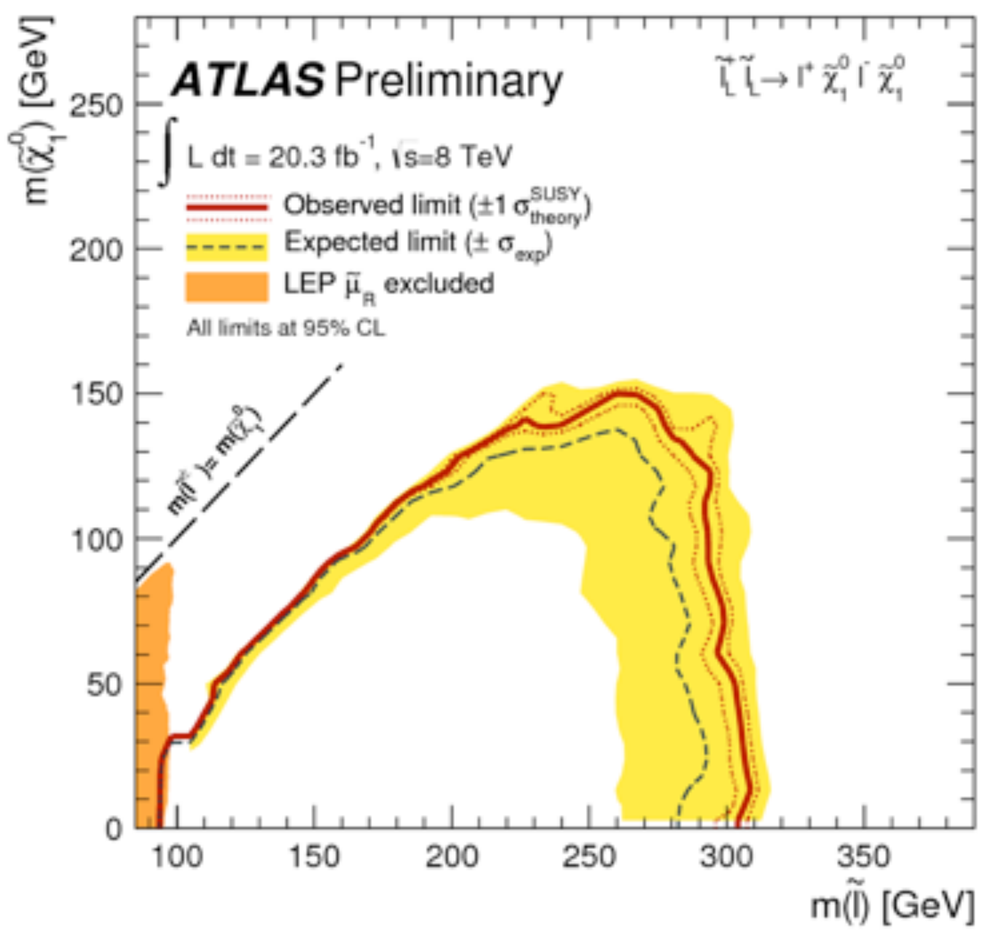
but let's take a step back first...

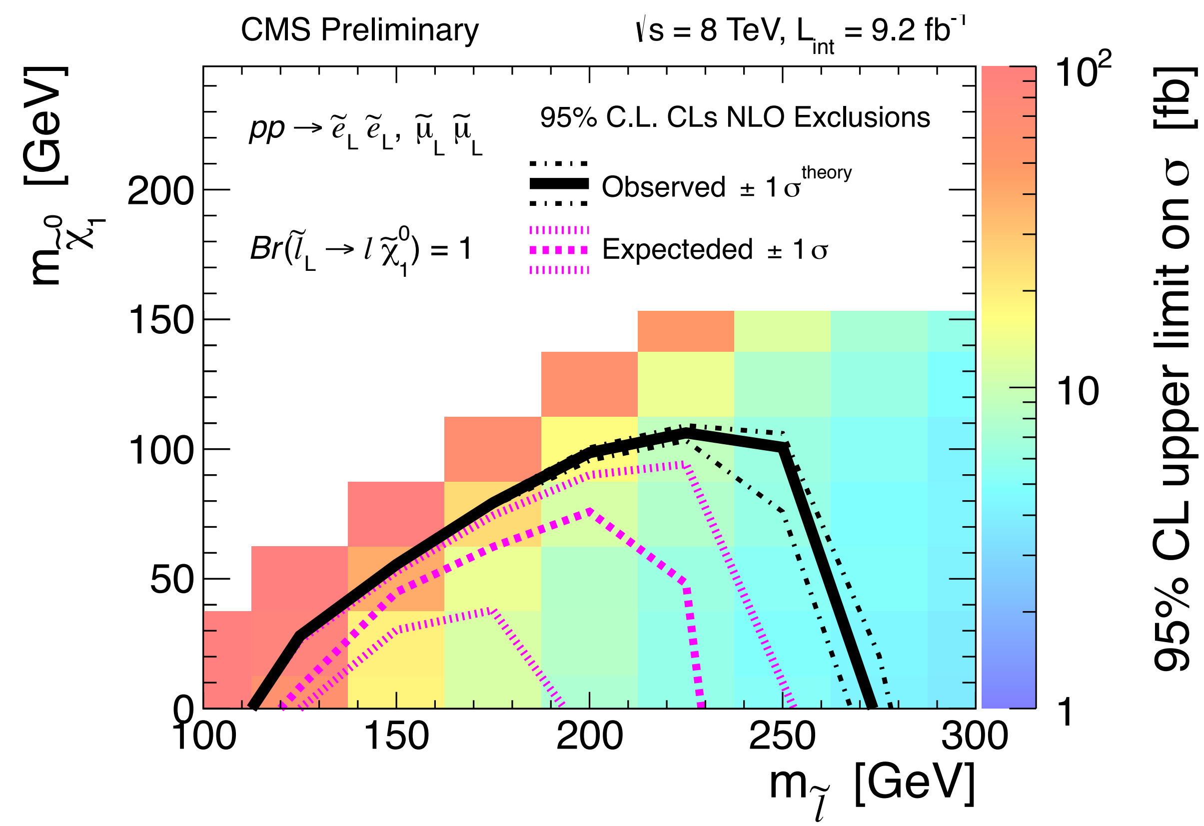
and talk about something (possibly) more archival:

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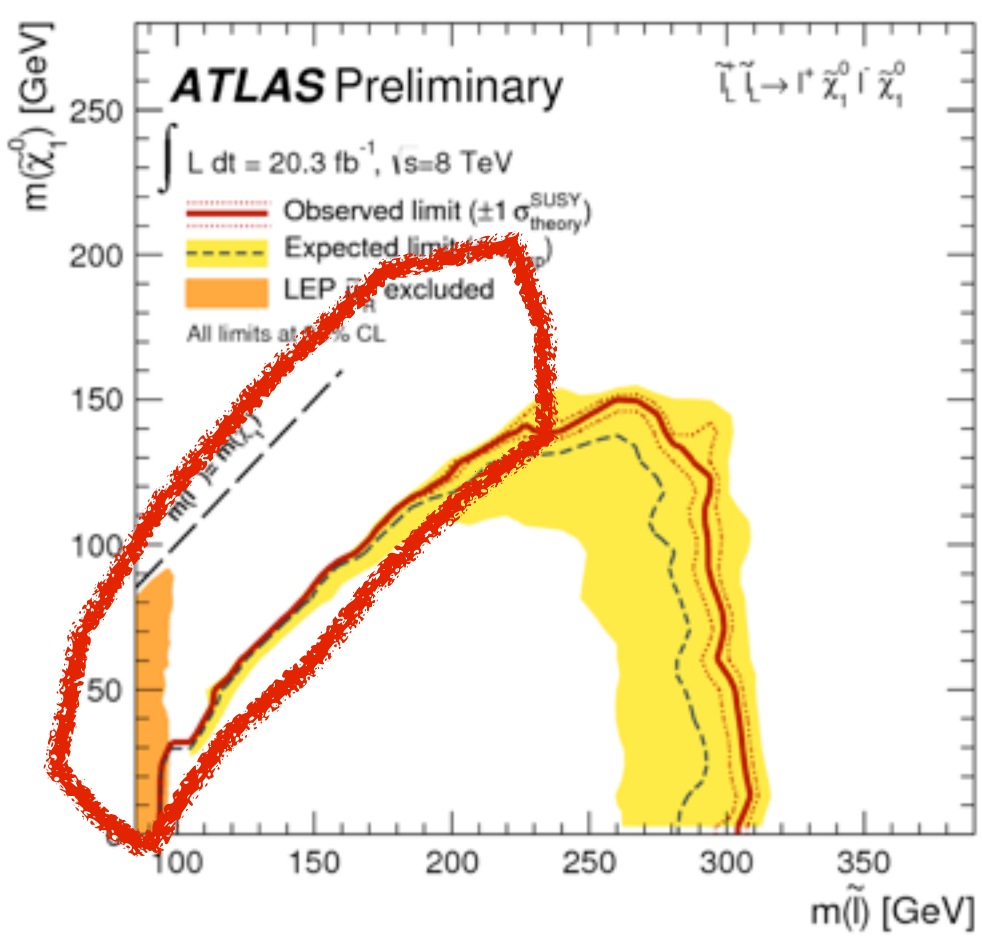
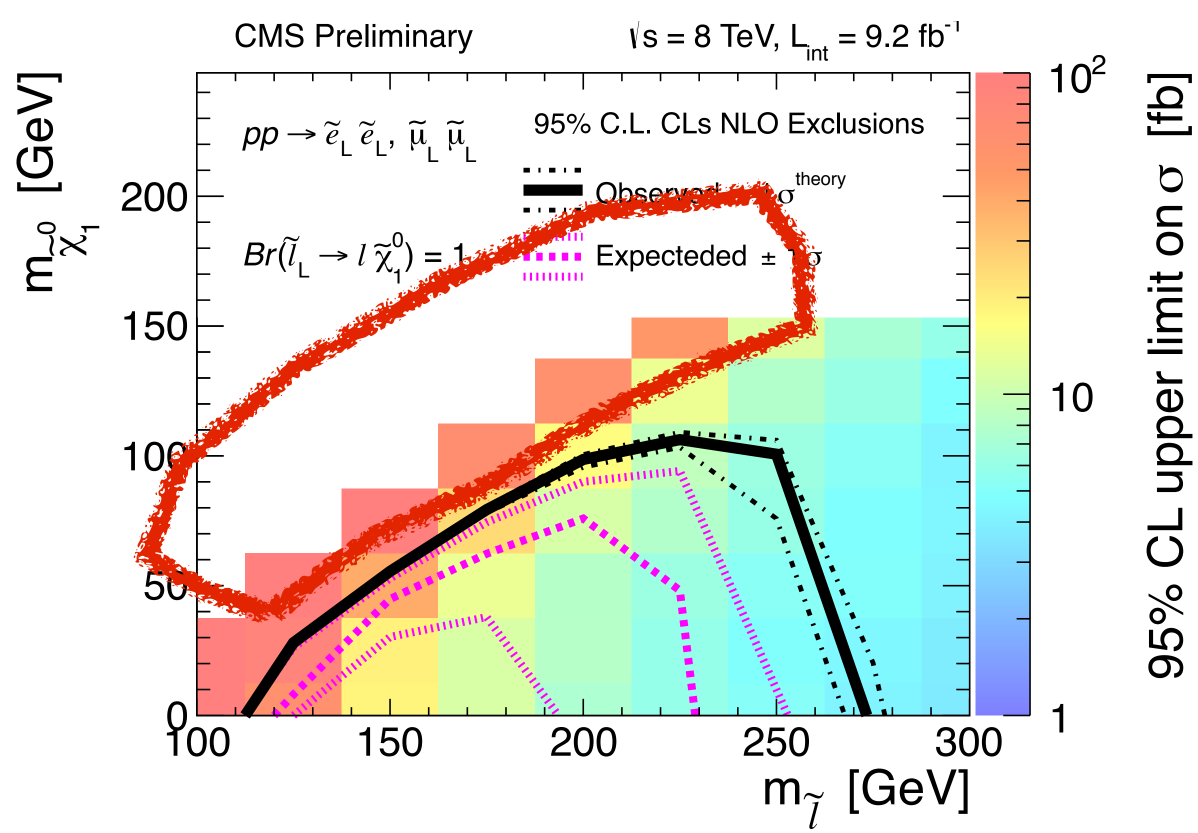
→ Exclude New Physics along the "WW-like Funnel"

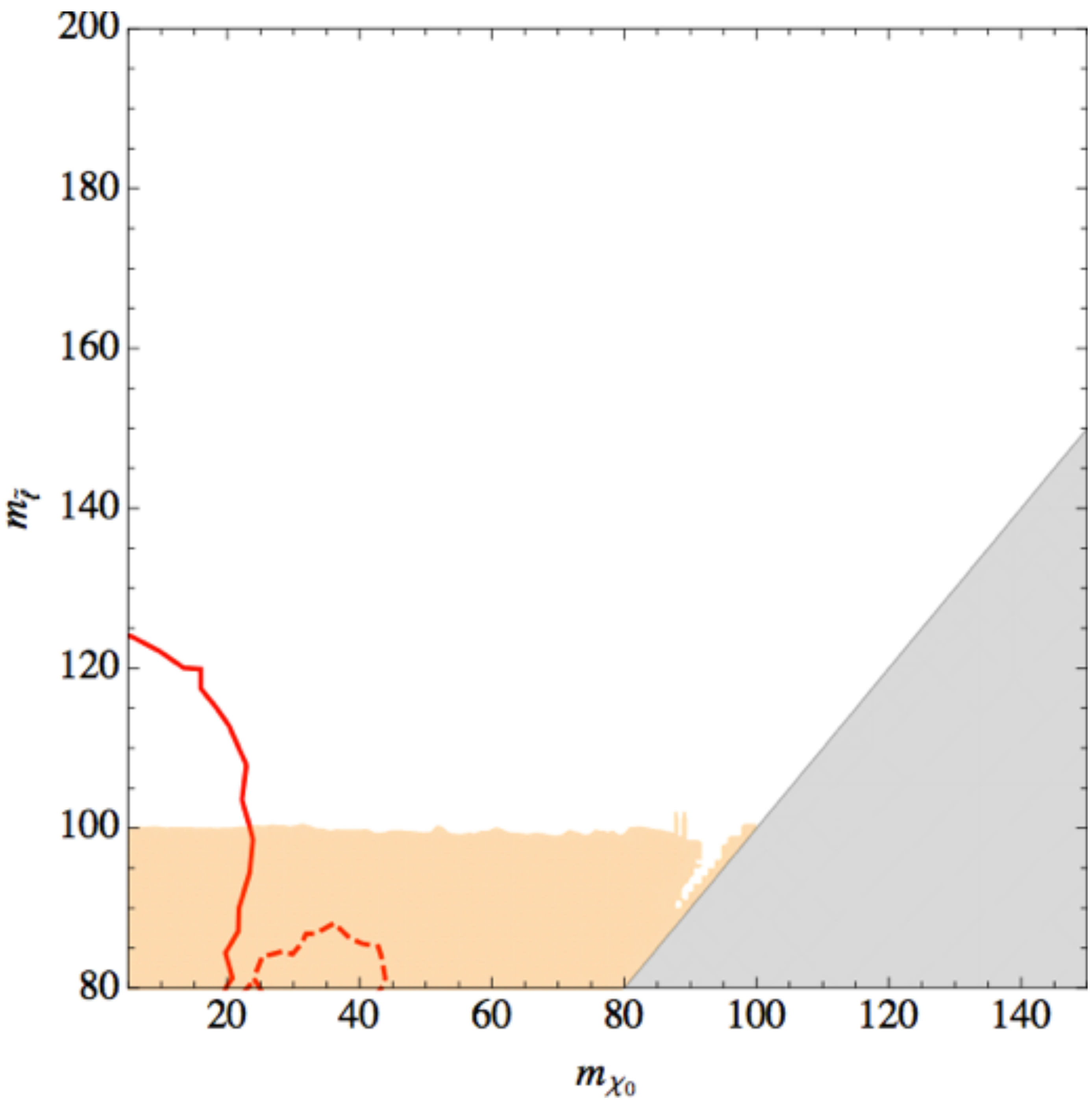




Slepton Exclusions from WW Measurement

- Treat the WW Measurement like a slepton search.
- Obtain 95% CL limits on slepton production
  - Do we trust the overall WW cross section calculation? We'd like to, but we don't know for sure...
  - Obtain limits with **shape+normalization** (powerful) or **shape-only** (robust!) of kinematic distributions

RH Slepton Exclusions from WW Measurement



LEP

CMS 9/fb LHC8 slepton search

ATLAS7

CMS7

CMS8

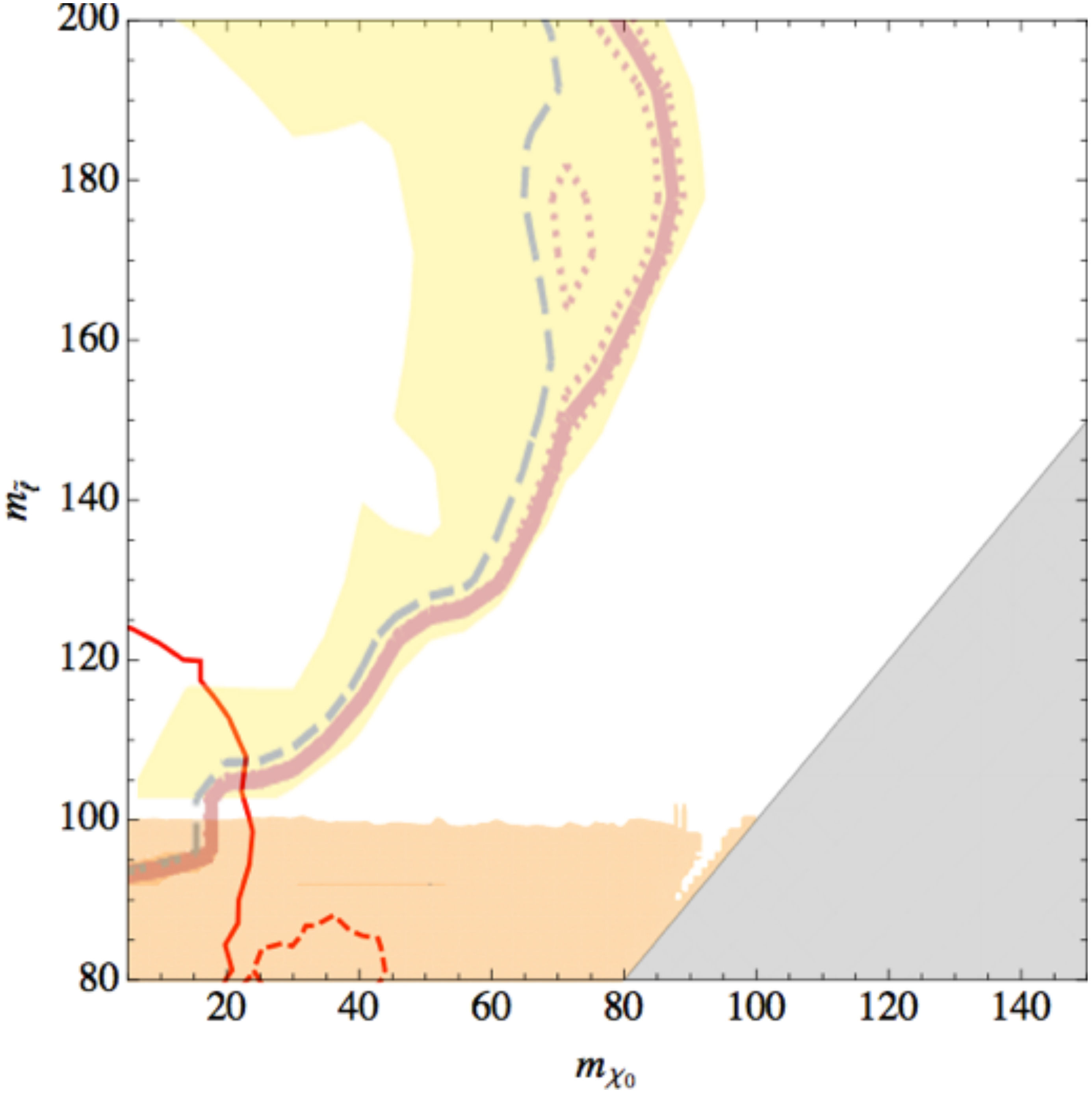
combined

——— shape only

- - - - - - - - shape + normalization

RH Slepton Exclusions from WW Measurement

UPDATE: ATLAS 20/fb Direct Search



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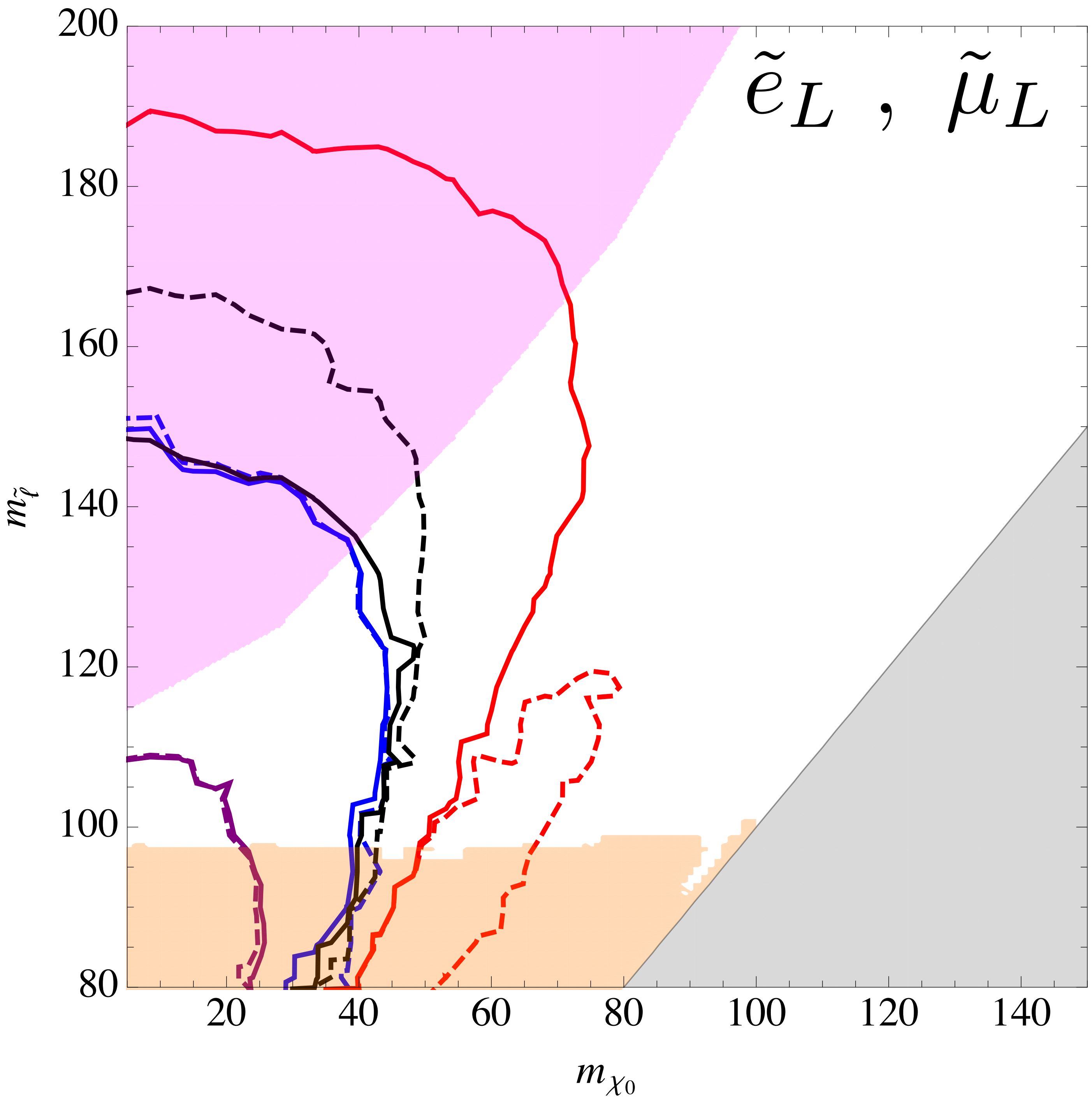
LH Slepton Exclusions from WW Measurement



LEP

CMS 9/fb LHC8 slepton search

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CMS8

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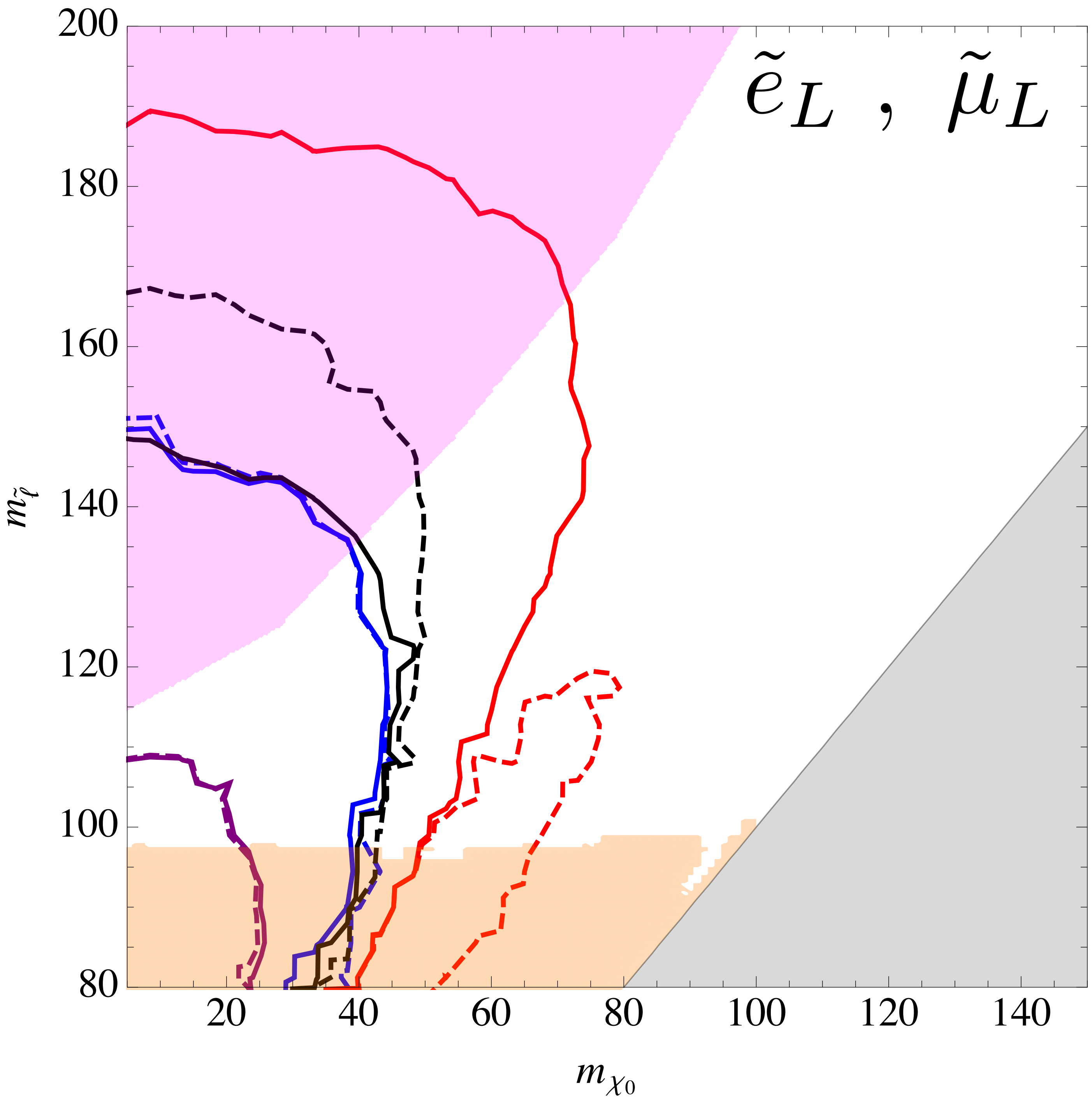
LH Slepton Exclusions from WW Measurement



LEP

CMS … rch

ATL

CMS

CMS

combined

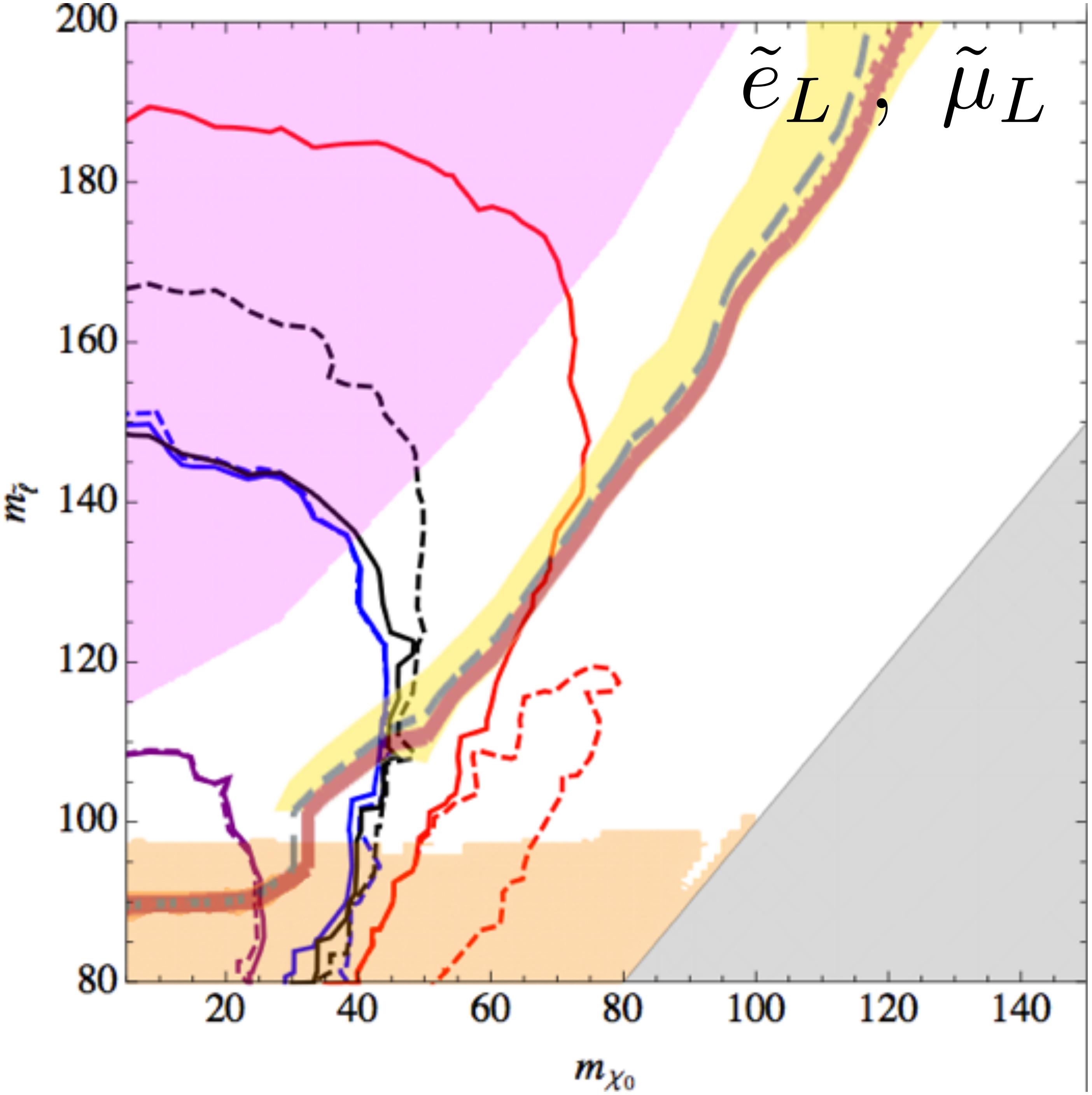
—— shape only

- - - - - - - shape + normalization

New EW constraints, complementary to other search strategies!

LH Slepton Exclusions from WW Measurement

UPDATE: ATLAS 20/fb Direct Search



LEP

CMS 9/fb LHC8 slepton search

ATLAS7

CMS7

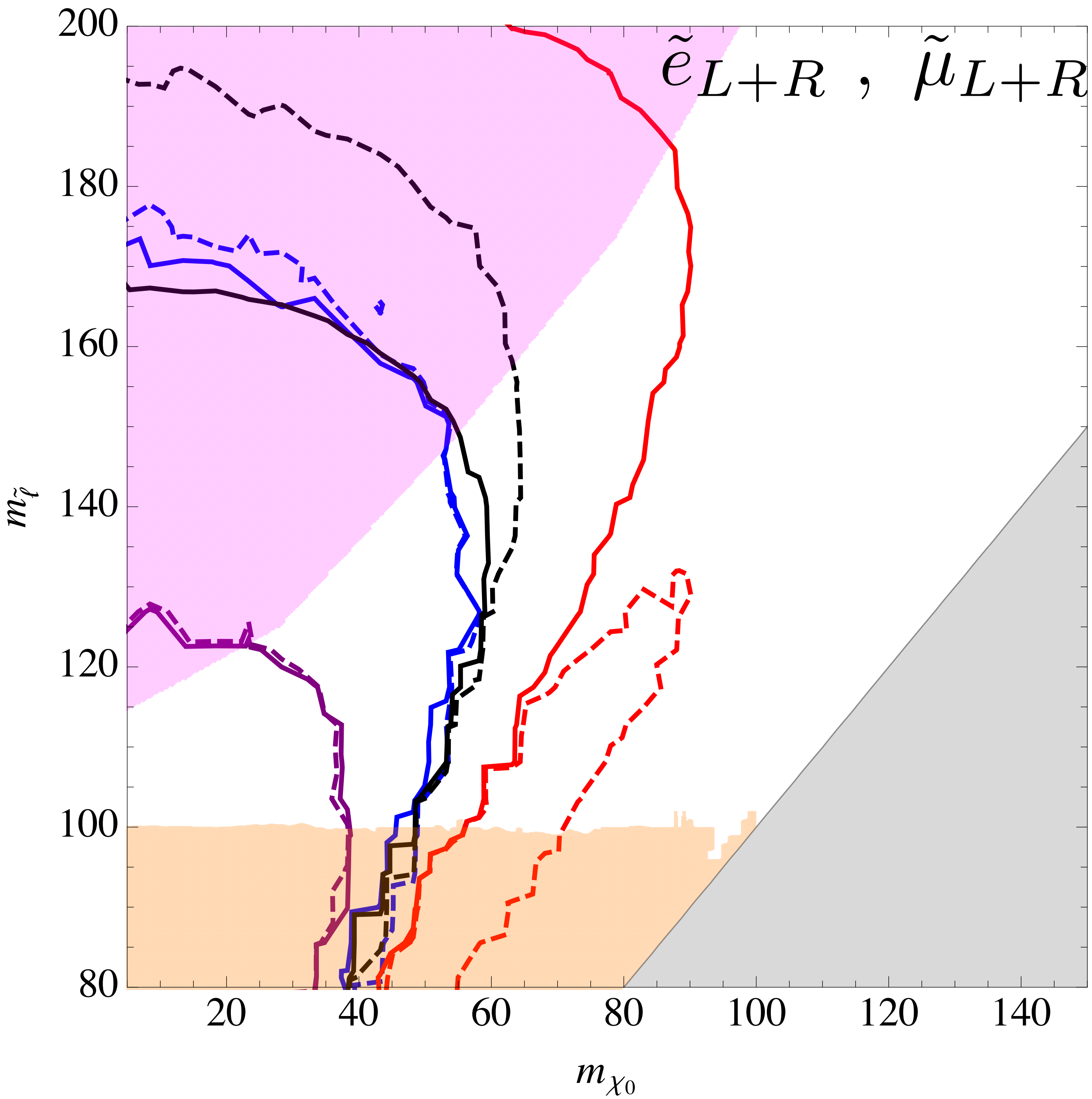
CMS8

combined

shape only

shape + normalization

LH + RH Slepton Exclusions from WW Measurement



LEP

CMS 9/fb LHC8 slepton search

ATLAS7

CMS7

CMS8

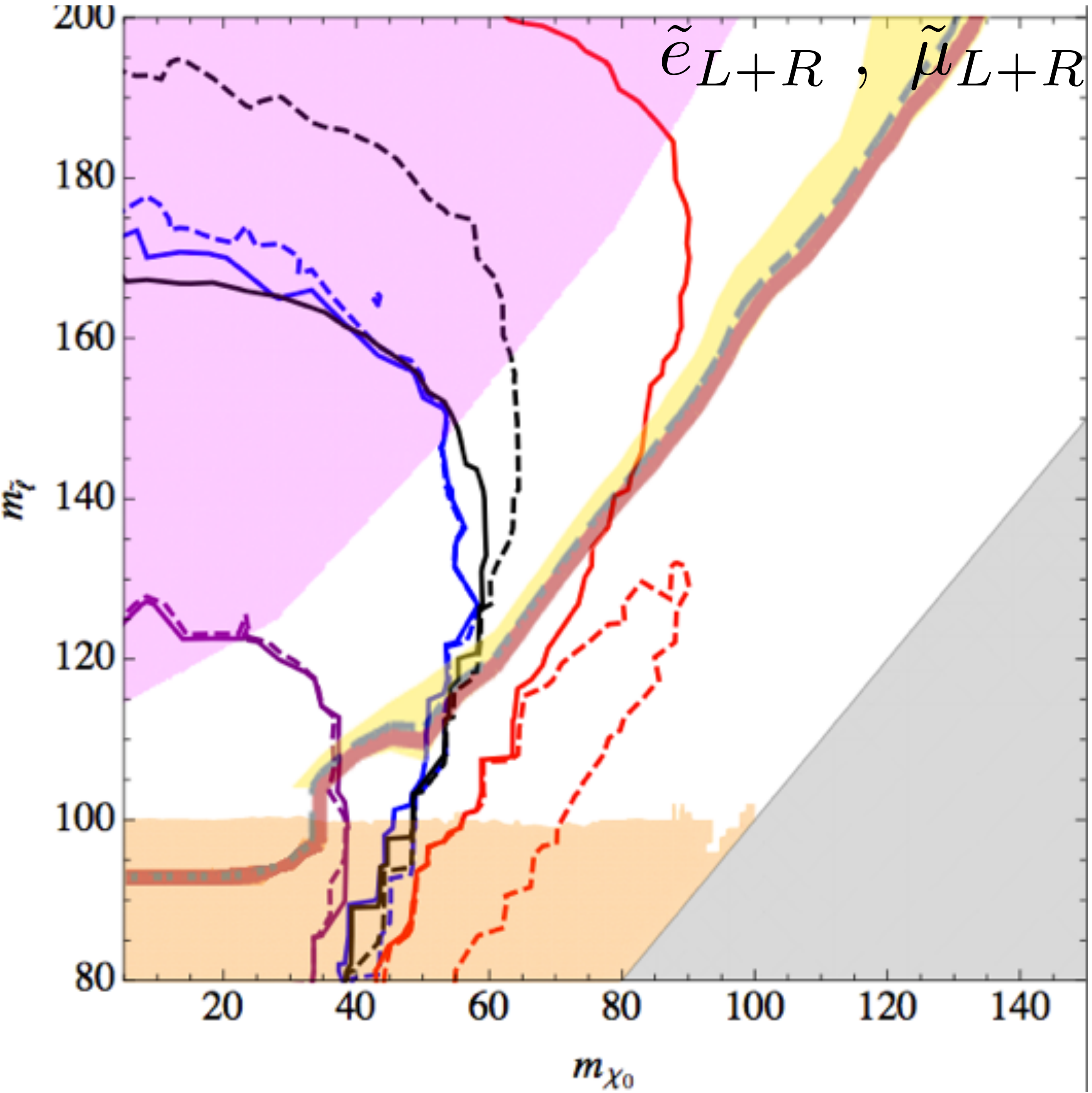
combined

—— shape only

- - - - - shape + normalization

LH + RH Slepton Exclusions from WW Measurement

UPDATE: ATLAS 20/fb Direct Search



LEP

CMS 9/fb LHC8 slepton search

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CMS7

CMS8

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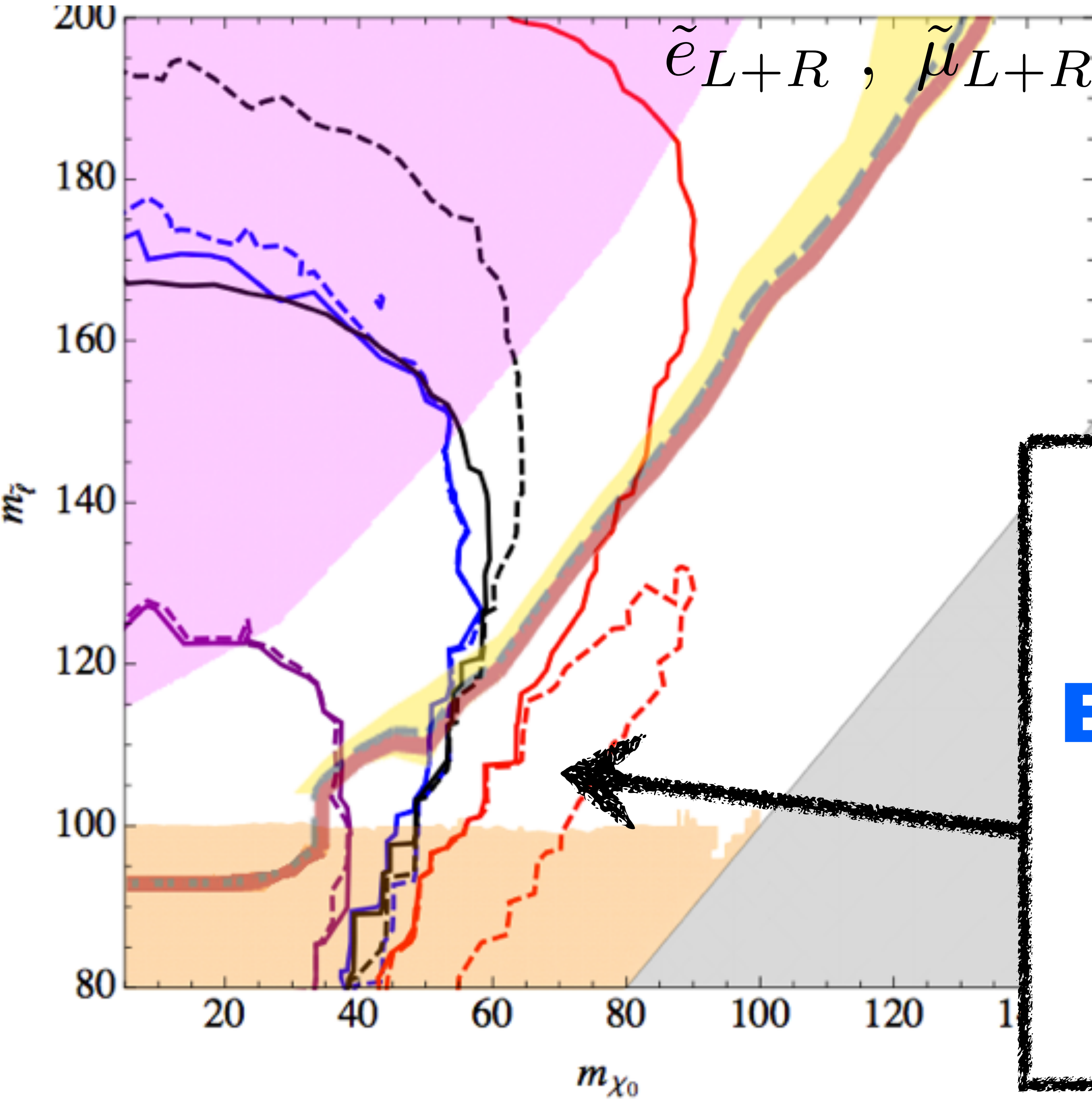
shape only

shape + normalization

LH + RH Slepton Exclusions from WW Measurement

UPDATE: ATLAS 20/fb Direct Search



LEP

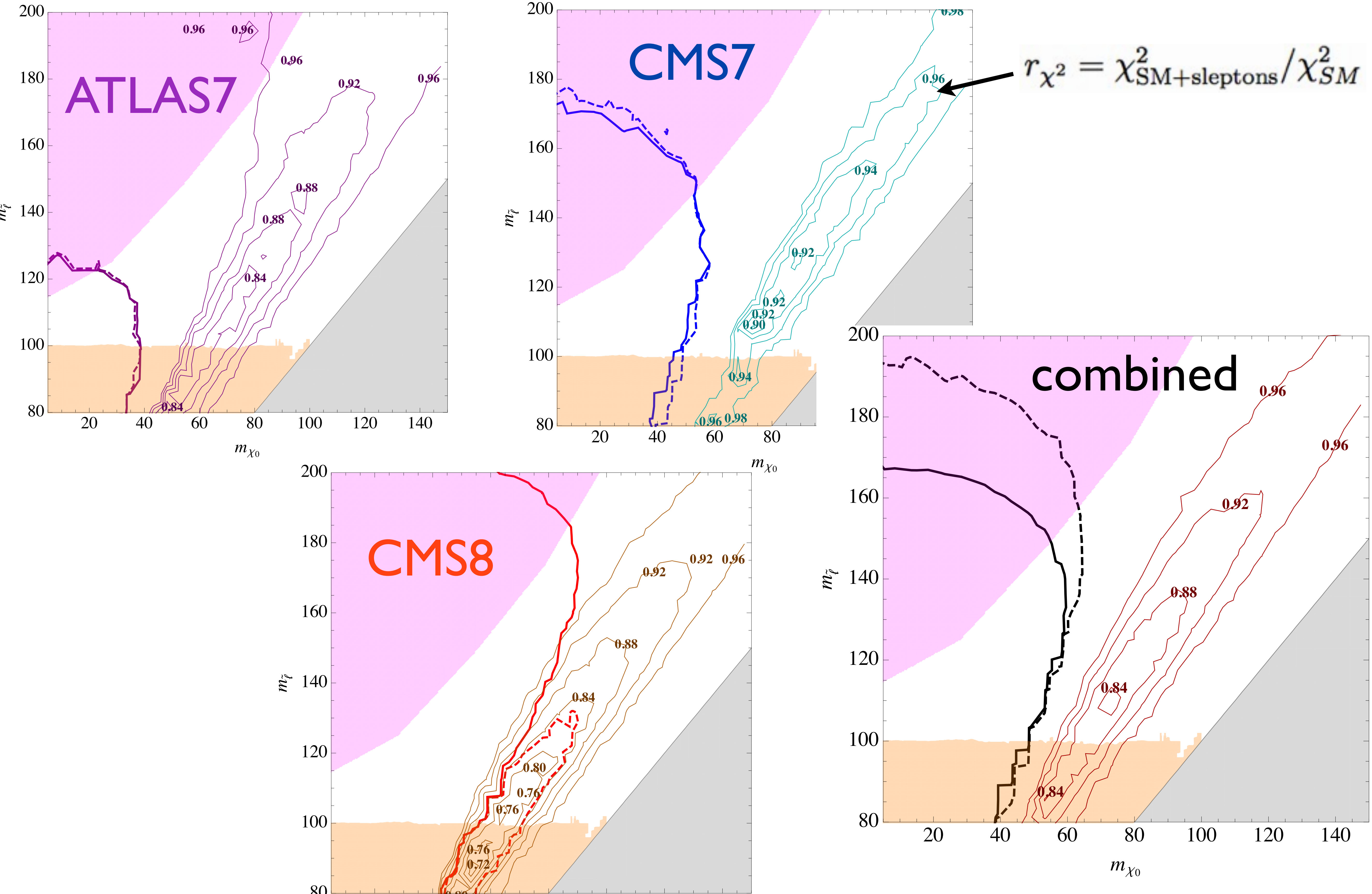
CMS 9/fb LHC8 slepton search

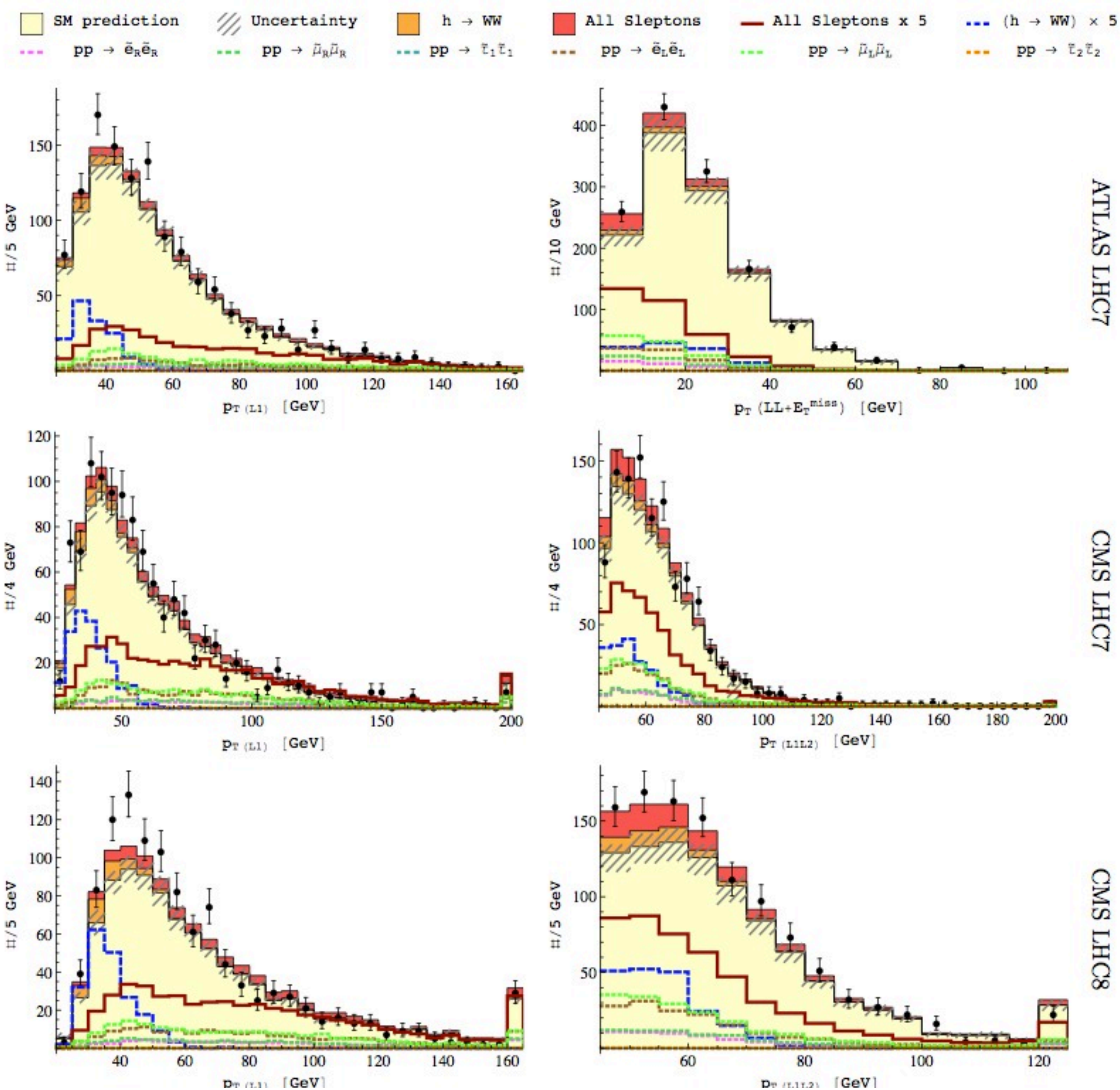
ATLAS7

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

Back to hypothesizing about New Physics...

Sleptons can improve WW fit




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

Are there any dangerous processes?

No!

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

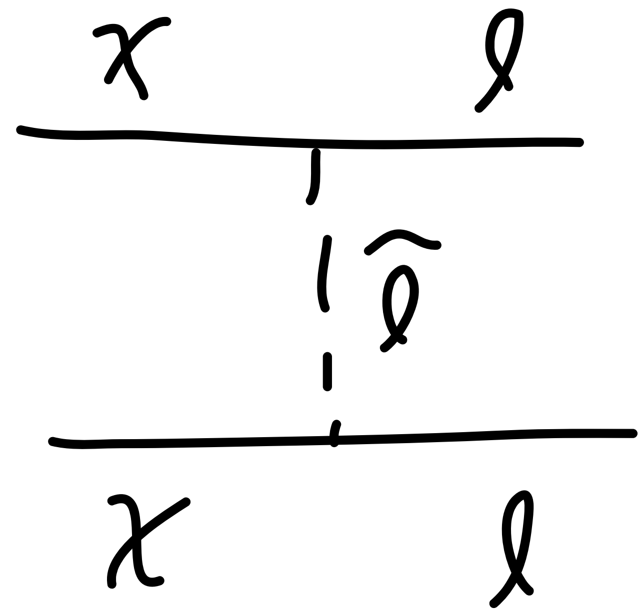
→ **That's our smoking gun!**

We sure would love to see more flavor-resolved kinematic distributions for WW.

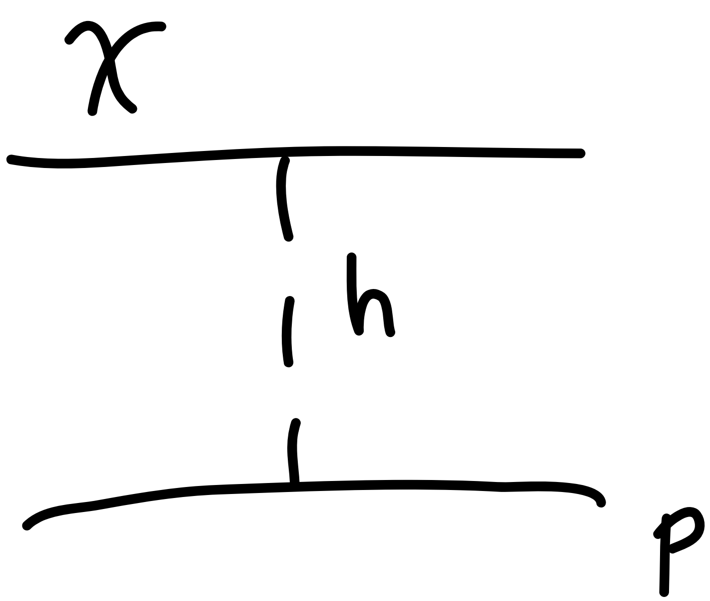
Also, 20/fb?

Can light sleptons do anything else for you?

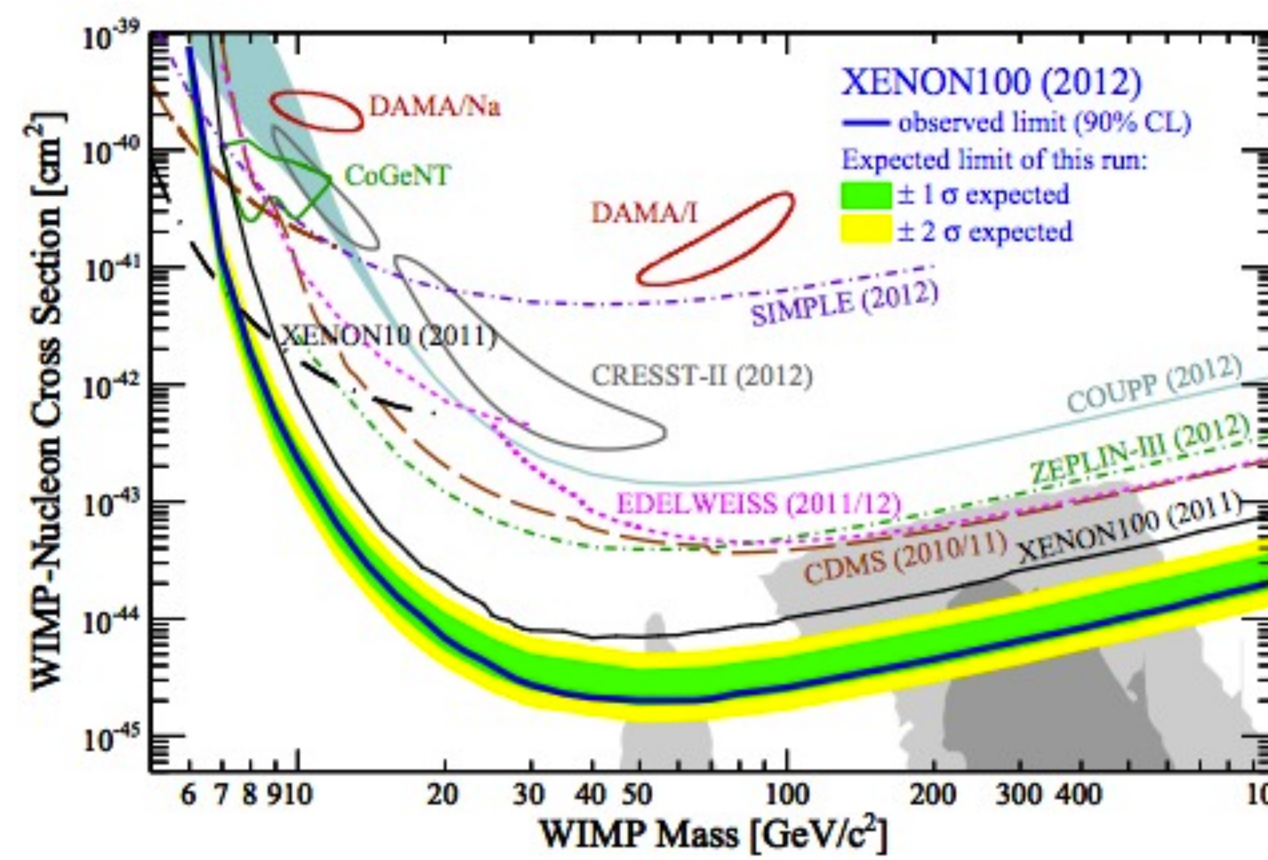
BINO DM!



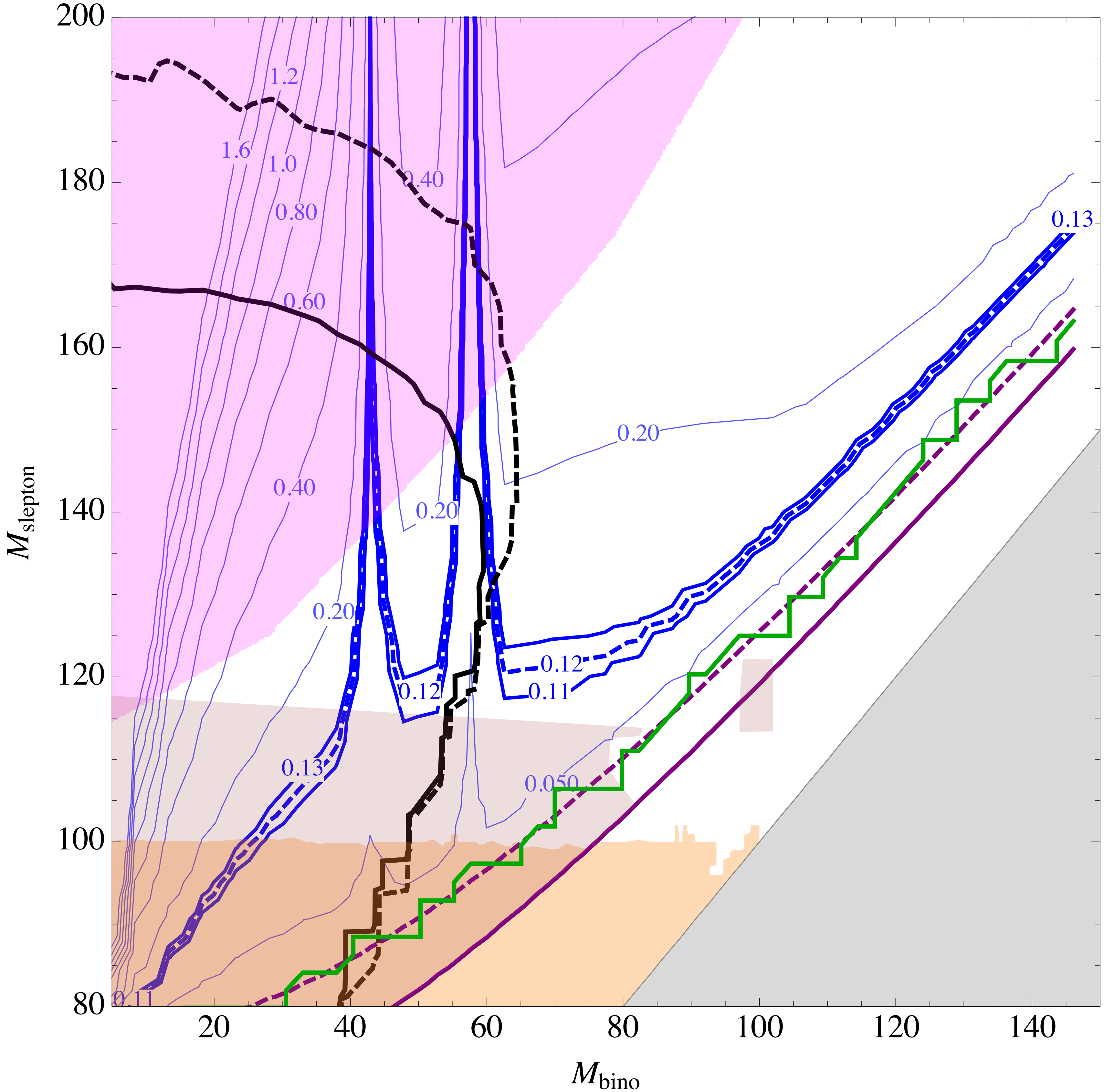
Can get right relic density



Direct Detection sails right through and is interesting for **Xenon1T!**



DM and light sleptons



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

μ = 400 GeV
tan β = 6

CMS slepton

LEP

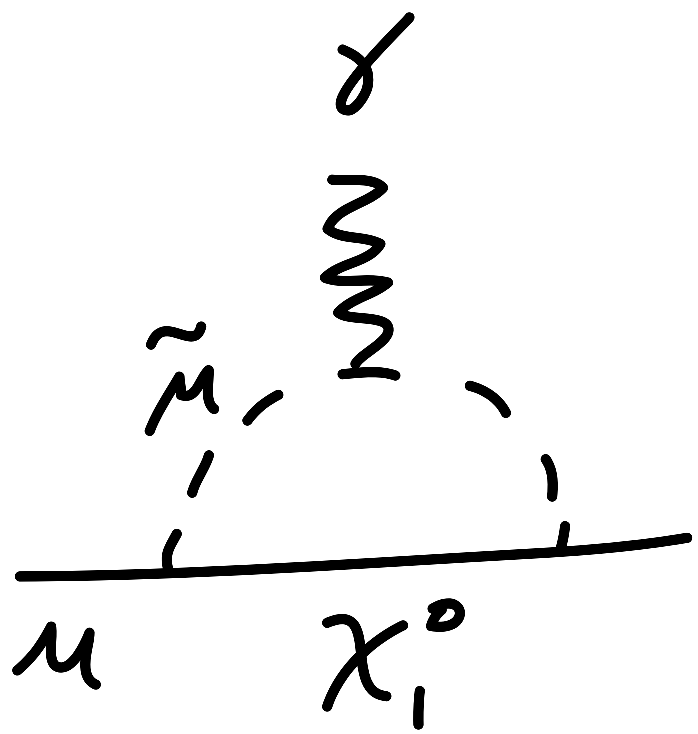
combined WW bounds

DM relic density

DM direct detection

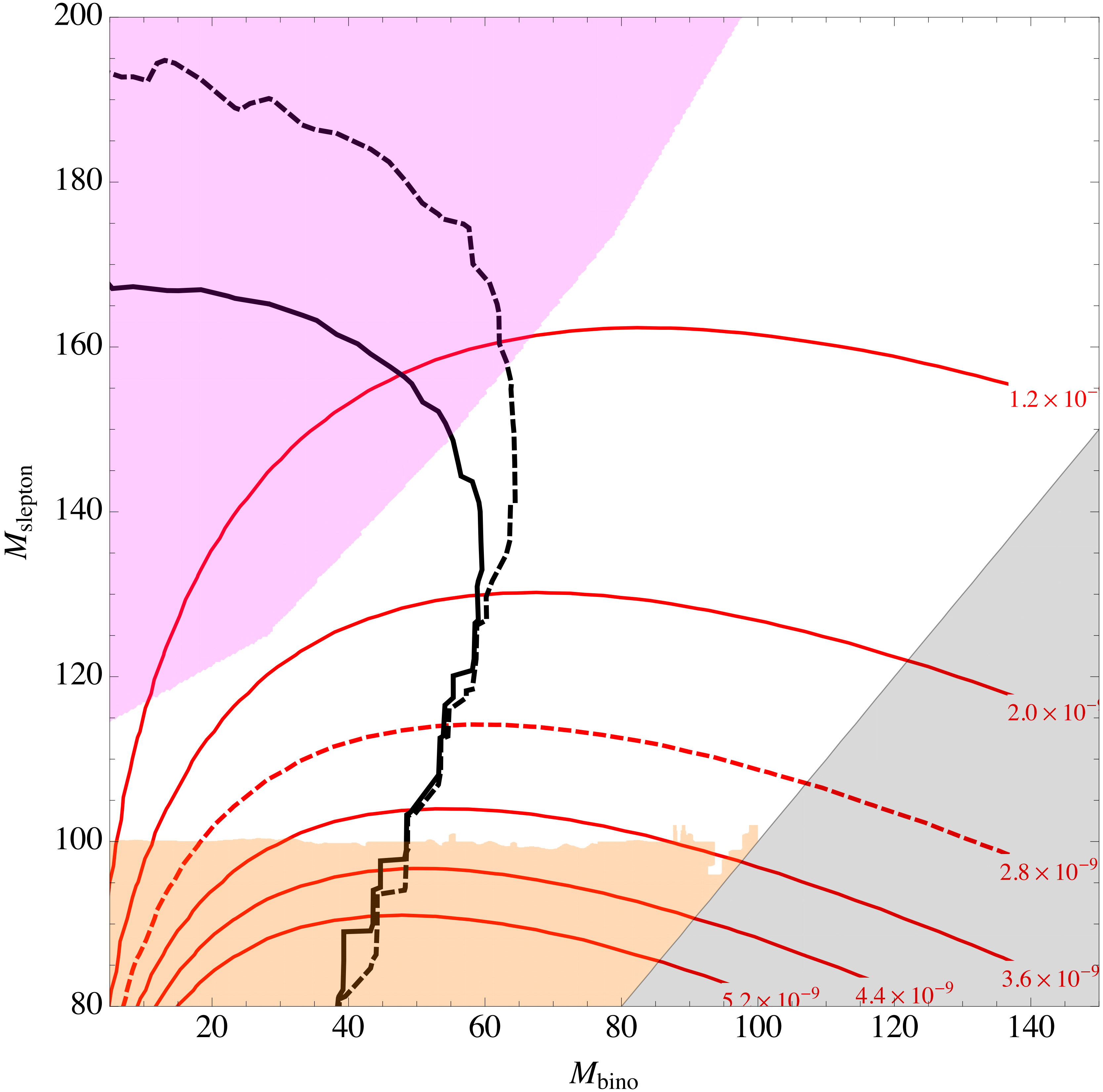
Can light sleptons do anything else for you?

Muon (g-2) !



$$\delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (2.8 \pm 0.8) \times 10^{-9}$$

g-2 and light sleptons



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

μ = 400 GeV
tan β = 6

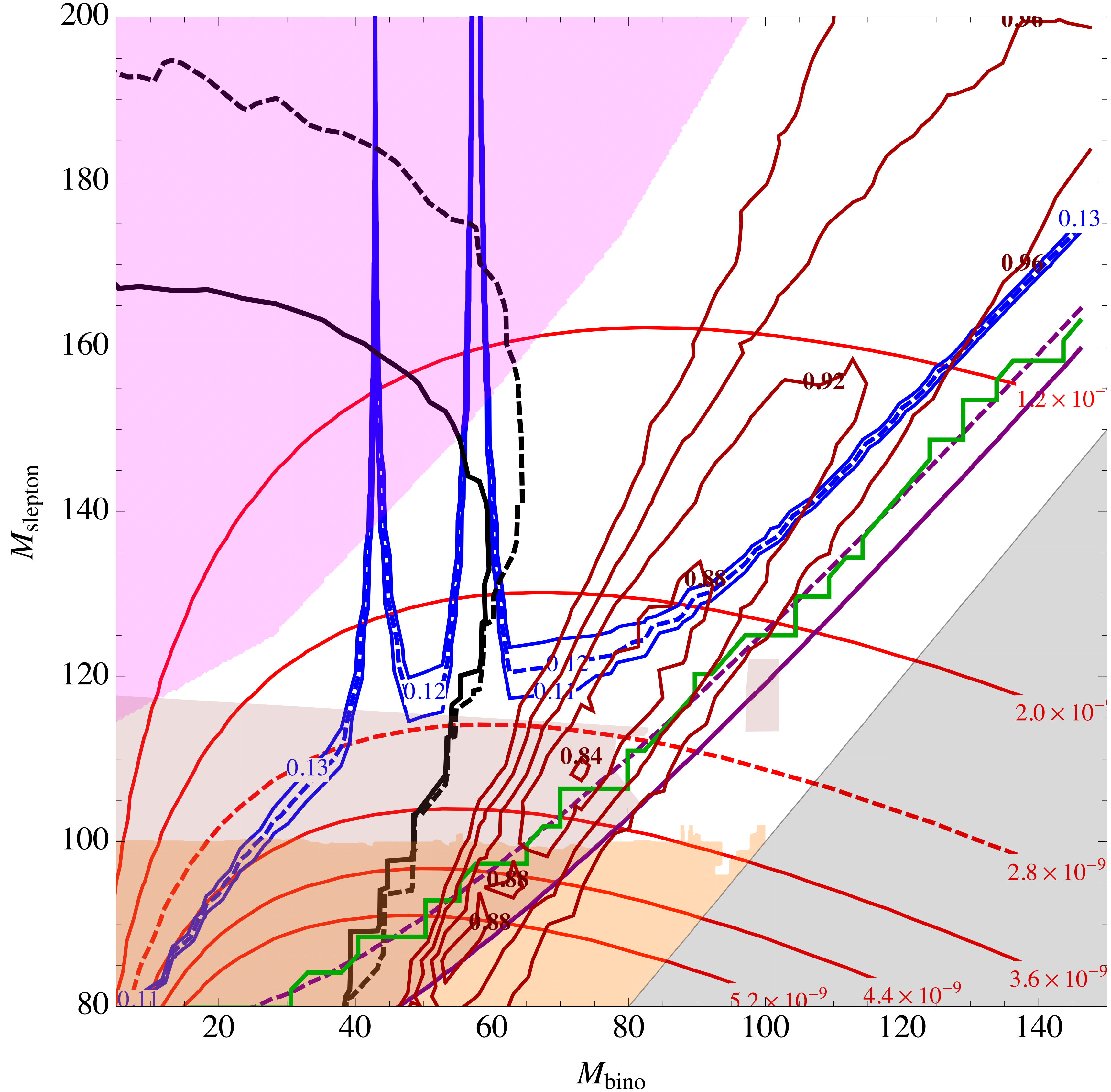
CMS slepton

LEP

combined WW bounds

g-2

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

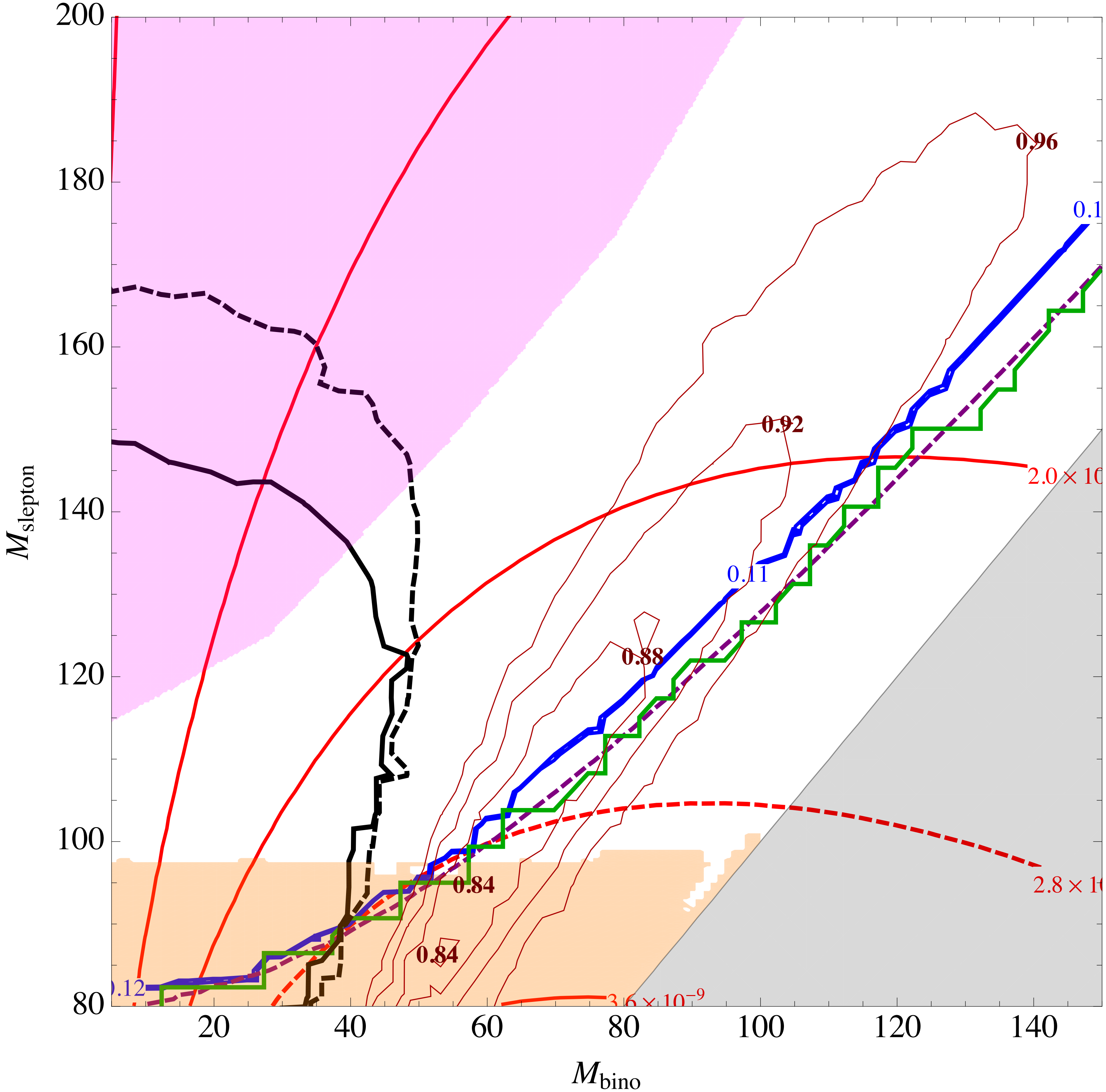
g-2

DM relic density

DM direct detection

WW preferred region

Could work with just LH sleptons too



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

μ ~ 1500 GeV
tan β ~ 15

CMS slepton

LEP

combined WW bounds

g-2

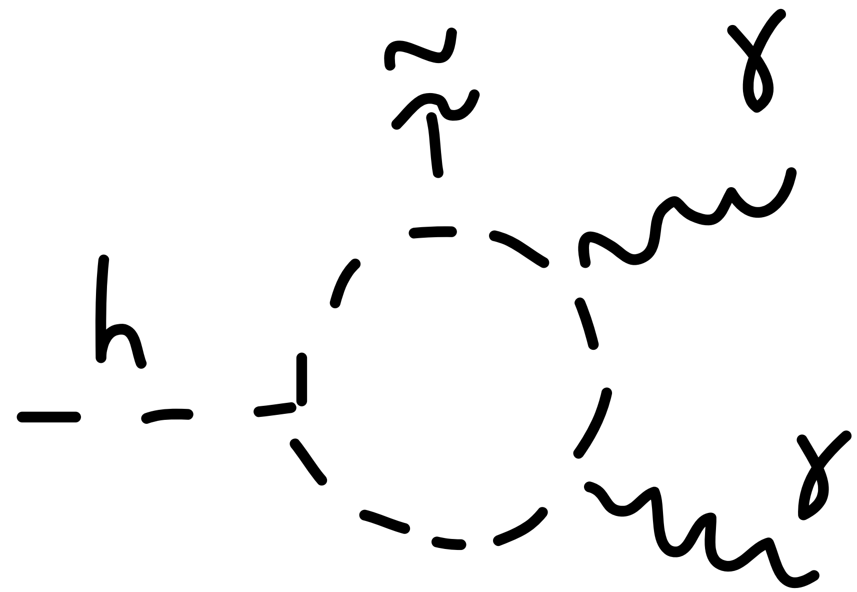
DM relic density

DM direct detection

WW preferred region

Can light sleptons do anything else for you?

h → γγ ?



Some enhancement (15%) possible
without diluting DM relic density.

Requires some slepton soft mass non-universality
→ FLV bounds OK!

What about h → WW?

- BSM pollution in the control region (m_{ll} > 100 GeV)* leads to an overestimation of WW background.
- For charginos, this overestimation was 'just right' to account for their pollution of the signal region (m_{ll} < 50GeV)*.
- The slightly harder slepton contribution is more skewed towards the control region.
- This leads to an OVERestimation of BG in the signal region

→ UNDERestimates higgs signal strength.

*ATLAS 7 TeV

Let's take a deep breath...

What are the likely SM explanations for WW excess?

SM/Experimental Explanations for WW

1. Statistical Fluctuation

* Naive combination of significances gives 2.8 σ deviation (correlations?). More with shape...

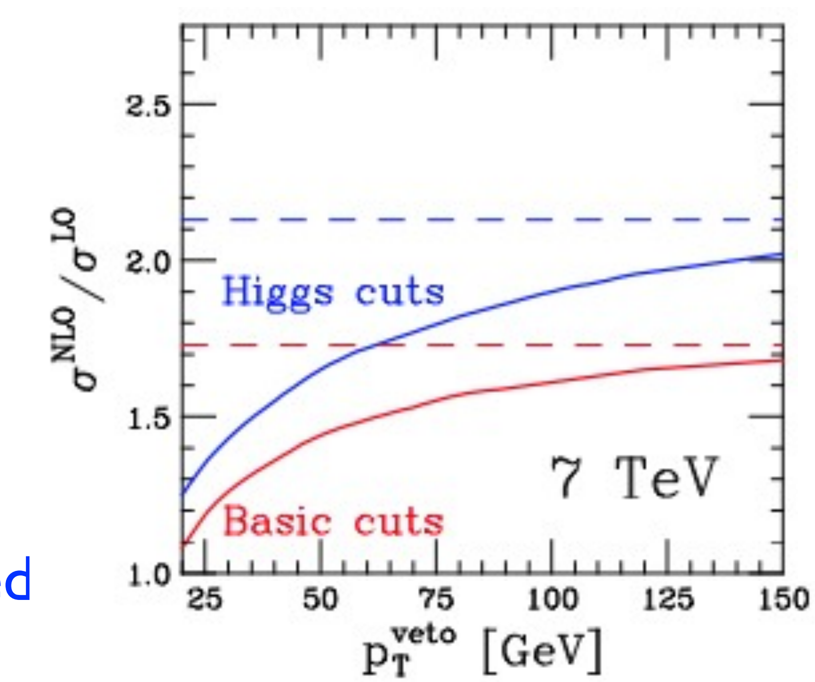
2. Inaccurate Background Estimation

* dominant BGs are top and W + jet, very data-driven and consistent across experiments
* DY is large in ATLAS and small in CMS, both are high and consistent with each other
* No BG 'jumps out' as being able to explain the difference in predicted & observed shape

3. Inaccurate prediction for WW production cross section

* higher-order EW effects are too small, and in wrong direction
  (Bierweiler, Kasprzik, Kuhn, Uccirati 1208.3147)
* higgs interferes destructively as well
* QCD? NNLO would have to be ~20% effect..... NNLL+approx NNLO is ~ 3% (1307.3249 Dawson, Lewis, Zeng)

4. Inaccurate Signal Acceptance Estimation



* Biggest uncertainty from **jet veto**, but effect does not seem strong enough to explain 20% deviation
  Campbell, Ells, Williams 1105.0020
* ATLAS and CMS use ***different MC approaches*** and ***different jet clusterings/thresholds.*** **They agree!**
* QCD NLO contributions would have to be *softer* than expected to increase WW rate after jet veto. *Weird!*
* WWj, WWjj contributions might need to be treated more carefully.

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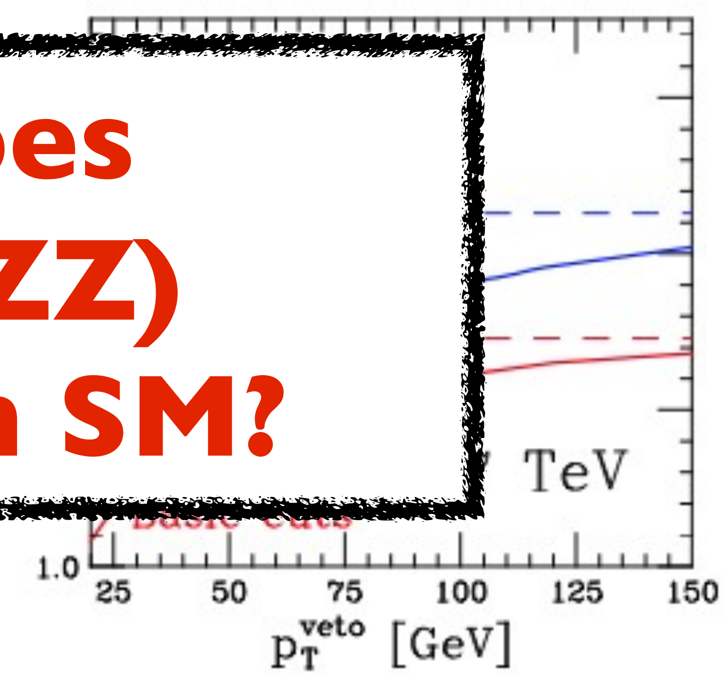

Why does σ(pp → ZZ) agree with SM?

SM/Experimental Explanations for WW

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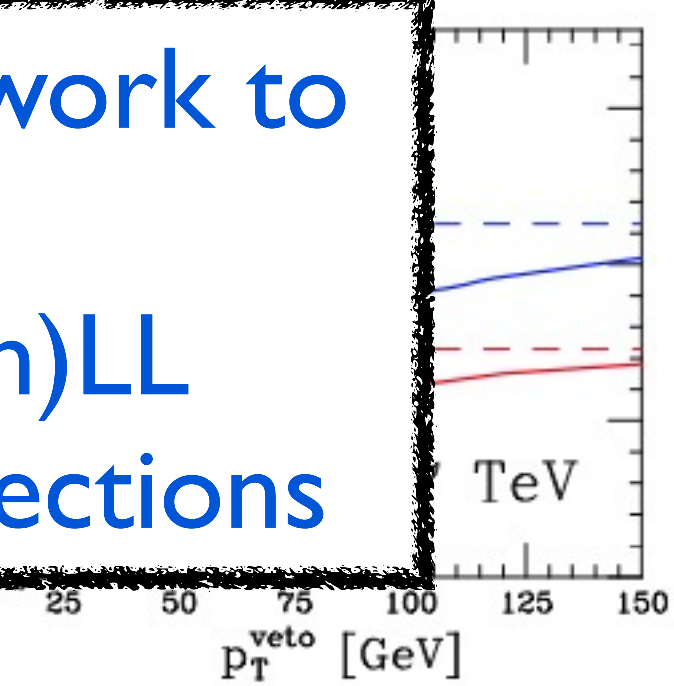
Requires more work to compute NNLO+N^(n)LL diboson cross sections

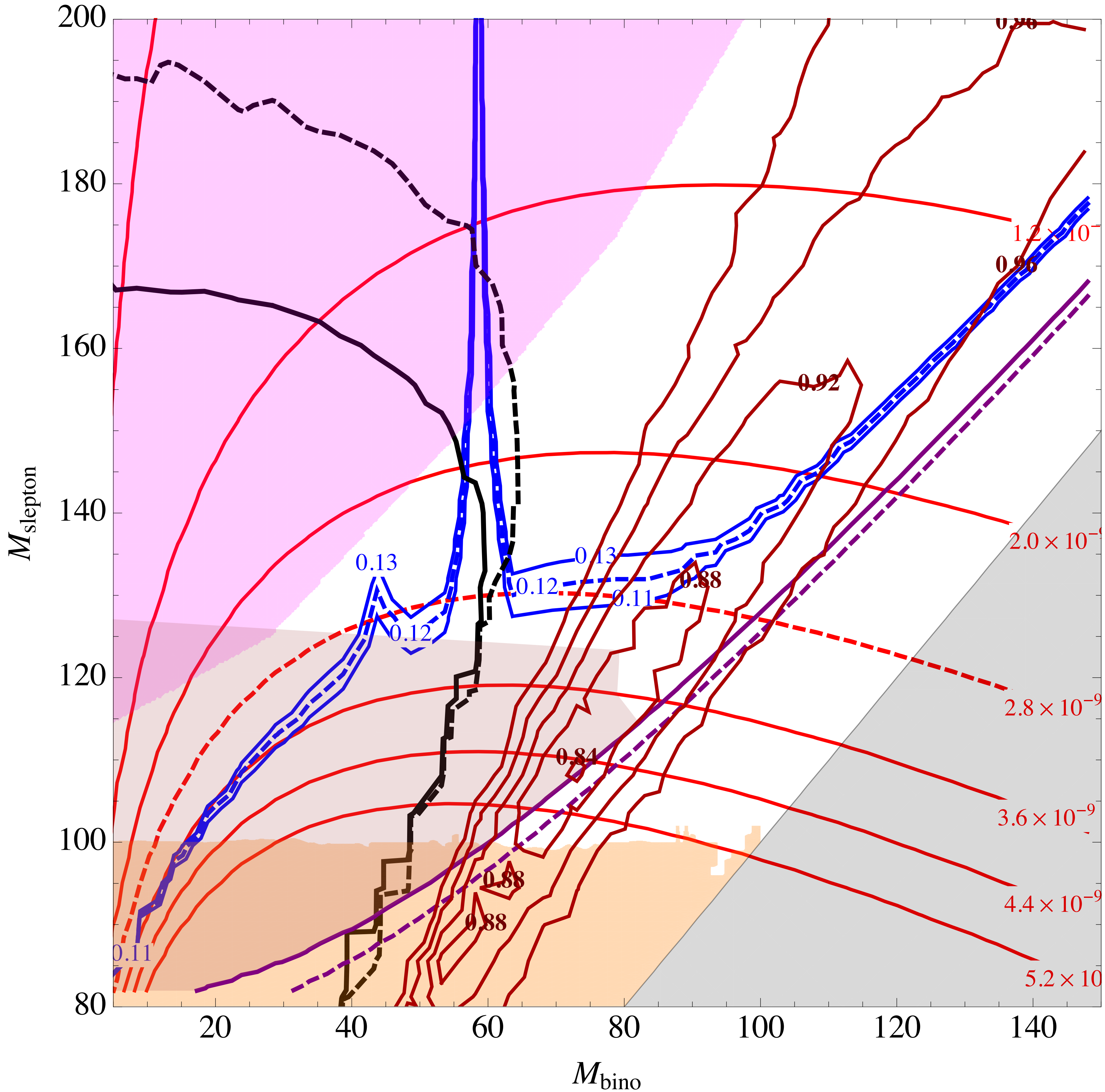


Conclusions

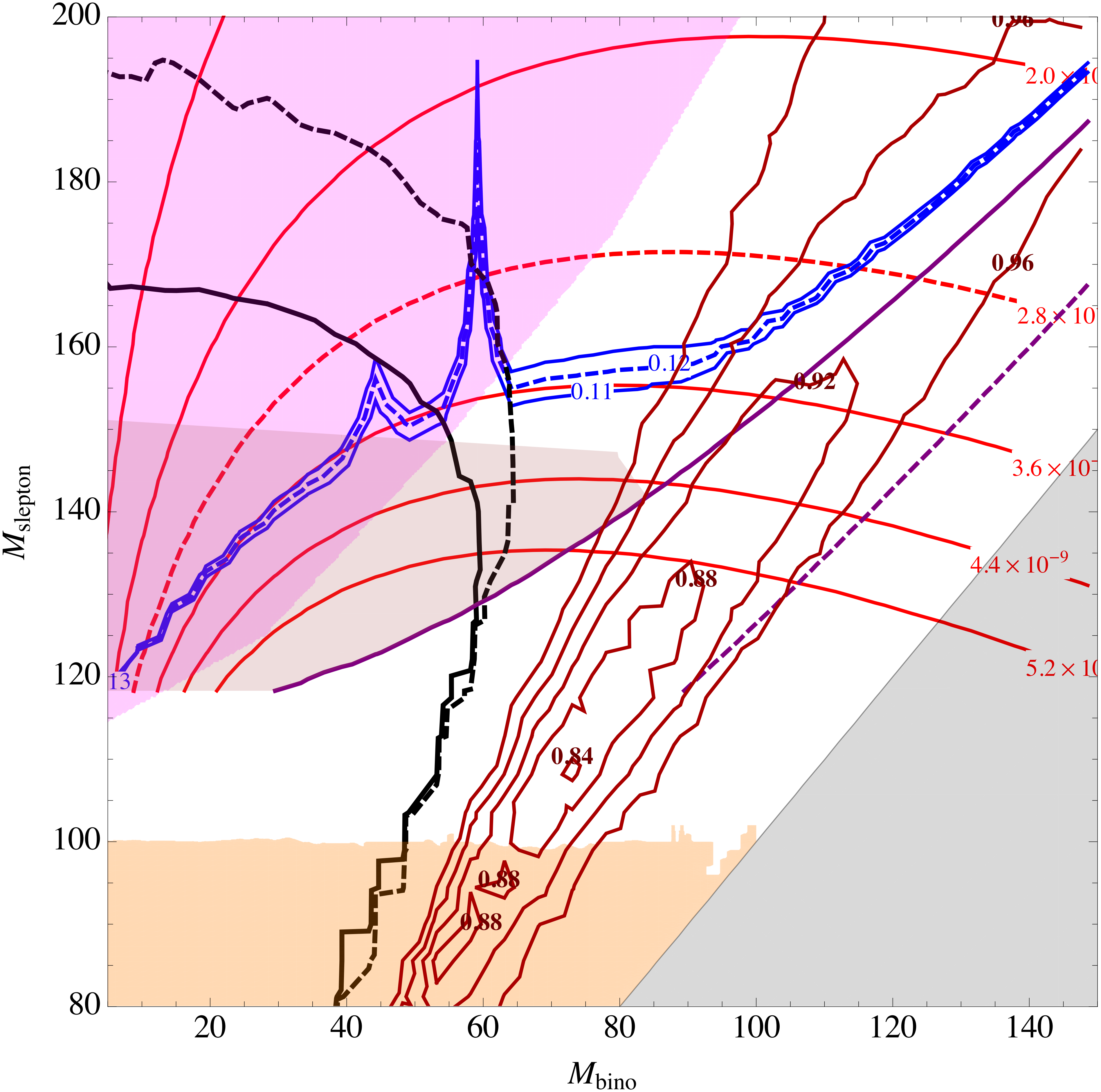
- LHC SM Standard Candles can set EW bounds without requiring LEP-precision.
- WW sets bounds on EW physics that is invisible to other searches! (Sleptons, Higgsinos, ...)
- WW discrepancy is consistent enough to be interesting to theorists.
- New Physics can fit WW measurements better than SM:
  - **Chargino explanation** (real Ws) → tested soon with SS dileptons!
  - **Slepton explanation** (not Ws) → Can explain more phenomena, harder to see.

    → Want flavor-resolved WW measurement!
- SM calculations should be improved to NNLO+N^(n)LL. Partial progress is starting to be made.

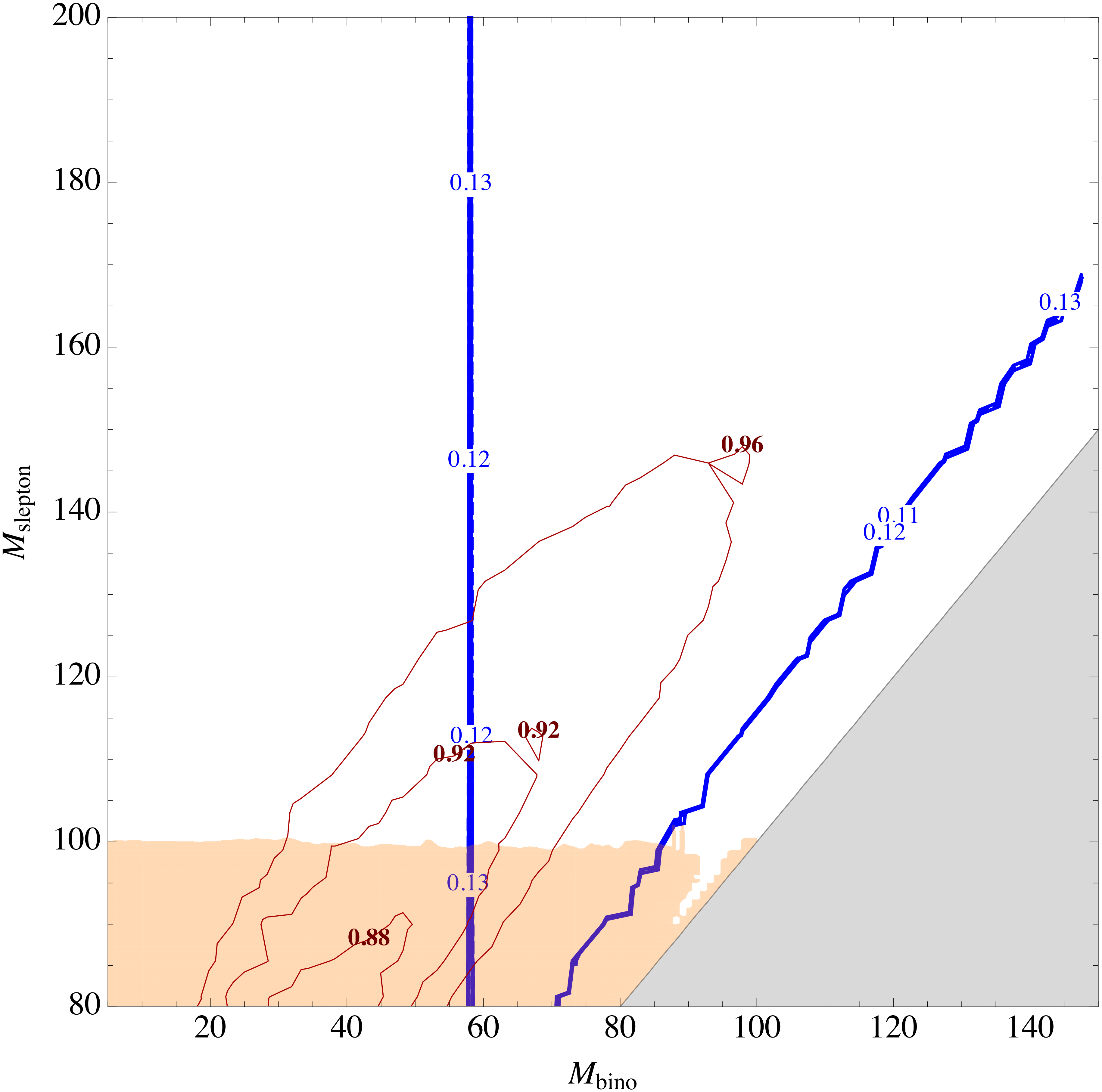
Backup Slides



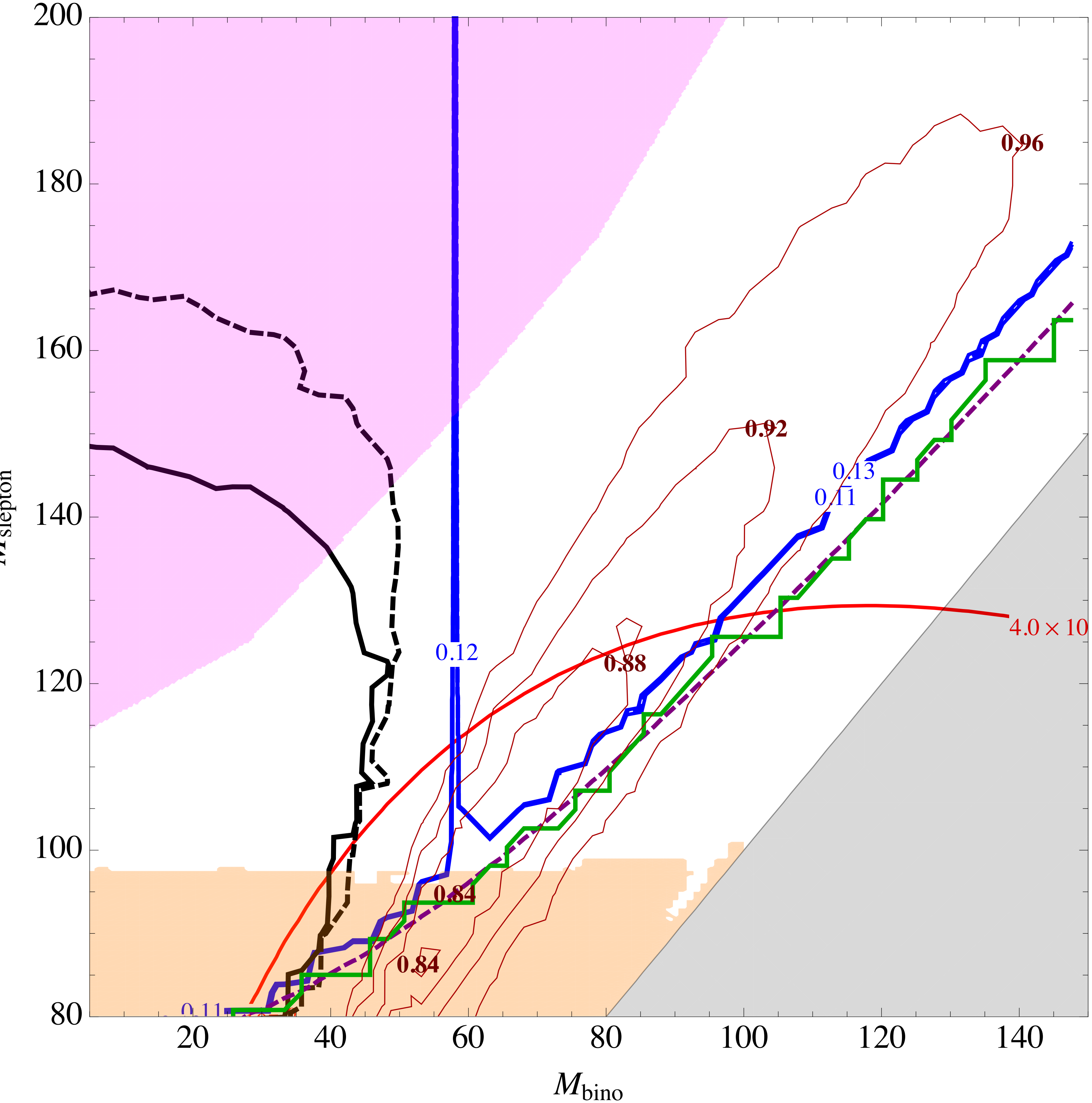
tanbeta 6
mu 600



tanbeta 12
mu 600



HEAVYSTAU
12 R gen only
tb_4
mu_600
M2_600



HEAVYSTAU
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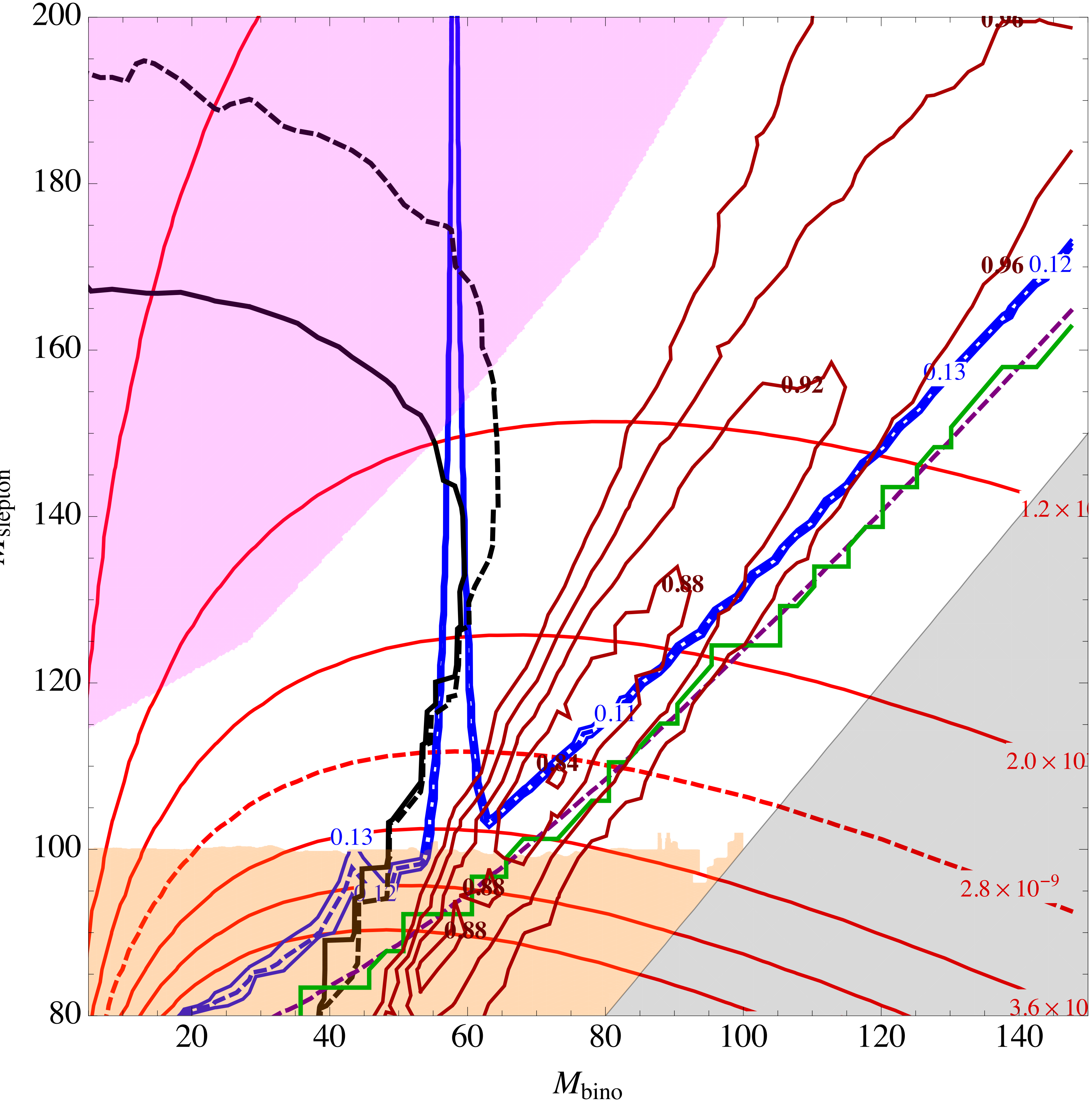
tb_4
mu_600
M2_600



HEAVYSTAU
12 L+R gen only
tb_4
mu_600
M2_600