Naturalness, Supersymmetry and Light Higgsinos

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⋆ SUSY solves the big hierarchy problem. Low scale physics does not have quadratic sensitivity to high scales if the low scale theory is embedded into a bigger framework with a high mass scale, Λ.

⋆ All talk about naturalness of weak scale SUSY models and associated fine-tuning has, at most, to do with logarithmic sensitivity to Λ.

Much discussion has revolved around the well-known (loop-corrected) minimization condition (written in terms of the parameters of the weak-scale theory),

$$\frac{M_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2,$$

requiring no large cancellations on the RHS.[a]

$$\Delta_{\rm EW} = max\left(\frac{m_{H_u}^2}{\frac{1}{2}M_Z^2}\frac{\tan^2\beta}{\tan^2\beta-1}, \frac{\Sigma_u^u}{\frac{1}{2}M_Z^2}\frac{tan^2\beta}{\tan^2\beta-1}, \ldots\right).$$

[a]In NUHM2, the choice of A_0 that makes Σ_u^u small, simultaneously raises the Higgs boson mass.

$\Delta_{\rm EW}$ knows nothing about the high scale physics, or the logs that we mentioned above. To see these, write

$m^2_{H_u,H_d} = m^2_{H_u,H_d}(\Lambda) + \delta m^2_{H_u,H_d}$, etc.

The logs are sitting in the $\delta m^2_{\bullet}$ terms.

Define $\Delta_{\rm HS}$ analogously to $\Delta_{\rm EW}$.

$\Delta_{\rm HS}$ is a sensible measure of fine-tuning in that it knows about the high scale origins via the logs. If there are large cancellations between $m^2_{\bullet}(\Lambda)$ and $\delta m^2_{\bullet}(\Lambda)$, the theory is regarded as fine-tuned. A VERY HIGH STANDARD!

However, $\Delta_{\rm HS}$ knows nothing about the correlations between various parameters that are present when the weak scale theory is derived from a high scale theory with fewer parameters.

To see these correlations, rewrite everything on the RHS in terms of the parameters of the theory defined at the scale Λ, *e.g.* (at one-loop)

$$
\begin{aligned}
-2\mu^2(m_{\rm weak}) &= -2.18\mu^2 \\
-2m_{H_u}^2(m_{\rm weak}) &= 3.84M_3^2 + 0.32M_3M_2 + 0.047M_1M_3 - 0.42M_2^2 \\
&\quad +0.011M_2M_1 - 0.012M_1^2 - 0.65M_3A_t - 0.15M_2A_t \\
&\quad -0.025M_1A_t + 0.22A_t^2 + 0.004m_3A_b \\
&\quad -1.27m_{H_u}^2 - 0.053m_{H_d}^2 \\
&\quad +0.73m_{Q_3}^2 + 0.57m_{U_3}^2 + 0.049m_{D_3}^2 - 0.052m_{L_3}^2 + 0.053m_{E_3}^2 \\
&\quad +0.051m_{Q_2}^2 - 0.11m_{U_2}^2 + 0.051m_{D_2}^2 - 0.052m_{L_2}^2 + 0.053m_{E_2}^2 \\
&\quad +0.051m_{Q_1}^2 - 0.11m_{U_1}^2 + 0.051m_{D_1}^2 - 0.052m_{L_1}^2 + 0.053m_{E_1}^2,
\end{aligned}
$$

In a theory with universal scalar masses m_0 and universal gaugino masses $m_{1/2}$ and a universal A-parameter A_0 this collapses to,

$$-2m_{H_u}^2(m_{\rm weak}) = 3.78m_{1/2}^2 - 0.82A_0m_{1/2} + 0.22A_0^2 + 0.013m_0^2$$

.

We can substitute this along with analogous expression for $m_{H_d}^2$ (which usually makes a small effect) into the M_Z^2 expression that we had, and again require no large cancellations.

Clearly, the inclusion of the correlations make an important difference as they allow some cancellations between $m_\bullet^2(\Lambda)$ and the $\delta m_\bullet^2$ without counting to the fine-tuning.

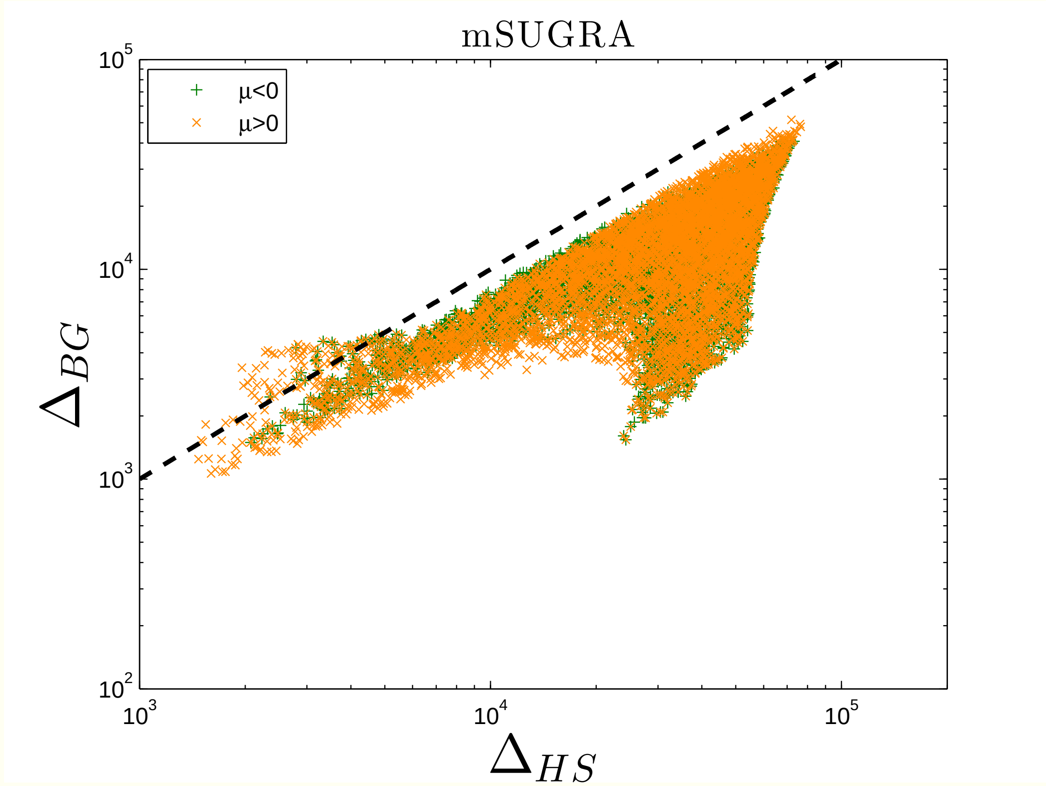
Related to the often-used Barbieri-Guidice $\Delta_{\rm BG}$ measure first introduced by EENZ.

$$\Delta_{\rm BG} \equiv \frac{(\delta M_Z^2/M_Z^2)}{(\delta p_i/p_i)} ,$$

where the p_i are various high scale parameters that determine M_Z^2.

$$\Delta_{\rm HS} > \Delta_{\rm BG} > \Delta_{\rm EW}.$$

$\Delta_{\rm HS}$ and $\Delta_{\rm BG}$ are strongly correlated except in special regions where parameter correlations lead to automatic cancellations in high scale models.



$\Delta_{\rm HS}$ and $\Delta_{\rm BG}$ are strongly correlated except in the hyperbolic-branch/focus point region of mSUGRA, where $\Delta_{\rm BG}$ becomes small as expected.

Similar correlation in NUHM2 model where $m_{H_u}^2$ and $m_{H_d}^2$ (or equivalently, μ and m_A) are taken to be independent of m_0.

What use is $\Delta_{\rm EW}$ if it does not know about logs?

Imagine a high scale theory in which the combination $m_{H_u}^2(\Lambda) + \delta m_{H_u}^2$ is automatically small. In such a theory, $\Delta_{\rm EW}$ is a perfectly sensible fine-tuning measure!

- ⋆ In the NUHM2 model – mSUGRA + $m_{H_u}^2$, $m_{H_d}^2$ as independent parameters – this is guaranteed for special values of $m_{H_u}^2$, so "all we have to do" is find the theory that leads to this value of $m_{H_u}^2$!
- ⋆ The FP/HB region of mSUGRA and its generalizations if $\Lambda \sim M_P$ has partial automatic cancellations.
- ⋆ Mixed-modulus-anaomaly-mediated-SUSY-breaking models aka mirage-mediation models, for special values of α.

Properties of $\Delta_{\rm EW}$.

- ⋆ $\Delta_{\rm EW}$ is essentially determined by the SUSY spectrum.
- ⋆ If $\Delta_{\rm EW}$ is large, the underlying theory that leads to the spectrum will be fine-tuned. A small $\Delta_{\rm EW}$ does not imply the theory is not fine-tuned, but leaves open the possibility of finding such a theory.

  Low $\Delta_{\rm EW} \Longrightarrow$ low $|\mu|$, but top squarks may be in 1-4 TeV range, with $1^{st}/2^{nd}$ squarks even heavier.

  Many aspects of the phenomenology depend just on the spectrum, so this can be investigated even without knowledge of the underlying high scale theory that leads to low fine-tuning. Beware though of pheno implications that depend on correlations in the spectrum.

We think low $|\mu|$ more basic to fine-tuning considerations than light stops. This feature is hidden by many analyses of fine-tuning.

Very generally, light higgsinos are a necessary feature of models with low fine-tuning.

ONE CAVEAT

In the strong plug for light higgsinos, we have implicitly assumed that the higgsino mass arises in a supersymmetric manner through the superpotential μ, and not through a SUSY breaking higgsino mass term: see, e.g. arXiv:1110.6670.

This is indeed the case in most models that I am aware of.

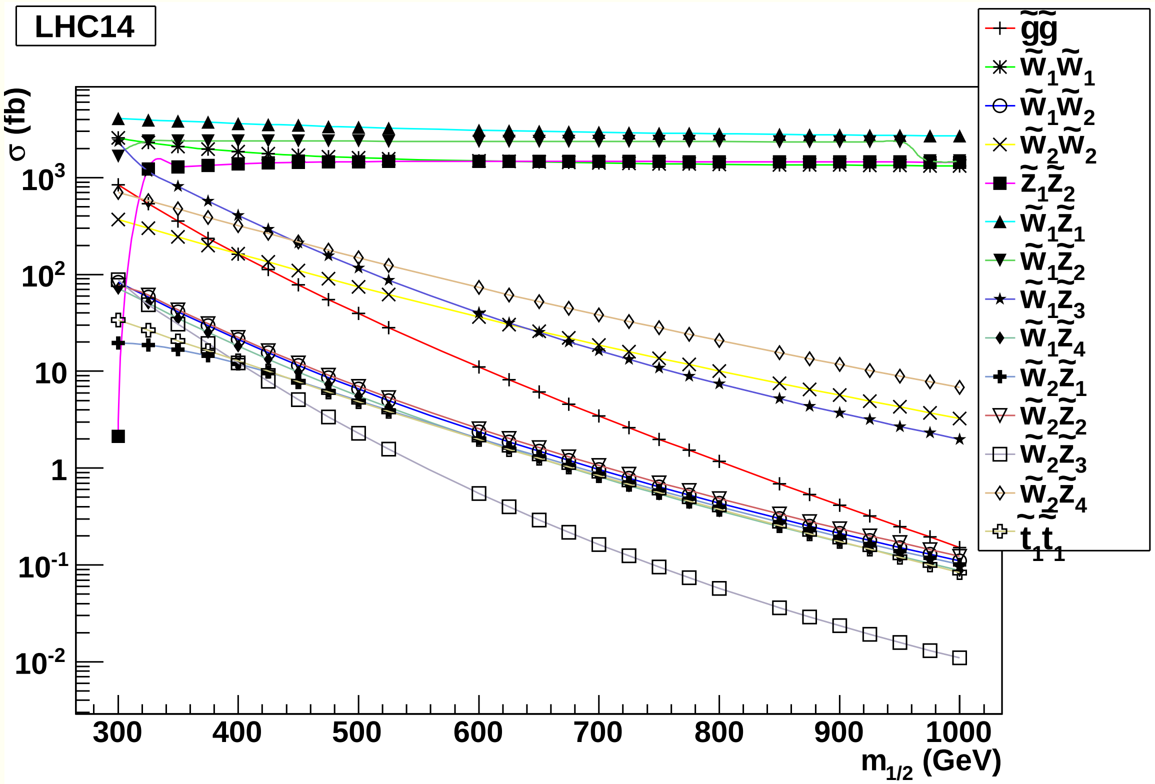
A higgsino mass may lead to hard-SUSY breaking if the low energy theory includes SM singlets.

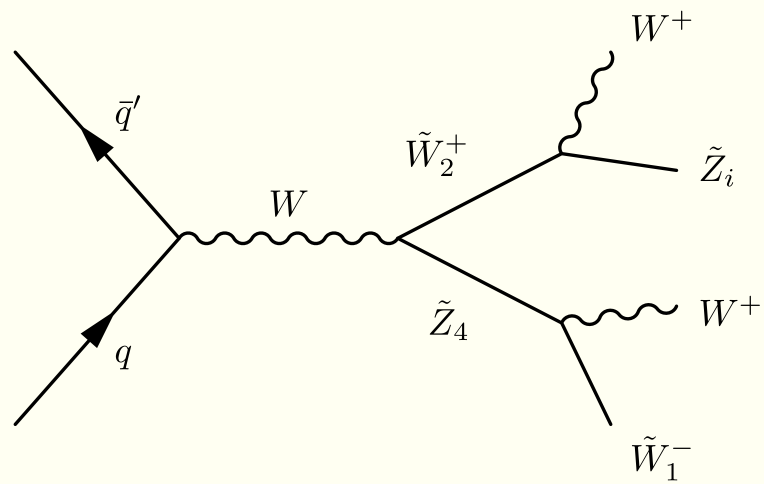
Phenomenology with light higgsinos.

- ⋆ Higgsino-like states $\widetilde{W}_1^{\pm}$, $\widetilde{Z}_2$, $\widetilde{Z}_1$ must be present with masses $\sim |\mu|$, and generically small splittings.
- ⋆ If $|M_{1,2}|$ also happen to be comparable to $|\mu|$, these states would be easy to access at the LHC ia $\widetilde{W}_1\widetilde{Z}_2$ production, or at a *LC via $\widetilde{W}_1\widetilde{W}_1$, $\widetilde{Z}_1\widetilde{Z}_2$ and $\widetilde{Z}_2\widetilde{Z}_2$ production. Heavier -inos may also be accessible.
- ⋆ In the generic case, the small mass gap may make it difficult to see direct higgsino production signals at the LHC because decay products are very soft.
- ⋆ Light higgsinos with a small mass gap will lead to one-sided events and likely be distinguishable from two-photon production of heavy flavours at the *LC.
- ⋆ A novel signal is also possible at the LHC if $|M_2| \lesssim 0.8 - 1$ TeV, something that is possible but not compulsory for low $\Delta_{\rm EW}$.

Light higgsinos at the LHC

Unified gaugino masses for definiteness, $\mu = 150$ GeV

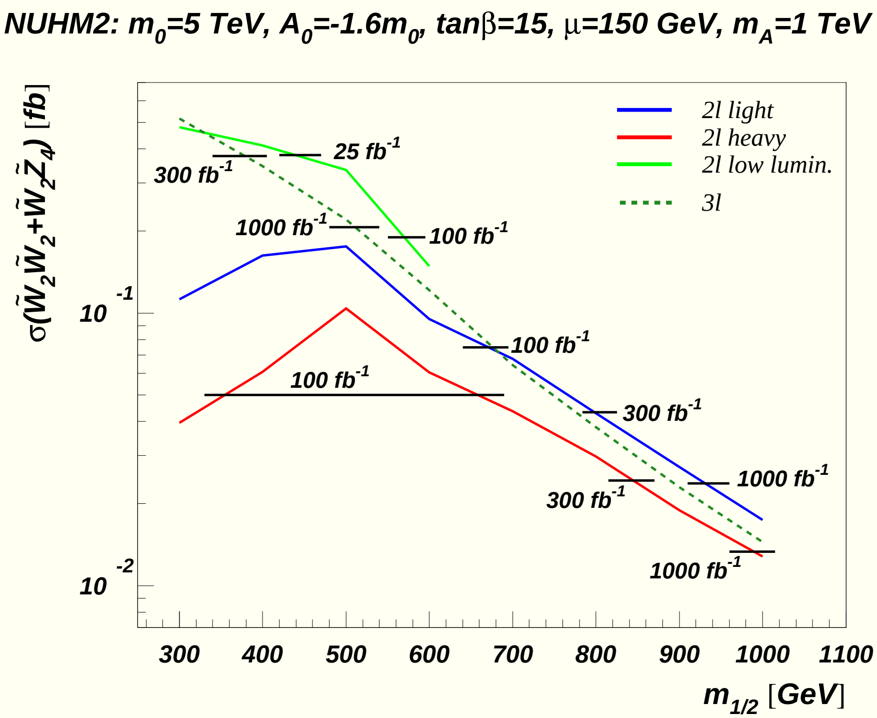




$\gtrsim 10$ fb $\widetilde{W}_2 \widetilde{Z}_4$ cross section out to $m_{1/2} \sim 1$ TeV

Decays of the parent $\widetilde{W}_2$ and $\widetilde{Z}_4$ that lead to W boson pairs give the same sign 50% of the time.

Require exactly two isolated, same sign dileptons with $|p_T(\ell)| > 20$ GeV, and no tagged b-jets (60% eff.) $m_T^{\rm min} > 125$ GeV cut removes WZ and $t\bar{t}$ backgrounds.



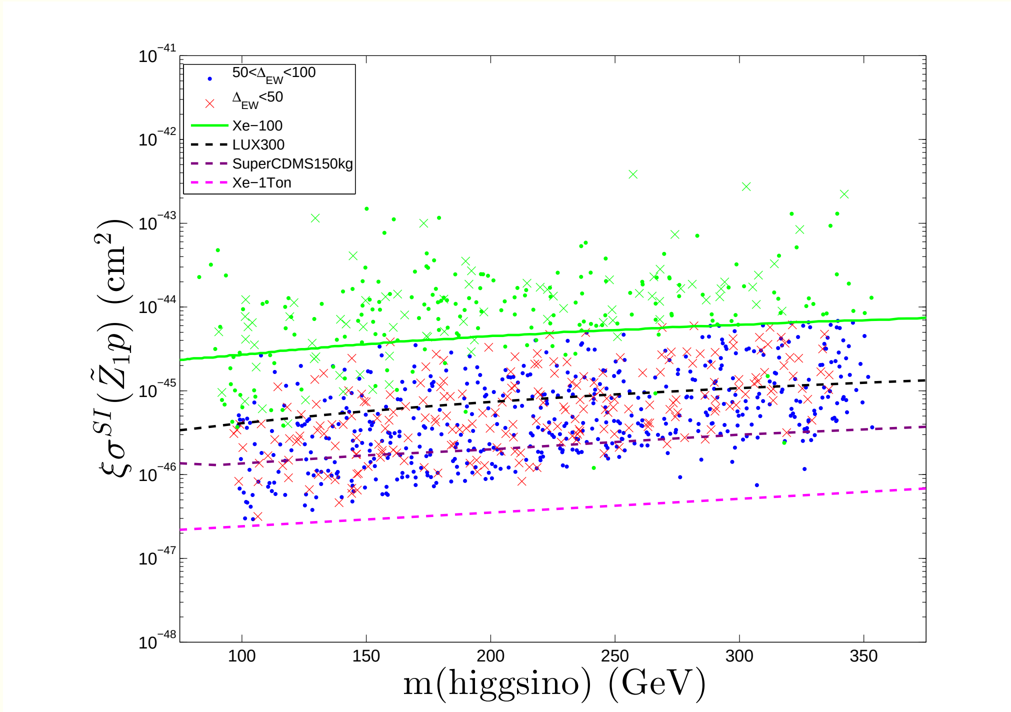
arXiv:1303.3816

Limited jet activity distinguishes $\ell^\pm \ell'^\pm$ events from gluino pair production events.

Reach to $m_{1/2} \sim 680$ (1000) GeV for 100 (1000) fb^{-1}. In low μ models, this is better than the canonical trilepton reach of 400 (500) GeV for 300 (1000) fb^{-1}.

In models with gaugino mass unification, this channel offers a better reach than the usual $\tilde{g}\tilde{g}$ channel. More importantly, this is an independent search channel.

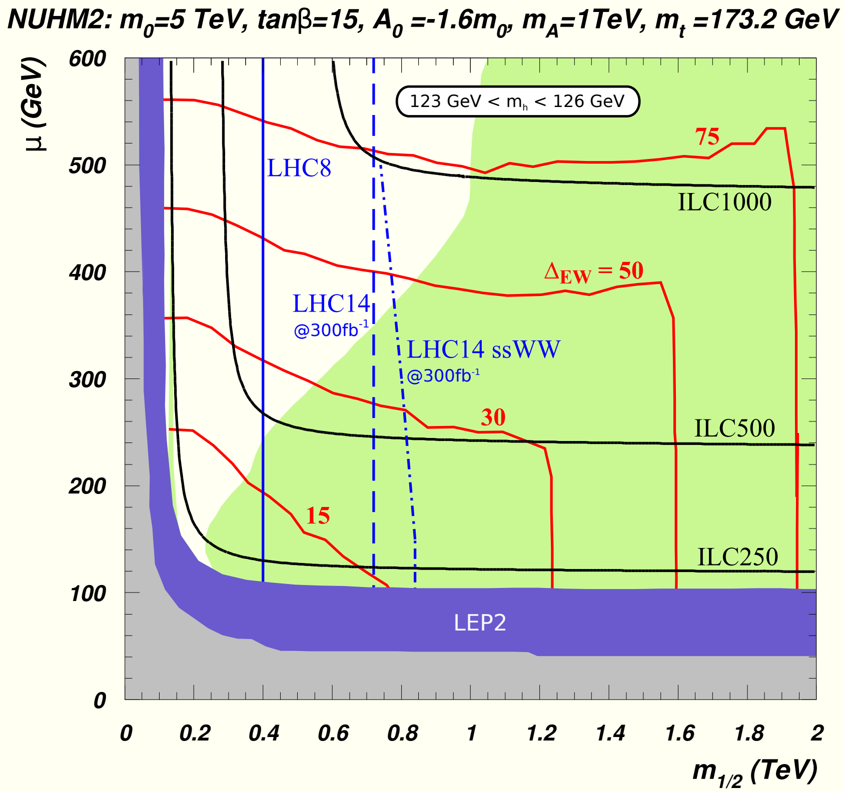
Light higgsinos will not saturate the DM relic density. However, because gluinos cannot be too heavy, in models with unified gaugino masses, the LSP must contain a significant gaugino component. The LSP contribution to the thermal relic density cannot be arbitrarily small.



arXiv:1303.3816

Ton-sized detectors will see a direct detection signal.[a]

[a]There is a noteworth caveat, since particles in the sector where the rest of the DM resides may dilute this density via entropy production after LSP freeze out.



arXiv:1306.3148

In these low $|\mu|$ models, the rate-limited $W^\pm W^\pm$ potentially offers the largest reach at a HL LHC....out to $m_{1/2} \sim 1$ TeV! It beats the canonical gluino search strategy if gaugino masses unify at $M_{\rm GUT}$.

An e^+e^- LC with $\sqrt{s} \stackrel{<}{\sim} 500 - 700$ GeV will likely find light higgsinos, or force us to conclude SUSY models are significantly fine-tuned.

Final remarks

- ⋆ Obituaries of SUSY are premature. Models with modest electroweak fine-tuning ($\Delta_{\rm EW} = 10-30$) and correct Higgs boson mass exist. These satisfy our necessary criteria for fine-tuning. Eagerly awaiting LHC14.
- ⋆ Small $|\mu|$, and associated light higgsinos, is a fundamental and necessary (but not sufficient) criterion for low fine-tuning.
- ⋆ $\Delta_{\rm EW}$ is "directly" measurable (in principle) so we can tell for sure that a given SUSY spectrum is fine-tuned if $\Delta_{\rm EW}$ turns out to be large.... (though in this happy circumstance, we may well not care!!!!)
- ⋆ Light, thermal higgsinos cannot saturate the total CDM; nonetheless always enough higgsino DM fraction to reveal itself in direct and indirect DM searches.
- ⋆ Novel SS dilepton signal with low hadronic activity possible at the LHC.
- ⋆ A *LC with $\sqrt{s} \gtrsim (500)700$ GeV could be a discovery machine for light higgsinos for $\Delta_{\rm EW} \lesssim (15)30$.