Improved $\left( g - 2 \right)_{\mu}$ measurements and Supersymmetry
• EW sector may be hiding key to new physics

• Modest production cross section, mass bounds from the LHC rather week

• May show up elsewhere: DM experiments, \((g - 2)_\mu\) ....
MSSM Superpotential

\[ W_{\text{MSSM}} = \bar{u}Y_u Q H_u - \bar{d}Y_d Q H_d - \bar{e}Y_e L H_d + \mu H_u H_d \]

Soft Breaking Terms

\[ \mathcal{L}^{\text{MSSM soft}} = -\frac{1}{2} \left( M_3 \tilde{g} \tilde{g} + M_2 \tilde{W} \tilde{W} + M_1 \tilde{B} \tilde{B} + c.c. \right) \]

\[ - \left( \bar{\tilde{u}} a_u \tilde{Q} H_u - \bar{\tilde{d}} a_d \tilde{Q} H_d - \bar{\tilde{e}} a_e \tilde{L} H_d + c.c. \right) \]

\[ - \tilde{Q} ^\dagger m^2_Q \tilde{Q} - \bar{L} ^\dagger m^2_L \bar{L} - \bar{\tilde{u}} m^2_{\tilde{u}} \bar{\tilde{u}} ^\dagger - \bar{\tilde{d}} m^2_{\tilde{d}} \bar{\tilde{d}} ^\dagger - \bar{\tilde{e}} m^2_{\tilde{e}} \bar{\tilde{e}} ^\dagger \]

\[ - m^2_{H_u} H_u^* H_u - m^2_{H_d} H_d^* H_d - \left( b H_u H_d + c.c. \right) \]
Masses and mixing are determined by U(1) and SU(2) gaugino masses $M_1$, $M_2$ and Higgs mass parameter $\mu$.

**Neutralino Mass Matrix**

$$M_N = \begin{pmatrix}
M_1 & 0 & -M_Z c_\beta s_W & M_Z s_\beta s_W \\
0 & M_2 & M_Z c_\beta c_W & -M_Z s_\beta c_W \\
-M_Z c_\beta s_W & M_Z c_\beta c_W & 0 & -\mu \\
M_Z s_\beta s_W & -M_Z s_\beta c_W & -\mu & 0
\end{pmatrix}$$

**Chargino Mass Matrix**

$$M_C = \begin{pmatrix}
M_2 & \sqrt{2}M_W c_\beta \\
\sqrt{2}M_W s_\beta & \mu
\end{pmatrix}$$

Four Parameters $M_1, M_2, \mu, \tan \beta$
Sleptons

Slepton Mass Matrix

\[ M^2_L = \begin{pmatrix} m_l^2 + m_{LL}^2 & m_l X_l \\ m_l X_l & m_l^2 + m_{RR}^2 \end{pmatrix} \]

\[ m_{LL}^2 = m_L^2 + (I_l^{3L} - Q f s_w^2) M_Z^2 c_\beta^2 \]

\[ m_{RR}^2 = m_R^2 + Q f s_w^2 M_Z^2 c_\beta \]

\[ X_l = A_l - \mu (\tan \beta)^2 I_l^{3L} \]

Parameters \( M_1, M_2, \mu, \tan \beta, m_{\tilde{L}}, m_{\tilde{R}} \)
Constraints

Direct Searches at LHC

• LHC searches restricted to simplified models. Sparticles except those relevant to the signal are taken to be decoupled.

• $\tilde{\chi}^\pm_1$ and $\tilde{\chi}^0_2$ taken to be mass-degenerate and purely wino. $\tilde{\chi}^0_1$ is assumed to be purely bino.

• All three generations of sleptons and sneutrinos assumed mass degenerate. In MSSM:

$$m_{\tilde{\nu}}^2 = m_{\tilde{l}}^2 + \frac{1}{2}m_Z^2\cos2\beta$$

• Heavier gauginos $\tilde{\chi}^0_3, \tilde{\chi}^0_4, \tilde{\chi}^\pm_2$ assumed to be decoupled.

• No sensitivity to parameters like $\tan\beta$.

Proper recasting is important

Indirect Constraints

• Muon (g-2).

• WMAP/PLANCK relic density.

• Spin independent direct detection data from XENON/LUX.

• Indirect detection constraints of dark matter.
Searches at the LHC

Proper recasting is important — checkMATE
Searches at the LHC

Proper recasting is important → checkMATE
Muon (g-2)

- Currently large discrepancy from the SM > (3σ).
  \[ a_\mu^{exp} - a_\mu^{SM} = (28.02 \pm 7.37) \times 10^{-10} \]  
  Keshavarzi, Nomura, Teubner ‘19

- Assuming upcoming Fermilab Run-I result to have the same central value and same exp. uncertainty, combined data corresponds to \( \sim 5.4 \sigma \) discrepancy,
  \[ a_\mu^{exp} - a_\mu^{SM} = (28.02 \pm 5.2) \times 10^{-10} \]

- New "world average" appeared modest impact on our analysis.  
  Aoyama et al ‘20

- SUSY contributions from Chargino-Sneutrino and Smuon-Neutralino loop

- Contribution \( \sim \tan\beta \), can reconcile the anomaly
DM Constraints

**Relic Density**

Some annihilation channels that could give right relic density:

There can be coannihilations with sparticles of slightly heavier masses:

A well-tempered bino-wino or bino-higgsino LSP is favorable for chargino co-annihilation while a bino dominated LSP will work for slepton co-annihilation.

**Direct Detection**

Diagrams contributing to SI interactions

Diagrams contributing to SD interactions
**Parameter Scanning**

**Chargino co-annihilation region:**

100 GeV \leq M_1 \leq 1 \text{ TeV} , \quad M_1 \leq M_2 \leq 1.1 M_1 ,

1.1 M_1 \leq \mu \leq 10 M_1 , \quad 5 \leq \tan \beta \leq 60 ,

100 \text{ GeV} \leq m_{\tilde{\chi}_L} \leq 1 \text{ TeV} , \quad m_{\tilde{\chi}_R} = m_{\tilde{\chi}_L} .

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**Slepton co-annihilation region:**

**Case-L: SU(2) doublet**

100 \text{ GeV} \leq M_1 \leq 1 \text{ TeV} , \quad M_1 \leq M_2 \leq 10 M_1 ,

1.1 M_1 \leq \mu \leq 10 M_1 , \quad 5 \leq \tan \beta \leq 60 ,

M_1 \text{ GeV} \leq m_{\tilde{l}} \leq 1.2 M_1 , \quad M_1 \leq m_{\tilde{\chi}_R} \leq 10 M_1 .

**Case-R: SU(2) singlet**

100 \text{ GeV} \leq M_1 \leq 1 \text{ TeV} , \quad M_1 \leq M_2 \leq 10 M_1 ,

1.1 M_1 \leq \mu \leq 10 M_1 , \quad 5 \leq \tan \beta \leq 60 ,

M_1 \text{ GeV} \leq m_{\tilde{l}} \leq 1.2 M_1 , \quad M_1 \leq m_{\tilde{\chi}_L} \leq 10 M_1 .

MC, S.Heinemeyer, I.Saha 2006.15157

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**Packages used** SuSpect, SUSYHIT, GM2Calc, micrOMEGAs, CheckMATE.
Chargino Co-annihilation

Current $(g - 2)_{\mu}$ limit

Anticipated future $(g - 2)_{\mu}$ limit

Upper and lower bounds from $(g - 2)_{\mu}$ and LHC searches (for compressed spectrum)
Chargino Co-annihilation

Current $(g - 2)_\mu$ limit

Anticipated future $(g - 2)_\mu$ limit

Slepton-pair production $\rightarrow (2l + \text{missing } E_T)$ provides important search channel ...

R-sleptons heavy, Considerable BR for $\tilde{e}_L(\tilde{\mu}_L) \rightarrow \tilde{\chi}_1^\pm e(\mu)$ Less no. of signal leptons.
Slepton Co-annihilation: Case-L

Current \((g - 2)_{\mu}\) limit

Anticipated future \((g - 2)_{\mu}\) limit

The left-sleptons and sneutrinos are close in mass to the LSP → stau not far away
Slepton Co-annihilation: Case-L

Figure 8: The results of our parameter scan in the $\tilde{\chi}^\pm_1 - \tilde{\chi}^0_0$ plane for the $\tilde{\chi}^\pm_1$-coannihilation Case-L.

The color coding as in Fig. 4.

In Fig. 9 we show the results in the $m_{\tilde{\chi}^0_1} - m_{\tilde{\chi}^\pm_1}$ plane with the same color coding as in Fig. 7.

The $(g \neq 2)\mu$ limits on $m_{\tilde{\chi}^0_0}$ become slightly stronger for larger chargino masses, as expected from Eq. (19), and upper limits on the chargino mass are set at $\geq 3\, \text{TeV}$ ($\geq 2.5\, \text{TeV}$) for the current (anticipated future) precision in $\mu$. The LHC limits cut away a lower wedge going up to $m_{\tilde{\chi}^\pm_1} < \geq 600\, \text{GeV}$, driven by the bound in Eq. (5), shown as the red dashed line in Fig. 1a.

As in the $\tilde{\chi}^\pm_1$-coannihilation case, also here the upper limit on $m_{\tilde{\chi}^0_1}$ is strongly reduced w.r.t. the "naive" application, which goes up to $m_{\tilde{\chi}^0_1} \leq 1100\, \text{GeV}$ for negligible $m_{\tilde{\chi}^0_0}$. The reason for the weaker limit can be attributed to two factors. First, the significant branching ratios of $\text{BR}(\tilde{\chi}^\pm_1 \rightarrow \tilde{\nu}_1 \nu)$ and $\text{BR}(\tilde{\chi}^0_2 \rightarrow \tilde{\nu}_1 \tau)$, respectively, which are considered to be absent in the ATLAS analysis. Second, the notably large branching ratio of $\tilde{\chi}^0_0$ to the invisible modes $\tilde{\nu}_1 \nu$.

Tab. 3 gives an idea of the relevant BRs of two sample points taken from the parameter space of Case-L, with their mass spectra given in the same table. This again emphasizes the importance of the recasting of the LHC searches that we have applied.

The results for the $\tilde{\chi}^\pm_1$-coannihilation Case-L in the $m_{\tilde{\chi}^0_1} - \tan\beta$ plane are presented in Fig. 10. The overall picture is similar to the $\tilde{\chi}^\pm_1$-coannihilation case shown above in Fig. 6.

Larger LSP masses are allowed for larger $\tan\beta$ values. On the other hand the combination of small $m_{\tilde{\chi}^0_0}$ and large $\tan\beta$ leads to a too large contribution to $\mu$ and is thus excluded.

As in Fig. 6 we also show the limits from $H/A$ searches at the LHC, where we set (as above) $m_{\tilde{\chi}^0_0} = M_A/2$, i.e. roughly to the requirement for $A$-pole annihilation, where points above the black lines are experimentally excluded. In this case for the current $(g \neq 2)\mu$ limit substantially more points passing the $(g \neq 2)\mu$ constraint "survive" below the black...
Slepton Co-annihilation: Case-R

Right-sleptons are close in mass to LSP.

Small $\mu$ is favored, tension between DD and $\left(g - 2\right)_{\mu}$. 
Slepton Co-annihilation: Case-R

Current \((g-2)_{\mu}\) limit

Anticipated future \((g-2)_{\mu}\) limit

Left-sleptons can not be too heavy to have relevant contribution to \((g-2)_{\mu}\).

Get stringent constraint from LHC.
Further Comments

Larger $\tan \beta$ can easily satisfy $(g - 2)_\mu$.  

Tension between DD and $(g - 2)_\mu$.  

Chargino co-annihilation 

Slepton Co-annihilation 

Case-R 

A-pole annihilation restricted
Points satisfying \((g - 2)_{\mu}\), DM and LHC constraints, masses in GeV.
Conclusions

• Direct LHC bounds still have ample room for sub-TeV EW SUSY particles.

• It is possible to constrain the EW MSSM with the help of indirect constraints along with the direct collider limits.

• DM constraints and muon (g-2) constraint put effective upper limit on EW SUSY masses while LHC limits restrict the mass ranges from below.

• LHC exclusion bound strongly depends on EW gaugino composition. Proper recasting of ATLAS/CMS analysis relaxes the existing bounds.

• Future colliders, HL-LHC, ILC/CLIC also have significant prospect for detection.

• New experimental results for $(g - 2)_\mu$ from Fermilab, J-PARC .... STAY TUNED!!!
THANK YOU!
BACKUP
Large discrepancy from the SM (more than $3\sigma$):

$$a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (28.02 \pm 7.37) \times 10^{-10}.$$  
Keshavarzi, Nomura, Teubner ‘19

- Important probe for new physics. $\frac{\delta a_i}{a_i} \sim \frac{m_i^2}{\Lambda^2}$.
- SM contributions: QED, weak, hadronic vacuum polarization, hadronic light by light scattering.
- QED: complete calculation up to 5 loops. EW: two loops.  
Aoyama, Hayakawa, Kinoshita, Nio ‘17, Ishikawa, Nakazawa, Yasu ‘18, Heinemeyer, Stöckinger, Weiglein ‘04
- Uncertainty dominated by non-perturbative, hadronic sector.
SUSY contributions to \((g - 2)_\mu\)

\[
\Delta a_\mu (\tilde{W}, \tilde{H}, \tilde{\nu}_\mu) \simeq 15 \times 10^{-9} \left( \frac{\tan \beta}{10} \right) \left( \frac{(100 \text{ GeV})^2}{M_{2\mu}} \right) \left( \frac{f_C}{1/2} \right),
\]

\[
\Delta a_\mu (\tilde{W}, \tilde{H}, \tilde{\mu}_L) \simeq -2.5 \times 10^{-9} \left( \frac{\tan \beta}{10} \right) \left( \frac{(100 \text{ GeV})^2}{M_{2\mu}} \right) \left( \frac{f_N}{1/6} \right),
\]

\[
\Delta a_\mu (\tilde{B}, \tilde{H}, \tilde{\mu}_L) \simeq 0.76 \times 10^{-9} \left( \frac{\tan \beta}{10} \right) \left( \frac{(100 \text{ GeV})^2}{M_{1\mu}} \right) \left( \frac{f_N}{1/6} \right),
\]

\[
\Delta a_\mu (\tilde{B}, \tilde{H}, \tilde{\mu}_R) \simeq -1.5 \times 10^{-9} \left( \frac{\tan \beta}{10} \right) \left( \frac{(100 \text{ GeV})^2}{M_{1\mu}} \right) \left( \frac{f_N}{1/6} \right),
\]

\[
\Delta a_\mu (\tilde{\mu}_L, \tilde{\mu}_R, \tilde{B}) \simeq 1.5 \times 10^{-9} \left( \frac{\tan \beta}{10} \right) \left( \frac{(100 \text{ GeV})^2}{m_{\tilde{\mu}_L}^2 m_{\tilde{\mu}_R}^2 / M_{1\mu}} \right) \left( \frac{f_N}{1/6} \right).
\]

Endo, Hamaguchi, Iwamoto, Yoshinaga’13