$\tilde{\nu}$ NLSP at the LHC

arXiv: 0911.4132

work done with Brock Tweedie

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Outline

1. Motivation and the main goal of the project.

2. Generic features of the spectrum, types of spectra.

3. Cascades and signatures in the "ideal world":

   - Counting of the leptonic events.

   - Structure in the dileptonic channel.

   - Structure in the trileptonic channel.

   - Jet-lepton invariant mass

4. Real signatures and main worries:

   - What is realistic? Backgrounds.

   - Check the proposed tools on realistic spectra.

5. Conclusions and outlook.

$\tilde{\nu}$ at the bottom of SUSY-spectrum

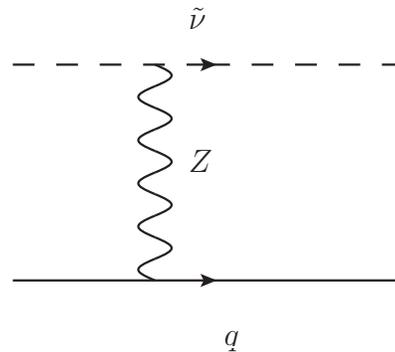How $\tilde{\nu}$ can be at the bottom of the SUSY spectrum?

Can it be LSP, DM candidate?

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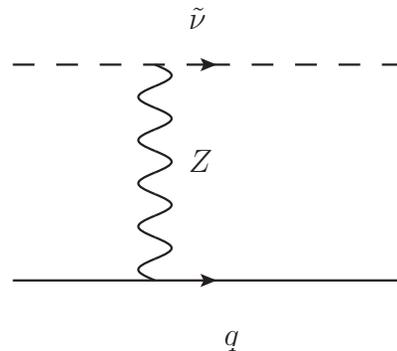
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No

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How $\tilde{\nu}$ can be at the bottom of the SUSY spectrum?

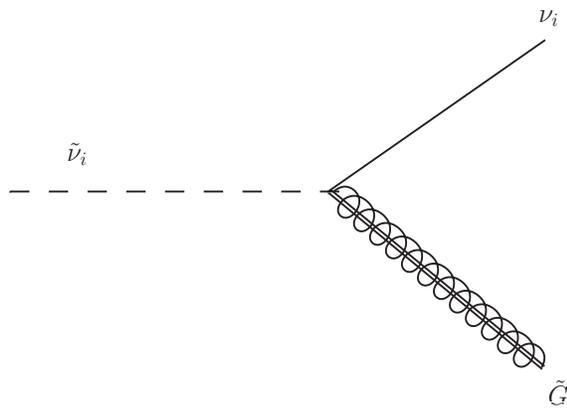Can it be LSP, DM candidate?

No

The cross-section for the direct detection is too big! If it had been a DM, we would have already had signals in the direct detection experiments!

$\tilde{\nu}$ **NLSP**

Two possible giveaways:

- Give up on R-parity, allow $\tilde{\nu}$ to decay into the SM particles

- Consider gravitino LSP, allow "invisible sneutrino decay"

Top down motivation

$\tilde{\nu}$ at the bottom of the spectrum is not easy to get, but nevertheless it is possible:

- we find $\tilde{\nu}$ NLSP in a big portion of GGM parameter space (nonetheless it is very hard to get $\tilde{\nu}$ NLSP in minimal gauge mediation).

- There were some works, pointing out that $\tilde{\nu}$ can be at the bottom of the spectrum in high-scale mediation models (e.g. gaugino mediation). In these models $\tilde{G}$ LSP is less natural, but not impossible.

Motivation and main questions

If $\tilde{\nu}$ is an NLSP, the last step in the cascade is completely invisible.
From the point of view of collider behavior looks very similar (too similar) to the neutralino LSP (or long lived NLSP).

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From the point of view of collider behavior looks very similar (too similar) to the neutralino LSP (or long lived NLSP).

- Is it possible practically distinguish between two these possibilities, at least in some cases?

- Will it be possible to figure out that gravitino is a real LSP, in spite of the fact that we will never see "real decays" into that state?

Slepton doublet

Sneutrino does not come alone. It is a part of the $SU(2)$ doublet together with charged, LH doublet.

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What is the splitting?

Neglecting the left-right mixing, all the splitting comes from the D-terms

$$m_{\tilde{l}} - m_{\tilde{\nu}} = -\frac{m_W^2 \cos(2\beta)}{m_{\tilde{l}} + m_{\tilde{\nu}}} > 0 \ .$$

Example: $m_{\tilde{l}} = 150 \ \text{GeV}$, $\tan \beta = 10$.

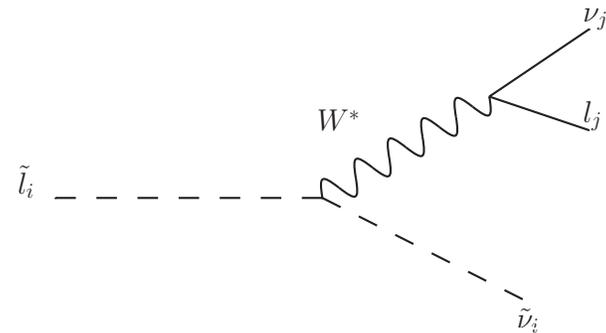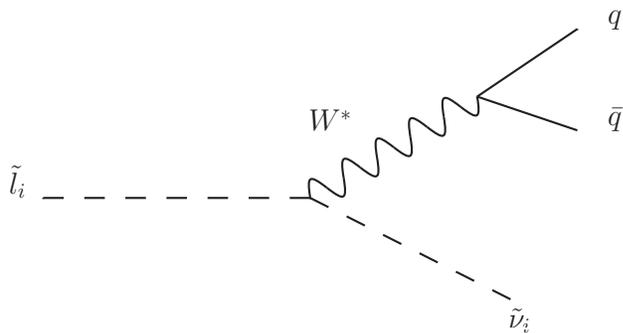The splitting is $\Delta m \approx 21 \ \text{GeV}$.

How does slepton decay?

If a charged LH slepton is produced (either directly or in cascade), how does it decay?

Assume:

the whole LH doublet sits at the bottom of the SUSY spectrum.

Decays via W^*

Remarks about LH slepton decay

- most of the time ($\gtrsim 2/3$) decays into jets

- 20 % of time can decay emitting lepton

- flavor correlation of the lepton with the parent slepton is lost.

- decay products may often be quite soft (splitting of several dozens GeV)

- soft jets - useless

- relatively soft, but visible lepton - may be useful, but not in direct production

When is our analysis valid?

One may worry that our conclusions do not hold in the following cases:

- the splitting $\tilde{l} - \tilde{\nu}$ is affected by LR mixing – further assume small A-terms, mixing due to Yukawa is a small correction

- two body decays into Gravitino are competative
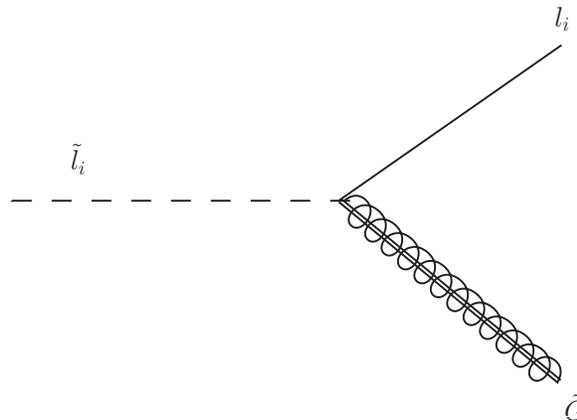
When is our analysis valid

- direct decays into gravitino are important only if SUSY-breaking scale $\sim 2 - 3\,\mathrm{TeV}$ – usually not important

- strong flavor non-degeneracy. If, e.g. $m_{\tilde{\tau}} < m_{\tilde{\nu}_\mu}$, other decay chain get opened. This can happen (usually in high-scale mediation) if $m_{H_d} \gg m_{H_u}$. We will not consider this possibility further.

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- Direct EW production - either very hard to trigger or very hard to reduce backgrounds (or both).

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We will further concentrate on :

- QCD production

- Leptonic channel – see if it is different from neutralino LSP

- Keep in mind - flavor uncorrelated (w/ its parents) leptons (may be quite soft)

"Active" vs. "inactive" spectra

Usually the mixing in the gaugino-Higgsino sector is not big. It is not difficult to distinguish bino-like neutralino vs. Higgsino vs. wino. Consider a spectrum with

$$m(\tilde{e}_r) > m(\tilde{B}) \ .$$

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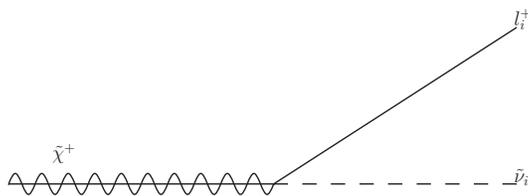
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If the ordering is different, the spectrum becomes active, phenomenology similar to leptogenic SUSY w/o CHAMP.

Counting hard leptons.

Simple analysis:

- Only QCD production

- No decays into Higgsinos

- Phase space effects in decays are neglegible
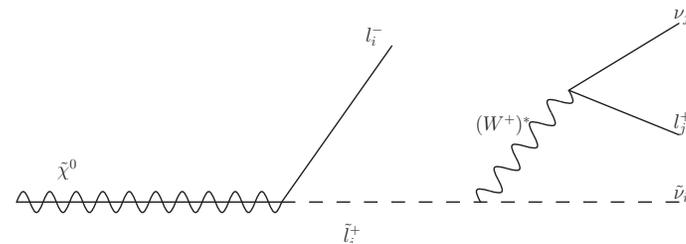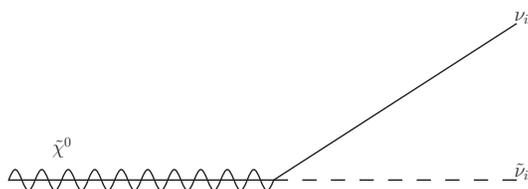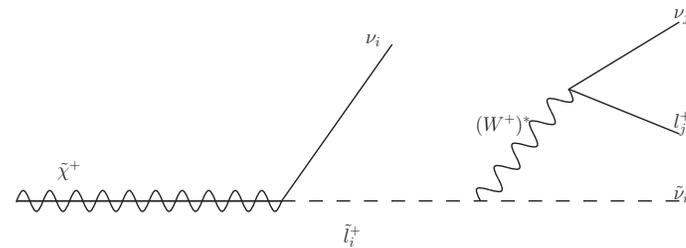
- τ are never leptons

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Important results:

- monoleptonic:dileptonic = 4:1

- never have two leptons from the same side of the chain

- leptons inside the dileptonic channel are never correlated:
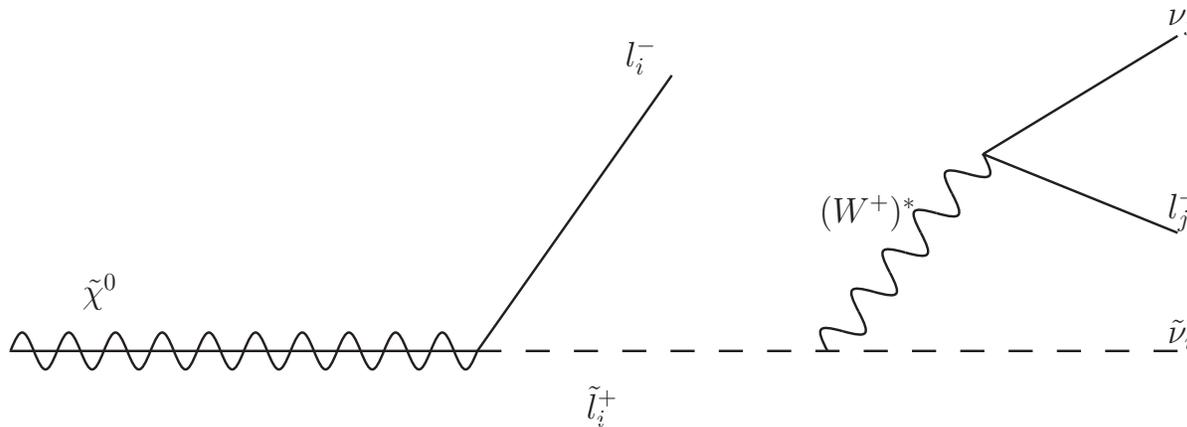
$$OSOF = OSSF = SSOF = SSSF$$

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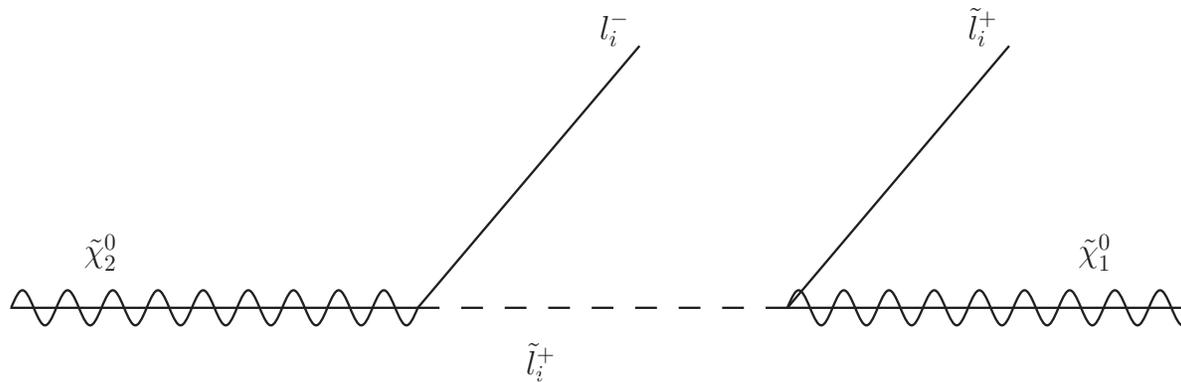- can give two leptons from the same chain
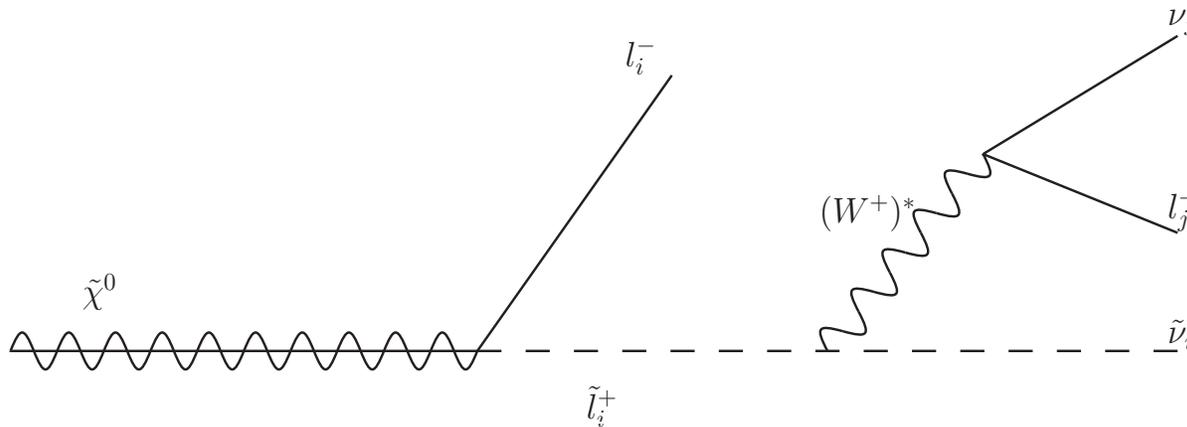
Opposite sign, uncorrelated flavor lepton pairs

Lepton counting - summary

- Monoleptonic channel : dileptonic channel – 4:1 if "soft leptons" are not taken into account, with the "soft leptons" – around 3:1 (exact numbers strongly depend on production mechanism)

- The structure of the the dileptonic channel changes: OSOF $\sim$ OSSF $>$ SSOF $\sim$ SSSF

- OS sign excess can account 15 % . . . 50 % of all dileptonic events; depends on production mechanism

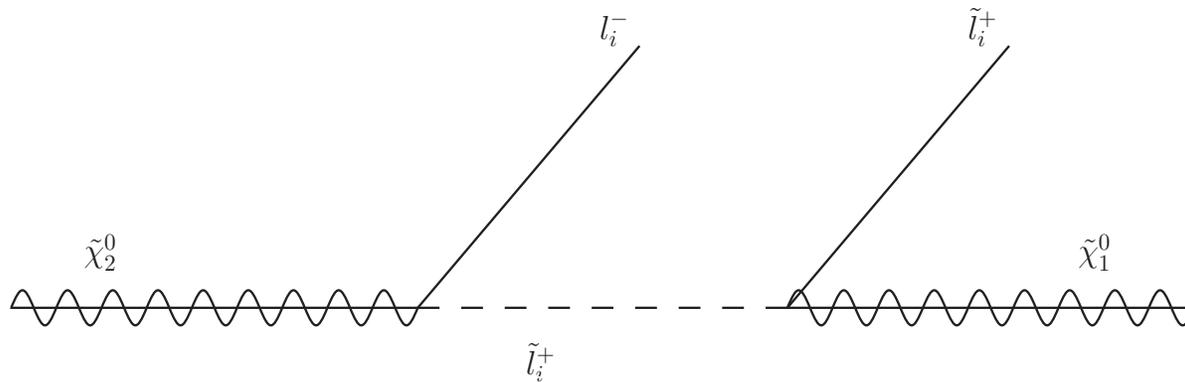- Unlike in lots of other SUSY patterns we do not expect any OSSF excess

How do we treat 2l signal

Take one step backwards: interesting signal in dileptonic channel in neutralino-LSP SUSY: OSSF leptons, coming from
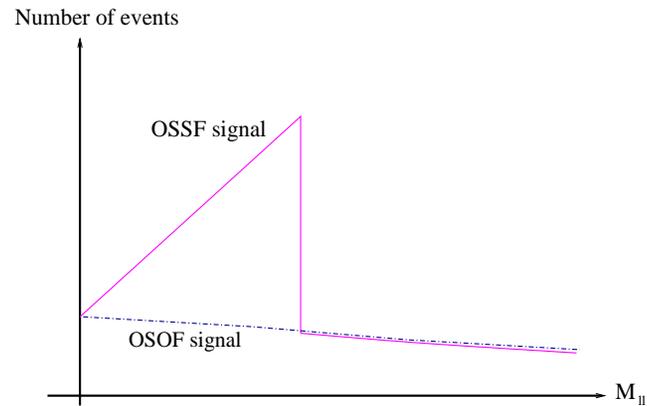
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- sits on top of the SUSY background - OSSF pairs from different chains

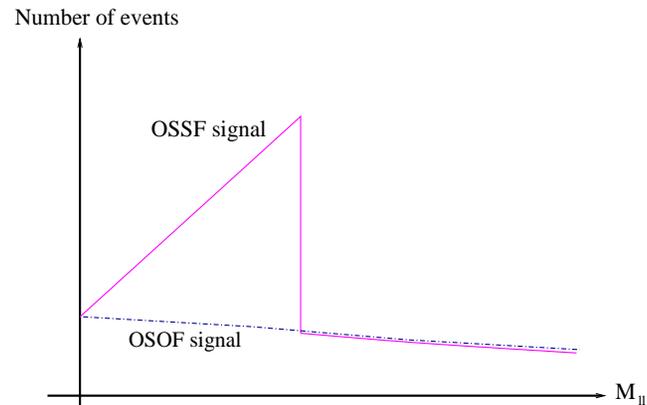- can be purified by OSSF-OSOF subtraction

OSSF-OSOF subtraction
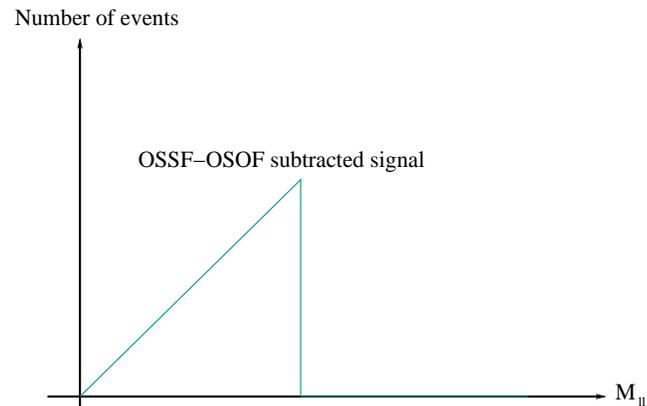
Characteristic shape of the OSSF & OSOF signal:

Number of events

OSSF signal

OSOF signal

M_{ll}

OSSF-OSOF subtraction

Characteristic shape of the OSSF & OSOF signal:

Subtract OSSF-OSOF

Ramp-and-edge structure is clear after subtraction

Signal in 2l channel

We also have a signal in 2l channel. Those are correlated pairs of leptons coming from neutralinos decay.

Our signal is placed both in OSOF and OSSF bins. Sits on top of the background, equally distributed between OSOF, OSSF, SSOF, SSSF.

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Procedure: perform OS-SS subtraction to purify the signal.

Shape of the signal

Our decays: 2 body $\to$ 3 body.

What is the shape of the dilepton invariant mass?

Without spins – just bump (*Thomas, Tucker-Smith, Weiner 2007*).
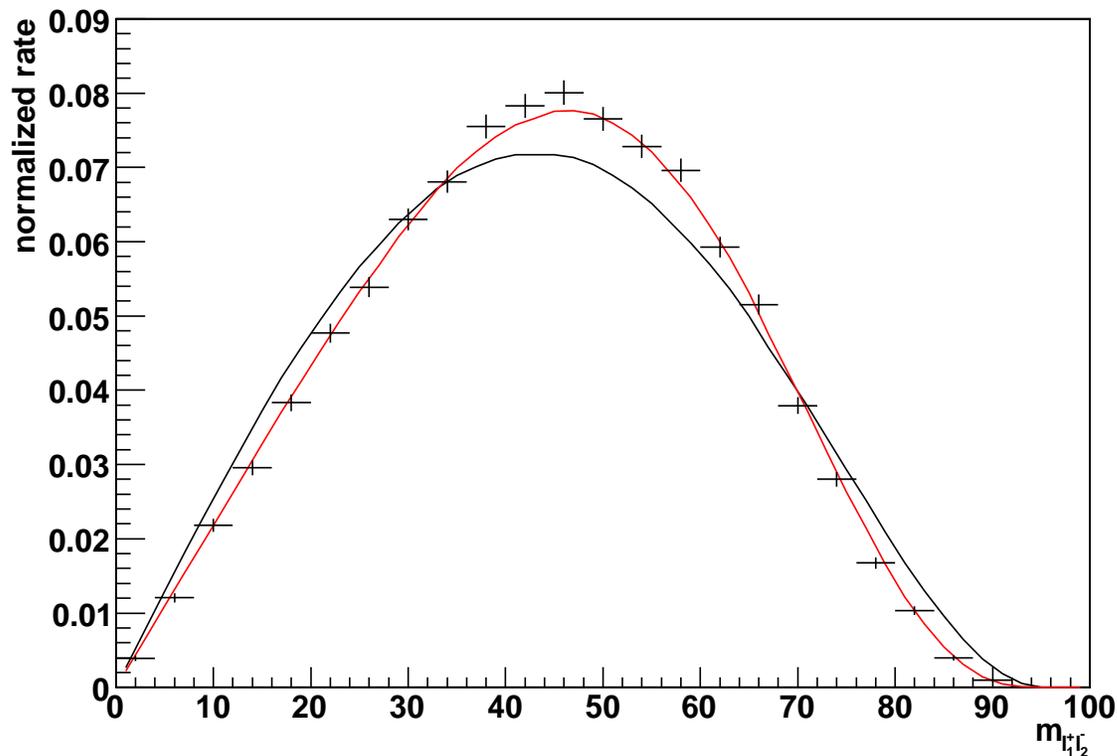
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Trileptonic channel

How can we get 3l?

2l (OS, random flavor) from one side of the event, one lepton from another side of the event.

Why do we need 3l channel?

- Easier to beat backgrounds than in 2l.

- Can give an additional evidence.

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Procedure:

Pair the softest lepton among three with the opposite sign lepton among two hard leptons. If there is an ambiguity – do not include the event in the current analysis. Expect – M_{ll} of these pairs will reproduce the same bump, as OS dileptons.

Jet-lepton invariant mass

If our production is squark-anti-squark dominated:
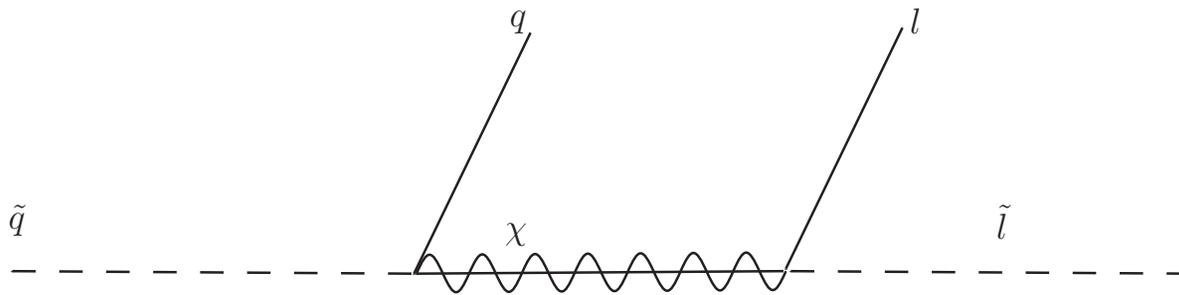
- may carry important information about the masses of squark and gaugino

- may be an important discriminator (the most "dangerous" fakers do not have this channel)

- ideally should give a clean edge-like distribution

- gluino dominated production – usually two jets in each gluino decay. The information is lost
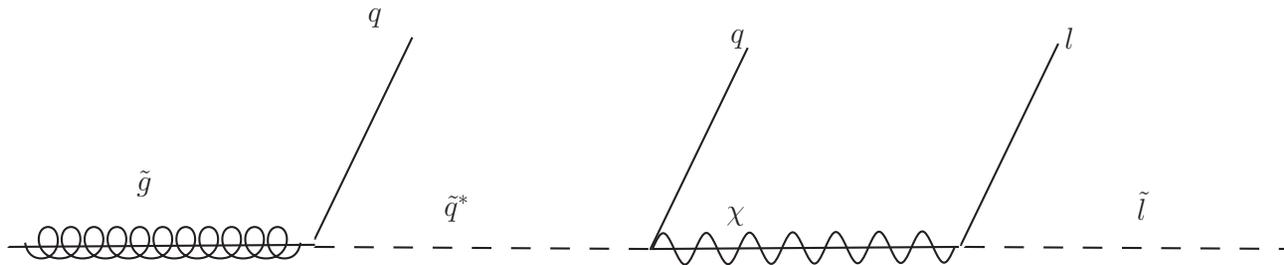
- suffers from irreducible combinatorial background

- if squark is off-shell – we also do not expect any feature

SUSY fakers

Which supersymmetric spectrum can fake such behavior?

SUSY fakers

Which supersymmetric spectrum can fake such behavior?

- spectra w/ OSSF excess are not good fakers. In our case flavor correlation is lost

- "flavorful SUSYs" – cannot be completely anarchical, at least in two first generations

- all scalars are heavy, wino and bino at the bottom of the spectrum. Heavy chargino and neutralino decay into the neutralino LSP through $W^\pm$, Z (on or off-shell) and Higgs.

Faking $\tilde{\nu}$ NLSP by Ws

Most dangerous faker:

$$m(\tilde{l}), m(\tilde{e}_r) > m(\tilde{W}) > m(\tilde{B})$$

All leptons come from W decays

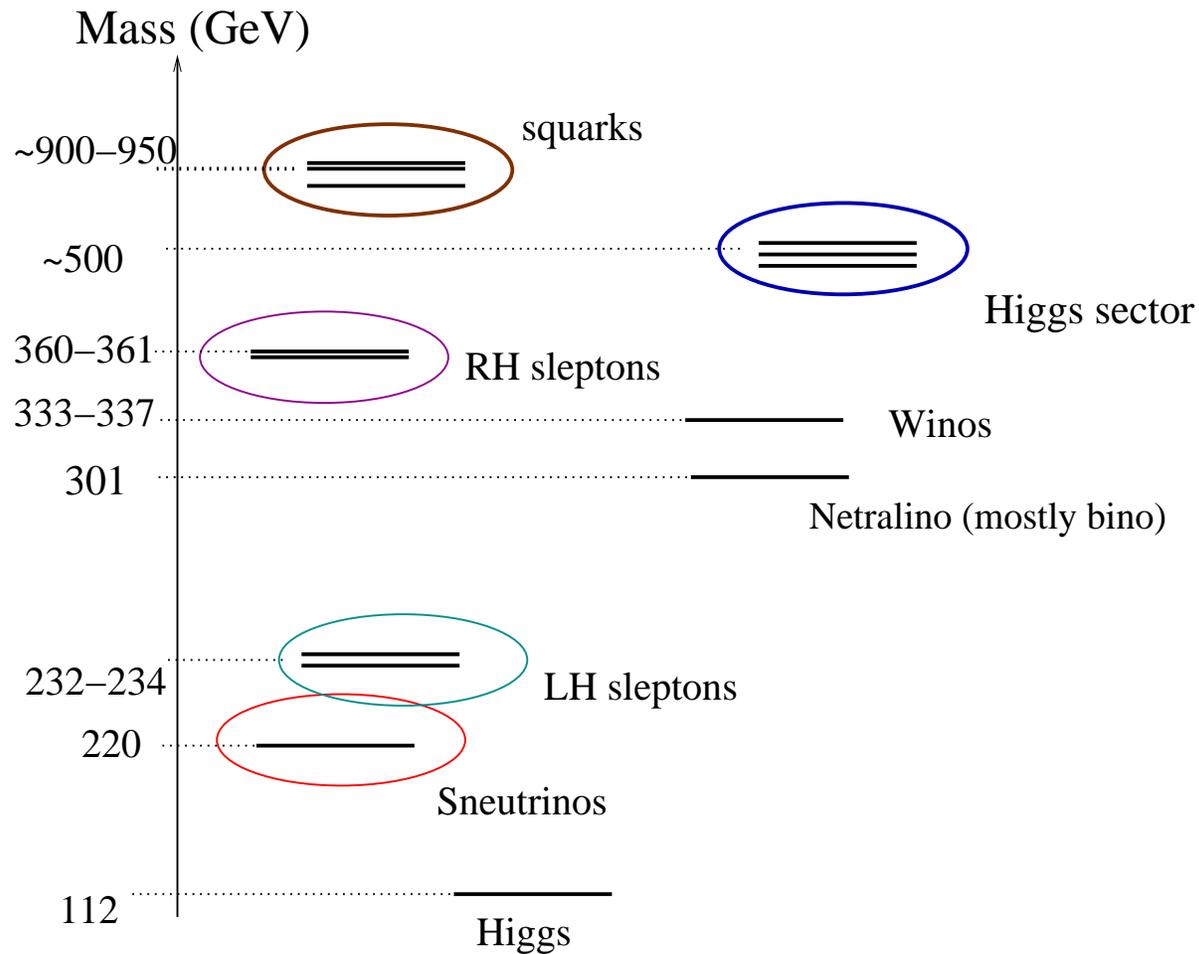# Faking $\tilde{\nu}$ NLSP by Ws

Most dangerous faker:

$$m(\tilde{l}), m(\tilde{e}_r) > m(\tilde{W}) > m(\tilde{B})$$

All leptons come from W decays

- leptons are uncorrelated but might have OS excess due to production mechanism

- no feature in M_{ll}

- monoleptonic:dileptonic ratio is much bigger

- no feature in M_{jl}

Representative spectrum

Inactive spectrum with squark production

Backgrounds

Main SM backgrounds

- $t\bar{t}$ (1l, 2l, 3l), $\sigma_{total} \approx 600$ pb

- $W\,W$+jets (1l, 2l, 3l), $\sigma_{total} \sim \mathcal{O}(100\ \mathrm{pb})$

- $\tau^+\tau^-$+jets (dangerous for 2l)

- W+jets (1l) (after hard cuts $\sigma \sim \mathcal{O}(1\ \mathrm{pb})$

- $W Z^*$ (might impair 2l, 3l)

- might also worry about $b\bar{b}$, $c\bar{c}$ for 1l – we do not discuss these backgrounds here

Cuts

- QCD production $p_t(j1), p_t(j2) > 300 \text{ GeV}$. Cut is harder than usual since OSSF-OSOF subtraction reduces $t\bar{t}$ in 2l channel, but our subtraction does not. We should just tighten the cuts.

- QCD: $E_T^{miss} > 200 \text{ GeV}$.

- $M_{TW}^2 \equiv 2|\vec{l}_T||\vec{E}_T^{miss}|(1 - \cos\phi) > (100 \text{ GeV})^2$ – effectively removes W+jets and monoleptonic $t\bar{t}$ (which is also effectively W+jets).

# What leptons do we rely on?

- Isolation cuts for tight lepton: less than 10 % hadronic activity in $\Delta R < 0.4$ around the lepton

- Isolation cuts for the loose leptons: more than 10 % hadronic activity in $\Delta R < 0.4$ around the lepton, but the p_t of the hadronic activity in that cone does not exceed $10 \; \mathrm{GeV}$

- Reconstruct leptons with $p_t > 5 \; \mathrm{GeV}$. Very safe for muons, probably OK for electrons with good isolation cuts (as we have).

- Never use loose leptons in 1l or 2l channel

- Multilepton channel – at least 2 tight leptons
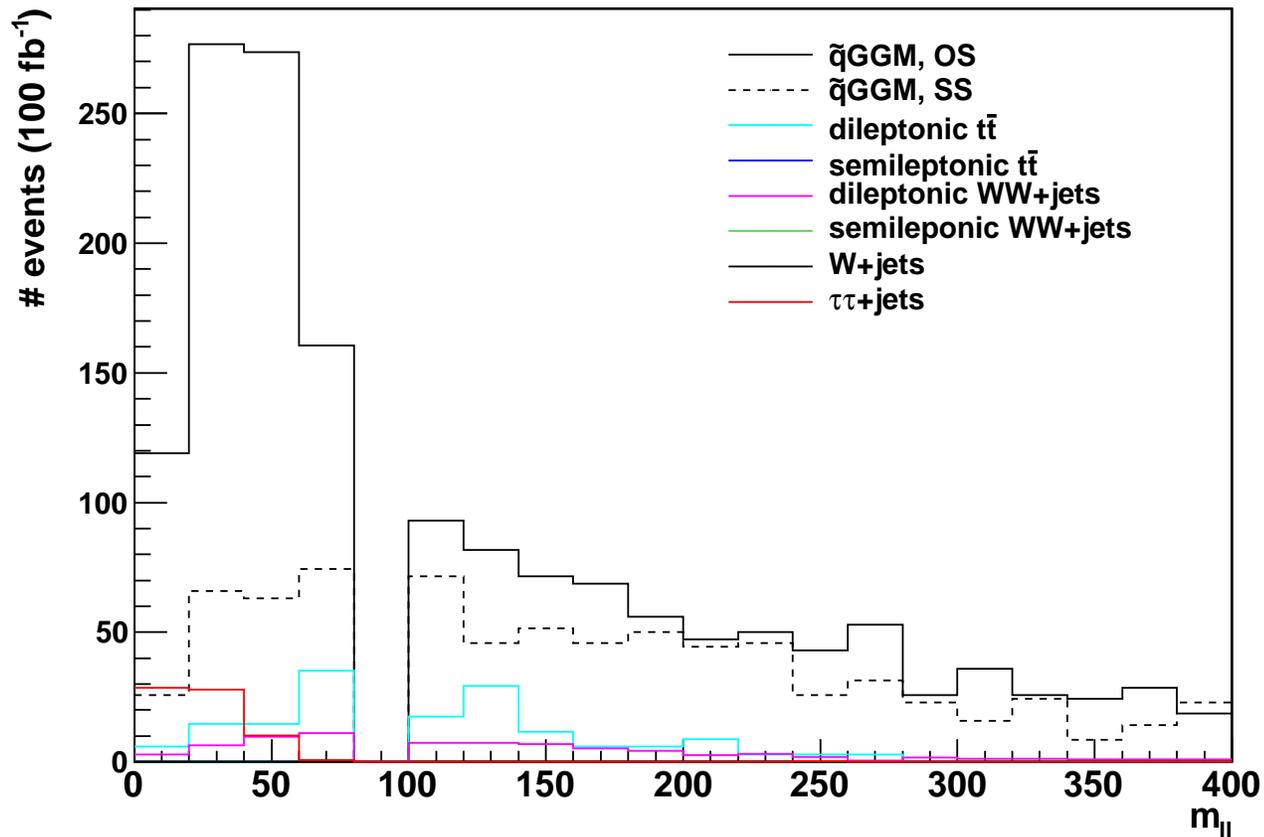
Count the leptons
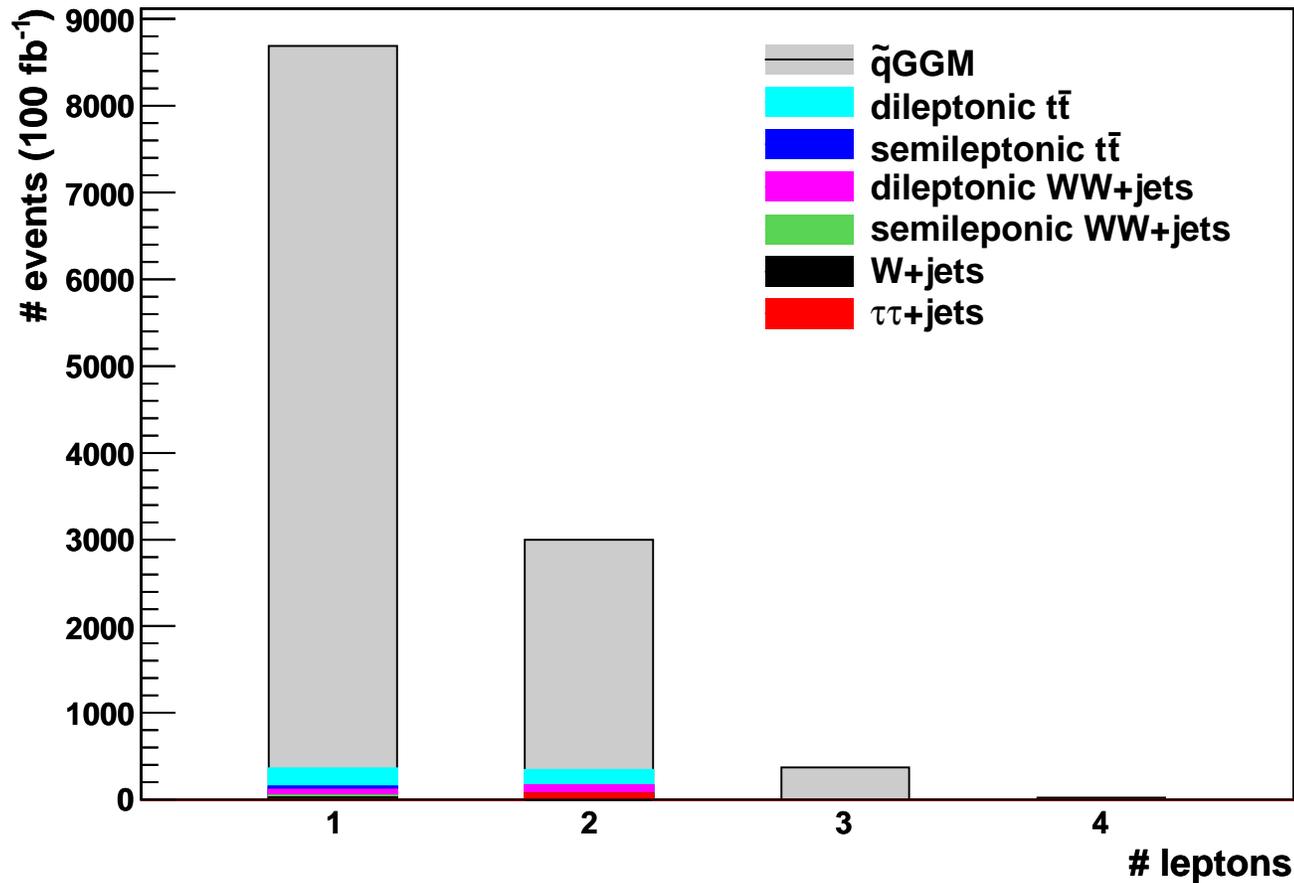
Monoleptonic:dileptonic $\sim$ 3:1
agrees up to order one number with what we expect
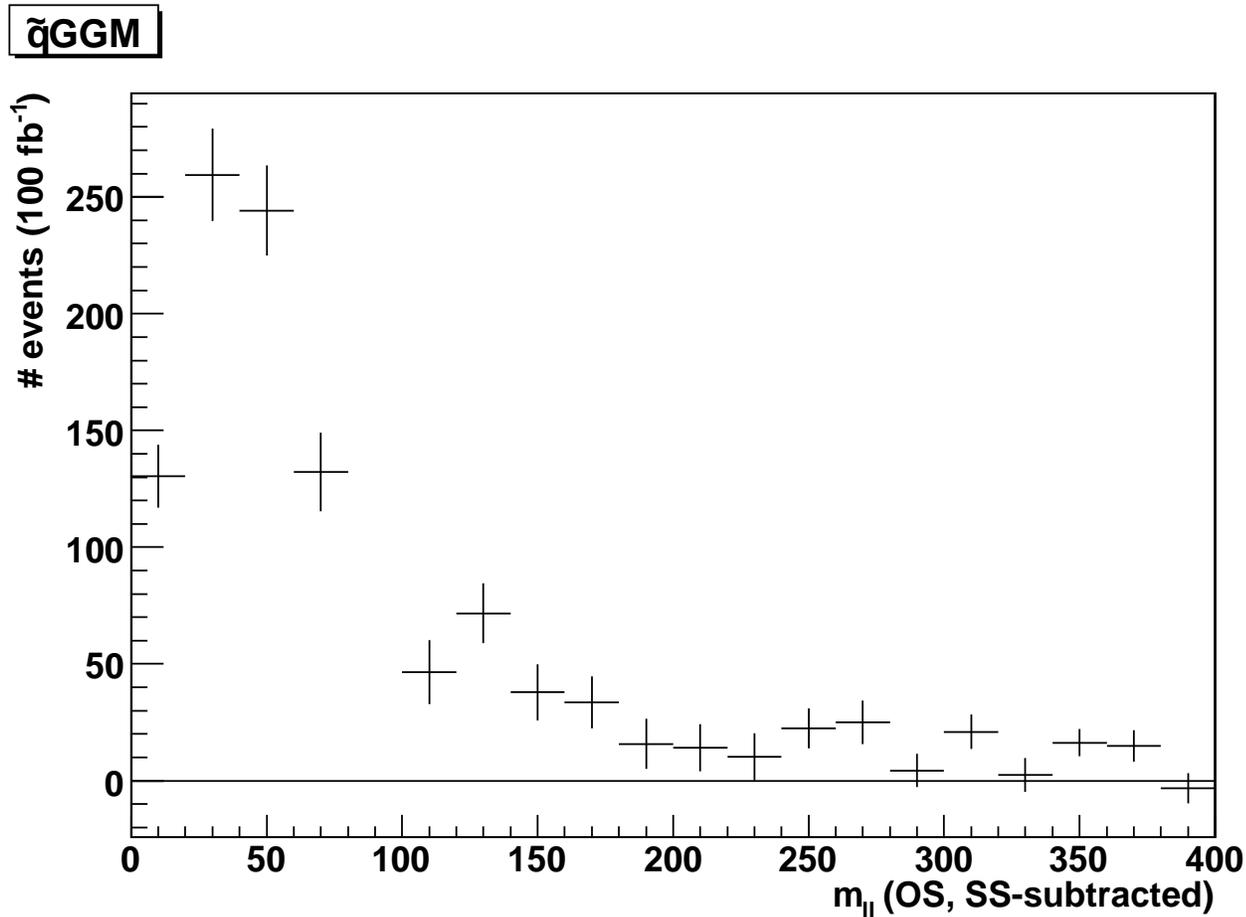
Structure of the 2l channel
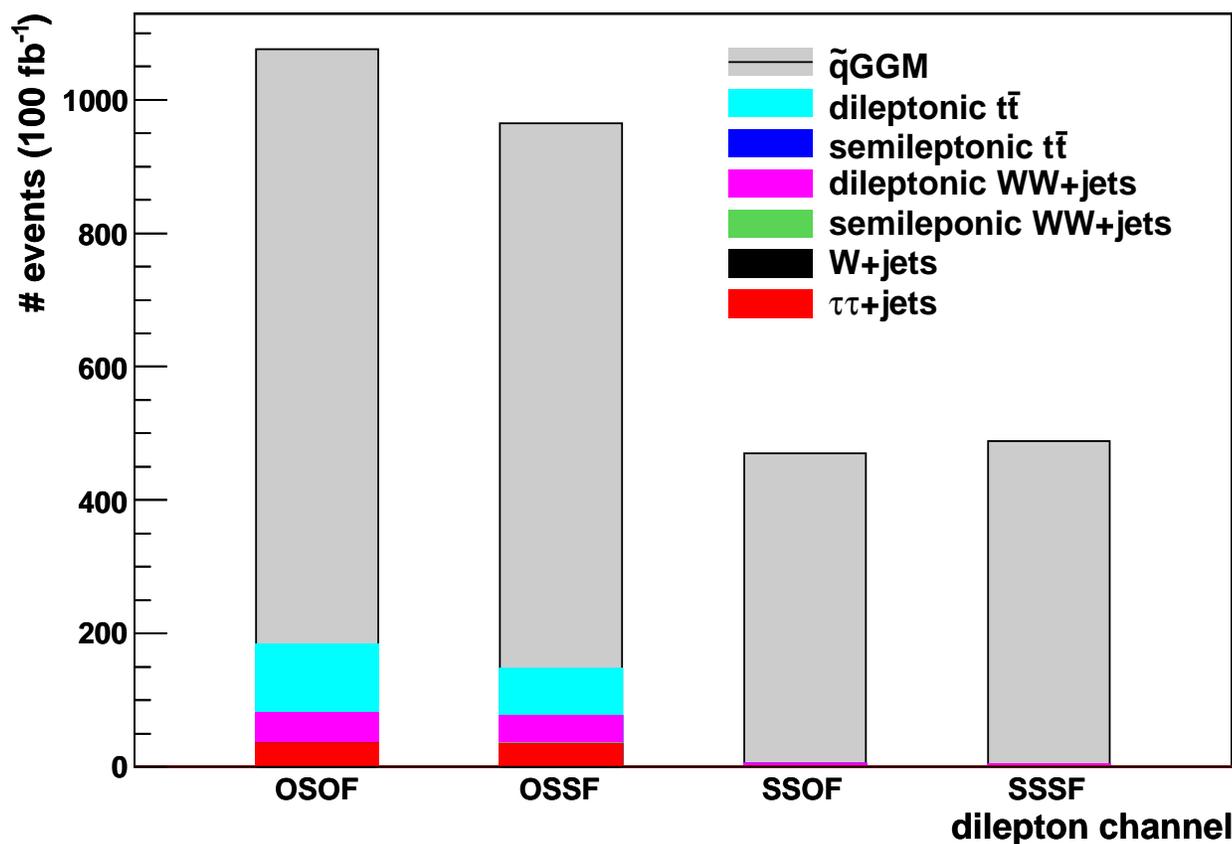
OSOF ~ OSSF > SSOF ~ SSSF
OSSF is bit smaller than OSOF due to Z misreconstruction
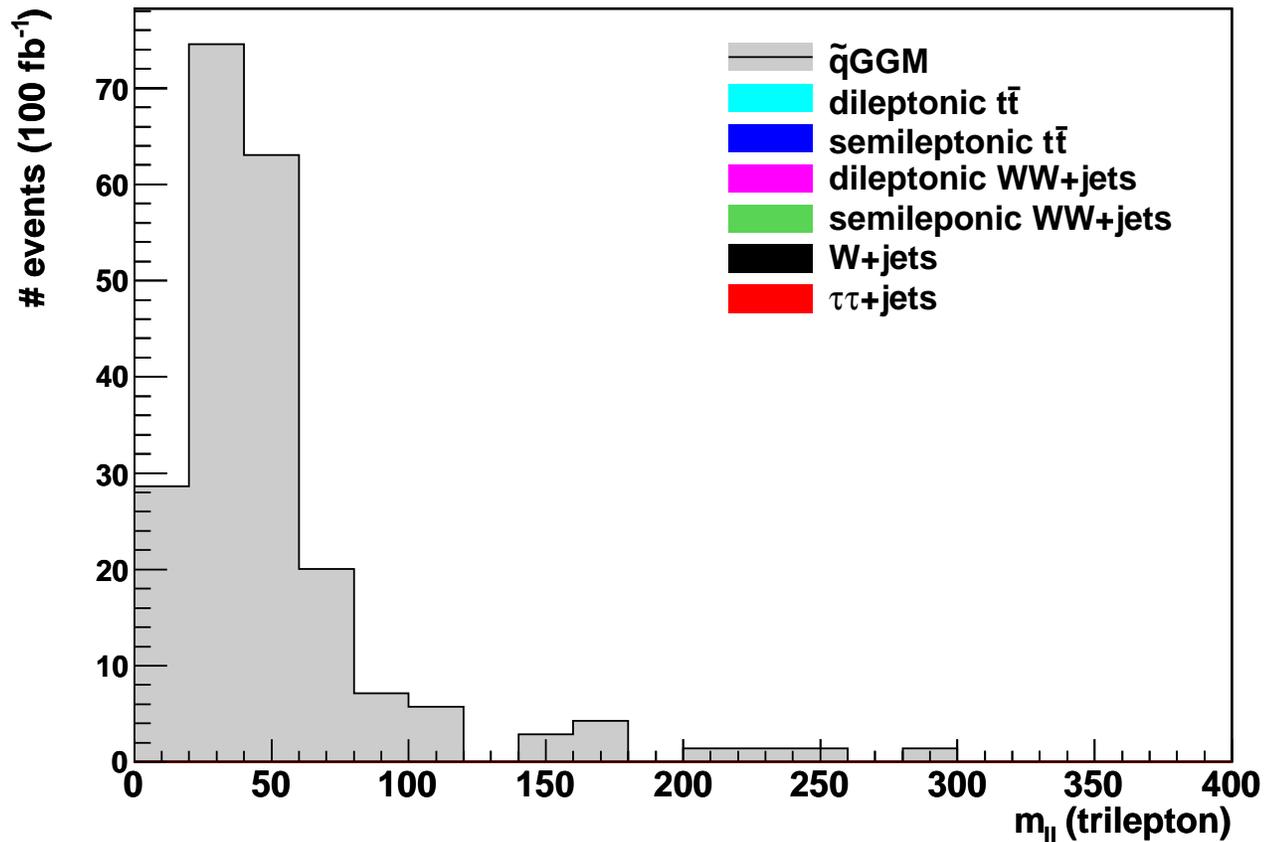
M_{ll} in 2l channel

Same sign signal has no structure, OS sign signal has a bump.
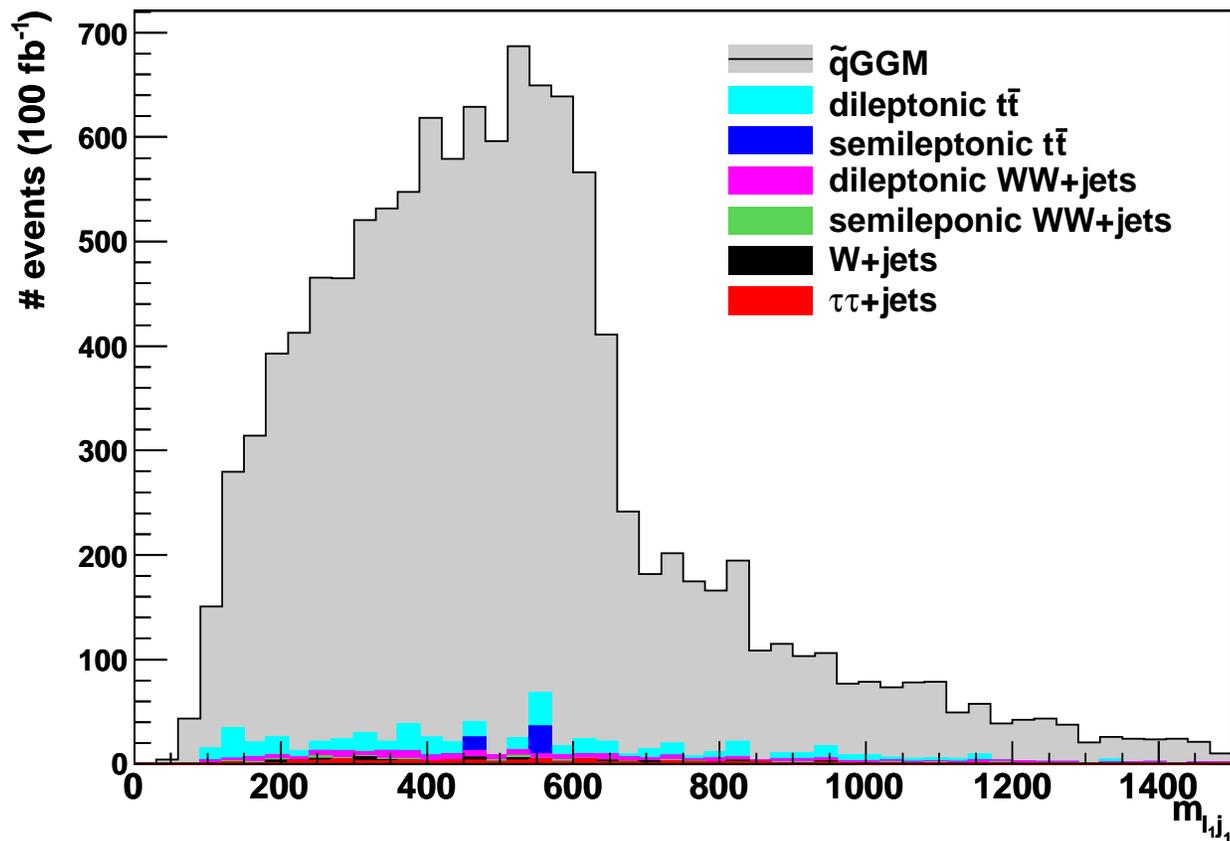
Sign subtraction

Predicted bumps are at 31 GeV and 40 GeV sitting one on top of each other.

3l channel

OS pairing in 3l channel. The structure is the same as it is in the 2l channel.

M_{jl} invariant mass

With the given spectrum the cascade $\tilde{q} \rightarrow \tilde{\chi} \rightarrow \tilde{l}$ is expected to give an edge at 625 GeV.

Gluino production

Consider now a similar specrum with $m_{\tilde{g}} \ll m_{\tilde{q}}$. In this case the production is gluino dominated and as a result we almost get winos as gaugino states. The signal is smaller compared to the squark production. Is it visible?

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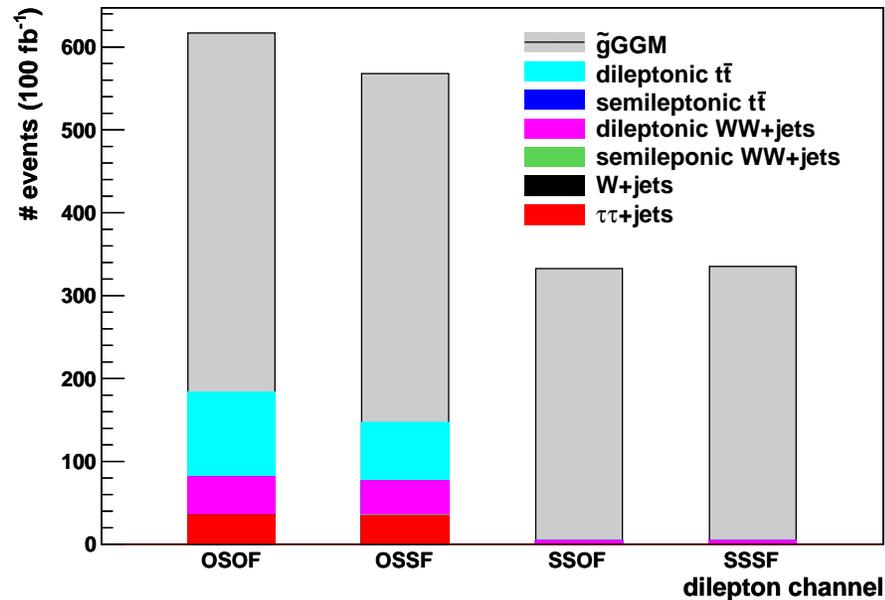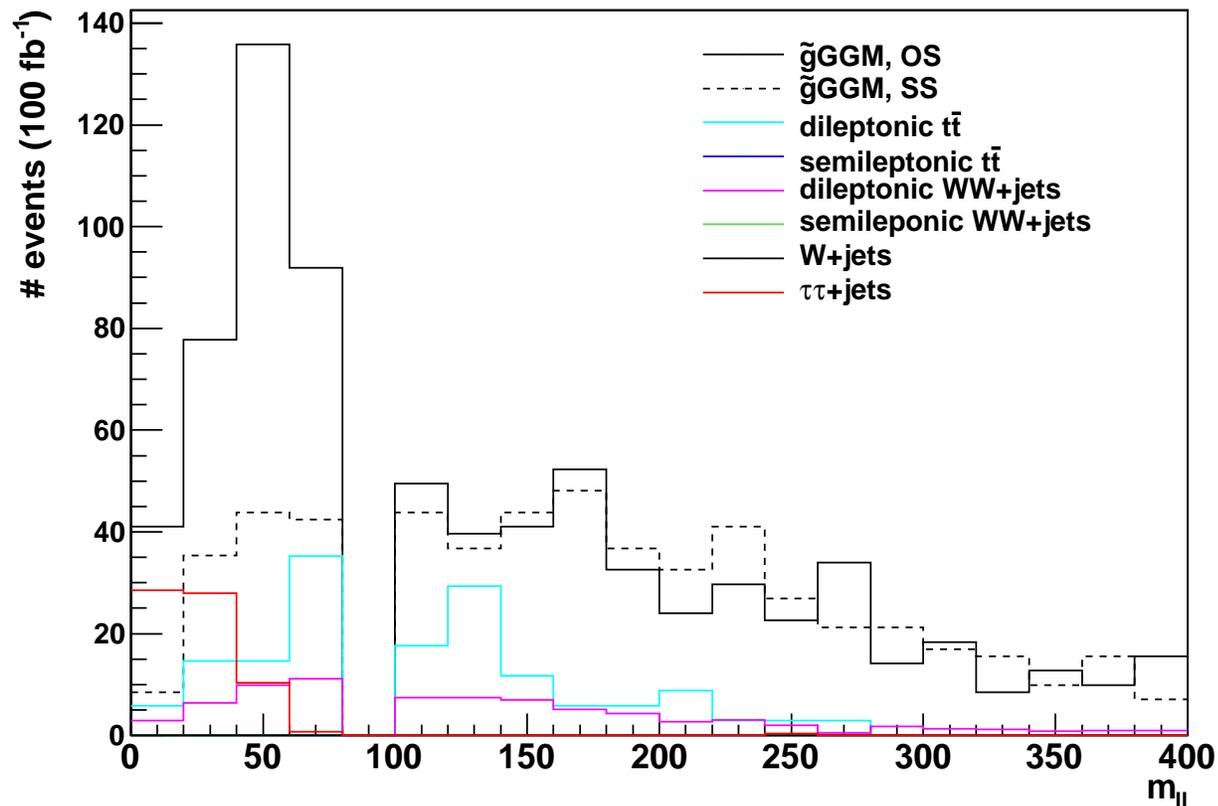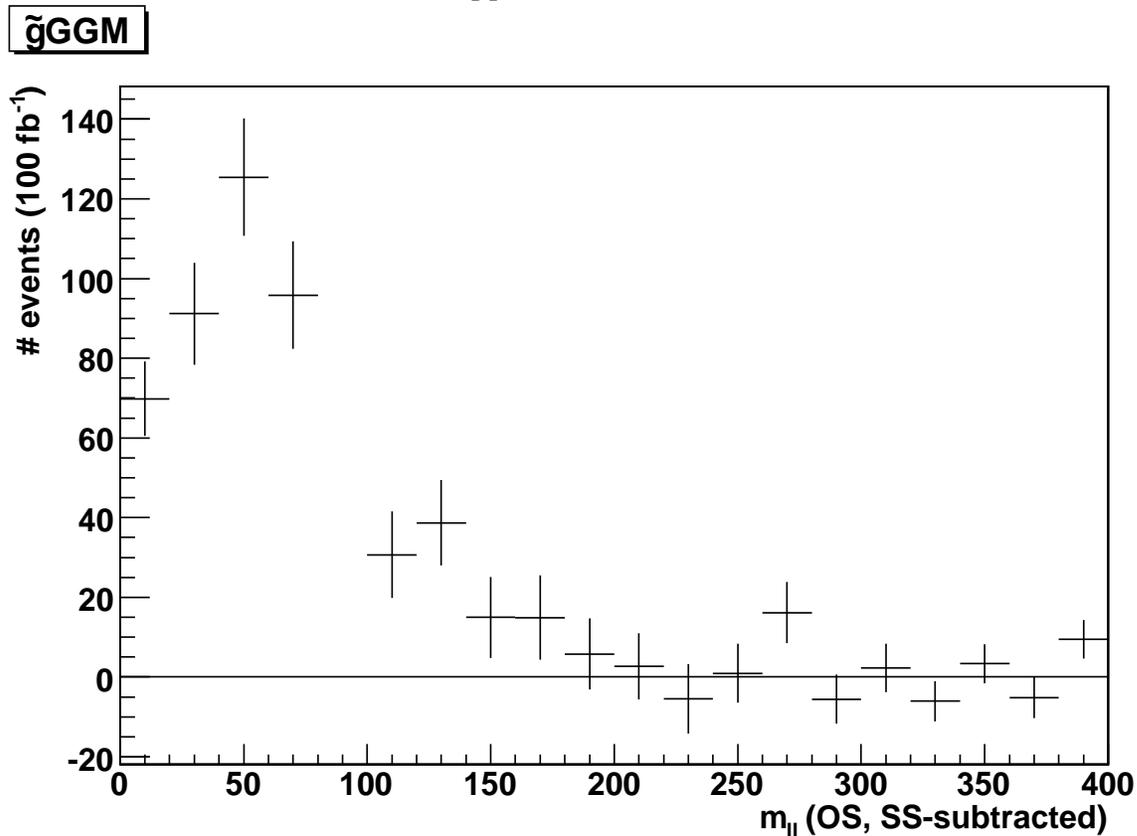
Signal to background

It looks that even with the cuts the signal is dangerously comparable to the background. Nonetheless the distribution of the signal is different.

Sign subtraction

From the sign subtraction plot we clearly see the bump around 50 GeV. As we saw the background has a random distribution and it is neglebible at the interesting region.

Conclusions and outlook

- $\tilde{\nu}$ NLSP is an interesting possibility and it is well motivated question how one can possibly distinguish it from the $\tilde{\chi}^0$ LSP.

- We showed that very big class of models (the "inactive spectra") have very distinct collider signatures.

- The signatures of the "inactive spectra" is not easy to fake and if discovered should be considered as clear evidence for $\tilde{\nu}$ NLSP.

- With careful analysis one can probably use similar tools (slightly modified) to analyse the "active spectra", covering the whole range of possibilities for $\tilde{\nu}$ NLSP (work in progress).