Slepton mass measurement in a $\tilde{\tau}$ co-annihilation scenario

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Outline

This is a status report !!!

1. Outline
2. Studying SUSY in rich models
3. A bench-mark point: STC4
   - STC4 @ 500 GeV
   - STC4 @ 500 GeV: Globaly
   - STC4 @ 500 GeV: $\tilde{e}, \tilde{\mu}$
   - STC4 @ 500 GeV: $\tilde{\tau}_1$
     - Massive SGV $\gamma\gamma$ production
     - Fitting the $\tilde{\tau}_1$ end-point
4. Outlook & Conclusions

Aim of the study

Suppose SUSY is there and has a rich spectrum of sparticles accessible at the ILC. Then:

- Easy - wrt. things like $\tilde{H}$ only, WIMP only: Lots to see.
- Hard - wrt. things like $\tilde{H}$ only, WIMP only: Lots to Disentangle.

Specifically:

- When data starts coming in, what is is first light ?
- How do we quickly determine a set of model parameters ?
- What is then the optimal use of beam-time in such a scenario ?
- And in a staged approach ?
- Spectrum in continuum vs. threshold-scans?
- Special points, eg. between $\tilde{\tau}_1\tilde{\tau}_2$ and $\tilde{\tau}_2\tilde{\tau}_2$ thresholds.
- Clean vs. high cross-section.
- And so on ...

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SUSY signatures and backgrounds

Background from SM:

- Real missing energy + pair of SM-particles = di-boson production, with neutrinos:
  - $WW \to \ell\nu\ell\nu$
  - $ZZ \to f\bar{f}\nu\nu$
- Fake missing energy + pair of SM-particles = $\gamma\gamma$ processes, ISR, single IVB.
  - $e^+e^- \to e^+e^-\gamma\gamma \to e^+e^-f\bar{f}$, with both e^+e^- un-detected.
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Observables:

Observable	Gives	If
Edges (or average and width)	Masses	... not too far from threshold
Shape of spectrum	Spin	
Angular distributions	Mass, Spin	
Invariant mass distributions from full reconstruction	Mass	... cascade decays
Angular distributions from full reconstruction	Spin, CP,	... masses known
Un-polarised Cross-section in continuum	Mass, coupling	
Polarised Cross-section in continuum	Mass, coupling, mixing	
Decay product polarisation	Mixing	... $\tilde{\tau}$ decays
Threshold-scan	Mass(es), Spin	

Observables: Pair-production, two-body decay

Consider $e^+e^- \rightarrow XX$, followed by $X \rightarrow UY$, where Y is a detectable (SM) particle. Then

- $E_{Y\ max(min)} = \frac{E_{Beam}}{2}\left(1 - \left(\frac{M_U}{M_X}\right)^2\right)\left(1 \overset{+}{(-)} \sqrt{1 - \left(\frac{M_X}{E_{Beam}}\right)^2}\right)$, so that
- $M_X = E_{Beam}\sqrt{1-(\Delta/\Sigma)^2}$
- $M_U = E_{Beam}\sqrt{1-(\Delta/\Sigma)^2}\sqrt{1-\Sigma/E_{Beam}}$
  $(\Delta = E_{Y\ max} - E_{Y\ min}; \Sigma = E_{Y\ max} + E_{Y\ min})$

If the spectrum is flat (eg if X is a sfermion) between the end-points:

- $< E_Y >= (E_{Y\ max} + E_{Y\ min})/2$ and $\sigma_{E_Y} = \sqrt{(E_{Y\ max} - E_{Y\ min})/12}$, which gives
- $M_U = E_{Beam}\sqrt{1 - \frac{2<E_Y>}{E_{Beam}}}\sqrt{1 - \left(\frac{6\sigma^2_{E_Y}}{<E_Y>}\right)^2}$
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Example: STC4

STC4-8

- 11 parameters.
- Separate gluino
- Higgs, un-coloured, and coloured scalar parameters separate

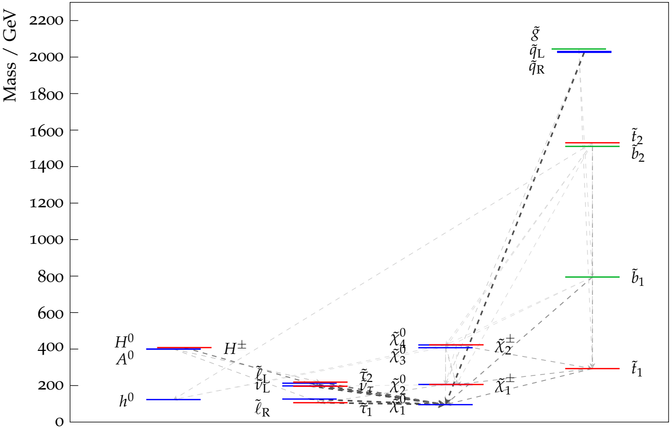
Parameters chosen to deliver all constraints (LHC, LEP, cosmology, low energy).

At E_{CMS} = 500 GeV:

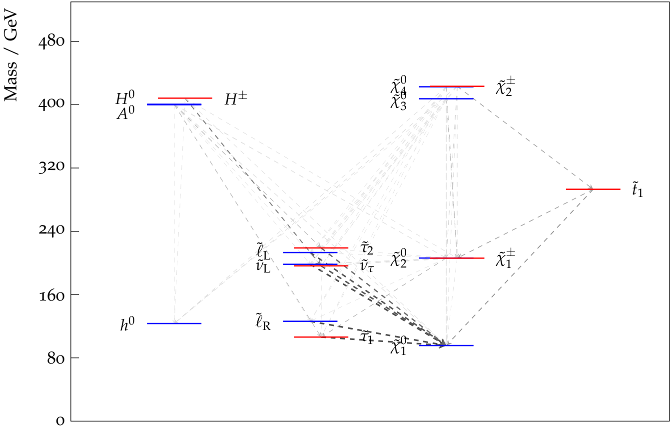
- All sleptons available.
- No squarks.
- Lighter bosinos, up to $\tilde{\chi}^0_3$ (in $\mathrm{e}^+\mathrm{e}^- \rightarrow \tilde{\chi}^0_1 \tilde{\chi}^0_3$)

(See H. Baer, J. List, arXiv:1307:0782.)

Full STC4 mass-spectrum



Zoomed STC4 mass-spectrum



Channels and observables at 250, 350 and 500 GeV

Channel	Threshold	Available at	Can give
$\tilde{\tau}_1\tilde{\tau}_1$	212	250	$M_{\tilde{\tau}_1}$, $\tilde{\tau}_1$ nature, τ polarisation
$\tilde{\mu}_R\tilde{\mu}_R$	252	250+	+ $M_{\tilde{\mu}_R}$, $M_{\tilde{\chi}^0_1}$, $\tilde{\mu}_R$ nature
$\tilde{e}_R\tilde{e}_R$	252	250+	+ $M_{\tilde{e}_R}$, $M_{\tilde{\chi}^0_1}$, $\tilde{e}_R$ nature
$\tilde{\chi}^0_1\tilde{\chi}^0_2$ *)	302	350	+ $M_{\tilde{\chi}^0_2}$, $M_{\tilde{\chi}^0_1}$, nature of $\tilde{\chi}^0_1$, $\tilde{\chi}^0_2$
$\tilde{\tau}_1\tilde{\tau}_2$ *)	325	350	+ $M_{\tilde{\tau}_2}\theta_{mix}$ $\tilde{\tau}$
$\tilde{e}_R\tilde{e}_L$ *)	339	350	+ $M_{\tilde{e}_L}$, $\tilde{\chi}^0_1$ mixing, $\tilde{e}_L$ nature
$\tilde{\nu}_{\tilde{\tau}}\tilde{\nu}_{\tilde{\tau}}$	392	500	7 % visible BR ($\rightarrow \tilde{\tau}_1 W$)
$\tilde{\chi}^{\pm}_1\tilde{\chi}^{\pm}_1$ *)	412	500	+ $M_{\tilde{\chi}^{\pm}_1}$, nature of $\tilde{\chi}^{\pm}_1$
$\tilde{e}_L\tilde{e}_L$ *)	416	500	+ $M_{\tilde{e}_L}$, $M_{\tilde{\chi}^0_1}$, $\tilde{e}_L$ nature
$\tilde{\mu}_L\tilde{\mu}_L$ *)	416	500	+ $M_{\tilde{\mu}_R}$, $M_{\tilde{\chi}^0_1}$, $\tilde{\mu}_R$ nature
$\tilde{\tau}_2\tilde{\tau}_2$ *)	438	500	+ $M_{\tilde{\tau}_2}$, $M_{\tilde{\chi}^0_1}$, $\tilde{\tau}_2$ nature, θ_{mix} $\tilde{\tau}$
$\tilde{\chi}^0_1\tilde{\chi}^0_3$ *)	503	500+	+ $M_{\tilde{\chi}^0_3}$, $M_{\tilde{\chi}^0_1}$, nature of $\tilde{\chi}^0_1$, $\tilde{\chi}^0_3$

*): Cascade decays.

+ invisible $\tilde{\chi}^0_1\tilde{\chi}^0_1$, $\tilde{\nu}_{\tilde{e},\tilde{\mu}}\tilde{\nu}_{\tilde{e},\tilde{\mu}}$.

Features of STC4 @ 500 GeV

- The $\tilde{\tau}_1$ is the NLSP.
- For $\tilde{\tau}_1$: $E_{\tau,min} = 2.3\ \mathrm{GeV}$, $E_{\tau,max} = 45.5\ \mathrm{GeV}$:
  $\gamma\gamma - background \Leftrightarrow pairs - background$.
- For $\tilde{\tau}_2$: :$E_{\tau,min} = 52.4\ \mathrm{GeV}$, $E_{\tau,max} = 150.0\ \mathrm{GeV}$:
  $WW \rightarrow l\nu l\nu - background \Leftrightarrow Polarisation$.
- For $\tilde{\mathrm{e}}_\mathrm{R}$or $\tilde{\mu}_\mathrm{R}$: :$E_{l,min} = 7.3\ \mathrm{GeV}$, $E_{l,max} = 99.2\ \mathrm{GeV}$: Neither $\gamma\gamma$ nor $WW \rightarrow l\nu l\nu$ background severe.
- For pol=(1,-1): $\sigma(\tilde{\mathrm{e}}_\mathrm{R}\tilde{\mathrm{e}}_\mathrm{R})$ = 1.3 pb !
- $\tilde{\tau}$ NLSP $\rightarrow \tau$:s in most SUSY decays $\rightarrow$ SUSY is background to SUSY.
- For pol=(-1,1): $\sigma(\tilde{\chi}^0_2\tilde{\chi}^0_2)$ and $\sigma(\tilde{\chi}^+_1\tilde{\chi}^-_1)$ = several hundred fb and BR(X$\rightarrow \tilde{\tau}$) $>$ 70 %. For pol=(1,-1): $\sigma(\tilde{\chi}^0_2\tilde{\chi}^0_2)$ and $\sigma(\tilde{\chi}^+_1\tilde{\chi}^-_1) \approx 0$.

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STC4 @ 500 GeV

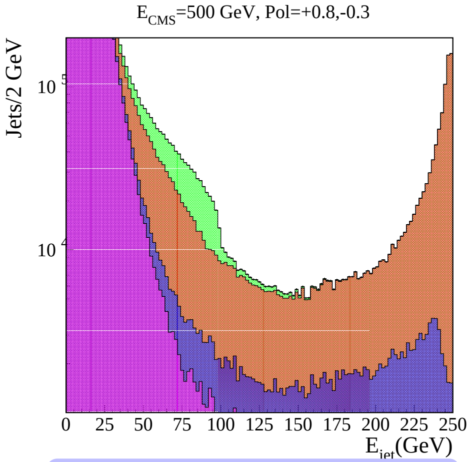
Strategy:

- Global preselection to reduce SM, while efficiency for all signals stays above $\sim$ 90 %.
- The further select for all sleptons ($\tilde{e}_R, \tilde{e}_L, \tilde{\mu}_R, \tilde{\mu}_L, \tilde{\tau}_1$).
- Next step: specific selections for $\tilde{e}_R$ and $\tilde{\mu}_R$, for $\tilde{e}_L$ and $\tilde{\mu}_L$, and for $\tilde{\tau}_1$.
- Last step: add particle id to separate $\tilde{e}$ and $\tilde{\mu}$, special cuts for $\tilde{\tau}_1$.
- Check results both for RL and LR beam-polarisation.

STC4 global

After a few very general cuts:

- Missing energy > 100
- Less than 10 charged tracks
- $|\cos\theta_{Ptot}| < 0.95$
- Exactly two τ-jets
- Visible mass < 300 GeV
- θ_{acop} between 0.15 and 3.1



Magenta: $\gamma\gamma$, Blue: 3f,
Red: Rest of SM, Green: SUSY.

STC4 sleptons @ 500 GeV: $\tilde{e}$, $\tilde{\mu}$

- Selections for $\tilde{\mu}$ and $\tilde{e}$:
  - Correct charge.
  - P_T wrt. beam and one ℓ wrt the other.
  - Tag and probe, ie. accept one jet if the other is "in the box".
- Further selections for R:
  - Cuts on polar angle and angle between leptons.
- E_{jet}, beam-pol 80%,-30%...
- Further selections for L (LR):
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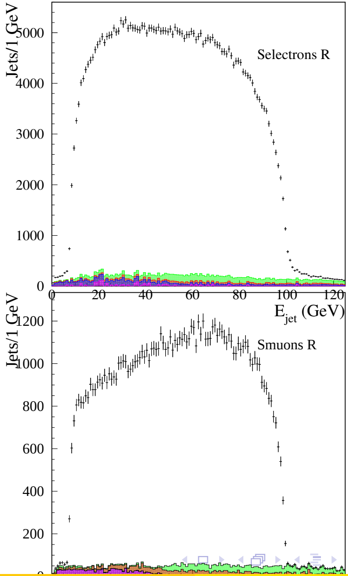

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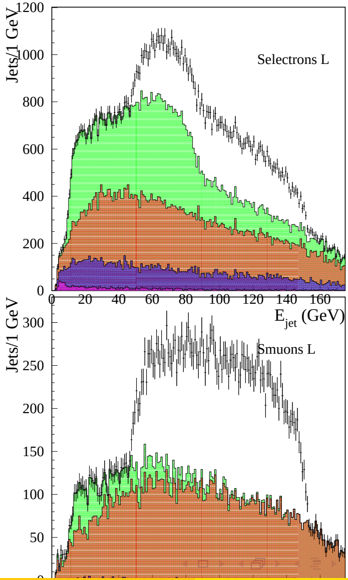
  - $q_{jet} \cos\theta_{jet}$
  - $M_{vis} \neq M_Z$



Masses from $\tilde{e}$, $\tilde{\mu}$ in the continuum

- In $\mathrm{R}[E_{min}, E_{max}]$, the MVB exists and is $\min(\max)(E_\ell)$ (!)
- In presence of background this won't work.
- Try to mitigate the effect of extreme cases:
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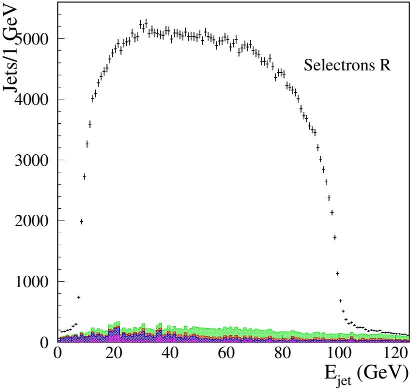

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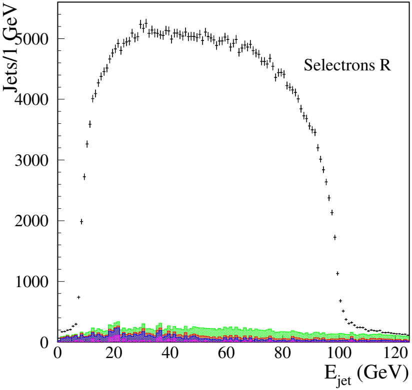

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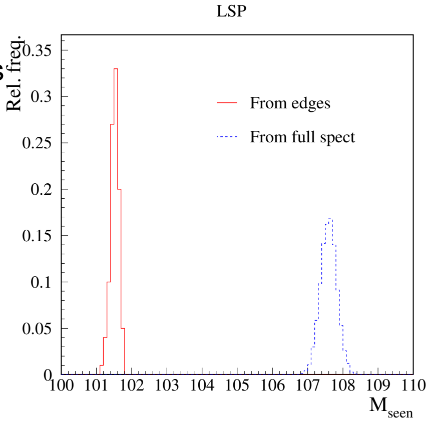

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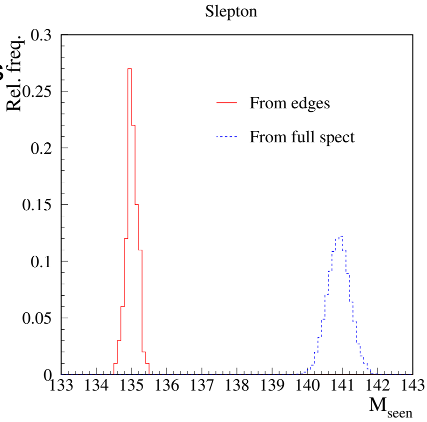

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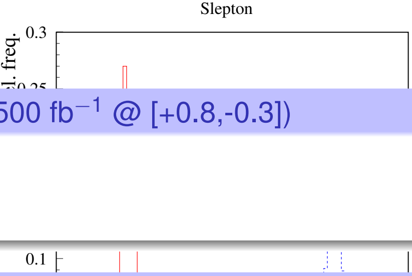


Results from edges (E_{CMS}=500, 500 fb^{-1} @ [+0.8,-0.3])

$$M_{\tilde{e}_R} = 135.01 \pm 0.19\ \mathrm{GeV}/c^2$$
$$M_{\tilde{\chi}^0_1} = 101.51 \pm 0.14\ \mathrm{GeV}/c^2$$

Results for full spectrum (E_{CMS}=500, 500 fb^{-1} @ [+0.8,-0.3])

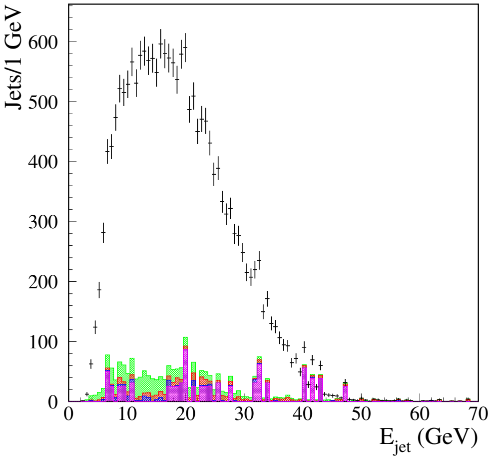
$$M_{\tilde{e}_R} = 140.90 \pm 0.33\mathrm{GeV}/c^2$$
$$M_{\tilde{\chi}^0_1} = 107.61 \pm 0.23\ \mathrm{GeV}/c^2$$

- Make calibration curve with ToyMC.

STC4 sleptons @ 500 GeV:$\tilde{\tau}_1$

Selections for $\tilde{\tau}_1$:

- Correct charge.
- P_T wrt. beam and one τ wrt the other.
- $M_{jet} < M_\tau$
- $E_{vis} < 120$ GeV,$M_{vis} \in [20, 87]$ GeV.
- Cuts on polar angle and angle between leptons.
- Little energy below 30 deg, or not in τ-jet.
- At least one τ-jet should be hadronic.
- Anti-$\gamma\gamma$ likelihood.



Massive SGV $\gamma\gamma$ production

- Note the few $\gamma\gamma$ events just at the end-point !
- Don't want to do "dirty tricks" to fit the end-point $\Rightarrow$ need more stat.
- But I've already used all existing generated events, and that only represents 20 fb^{-1}, but is nevertheless 580 GB in 1134 stdheps $\Rightarrow$
- Generate on-the-fly inside SGV.
- Callable Whizard is already an option in SGV, but:
  - Most control in Whizard steering-file, not in SGV.
  - Can't set unique seed to event-generation per job in SGV.
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Massive SGV $\gamma\gamma$ production

- Using the existing meta-data files for aa_2f, easy to script a massive production.
- Specify wanted integrated lumi, maximum number of events/job , and the set of meta-data files to parse.
- On the German NAF:
  - 1615 jobs of 0.5 MEvents
  - Total generated: 0.8 GEvents.
  - Wall-clock time first started to last completed: 3 hours (with typically 200-300 jobs running at the same time).
  - Written to analysis ntuple: 83 MEvents, size 330 GB (compare: would have needed TB:s of stdheps!)
- Some notes:
  - The cross-section of the channels was corrected wrt. the DBD numbers (to take care of not only the ratio of number of γ:s to electrons, but also the different beam-profiles.
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Fitting the $\tilde{\tau}_1$ end-point

- Only the upper end-point is relevant.
- Background subtraction:
  - $\tilde{\tau}_1$: Important SUSY background,but region above 45 GeV is signal free. Fit exponential and extrapolate.
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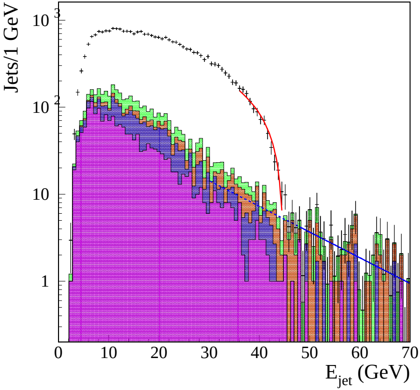

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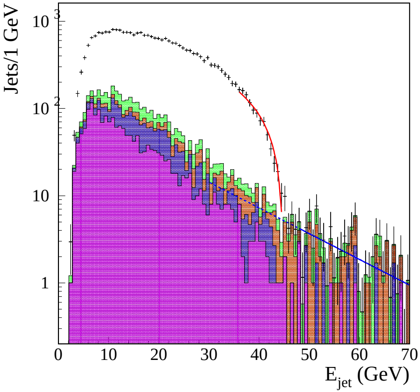

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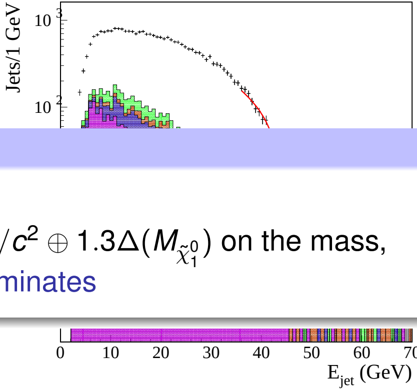

Results for $\tilde{\tau}_1$

$E_{max,\tilde{\tau}_1} = 44.51^{+0.12}_{-0.10}\mathrm{GeV}$

Translates to an error of $\sim 0.06\mathrm{GeV}/c^2 \oplus 1.3\Delta(M_{\tilde{\chi}_1^0})$ on the mass, where the error from $M_{\tilde{\chi}_1^0}$ largely dominates

Reminder: SPS1a' results (Phys.Rev.D82:055016,2010)

The previous $\tilde{\tau}$ study in the very similar model SPS1a' gave:

Results for $\tilde{\tau}_1$

$M_{\tilde{\tau}_1} = 107.73^{+0.03}_{-0.05}\mathrm{GeV}/c^2 \oplus 1.3\Delta(M_{\tilde{\chi}_1^0})$

The error from $M_{\tilde{\chi}_1^0}$ largely dominates

Results for $\tilde{\tau}_2$

$M_{\tilde{\tau}_2} = 183^{+11}_{-5}\mathrm{GeV}/c^2 \oplus 18\Delta(M_{\tilde{\chi}_1^0})$

The error from the endpoint largely dominates

Results from cross-section for $\tilde{\tau}_1$

$\Delta(N_{signal})/N_{signal} = 3.1\% \rightarrow \Delta(M_{\tilde{\tau}_1}) = 3.2\mathrm{GeV}/c^2$

Results from cross-section for $\tilde{\tau}_2$

$\Delta(N_{signal})/N_{signal} = 4.2\% \rightarrow \Delta(M_{\tilde{\tau}_2}) = 3.6\mathrm{GeV}/c^2$

End-point + Cross-section $\rightarrow \Delta(M_{\tilde{\chi}_1^0}) = 1.7\mathrm{GeV}/c^2$

Also: τ polarisation in $\tilde{\tau}_1$ decays

$\Delta(\mathcal{P}_\tau)/\mathcal{P}_\tau = 9\ \%$.

Outlook & Conclusions

- Study best method to analyse spectra, eg
  - Optimal statistic for clean signals.
- Specific reconstruction methods for e, μ, and τ.
- Make a coherent SGV study of all channels, at all E_{CMS} stages.
  - Also channels not studied in SPS1a'
  - Exploit more complex decay cascades.
- Status:
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  - Need to further study the parameter extraction for L-sleptons (SUSY background).
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Thank You !

BACKUP

BACKUP SLIDES

Observables: Pair-production, two-body decay (less text)

- So, there are two SUSY parameters, and two independent observables in the spectrum.
- Any pair of observables can be chosen, edges, average, standard deviation, width, ...
- Which choice is the best depends on the situation.
- Just a bit of algebra to extract the two SUSY masses.
- Note that if $E_{beam} >> M_X$, there is just one observable (low edge becomes 0, width becomes average/2), so one should not operate too far above threshold !
- Note that there are two decays in each event: two measurements per event.
- Also note that there are not enough measurements to make a constrained fit, even assuming that the two SUSY particles in the two decays are the same: (2 $\times$ 4 unknown components of 4-momentum (=8)) - (total E and p conservation (=4) + 2

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However:

- If the masses are known from other measurements, there are enough constraints.
- Then the events can be completely reconstructed ...
- ... and the angular distributions both in production and decay can be measured.
- From this the spins can be determined, which is essential to determine that what we are seeing is SUSY.

Furthermore:

- Looking at more complicated decays, such as cascade decays, there are enough constraints if some (but not all) masses are known.
- Allows to reconstruct eg. the slepton mass in $\tilde{\chi}^0_2 \to \tilde{\ell}\ell \to \ell\ell\tilde{\chi}^0_1$ if chargino and LSP masses are known.
- Order-of-magnitude better mass resolution.

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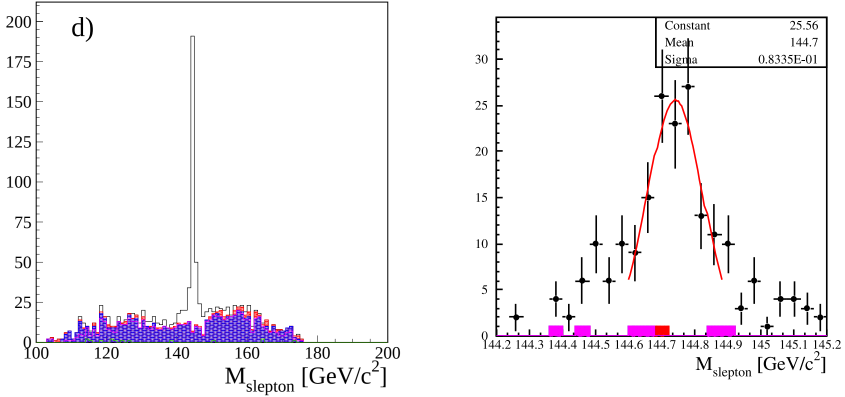

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- The cross-section in $e^+e^- \to XX$ close to threshold depends both on coupling, spin and kinematics (= β).
- The distribution of the angle between the two SM-particles depends on β, in a complicated, but calculable way.
- The cross-section is different for L and R SUSY particles.
- So checking how much the cross-section changes when switching beam-polarisations measures mixing.
- Measure the helicity of the SM particle $\to$ properties of the particles in the decay, ie. in addition to the produced X, also the invisible U. In one case this is possible: In $\tilde{\tau} \to \tau\tilde{\chi}^0_1 \to X\nu_\tau\tilde{\chi}^0_1$.

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Extracting the $\tilde{\tau}$ properties

See Phys.Rev.D82:055016,2010

Use polarisation (0.8,-0.22) to reduce bosino background.

From decay kinematics:

- $M_{\tilde{\tau}}$ from $M_{\tilde{\chi}_1^0}$ and end-point of spectrum = $E_{\tau,max}$.
- Other end-point hidden in $\gamma\gamma$ background:Must get $M_{\tilde{\chi}_1^0}$ from other sources. ($\tilde{\mu}$, $\tilde{e}$, ...)

From cross-section:

- $\sigma_{\tilde{\tau}} = A(\theta_{\tilde{\tau}}, \mathcal{P}_{beam}) \times \beta^3/s$, so
- $M_{\tilde{\tau}} = E_{beam}\sqrt{1-(\sigma s/A)^{2/3}}$: no $M_{\tilde{\chi}_1^0}$!

From decay spectra:

- $\mathcal{P}_{\tau}$ from exclusive decay-mode(s): handle on mixing angles $\theta_{\tilde{\tau}}$ and $\theta_{\tilde{\chi}_1^0}$

Topology selection

Take over SPS1a' $\tilde{\tau}$ analysis principle

$\tilde{\ell}$ properties:

- Only two particles (possibly τ:s:s) in the final state.
- Large missing energy and momentum.
- High Acolinearity, with little correlation to the energy of the τ decay-products.
- Central production.
- No forward-backward asymmetry.

+ anti $\gamma\gamma$ cuts.

Select this by:

- Exactly two jets.
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- $\tilde{\tau}_1$:
  - $(E_{jet1} + E_{jet2}) \sin\theta_{acop} < 30$ GeV.
- $\tilde{\tau}_2$:
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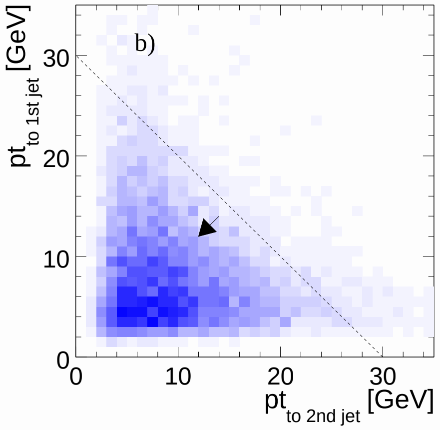
  - Cut on Signal-SM LR of $f(q_{jet1} \cos\theta_{jet1}, q_{jet2} \cos\theta_{jet2})$

Efficiency 15 (22) %



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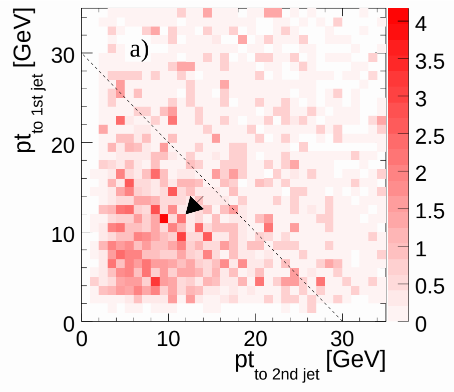

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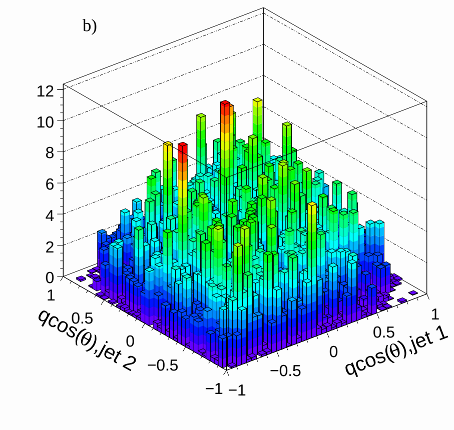

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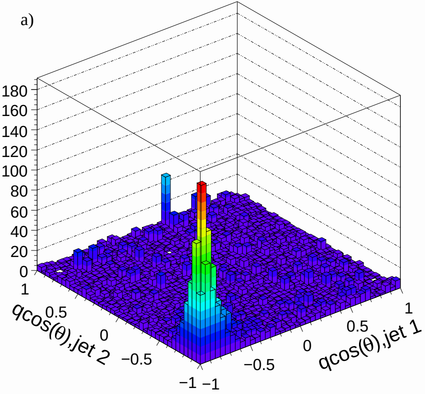

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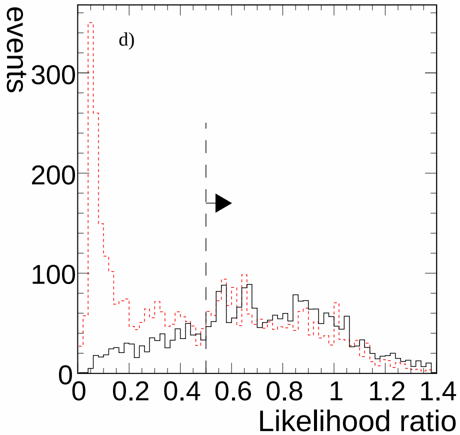

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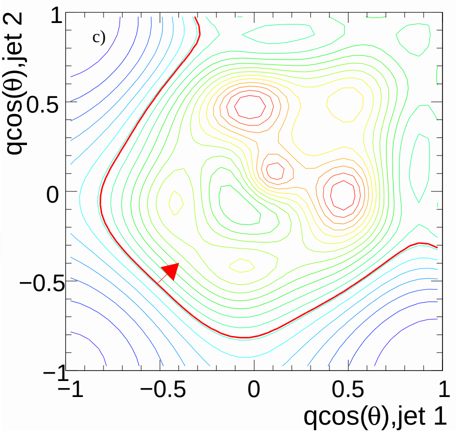

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$\tilde{\mu}$ channels

Use “normal” polarisation (-0.8,0.22).

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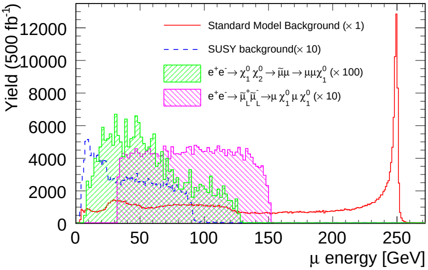
- $\tilde{\chi}^0_1\tilde{\chi}^0_2 \rightarrow \mu\tilde{\mu}_R\tilde{\chi}^0_1 \rightarrow \mu\mu\tilde{\chi}^0_1\tilde{\chi}^0_1$

- Momentum of μ:s
- E_{miss}
- $M_{\mu\mu}$



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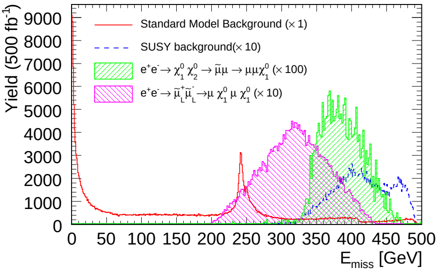

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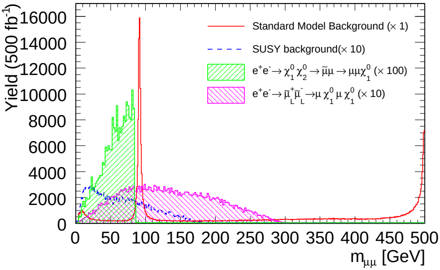


$\tilde{\mu}_L \tilde{\mu}_L$

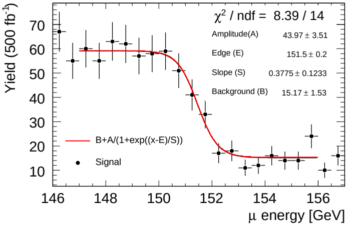
Selections

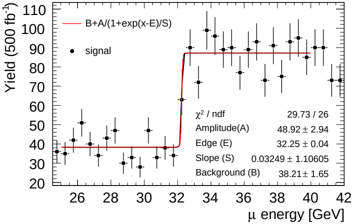
- $\theta_{missingp} \in [0.1\pi; 0.9\pi]$
- $E_{miss} \in [200, 430]\mathrm{GeV}$
- $M_{\mu\mu} \notin [80.100]\mathrm{GeV}$ and > 30 GeV/c^2

Masses from edges. Beam-energy spread dominates error.

$\Delta(M_{\tilde{\chi}^0_1}) = 920\mathrm{MeV}/c^2$

$\Delta(M_{\tilde{\mu}_L}) = 100\mathrm{MeV}/c^2$





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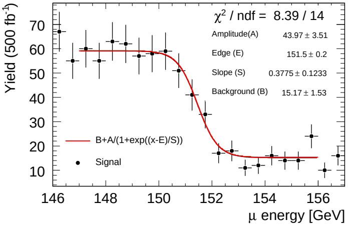

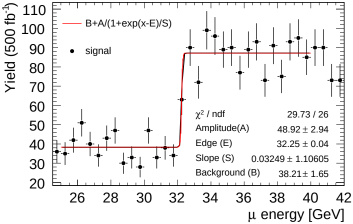

$\tilde{\chi}_1^0\ \tilde{\chi}_2^0$

Selections

- $\theta_{missingp} \in [0.2\pi; 0.8\pi]$
- $p_{Tmiss} > 40\mathrm{GeV}/c$
- β of μ system > 0.6.
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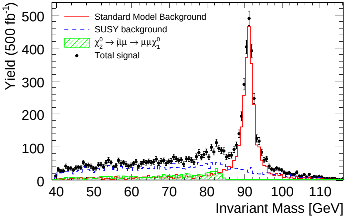

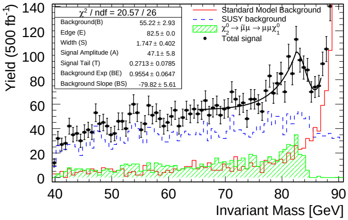

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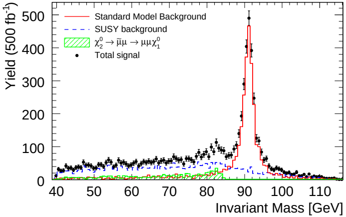

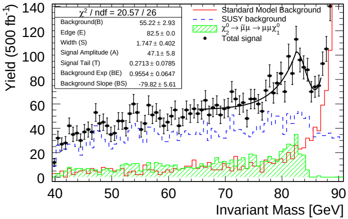

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From these spectra, we can estimate $M_{\tilde{\mathrm{e}}_{\mathrm{R}}}$, $M_{\tilde{\mu}_{\mathrm{R}}}$ and $M_{\tilde{\chi}^0_1}$ to < 1 GeV.

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So: Next step is $M_{\tilde{\mu}_{\mathrm{R}}}$ from threshold:

- 10 points, 10 fb^{-1}/point.
- Luminousity $\propto E_{CMS}$, so this is $\Leftrightarrow$ 170 fb^{-1} @ E_{CMS}=500 GeV.

Error on $M_{\tilde{\mu}_{\mathrm{R}}}$ = 197 MeV

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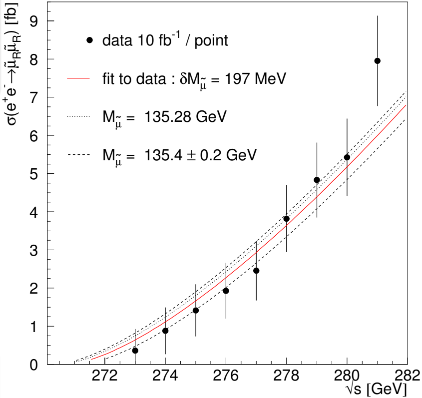

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