SUSY precission studies at the ILC
- the rich STCx model

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Outline

1. Outline
2. Studying SUSY in rich models
3. A bench-mark point
   - STC4 @ 500 GeV
4. Outlook & Conclusions

Aim of the study

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

- Easy - compared to things like Higgsinos only, WIMP only: Lots to see.
- Hard - compared to things like Higgsinos 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 approximate 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.

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SUSY signatures and backgrounds

What we look for and like to measure is:

- NLSP pairs ⇔ Missing energy and momentum + pairs of the SM partner ($\tilde{\tau}_1$ gives τ, $\tilde{\mathrm{e}}$ gives e, $\tilde{\mathrm{t}}$ gives t gives jet, ...)
  - Note:
    - Amount of missing stuff might span a wide range: Eg. small mass-difference between heavy sparticles gives large missing E, but little missing p.
    - If NLSP is a bosino, SM partner is a IVB, possibly far off-shell. At small mass differences, the set of SM particles might be non-obvious.
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  - $WW \to \ell\nu\ell\nu$
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- Fake missing energy + pair of SM-particles = $\gamma\gamma$ processes, ISR, single IVB.
  - $\mathrm{e^+e^-} \to e^+e^-\gamma\gamma \to e^+e^-f\bar{f}$, 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)	

Example: STC4

STC4-8

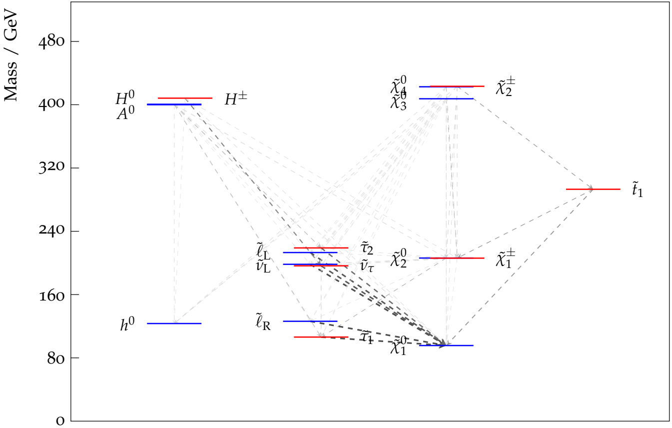
- 11 parameters.
- Separate gluino
- Higgs, un-coloured, and coloured scalar parameters separate

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.)

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 $\tilde{e}_R$or $\tilde{\mu}_R$: :$E_{l,min} = 7.3\ \mathrm{GeV}$, $E_{l,max} = 99.2\ \mathrm{GeV}$: Neither $\gamma\gamma$ nor $WW \rightarrow l\nu l\nu$ background severe.
- For pol=(1,-1): $\sigma(\tilde{e}_R\tilde{e}_R)$ = 1.3 pb !
- $\tilde{\tau}$ NLSP $\rightarrow$ τ: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 ($\tilde{\mathrm{e}}_{\mathrm{R}}, \tilde{\mathrm{e}}_{\mathrm{L}}, \tilde{\mu}_{\mathrm{R}}, \tilde{\mu}_{\mathrm{L}}, \tilde{\tau}_1$).
- Next step: specific selections for $\tilde{\mathrm{e}}_{\mathrm{R}}$ and $\tilde{\mu}_{\mathrm{R}}$, for $\tilde{\mathrm{e}}_{\mathrm{L}}$ and $\tilde{\mu}_{\mathrm{L}}$, and for $\tilde{\tau}_1$.
- Last step: add particle id to separate $\tilde{\mathrm{e}}$ and $\tilde{\mu}$, special cuts for $\tilde{\tau}_1$.
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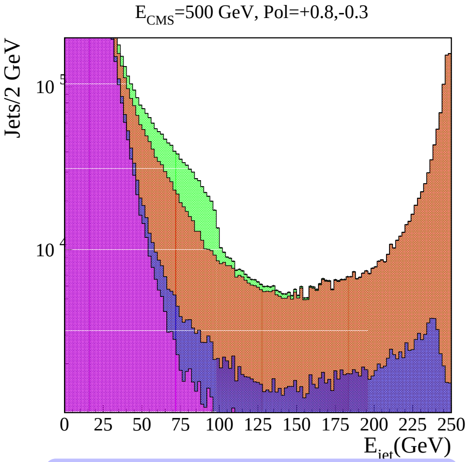
STC4 global

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 early discovery: $\tilde{e}_R$

Early discovery channel:
crossection in the pb-range.

- Few simple cuts.
- Simple observable: E_{vis}: Peak and width gives $M_{\tilde{e}_R}$ and $M_{\tilde{\chi}^0_1}$.
- See the signal appearing after
  - 1 fb^{-1}
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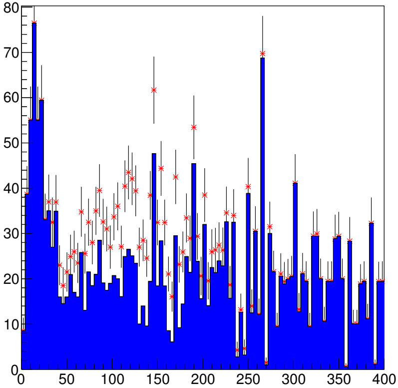
Visible Energy @ 1 fb-1



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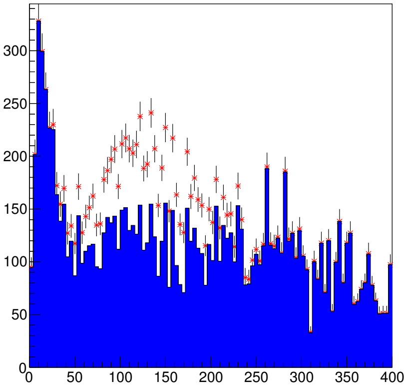
Visible Energy @ 5 fb-1



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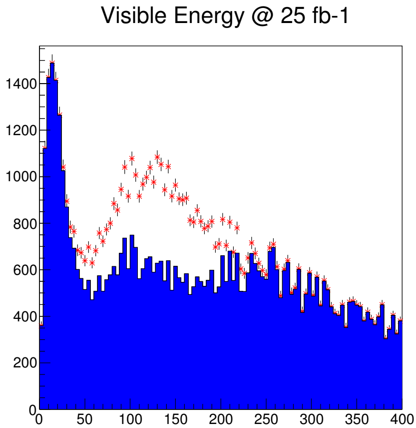

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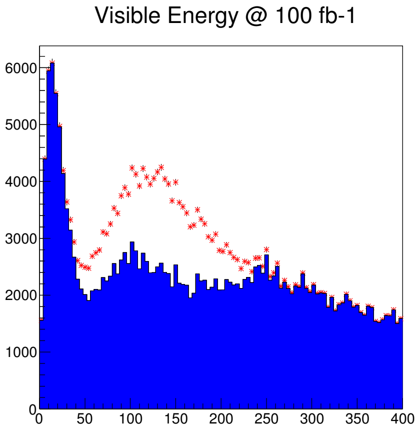

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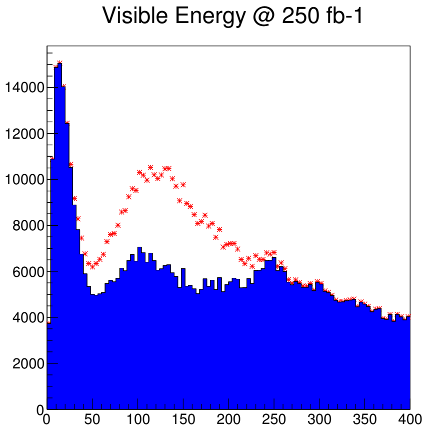

STC4 sleptons @ 500 GeV: $\tilde{\mathrm{e}}, \tilde{\mu}$

- Selections for $\tilde{\mu}$ and $\tilde{\mathrm{e}}$:
  - 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%...
- ... or beam-pol -80%,30%.
- Further selections for L (LR):
  - $q_{jet} \cos\theta_{jet}$
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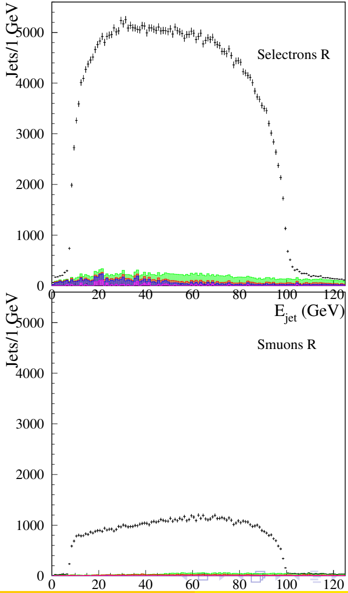

STC4 sleptons @ 500 GeV:$\tilde{e}$, $\tilde{\mu}$

- Selections for $\tilde{\mu}$ and $\tilde{e}$:
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  - Tag and probe, ie. accept one jet if the other is “in the box”.
- Further selections for R:
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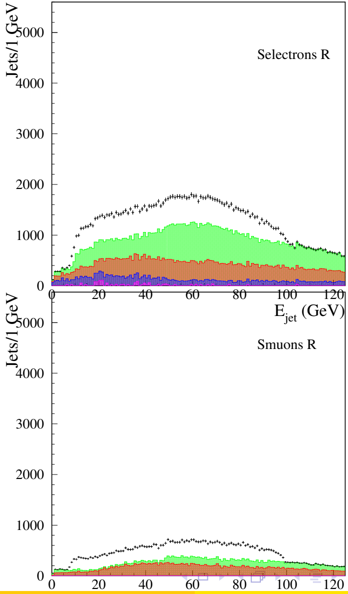

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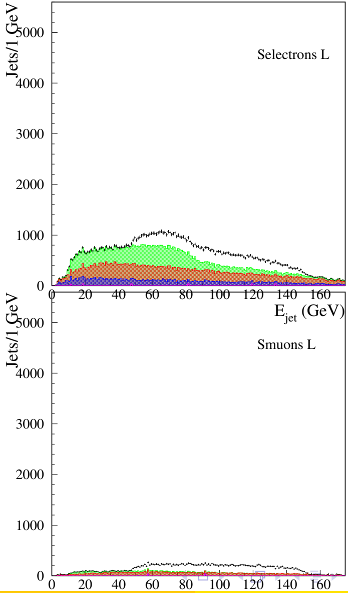

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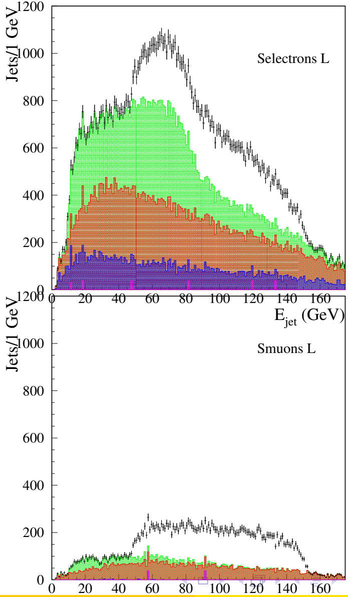

$\tilde{\mu}_R$ threshold scan

From these spectra, we can estimate $M_{\tilde{e}_R}$, $M_{\tilde{\mu}_R}$ and $M_{\tilde{\chi}_1^0}$ to < 0.5 GeV.

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

Error on $M_{\tilde{\mu}_R}$ = 197 MeV $\Rightarrow$ more studies needed to see if the contimuum can match this.

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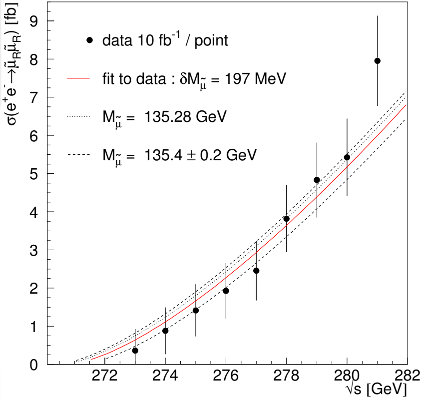

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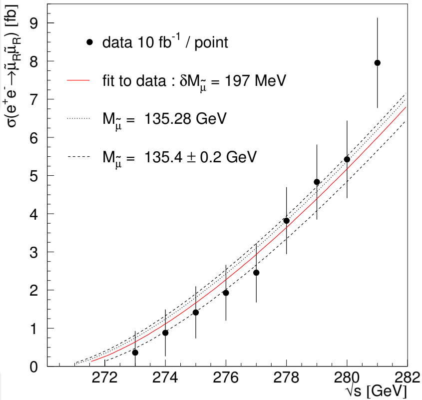
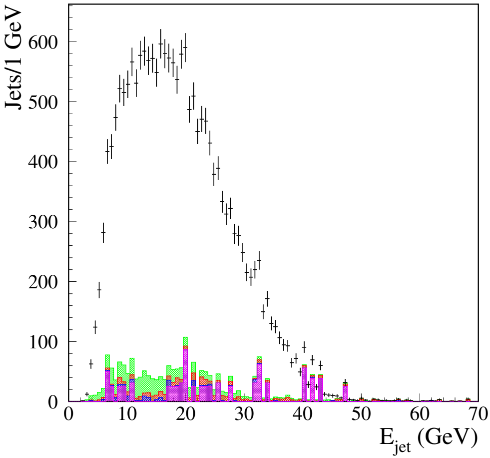


STC4 sleptons @ 500 GeV: $\tilde{\tau}_1$

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.
- Anit-$\gamma\gamma$ likelihood.



Fitting the $\tilde{\tau}$ mass (SPS1a')

Results for old analysis of SPS1a' (See Phys.Rev.D82:055016,2010).

- 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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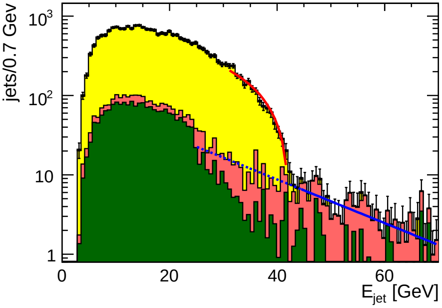

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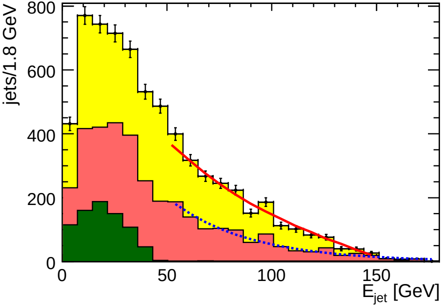

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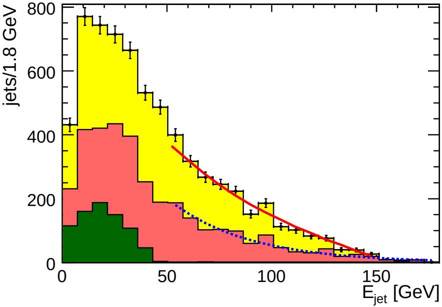

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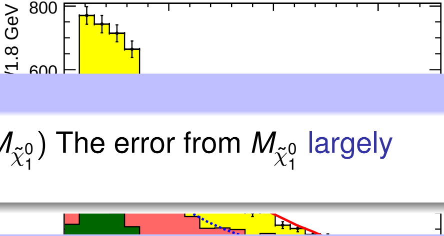

Results for $\tilde{\tau}_1$

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

Results for $\tilde{\tau}_2$

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

- Fit line to (data-background fit).

Fitting the $\tilde{\tau}$ mass (SPS1a')

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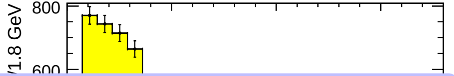

Results from cross-section for $\tilde{\tau}_1$

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

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 $\rightarrow \Delta(M_{\tilde{\chi}^0_1}) = 1.7\mathrm{GeV}/c^2$

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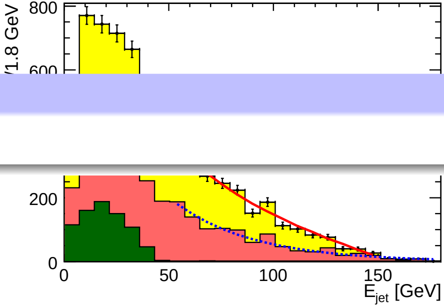

Also: τ polarisation in $\tilde{\tau}_1$ decays

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

Outlook & Conclusions

- Study best method to analyse spectra, eg
  - edge detection in noisy spectra with methods borrowed from image processing (S. Caiazza thesis).
  - 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.
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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 $\tilde{\chi}_2^0 \to \tilde{\ell}\ell \to \ell\ell\tilde{\chi}_1^0$ if chargino and LSP masses are known.
- Order-of-magnitude better mass resolution.

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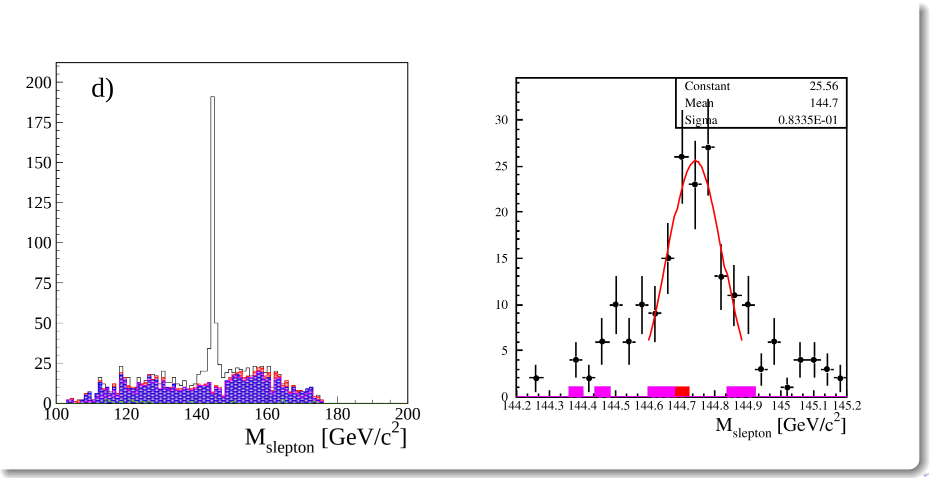

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Observables

But this is not all !

- The cross-section in $\mathrm{e^+e^-} \rightarrow XX$ 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 $\rightarrow$ 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 $\tilde{\tau} \rightarrow \tau\tilde{\chi}^0_1 \rightarrow X\nu_\tau\tilde{\chi}^0_1$.

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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. ($\tilde{\mu}$, $\tilde{\mathrm{e}}$, ...)

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.
- $N_{ch} < 10$
- Vanishing total charge.
- Charge of each jet = $\pm$ 1,
- $M_{jet} < 2.5\ \mathrm{GeV}/c^2$,
- E_{vis} significantly less than E_{CMS}.
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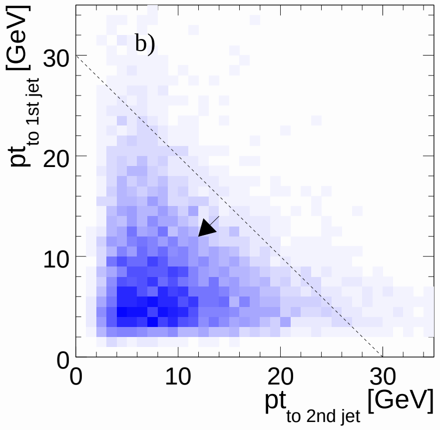
$\tilde{\tau}_1$ and $\tilde{\tau}_2$ further selections

- $\tilde{\tau}_1$:
  - $(E_{jet1} + E_{jet2}) \sin\theta_{acop} < 30$ GeV.
- $\tilde{\tau}_2$:
  - Other side jet not e or μ
  - Most energetic jet not e or μ
  - Cut on Signal-SM LR of $f(q_{jet1} \cos\theta_{jet1}, q_{jet2} \cos\theta_{jet2})$

Efficiency 15 (22) %



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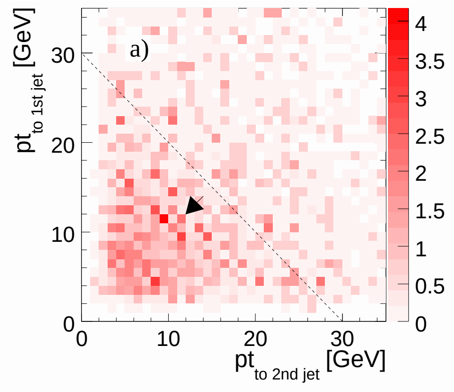

$\tilde{\tau}_1$ and $\tilde{\tau}_2$ further selections

- $\tilde{\tau}_1$:
  - $(E_{jet1} + E_{jet2}) \sin\theta_{acop} < 30$ GeV.
- $\tilde{\tau}_2$:
  - Other side jet not e or μ
  - Most energetic jet not e or μ
  - Cut on Signal-SM LR of $f(q_{jet1} \cos\theta_{jet1}, q_{jet2} \cos\theta_{jet2})$

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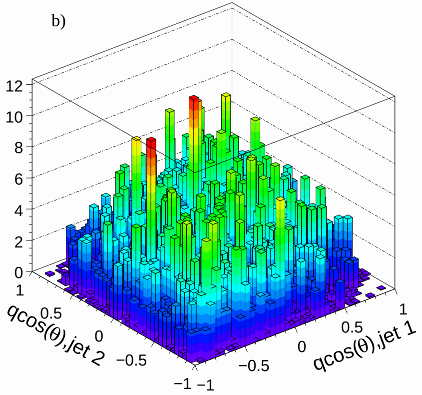

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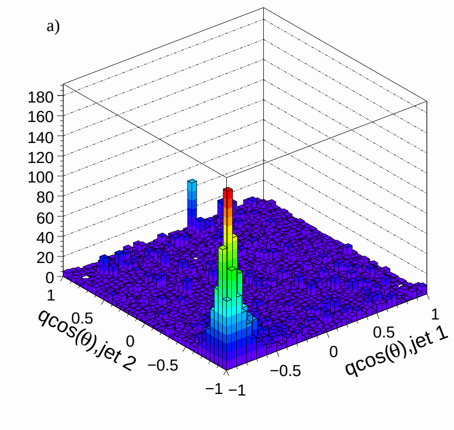

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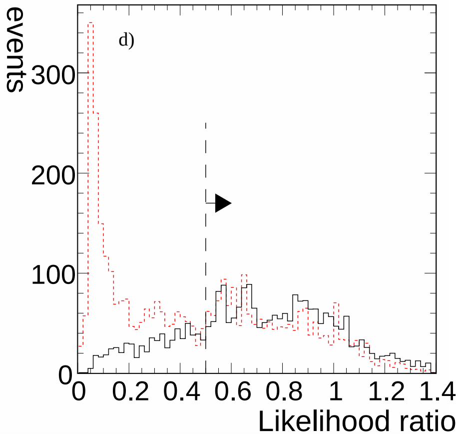

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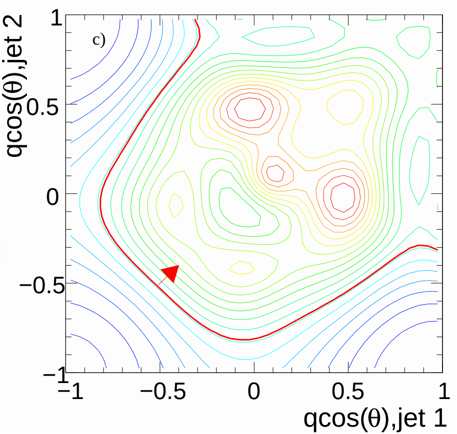

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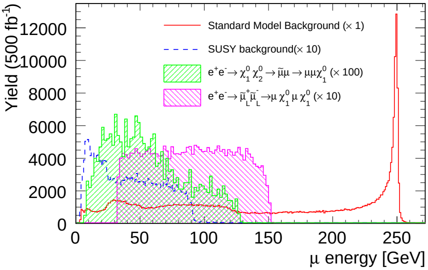
Efficiency 15 (22) %

$\tilde{\mu}$ channels

Use "normal" polarisation (-0.8,0.22).

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

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



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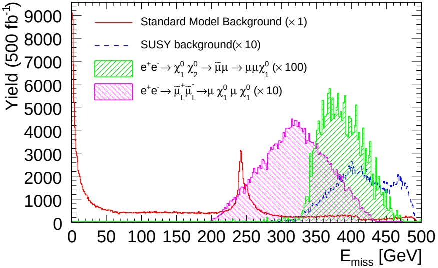

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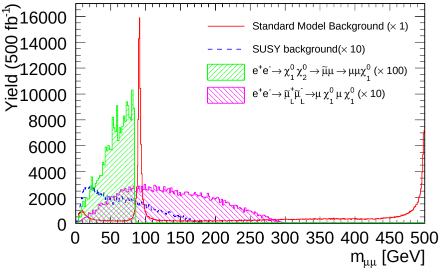


$\tilde{\mu}_L \tilde{\mu}_L$

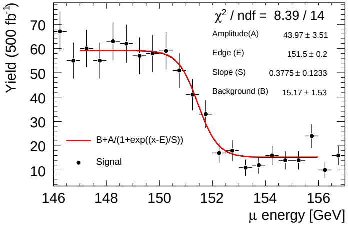
Selections

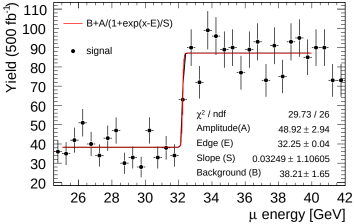
- $\theta_{missingp} \in [0.1\pi; 0.9\pi]$
- $E_{miss} \in [200, 430]\mathrm{GeV}$
- $M_{\mu\mu} \notin [80.100]\mathrm{GeV}$ and > 30 GeV/c^2

Masses from edges. Beam-energy spread dominates error.

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

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





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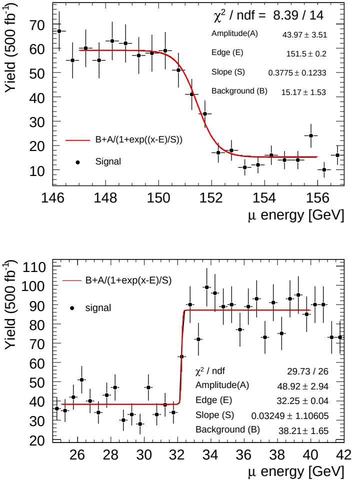


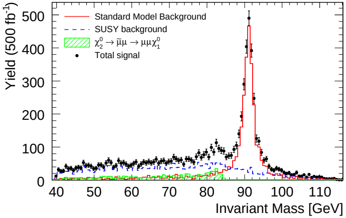
$\tilde{\chi}_1^0\ \tilde{\chi}_2^0$

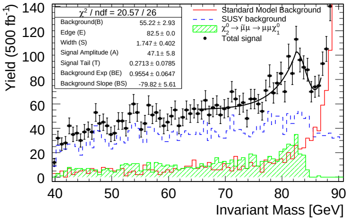
Selections

- $\theta_{missingp} \in [0.2\pi; 0.8\pi]$
- $p_{Tmiss} > 40\mathrm{GeV}/c$
- β of μ system > 0.6.
- $E_{miss} \in [355, 395]\mathrm{GeV}$

Masses from edges. Beam-energy spread dominates error.

$\Delta(M_{\tilde{\chi}_2^0}) = 1.38\mathrm{GeV}/c^2$





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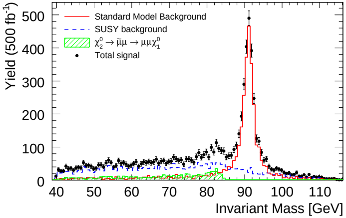

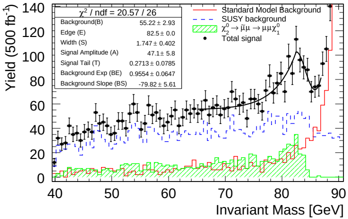

$\tilde{\mu}_R$ threshold scan

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

$\tilde{\mu}_R$ threshold scan

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

So: Next step is $M_{\tilde{\mu}_R}$ 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 $M_{\tilde{\mu}_R}$ = 197 MeV

$\tilde{\mu}_R$ threshold scan

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

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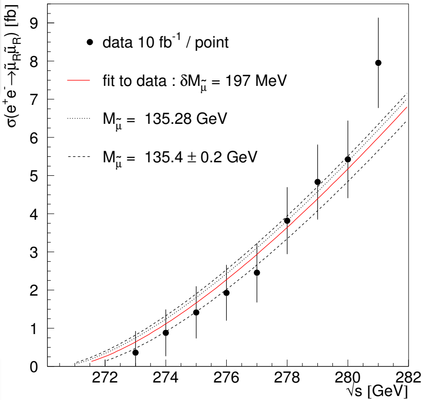

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