SUSY precission studies at the ILC
- the experimental angle

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LCWS, Tokyo, Japan, November 2013

Outline

SUSY, as an experimentalist sees it

What does SUSY look like experimentally ?
What are the problems to face ?

Generically:

- $e^+e^- \rightarrow \tilde{X}\bar{\tilde{X}} \rightarrow X\bar{X}\tilde{Y}\bar{\tilde{Y}}$
- $\tilde{Y}$ might be stable, or further decay, $\tilde{Y} \rightarrow Y\tilde{U}$.
- Finally, one ends up with SM particles, and a lightest SUSY particle, the LSP.

- If R-parity (RP) is conserved, the LSP is stable. From cosmology and cosmic rays, this particle must be neutral and un-coloured.
- Ie.: Experimentally, it's like a heavy "neutrino".

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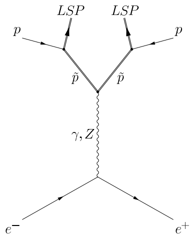

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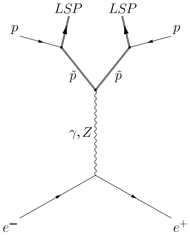

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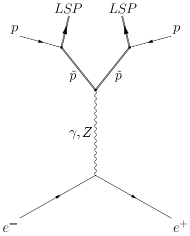

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SUSY signatures

Therefore:

- Conserved RP : Missing energy from the LSP, particle id of the SM products.
- Violated RP (RPV) : LSP *can* be charged and/or coloured, as the cosmological arguments evaporates. Odd signatures either a log-lived LSP, or an LSP that decays in the detector. *Won't talk about this*.

Furthermore:

- Amount of missing energy very important.
- Depends on the mass-difference between the last SUSY particle in the chain and the LSP.
- There is always an NLSP (Next to Lightest SUSY Particle), which is special:
  - It can only decay to it's SM-partner and the LSP.
  - It can be pair-produced.

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So, 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, $\tilde{e}$ gives e, $\tilde{t}$ 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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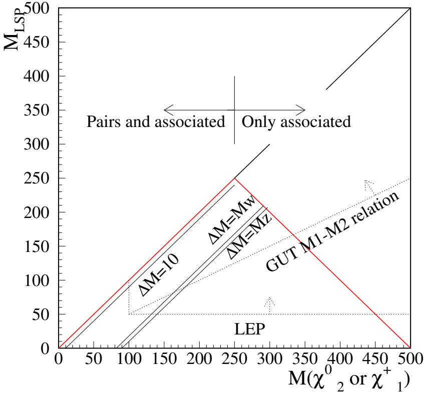
Bosino signatures

Depending on order of μ, M_1, and M_2, and on GUT-scale U(1)$\otimes$SU(2) mass-unification:

- $\mu << M_1, M_2$:
  - LSP and NLSP both higgsino, very low ΔM.
- $M_2 < M_1 << \mu$:
  - LSP Wino, NLSP is $\tilde{\chi}_1^{\pm}$, and is close.
- $M_1 < M_2 << \mu$:
  - LSP Bino, NLSP is near degenrate $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$.
- If GUT $M_1 - M_2$ relation, $\Delta M < M_{LSP}$.



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

- 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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So, suppose we have observed SUSY. What kind of numbers can we extract from the data ?

- Two-body decays: spectra w/ end-points
  - Function of the masses and E_{CMS}.
- Cross-section in continuum
  - Function of mass of produced sparticle , it's mixing, and of E_{CMS} and beam polarisation.
- Angular distribution of seen stuff
  - Function of sparticle spin, mass, s vs. t-channel and E_{CMS}.
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- Differential cross-section
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The spectrum of E'_Y has end-points the rectangular distribution $E_Y \in [\frac{E_{Beam}}{2}\left(1-(M_U/M_X)^2\right)(1-\beta), \frac{E_{Beam}}{2}\left(1-(M_U/M_X)^2\right)(1+\beta)]$.

$\beta = \sqrt{1-\left(\frac{M_X}{E_{Beam}}\right)^2}$

If Y is a sfremion or a neutralino, in addition the spectrum is flat between the end-points. Then:

- Average is $\frac{E_{Beam}}{2}\left(1-(M_U/M_X)^2\right)$,
- the width is $E_{Beam}\left(1-(M_U/M_X)^2\right)\beta$;
- the standard deviation is the width divided by $\sqrt{12}$.

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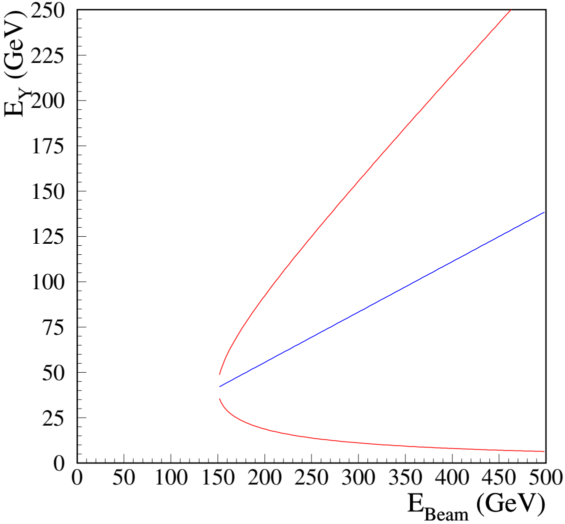
Graphically, for M_X = 150 GeV, M_U = 100 GeV.



Observables: Pair-production, two-body decay

- 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: (2×4 unknown components of 4-momentum (=8)) - (total E and p conservation (=4) + 2 equal-mass constraints) = 2 remaining unknowns.

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- 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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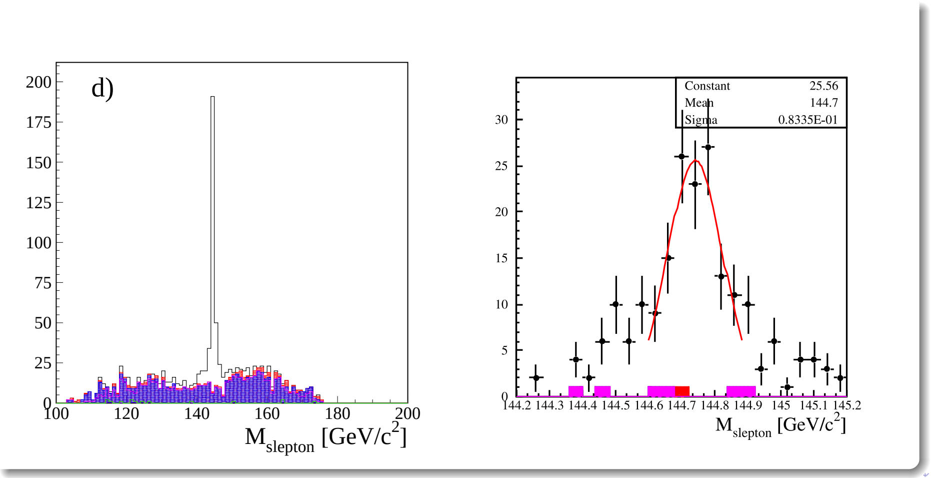

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- The cross-section in $e^+e^- \to XX$ close to threshold depends both on coupling, spin and kinematics (= β).
- The distribution of the angle between the two SM-particles depends on β, in a complicated, but calculable way.
- The cross-section is different 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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Example: SPS1a'/STC4

(See also D. Krücker's talk on Tuesday)

STC4-8

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

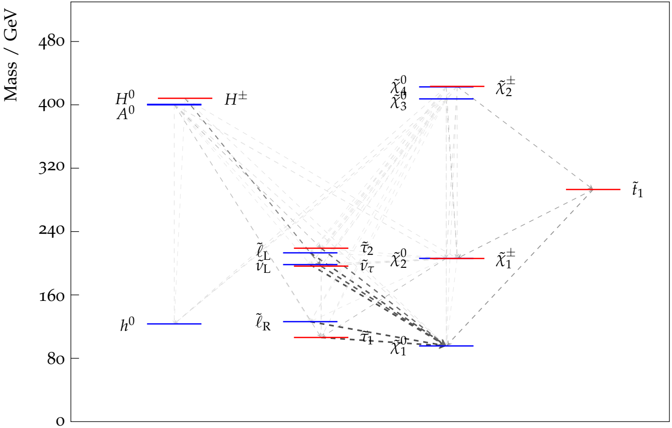
Parameters chosen to deliver all constraints (LHC, LEP, cosmology, low energy).

At E_{CMS} = 500 GeV:

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

(For STC4-8, see H. Baer, J. List, arXiv:1307:0782. For SPS1a', see J. List, P. Bechtle, P. Schade, M.B., PRD 82,no5 (2010), arXiv:0908.0876)

STC4 mass-spectrum



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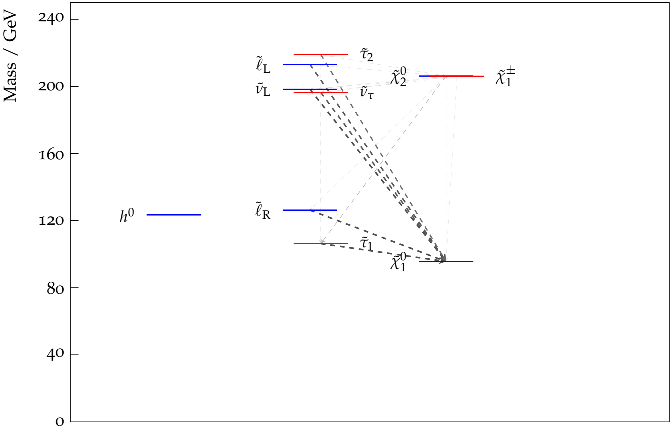

Channels and observables at 250, 350 and 500 GeV

Channel	Threshold	Available at	Can give
$\tilde{\tau}_1\tilde{\tau}_1$	212	250	$M_{\tilde{\tau}_1}$, $\tilde{\tau}_1$ nature
$\tilde{\mu}_R\tilde{\mu}_R$	252	250+	+ $M_{\tilde{\mu}_R}$, $M_{\tilde{\chi}^0_1}$, $\tilde{\mu}_R$ nature, τ polarisation
$\tilde{e}_R\tilde{e}_R$	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	8 % 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 SPS1a'/STC4

- In SPS1a' and the STC points, the $\tilde{\tau}_1$ is the NLSP.
- For $\tilde{\tau}_1$: $E_{\tau,min} = 2.6\ \mathrm{GeV}$, $E_{\tau,max} = 42.5\ \mathrm{GeV}$:
  $\gamma\gamma - background \Leftrightarrow pairs - background$.
- For $\tilde{\tau}_2$: :$E_{\tau,min} = 35.0\ \mathrm{GeV}$, $E_{\tau,max} = 152.2\ \mathrm{GeV}$:
  $WW \rightarrow l\nu l\nu - background \Leftrightarrow Polarisation$.
- $\tilde{\tau}$ 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$\rightarrow \tilde{\tau}$) $>$ 50 %. For pol=(1,-1): $\sigma(\tilde{\chi}^0_2\tilde{\chi}^0_2)$ and $\sigma(\tilde{\chi}^+_1\tilde{\chi}^-_1) \approx 0$.
- For pol=(-1,1): $\sigma(\tilde{\mathrm{e}}_\mathrm{R}\tilde{\mathrm{e}}_\mathrm{R})$ = 1.3 pb !
- For $\tilde{\mathrm{e}}_\mathrm{R}$or $\tilde{\mu}_\mathrm{R}$: :$E_{l,min} = 6.6\ \mathrm{GeV}$, $E_{l,max} = 91.4\ \mathrm{GeV}$: Neither $\gamma\gamma$ nor $WW \rightarrow l\nu l\nu$ background severe.

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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:

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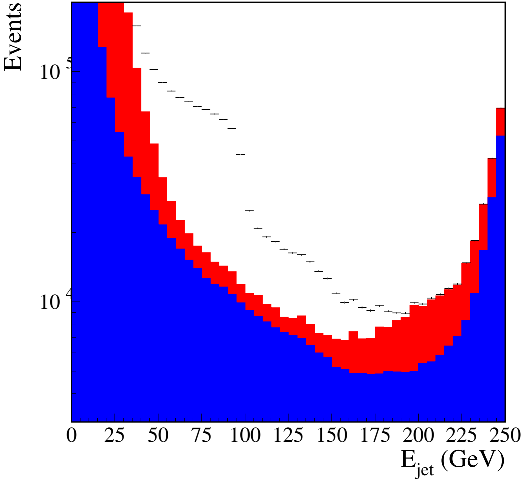

Extracting the $\tilde{\tau}$ properties

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,
- $M_{jet} < 2.5$ GeV/c^2,
- E_{vis} significantly less than E_{CMS}.
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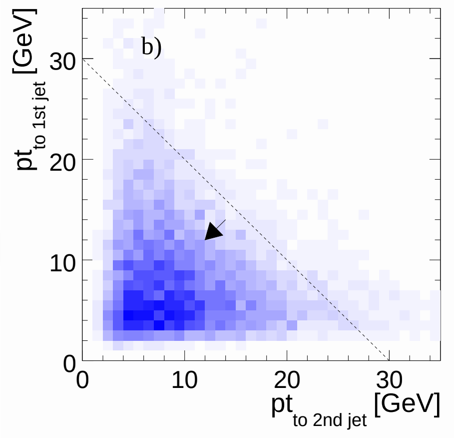
$\tilde{\tau}_1$ and $\tilde{\tau}_2$ further selections

- $\tilde{\tau}_1$:
  - $(E_{jet1} + E_{jet2}) \sin\theta_{acop} < 30$ 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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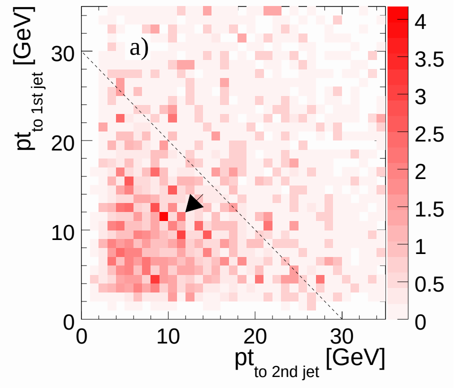

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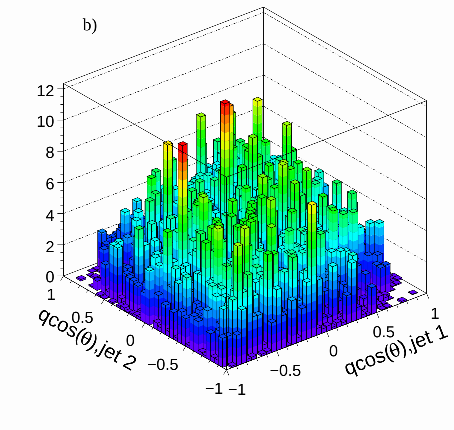

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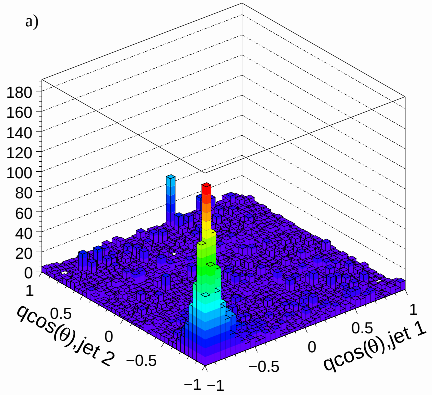

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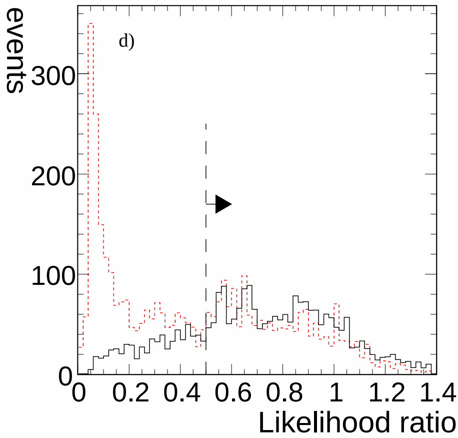

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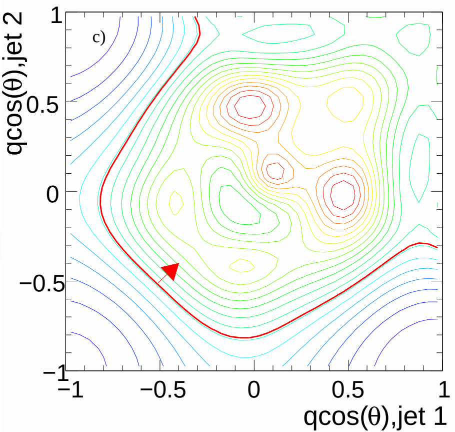

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Fitting the $\tilde{\tau}$ mass

- 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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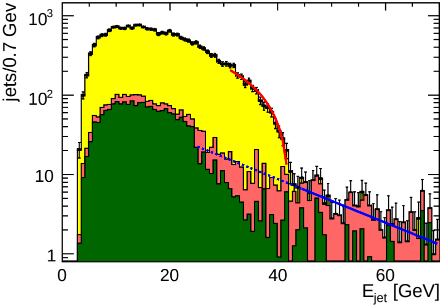

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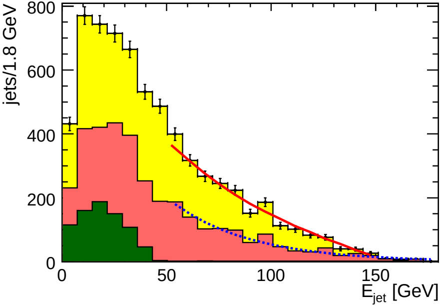

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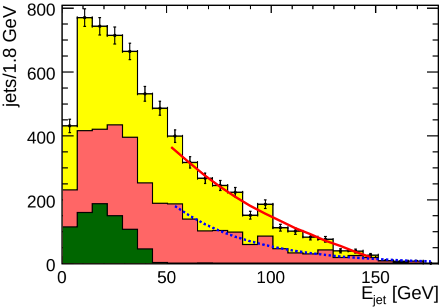

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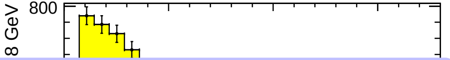

Results for $\tilde{\tau}_1$

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

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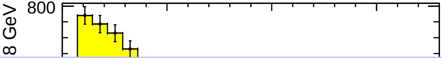
- Background subtraction:
  - $\tilde{\tau}_1$: Important SUSY
  - no SUSY background



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

- Fit line to (data-background fit).

Fitting the $\tilde{\tau}$ mass

- Only the upper end-point is relevant.
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  - $\tilde{\tau}_1$: Important SUSY

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

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

extrapolate.

  - $\tilde{\tau}_2$: $\sim$ no SUSY background above 45 GeV. Take background from SM-only simulation and fit exponential.
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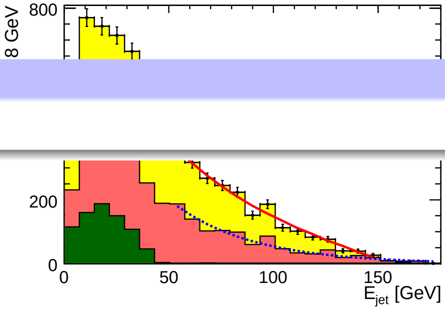
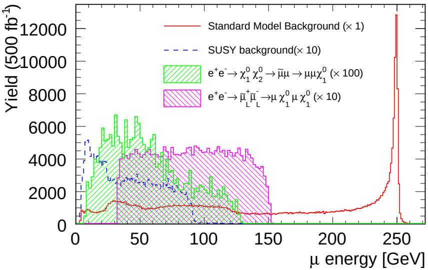


$\tilde{\mu}$ channels

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

- $\tilde{\mu}_{\mathrm{L}}\tilde{\mu}_{\mathrm{L}} \to \mu\mu\tilde{\chi}^0_1\tilde{\chi}^0_1$
- $\tilde{\chi}^0_1\tilde{\chi}^0_2 \to \mu\tilde{\mu}_{\mathrm{R}}\tilde{\chi}^0_1 \to \mu\mu\tilde{\chi}^0_1\tilde{\chi}^0_1$

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



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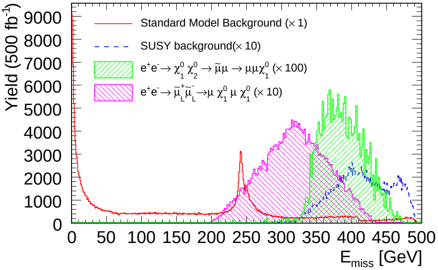

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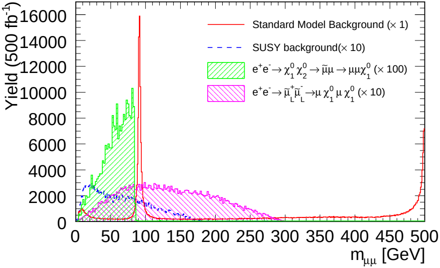


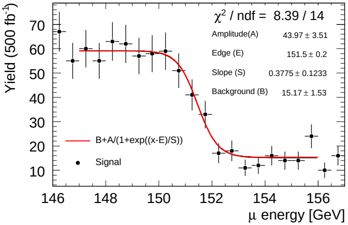
$\tilde{\mu}_L \tilde{\mu}_L$

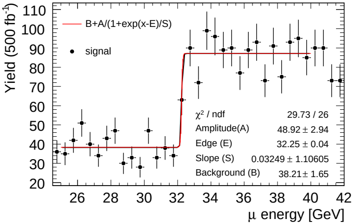
Selections

- $\theta_{missingp} \in [0.1\pi; 0.9\pi]$
- $E_{miss} \in [200, 430]\mathrm{GeV}$
- $M_{\mu\mu} \notin [80.100]\mathrm{GeV}$ 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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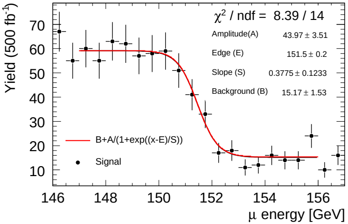
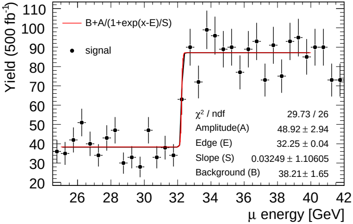




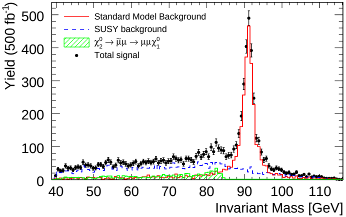
$\tilde{\chi}_1^0 \; \tilde{\chi}_2^0$

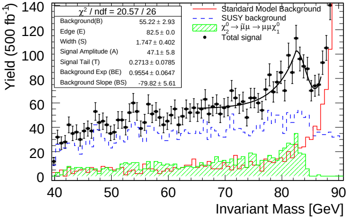
Selections

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

Masses from edges. Beam-energy spread dominates error.

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





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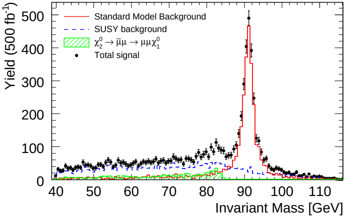

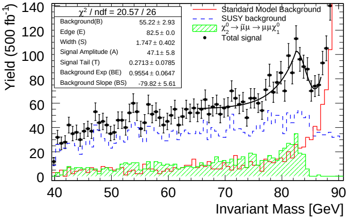

$\tilde{\mu}_R$ threshold scan

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

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

Error on $M_{\tilde{\mu}_R}$ = 197 MeV

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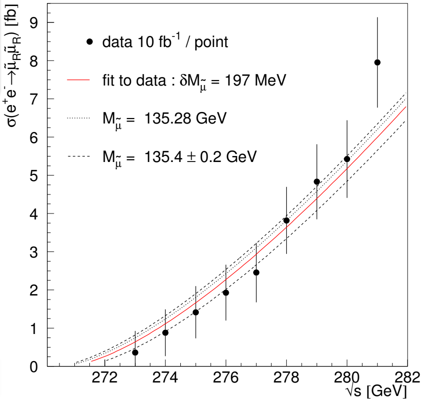

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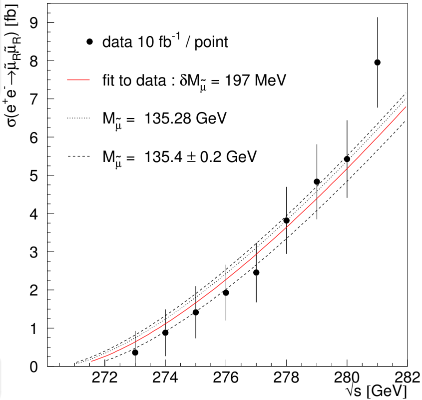

Outlook (STC4)

- Study edge detection in spectra with methods borrowed from image processing.
- Currently being developed for $\tilde{e}_R$ (S. Caiazza thesis). Also adopted to “Point 5” (model with on-shell IVB bosino decays).
- Make a coherent SGV study of all channels, at all E_{CMS} stages.
  - Also channels not studied in SPS1a'
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Conclusions

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- Lepton-collider: Initial state is known.
- Production is EW ⇒
  - Small theoretical uncertainties.
  - No "underpaying event".
  - Low cross-sections also for background.
  - Trigger-less operation, so that even very soft stuff will be on tape.
- Many observables accessible: Spectra, angular distributions, total and differential cross-sections, branching ratios, ...
- Often measurable to per mil level.
- I've shown as an example what can be measured in the STC4 bench-mark. Please check out other cases presented this week:
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