Pinning down the invisible sneutrino at the ILC

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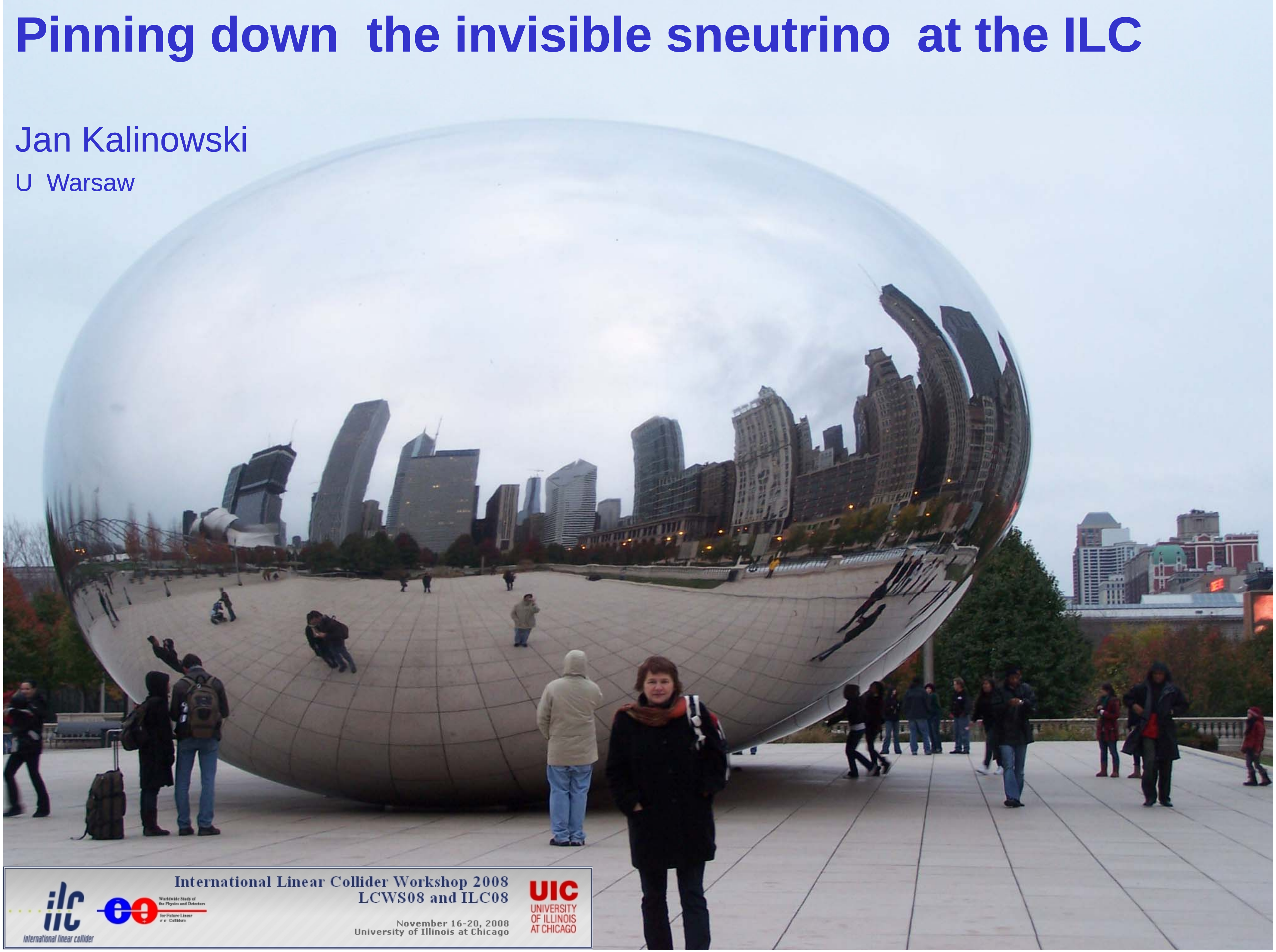

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Outline

- Motivation
- The setup
    - Signal and background processes
    - Imposing cuts
- Results
- Summary and outlook

In collaboration with W. Kilian, J. Reuter, T. Robens, K. Rolbiecki, JHEP10(2008)090

Motivation

Standard way of determining sneutrino mass

Martyn '03

- select $e_L^- e_R^+ \to \tilde{\nu}_e \tilde{\nu}_e \to e^- \tilde{\chi}_1^+ \, e^+ \tilde{\chi}_1^-$ with subsequent $\tilde{\chi}_1^\pm \to q\bar{q}' \, \tilde{\chi}_1^0$
- primary lepton energy spectra => sneutrino and chargino mass
- di-jet invariant mass spectrum => $\tilde{\chi}_1^\pm - \tilde{\chi}_1^0$ mass difference
- for tau-sneutrino more problematic due to ♦ decay

In some scenarios, e.g. SPS1a' $m_{\tilde{\chi}^\pm} > m_{\tilde{\nu}}$

- dominant decay $\tilde{\nu} \to \tilde{\chi}^0 \nu$
- invisible decay products
- can nevertheless 'see' sneutrino in the inverse process

$$\tilde{\chi}^\pm \to \ell^\pm \tilde{\nu}_\ell$$

already exploited by Freitas, Porod Zerwas '05

Setup

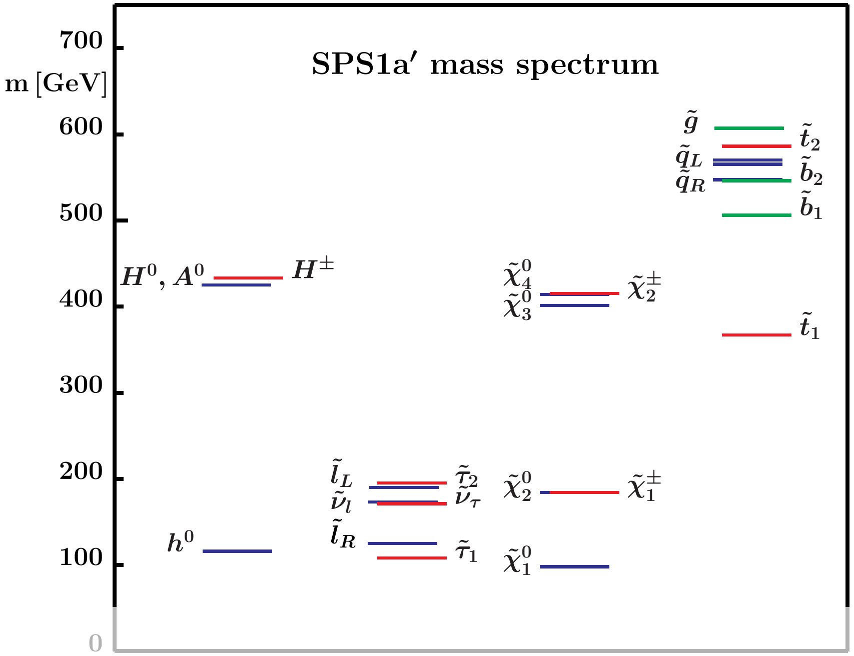
What's new???

- Revisit the analysis using full matrix element for both signal and background
  - ✓ include all interference and off-shell effects
  - ✓ get a handle on multi-particle final states (up to 10 particles)
  - ✓ include all SUSY and SM reducible and irreducible background
- Tools:
  - ✓ Monte Carlo event generator WHIZARD (Kilian, Ohl, Reuter)
  - ✓ matrix element generator O'Mega (Moretti, Ohl, Reuter)
  - ✓ so far LO MC for production+ decay implemented
- Environment
  - ✓ e+e- at E_{CM} = 500 GeV
  - ✓ bremss- and beamstrahlung automatically included

Working scenario: SPS1a'

mSUGRA point:

m_0	70 GeV
$m_{1/2}$	250 GeV
A_0	-300 GeV
$\tan\beta$	10
sign μ	$+$



Parameter	Value	Decay	BR
m_h	116.0 GeV	$\tilde{\chi}_1^+ \to \tilde{\tau}_1^+ \nu_\tau$	53.6 %
m_A	424.9 GeV	$\tilde{\chi}_1^+ \to \tilde{\nu}_\ell \ell^+$	13.3 %
$m_{\tilde{\chi}_1^0}$	97.7 GeV	$\tilde{\chi}_1^+ \to \tilde{\nu}_\tau \tau^+$	18.5 %
$m_{\tilde{\chi}_2^0}$	183.9 GeV	$\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 W^+$	1.3 %
$m_{\tilde{\chi}_1^\pm}$	183.7 GeV	$\tilde{\ell}_R^- \to \tilde{\chi}_1^0 \ell^-$	100.0 %
$m_{\tilde{\chi}_2^\pm}$	415.4 GeV	$\tilde{\ell}_L^- \to \tilde{\chi}_1^0 \ell^-$	92.5 %
$m_{\tilde{\ell}_R}$	125.3 GeV	$\tilde{\ell}_L^- \to \tilde{\chi}_1^- \nu_\ell$	4.9 %
$m_{\tilde{\ell}_L}$	189.9 GeV	$\tilde{\ell}_L^- \to \tilde{\chi}_2^0 \ell^-$	2.6 %
$m_{\tilde{\nu}_\ell}$	172.5 GeV	$\tilde{\chi}_2^0 \to \tilde{\tau}_1^\pm \tau^\mp$	57.8 %
$m_{\tilde{\tau}_1}$	107.9 GeV	$\tilde{\chi}_2^0 \to \tilde{\nu}_\tau \bar{\nu}_\tau$ + cc.	15.2 %
$m_{\tilde{\tau}_2}$	194.9 GeV	$\tilde{\chi}_2^0 \to \tilde{\nu}_\ell \bar{\nu}_\ell$ + cc.	11.1 %
$m_{\tilde{\nu}_\tau}$	170.5 GeV	$\tilde{\chi}_2^0 \to \tilde{\ell}^\pm \ell^\mp$	2.4 %
$\Gamma(\tilde{\chi}_1^\pm)$	77.3 MeV	$\tilde{\tau}_2^- \to \tilde{\chi}_1^0 \tau^-$	86.8%
$\Gamma(\tilde{\nu}_\ell)$	121.5 MeV	$\tilde{\tau}_2^- \to \tilde{\chi}_2^0 \tau^-$	4.6%
$\Gamma(\tilde{\nu}_\tau)$	117.4 MeV	$\tilde{\tau}_2^- \to \tilde{\chi}_1^- \nu_\tau$	8.6%

Signal

Chargino pair production with subsequent leptonic decay

$$e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-$$

$$\tilde{\nu}_\ell \ell^+ \qquad \tilde{\nu}_\ell^* \ell^-$$

- $\sigma(\tilde{\chi}_1^+ \tilde{\chi}_1^-) = 173.6$ fb $\tilde{\chi}_1^+ \rightarrow \tilde{\nu}_\ell \ell^+$,R(
) = 13%
- sneutrino decays invisibly
- final state: two opposite-charge leptons + missing energy
- select leptons of different flavor

Proper signal

$$e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tilde{\nu}_e^* e^- \tilde{\nu}_\mu \mu^+ \rightarrow e^- \mu^+ \bar{\nu}_e \nu_\mu \tilde{\chi}_1^0 \tilde{\chi}_1^0$$

Signature: $e^-\mu^+ + E_{miss}$

Irreducible SUSY processes

$$e^+e^- \to X \to e^-\mu^+\bar{\nu}_e\nu_\mu\tilde{\chi}_1^0\tilde{\chi}_1^0$$

like

- chargino decays to W+neutralino
- single-resonant diagrams
- non-resonant diagrams
- slepton-pair production
- SM decaying to SUSY, ….

Proper:	3.06 fb	(2.50 fb with -strahlung)
6-fermion:	4.69 fb	(3.94 fb with -strahlung)

Signal: proper + irreducible SUSY

SUSY background

- SUSY: different sources - here according to # ♦'s

Process	500 GeV	σ [fb], presel.
SUSY τ Bkgd.	$ee \to \tau\tau\tilde{\chi}_1^0\tilde{\chi}_1^0 \to e\mu\tilde{\chi}_1^0\tilde{\chi}_1^0 4\nu$	4.107(7)
SUSY $\tau\nu$ Bkgd.	$ee \to \tau\tau\tilde{\chi}_1^0\tilde{\chi}_1^0 2\nu \to e\mu\tilde{\chi}_1^0\tilde{\chi}_1^0 6\nu$	3.245(10)
SUSY τe Bkgd.	$ee \to e\tau\bar{\nu}_e\nu_\tau\tilde{\chi}_1^0\tilde{\chi}_1^0 \to e\mu\tilde{\chi}_1^0\tilde{\chi}_1^0 4\nu$	3.691(9)
SUSY $\tau\mu$ Bkgd.	$ee \to \mu\tau\nu_\mu\bar{\nu}_\tau\tilde{\chi}_1^0\tilde{\chi}_1^0 \to e\mu\tilde{\chi}_1^0\tilde{\chi}_1^0 4\nu$	2.617(10)

Compare to

Signal	$ee \to e\mu\bar{\nu}_e\nu_\mu\tilde{\chi}_1^0\tilde{\chi}_1^0$	3.940(8)

Signal / SUSY Bkgd ~ 1 / 3

Preselection:

5^0 cut for the final electron

1^0 cut for particles vanishing in the beam pipe

SM background

- WW, single W, tau pairs

Process	500 GeV	σ [fb], presel.
SM WW Bkgd.	$ee \to e\mu 2\nu$	152.42(25)
SM $e\tau$ Bkgd.	$ee \to e\tau 2\nu \to e\mu 4\nu$	26.522(12)
SM $\mu\tau$ Bkgd.	$ee \to \mu\tau 2\nu \to e\mu 4\nu$	15.569(54)
SM ν Bkgd.	$ee \to e\mu 4\nu$	0.145(1)
SM τ Bkgd.	$ee \to \tau\tau \to e\mu 4\nu$	32.679(98)
SM $\tau\nu$ Bkgd.	$ee \to \tau\tau 2\nu \to e\mu 6\nu$	3.852(10)

- Photon induced: tau pairs, charm pairs, …

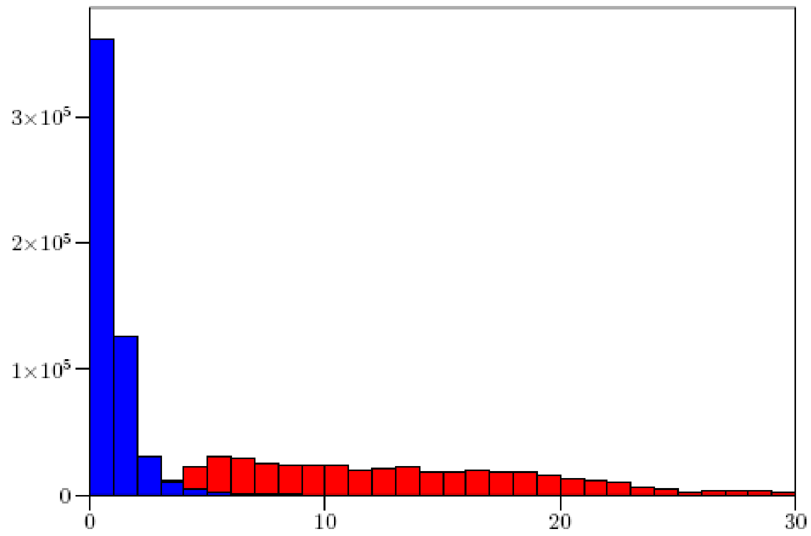
SM $\gamma \to \tau$ Bkgd.	$\gamma^*\gamma^* \to \tau\tau \to e\mu 2\nu$	21392(70)
SM $\gamma \to c$ Bkgd.	$\gamma^*\gamma^* \to c\bar{c} \to e\mu jj 2\nu$	1089(4)
SM $\gamma \to W$ Bkgd.	$\gamma^*\gamma^* \to WW \to e\mu 2\nu$	1.094(6)
SM $\gamma \to \tau\nu_\tau$ Bkgd.	$\gamma^*\gamma^* \to \tau\tau 2\nu \to e\mu 8\nu$	0.077(1)
SM $\gamma \to \ell\tau$ Bkgd.	$\gamma^*\gamma^* \to (e,\mu)\tau 2\nu \to e\mu 4\nu$	0.404(2)

Signal / Bkgd ~ 1 / 10^5

Event selection

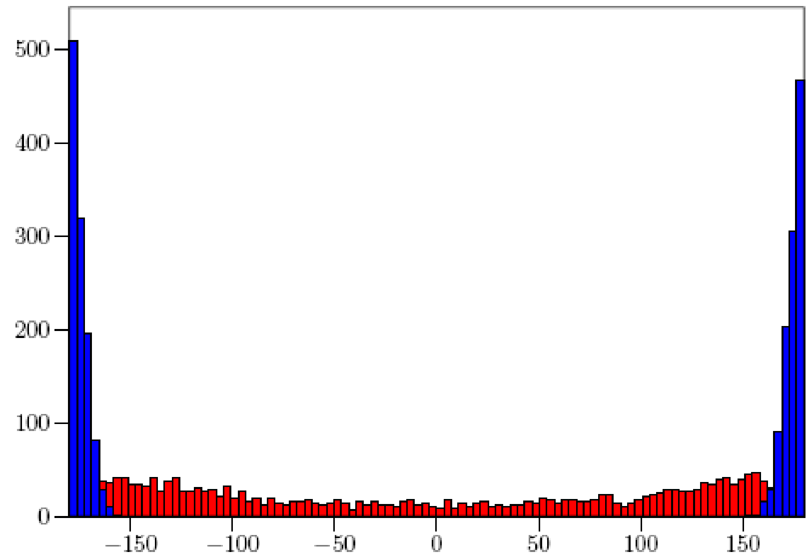
- Many different background processes with different kinematics
- Dominant: photon-induced tau-pair: low p_T, back-to-back

Example: p_T and 👎♐ of signal and ♦♦ background



$p_\perp(e^-)[\mathrm{GeV}]$

cut on $p_\perp$ cuts out 99.58 % of background, 11 % of signal



$\Delta\,\phi$ [deg]

renormalized after $p_\perp$ cuts

cut on $\Delta\phi$ cuts out 99.68 % of background, 25 % of signal

Suppressing the background

Set of cuts:

$$2\text{GeV} \leq p_\perp(e,\mu) \qquad 4\text{GeV} \leq p_\perp(e) + p_\perp(\mu)$$

$$1\text{GeV} \leq E(e,\mu) \leq 40\text{GeV}, \; -150^o \leq \Delta\phi \leq 150^o,$$

$$15^o \leq \theta(e) \leq 155^o, \; 25^o \leq \theta(\mu) \leq 165^o$$

After the cuts:

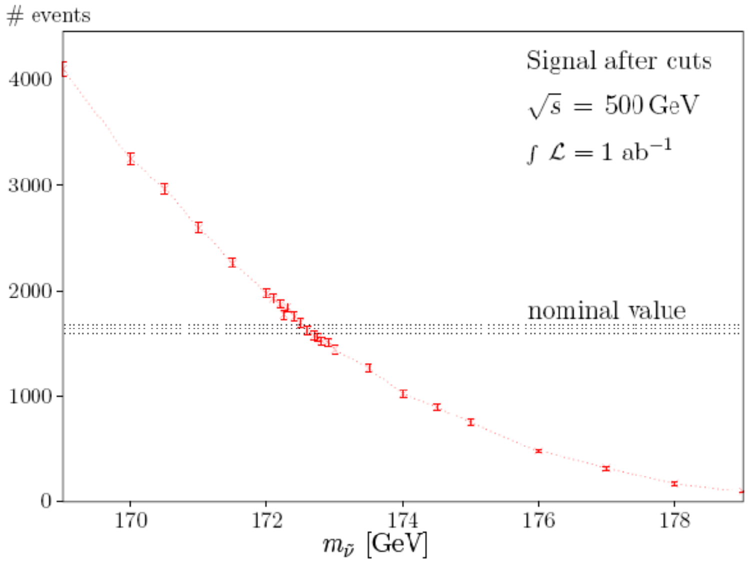
Process	σ [fb], presel.	σ^{cut} [fb]
Signal	3.940(8)	1.639(3)
SUSY τ Bkgd.	4.107(7)	0.978(2)
SUSY $\tau\nu$ Bkgd.	3.245(10)	0.818(3)
SUSY τe Bkgd.	3.691(9)	1.102(8)
SUSY $\tau\mu$ Bkgd.	2.617(10)	0.966(8)
SM WW Bkgd.	152.42(25)	0.736(2)
SM $e\tau$ Bkgd.	26.522(12)	0.317(1)
SM τ Bkgd.	32.679(98)	< 0.001
SM $\gamma \to \tau$ Bkgd.	21392(70)	0.273(2)
SM $\gamma \to c$ Bkgd.	1089(4)	< 0.001

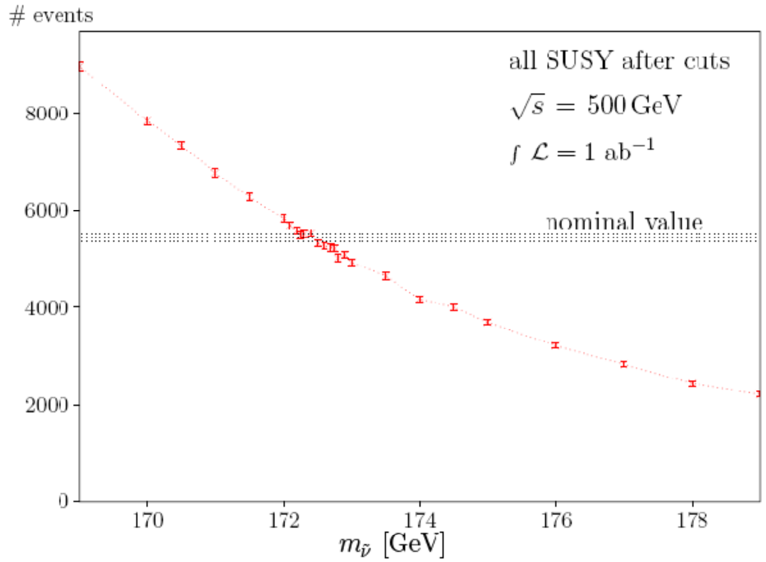
SM almost disappears, SUSY still substantial

Determining the sneutrino mass: 1

- The dependence on the sneutrino mass enters
  - in the production (t-channel exchange)
  - in the decay $\tilde{\chi}_1^+ \to \tilde{\nu}_\ell \ell^+$

For the SPS1a' point strong dependence since $\tilde{\chi}_1^\pm, \tilde{\nu}$ close in mass





$\Longrightarrow \quad m_{\tilde{\nu}} \sim 172.50 \pm 0.75$ GeV

Determining the sneutrino mass: 2

Assuming
a) no beam- and bremsstrahlung
b) on-shell kinematics

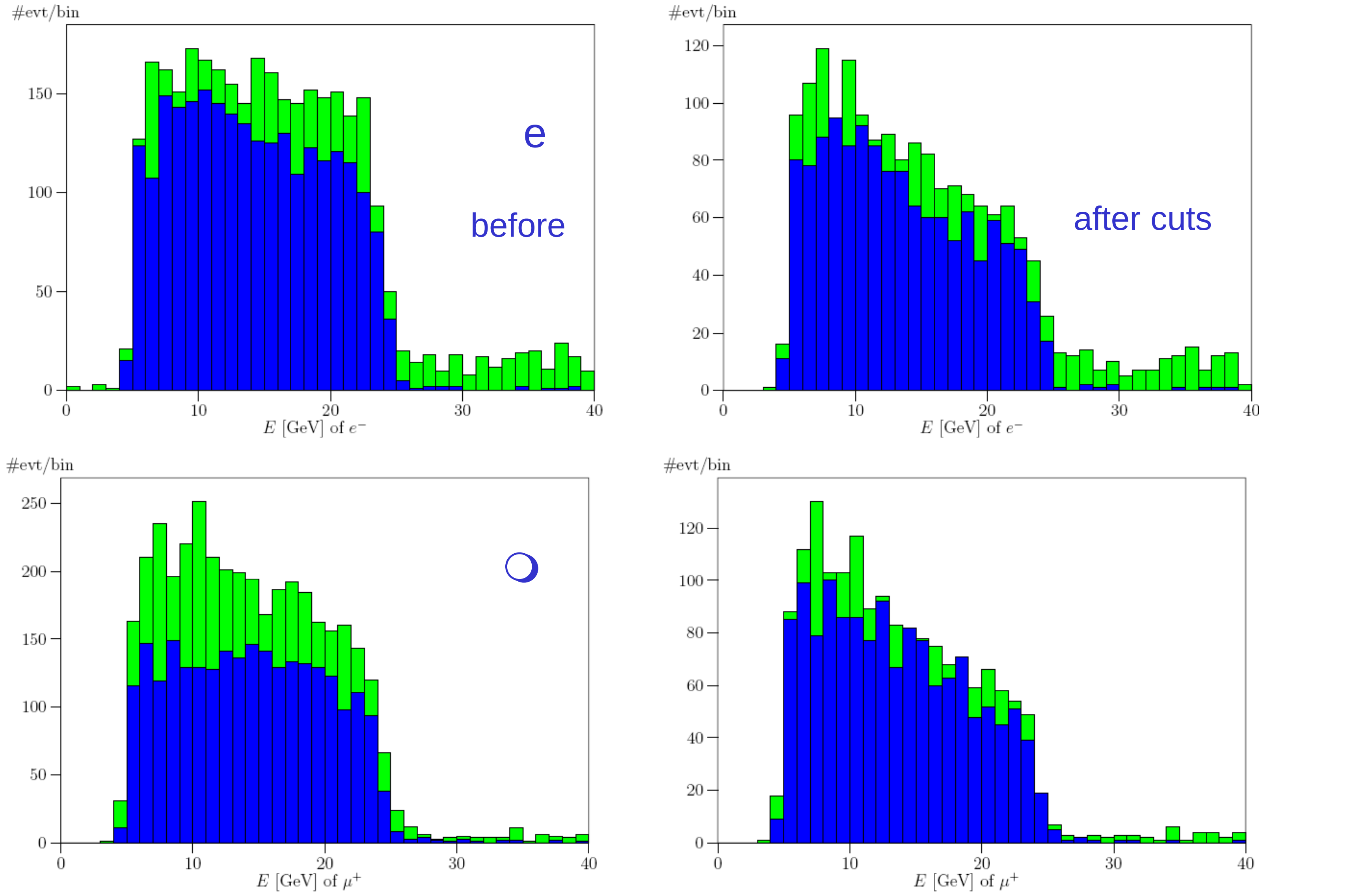
the lepton energy spectrum flat between endpoints E_{min}, E_{max}

$$m_{\tilde{\chi}_1^\pm} = \sqrt{s}\frac{\sqrt{E_{\min}E_{\max}}}{E_{\min}+E_{\max}}\,, \qquad m_{\tilde{\nu}_\ell} = m_{\tilde{\chi}_1^\pm}\sqrt{1-\frac{2(E_{\min}+E_{\max})}{\sqrt{s}}}$$

However, spectrum distorted because of

- chargino polarization effects
- beam- and bremsstrahlung
- off-shell and interference effects
- SUSY background, in particular ♦
- SM background
- response of signal to selection cuts

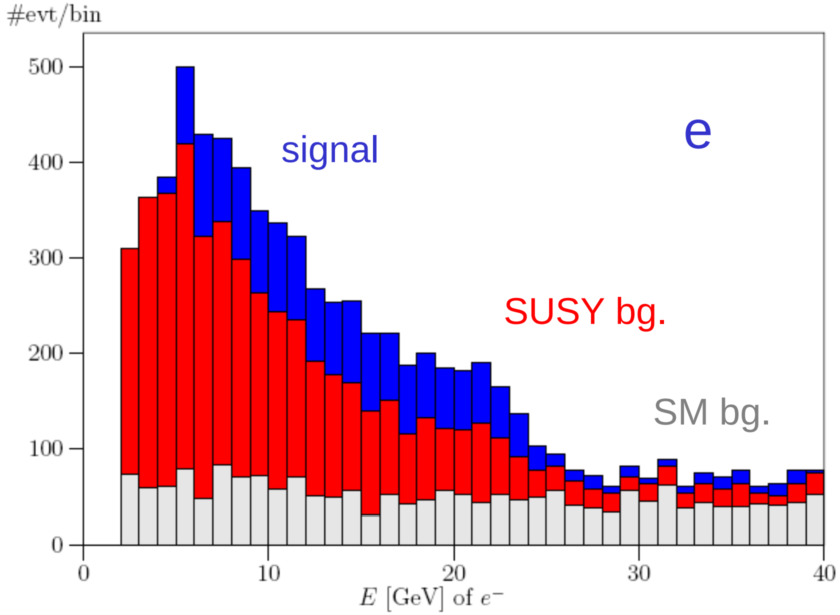
Effect of cuts

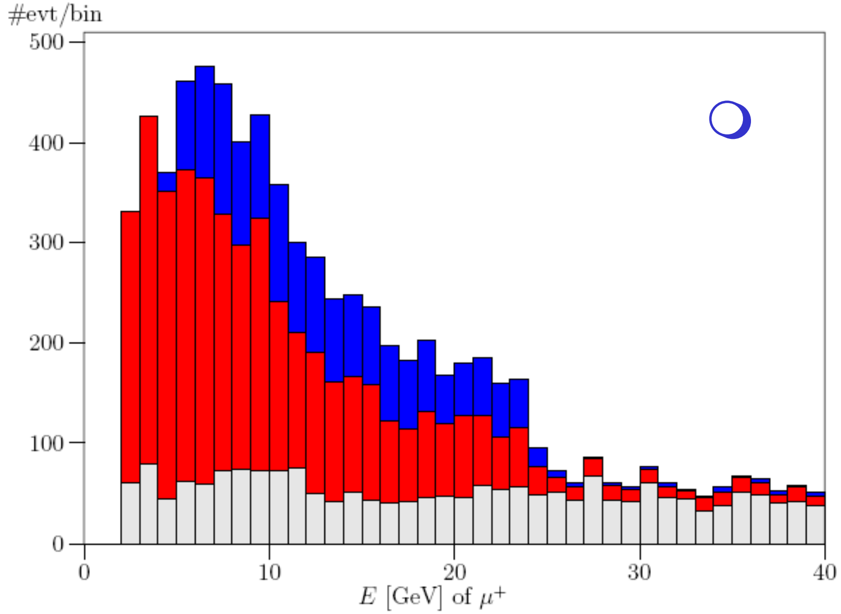


blue – proper signal

green – irred. SUSY

Determining the sneutrino mass: 2





Lower edge difficult to identify

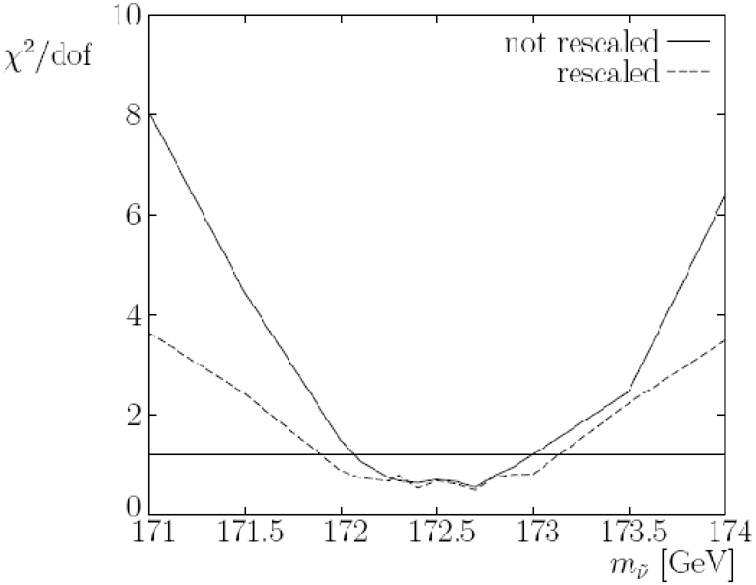
Assuming chargino mass known

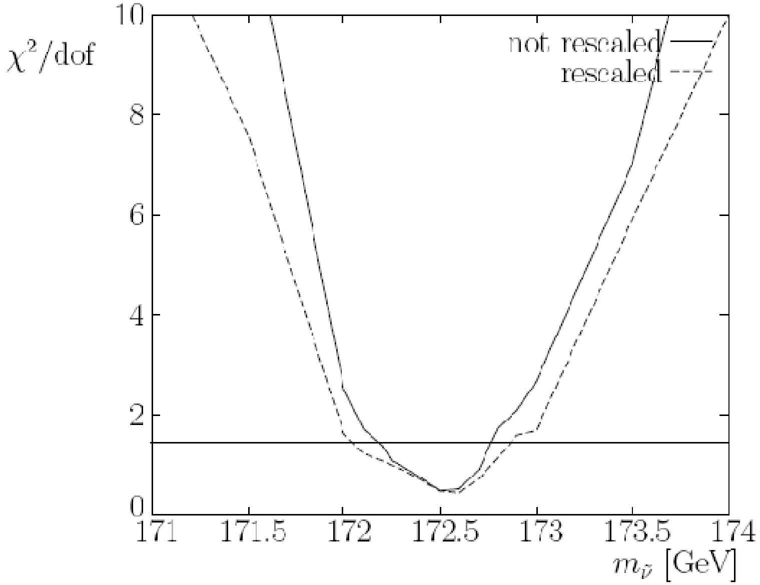
$$m^2_{\tilde{\nu}_\ell} = m^2_{\tilde{\chi}^\pm_1} \left(1 - \frac{4\,E_{\max}}{\sqrt{s}} \frac{1}{1+\beta}\right) \quad \Rightarrow \quad m_{\tilde{\nu}} = 173.1 \pm 1.3\,\mathrm{GeV}$$

Determining the sneutrino mass: 3

Binned ch² fit: generate MC control samples for varying sneutrino mass

$$\chi^2(m_{\tilde{\nu}}) = \sum_i \frac{(N_i^{\rm tr} - N_i^{\rm con}(m_{\tilde{\nu}}))^2}{N_i^{\rm tr} + N_i^{\rm con}(m_{\tilde{\nu}})}$$





method → / limit ↓	full range rescaled	full range not rescaled	edge rescaled	edge not rescaled
lower	171.9	172.1	172.1	172.2
upper	173.1	173.0	172.9	172.8

nominal

$$m_{\tilde{\nu}} = 172.52\ \text{GeV}$$

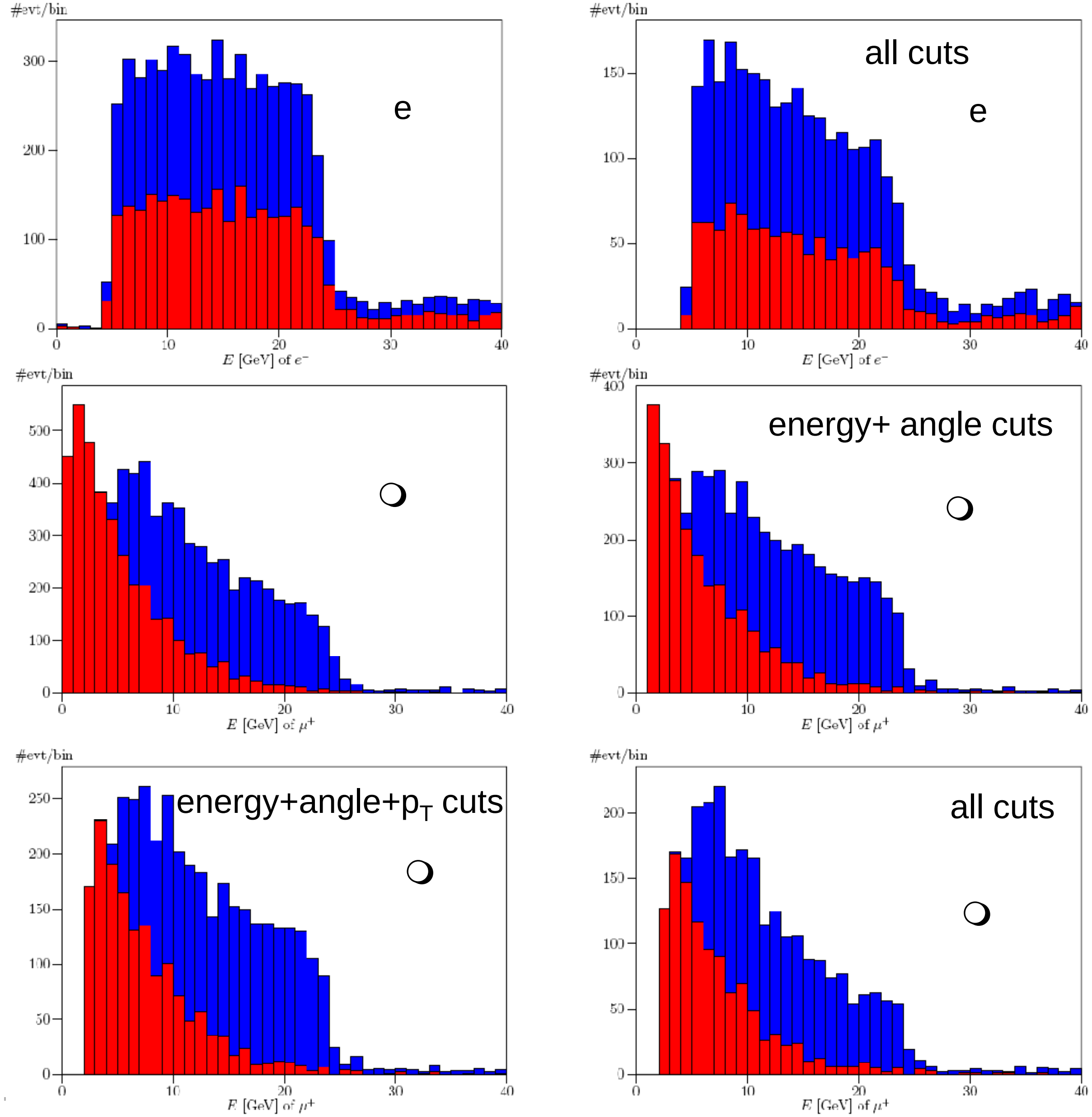
Summary

- ”Invisible” sneutrino becomes visible in leptonic decays of charginos
- our analysis included
  - full matrix element for 2 -> n processes (n $\leq$ 10)
  - off-shell and interference
  - all SUSY and SM background, including gamma-induced
- mass measurement possible but not easy
- three methods for sneutrino mass from leptonic decays of charginos
  - production cross section – good control of normalisation necessary
  - lepton energy spectra – strong effect of kinematic cuts
  - chi2 fit to templates with varying sneutrino mass

Outlook: NLO production implemented into WHIZARD (Kilian, Reuter, Robens)
NLO decays calculated (Rolbiecki, Fujimoto ea)

⇒ Full NLO MC analysis feasible in future

Proper vs irred. SUSY, 800 GeV

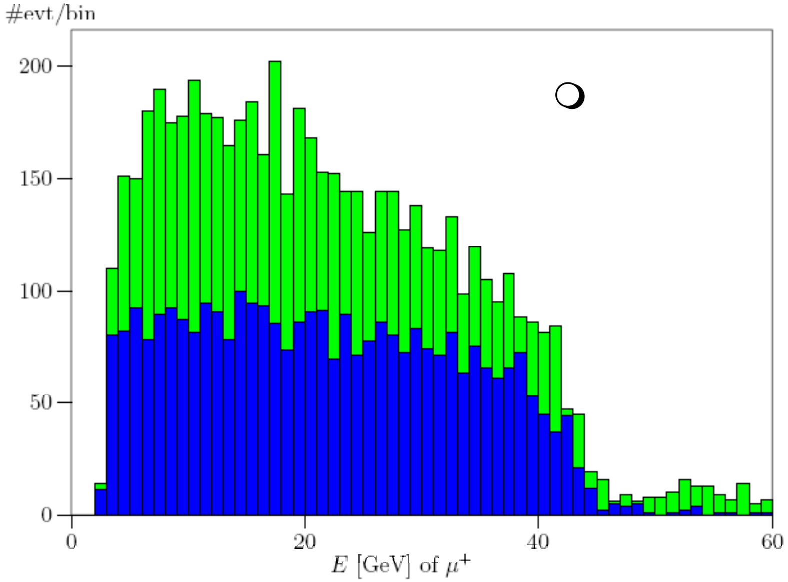


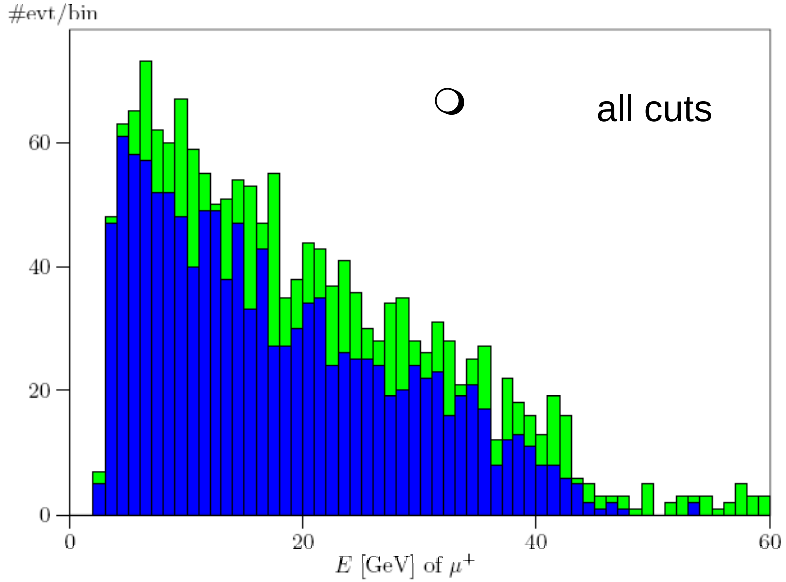
signal

SUSY bg.

Ecm=800 GeV

signal





all