Physics Working Group I: Missing Energy Summary

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Konstantin Matchev, Bill Morse, Graham Wilson

ALCPG07 – Oct. 26th, 2007

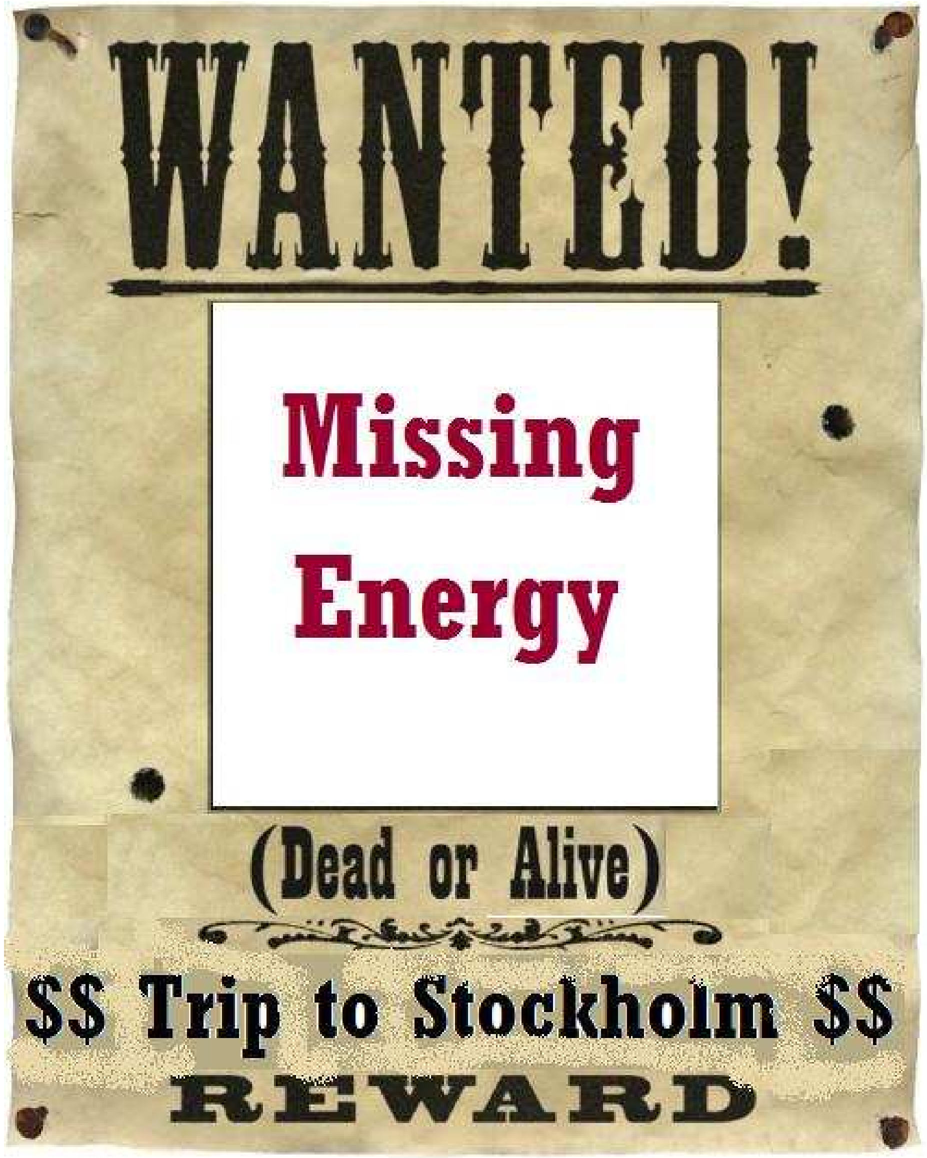
Contributions

- **Something out of nothing: dark matter observation and mass determination in photon + missing energy events at the ILC**
  by Partha Konar
- **Preliminary Study of BeamCal Capabilities in the Detection of the Two Photon Signal**
  by Uriel Nauenberg
- **Solving the LHC Inverse Problem at ILC: Close Mass Chargino Analyses**
  by James Gainer
- **Higgs decays to invisible modes at the LHC and ILC**
  by Heather Logan
- **Electroweak Baryogenesis in the (n)MSSM and ILC Physics**
  by Carlos Wagner
- **Missing Energy in the channel - stop to neutralino and charm- and mass precision measurement**
  by Caroline Milstene

Charge to Conveners

1. What does the physics require of the detector, in terms of coverage and capability. Are present detectors missing some important physics?
2. How does the detector performance tradeoff with physics output? What performance do we really need?
3. Is the technology "there" for the required detectors and performance? What needs more work?

0. How do we find something that's missing?



0. How do we find something that's missing?

- Identify one particular process with distinct signature, analyze in maximally model-independent way OR
- Pick a specific model with a well-motivated set of parameters and study the possible signatures

In both cases, we cannot view the ILC as an isolated machine. Obviously, input from the LHC is expected. But input from cosmology, flavor physics,... which is available right now should (and is) taken into account.

And the SM background needs to be known as precisely as possible.

Benchmark modes for Missing Energy

- Photon + ME
- Invisible Higgs
- Small mass splittings

Missing Energy

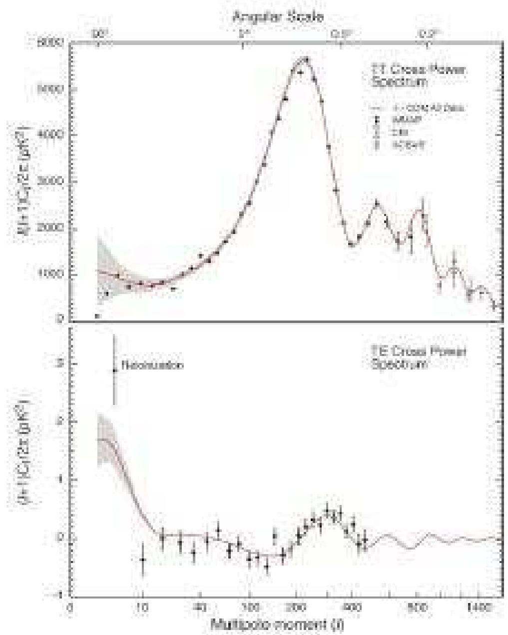
Results from WMAP

Universe density $\Omega_0 = 1.02 \pm 0.02$

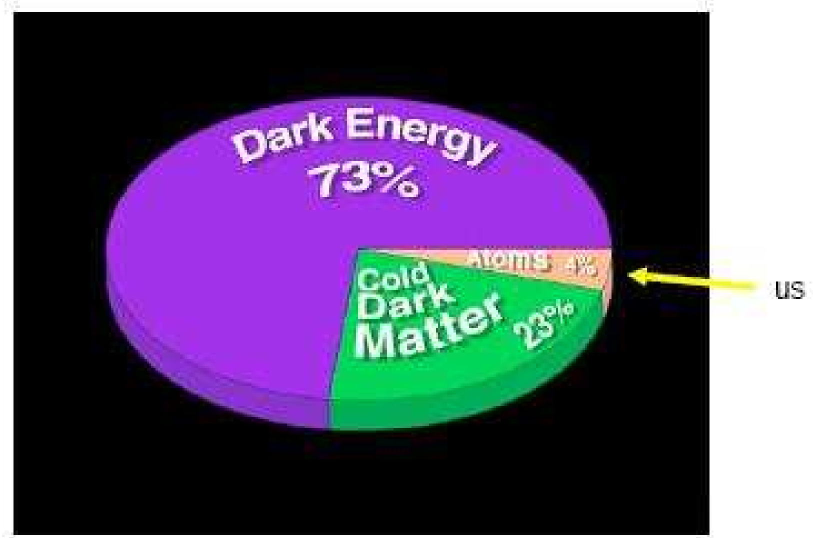
Dark energy density $\Omega_\Lambda = 0.73 \pm 0.04$

Total matter density $\Omega_M = 0.27 \pm 0.05$ → Dark matter is non-baryonic

Baryon matter density $\Omega_b = 0.044 \pm 0.004$



Our Universe:



from C. Wagner's talk

Photon + ME – WIMPs

P.Konar, K. Kong, H. Lee, K. Matchev, M. Perelstein

Assume dark matter entirely due to a single new stable particle, WIMP χ. Dark matter relic abundance depends on cross section for

$$\chi\chi \to X_i \bar{X}_i$$

At colliders we study (ILC: $X_i = e^+$)

$$X_i \bar{X}_i \to \chi\chi$$

Detailed balance equation for spin-averaged cross sections:

$$\sigma(X_i \bar{X}_i \to \chi\chi) = \sigma(\chi\chi \to X_i \bar{X}_i) 2 \frac{v_X^2 (2S_X + 1)^2}{v_\chi^2 (2S_\chi + 1)^2}$$

v relative velocity in c.m. frame, S spin.

Photon + ME – WIMPs

P.Konar, K. Kong, H. Lee, K. Matchev, M. Perelstein

Assume fraction $\kappa_e = \sigma(\chi\chi \to e^+e^-)/\sigma_{an}$, c.m. energy slightly above 2χ threshold,

$$\sigma(e^+e^- \to \chi\chi) = 2^{2(J_0-1)}\kappa_e\sigma_{an}\frac{4}{(2S_\chi+1)^2}\left(1-\frac{4M_\chi}{s}\right)^{1/2+J_0}$$

J_0 angular momentum of dominant partial wave in χ annihilation, M_χ mass of WIMP.

Photon + ME – WIMPs

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J_0 angular momentum of dominant partial wave in χ annihilation, M_χ mass of WIMP.

Tag on extra photon from beam-/bremstrahlung. If γ sufficiently soft ($E_\gamma \ll \sqrt{s} - M_\chi$) or collinear, γ radiation factorizes from hard cross section,

$$\frac{d\sigma(e^+e^- \to \chi\chi\gamma)}{dx\,d\cos\theta} \approx \frac{\alpha}{\pi}\frac{1+(1-x)^2}{x}\frac{1}{\sin^2\theta}\hat{\sigma}(e^+e^- \to \chi\chi)$$

$$x = 2E_\gamma/\sqrt{s}$$

Photon + ME – Forward Coverage

P. Konar, K. Kong, H. Lee, K. Matchev, M. Perelstein

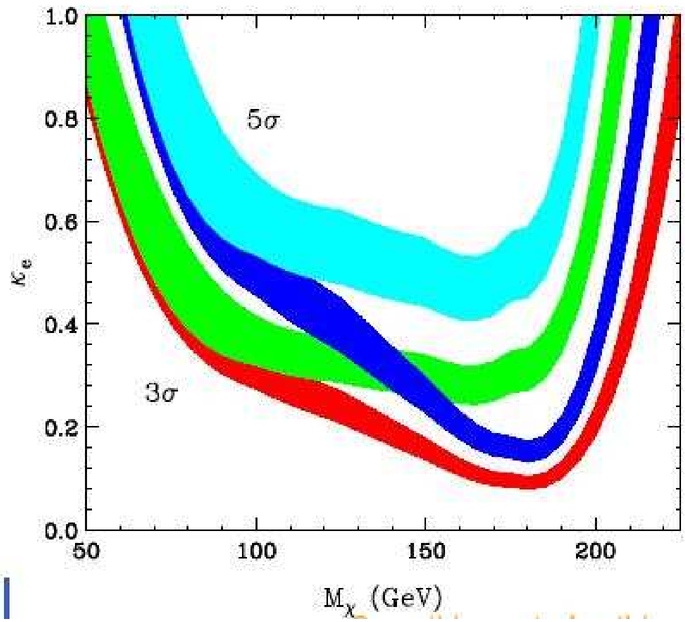
SM backgrounds from $e^+e^- \to \nu\bar{\nu}\gamma$, $e^+e^- \to e^+e^-\gamma$.

$e^+e^- \to e^+e^-\gamma$ can be eliminated by cut on p_T^γ.

Photon + ME – Forward Coverage

P. Konar, K. Kong, H. Lee, K. Matchev, M. Perelstein

- $\sin\theta_\gamma > 0.1$
- $p_{T_\gamma} > 7.5\ GeV$ *(suppress Bhabha : mask calorimeter acceptance of 1^o)*
- χ non-relativistic and E_γ below threshold-
  $\frac{\sqrt{s}}{2}\left(1-\frac{8M_\chi^2}{s}\right) \le E_\gamma \le \frac{\sqrt{s}}{2}\left(1-\frac{4M_\chi^2}{s}\right)$



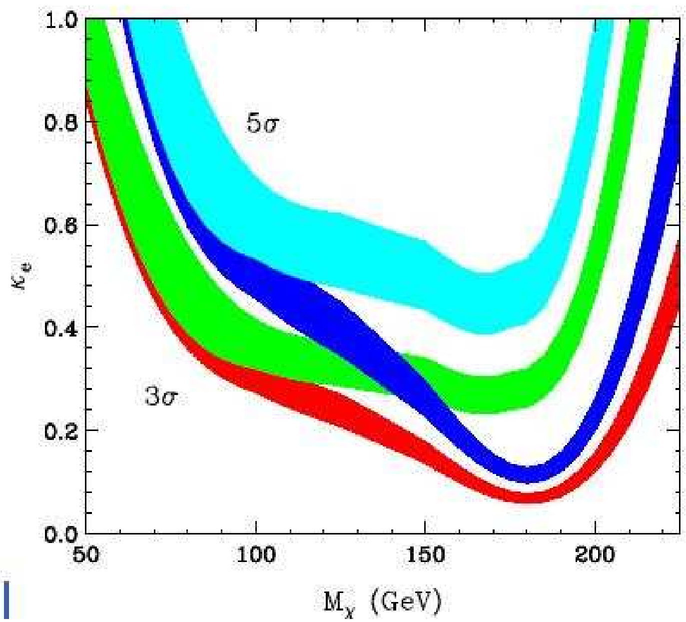
- Discovery reach for $\mathcal{L} = 500 fb^{-1}$ ILC
- No polarization.
- For p-annihilator WIMP
- (red, blue) band include a systematic uncertainty of 0.3%

Photon + ME – Forward Coverage

P. Konar, K. Kong, H. Lee, K. Matchev, M. Perelstein

- $\sin\theta_\gamma > 0.1$
- $p_{T_\gamma} > 3.0\ GeV$ *(suppress Bhabha : BeamCAL acceptance of 0.38^o)*
- χ non-relativistic and E_γ below threshold-

$$\frac{\sqrt{s}}{2}\left(1 - \frac{8M_\chi^2}{s}\right) \le E_\gamma \le \frac{\sqrt{s}}{2}\left(1 - \frac{4M_\chi^2}{s}\right)$$



- Discovery reach for $\mathcal{L} = 500 fb^{-1}$ ILC
- No polarization.
- For p-annihilator WIMP
- (red, blue) band include a systematic uncertainty of 0.3%
- Revised from better beam-CAL acceptance.

Photon + ME – MSSM

C. F. Berger, J. Gainer, J. L. Hewett, B. Lillie, T. G. Rizzo

Study 242 “random” points in MSSM parameter space (which are problematic at the LHC), tens of analysis channels. Of the 242 points, 91 only produce $\tilde{\chi}_1^0$s at a 500 GeV collider and nothing else $\Rightarrow$ 500 GeV may not be enough!.
Thus one of the channels studied:

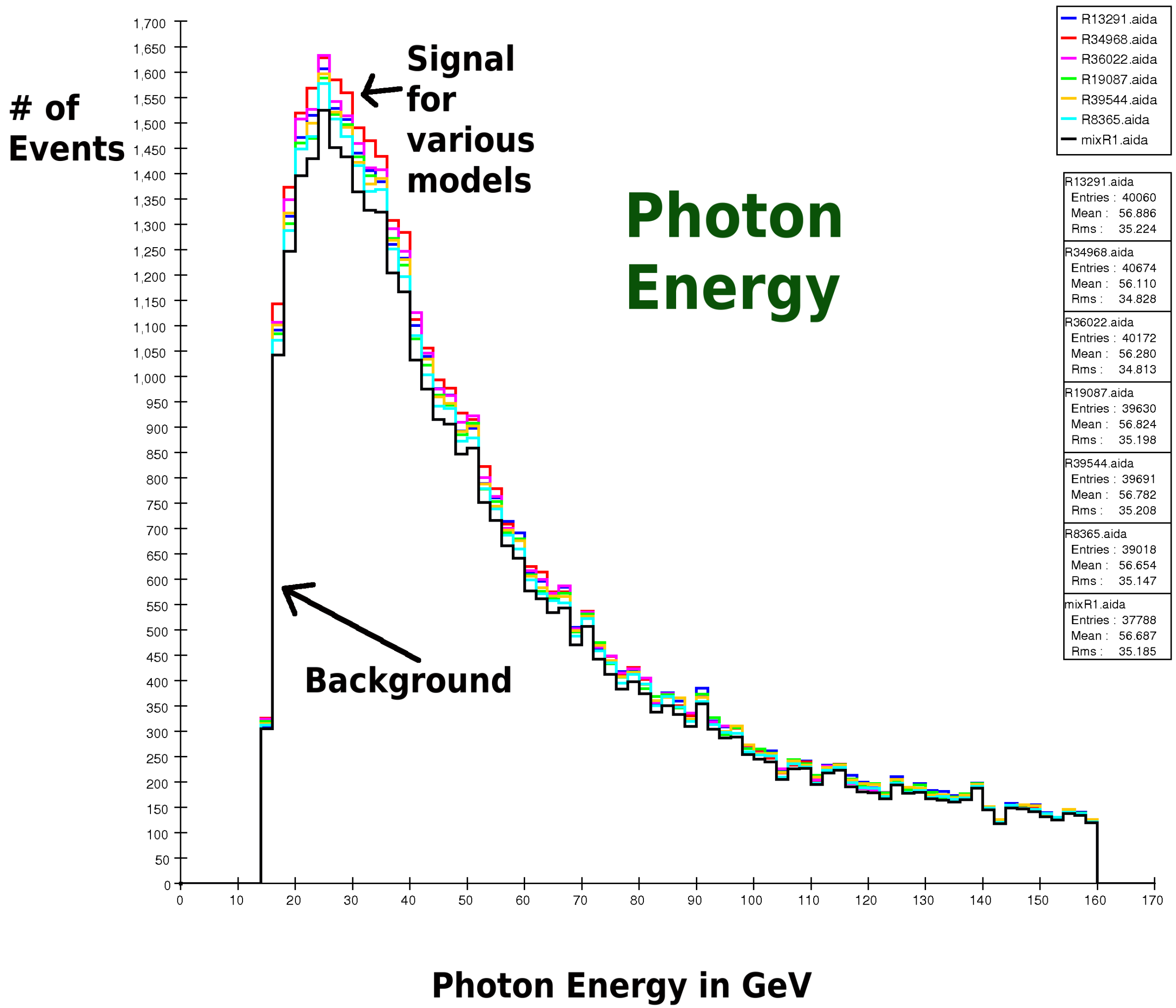
$$e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0\gamma$$

The main backgrounds are

1. $\nu\bar{\nu}$ **production with associated photon**
2. $\tilde{\nu}\tilde{\nu}^*$ **production with associated photon**

Photon + ME – MSSM, Results

C. F. Berger, J. Gainer, J. L. Hewett, B. Lillie, T. G. Rizzo



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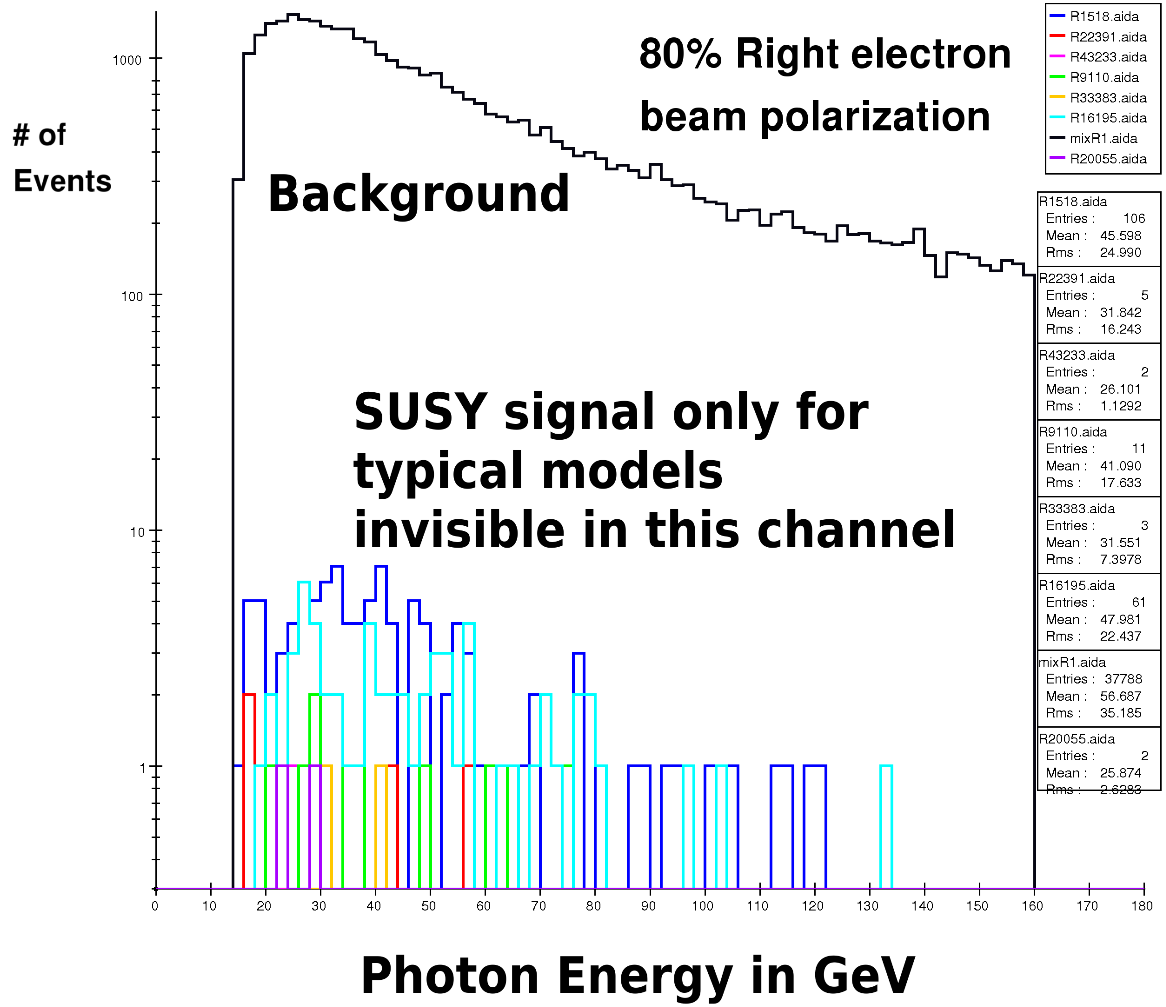

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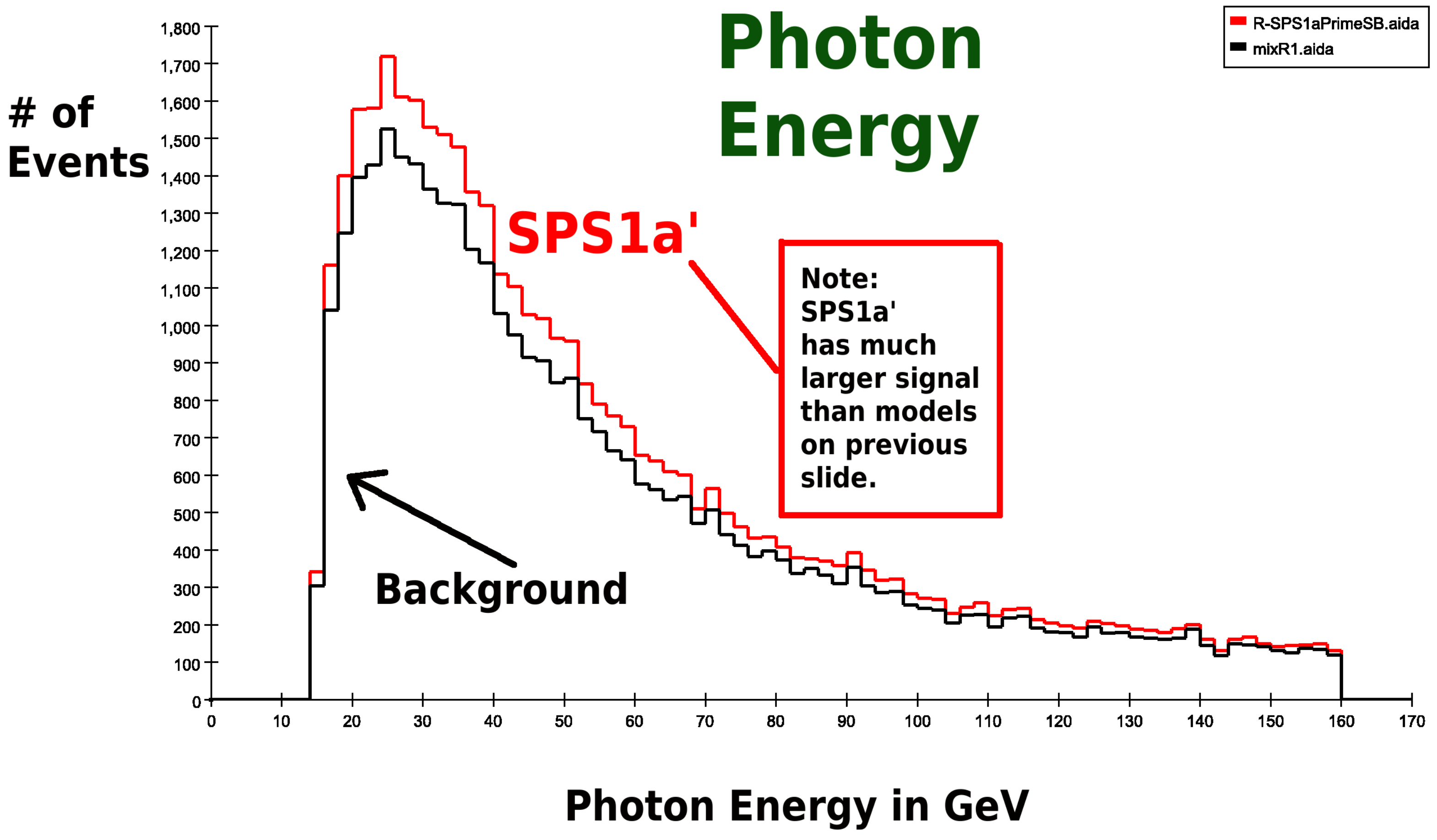


Photon + ME – MSSM, Results

C. F. Berger, J. Gainer, J. L. Hewett, B. Lillie, T. G. Rizzo

At 500 GeV, out of 242 (semi-)random points in MSSM parameter space (= models), **91 have only $\tilde{\chi}_1^0$s accessible**.

With 500 fb^{-1}, 80% e^- polarization (no positron polarization), and the current SiD design = no tracking below 142 mrad, forward coverage down to 5 mrad, **only 3 of these models are observable above background**.

SPS1a' has much higher event rate compared to all of these 242 points (holds for other channels, too).

Improvement: **positron polarization**: background $\sigma_L^B \sim 50\sigma_R^B$, signal either $\sigma_L^S \sim \sigma_R^S$ or $\sigma_L^S \ll \sigma_R^S$.

Invisible Higgs

H. Logan

If neutral (quasi)stable particle with mass $< m_H/2$ and EW strength coupling to H, then $H \to$ invisible the dominant decay mode. E. g.

- $H \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$ (MSSM, NMSSM)
- $H \to SS$ (scalar dark matter)
- $H \to KK$ neutrinos (extra dimensions)
- $\ldots$

Production mechanisms:

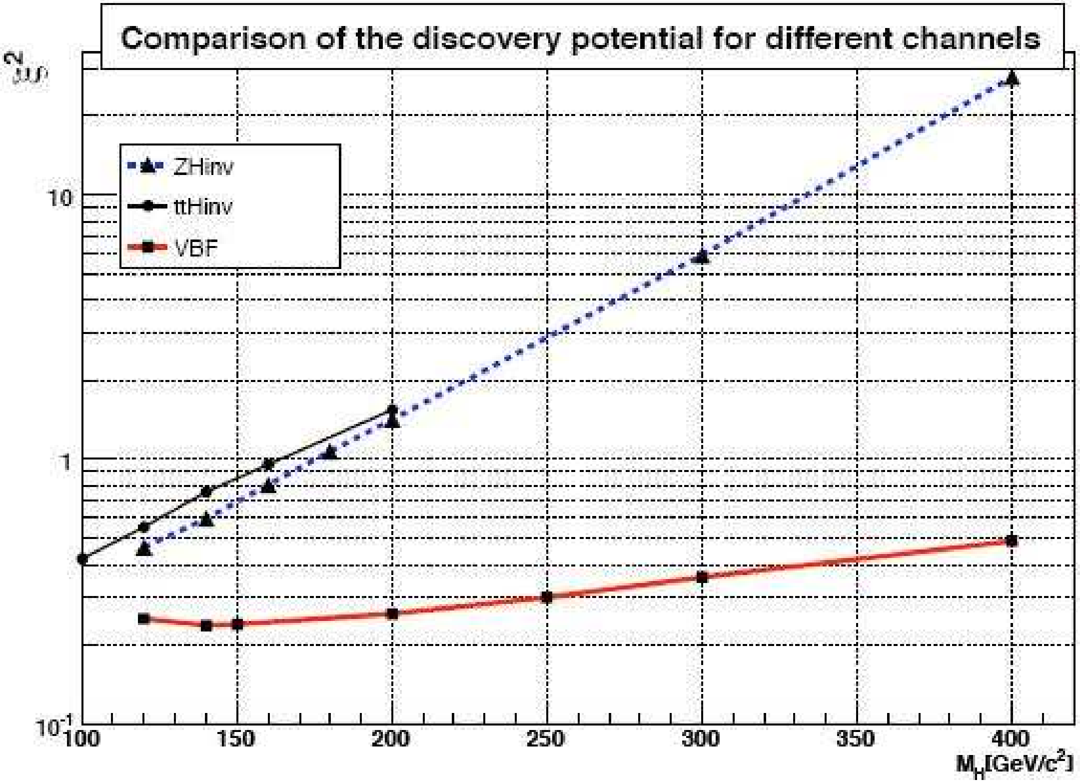
- VBF $\to H_{\text{inv}}$
- Higgs-strahlung off Z

Invisible Higgs at the LHC

H. Logan

95% CL exclusion limits with 30 fb^{-1} at LHC

ξ^2 is a scaling factor: $\sigma \times \mathrm{BR}(H \to \mathrm{invis}) \equiv \xi^2 \sigma_{\mathrm{SM}}$



ZH_{inv} – uses $Z \to \ell^+\ell^-$

VBF looks very good, but not clear how well events can be triggered.

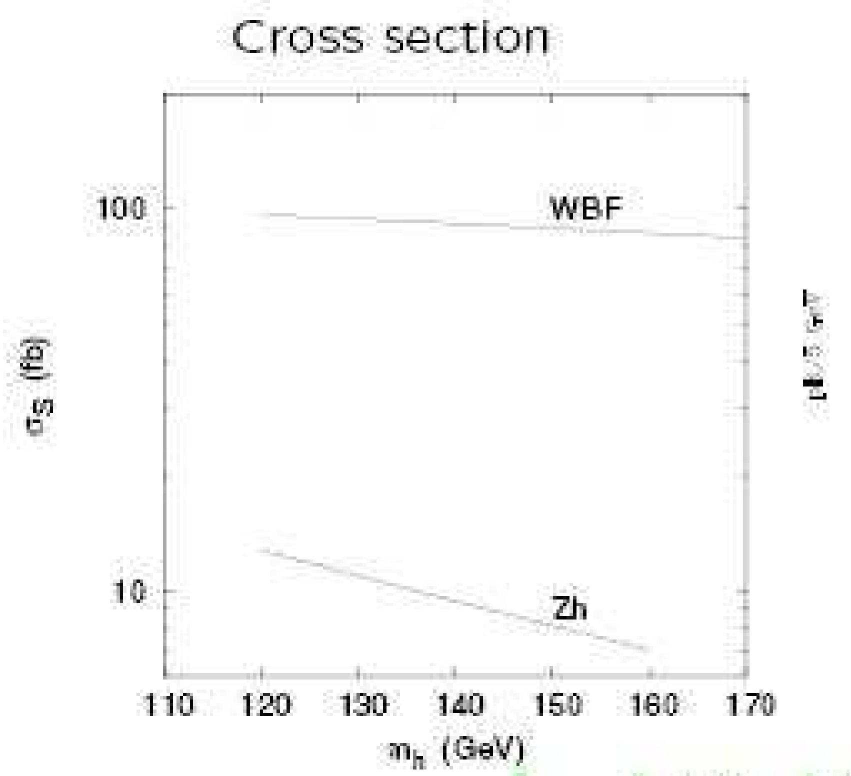
$t\bar{t}H_{\mathrm{inv}}$ – may be room for improvement? ATLAS study in progress.

[Plot from ATL-PHYS-PUB-2006-009]

LHC - Higgs Mass Measurement

H. Davoudiasl, T. Han, H. Logan

Signal rate depends on m_H:



Mass determination from ratio of VBF to Higgsstrahlung – branching ratio assumption drops out

LHC - Higgs Mass Measurement

H. Davoudiasl, T. Han, H. Logan

Higgs mass determination from ratio method with 10 (100) fb^{-1}:

m_h (GeV)	120	140	160
$r = \sigma_S(Zh)/\sigma_S(\text{WBF})$	0.132	0.102	0.0807
$(dr/dm_h)/r$ (1/GeV)	−0.011	−0.013	−0.013
Total uncert., $\Delta r/r$	41% (16%)	54% (20%)	72% (25%)
Δm_h (GeV)	36 (14)	43 (16)	53 (18)

Davoudiasl, Han & H.L. (2004)

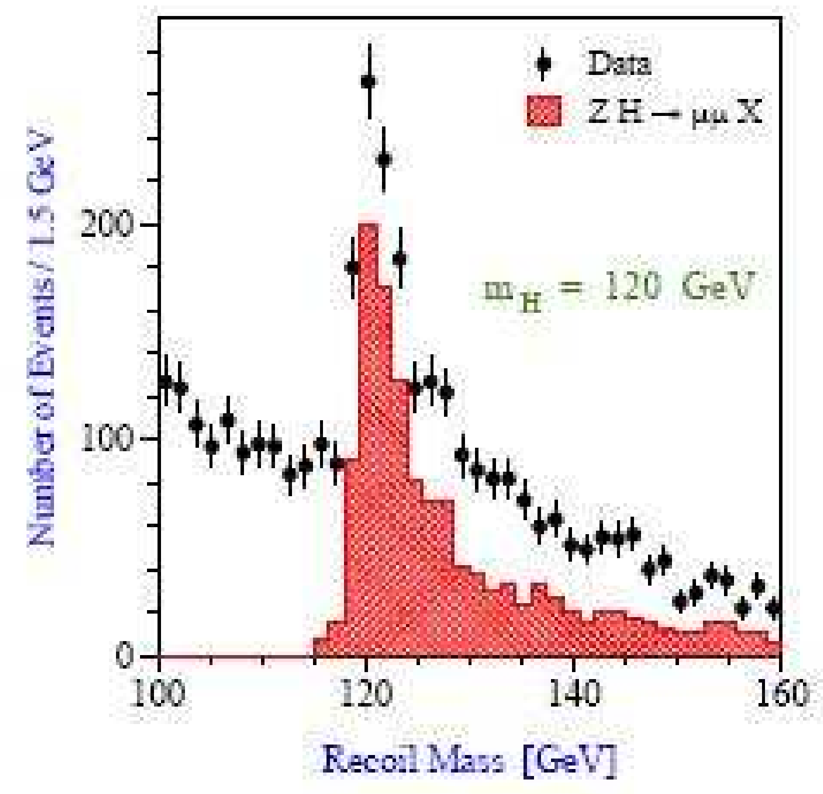
Ratio method:

$\Delta m_H = 36/43/53\ (14/16/18)$ GeV with 10 (100) fb^{-1}

Assumed $\xi^2 = 1$ for signal statistics.

H. Logan

Study Higgsstrahlung, $ZH \to \mu\mu X$, measure recoil mass



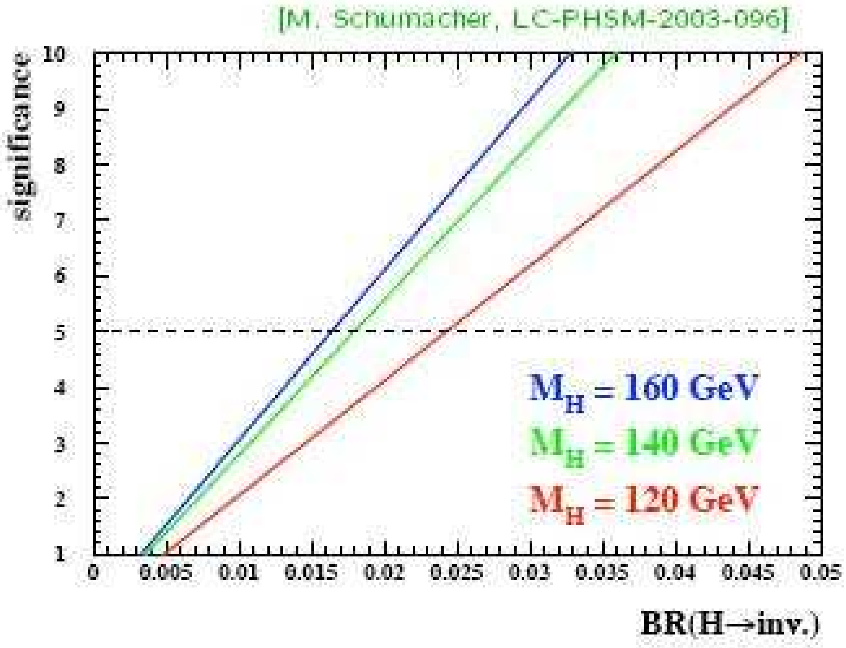
[TESLA TDR] $m_H = 120$ GeV, $\sqrt{s} = 350$ GeV, $\int \mathcal{L} = 500$ fb^{-1}, $\mu\mu$ only

Invisible Higgs at the ILC

H. Logan

Higgstrahlung, $Z \to q\bar{q}$

Discovery reach: $500\ \text{fb}^{-1}$ at $\sqrt{s} = 350$ GeV



5σ discovery for BR_{inv} down to
$\sim 2.5\%$ for $m_H = 120$ GeV
$\sim 1.5\%$ for $m_H = 140, 160$ GeV

Invisible Higgs – LHC vs. ILC

H. Logan

Can improve precision of mass measurement at ILC by running near threshold (Bambade, Richard). Much less luminosity needed for comparable precision because of higher cross section and less background under Higgs recoil peak.

Final score: Invisible Higgs mass determination at the LHC indirect from ratio of rates, $\Delta M \sim 15$ GeV. At the ILC direct determination from recoil spectrum, model independent, $\Delta M \sim 30$ MeV.

Ability to run ILC at variable c.m. energy greatly improves precision.

Small Mass Splittings – MSSM

C. F. Berger, J. Gainer, J. L. Hewett, B. Lillie, T. G. Rizzo

Recall, study of 242 "random" points in MSSM parameter space. Search strategy for charginos depends on $\Delta m = m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$.

- $\Delta m \lesssim m_\pi$: Stable charged particle search
- $m_\pi \lesssim \Delta m \lesssim 1$GeV: Radiative chargino search
- $\Delta m \gtrsim 1$ GeV:
  - 4 jet + missing energy
  - 2 jet, muon + missing energy
  - 2 muons + missing energy

Radiative Chargino Search – Cuts

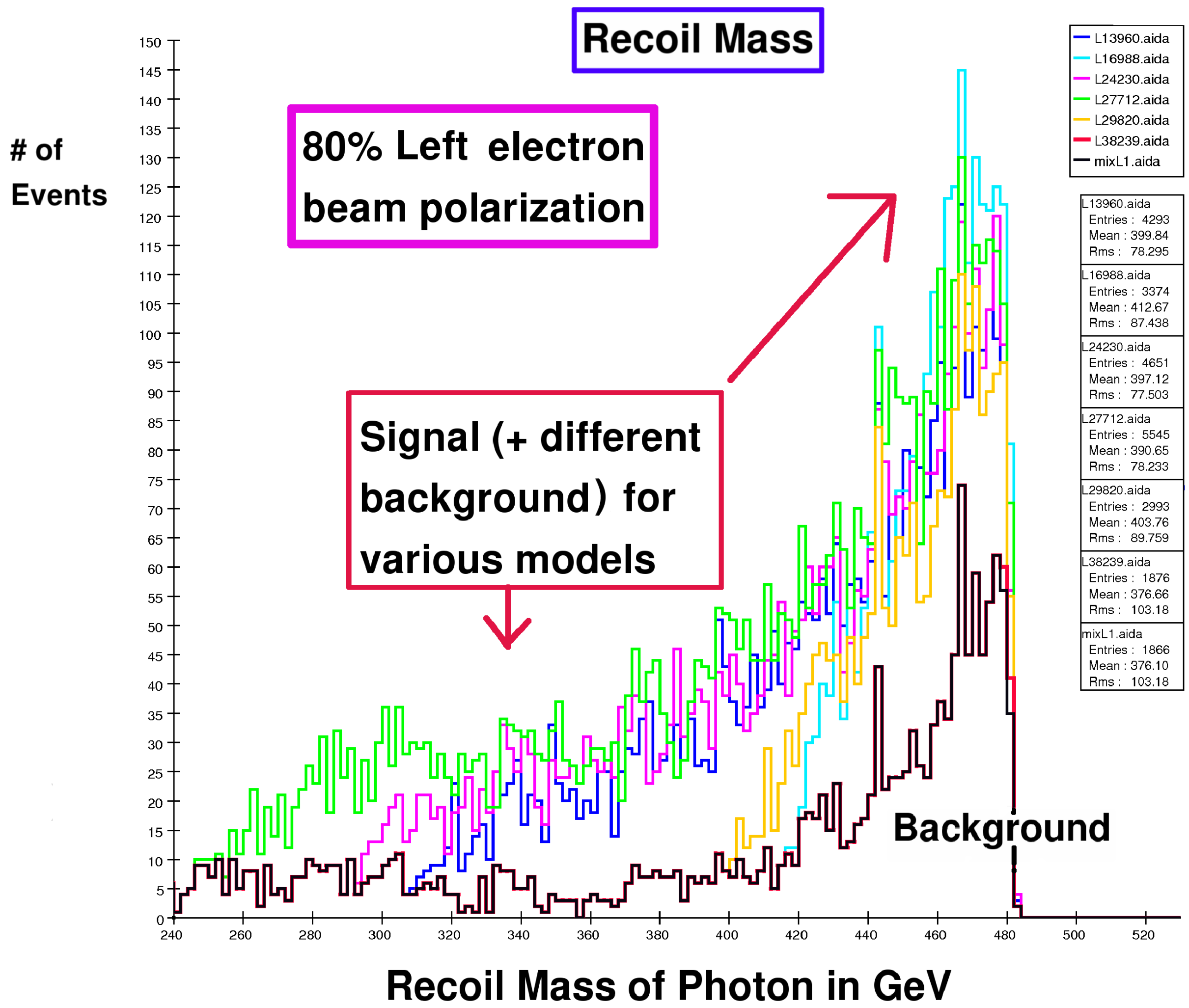
C. F. Berger, J. Gainer, J. L. Hewett, B. Lillie, T. G. Rizzo

Main backgrounds from $e\gamma$ and $e^+e^- \longrightarrow W^+W^-$. Following Riles et al (1990), OPAL, Gunion and Mrenna (2001):

1. Exactly one photon with $p_T > 0.035\sqrt{s}$ and no other charged tracks within 25 degrees
2. No identified (i.e. above 142 mrad) electrons or muons in the event
3. $1 <$ number of charged tracks < 11
4. $E_{\text{vis, other particles}} - E_\gamma < 0.35\sqrt{s}$
5. $\frac{p_{T,vis}}{E_{T,vis}} > 0.4$ and $\frac{p_{T,vis}}{p_{tot}} > 0.2$.
6. $M_{recoil} = \sqrt{s}\sqrt{\left(1 - 2E_\gamma/\sqrt{s}\right)} > 160$ GeV

Radiative Charginos – Results

C. F. Berger, J. Gainer, J. L. Hewett, B. Lillie, T. G. Rizzo



Radiative Charginos – Results

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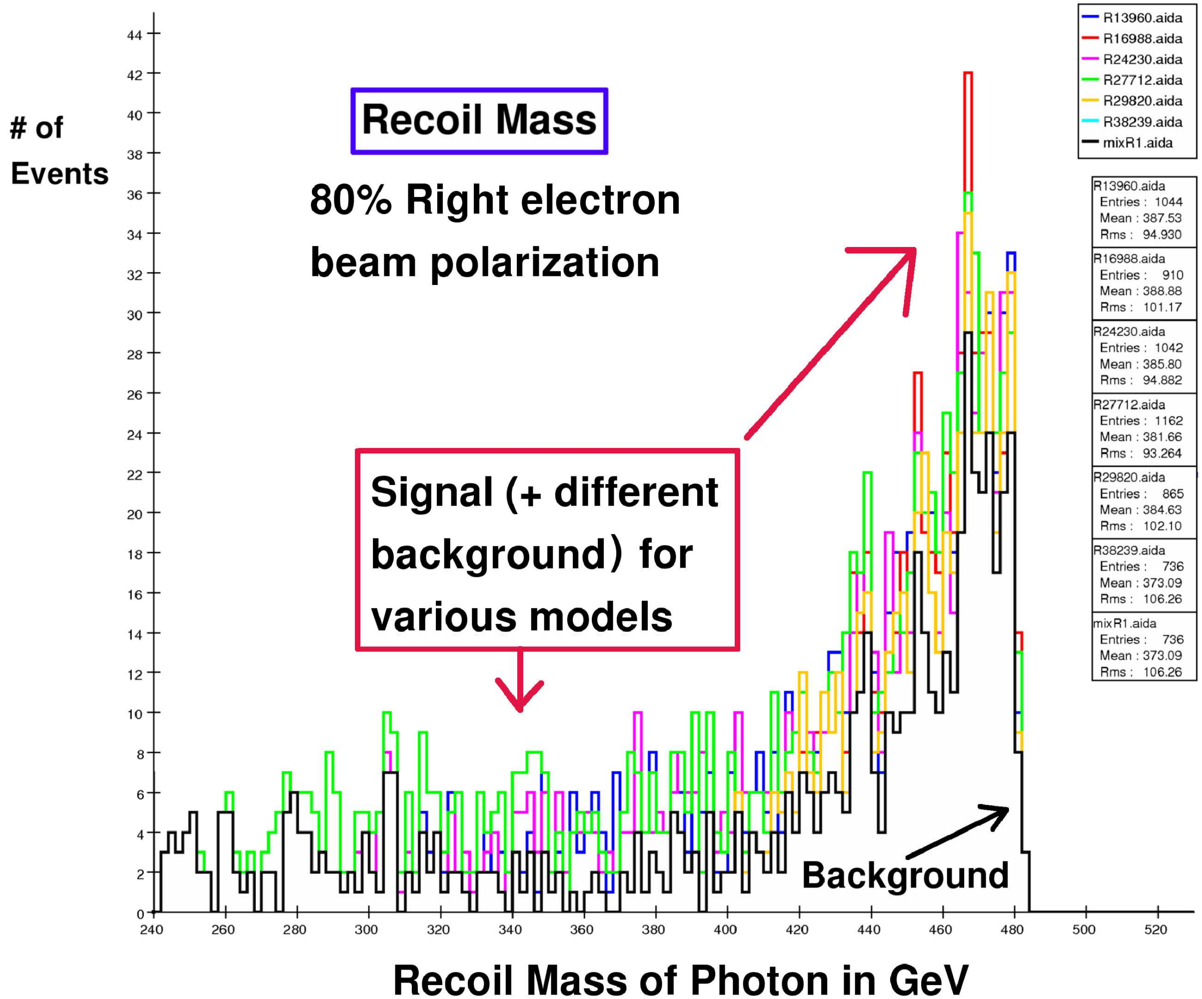


C. F. Berger, J. Gainer, J. L. Hewett, B. Lillie, T. G. Rizzo

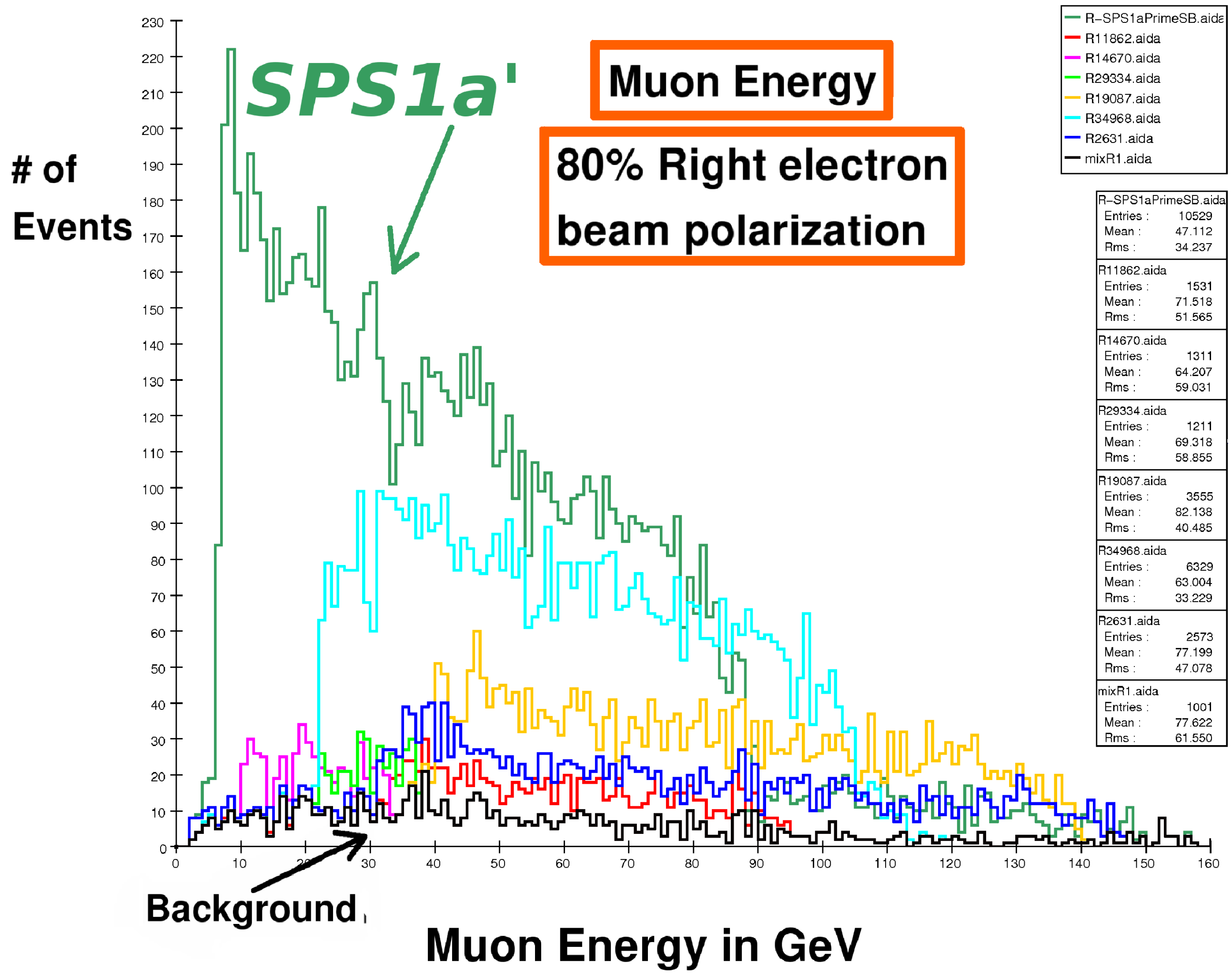
$$e^+e^- \to \tilde{l}^+\tilde{l}^- \to l^+l^-\tilde{\chi}_1^0\tilde{\chi}_1^0$$

Main SM backgrounds:

- W pair production with each W decaying leptonically
- Z pair production with one Z decaying to charged leptons the other to neutrinos
- Processes with γ in initial state ($\gamma\gamma- > l^+l^-$ or processes where an initial electron or photon is kicked into the detector)

MSSM – Sleptons, Results, SiD

C. F. Berger, J. Gainer, J. L. Hewett, B. Lillie, T. G. Rizzo



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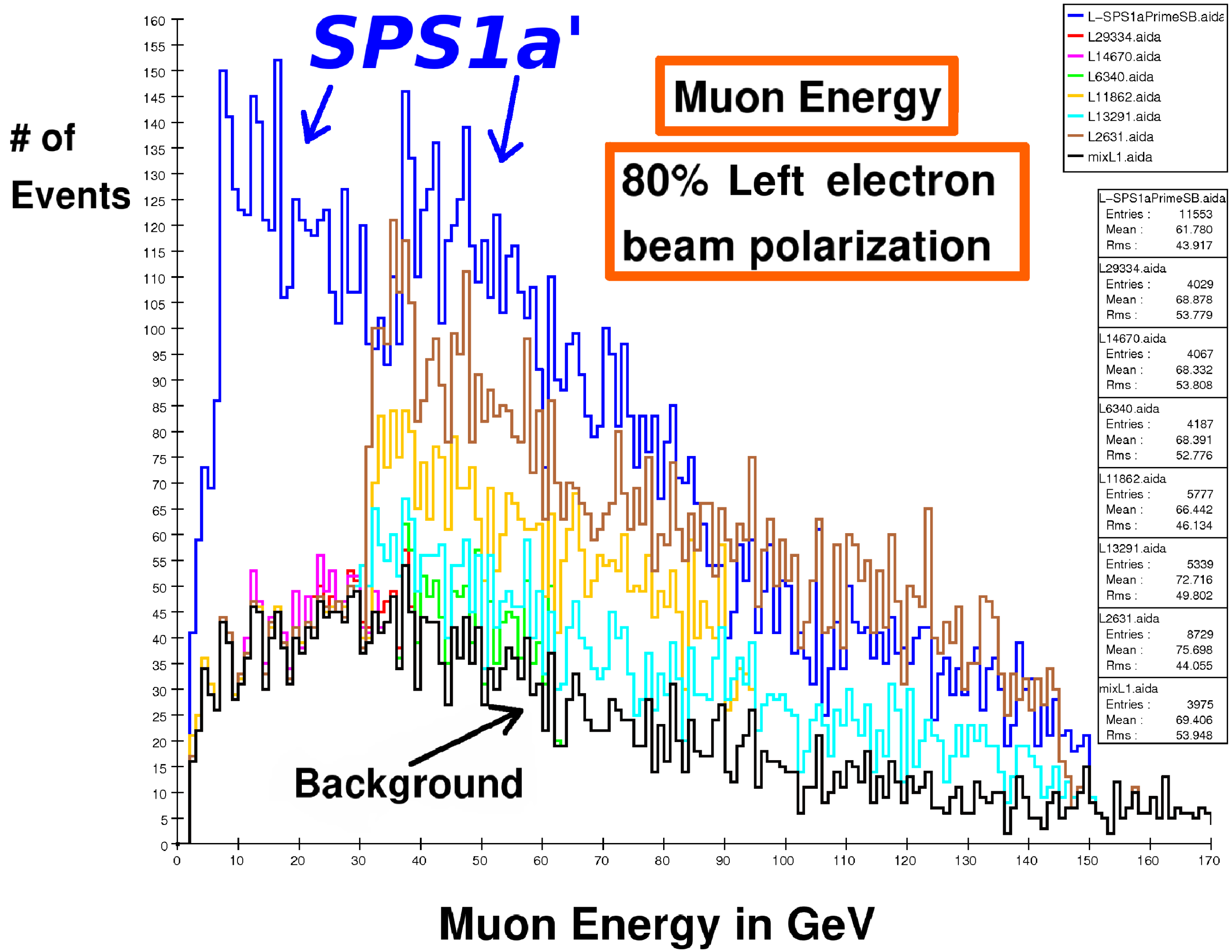

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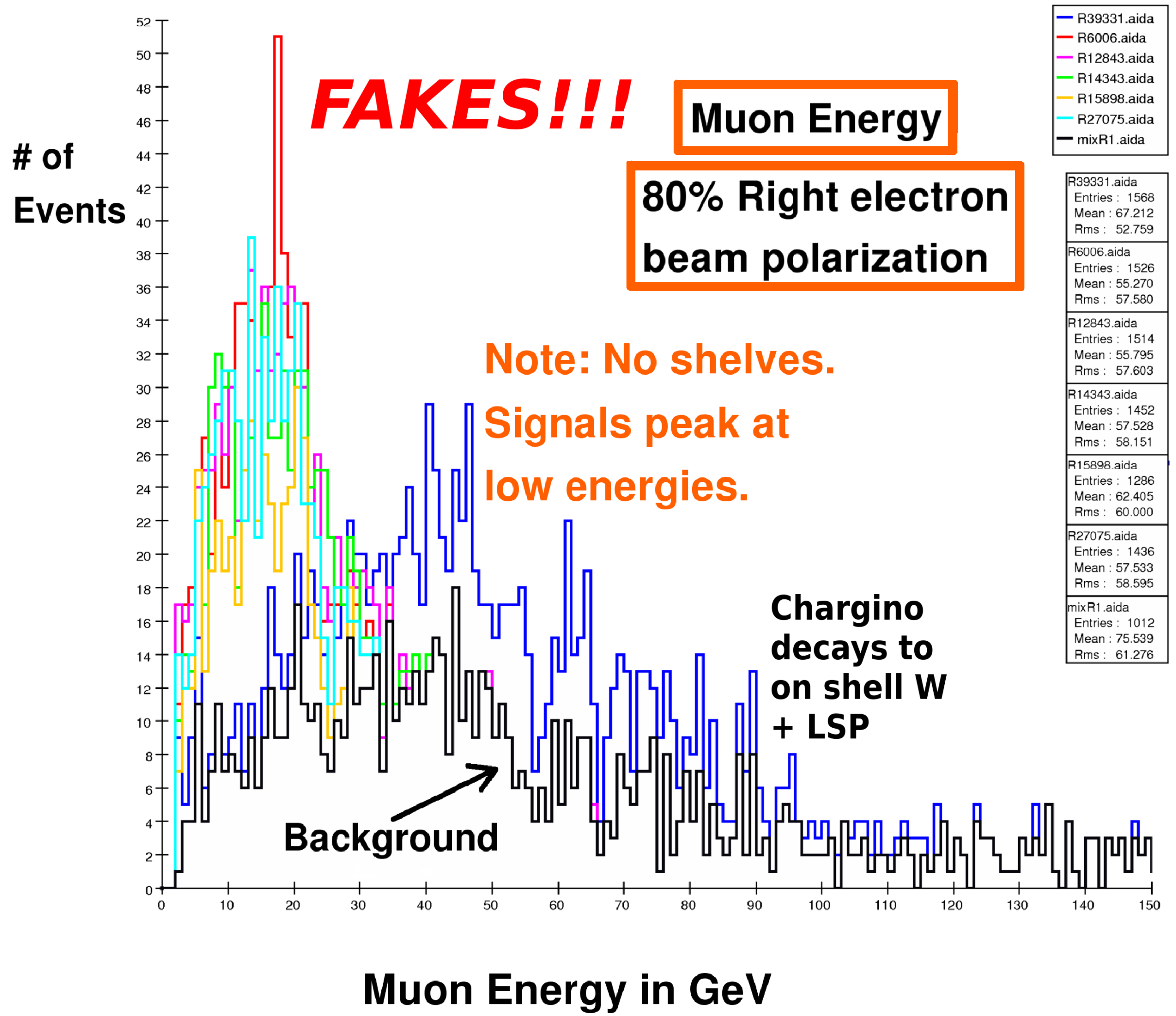


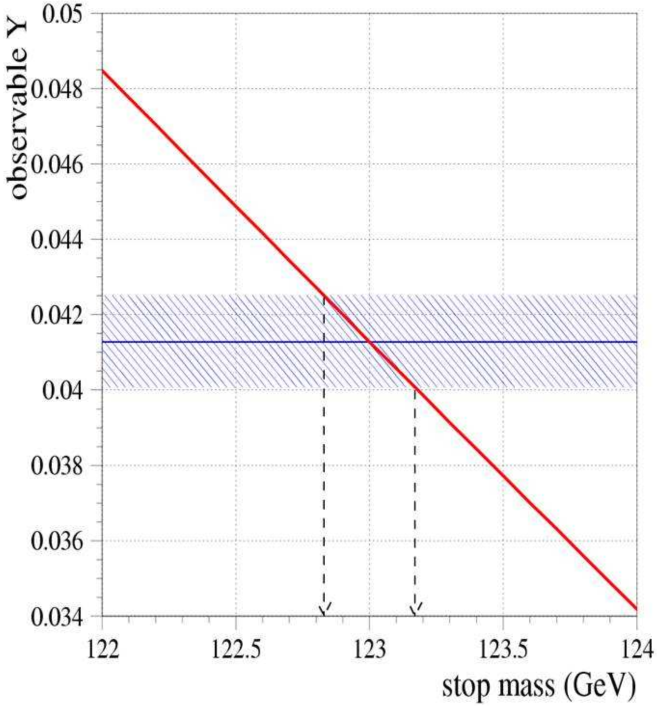
Stop Mass Measurement

A. Freitas, C. Milstene, M. Schmitt, A. Sopczak

Idea: measure ratio Y between events at threshold and at peak of stop pair production cross section, channel

$$e^+e^- \to \tilde{t}\bar{\tilde{t}} \to c\bar{c}\tilde{\chi}_1^0\tilde{\chi}_1^0$$

Cross section very sensitive to stop mass.



Stop Mass Measurement – Results

A. Freitas, C. Milstene, M. Schmitt, A. Sopczak

Multi-jet final states due to gluon radiation and fragmentation. Charm tagging at higher c.m. energy challenge for vertex detector.

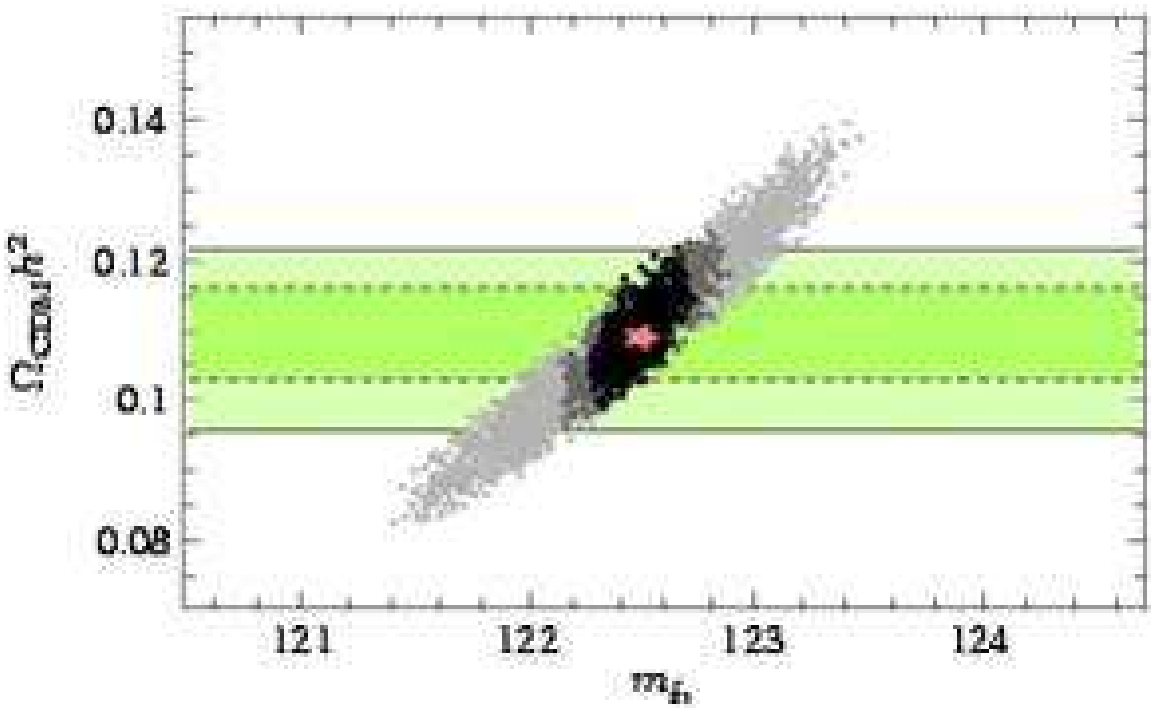
Two analyses, one cut-based, one neural net (iterative discriminant analysis), both yield similar results:

- No polarization: Unambiguous discovery
- +80%/-60% beam polarization: precision measurement
- Error on stop mass of order 0.45 GeV.

Stop Mass – Relic Abundance

A. Freitas, C. Milstene, M. Schmitt, A. Sopczak

If light scalar top partner with mass $< m_t$, and $m_{\tilde{t}} - m_{\tilde{\chi}_1^0} \sim$ 15-30 GeV, co-annihilation between stop and LSP $\Rightarrow$ correct relic abundance.



nMSSM

C. Balasz, M. Carena, A. Freitas, C. Wagner

nMSSM has extra singlet chiral superfield.
Consequences:

- **Baryon asymmetry without need for light squarks**

  A. Menon, D. Morrissey, C. Wagner

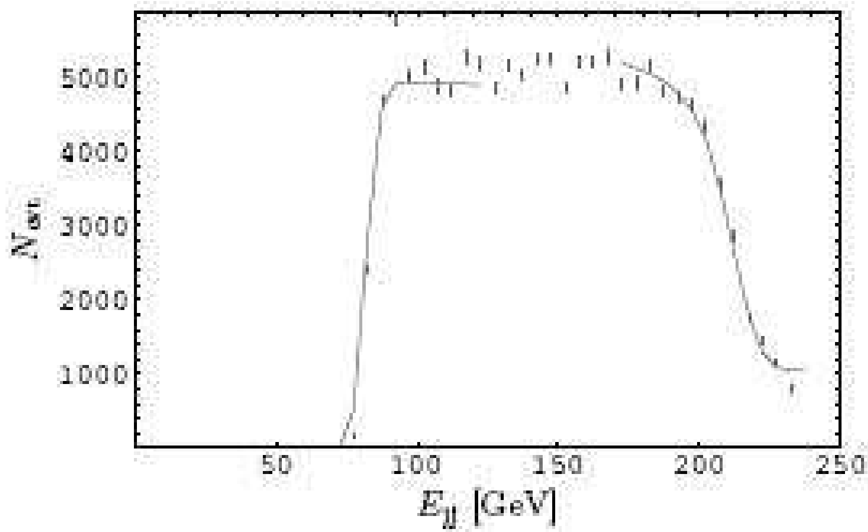
- m_h **naturally above experimental bounds**
- $\tilde{\chi}_1^0$ **admixture of fermion component of singlet and Higgsinos,** $m_{\tilde{\chi}_1^0} < 70$ **GeV**
- **lightest Higgs decays invisibly into** $\tilde{\chi}_1^0$**s**
- **charginos and neutralinos naturally light**

C. Balasz, M. Carena, A. Freitas, C. Wagner

Jets from Chargino Production

Information on the mass difference of the lightest chargino and neutralino may be obtained form the energy distributin of the jets proceeding from chargino decay $\tilde{\chi}_1^{\pm} \to \chi_1^0 W^{\pm}$

$$e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^- \to W^+W^- \tilde{\chi}_1^0\tilde{\chi}_1^0 \to jj\,l^{\pm} + \not{E}$$



$\Delta R = \sqrt{(\phi_1-\phi_2)^2+(\eta_1-\eta_2)^2} < 0.3$

$p_t > 12\,\text{GeV},\ \not{E} > 100\,\text{GeV}$

$|m_{jj} - M_W| < 10$ GeV

$m_{t,\text{miss}} > 150\,\text{GeV}$

$P(e^+)/P(e^-) = \text{right/left}$,
(increases both signal and bckgd.)

$$E_{\text{min,max}} = \frac{1}{4m^2_{\tilde{\chi}_1^\pm}}\left[(m^2_{\tilde{\chi}_1^\pm} - m^2_{\tilde{\chi}_1^0} + M_W^2)\sqrt{s} \mp \sqrt{\lambda(m^2_{\tilde{\chi}_1^\pm}, m^2_{\tilde{\chi}_1^0}, M_W^2)(s-4m^2_{\tilde{\chi}_1^\pm})}\right].$$

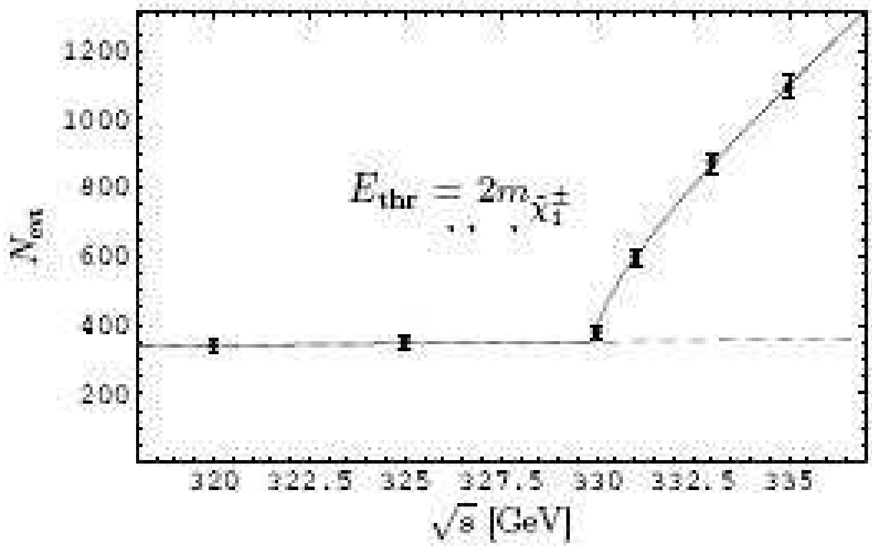
nMSSM – ILC Mass Measurements

C. Balasz, M. Carena, A. Freitas, C. Wagner

Threshold Scan for Chargino Pair Production

$P(e^+)/P(e^-) = \text{right/left}$.

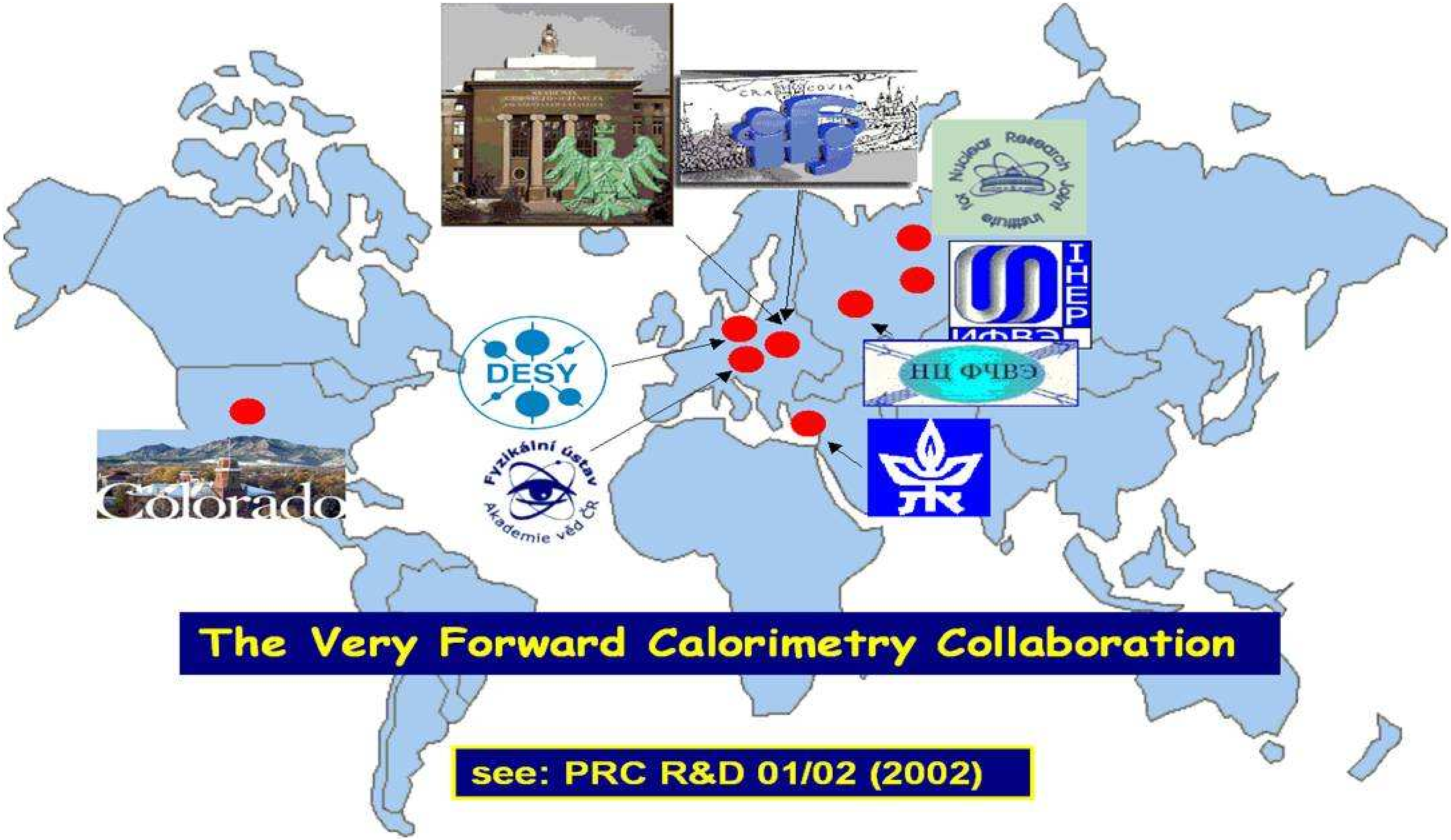
$10\,\text{fb}^{-1}$ luminosity is spent per point, amounting to total of $60\,\text{fb}^{-1}$.



$m_{\tilde{\chi}_1^\pm} = 164.98 \pm 0.05$ GeV.

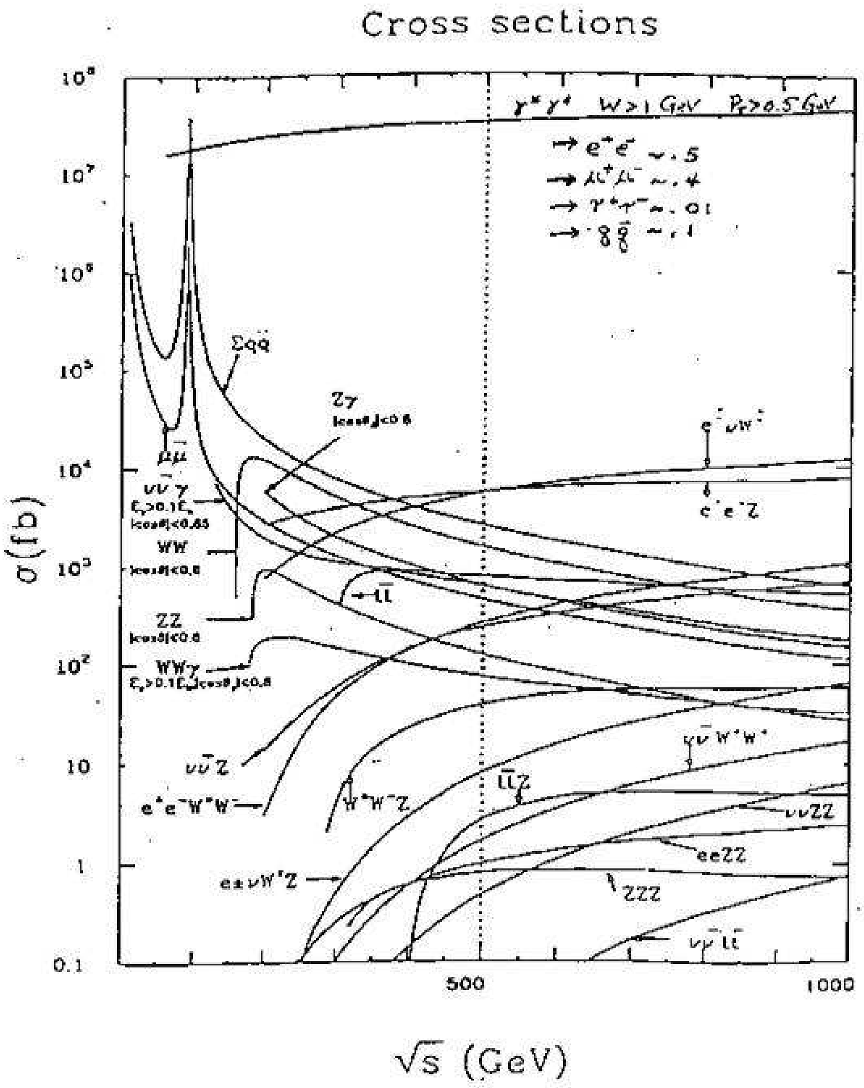
$m_{\tilde{\chi}_1^0} = 33.3^{+0.4}_{-0.3}$ GeV

Very Forward Calorimetry Collaboration



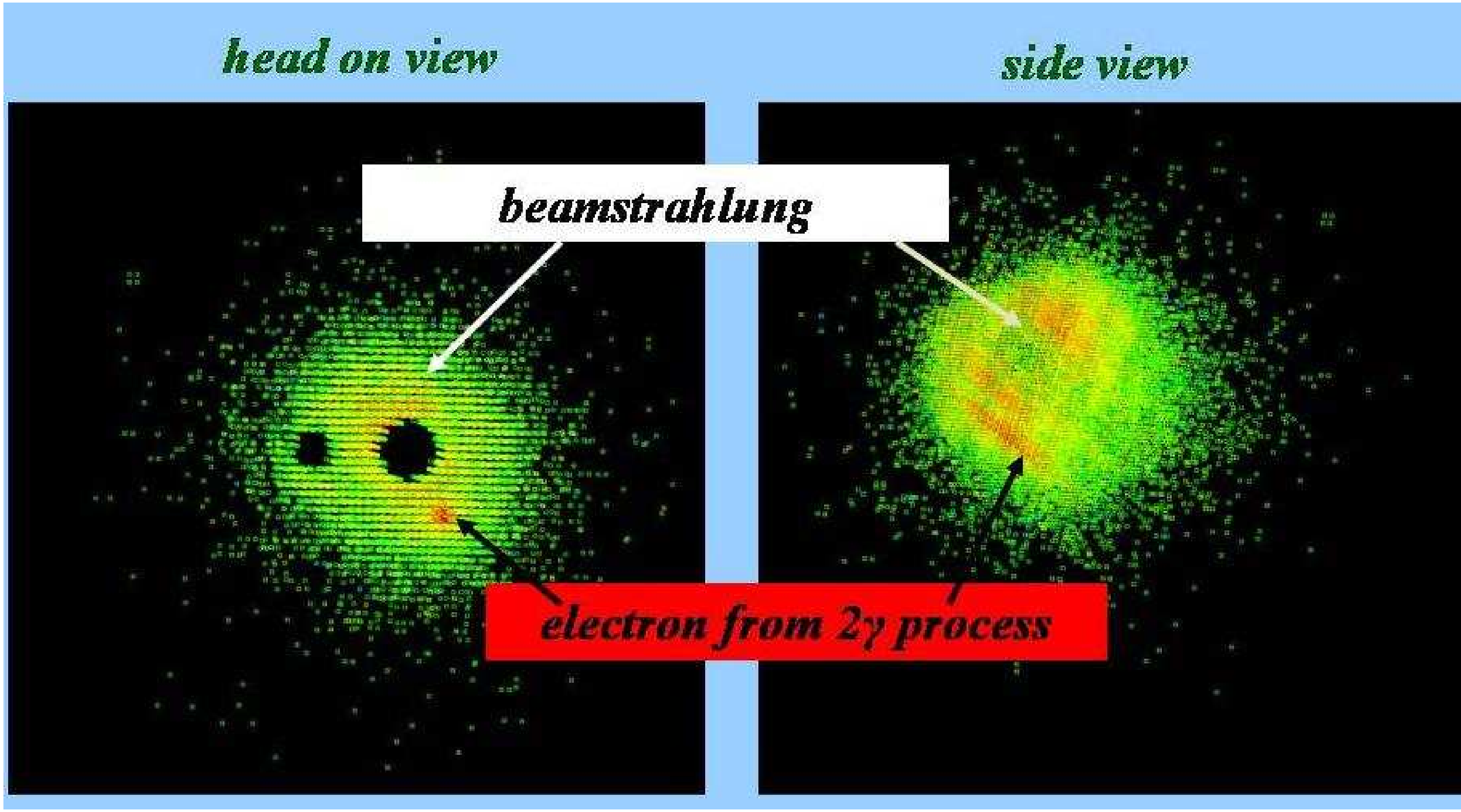
2-Photon Background

T. Dunn, J. Gill, G. Oleinik, U. Nauenberg, J. Yu, F. Yi



2-Photon – BeamCal

T. Dunn, J. Gill, G. Oleinik, U. Nauenberg, J. Yu, F. Yi



2-Photon – BeamCal Study

T. Dunn, J. Gill, G. Oleinik, U. Nauenberg, J. Yu, F. Yi

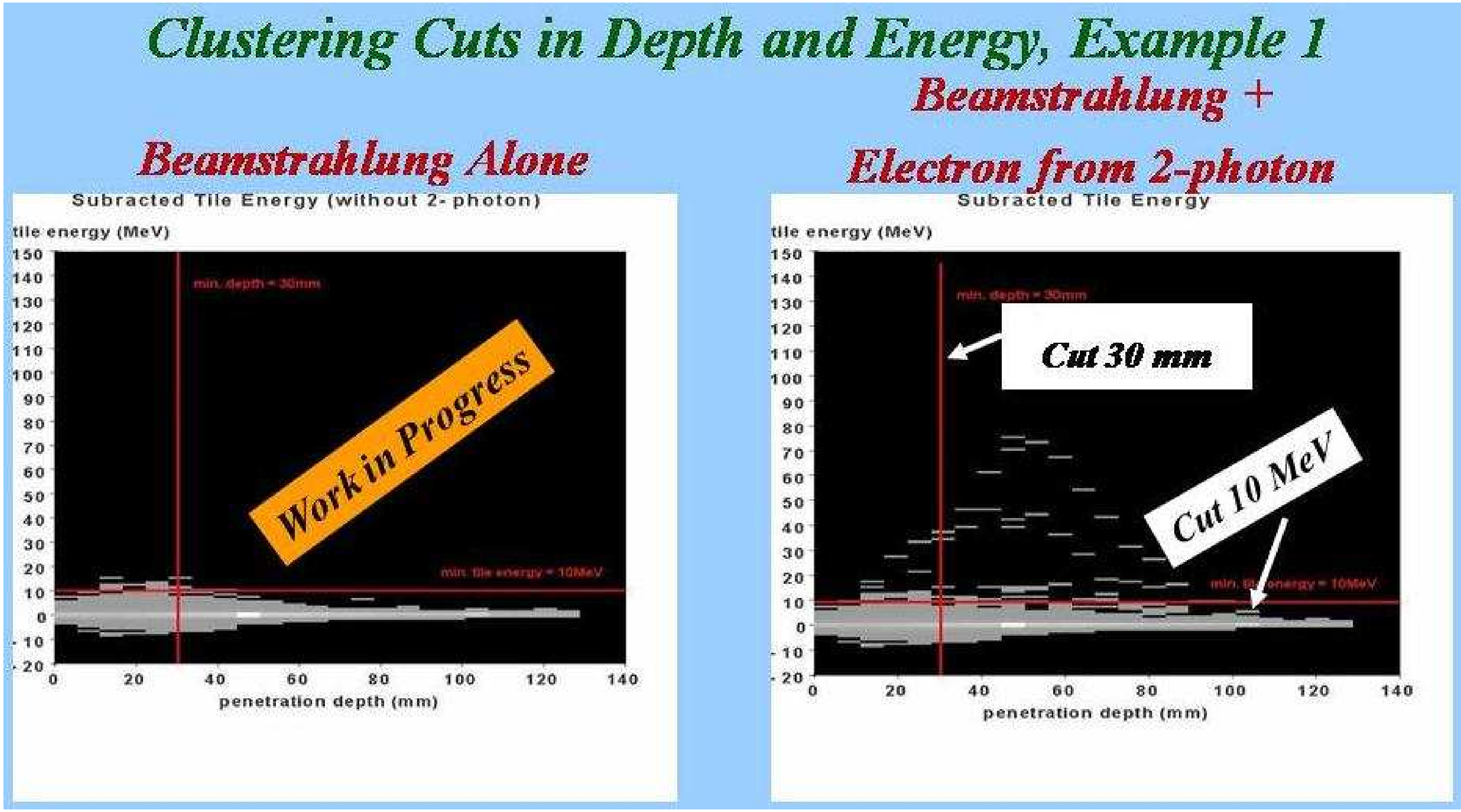
Goal: measure p_T of electron from 2γ processes, prove that $p_{T,\text{tot}} = 0$, remove event because it's not BSM.

Study cuts around e in a cylinder around the electron. Find optimal trade-off between resolution (beamstrahlung mixes in, the bigger the radius) and percent of energy of electron captured (electron showers)

Cut at $\sim 20 - 25$ mm, corresponding to 10 mrad $\Rightarrow$ at a beam energy of 250 GeV each, this corresponds to the ability to see missing $p_T > 2.5$ GeV!

2-Photon – BeamCal, Cuts

T. Dunn, J. Gill, G. Oleinik, U. Nauenberg, J. Yu, F. Yi



Summary

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