Overview of New Physics Searches at the ILC

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LINEAR COLLIDER COLLABORATION

Contents

- Direct search for new physics at ILC
  → with focus on SUSY Electroweak Sector

Science Council of Japan

Excerpt from Science Council of Japan's report
(unofficial translation by H. Yamamoto):

- We acknowledge the academic case as particle physics regarding the high-precision studies of the Higgs particle and the top quark as well as searches for physics beyond the standard model by the ILC project. On the other hand, as for the strategy to search for undiscovered particles and physics beyond the standard model, clearer and more persuasive arguments - including the relation with the LHC which is planned to be upgraded - are desired that measures up to the huge investment required for this project.

→ **BSM physics case at the ILC needs to be sharpened!**

(in a way that people reporting to places like the SCJ can easily present)

Introduction

- The bottom line:
  - **We must continue to update the case for the ILC, taking into account the latest results in both theory and experiment.**

- The Higgs discovery in 2012 sparked many discussions well into the year 2013 and will likely to continue for years to come.
  - **The case for precision Higgs studies at the ILC is now fairly mature.**

- The BSM physics case will be affected by other experiments, many of which will run before the ILC starts!
  - **LHC / HL-LHC,** SuperKEKB, LFV, Neutrino, Dark Matter, …

- The absence of any direct experimental evidence (so far) for new particles other than the Higgs means that we still have to work with many possibilities, e.g.:
  - **what if LHC finds a new particle in the 14 TeV run?**
  - what if the new particle is heavier than 500 GeV?
  - what if it doesn't find anything?
  - etc.

Snowmass Whitepaper

- ILC Snowmass Whitepaper for BSM Physics:
  - "Physics Case for the ILC Project: Perspective from Beyond the Standard Model" [arXiv:1307.5248]

- **A concise report on the ILC capabilities for direct BSM searches.**

- I will review a few selected topics in this talk.

Higgs mass and Naturalness

- With the Higgs mass now fixed at ~125 GeV, the question of naturalness can be discussed in concrete terms.
  - We now know in the context of the **MSSM:**
    - The top squark mass must be either heavy or have a large L-R mixing
    - The fine-tuning now stands at around ~10^{-2}
    - But there is an exciting window of opportunity for the ILC: **Higgsinos**

SUSY is a special case. There is a potentially large positive contribution to the Higgs mass term that must be cancelled.

$$m_Z^2 = 2\,\frac{M_{Hd}^2 - \tan^2\beta M_{Hu}^2}{\tan^2\beta - 1} - 2\mu^2$$

No large cancellations:

$\mu \lesssim 200$ GeV	Higgsino mass
$m(\tilde{t}) \lesssim 1$ TeV	stop mass
$m(\tilde{g}) \lesssim 3$ TeV	gluino mass

Optimistically, we will get there at HL-LHC.

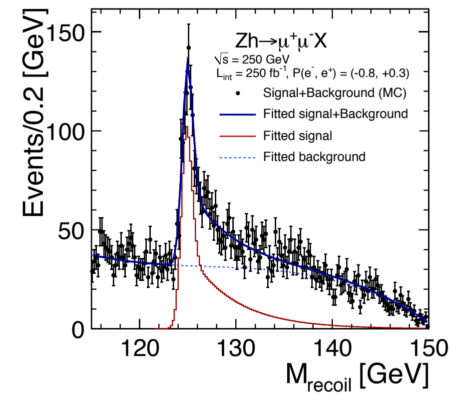
M. Peskin, Snowmass

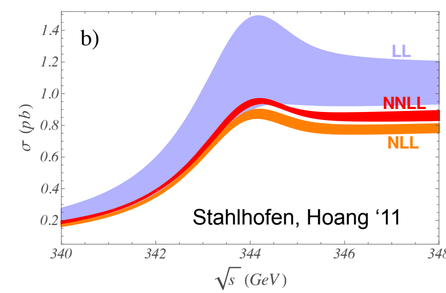
- If the LSP is Higgsino-like, the typically degenerate spectrum of masses makes it very challenging for the LHC to observe the Higgsinos.
- **ILC can find them.**

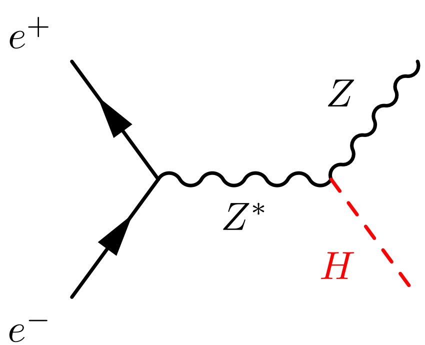
Physics at the ILC

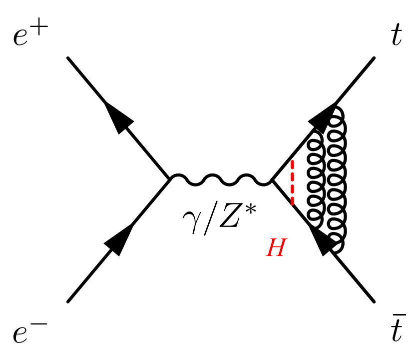
Main goals of the ILC physics program:

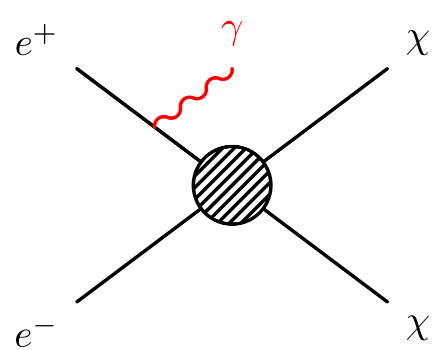
- **Direct searches for new physics**
  - Model-independent discovery reach for **color-neutral states** (e.g. dark matter) significantly exceeds that of LHC
- **Precise measurements of**
  - The **Higgs sector, top quark, W/Z bosons**
  - Sensitivity to new physics through **tree-level** and **quantum effects**
  - **GUARANTEED!**

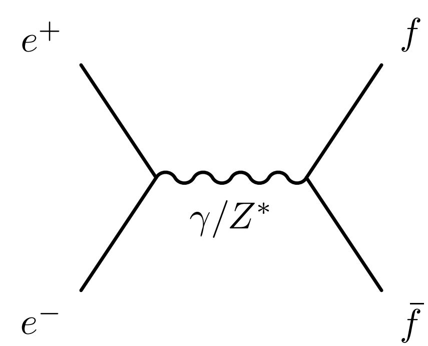












Supersymmetric Particles

spin	0	1/2	1
	squark	quark	
Quark family	$\begin{pmatrix}\tilde{u}_L\\ \tilde{d}_L\end{pmatrix}$ $\begin{pmatrix}\tilde{c}_L\\ \tilde{s}_L\end{pmatrix}$ $\begin{pmatrix}\tilde{t}_L\\ \tilde{b}_L\end{pmatrix}$ $\tilde{u}_R$ $\tilde{c}_R$ $\tilde{t}_R$ $\tilde{d}_R$ $\tilde{s}_R$ $\tilde{b}_R$	$\begin{pmatrix}u_L\\ d_L\end{pmatrix}$ $\begin{pmatrix}c_L\\ s_L\end{pmatrix}$ $\begin{pmatrix}t_L\\ b_L\end{pmatrix}$ u_R c_R t_R d_R s_R b_R	
	slepton	lepton	
Lepton family	$\begin{pmatrix}\tilde{\nu}_{eL}\\ \tilde{e}_L\end{pmatrix}$ $\begin{pmatrix}\tilde{\nu}_{\mu L}\\ \tilde{\mu}_L\end{pmatrix}$ $\begin{pmatrix}\tilde{\nu}_{\tau L}\\ \tilde{\tau}_L\end{pmatrix}$ $\tilde{e}_R$ $\tilde{\mu}_R$ $\tilde{\tau}_R$	$\begin{pmatrix}\nu_{eL}\\ e_L\end{pmatrix}$ $\begin{pmatrix}\nu_{\mu L}\\ \mu_L\end{pmatrix}$ $\begin{pmatrix}\nu_{\tau L}\\ \tau_L\end{pmatrix}$ e_R μ_R τ_R	
	Higgs boson	Higgsino	
Higgs particles	$\begin{pmatrix}\phi_1^0\\ \phi_1^-\end{pmatrix}$ $\begin{pmatrix}\phi_2^+\\ \phi_2^0\end{pmatrix}$	$\begin{pmatrix}\tilde{\phi}_1^0\\ \tilde{\phi}_1^-\end{pmatrix}$ $\begin{pmatrix}\tilde{\phi}_2^+\\ \tilde{\phi}_2^0\end{pmatrix}$	
		Gagino	Gauge boson
Gauge particle		$\tilde{\gamma}$ $\tilde{Z}^0$ $\tilde{W}^\pm$ $\tilde{g}$	γ Z^0 $W^\pm$ g

Colored

Color neutral

Extended Higgs
h, H, A, H⁺, H⁻

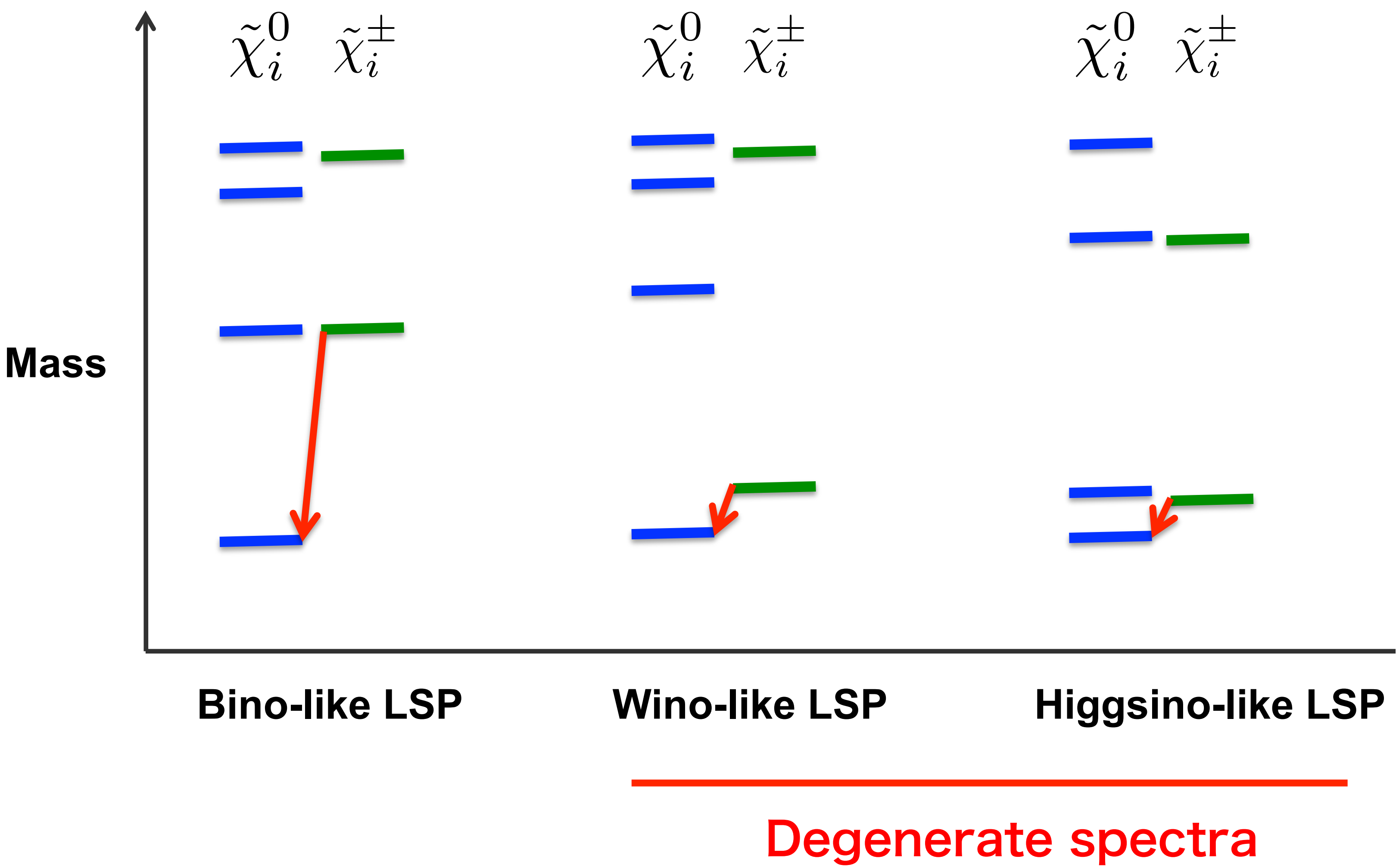
$(\tilde{\gamma}, \tilde{Z}^0, \tilde{\phi}_1^0, \tilde{\phi}_2^0) \rightarrow (\tilde{\chi}_1^0,\ \tilde{\chi}_2^0,\ \tilde{\chi}_3^0,\ \tilde{\chi}_4^0)$ **Neutralino**

$(\tilde{W}^\pm,\ \tilde{\phi}^\pm) \rightarrow (\tilde{\chi}_1^\pm,\ \tilde{\chi}_2^\pm)$ **Chargino**

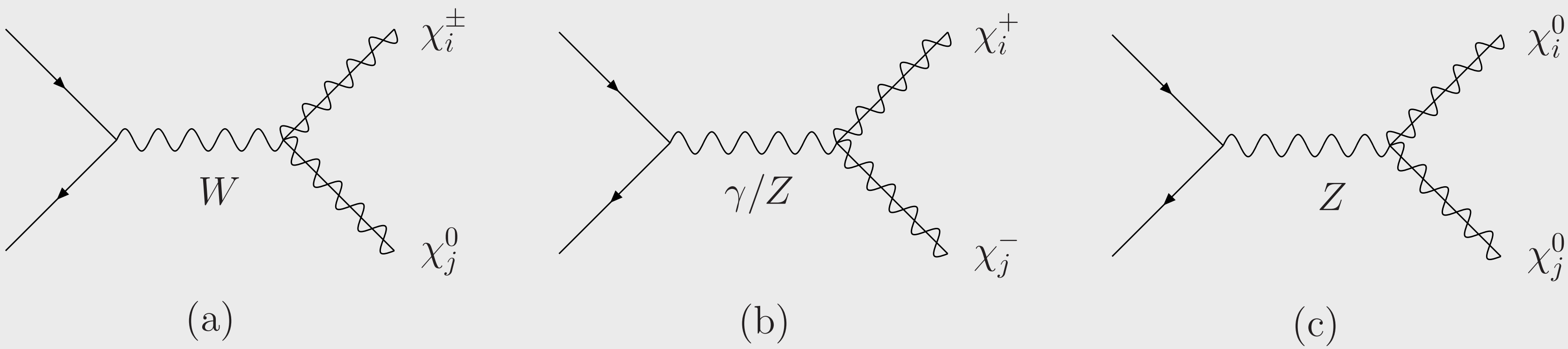
Gauge eigenstates Mass eigenstates

Lightest SUSY Particle (LSP) = Dark Matter candidate (if R-parity is conserved)

SUSY Electroweak Sector



Chargino / Neutralino Production



For LHC:

$$p\bar{p} \to \tilde{\chi}_1^\pm \tilde{\chi}_2^0 X,\ \tilde{\chi}_1^+ \tilde{\chi}_1^- X,\ \ldots$$

For ILC:

$$e^+e^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^-,\ \tilde{\chi}_2^+ \tilde{\chi}_2^-,\ \tilde{\chi}_1^0 \tilde{\chi}_2^0,\ \ldots$$

Decays:

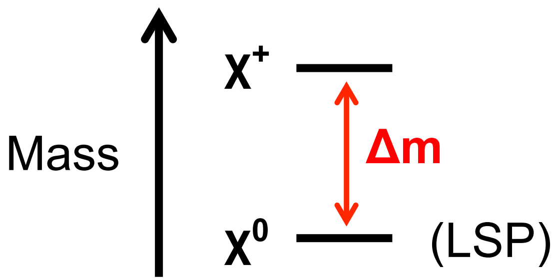
$$\tilde{\chi}_1^\pm \to W^\pm \tilde{\chi}_1^0$$

$$\tilde{\chi}_2^0 \to (Z/h) \tilde{\chi}_1^0$$

$$\cdots$$

Chargino / Neutralino Search

Search for decays into Dark Matter
e.g. C1→N1 decay



$$\tilde{\chi}_1^+ \rightarrow W^{+(*)} \tilde{\chi}_1^0 \rightarrow f f' \tilde{\chi}_1^0$$

Typically,

$$N_{\rm sig}^{pp} > N_{\rm sig}^{e^+e^-}$$

$$N_{\rm bkg}^{pp} \gg N_{\rm bkg}^{e^+e^-}$$

Large mass difference (Δm > mW)

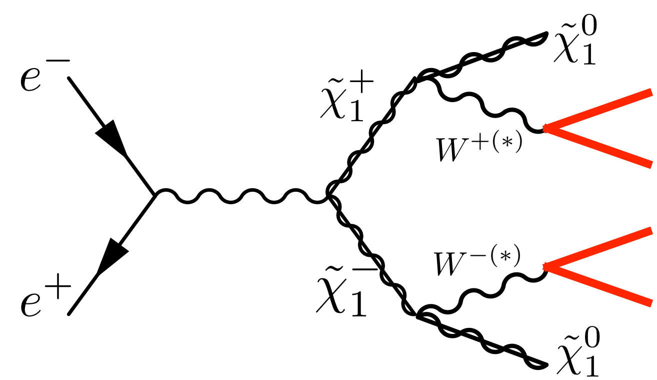
→ Signature: hard jets / leptons

→ High mass reach at LHC/HL-LHC

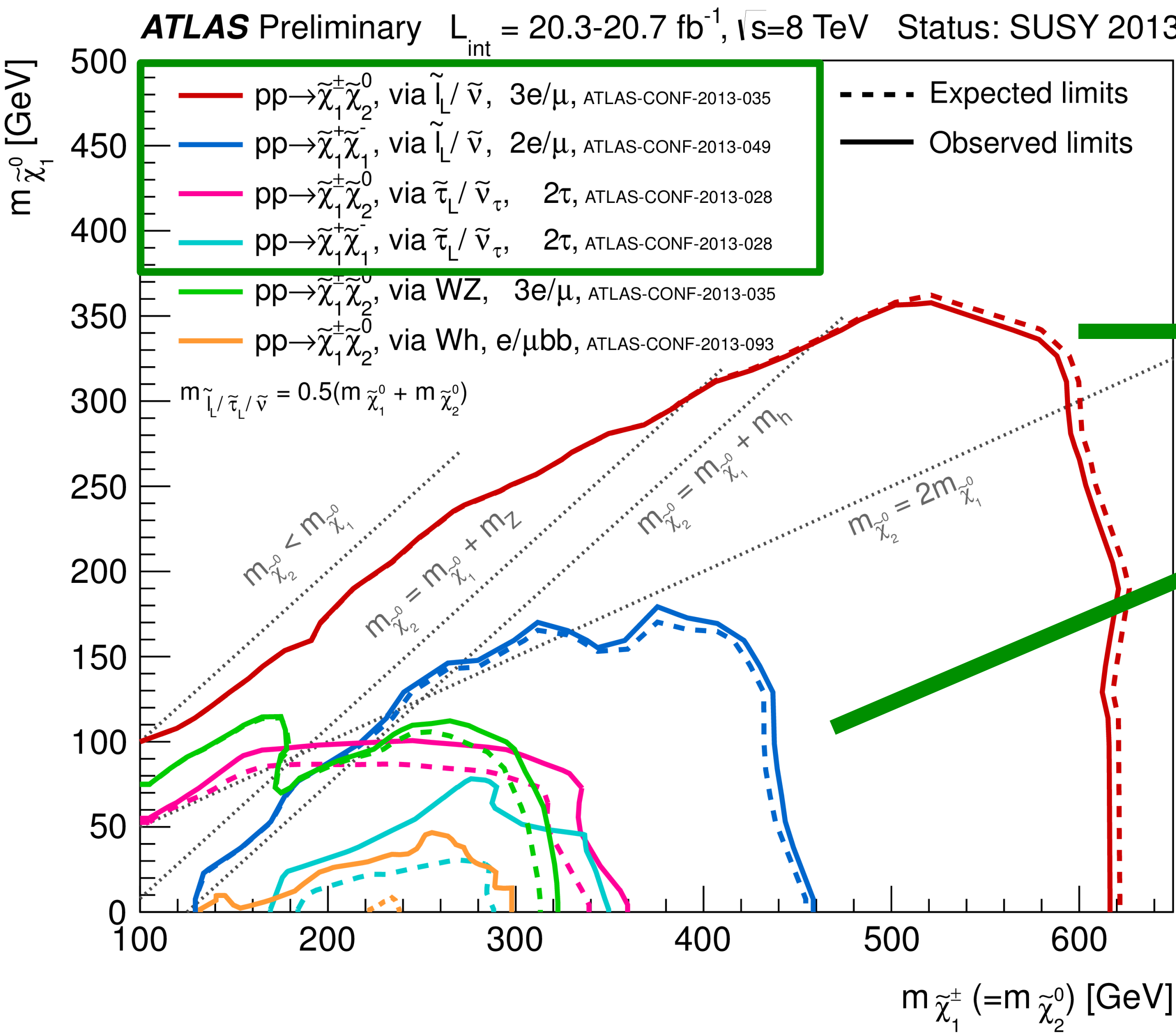
Small mass difference (Δm < mW)

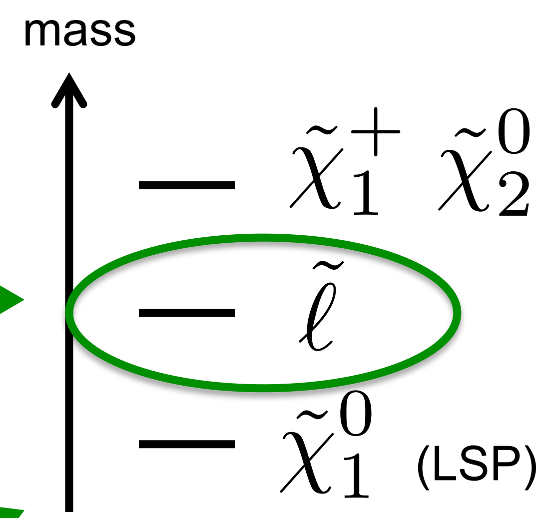
→ Signature: soft particles

→ High sensitivity at ILC



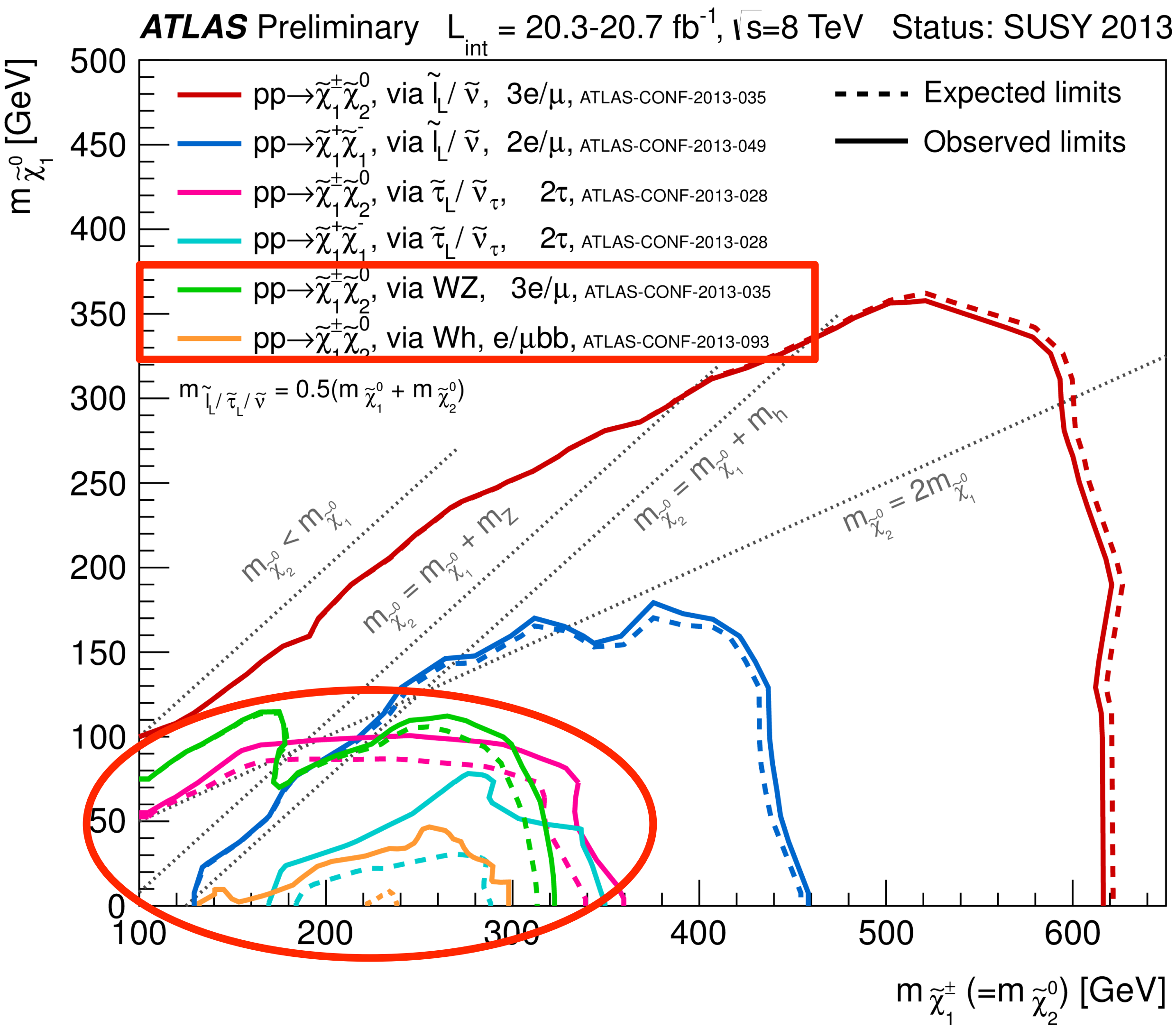
Electroweakino Search at LHC

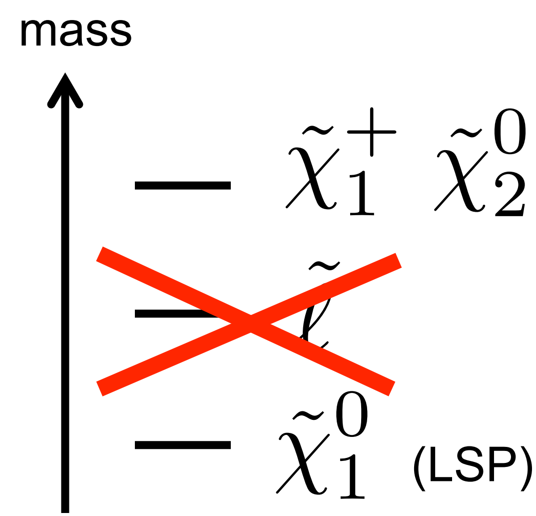




Constraints for specific mass hierarchy

Electroweakino Search at LHC





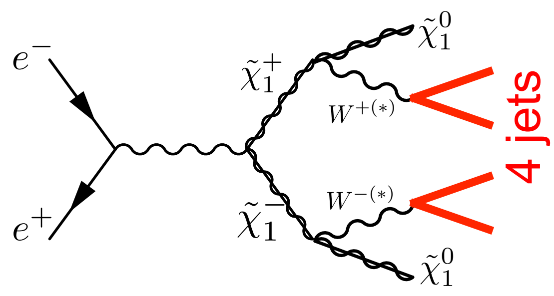
$$\mathcal{B}(\tilde{\chi}_2^0 \to Z/h\,\tilde{\chi}_1^0)$$

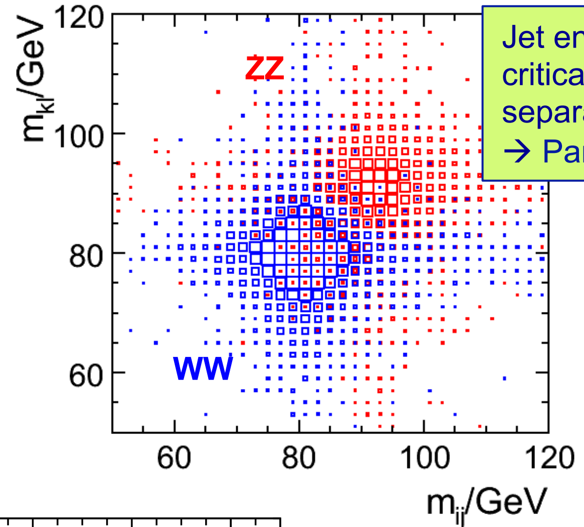
Assumes 100% BR

Not true in general due to Gaugino / Higgsino mixing

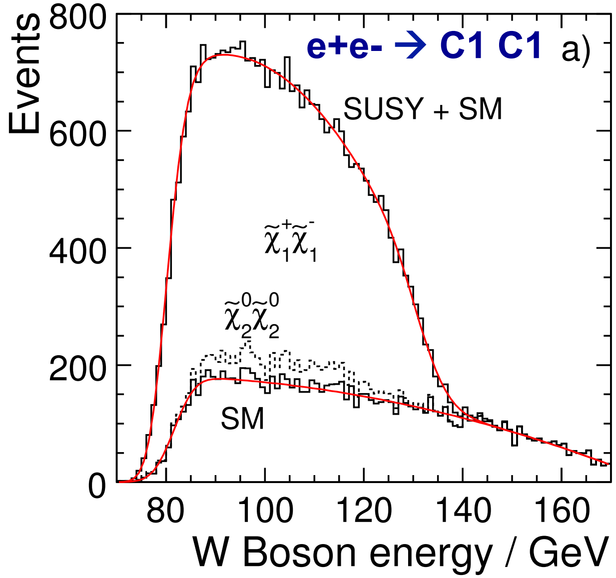
Gaugino Search at ILC

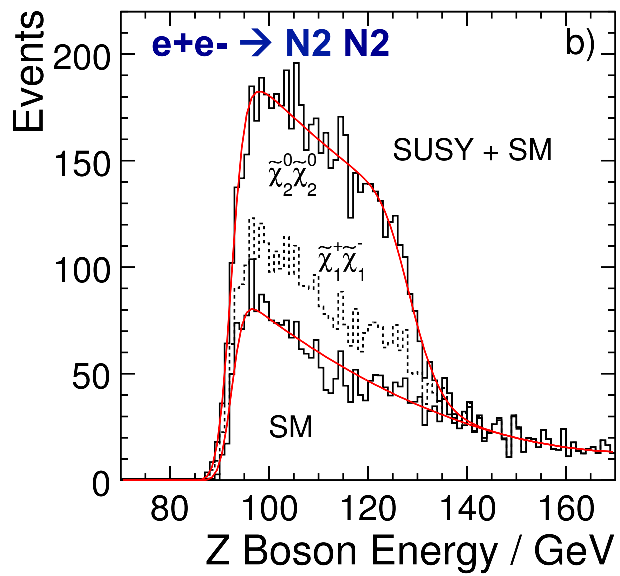
Reconstruct the hadronic decay of the chargino: **4 jets + missing 4-momentum**





Jet energy resolution critical for W/Z separation
→ Particle Flow





Suehara, List [arXiv:0906.5508]

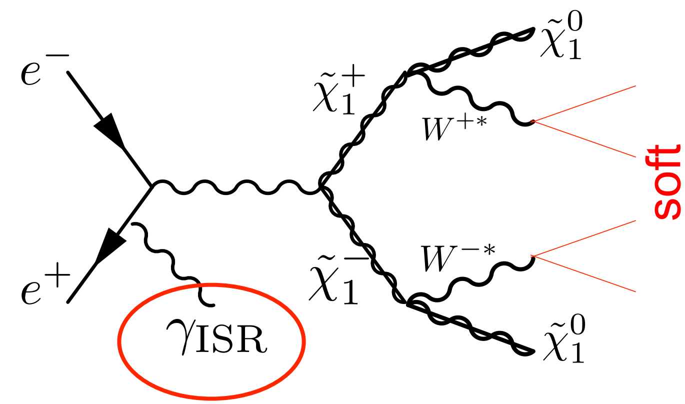
Gauginos can be discovered with mass precision O(1%)

Higgsino Search at ILC

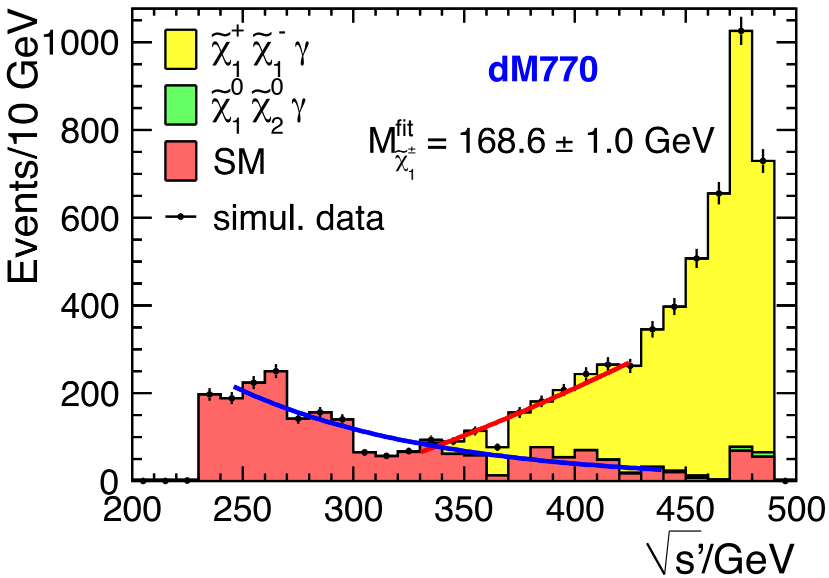
Signature: ISR photon + soft particles

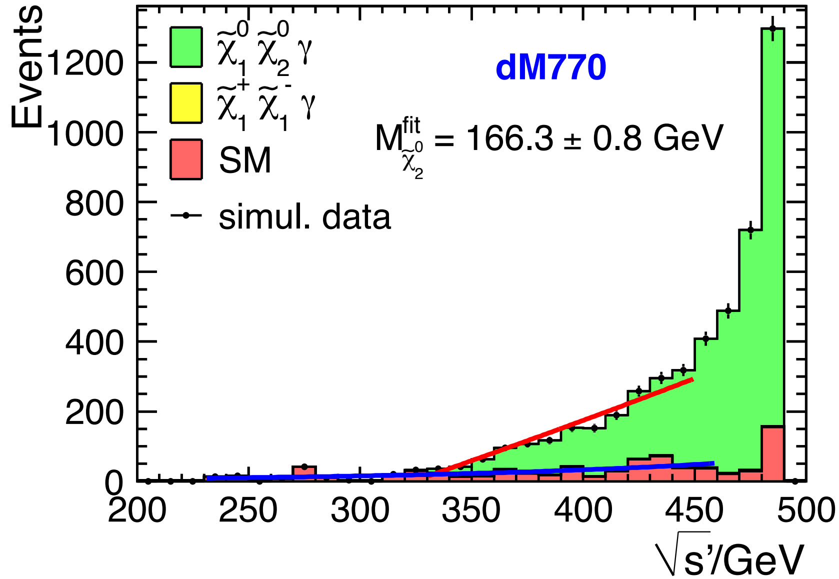
ISR tag reduces two-photon backgrounds.

Hermeticity essential for ISR tag → Forward Calo.
Reconstruction of low pT tracks → Silicon Tracking

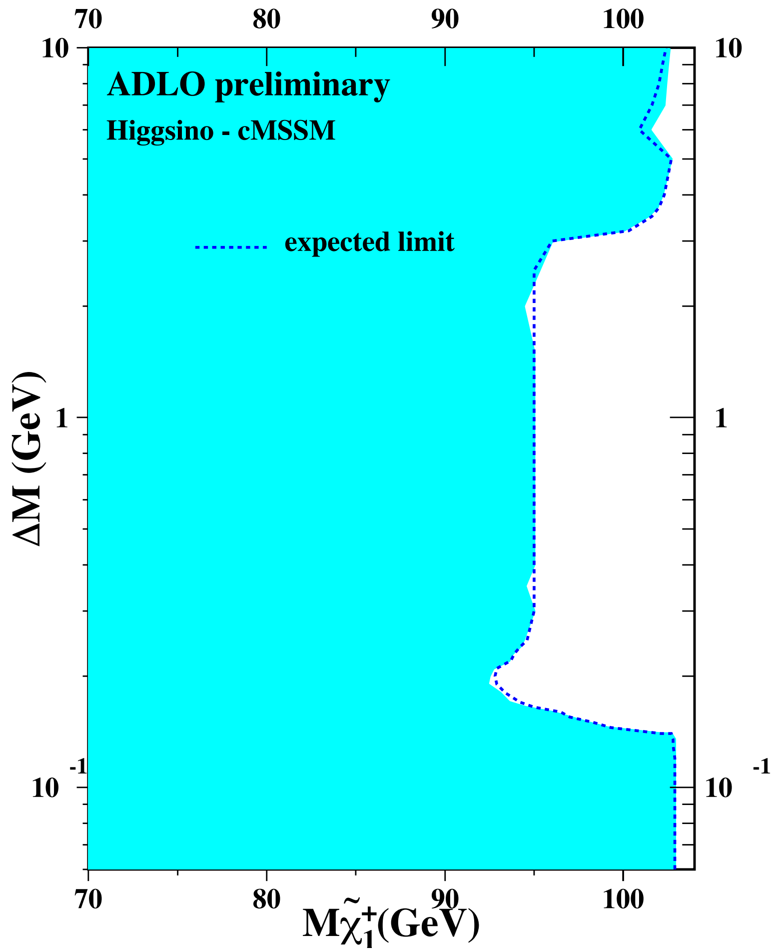


Berggren, Bruemmer, List, Moortgat-Pick, Robens, Rolbiecki, Sert [arXiv:1307.3566]

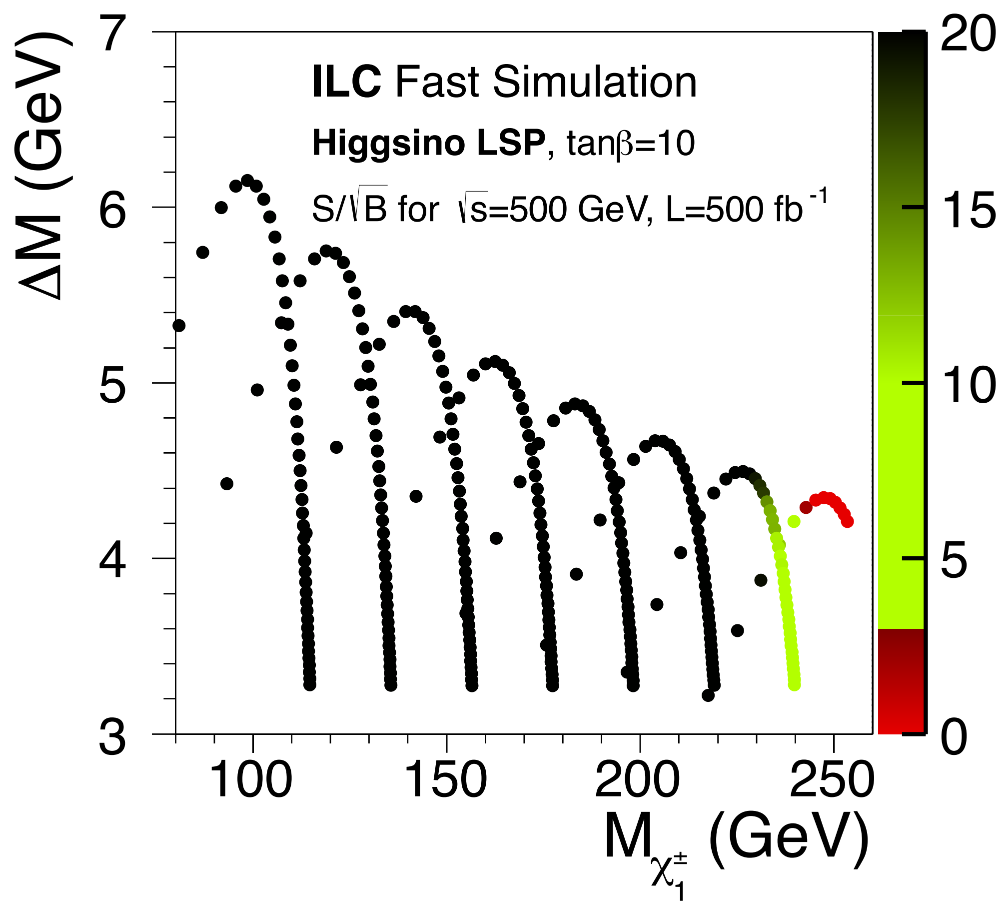




Higgsinos can be discovered with mass precision O(1%)



LEP2 Combination

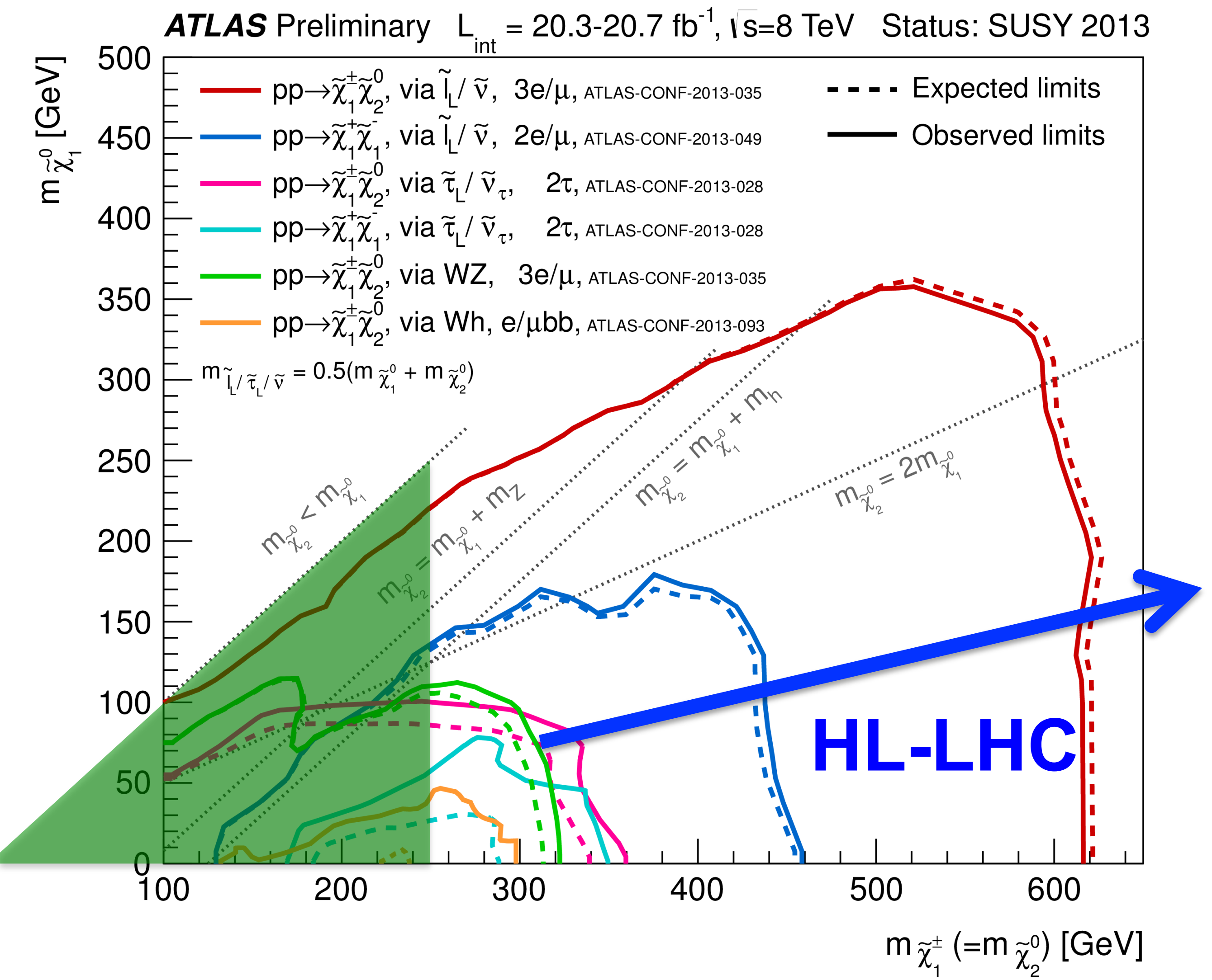


ILC Fast Simulation

Berggren, Han, List, Padhi, Su, TT

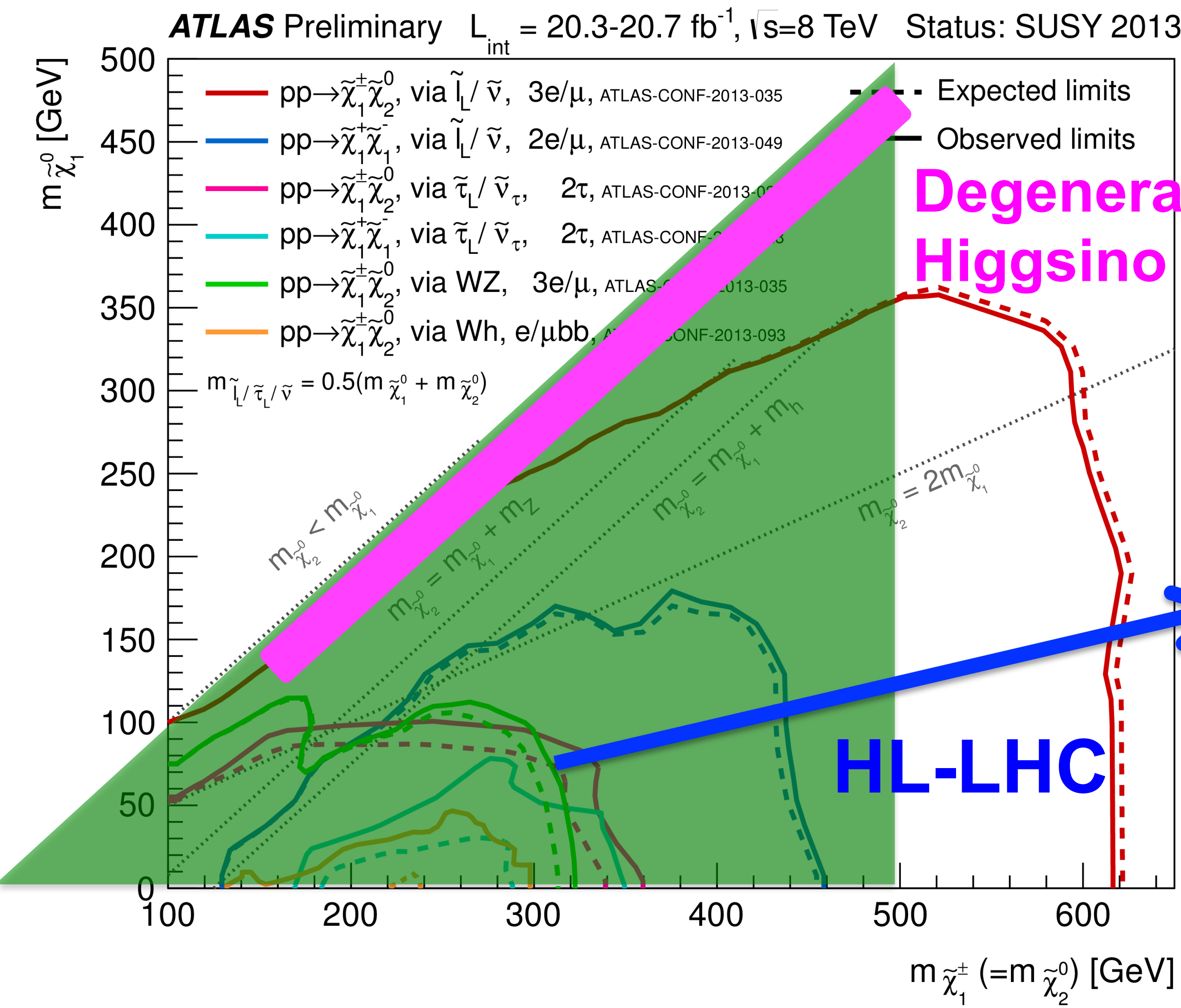
[arXiv:1309.7342]

Electroweakino Search



ILC 500 GeV
no assumptions!

Electroweakino Search



Degenerate spectra:
Higgsino / Wino LSP

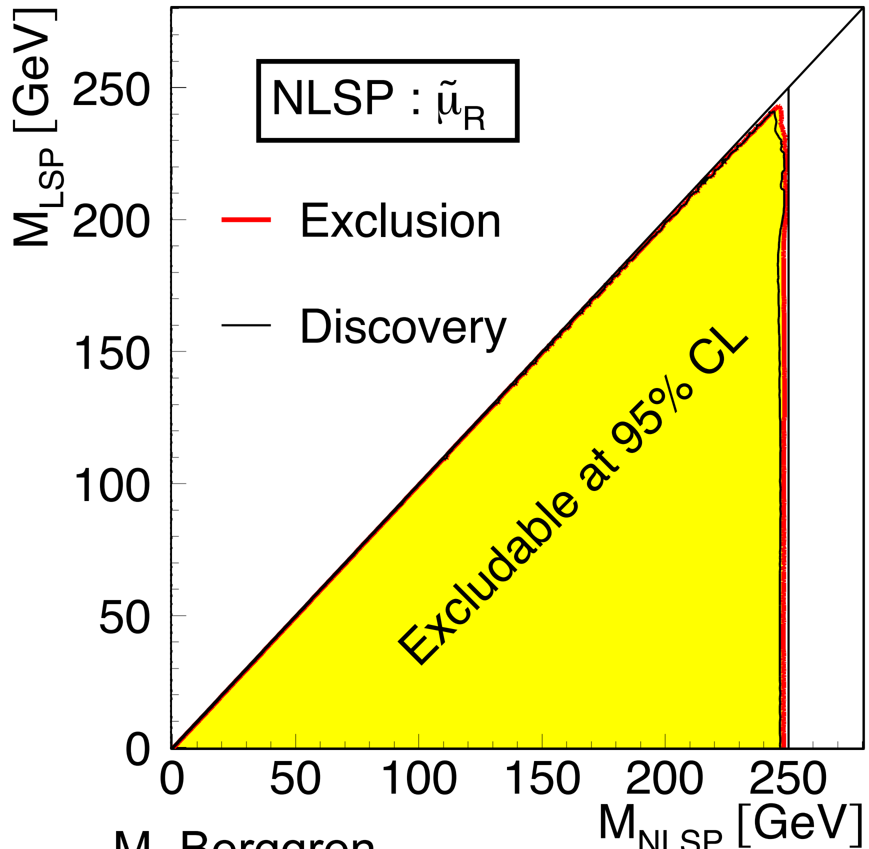
ILC 1 TeV
no assumptions!

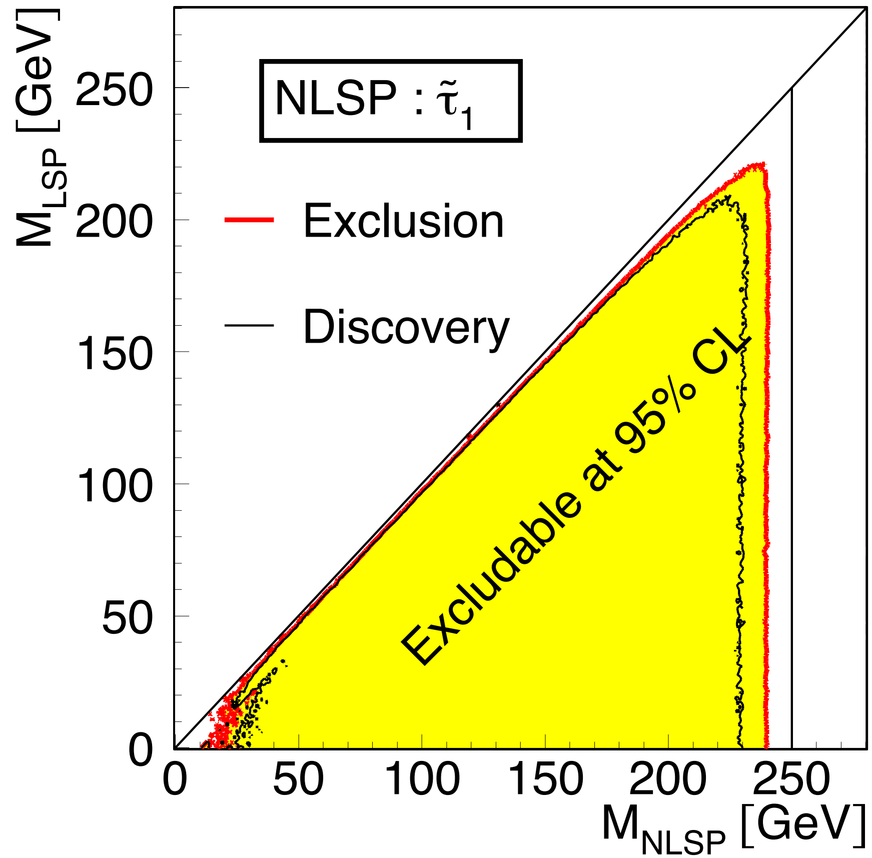
→ Synergy of HL-LHC and ILC

Slepton Search at ILC

smuon → LSP + muon

stau → LSP + tau



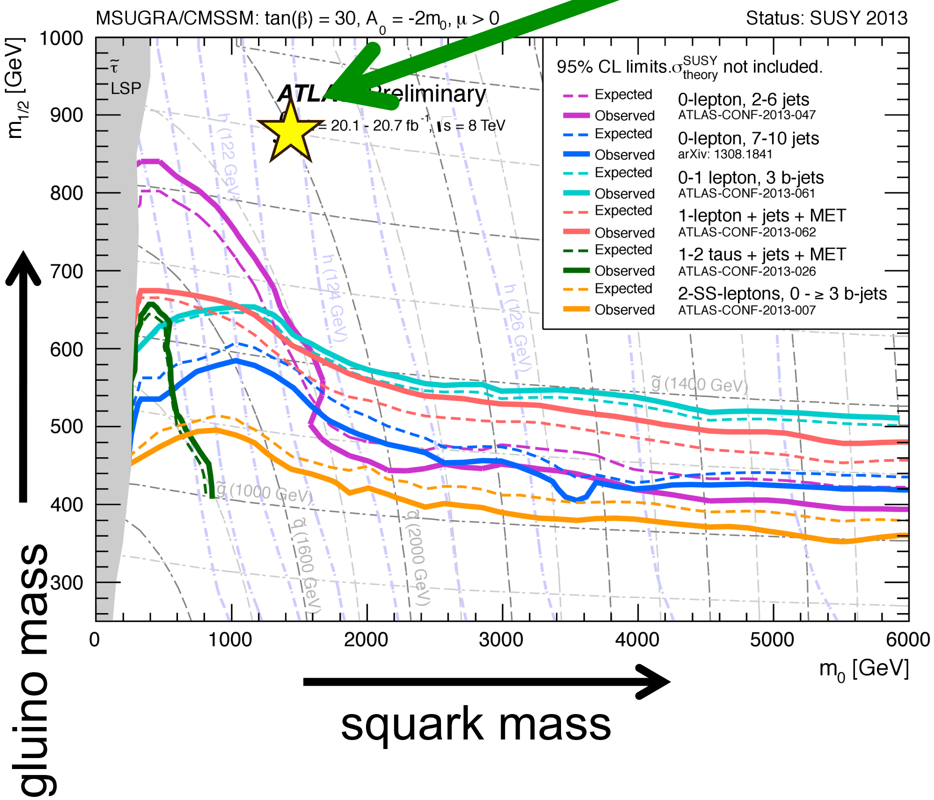


M. Berggren

Discovery reach: mass up to $\sqrt{s}/2$

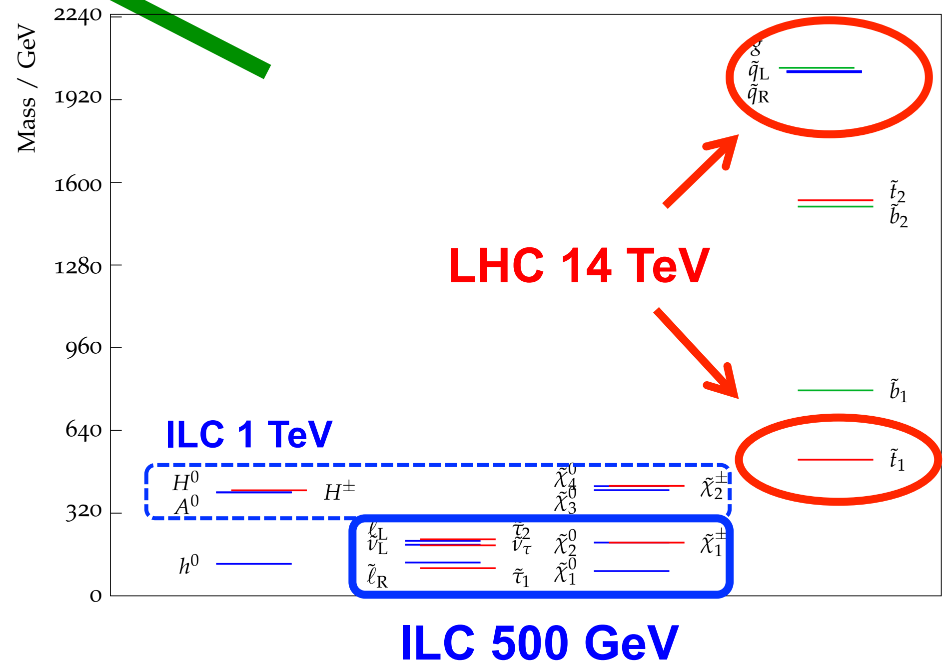
An Optimistic Story

CMSSM search @ LHC



Benchmark [quoted in arXiv:1307.5248]

Pre-LHC cMSSM fit based on electroweak & flavor observables (w/o mass unification at GUT scale)



→ Discover SUSY with LHC/ILC synergy

Summary

The ILC will be the energy frontier in e+e- collisions.

→ Since it is linear, it energy can be extended in the future

→ The technical design is complete

Unique measurements using e+e- collisions:

→ Direct search for new physics: mass reach of approx. $\sqrt{s}/2$

Search for Gaugino, Higgsino, Slepton

→ Precise study of Higgs, top, W/Z:

Absolute ZH cross section measurement → 250 GeV

Precise determination of all Higgs couplings → 500 GeV, 1 TeV

→ Both have great LHC/ILC synergies!

Personal Remarks

Personal answers to the questions that were raised at the beginning:

- **What if LHC finds a new particle in the 14 TeV run?**
  - **Study them at the ILC!**

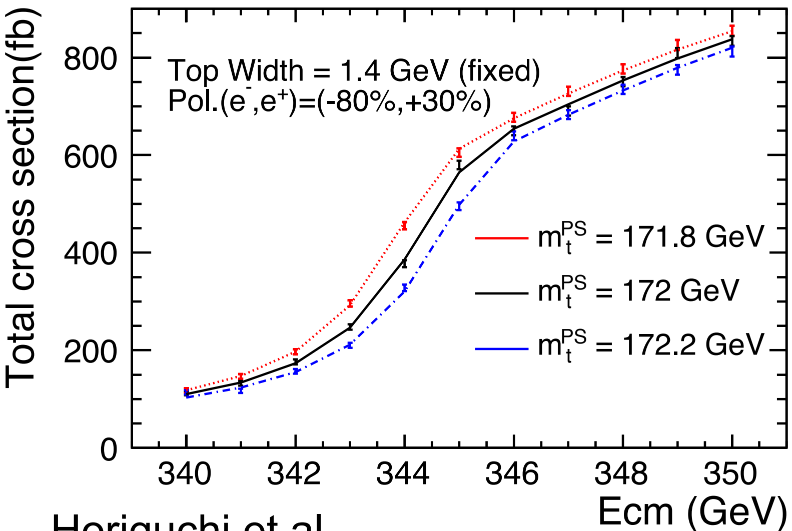
- **What if the new particle is heavier than 500 GeV?**
  - Many new physics models predict **accompanying particles** which are lighter and difficult to detect at the LHC. **ILC can search them.**
  - **In the future,** we will eventually want to run e+e- collisions at the resonance. The linear collider the only realistic option to reach energies beyond 1 TeV. **The ILC will then become a prelude to a 50 year program in linear e+e- collisions.**

- **What if it doesn't find anything?**
  - Proceed with the **precision Higgs/top/W/Z studies to challenge the SM.**

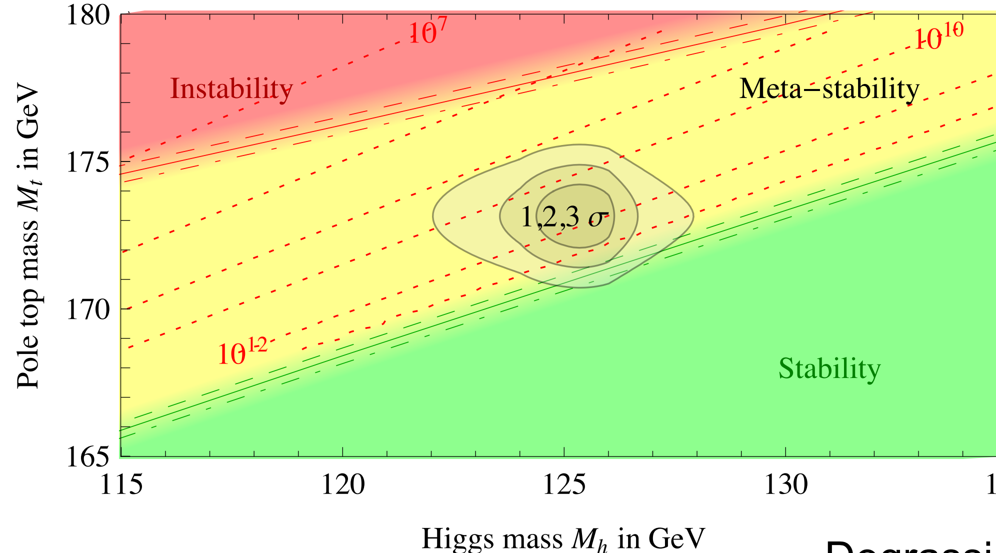
Additional Slides

Top Physics at ILC

At ttbar threshold ~350 GeV: precise measurement of the top mass



Horiguchi et al.



Degrassi

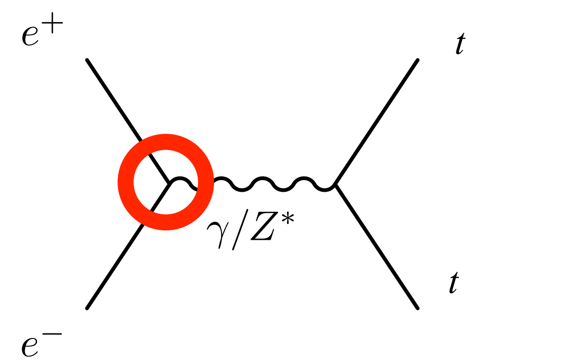
At 500 GeV:

Beam Polarization → disentangle γ/Z

A_{FB}, A_{LR}, A_{hel}, etc

Precise measurement of the ttZ / ttγ form factors

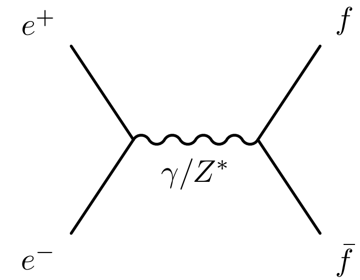
See: ILC TDR

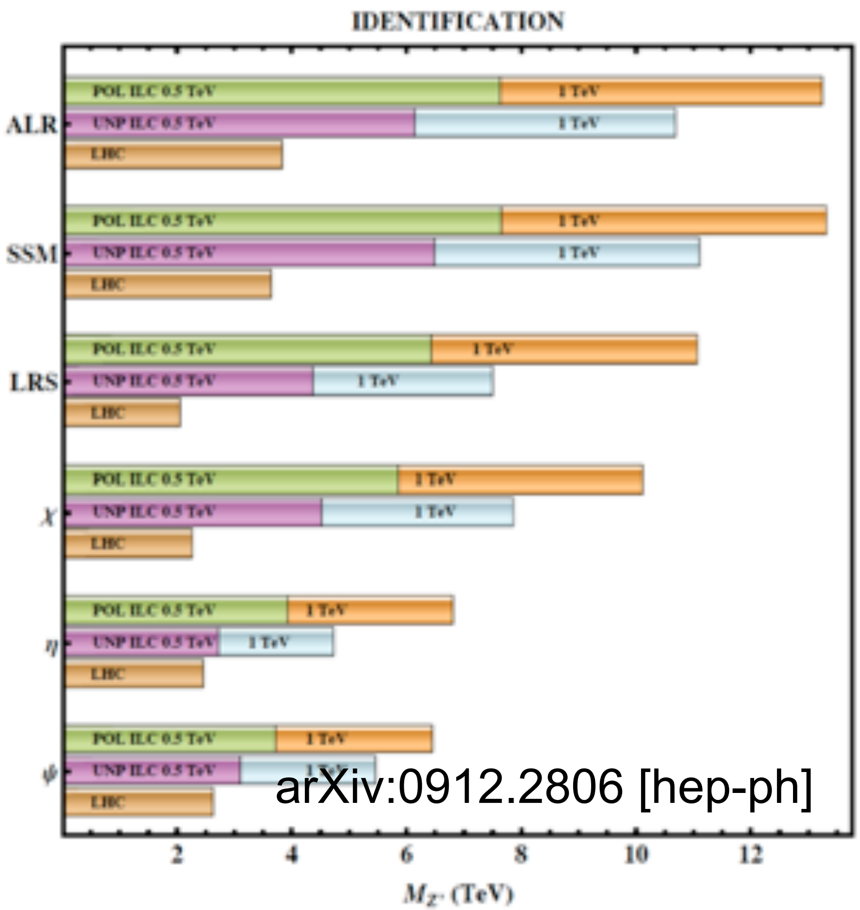


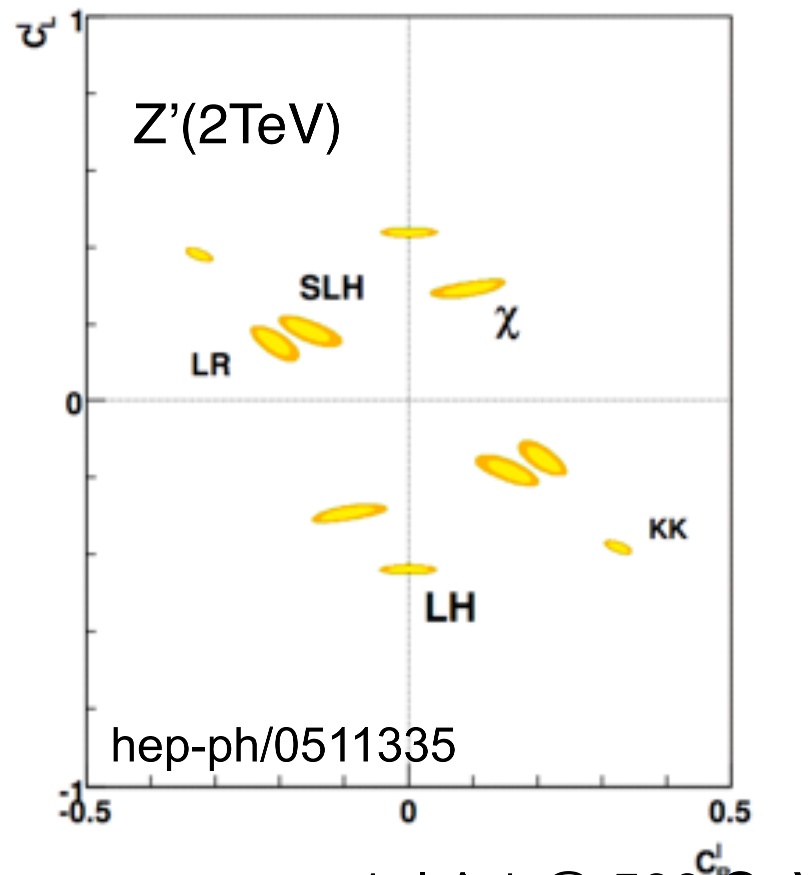
$$\Gamma_{\mu}^{ttX}(k^2,\, q,\, \overline{q}) = ie\left\{\gamma_\mu \left(\widetilde{F}_{1V}^{X}(k^2) + \gamma_5 \widetilde{F}_{1A}^{X}(k^2)\right) + \frac{(q-\overline{q})_\mu}{2m_t}\left(\widetilde{F}_{2V}^{X}(k^2) + \gamma_5 \widetilde{F}_{2A}^{X}(k^2)\right)\right\},$$

Search for Z’ boson

Polarized differential cross sections: LL/RR/LR/RL
Forward-backward asymmetries







1ab^-1 @ 500 GeV