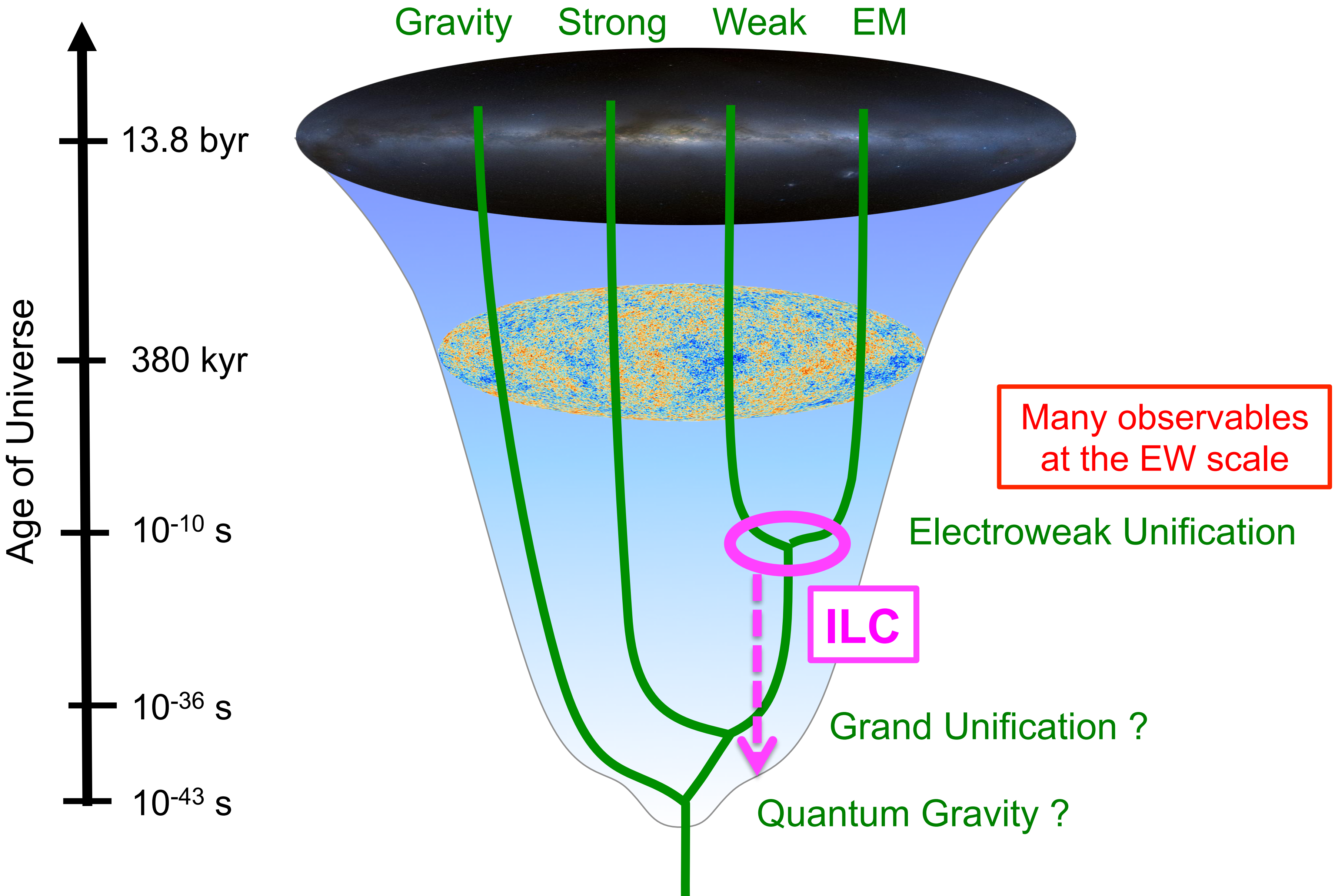
Overview of ILC Physics Case

Tomohiko Tanabe (U. Tokyo)
August 30, 2014
General Meeting, ILC Physics WG @ KEK

Towards a fundamental theory



Gravity Strong Weak EM

Age of Universe

13.8 byr

380 kyr

10^{-10} s

10^{-36} s

10^{-43} s

Many observables
at the EW scale

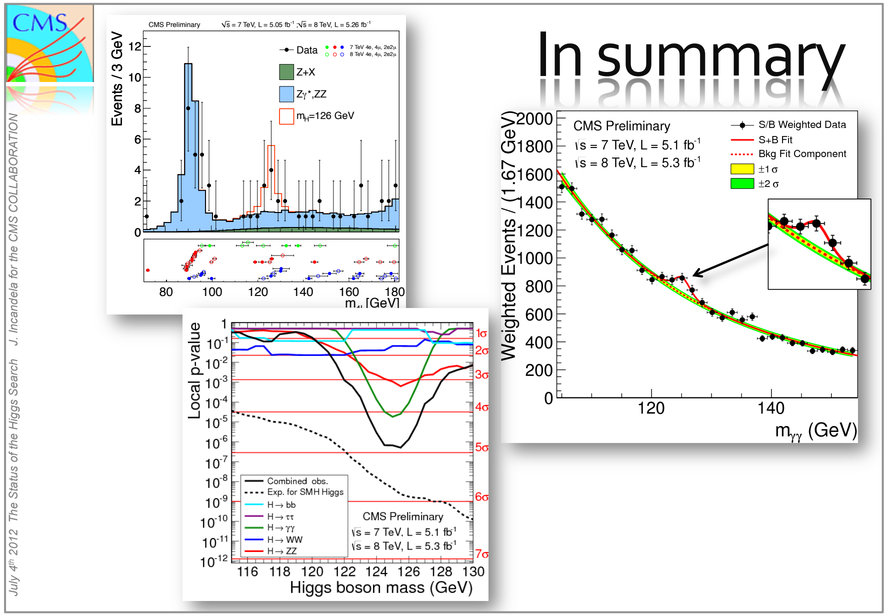
Electroweak Unification

ILC

Grand Unification ?

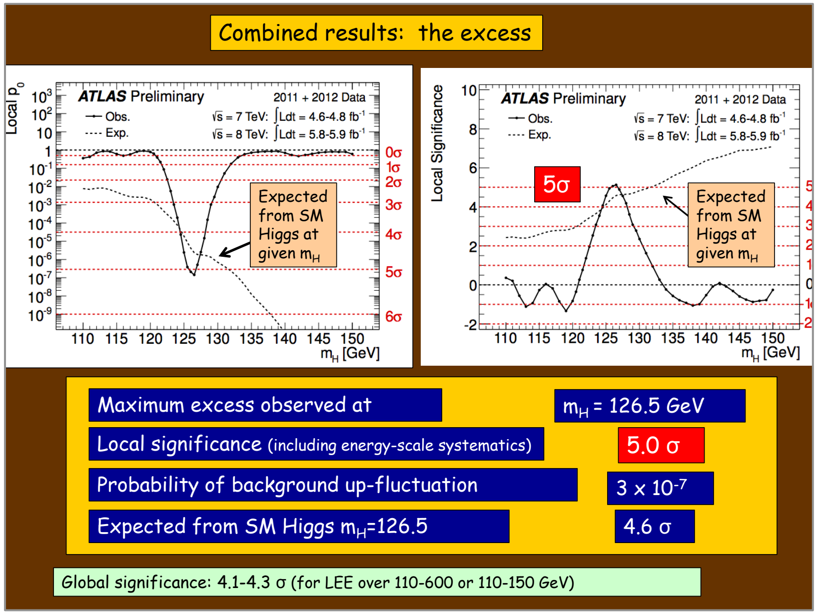
Quantum Gravity ?

July 4, 2012



In summary

July 4th 2012 The Status of the Higgs Search J. Incandela for the CMS COLLABORATION



Combined results: the excess

Maximum excess observed at	m_H = 126.5 GeV
Local significance (including energy-scale systematics)	5.0 σ
Probability of background up-fluctuation	3 x 10^{-7}
Expected from SM Higgs m_H=126.5	4.6 σ

Global significance: 4.1-4.3 σ (for LEE over 110-600 or 110-150 GeV)

Electroweak Symmetry Breaking

- With the discovery of the Higgs boson, we now understand how electroweak symmetry breaking (EWSB) occurs: via the expectation value of the Higgs field. **However, we do yet know the physics behind the EWSB.**

- Many **new physics** models which attempt to explain EWSB predict the existence of new forces/particles and modifications to the (SM) properties of **Higgs boson**, **top quark**, and **W/Z bosons**.

- It is **important to test these predictions** since they could be connected to the well-established observed phenomena which must require **new physics**, e.g.
  - baryon asymmetry
  - neutrino mixing
  - dark matter
  - …

Physics behind EWSB at TeV scale

There are two possible scenarios for the physics behind EWSB around the TeV scale:

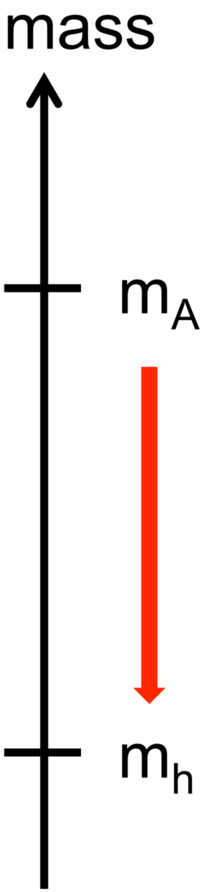
1. **Supersymmetry (SUSY):** SUSY breaking triggers EWSB.

2. **Composite Higgs:** a QCD-like theory is behind EWSB.

The **Higgs boson** and the **top quark** are crucial probes to distinguish these possibilities.

Higgs Physics at ILC

Deviation in Higgs Couplings



Many new physics models predict deviations in the properties of SM particles. **The size of the deviation depends on the scale of new physics.**

Example 1: MSSM (tanβ=5, radiative corrections ≈ 1)

$$\frac{g_{hbb}}{g_{h_{\mathrm{SM}}bb}} = \frac{g_{h\tau\tau}}{g_{h_{\mathrm{SM}}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \mathrm{TeV}}{m_A}\right)^2$$

heavy Higgs mass

Example 2: Minimal Composite Higgs Model

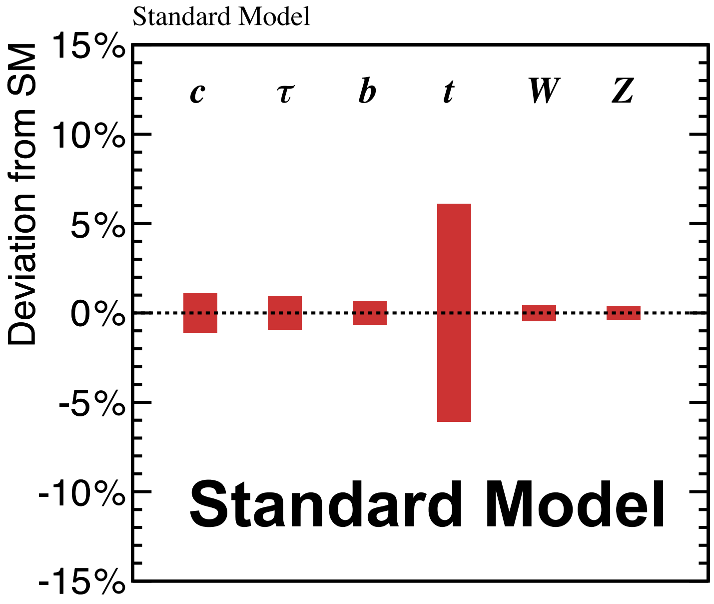
$$\frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 8.3\% \left(\frac{1\ \mathrm{TeV}}{f}\right)^2$$

composite scale

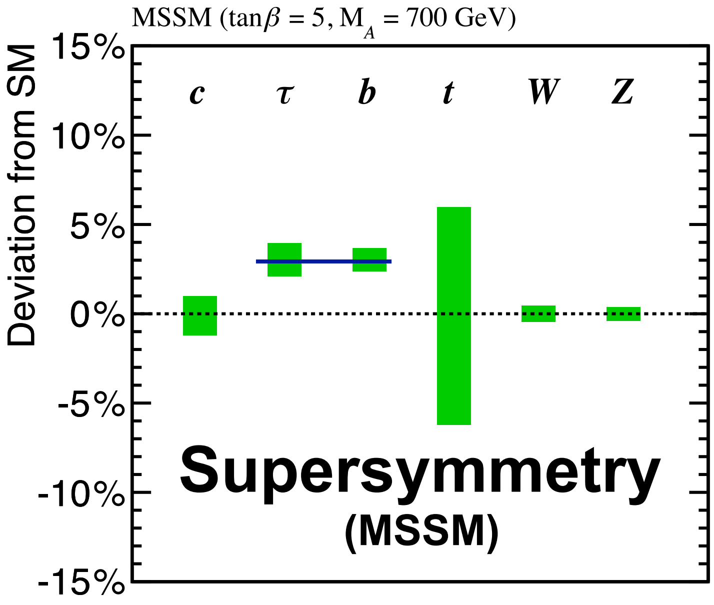
New physics at 1 TeV gives only a few percent deviation.
e+e- collider is needed to probe these scales via Higgs couplings.

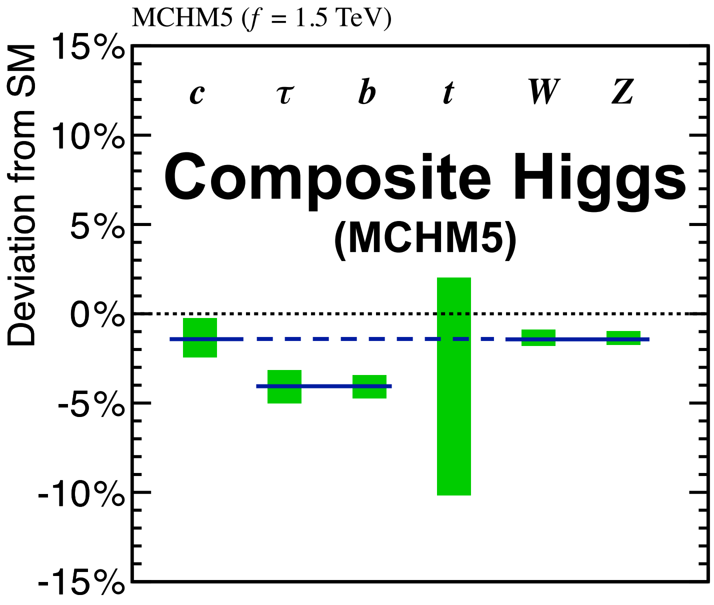
Impact of BSM on Higgs Sector

Deviations in Higgs couplings is a signature of many BSM theories. **The pattern of the deviations is often specific to certain models.** The precision Higgs coupling measurements at the ILC at the 1%-level enable us to discriminate the different models.

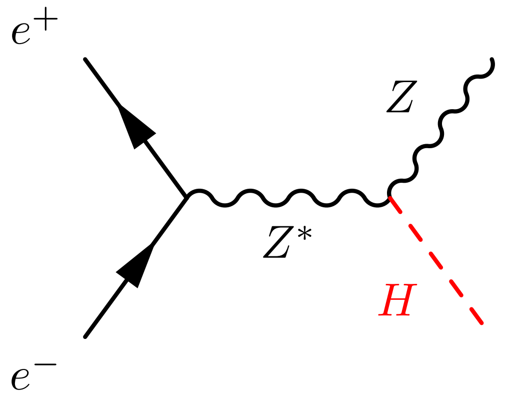


Lumi 1920 fb-1, sqrt(s) = 250 GeV
Lumi 2670 fb-1, sqrt(s) = 500 GeV

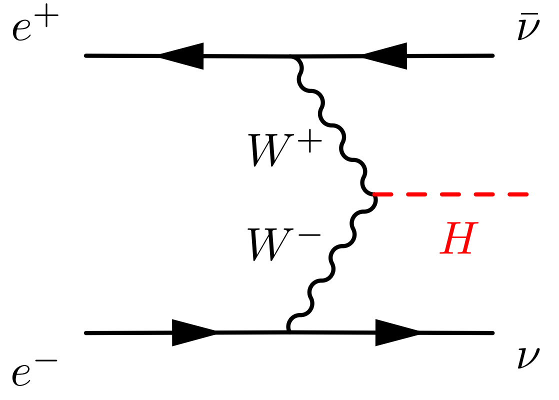




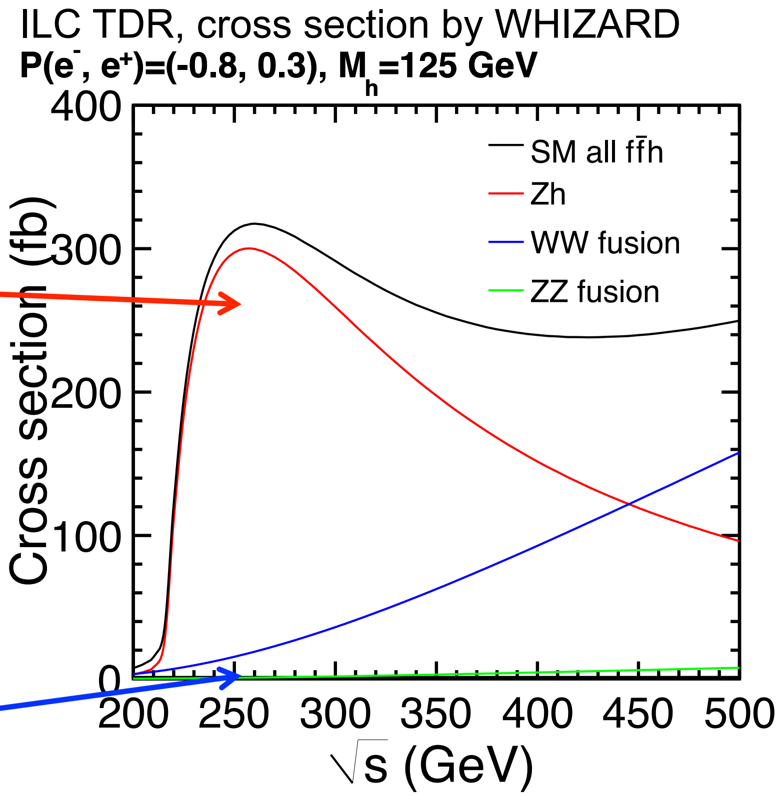
Higgs Production at ILC



Higgs-strahlung
peaks around 250 GeV



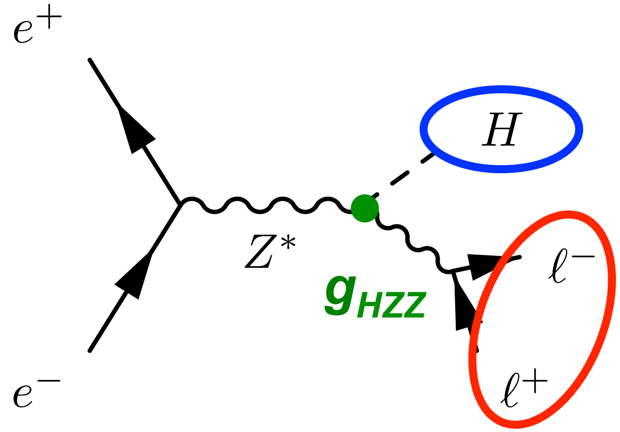
WW fusion
dominates at high energies

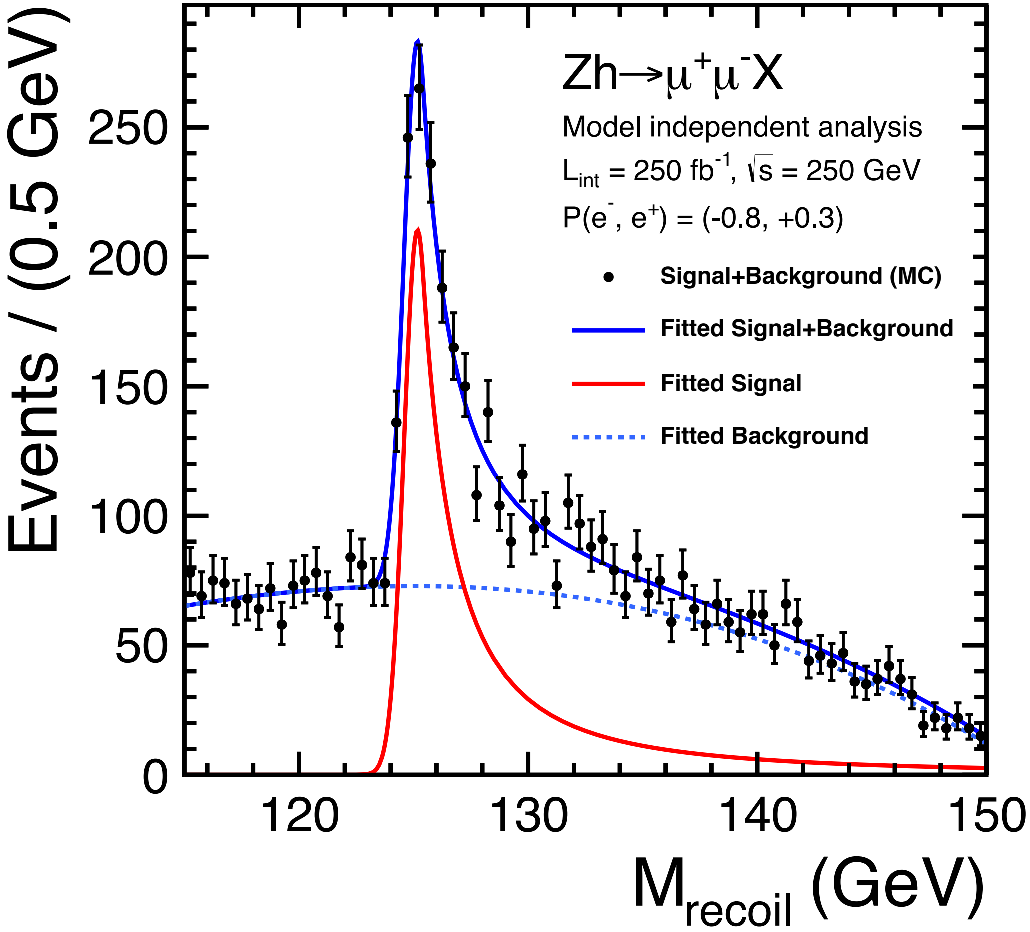


	250 GeV	500 GeV
σ(e⁺e⁻ → ZH)	303 fb	100 fb
σ(e⁺e⁻ → vvH)	16 fb	150 fb
Int. Luminosity	250 fb^{-1}	500 fb^{-1}
# ZH events	76,000	50,000
# vvH events	4,000	75,000

Expected number
of Higgs events

Higgs Recoil Mass





Reconstruct Z boson leptonic decay.
Reconstruct Higgs mass without looking at the Higgs decay

$$m^2_{\text{recoil}} = (\sqrt{s} - E_{\ell\ell})^2 - |\vec{p}_{\ell\ell}|^2$$

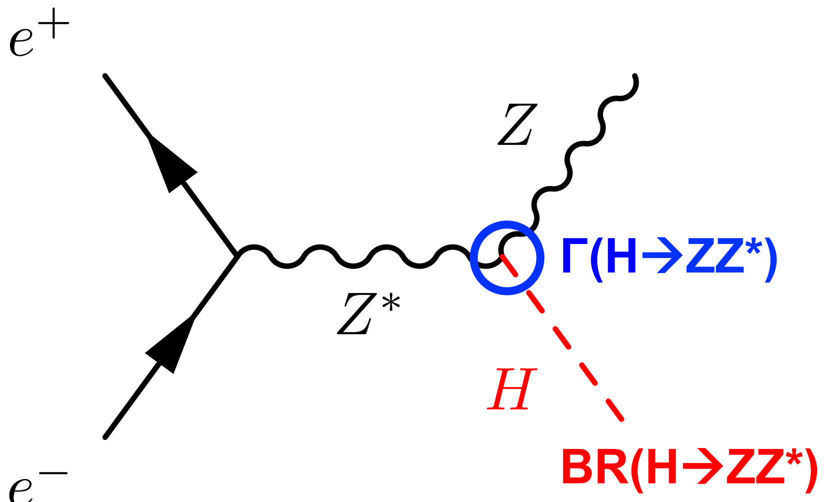
Model-independent, absolute measurement of the Higgs mass and σ(Zh):
$\Delta m_h \leq 15$ MeV, $\sigma_{Zh} \leq 1.2\%$ (√s=250 GeV, L=1150 fb-1)

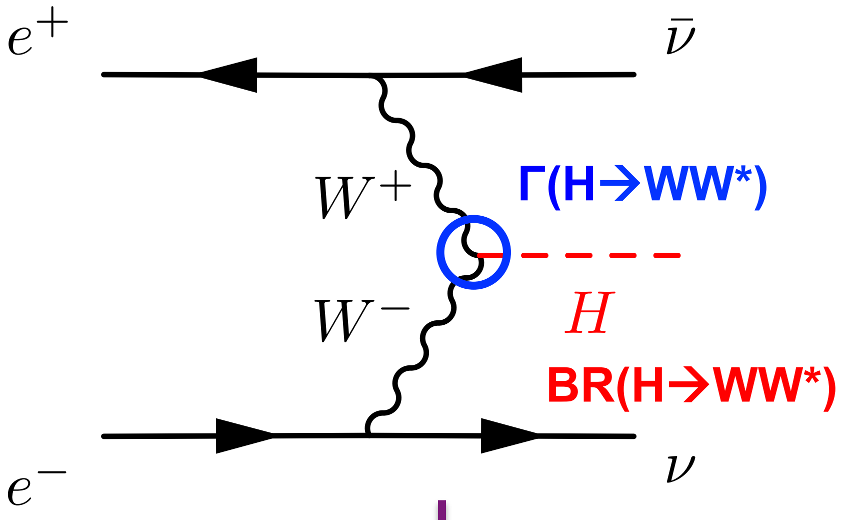
Higgs Coupling Determination

Total decay width needed to fix the absolute couplings

$$g_i^2 \propto \Gamma_i = \mathrm{BR}_i \times \Gamma_H$$

Partial Width & Branching Ratio measurements with Z/W:





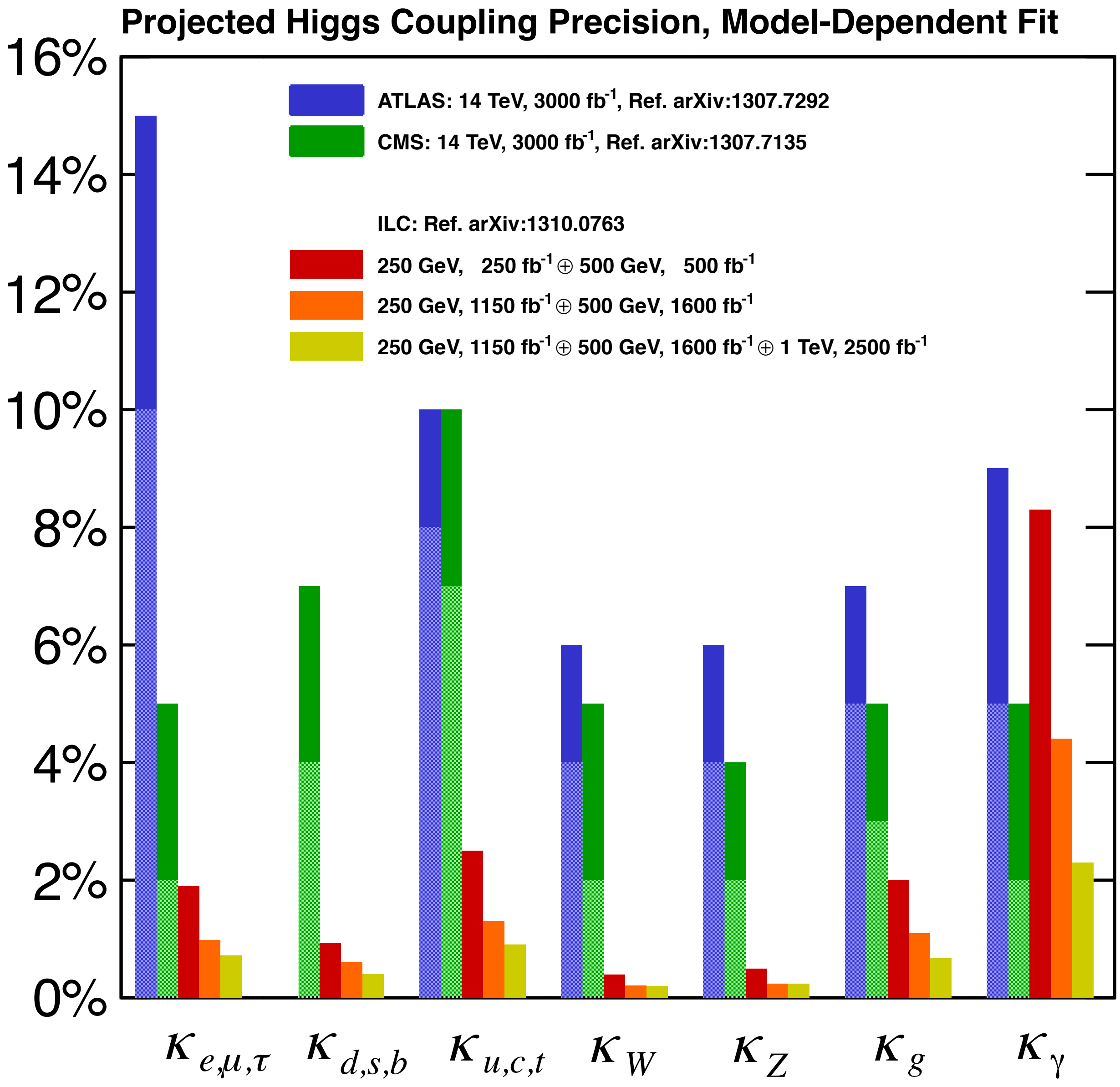
ZHH at 250 GeV alone requires very high statistics since BR(H→ZZ*) ~ 2%.

Very small cross section at 250 GeV. Clean reaction at 500 GeV

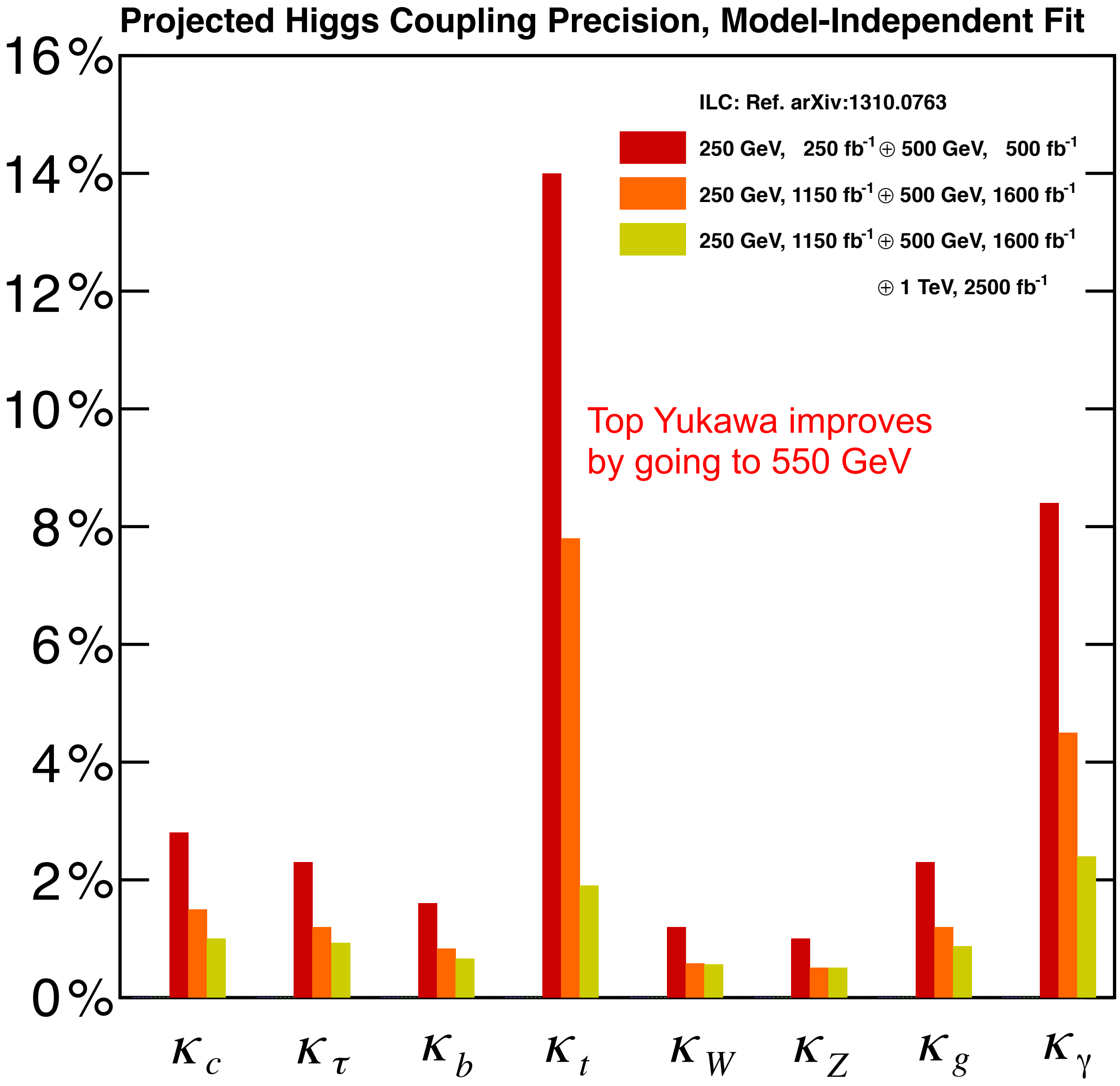
Combination of 250 GeV & 500 GeV data essential for the precise determination of Higgs couplings

Higgs Couplings (1/2)

[With assumptions; not model-independent.]



Higgs Couplings (2/2)



Top Yukawa improves by going to 550 GeV

Better hγγ with LHC/ILC synergy

Excellent b-tagging c-tagging at ILC

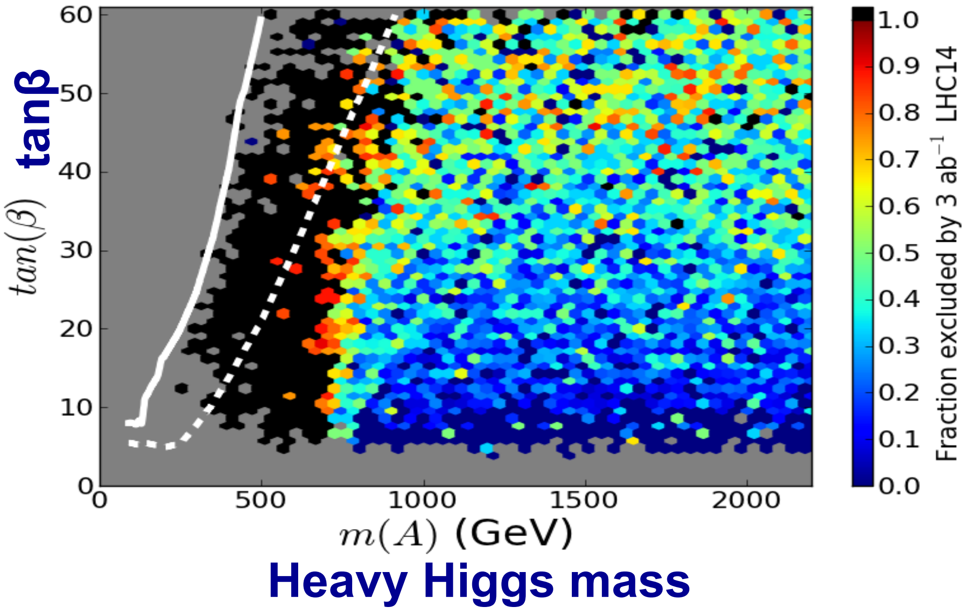
Model-independent coupling determination unique to ILC

MSSM Heavy Higgs Bosons

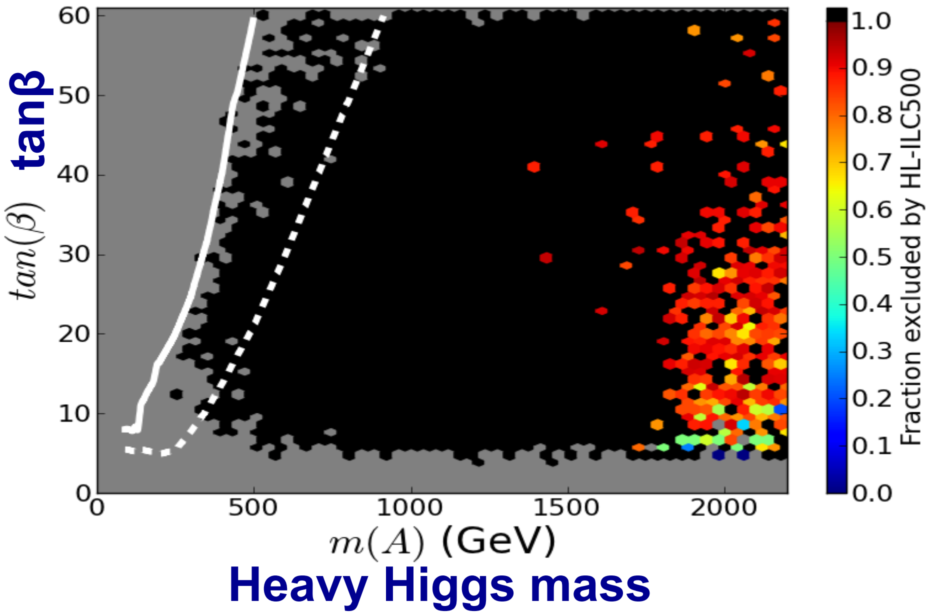
Exclusions of pMSSM points via Higgs couplings (combining hγγ, hττ, hbb)

Cahill-Rowley, Hewett, Ismail, Rizzo, arXiv:1407.7021 [hep-ph]

HL-LHC 3000 fb-1



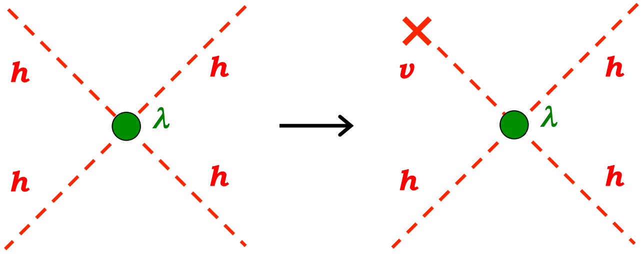
ILC (1150 fb^{-1}@250 GeV & 1600 fb^{-1}@500 GeV)

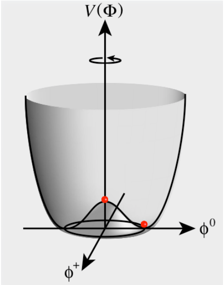


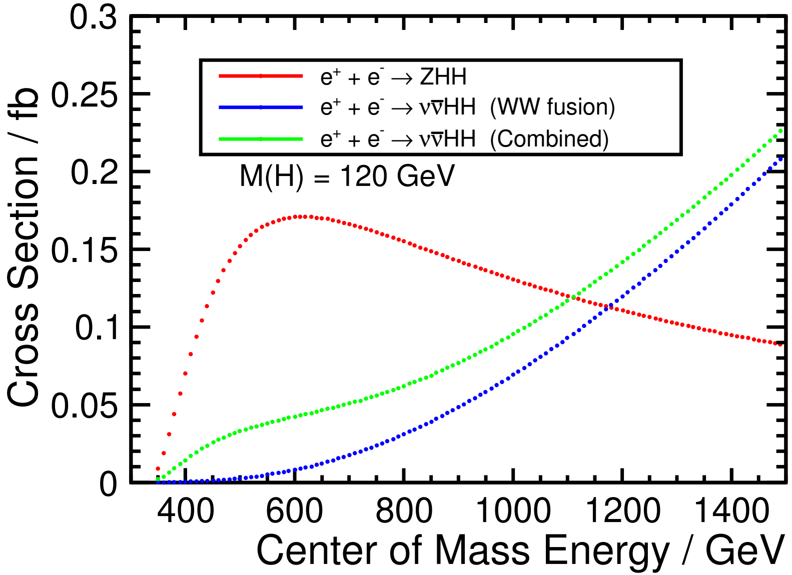
Precision Higgs coupling measurements
sensitive probe for heavy Higgs bosons
mA ~ 2 TeV reach for any tanβ at the ILC

Higgs Self-Coupling

Existence of hhh coupling =
Direct evidence of vacuum condensation

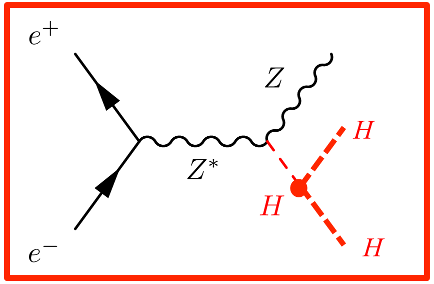


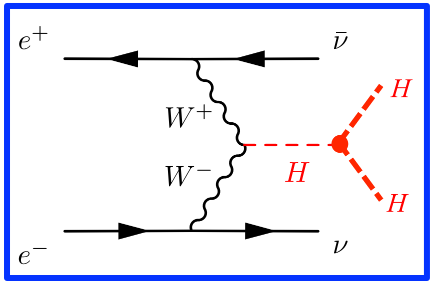




Challenging measurement because of:

- Small cross section (Zhh 0.2 fb at 500 GeV)
- Many jets in the final state
- Presence of interference diagrams





arXiv:1310.0763	ILC500	ILC500-up	ILC1000	ILC1000-up
$\sqrt{s}$ (GeV)	500	500	500/1000	500/1000
$\int \mathcal{L}dt$ (fb^{-1})	500	1600‡	500+1000	1600+2500‡
$P(e^-, e^+)$	$(-0.8, 0.3)$	$(-0.8, 0.3)$	$(-0.8, 0.3/0.2)$	$(-0.8, 0.3/0.2)$
$\sigma\,(ZHH)$	42.7%		42.7%	23.7%
$\sigma\,(\nu\bar{\nu}HH)$	–	–	26.3%	16.7%
λ	83%	46%	21%	13%

Ongoing analysis improvements towards O(10)% measurement

Baryon Asymmetry of Universe

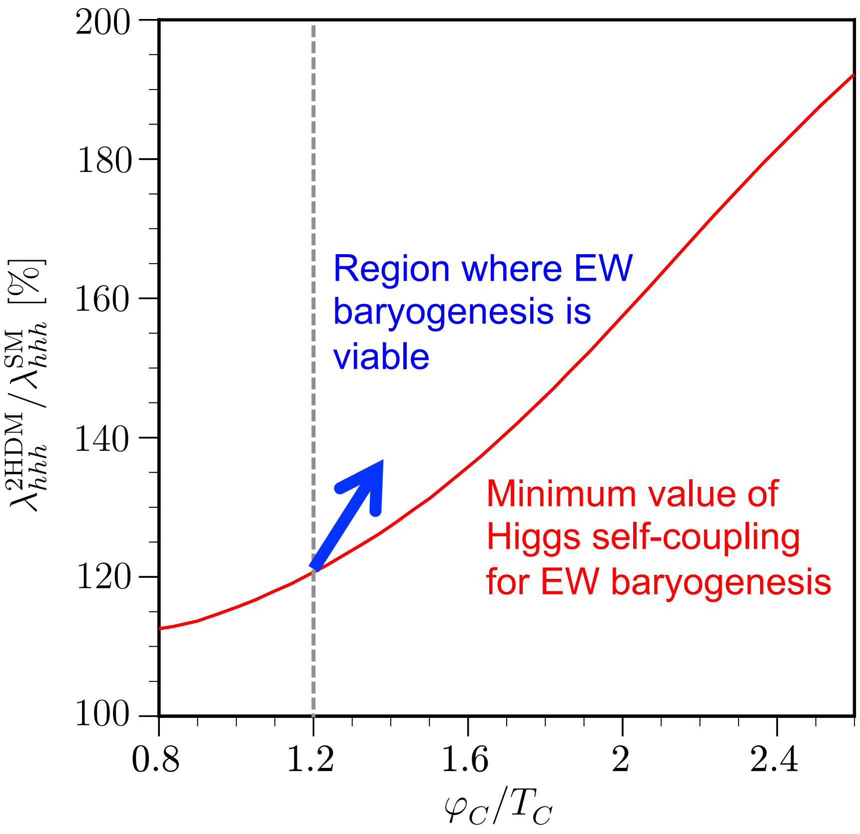
There are different models of baryogenesis at different energy scales. Some examples:

- EW scale: EW baryogenesis → can be probed at the ILC
- Middle scale: Affleck-Dine baryogenesis
- GUT scale: Leptogenesis

A generic feature of new physics models with electroweak baryogenesis typically predict large deviations in Higgs coupling measurements which can be tested at the ILC

Example of EW baryogenesis in a 2HDM model (Senaha, Kanemura):

Ratio of Higgs self-coupling 2HDM / SM



Region where EW baryogenesis is viable

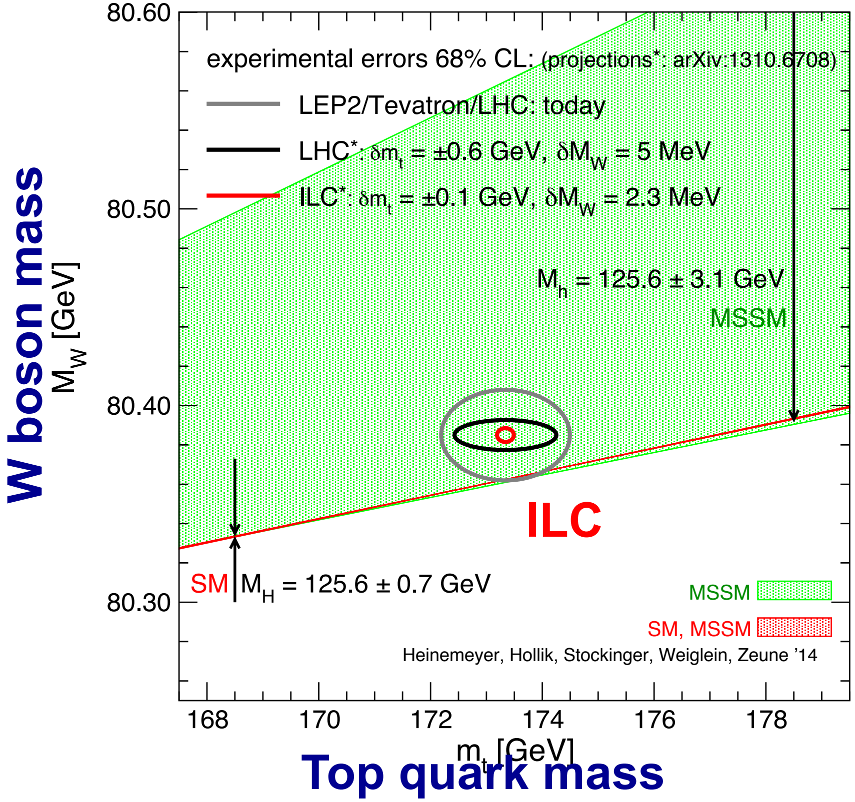
Minimum value of Higgs self-coupling for EW baryogenesis

φ_C Higgs field vev at critical temperature T_C

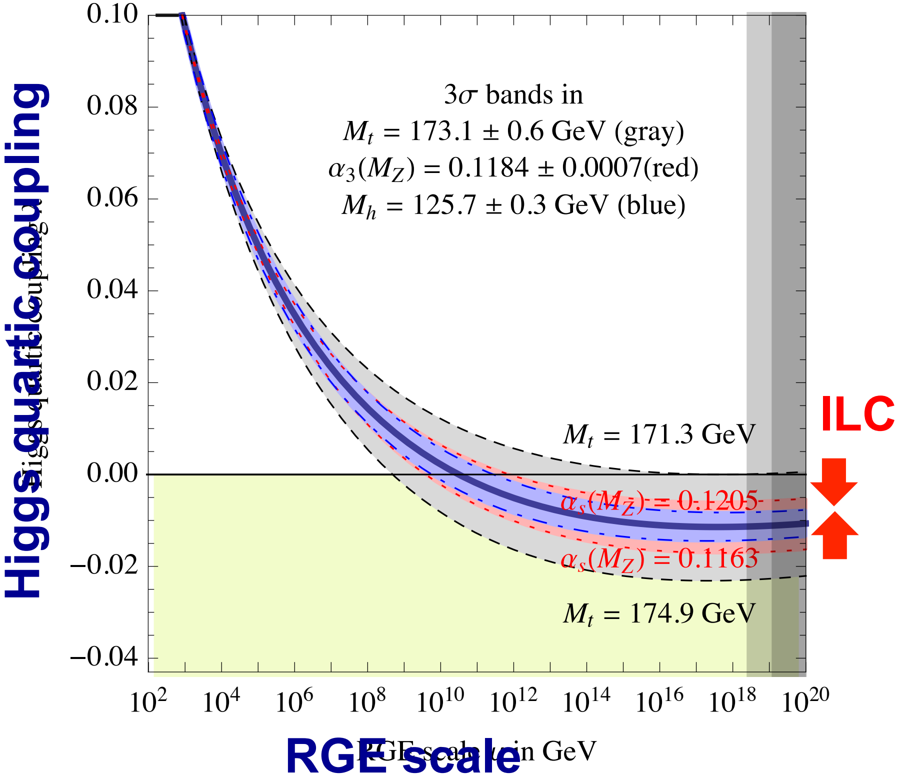
Top Physics at ILC

Top quark mass

- The top quark mass is a fundamental parameter for both SM and BSM.
- With L=100 fb^{-1} at the ILC around the pair production threshold (~350 GeV), the **top mass in the MSbar scheme** can be measured to **100 MeV**. (At least factor 5 improvement over HL-LHC.) The measurement is limited by the theoretical uncertainty associated with the slow convergence in the perturbation theory.



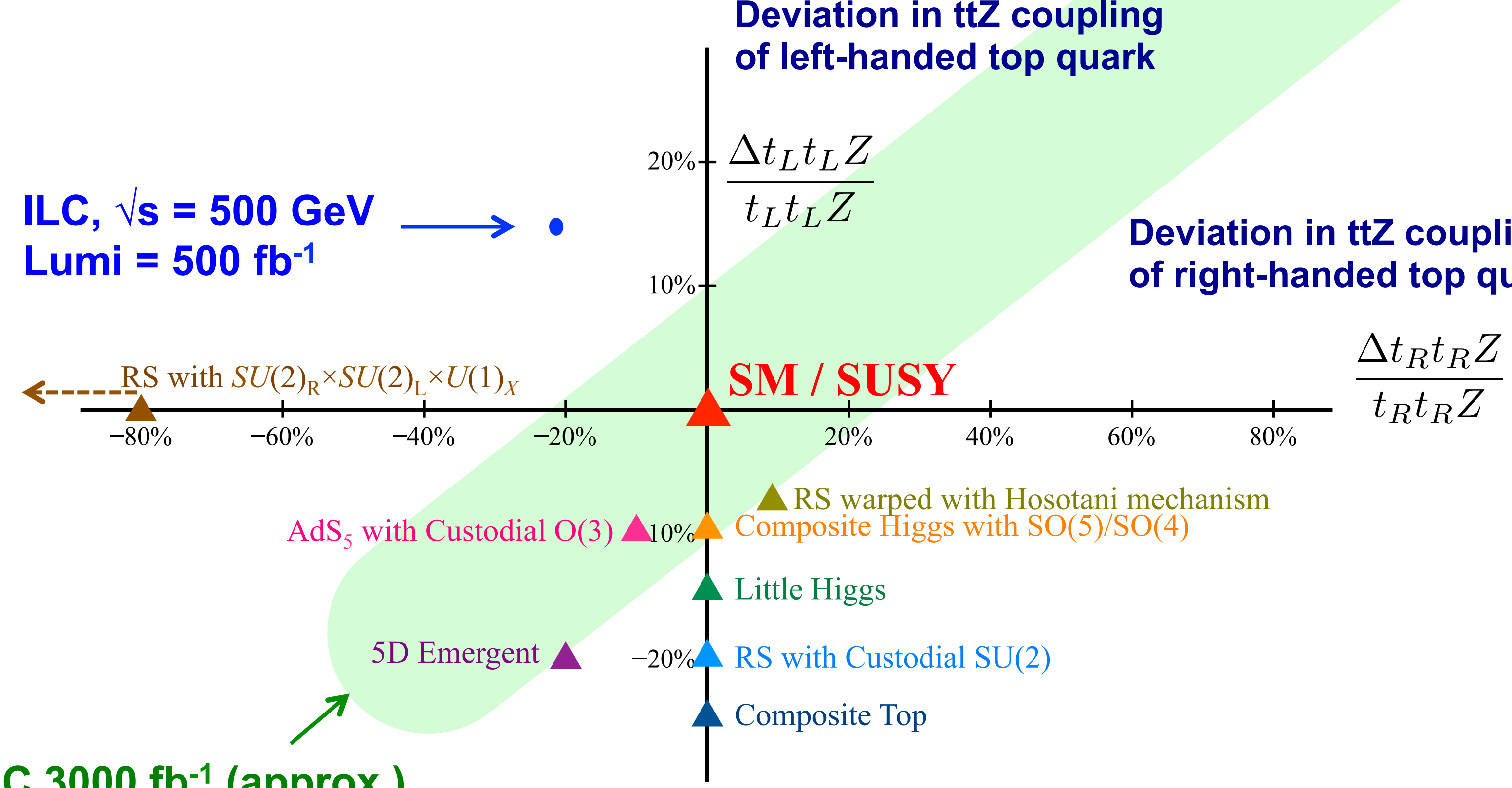
Heinemeyer et al.



Degrassi et al., JHEP 1208 (2012) 098

Impact of BSM on Top Sector

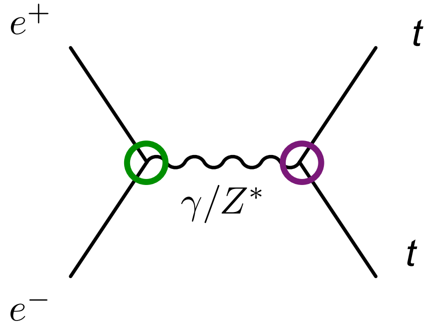
Composite Higgs theories have an impact on the top sector. Composite Higgs models can be tested at the ILC through precise measurements of the top couplings. Beam polarization (both e- and e+) is essential to distinguish the ttZ and ttγ couplings.



HL-LHC 3000 fb^{-1} (approx.)
Based on Baur, Juste, Orr, Rainwater, PRD71, 054013 (2005)

Deviations for different models for new physics scale at ~1 TeV.
Based on F. Richard, arXiv:1403.2893

Top Coupling Measurements



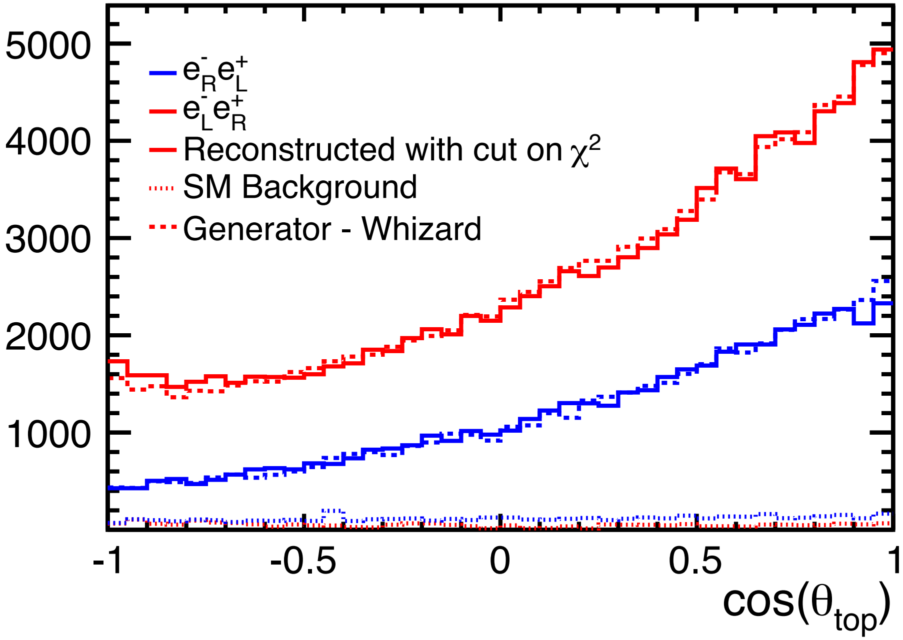
Measure cross section σ and asymmetries A_{FB}, A_{hel} to measure the top form factors $F^{tt\gamma}_{1L}$, $F^{tt\gamma}_{1R}$, F^{ttZ}_{1L}, F^{ttZ}_{1R}

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

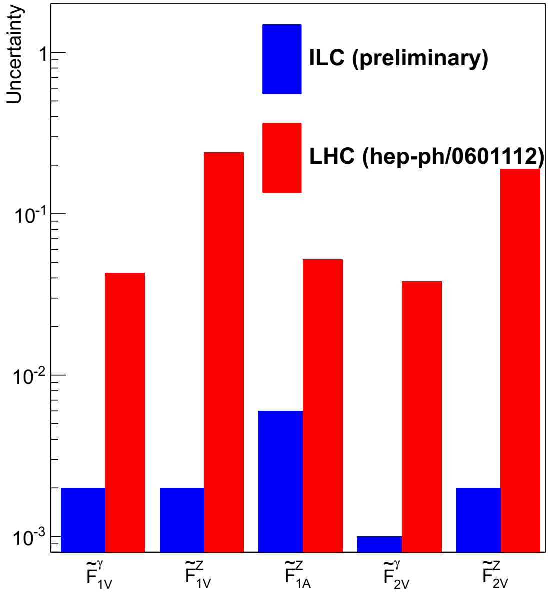
At 500 GeV: large asymmetries & high statistics

Polarization needed to extract all observables

Reconstructed top angle



Expected precision



Amjad et al. arXiv:1307.8102

Searches for direct production of SUSY / DM at the ILC

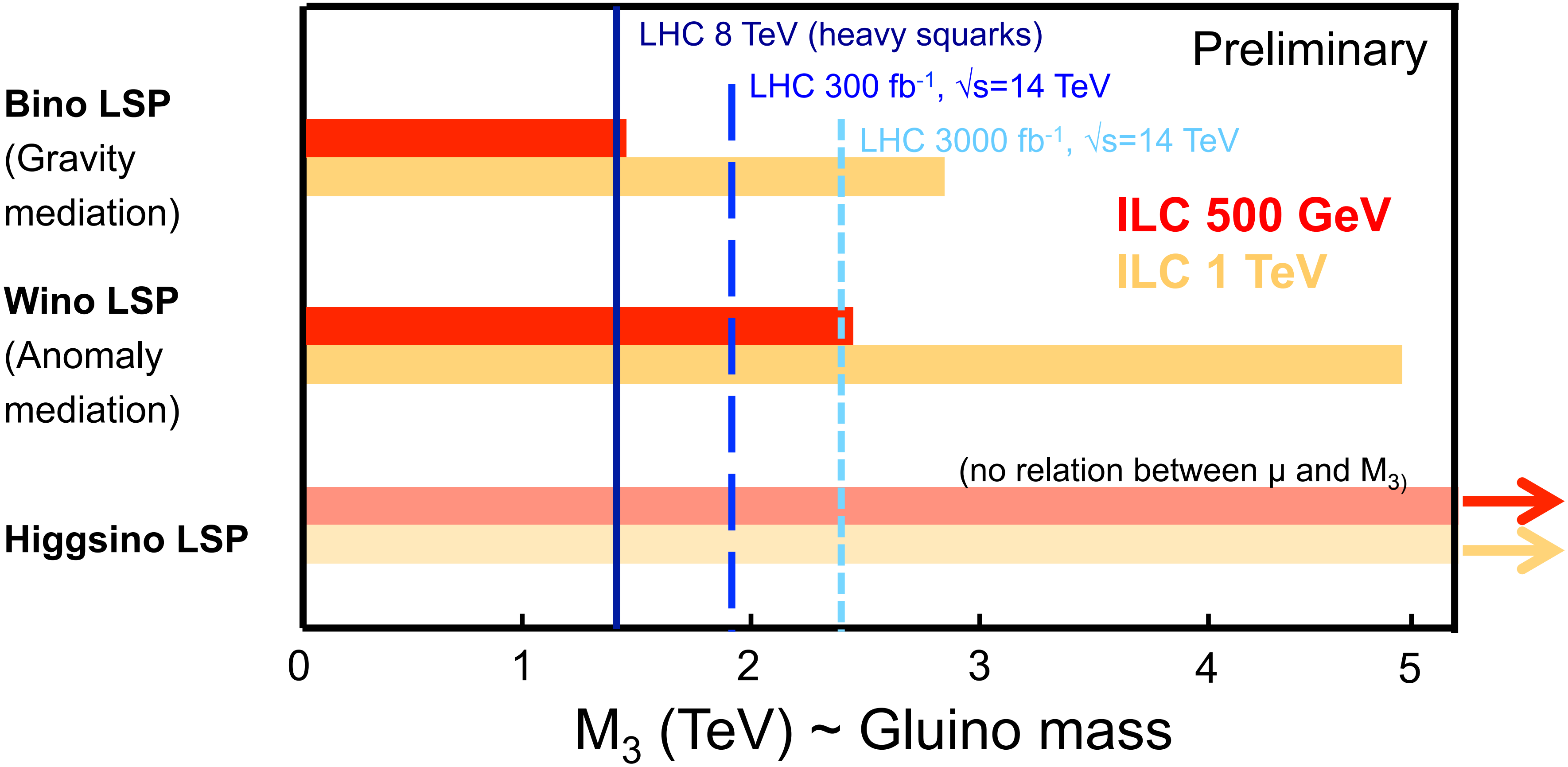
Sensitivity to SUSY

[this comparison is for illustration only; specific channels should be looked at for actual comparisons]

Examples of model-independent SUSY searches

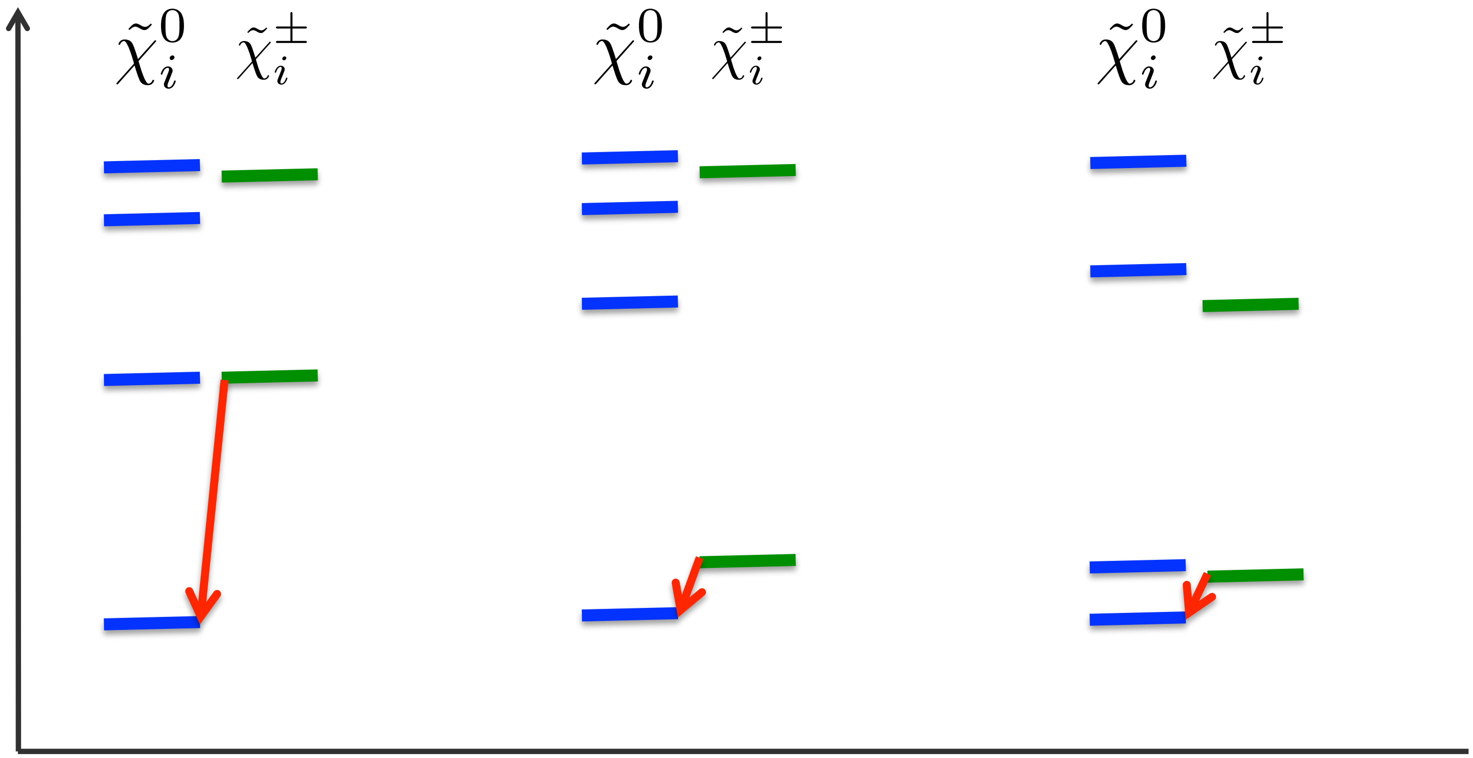
- LHC: Gluino search
- ILC: Chargino/Neutralino search

Compare using gaugino mass relations



[Assumptions: MSUGRA/GMSB relation $M_1 : M_2 : M_3 = 1 : 2 : 6$; AMSB relation $M_1 : M_2 : M_3 = 3.3 : 1 : 10.5$]

SUSY Electroweak Sector

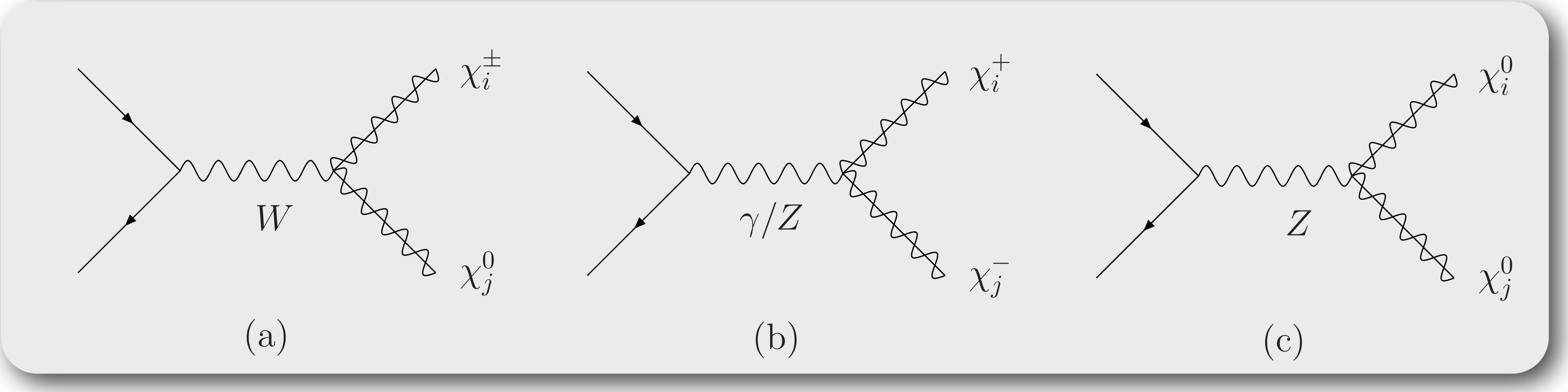


Bino-like LSP **Wino-like LSP** **Higgsino-like LSP**

Degenerate spectra

(depends on mixing)

SUSY EW Production



For LHC:

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

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:

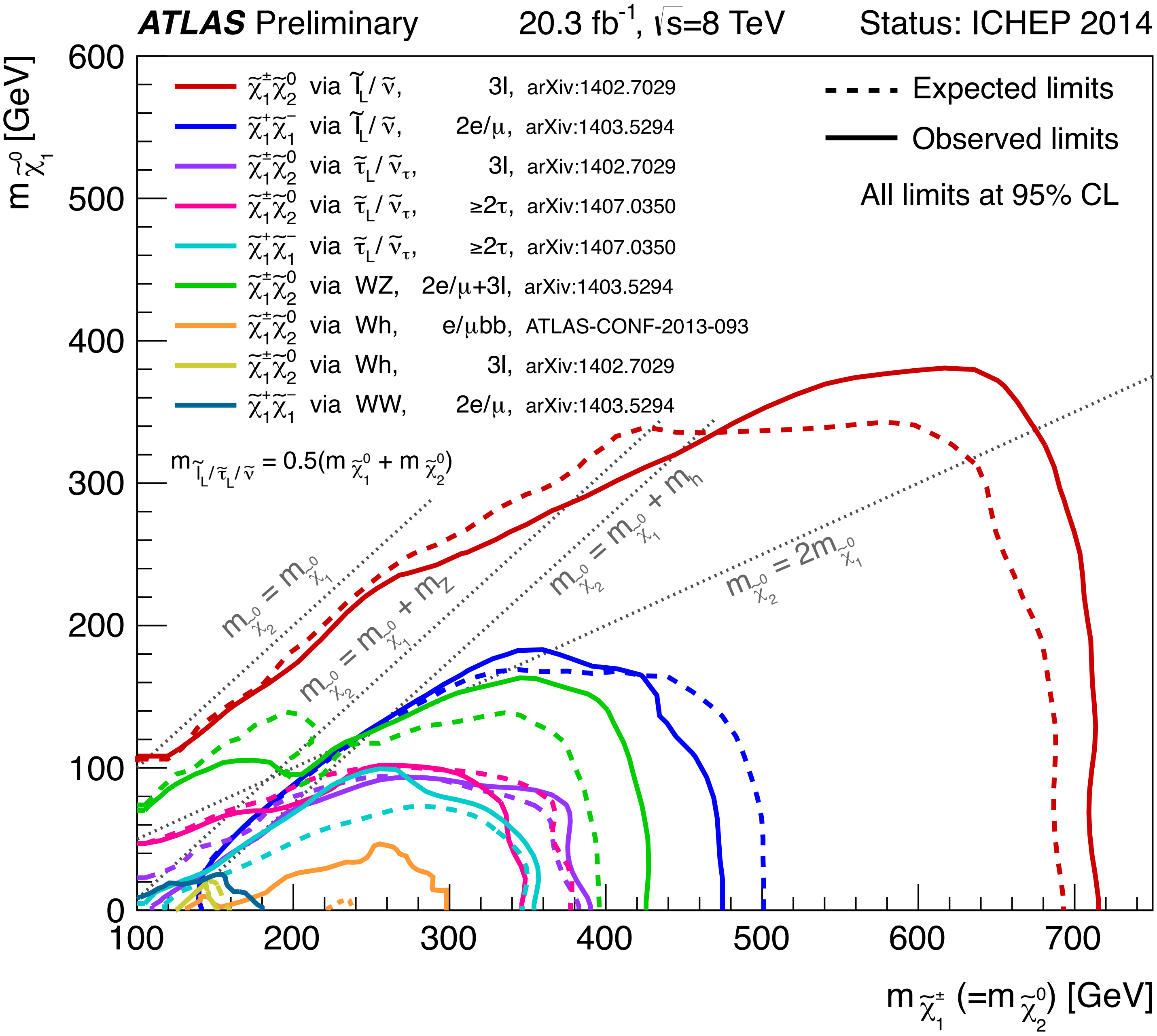
$$\tilde{\chi}_1^\pm \to W^\pm \tilde{\chi}_1^0$$

$$\tilde{\chi}_2^0 \to (Z/\underset{\uparrow \text{ Higgs!}}{h})\tilde{\chi}_1^0$$

$$\ldots$$

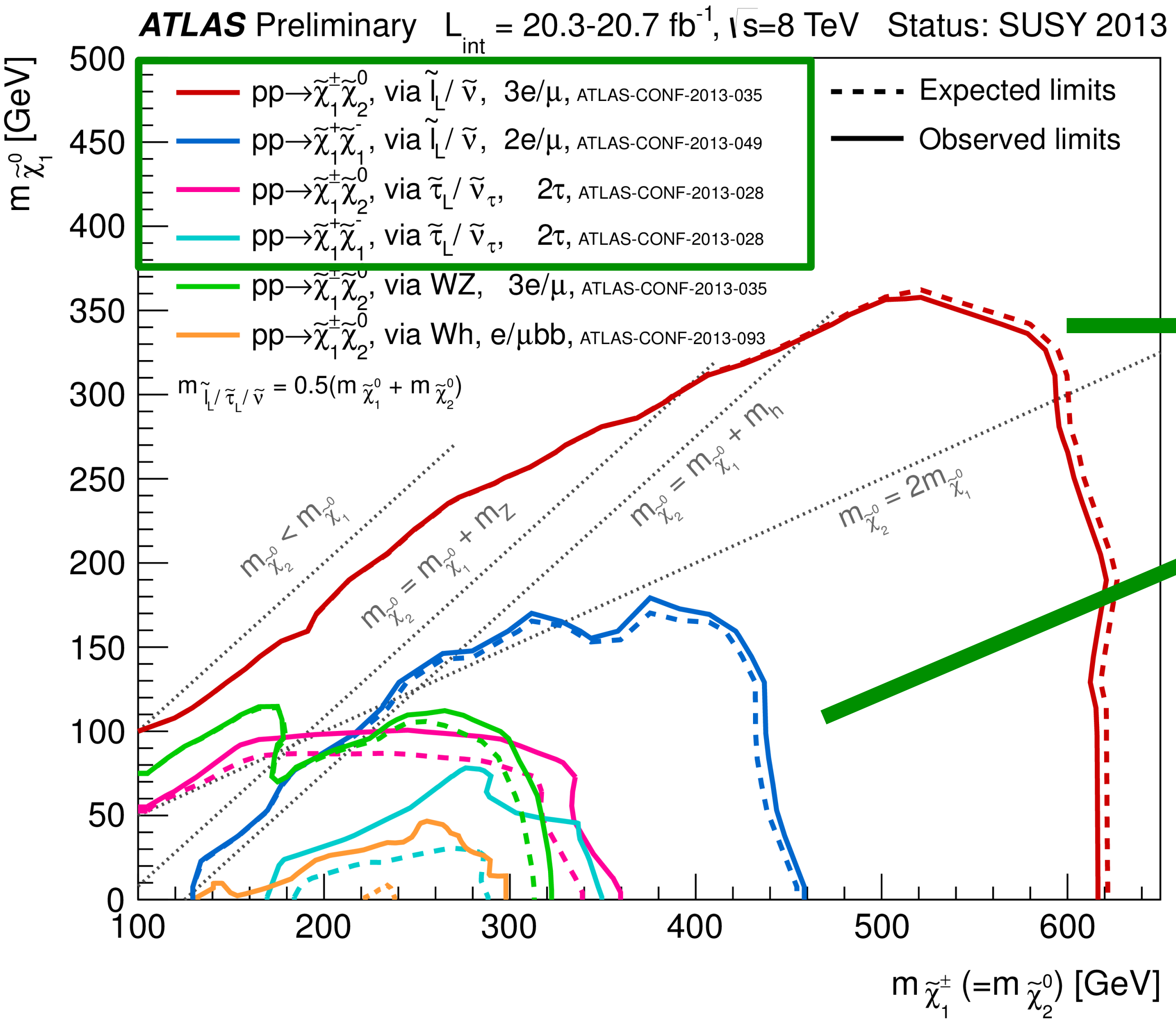
Higgs!

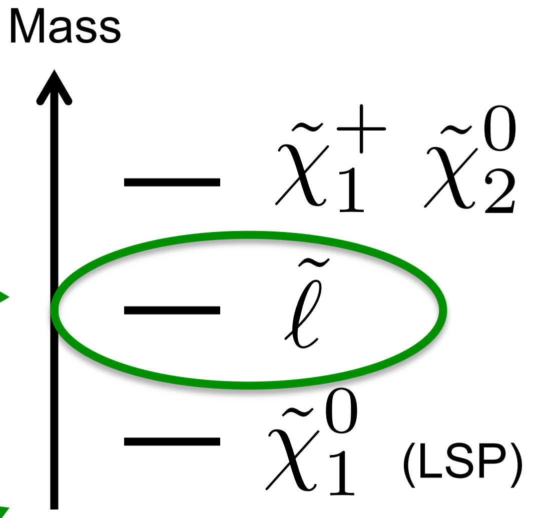
SUSY EW @ LHC



ATLAS Preliminary
20.3 fb^{-1}, $\sqrt{s}$=8 TeV
Status: ICHEP 2014
$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via $\tilde{l}_L/\tilde{\nu}$, 3l, arXiv:1402.7029
$\tilde{\chi}_1^{+}\tilde{\chi}_1^-$ via $\tilde{l}_L/\tilde{\nu}$, 2e/μ, arXiv:1403.5294
$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via $\tilde{\tau}_L/\tilde{\nu}_\tau$, 3l, arXiv:1402.7029
$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via $\tilde{\tau}_L/\tilde{\nu}_\tau$, ≥2$\tau$, arXiv:1407.0350
$\tilde{\chi}_1^{+}\tilde{\chi}_1^-$ via $\tilde{\tau}_L/\tilde{\nu}_\tau$, ≥2$\tau$, arXiv:1407.0350
$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via WZ, 2e/μ+3l, arXiv:1403.5294
$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via Wh, e/μbb, ATLAS-CONF-2013-093
$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via Wh, 3l, arXiv:1402.7029
$\tilde{\chi}_1^{+}\tilde{\chi}_1^-$ via WW, 2e/μ, arXiv:1403.5294
Expected limits
Observed limits
All limits at 95% CL
$m_{\tilde{l}_L/\tilde{\tau}_L/\tilde{\nu}} = 0.5(m_{\tilde{\chi}_1^0} + m_{\tilde{\chi}_2^0})$
$m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^0}$
$m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^0} + m_Z$
$m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^0} + m_h$
$m_{\tilde{\chi}_2^0} = 2m_{\tilde{\chi}_1^0}$
$m_{\tilde{\chi}_1^0}$ [GeV]
600
500
400
300
200
100
0
100
200
300
400
500
600
700
$m_{\tilde{\chi}_1^\pm}$ (=$m_{\tilde{\chi}_2^0}$) [GeV]

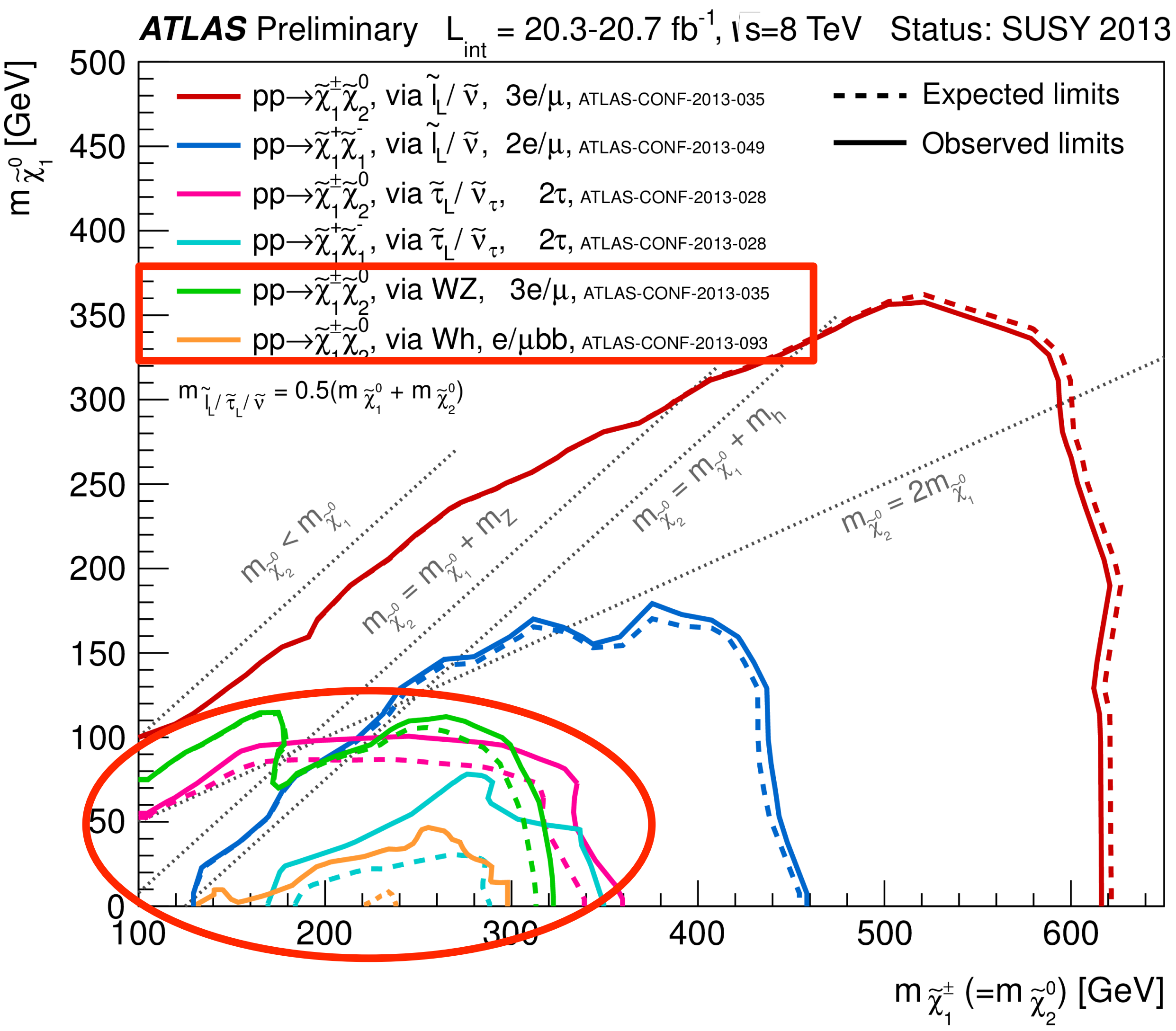
SUSY EW @ LHC

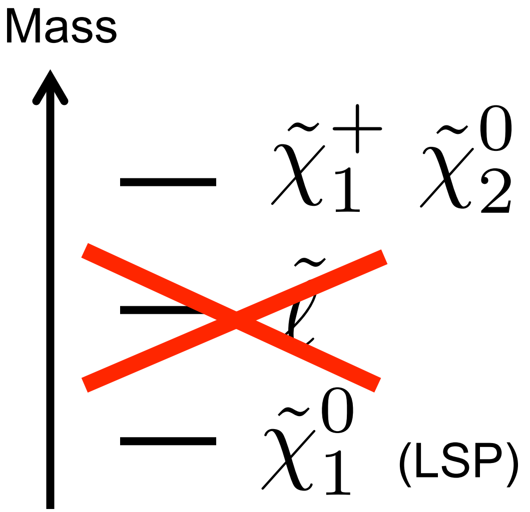




Sensitive to particular mass spectra

SUSY EW @ LHC

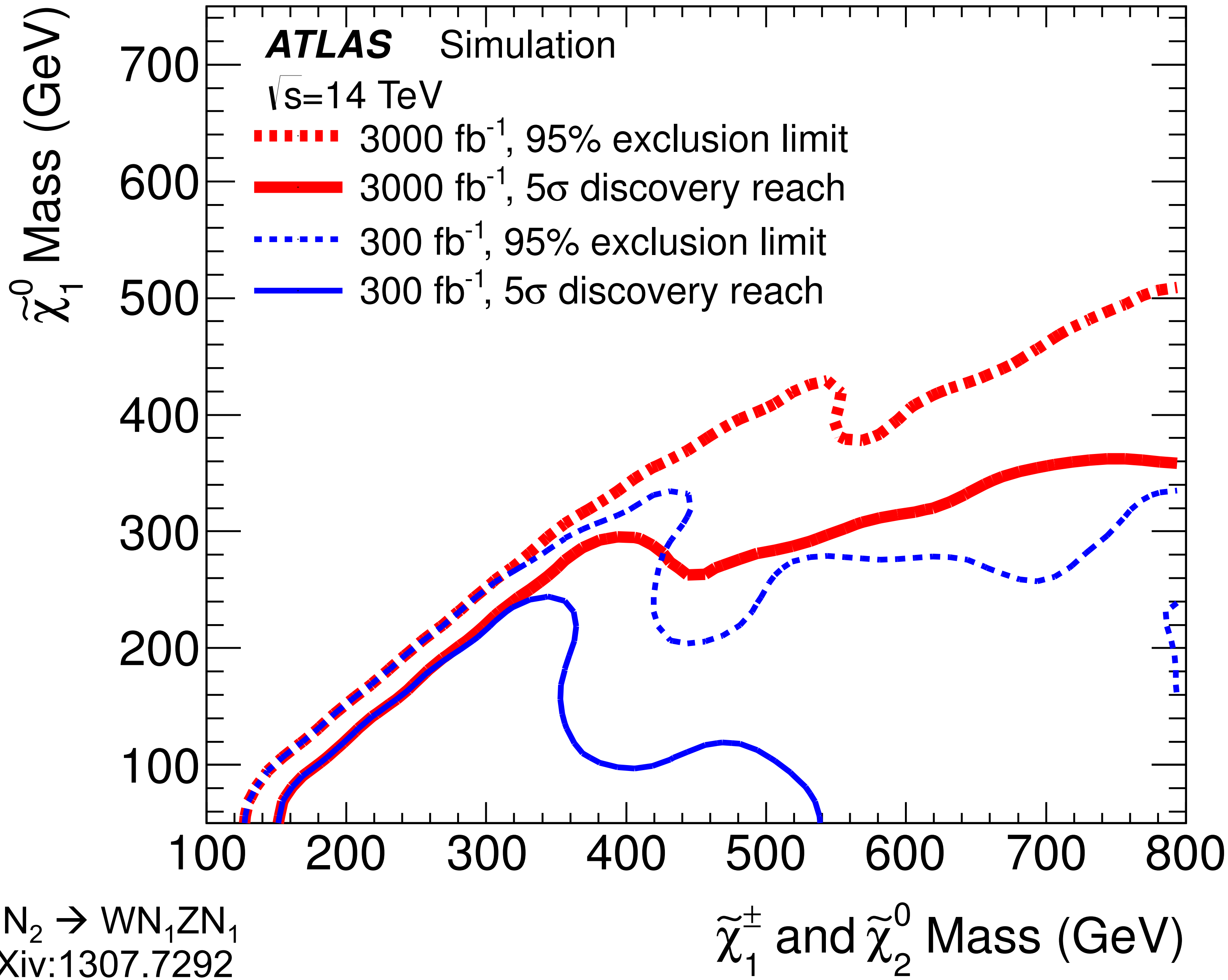




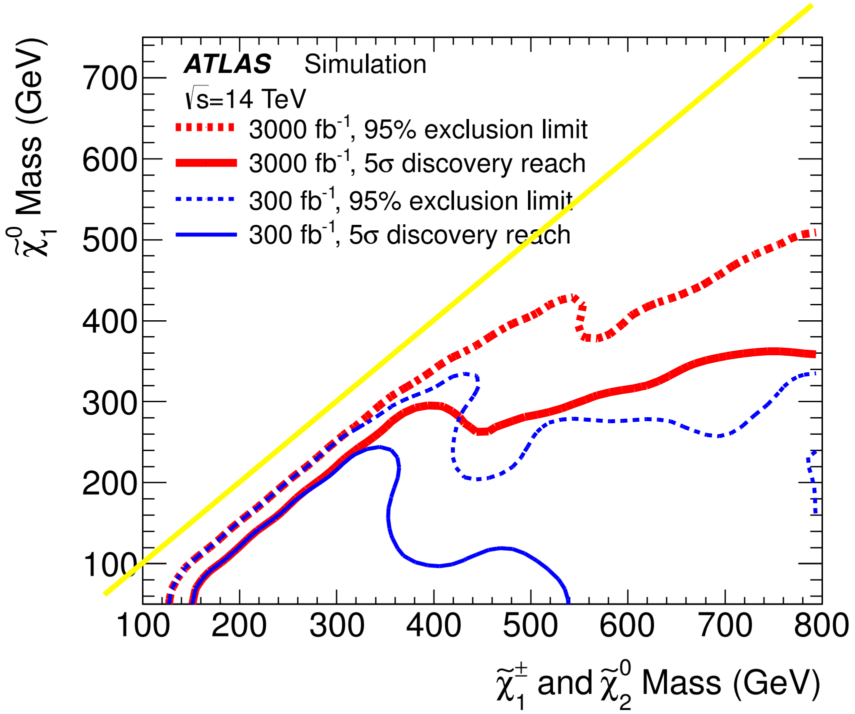
$$\mathcal{B}(\tilde{\chi}_2^0 \to Z/h\,\tilde{\chi}_1^0)$$

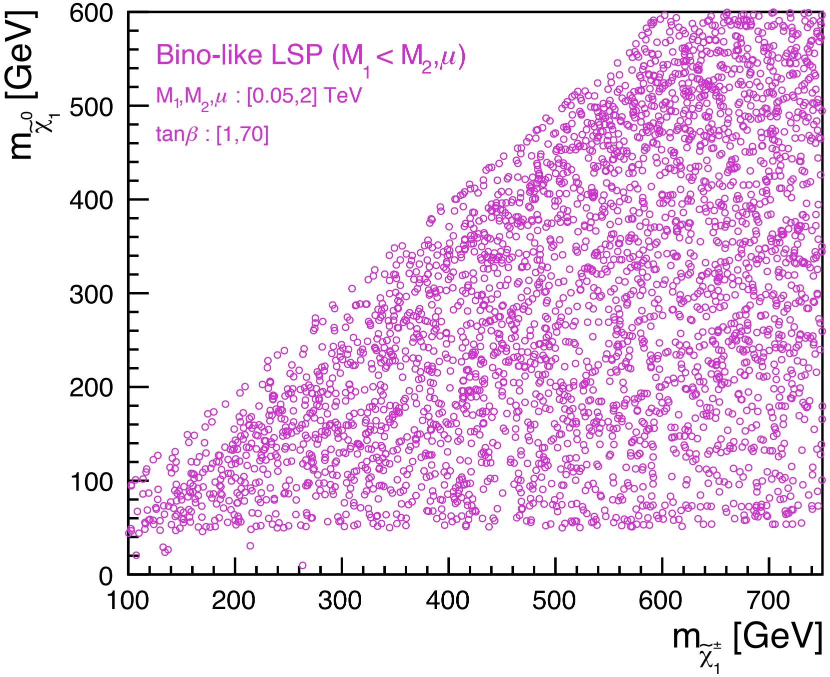
100% assumed, but not generally true due to neutralino mixing

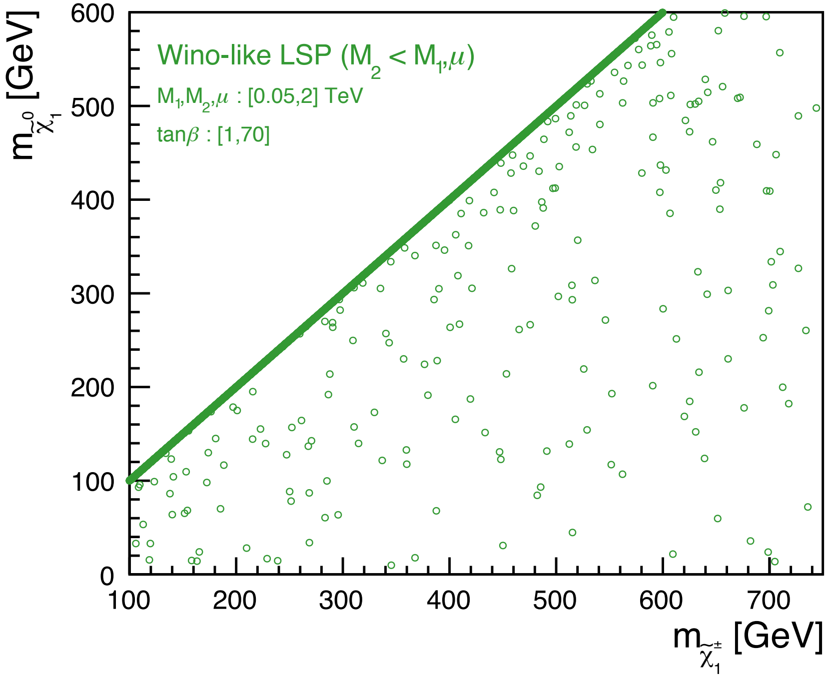
SUSY EW @ HL-LHC

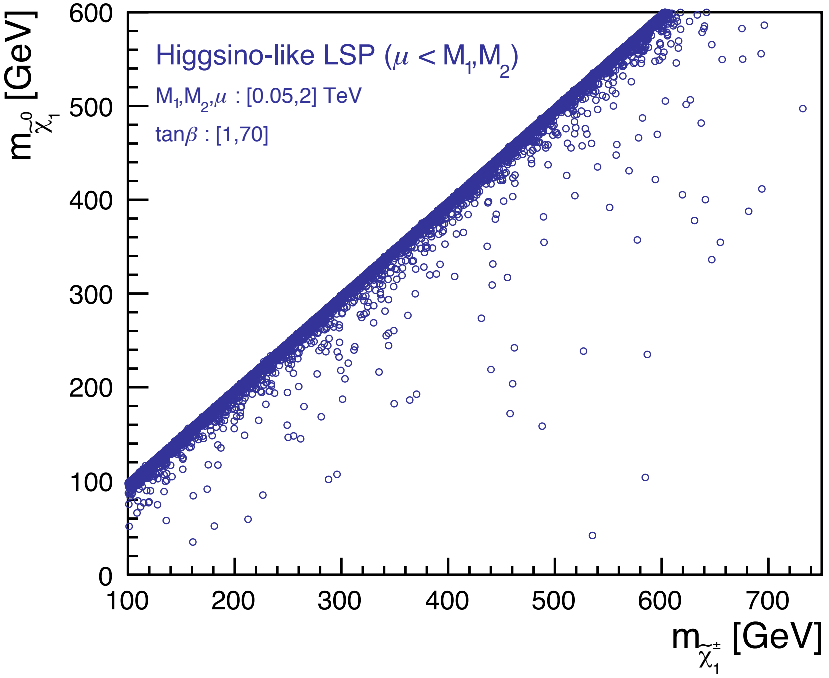


$C_1N_2 \rightarrow WN_1ZN_1$
arXiv:1307.7292

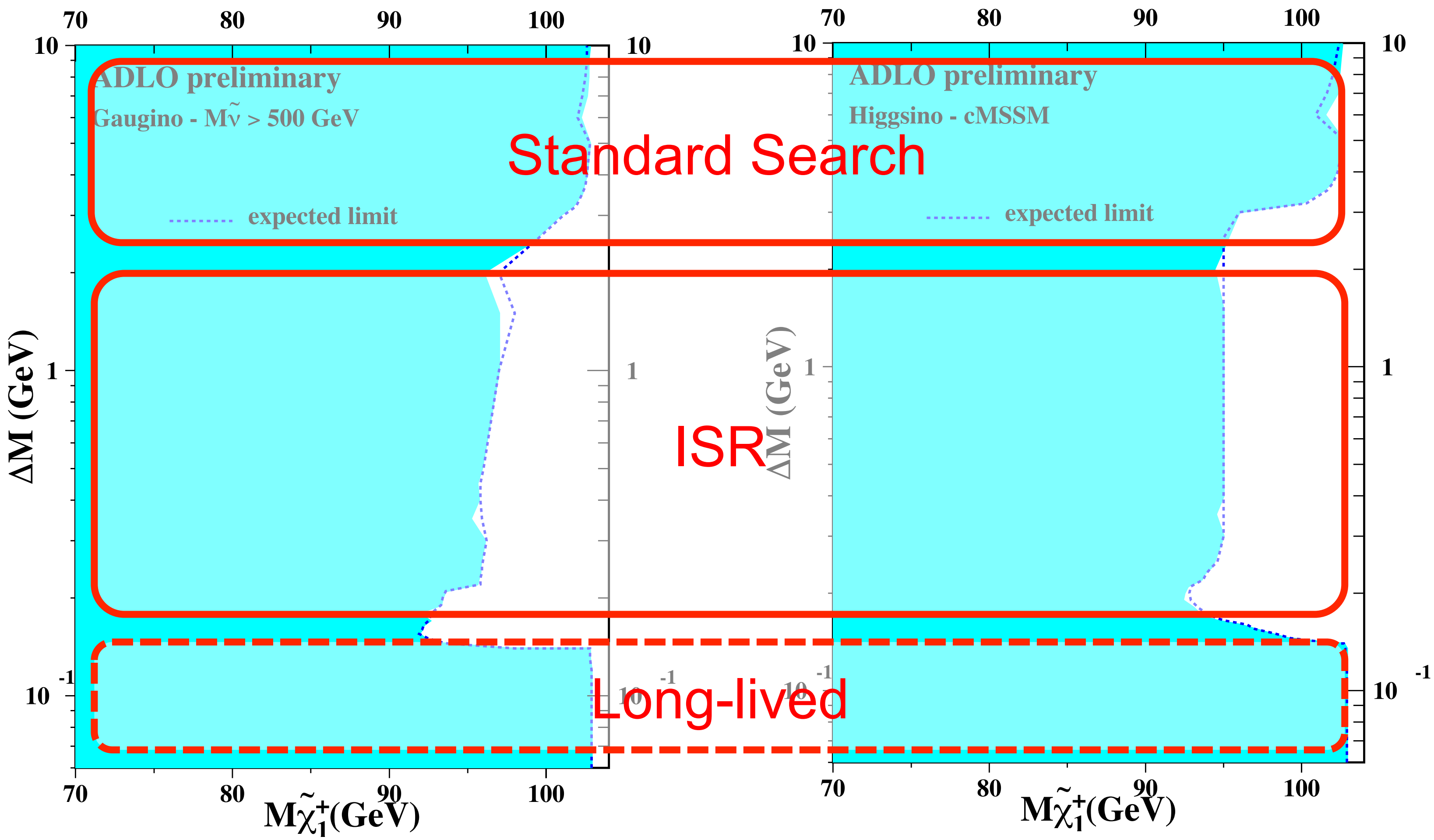

ATLAS Simulation
√s=14 TeV
3000 fb^{-1}, 95% exclusion limit
3000 fb^{-1}, 5σ discovery reach
300 fb^{-1}, 95% exclusion limit
300 fb^{-1}, 5σ discovery reach
$\tilde{\chi}_1^0$ Mass (GeV)
$\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ Mass (GeV)
100
200
300
400
500
600
700
800


Bino-like LSP ($M_1 < M_2,\mu$)
M_1,M_2,μ : [0.05,2] TeV
$\tan\beta$: [1,70]
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_1^\pm}$ [GeV]
0
100
200
300
400
500
600
700


Wino-like LSP ($M_2 < M_1,\mu$)
M_1,M_2,μ : [0.05,2] TeV
$\tan\beta$: [1,70]
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_1^\pm}$ [GeV]
0
100
200
300
400
500
600
700


Higgsino-like LSP ($\mu < M_1,M_2$)
M_1,M_2,μ : [0.05,2] TeV
$\tan\beta$: [1,70]
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_1^\pm}$ [GeV]
0
100
200
300
400
500
600
700

SUSY EW @ LEPII



Gaugino

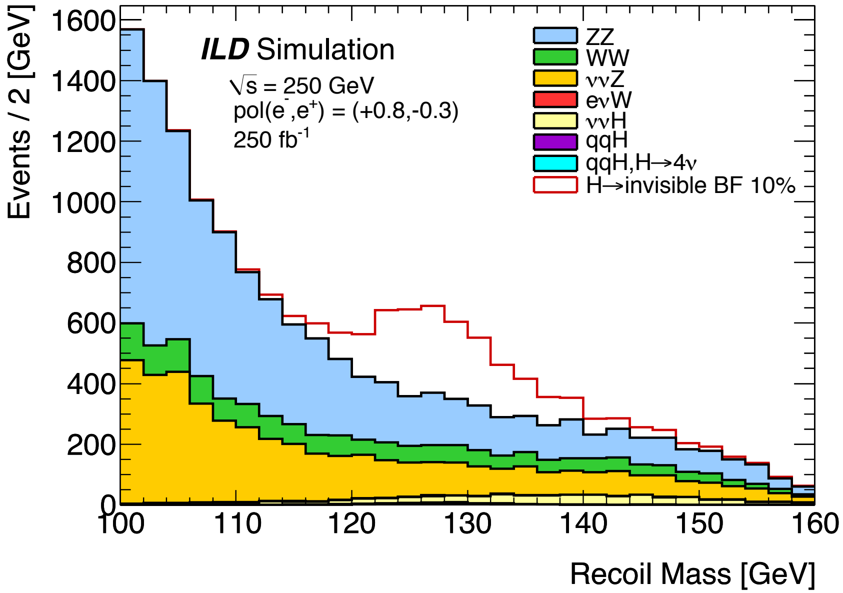
Higgsino

WIMP Dark Matter @ ILC

WIMP searches at colliders are complementary to direct/indirect searches.

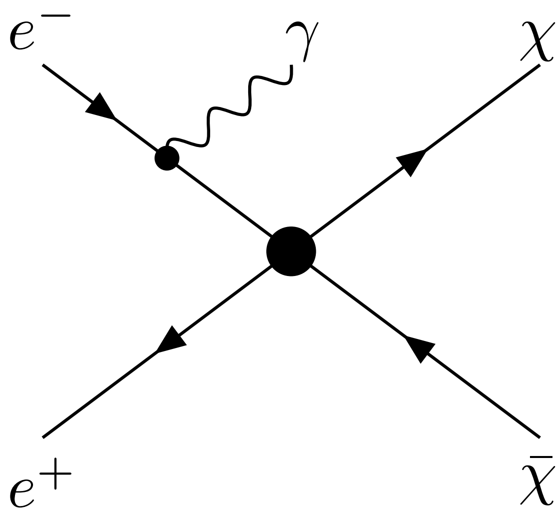
Examples at the ILC:

Higgs Invisible Decay



BR(H→invis.) < 0.4%
at 250 GeV, 1150 fb^{-1}

Monophoton Search

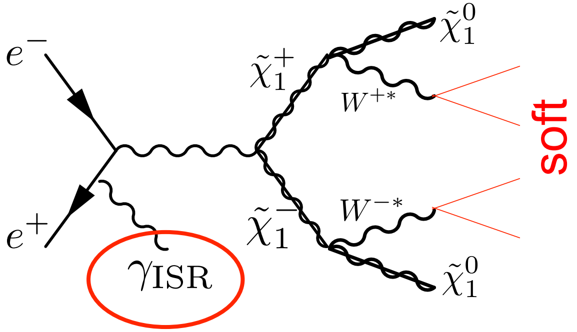


→ DM mass sensitivity
nearly half the CM energy

SUSY-specific signatures (decays to DM)

- light Higgsino, light stau, etc.

Higgsino decays to DM with small mass differences



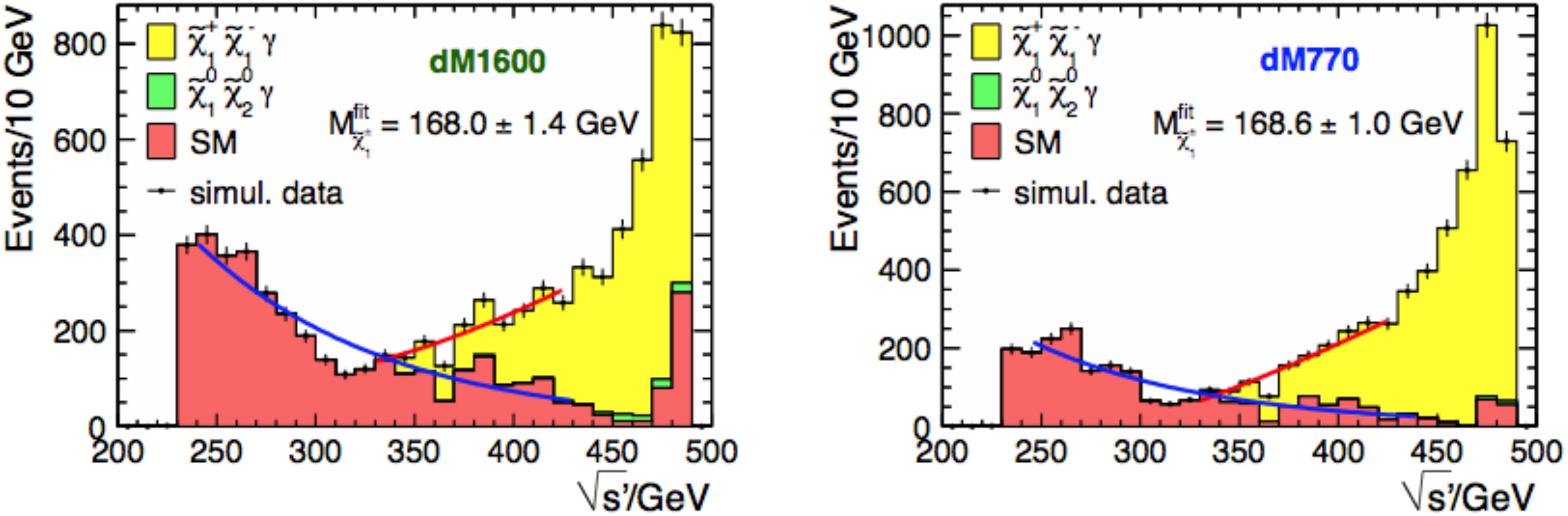
Study of Higgsino pair production, with ISR tag

Benchmark models with
m(NLSP) – M(LSP) = 1.6 GeV and 0.8 GeV

$$\sigma(e^+e^- \rightarrow \tilde\chi_1^+\tilde\chi_1^-) = 78.7\ (77.0)\ \mathrm{fb}$$

$$\Delta M = 1.60\ (0.77)\ \mathrm{GeV}$$

Berggren, Bruemmer, List, Moortgat-Pick, Robens, Rolbiecki, Sert,
EPJ C73 (2013) 2660 [arXiv:1307.3566]



√s=500 GeV, Lumi=500 fb-1, P(e-,e+)=(-0.8,+0.3)
LSP mass resolution ~1%

Slepton decays to DM with small mass differences

Study of stau pair production at the ILC

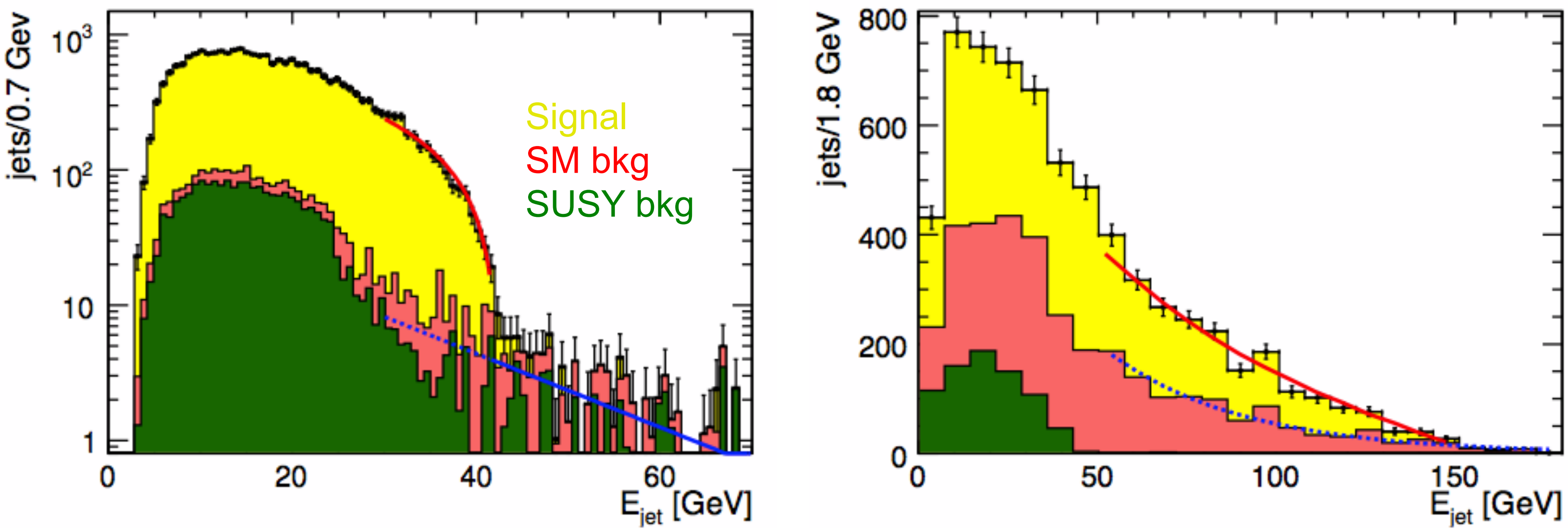
Observation of lighter and heavier stau states with decay to DM + hadronic tau

Benchmark point: m(LSP) = 98 GeV, m(stau1) = 108 GeV, m(stau2) = 195 GeV

$$\sigma(e^+e^- \to \tilde{\tau}_1^+\tilde{\tau}_1^-) = 158 \text{ fb}$$

$$\sigma(e^+e^- \to \tilde{\tau}_2^+\tilde{\tau}_2^-) = 18 \text{ fb}$$

Bechtle, Berggren, List, Schade, Stempel, arXiv:0908.0876, PRD82, 055016 (2010)



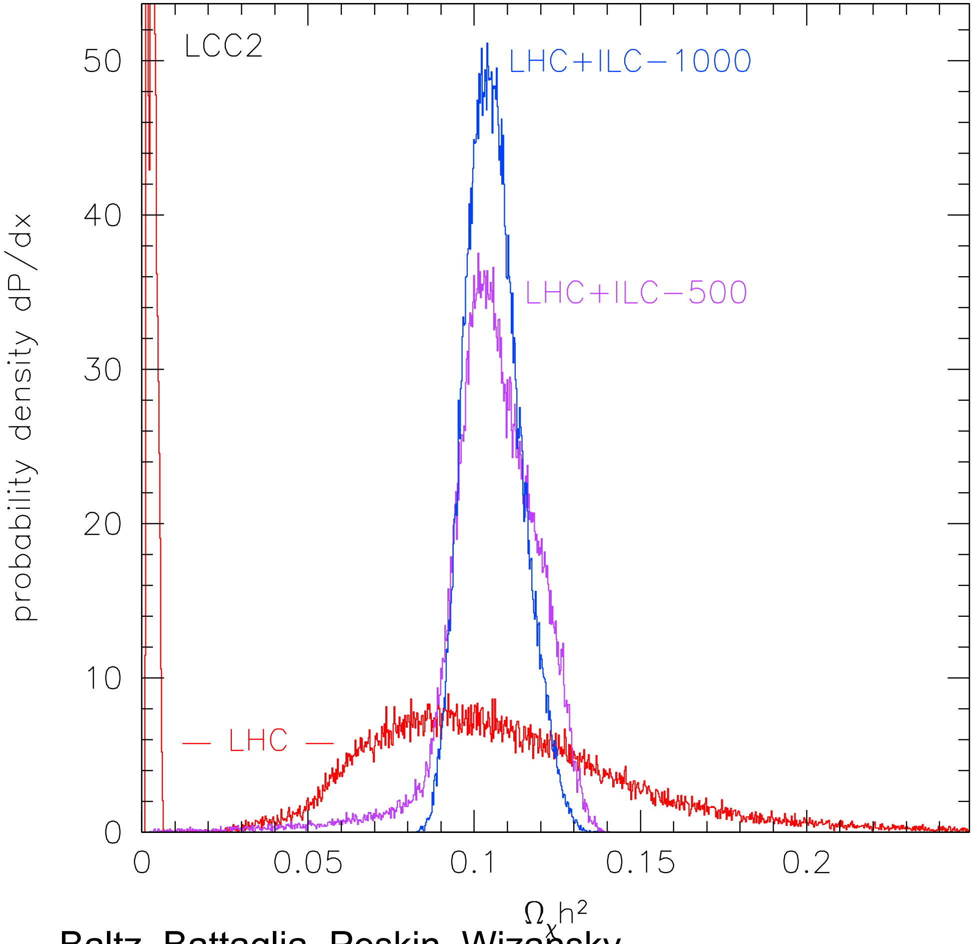
√s=500 GeV, Lumi=500 fb-1, P(e-,e+)=(+0.8,-0.3)

Stau1 mass ~0.1%, Stau2 mass ~3% → LSP mass ~1.7%

DM Relic Abundance

WMAP/Planck (68% CL)

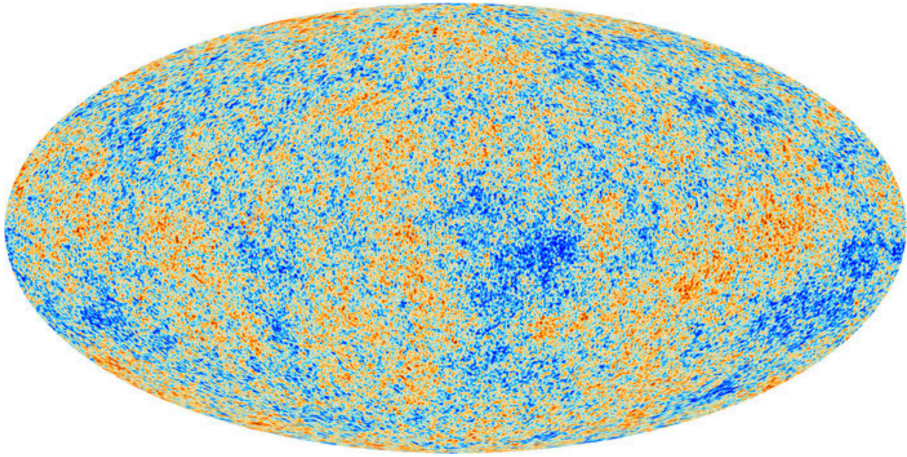
$$\Omega_c h^2 = 0.1196 \pm 0.0027$$



Baltz, Battaglia, Peskin, Wizansky
PRD74 (2006) 103521, arXiv:hep-ph/0602187

**This particular benchmark point is excluded. Update is in progress.*

ESA/Planck



Once a DM candidate is discovered, crucial to check the consistency with the measured DM relic abundance.

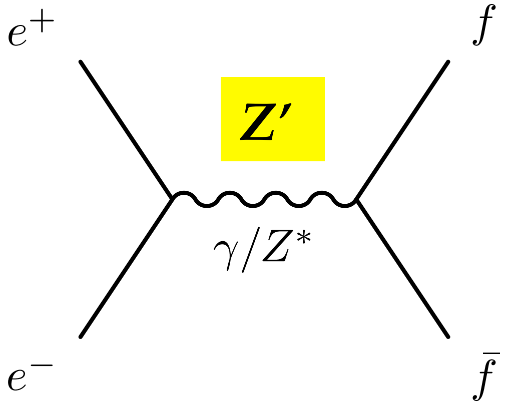
→ ILC precise measurements of mass and cross sections

Z' : Heavy Neutral Gauge Bosons

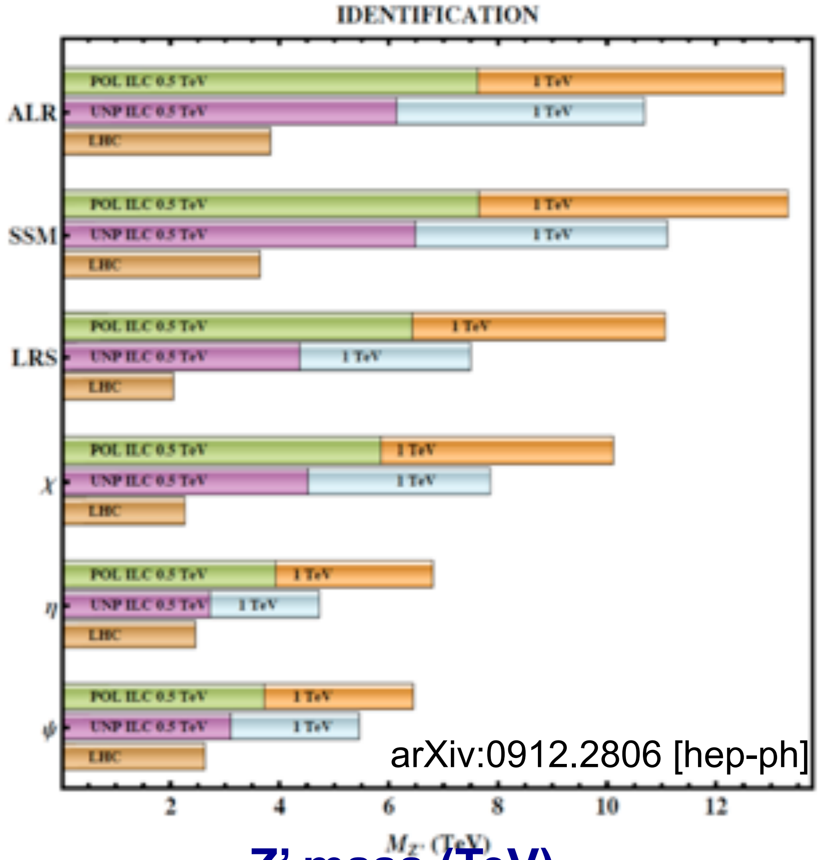
New gauge forces imply existence of heavy gauge bosons (Z')

Complementary approaches LHC/ILC

- LHC: Direct searches for Z' (mass determination)
- ILC: Indirect searches via interference effects (coupling measurements and model discrimination) – beam polarizations improve reach and discrimination power

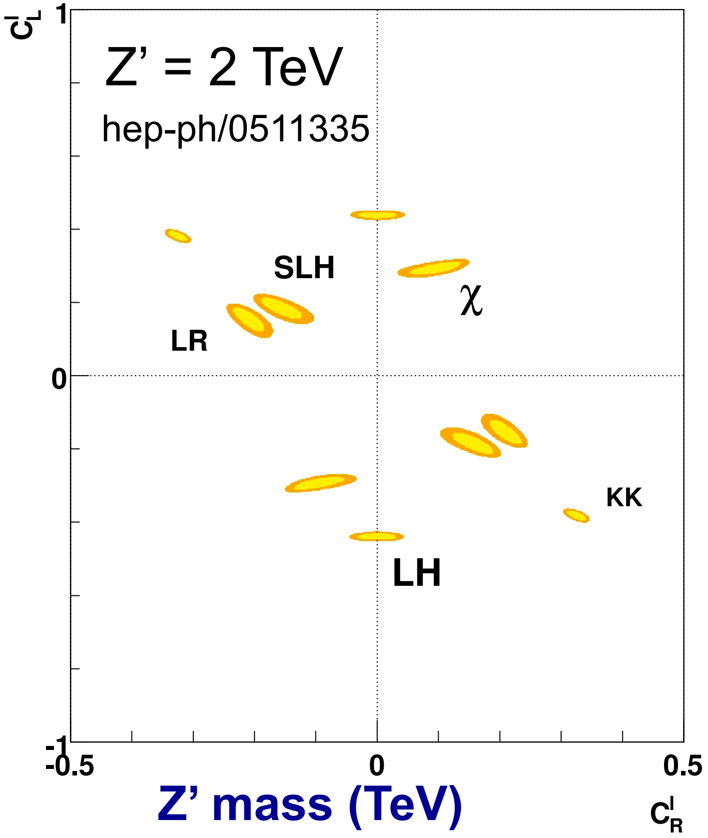


Models with Z' boson



arXiv:0912.2806 [hep-ph]

Z' mass (TeV)



Z' = 2 TeV

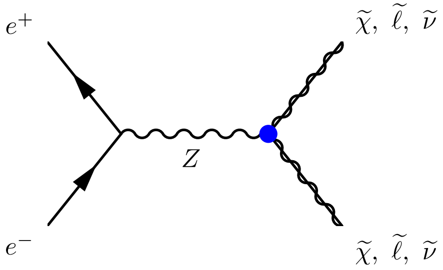
hep-ph/0511335

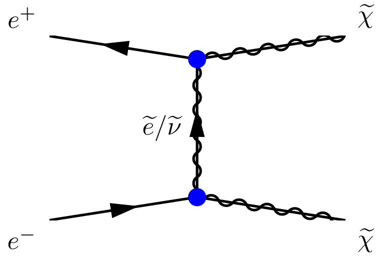
Z' mass (TeV)

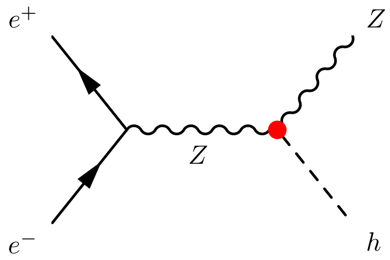
Summary

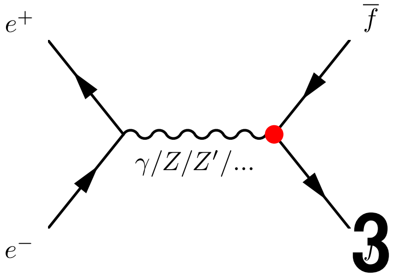
- ILC is a proposed **energy frontier** machine in e+e- collisions. The technology is ready. We have a country interested in hosting it. The extendability of linear colliders provide a **clear path for the future**.

- ILC will address **fundamental questions** in particles physics associated with **new physics at the TeV scale**.
  - What is the physics behind the **electroweak symmetry breaking**?
    - Supersymmetry, composite Higgs, …
    - Precise measurements of Higgs / top and direct searches
  - What is the nature of **dark matter**?
    - Searches complementary to direct/indirect/LHC
      - Higgs invisible width, monophotons, SUSY-specific
    - Cross section measurements → relic abundance





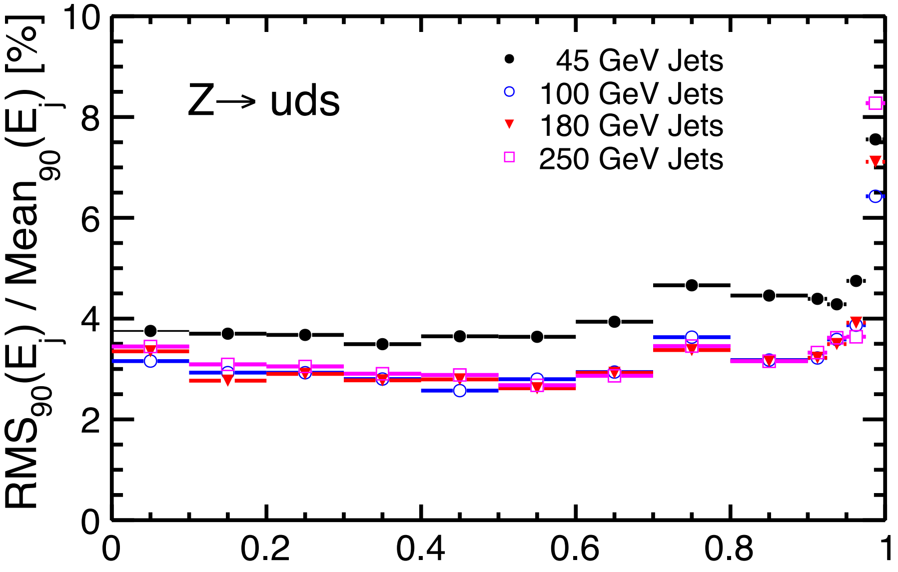


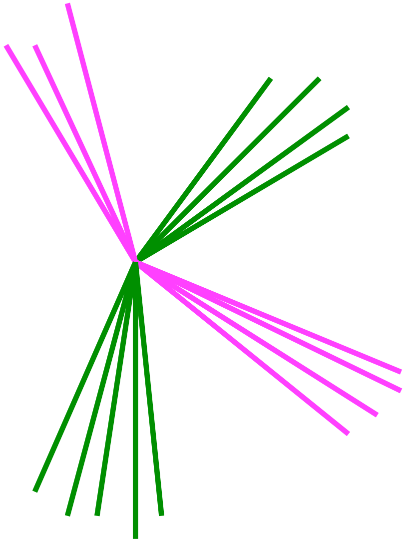


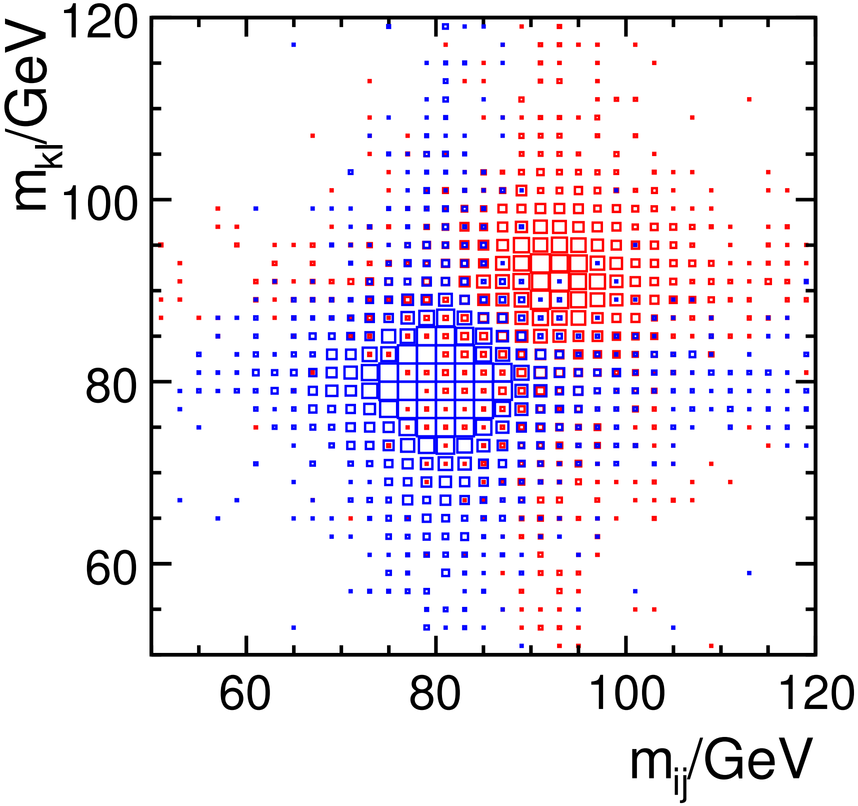
Additional Slides

Jet Energy Resolution

Full simulation ILD detector model for TDR

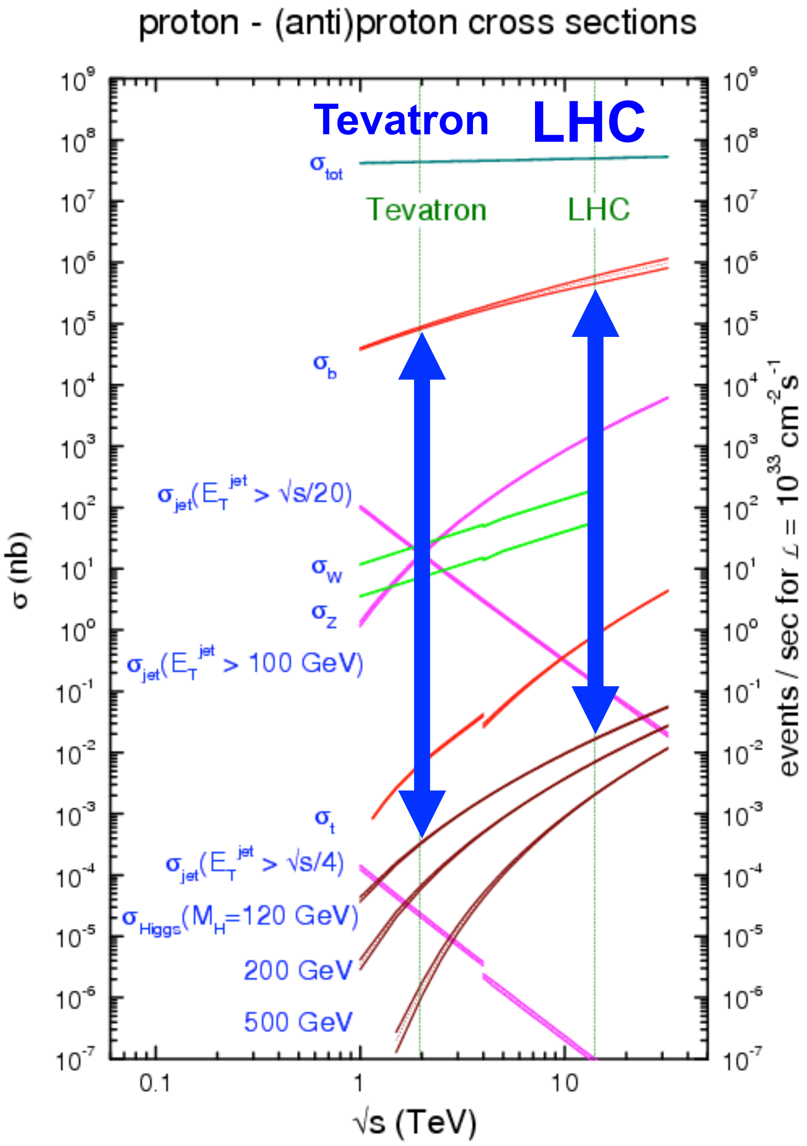






3-4% jet energy resolution
→ Good W/Z separation

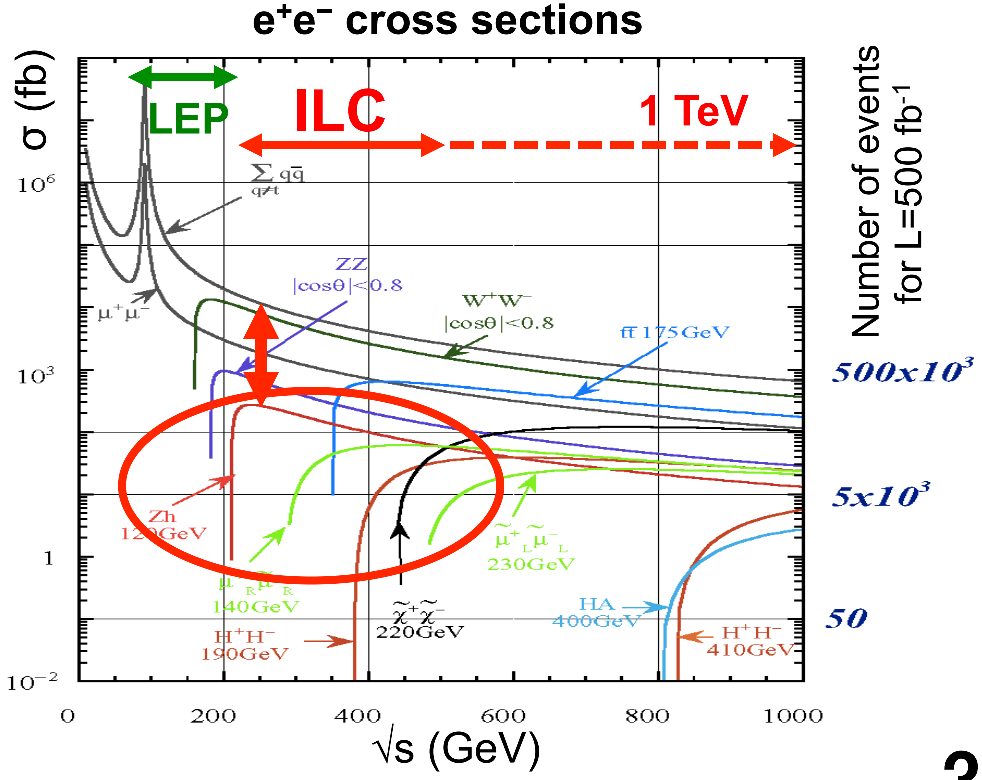
Cross Sections


proton - (anti)proton cross sections

Typically,

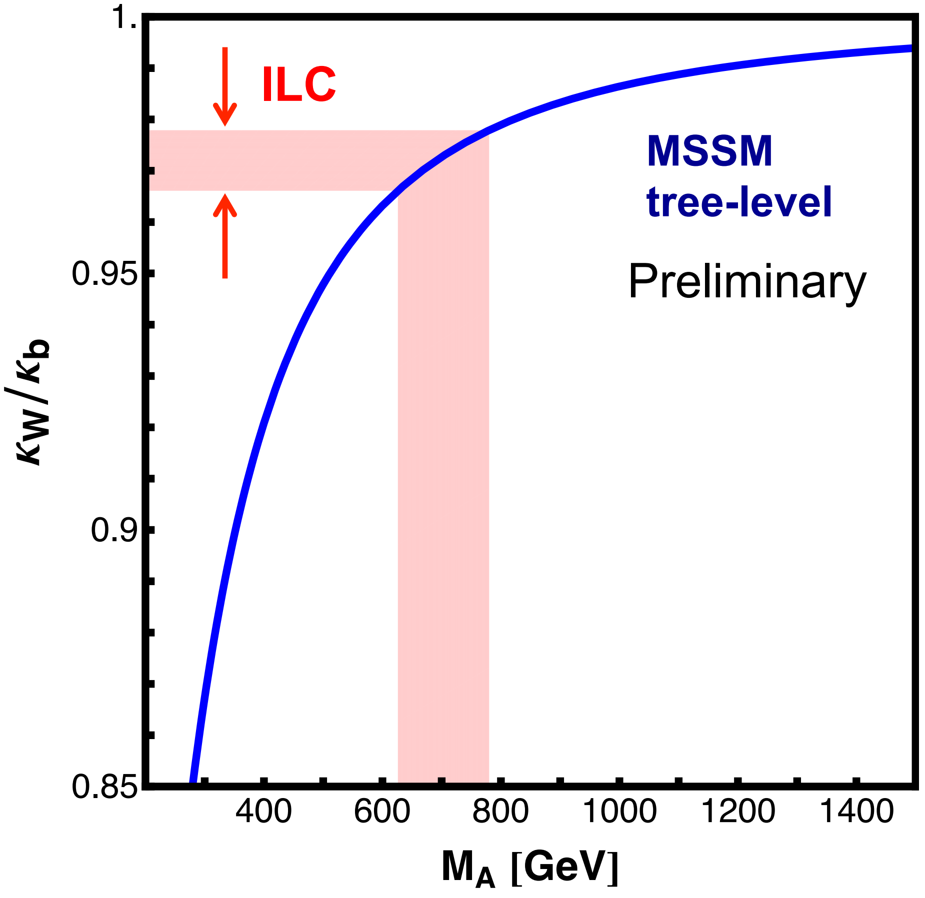
$$N^{pp}_{\rm sig} > N^{e^+e^-}_{\rm sig}$$

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


e^+e^- cross sections

Heavy Higgs Predictions

If deviations in Higgs couplings consistent with an extended Higgs sector are found, the heavy Higgs mass can be predicted from the size of the deviation. Here we give an example based on the MSSM.



The effect of the multiple Higgs fields manifests as deviations in Higgs couplings of the lightest (SM-like) Higgs boson.

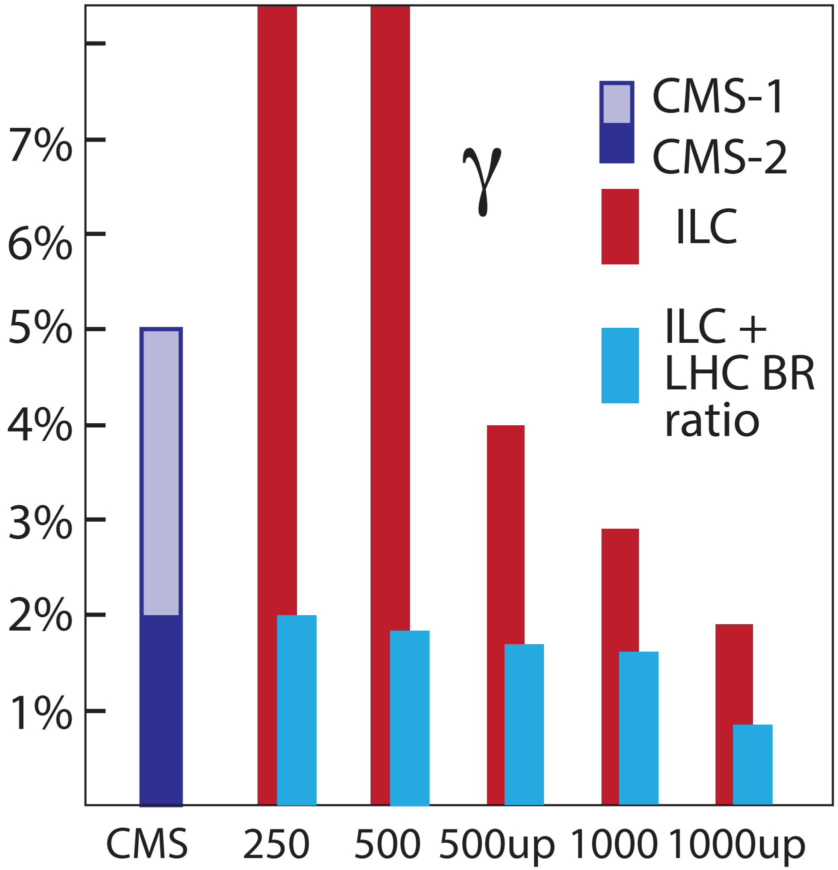
The size of the deviations depends on the mass of the heavy Higgs (MSSM)

The mass of the heavy Higgs can be predicted with precise Higgs measurements at the ILC

n.b. systematic uncertainties are suppressed by taking the ratio of the couplings.

Lumi 1920 fb-1, sqrt(s) = 250 GeV
Lumi 2670 fb-1, sqrt(s) = 500 GeV

Improving hγγ coupling precision



M. Peskin, arXiv:1312.4974

Beautiful example of LHC/ILC synergy

Combine:

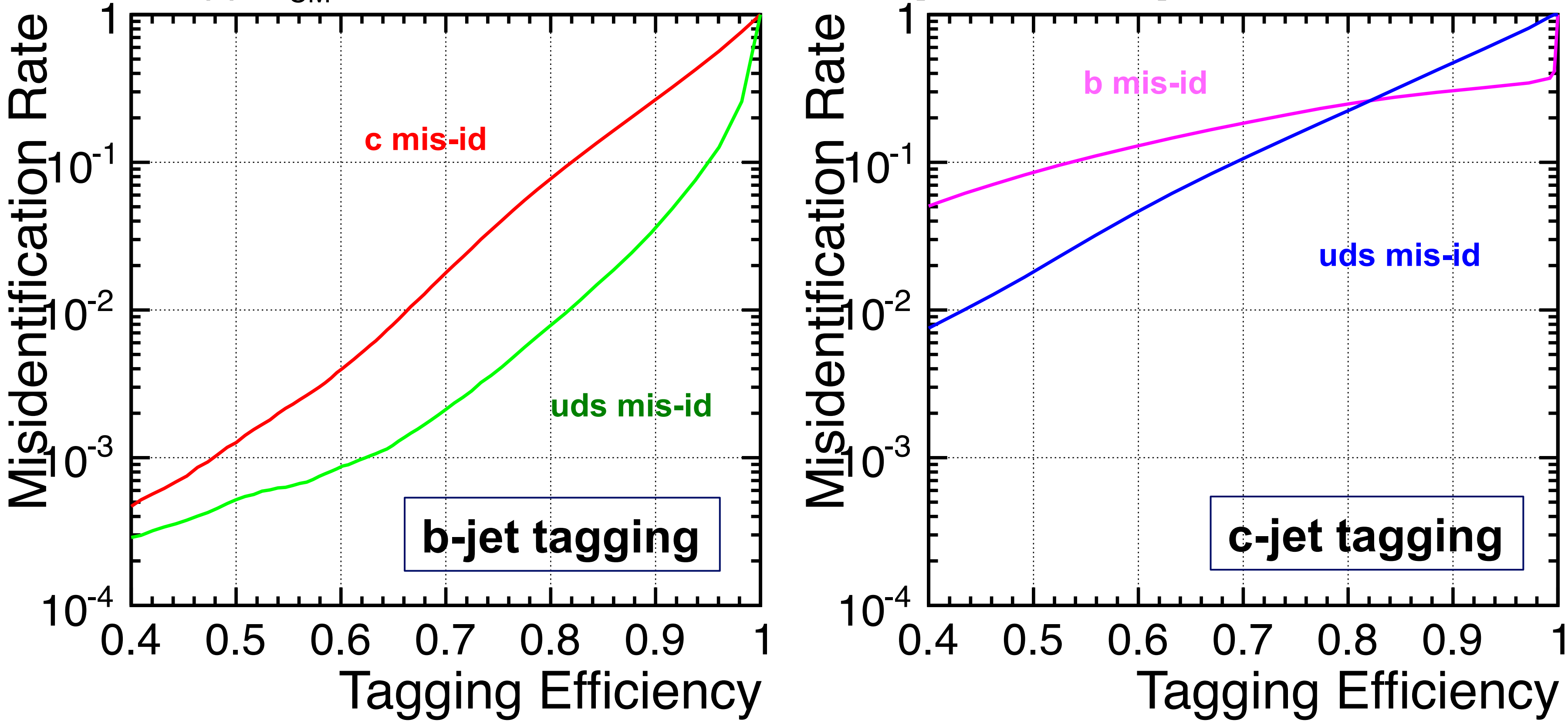
1. HL-LHC g(hγγ)/g(hZZ)
2. ILC g(hZZ)

(both model-independent)

→ Precise model-independent measurement of g(hγγ) !

Higgs Hadronic Decays: Flavor Tagging

Z→qq, E_{CM}=91.2 GeV, ILD Full Simulation [Suehara, TT]

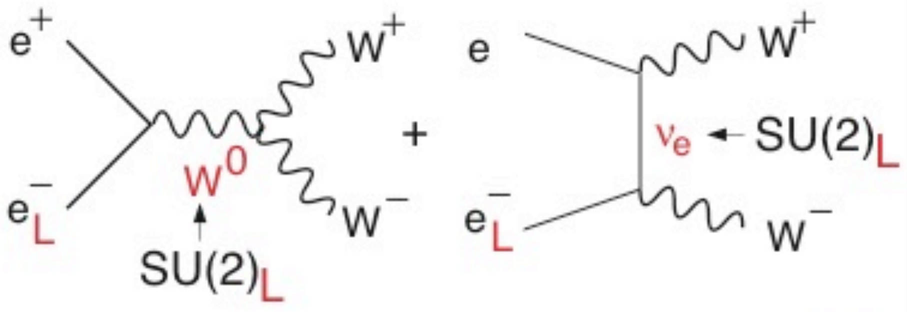


ILC detectors allow high performance b/c/g tagging
Precise measurement of BR(H→bb, cc, gg)

Power of Beam Polarization

[Fujii]

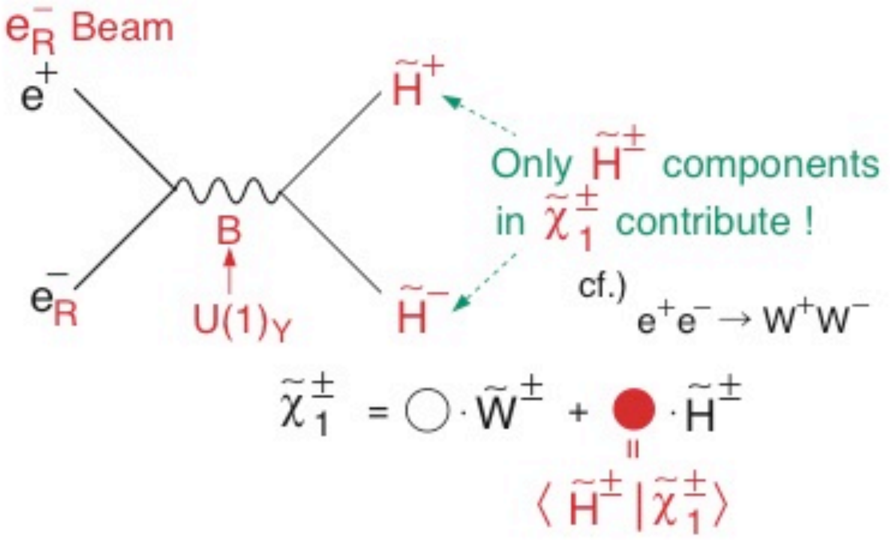
W^+W^- (Largest SM BG)



In the symmetry limit, $\sigma_{WW} \to 0$ for e^-_R !

BG Suppression

Chargino Pair



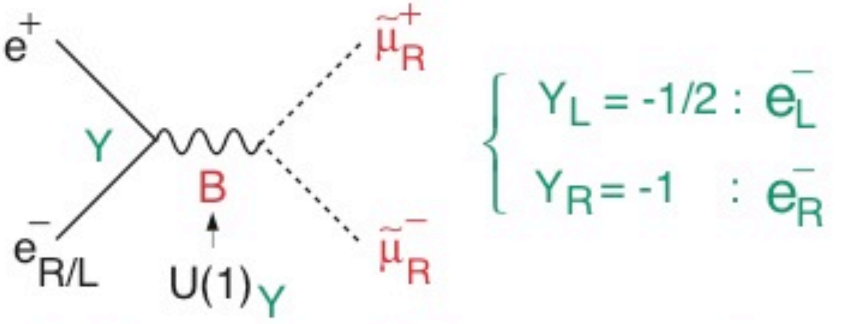
Only $\tilde{H}^\pm$ components in $\tilde{\chi}^\pm_1$ contribute !

cf.) $e^+e^- \to W^+W^-$

$$\tilde{\chi}^\pm_1 = \bigcirc \cdot \tilde{W}^\pm + \bullet \cdot \tilde{H}^\pm, \quad \bullet = \langle \tilde{H}^\pm | \tilde{\chi}^\pm_1 \rangle$$

Decomposition

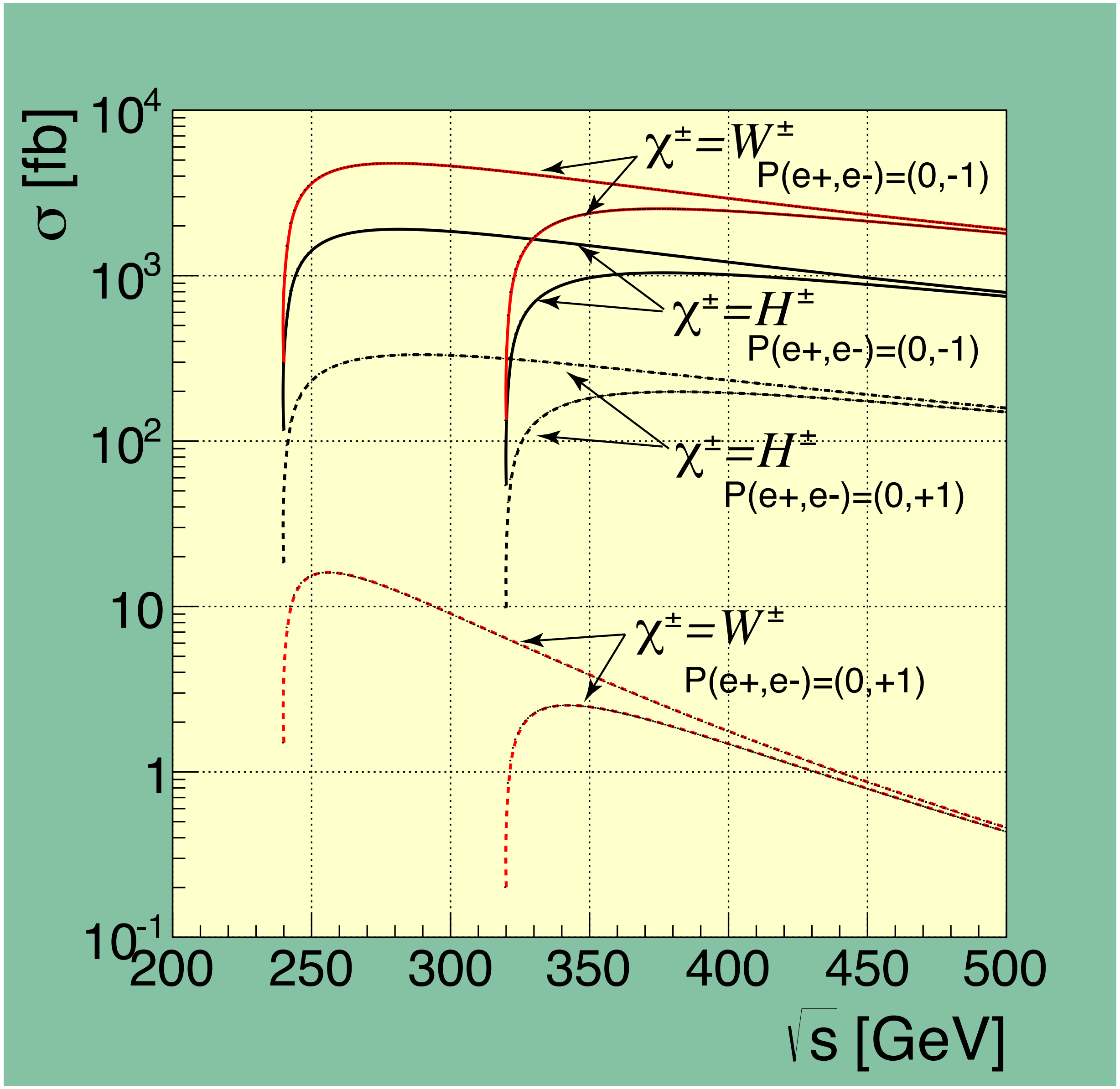
Slepton Pair



$Y_L = -1/2$: e^-_L
$Y_R = -1$: e^-_R

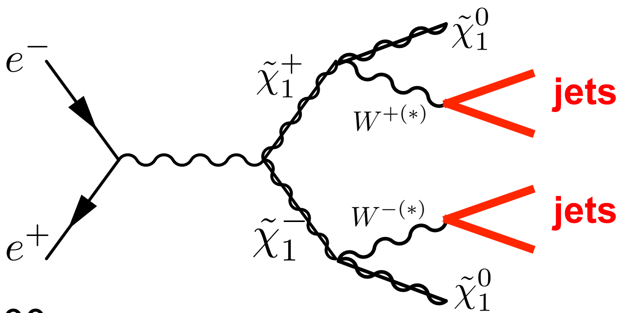
In the symmetry limit, $\sigma_R = 4\,\sigma_L$!

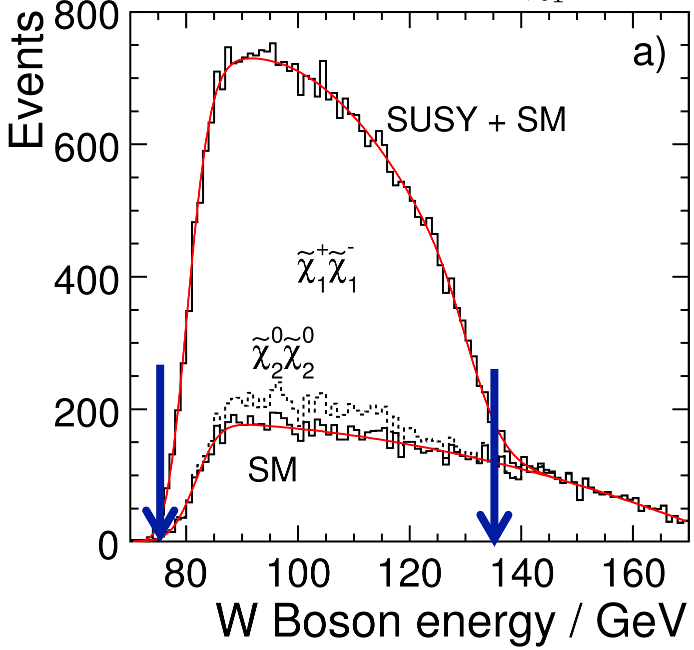
Signal Enhancement


σ [fb]
10^4
10^3
10^2
10
1
10^{-1}
200
250
300
350
400
450
500
$\sqrt{s}$ [GeV]
$\chi^{\pm}=W^{\pm}$ P(e+,e-)=(0,-1)
$\chi^{\pm}=H^{\pm}$ P(e+,e-)=(0,-1)
$\chi^{\pm}=H^{\pm}$ P(e+,e-)=(0,+1)
$\chi^{\pm}=W^{\pm}$ P(e+,e-)=(0,+1)

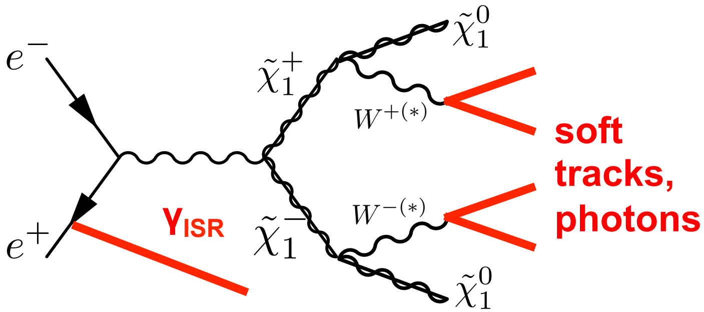
Fujii

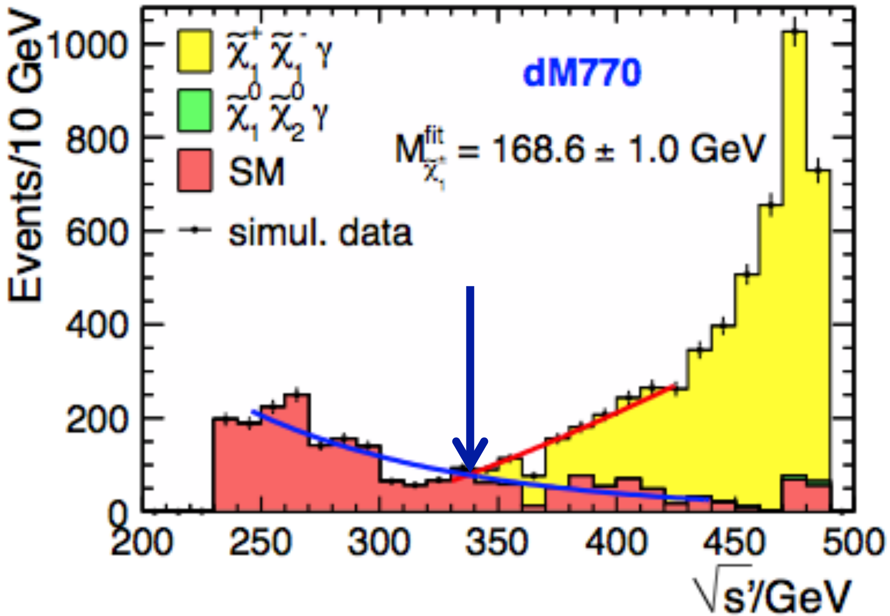
SUSY Precision Measurements





Suehara, List, arXiv:0906.5508





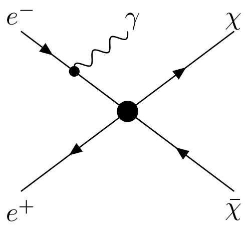
Berggren, Bruemmer, List, Moortgat-Pick, Robens, Rolbiecki, Sert, EPJ C73 (2013) 2660 [arXiv:1307.3566]

Mass determination via kinematic edges

Large mass differences between chargino/neutralino; decays to jets.
O(1)% mass precision

Small mass differences between chargino/neutralino; ISR photon tag.
O(1)% mass precision

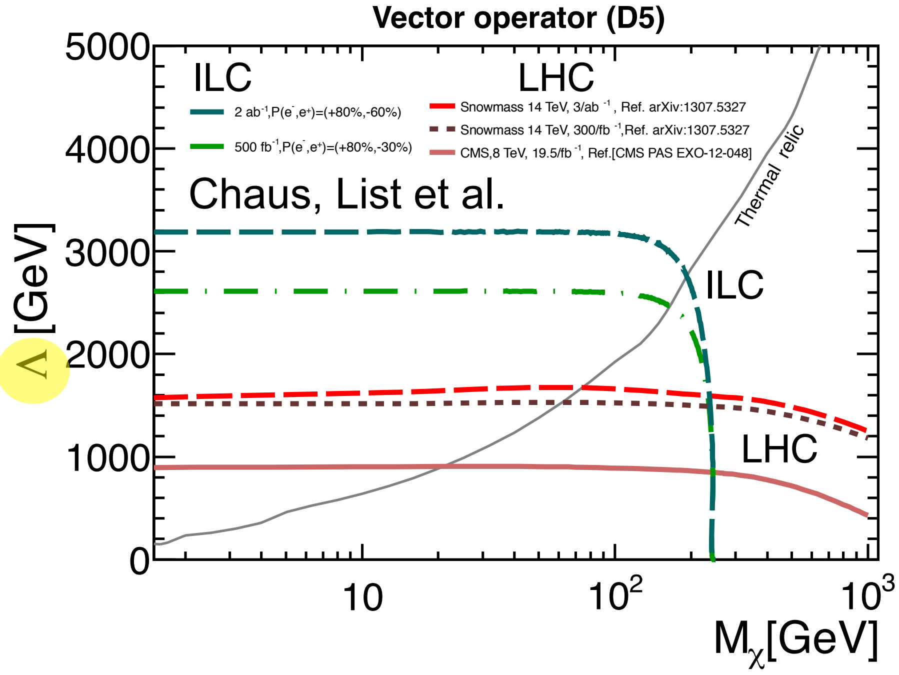
DM: Effective Operator Approach

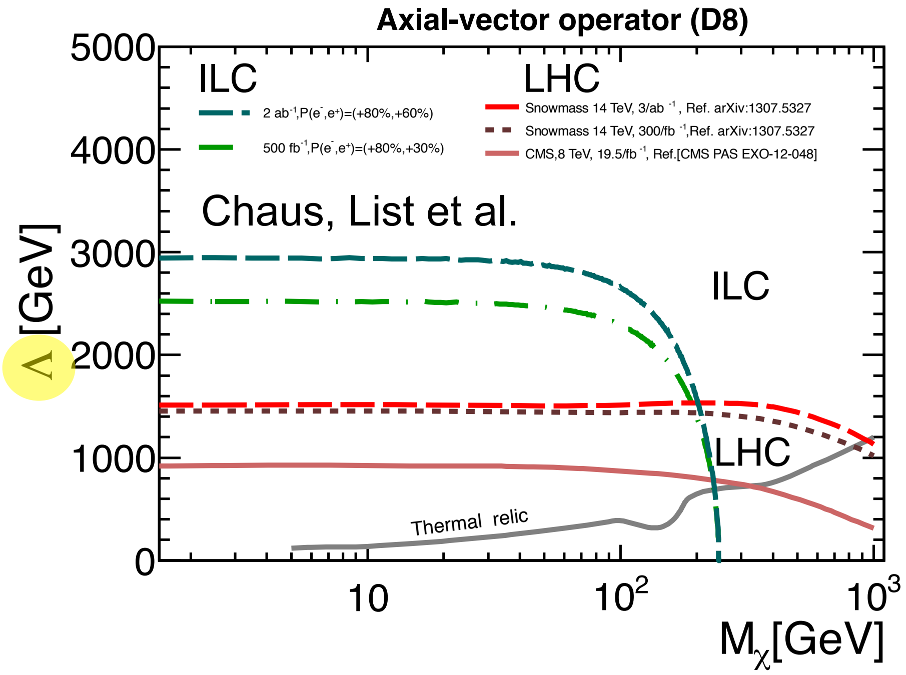


$$\mathcal{L}_{\text{int}} = \frac{1}{\Lambda^2}\mathcal{O}_i$$

$$\mathcal{O}_V = (\bar{\chi}\gamma_\mu\chi)(\bar{\ell}\gamma^\mu\ell)$$

$$\mathcal{O}_A = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{\ell}\gamma^\mu\gamma^5\ell)$$





LHC sensitivity: Mediator mass up to Λ~1.5 TeV

ILC sensitivity: Mediator mass up to Λ~3 TeV for DM mass up to ~√s/2