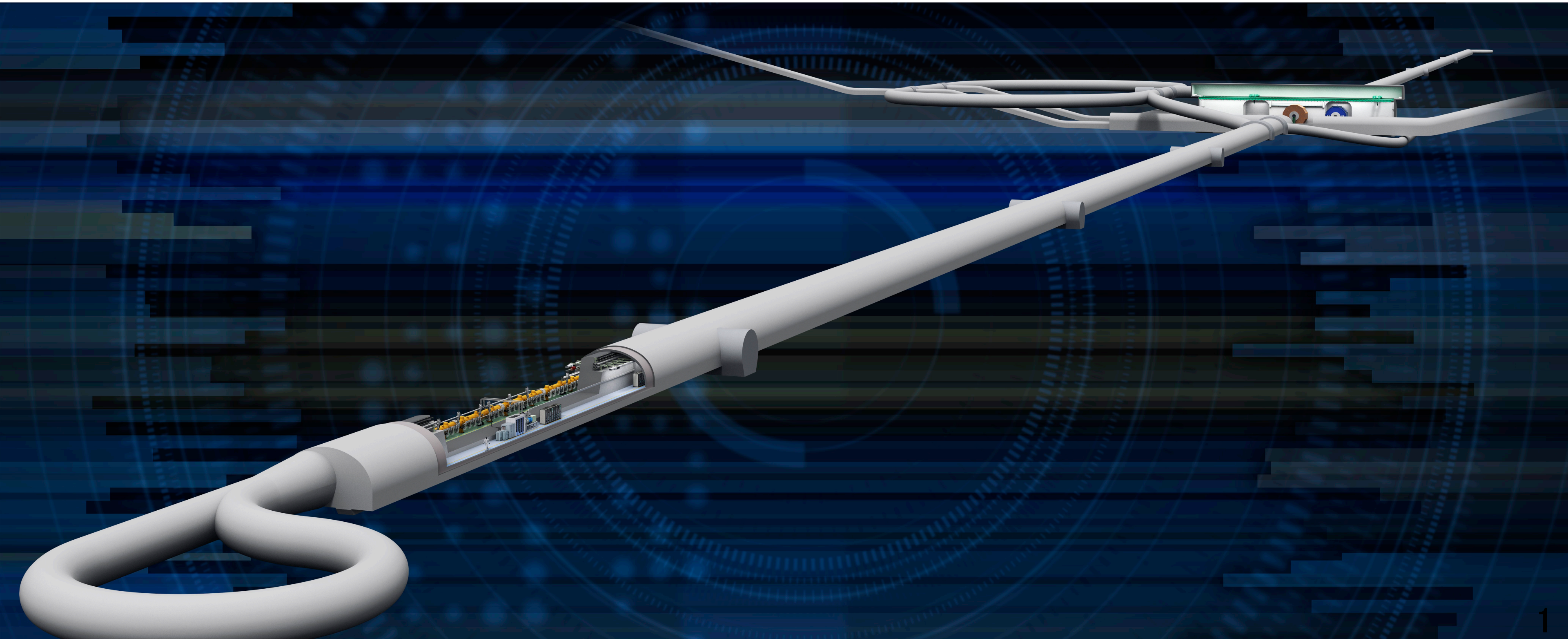
BSM Physics – Where are we, what is missing?

Tomohiko Tanabe (U. Tokyo)

September 8, 2014

ILD Meeting in Oshu City



Making the ILC Physics Case

- Recently, much attention was given to the **precision** of Higgs measurements when making the physics case for the ILC.

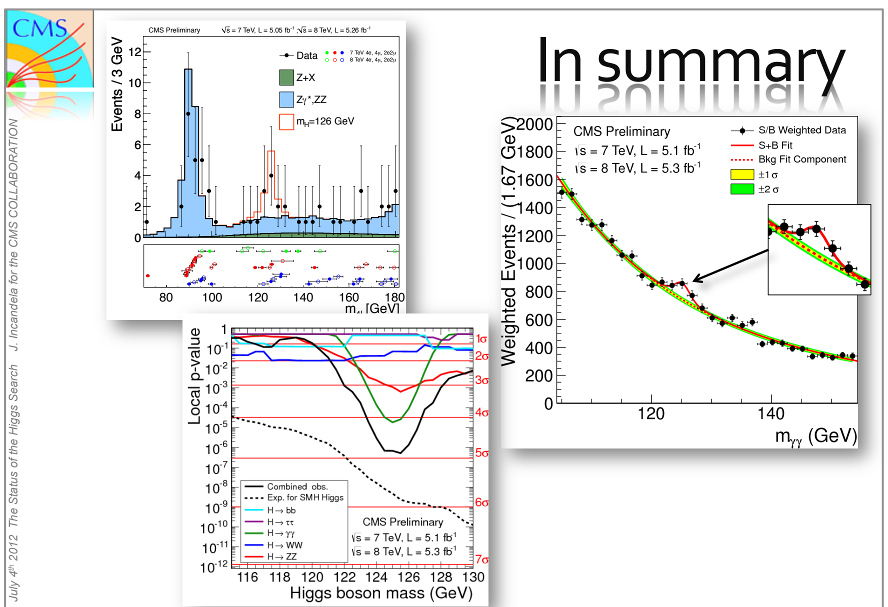
- While this worked when the audience consists of collider physicists (e.g. Snowmass), it is clearly **not sufficient** when a wider audience is involved.

- **The ILC physics case should be presented in terms of the big pictures in particle physics!**

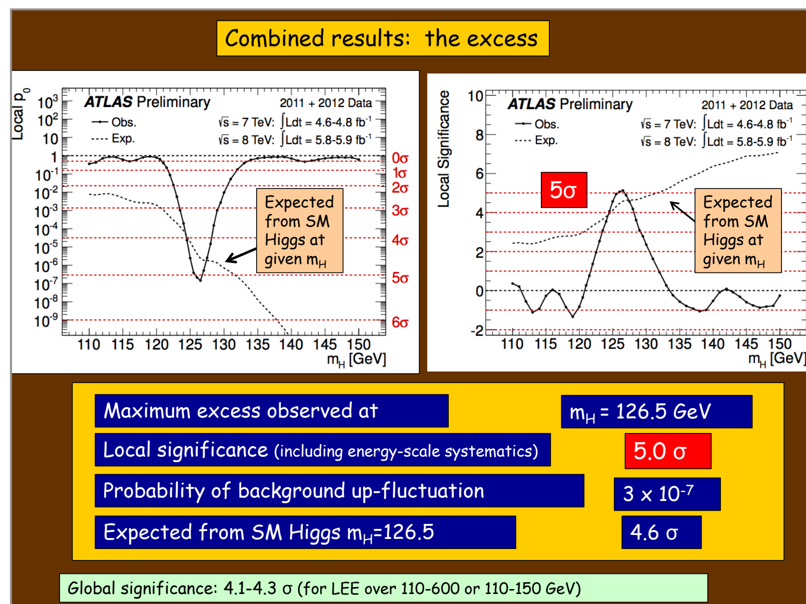
- In this talk, I will give an example of such a presentation. This is by no means meant to be complete and your comments and suggestions are always welcome!

- Where possible, I will also try to point out the implications for physics studies with ILD.

July 4, 2012

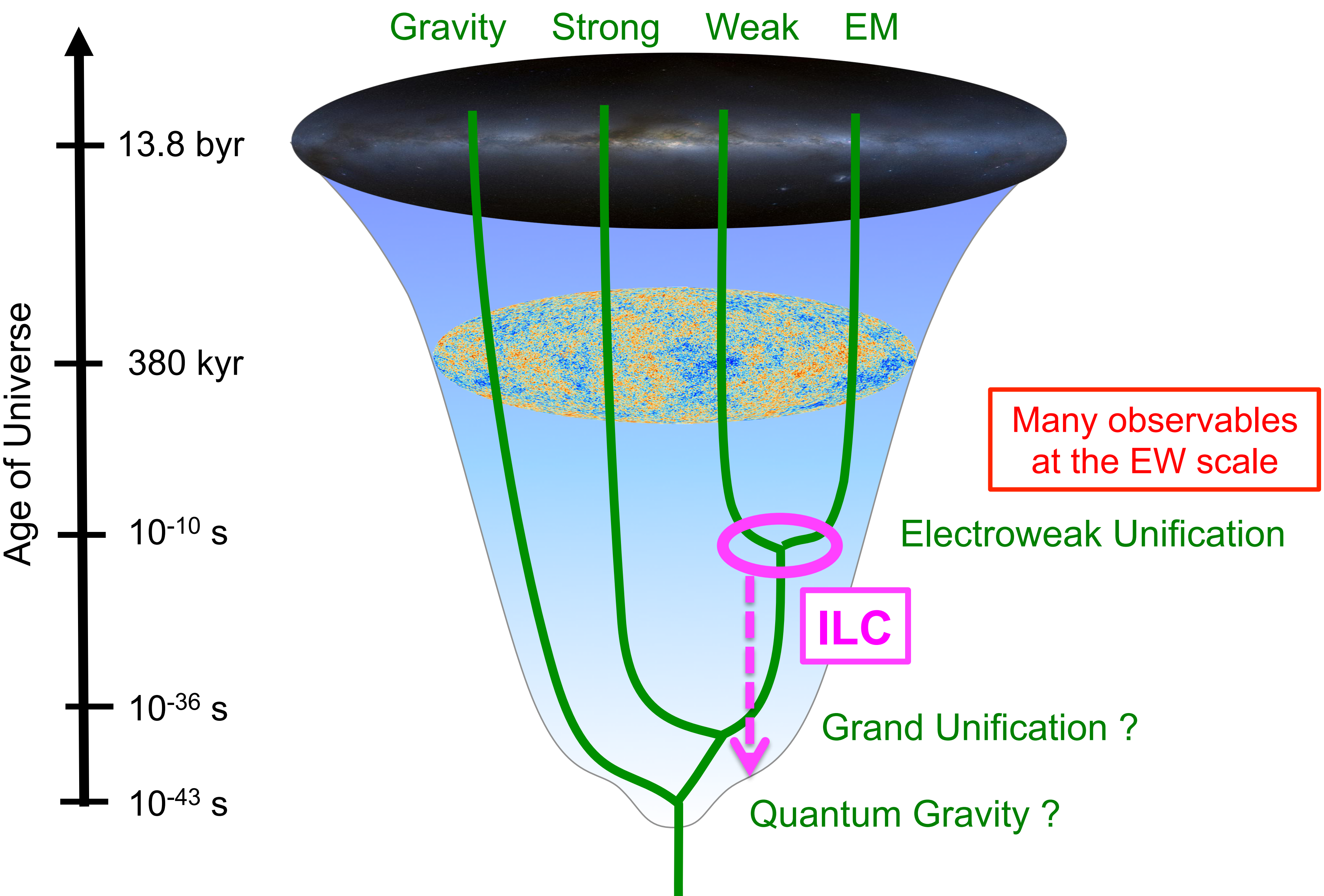


CMS
In summary
July 4th 2012 The Status of the Higgs Search J. Incandela for the CMS COLLABORATION
CMS Preliminary
Events / 3 GeV
Data
Z+X
Zγ*,ZZ
m_H=126 GeV
Local p-value
Higgs boson mass (GeV)
Combined obs.
Exp. for SMH Higgs
H→bb
H→ττ
H→γγ
H→WW
H→ZZ
√s = 7 TeV, L = 5.1 fb⁻¹
√s = 8 TeV, L = 5.3 fb⁻¹
Weighted Events / (1.67 GeV)
S/B Weighted Data
S+B Fit
Bkg Fit Component
±1 σ
±2 σ
m_γγ (GeV)



Combined results: the excess
ATLAS Preliminary
2011 + 2012 Data
Obs.
Exp.
√s = 7 TeV: ∫Ldt = 4.6-4.8 fb⁻¹
√s = 8 TeV: ∫Ldt = 5.8-5.9 fb⁻¹
Local p0
Local Significance
Expected from SM Higgs at given m_H
5σ
m_H [GeV]
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)

Toward a fundamental theory



Electroweak Symmetry Breaking

- With the discovery of the Higgs boson, we now understand how electroweak symmetry breaking 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

Two possible scenarios for the physics behind EWSB which can be probe by the ILC:

Supersymmetry (SUSY):

SUSY breaking triggers EWSB.

Composite Higgs:

QCD-like theory is behind EWSB.

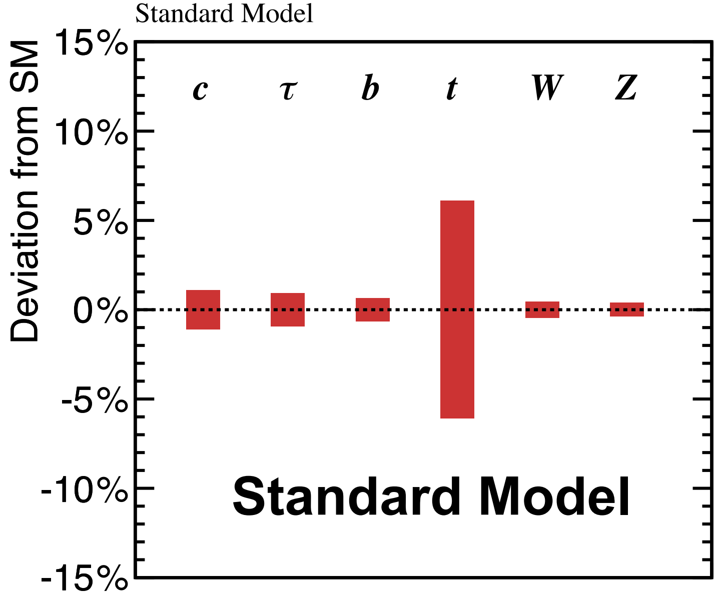
[AdS/CFT → connection with warped extra-dimensional theories]

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

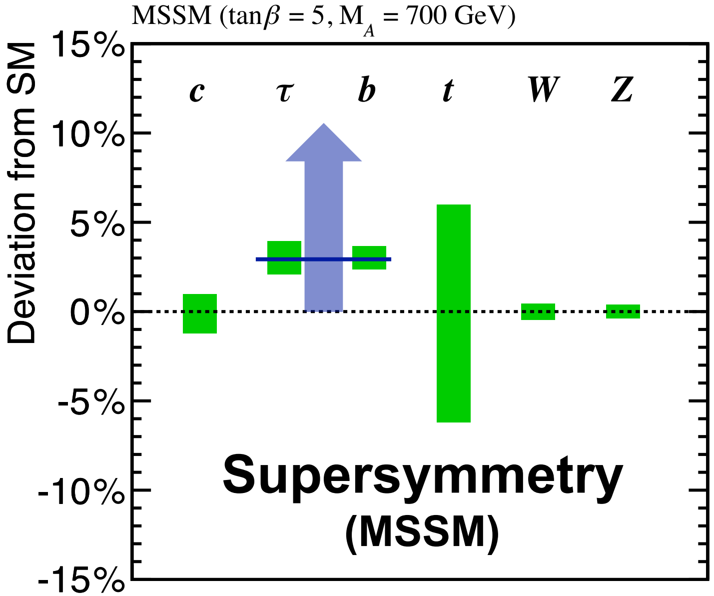
The discovery of **new particles** and their precise measurements provide the ultimate test of these possibilities.

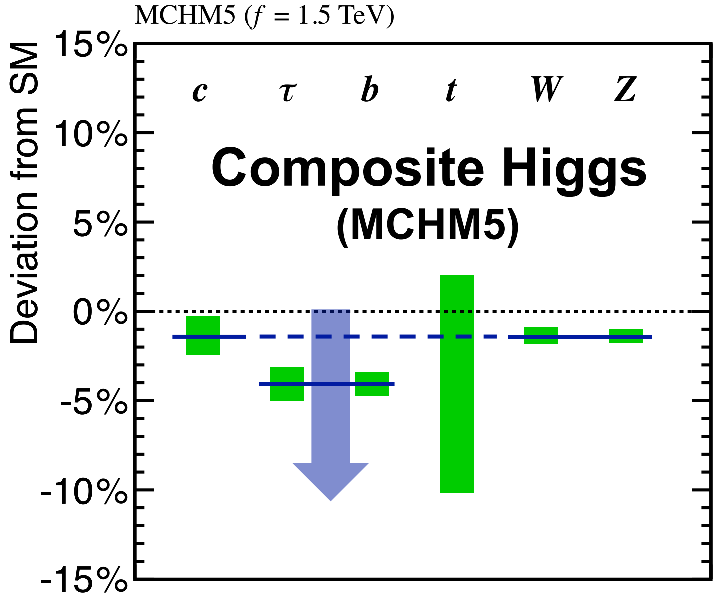
Impact of BSM on Higgs Sector

Deviations in Higgs couplings are a signature of BSM theories. **The deviation pattern is often specific to the model.** 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

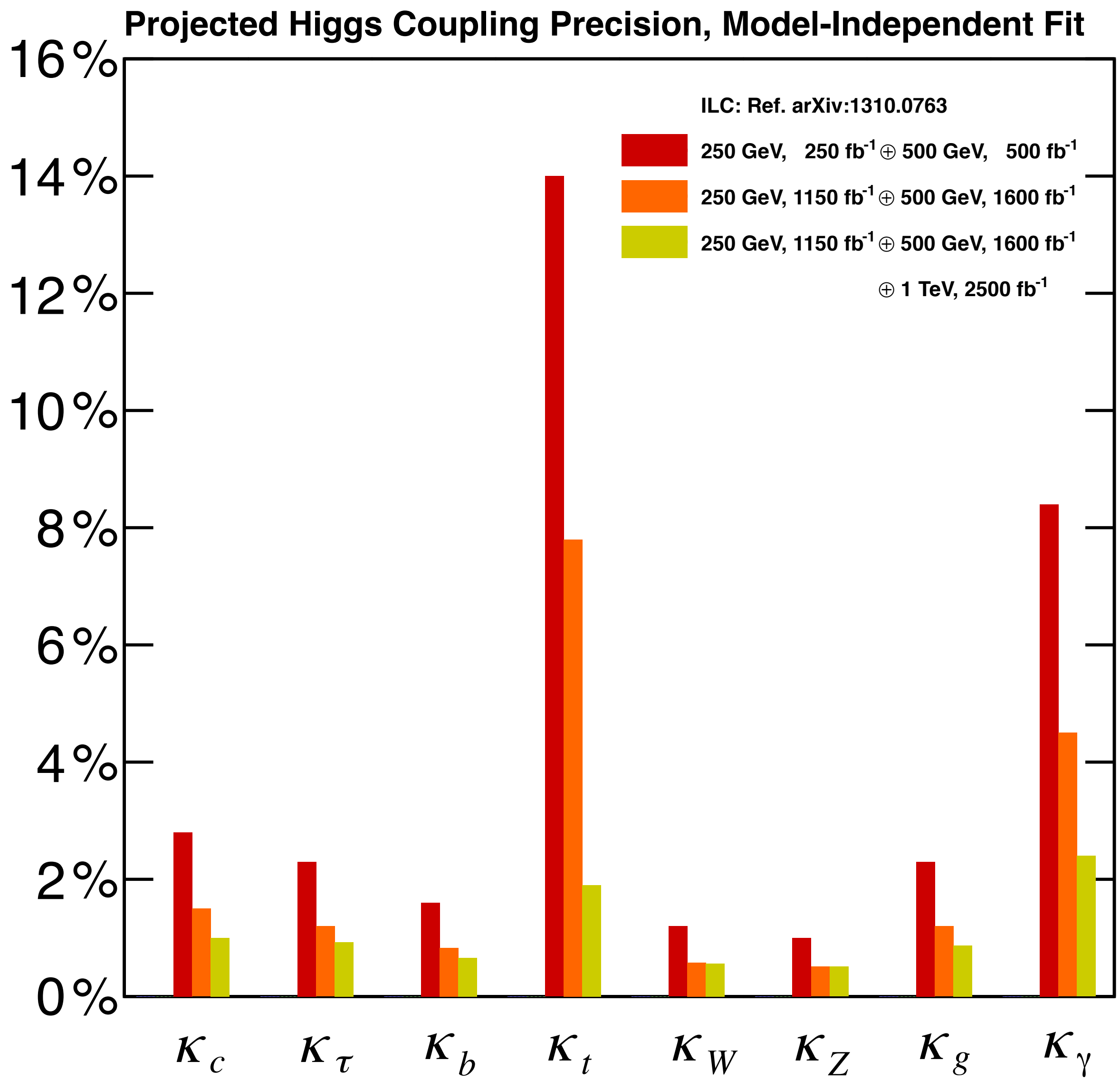




Should be refined taking into account theoretical considerations e.g. loop corrections.

Higgs Couplings

[Model-independent coupling determination unique to ILC]



Top Yukawa improves by going to 550 GeV

Excellent b-tagging c-tagging at ILC

Better hγγ with LHC/ILC synergy

Systematic uncertainties need to be evaluated to demonstrate <1% precision.

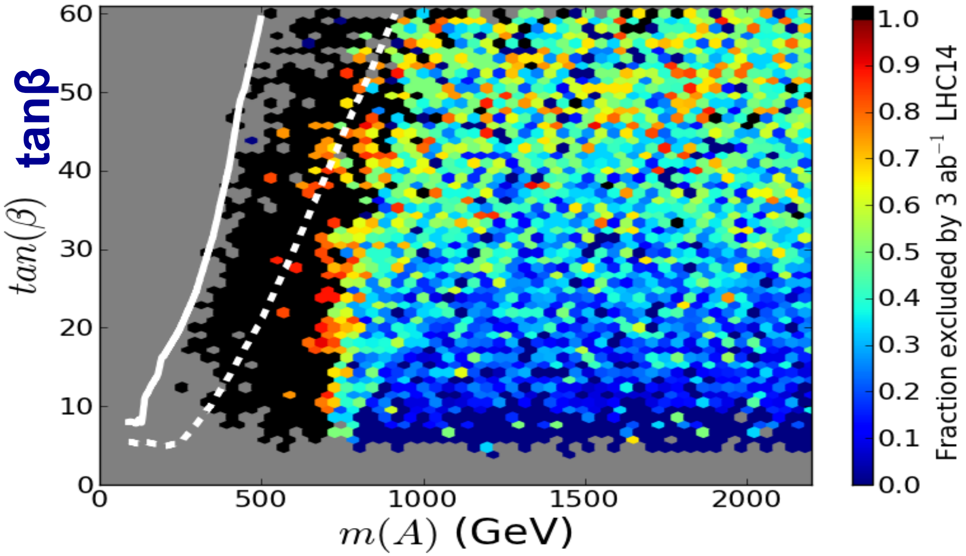
MSSM Heavy Higgs Bosons

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

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

HL-LHC 3000 fb-1

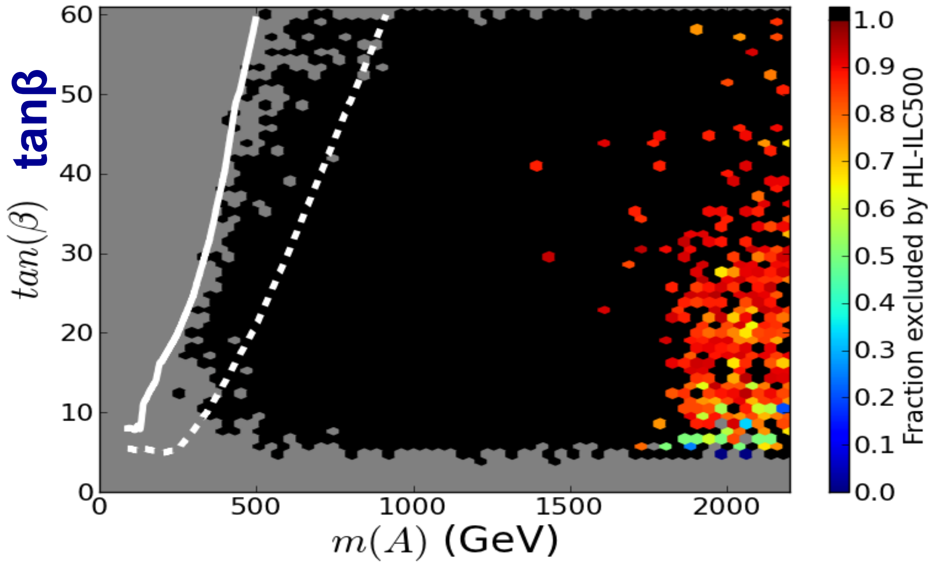
tanβ



Heavy Higgs mass

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

tanβ



Heavy Higgs mass

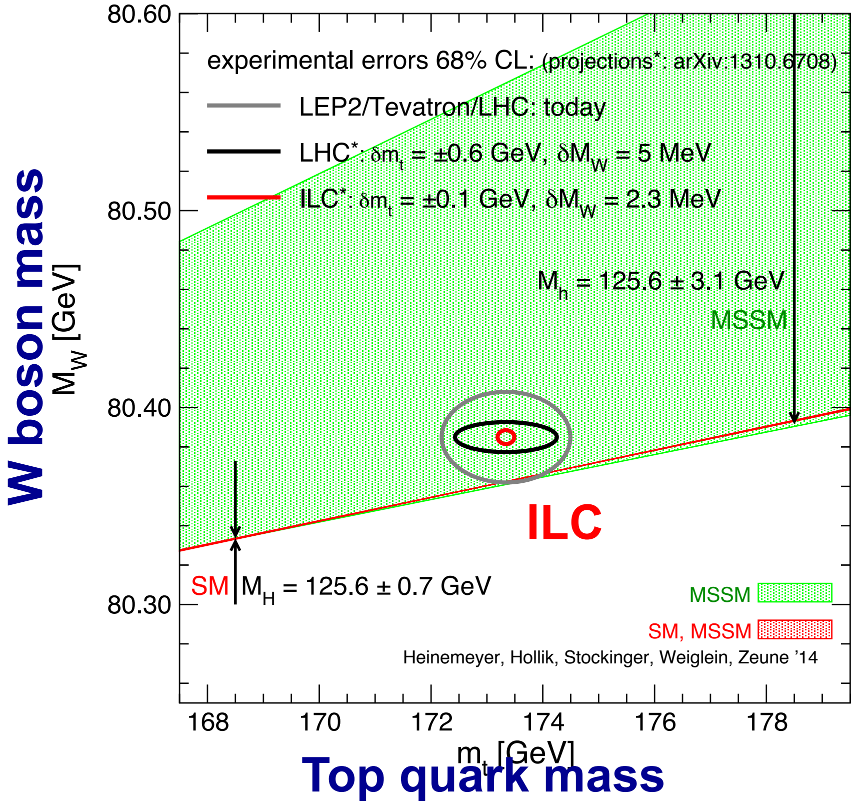
Precision Higgs coupling measurements sensitive probe for heavy Higgs bosons:
mA ~ 2 TeV reach for <u>any</u> tan*β* at the ILC

Can we apply a global fit strategy of all observables (e.g. couplings, mass) for the reach of new particles?

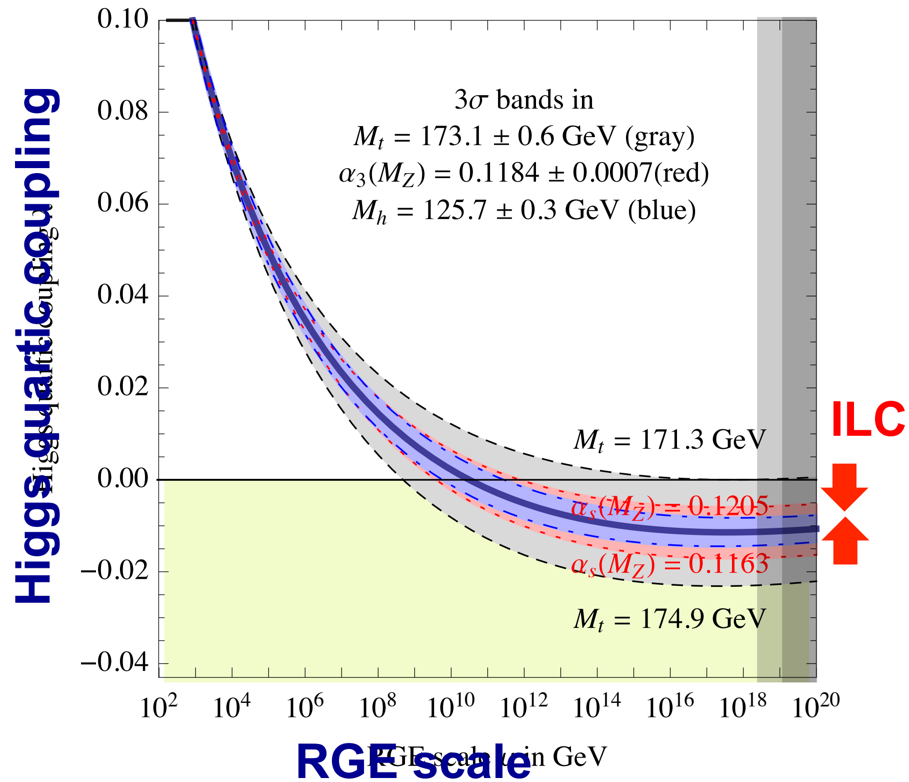
→ Require collaboration between experimentalists with theorists

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.

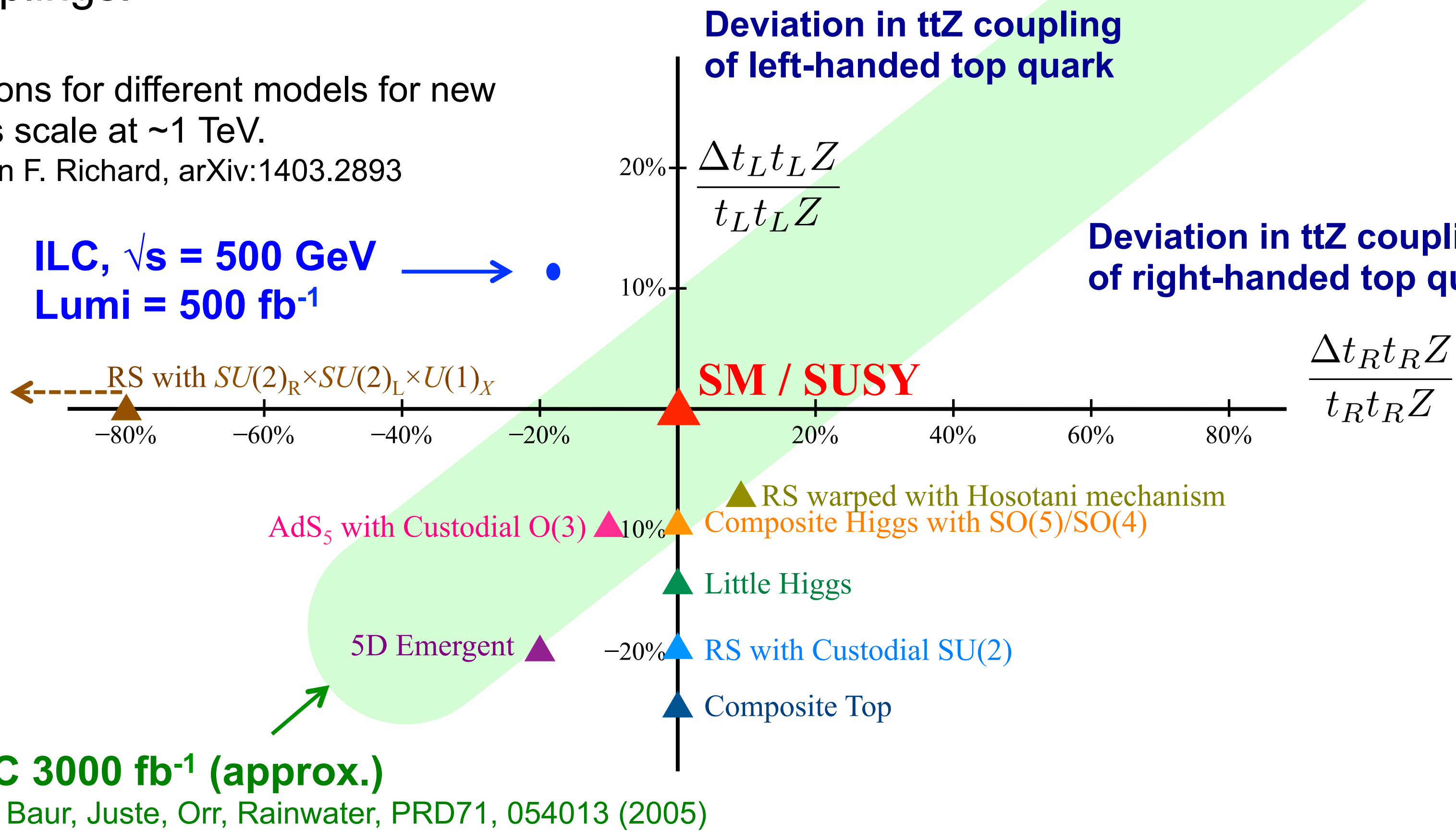


Degrassi et al., JHEP 1208 (2012) 098

Impact of BSM on Top Sector

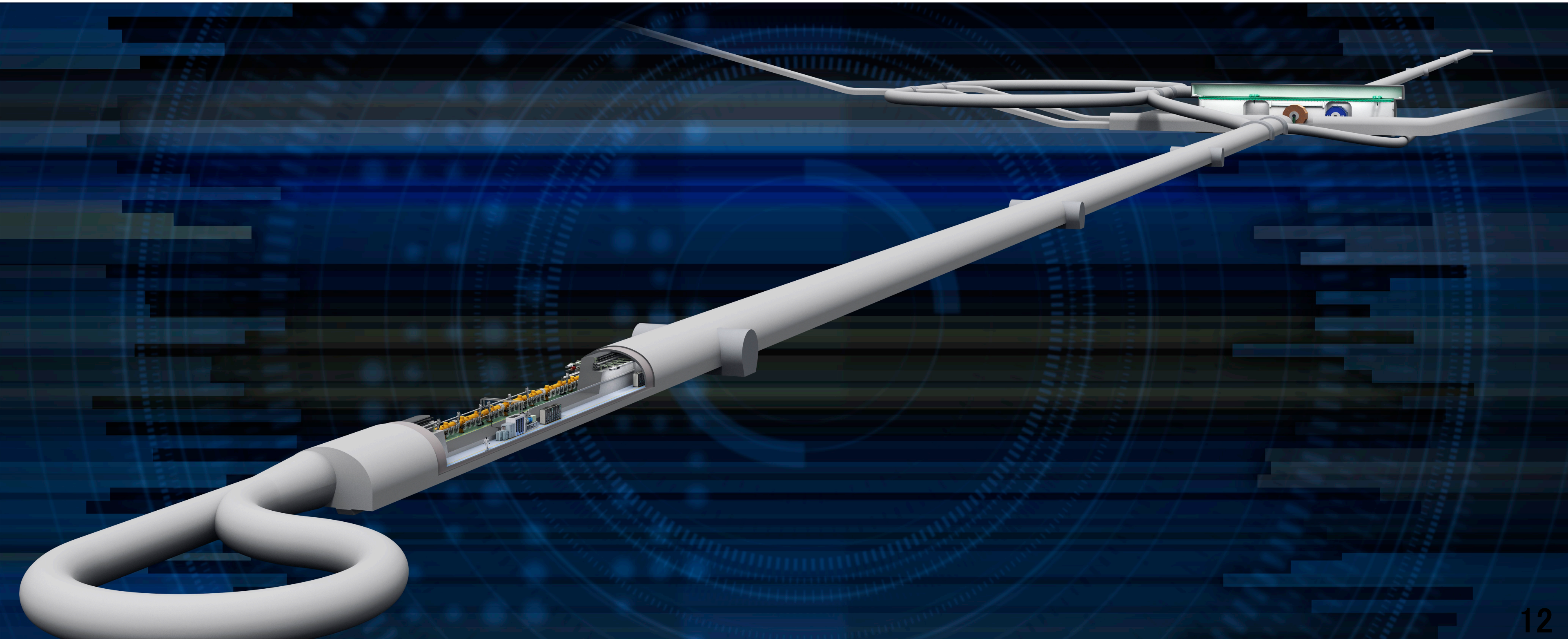
Composite Higgs theories have an impact on the top sector. Composite Higgs models can be tested at the ILC through precise measurements of the top couplings. Beam polarization (both e- and e+) is essential to distinguish the ttZ and ttγ couplings.

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



Should show deviations as a function of the new physics scale for selected models

Direct Searches: SUSY and DM



SUSY: LHC vs. ILC

"LHC has excluded MSSM up to high masses"	**vs.**	"LHC leaves out holes in MSSM parameter space"
"ILC can set model-indep. limits on SUSY particles"	**vs.**	"There is nothing interesting left within the reach of ILC"

These statements are all true to a certain extent…

The Big Picture:

SUSY is only complete with SUSY breaking implemented!

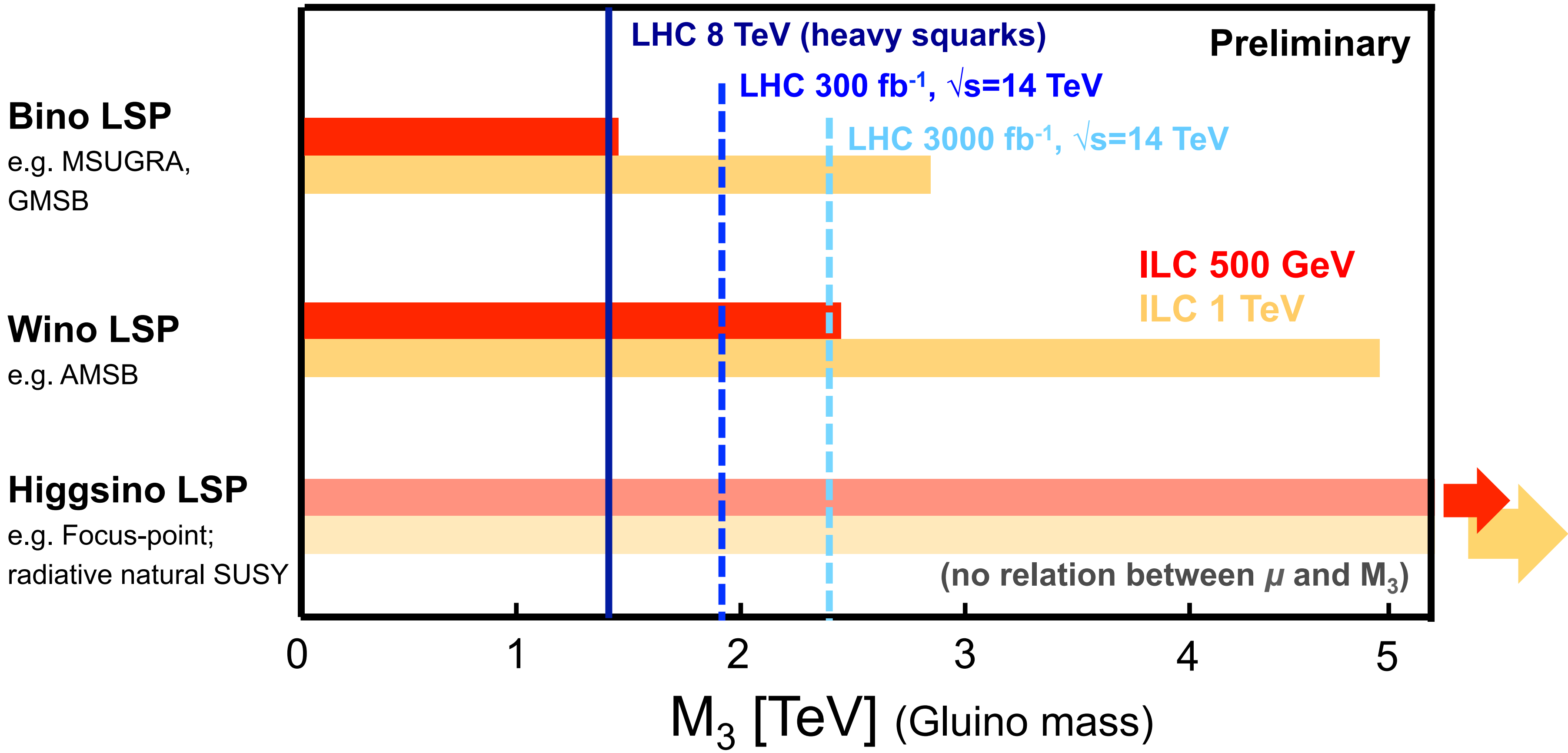
An example of connecting the "high mass reach of LHC" with "model-independent reach of ILC":

Gluino @ LHC vs. **Chargino/Neutralino @ ILC**

assuming various gaugino mass relations (e.g. GMSB, AMSB) and LSP types (Bino, Wino, Higgsino)

Sensitivity to SUSY

Compare SUSY sensitivity in terms of the same mass scale
Gluino @ LHC vs. **Chargino/Neutralino @ ILC**
…under various assumptions of gaugino mass relations



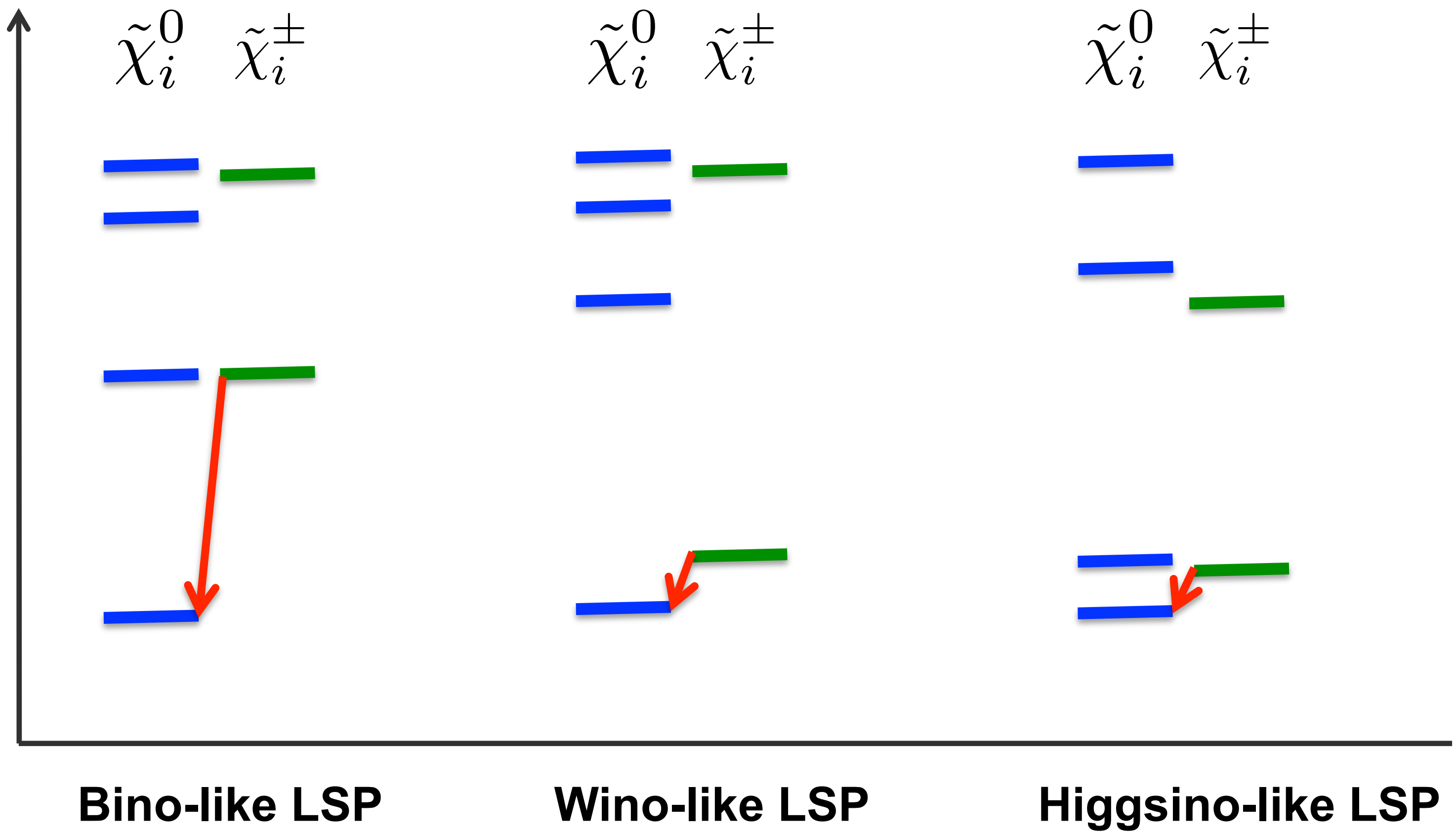
[Bino LSP: HL-LHC✔] [Wino LSP: HL-LHC~ILC500] [Higgsino LSP: ILC500 ✔]
(Reach of 1 TeV ILC truly amazing)

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

“But LHC can also search for charginos/neutralinos directly.”

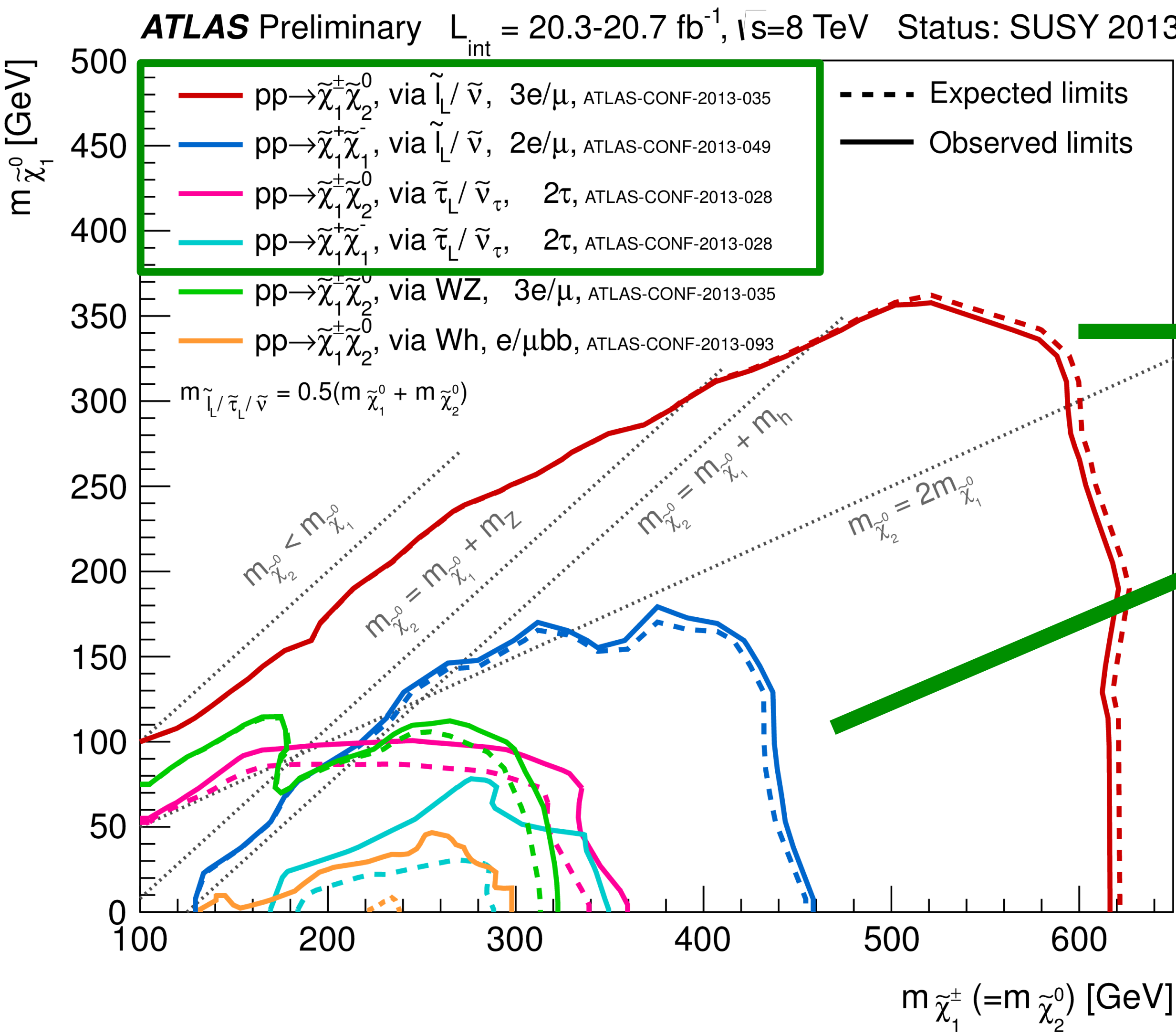
→ Fine, let’s compare the chargino/neutralino reach between LHC/ILC.

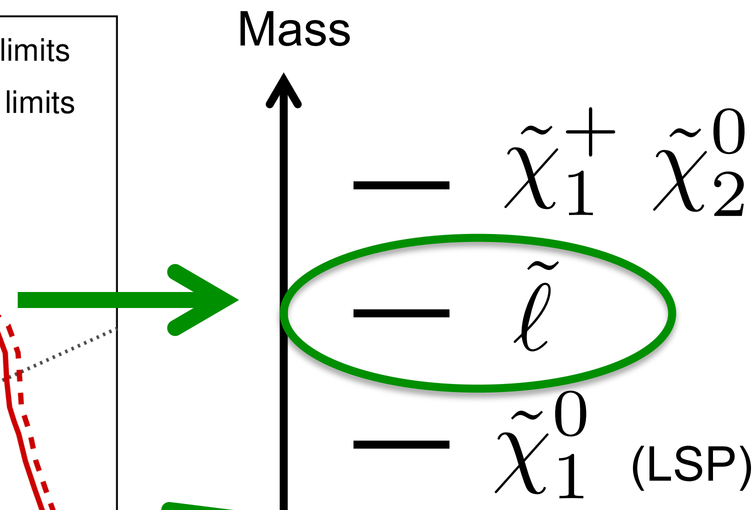
SUSY Electroweak Sector



LSP/NLSP tend to be degenerate
depending on mixing

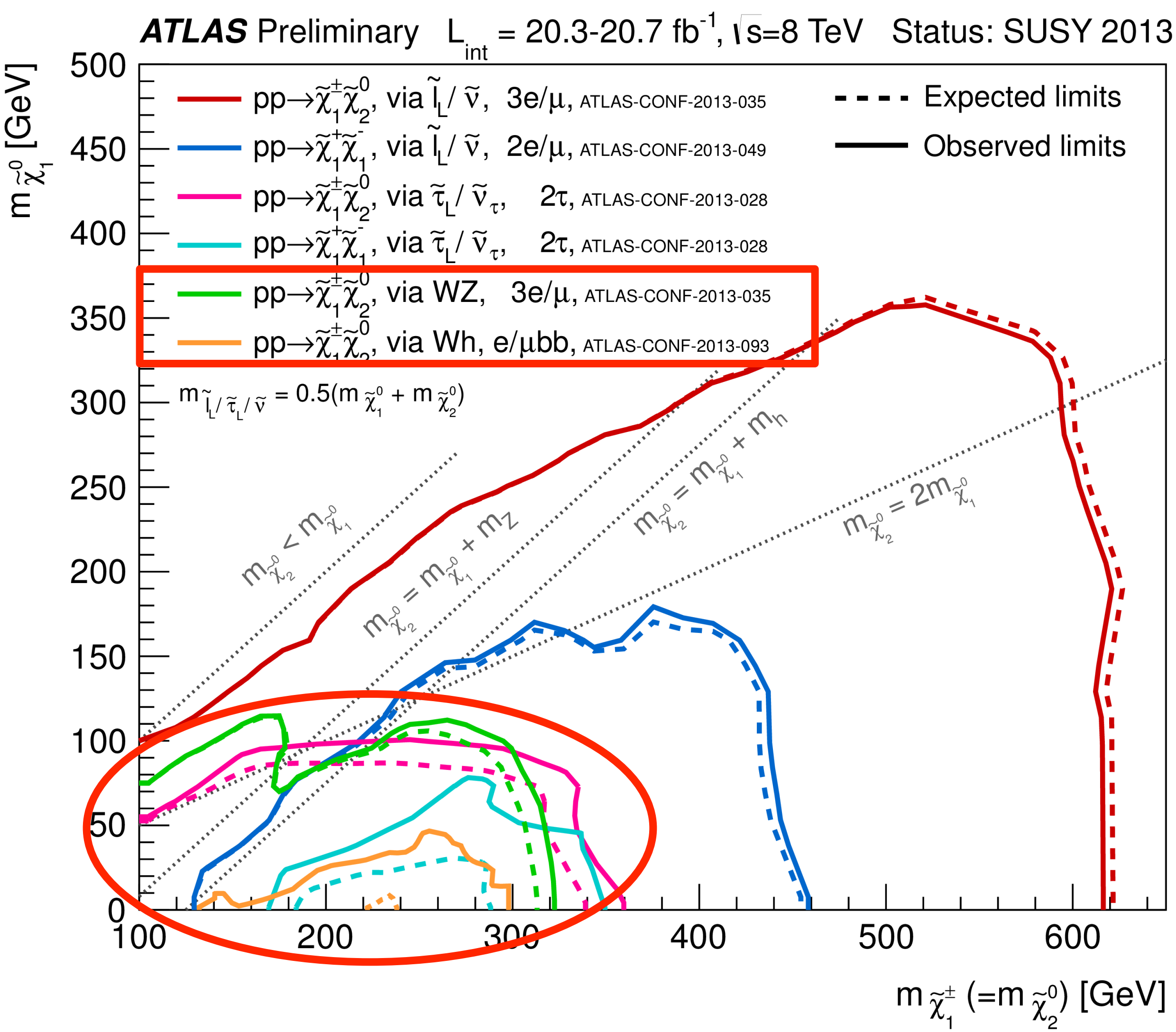
SUSY EW @ LHC

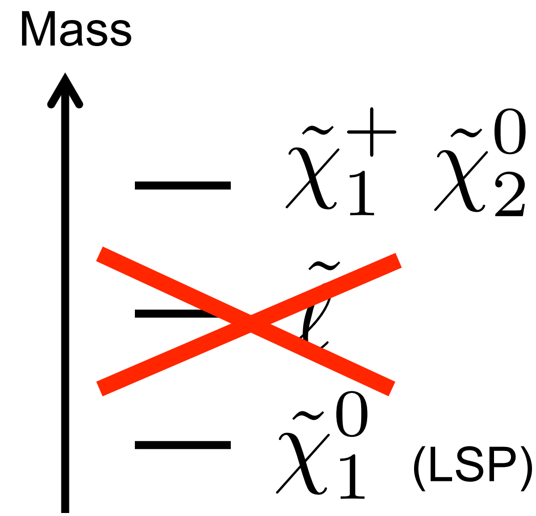




Sensitive to particular mass spectra

SUSY EW @ LHC





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

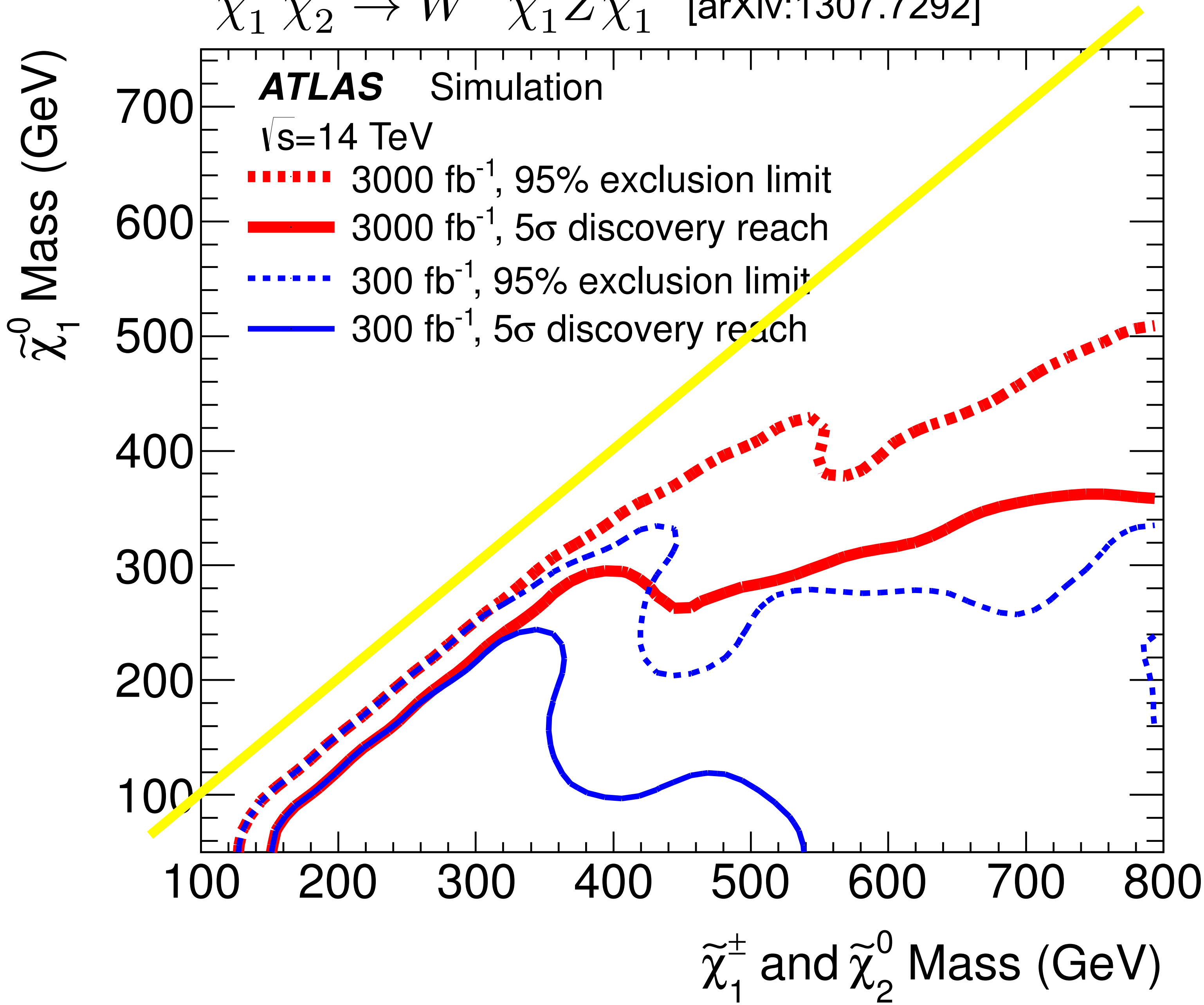
or

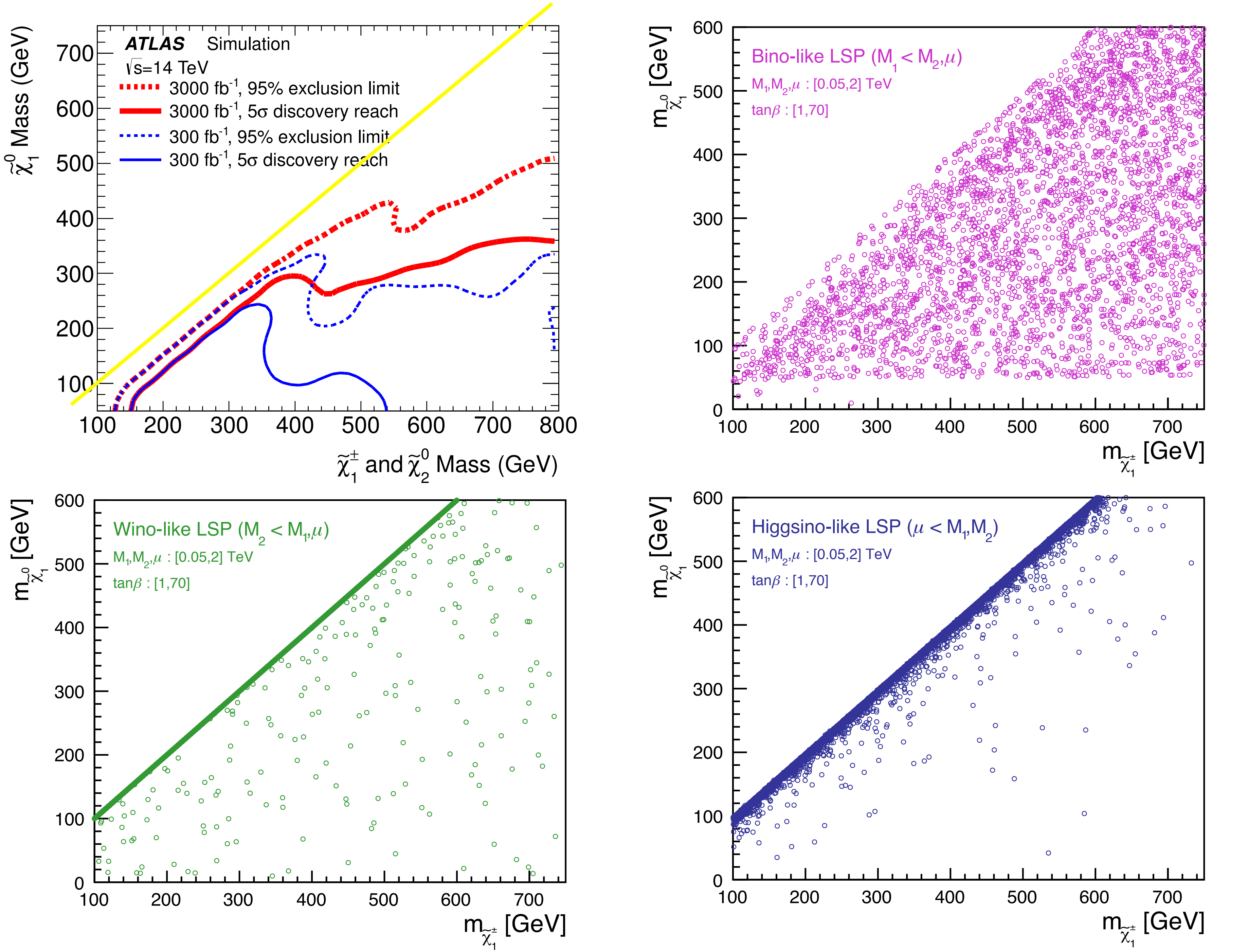
$\mathcal{B}(\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0)$

100% assumed; NOT generally true due to neutralino mixing

SUSY EW @ HL-LHC

$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to W^{\pm}\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$ [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
χ̃01 Mass (GeV)
χ̃±1 and χ̃02 Mass (GeV)
Bino-like LSP (M1 < M2,μ)
M1,M2,μ : [0.05,2] TeV
tanβ : [1,70]
Wino-like LSP (M2 < M1,μ)
M1,M2,μ : [0.05,2] TeV
tanβ : [1,70]
Higgsino-like LSP (μ < M1,M2)
M1,M2,μ : [0.05,2] TeV
tanβ : [1,70]
m χ̃01 [GeV]
m χ̃±1 [GeV]

Higgsino decays with small mass differences

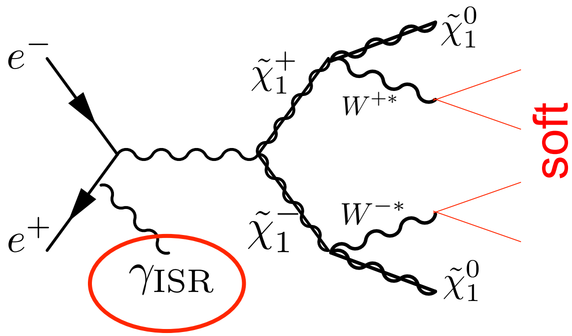
Study of Higgsino pair production, with ISR tag

Benchmark models with

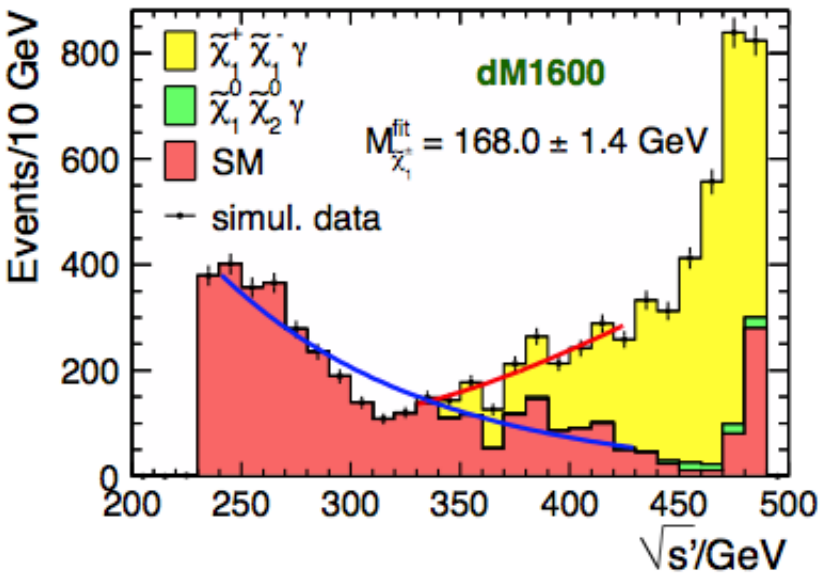
m(NLSP) – M(LSP) = 1.6 GeV and 0.8 GeV

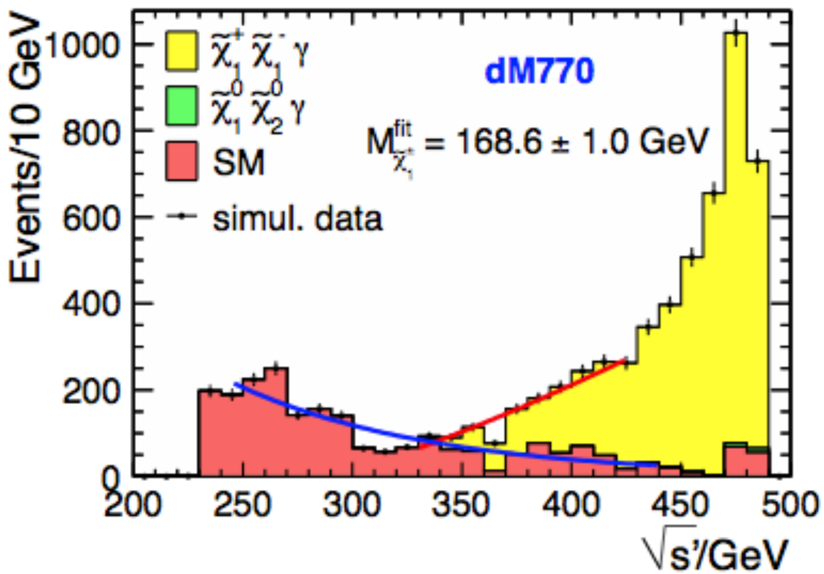
$$\sigma(e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-) = 78.7\ (77.0)\ \text{fb}$$

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



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



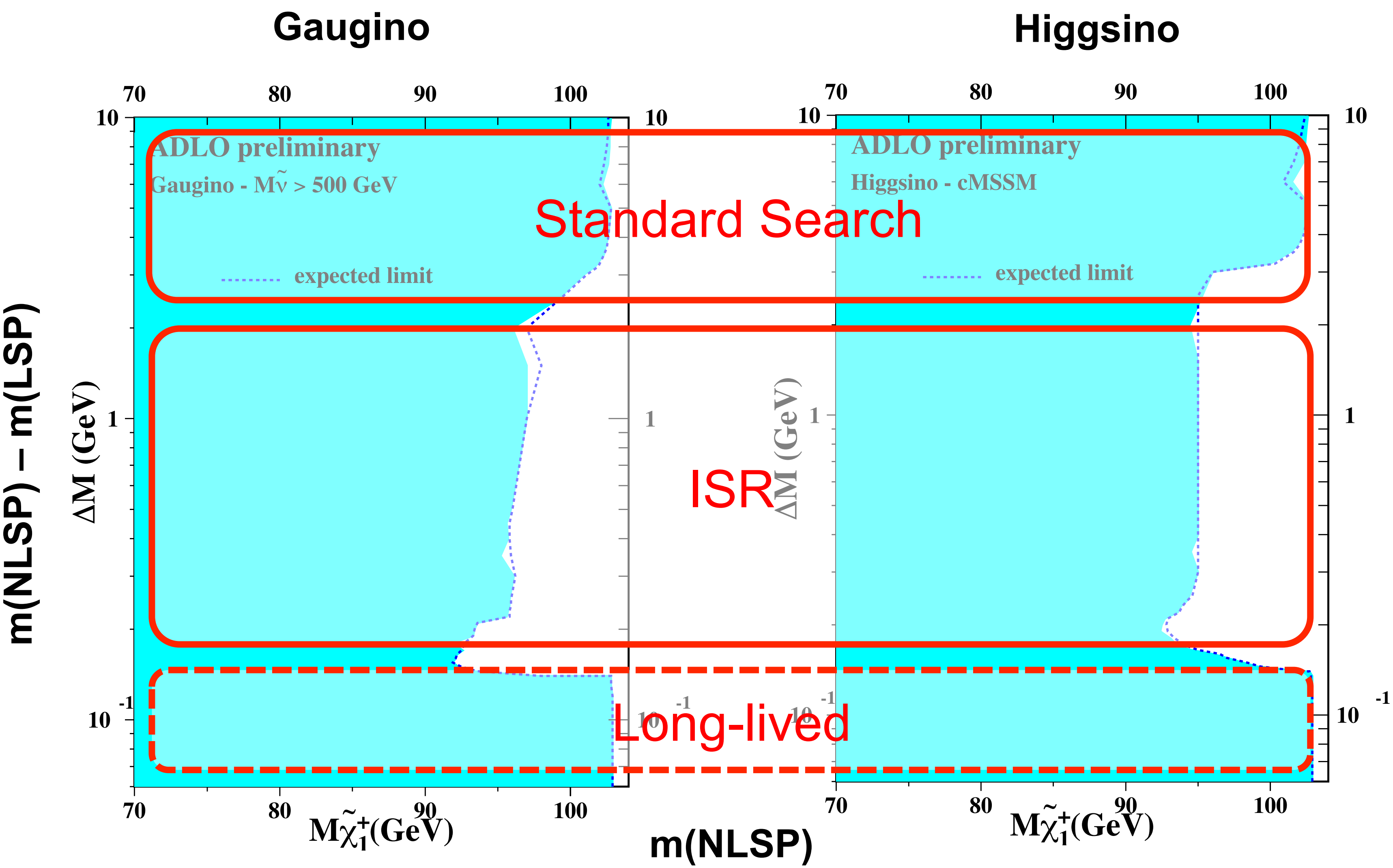


$\sqrt{s}$=500 GeV, Lumi=500 fb^{-1}, P(e-,e+)=(-0.8,+0.3) → LSP mass resolution ~1%

What is the smallest mass difference can we detect with ILD?

Low pT tracking, soft photons, hermeticity

SUSY EW @ LEPII

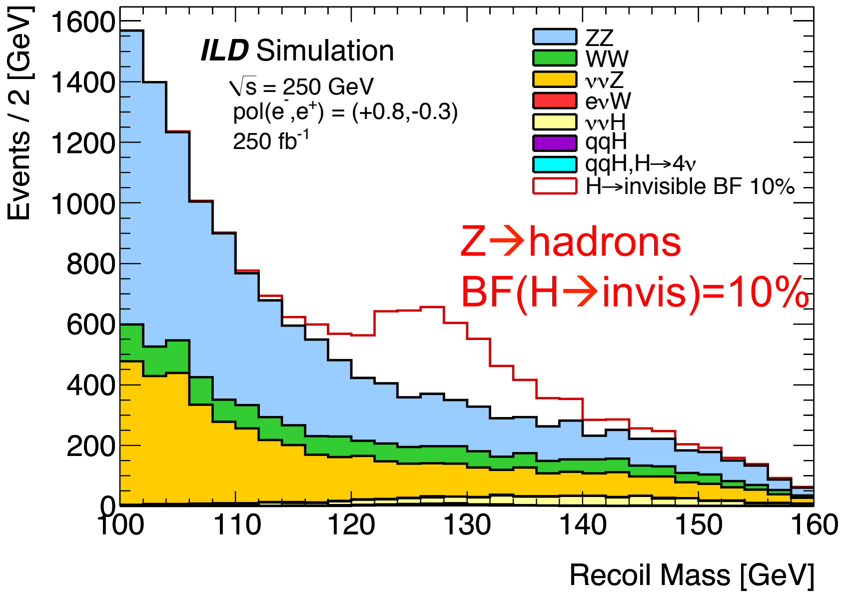


Very small mass differences result in stable tracks → excluded by LHC.
Can ILC cover small differences down to this LHC limit?

WIMP Dark Matter @ ILC

WIMP searches at colliders are complementary to direct/indirect searches.
Examples at the ILC:

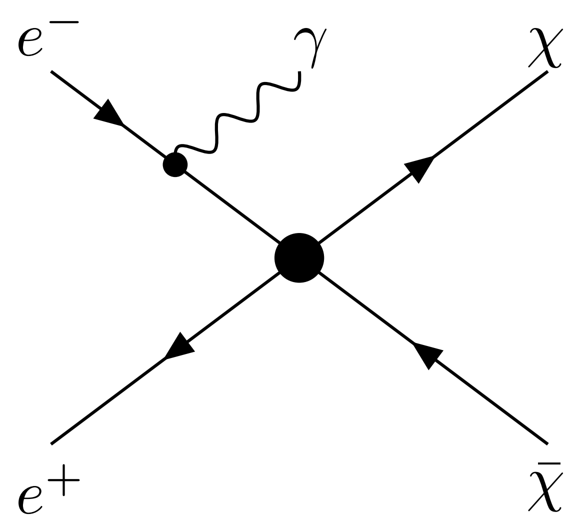
Higgs Invisible Decays



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

Impact of jet energy resolution

Monophoton Searches



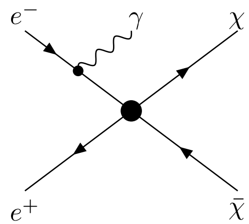
→ DM mass sensitivity nearly half √s

Soft photons, forward detectors

SUSY-specific signatures (decays to DM)

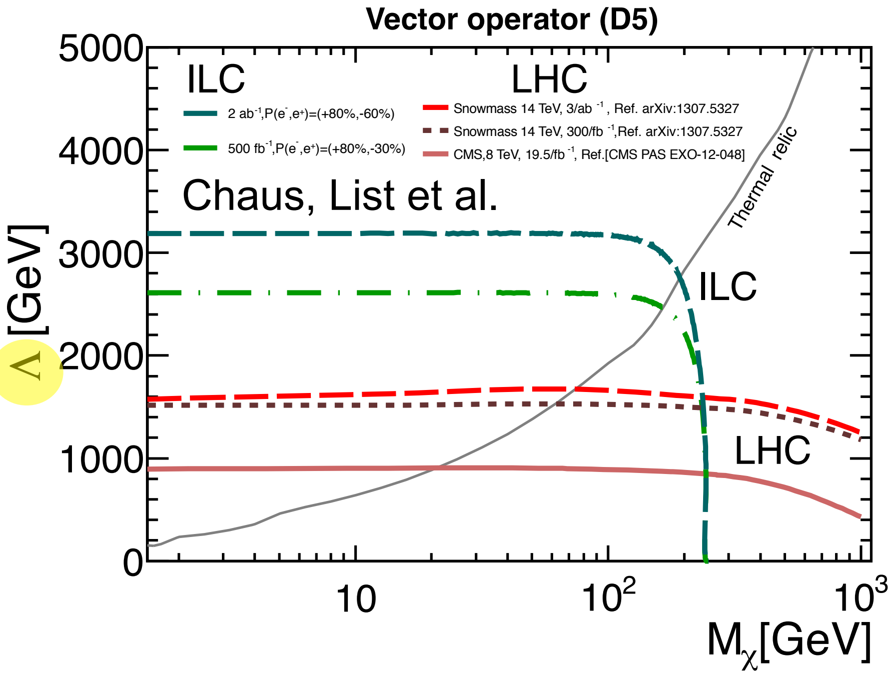
- light Higgsino, light stau, etc.

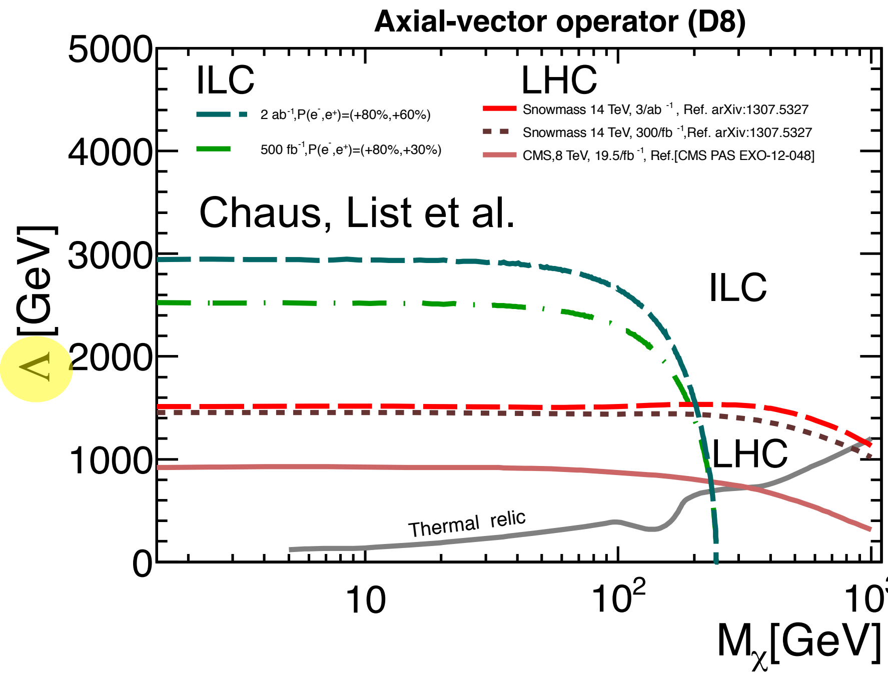
Monophotons: Effective Operators



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

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





LHC sensitivity: Mediator mass up to Λ~1.5 TeV for large DM mass

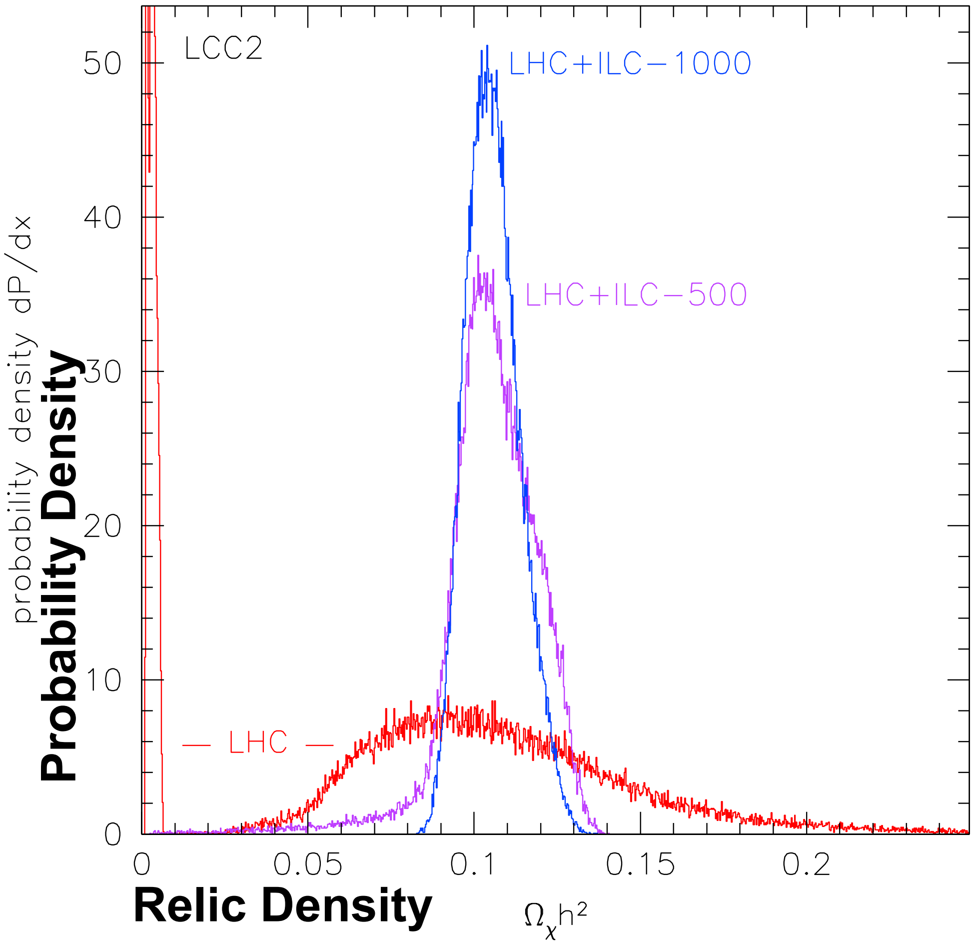
ILC sensitivity: Mediator mass up to Λ~3 TeV for DM mass up to ~√s/2

How do these limits translate to e.g. MSSM Wino/Higgsino LSP models?

Connection with DM Relic Abundance

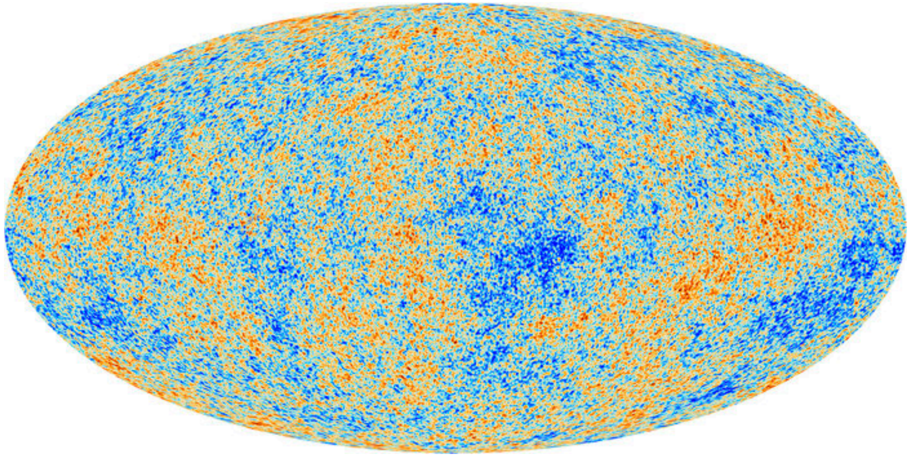
WMAP/Planck (68% CL)

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



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

ESA/Planck



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

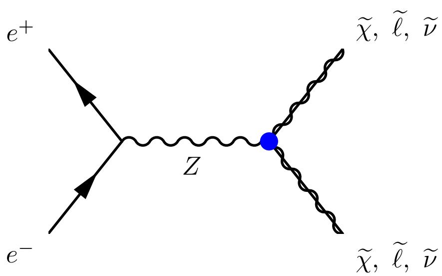
→ ILC's precise measurements of the mass and cross sections provide crucial input.

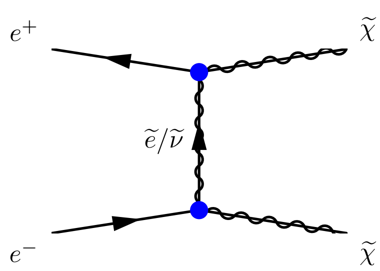
Need to update using latest constraints at viable benchmark points

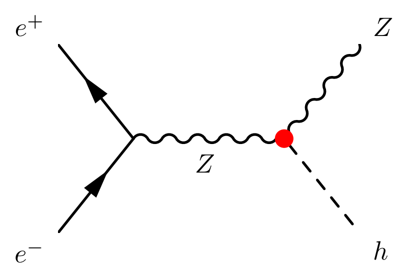
Summary

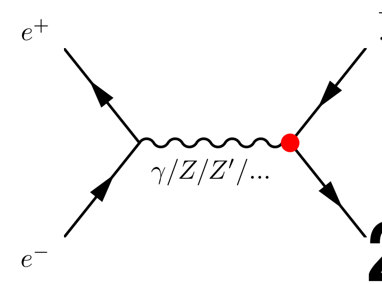
- Precision is one of the greatest strengths of ILC. However, we should put the **physics motivations** first, e.g.
  - What is the physics behind **electroweak symmetry breaking**?
  - What is the nature of **dark matter**?
- In this context,
  - **Higgs and top are also "BSM"**
  - **Direct searches important at ILC, can exceed HL-LHC**

- We should continue to refine the ILC physics case taking into account the results and future prospects of LHC/HL-LHC.
- Require close collaboration among theorists and experimentalists
- In the detector optimization, need to ensure the ILC physics case remains intact.

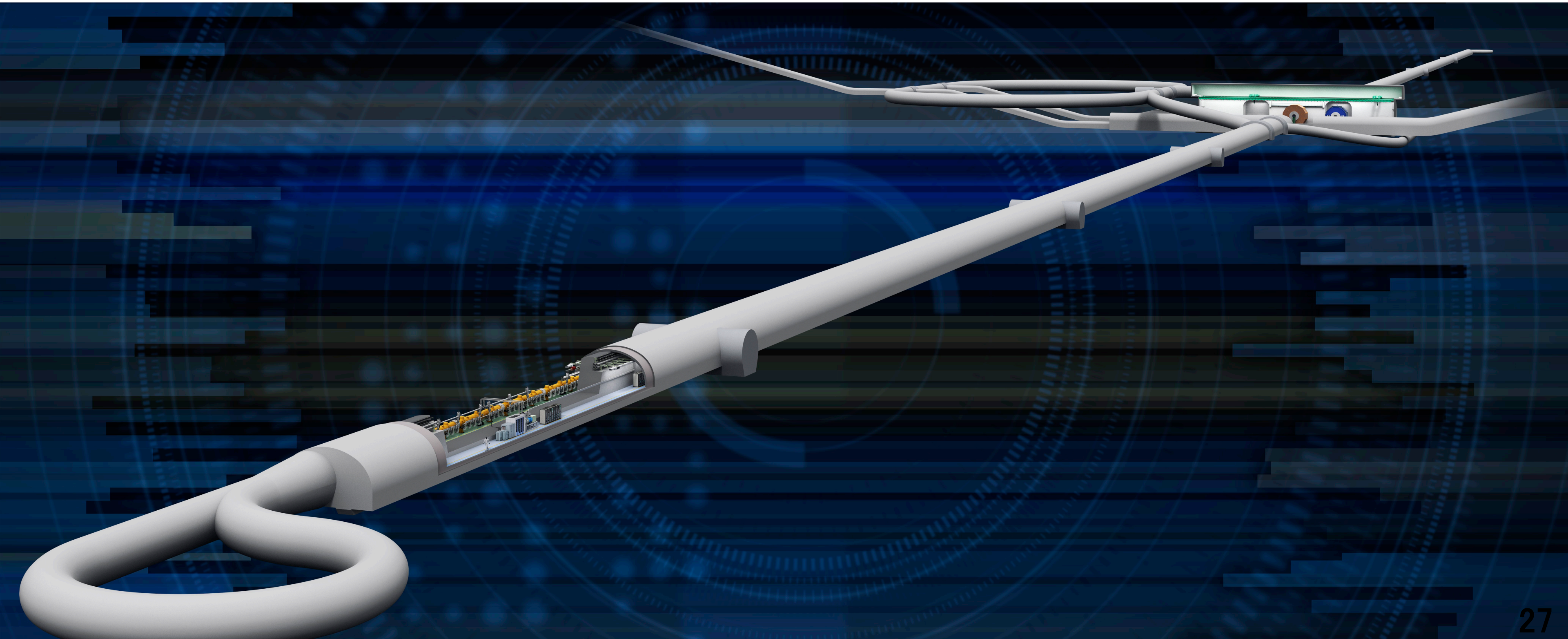








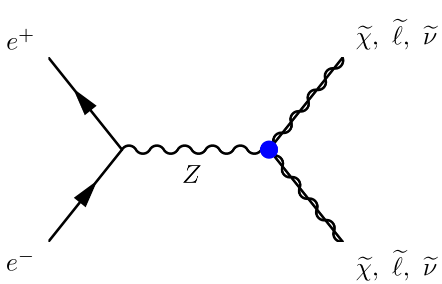
Additional Slides

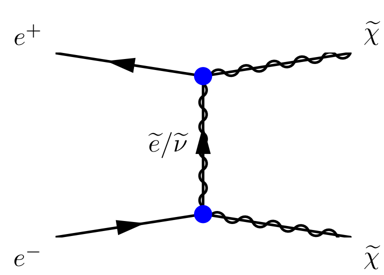


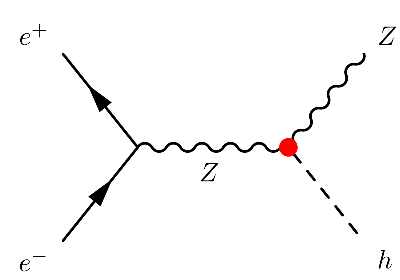
Summary

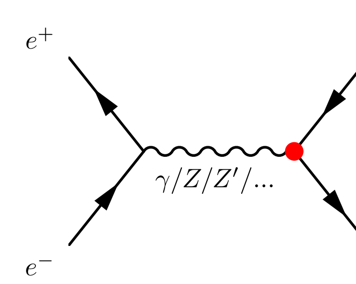
- ILC is a proposed **energy frontier** machine in e+e- collisions. The technology is ready. We have a country interested in hosting it. The extendability of linear colliders provide a **clear path for the future**.

- 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

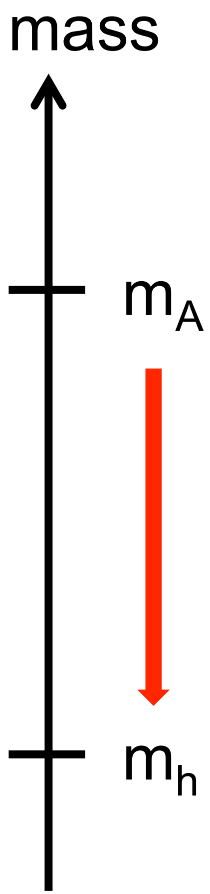








Deviation in Higgs Couplings



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

<u>Example 1:</u> MSSM (tanβ=5, radiative corrections ≈ 1)

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

heavy Higgs mass

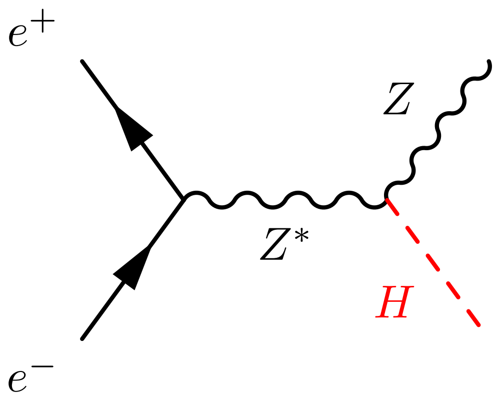
<u>Example 2:</u> Minimal Composite Higgs Model

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

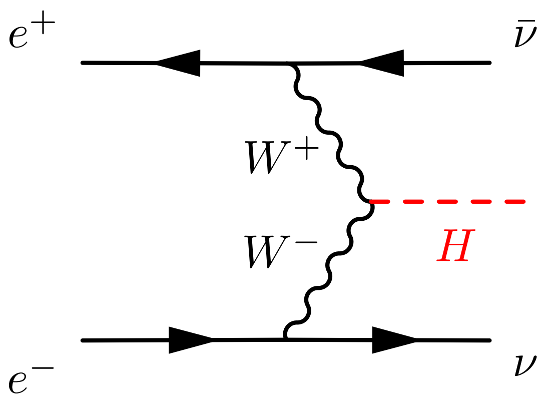
composite scale

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

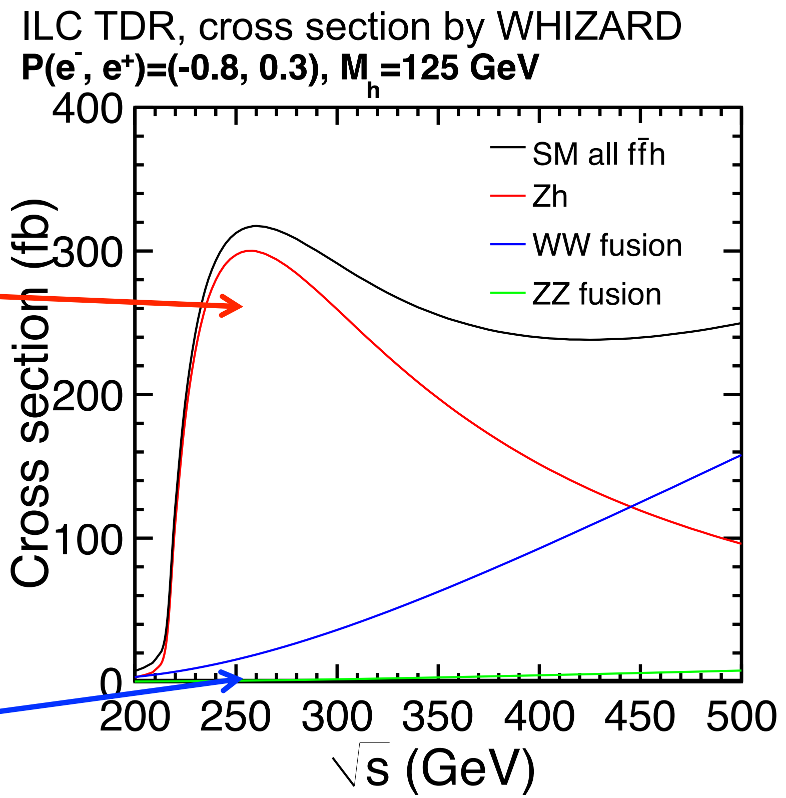
Higgs Production at ILC



Higgs-strahlung
peaks around 250 GeV



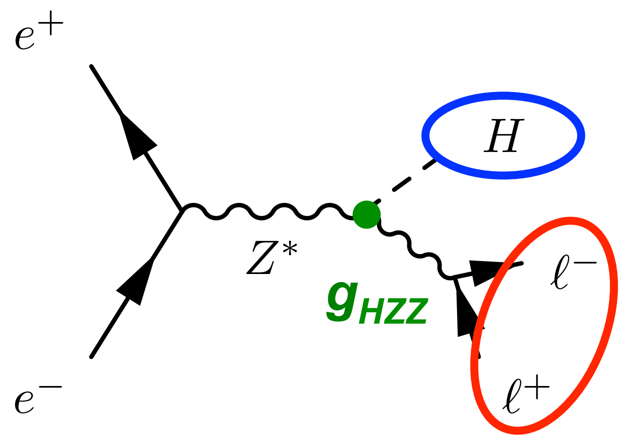
WW fusion
dominates at high energies

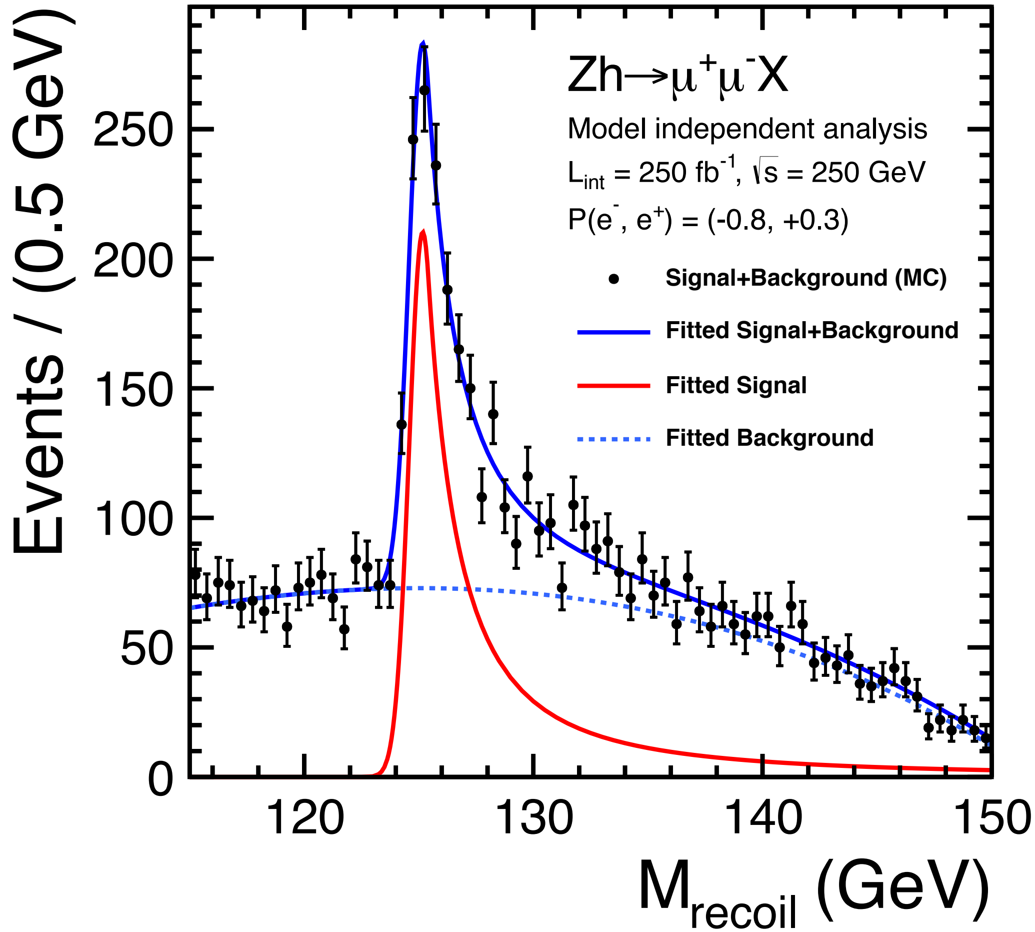


	250 GeV	500 GeV
$\sigma(e^+e^- \to ZH)$	303 fb	100 fb
$\sigma(e^+e^- \to \nu\nu H)$	16 fb	150 fb
Int. Luminosity	250 fb^{-1}	500 fb^{-1}
# ZH events	76,000	50,000
# vvH events	4,000	75,000

Expected number of Higgs events

Higgs Recoil Mass





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

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

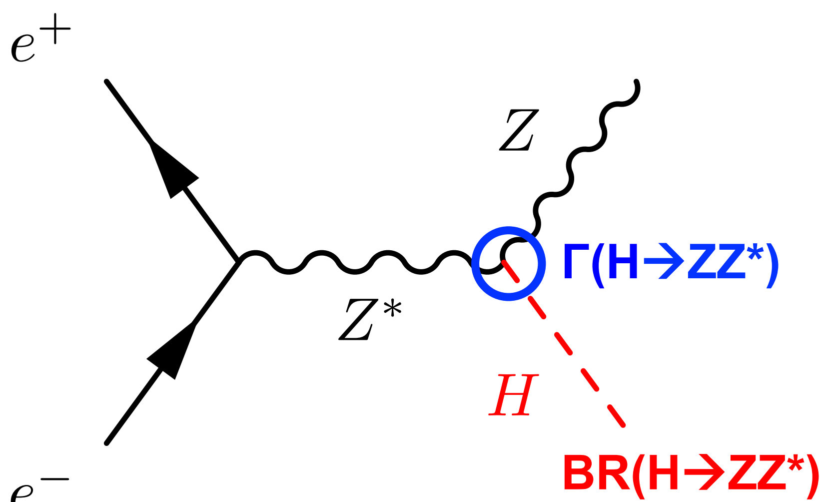
Model-independent, absolute measurement of the Higgs mass and σ(Zh):
$\Delta m_h \leq 15$ MeV, $\sigma_{Zh} \leq 1.2\%$ (√s=250 GeV, L=1150 fb-1)

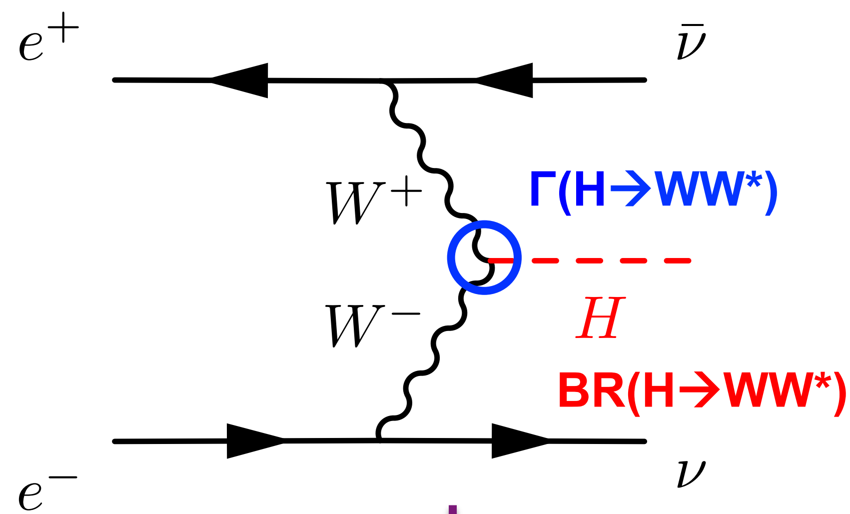
Higgs Coupling Determination

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:





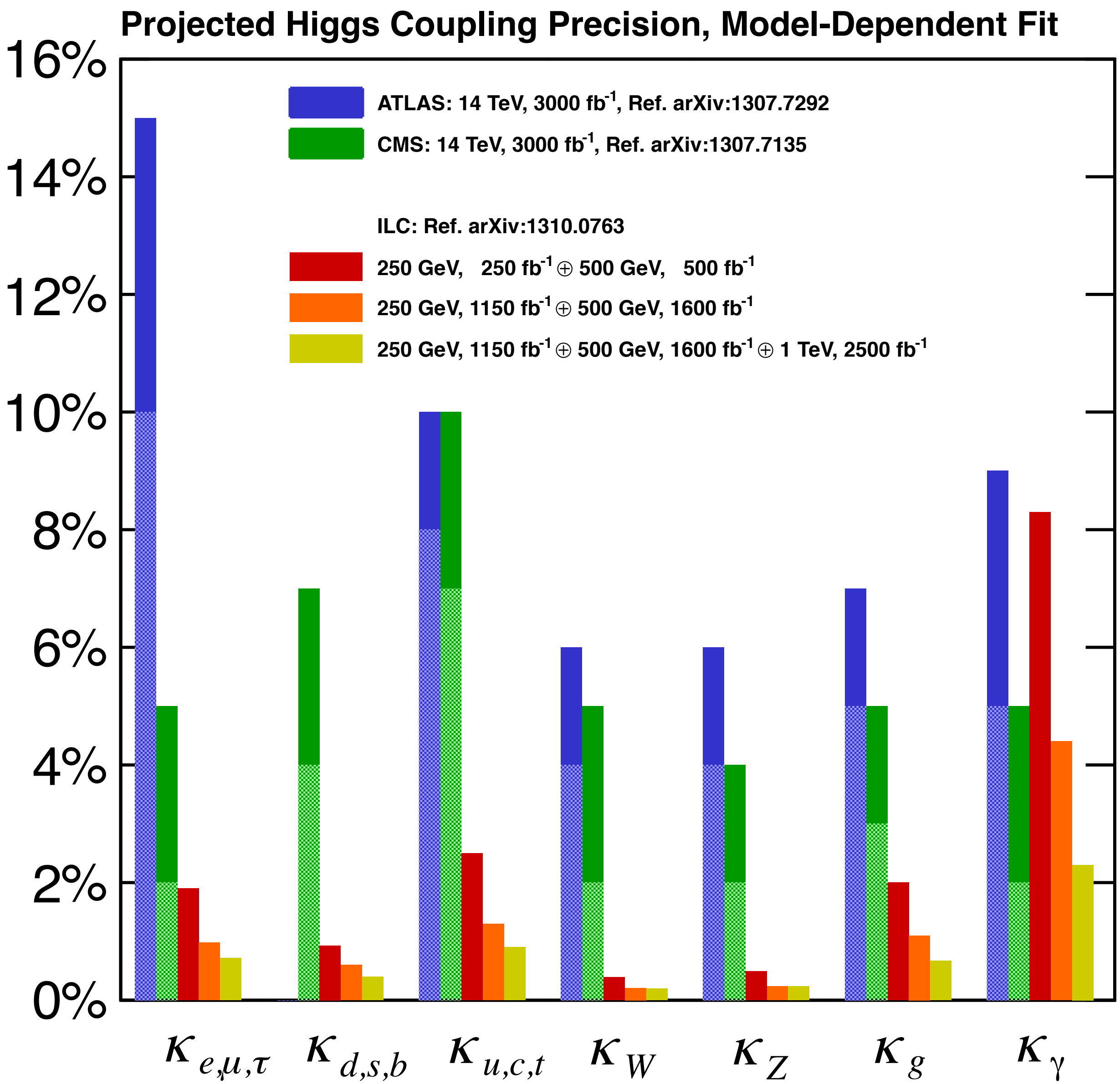
ZHH at 250 GeV alone requires very high statistics since BR(H→ZZ*) ~ 2%.

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

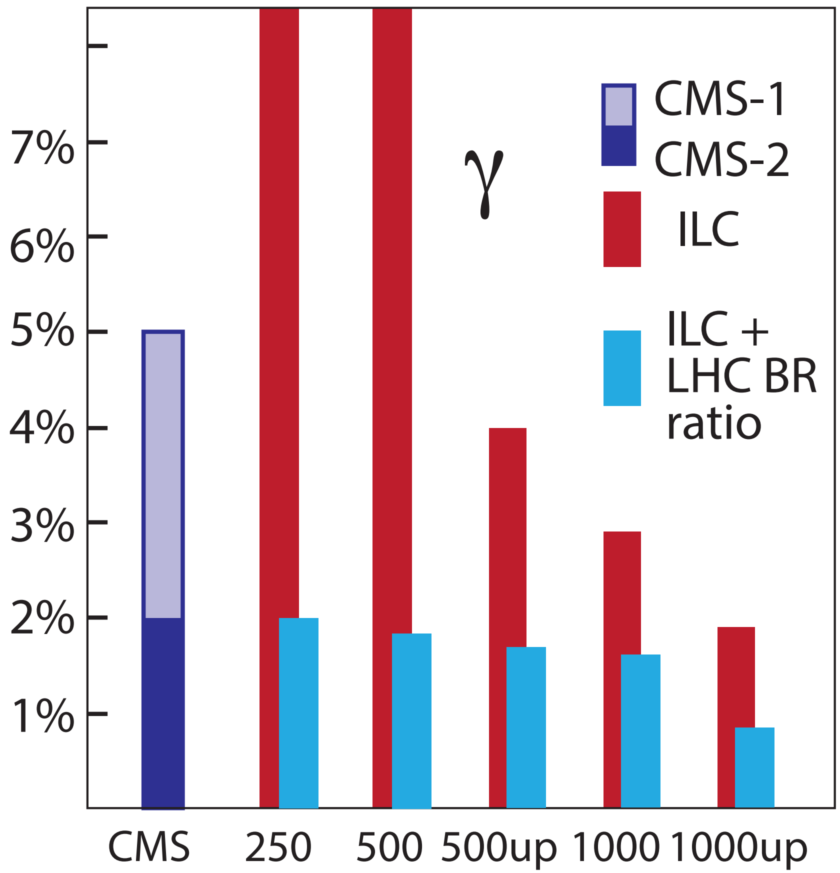
Combination of 250 GeV & 500 GeV data essential for the precise determination of Higgs couplings

Higgs Couplings (1/2)

[With assumptions; not model-independent.]



Improving hγγ coupling precision



M. Peskin, arXiv:1312.4974

Beautiful example of LHC/ILC synergy

Combine:

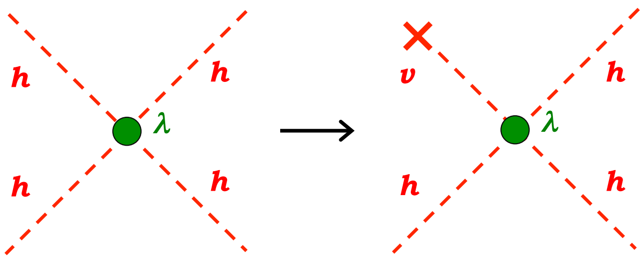
1. HL-LHC g(hγγ)/g(hZZ)
2. ILC g(hZZ)

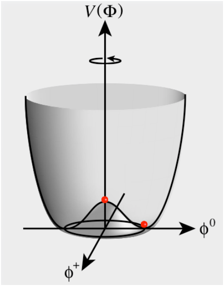
(both model-independent)

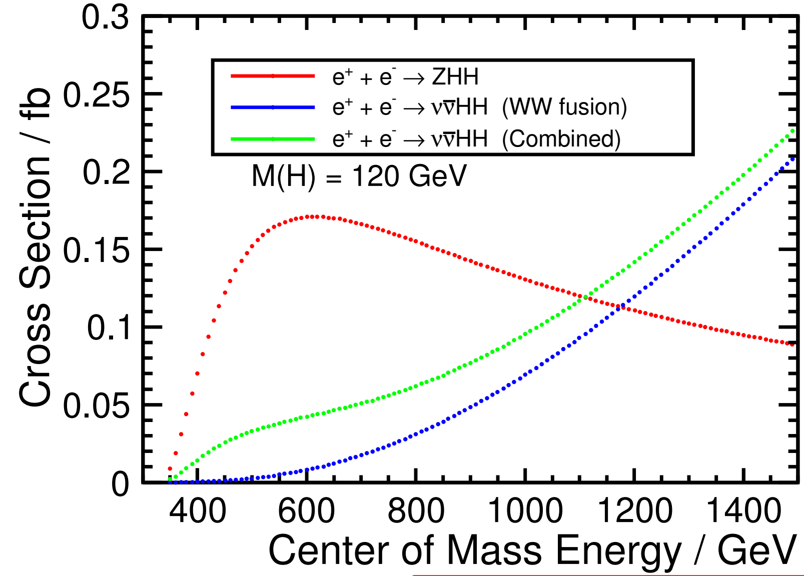
→ Precise model-independent measurement of g(hγγ) !

Higgs Self-Coupling

Existence of hhh coupling =
Direct evidence of vacuum condensation

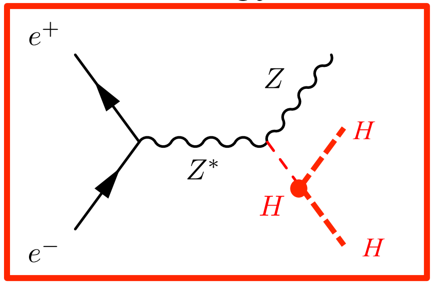


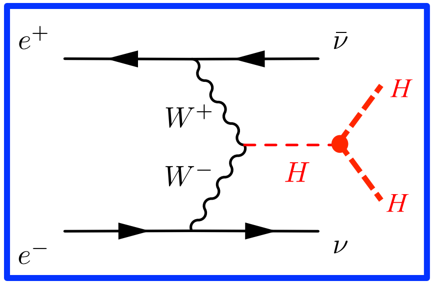




Challenging measurement because of:

- 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

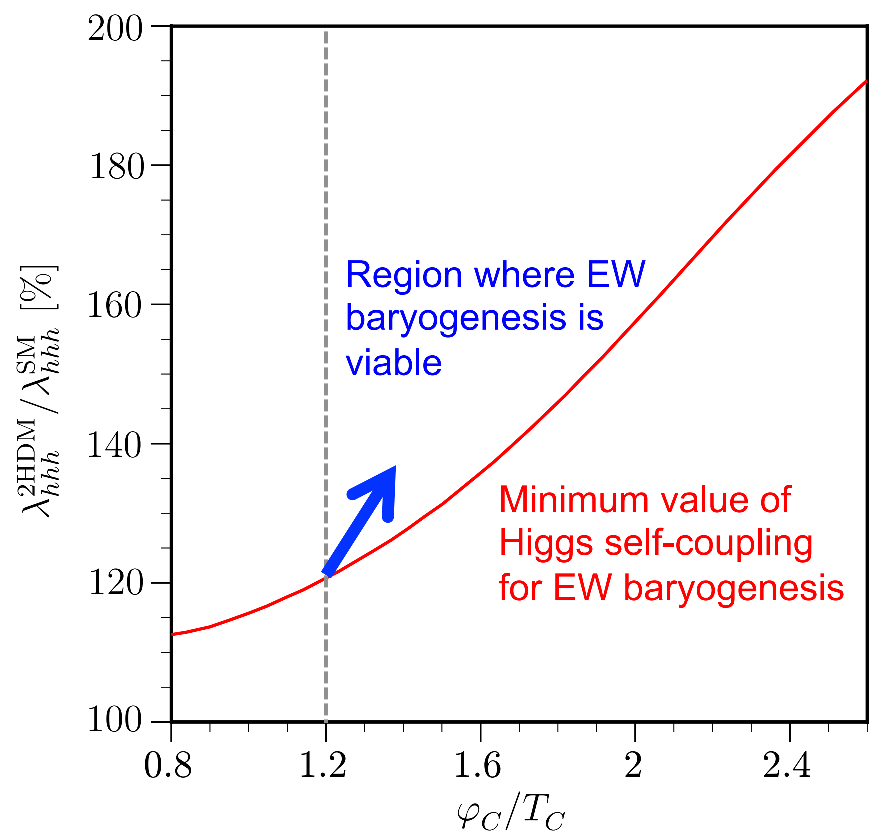
There are different models of baryogenesis at different energy scales. Some examples:

- 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

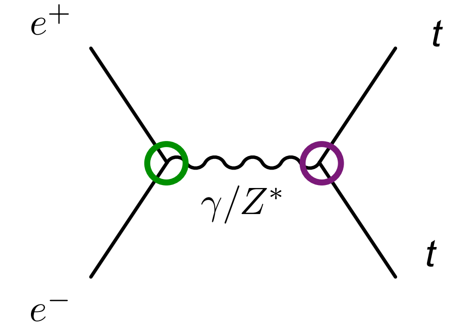
Example of EW baryogenesis in a 2HDM model (Senaha, Kanemura):

Ratio of Higgs self-coupling 2HDM / SM



φ_C Higgs field vev at critical temperature T_C

Top Coupling Measurements



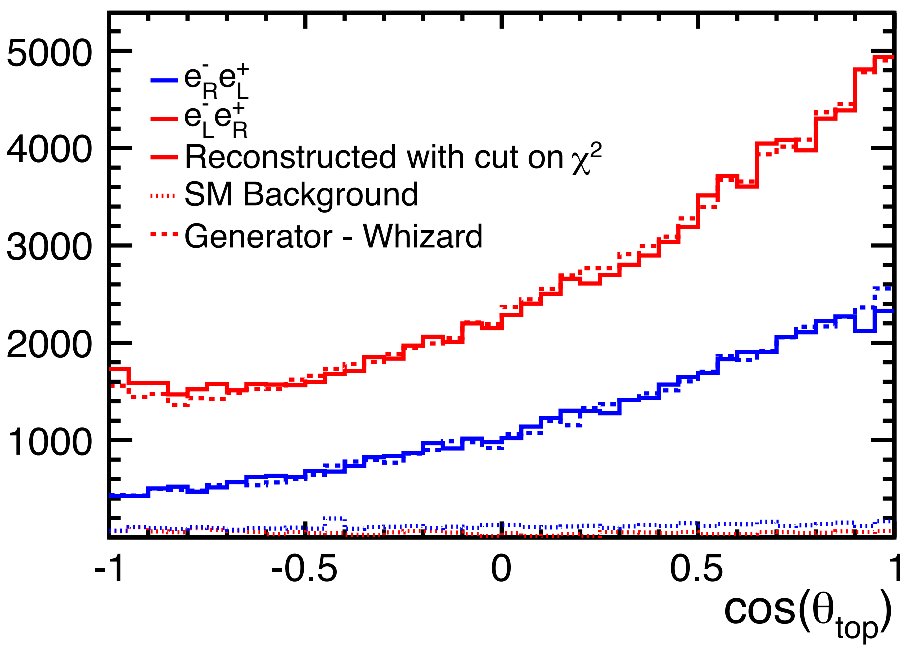
Measure cross section σ and asymmetries A_{FB}, A_{hel} to measure the top form factors $F^{tt\gamma}_{1L}$, $F^{tt\gamma}_{1R}$, F^{ttZ}_{1L}, F^{ttZ}_{1R}

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

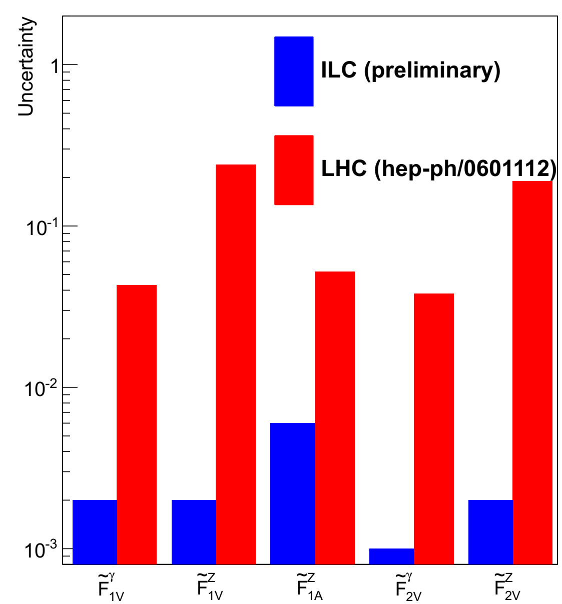
At 500 GeV: large asymmetries & high statistics

Polarization needed to extract all observables

Reconstructed top angle

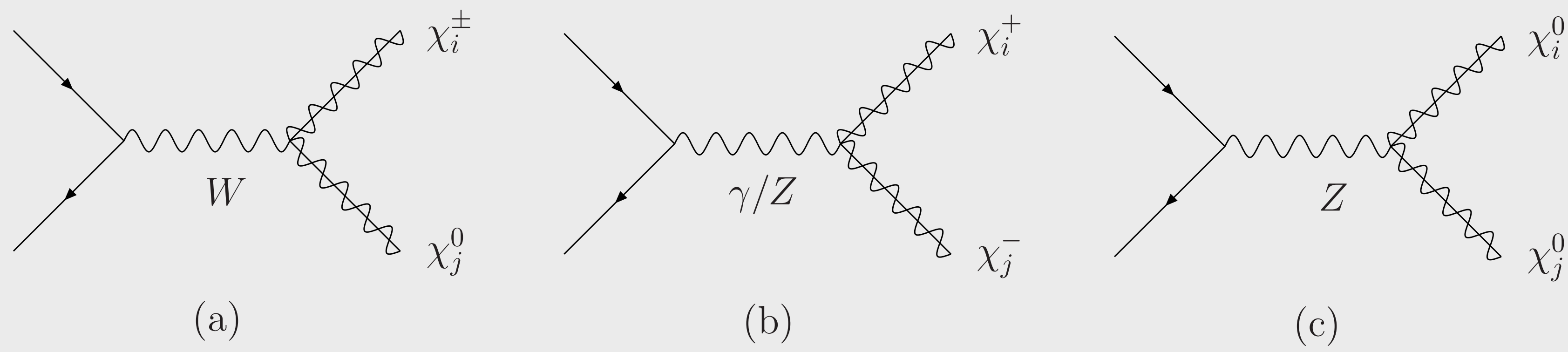


Expected precision



Amjad et al. arXiv:1307.8102

SUSY EW 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:

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

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

$$\ldots$$

Higgs!

Slepton decays to DM with small mass differences

Study of stau pair production at the ILC

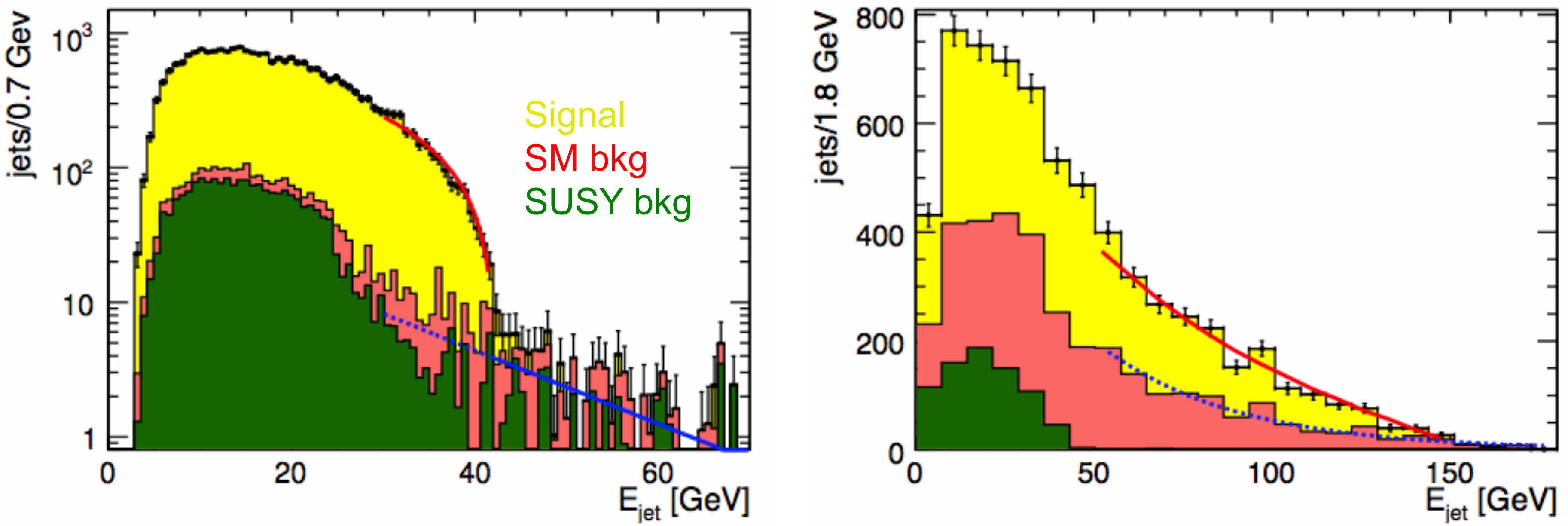
Observation of lighter and heavier stau states with decay to DM + hadronic tau

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)

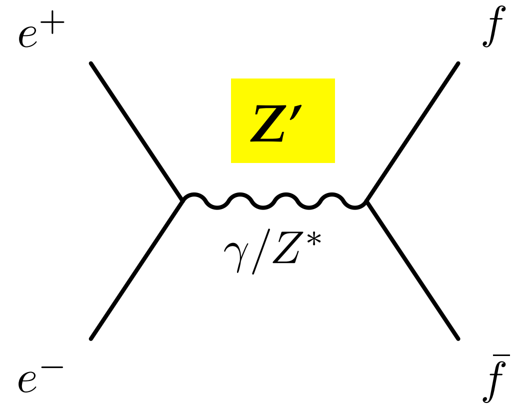
Stau1 mass ~0.1%, Stau2 mass ~3% → LSP mass ~1.7%

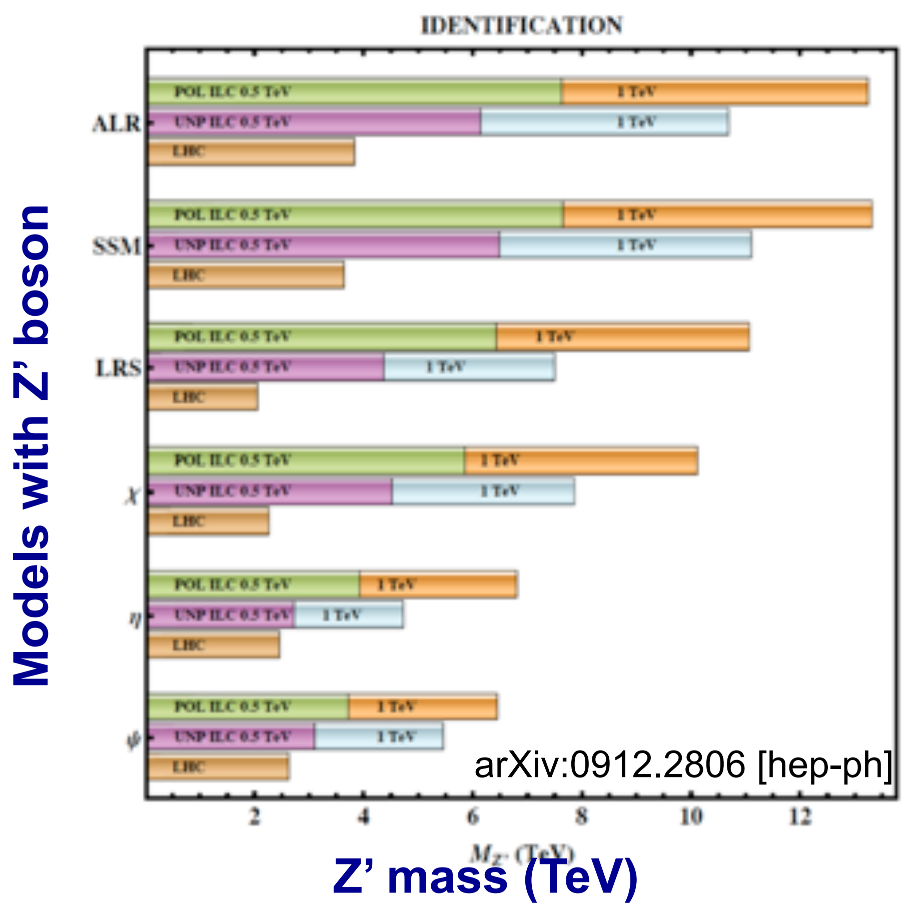
Z' : Heavy Neutral Gauge Bosons

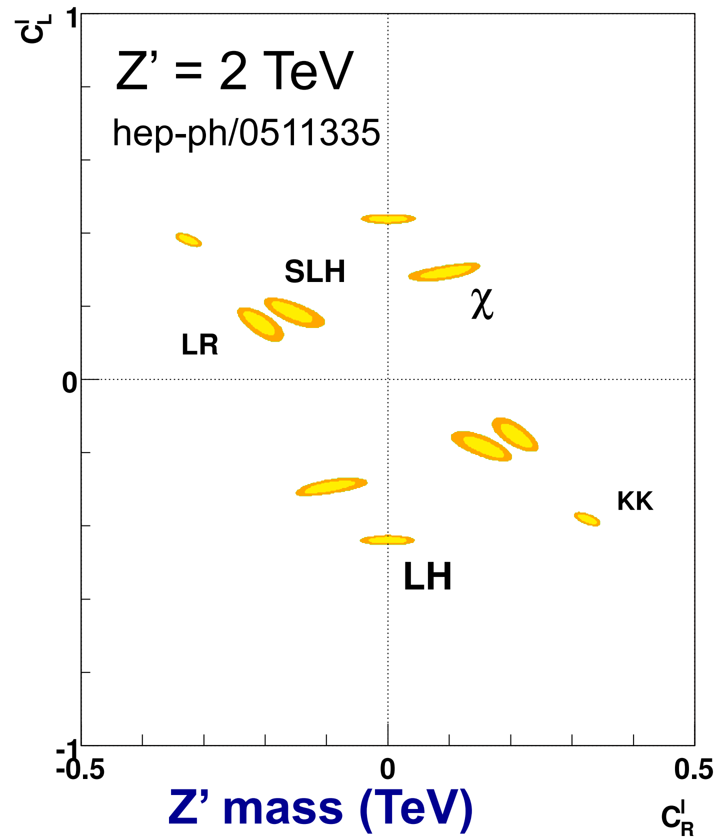
New gauge forces imply existence of heavy gauge bosons (Z')

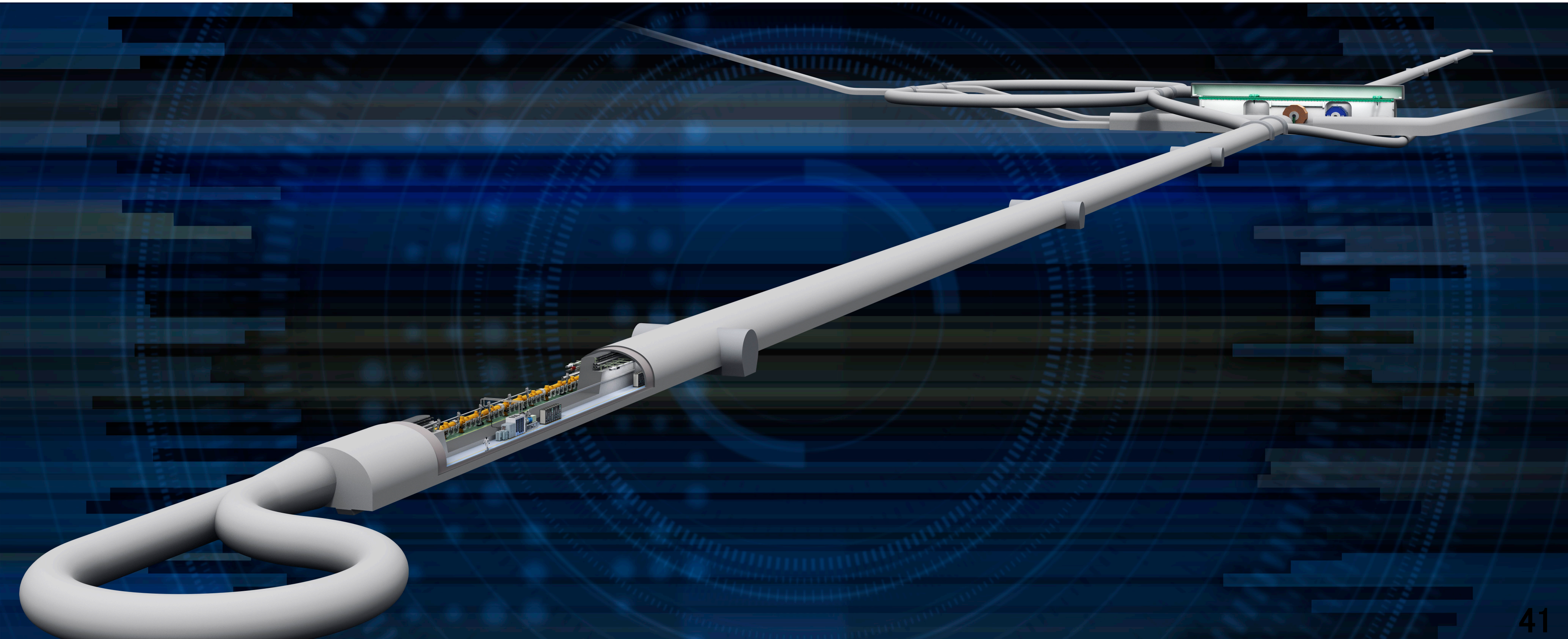
Complementary approaches LHC/ILC

- 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

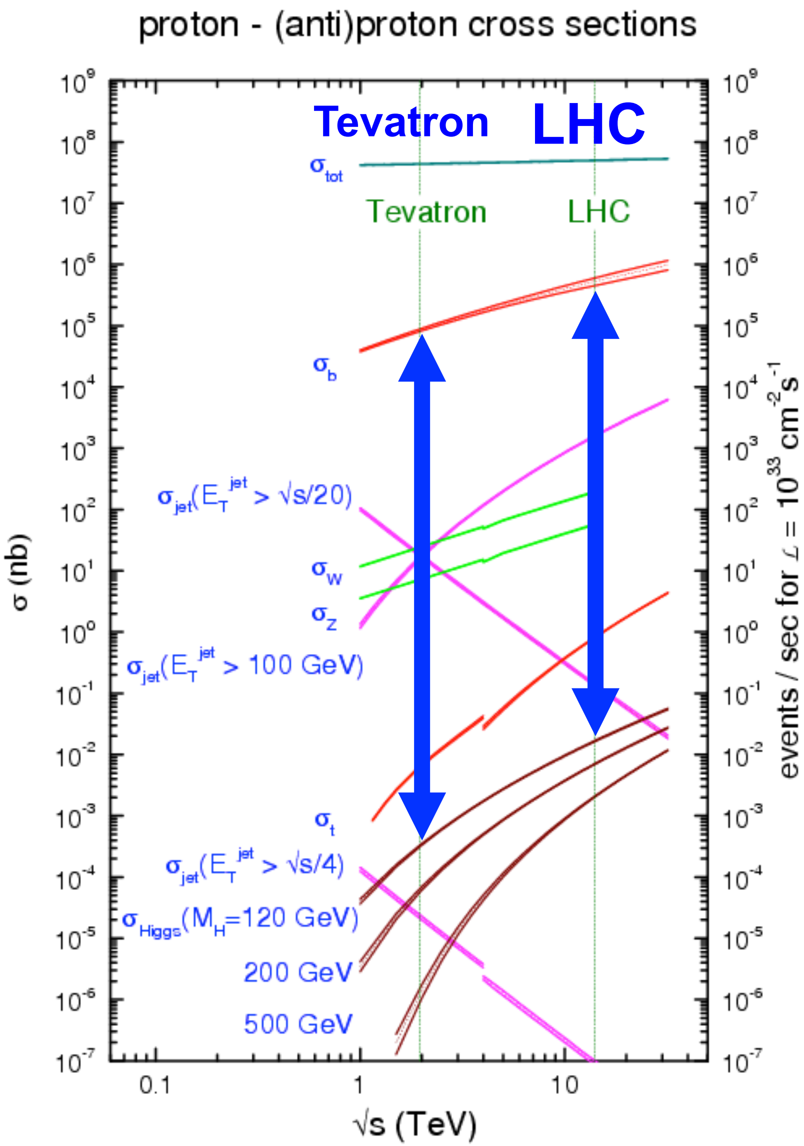








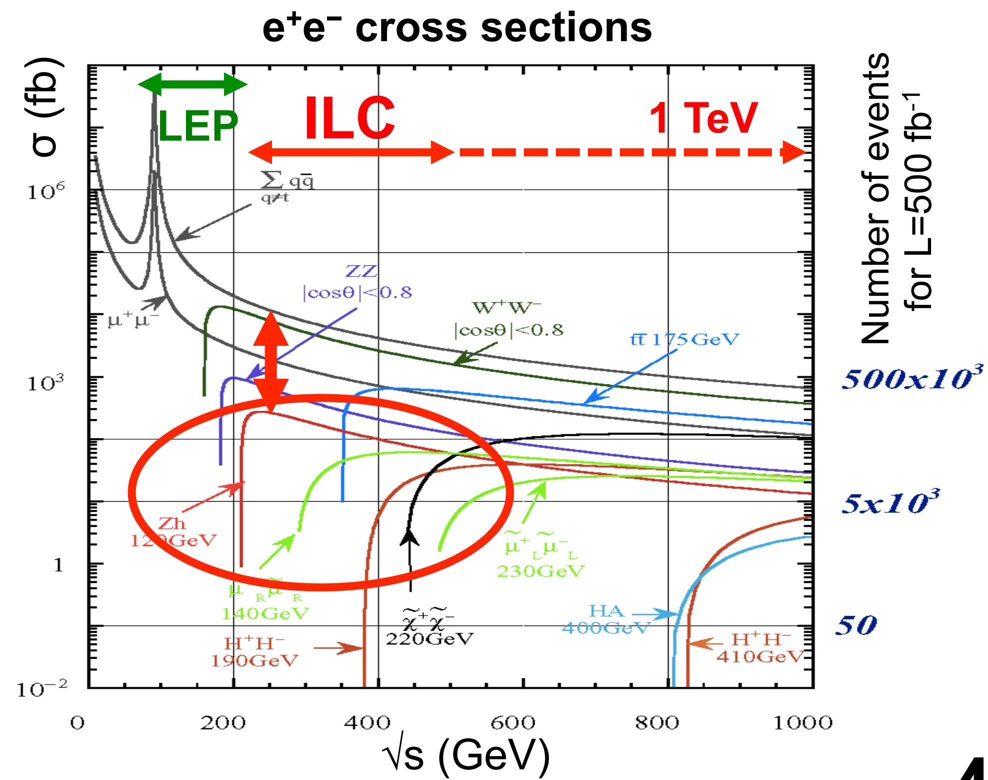
Cross Sections



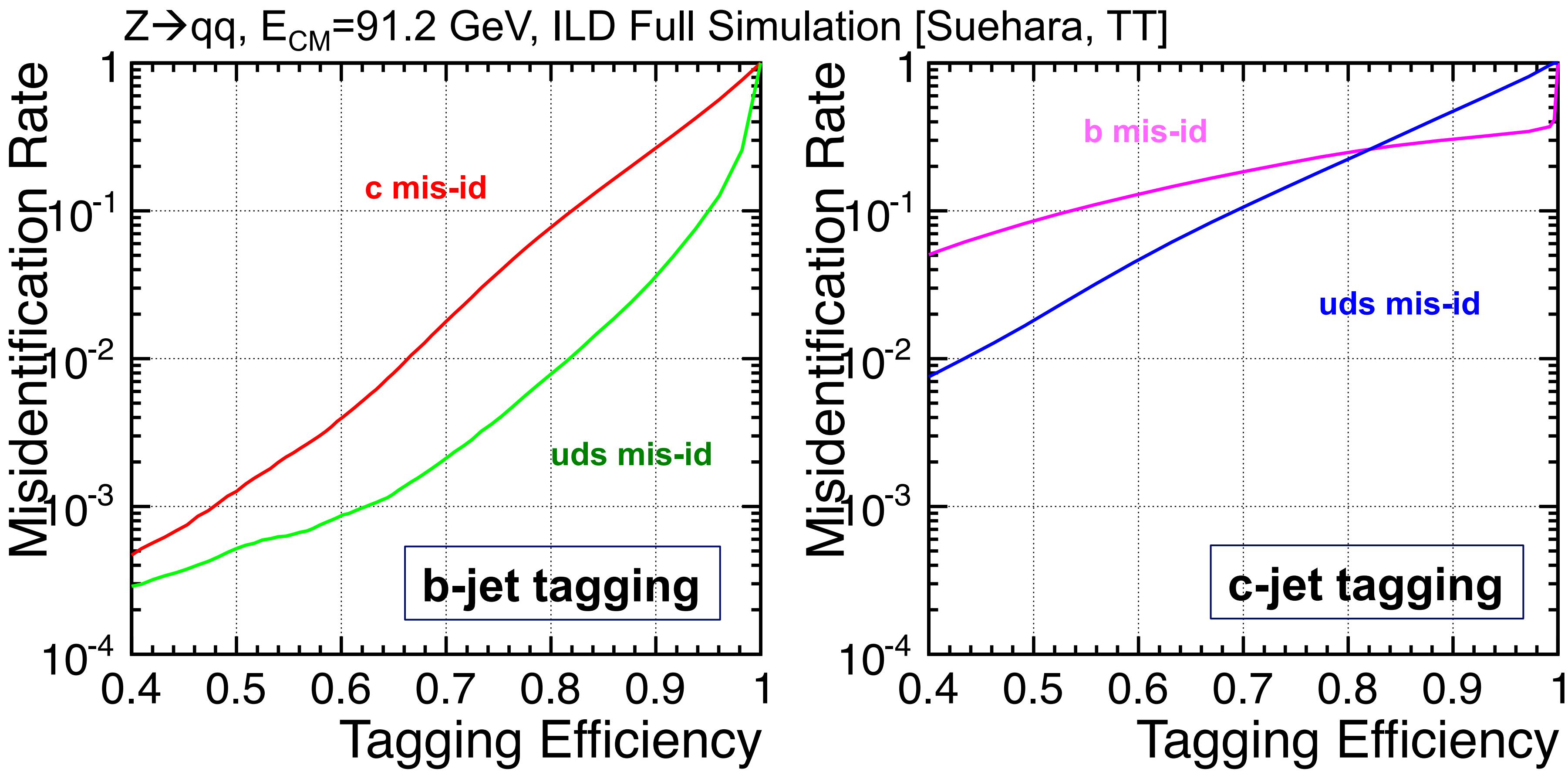
Typically,

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

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



Higgs Hadronic Decays: Flavor Tagging

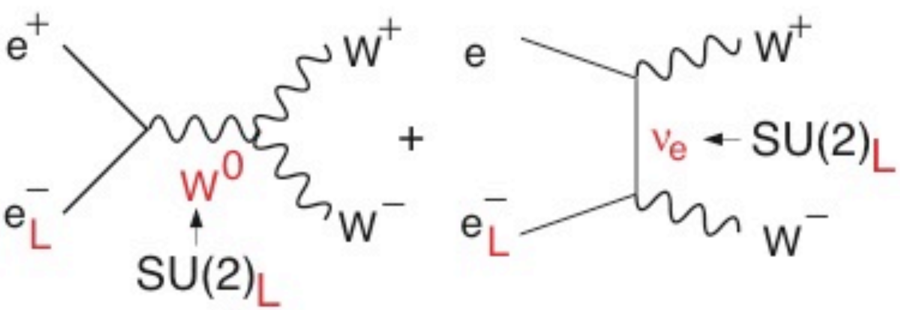


ILC detectors allow high performance b/c/g tagging
Precise measurement of BR(H→bb, cc, gg)

Power of Beam Polarization

[Fujii]

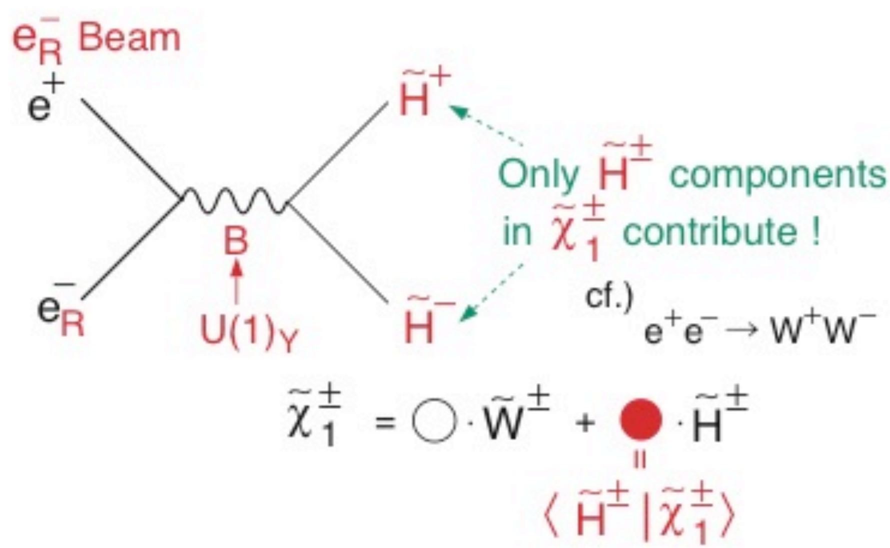
W^+W^- (Largest SM BG)



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

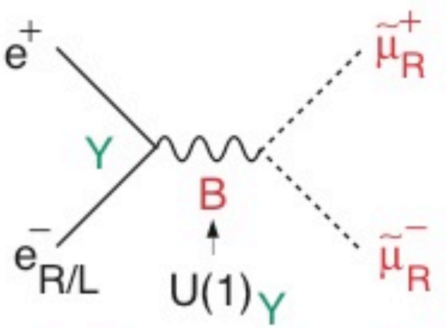
BG Suppression

Chargino Pair



Decomposition

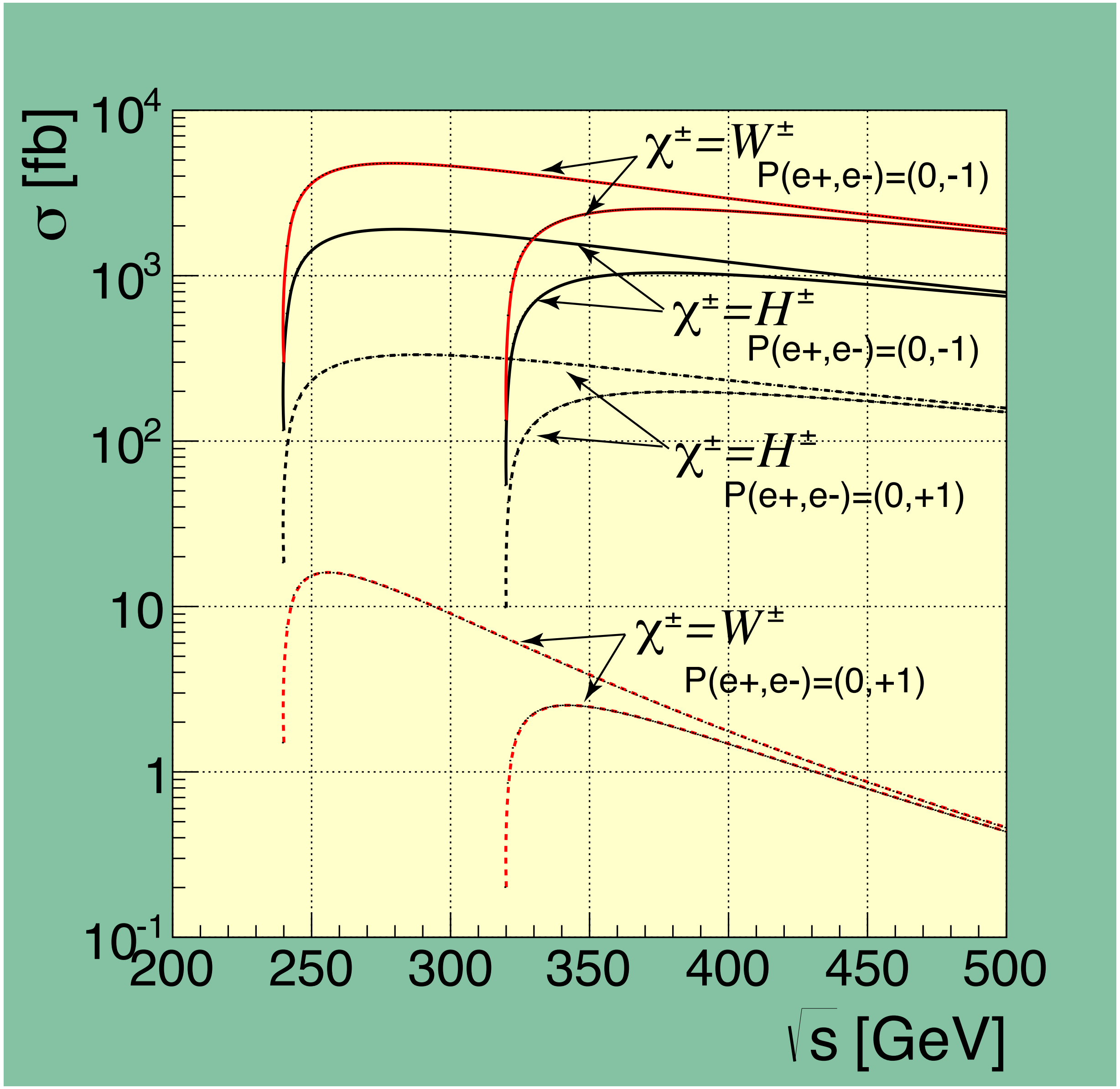
Slepton Pair



$$\begin{cases} Y_L = -1/2 : e^-_L \\ Y_R = -1 \quad : e^-_R \end{cases}$$

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

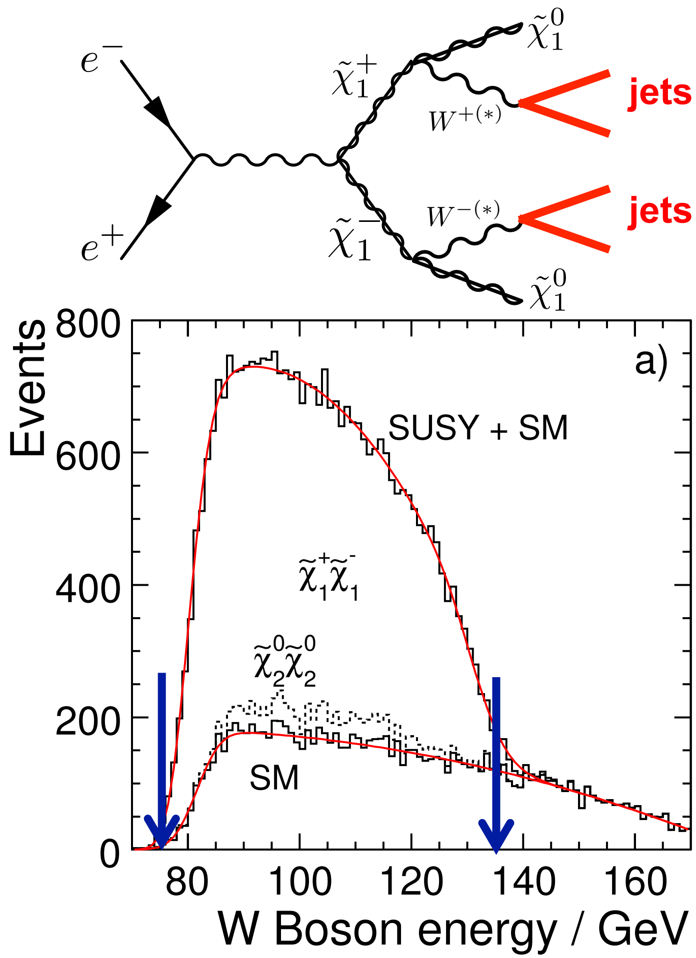
Signal Enhancement



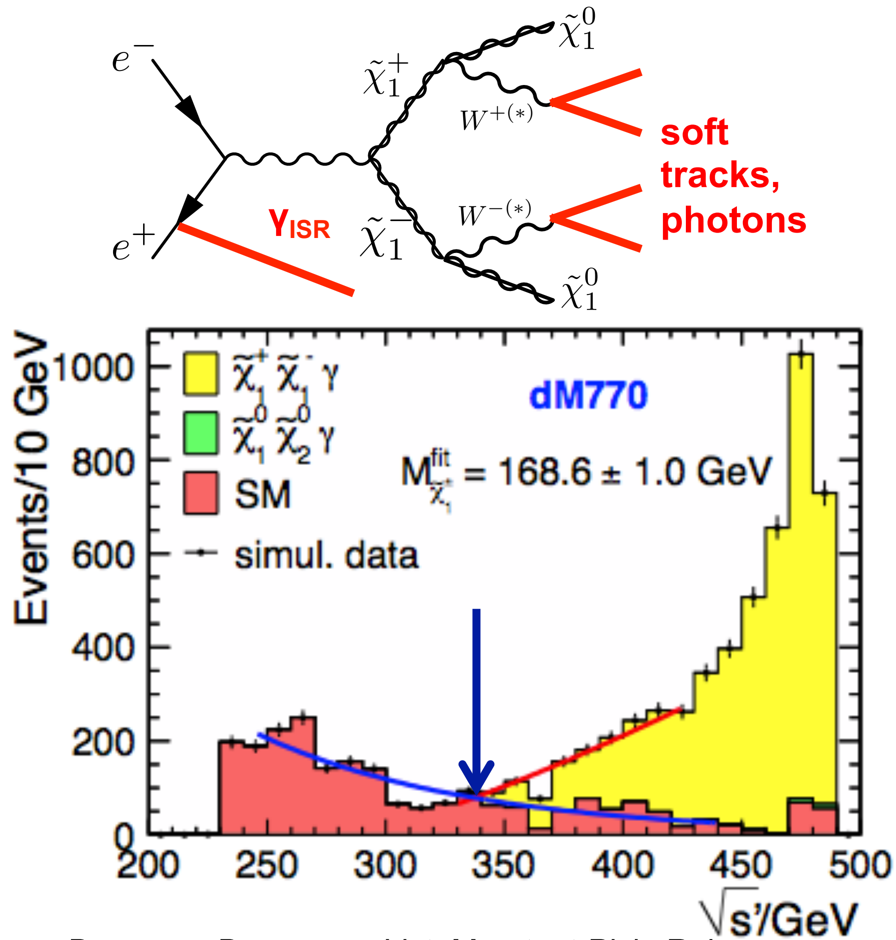
σ [fb]
10^4
10^3
10^2
10
1
10^{-1}
200
250
300
350
400
450
500
$\sqrt{s}$ [GeV]
$\chi^{\pm}=W^{\pm}$
P(e+,e-)=(0,-1)
$\chi^{\pm}=H^{\pm}$
P(e+,e-)=(0,-1)
$\chi^{\pm}=H^{\pm}$
P(e+,e-)=(0,+1)
$\chi^{\pm}=W^{\pm}$
P(e+,e-)=(0,+1)

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