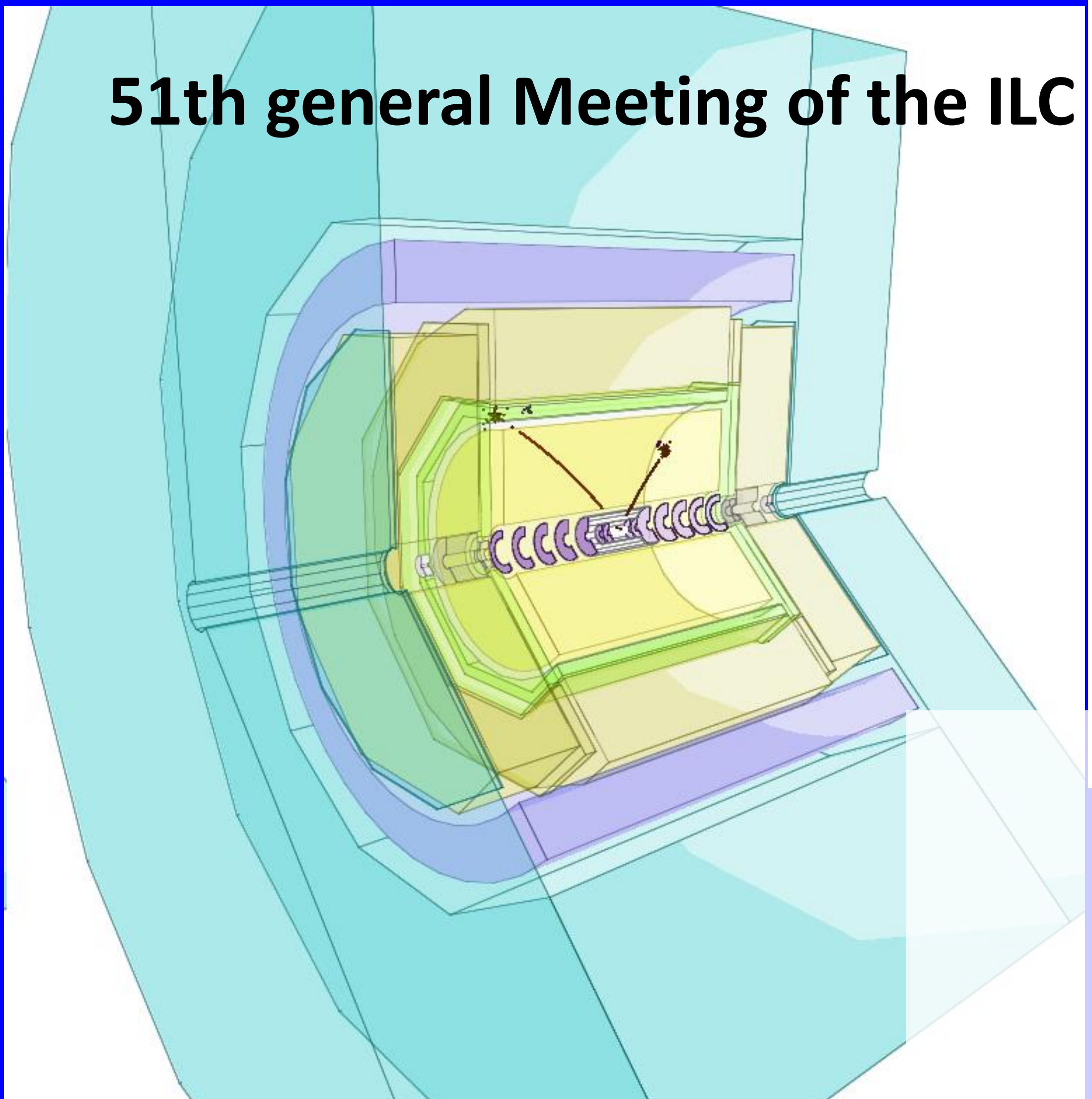
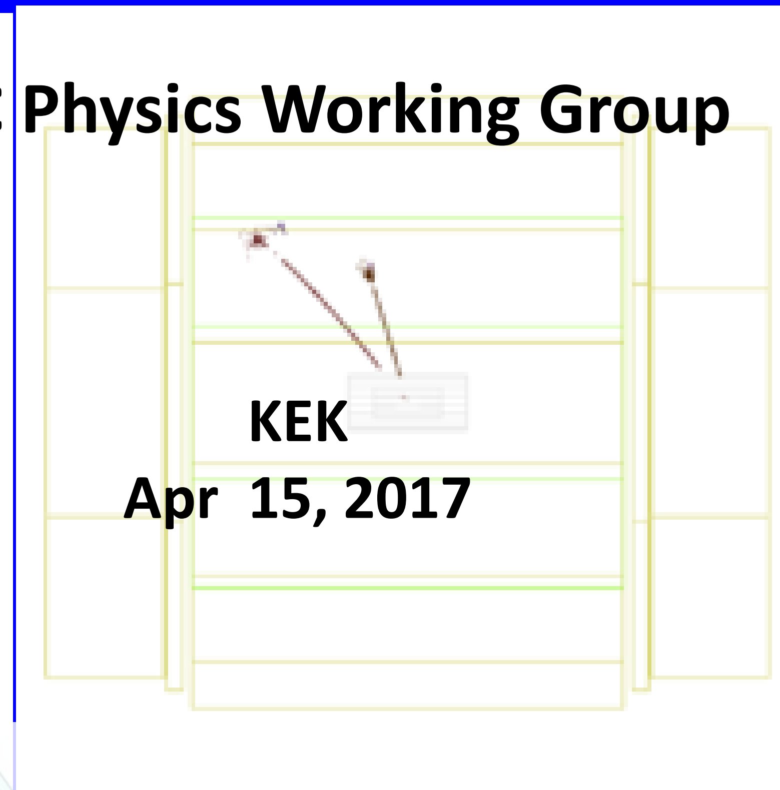
ILC Staging For New Physics

51th general Meeting of the ILC Physics Working Group





KEK

Apr 15, 2017

Jacqueline Yan (KEK)

Outline

- **Goal of BSM Working Group**

  With a focus on staging

- **Ongoing Studies**

- **Summary**

Outline

- **Goal of BSM Working Group**
  With a focus on staging
- Ongoing Studies
- Summary

BSM studies for Staging

- Since LCWS2016, intense efforts are being dedicated to **strengthening the physics case at an initial stage of √s = 250 GeV**

During discussion at the annual detector meeting (Mar 30-31), it was mentioned that …

<u>This is an **extremely crucial (last?) chance** for us to demonstrate the attractiveness of a **250 GeV ILC as a complete project**</u>

While preparing the scope for higher energies

What are the contributions from (direct) new physics search ?

There is no denying that lower energies cast a limit on direct particle search

Nevertheless ……

BSM studies for Staging

it was mentioned that …

This is an **extremely crucial (last?) chance** for us to demonstrate the attractiveness of a

250 GeV ILC as a complete project

While preparing the scope for higher energies

this is the very reason that, along with Higgs/EW, we must **make the picture complete by demonstrating the ILC's potential for new particle discovery at lower energies**

no matter how difficult

Supporting document that follows up the ICFA letter

https://arxiv.org/abs/1702.05333

submitted Feb 17, 2017

The Potential of the ILC for Discovering New Particles

Document Supporting the ICFA Response Letter to the ILC Advisory Panel

LCC Physics Working Group

Keisuke Fujii[1], Christophe Grojean[2,3,4], Michael E. Peskin[5](conveners); Tim Barklow[5], Yuanning Gao[6], Shinya Kanemura[7], Hyungdo Kim[8], Jenny List[2], Mihoko Nojiri[1,9], Maxim Perelstein[10], Roman Pöschl[11], Jürgen Reuter[2], Frank Simon[12], Tomohiko Tanabe[13], James D. Wells[14], Jaehoon Yu[15]; Howard Baer[16], Mikael Berggren[2], Sven Heinemeyer[17], Suvi-Leena Lehtinen[2], Junping Tian[13], Graham Wilson[18], Jacqueline Yan[1]; Hitoshi Murayama[9,19,20], James Brau[21]

Until now most studies about direct particle search have been conducted at $\sqrt{s}$ = 500 GeV ‥‥..

however 500 GeV is not the only place

Abstract

This paper addresses the question of whether the International Linear Collider has the capability of discovering new particles that have not already been discovered at the CERN Large Hadron Collider. We summarize the various paths to discovery offered by the ILC, and discuss them in the context of three different scenarios: 1. LHC does not discover any new particles, 2. LHC discovers some new low mass states and 3. LHC discovers new heavy particles. We will show that in each case, ILC plays a critical role in discovery of new phenomena and in pushing forward the frontiers of high-energy physics as well as our understanding of the universe in a manner which is highly complementary to that of LHC.

For the busy reader, a two-page executive summary is provided at the beginning of the document.

outline of supporting document that follows up the ICFA letter

<Precision measurement of SM physics >

New Higgs properties

- Model independent Higgs couplings, invisible decay modes, CP phase
  best at $\sqrt{s}$ =250 GeV
- Higgs self coupling: 26% (10%) at $\sqrt{s}$ = 500 GeV (1 TeV)

New top quark properties

- m_t: threshold scan at $\sqrt{s}$~350 GeV
- top electroweak couplings at $\sqrt{s}$ >= 500 GeV

Covered in this talk

New force carriers

- Search for heavy gauge bosons in e+e− → ff
  start from $\sqrt{s}$ = 250, can reach multi-TeV Z' mass at $\sqrt{s}$ >= 500 GeV

<Direct new particle search>

Favorable at higher energies, but ready to start at $\sqrt{s}$ = 250 GeV

- **Additional light scalars**
- **Natural SUSY particles**
- **WIMPs**

We aim for sufficient studies of direct new particle search based on ILD detector simulation for the "staging" option

Direct searches at √s = 250 GeV and 350 GeV

- Dark matter particles (Mono-photon WIMP search)
- Natural SUSY (Higgsinos), ΔM 5– 20 GeV
- Extra spin-less bosons, light Higgs(like) states
- Heavy gauge boson Z' using e+e- → ff

much higher luminosity and polarized beams adds significant reach wrt LEP2

And the full window to direct searches opens up at √s => 500

for all of the above

- JHEPC set up a sub-committee to investigate the staging issue

  final report expected in early June

- We need to take actions in order to **provide results in a timely manner**

  Monitor progress and work force,, propose new topics, collaborate with theorists, etc…

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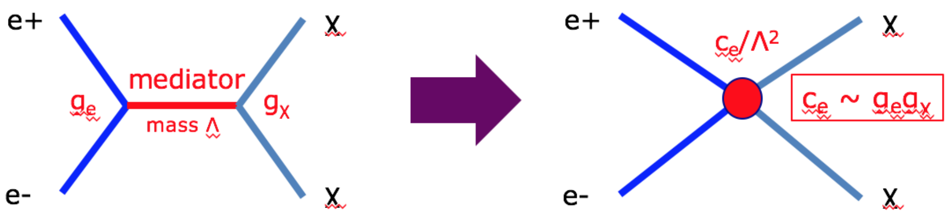
WIMP Search at ILC

Ongoing studies by M. Habermehl, S. Matsumoto, T. Tanabe et al.

[1] Theory studies: classify WIMPs according to quantum number (e.g. singlet-like fermion WIMP)

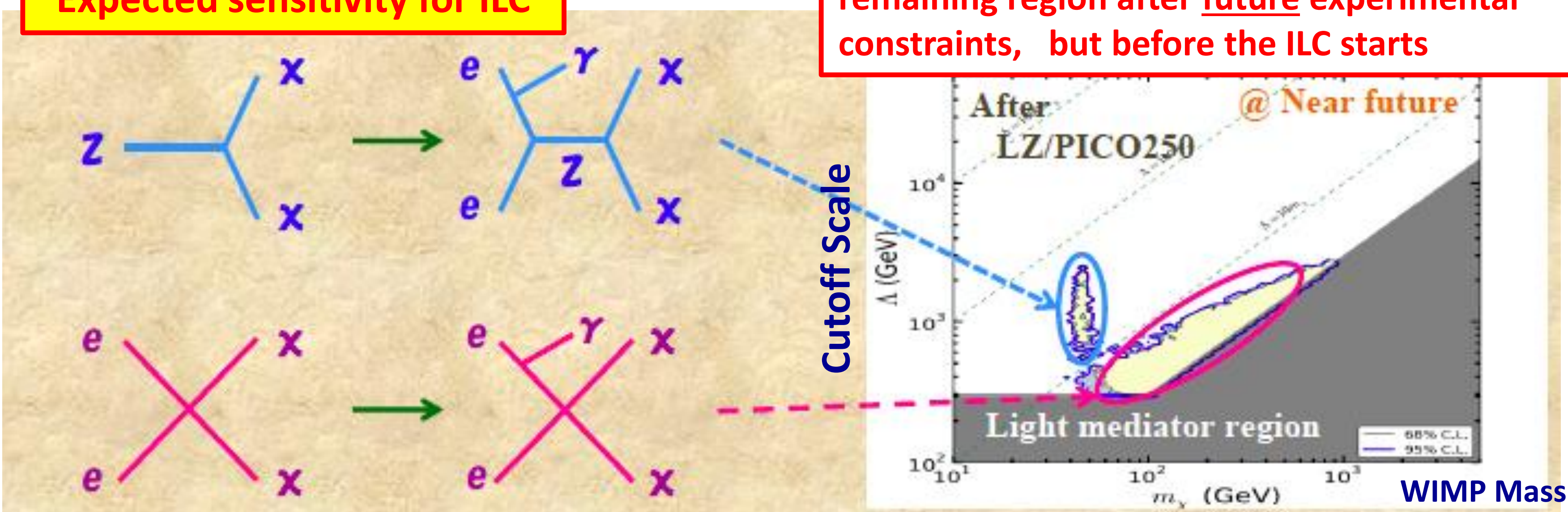


Effective Field Theory & **Simplified Models** to compare WIMP reach between ILC and other experiments (e.g. direct detection and LHC)

Scan performed over multi-dimensional parameter

Expected sensitivity for ILC

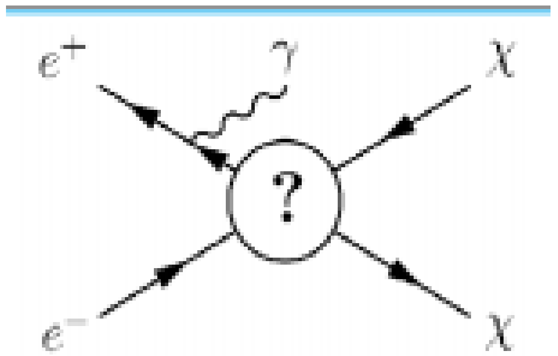
remaining region after future experimental constraints, but before the ILC starts



can be probed up to ～ √s/2

- Study ongoing to include projection from ILC mono-photon search.

WIMP Search at ILC



[2] experimental study of WIMP pair production

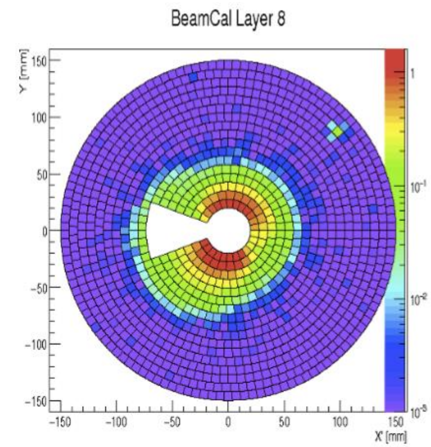
- **ISR photon tag : e+ e- → χ χ γ**
- Single γ in empty detector : observe Eγ and θγ
- Signal efficiency ~90%
- main bkg: Neutrino pairs : e+e- → νν (n)γ
  Bhabha scattering: e+e- → e+e-γ

- **can be probed for up to ∼ √s/2**
- **sensitive up to Λ = 3-4 TeV**

[3] Impact on Detector Optimization

Study of **improved Bhabha rejection by repositioning of BeamCal**
→ Sensitivity improve by 15% for right polarization

- **After full H20 run → Λ∼3 TeV**
- **Upgrade to 1 TeV → Λ∼4.5 TeV** (from full ILD simulation studies)



Status and Plans

(1) Full simulation studies (√s = 250 – 500 Gev) by M. Habermehl (DESY)

effort to be increased at 250 GeV !

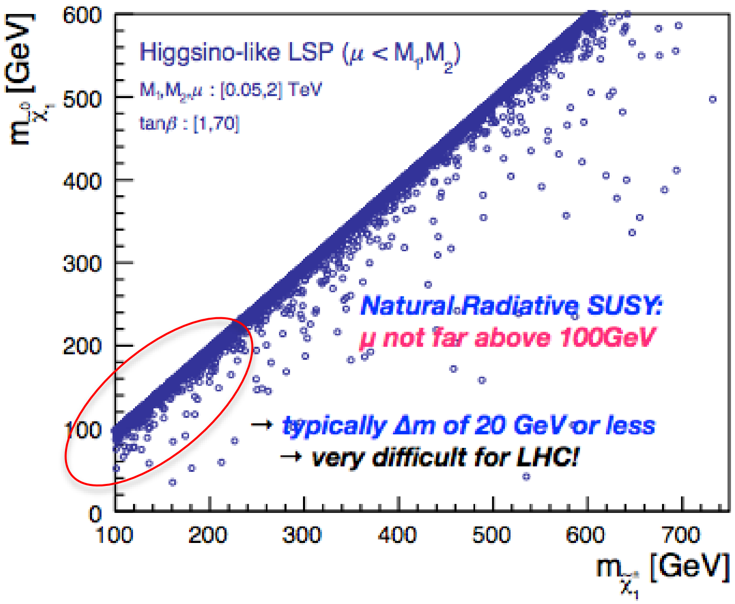
(2) Phenomenology studies by S. Matsumoto (IPMU)

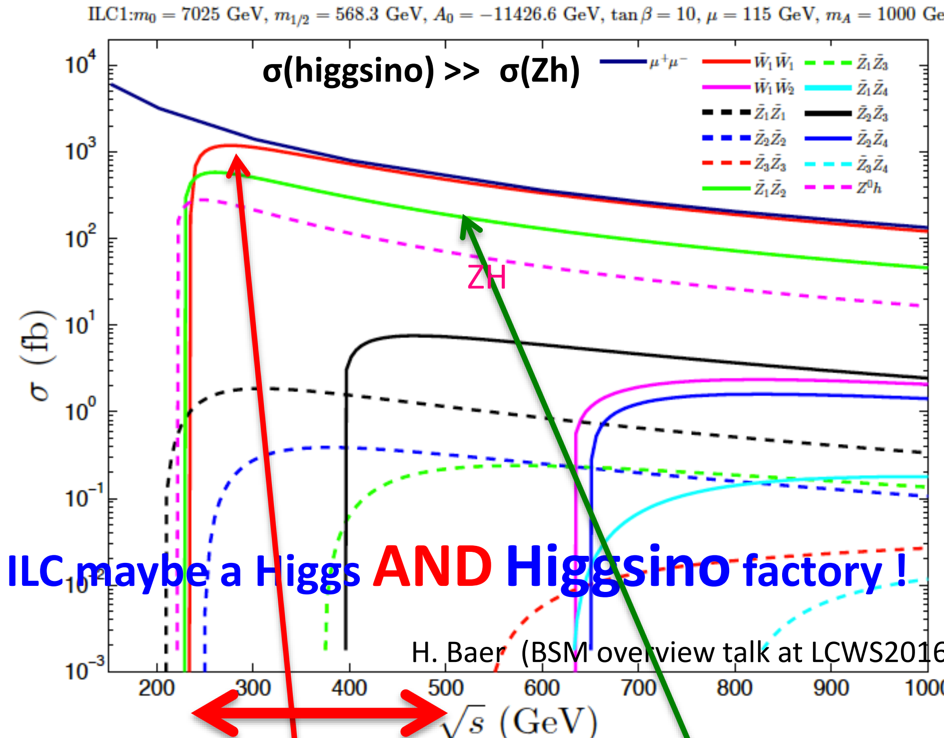
(3) Next step: **integration of the two studies**

ILC is expected to either discover or exclude natural SUSY

$M_{Higgsinos}$ ∼100 GeV
small μ, stops , gluinos ~ few TeV

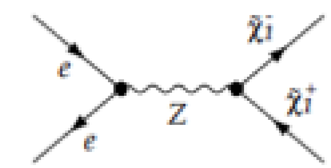
Small ΔM (< 20 GeV) no problem for clean ILC environment



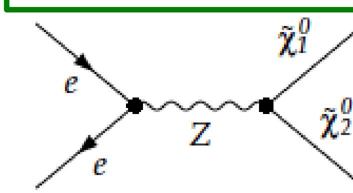


ILC maybe a Higgs AND Higgsino factory !

Charginos ($\chi_1^+ \chi_1^-$)



Neutralinos ($\chi_1^0 \chi_2^0$)



Study carried out for **discovery and precision measurement** of

4 light Higgsinos <u>within reach of ILC √s >= 250 GeV,</u>

ΔM: 4 – 20 GeV, <u>just beyond reach of HL-LHC</u>

Based on full ILD simulation

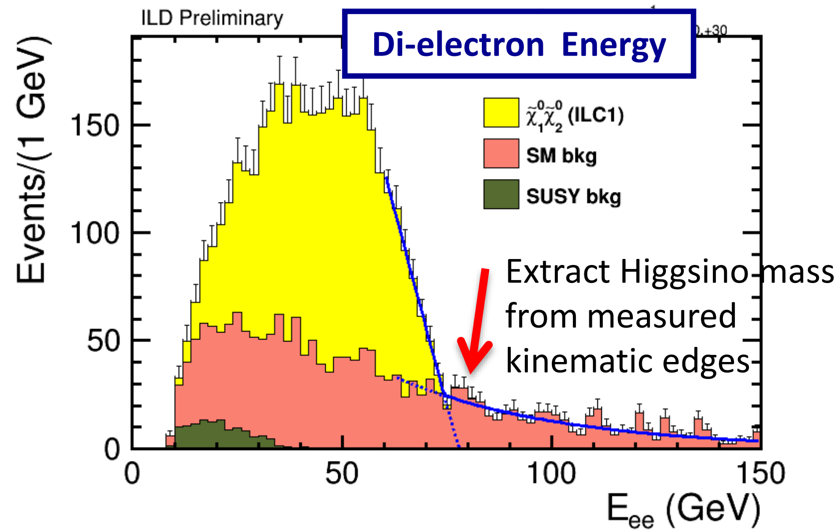
Details on next page

Higgsino mass and cross sections can be measured to better than O(1)% precision at ILC

J. Yan , T. Tanabe, K. Fujii et al

Demonstrated for various benchmarks with small ΔM using full ILD detector simulation without IRS tag

Unit: GeV	ILC1	ILC2	nGMM1
M(N1)	102.7	148.1	151.4
M(N2)	124.0	157.8	155.8
ΔM(N2,N1)	**21.3**	**9.7**	**4.4**
M(C1)	117.3	158.3	158.7
ΔM(C1,N1)	**14.6**	**10.2**	**7.3**



- Paper in progress,
- Abstract submitted to EPS-HEP2017

determine SUSY model parameters using Higgsino observations

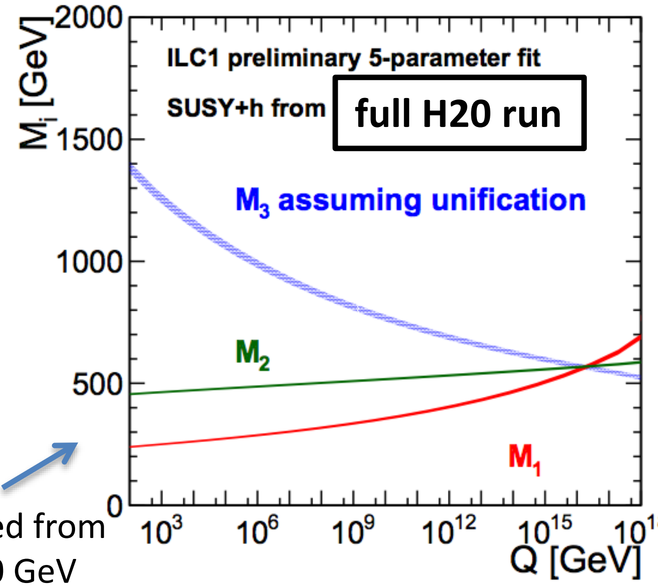
S. Lehtinen (DESY) et al

Measure light Higgsinos with O(%) precision

Determine gaugino mass M1, M2

Global χ^2 fit of to observables

test GUT unification hypotheses and predict gluino mass (M3)



√s = 250, 350, 500 GeV, scaled from full simulation studies at 500 GeV

Extra light scalars

	Range	Mass [GeV]	BR1 (%)	BR2 (%)
a_1	[9.9,10.4]	10.0	$\tau^+\tau^-$ (81)	gg (16)
h_1	[53,59]	55.7	$a_1 a_1$ (72)	$b\bar{b}$ (23)

- Theoretically motivated
- Survives LHC searches
- **ILC is ideal environment for studying light scalar properties, *at any energy***

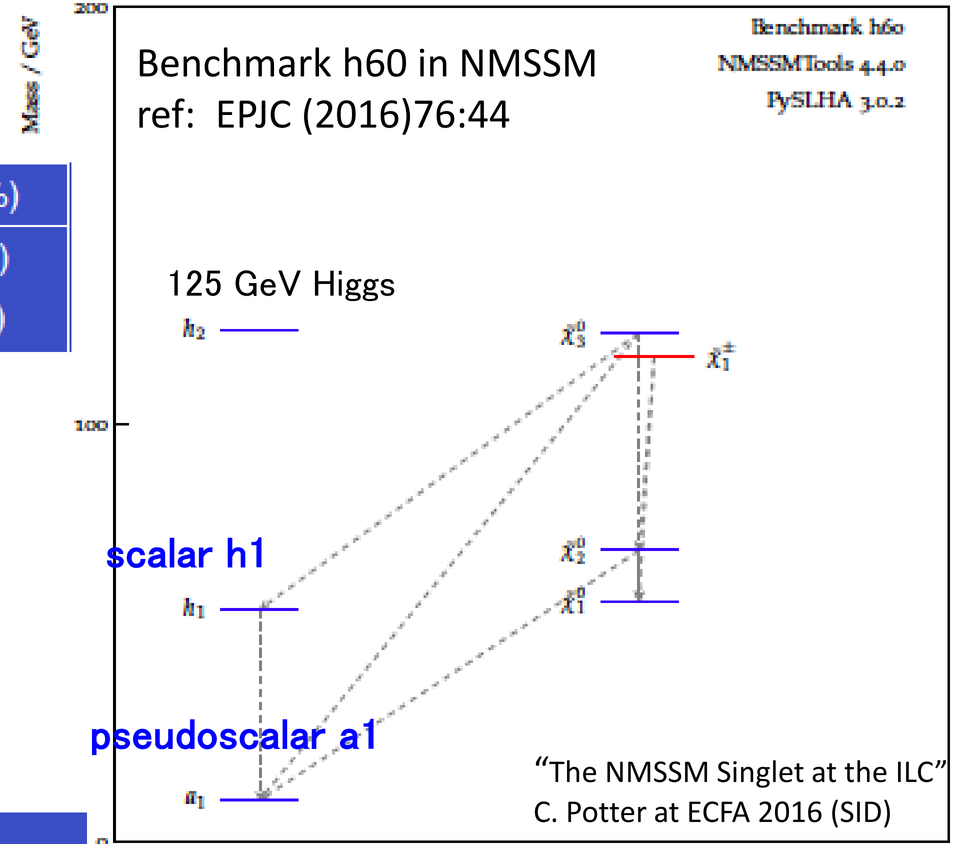
※ mh1 ≈ 60 GeV motivated by LEP excess in Zbb

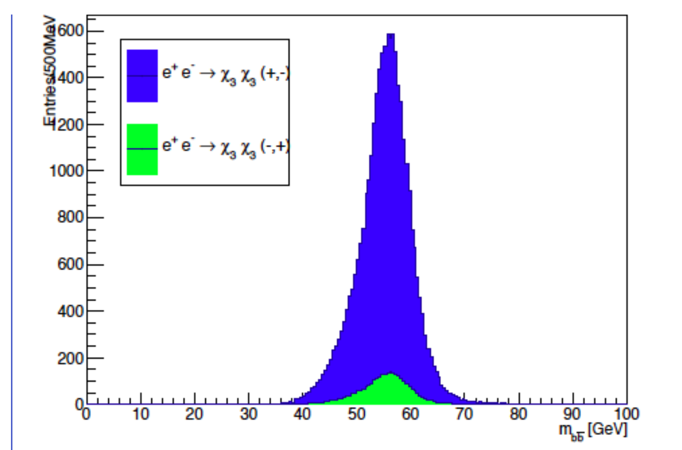
MG5_aMC@NLO Cross Sections

$\sqrt{s}$	process	$\sigma_{+,-}$ [fb]	$\sigma_{-,+}$ [fb]
m_Z	$e^+e^- \to a_1 h_1$	1.2 x 10^5	8.0 x 10^6
250 GeV	$e^+e^- \to \chi_3\chi_3$	4.4	0.37
500 GeV	$e^+e^- \to \chi_2^+\chi_2^-$	190	30

√s=250, 350 GeV: e+e- →χ3χ3, χ2χ2, χ1+χ1-, bkg: 2f, 4f, 6f

√s = 500 GeV: additional e+e- →χ2+χ2-, bkg slightly reduced

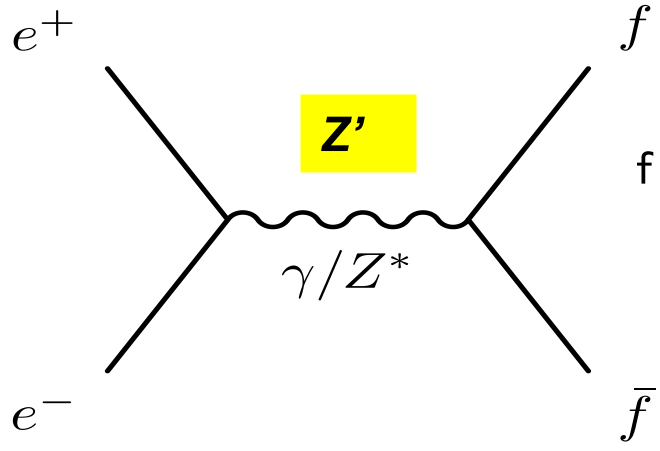




Reconstructed h1→bb in e+e- → χ3χ3 at 500GeV, 2000 fb-1 (SID)

Heavy Neutral Gauge Boson Z'

New gauge interaction indicate the existence of heavy gauge boson



f = μ, e, τ, q

LHC/ILC synergy !

LHC

discover new resonance state in 2 fermion invariant mass

→ determine Z' mass

ILC

measure interference effect

(Zff coupling, angular distr, etc)

→ discriminate new physics model

beam polarization is a powerful tool in separating left/right-handed couplings

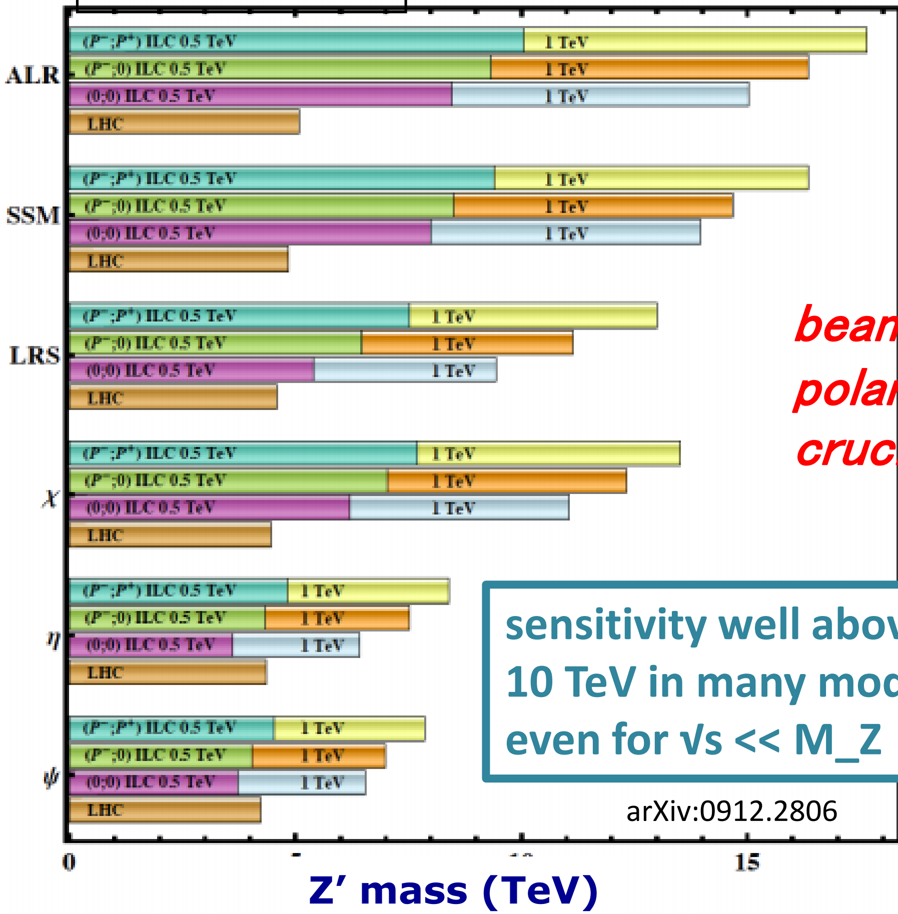
favorable at >= 500 GeV, but

certainly meaningful starting from 250 GeV

H.Yamashiro working on study of Z→$\mu\mu$ process, more studies underway

Heavy Neutral Gauge Boson Z': ILC Potential

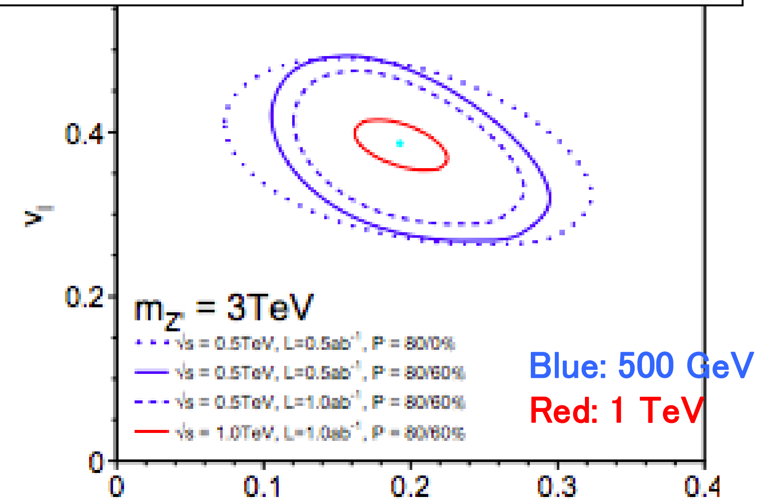
Z' mass reach



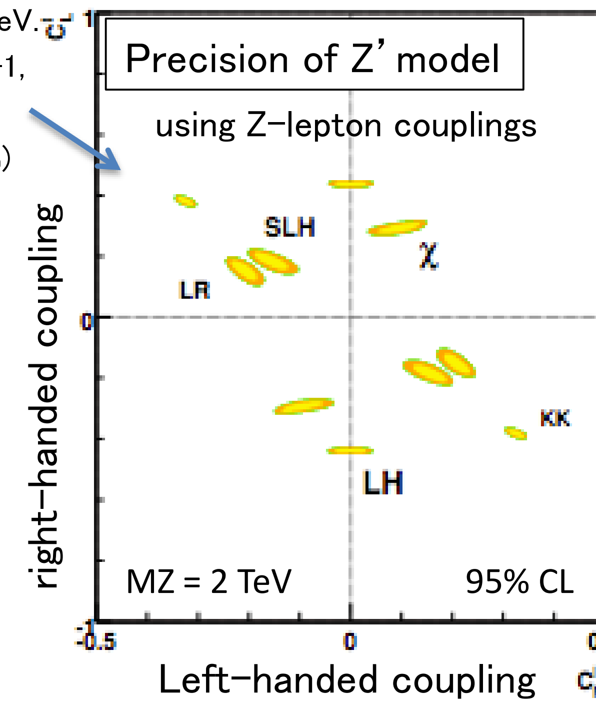
beam polarization is crucial

sensitivity well above 10 TeV in many models even for √s << M_Z

Precision of vector/axial Z-lepton couplings



√s=500 GeV, L=1000 fb−1, P(e−,e+) = (80%/60%)



- LHC(14 TeV) excluded wide range for < 2.4 TeV
- **exceeded by ILC(500 GeV) in most models**
- **ILC(1 TeV) significantly overtakes LHC in all cases**

Outline

- Goal of BSM Working Group
- Ongoing Studies
- **Summary**

Summary for BSM-specific Staging

- ILC is ready to take on the challenges that LHC results set ahead for us

  the 750 GeV excess showed clearly that LHC results could have given a new input and the ILC was capable to contribute

- We aim to provide a **clear vision on the potential of new physics at the ILC,**

  for any center of mass energy

  demonstrated in the "follow up document to ICFA letter ", mainly at $\sqrt{s}$ >= 500 GeV

- In order to demonstrate the **full value and "completeness" of ILC at 250 GeV**, it is becoming **increasingly urgent to strengthen the BSM case**

- **still plenty of space for direct new particle search at lower energies**

  WIMP, Higgsino , WIMP, extra light scalars, heavy gauge bosons

  benefit from increased luminosity (w.r.t. LEP) and clean ILC environment (w.r.t. LHC)

- **Much input from various physics study teams is needed**

  before report for 250 GeV ILC is due by June 2017

Dedicated BSM WG conveners provide support for newcomers/ongoing studies

We anticipate your participation to make the ILC physics case as strong as possible!

MSSM

Extra light scalars

Obtaining a light Higgs with SM-like couplings

[J. Gunion, H. Haber, hep-ph/0207010]

$\to$ $\mathcal{CP}$ conserving 2HDM in the Higgs basis ($\langle H_1 \rangle = v/\sqrt{2}$, $\langle H_2 \rangle = 0$)

$$\mathcal{V} = \ldots + \tfrac{1}{2} Z_1 (H_1^\dagger H_1)^2 + \ldots + \left[\tfrac{1}{2} Z_5 (H_1^\dagger H_2)^2 + Z_6 (H_1^\dagger H_1)(H_1^\dagger H_2) + \text{h.c.} \right] + \ldots$$

$\Rightarrow$ $\mathcal{CP}$-even mass matrix:

$$\mathcal{M}^2 = \begin{pmatrix} Z_1 v^2 & Z_6 v^2 \\ Z_6 v^2 & M_A^2 + Z_5 v^2 \end{pmatrix}$$

with mixing angle $\cos(\beta - \alpha) \equiv c_{\beta-\alpha}$

Decoupling limit: $M_A^2 \gg Z_i v^2$

$\Rightarrow m_h^2 \sim Z_1 v^2$, $|c_{\beta-\alpha} \ll 1|$, h is SM-like

Alignment limit: $Z_6 = 0$ and $Z_1 < Z_5 + M_A^2/v^2$

$\Rightarrow$ h is identical to the SM Higgs, $c_{\beta-\alpha} = 0$

$Z_6 = 0$ and $Z_1 > Z_5 + M_A^2/v^2$

$\Rightarrow$ H is identical to the SM Higgs, $c_{\beta-\alpha} = 1$

Extra light scalars

Alignment limit: see e.g.

[M. Carena, I. Low, N. Shah, C. Wagner '13][M. Carena, H. Haber, I. Low, N. Shah, C. Wagner '14]

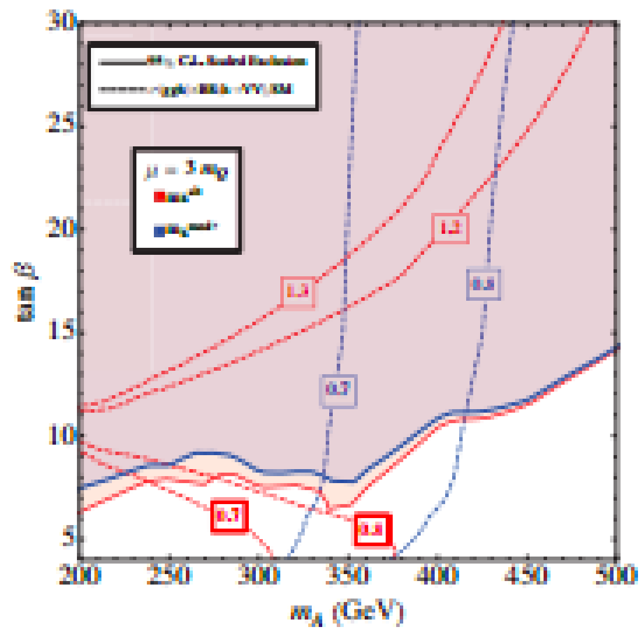
In the MSSM $Z_6 = 0$ can be obtained through an "accidental" cancellation between tree-level and loop contribution, roughly at:

$$\tan\beta \sim \left[M_h^2 + M_Z^2 + \frac{3m_t^2\mu^2}{4\pi^2v^2M_S^2}\left(\frac{A_t^2}{2M_S^2} - 1\right)\right] / \left[\frac{3m_t^2}{4\pi^2v^2}\frac{\mu A_t}{M_S^2}\left(\frac{A_t^2}{6M_S^2} - 1\right)\right]$$

Compare: $m_h^{\text{mod}+}$ and m_h^{alt} :
$A_t/M_S = 2.45$, $A_t = A_f$,
$M_S = m_{\tilde{f}} \geq 1$ TeV, $m_{\tilde{g}} = 1.5$ TeV,
$M_2 = 2\,M_1 = 200$ GeV, μ adjustable

(low M_A and $\tan\beta$: tune $M_S \geq 1$ TeV to obtain $M_h \geq 122$ GeV)

$\Rightarrow$ SM-like Higgs for all M_A



BSM Search Strategy at ILC

Focus on three cases based on the results of the (HL)-LHC:

Case 1: No discovery at LHC

- SUSY: Discovery anticipated for light SUSY particles (e.g. Higgsino)
- Dark Matter: Discovery anticipated for DM that can be seen at the ILC
- Precision measurements might give first discovery of new BSM interactions

Case 2: LHC discovers light new particles (can be seen at the ILC)

- SUSY: ILC will probe the new particles in detail; may discover more.
- Dark Matter: ILC will address the question of whether any of the new discovered particles is DM
- Precision measurements sensitive to heavy particles beyond LHC reach.

Case 3: LHC discovers heavy new particles

- SUSY: It is probable that ILC will discover new light particles.
- Dark Matter: Same as in Case 2, via measurements of the new light particles.
- Precision measurements test if there are additional heavy particles beyond the LHC reach.

From slides of T. Tanabe

Goal of BSM sub-Working group:

Provide a clear vision on the discovery potential of new physics at the ILC

- **Direct search for new particles**
  complementary to the LHC

- Probe new physics through precision measurements of SM physics

Significant progress made during the past year

a variety of BSM talks at LCWS2016 in Morioka
on natural SUSY theory, dark matter particles, Higgsinos, etc....

Outstanding performance at the LHC in extending exclusion region of SUSY

From " BSM sub-WG summary talk" at LCWS2016, J. Yan

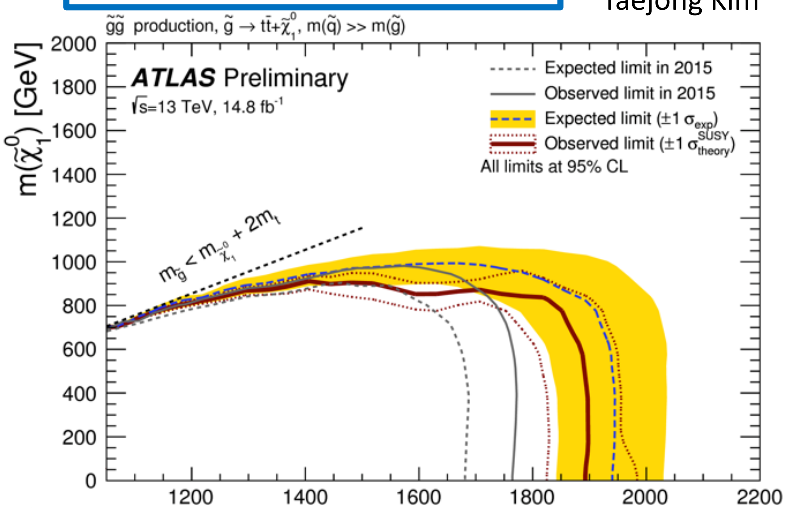
- With even partial 2016 data, extended the SUSY parameter space excluded by previous LHC searches
- Results with much larger data in 2016 will be coming soon.
- Great prospects for HL-LHC to discover SUSY in wide range of models
  (from simulation studies at slightly increased √s, and at 3000 fb^{-1})

similar for resonances (e.g. heavy gauge boson) , Dark Matter, etc….

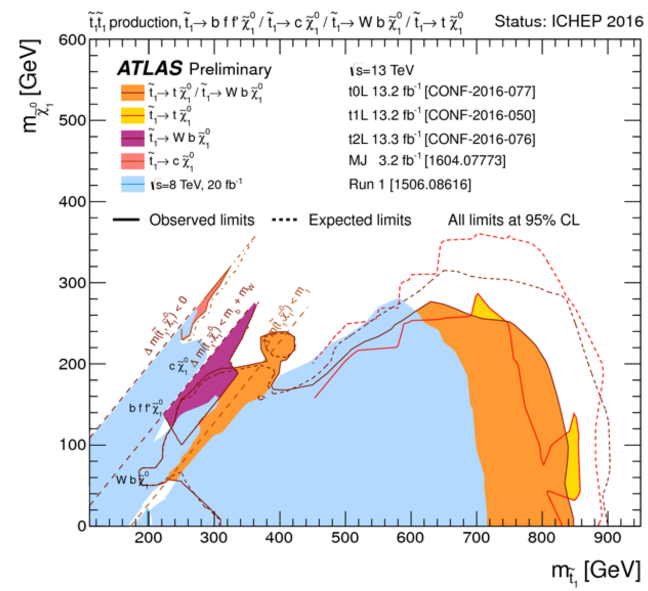
LHC results in colored sector are significantly challenging SUSY !

Gluino Pair Production
- pushed up to ~1.9 TeV

From talk of Taejong Kim



Squark Pair Production
- stop excluded <~900 GeV



if we assume natural SUSY,
gluino and stop cannot be too heavy

Remaining region is very narrow

New gaps filled by recent stop searches
stops may be the first to be discovered at the LHC

Exotica searches at the LHC (ATLAS)

D. Hernandez et al

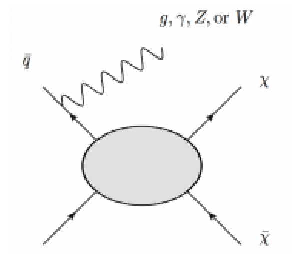
Predicted by many New Physics models: **resonances**

- Heavy gauge bosons (Z', W'): GUT, Sequential Standard Mode (SSM).
- Kaluza-Klein excitations: Randall-Sundrum extra-dimensions.
- LSP: SUSY.
- Extra Higgs bosons.
- ...

- So far, **all data consistent with SM** expectations.
- No new exciting deviation this year

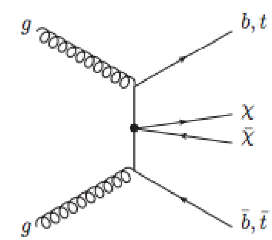
Broad variety of BSM searches at the LHC

Dark Matter



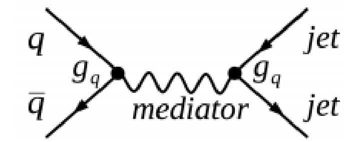
Mono-X

ISR tag for DM pair production
X = jet, γ, W/Z,t/b or H



Associated production

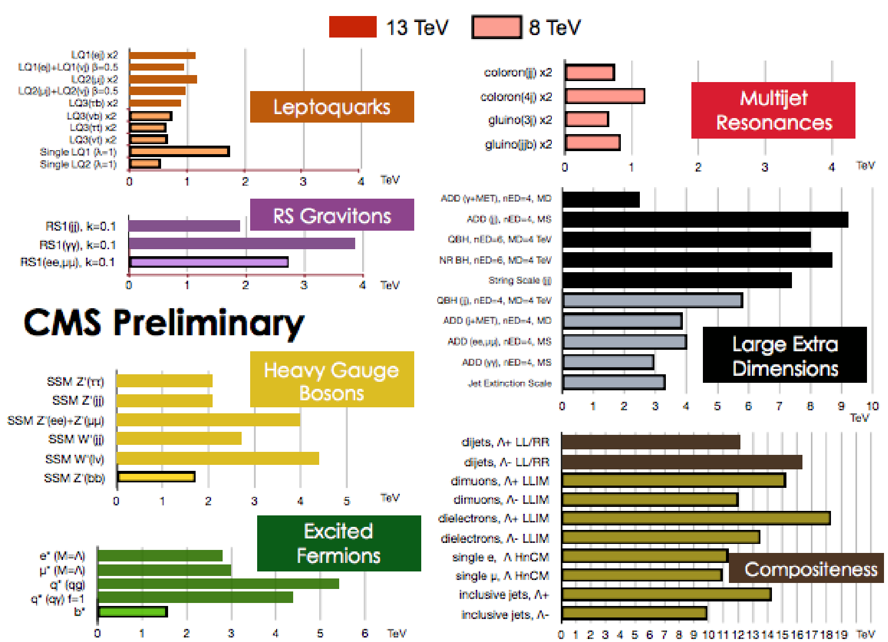
associated production
with other particles



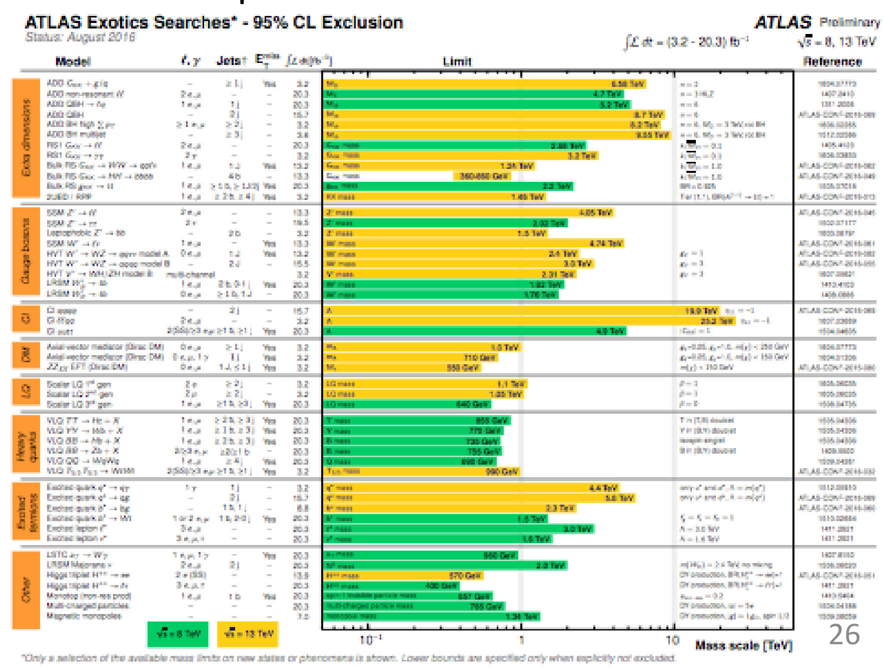
Mediator

mediator
(dijet resonance)

- **New limits significantly extend the Run 1 results.**
- Many channels with 13 TeV data not yet released.
- New results expected for winter conferences.

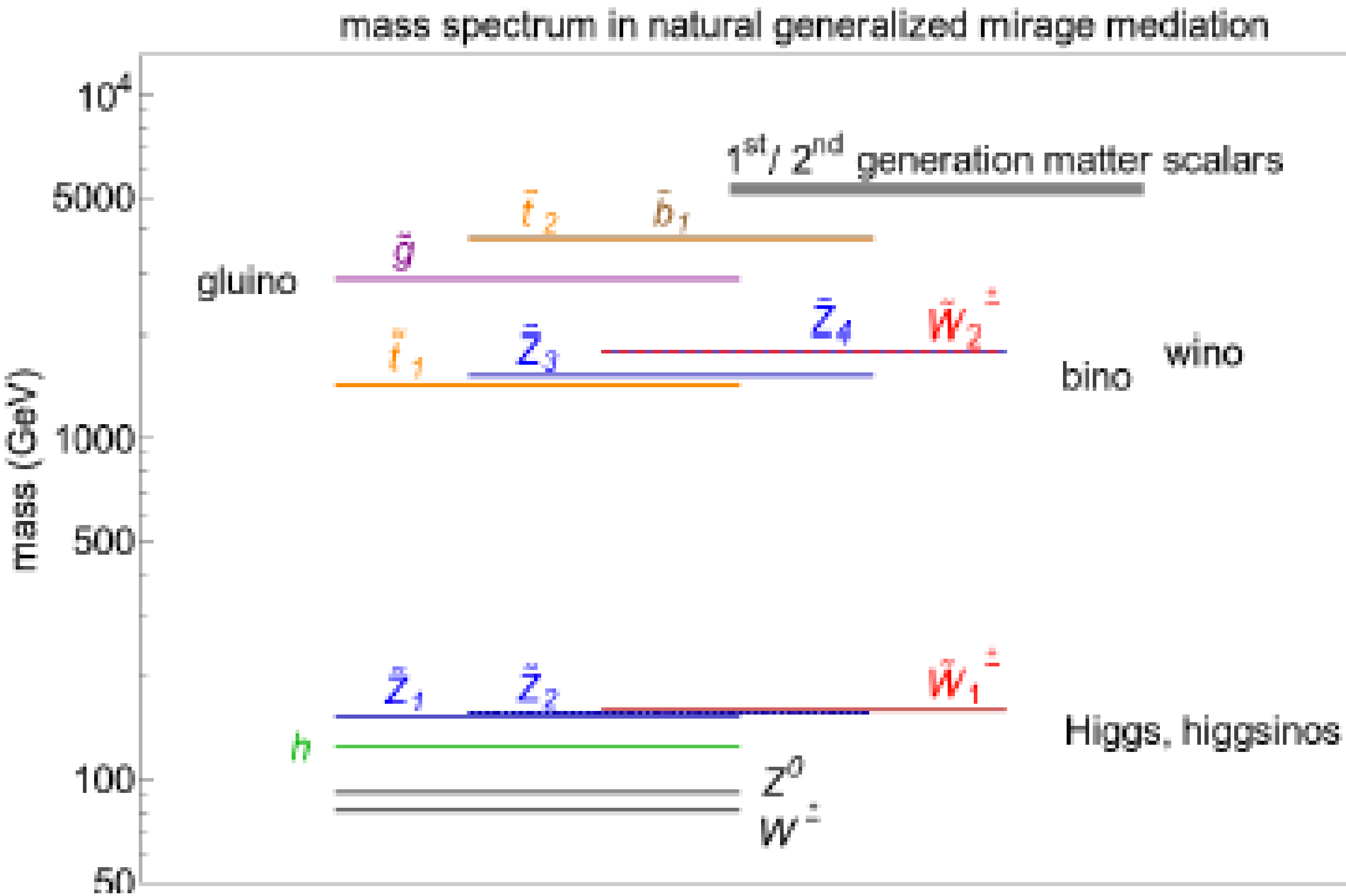


CMS Exotica Physics Group Summary – ICHEP, 2016



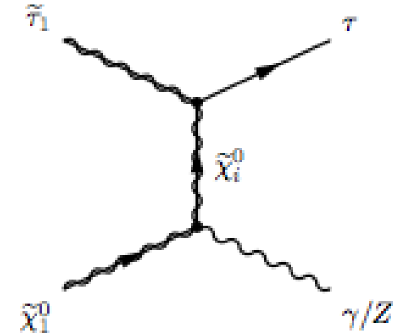
BSM perspective: why ILC is the right machine for SUSY discovery

H. Baer (BSM overview talk)



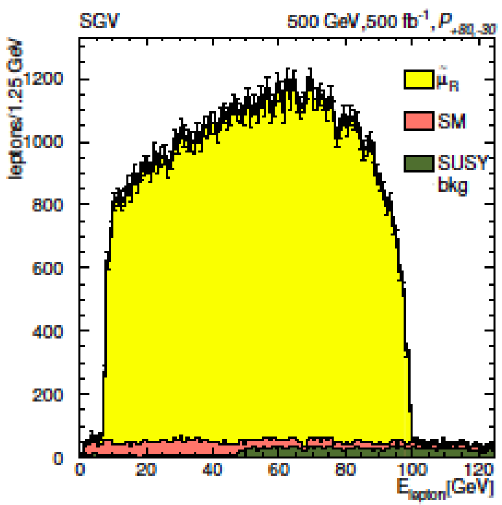
SUSY co-annihilation

M. Berggren et al

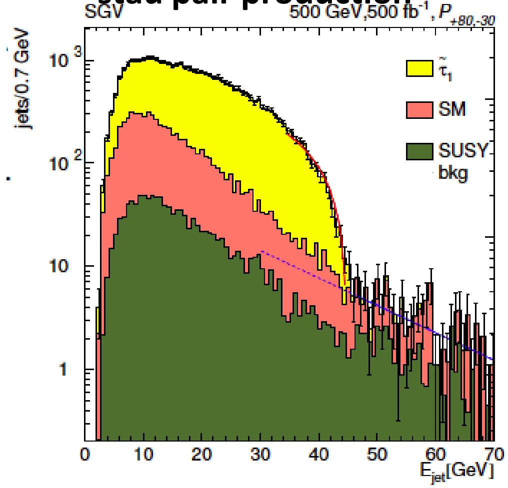


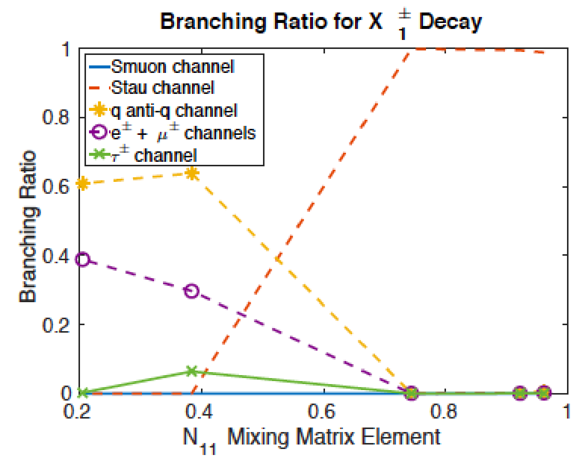
- SUSY models with compressed spectrum (mass gap ∼ 10 GeV) in accordance with DM abundance as observed by Planck
- At LHC, too difficult, hardly excluded , but accessible at ILC

smuon, selectron pair production



stau pair production





sensitive observables for mixing measurements
polarized cross sections, BRs, etc…

Per-mille precision measurements of slepton masses

%-level precision measurements of mixing parameters (θ_stau , N_11)

Expected precisions for sparticle masses and mixings should allow us to measure DM with a precision close to Planck's CMB results.

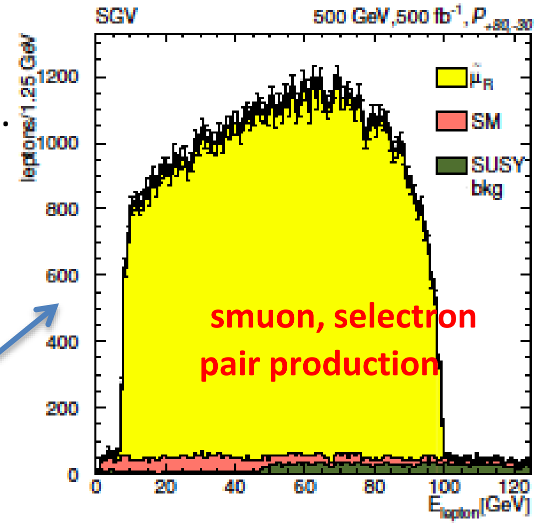
SUSY co-annihilation

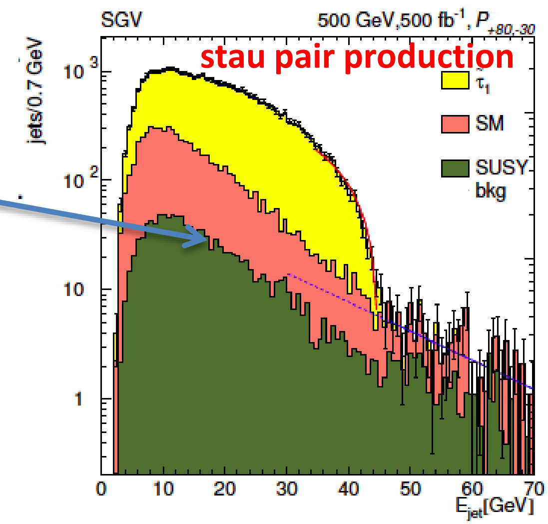
M. Berggren et al

- SUSY models with rich and compressed spectrum are the best fit to data.
- At LHC: not excluded (except for mSUGRA), If exists, may discover soon

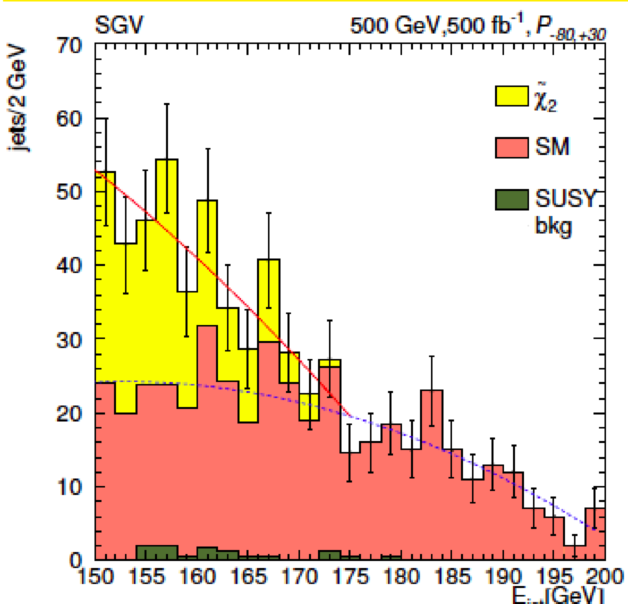
Look at pair-production

- $$E'_{\substack{max\\min}} = \frac{E_{Beam}}{2}\left(1-\left(\frac{M_{\tilde{\chi}_1^0}}{M_{\tilde{\ell}}}\right)^2\right)\left(1\pm\sqrt{1-\left(\frac{M_{\tilde{\ell}}}{E_{Beam}}\right)^2}\right)$$
- Two observables($E'_{\substack{max\\min}}$) and two parameters ($M_{\tilde{\ell}}$ and $M_{\tilde{\chi}_1^0}$).
- For $\tilde{e}_R$ and $\tilde{\mu}_R$, $E'_{\substack{max\\min}}$ can be measured very well at the ILC.
- E'_{max} can be well measured for $\tilde{\tau}_1$
- $\Rightarrow$ Use $\tilde{e}_R$ and $\tilde{\mu}_R$ to determine $M_{\tilde{\chi}_1^0}$, end-point of $E_{\tau-jet}$ for $M_{\tilde{\tau}_1}$.





STC4 bosinos @ 500 GeV: $\tilde{\chi}_1^0\tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1\tau\tilde{\chi}_1^0$



- fit to endpoint of Ejet
  → **determine M(χ20)**
- Signature: two τ's + nothing
- E_jet_max: 175.0+/-1.6 GeV
  → **ΔM (χ20)= 3 GeV**