DM & SUSY Direct Search at ILC

Tomohiko Tanabe (U. Tokyo)

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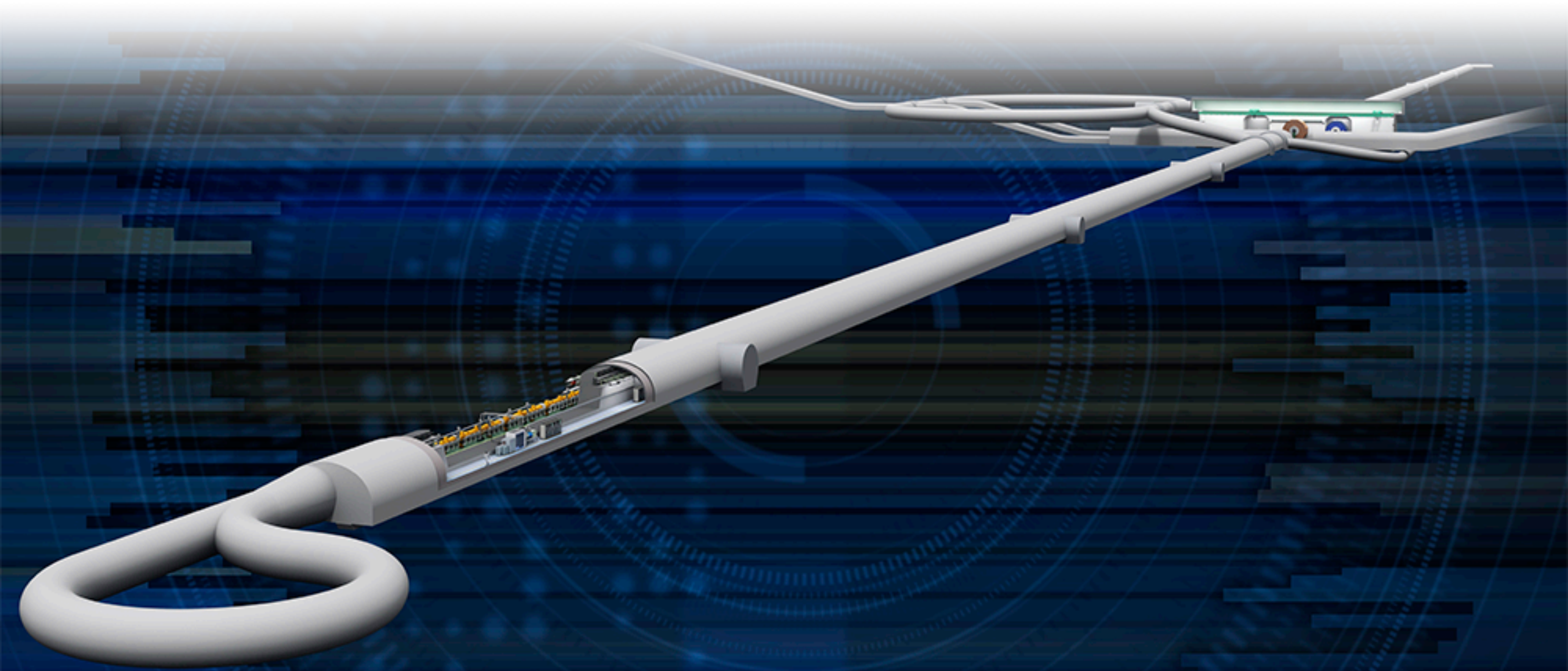
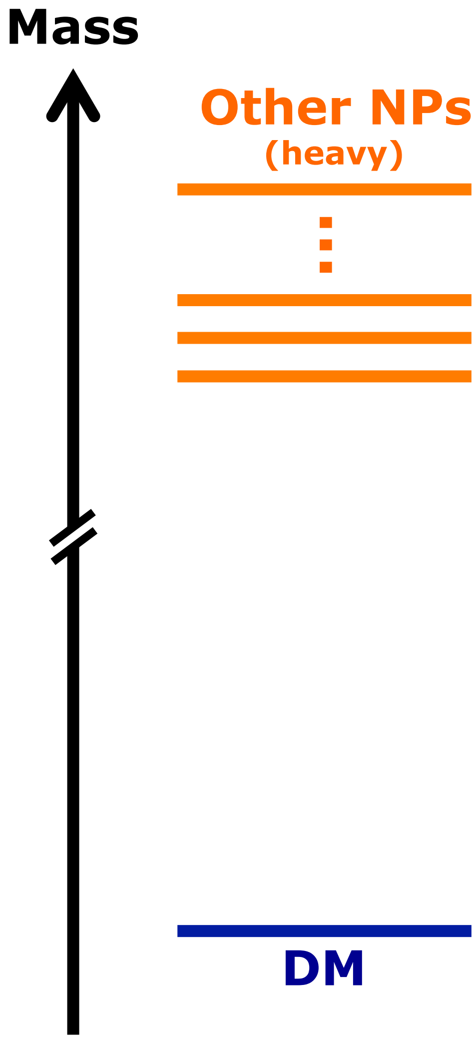


Contents

- **The ILC has access to new physics via:**
  - Precision Higgs measurements
  - Precision top measurements
  - Direct searches
    - Search for DM
    - Search for SUSY particles (incl. DM)
  - Other precision probes of indirect search for new particles

- **I will cover the last two topics.**

Mass Spectra for DM



If DM is the only particle that is kinematically accessible:

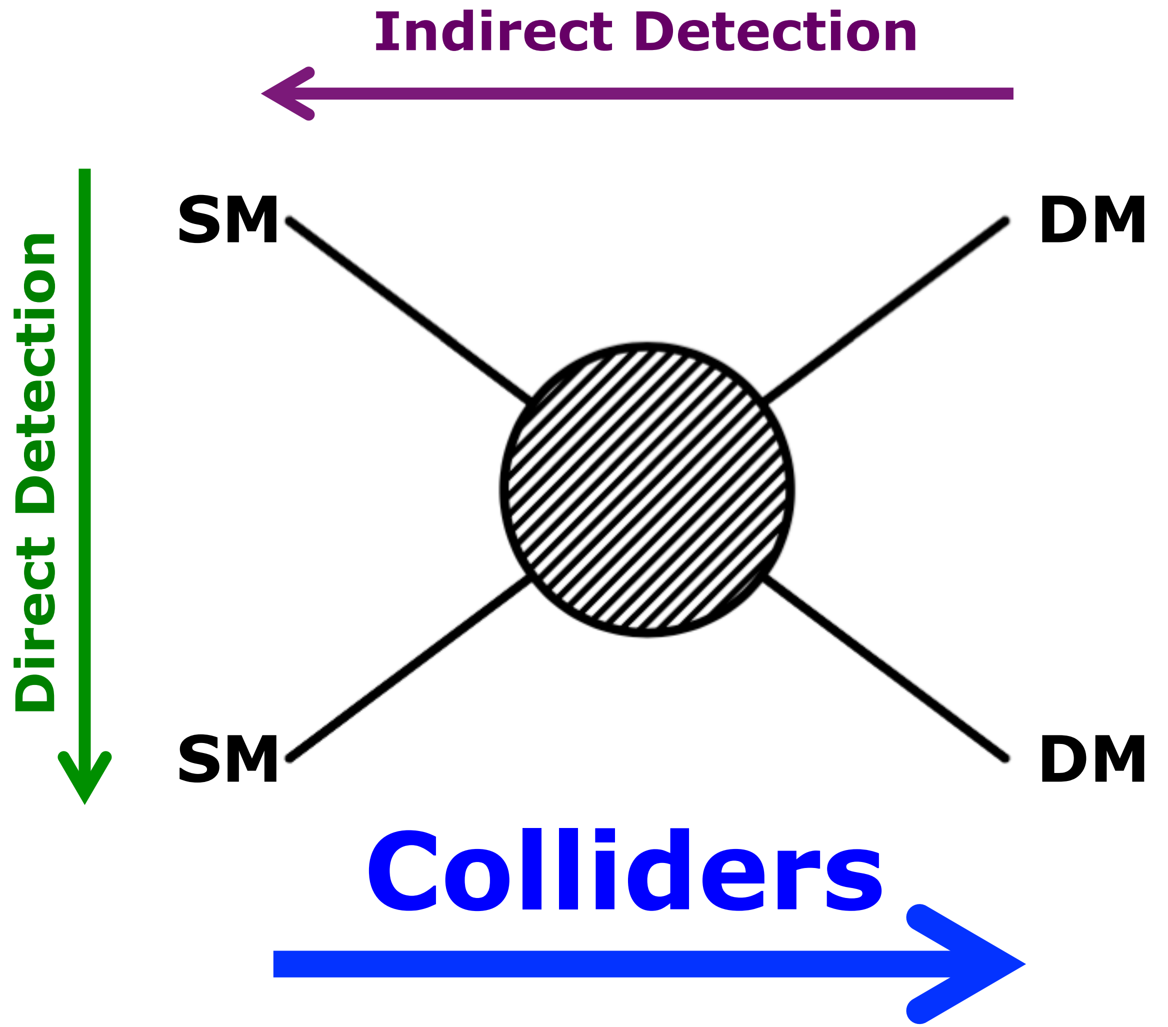
At LHC:
Discovery possible

At ILC:
Discovery possible

Reach depends on type of DM → complementarity between LHC/ILC

LHC and ILC have complementary capabilities in DM searches.

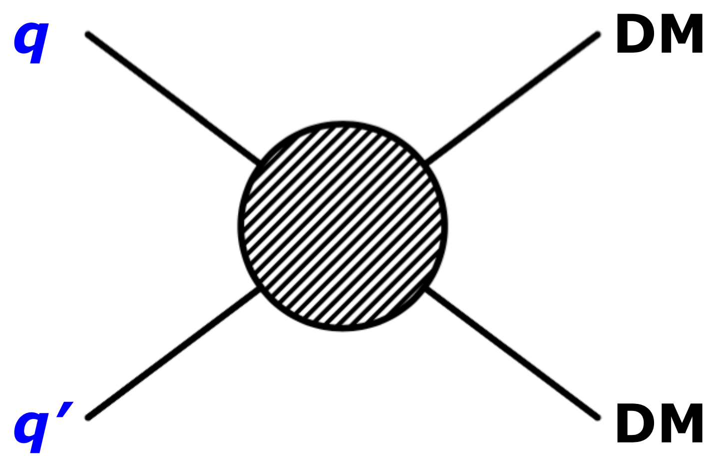
Dark Matter Searches



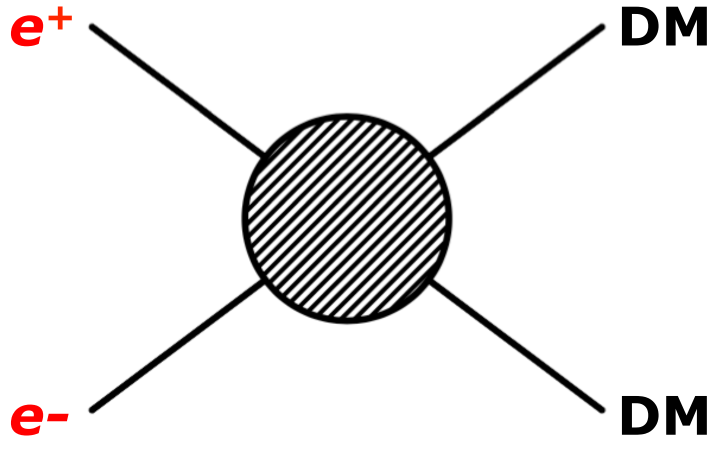
Complementary ways to search for DM

Dark Matter Searches

LHC



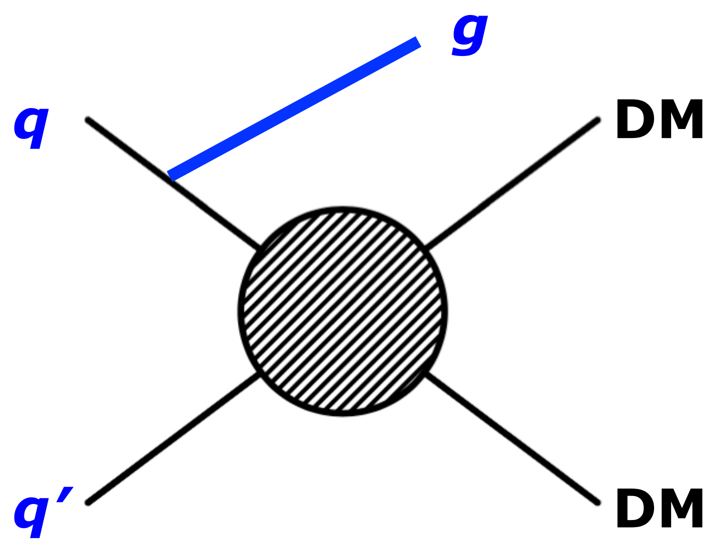
ILC



different initial state → complementary sensitivity to DM

Dark Matter Searches

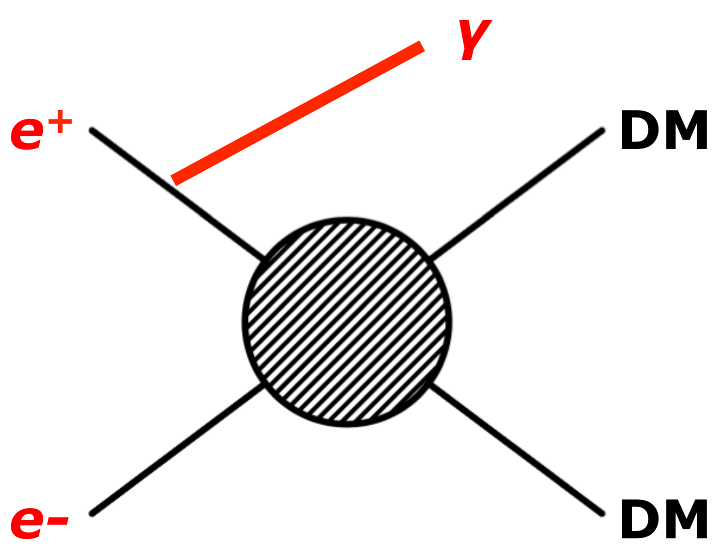
LHC



mono-jets

also,
mono-photons
mono-Z/W/H

ILC

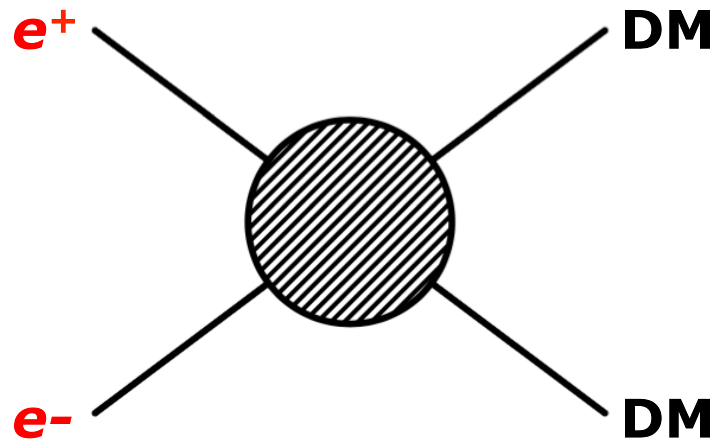


mono-photons

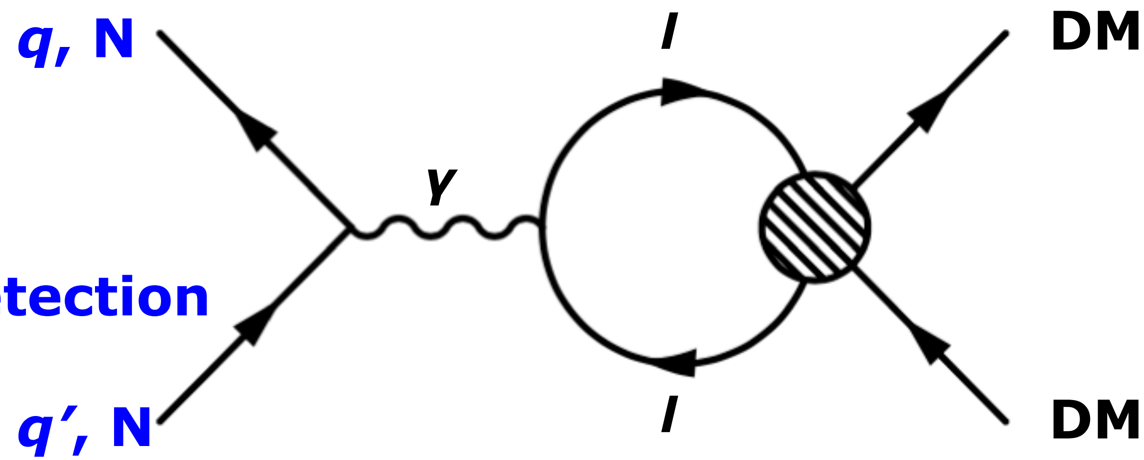
different initial state → complementary sensitivity to DM

e.g.) Leptophilic DM

ILC

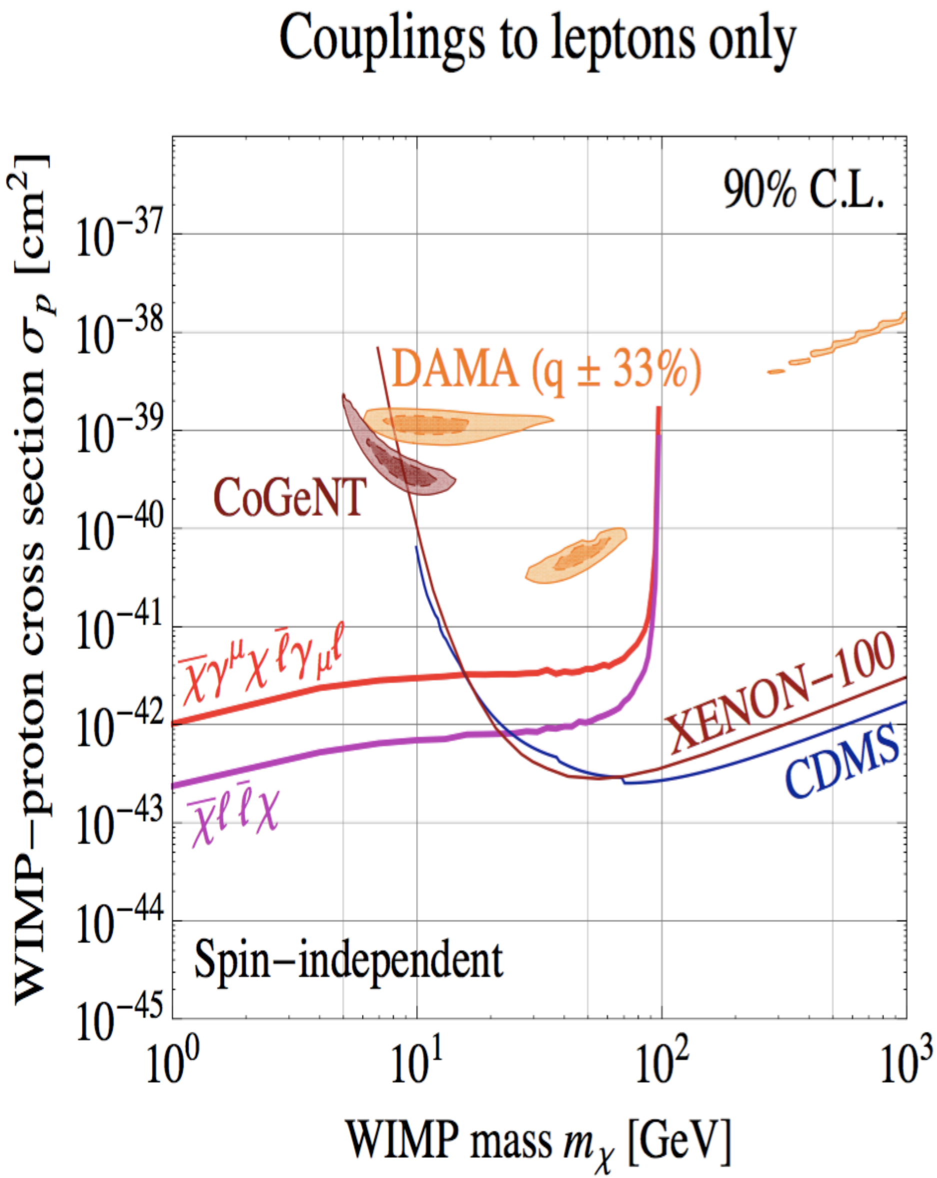


LHC,
Direct Detection



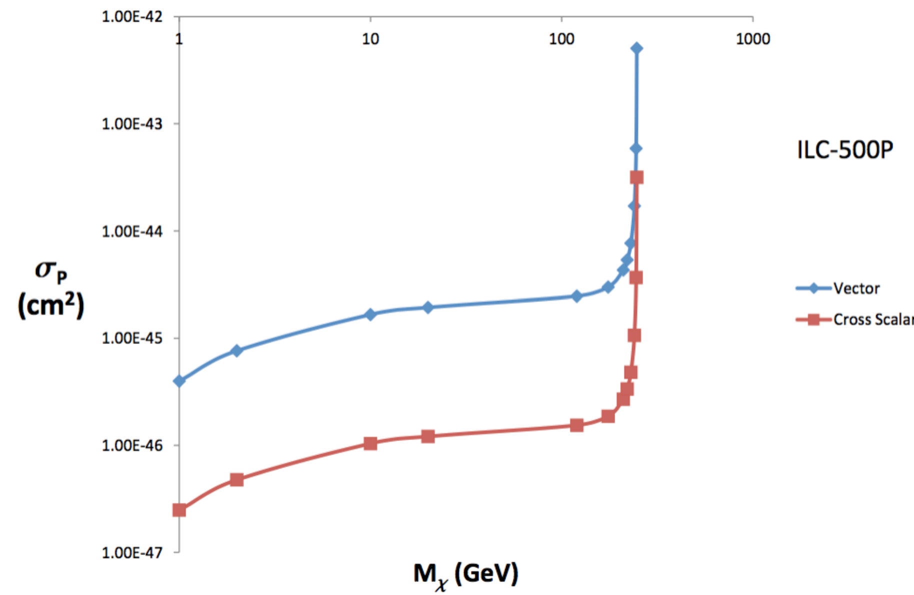
→ loop suppression

ILC has unique sensitivity to electron-DM coupling

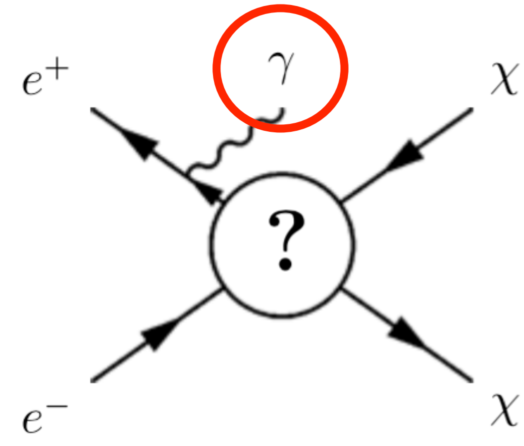


LEP limits
[Fox, Harnik, Kopp, Tsai, 1103.0240]

ILC 500 GeV
[Chae, Perelstein, 1211.4008]



Mono-photon Status (1)



Signal:

WIMP pair production with ISR photon

e+ e- → DM DM **γ**

- Initial state radiation (**ISR**) photon
- Missing energy + missing momentum

Observables: $\mathbf{E_\gamma}$, $\mathbf{\theta_\gamma}$

DM mass reach ~√s/2

Backgrounds:

Radiative neutrino production

e+ e- → ν ν **γ**

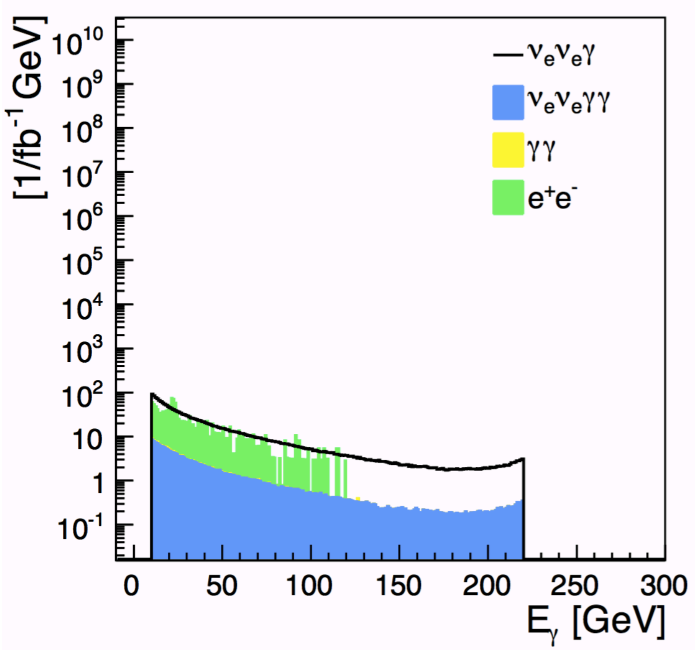
→ ν ν **γ γ** ...

Contribution will be known / can be calibrated.

Bhabha scattering

e+ e- → e+ e- **γ**

where the electrons go down the beam pipe undetected. Coverage of forward detectors crucial.



[C.Bartels, Ph.D. Thesis at DESY]

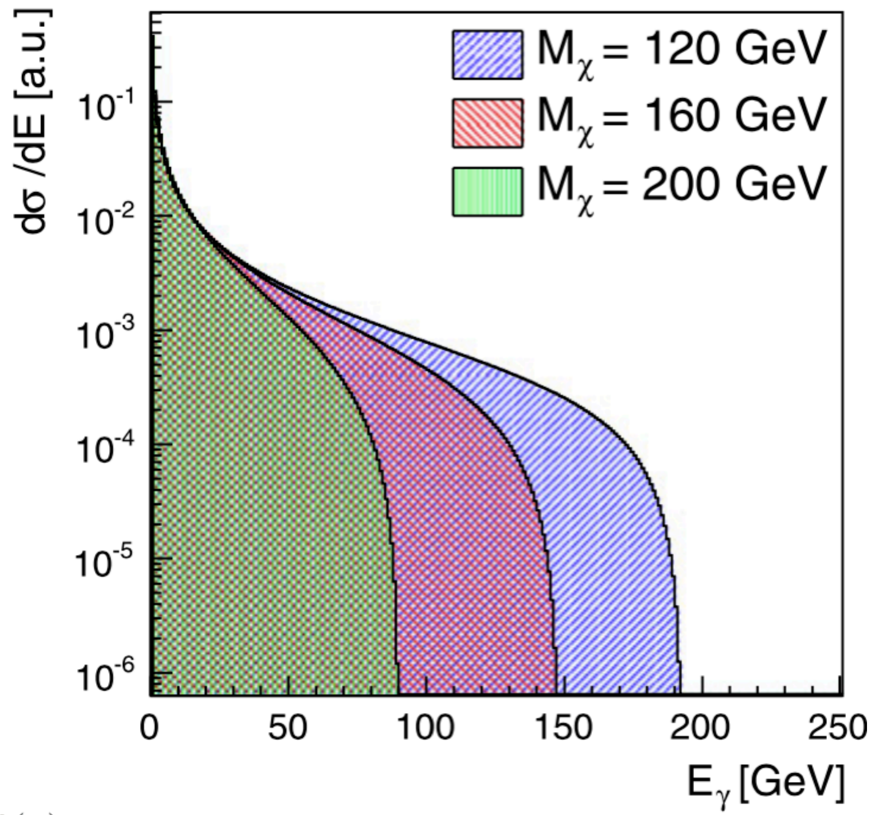
Mono-photon Status (2)

Geant4-based full simulation study

- Publication:
  C. Bartels, M. Berggren, J. List, EPJC 72:2213 [arXiv:1206.6639]

- $\sqrt{s}$ = 500 GeV
- 1 GeV < M_{WIMP} < 250 GeV

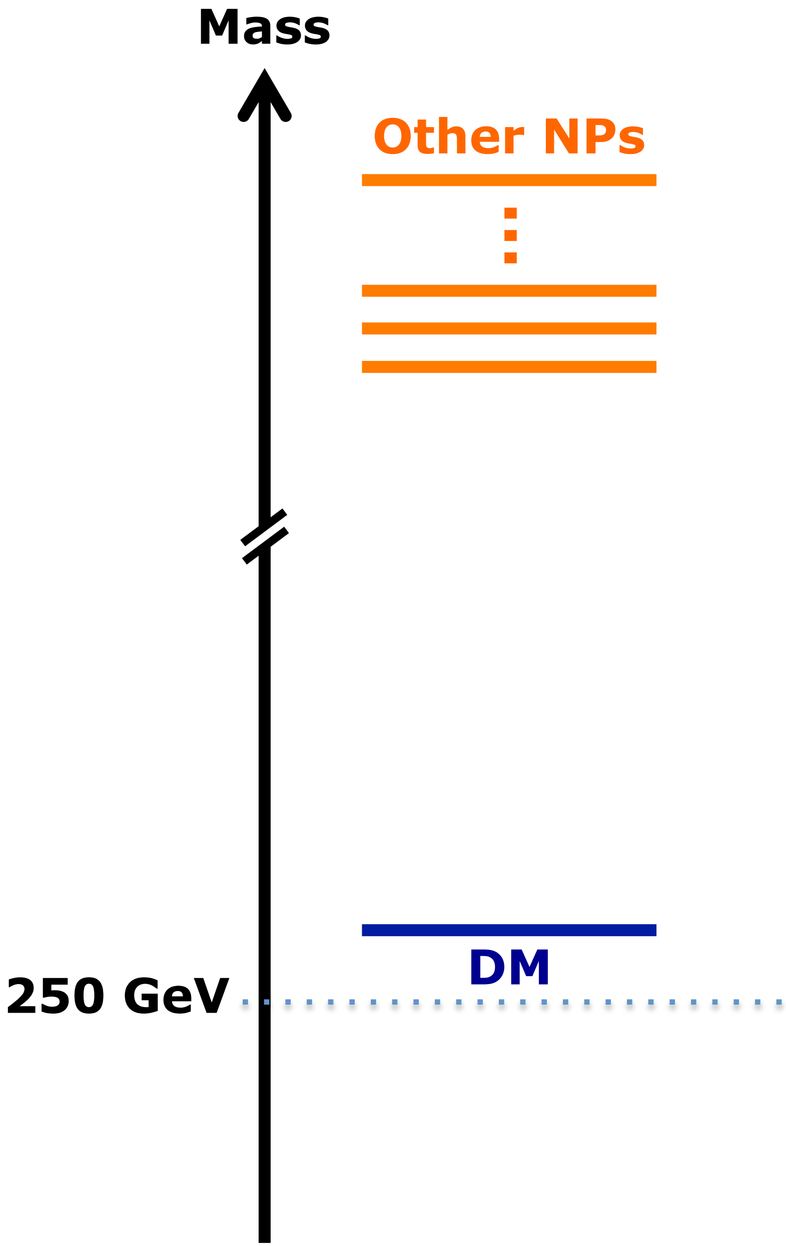
- WHIZARD 1.96
- ilcsoft v01-06
- Beam parameters: RDR
- Detector models:
  LDC_PrimeSc_02, ILD_00



Update plan:

- Other $\sqrt{s}$, WHIZARD 2, latest software tools,
  TDR parameters, ILD_v1_o5 model

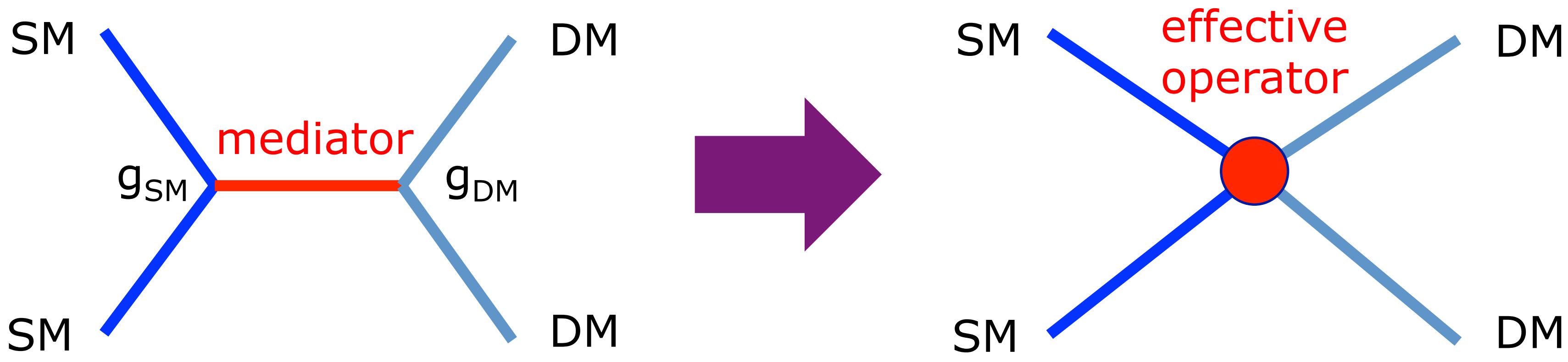
What if...?



Indirect searches can exceed reach of direct search

Effective Field Theory

New physics interaction mediated by a heavy particle can be integrated out to give a four-point contact interaction:



$$\left(\frac{g_f g_\chi}{q^2 - M^2}\right)(\overline{f}\gamma_\mu f)(\overline{\chi}\gamma^\mu \chi)$$

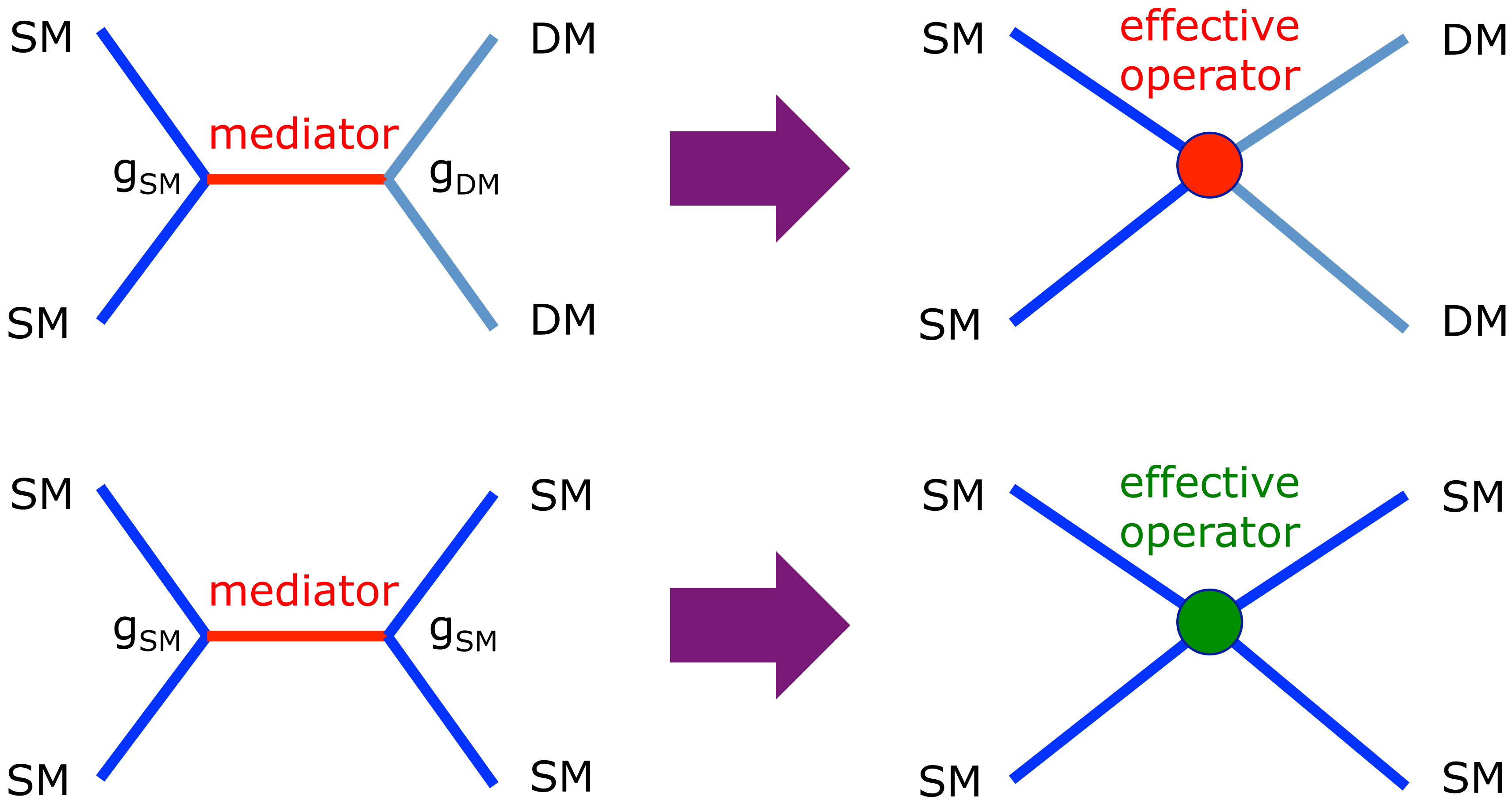
$$\frac{1}{\Lambda^2}(\overline{f}\gamma_\mu f)(\overline{\chi}\gamma^\mu \chi)$$

EFT is valid for $\mathbf{M_{med} >> 2M_{DM}}$; identify: $\Lambda = M/\sqrt{g_f g_\chi}$

*Outside the domain of validity, must take into account effects of on-shell resonance enhancement and off-shell production.

Effective Field Theory

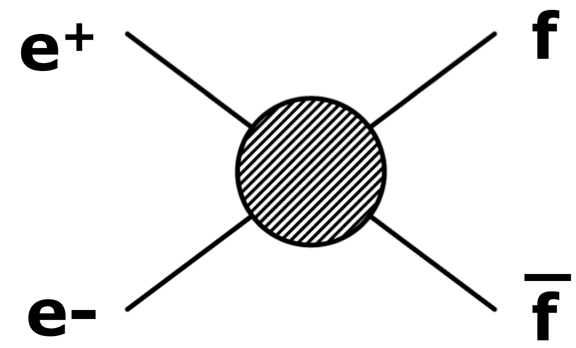
New physics interaction mediated by a heavy particle can be integrated out to give a four-point contact interaction:



*In general, t-channel diagrams also exist

e+e- → 2 fermion process

- **e+e- → ff**
  - with f = u/d/s, c, b, t, e, μ, τ
  - **e+e- → WW, ZZ** may also be useful



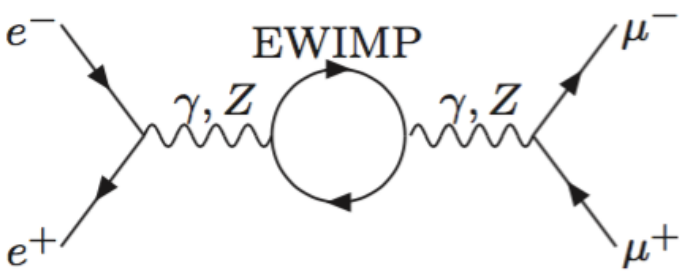
- **Observables:**
  - Polarized cross sections
  - Forward backward asymmetries
    (or equivalently differential cross section)

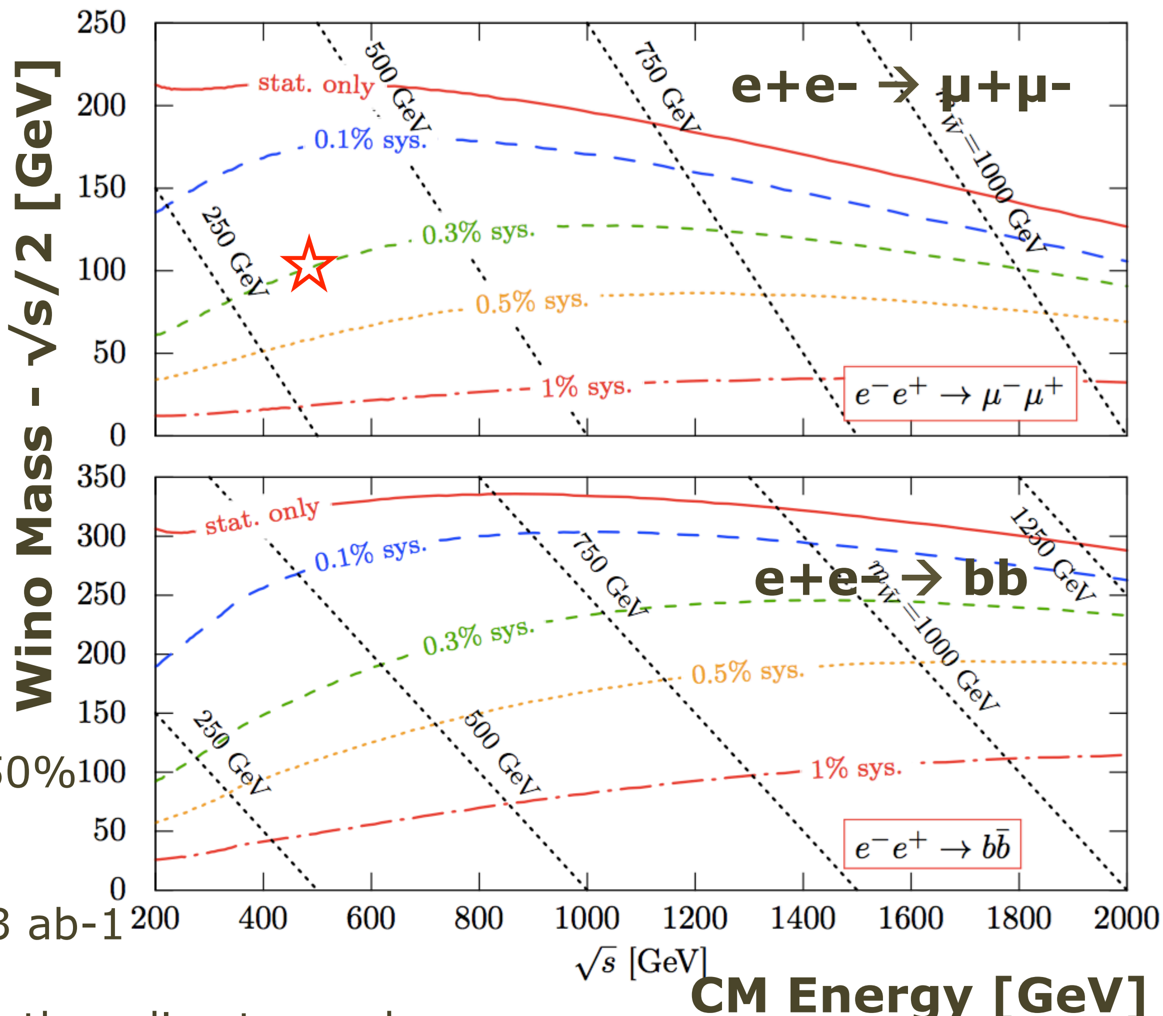
- The large cross section of these events implies measurements will quickly become **systematically limited.** Need to demonstrate control of all the relevant systematics; **it will immediately pay off !**

	Z' study **[TDR]**	**Baseline** **[Snowmass]**	**LumiUp** **[Snowmass]**
Luminosity	0.2%	0.1%	0.05%
Polarization	0.25%	0.1%	0.05%
b-tagging	0.5%	0.3%	0.15%

e+e- → 2f [SUSY DM example]

[Harigaya, Ichikawa, Kundu, Matsumoto & Shirai 1504.03402]





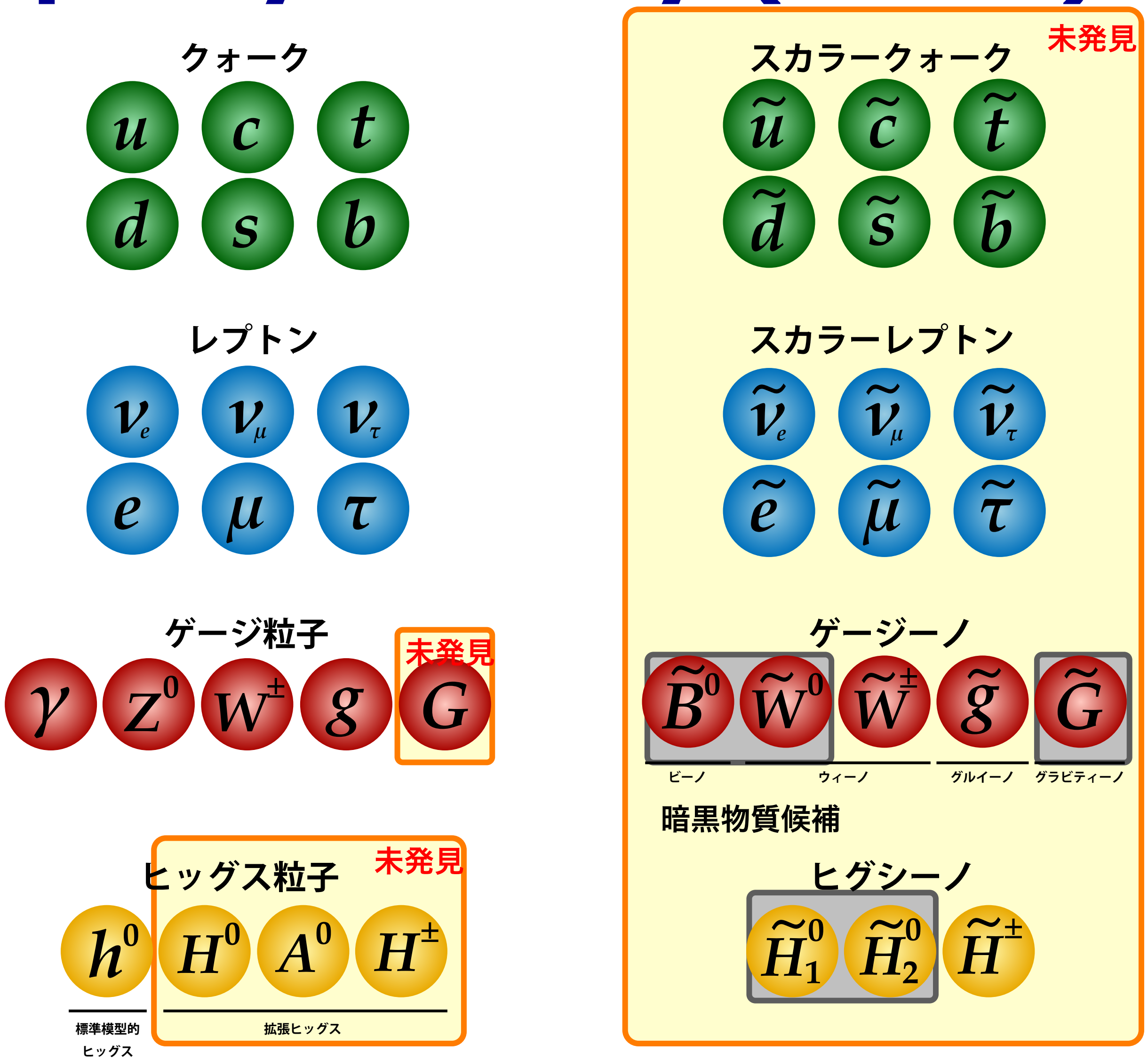
Binned likelihood analysis of differential cross sections, comparing expected number of events in BSM vs. that of SM.

Efficiencies assumed:
leptons 100%, b-jet 80%, c-jet 50%

Other assumptions
P(e-,e+) = (-0.8,+0.6), Lumi = 3 ab-1

Indirect reach significantly higher than direct search
<u>if systematics is under control</u>
e.g. for √s=500 GeV, e+e- →μ+μ- :
Wino mass reach = 350 GeV (for total systematics 0.3%)

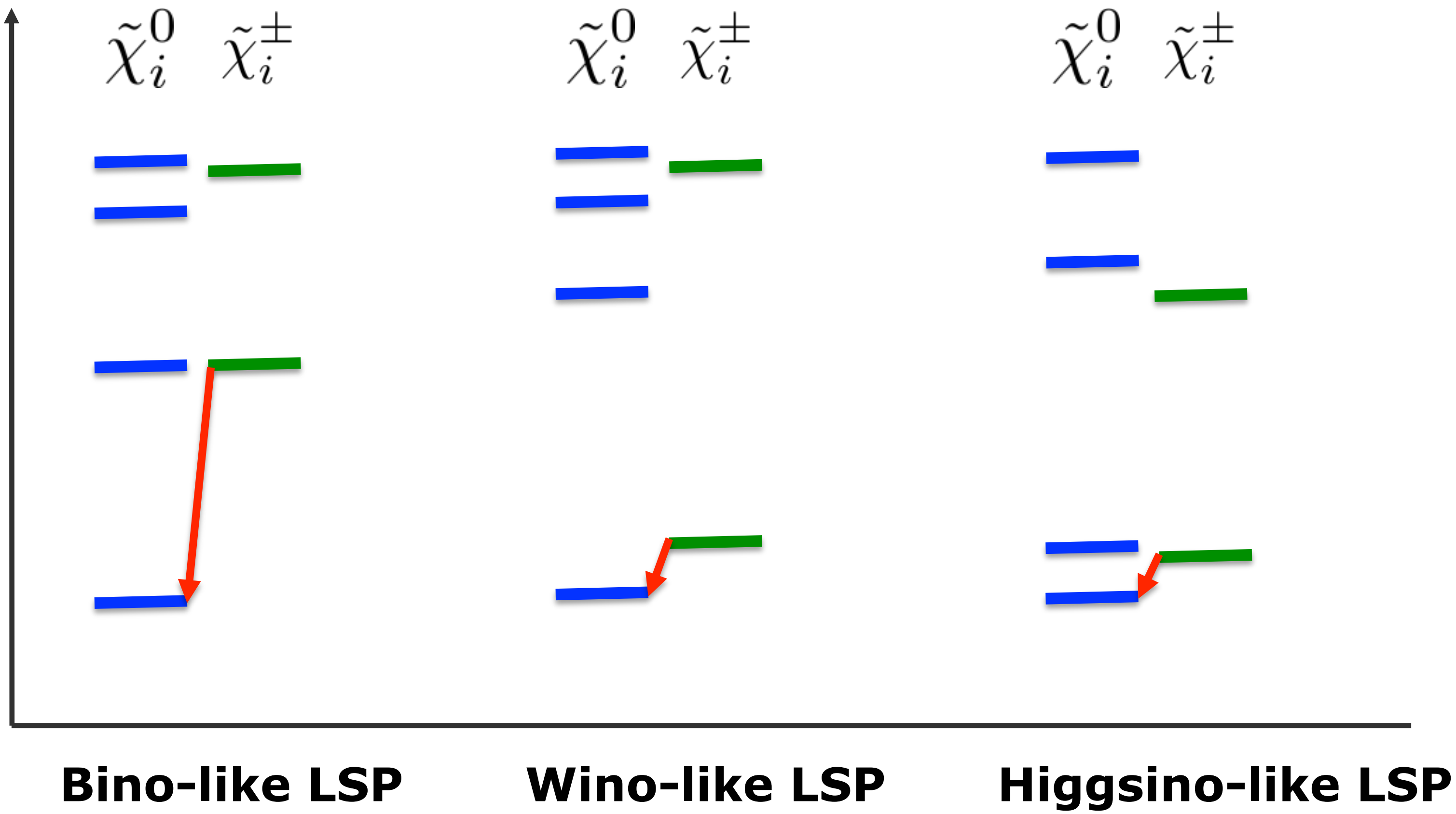
Supersymmetry (SUSY)



SUSY:

- ✓ Solves hierarchy problem
- ✓ Road to GUT
- ✓ Offers DM candidate

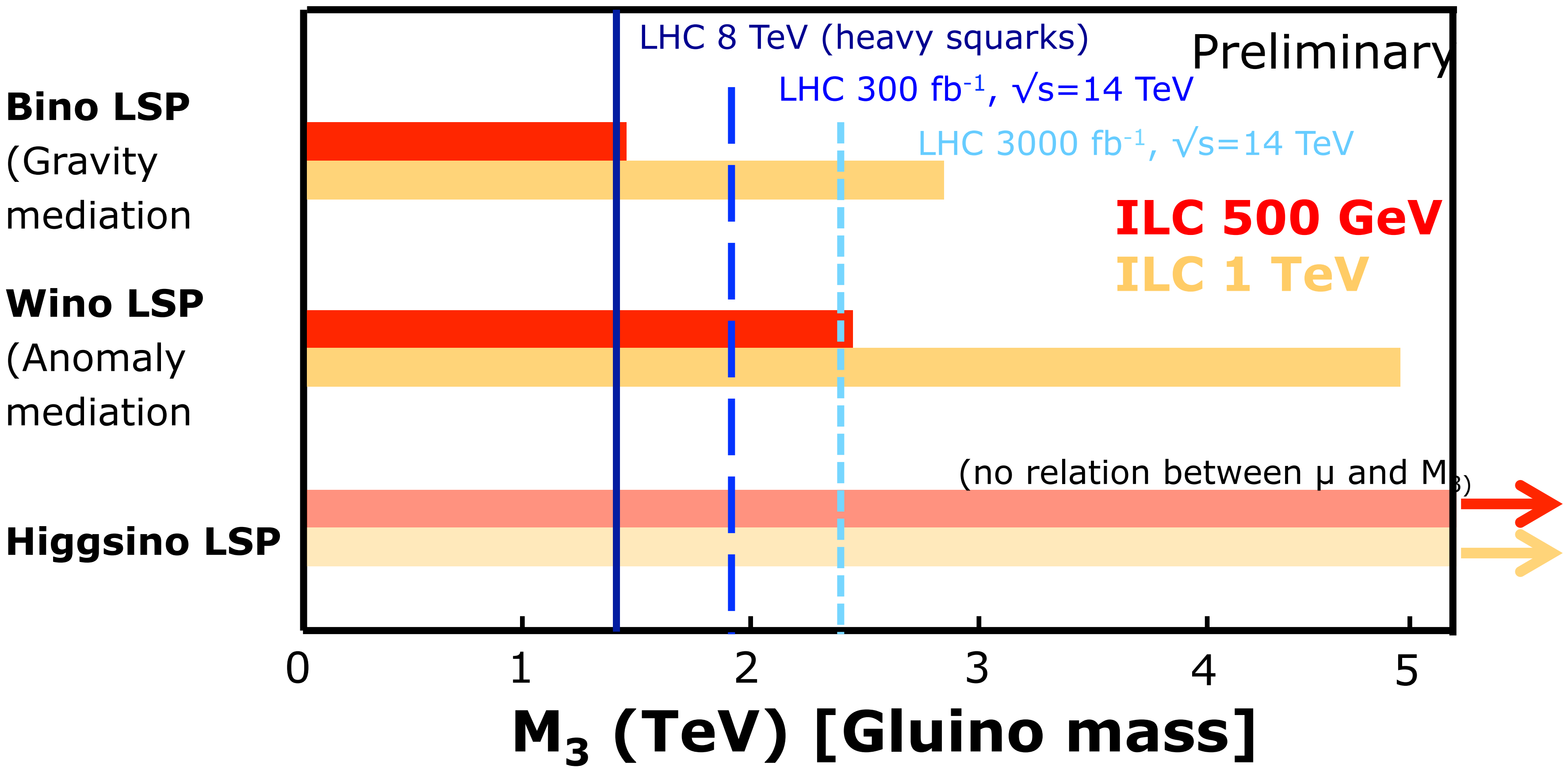
SUSY Electroweak Sector



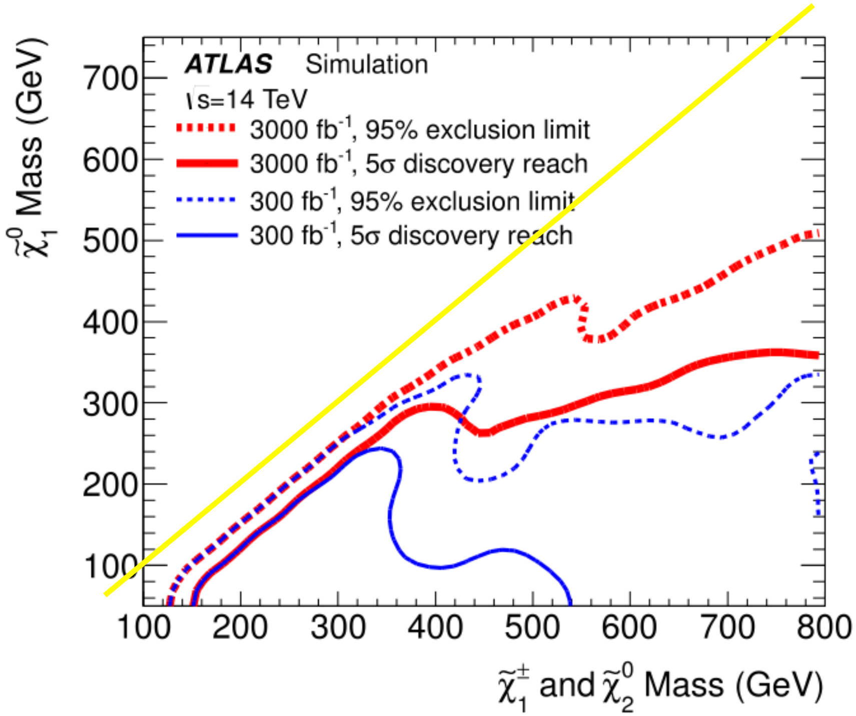
LSP/NLSP typically degenerate
(depends on mixing)

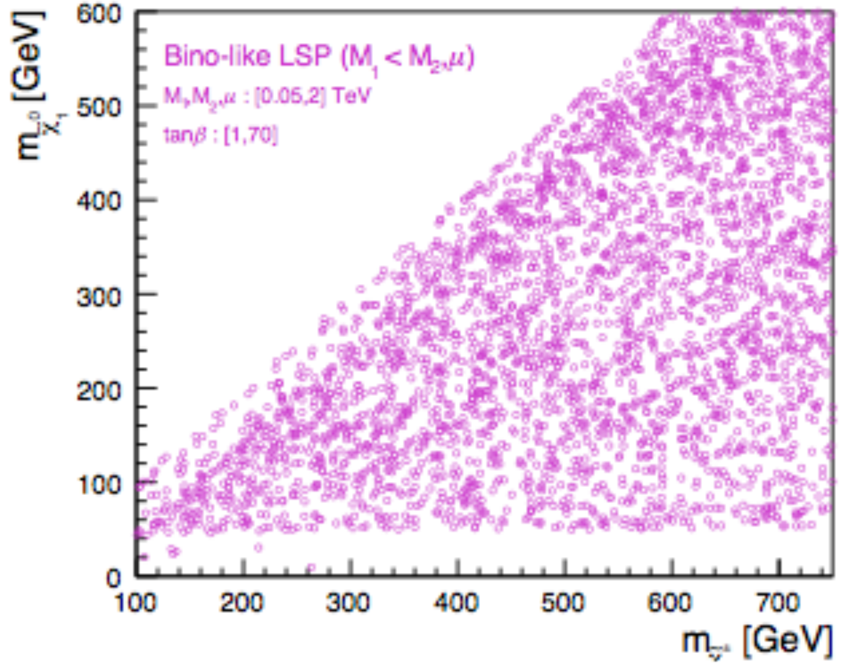
Sensitivity to SUSY

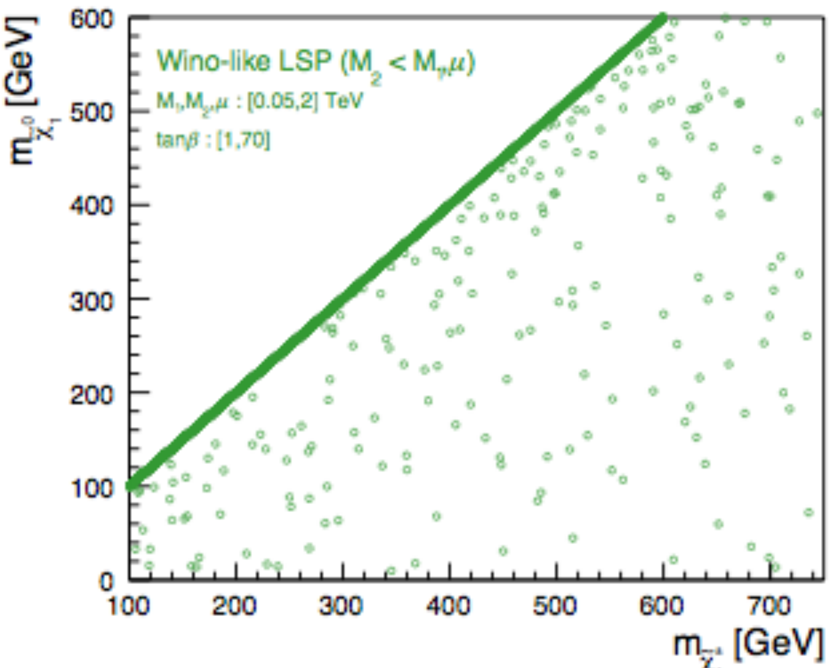
Gluino search at LHC
Chargino/Neutralino search at ILC
→ Comparison assuming gaugino mass relations

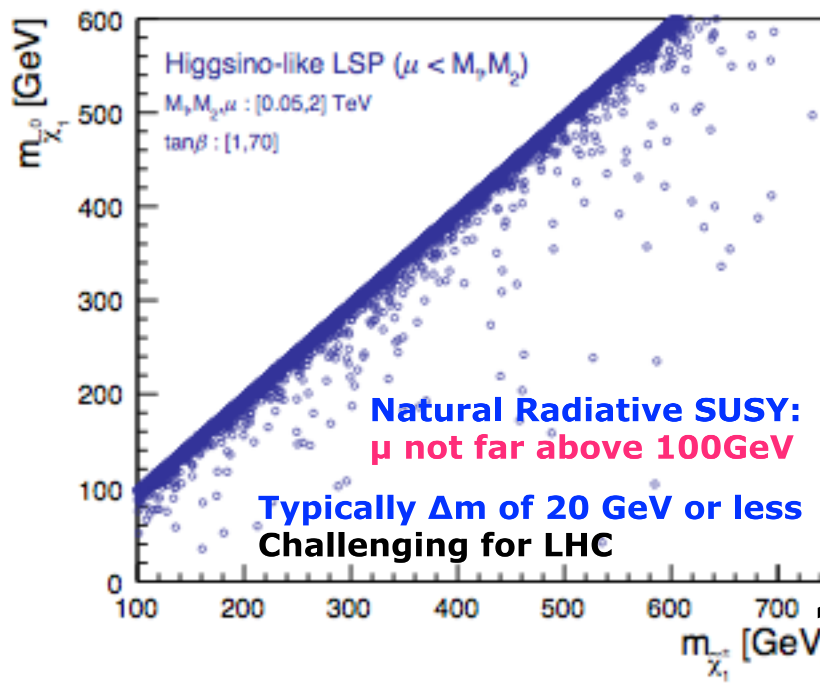


*Assumptions: MSUGRA/GMSB relation $M_1:M_2:M_3$ = 1:2:6;
AMSB relation $M_1:M_2:M_3$ = 3.3:1:10.5


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)


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]


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]

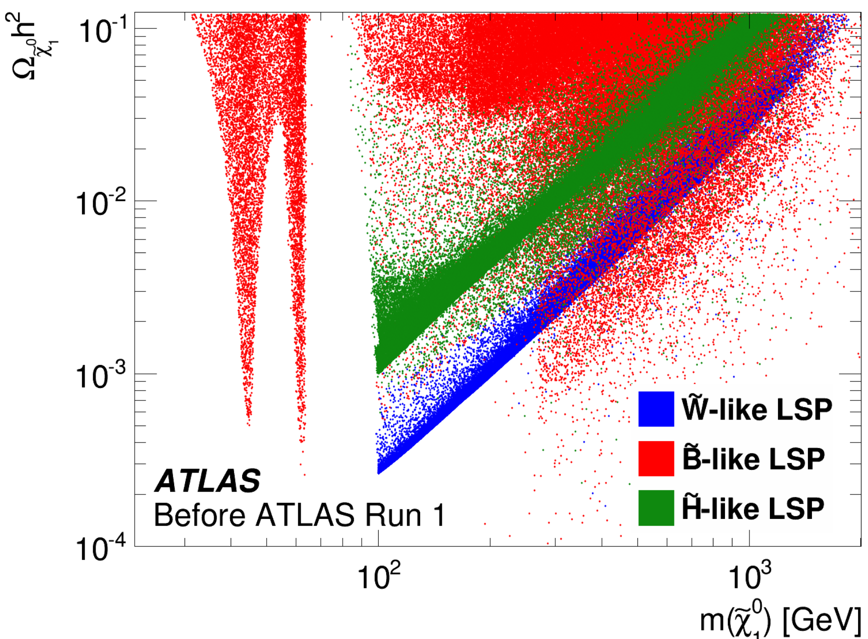

Higgsino-like LSP ($\mu < M_1, M_2$)
M_1, M_2, μ : [0.05,2] TeV
$\tan\beta$: [1,70]
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_1^\pm}$ [GeV]
Natural Radiative SUSY:
μ not far above 100GeV
Typically Δm of 20 GeV or less
Challenging for LHC

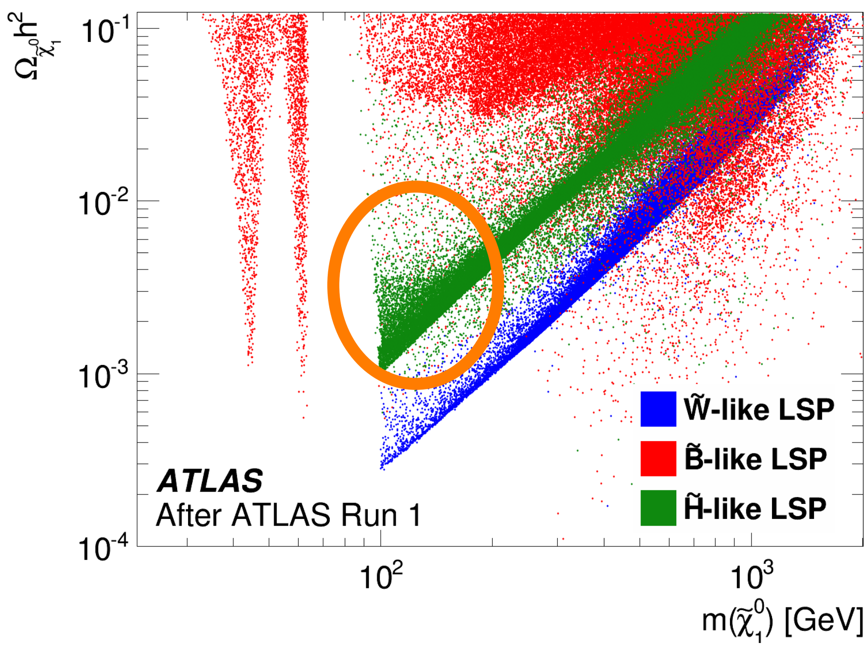
Naturalness and Light Higgsino

Naturalness arguments [e.g. Baer et al, 1207.3343] imply existence of **light Higgsinos at O(100) GeV.**

Higgsino LSP scenarios typically lead to **compressed spectra:**
→ small mass gaps between LSP and NLSPs

Small mass gaps (20 MeV < ΔM < 30 GeV) challenging for LHC
→ No problem for ILC





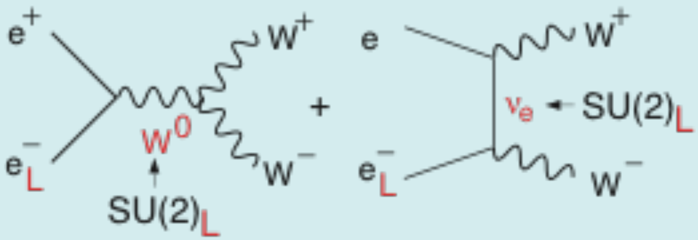
[1508.06608]

Power of Beam Polarization

K. Fujii

Bkg. Suppression

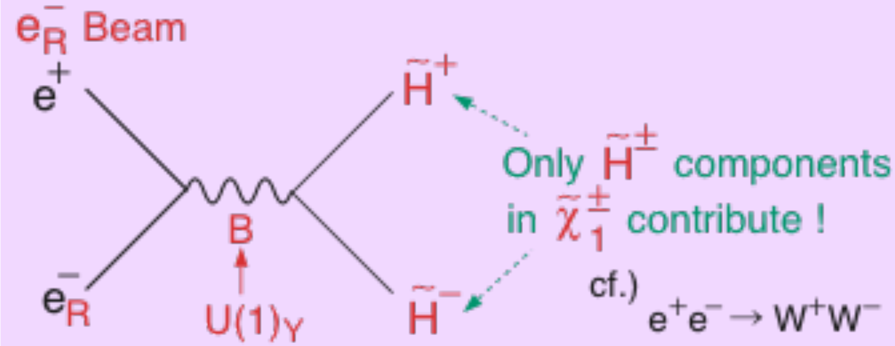
W^+W^- (Largest SM bkg in SUSY searches)



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

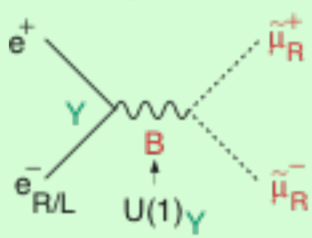
Decomposition

Chargino pair



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

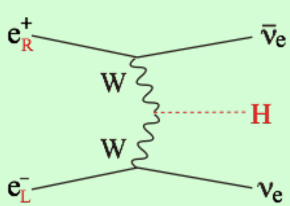
Slepton pair



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

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

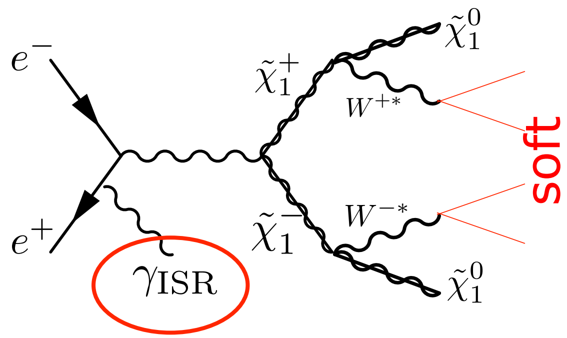
WW-fusion Higgs prod.



Pol(e^-)	-0.8
Pol (e^+)	+0.3
$(\sigma/\sigma_0)_{\nu\nu H}$	1.8x1.3=**2.34**

Signal Enhancement

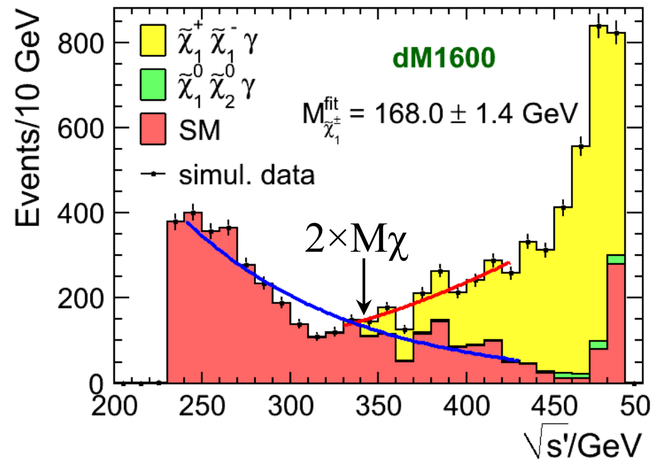
Higgsinos in Natural SUSY (ΔM~1 GeV)

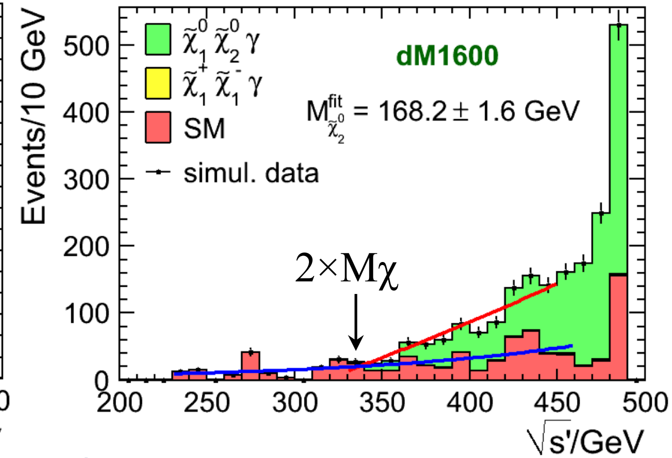


[Berggren et al. 1307.3566]

M(C1) ~ M(N1) ~ 170 GeV, **ΔM ~ 1.6 and 0.8 GeV**
Only very soft particles in the final states
→ Require a hard ISR to reduce large two-photon background.

Separation of chargino and neutralino channels clearly possible:





Precision Expected for 500 GeV, 500 fb-1 P(e-,e+)=(-0.8,+0.3)

Production Cross section

$$\sigma(\gamma\tilde{\chi}_0^+\tilde{\chi}_0^-) \approx 80 \text{ fb}$$

$$\sigma(\gamma\tilde{\chi}_1^0\tilde{\chi}_2^0) \approx 50 \text{ fb}$$

$\Delta M = 1.6$ GeV

$$\delta(\sigma\times BR) \simeq 3\%$$

$$\delta M_{\tilde{\chi}_1^\pm}(M_{\tilde{\chi}_1^0}) \simeq 2.1(3.7)\,\text{GeV}$$

$$\delta\Delta M(\tilde{\chi}_1^\pm,\tilde{\chi}_1^0) \simeq 70\,\text{MeV}$$

$\Delta M = 0.8$ GeV

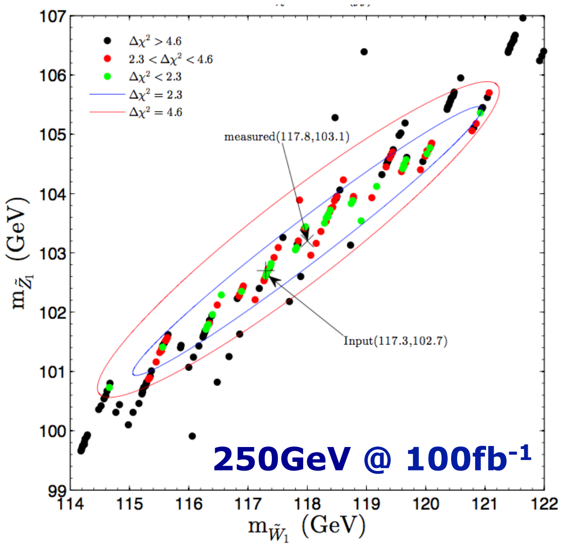
$$\delta(\sigma\times BR) \simeq 1.5\%$$

$$\delta M_{\tilde{\chi}_1^\pm}(M_{\tilde{\chi}_1^0}) \simeq 1.5(1.6)\,\text{GeV}$$

$$\delta\Delta M(\tilde{\chi}_1^\pm,\tilde{\chi}_1^0) \simeq 20\,\text{MeV}$$

Gaugino Mass Extraction

[Baer et al. 1404.7510]



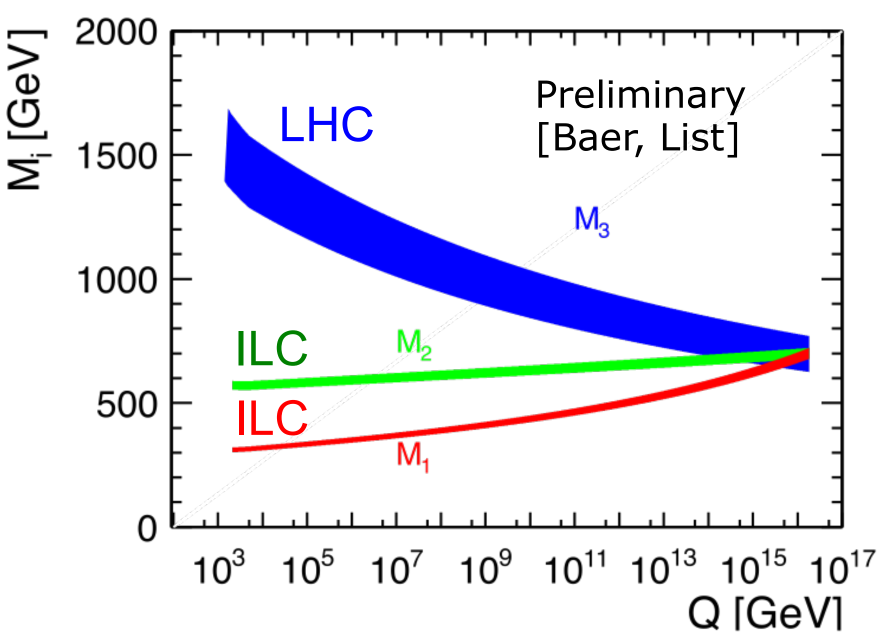
$$e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^0\tilde{\chi}_2^0$$

M(C1)~118 GeV, M(N1)~103 GeV

→ **ΔM=15GeV**

In this benchmark point, M_1 and M_2 are expected to be measured to few % or better.

→ Test of gaugino mass relation



Assume:

Gluino discovery @ LHC

Ewkino discovery @ ILC

→ Test of gaugino mass relation by LHC/ILC synergy

→ Discrimination of SUSY breaking models

Full simulation study is started.

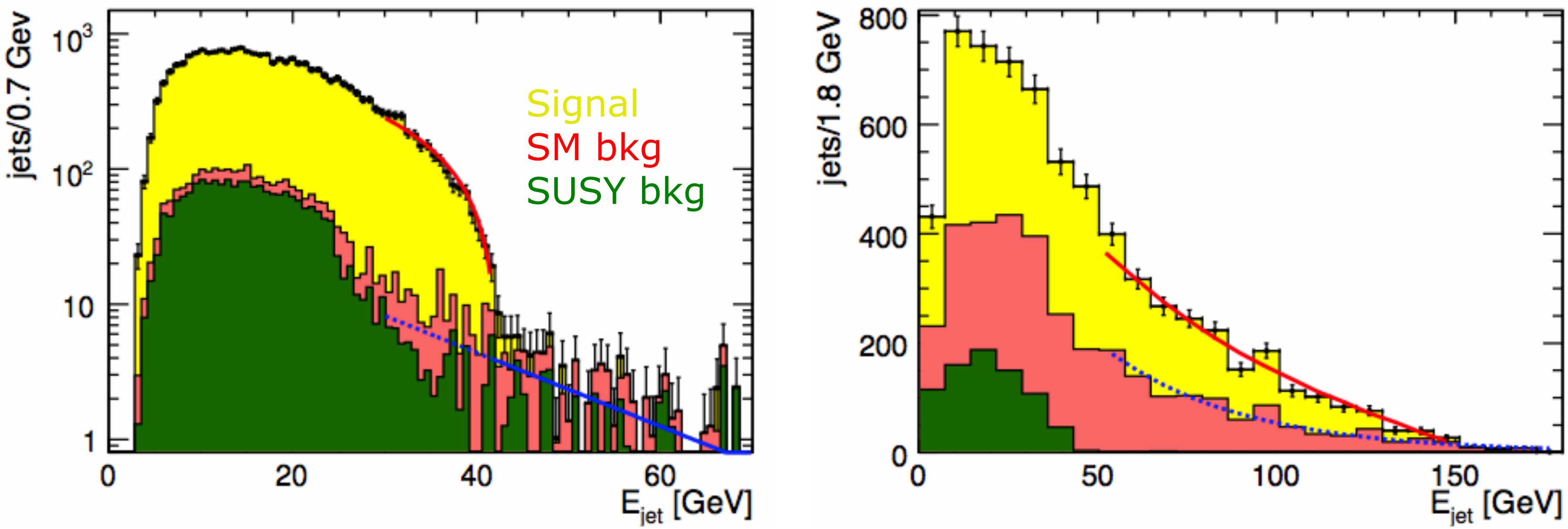
Stau coannihilation (ΔM~10 GeV)

Study of stau pair production at the ILC
Observation of lighter and heavier stau states with decay to neutralino + hadronic tau

Benchmark point:
m(N1) = 98 GeV
m(Stau1) = 108 GeV
m(Stau2) = 195 GeV

$$\sigma(e^+e^- \to \tilde{\tau}_1^+\tilde{\tau}_1^-) = 158\ \mathrm{fb}$$
$$\sigma(e^+e^- \to \tilde{\tau}_2^+\tilde{\tau}_2^-) = 18\ \mathrm{fb}$$

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

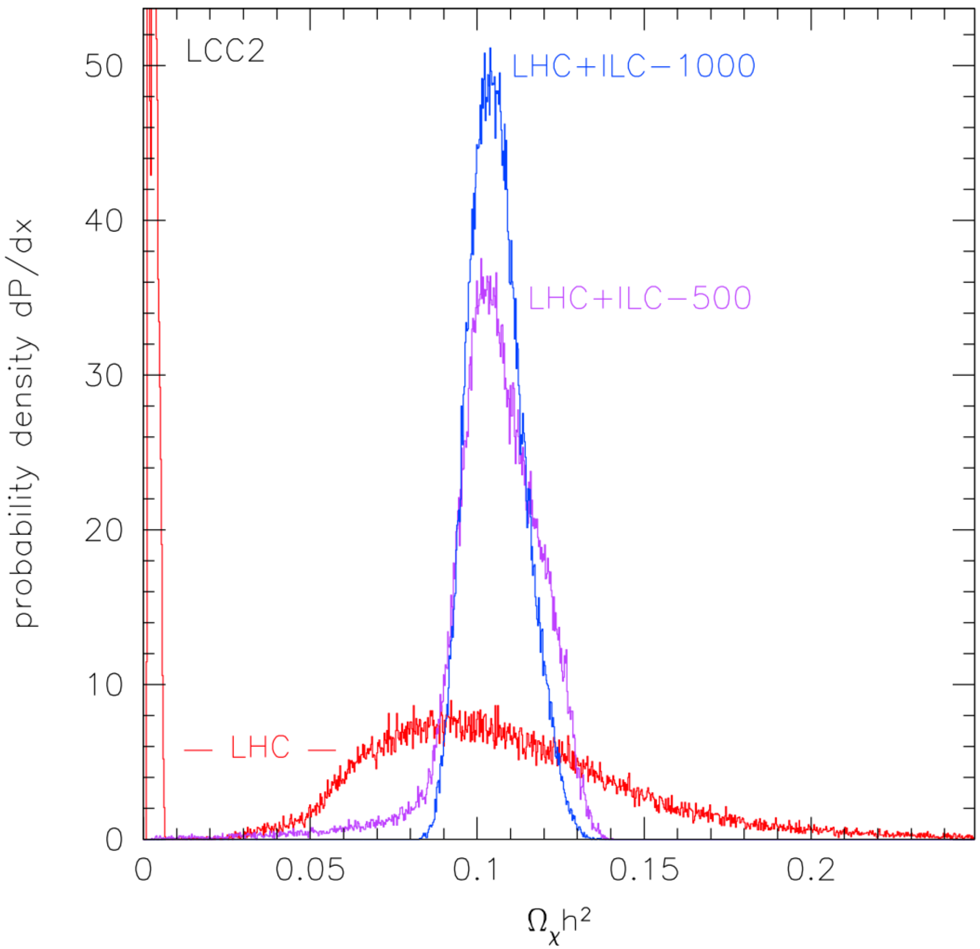


√s=500 GeV, Lumi=500 fb-1, P(e-,e+)=(+0.8,-0.3)
Stau1 mass ~0.1%, Stau2 mass ~3% → **LSP mass ~1.7%**

DM Relic Abundance

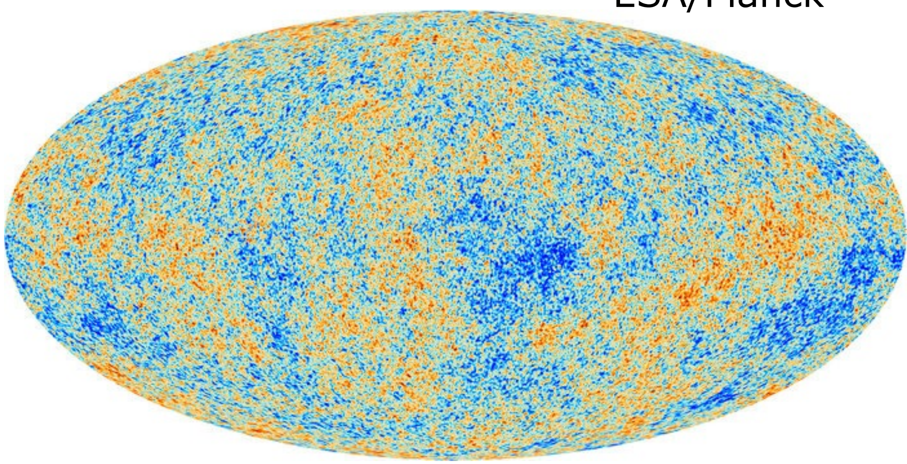
WMAP/Planck (68% CL)

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



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

ESA/Planck



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

Precise measurements of mass and couplings at the ILC
→ DM relic density

Summary

ILC capabilities for new physics:

- Higgs, top, direct searches, other indirect probes.

Dark Matter:

- Collider search complementary to direct detection / indirect detection
- ILC advantages:
  - Electron-DM coupling
  - Precise measurements allow check with observed DM relic density

SUSY:

- Well-motivated even after LHC data. Important parameter space remains to be explored.
- ILC advantages:
  - Compressed spectra (challenging for LHC)
  - Coupling structure determination (via beam polarization)
  - Discrimination of SUSY breaking mechanism (gaugino mass relations)

Indirect probes (e.g. e+e- → 2f):

- Mass reach can be higher than $\sqrt{s}/2$ if systematics is under control.
- Dedicated studies on systematics are desired.