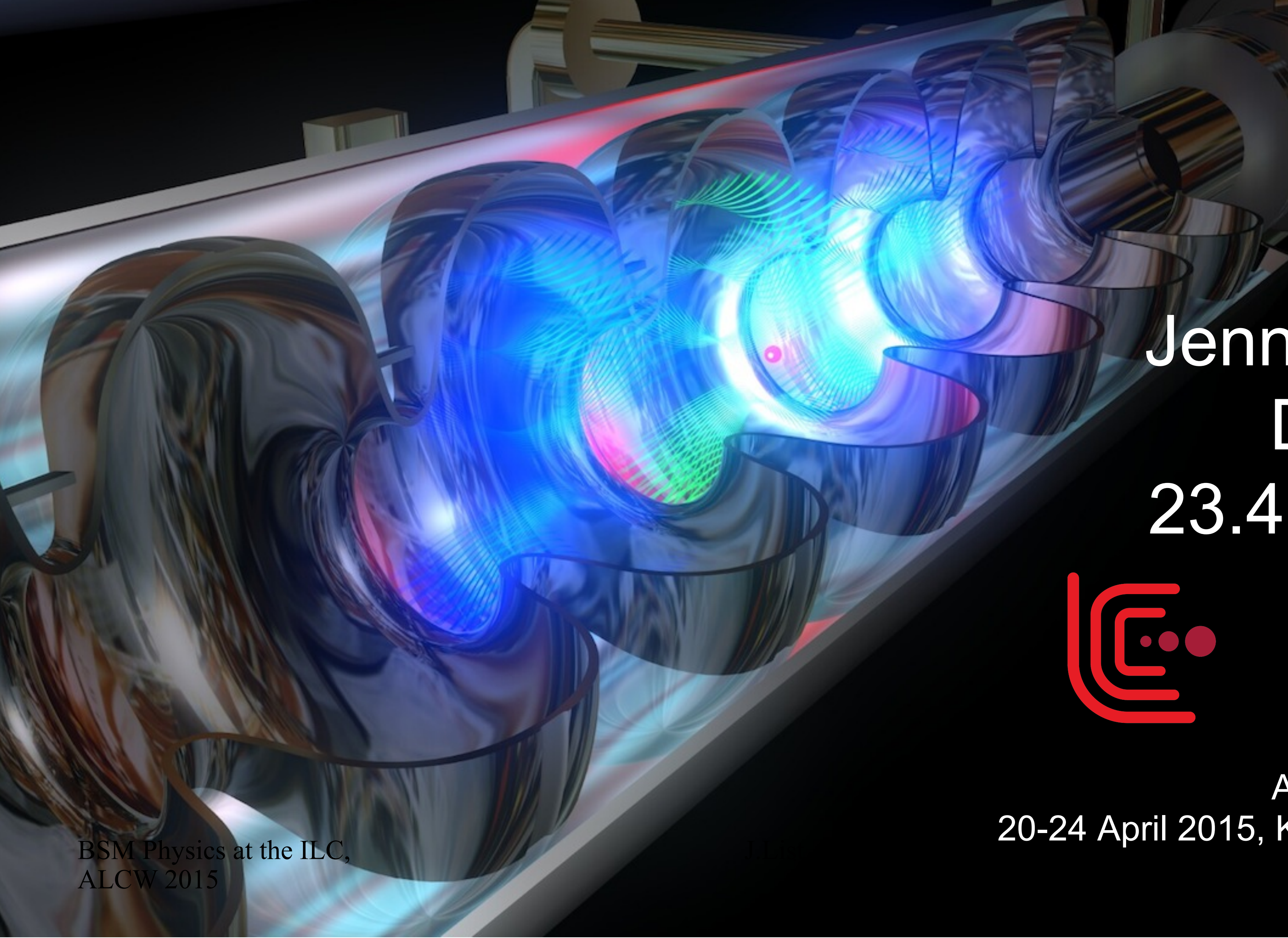
Beyond the Standard Model Physics at the International Linear Collider



Jenny List
DESY
23.4.2015

AWLC 2015
20-24 April 2015, KEK, Japan

Outline

- Introduction:
  Role of BSM in ILC Physics Case
- Two more detailed examples:
  - Light Higgsinos
  - WIMP Dark Matter
- Implications for ILD & SiD
- Conclusions

Introduction: The Role of BSM in the ILC Physics Case

Why think about BSM@ILC *now*?

1. Fascinating for the general public...
   c.f. Ogada, Yamashita: outreach outside HEP is one of the most important tasks now
2. ... and for our community
   => explain unique ILC discovery potential
3. Challenging requirements for our detector concepts and our machine
   => we should make sure we do not miss anything!

We cannot guarantee a discovery

- Video message from Koshiba: “If we knew already the outcome, we wouldn’t need to perform an experiment”
- Non-discoveries give crucial information, eg non-discovery of “plain-vanilla” SUSY at LHC run I:

Naturalness, g_μ-2, M_W, CDM

LHC Results

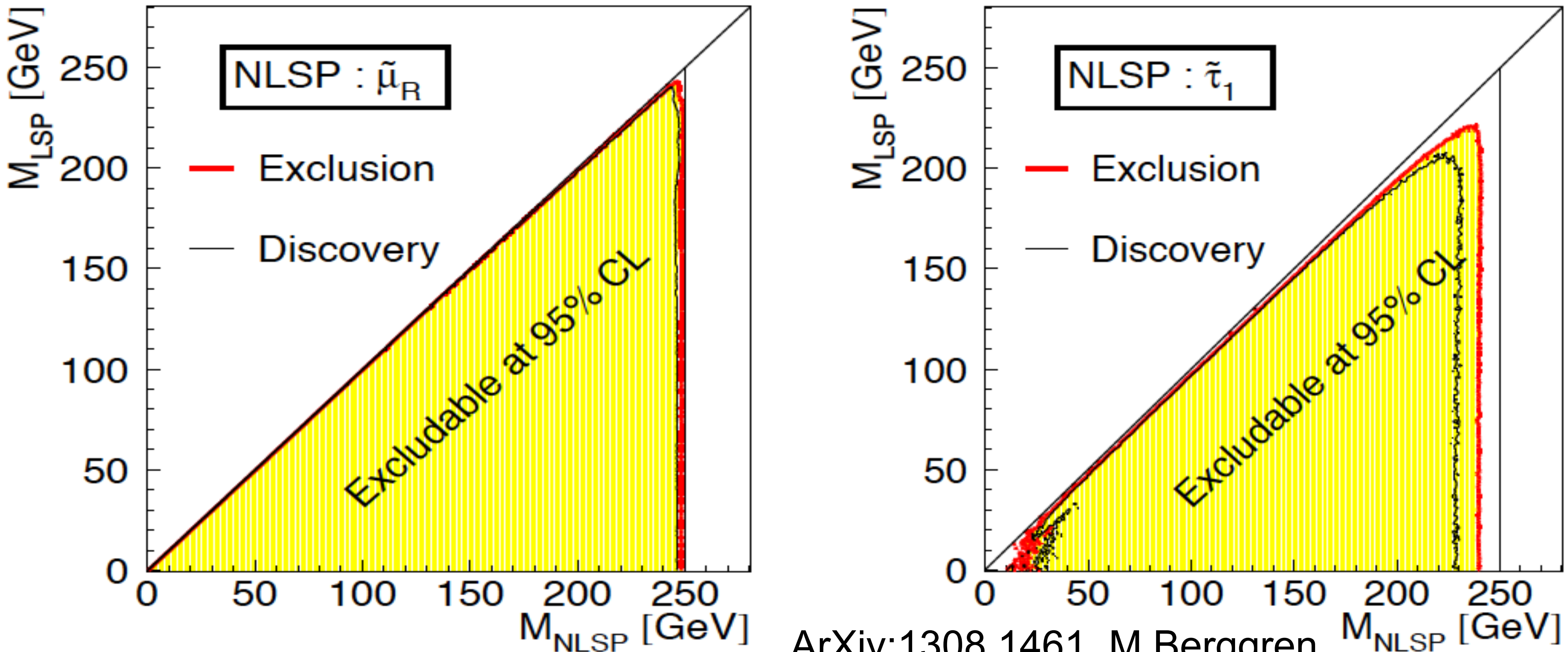
Light
3rd gen. Squarks,
Sleptons,
Elektroweakinos

Mass Unification:
m_0,
$m_{½}$

Heavy
1st, 2nd gen. Squarks
Gluinos

=> **change in paradigm** of how we think about SUSY and how we search for it:
Natural SUSY, “simplified models”, ...

What can we guarantee?



ArXiv:1308.1461, M.Berggren

Loop-hole free, model-independent sensitivity down to very small mass differences

→

Will revolutionize our picture of BSM !

What will we learn at LHC 13/14 TeV?

Two general scenarios:

A. Discover significant deviation from SM in some direct search channel at the LHC 13/14 TeV

- What kind of particle is it, what is its mass, spin, couplings?
- What is the physics behind? Are there more new particles?

=> full-glory program for the ILC!

B. No deviation anywhere

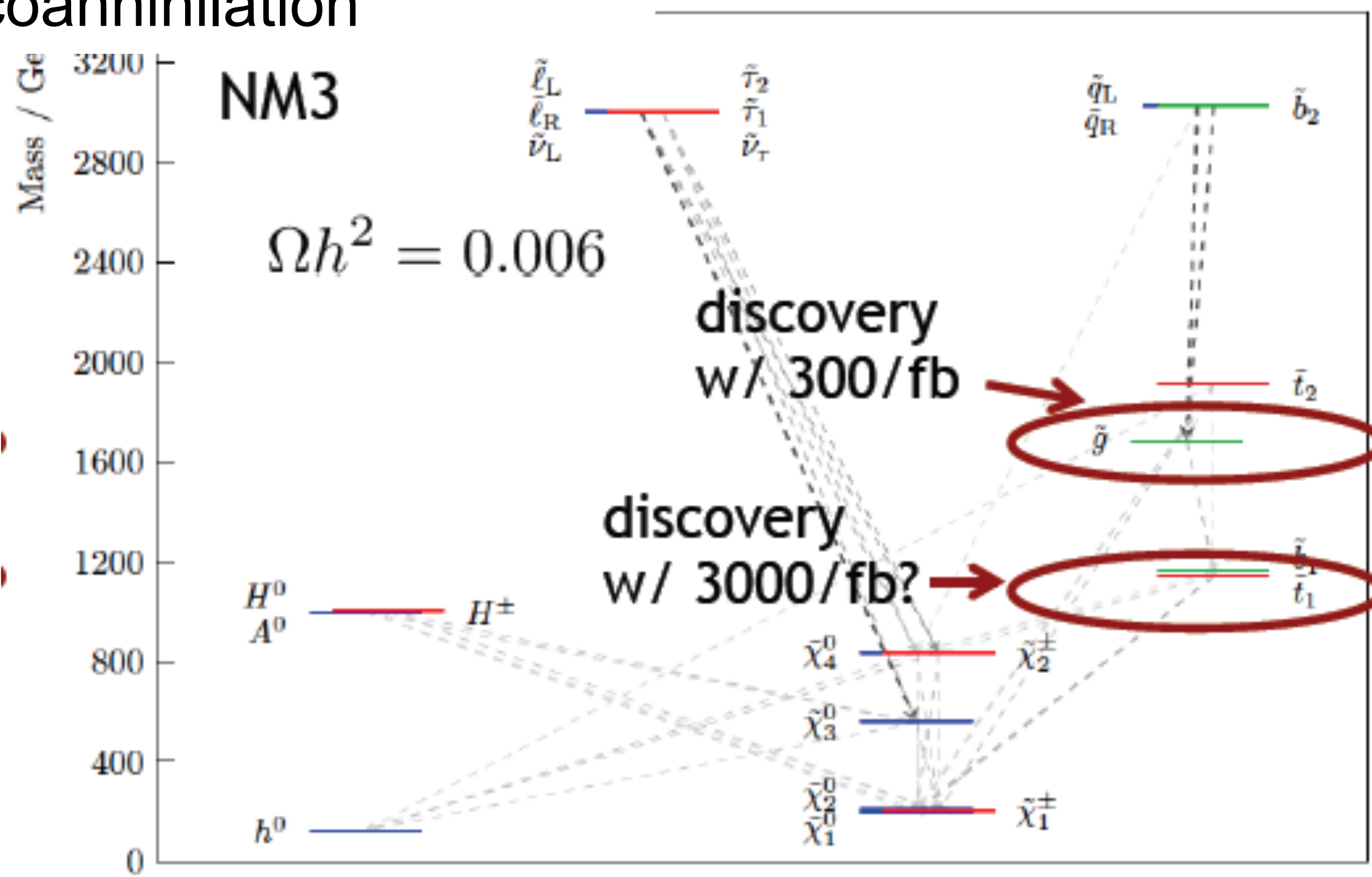
- What does this really tell us?
- Can there be something very well hidden?

We hope of course for A, but we have to be prepared for B!

Case A: Projections from CMS [CMS-PAS-SUS-14-012]

CMS analyzed 5 full MSSM models:

- 3 Natural SUSY models
- stau- / stop-coannihilation



Most likely LHC would discover not the lightest states!

Case A: Projections from CMS [CMS-PAS-SUS-14-012]

	Analysis	Luminosity (fb^{-1})	Model				
			NM1	NM2	NM3	STC	STOC
all-hadronic (+b-tag)	all-hadronic (H_T-H_T^{miss}) search	300				$< 3\sigma$	$3-5\sigma$
		3000				$3-5\sigma$	$> 5\sigma$
	all-hadronic (M_{T2}) search	300	$3-5\sigma$	$> 5\sigma$	$> 5\sigma$		
		3000	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$		
	all-hadronic $\tilde{b}_1$ search	300	$< 3\sigma$	$< 3\sigma$	$< 3\sigma$	$3-5\sigma$	$< 3\sigma$
		3000	$< 3\sigma$	$< 3\sigma$	$< 3\sigma$	$> 5\sigma$	$< 3\sigma$
single lepton	1-lepton $\tilde{t}_1$ search	300	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$3-5\sigma$	$< 3\sigma$
		3000	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$
monojet	monojet $\tilde{t}_1$ search	300					$3-5\sigma$
		3000					$3-5\sigma$
dilepton	$m_{\ell^+\ell^-}$ kinematic edge	300	$< 3\sigma$	$< 3\sigma$	$< 3\sigma$		
		3000	$> 5\sigma$	$< 3\sigma$	$< 3\sigma$		
multilepton	multilepton + b-tag search	300	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$3-5\sigma$	
		3000	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	
	multilepton search	300	$< 3\sigma$	$< 3\sigma$	$< 3\sigma$	$< 3\sigma$	
		3000	$3-5\sigma$	$3-5\sigma$	$< 3\sigma$	$3-5\sigma$	
	ewkino WH search	300		$< 3\sigma$			
		3000		$3-5\sigma$			

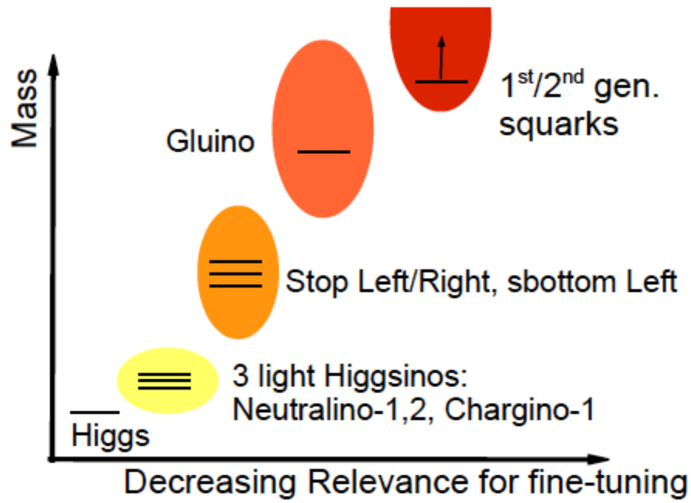
$< 3\sigma$ | $3-5\sigma$ | $> 5\sigma$

Still a lot left for ILC!

Light Higgsinos & Natural SUSY

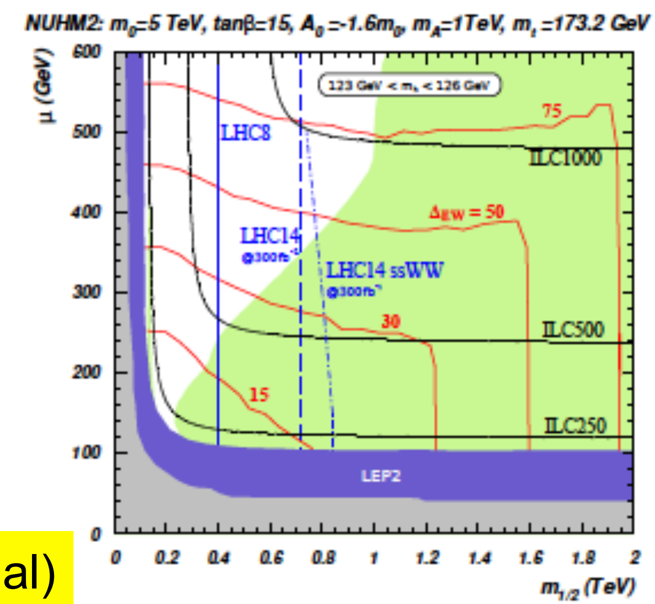
Case B example: Light Higgsinos

- Naturalness suggests $\mu \approx O(M_Z)$ (but > 100 GeV, LEP)
- Lightest Sparticles: 3 light, near-degenerate Higgsinos
- Mass splittings
  - depend on M_1, M_2
  - few GeV ... → ... sub-GeV (!)



LHC & ILC Projections [arXiv:1306.3148 [hep-ph]]

- LHC: gluino and like-sign di-boson searches
- ILC: hermetic sensitivity to $\mu \lesssim \sqrt{s}/2$

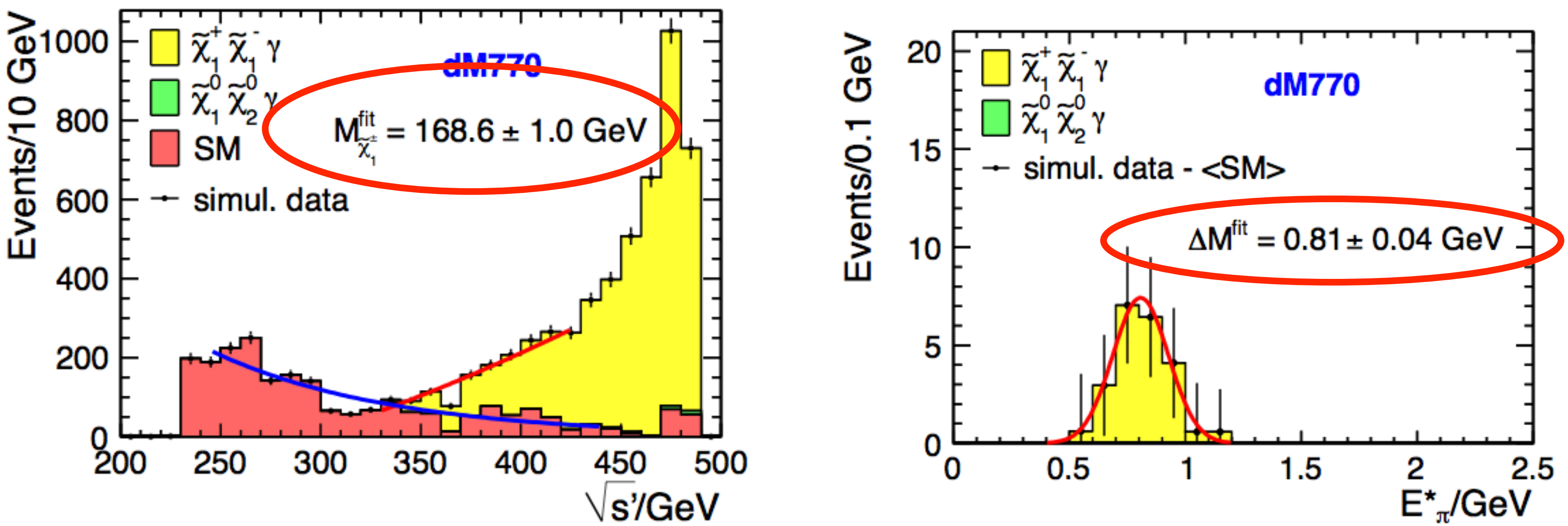


Theory-level study (H.Baer et al)

From Theory to Fast Simulation

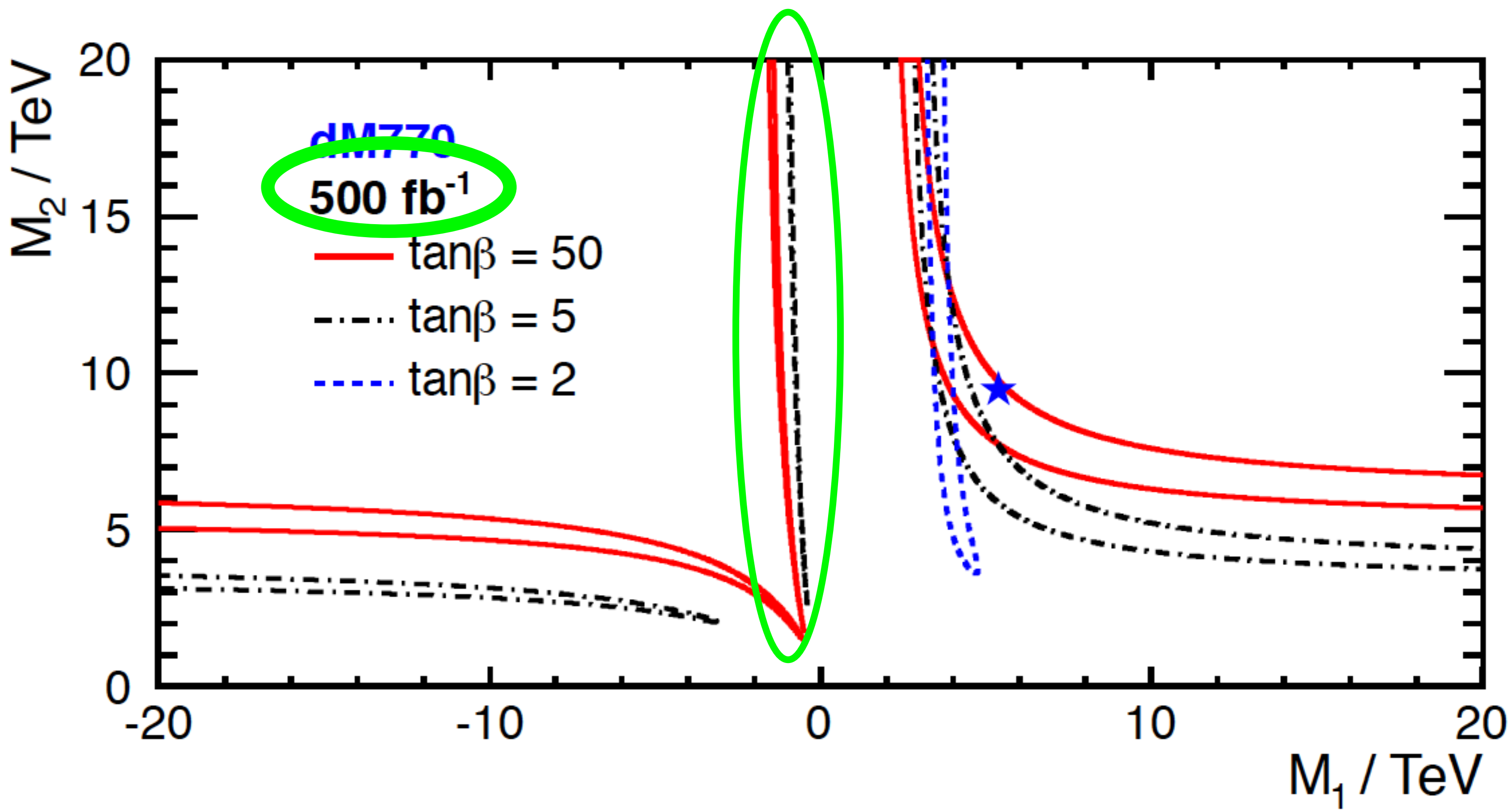
- Detector simulation study [EPJ C73 (2013) 2660]:
  - $\mu = 167\,\text{GeV},\ M_1 = 5\,\text{TeV},\ M_2 = 10\,\text{TeV}$
    $\Rightarrow \Delta M(\tilde{\chi}_1^\pm;\tilde{\chi}_1^0) \simeq 1\,\text{GeV}$ ← **Extreme case!**
  - $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-\gamma_{\text{ISR}}$ and $e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_1^0\gamma_{\text{ISR}}$
  - measure $M_{\tilde{\chi}_1^+}$ and $M_{\tilde{\chi}_2^0}$ from recoil against γ_{ISR}, $\Delta M(\tilde{\chi}_1^\pm;\tilde{\chi}_1^0)$ from decay products

+ cross sections to few %



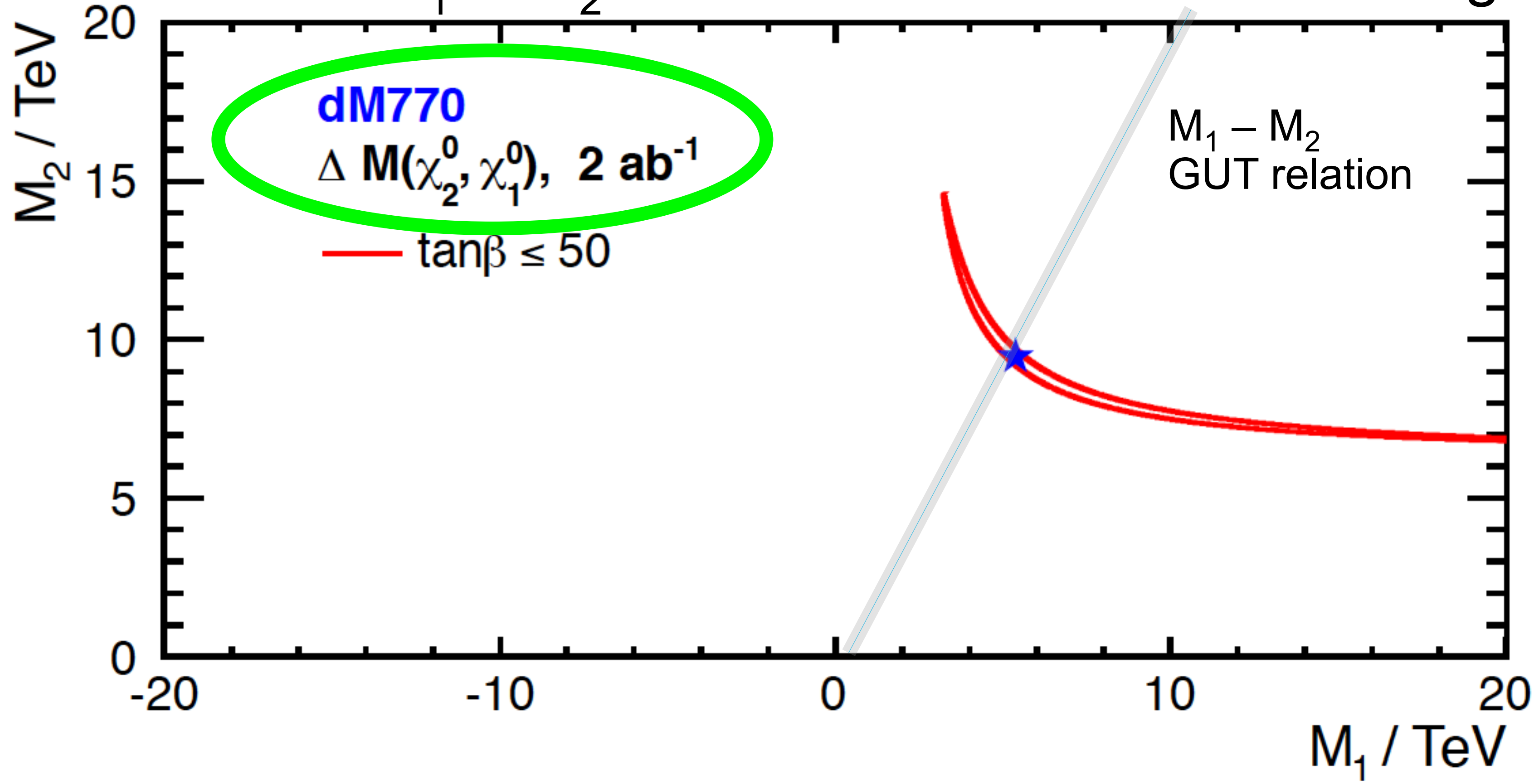
Parameter Determination?

- From $M_{\tilde{\chi}_1^+}$ and $M_{\tilde{\chi}_2^0}$ => μ to ± 0.5 GeV
- But can we learn about M_1 & M_2 ?



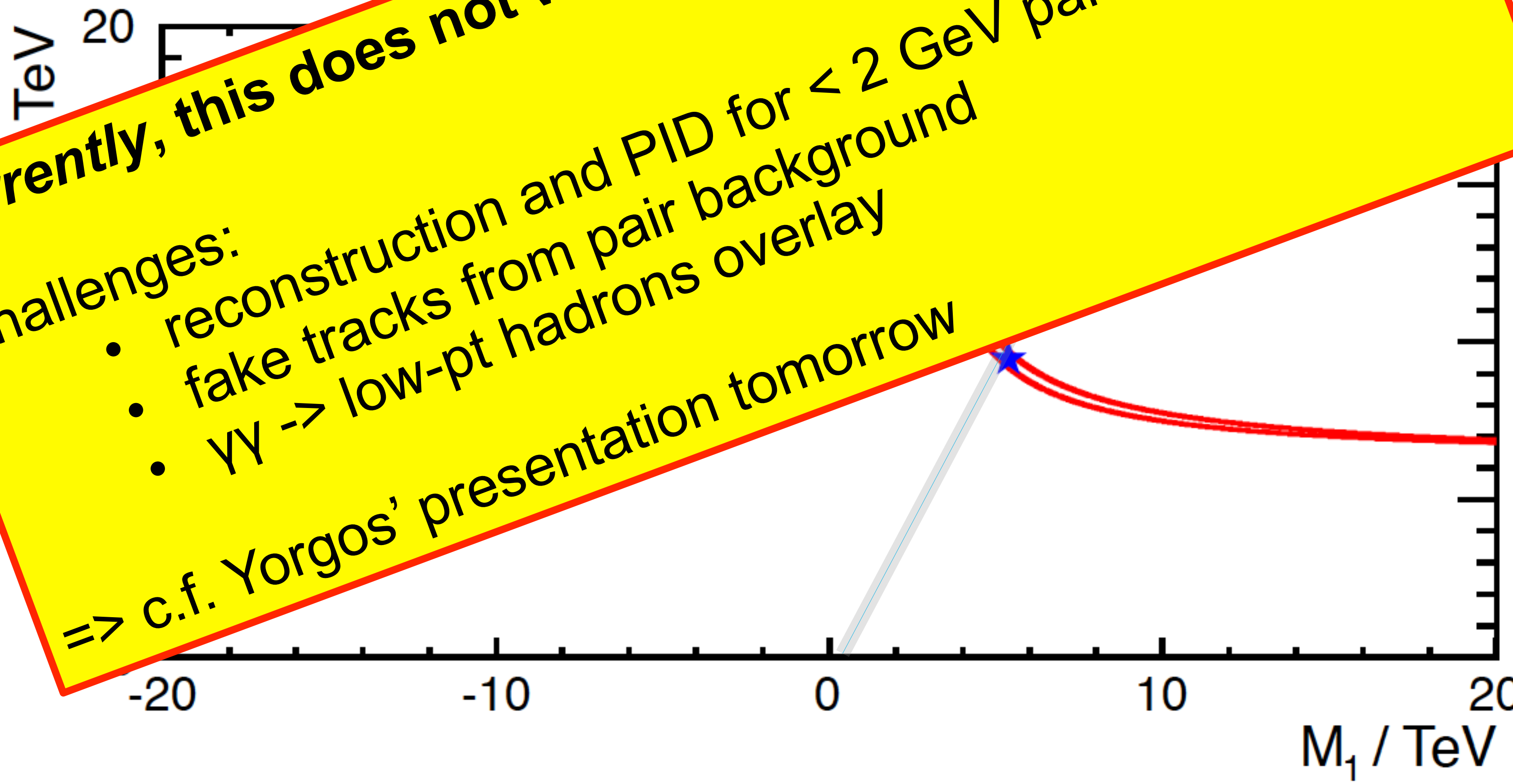
Parameter Determination!

- 500 fb^{-1}: determine μ to ± 0.5 GeV
- 2 ab^{-1} and neutralino mass difference
  => constrain M_1 & M_2 to narrow band in multi-TeV regime:



Parameter Determination!

- 500 fb^{-1}: determine μ to ± 0.5 G…
- 2 ab^{-1} and neutralino m…
  => constrain M… …ime:



Currently, this does not work in full detector simulation!

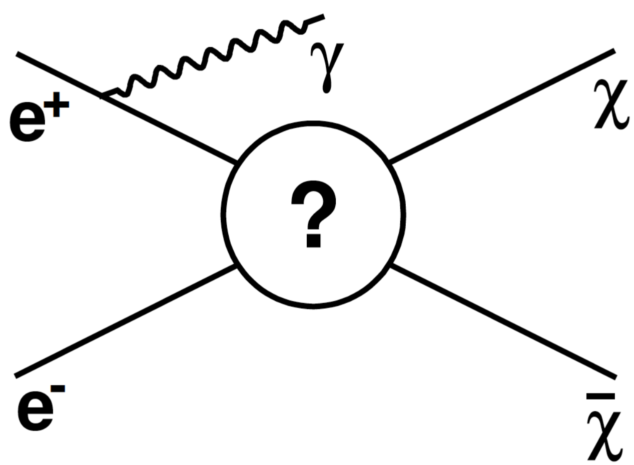
Challenges:

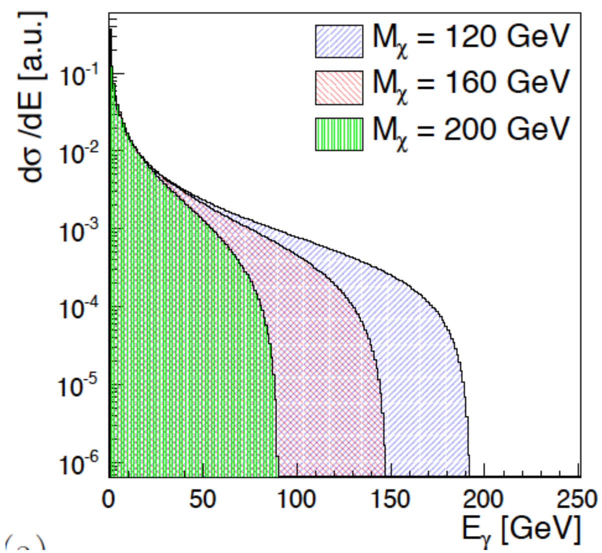
- reconstruction and PID for < 2 GeV particles
- fake tracks from pair background
- γγ -> low-pt hadrons overlay

=> c.f. Yorgos' presentation tomorrow

WIMP Dark Matter

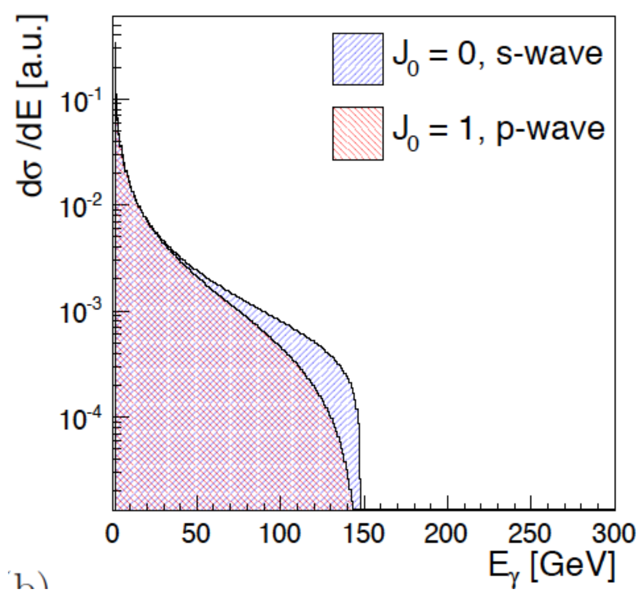
Case A or B example: WIMPs at the ILC



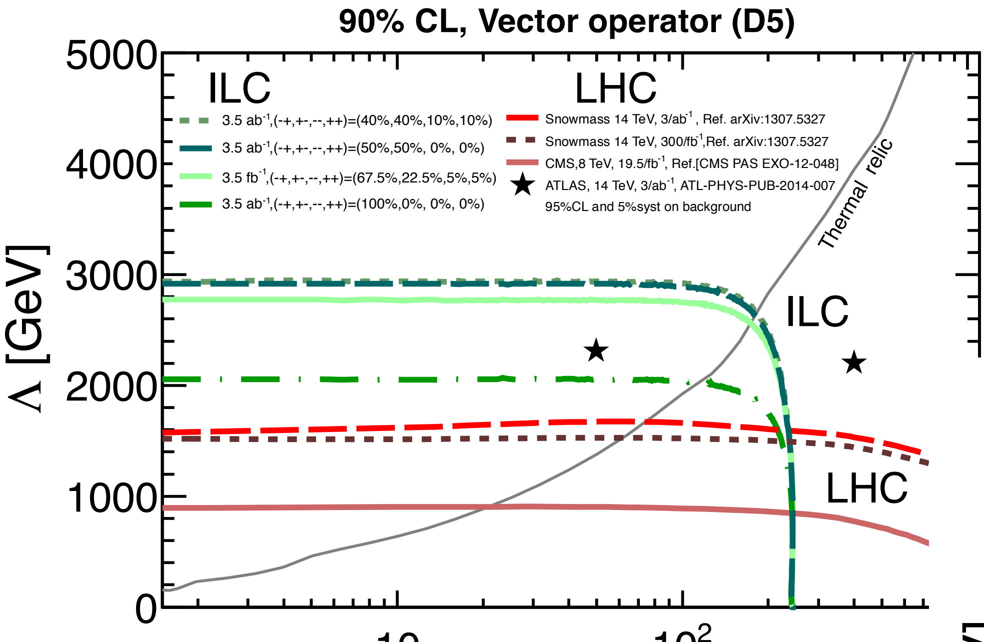


Know √s: E_γ spectrum offers

- Clean endpoint → mass
- Shape → dominant partial wave (s-channel: Spin of mediator)
- Can distingish eg SUSY vs UED
  [cf 0902.2000 [hep-ph] Konar et al,
  1503.08538 [hep-ph Kalinowski et al etc]]



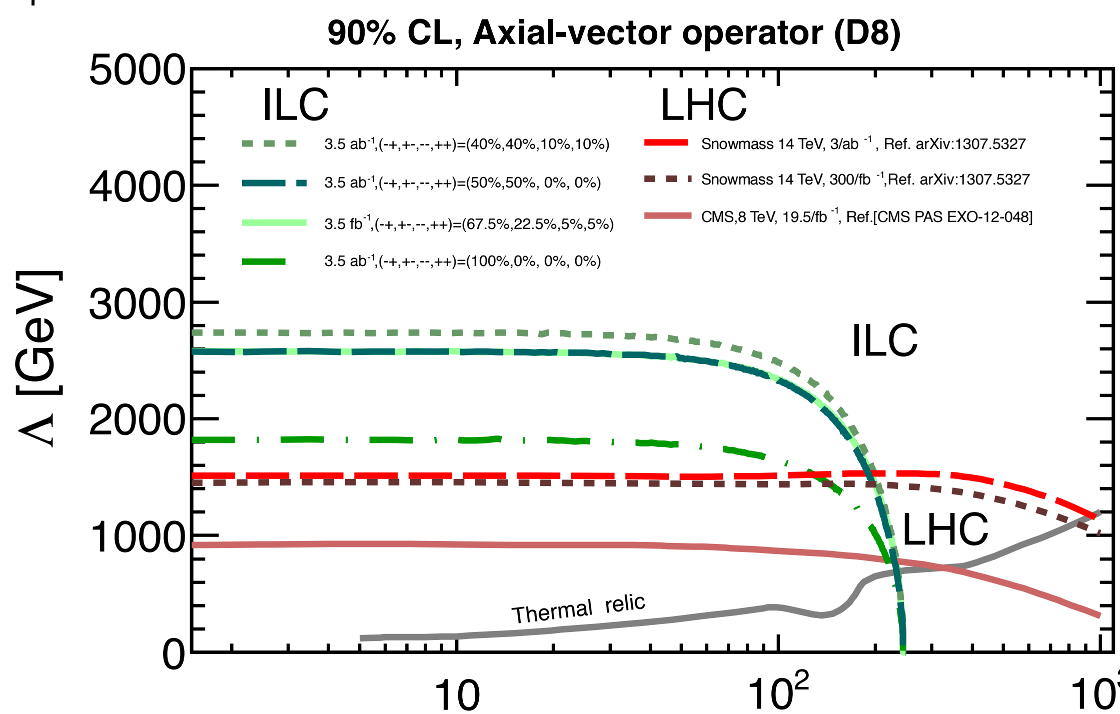
Sensitivity at LHC and ILC



PhD Thesis A.Chaus

Effective Operator approach:

- vector / axial-vector type of WIMP - fermion interaction
- suppression scale Λ



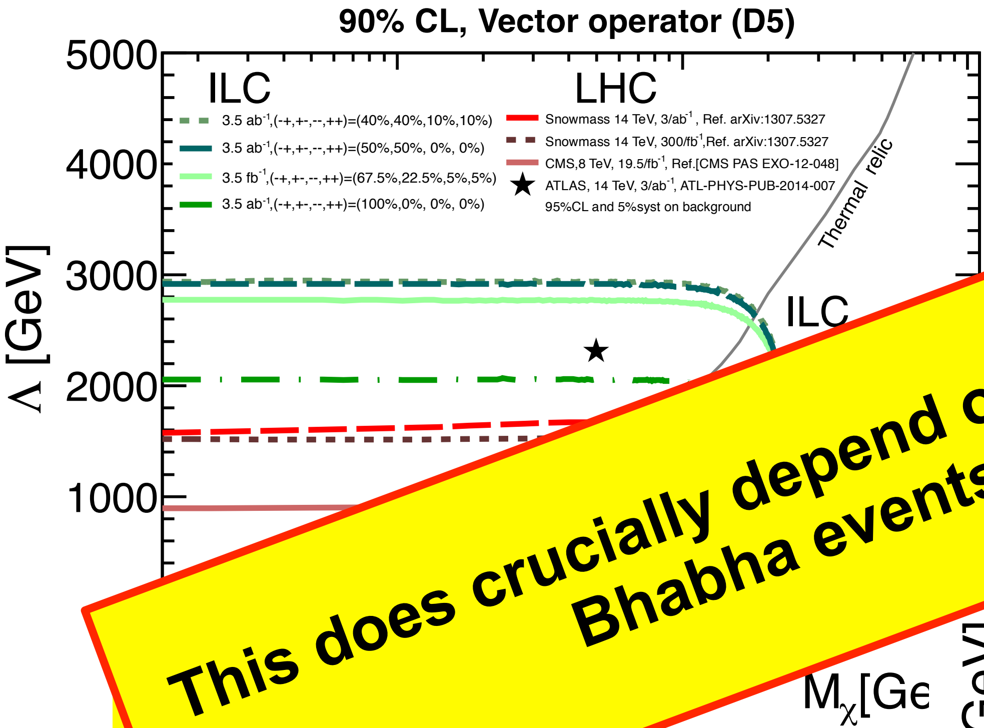
Note:

suppression scale Λ refers to

- LHC: WIMP – quark interaction
- ILC: WIMP – electron interaction

=> showing them in same plot is **model-dependent**!

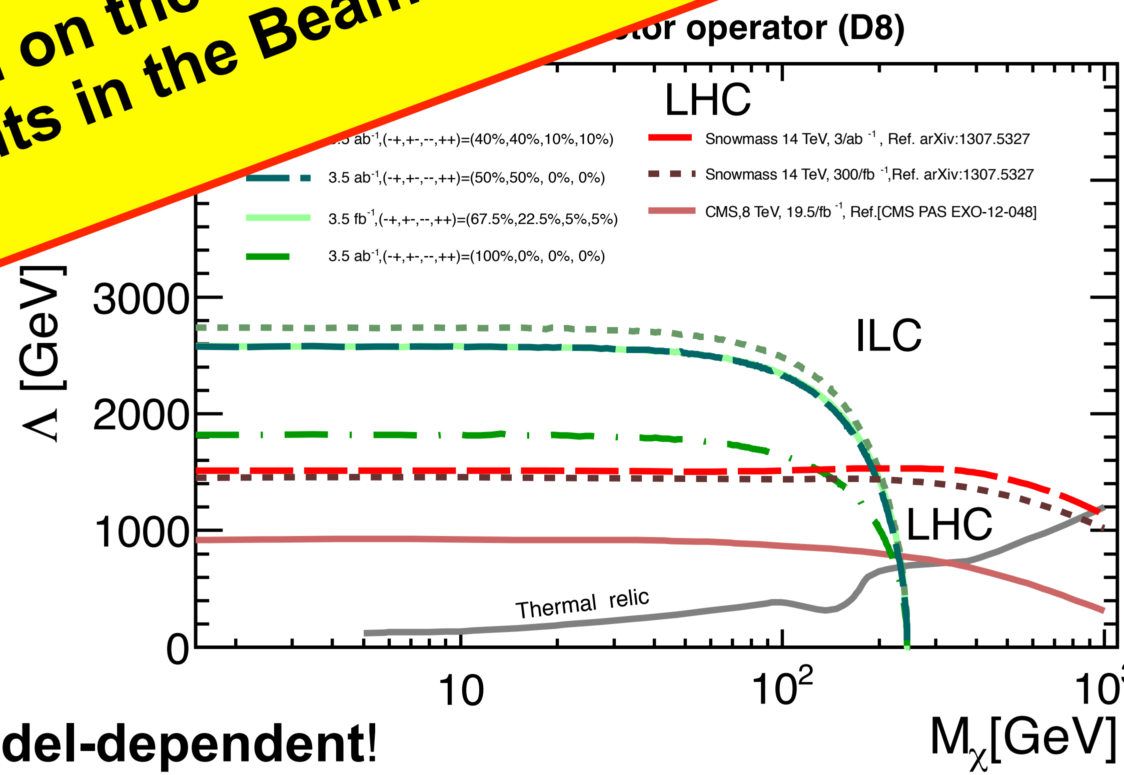
Mono-photons at LHC and ILC



Effective Op... ...ach:

- vector ...

This does crucially depend on the ability to veto radiative Bhabha events in the BeamCal!



No...

sup... ...sion scale Λ refers to

- LHC: WIMP – quark interaction
- ILC: WIMP – electron interaction

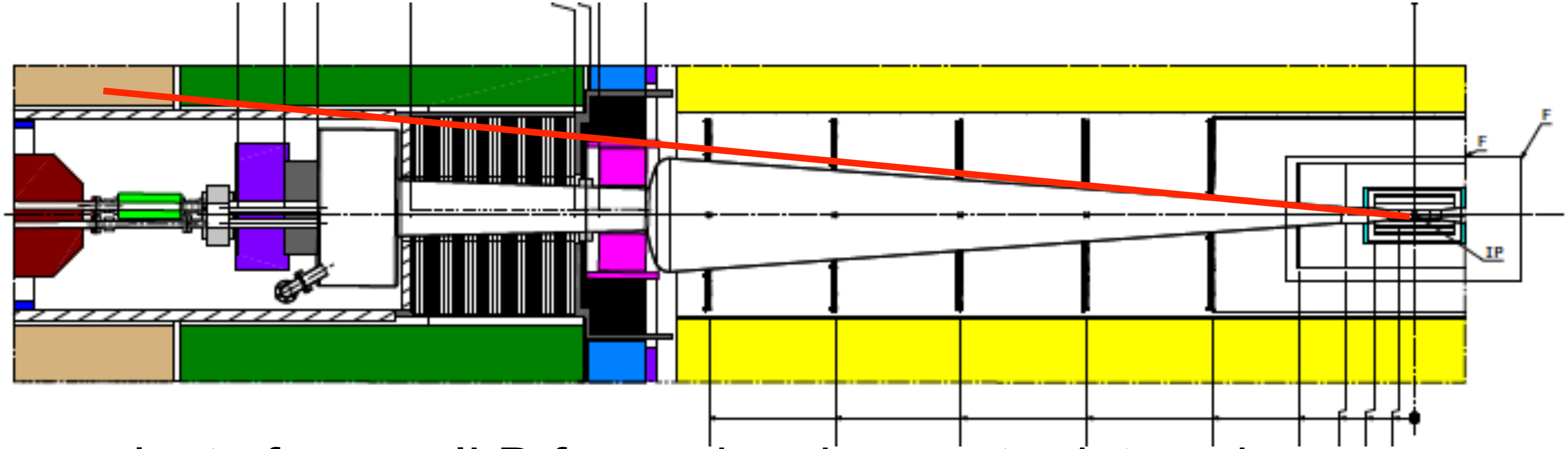
=> showing them in same plot is **model-dependent**!

Implications for ILD & SiD

1. Hermeticity in the forward region

- veto of radiative Bhabha events (eg WIMPs)
- veto of γγ / eγ events (BSM with small mass differences)

⇒ BeamCal, LumiCal *and* LHCal to close acceptance gap outside of LumiCal in ILD

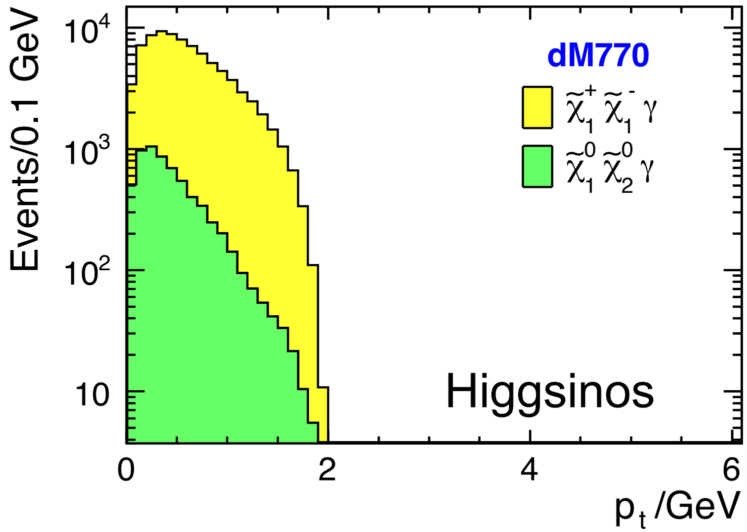


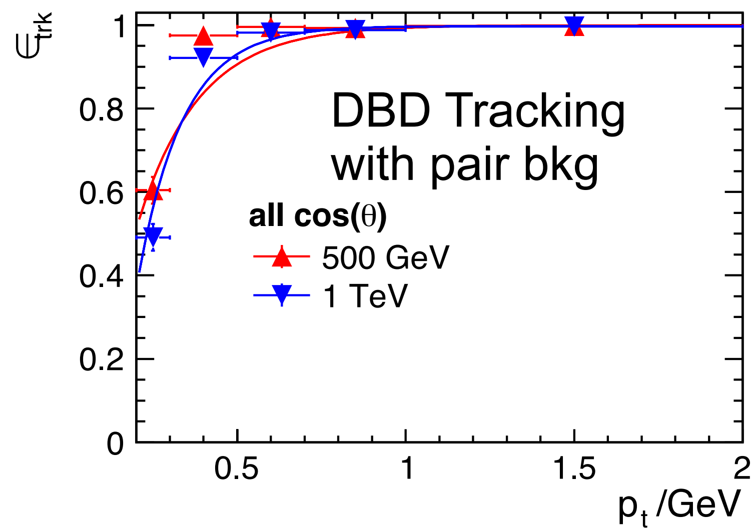
evaluate for new ILD forward region, up-to-date pair background & BeamCal reconstruction

... and using a dedicated Bhabha generator (eg BHWIDE)

2. Tracking for sub-GeV particles

- small mass differences
  => soft decay products!
- ILD-DBD tracking: efficiency not bad, but fakes from pair bkg?
- VTX & SIT stand-alone tracking?
- better time resolution in VTX?
- furthermore: masses of p, K etc not negligible in tracking



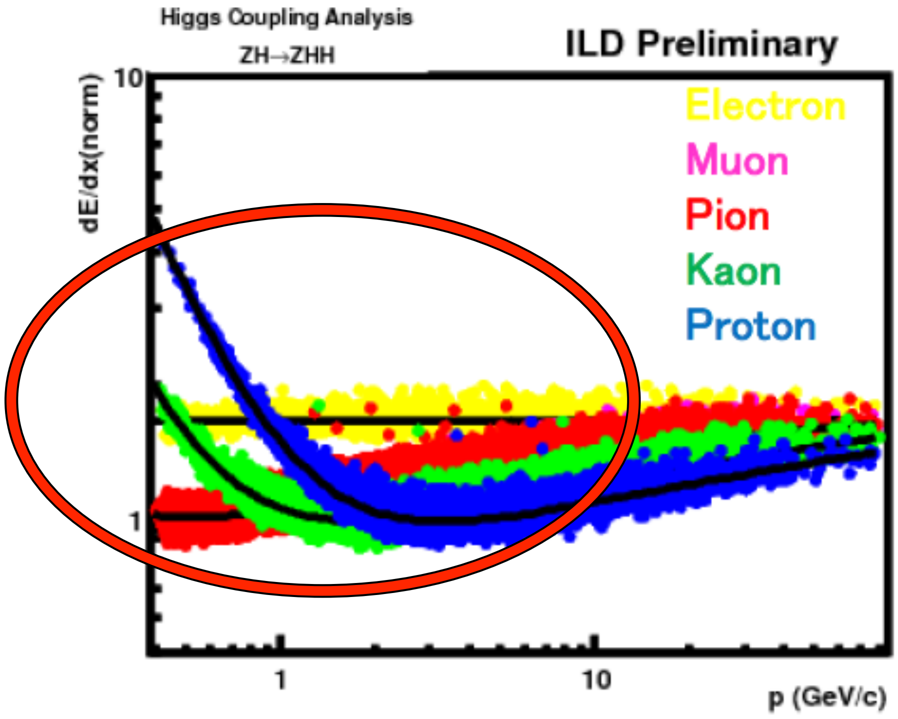


3. Particle ID

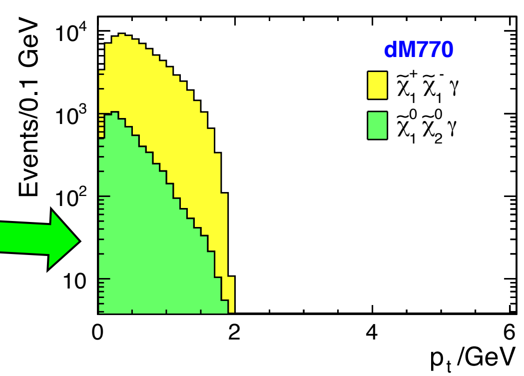
- dE/dx : cf talk by Masakazu in TPC session (Tue) particularly effective at low p
- cluster shapes (μ/π):

=> watch it: ~ ≤ 1GeV looks very different, need dedicated low E ID!

cf Yorgos (Fri)



- *neutral* Higgsinos decay to soft photons – any chance for these?



Conclusions

Conclusions

- e^+e^- collisions are essential to complement the LHC picture of BSM physics
- We cannot guarantee new particles, but we can guarantee the exploration of unknown territory highly relevant for our picture of BSM
- There are important requirements on the detectors for realizing the full BSM potential of the ILC
- We need still significant work on reconstruction tools before we can appreciate and evaluate the full capabilities of our proposed detectors.

Backup

How could ILC operation look like? [unofficial]

inital run at 500(+x) GeV

500fb^{-1} with f_P(+-,-+,++,-- =(0.4,0.4,0.1,0.1)

- exclude / discover SUSY with M<250 GeV
- best results for 4 years running for
  - most Higgs couplings
  - ew top couplings
  - anom. gauge couplings
  - m_W, m_H from kinematic reconstruction
- first glimpse at ttH, ZHH

4 y

tt threshold scan

200fb^{-1} at 350 GeV

- ultimate m_t, Γ_t, α_s
- QCD effects for ttH

1y

ZH run

500 fb^{-1} at250/ 350 GeV

- g_{HZZ}, H->inv.

3 y

maybe?

discoveries at LHC and/or ILC ?

scan thresholds (~100fb^{-1} each) for precision BSM program

Luminosity upgrade

more 500(+x) GeV data

~4ab-1 with f_P= (0.4,0.4,0.1,0.1)

- more precision **ZHH, ttH** et al
- increased **Dark Matter** sensitivity
- precision BSM spectrospocy
- model discrimination

further options

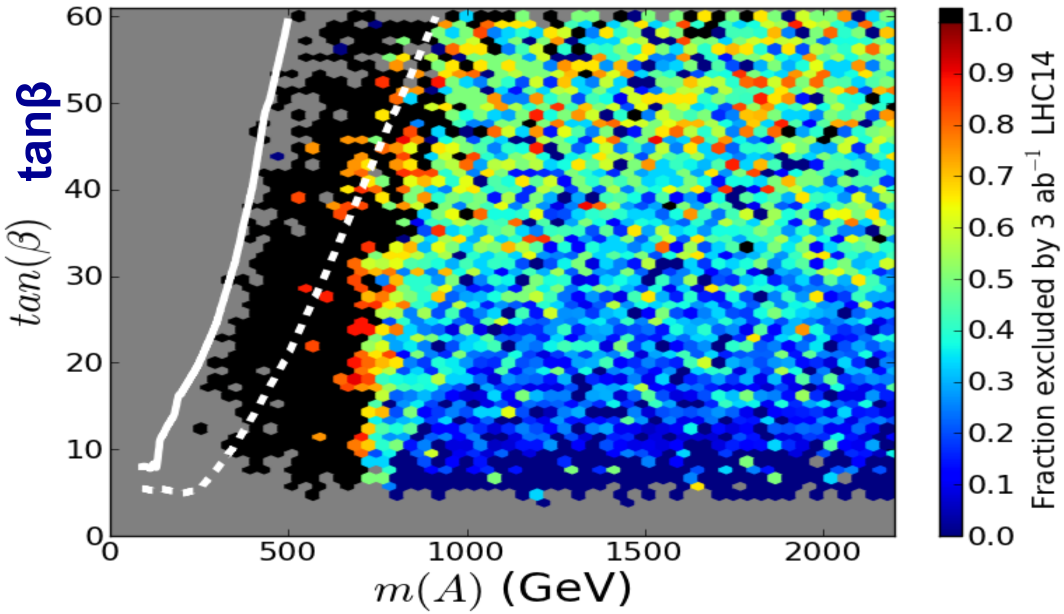
depend on results & money

- **TeV upgrade**
- more 250 GeV if needed
- WW threshold, Z pole, ...

What does this tell us about BSM?

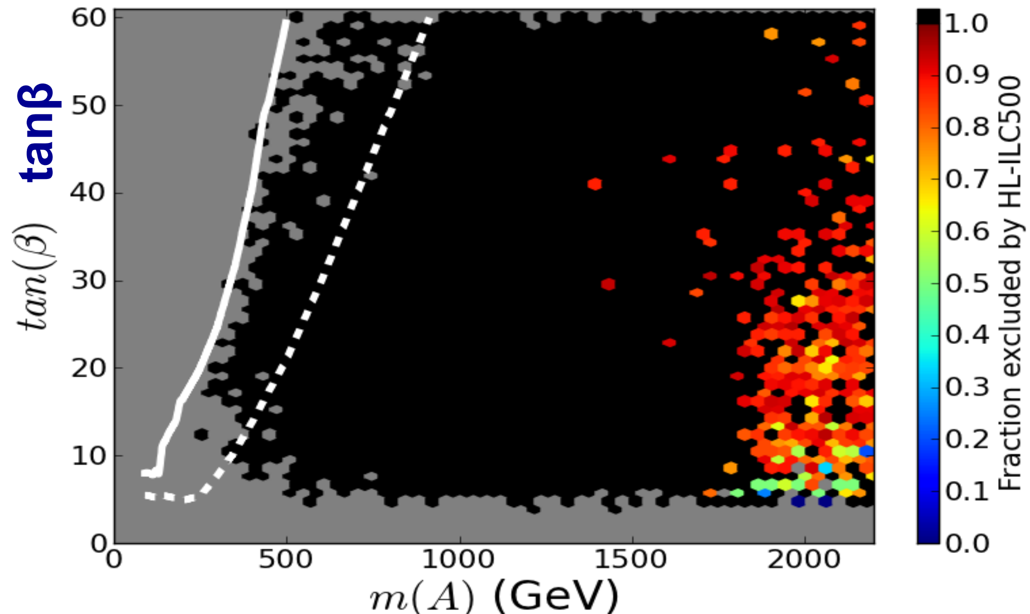
Constraining the pMSSM via Higgs couplings (combining hγγ, hττ, hbb)

HL-LHC 3000 fb-1



Heavy Higgs mass

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



Heavy Higgs mass

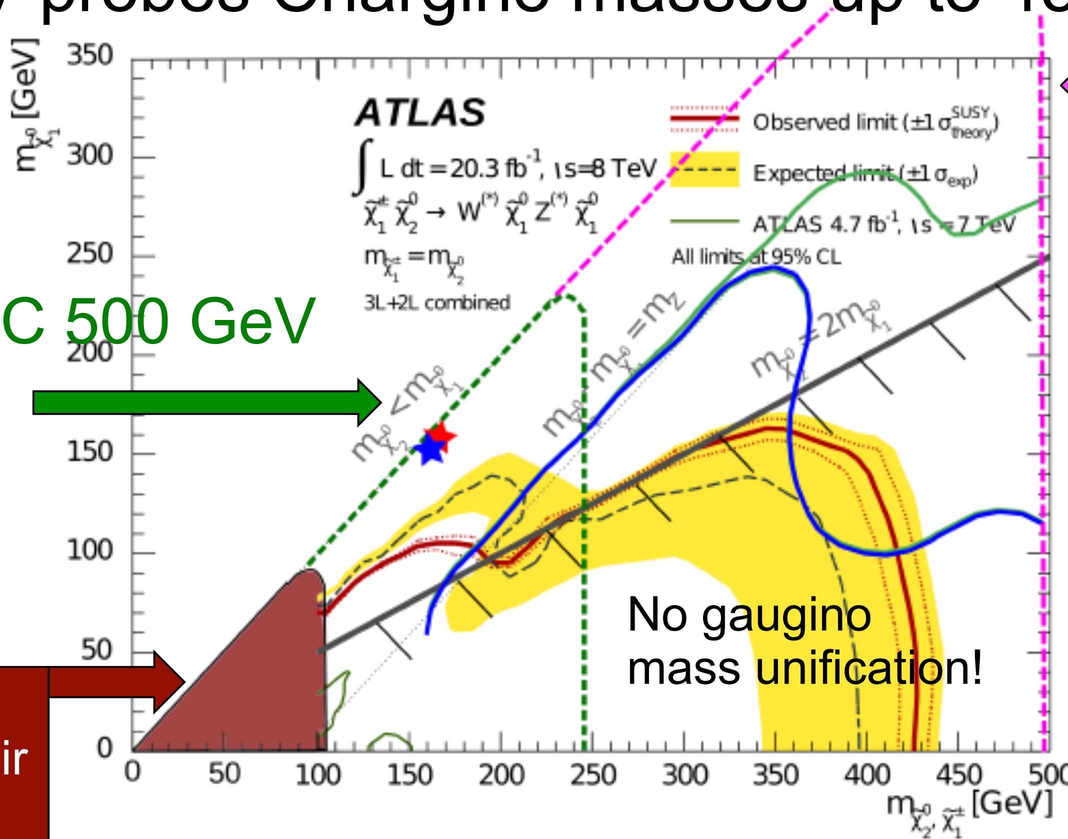
Cahill-Rowley, Hewett, Ismail, Rizzo, arXiv:1407.7021 [hep-ph]

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

And now a "case B" example

LHC 8 TeV probes Chargino masses up to 450 GeV ....

..but the most stringent general limit is still from:



LEP – chargino pair production, independent of chargino decay mode!

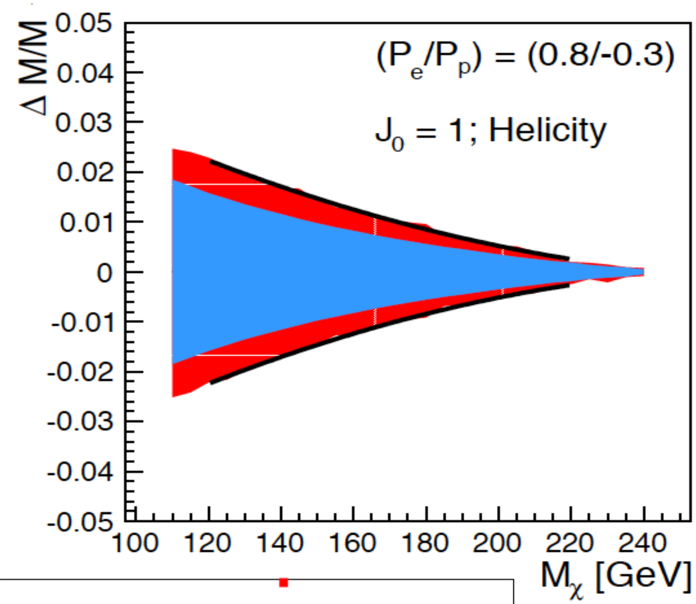
M.Berggren, ICHEP2014

...let's take a look at the star points ★★

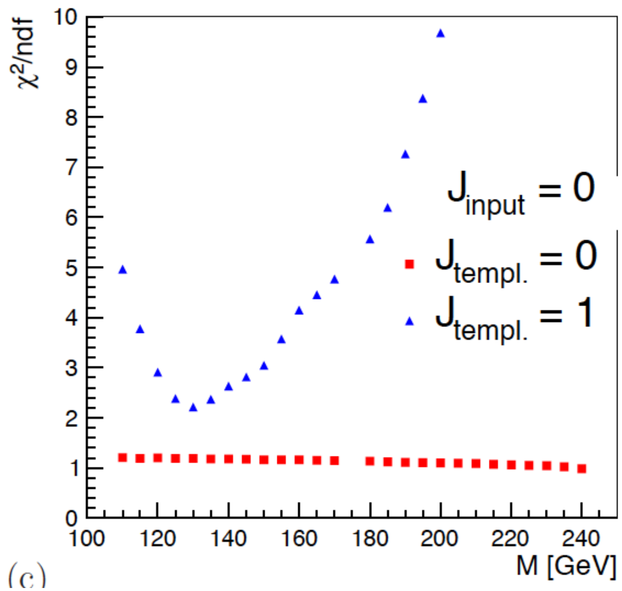
From EPJC 72 (2012) 2213, Bartels et al

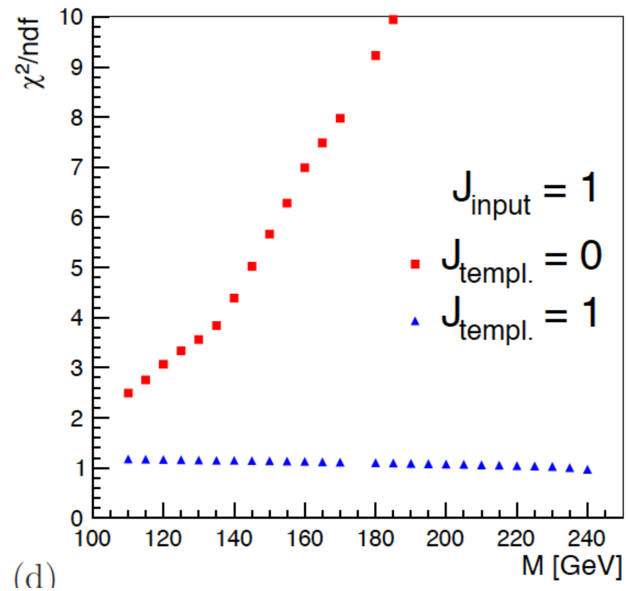
WIMP characterisation

- Mass measurement:
  eg ILC @ 500 GeV, 500fb^{-1}, κ_e = 10%
  P(e$^+$,e$^-$) = (-30%,80%)
  - 1-2% resolution
  - Dominated by conservative assumption on knowledge of beam energy spectrum



- Dominant partial wave deter-mination: correct hypothesis clearly favoured



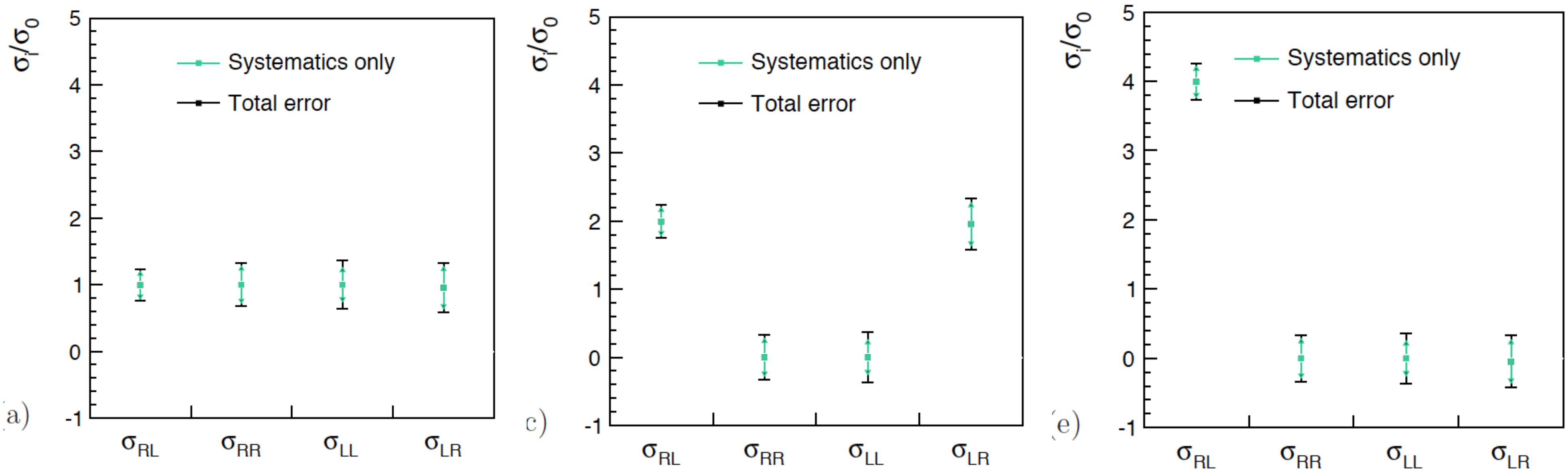


From EPJC 72 (2012) 2213, Bartels et al

Helicity Structure of WIMP-Fermion Interaction

- Measure cross-section with different beam helicities! Eg |P| = 80% / 30%, all four sign combinations (lumi split 200fb^{-1} +-/-+, 50fb^{-1} ++/--)
  NB: the more positron polarisation, the better!
- Three examplatory coupling scenarios:

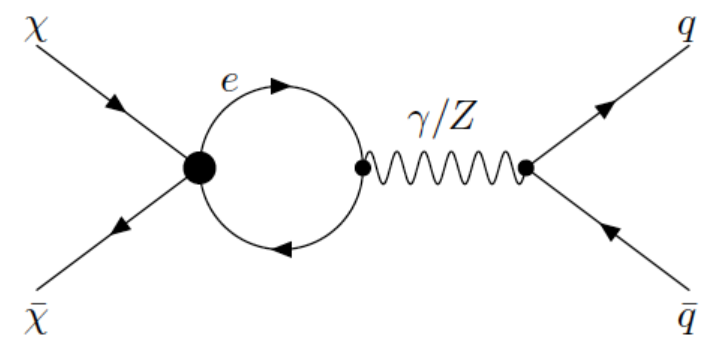
"Equal" "Helicity & Parity conserving" "Anti-SM"

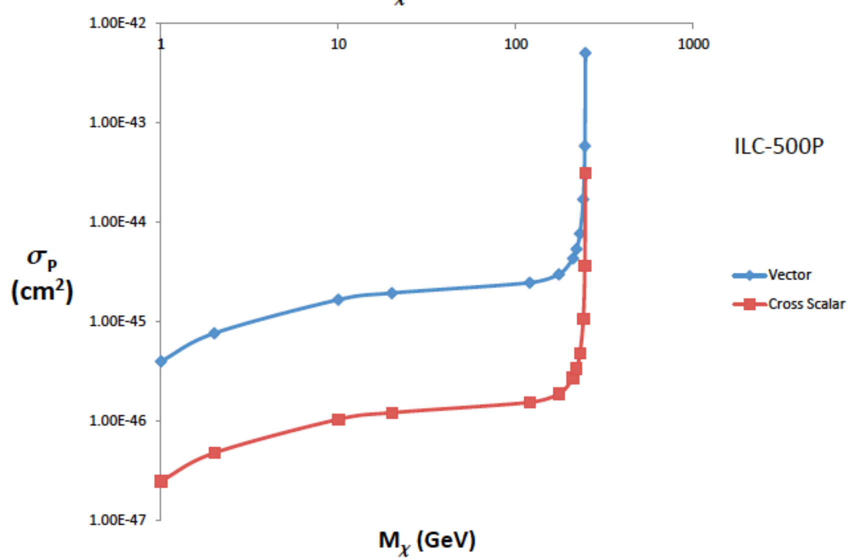


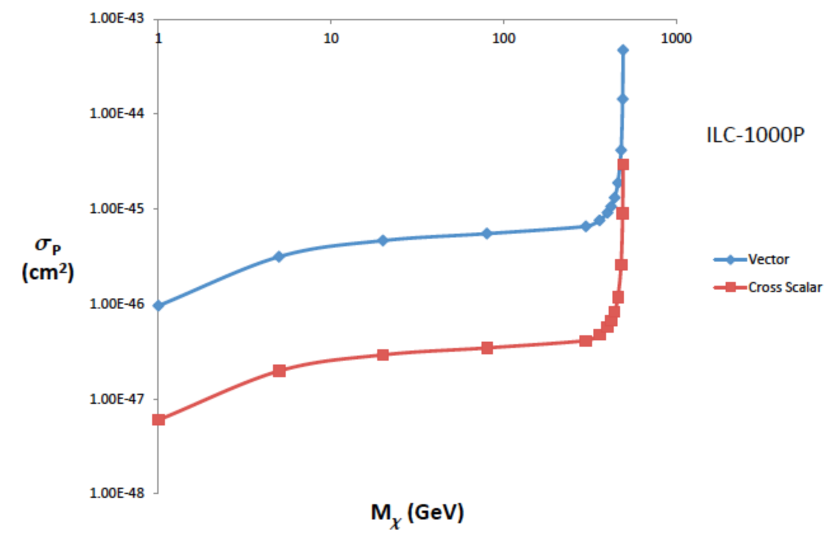
Clear distinction possible!

How to relate e^+e^- to Direct Searches?

- Will be model-dependent!
- Most conservative, ie minimal "unavoidable" X-Nucleon cross-section:
  - Assume no tree-level coupling to quark
  - Leaves us with loop contributions
- Direct searches need sensitivity of ~ $10^{-46..47}$ cm^2 to rule out model-indepedently lepton-WIMP couplings observable at ILC







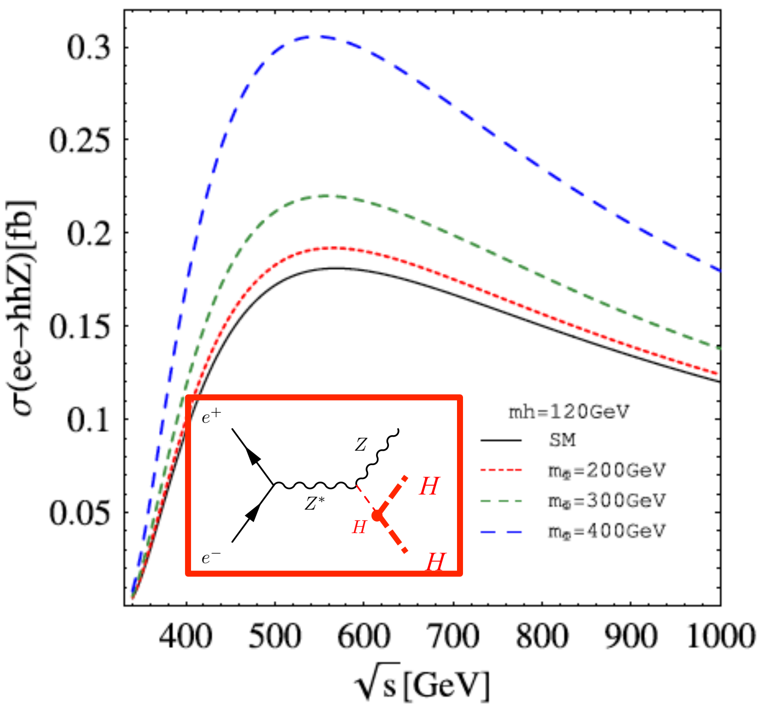
e^+e^- and pp / XN

- Relation between WIMP – lepton and WIMP – quark / nucleon interaction is *model-dependent*
- Is suppression scale Λ the same for quarks and leptons?
  - A priori not!
  - Eg: t-channel exchange of “squark / selectron”
  - Direct couplings vs loop couplings

=> e^+e^- *provides orthogonal and independent information, regardless whether LHC or DD discovers (case A) or just excludes (case B)*

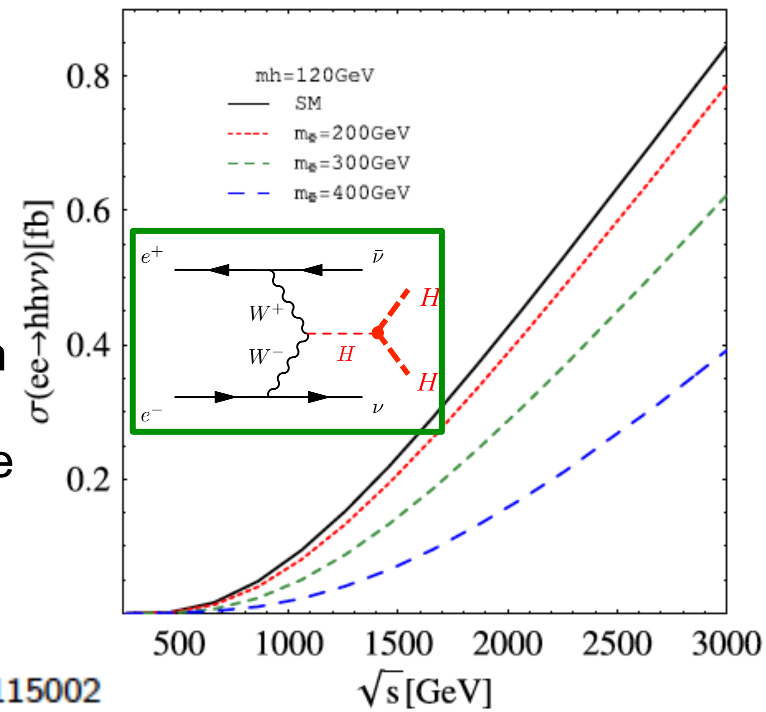
- Interesting interplay with indirect detection: how big is annihilation fraction into e^+e^- ?

Higgs Self-Coupling – eg 2HDM



- Loop-contributions with heavy Higgses (m_ϕ) modify λ
- Interference with different sign leads to opposite effects in ZHH and vvH

Phys.Rev. D82 (2010) 115002



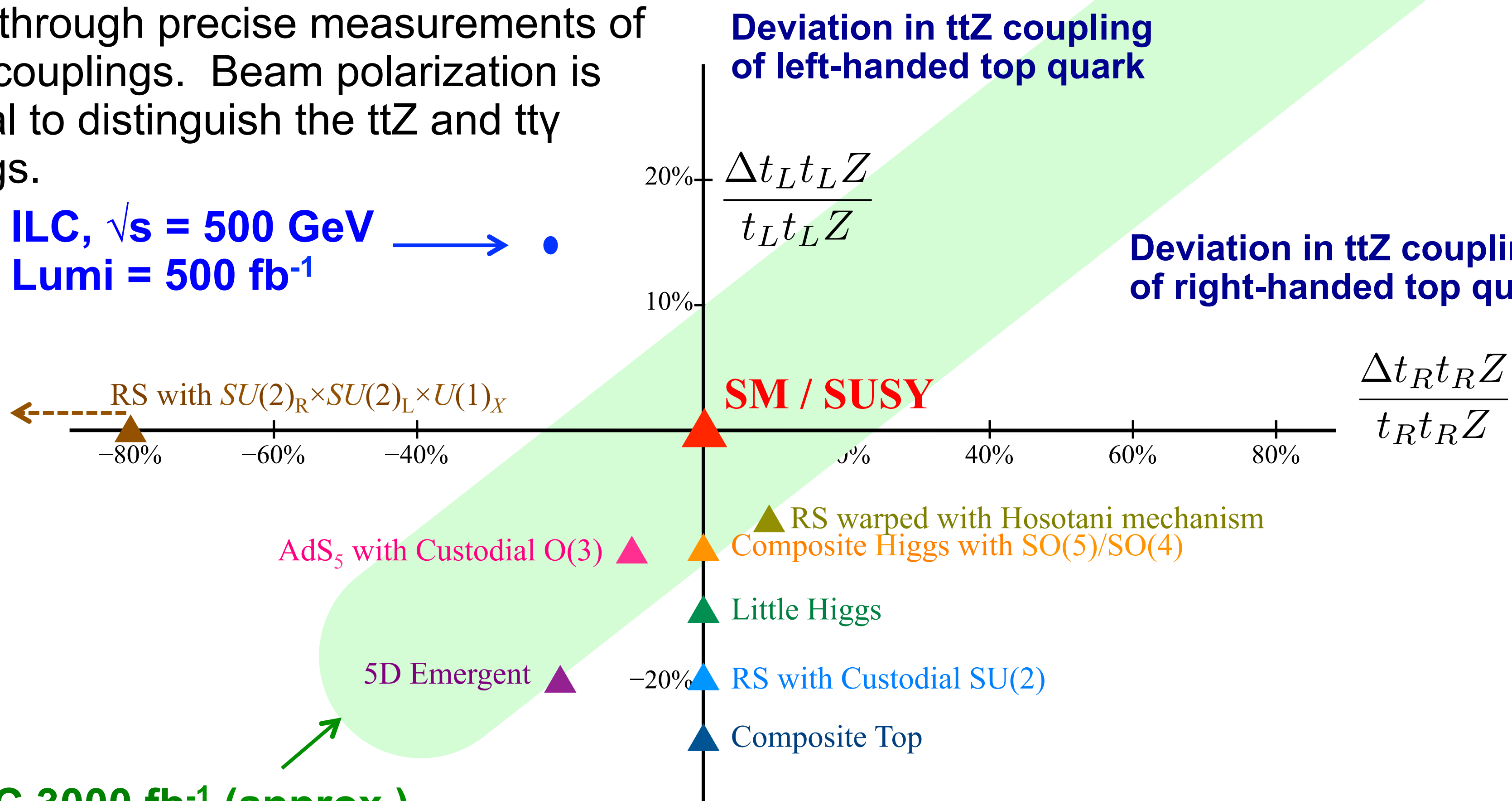
deviations in double Higgs cross-sections:

Model	m_h[GeV]	$\frac{\Gamma^{NP}_{hhh}-\Gamma^{SM}_{hhh}}{\Gamma^{SM}_{hhh}}$	LHC $\Delta r_{NP}^{gg\to hh}$	ee->ZHH $\Delta r_{NP}^{e^+e^-\to hhZ}$	$\Delta r_{NP}^{\gamma\gamma\to hh}$	ee->vvHH $\Delta r_{NP}^{e^+e^-\to hh\nu\bar{\nu}}$
THDM	120	+120%	−50%	+(80–70)%	+50%	−(80–50)%

beware when comparing numbers for δλ/λ!

Impact of BSM on Top Sector

Composite Higgs models can be tested at the ILC through precise measurements of the top couplings. Beam polarization is essential to distinguish the ttZ and ttγ couplings.



HL-LHC 3000 fb^{-1} (approx.)

Based on Baur, Juste, Orr, Rainwater, PRD71, 054013 (2005)

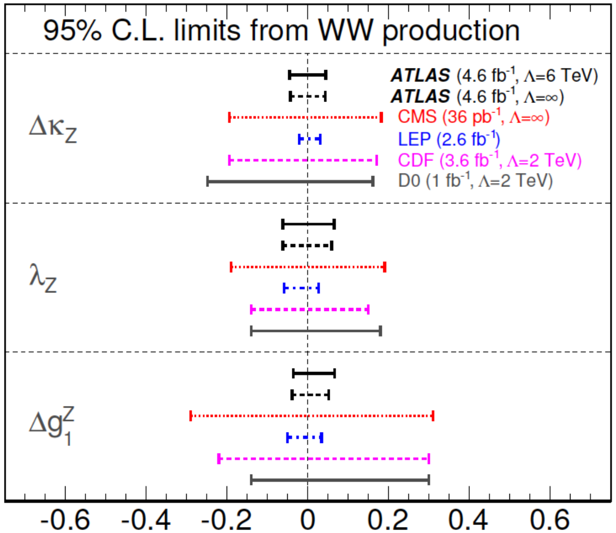
Deviations for different models for new physics scale at ~1 TeV.
Based on F. Richard, arXiv:1403.2893

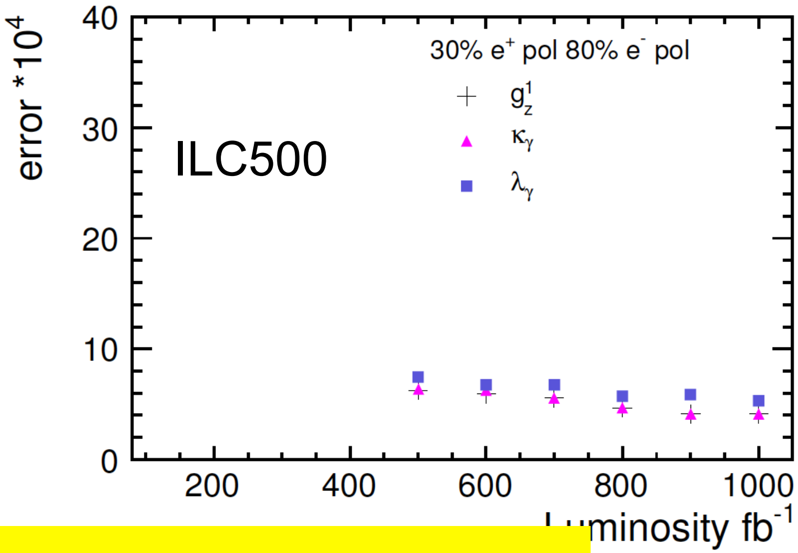
Charged Triple Gauge Couplings

- most general lorentz-invariant W^+W^-Z and $W^+W^-\gamma$ vertices: 14 complex couplings
- assume C and P conservation:
  6 real couplings: g_1^γ, g_1^Z, k_γ, k_Z, λ_γ and λ_Z
- g_1^γ fixed by em gauge invariance
- enforce $SU_L(2) \times U_Y(1)$ gauge relation:
  3 real couplings:

$$\begin{aligned}\Delta k_Z &= -\Delta k_\gamma \tan^2\theta_W + \Delta g_1^Z \\ \lambda_\gamma &= \lambda_Z\end{aligned}$$

- SM: $g_1^Z = k_\gamma = 1$, $\lambda_\gamma = 0$
- status: few percent precision from single parameter fits (LEP & LHC)





ILC: gains ~ 2 orders of magnitude, multi-parameter fits

The next quest for particle physics

With the discovery of a Higgs boson, we are now confident that electroweak symmetry breaking (EWSB) occurs via the expectation value of the Higgs field. **However, we do not 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

…

The **Higgs boson** and the **top quark** are crucial probes for the mechanism of EWSB

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.

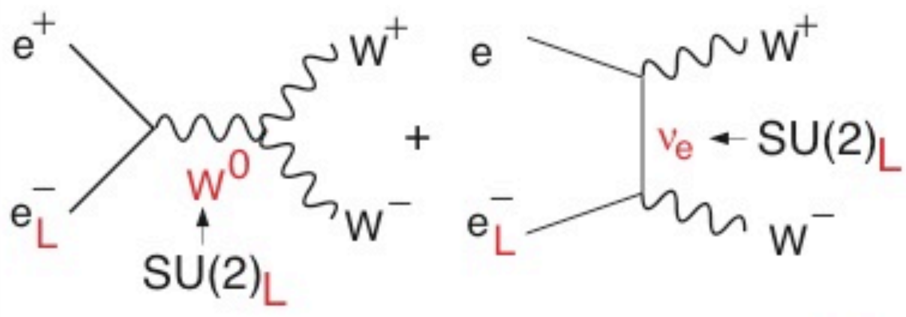
The **Higgs boson** and the **top quark** are crucial probes to distinguish these possibilities.

Operating the ILC: Beam Polarisation

BG Suppression

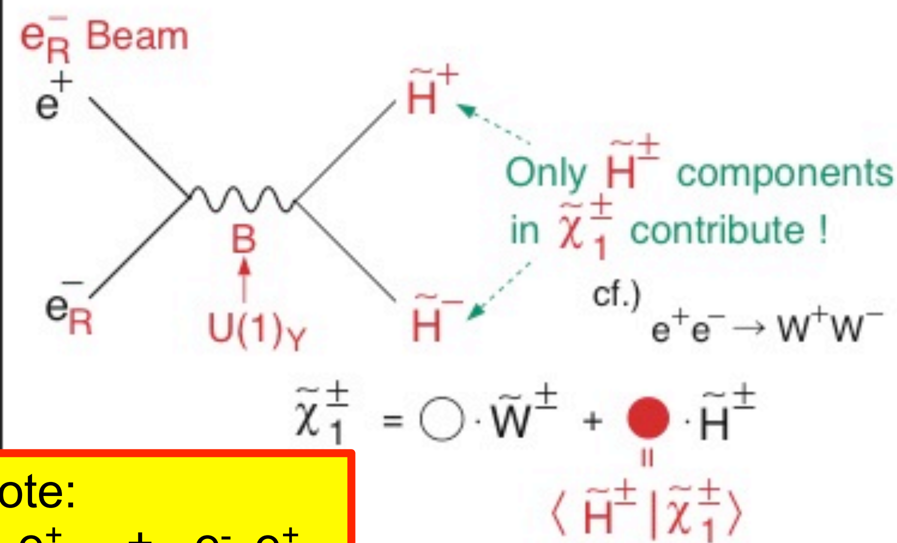
[K. Fujii]

W^+W^- (Largest SM BG)

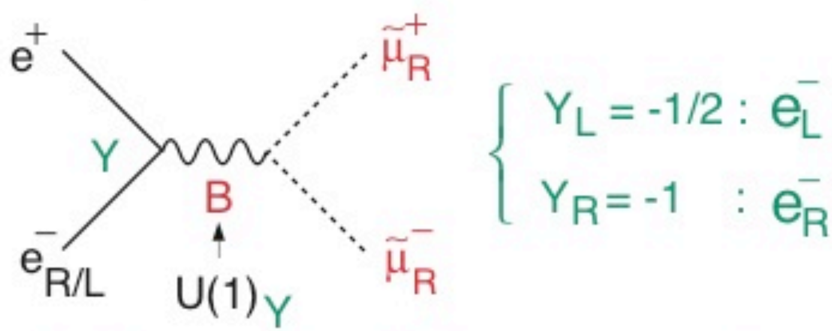


In the symmetry limit, $\sigma_{WW} \to 0$ for e^-_R !

Chargino Pair



Slepton Pair



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

Note:
$e^-_L e^+_R$ + $e^-_R e^+_L$
≠ unpolarised data!

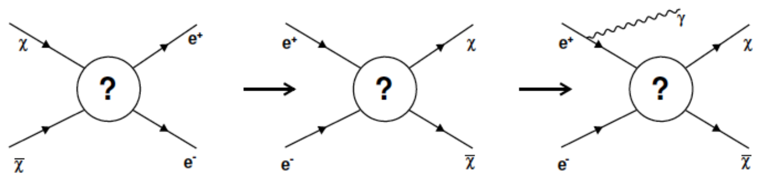
Decomposition

Signal Enhancement

Two theoretical approaches

"Cosmological" Approach - relate to Ω_{DM} and σ_{an}:

A. Birkedal et al. [hep-ph/0403004]



- M_χ - WIMP mass
- S_χ - WIMP spin
- k_e - Fraction of WIMP pair annihilation into e^+e^-, $\sigma \sim \kappa_e^{pol}$
- J - Angular momentum of dominant partial wave

Effective Operator Approach - well known from LHC.

ILC-Special: beam polarisation

- Vector:
  $\sigma_{LR} = \sigma_{RL} > 0,\ \sigma_{LL} = \sigma_{RR} = 0$
- Axial-vector and scalar:
  $\sigma_{LR} = \sigma_{RL} = 0,\ \sigma_{LL} = \sigma_{RR} > 0$

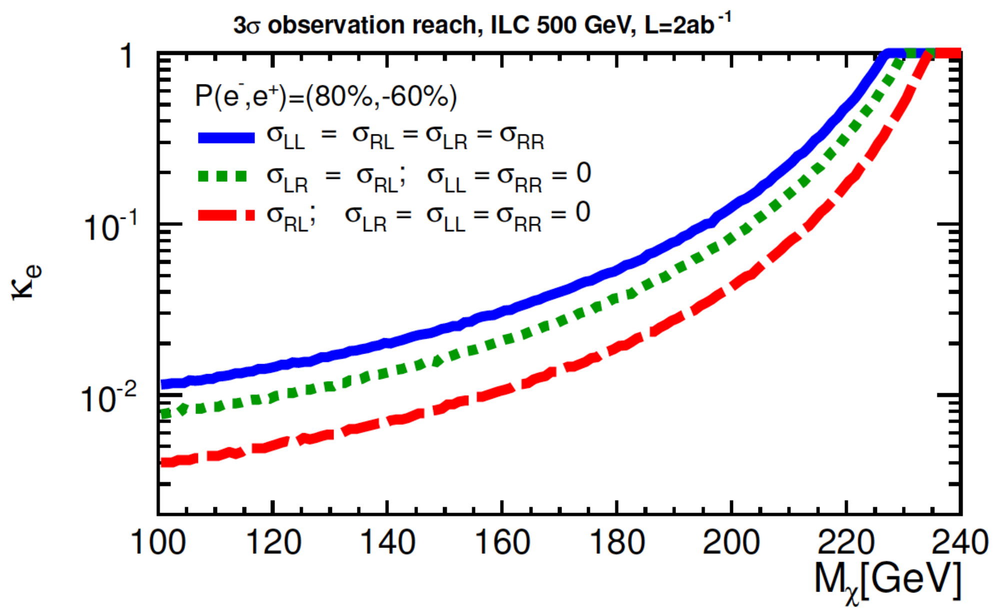
- M_χ - WIMP mass
- S_χ - WIMP spin = -$\frac{1}{2}$
- Λ - energy scale of the new physics that provides the coupling, $\sigma \sim \frac{1}{\Lambda^4}$
- Choice of operator

Observation reach: 500 GeV, **2ab⁻¹**

"Cosmological" Approach

- Spin -1/2
- P-wave

Can observe down to ~1 % annihilation fraction to e^+e^-



Effective Operator Approach

- Spin -1/2

Can observe up to Λ~2.5 TeV