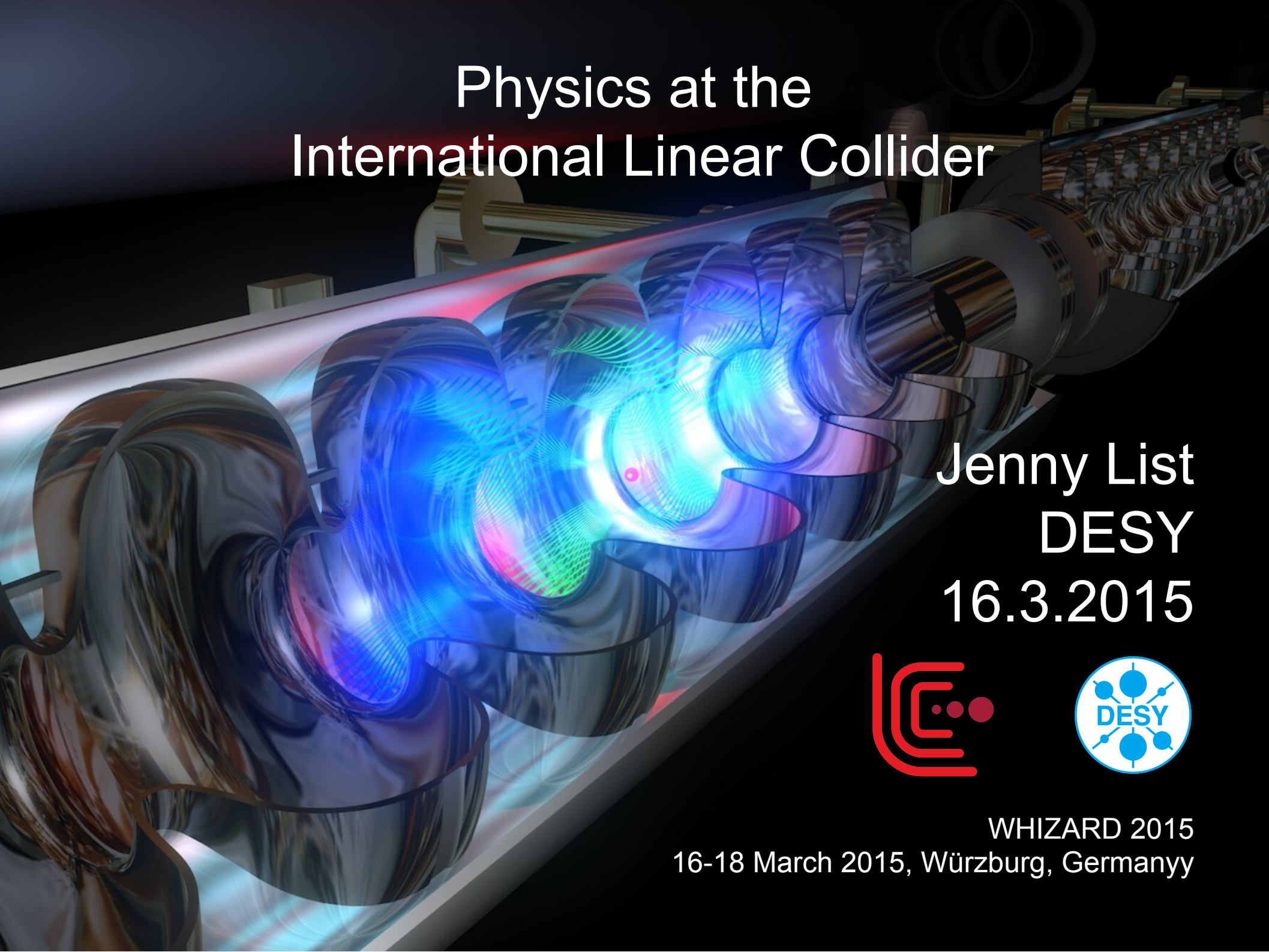
Physics at the International Linear Collider



Jenny List
DESY
16.3.2015

WHIZARD 2015
16-18 March 2015, Würzburg, Germanyy

Outline

- Introduction
- Precision Measurements
  - Profiling the Higgs Boson
  - Top and more
- New Particles
  - SUSY Examples
  - WIMP Dark Matter
- Conclusions

Introduction

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

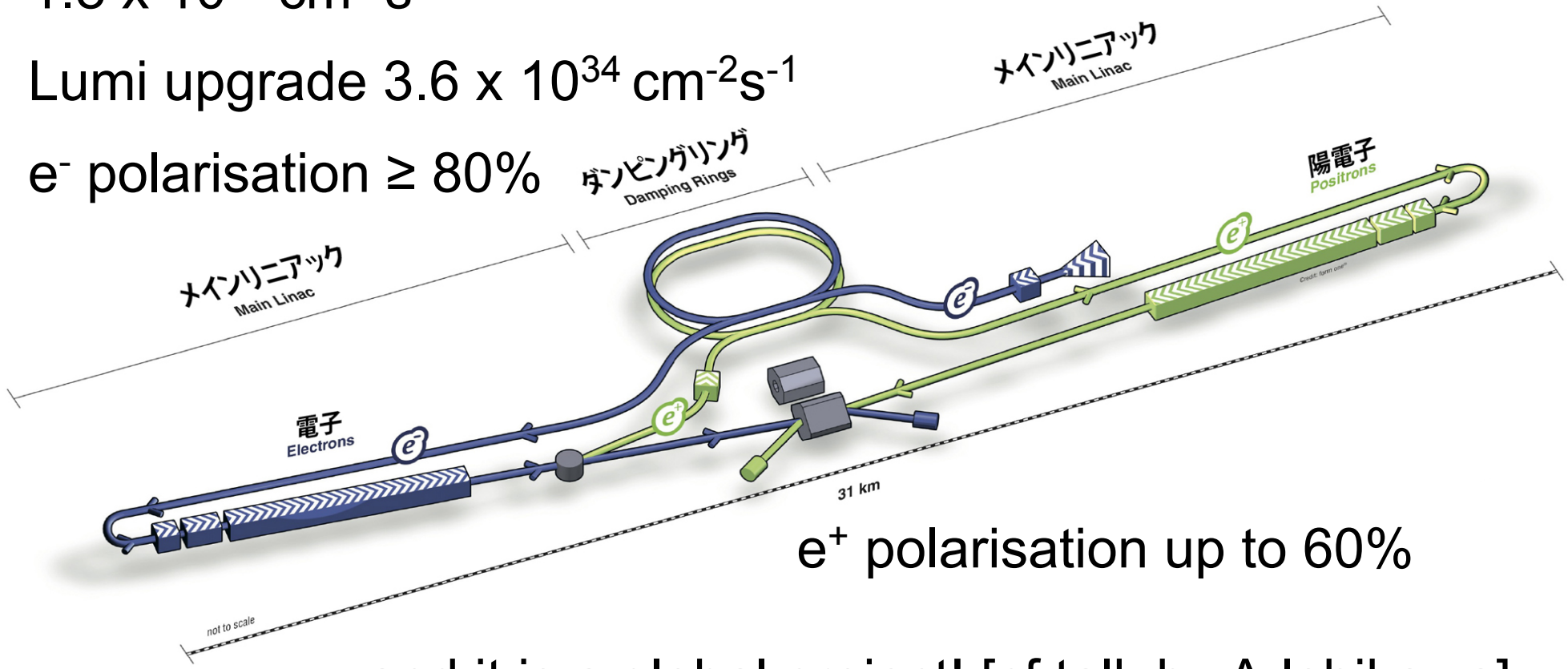
dark matter

…

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

The International Linear Collider

- e^+e^- collisions with $\sqrt{s}$ = 200...500 GeV, upgradable to 1 TeV
- Baseline Luminosity at 500 GeV:
  $1.8 \times 10^{34}\ cm^{-2}s^{-1}$
- Lumi upgrade $3.6 \times 10^{34}\ cm^{-2}s^{-1}$
- e^- polarisation ≥ 80%



e^+ polarisation up to 60%

… and it is a global project! [cf talk by A.Ishikawa]

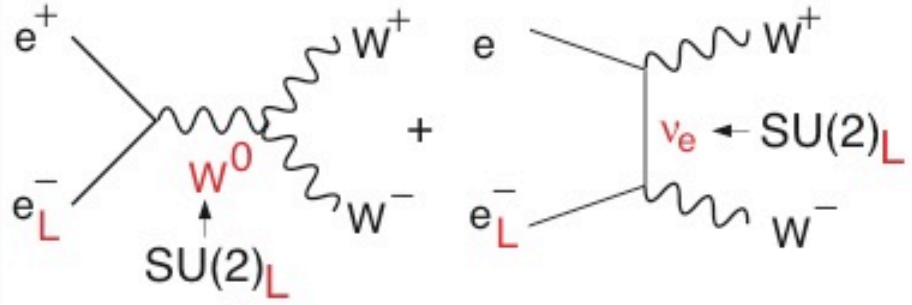
Operating the ILC: Reminder

- pulsed operation:
  - trains of N_{bunch} = 1315 / 2625 bunches
  - train repetition rate: 5 – 10 Hz
  - **enables triggerless readout of detectors**
- luminosity grows with energy – and with power consumption!
  - all ILC numbers respect the following limits for **total site power** (w/o detectors)

ECM [GeV]	**250**	**250**	**500**	**250**	**500**	**1000**
rep. rate [Hz]	5	10	**5**	10	5	**5**
N_{bunch}	1315	1315	**1315**	2625	2625	**2625**
inst. lumi [10^{34} / cm^2 / s]	0.75	1.5	**1.8**	3	3.6	**3.6-4.9**
total power [MW]	**100**	**160**	**160**	**190**	**200**	**300**

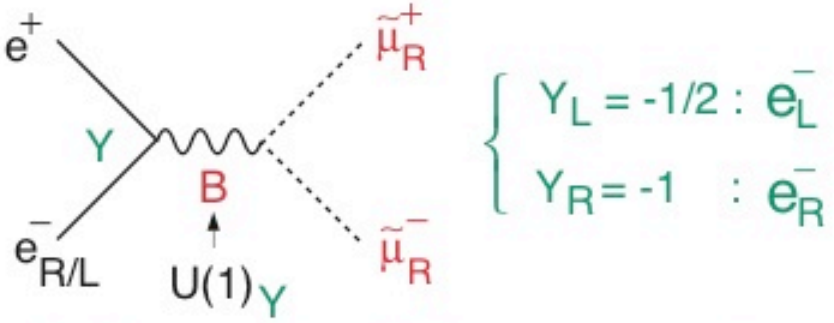
Operating the ILC: Beam Polarisation

W^+W^- (Largest SM BG)



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

Slepton Pair

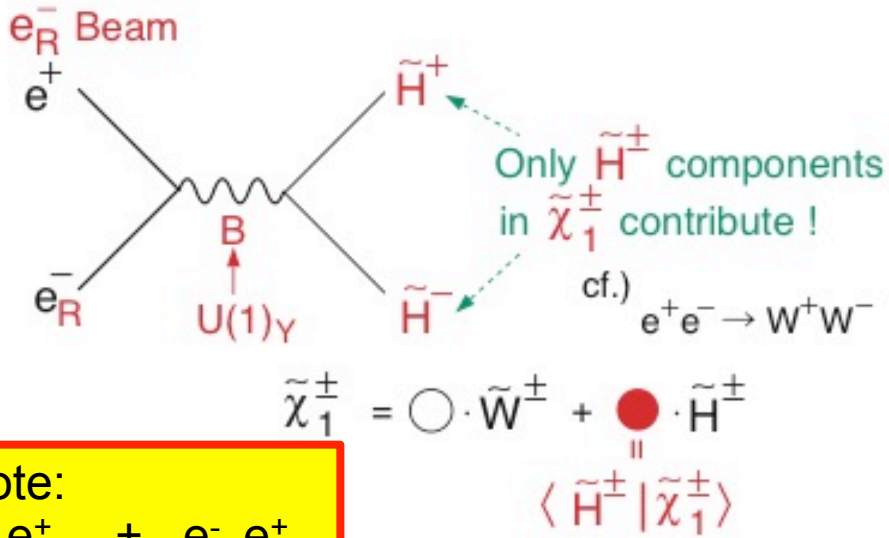


In the symmetry limit, $\sigma_R = 4\,\sigma_L$!

BG Suppression

[K. Fujii]

Chargino Pair



Note:
$e^-_L e^+_R$ + $e^-_R e^+_L$

≠ unpolarised data!

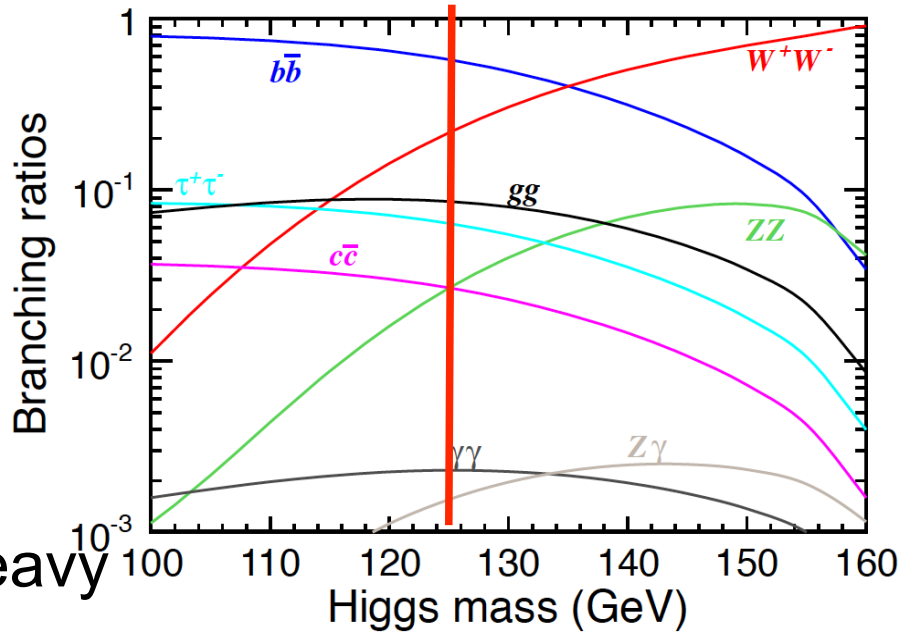
Decomposition

Signal Enhancement

Precision Measurements: Profiling the Higgs Boson

The beyond-LHC Higgs Menue

- Model-independent extraction of **all** couplings:
  - Absolute couplings, not ratios
  - No assumptions
- To precisions relevant for BSM:
  - No new physics yet → heavy
  - expect only small deviations of few percent max for M=1TeV:

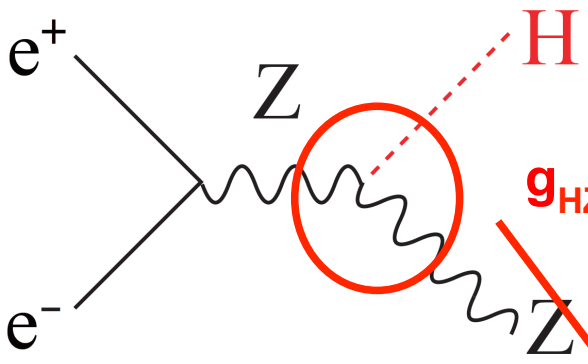


Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

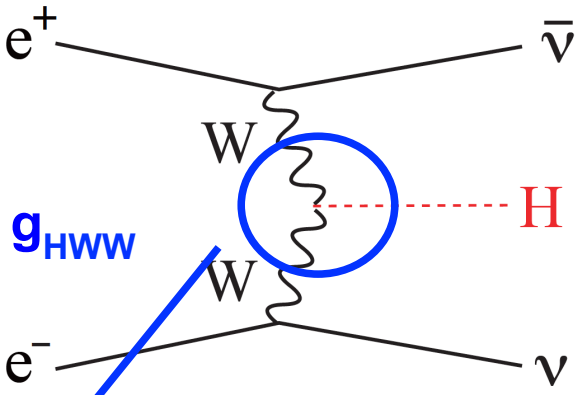
[Snowmass Higgs Report]

=> requires sub-percent precision!

Higgs Production in e^+e^- collisions



g_{HZZ}

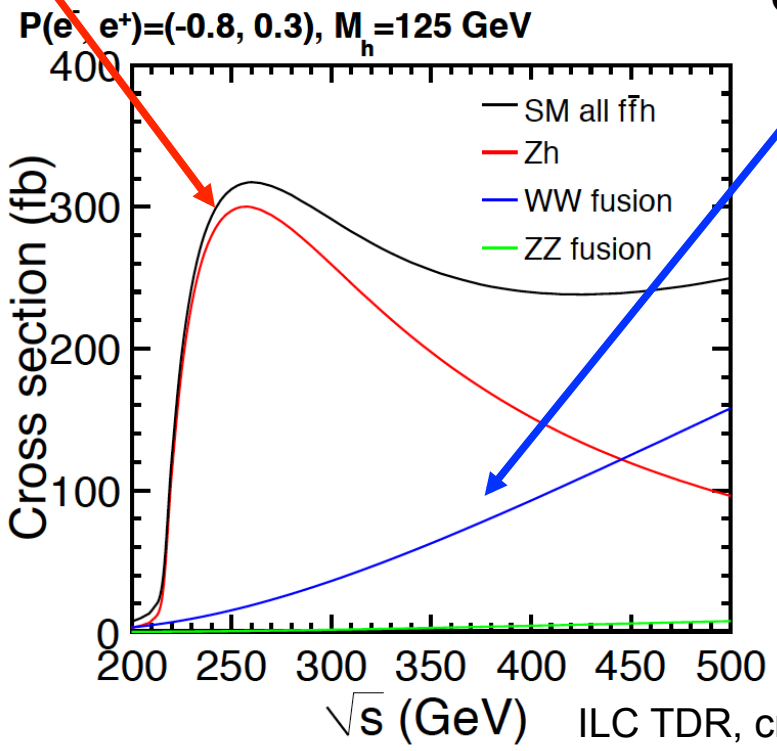


g_{HWW}

Higgs-Strahlung:

- g_{HZZ}
- M_H
- H -> invisible

Via recoil method: model-independent!



ILC TDR, cross section by WHIZARD

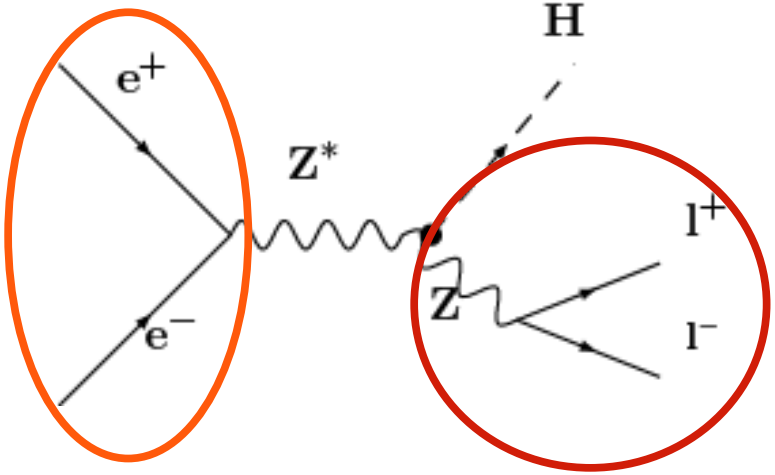
WW-Fusion:

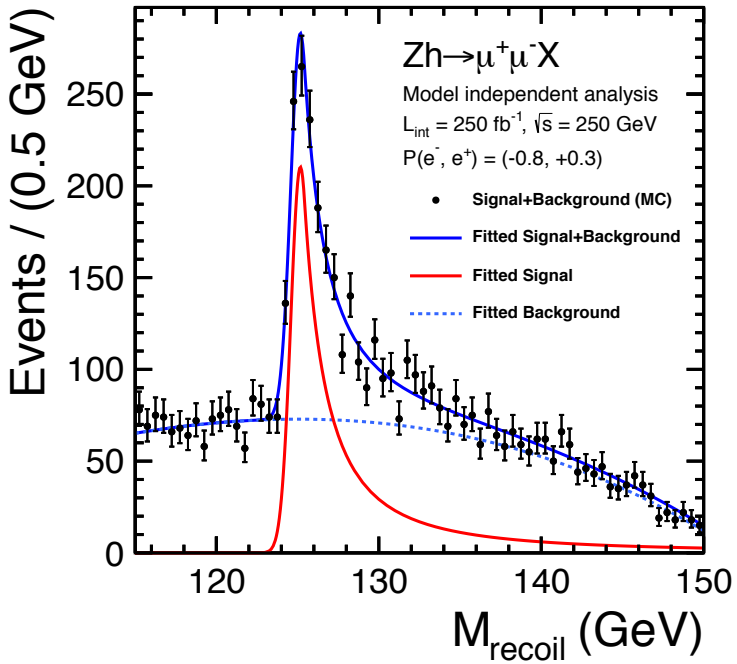
- High rates
- Precision $\sigma \times BR$

Access to absolute couplings

- Enabled by model-independent measurement of σ_{ZH}
- How? → recoil method:

$$M_H^2 = M_{recoil}^2 = s + M_Z^2 - 2E_Z\sqrt{s}$$





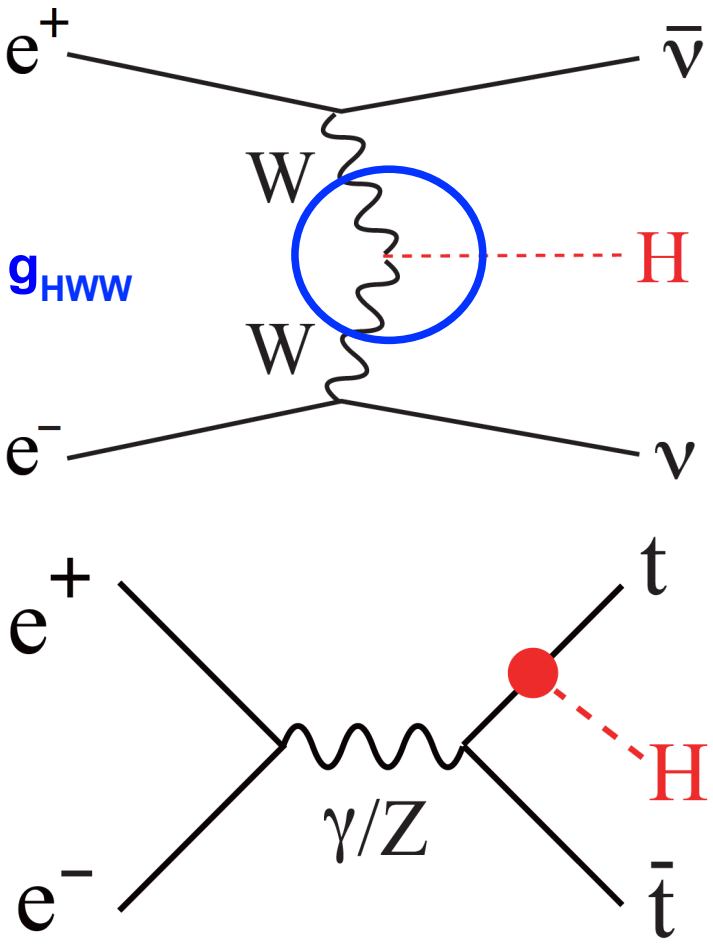
For 250 fb^{-1} at $\sqrt{s}$ = 250 GeV:

- δM_H = 32 MeV
- $\delta\sigma_{ZH}/\sigma_{ZH}$ = 2.6%
- BR (H->invis) < 0.7% @95% CL

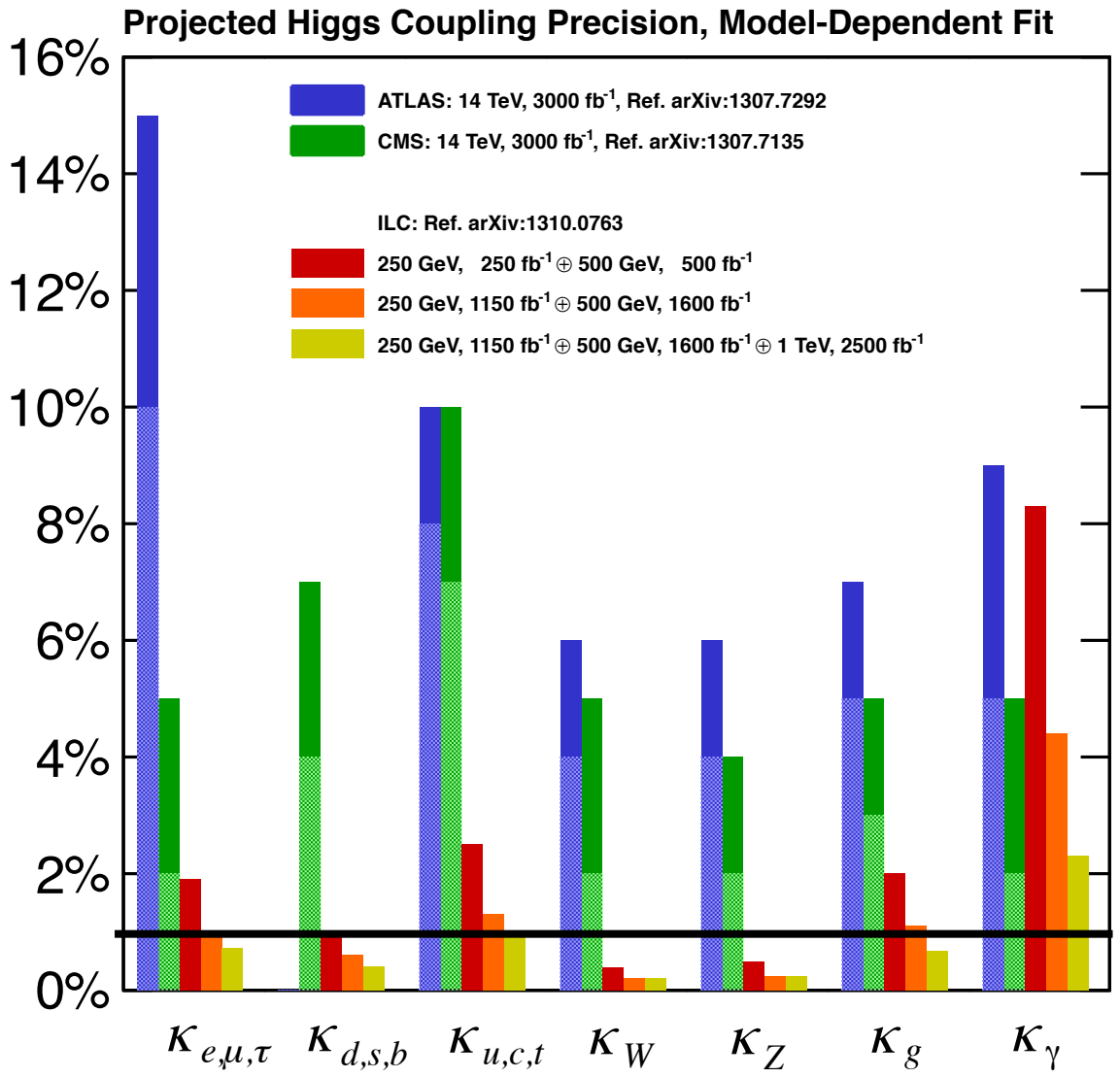
Statistically limited → 2x smaller for 1ab^{-1}

Total Width and ttH

- At $\sqrt{s} \geq 350$ GeV:
  - WW fusion sizable
  - Access to g_{HWW}…
  - …and Γ_H
  - Large statistics for σxBR measurements
- At $\sqrt{s} \geq 500$ GeV:
  - ttH production -> top Yukawa!
  - **8 fermion final state**
  - Significant NRQCD threshold enhancement → need **NLL or better**



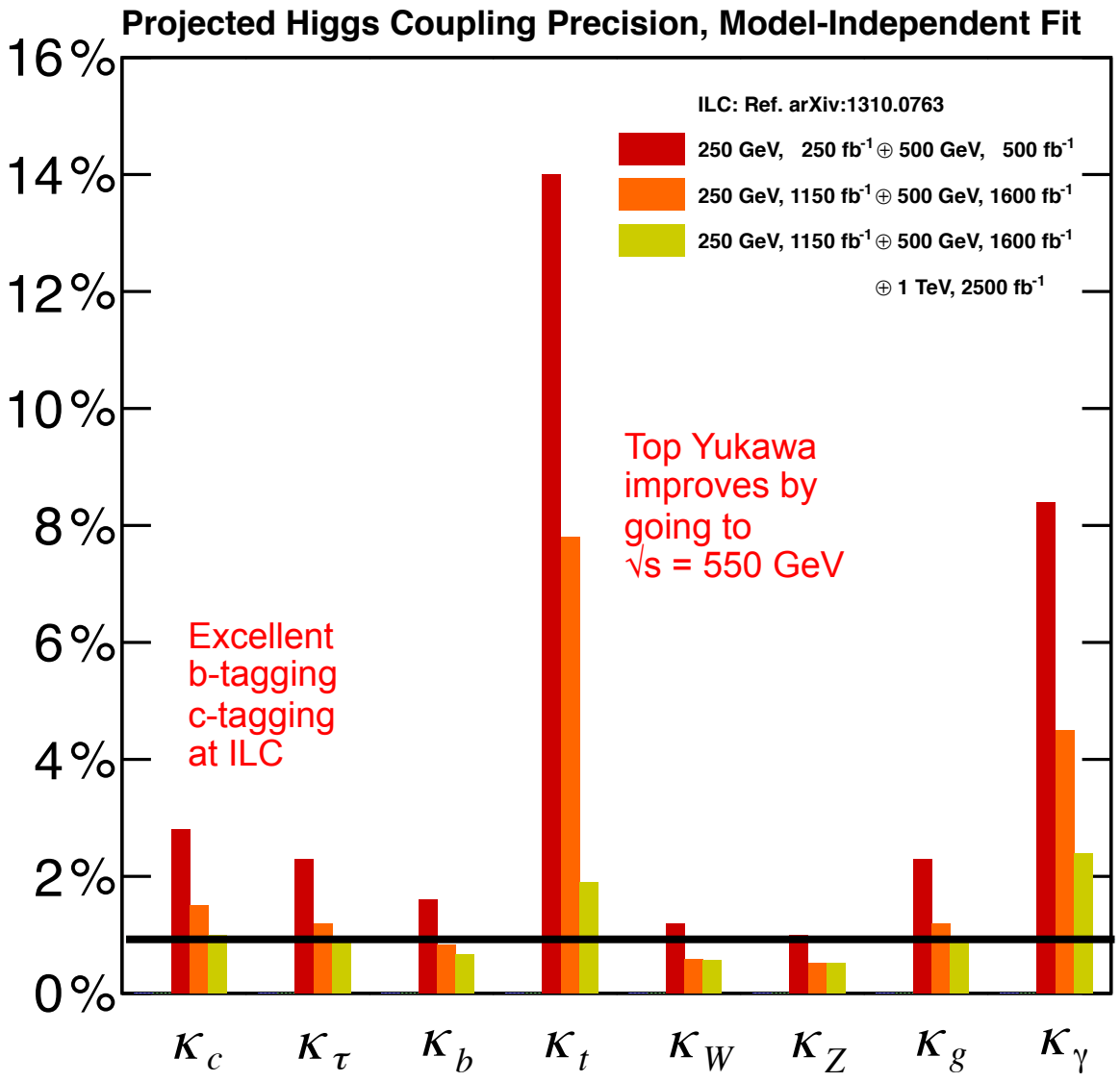
Higgs Couplings (1/2)



With LHC-style assumptions; not model-independent.

1% precision

Higgs Couplings (2/2)



Model-independent coupling determination unique to ILC

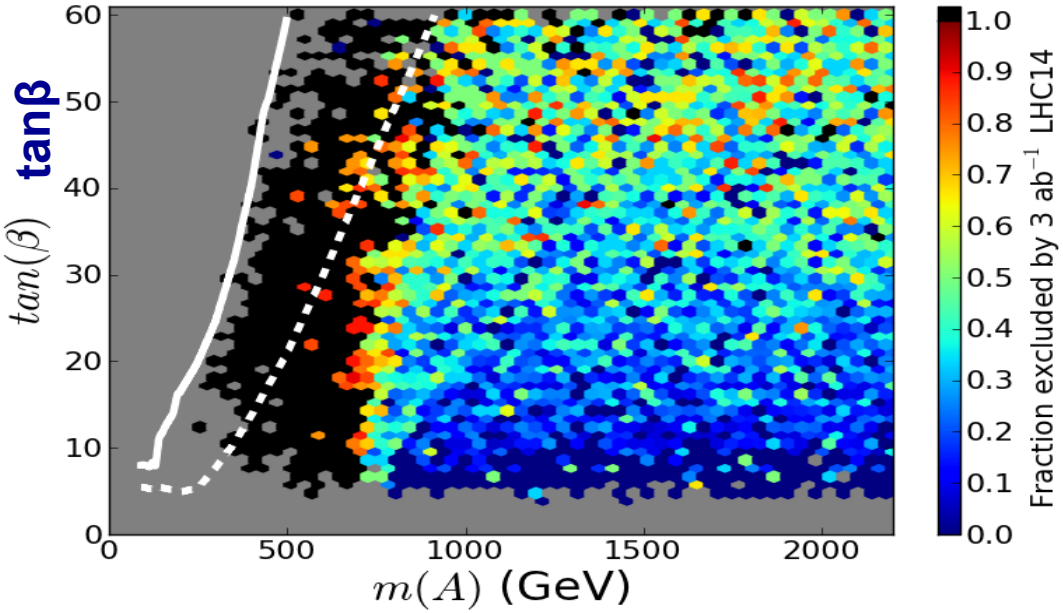
Better hγγ with LHC/ILC synergy

1% precision

What does this tell us about BSM?

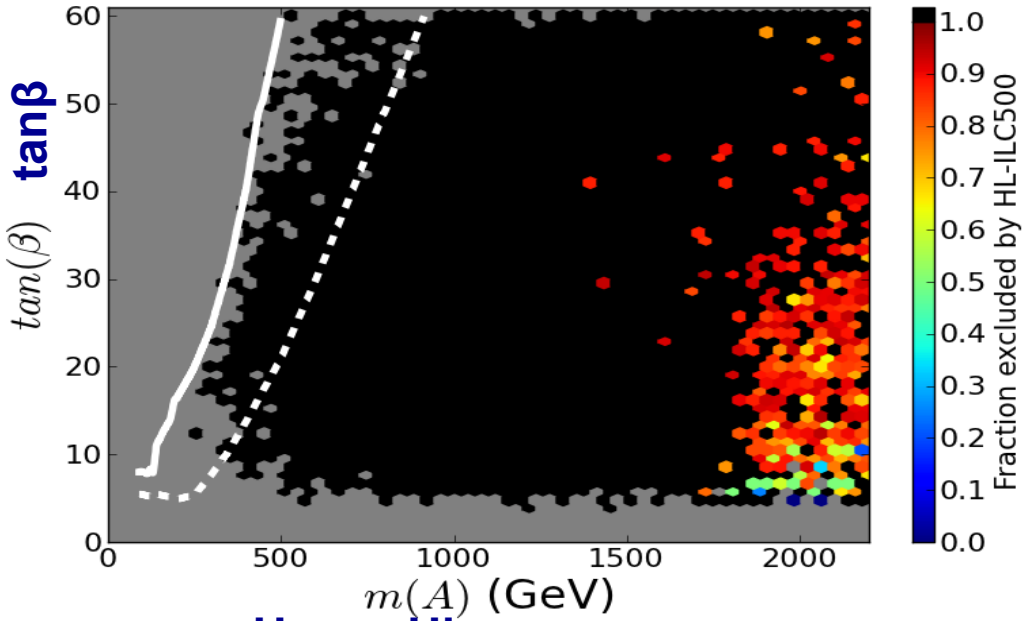
Constraining the pMSSM via Higgs couplings (combining hγγ, hττ, hbb)

HL-LHC 3000 fb-1



Heavy Higgs mass

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



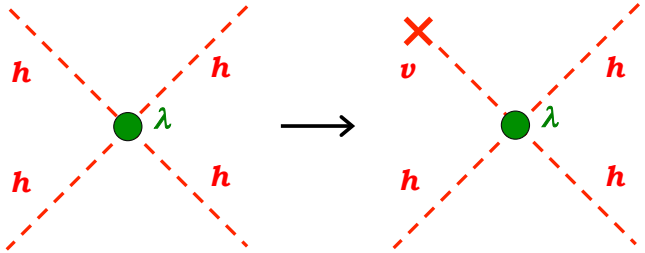
Heavy Higgs mass

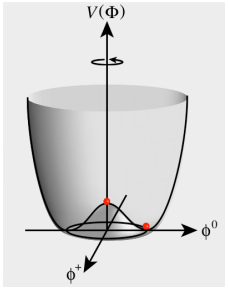
Cahill-Rowley, Hewett, Ismail, Rizzo, arXiv:1407.7021 [hep-ph]

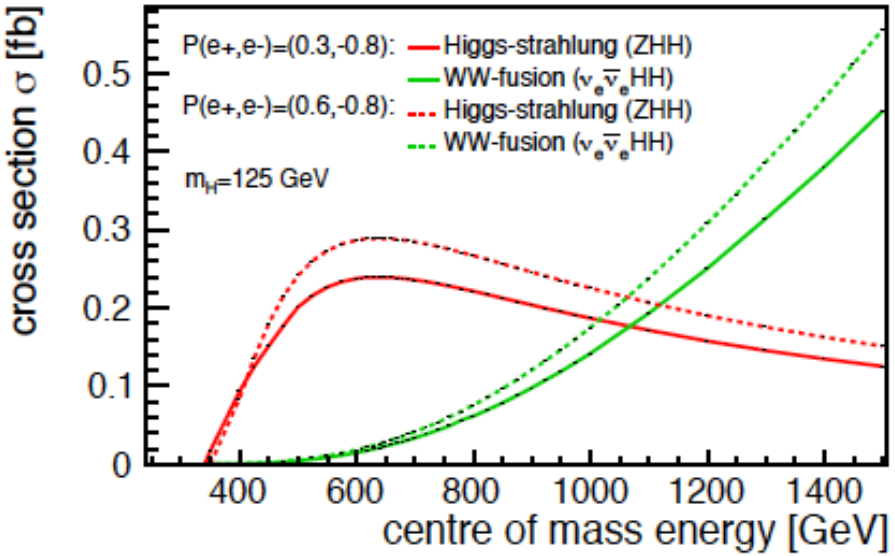
Precision Higgs coupling measurements sensitive probe for heavy Higgs bosons
m_A ~ 2 TeV reach for <u>any</u> tanβ at the ILC

Higgs Self-Coupling: $\sqrt{s} \geq 450$ GeV

Existence of hhh coupling λ =
Direct evidence of vacuum condensation

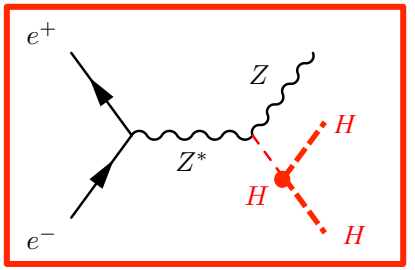


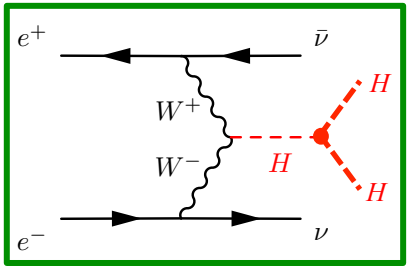




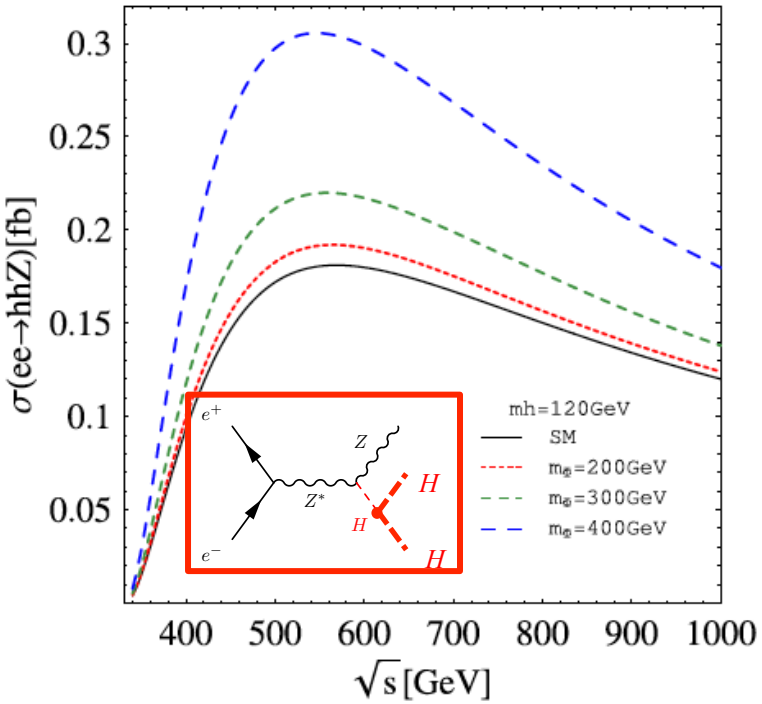
e^+e^- phenomenology:

- double Higgs production at tree-level via Higgstrahlung and WW-Fusion
- both processes include interference with further diagrams
- interference has different sign:
  - $\lambda > \lambda_{SM}$ => σ(ZHH) larger, σ(vvHH) smaller
  - $\lambda < \lambda_{SM}$ => σ(ZHH) smaller, σ(vvHH) larger
- important to measure ***both*** cross-sections
- all projected precisions on λ assume $\lambda = \lambda_{SM}$
- same NP model leads to different sizes of effect on σ(HH) at different ECM!

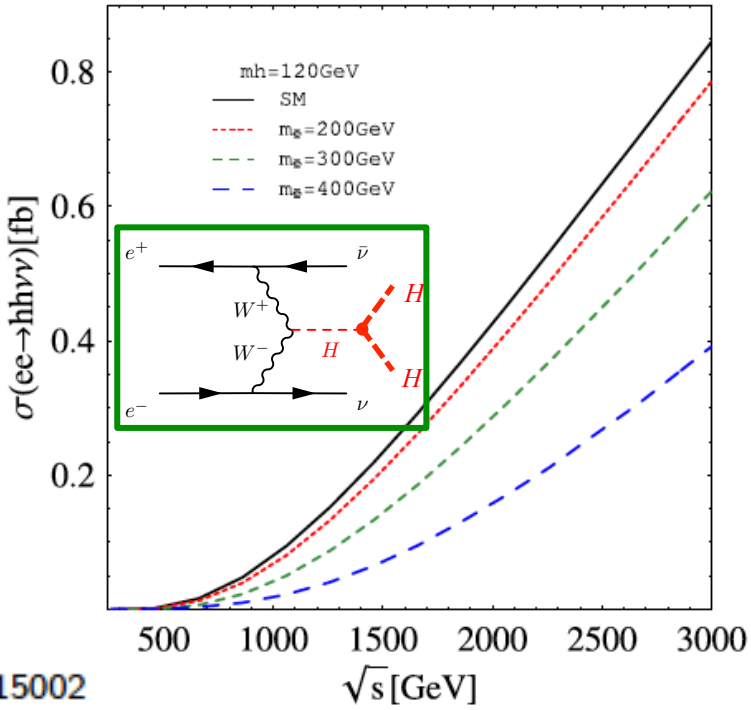




Higgs Self-Coupling – eg 2HDM



- 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:

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

beware when comparing numbers for δλ/λ!

Higgs Self-Coupling: ILC projections

- Snowmass snapshot (m_H = 120 GeV):

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	$1600^{\ddagger}$	500+1000	$1600{+}2500^{\ddagger}$
$P(e^-, e^+)$	$(-0.8, 0.3)$	$(-0.8, 0.3)$	$(-0.8, 0.3/0.2)$	$(-0.8, 0.3/0.2)$
$\sigma(ZHH)$	42.7%		42.7%	23.7%
$\sigma(\nu\bar{\nu}HH)$	–	–	26.3%	16.7%
λ	83%	46%	21%	13%

out-dated

- currently complete reanalysis ongoing, based on
  - HH -> bbbb 6 jets
  - HH -> bbWW* 8 jets

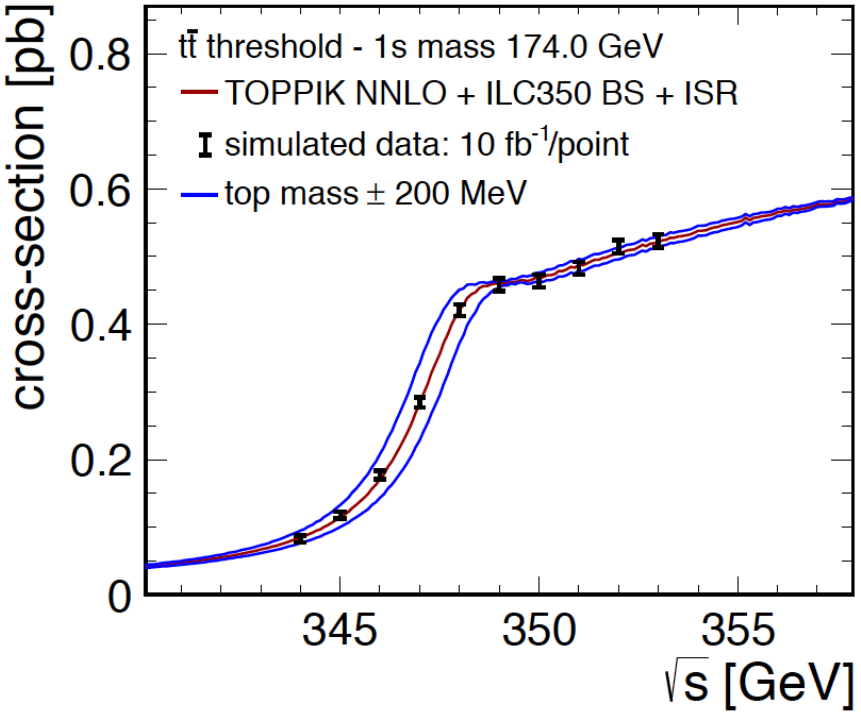
- improved analysis techniques for better suppressionof main background ZZH
  - kinematic fitting
  - matrix element methods, ...
- in any case: will require large integrated luminosities

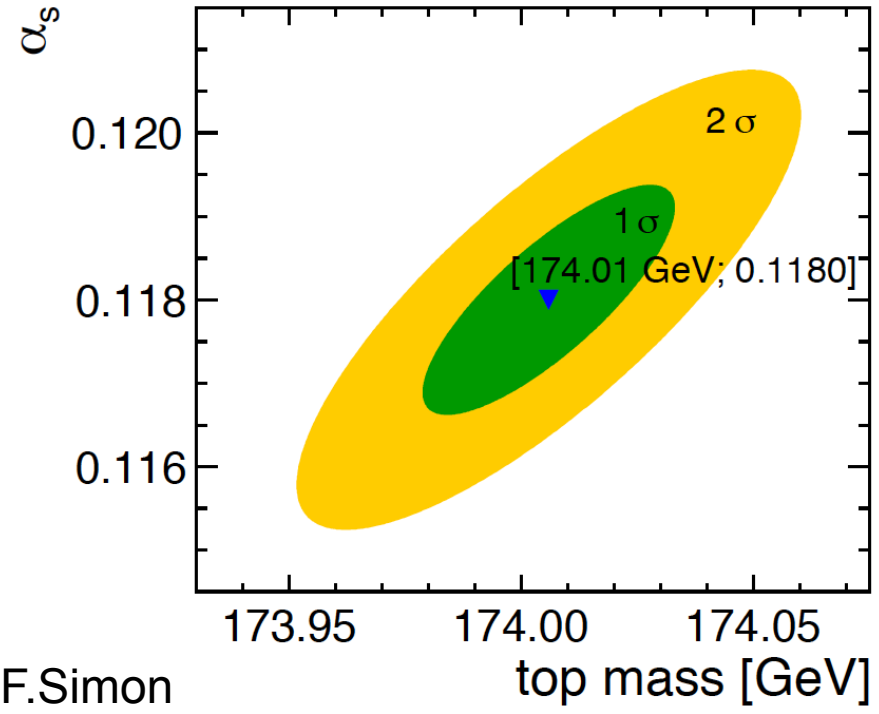
Precision Measurements: Top and more

Top Threshold Scan

- Unique: measure theoretically well-defined “1S” mass
- Fit of NNLO cross section to measured values near threshold yields (100 fb^{-1})

$$\Delta m_t^{\text{thresh}} = 34\,\text{MeV}\;\Delta\alpha_s(m_Z) = 0.0023\;\;\Delta\Gamma_t = 42\,\text{MeV}$$

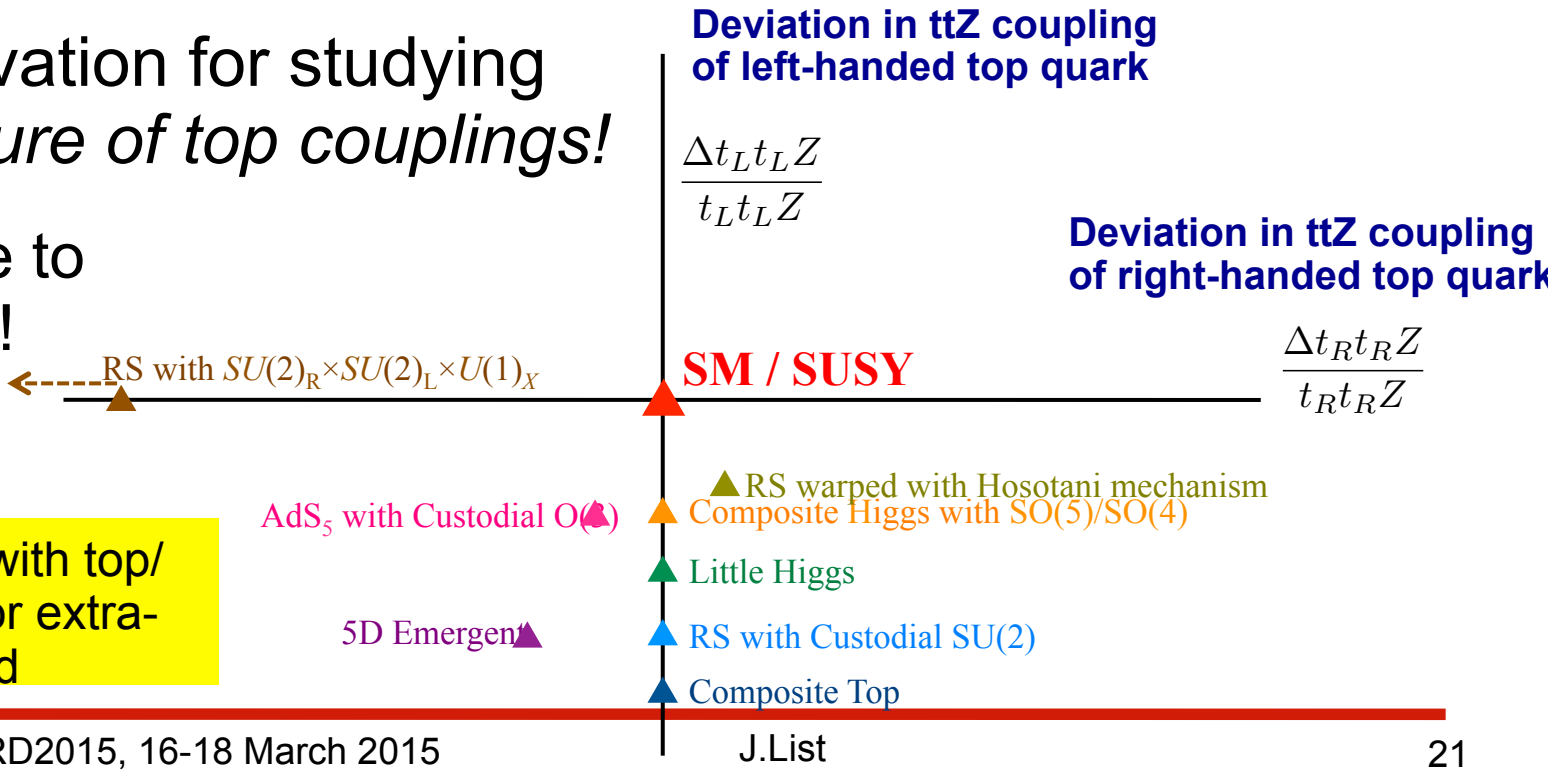




F.Simon

Top Quark Precision Measurements

- The top quark is special:
  - Why so much heavier?
  - Intimately connected to Higgs boson ($y_t \approx 1$)
  - Remember A_{FB}^{0b}(LEP) vs A_l(SLD): something going on in 3rd generation?
- Strong motivation for studying *chiral structure of top couplings!*
- ... ideal place to look for BSM!

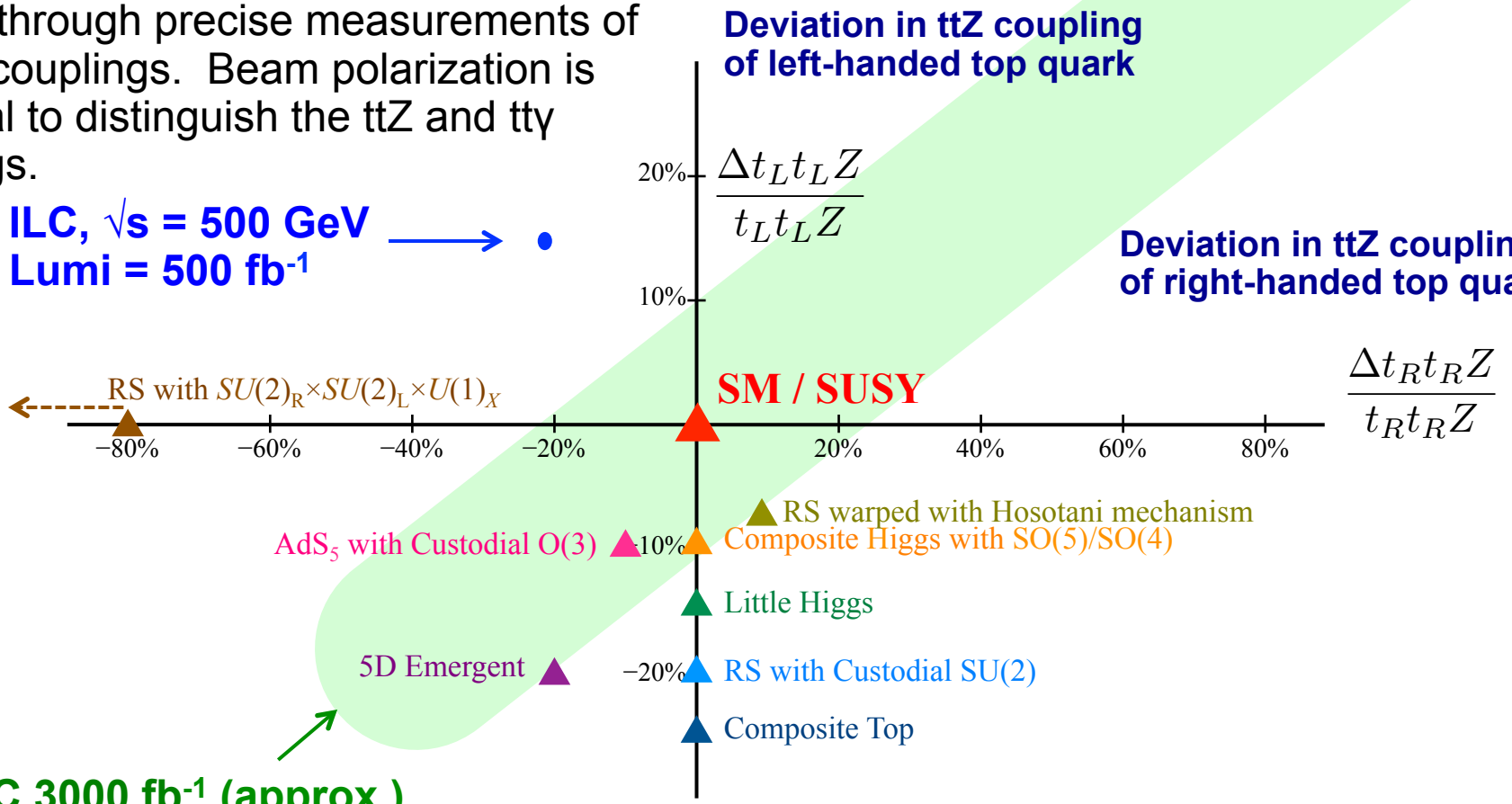


Compilation of models with top/ Higgs compositeness or extra-dimensions by F.Richard

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.

ILC, √s = 500 GeV
Lumi = 500 fb^{-1}



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

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

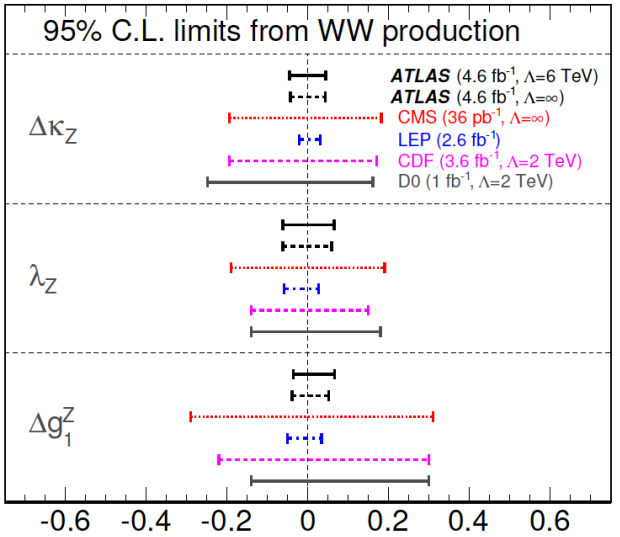
Deviations for different models for new physics scale at ~1 TeV.
Based on F. Richard, arXiv:1403.2893

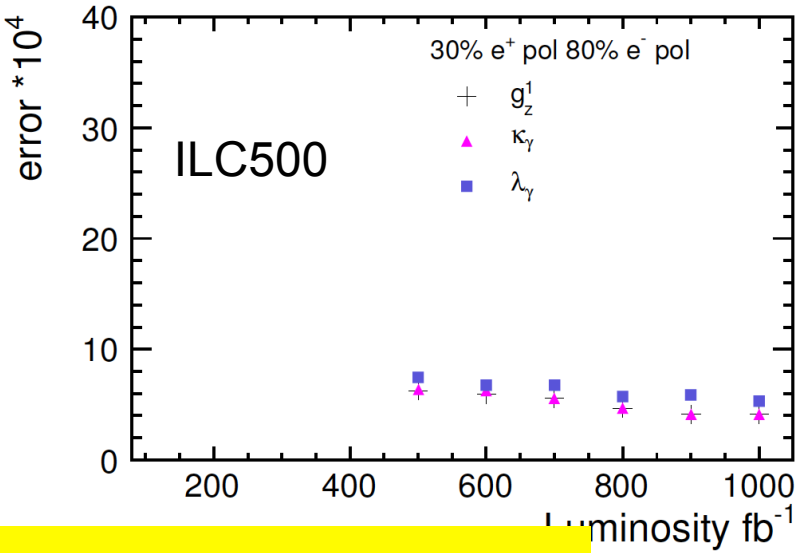
Charged Triple Gauge Couplings

- 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

New Particles

Direct Production of BSM particles

- Is this still possible at ILC
  - given LHC exclusion limits reach already beyond a TeV?
  - and when they even grow more stringent at LHC 13/14 TeV?
- Consider two 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 model behind? Are there more new particles?

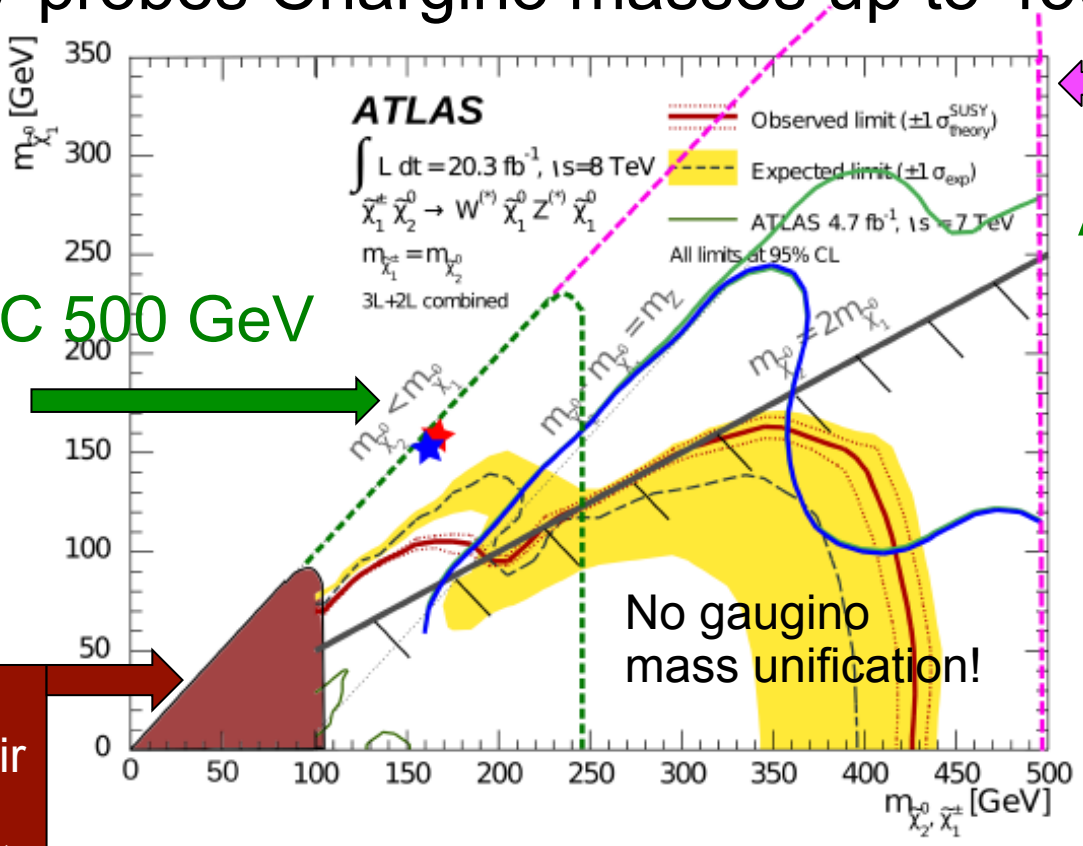
  B. No deviation anywhere
     - What does this really tell us?
     - Can there be something very well hidden?

We hope of cours for A, but let's look more closely at B!

Reading limits: Eg Charginos & Neutralinos

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

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



ILC 500 GeV

ILC 1 TeV

ATLAS projection 14 TeV 3 ab^{-1}

ATLAS projection 14 TeV 300 fb^{-1}

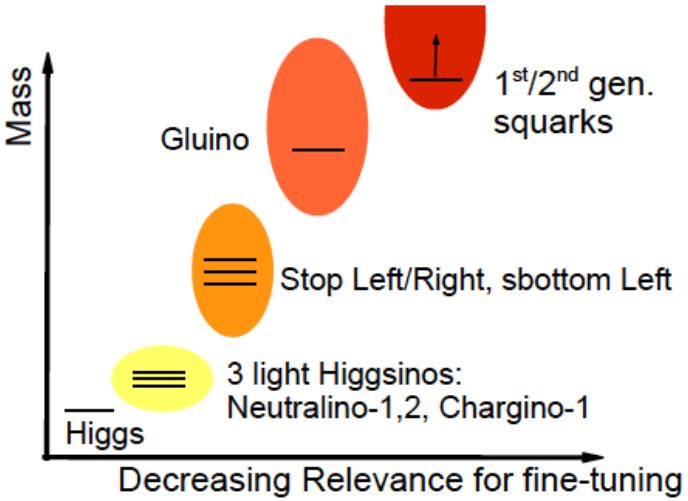
LEP – chargino pair production, independent of chargino decay mode!

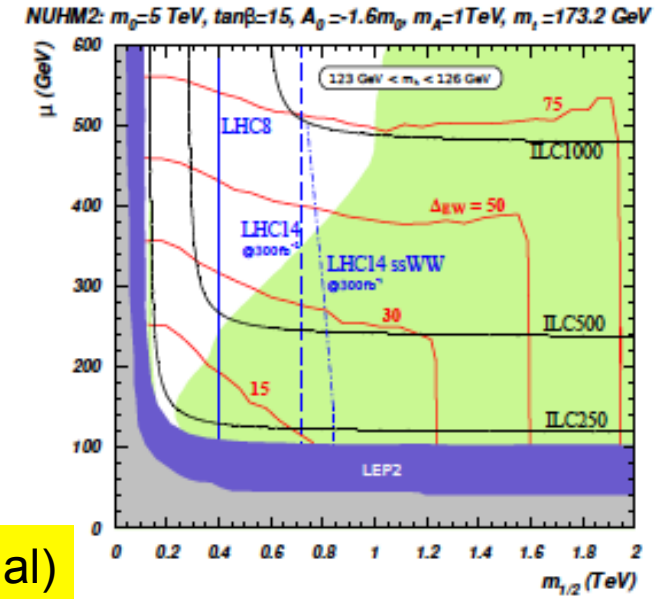
Loop-hole free, model-independent sensitivity down to very small mass differences

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

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 $\mu \lesssim \sqrt{s}/2$

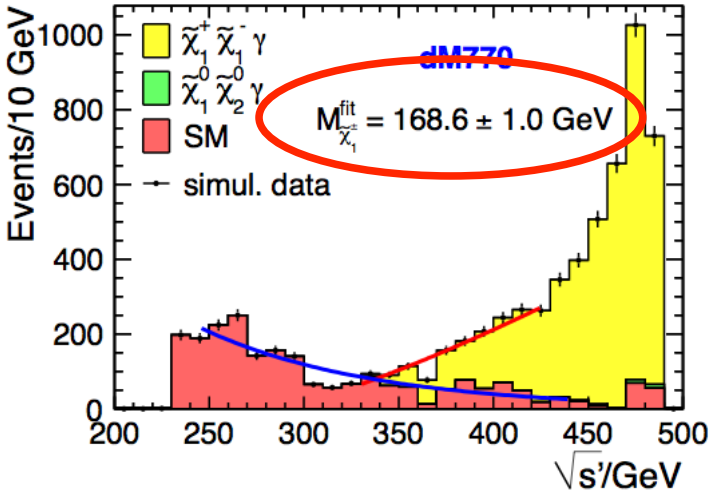
Theory-level study (H.Baer et al)

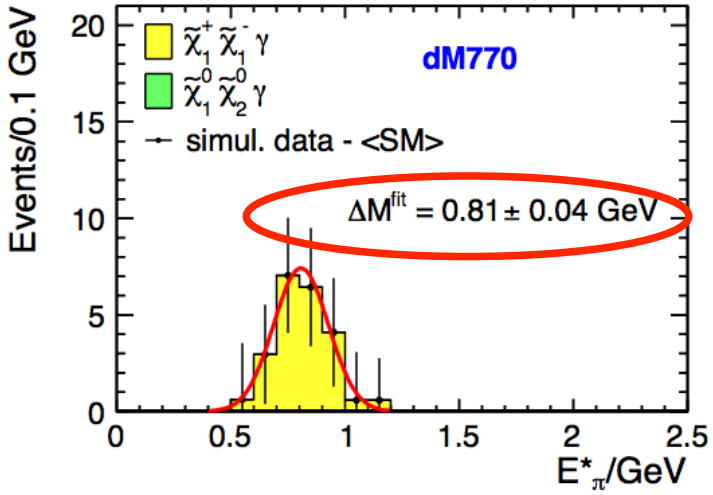
Can the detectors cope?

- Note: ILC detectors run without trigger
- Detector simulation study [EPJ C73 (2013) 2660]:
  - $\mu = 167\,\text{GeV},\ M_1 = 5\,\text{TeV},\ M_2 = 10\,\text{TeV}$
    $\Rightarrow \Delta M(\tilde{\chi}_1^{\pm}; \tilde{\chi}_1^0) \simeq 1\,\text{GeV}$
  - $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-\gamma_{\text{ISR}}$ 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

Extreme case!

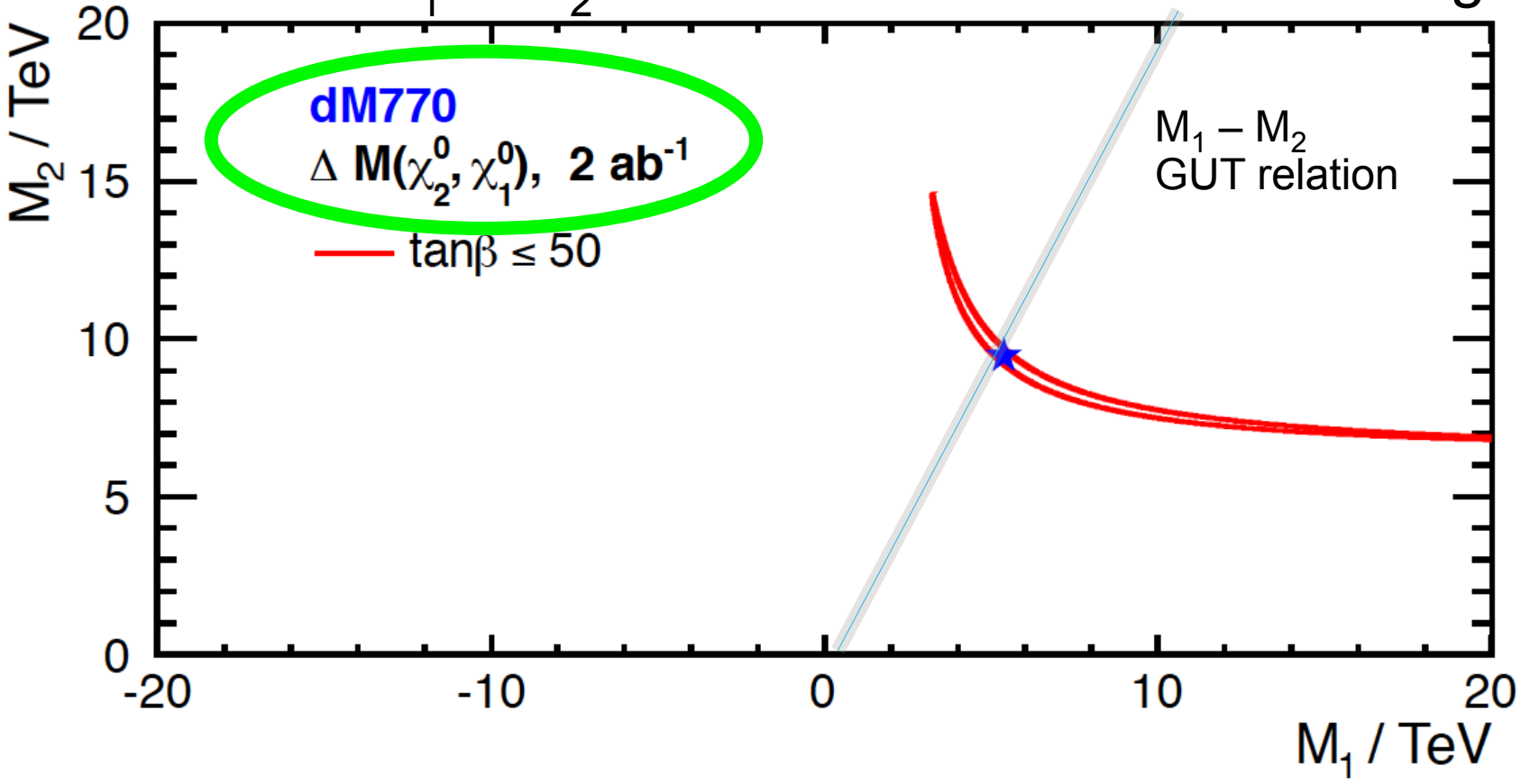
+ cross sections to few %



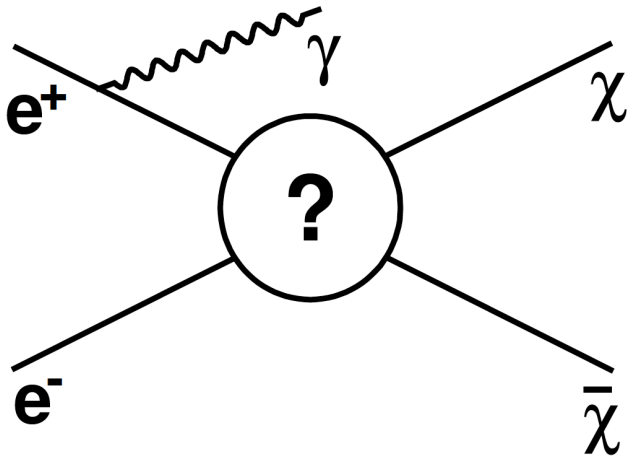


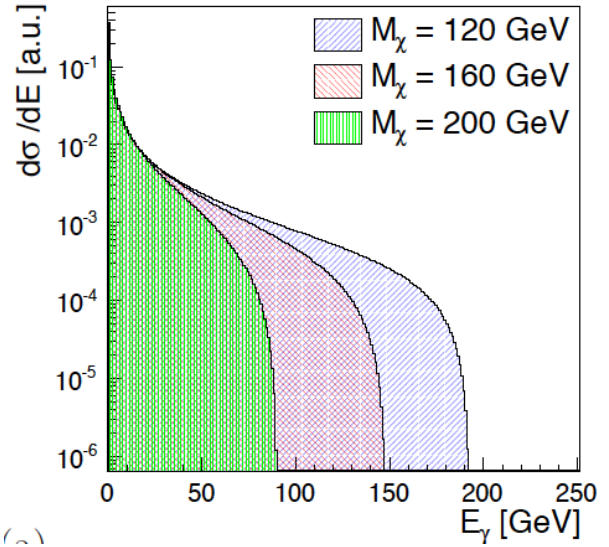
Parameter Determination!

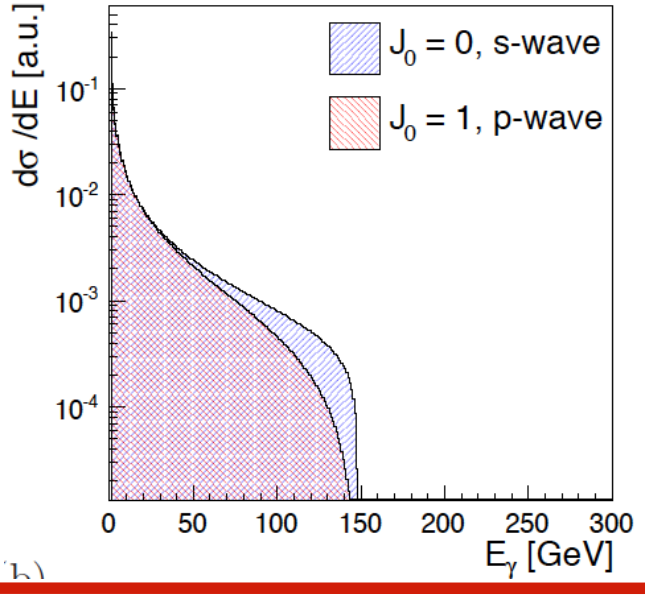
- 500 fb^{-1}: determine μ to ± 0.5 GeV
- 2 ab^{-1} and neutralino mass difference
  => constrain M_1 & M_2 to narrow band in multi-TeV regime:



Case A or B example: WIMPs at the ILC



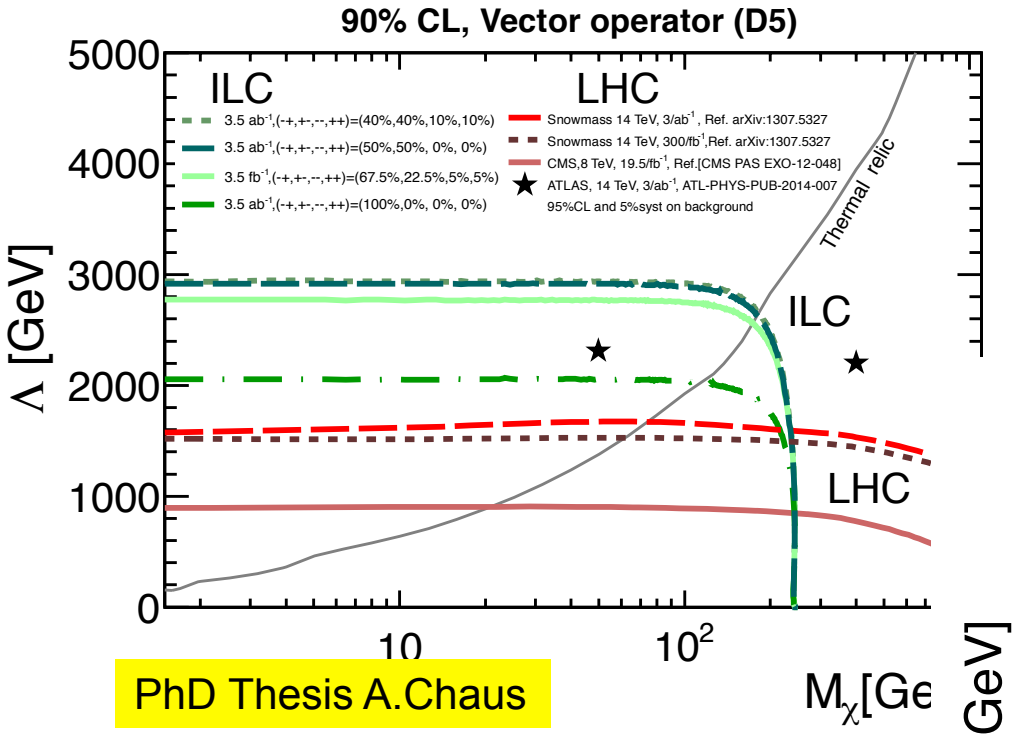




Know √s: E_γ spectrum offers

- 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]

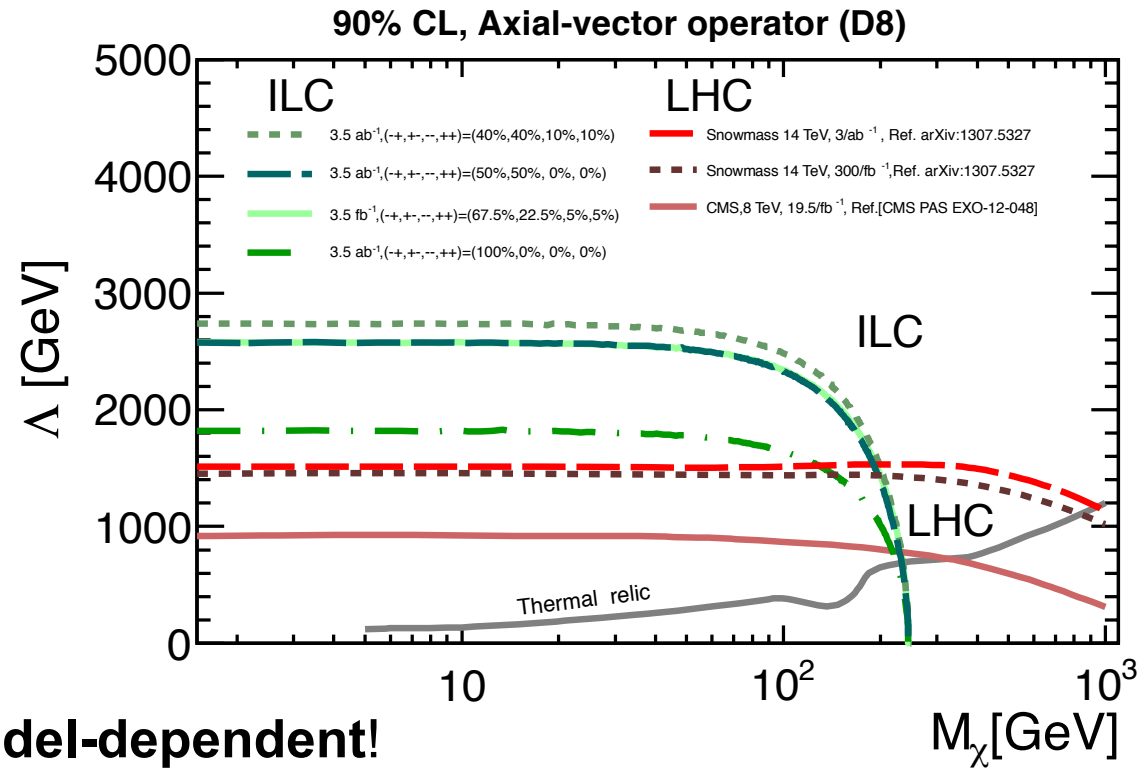
Mono-photons at LHC and ILC



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**!

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^- ?
- **more on WIMPs: talk by M.Habermehl on Wednesday**

Conclusions

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

discoveries at LHC and/or ILC ?

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

maybe?

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 spectroscopy
- model discrimination

further options

depend on results & money

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

Take Home Message I

e^+e^- collisions *at various* $\sqrt{s}$ are essential to complement the LHC picture of the Higgs boson, the top quark and BSM physics:

- The full profile of the 125-GeV Higgs boson
  - $\sqrt{s}$ = 250 or 350 GeV (ZH coupling)
  - *and* at $\sqrt{s} \approx$ 500 GeV (all the rest, incl. ZHH)
  - vvHH at $\sqrt{s} \approx$ 1 TeV: *complementary* information on BSM
- Top physics
  - starts at $\sqrt{s} = \geq$ 350 GeV (threshold scan)
  - ew chiral coupling measurements: $\sqrt{s} = \geq$ 400-450 GeV
  - Yukawa coupling: : $\sqrt{s} = \geq$ 500 GeV
- BSM, T/QGCs, di-fermions, .. : the higher $\sqrt{s}$ the better!

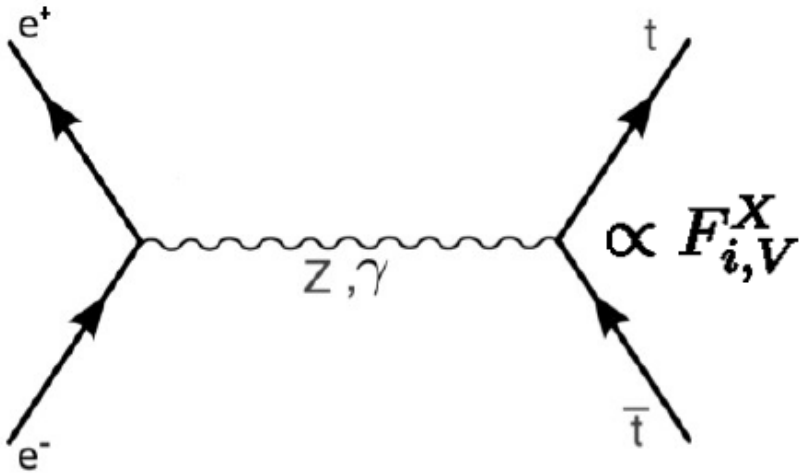
Take Home Message II

The ILC is the only technologically proven accelerator to cover *the full program:*

- A full precision profile of the 125 GeV **Higgs** sensitive to BSM contributions, incl. ZHH and ttH
- Precision measurements of mass, chiral couplings, rare decays, etc of the **Top** quark ….
- … and di-boson (e.g. TGCs) and di-fermion (Z') production allow **unprecedented scrutiny of the SM**
- **plus:** a unique **discovery potential** in important BSM scenarios, complementary to the LHC (light Higgsinos, small mass differences, WIMPs, light higgses…)

Backup

Testing the chiral structure of the SM



CP violating

$$\Gamma^{ttX}_{\mu}(k^2,q,\bar{q}) = -ie\left\{\gamma_\mu\left(F^X_{1V}(k^2)+\gamma_5 F^X_{1A}(k^2)\right)+\frac{\sigma_{\mu\nu}}{2m_\cdot}(q+\bar{q})^\mu\left(iF^X_{2V}(k^2)+\gamma_5 F^X_{2A}(k^2)\right)\right\}, \qquad (2)$$

$$\mathcal{F}^L_{ij} = -F^\gamma_{ij}+\left(\frac{-\frac{1}{2}+s_w^2}{s_w c_w}\right)\left(\frac{s}{s-m_Z^2}\right)F^Z_{ij}$$

$$\mathcal{F}^R_{ij} = -F^\gamma_{ij}+\left(\frac{s_w^2}{s_w c_w}\right)\left(\frac{s}{s-m_Z^2}\right)F^Z_{ij}\ ,$$

Pure γ or pure Z^0 : $\sigma \backsim (F_i)^2 \Rightarrow$ No sensitivity to sign of Form Factors

Z^0/γ interference : $\sigma \backsim (F_i) \Rightarrow$ Sensitivity to sign of Form Factors

Disentangling the couplings

At ILC **no** separate access to ttZ or ttγ vertex, but ...

ILC 'provides' two beam polarisations

There exist a number of observables sensitive to chiral structure, e.g.

σ_I x-section

$A^t_{FB,I} = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)}$ Forward backward asymmetry

$(F_R)_I = \frac{(\sigma_{t_R})_I}{\sigma_I}$ Fraction of right handed top quarks

⇩

Extraction of six (five) unknowns

$F^\gamma_{1V}, F^Z_{1V}, F^\gamma_{1A} = 0, F^Z_{1A}$

F^γ_{2V}, F^Z_{2V}

Analoguously for CP violating couplings: use 4 difference beam polarisation combinations

Physics behind EWSB at TeV scale

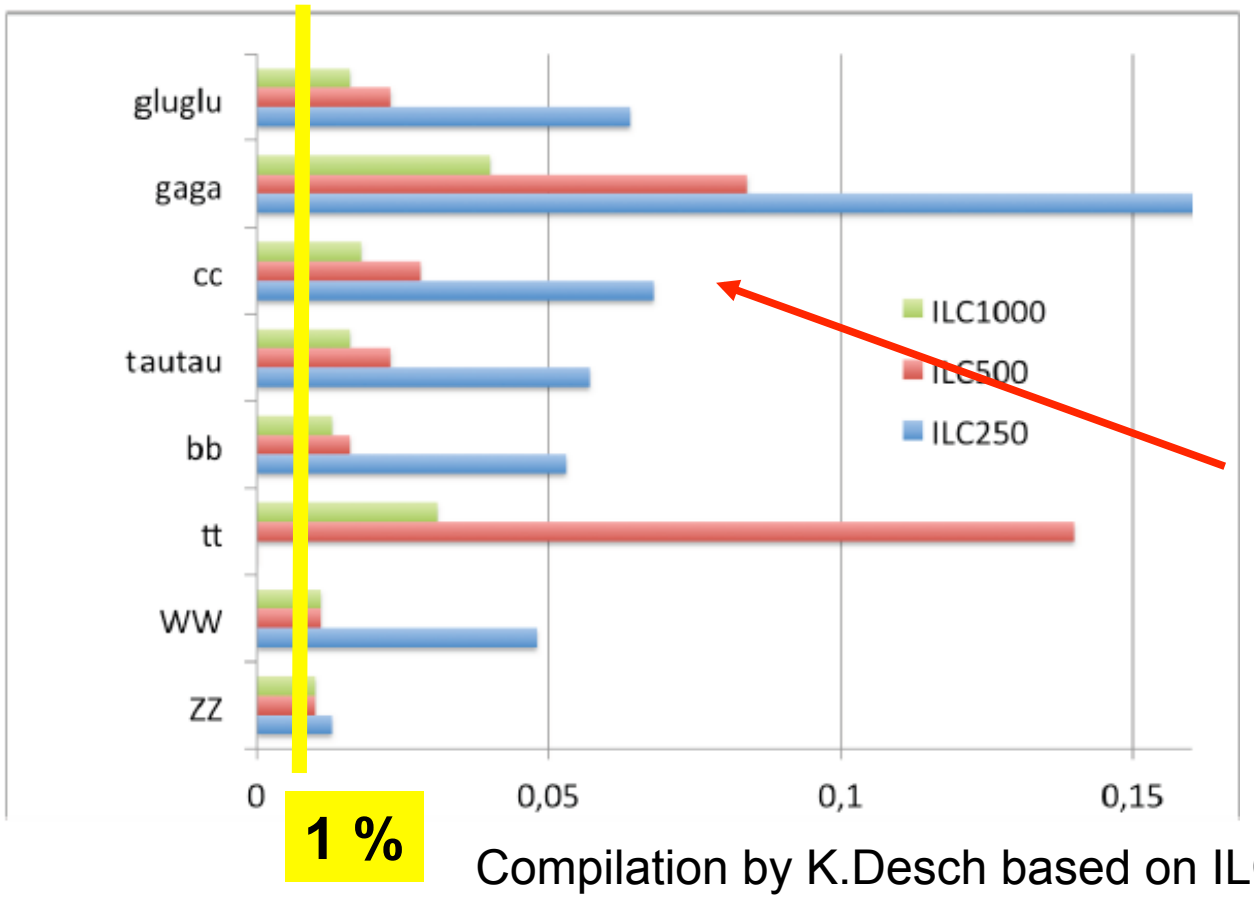
There are two possible scenarios for the physics behind EWSB around the TeV scale:

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.

Model-independent Coupling Determination

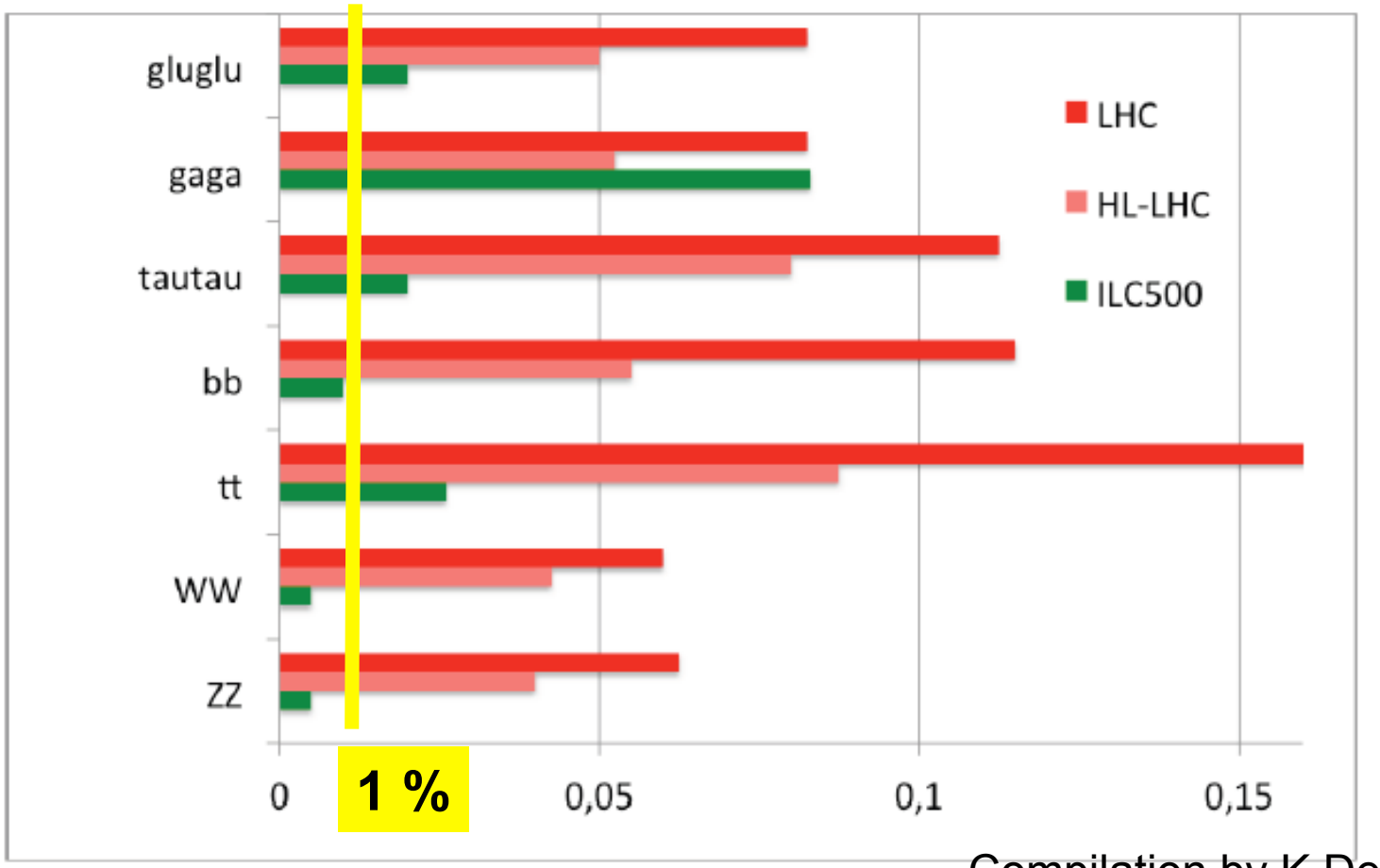


- Fully model-independent
- No assumptions
- ILC unique
- Note: cc!

Compilation by K.Desch based on ILC Higgs Snowmass Whitepaper

Precision sufficient to detect deviations expected in a variety of models

Global coupling fits a la LHC



Fineprint:

LHC: based on
W.Murray, HL-LHC workshop
Aix-lex-bains, slide 24
averaged ATLAS+CMS
average upper+lower range
(ATLAS+CMS differ considerably
for some parameters,
discussion on syst. errors
ongoing)

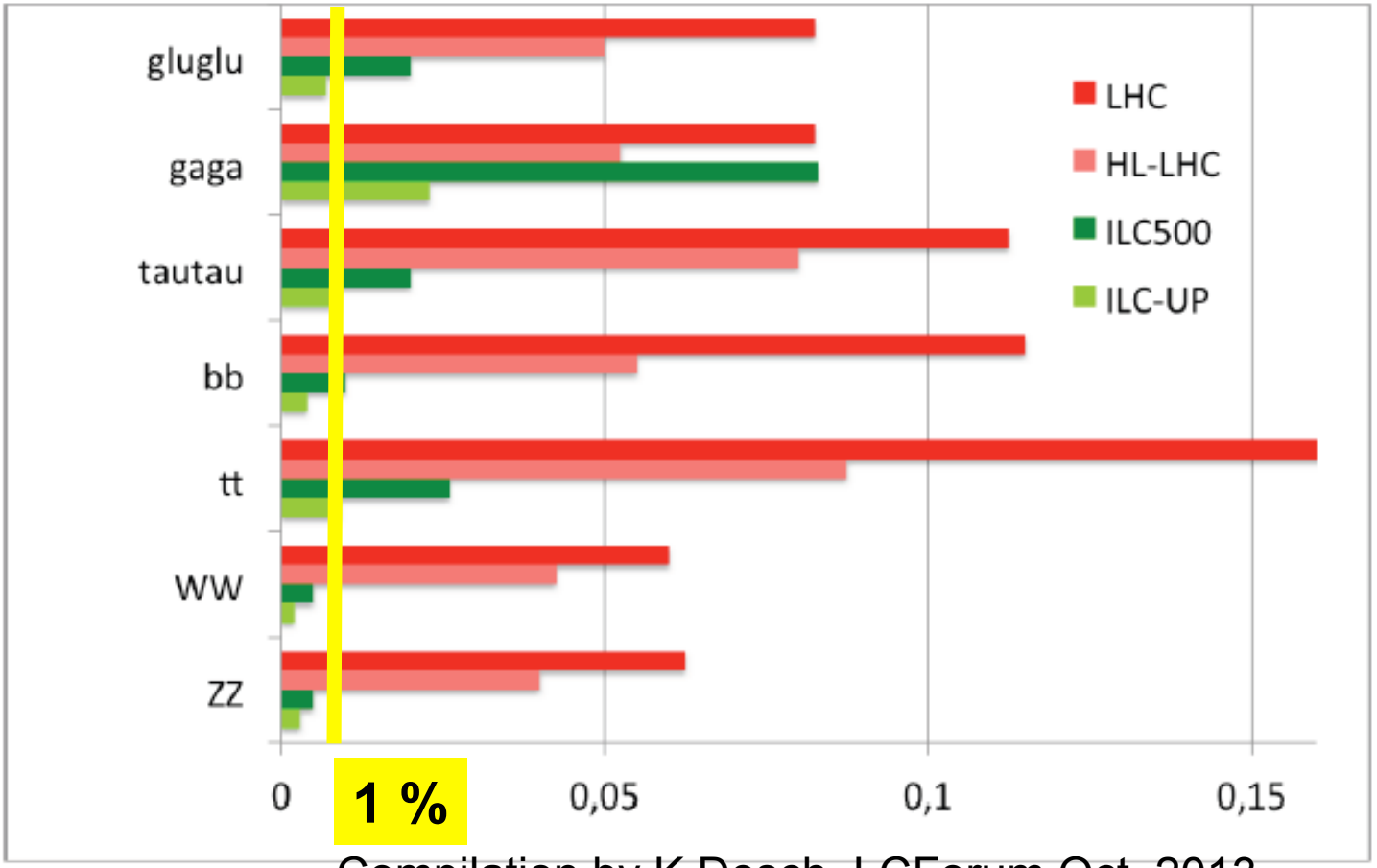
ILC: based on ILC white paper
arxiv:1310.0763

ILC-500 =
250 fb^{-1} @ 250 GeV +
500 fb^{-1} @ 500 GeV

Compilation by K.Desch, LCForum Oct. 2013

Significant improvement over HL-LHC, reaching sub-percent for WW, ZZ

Global coupling fits a la LHC



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average upper+lower range
(ATLAS+CMS differ considerably
for some parameters,
discussion on syst. errors
ongoing)

ILC: based on ILC white paper
arxiv:1310.0763

ILC-500 =
250 fb^{-1} @ 250 GeV +
500 fb^{-1} @ 500 GeV

ILC-UP =
1150 fb^{-1} @ 250 GeV +
1600 fb^{-1} @ 500 GeV+
2500 fb^{-1} @ 1000 GeV

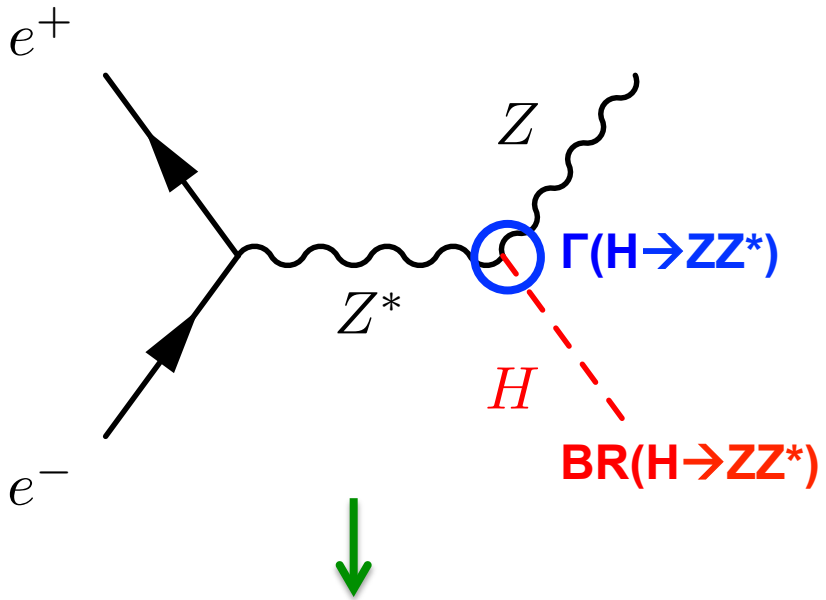
1TeV ILC: typically factor 2 improvement over ILC500, bb → sub-percent

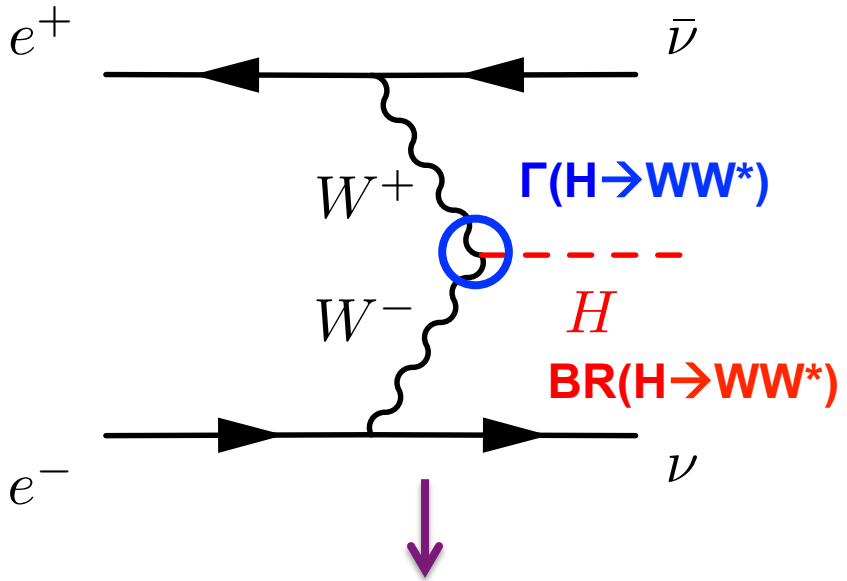
Higgs Coupling Determination

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:





ZH 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

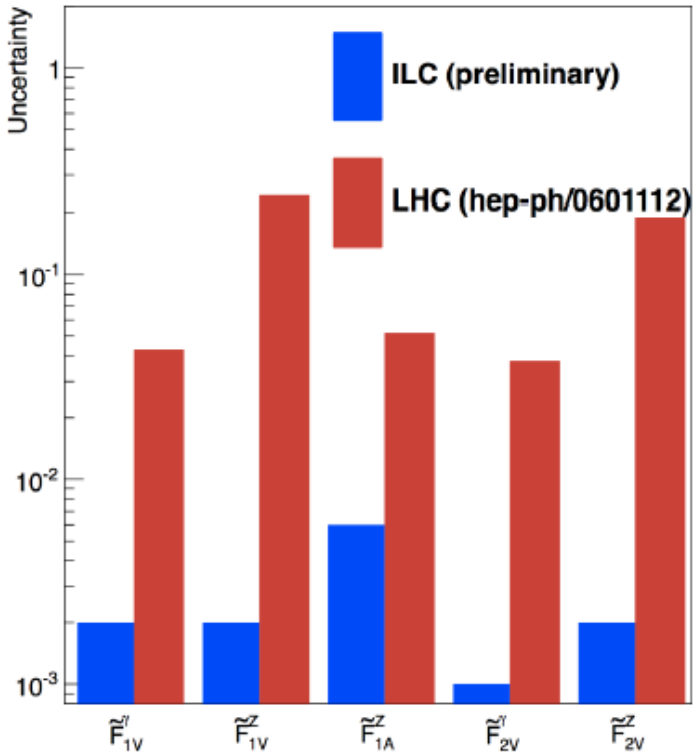
ILD Full Detector Simulation Study

ArXiv: 1307.8102

Precision: cross section ~ 0.5%, Precision A_{FB} ~ 2%, Precision λ_t ~ 3-4%

Accuracy on CP conserving couplings

Log scale!



- ILC might be up to two orders of magnitude more precise than LHC ($\sqrt{s}$ = 14 TeV, 300 fb^{-1})
  Disentangling of couplings for ILC
  One variable at a time For LHC

- However LHC projections from 8 years old study

- Strong encouragement to update these numbers!
  First step is Phys. Rev. Lett. 110 (2013) 172002 by CMS

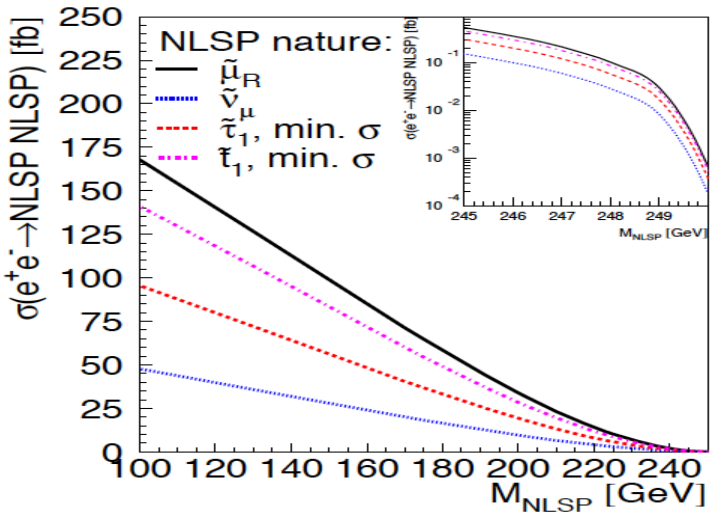
- Potential for CP violating couplings at ILC under study

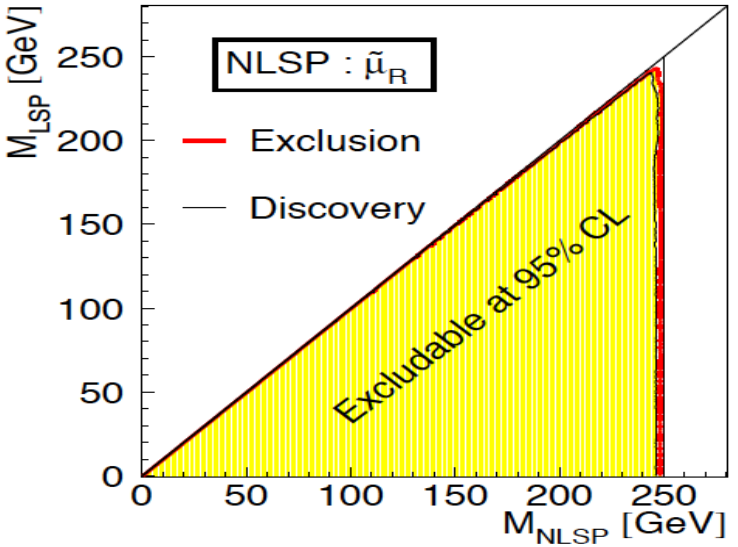
ILC will be indeed high precision machine for electroweak top couplings

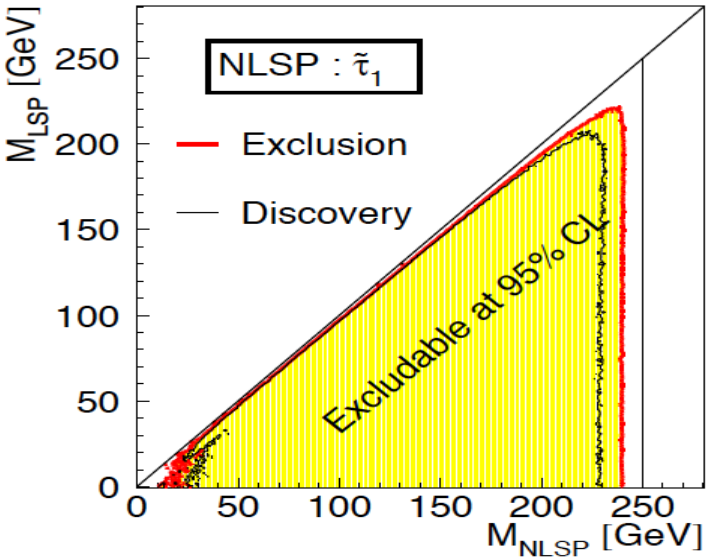
SUSY at the ILC

...is naturally simplified:

- NLSP pair production does only depend on mass of NLSPs:



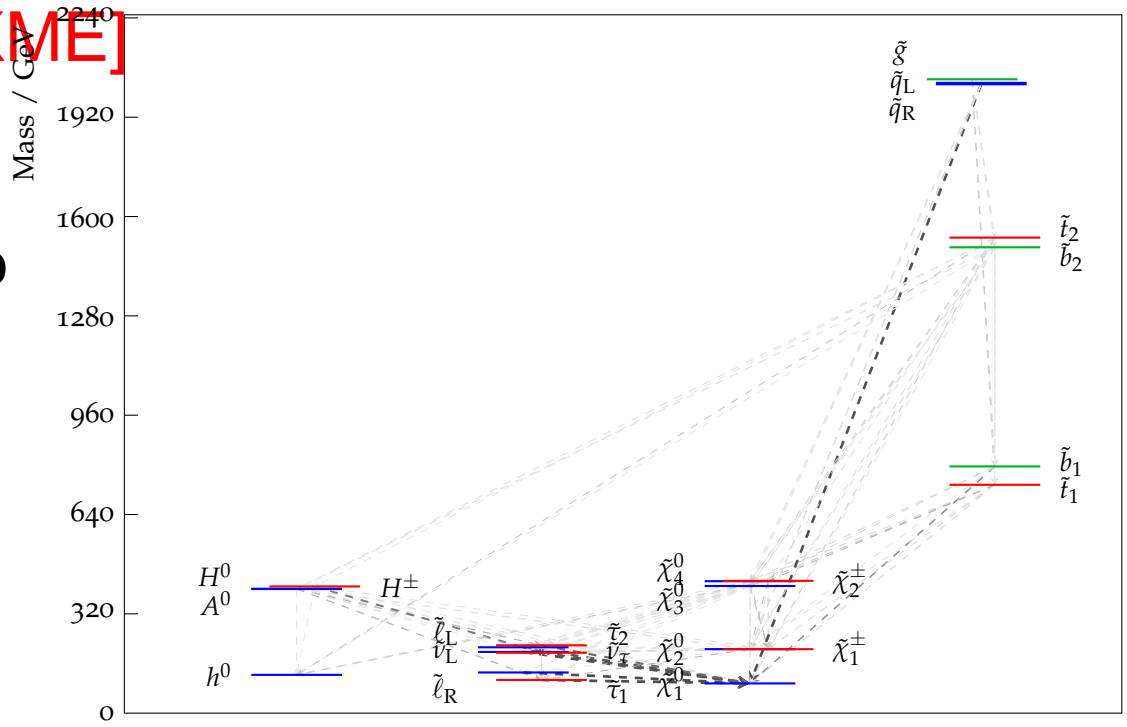




Loop-hole free, model-independent sensitivity down to very small mass differences

Case A: a rich SUSY spectrum

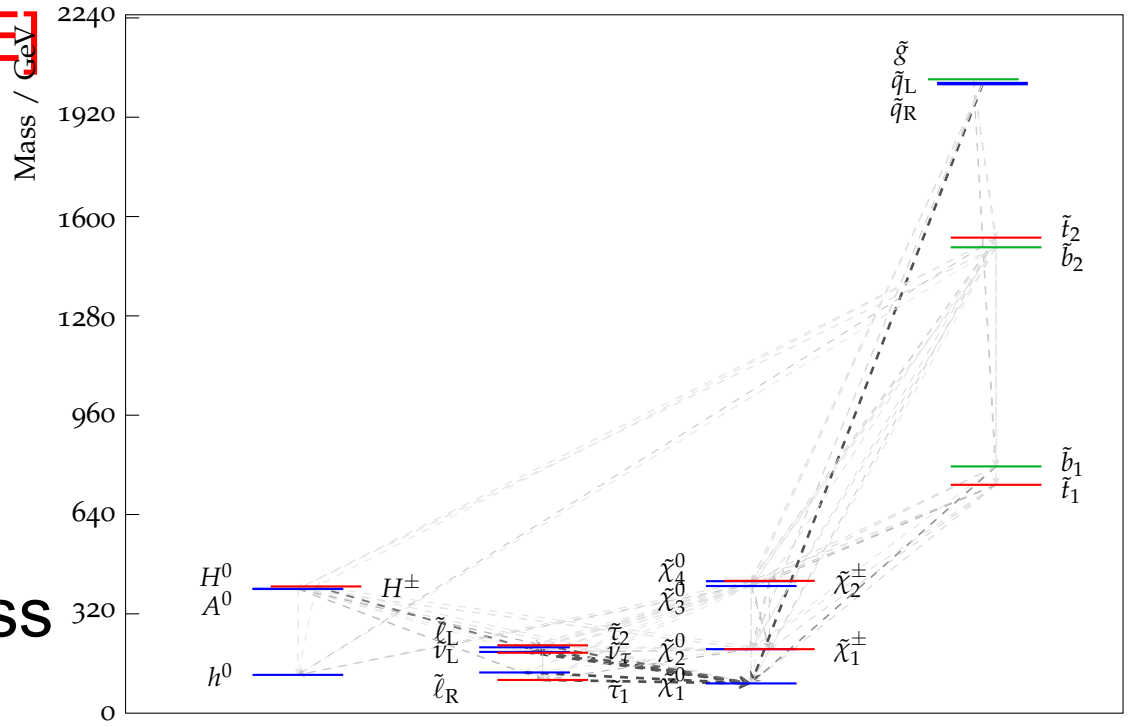
- STC8 [PhysRevD FIXME]
- LHC 14 TeV:
  - direct squark / gluino difficult due to high mass & long decay chains
  - direct stop/sbottom: first signal!
  - direct ewkino: evebntually....



- How do we know it's SUSY?
  - measure spin & couplings! => masses and cross-sections!

Case A: sbottom signal at LHC

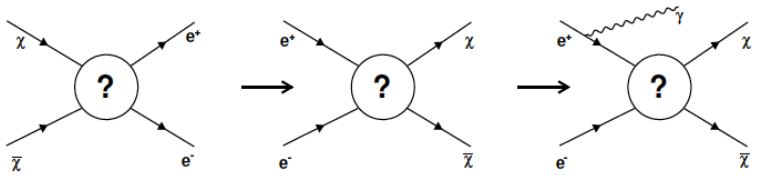
- plot from Batool FIXME]
- LHC 14 TeV:
  - can isolate direct sbottom production
  - determine endpoint in mass [fixme!]
- need to know LSP mass to convert endpoint into sbottom mass => ILC!



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:
  $\sigma_{LR} = \sigma_{RL} = 0,\ \sigma_{LL} = \sigma_{RR} > 0$

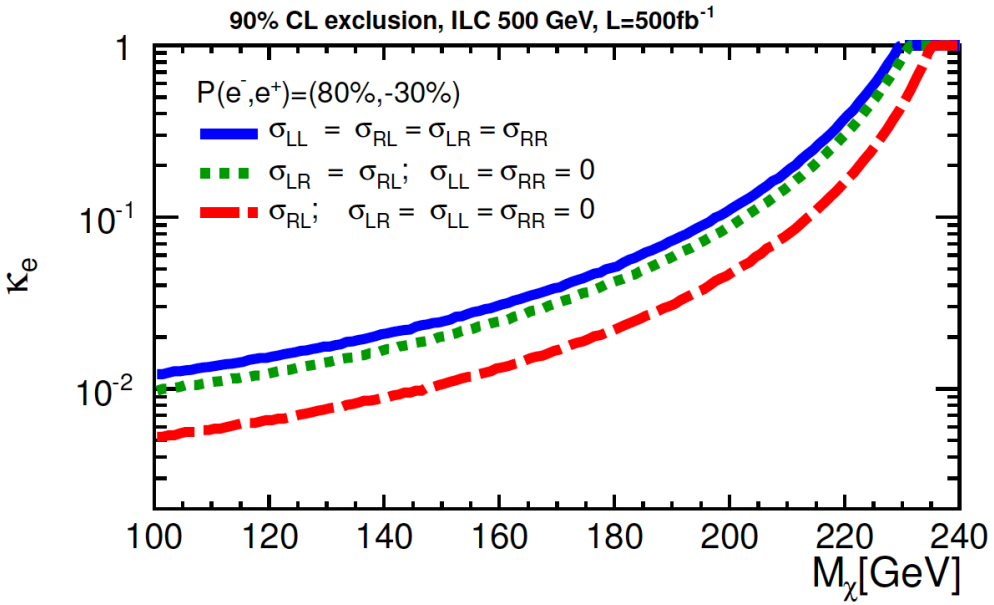
- M_χ - WIMP mass
- S_χ - WIMP spin $= -\frac{1}{2}$
- Λ - energy scale of the new physics that provides the coupling, $\sigma \sim \frac{1}{\Lambda^4}$
- Choice of operator

Exclusion reach: 500 GeV, **500fb^{-1}**

"Cosmological" Approach

- Spin -1/2
- P-wave

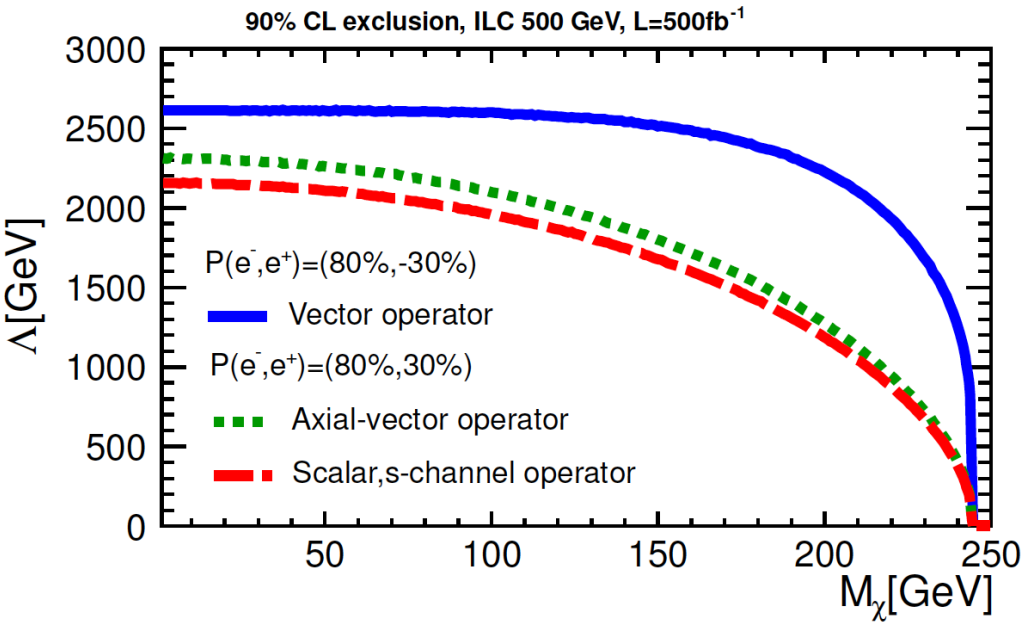
Can exclude down to ~1% annihilation fraction to e^+e^-



Effective Operator Approach

- Spin -1/2

Can exclude up to Λ~2.5 TeV

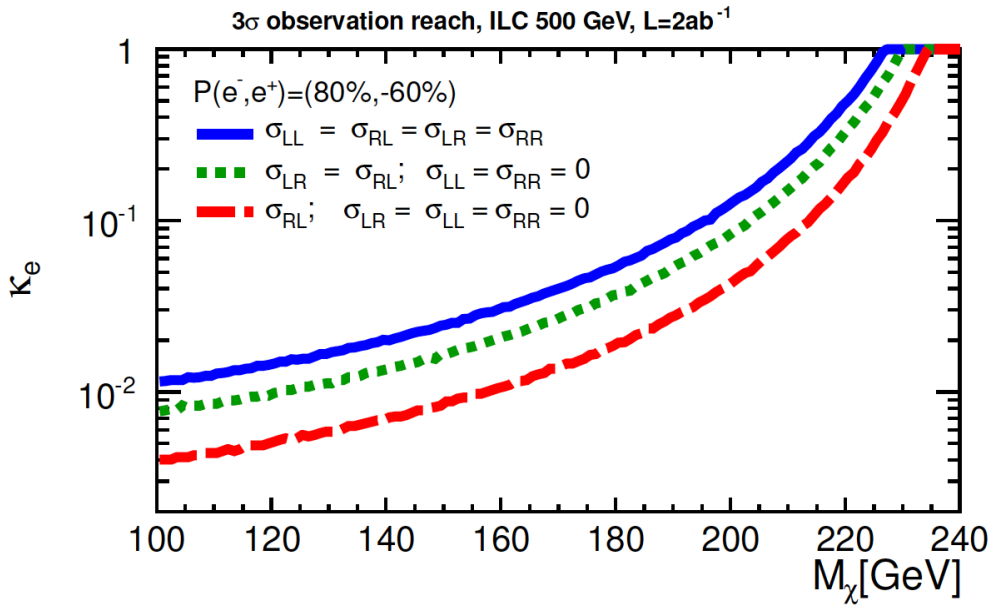


Observation reach: 500 GeV, **2ab^{-1}**

"Cosmological" Approach

- Spin -1/2
- P-wave

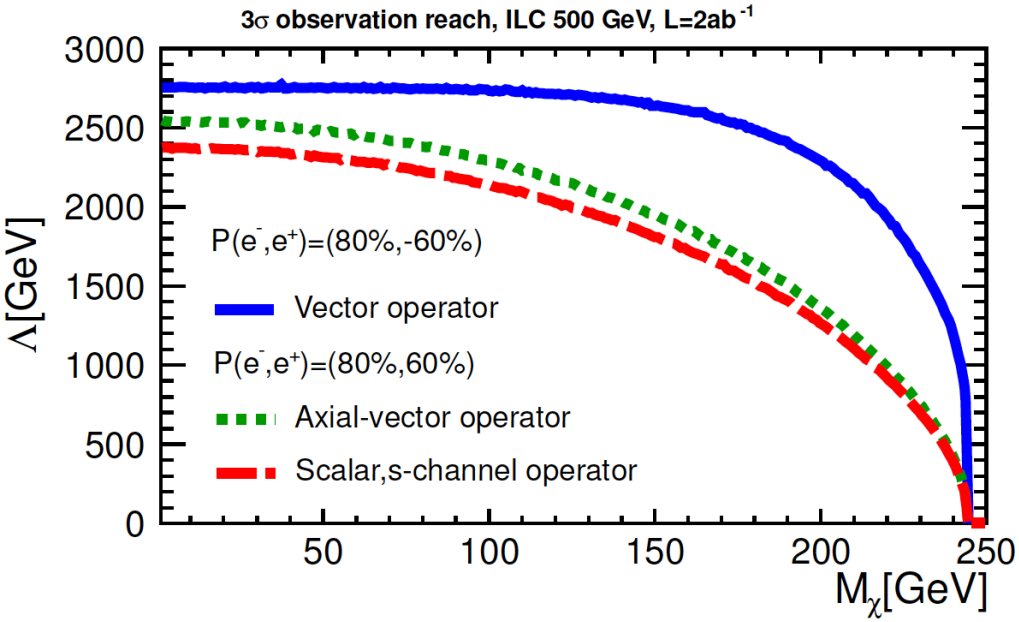
Can observe down to ~1 % annihilation fraction to e^+e^-



Effective Operator Approach

- Spin -1/2

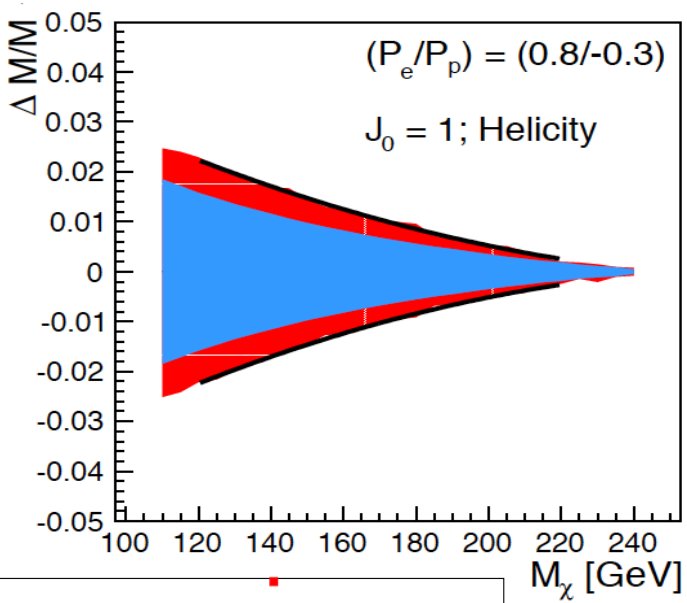
Can observe up to Λ~2.5 TeV



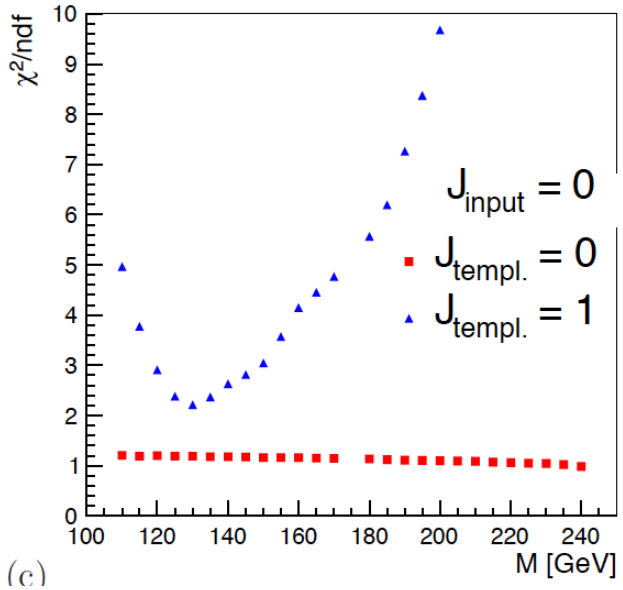
From EPJC 72 (2012) 2213, Bartels et al

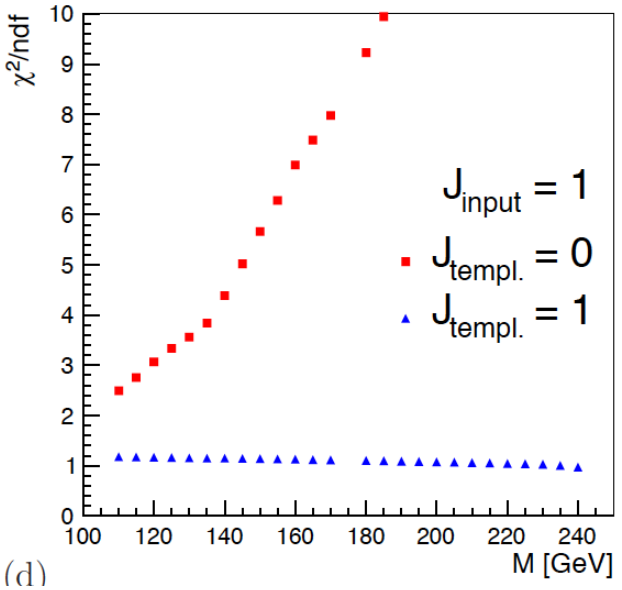
WIMP characterisation

- 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



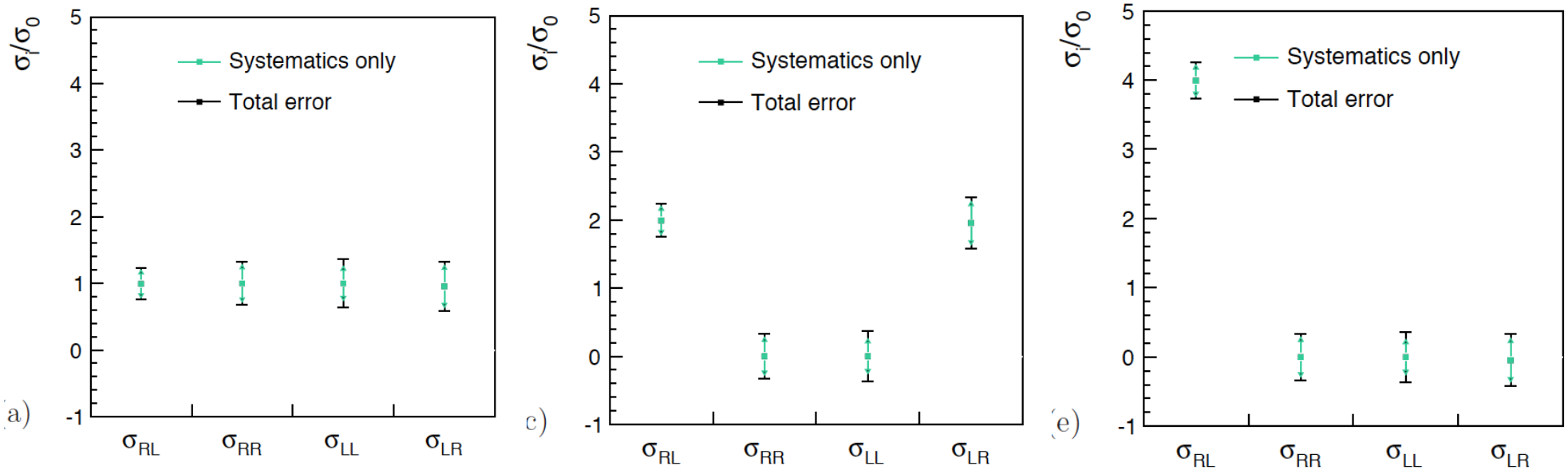


From EPJC 72 (2012) 2213, Bartels et al

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:

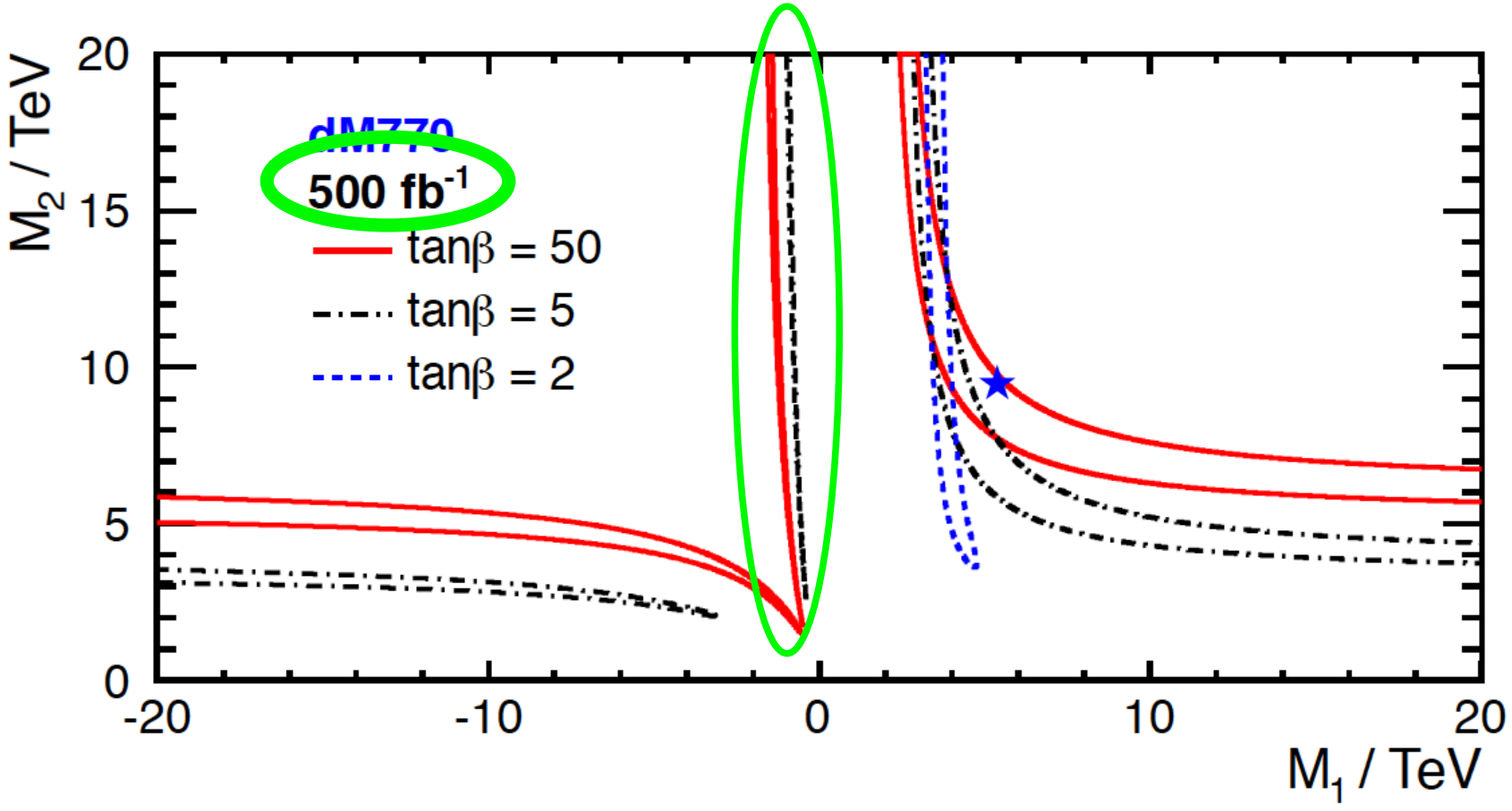
"Equal" "Helicity & Parity conserving" "Anti-SM"



Clear distinction possible!

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 ?



The ILC, Japan and the rest of the world

Technological Basis: SCRF

- superconducting cavities

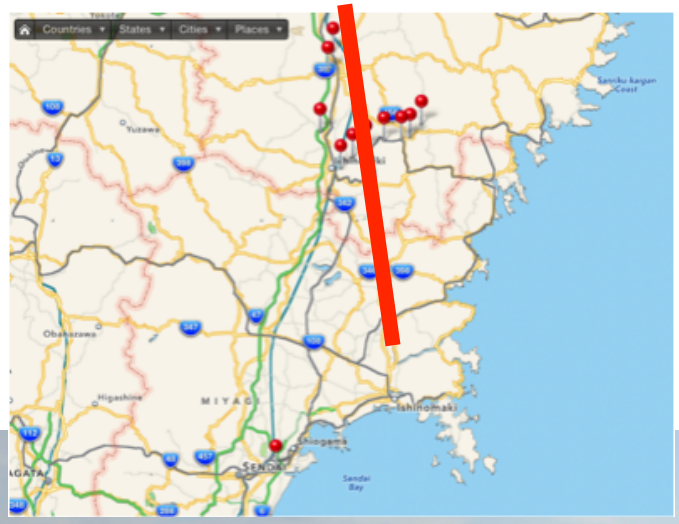
- > 10 years successful operation in FLASH @ DESY
- European XFEL: "5% ILC prototype" being built in Hamburg → mass production!

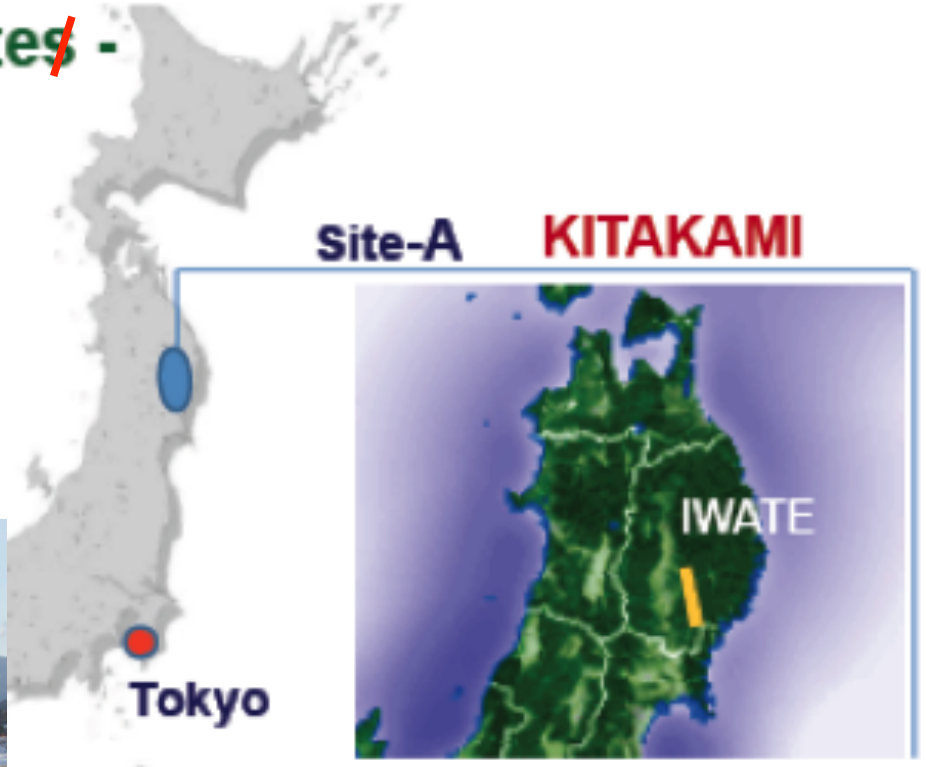
Parameter	Value
Av. field gradient	**31.5 MV/m**
Length	1.3026 m
Frequency	1.3 GHz
Quality factor Q0	> 1010
# 9-cell cavities	16024
# cryomodules	1855

A mature and proven technology

The ILC Site in Japan

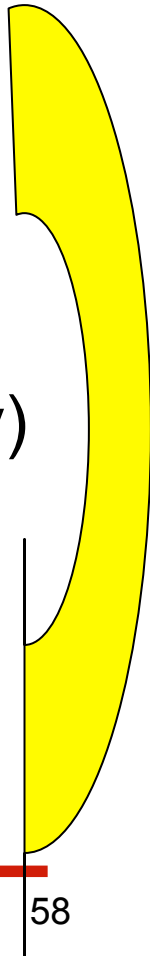
- Japanese Mountainous Sites -





2013/2014 - An exciting year for the ILC

- June: Publication of the Technical Design Report
- August: selection of candidate site - ILC goes Kitakami
- September:
  - Japanese Science Council recommends more detailed study of how to implement ILC in Japan
  - government announces start of diplomatic negotiations
- December: government grants 0.5M Yen for ILC preparation as requested by MEXT (Jap. Science Ministry)
- January: MEXT Minister visits DOE and talks about ILC
  → waiting for P5..
- May: MEXT establishes “Academic Experts Committee”, report due end FY15



And the rest of the world

- Update of the European Strategy: "*Europe looks forward to a proposal from Japan to discuss a posssible participation*"
- Asian Statement on ILC in Japan
- April 2013: US-Japan Science & Technology Joint High Level Committee discusses ILC (next meeting: July 2014)
- Jan 2014:
  Federation of Diet Members for the ILC writes to DoE
- May 2014: MEXT & Diet Members write to CERN DG and EU Commission
- Yesterday: presentation of US P5 report to HEPAP

A glimpse into the P5 report

Slides available at: http://science.energy.gov/hep/hepap/meetings/20140422/

Recall, the Charge specifies three budget scenarios, with ten-year profiles:

A. *FY2013 budget baseline: flat for 3 years, then +2% per year.*
B. *FY2014 President's budget request baseline: flat for 3 years, then +3% per year.*
C. *Unconstrained:* projects "*…needed to mount a leadership program addressing the scientific opportunities…*"

Difference between scenarios integrated over the decade is ~$0.5B.

"***…consider these scenarios not as literal budget guidance but as an opportunity to identify priorities and make high-level recommendations.***"

- Unlike other regions in the world, in recent years the U.S. particle physics program has not invested substantially in construction of experimental facilities. Addressing the Drivers in the coming and subsequent decades requires renewed investment in projects. In constant or near-constant budgets, this implies an increase in the fraction of the budget that is invested in new projects, which is currently approximately 16% (and was even lower before).

- **Recommendation 5: Increase the budget fraction invested in construction of projects to the 20%–25% range.**

- **Recommendation 10: Complete the LHC phase-1 upgrades and continue the strong collaboration in the LHC with the phase-2 (HL-LHC) upgrades of the accelerator and both general-purpose experiments (ATLAS and CMS). The LHC upgrades constitute our highest-priority near-term large project.**

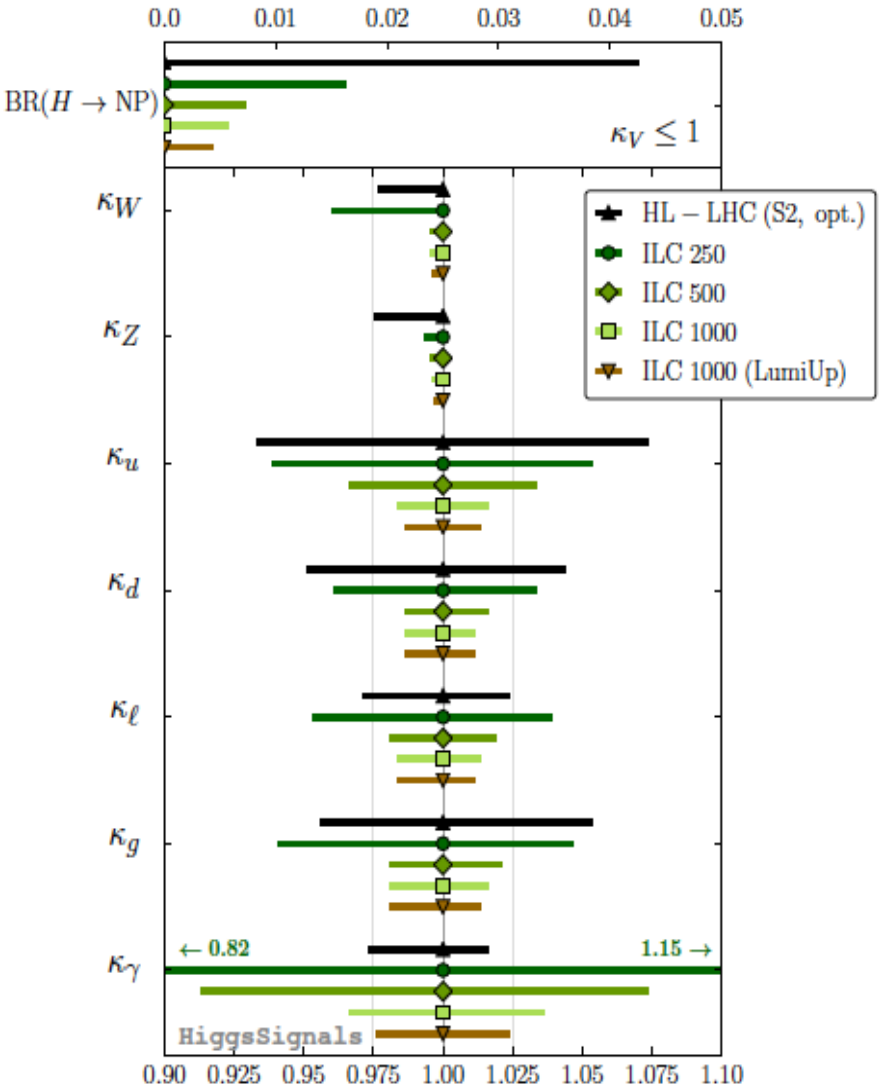
A glimpse into the P5 report - ILC

- As the physics case is extremely strong, we plan in all Scenarios for ILC support at some level through a decision point within the next five years.
  - If the ILC proceeds, there is a high-priority option in Scenario C to enable the U.S. to play world-leading roles.
  - Even if there are no additional funds available, some hardware contributions may be possible in Scenario B, depending on the status of international agreements at that time.
  - If the ILC does not proceed, then ILC work would terminate and those resources could be applied to accelerator R&D and advanced detector technology R&D.
- **Recommendation 11: Motivated by the strong scientific importance of the ILC and the recent initiative in Japan to host it, the U.S. should engage in modest and appropriate levels of ILC accelerator and detector design in areas where the U.S. can contribute critical expertise. Consider higher levels of collaboration if ILC proceeds.**

Note: The leading-role contribution to ILC is one of only 3 differences between scenarios B and C (c.f table 1), along with "enhancement" of LBNF and accelerator R&D!

- Should the ILC go forward, Scenario C would enable the U.S. to play world-leading roles in the detector program as well as provide critical expertise and accelerator components.
  - The interest expressed in Japan in hosting the International Linear Collider (ILC), a 500 GeV e^+e^- accelerator upgradable to 1 TeV, is an exciting development.
  - Decisions by governments on whether or not to proceed, and the levels of participation, depend on many factors beyond the scope of P5; however, we emphasize most strongly that the scientific justification for the project is compelling.

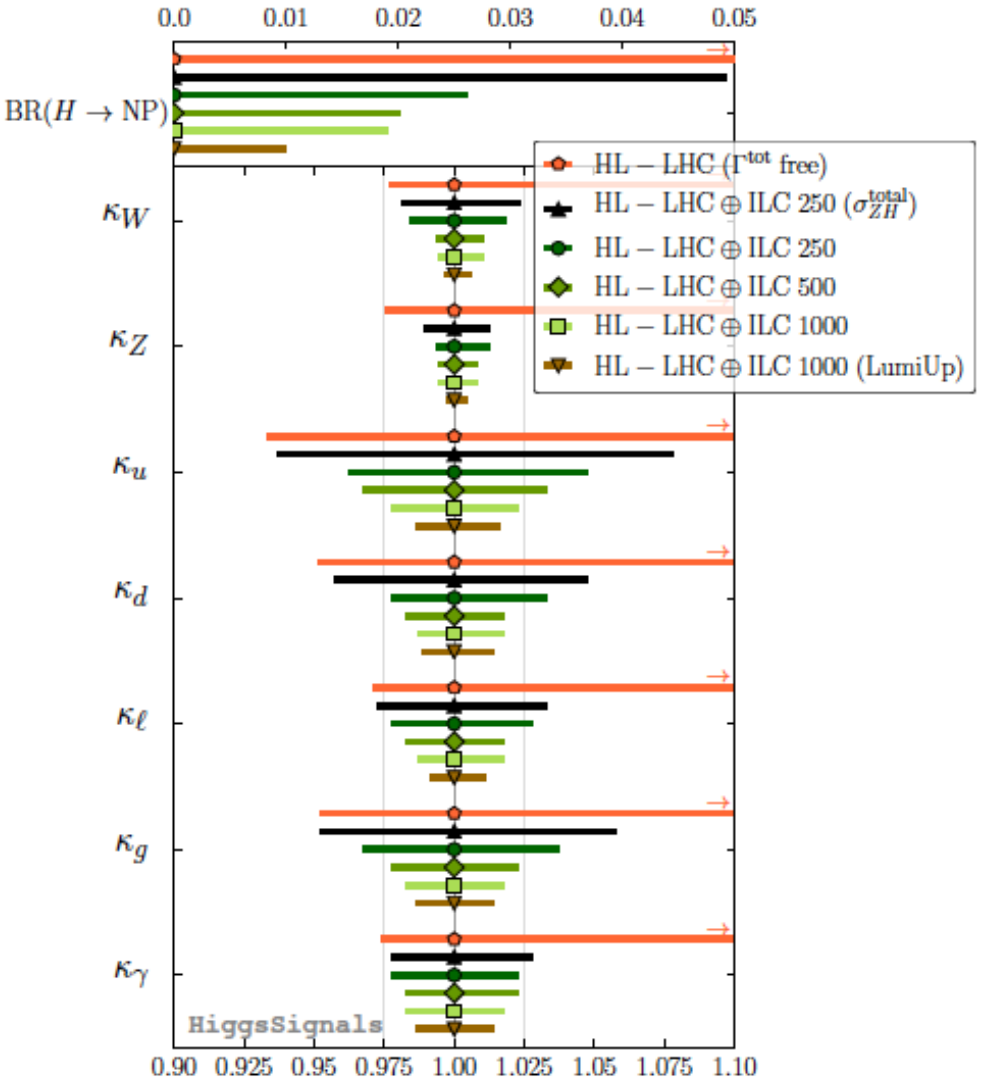
Slightly Model-dependent Coupling Fit



[arXiv:1403:1582]

- Assume κ_W, $\kappa_Z \leq 1$

Model-independent Coupling Fit

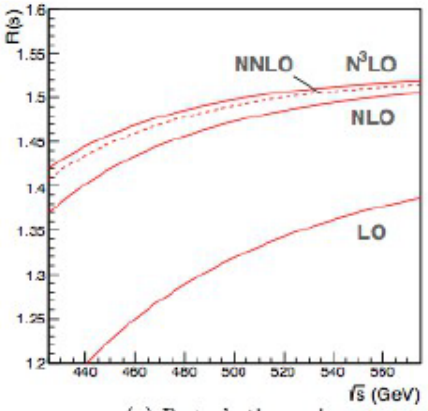


[arXiv:1403:1582]

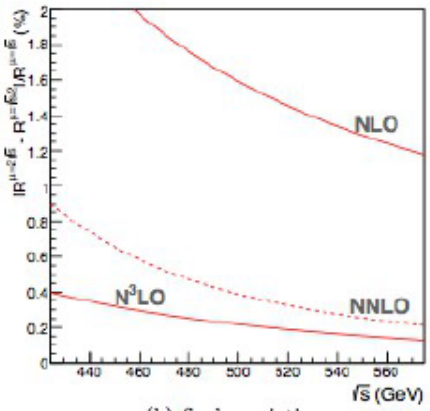
- Here: fully model-independent version
- Further improvements by assuming κ_W, $\kappa_Z \leq 1$ (slight model-dependence)
- ILC measurements: statistics limited, even in high lumi scenario

Top: Theoretical Uncertainties

✳QCD corrections are known up to N³LO



(a) Perturbation series

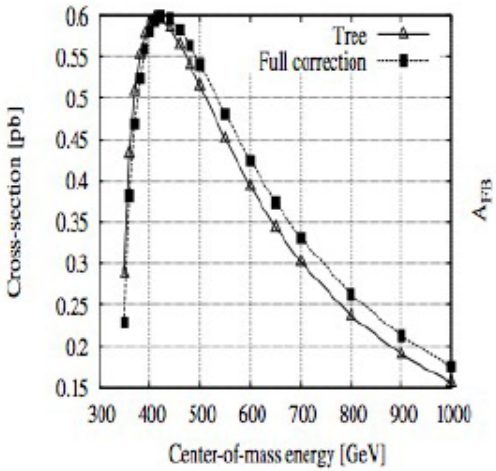


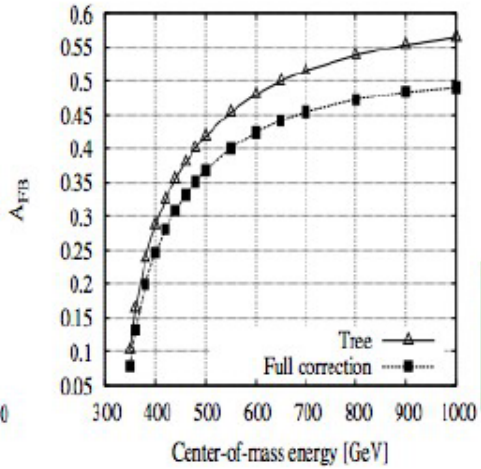
(b) Scale variations

QCD correction (N³LO) is at the per mil level

Kiyo, Maier, Maierhofer, Marquard, NCP B823 ('09)
Bernreuther, Bonciani, Gehrmann, Heinesch, Leineweber. NPB750 ('06)
Hoang, Mateu, Zebarjad, NPB813 ('09)

✳Electroweak corrections are known at one-loop level





EW correction at one-loop is ~5% for cross section ~10% for A_{FB}

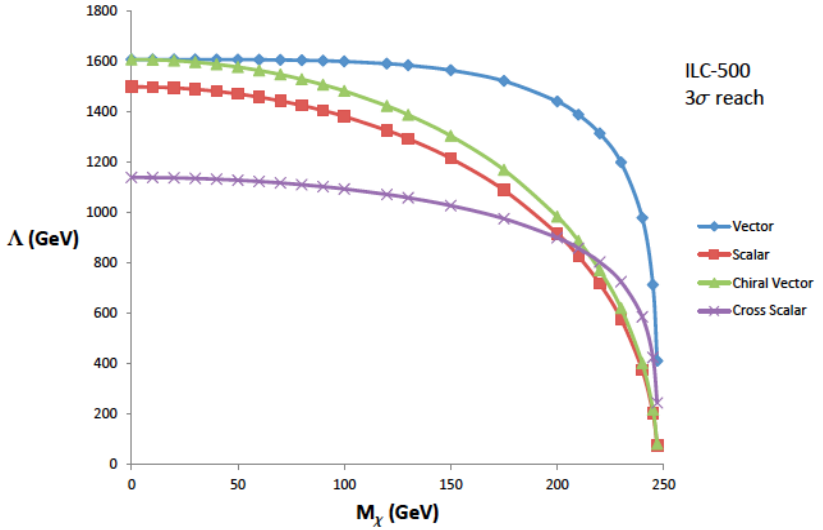
Fleischer, Leike, Riemann, Werthenbach, EJPC31 ('03)
Kheim, Fujimoto, Ishikawa, Kaneko, Kato, arXive:1211.1112

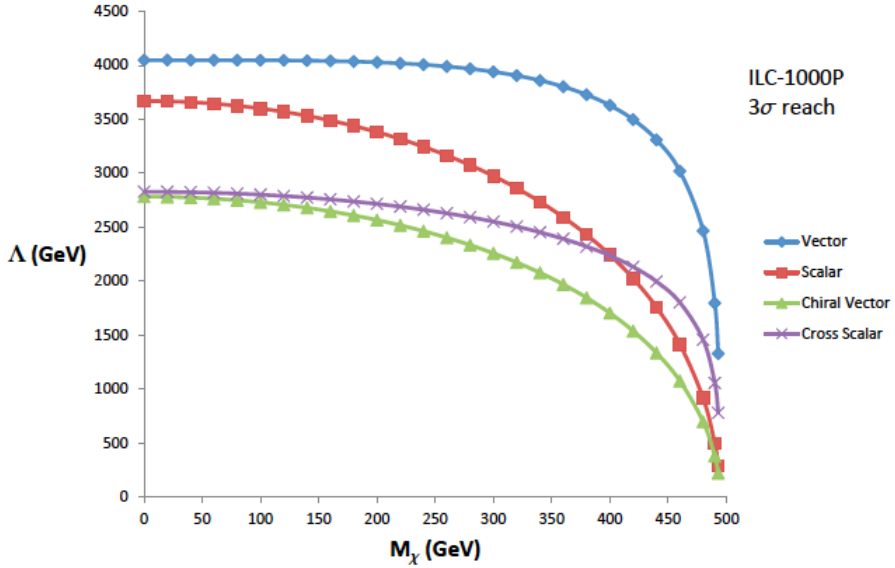
From 1211.4008, Chae & Perelstein

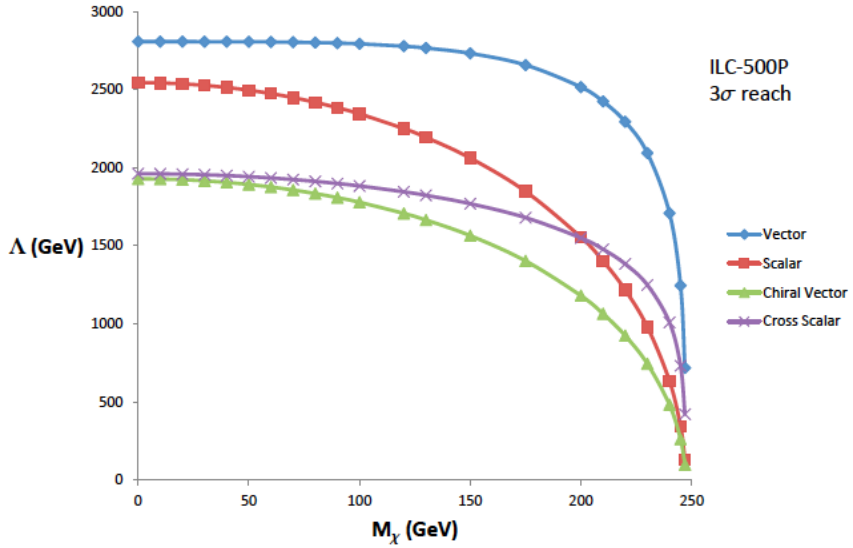
ILC: Projected sensitivity on Λ

Monophoton search:

- 3σ observation reach (99.x% CL)
- Polarised case $P(e^-,e^+) = (+80\%,-50\%)$: improves by ~factor 2
- Reach up to 3-4 TeV, far beyond E_{CM}

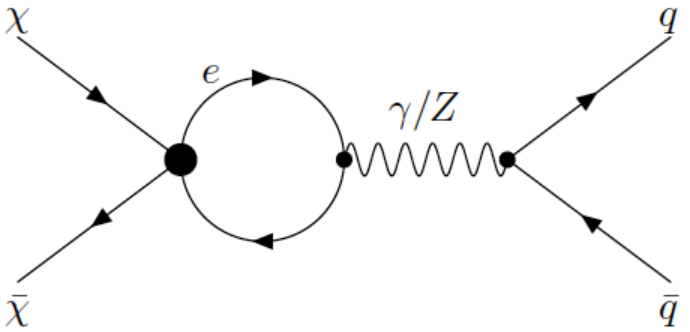


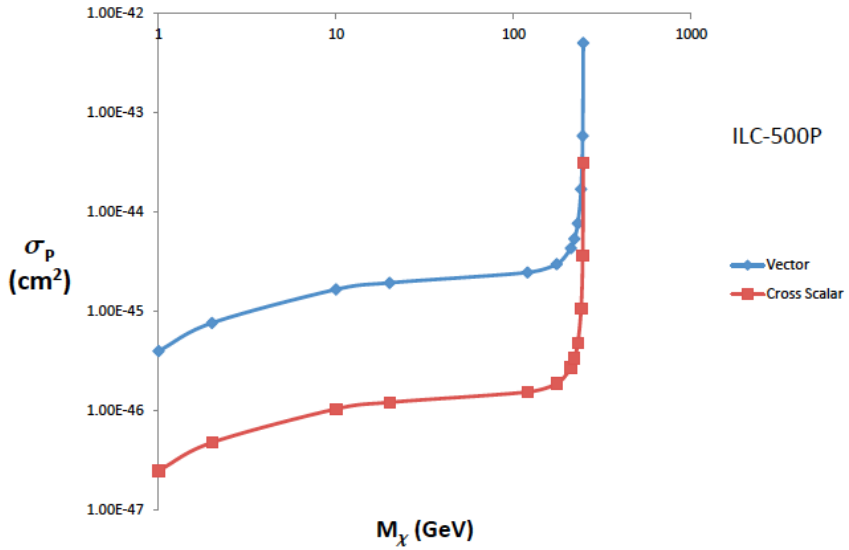


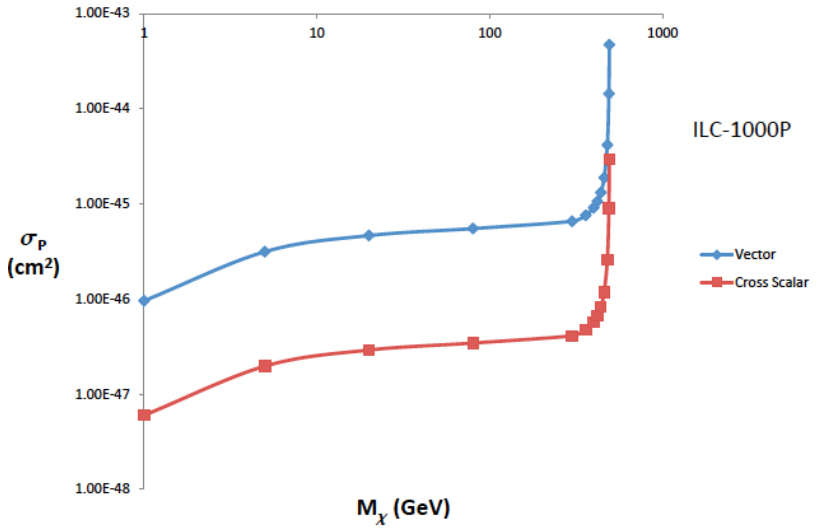


How to relate e^+e^- to Direct Searches?

- 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







Take Home Message (II)

- **Beyond ILC500**, LHC and others will guide the way for further ILC options/priorities:
  1TeV upgrade? GigaZ? γγ? …?
- The ILC is **ready to go**:
  - Cryomodule production industrialized for EU-XFEL
  - TDR has been published
  - A prospective site in Japan has been chosen
  - Japanese government setup evaluation panel
    → report expected end of FY15
  - Political negociations are starting....

We're living in exciting times - stay tuned!