Challenges for an Detector for Higgs Physics at the ILC - and other e^+e^- projects

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DESY

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CPAD Instrumentation Frontier Meeting
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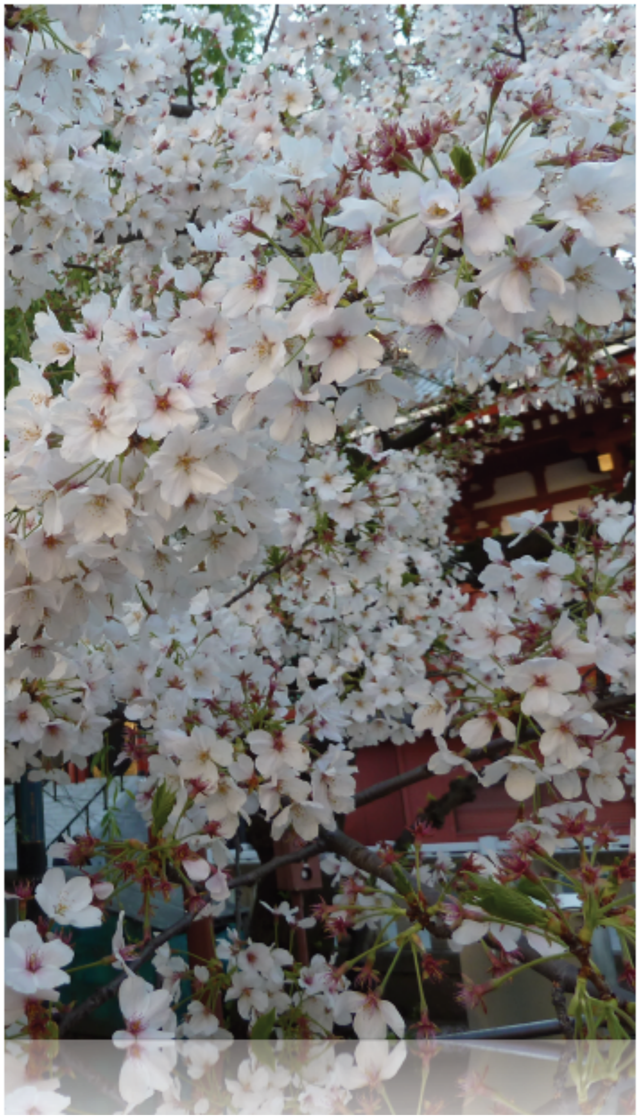
Outline



- Introduction:
  - What we need to learn about the Higgs in e^+e^- collisions
- The International Linear Collider and other e^+e^- projects
  - Accelerator properties
  - Key detector requirements
- Detector Challenges – taking a closer look at four examples
- Conclusions

Introduction: What we need to learn about the Higgs in e^+e^- collisions

After the Discovery...

With the discovery of a Higgs boson, we are just at the beginning:

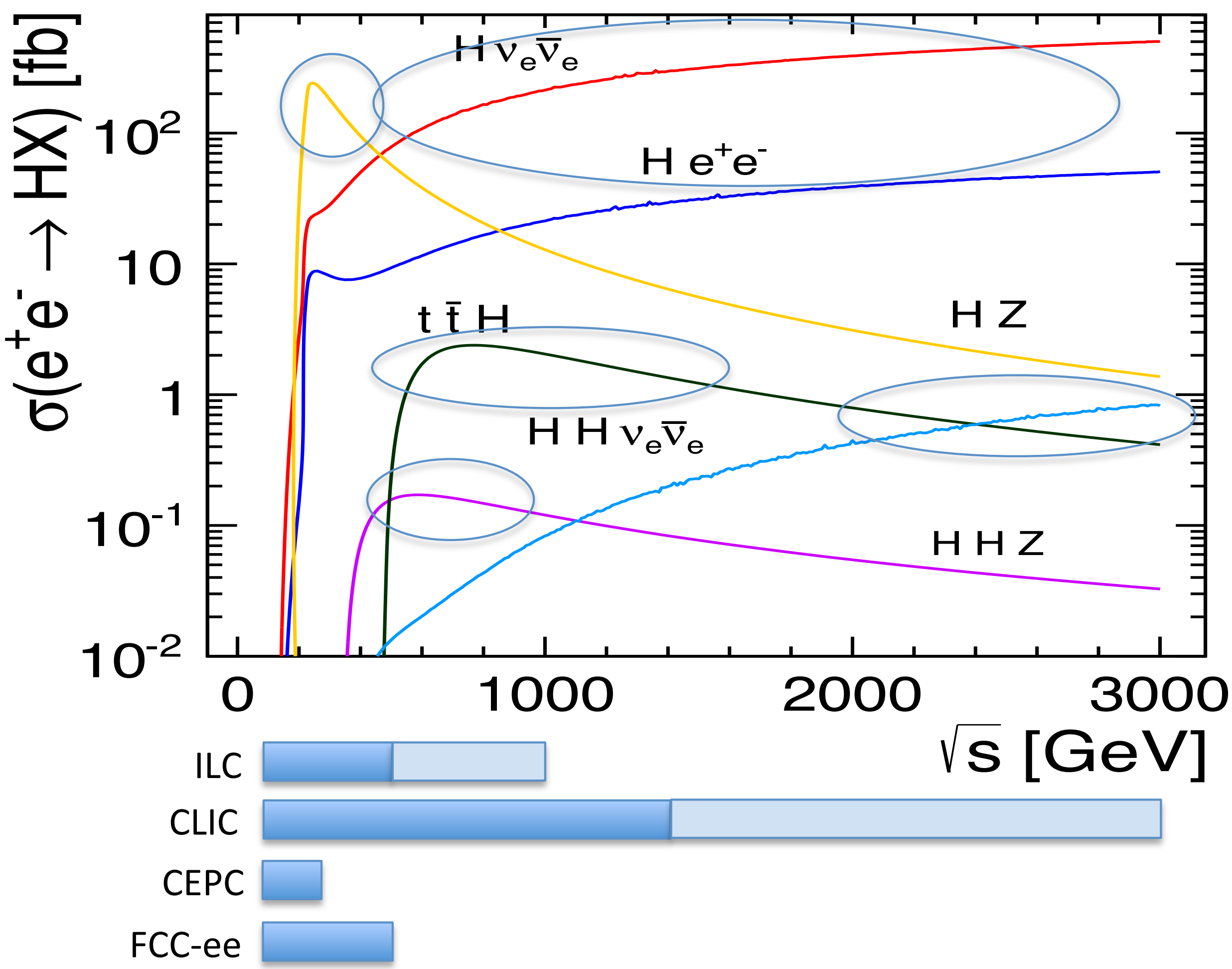
- **What is the physics behind EW symmetry breaking (EWSB)?**
- **What stabilizes the Higgs mass at the EW scale?**
- **Is the Higgs boson related to Dark Matter? Inflation? Baryogenesis? Or even Dark Energy?**

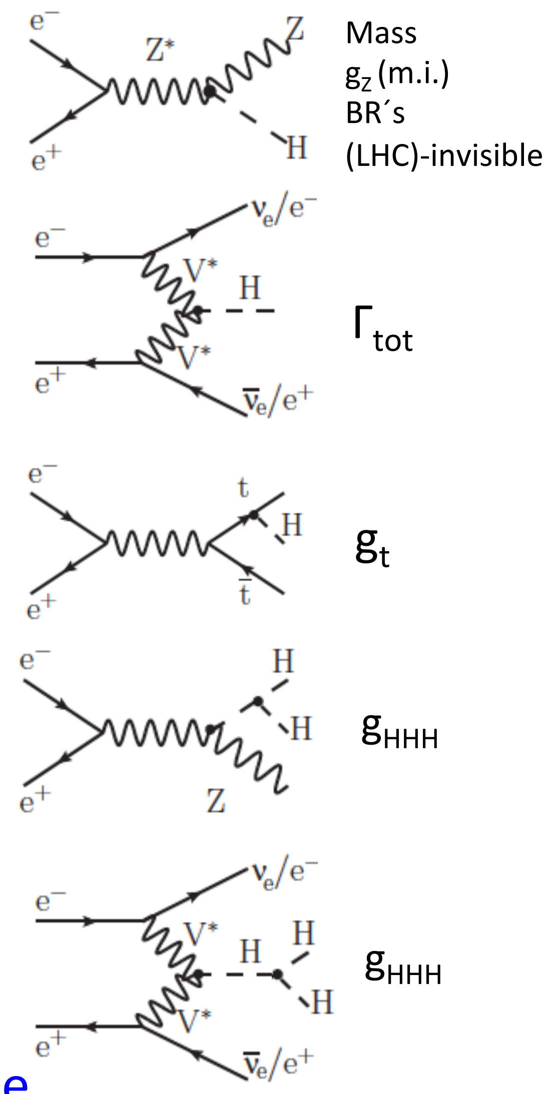
Our gateway to answer these and many other questions:

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

- **A full, model-independent, high-precision profile of the 125 GeV Higgs boson and the top quark**
- **Searches for additional Higgs bosons**
- **Searches for partners of the Higgs: eg Higgsinos**

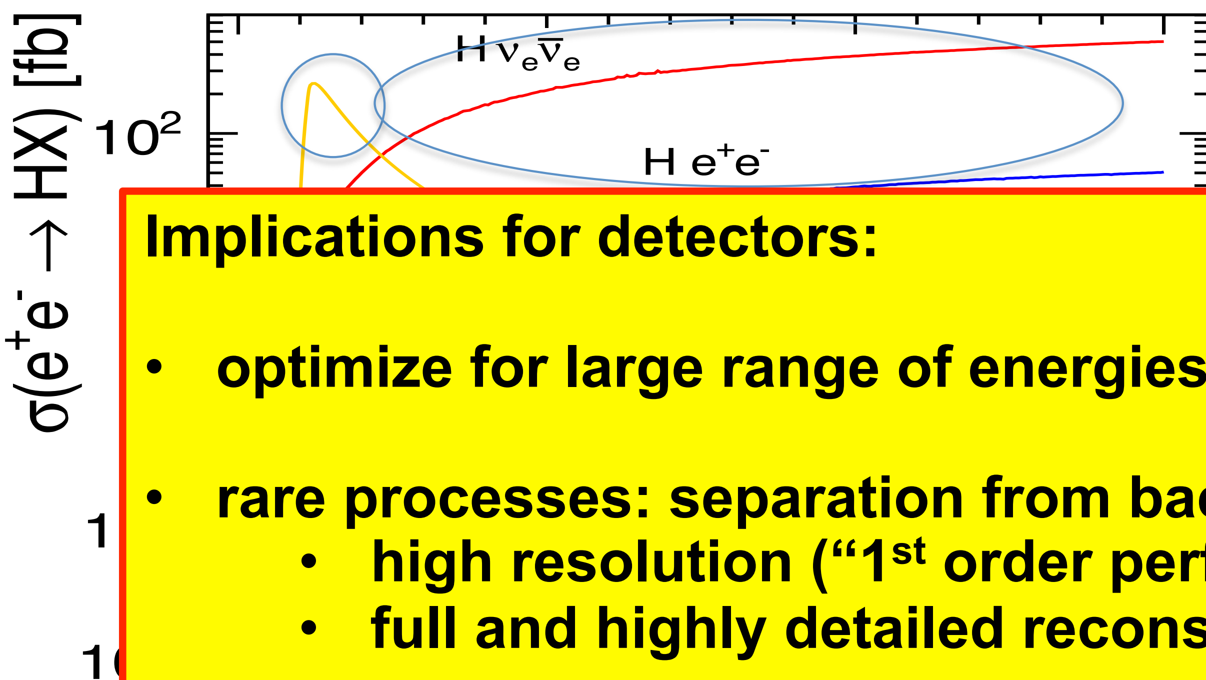
The e^+e^- Higgs Precision Program

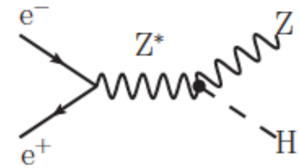




- Many processes at different √s needed & accessible

The e^+e^- Higgs Precision Program





Mass
g_Z (m.i.)
BR´s
(LHC)-invisible

Implications for detectors:

- **optimize for large range of energies**
- **rare processes: separation from backgrounds**
  - **high resolution ("1st order performance")**
  - **full and highly detailed reconstruction of each event**
- **high-statistics processes: systematics decisive**
  - **not only resolution**
  - **but also stability, calibration, alignment...**
    ("2nd order performance")

- Many processes at different √s needed & accessible

The e^+e^- Higgs Precision Program

Unique in e^+e^-:
measurement of the total ZH cross-section => the key to

- absolute normalization of all couplings
- access to total width
- invisible decays

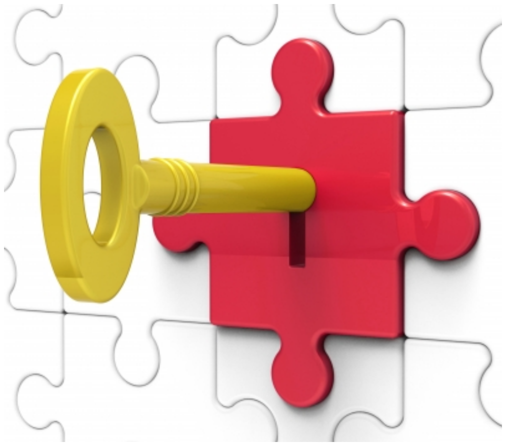


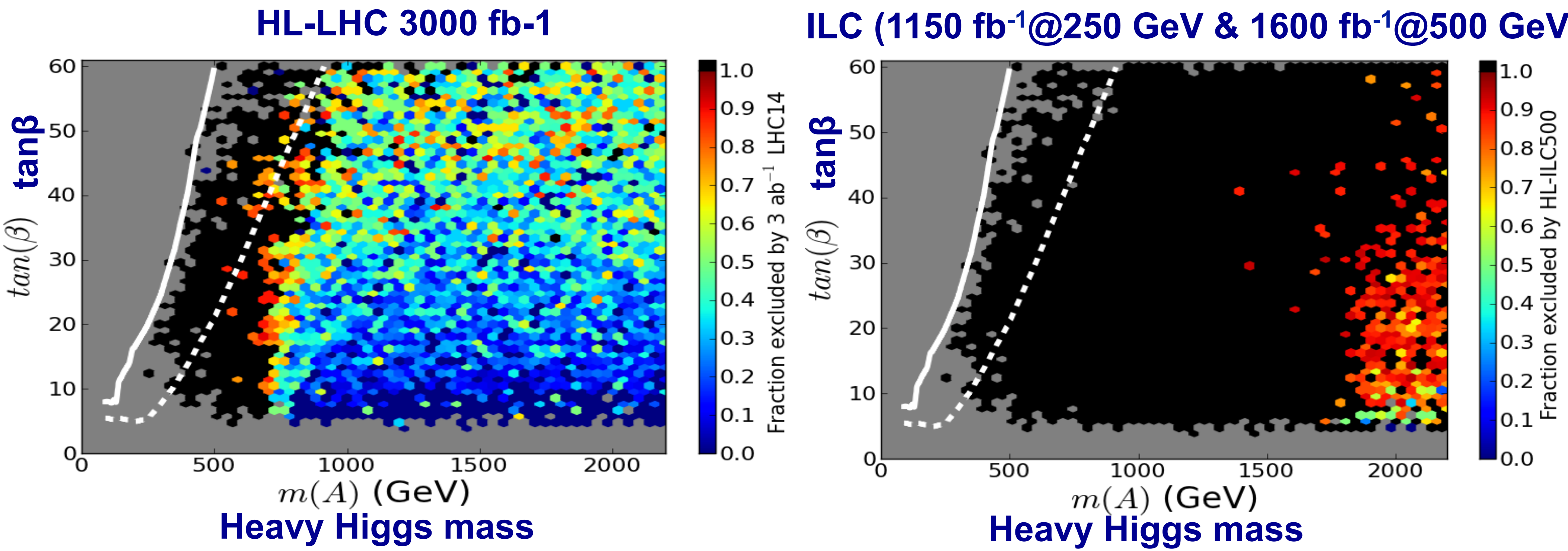
Image courtesy of Stuart Miles at FreeDigitalPhotos.net

enables a model-independent interpretation of all other measurements – from hadron colliders & e^+e^-

- σ x BR, incl. bottom, charm, gluon, τ...
- direct measurement of y_t
- CP admixtures
- ultimate challenge: self-coupling λ_{HHH}

Requirement: do this with sufficient precision to be sensitive to new physics effects!

Example: constraints on pMSSM from hγγ, hττ, hbb



[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

Searches for additional Higgs bosons

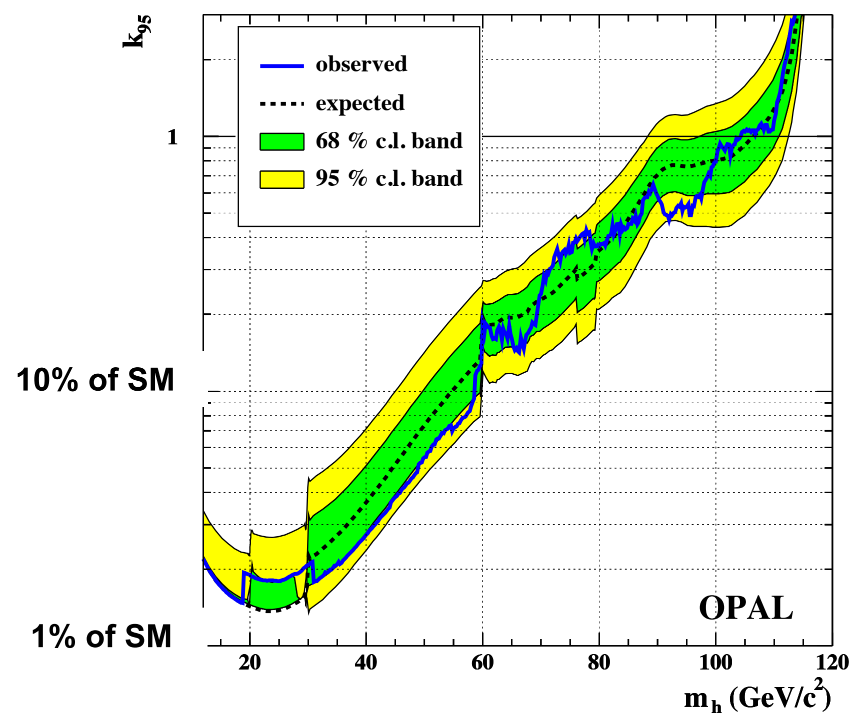
Since H125 looks roughly SM-like, additional Higgs bosons must have *suppressed* couplings to the Z boson

- “heavy”: H, A, $H^{\pm}$, $H^{\pm\pm}$, ...
- **“light”, with suppressed couplings to Z**:
  e.g. **h, a** in NMSSM

low mass region difficult for LHC

LEP limits still the best we have
[here e.g. h->hadrons, flavor independent]

leaves lot of opportunities for discoveries with the luminosity and beam polarization of future e^+e^- colliders!

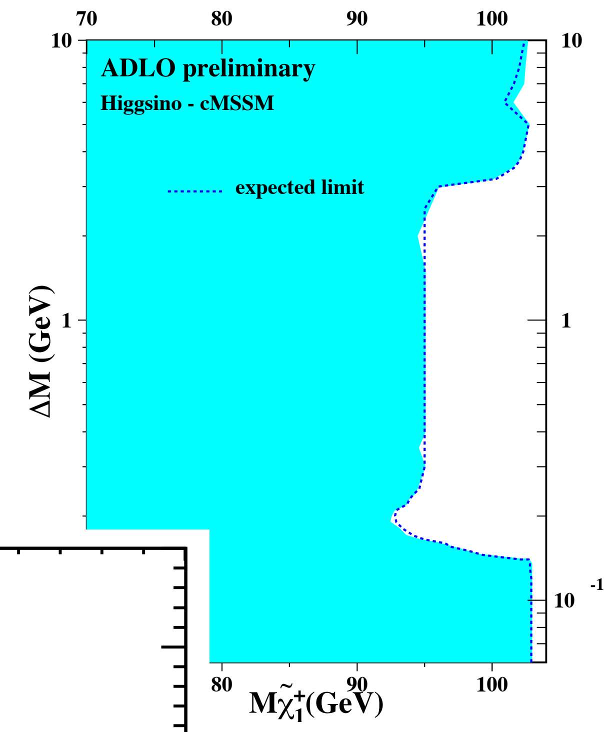


Higgs Partners: Higgsinos

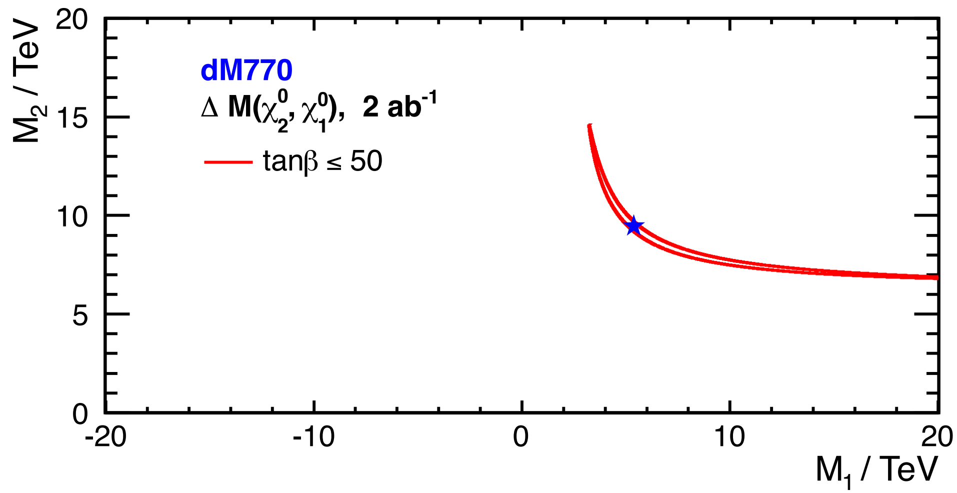
partners of the Higgs(es) naturally expected near EW scale

[c.f. e.g. H. Baer et al Phys.Rev.Lett. 109 (2012) 161802]

- if other new particles heavy => near-degenerate
- mass splittings ≈< 10 GeV, even sub-GeV
- very few and soft visible decay products
  => extremely challenging for LHC
  => also challenge for ILC detectors!
- but: offers sensitivity to multi-TeV physics!



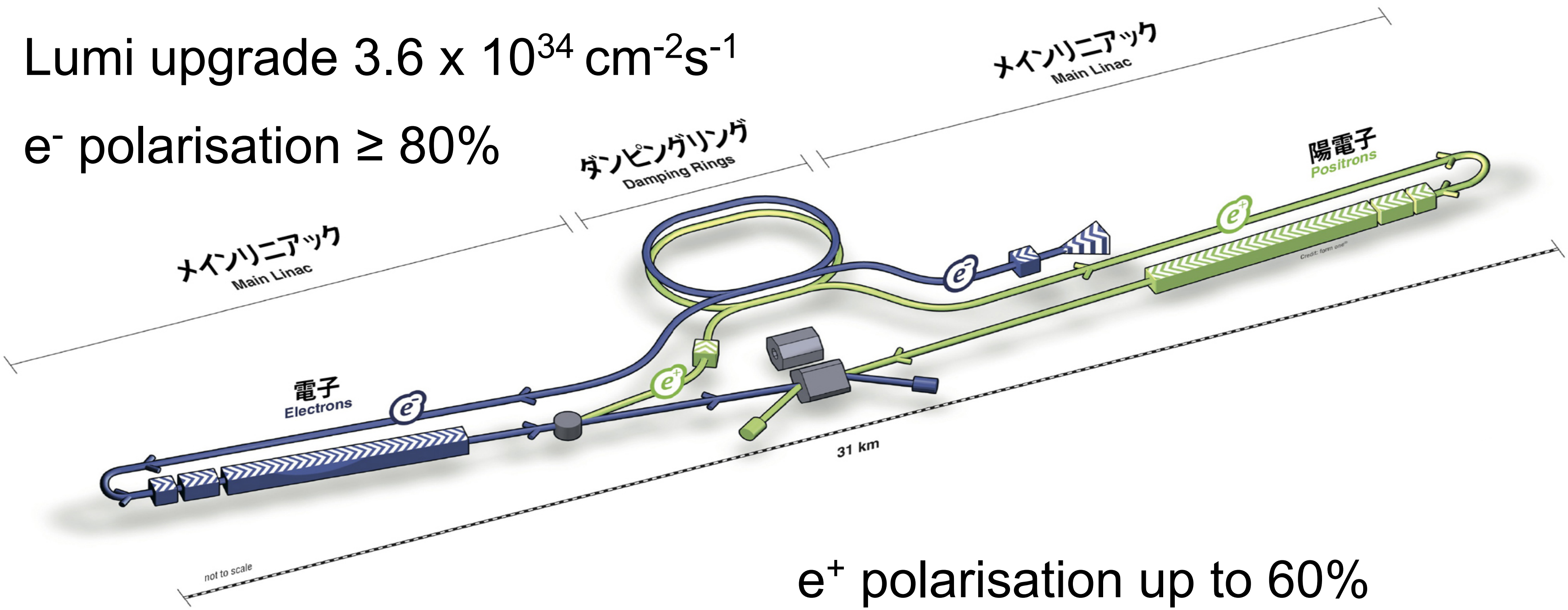
Higgsino parameter determination at ILC when detector challenges solved



The International Linear Collider and other e^+e^- Projects

The International Linear Collider

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

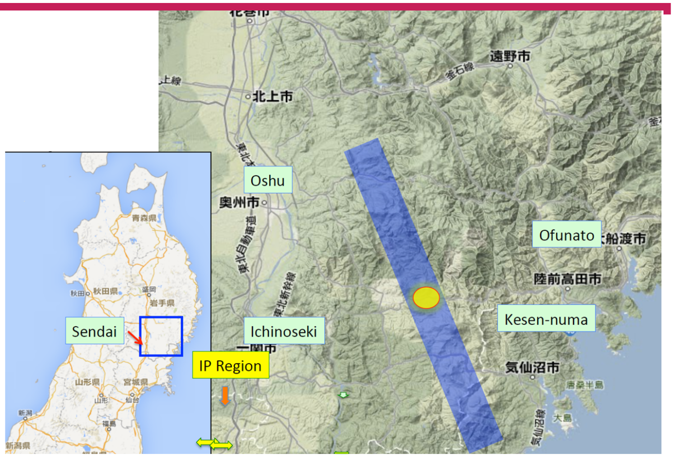


ILC Scheme | ©www.form-one.de

e^+ polarisation up to 60%

… and it is a global project!

ILC Status [K.Desch, DESY Theory WS 2015]



- technically ready to be built
- site chosen (Kitakami, northern Japan)
- interest from Japanese government to host ILC as international project
- internal expert review at MEXT (Japanese science ministry)
  - Physics – Cost – International Sharing
  - Final report: spring 2016
  - Behind the scenes: a lot...

Any reason to be optimistic:

- Japan very interested in large international lab (political top theme – far beyond physics)
- Strong statements in regional strategies (EU, US, Asia, ICFA)
- Strong physics case – even if no additional LHC discovery in near future

And its detector concepts

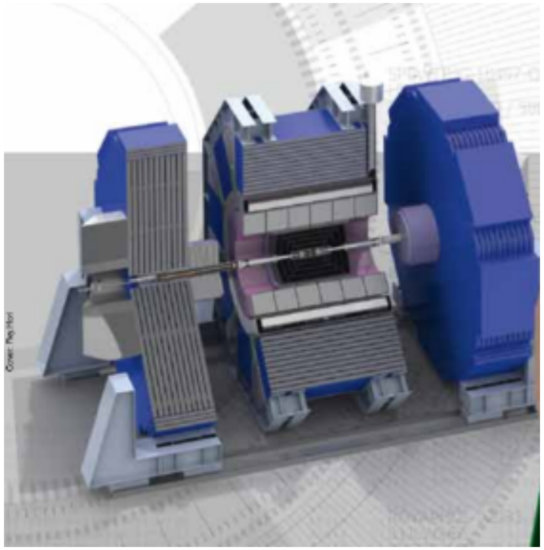
SiD

Tracker

- all Si
- R = 1.2m

B-field

- 5 T



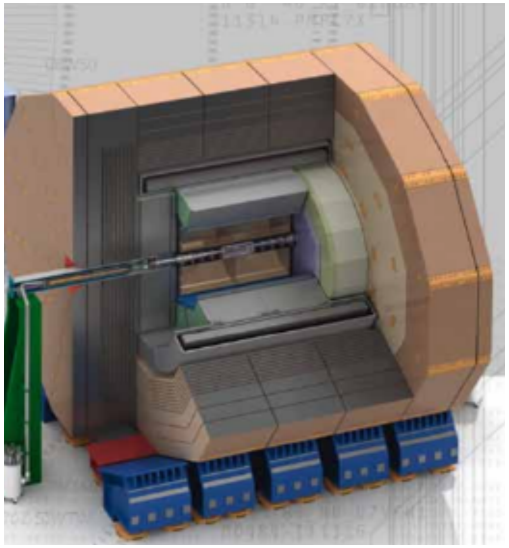
ILD

Tracker

- TPC + Si
- R = 1.8m

B-field

- 3.5 T



Common key design criteria:

- momentum resolution (=> total ZH x-section)
- vertexing (=> flavor tag, H-> bb/cc/ττ)
- jet energy resolution (=> total ZH x-section, H-> invis, ...)
- hermeticity (=> H-> invis, Higgsinos, ...)

⇒ low mass tracker (eg VTX: 0.15% rad. length / layer)

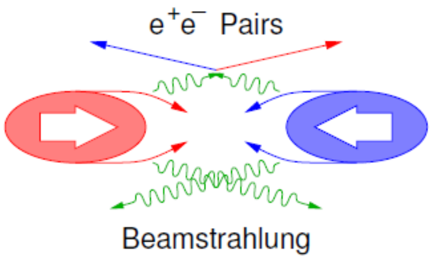
⇒ high granularity calorimeters optimised for particle flow

Operating the ILC

- pulsed operation:
  - trains of N_{bunch} = 1315 / 2625 bunches, **530 / 270 ns bunch spacing**
  - train repetition rate: 5 – 10 Hz => 199 – 99 ms break

enables
- **triggerless readout of detectors => sensitivity to “subtle” signatures**
- **power pulsing => low mass tracker, dense calorimeter**

- collisions:
  - luminosity *grows* with energy
  - minimize beamstrahlung => flat beams 500x5 nm^2

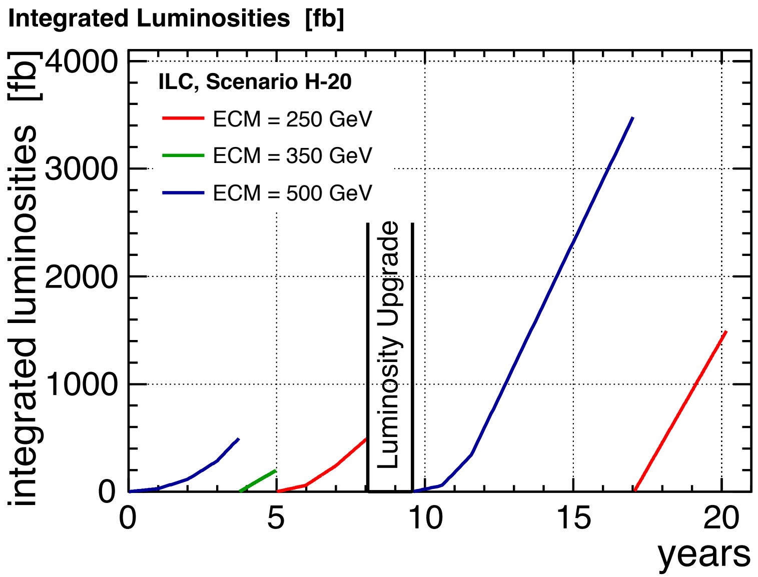


ECM [GeV]	250	250	500	250	500	1000
rep. rate [Hz]	5	10	**5**	10	5	**5**
N_{bunch}	1315	1315	**1315**	2625	2625	**2625**
inst. lumi [10^{34} / cm^2 / s]	0.75	1.5	**1.8**	3	3.6	**3.6-4.9**
total power [MW]	**100**	**160**	**160**	**190**	**200**	**300**

A possible ILC running scenario

[ILC Parameters Joint WG arXiv:1506.07830]

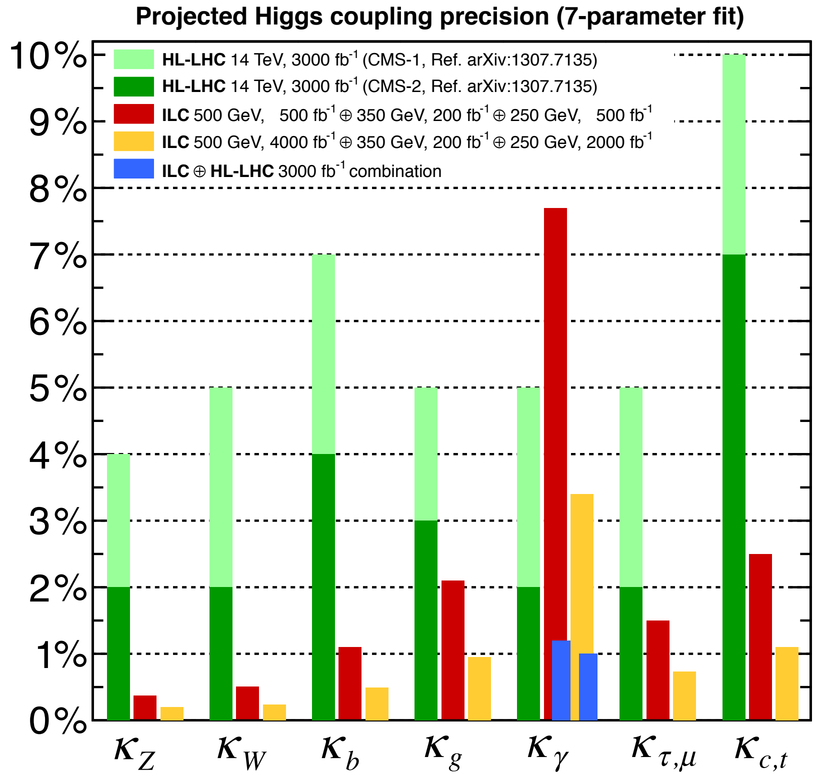
Stage	ILC500			ILC500 LumiUP		
$\sqrt{s}$ [GeV]	500	350	250	500	350	250
$\mathcal{L}$ [fb^{-1}]	500	200	500	3500	-	1500
time [a]	3.7	1.3	3.1	7.5	-	3.1



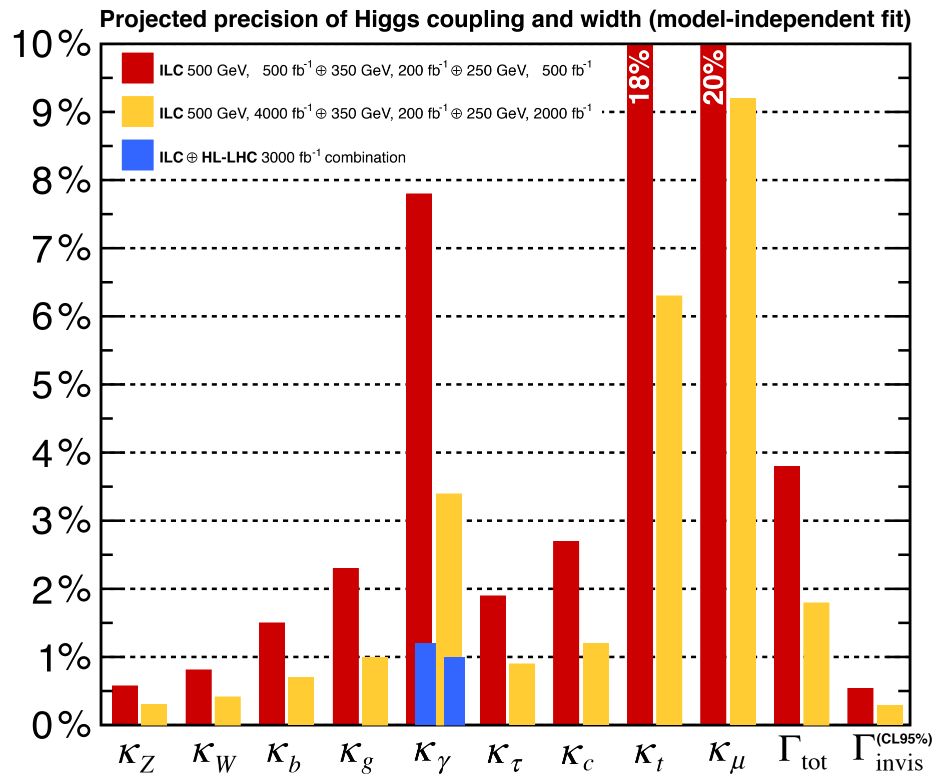
possible 20 year running scenario

...and resulting Higgs coupling precisions

model-dependent (LHC-style)

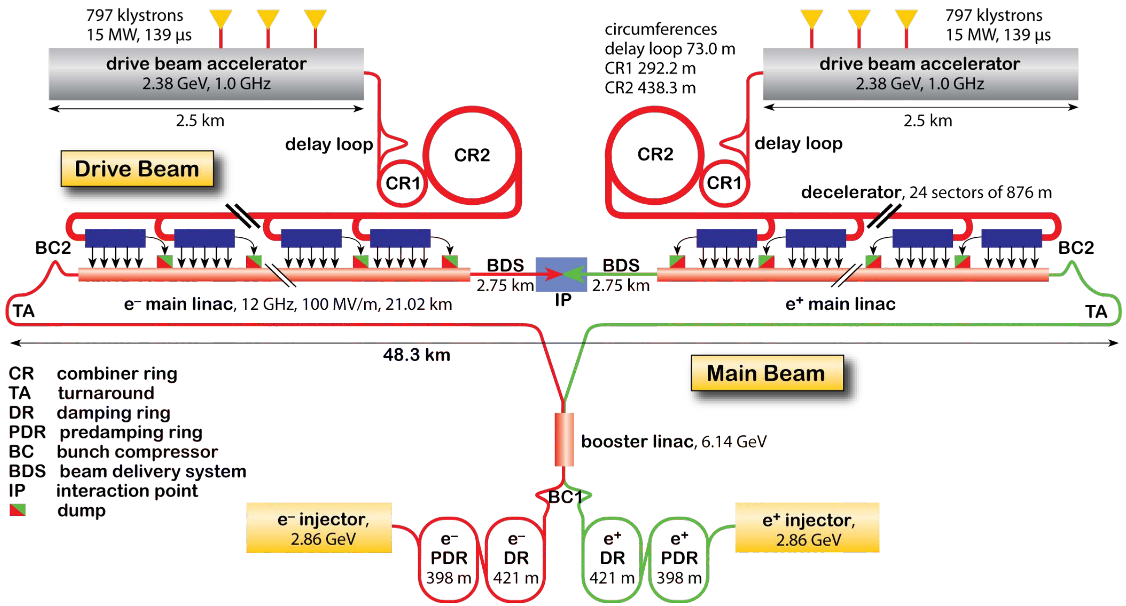


model-independent



For precisions < 1%,
systematic uncertainties need to be considered
– also in detector design!

The Compact Linear Collider



- **350 GeV – 3 TeV**
- trains with 312 bunches
- repetition rate 50 Hz
- total power:
  ~270MW @ 500 GeV
  ~600MW @ 3 TeV

Detector Challenges:
- **bunch spacing 0.5 ns**
- **50 Hz: power pulsing? -> cooling needed?**
- **huge background from beamstrahlung pairs**

Success of CDR studies:
immense background from e^+e^- pairs and γγ-> hadrons can be dealt with

Circular e^+e^- Colliders

CepC (China)

- 50 km, 2 IPs
- 90 - 240 GeV
- 2 x 10^{34} $cm^{-2}s^{-1}$ / IP
- bunch spacing: few μs
- power?   ~400-500 MW ?

FCC-ee (CERN)

- 80-100 km, 4 IPs
- 90 – 350 GeV
- 28 – 2 x 10^{34} $cm^{-2}s^{-1}$ / IP
- bunch spacing: 10 ns - 10 μs
- power "aim": 300 MW
  (current design does not achieve this)

no trains: continuous operation

=> good for physics:
low per-bunch luminosity, no beamstrahlung

⇒ bad for detectors:
no power pulsing possible, need cooling!
=> low-mass cooling systems

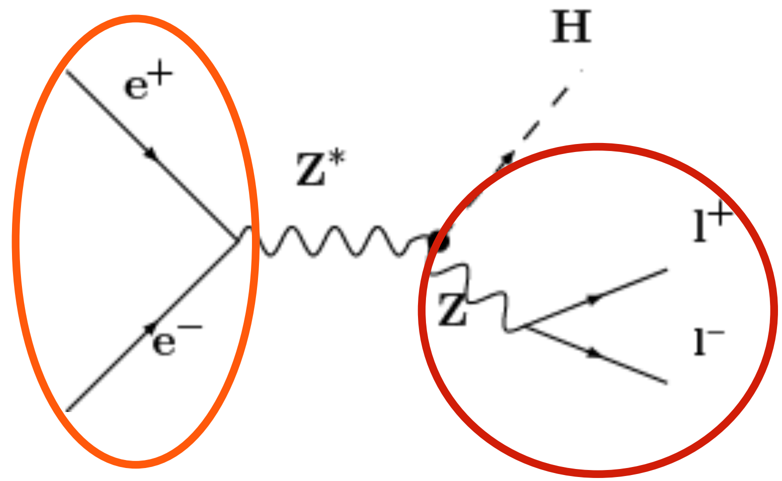
Detector “R&C”: Requirements and Challenges

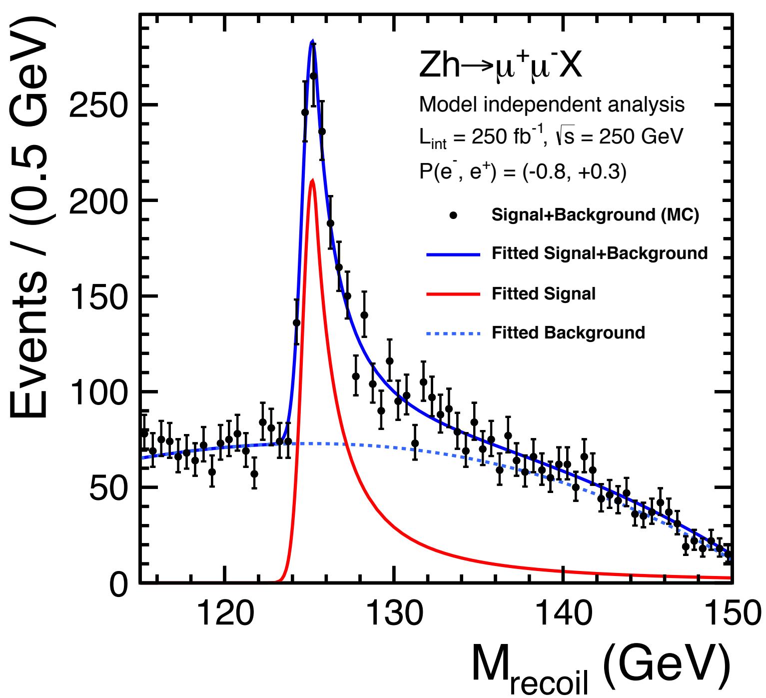
- The key: the total ZH cross section
- Indirect search for new physics: Higgs branching ratios
- Establishing the mexican hat: the Higgs self-coupling
- Identifying Higgs partners: Higgsinos

The model-independent measurement of σ_{ZH}

How? → recoil method:

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





initial state:
known event-by-event apart from

- **beam energy spread of accelerator**
- **beam strahlung**
- **ISR**

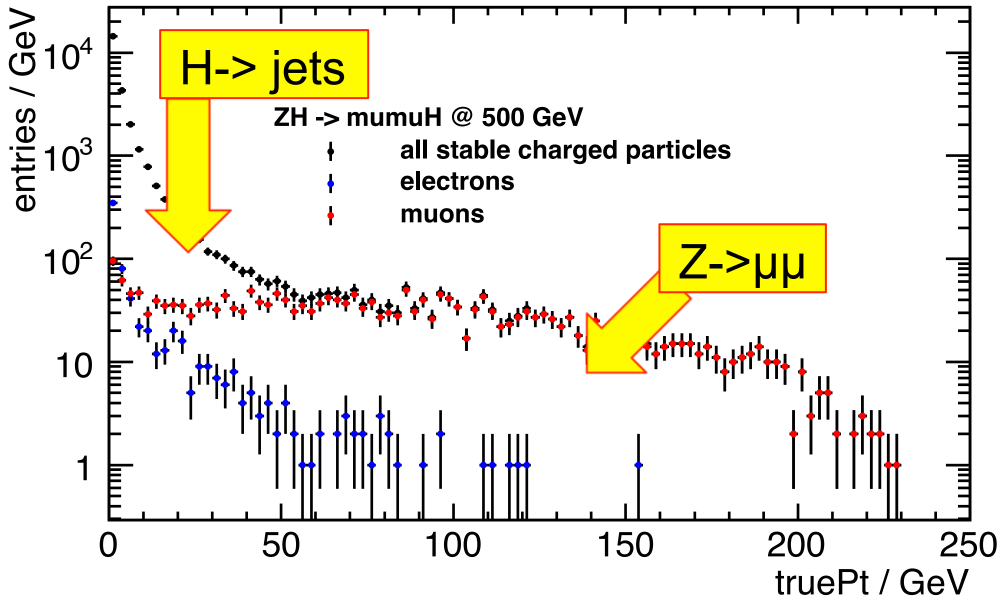
⇒ shape of peak is detector resolution folded with beam energy spectrum!

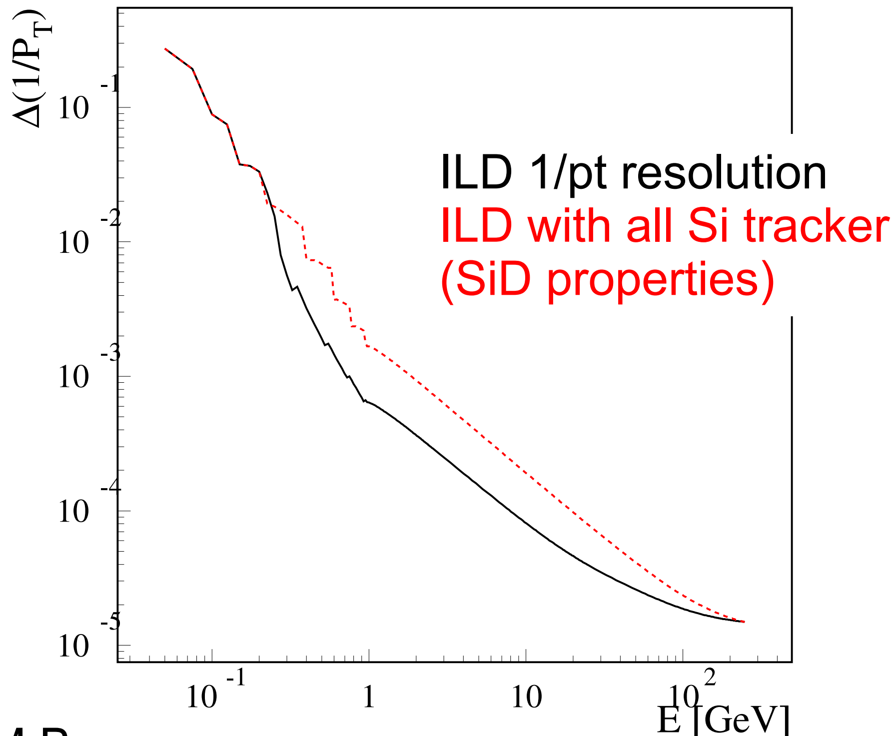
⇒ nuissance parameter...

Higgs Recoil: Momentum resolution

√s = 250 GeV:
  Z ~ at rest, $p_\mu \approx$ 45 GeV

higher √s : Z boosted
  => wide momentum range
  => more challenging!





M.Berggren

Gaseous tracker has less material
=> less multiple scattering

Challenges (not in simulation so far):
- **alignment**
- **field distortions in TPC**
- **stability of momentum scale: required to same level as resolution!**

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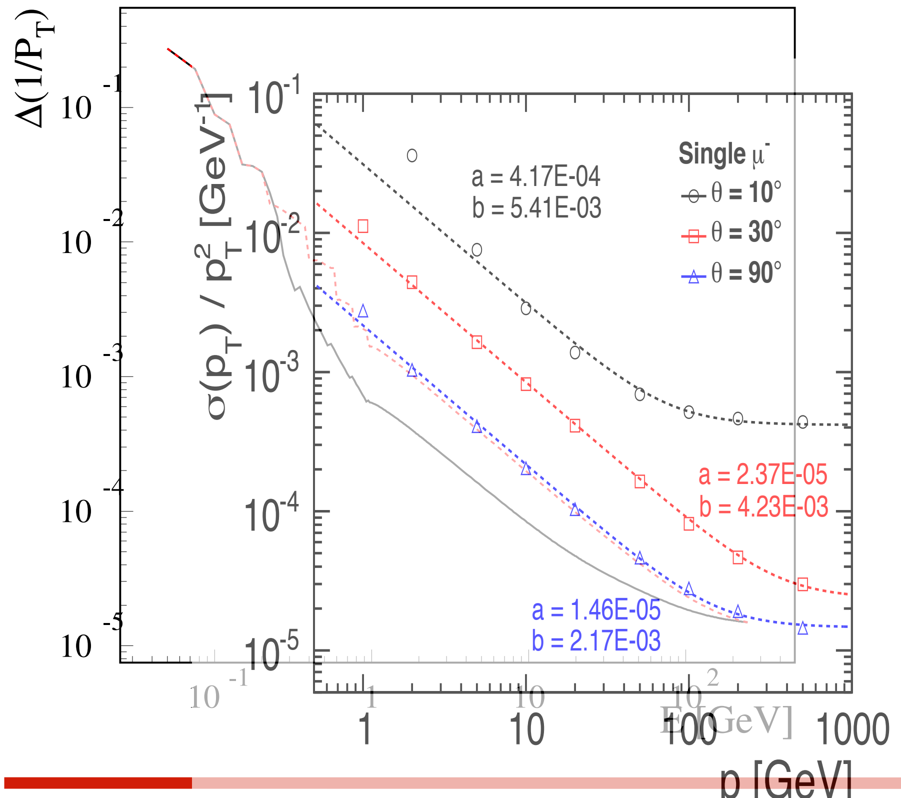

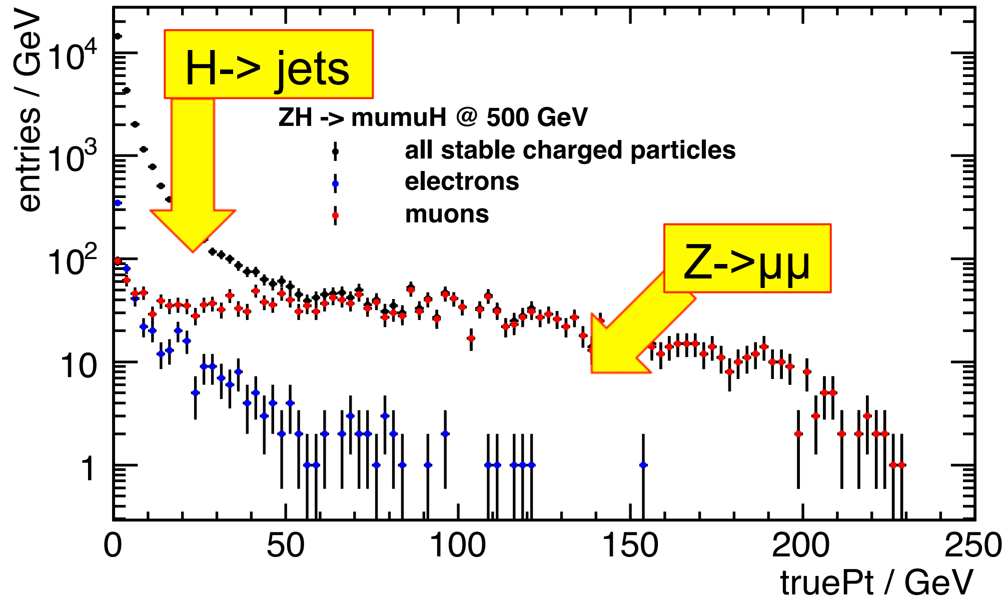

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Higgs recoil: Systematic Effects

luminosity: based on low-angle Bhabha's - current status ~2.6 10^{-3}, limited by
[**JINST 8 (2013) P08012**]

- theory (NLO EW ee->4e) ~2 10^{-3}
- **energy scale calibration/stability of LumiCal ~1 10^{-3}** (if scale known to 2 10^{-3})

beam polarisation:

- polarimeter detectors reach 2.5 10^{-3} or better [**JINST 10 (2015) 05, P05014, arXiv:1509.03178**]
- **long-term scale calibration to collision data**, eg WW angular spectra **~ 1 10^{-3}** , probably limited by knowledge of collision parameters [**JINST 9 (2014) P07003**]

shape of peak:

- beam energy spread, beamstrahlung, ISR: calibrate against Z recoil from ZZ -> μμX
- knowledge of momentum resolution: calibrate against Z lineshape from ZZ -> μμX

⇒ limited by ZZ statistics to ~ same order as ZH statistical uncertainty

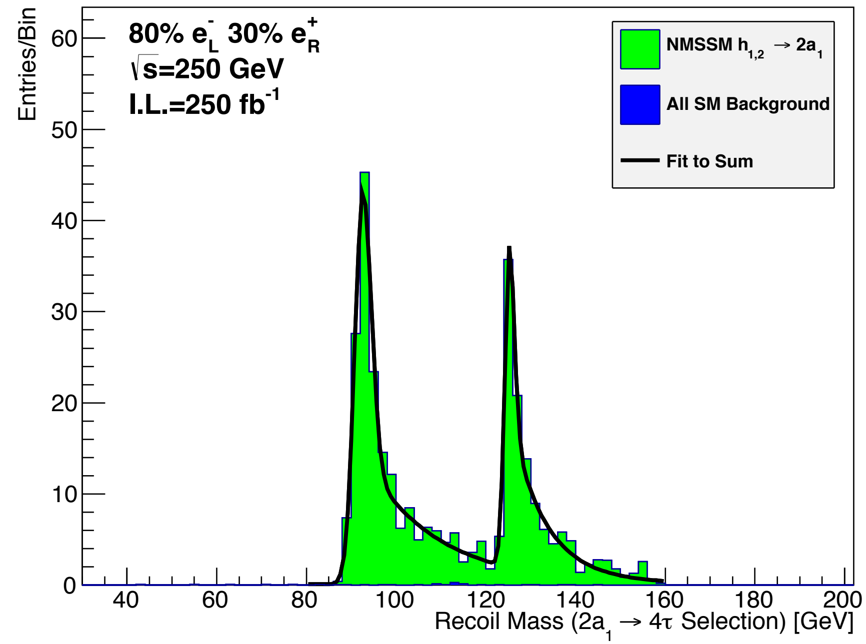
If no polarisation, no beamstrahlung (eg circular collider):
detector challenges:

- **energy scale of LumiCal**
- **modeling of momentum resolution**

Another recoil-flavour: Search for light Higgses

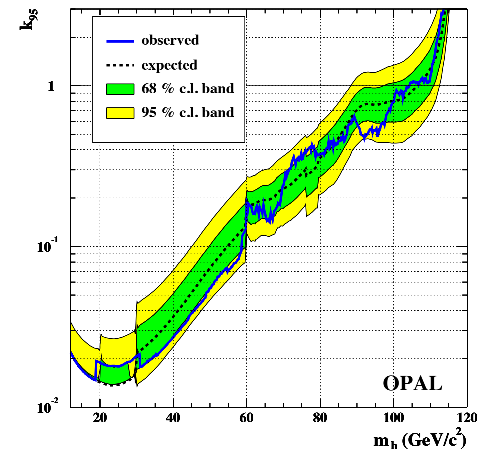
Do the same trick to search for $m_h < 125$ GeV

- Z boosted even at $\sqrt{s} = 250$ GeV
- small coupling to Z: tiny signals
- **=> momentum resolution even more crucial!**



C. Potter et al arXiv:1309.0021

- **high interest from theorists / model-builders**
- **currently no detailed ILC simulation study to show accessible range in coupling to Z**

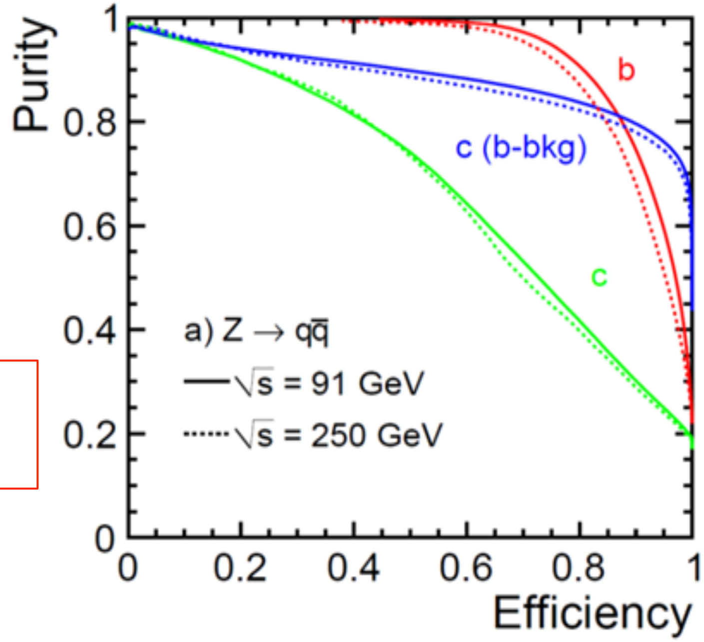


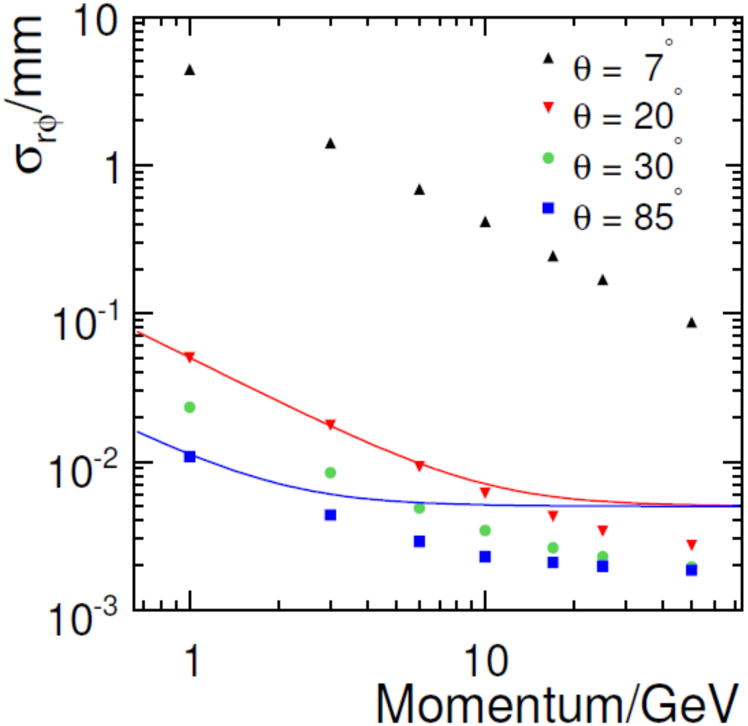
Phys.Lett. B597 (2004) 11-25

Higgs branching ratios – the usual (ILC) picture

high performance flavour tag

- secondary / tertiary vertex finding
- needs impact parameter resolution





full detector simulation

2-3 μm

“classic” difference between ILD & SiD: choice of time vs point resolution

LHC and ILC Vertex detectors

	LHC	ILC	Comment
Radiation Level	$>10^{16}$ NEQ (neutron equivalent)/cm^2 (3ab^{-1})	10^{10}NEQ/cm^2/yr	**~O(10^5) difference** FPCCD not a solution at LHC
Readout speed requirement (time structure of beam)	40MHz	5Hz (ILD FPCCD) 100kHz (ILD CMOS) 3MHz (SiD)	FPCCD not a solution at LHC
Hit density	2.4hits/cm^2/bunch (r=8cm) 12.5ns	~6hits/cm^2/bunch (r=1.6cm) 300ns	Factor of ~3 difference for a given pixel size

Key questions for ILC VTX:

- **do we need single BX readout / time stamping?**
  - SiD: always assumed this will be possible
  - ILD – TDR: conservative => 10-100µs,
    studying impact of pair background on charm-tagging
    => educated choice of time vs point resolution
- **ultra-low mass: aim for 0.15% of a rad. length per double layer**

Higgs branching ratios: a closer look

BR(H->bb):

potentially systematically limited for full ILC data set

- b-tagging efficiency?
- b fragmentation function?
- b-jet energy resolution/ scale?
- neutral hadron fraction?

BR (H->cc / gg / ττ):

statistically limited even for full ILC data set

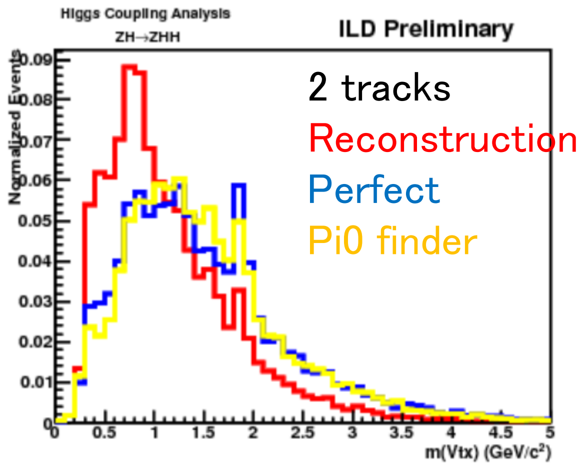
- high performance flavour tag / τ reconstruction
- currently:
  - rely mainly on secondary / tertiary vertex finding
  - impact parameter resolution

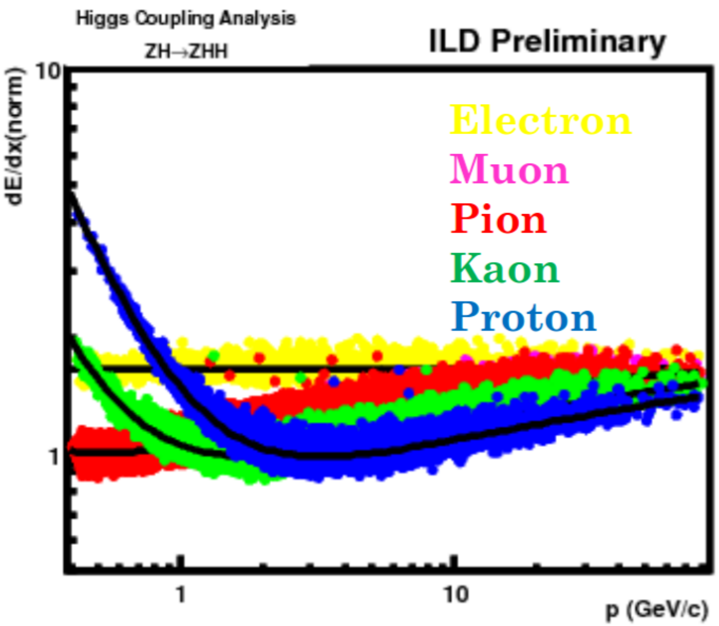
Are there other detector performance aspects which we do not yet consider or cover with the usual benchmarks?

Flavour Tag – can be augmented by

- lepton ID in jets: tag semi-leptonic decays
  => high granular calorimeter & dE/dx
- vertex mass: re-attach $\pi^0 \to \gamma\gamma$?
  (even better: improve π^0 by kinematic fit)
- particle identification:
  - improved impact parameter resolution with correct mass hypothesis
  - c -> s: which is π, which is K?
  - identify exclusive decay chains
  - and remember systematic uncertainties: verify / re-measure b/c-fragmentation, b/c charged multiplicity, ...

What is the actual dE/dx resolution of the ILD TPC?
What could be done with all-silicon?





Higgs Self-Coupling: The Challenge

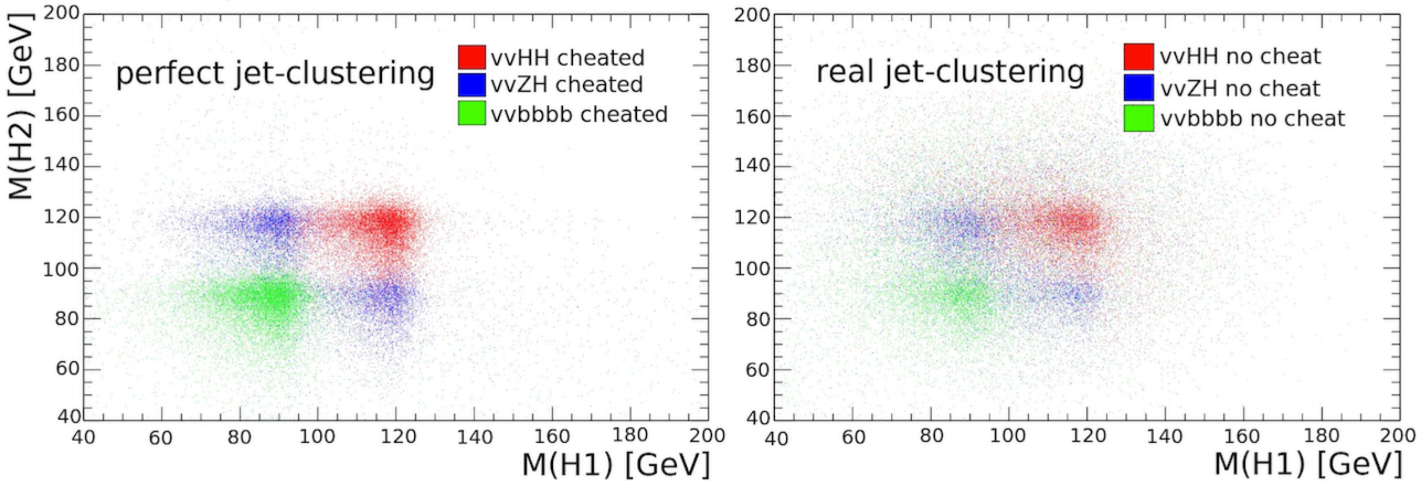
- very low cross section ~0.2 – 0.3 fb @ 500 GeV (depending on polarisation)

many channels, largest BR:

- Zbbbb (36%): 4-6 jets
- ZbbWW* (12%): 6-8 jets

experimental handles:

- flavour tag, lepton ID (s.a.)
- kinematic information => jet energy resolution



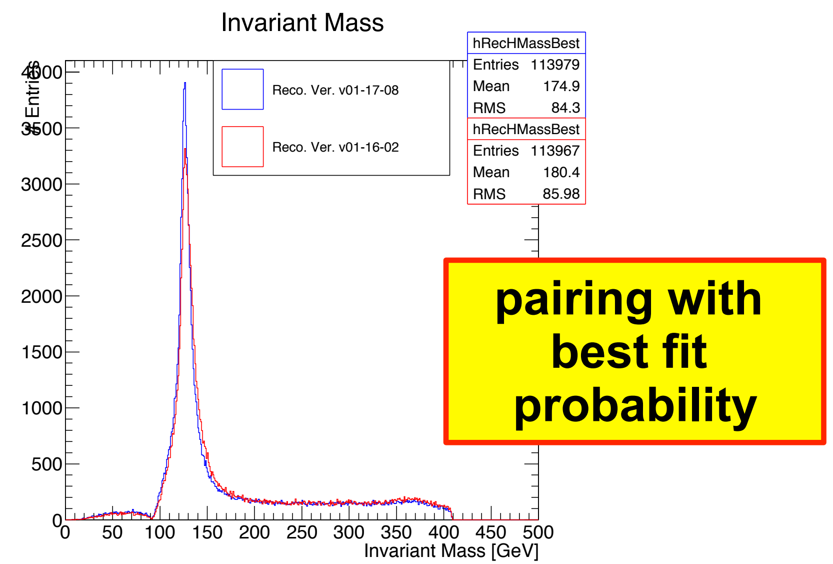
Excellent particle flow calorimetry: jet energy resolution in multi-jet final states limited by jet clustering

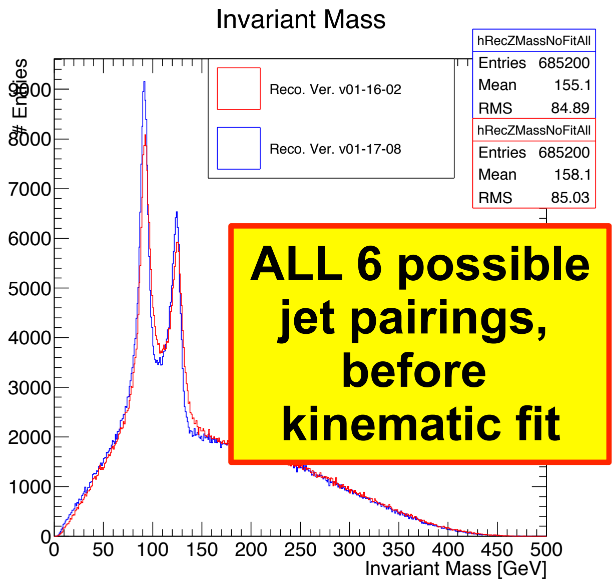
A. Ebrahimi

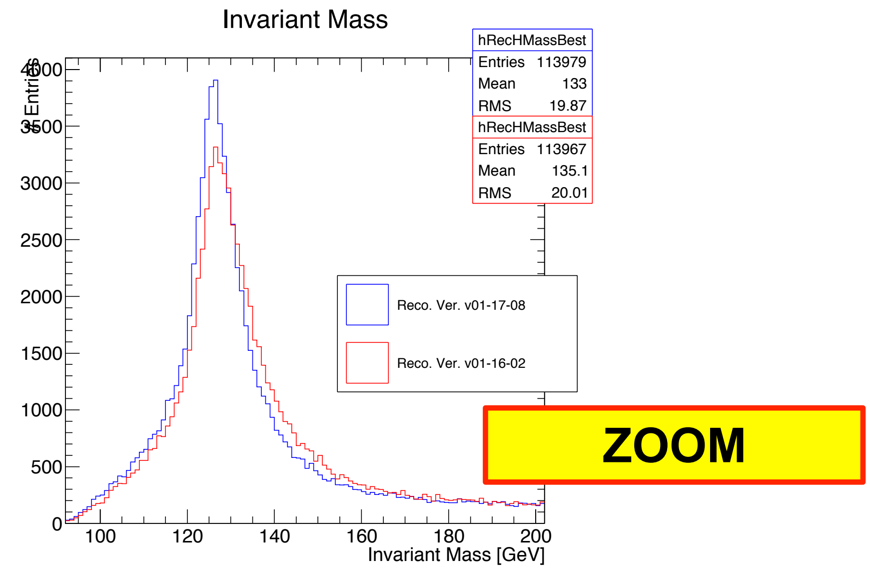
However: PFA improvement in 4-jet-events

- 500 GeV, ZH->qqbb
- ILD_o1_v05, stdreco
  - **v01-16-02 (~DBD)**
  - **v01-17-08 & improved photons**
- MarlinKinfit:
  - (E,p) conservation
  - soft Z mass constraint

=> impressive improvement even in 4 jet final state!





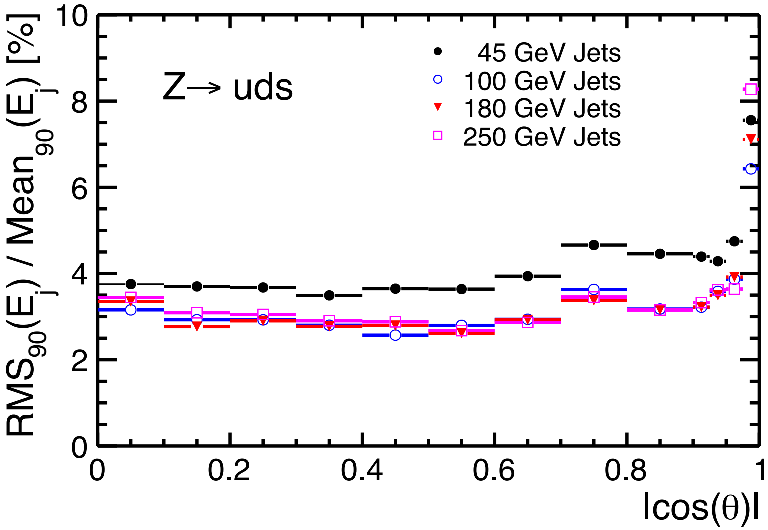


Jet Energy Resolution

Definition (eg in TDR):

- **ee->uu/dd/ss at fixed energy**
- **no ISR => $E_{jet} = E_{vis} / 2$**
- **$rms_{90} < \sigma$**

+ isolates detector performance
- but beware: not always close to physics



- PID: m_p (1 GeV) /E_{jet} (50 GeV) = 2% - compare to ~3% resolution!
- combined with flavour-tag: keep decay chains in same yet, incl. vertex-attached π^0
- neutral hadron fraction:
  - significant impact on JER
  - need to measure at ILC

particle	Pythia tune	OPAL tune	LEP data
p	1.2190	0.9110	0.9750 ± 0.0870
n	1.1661	0.8664	
K^0_S	1.1168	1.0150	1.0040 ± 0.0150
K^0_L	1.1057	1.0164	

The key: measure rate of K^0_S

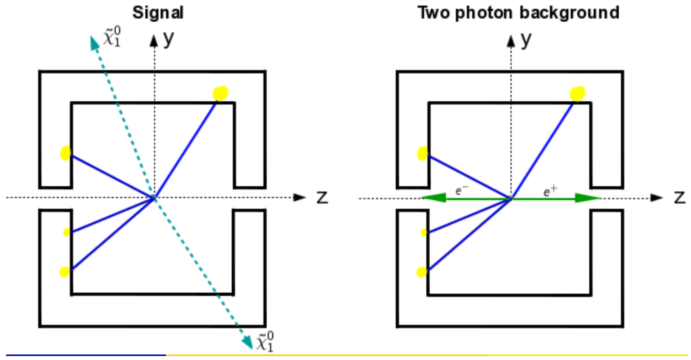
- **cτ = 2.7 cm**
- **eg 5 GeV K^0_S flies ~30 cm**

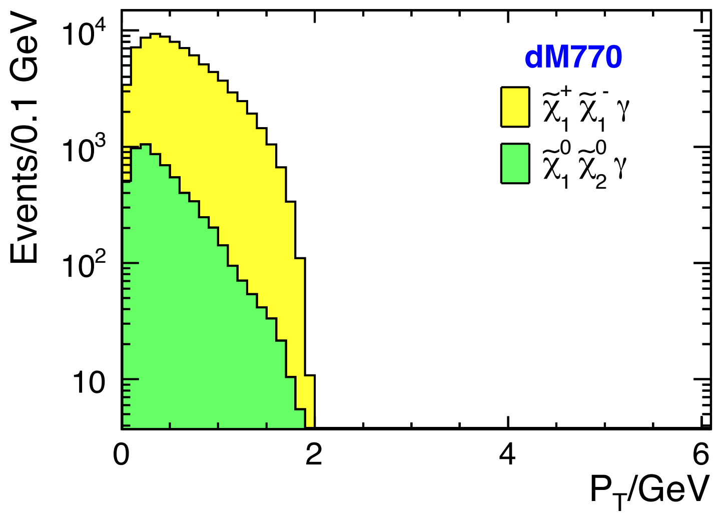
=> "V0" signature in TPC

H.Sert

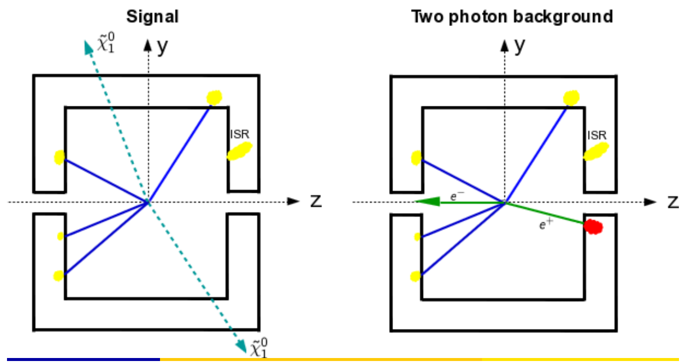
Higgsinos - the Challenge

- very few, soft visible particles
- in addition: tough background from two-photon processes





tag with ISR photon in detector



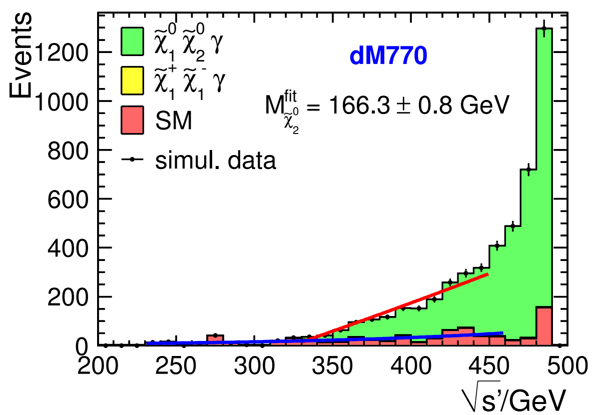
required to identify Higgsinos:

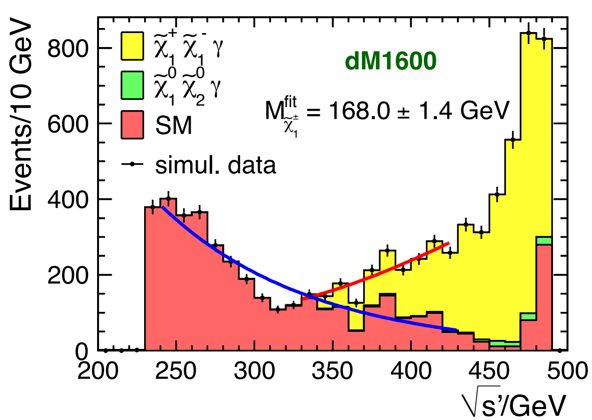
- **semi-leptonic chargino pairs => lepton ID for p<2 GeV**
- **exclusive decays: PID**
- **lifetime: high efficiency for vertex pattern recognition, also at low momenta!**

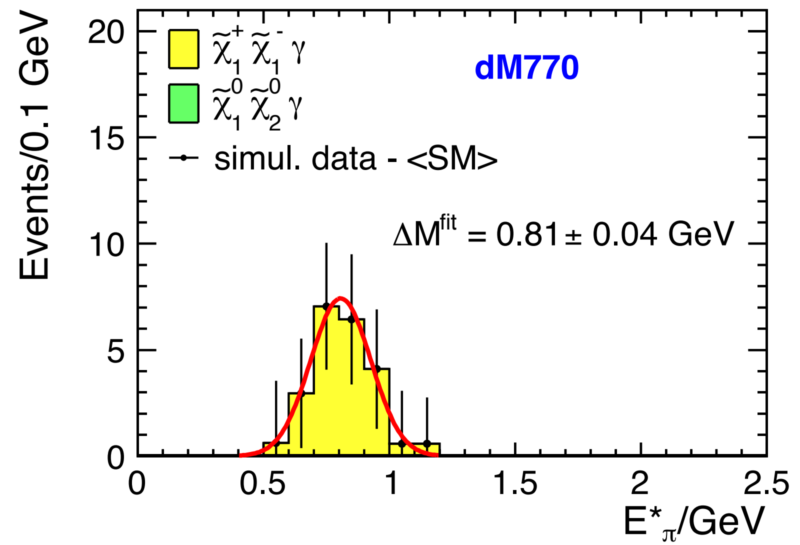
H. Sert

Higgsinos – the Analysis

**measure masses from recoil mass against ISR photon √s'
=> sensitive to intrinsic ECal resolution**







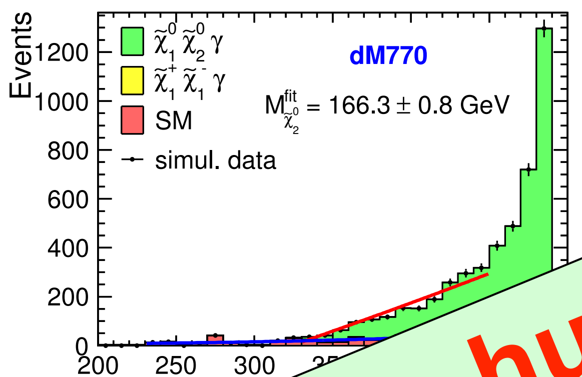
measure mass difference (~1 GeV!) from decay products boosted into Higgsino rest-frame

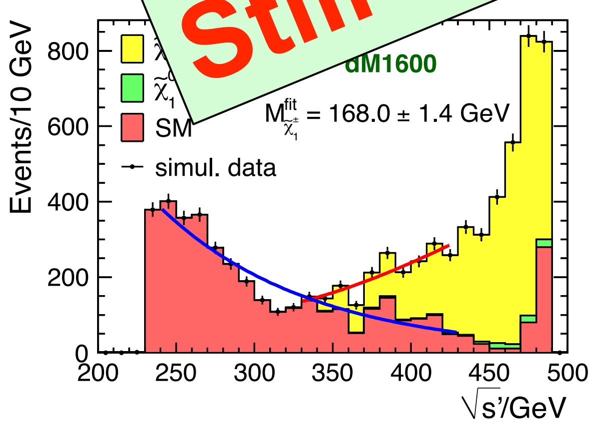
=> momentum resolution for < 2 GeV tracks crucial

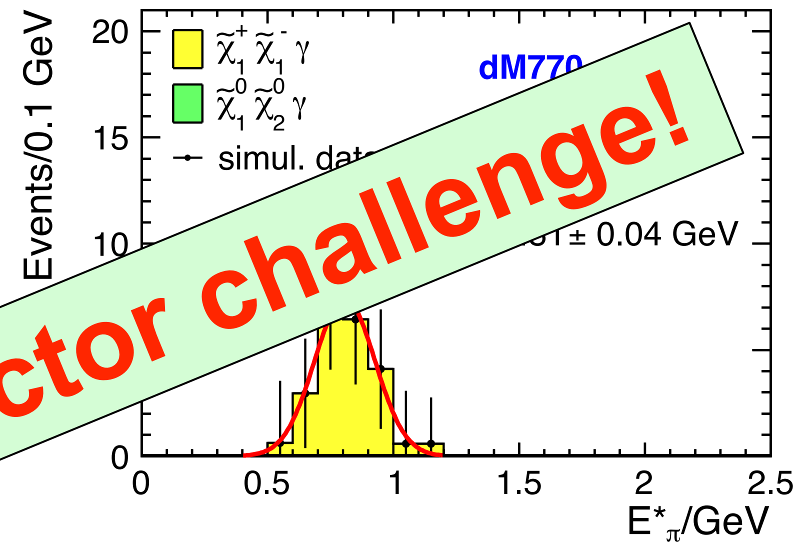
H. Sert

Higgsinos – the Analysis

measure masses from recoil mass against ISR photon √s'
=> sensitive to intrinsic ECal resolution







Still a huge detector challenge!

measure mass difference (~1 GeV!) from decay products boosted into Higgsino rest-frame

=> momentum resolution for < 2 GeV tracks crucial

Conclusions

Summary

- **A complete picture of the Higgs sector requires unique information from e^+e^- colliders**
(complementary to hadron colliders, model-independent)
- **Higgs physics relies on all classic detector performance aspects**: JER, flavour tag, momentum res., hermeticity
    - crucial: low mass, low power, high granularity detectors
    - need to consider machine properties => significant differences between ILC/CLIC and circular colliders?
- **underestimated / not sufficiently studied so far:**
    - particle ID: impact on flavour tag, JER
    - helper measurements: eg neutral hadron fraction => K^0_S
    - reconstruction and ID of low momentum particles (< 2 GeV)
    - alignment / calibration / stability

Summary – ILC Detectors

Status

- well understood detector concepts, incl. integration, mechanics etc at adequate level for phase of project
- 1st order detector performance in many aspects demonstrated in testbeam, some technical/engineering challenges remain
  => ready to get serious!
- 2nd order performance: more detail, redundancy, control of systematics: might make *the* difference!

Wish list & challenges

- single bunch crossing read-out / time stamping for vertex detector – while maintaining point resolution !
- alignment, stability; ILD: TPC distortions
- fully demonstrate power-pulsing: 5 Hz .... 10 Hz continuous
- particle ID, low momentum particles

Thank You

.... for listening

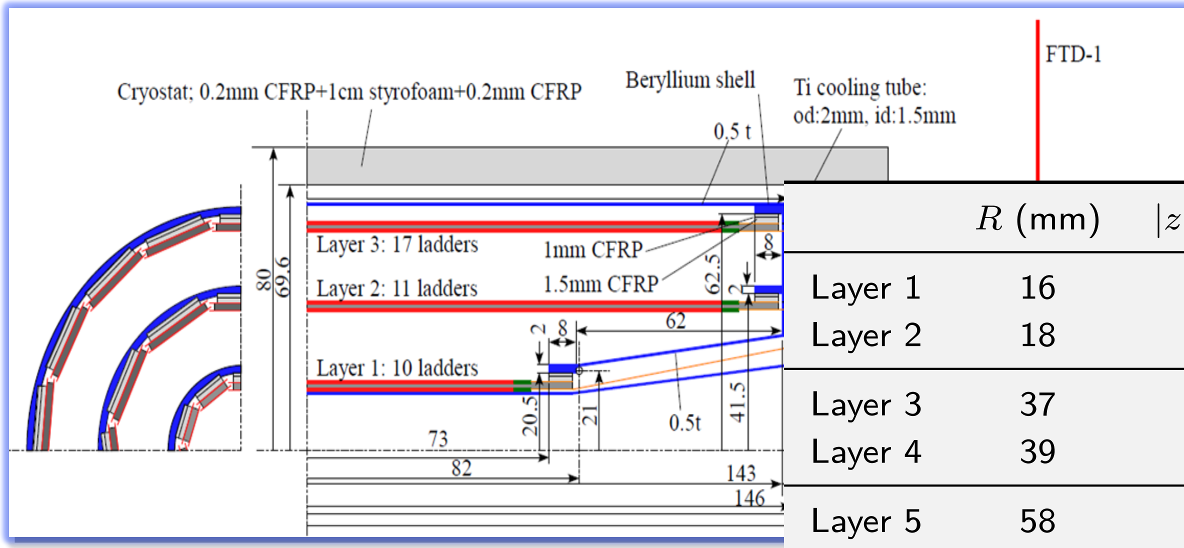
And thanks to all people from whom I stole material while preparing this talk:

- Ties Behnke
- Mikael Berggren
- Klaus Desch
- Masakazu Kurata
- Hale Sert
- Junping Tian
- Ali Ebrahimi

.... and of course SiD & ILD, ILC TDR VOL 4, CLIC CDR, CepC pre-CDR, FCC-ee webpage.....

Backup

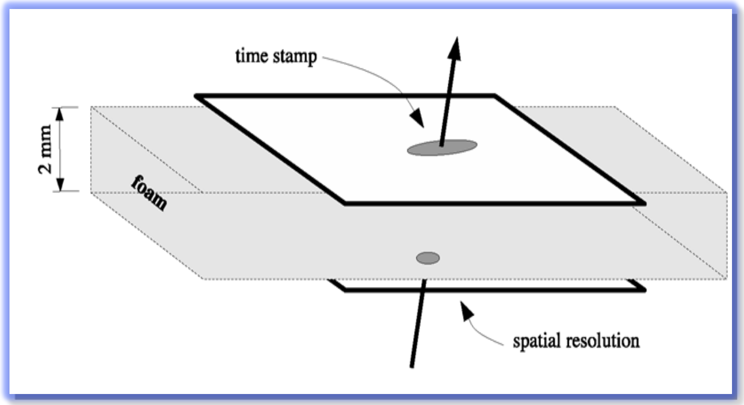
ILD Vertex detector



double layer structure:

	R (mm)	$\lvert z \rvert$ (mm)	$\lvert \cos\theta \rvert$	σ (μm)	Readout time (μs)
Layer 1	16	62.5	0.97	2.8	50
Layer 2	18	62.5	0.96	6	10
Layer 3	37	125	0.96	4	100
Layer 4	39	125	0.95	4	100
Layer 5	58	125	0.91	4	100
Layer 6	60	125	0.9	4	100

	CMOS 4		CMOS 5	
layer	σ_{sp} (μm)	σ_{time} (μs)	σ_{sp} (μm)	σ_{time} (μs)
L1 / L2	4 / 4	4 / 4	3 / 3	1 / 1
L3 / L4	4 / 4	8 / 8	3 / 3	2 / 2
L5 / L6	4 / 4	8 / 8	3 / 3	2 / 2



Summary

- CLIC:
  - CDR: demonstrated that ILC detector concepts work with few modifications
  - challenge: few ns BX rate (TPC can't cope ?!)
- Circular colliders:
  - bunch distance ~=CLIC
  - but: no trains!
    => no power pulsing => cooling systems!
  - needs a full design study – ILC detectors do not apply out of the box
  - challenges:
    - ultra-fast read-out
    - low mass cooling

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, ...

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 $\sqrt{s}$ ≈ 500 GeV (all the rest, incl. ZHH)
  - ννHH at $\sqrt{s}$ ≈ 1 TeV: *complementary* information on BSM
- Top physics
  - starts at $\sqrt{s}$ = ≥ 350 GeV (threshold scan)
  - ew chiral coupling measurements: $\sqrt{s}$ = ≥ 400-450 GeV
  - Yukawa coupling: : $\sqrt{s}$ = ≥ 500 GeV
- BSM, T/QGCs, di-fermions, .. : the higher $\sqrt{s}$ the better!

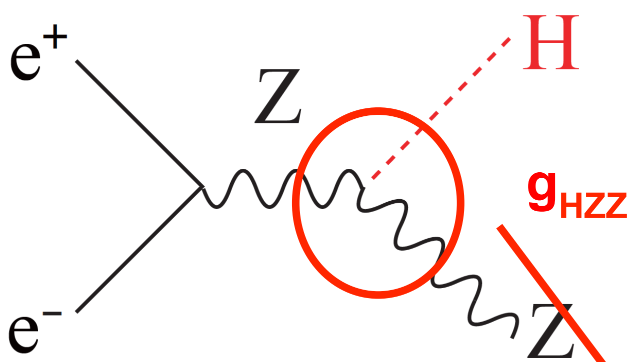
Take Home Message II

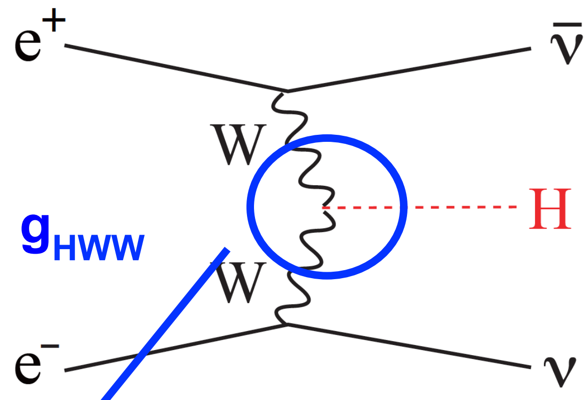
The ILC is the only technologically proven accelerator to cover *the full program:*

- 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 potentia**l in important BSM scenarios, complementary to the LHC (light Higgsinos, small mass differences, WIMPs, light higgses...)

Precision Measurements: Profiling the Higgs Boson

Higgs Production in e^+e^- collisions

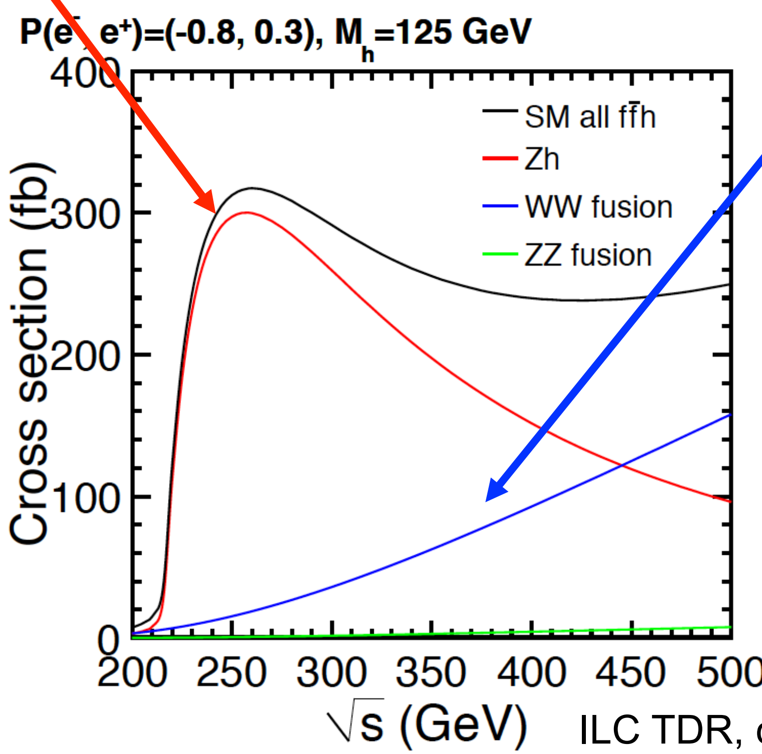




Higgs-Strahlung:

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

Via recoil method: model-independent!



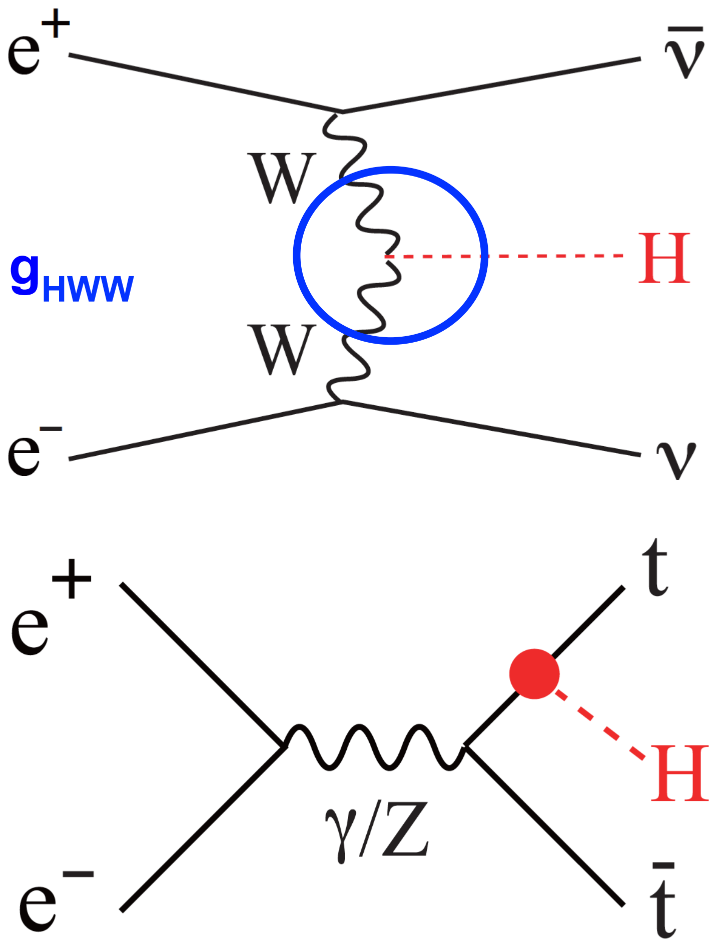
ILC TDR, cross section by WHIZARD

WW-Fusion:

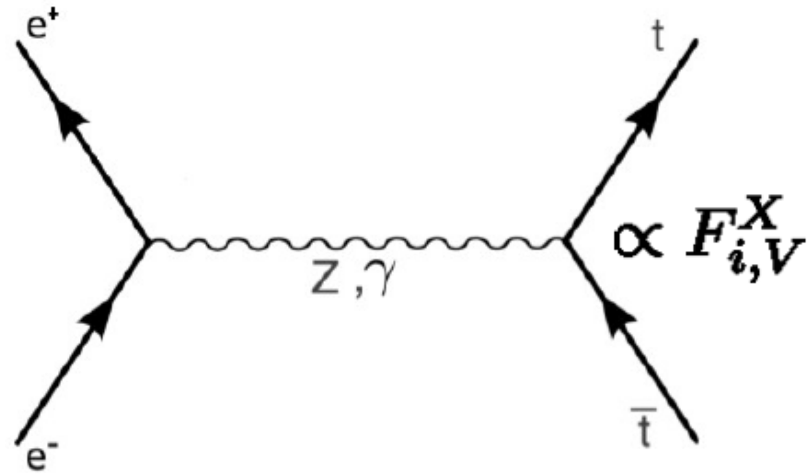
- High rates
- Precision σ x BR

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**



Testing the chiral structure of the SM



CP violating

$$\Gamma_\mu^{ttX}(k^2,q,\bar{q}) = -ie\left\{\gamma_\mu\left(F_{1V}^X(k^2)+\gamma_5 F_{1A}^X(k^2)\right)+\frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\mu\left(iF_{2V}^X(k^2)+\gamma_5 F_{2A}^X(k^2)\right)\right\}, \quad (2)$$

$$\mathcal{F}_{ij}^L = -F_{ij}^\gamma + \left(\frac{-\frac{1}{2}+s_w^2}{s_w c_w}\right)\left(\frac{s}{s-m_Z^2}\right)F_{ij}^Z$$

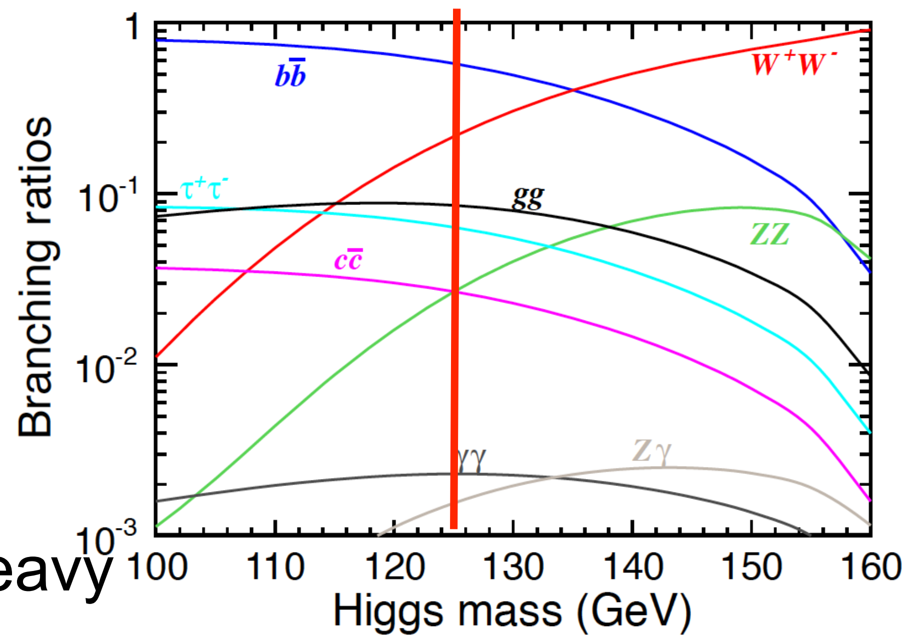
$$\mathcal{F}_{ij}^R = -F_{ij}^\gamma + \left(\frac{s_w^2}{s_w c_w}\right)\left(\frac{s}{s-m_Z^2}\right)F_{ij}^Z ,$$

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

The beyond-LHC Higgs Menue

- Model-independent extraction of **all** couplings:
  - Absolute couplings, not ratios
  - No assumptions



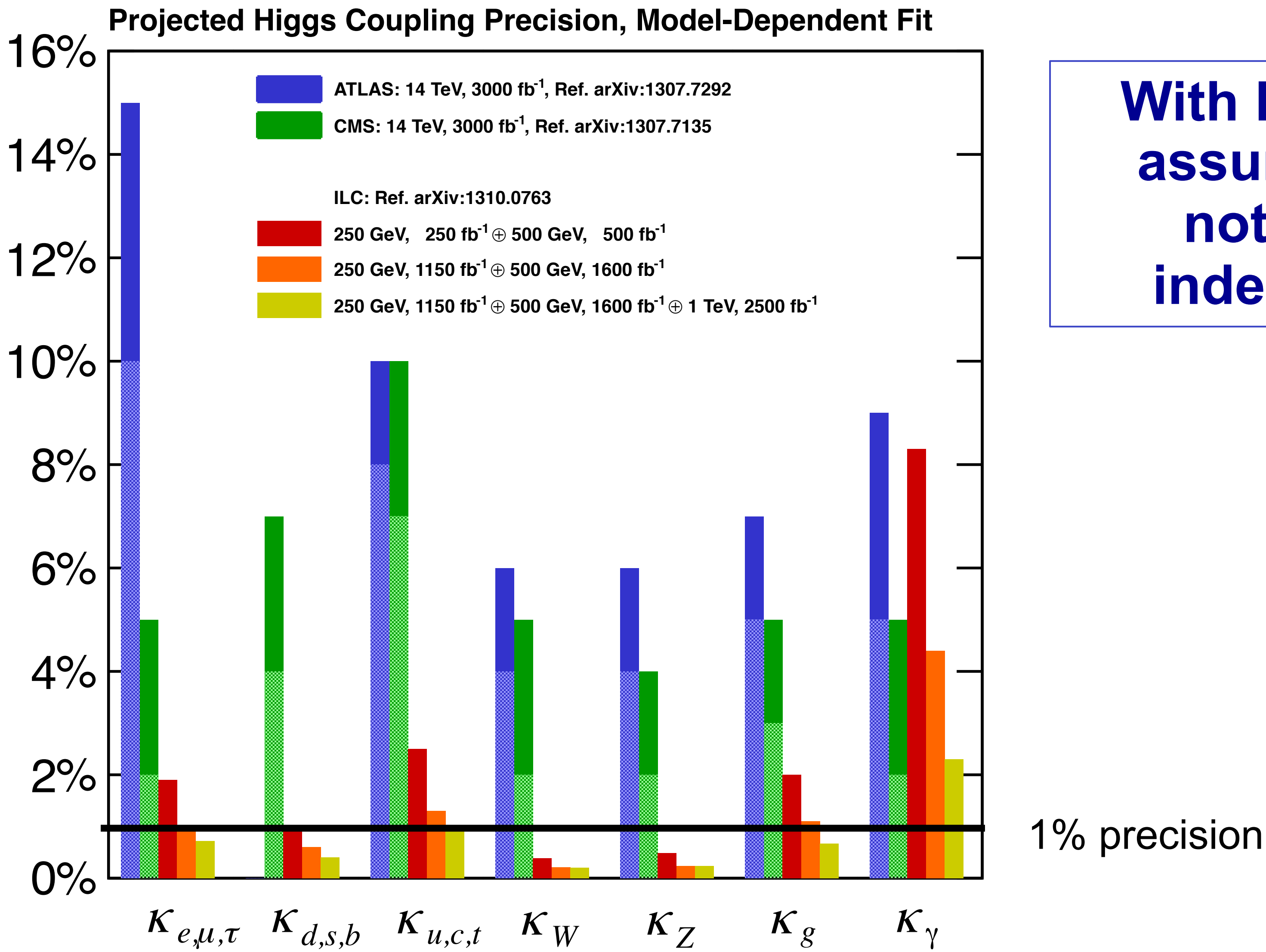
- To precisions relevant for BSM:
  - No new physics yet → heavy
  - expect only small deviations of few percent max for M=1TeV:

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]

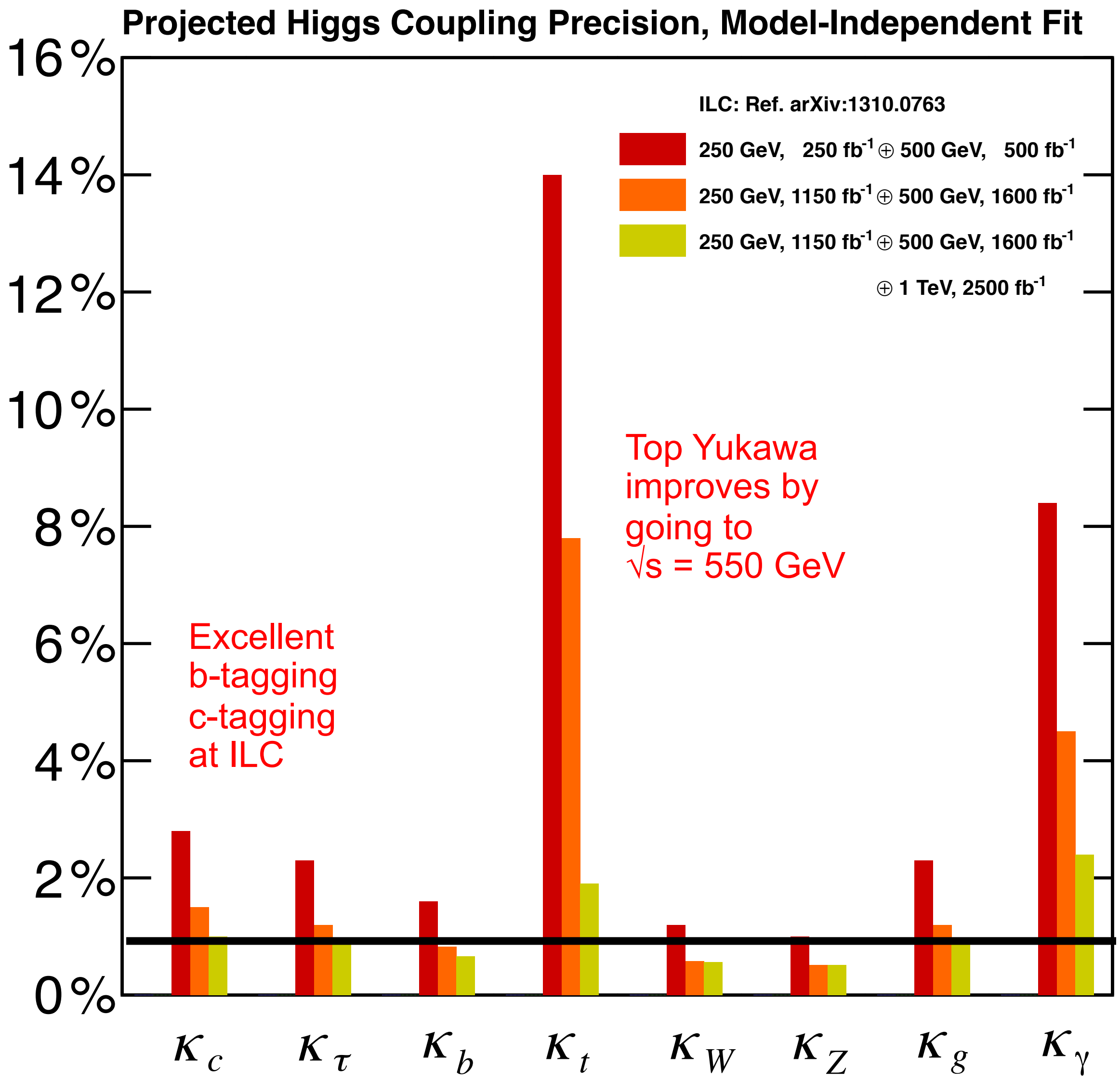
=> requires sub-percent precision!

Higgs Couplings (1/2)



With LHC-style assumptions; not model-independent.

Higgs Couplings (2/2)



Model-independent coupling determination unique to ILC

Better hγγ with LHC/ILC synergy

1% precision

Disentangling the couplings

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

ILC 'provides' two beam polarisations

$P(e^-) = \pm 80\%$ $\qquad$ $P(e^+) = \mp 30\%$

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

$$F^{\gamma}_{1V},\ F^{Z}_{1V},\ F^{\gamma}_{1A} = 0,\ F^{Z}_{1A}$$

$$F^{\gamma}_{2V},\ F^{Z}_{2V}$$

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

Physics behind EWSB at TeV scale

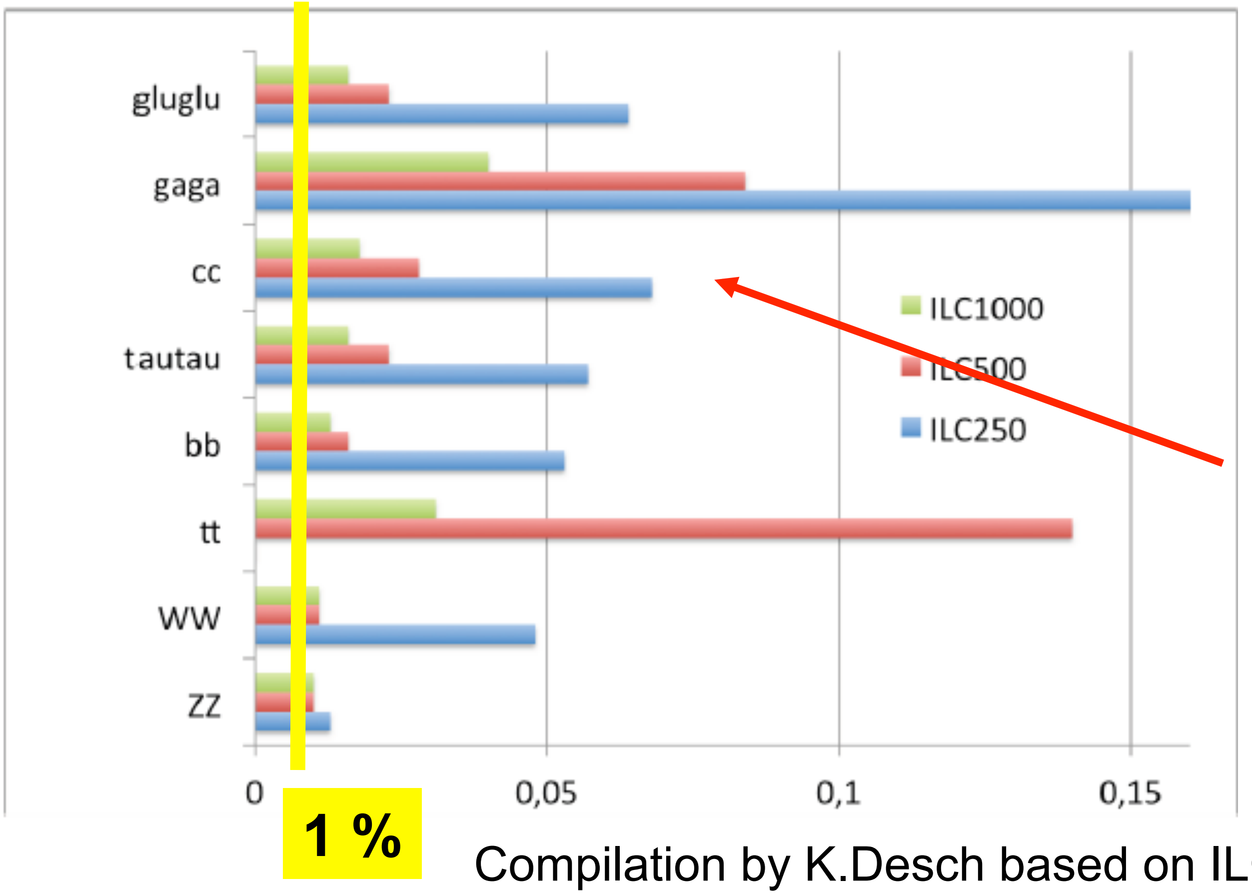
There are two possible scenarios for the physics behind EWSB around the TeV scale:

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

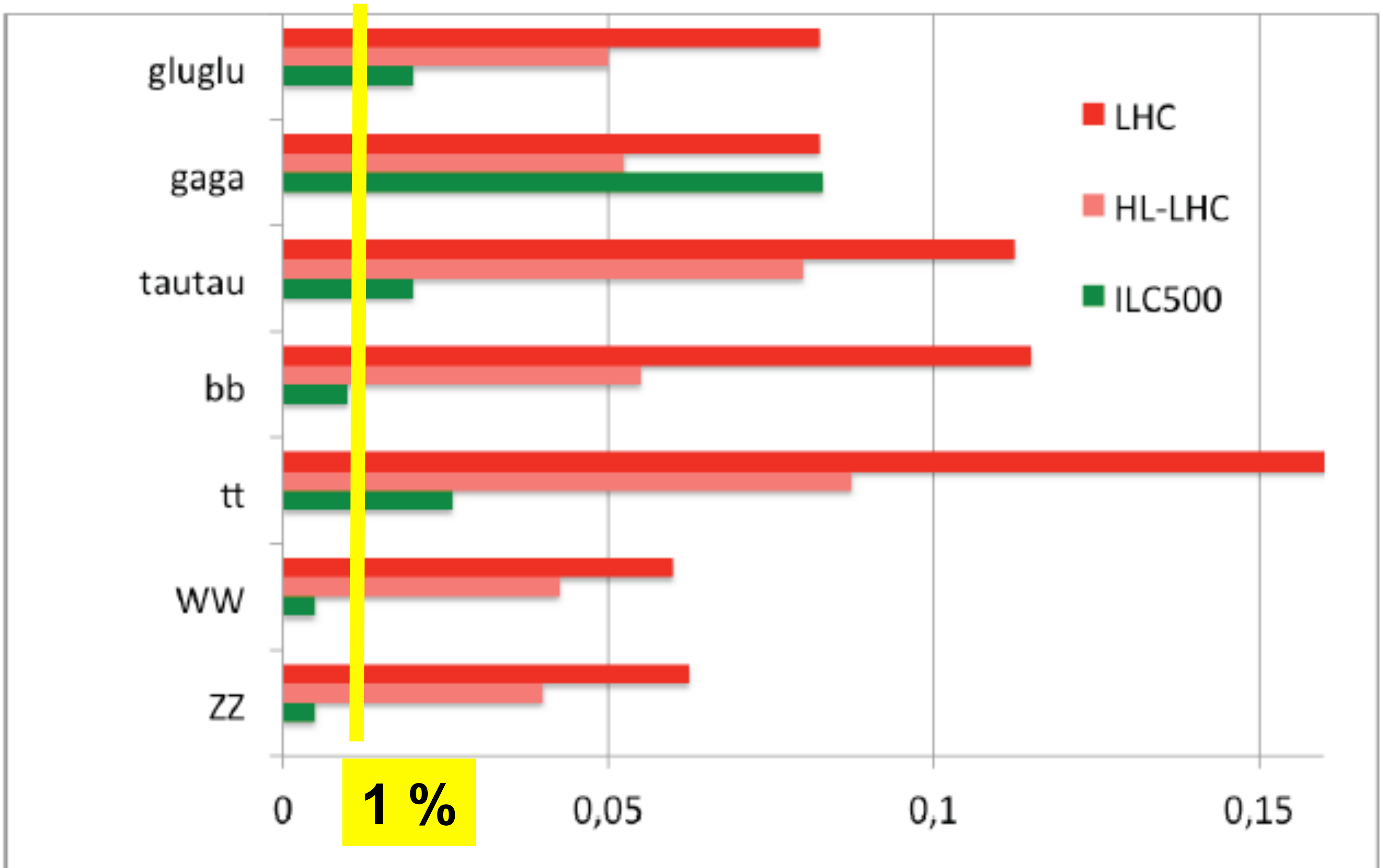


- Fully model-independent
- No assumptions
- ILC unique
- Note: cc!

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)

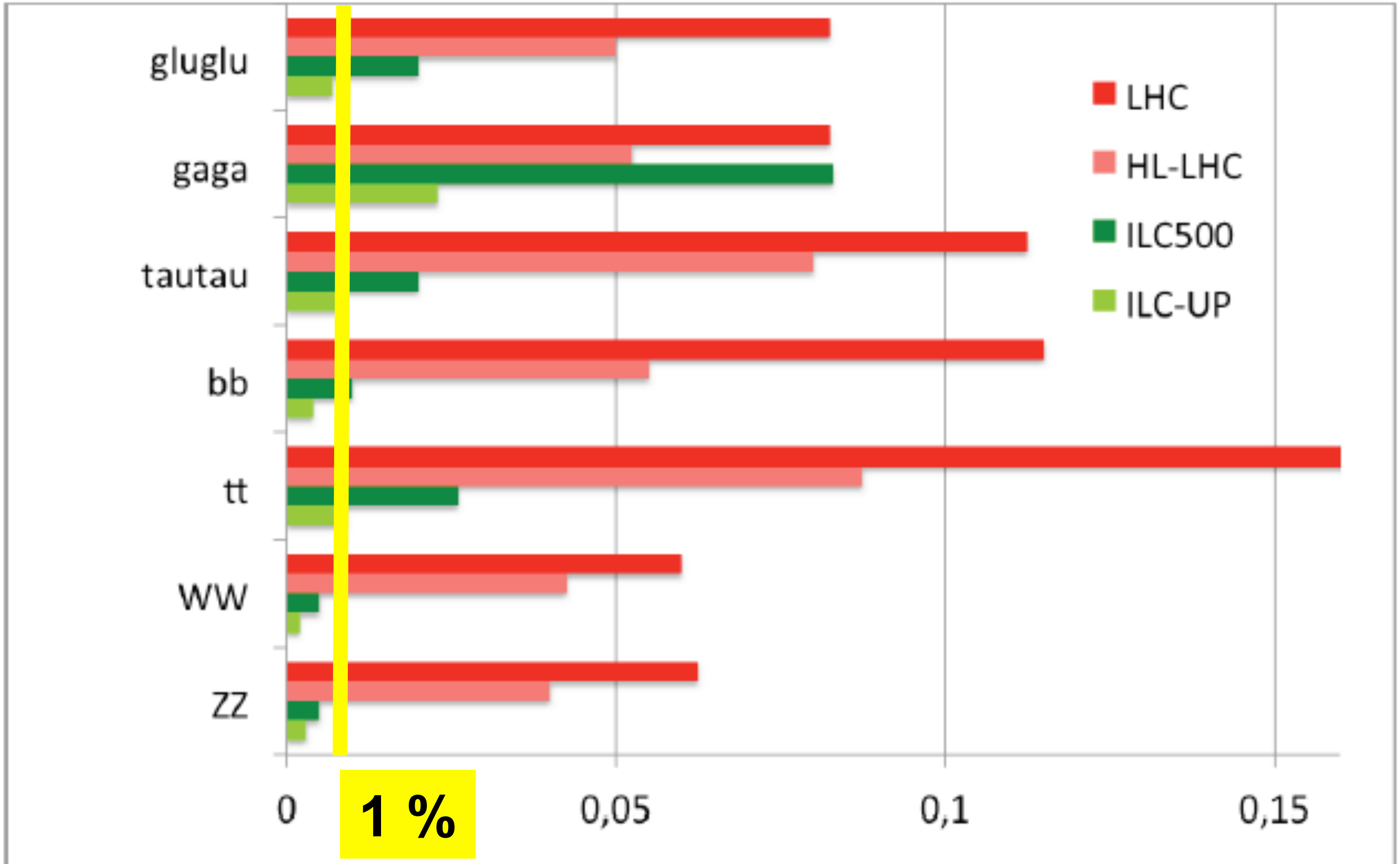
ILC: based on ILC white paper
arxiv:1310.0763

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



Compilation by K.Desch, LCForum Oct. 2013

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

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

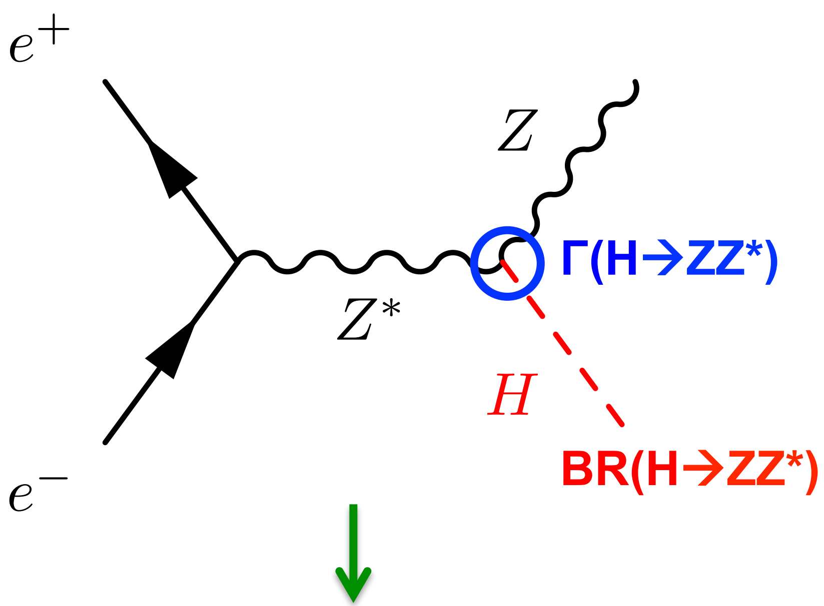
1TeV ILC: typically factor 2 improvement over ILC500, bb → sub-percent

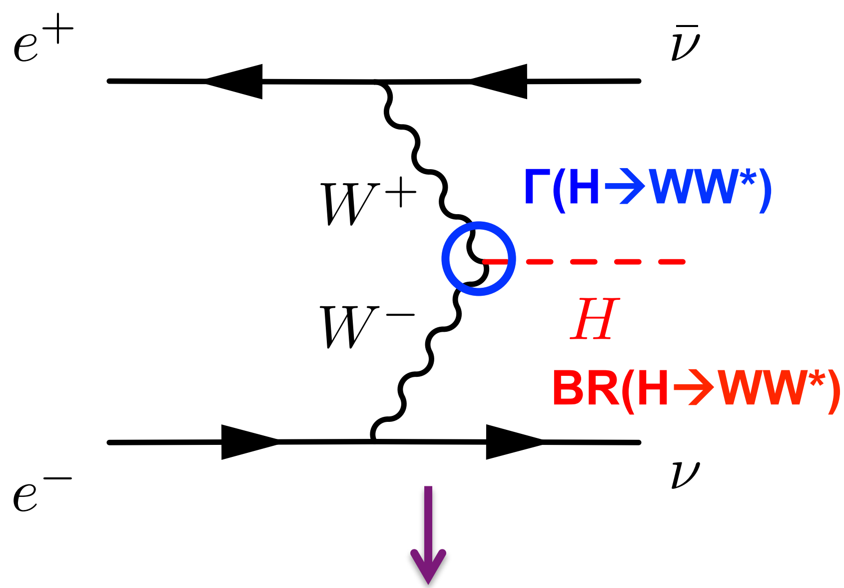
Higgs Coupling Determination

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:





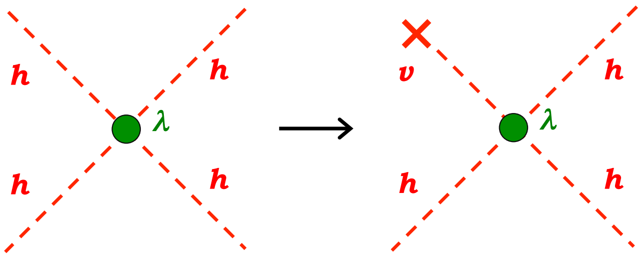
ZH at 250 GeV alone requires very high statistics since BR(H→ZZ*) ~ 2%.

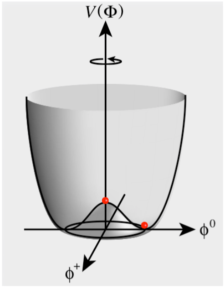
Very small cross section at 250 GeV. Clean reaction at 500 GeV

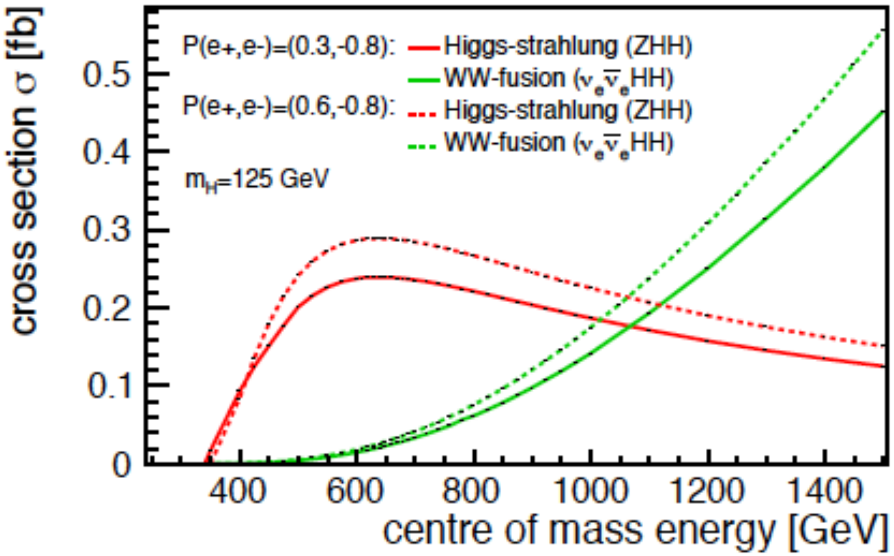
Combination of 250 GeV & 500 GeV data essential for the precise determination of Higgs couplings

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

Existence of hhh coupling λ =
Direct evidence of vacuum condensation

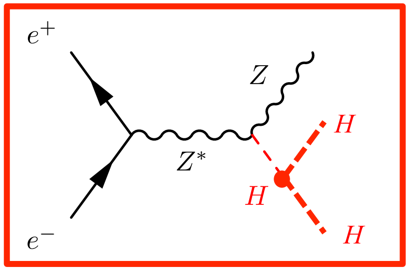


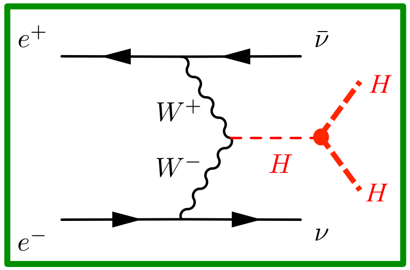




e^+e^- phenomenology:

- 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(ννHH) smaller
  - $\lambda < \lambda_{SM}$ => σ(ZHH) smaller, σ(ννHH) 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!



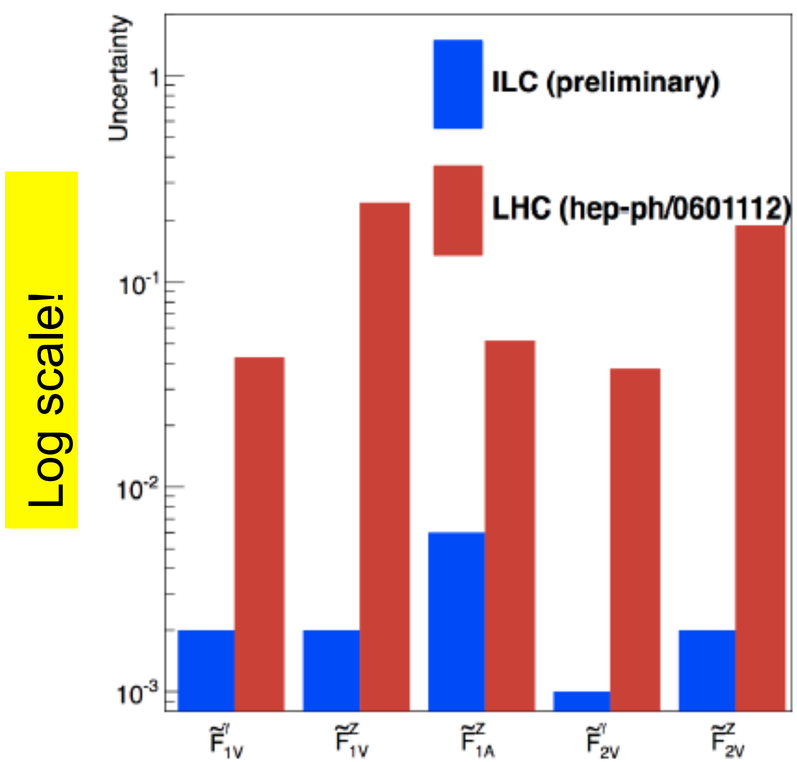


ILD Full Detector Simulation Study

ArXiv: 1307.8102

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

Accuracy on CP conserving couplings



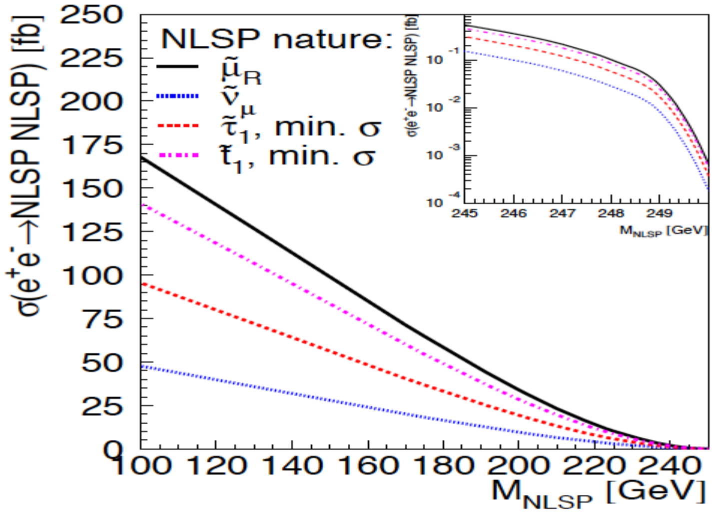
- ILC might be up to two orders of magnitude more precise than LHC ($\sqrt{s}$ = 14 TeV, 300 fb^{-1})
  Disentangling of couplings for ILC
  One variable at a time For LHC
- However LHC projections from 8 years old study
- Strong encouragement to update these numbers!
  First step is Phys. Rev. Lett. 110 (2013) 172002 by CMS
- Potential for CP violating couplings at ILC under study

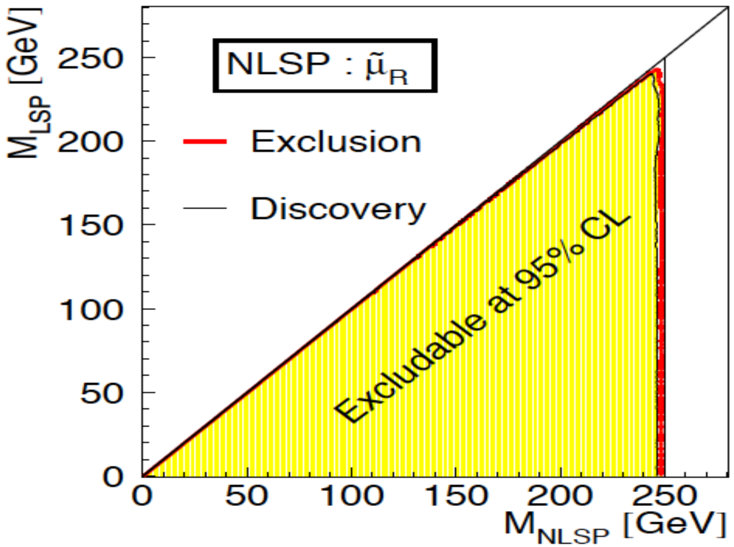
ILC will be indeed high precision machine for electroweak top couplings

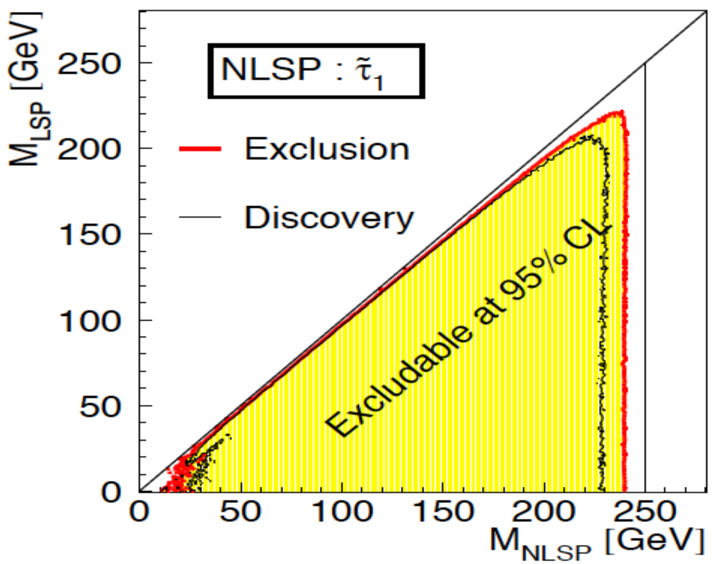
SUSY at the ILC

...is naturally simplified:

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



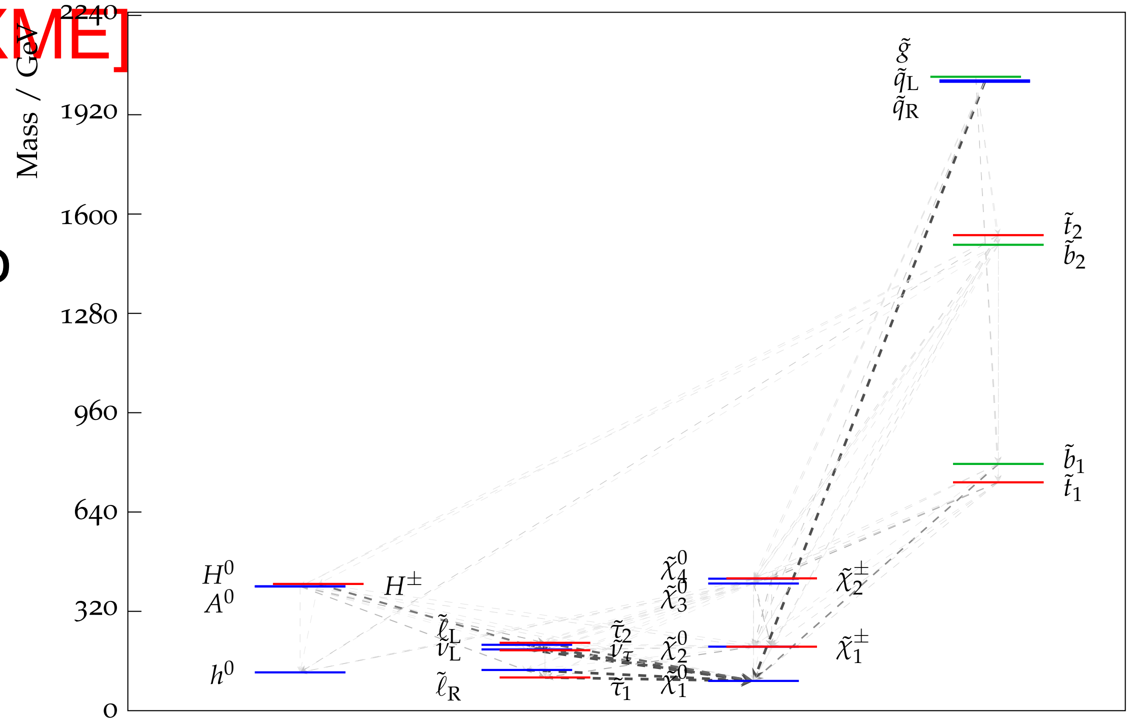




Loop-hole free, model-independent sensitivity down to very small mass differences

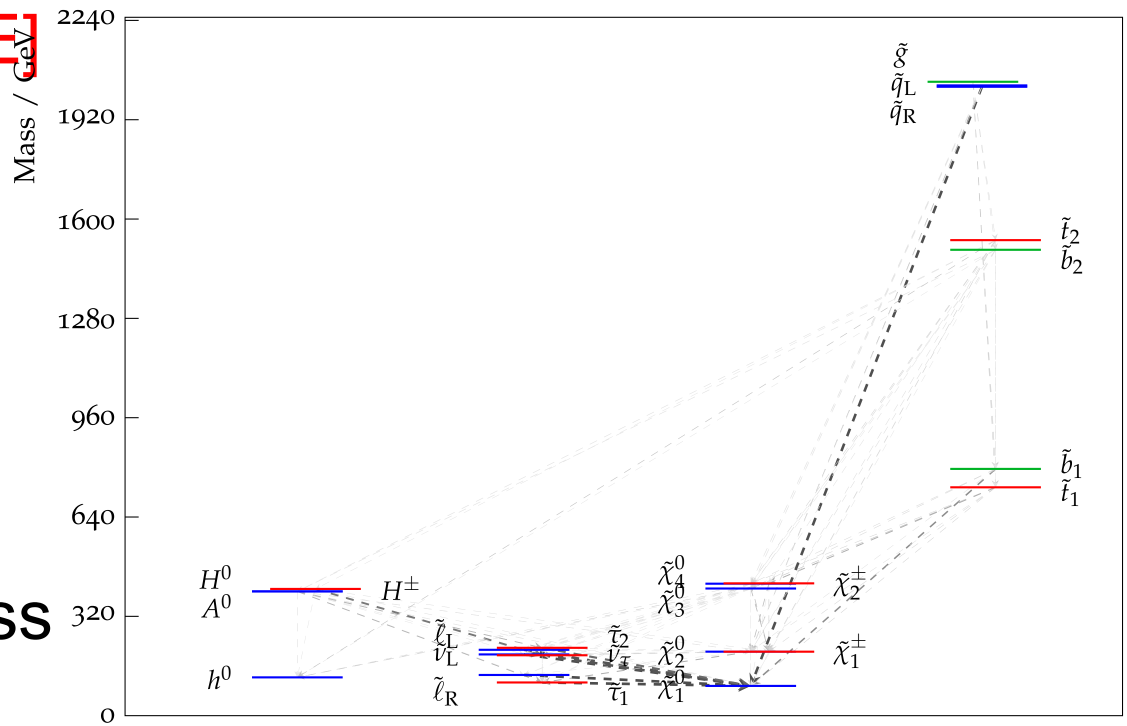
Case A: a rich SUSY spectrum

- 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

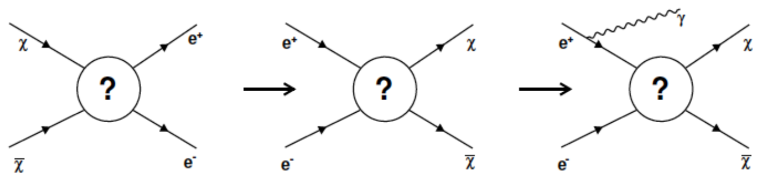
- plot from Batool FIXME]
- LHC 14 TeV:
  - can isolate direct sbottom production
  - determine endpoint in mass [fixme!]
- need to know LSP mass to convert endpoint into sbottom mass => ILC!



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

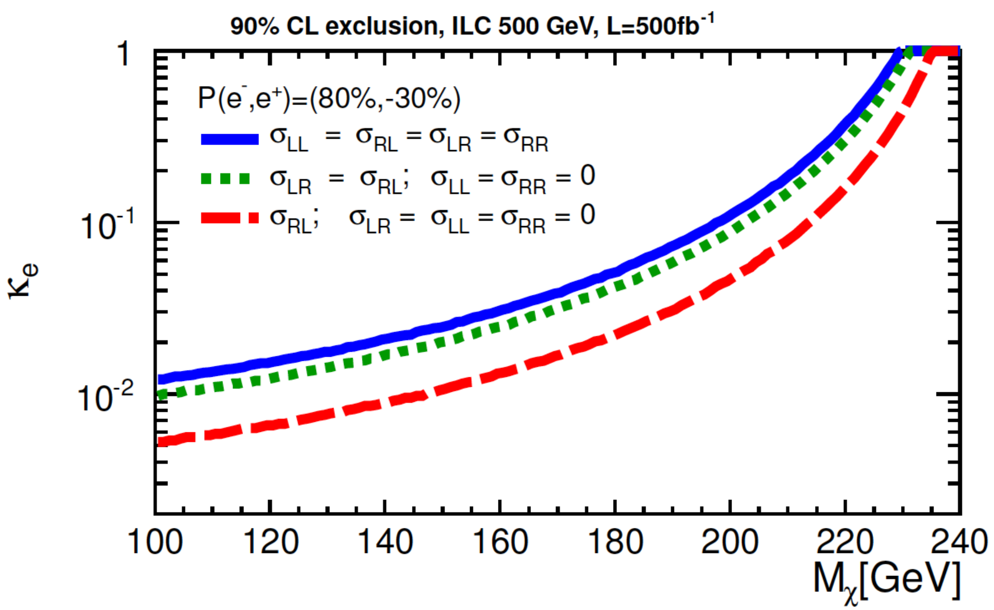
- M_χ - WIMP mass
- S_χ - WIMP spin $=$ -$\frac{1}{2}$
- Λ - energy scale of the new physics that provides the coupling, $\sigma \sim \frac{1}{\Lambda^4}$
- Choice of operator

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

“Cosmological” Approach

- Spin -1/2
- P-wave

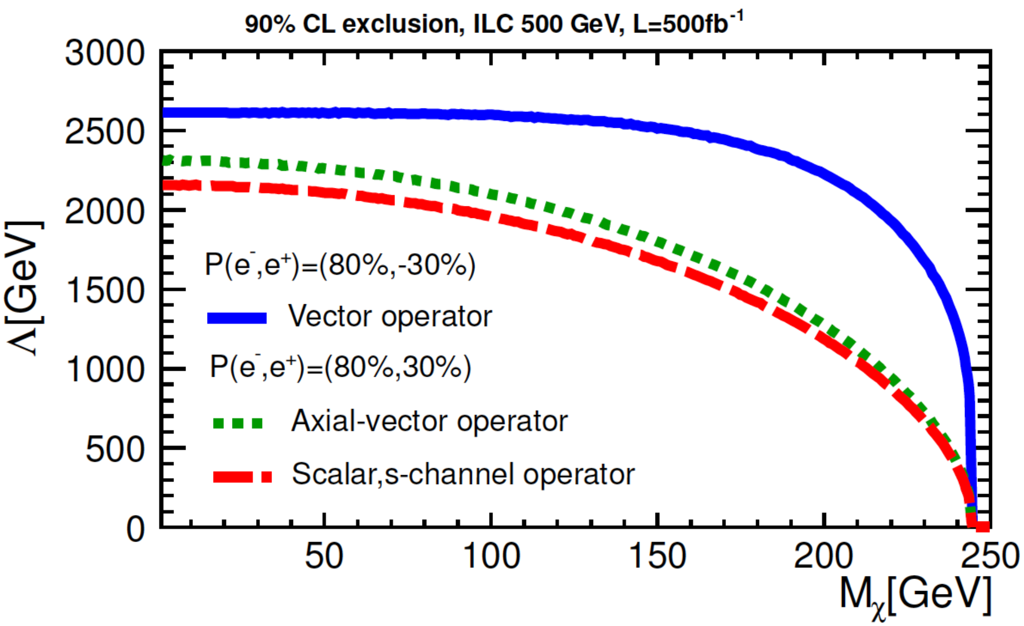
Can exclude down to ~1% annihilation fraction to e^+e^-



Effective Operator Approach

- Spin -1/2

Can exclude up to Λ~2.5 TeV

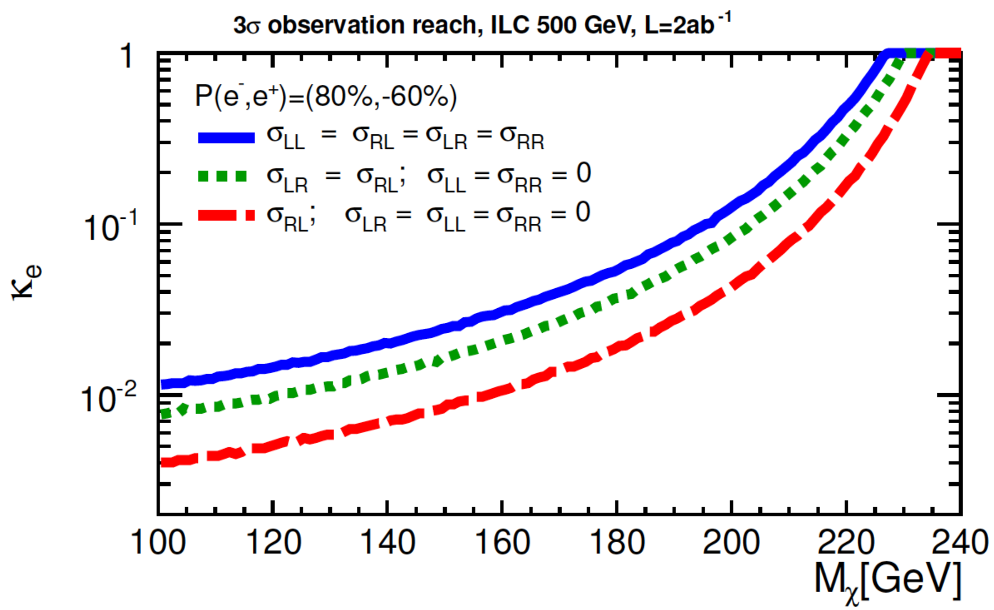


Observation reach: 500 GeV, **2ab^{-1}**

"Cosmological" Approach

- Spin -1/2
- P-wave

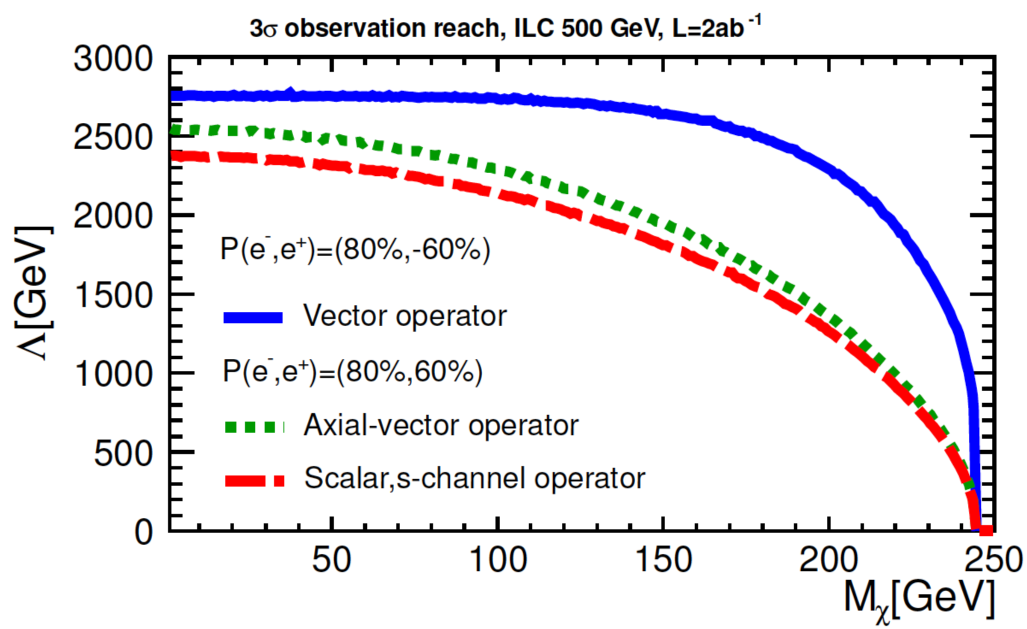
Can observe down to ~1 % annihilation fraction to e^+e^-



Effective Operator Approach

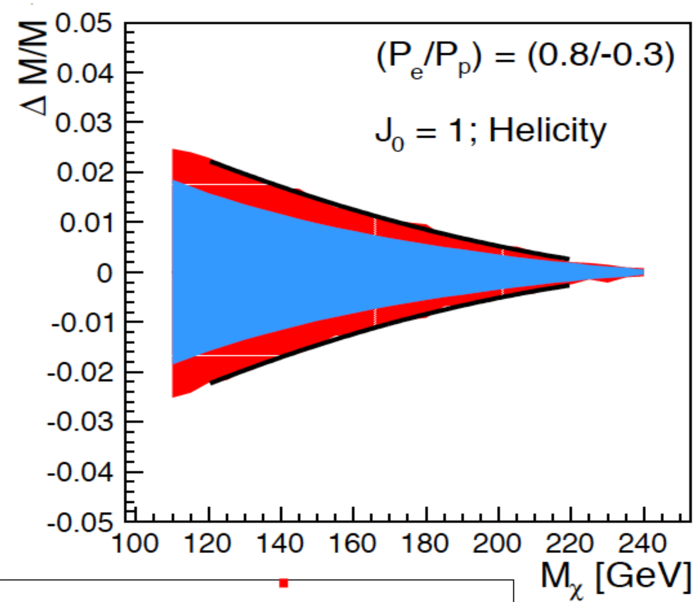
- Spin -1/2

Can observe up to Λ~2.5 TeV

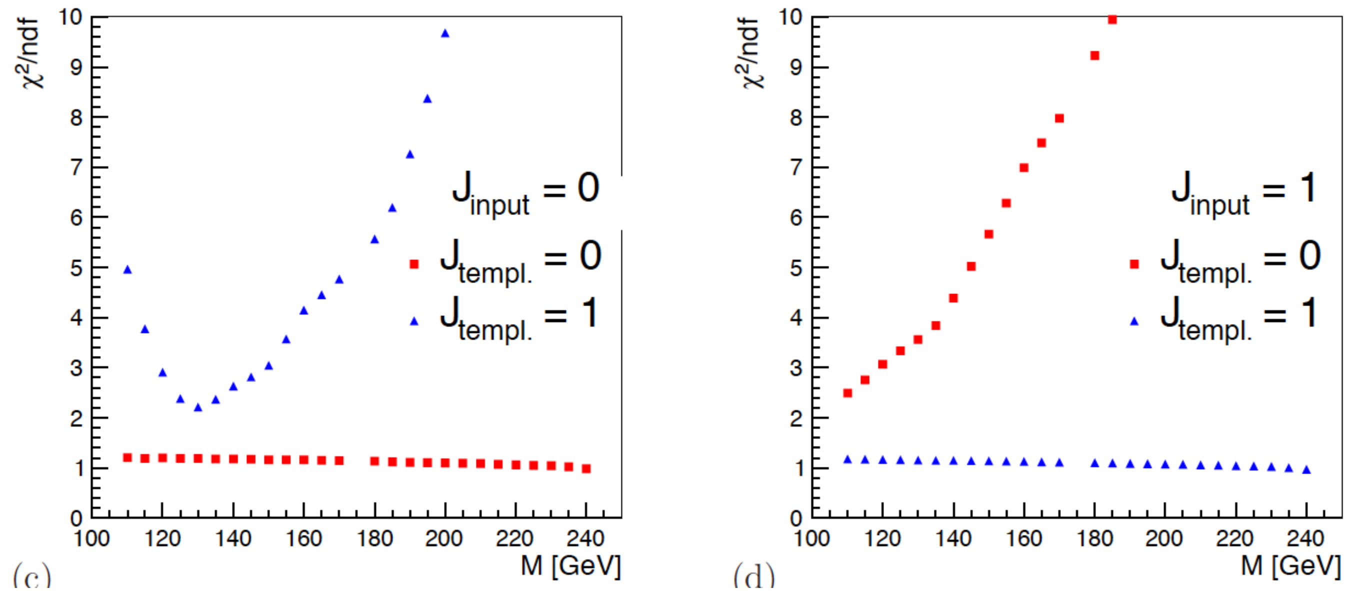


WIMP characterisation

- 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

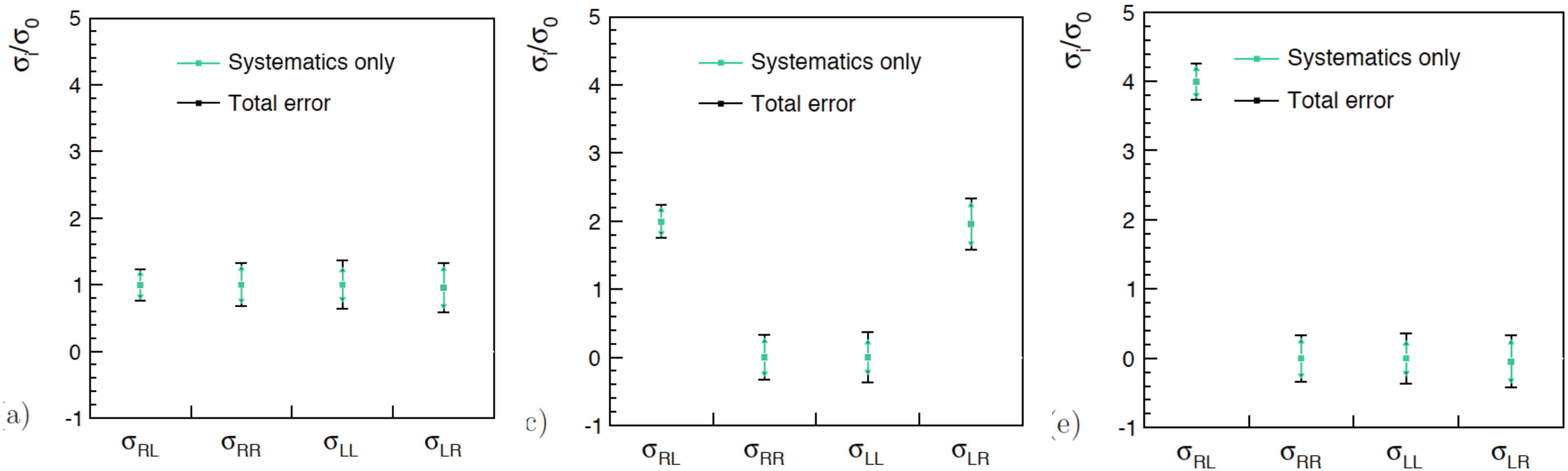


From EPJC 72 (2012) 2213, Bartels et al

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:

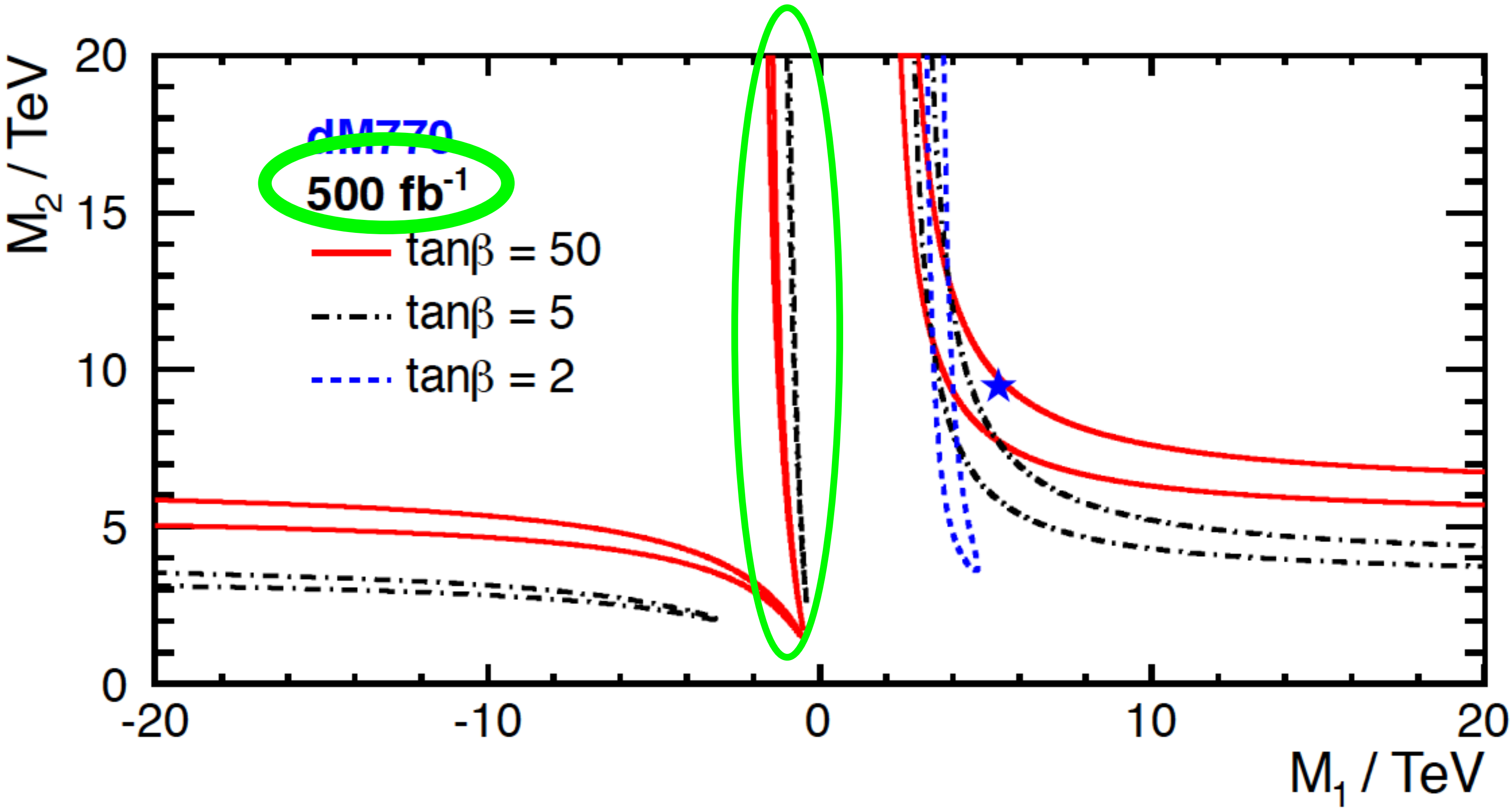
"Equal" "Helicity & Parity conserving" "Anti-SM"



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

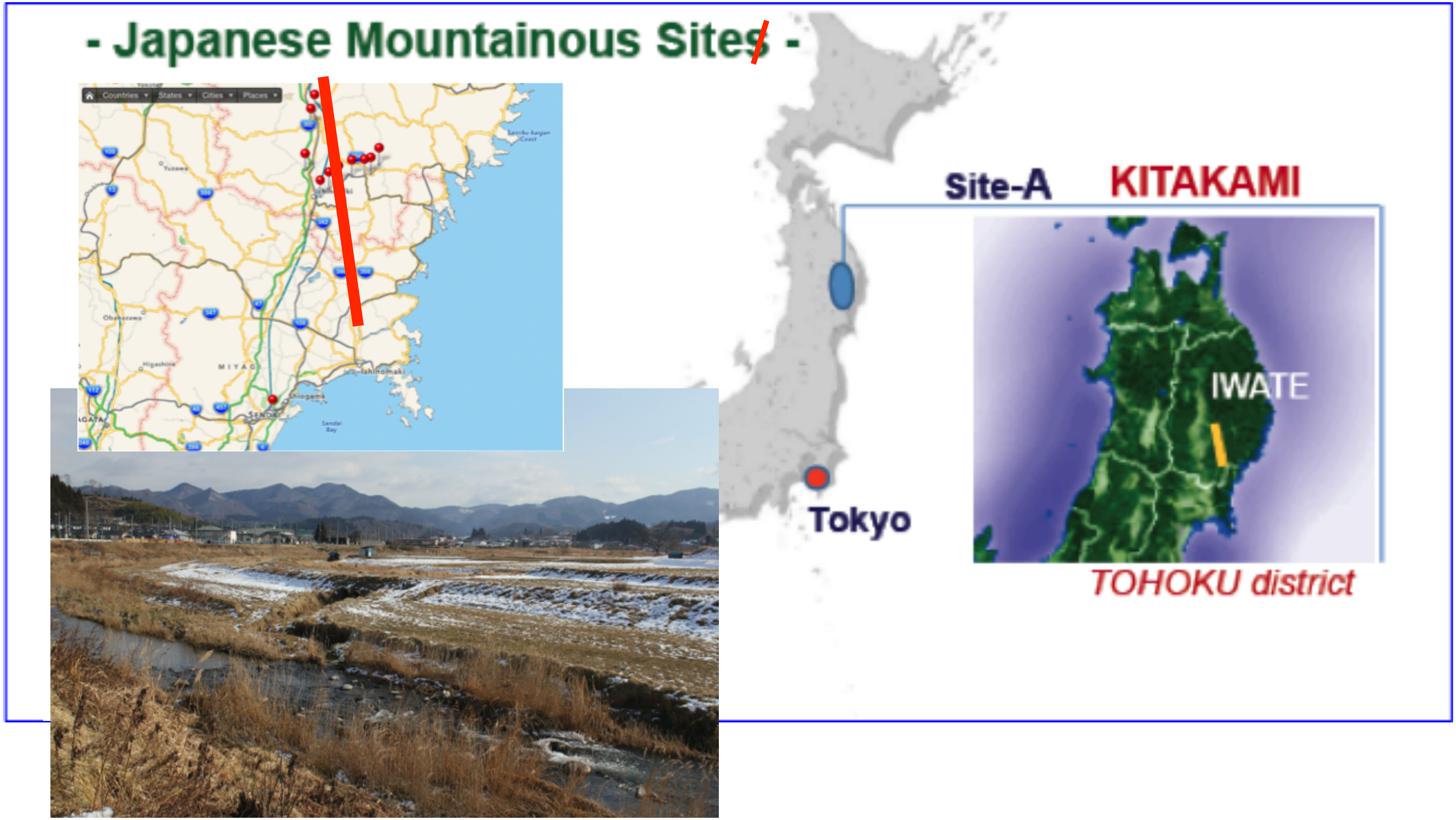
- superconducting cavities

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

A mature and proven technology

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

The ILC Site in Japan



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.**

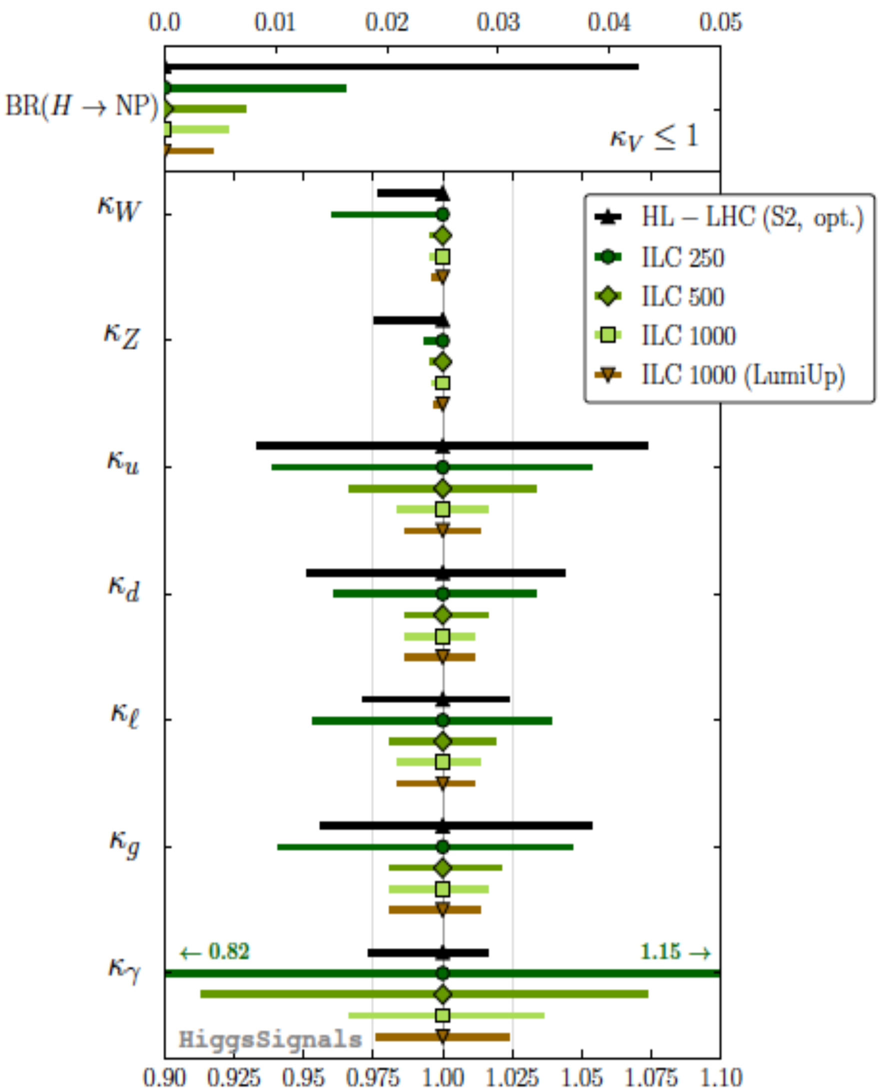
A glimpse into the P5 report - ILC

- 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.

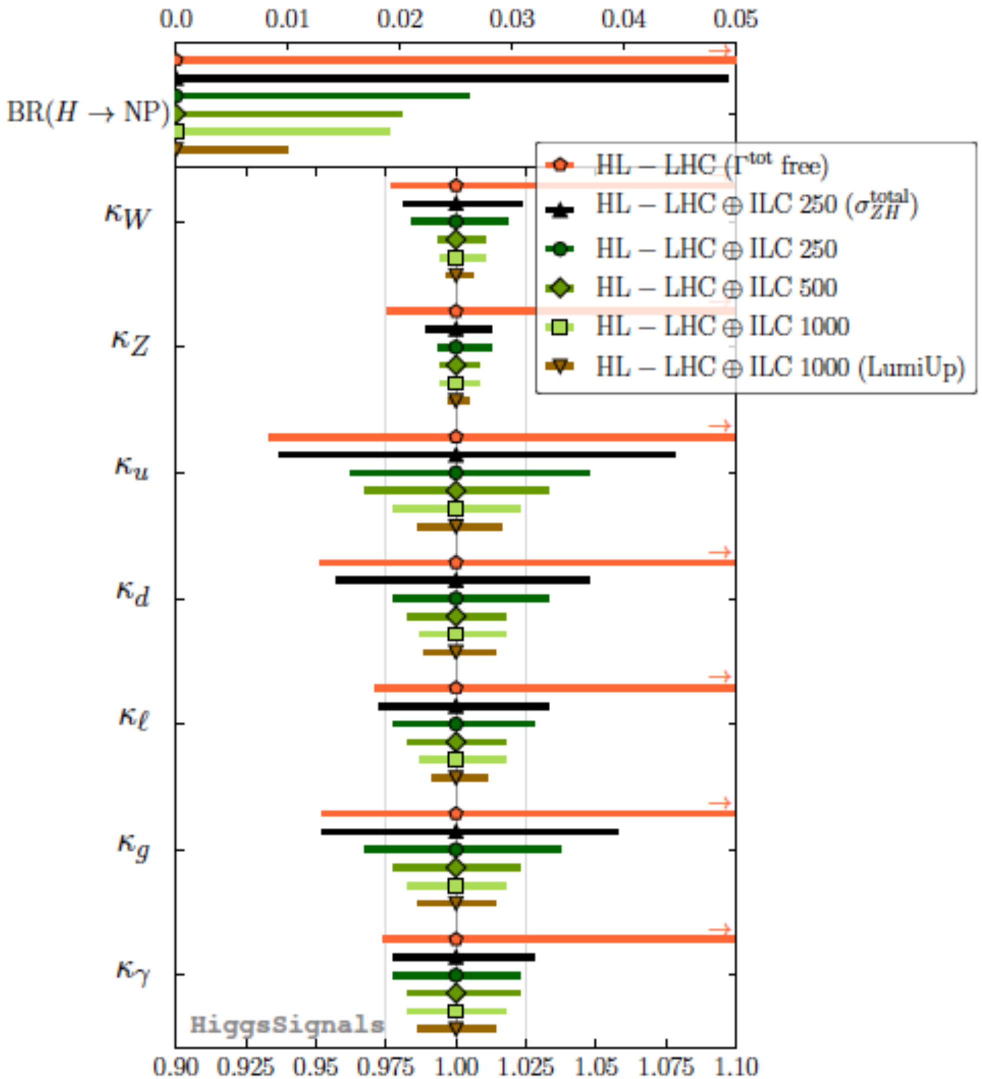
Slightly Model-dependent Coupling Fit



[arXiv:1403:1582]

- Assume κ_W, $\kappa_Z \leq 1$

Model-independent Coupling Fit

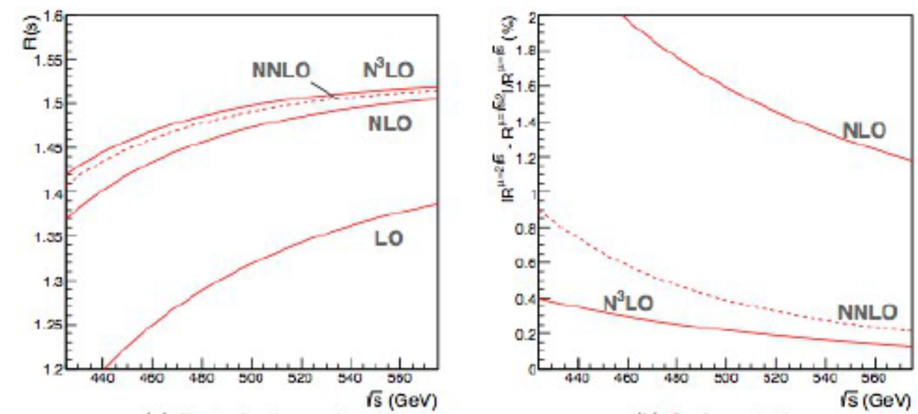


[arXiv:1403:1582]

- 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 N^3LO

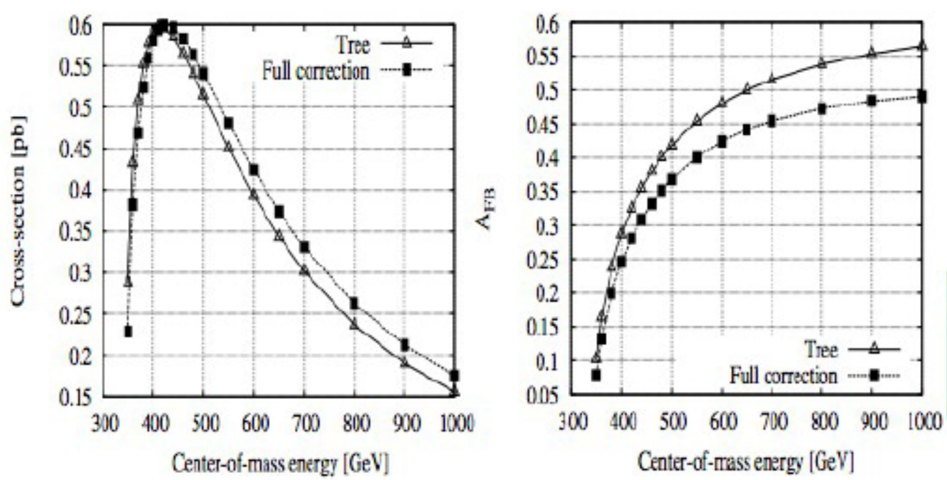


(a) Perturbation series (b) Scale variations

QCD correction (N^3LO) 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

Higgs Self-Coupling: ILC projections

- Snowmass snapshot (m_H = 120 GeV):

out-dated

arXiv:1310.0763	ILC500	ILC500-up	ILC1000	ILC1000-up
$\sqrt{s}$ (GeV)	500	500	500/1000	500/1000
$\int \mathcal{L} dt$ (fb^{-1})	500	1600‡	500+1000	1600+2500‡
$P(e^-, e^+)$	$(-0.8, 0.3)$	$(-0.8, 0.3)$	$(-0.8, 0.3/0.2)$	$(-0.8, 0.3/0.2)$
$\sigma\,(ZHH)$	42.7%	[illegible]	42.7%	23.7%
$\sigma\,(\nu\bar{\nu}HH)$	–	–	26.3%	16.7%
λ	83%	46%	21%	13%

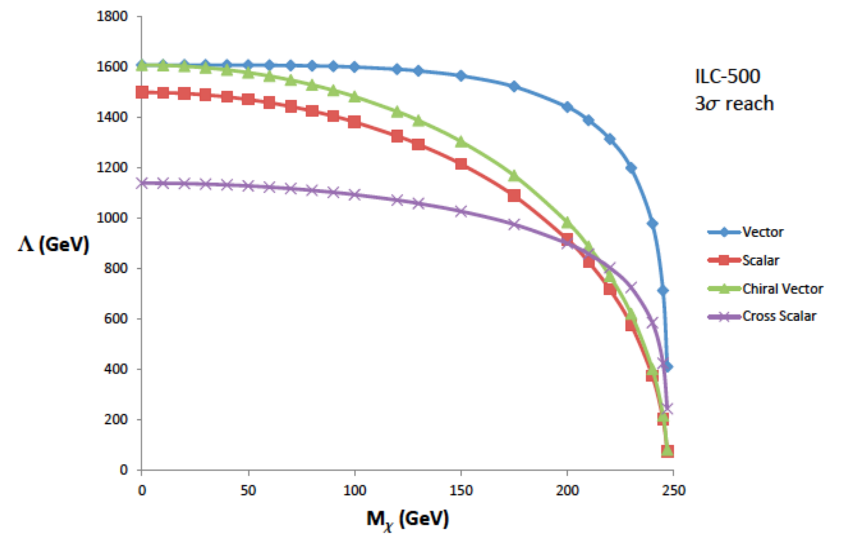
- currently complete reanalysis ongoing, based on
  - HH -> bbbb 6 jets
  - HH -> bbWW* 8 jets

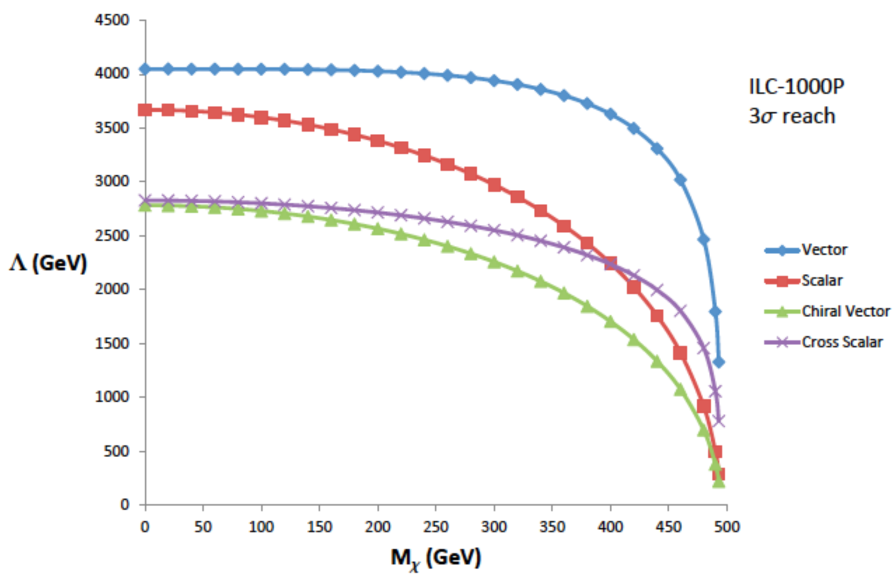
- improved analysis techniques for better suppressionof main background ZZH
  - kinematic fitting
  - matrix element methods, ...
- in any case: will require large integrated luminosities

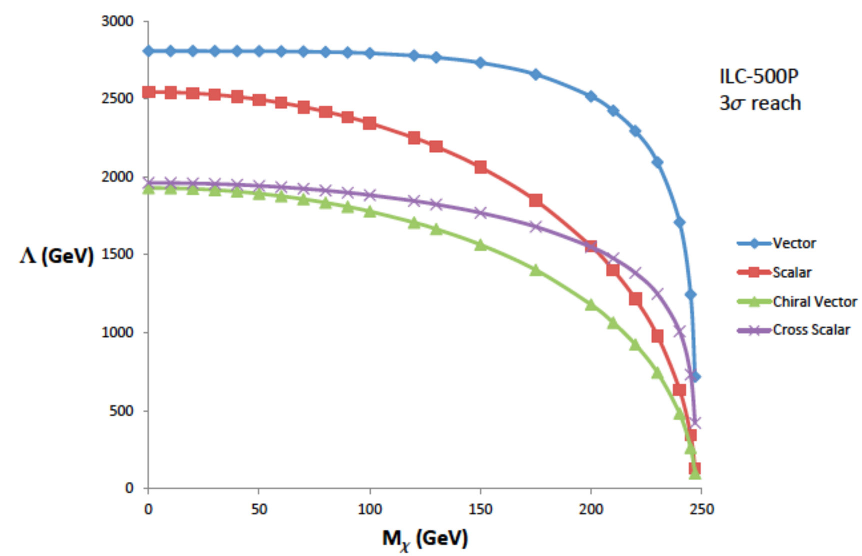
ILC: Projected sensitivity on Λ

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}

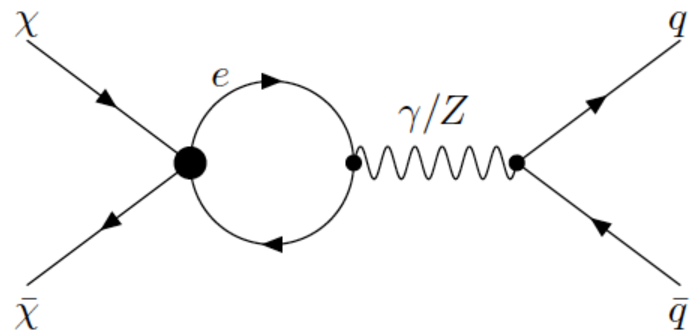


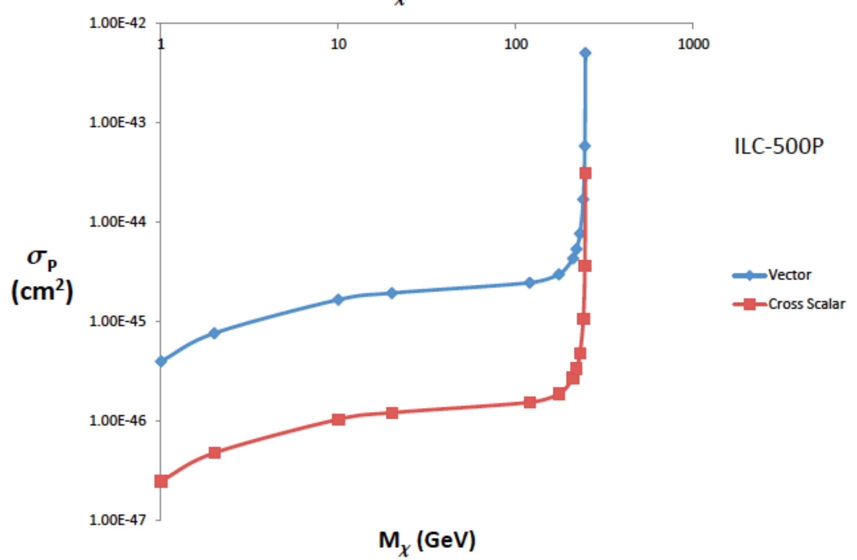


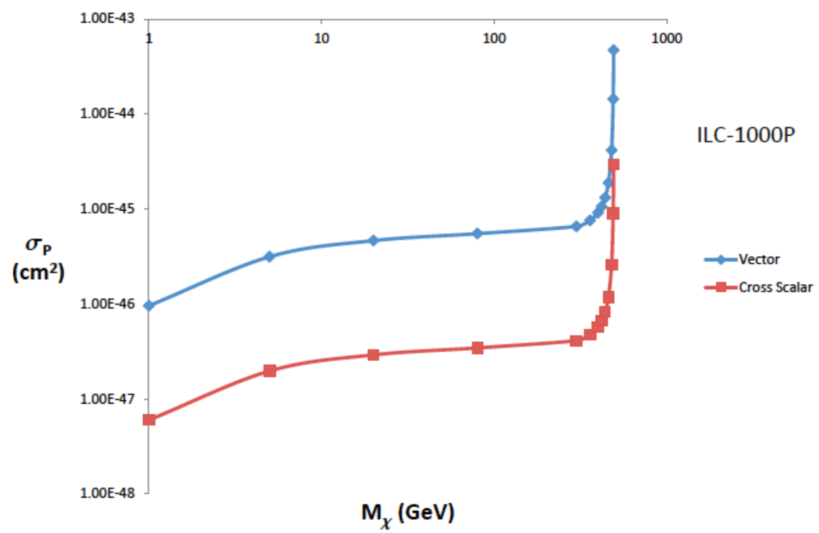


How to relate e$^+$e$^-$ to Direct Searches?

- 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....

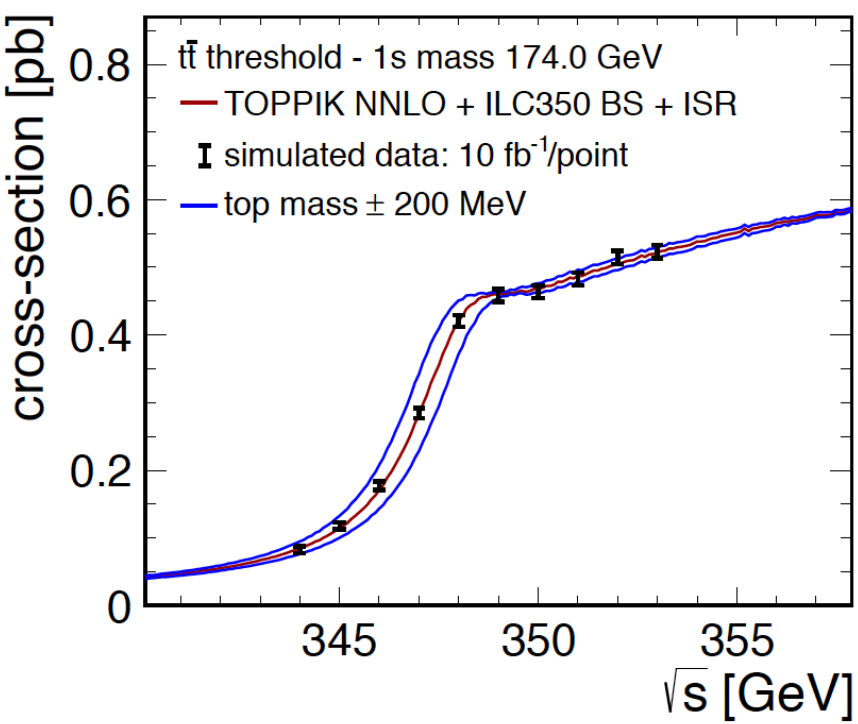
We're living in exciting times - stay tuned!

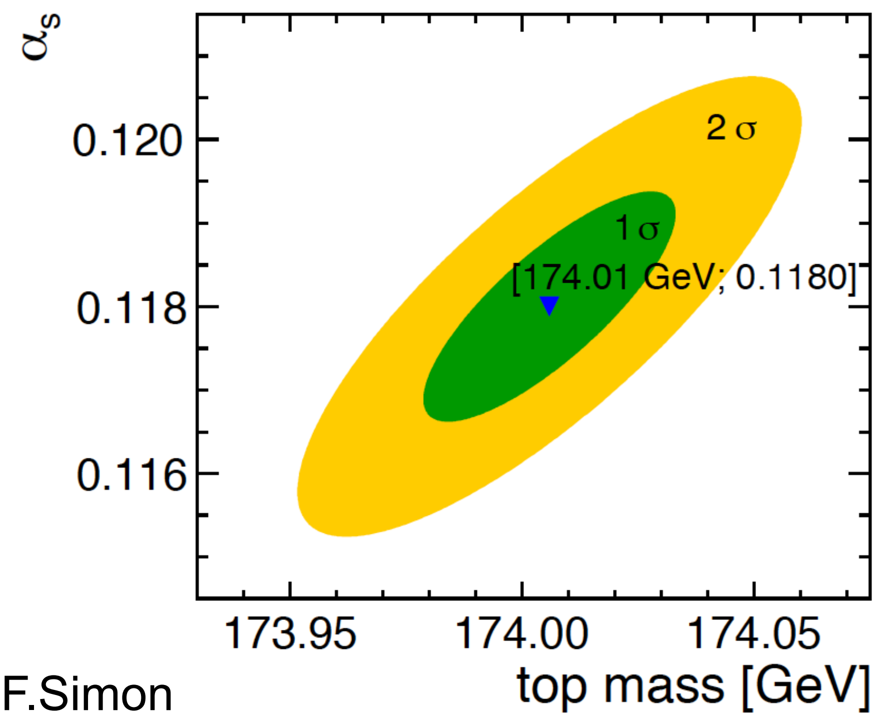
Precision Measurements: Top and more

Top Threshold Scan

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

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

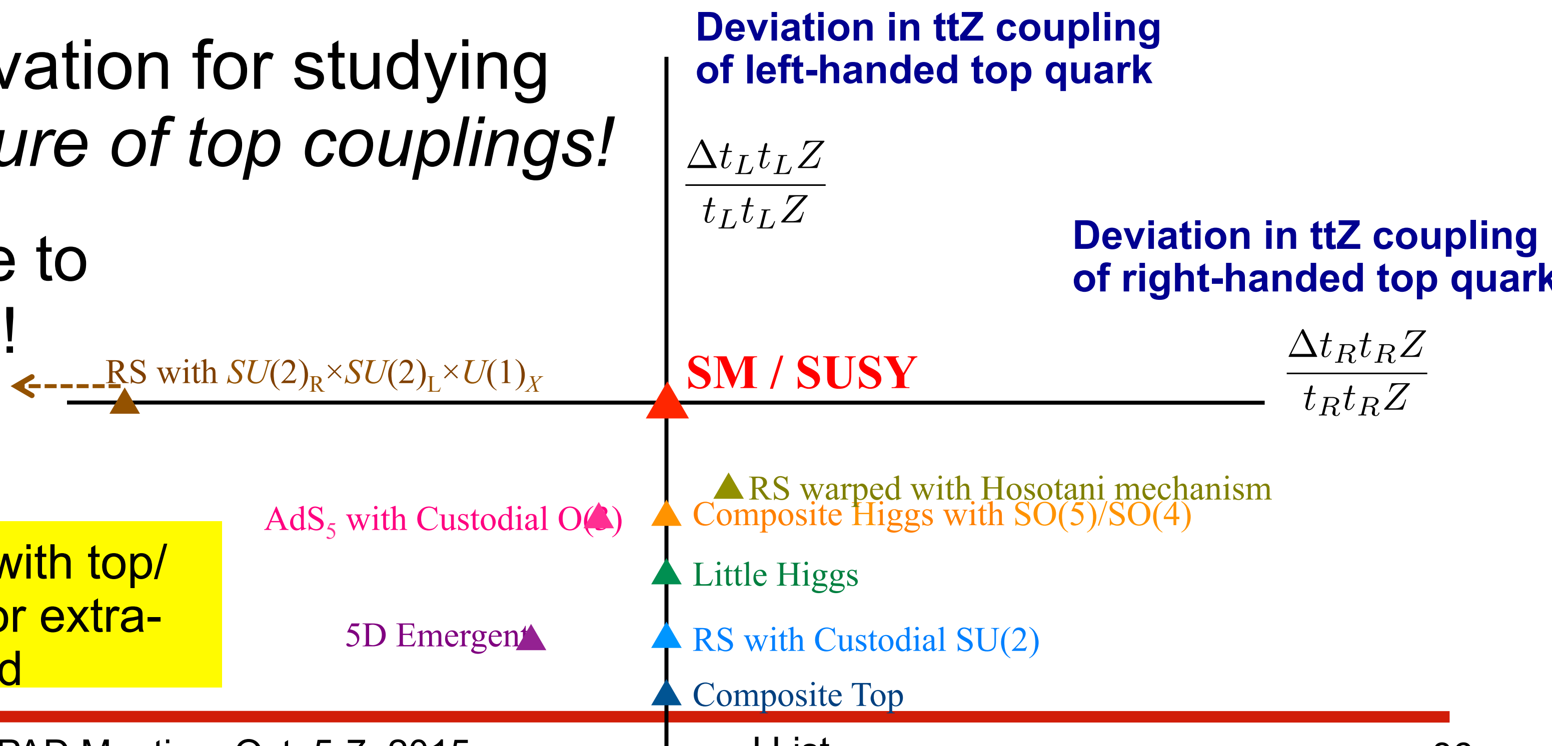




F.Simon

Top Quark Precision Measurements

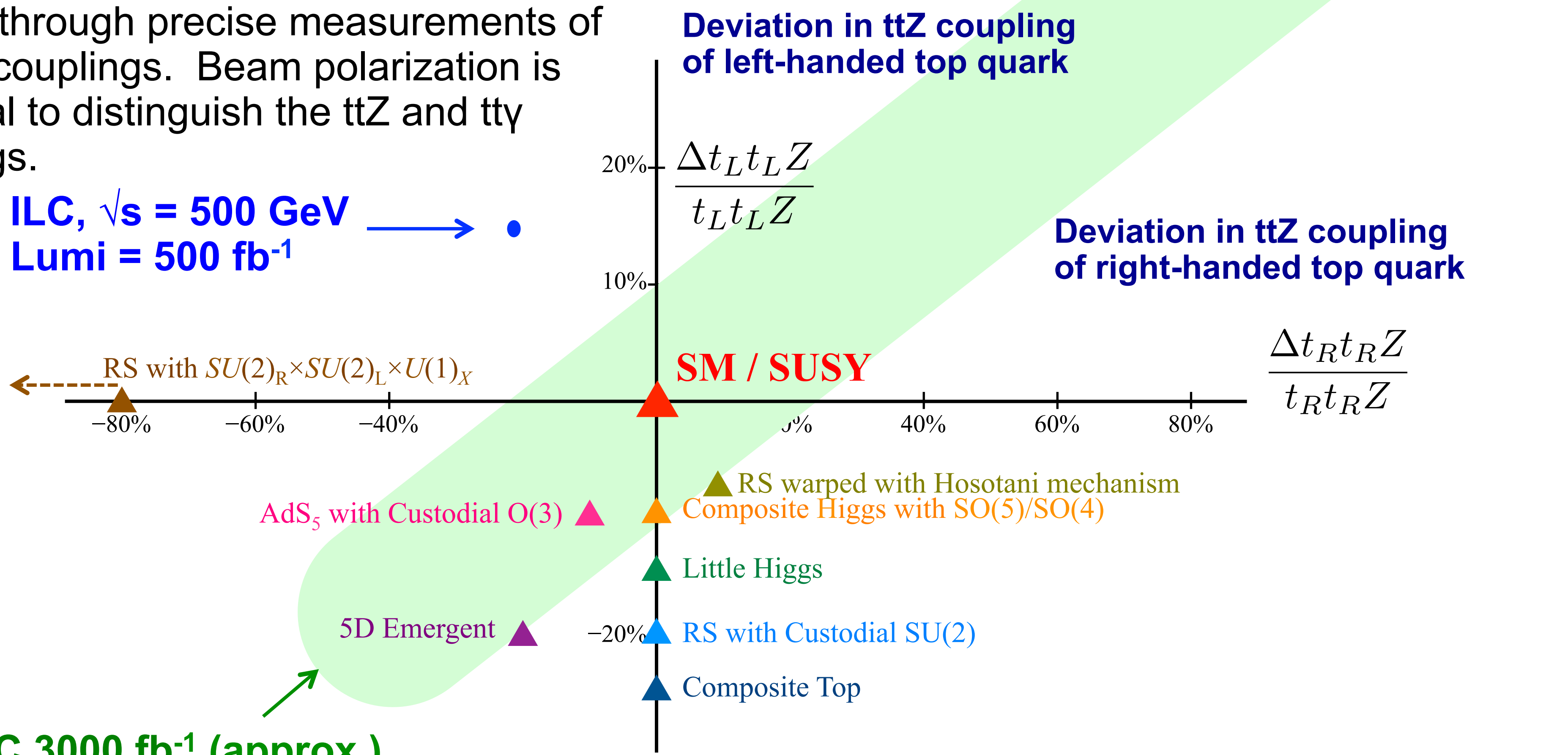
- The top quark is special:
  - Why so much heavier?
  - Intimately connected to Higgs boson ($y_t \approx 1$)
  - Remember A_{FB}^{0b}(LEP) vs A_l(SLD): something going on in 3rd generation?
- Strong motivation for studying *chiral structure of top couplings!*
- ... ideal place to look for BSM!



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.



HL-LHC 3000 fb^{-1} (approx.)
Based on Baur, Juste, Orr, Rainwater, PRD71, 054013 (2005)

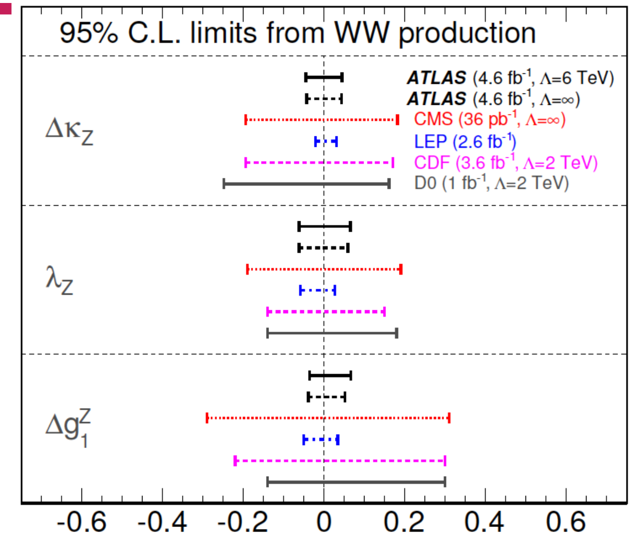
Deviations for different models for new physics scale at ~1 TeV.
Based on F. Richard, arXiv:1403.2893

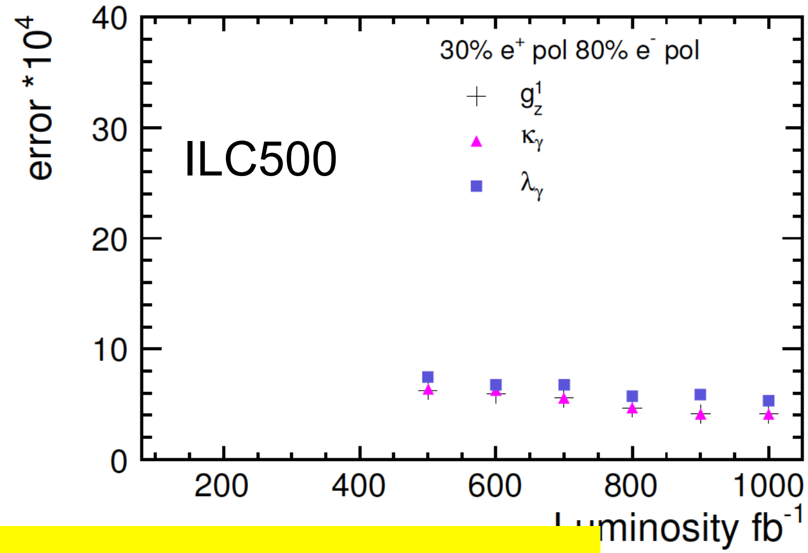
Charged Triple Gauge Couplings

- 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?

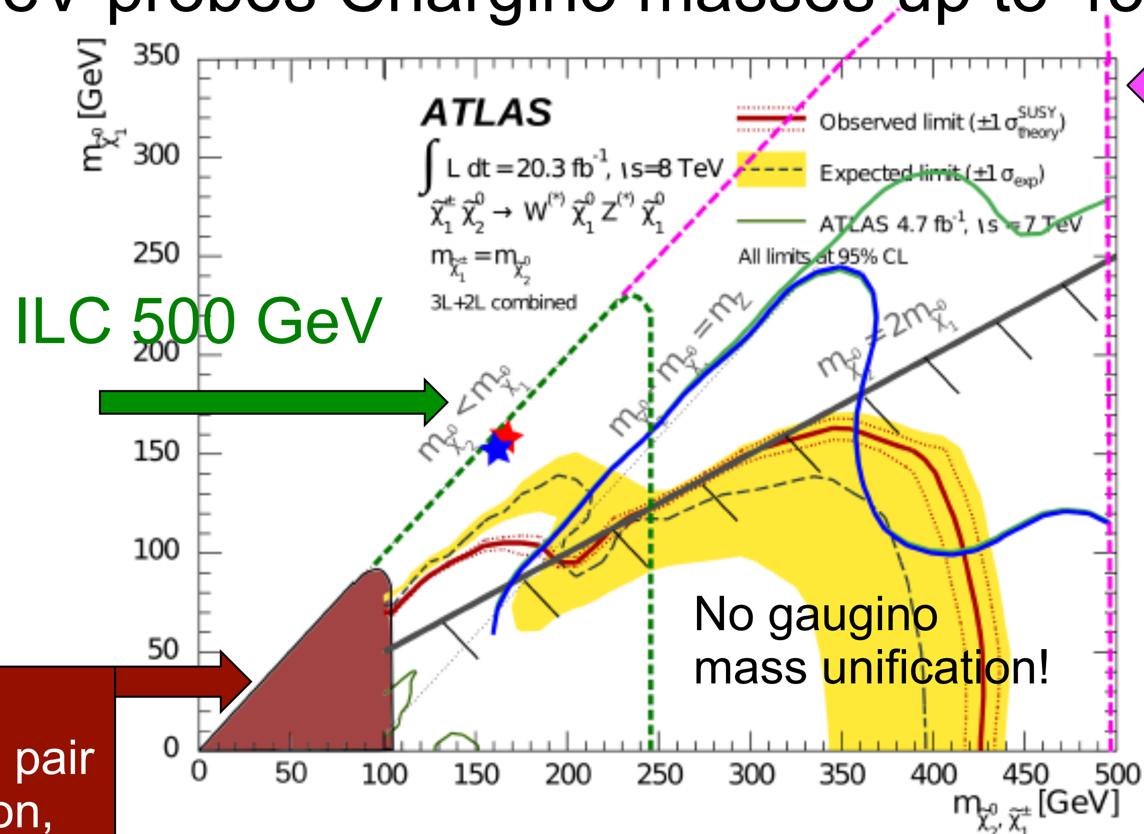
B. No deviation anywhere
   - What does this really tell us?
   - Can there be something very well hidden?

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:



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

ATLAS projection 14 TeV 3 ab^{-1}

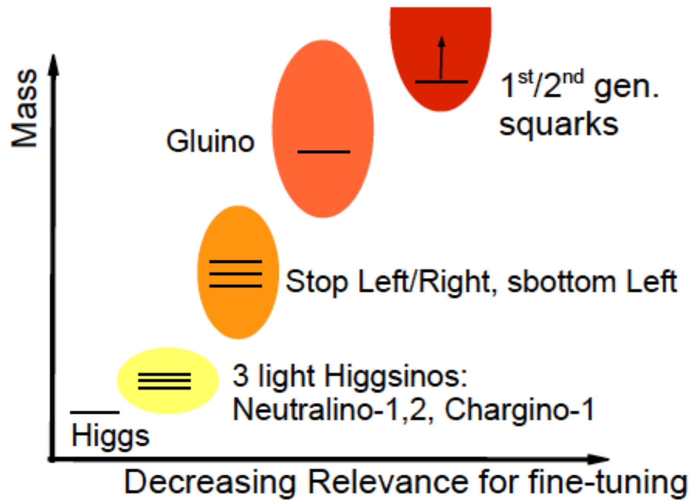
ATLAS projection 14 TeV 300 fb^{-1}

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

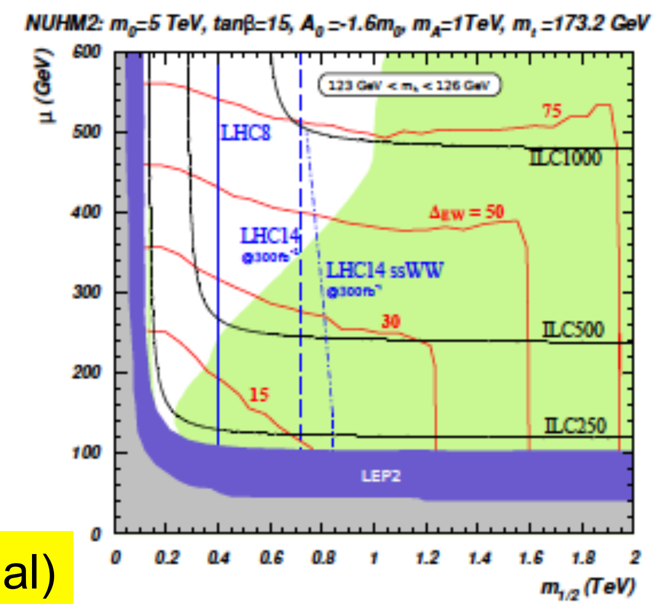
...let's take a look at the star points ★★

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

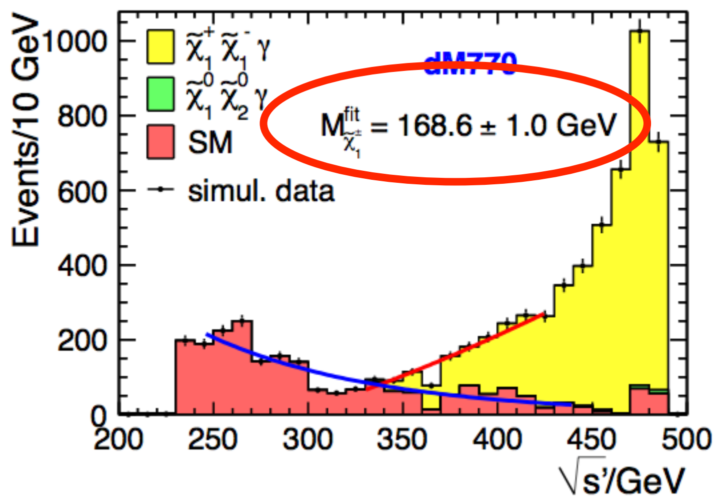
Theory-level study (H.Baer et al)

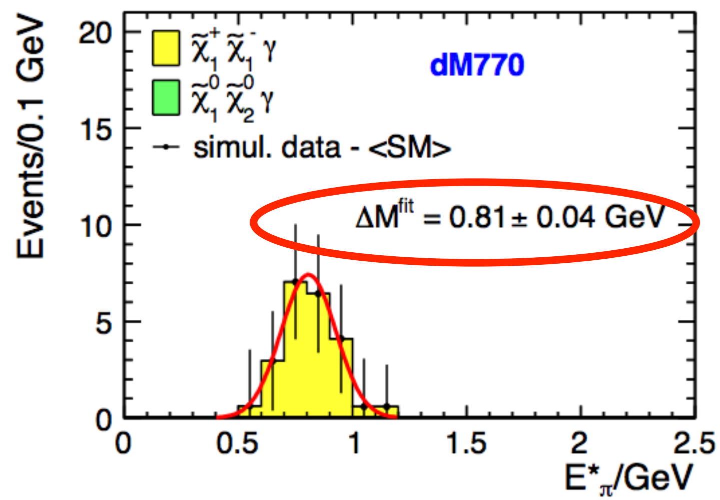
Can the detectors cope?

- 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!

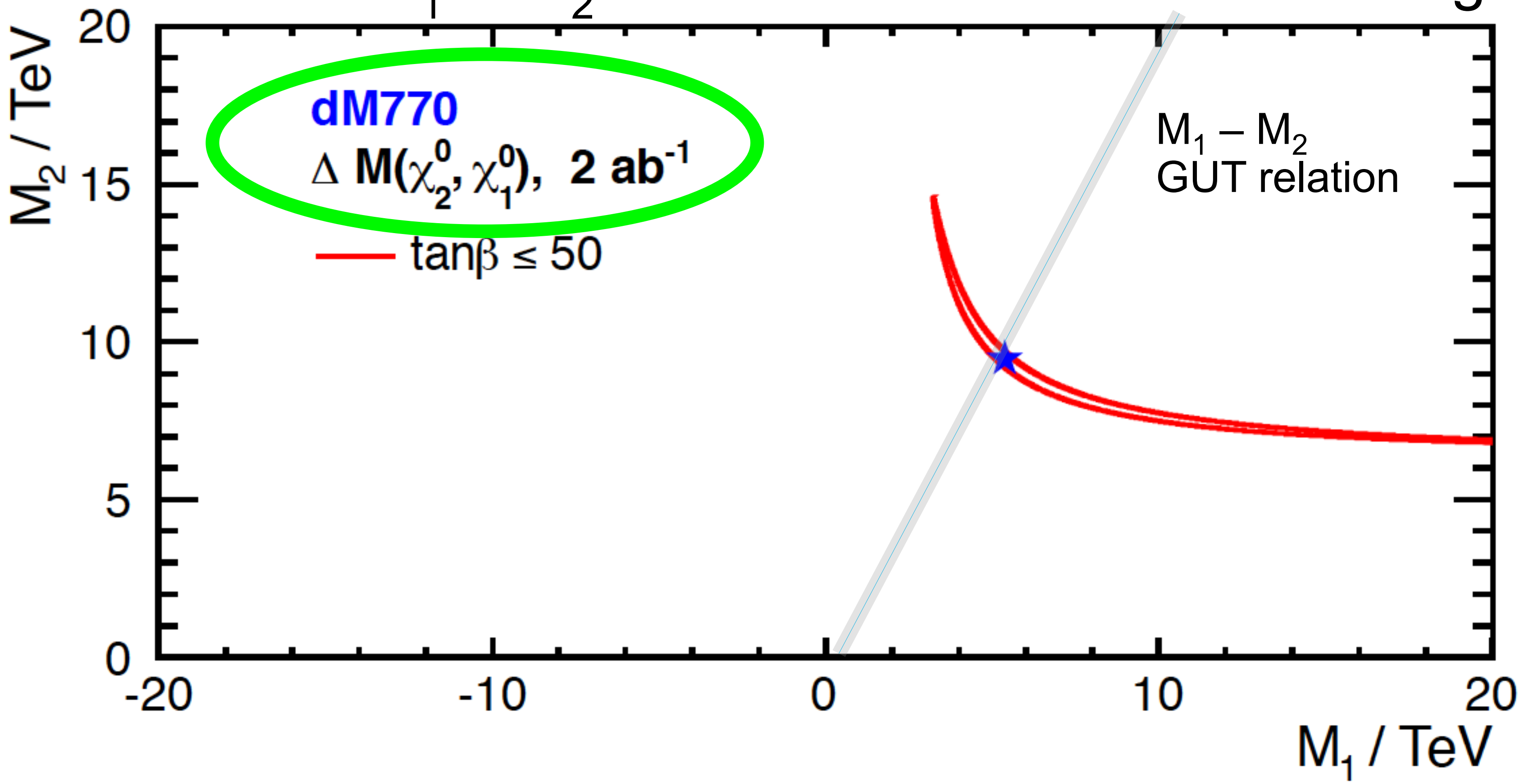
+ cross sections to few %



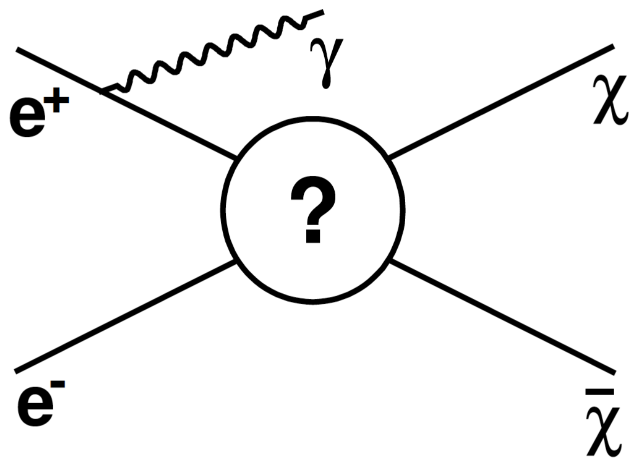


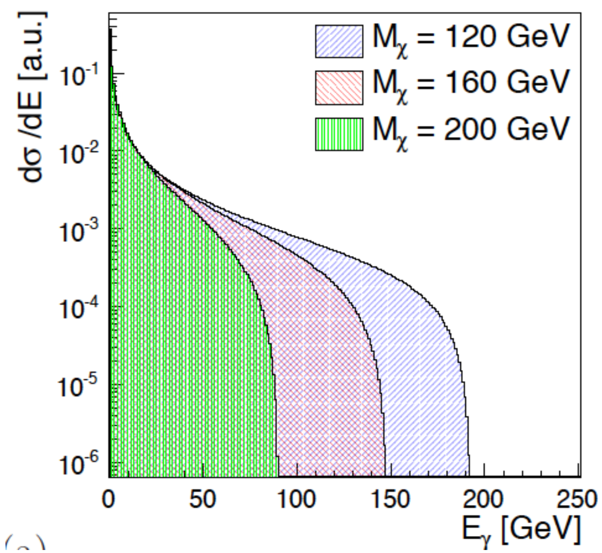
Parameter Determination!

- 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:



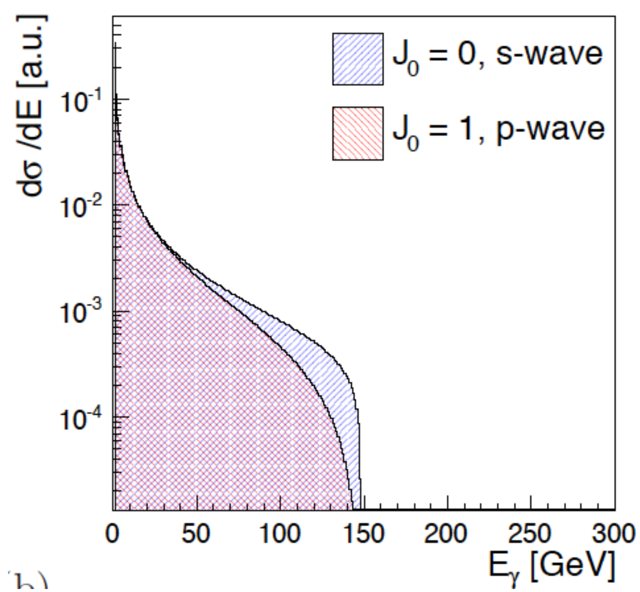
Case A or B example: WIMPs at the ILC



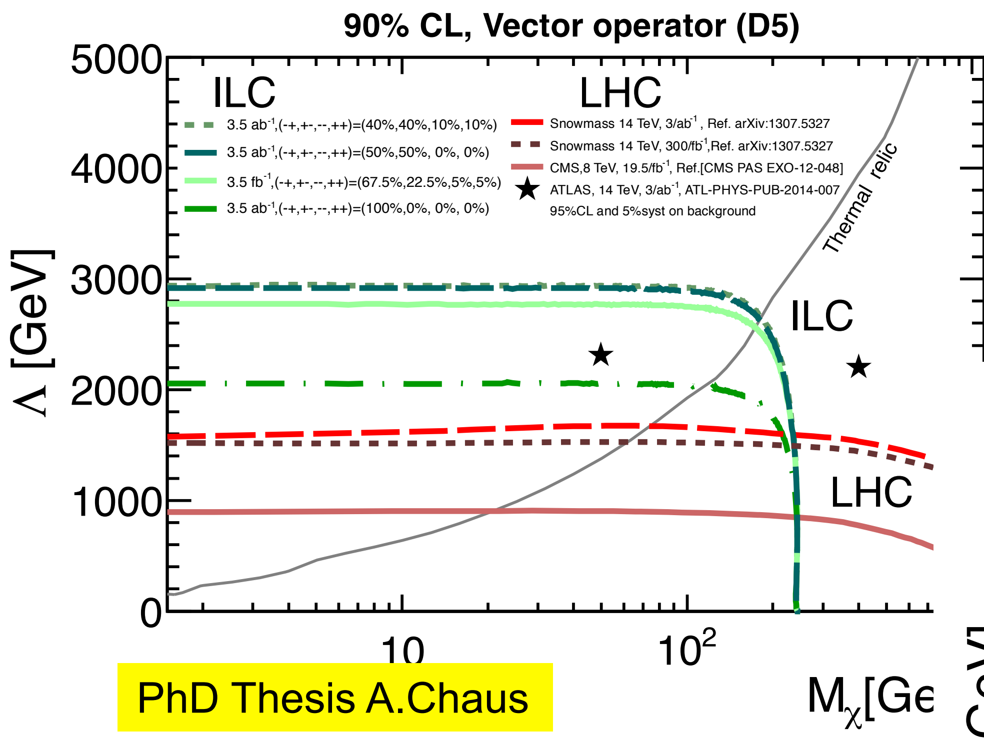


Know √s: E_γ spectrum offers

- 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]



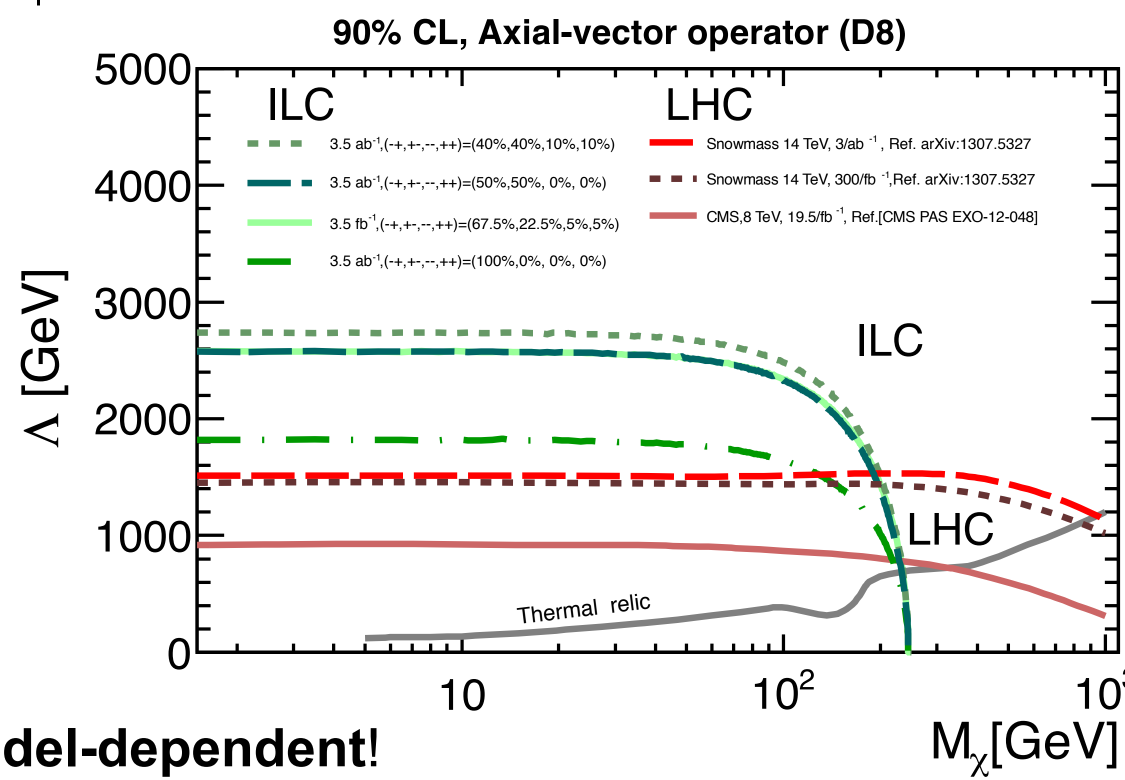
Mono-photons at LHC and ILC



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

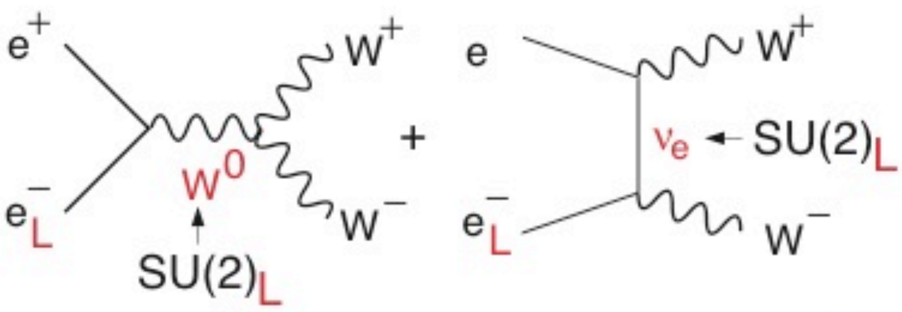
- Relation between WIMP – lepton and WIMP – quark / nucleon interaction is *model-dependent*
- Is suppression scale Λ the same for quarks and leptons?
  - A priori not!
  - Eg: t-channel exchange of “squark / selectron”
  - Direct couplings vs loop couplings

=> 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**

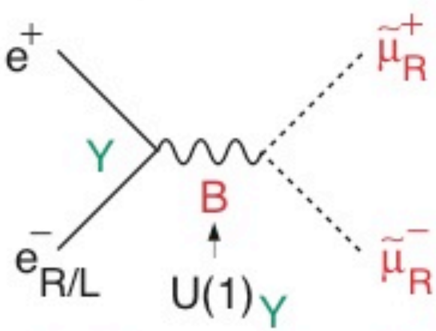
Operating the ILC: Beam Polarisation

W^+W^- (Largest SM BG)



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

Slepton Pair



$Y_L = -1/2 : e^-_L$

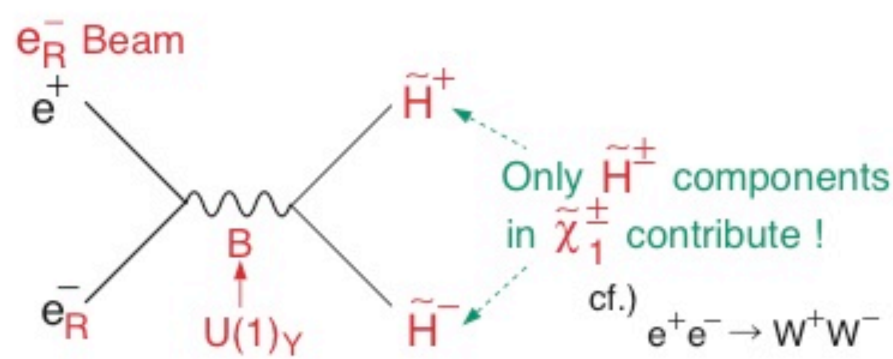
$Y_R = -1 \quad : e^-_R$

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

BG Suppression

[K. Fujii]

Chargino Pair



$\tilde{\chi}^\pm_1 = \bigcirc \cdot \tilde{W}^\pm + \bullet \cdot \tilde{H}^\pm$

$\langle \tilde{H}^\pm | \tilde{\chi}^\pm_1 \rangle$

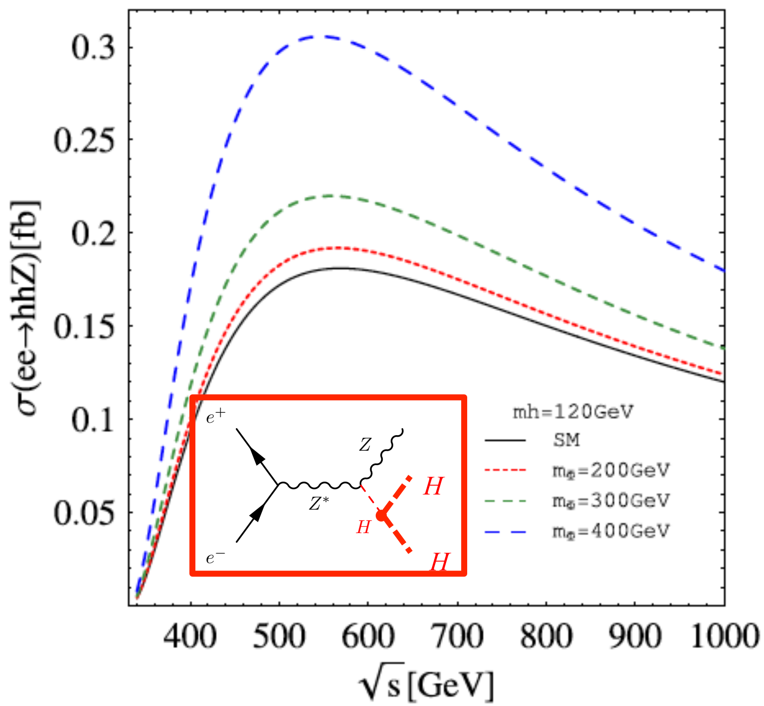
Note:
$e^-_L e^+_R \; + \; e^-_R e^+_L$

$\neq$ unpolarised data!

Decomposition

Signal Enhancement

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

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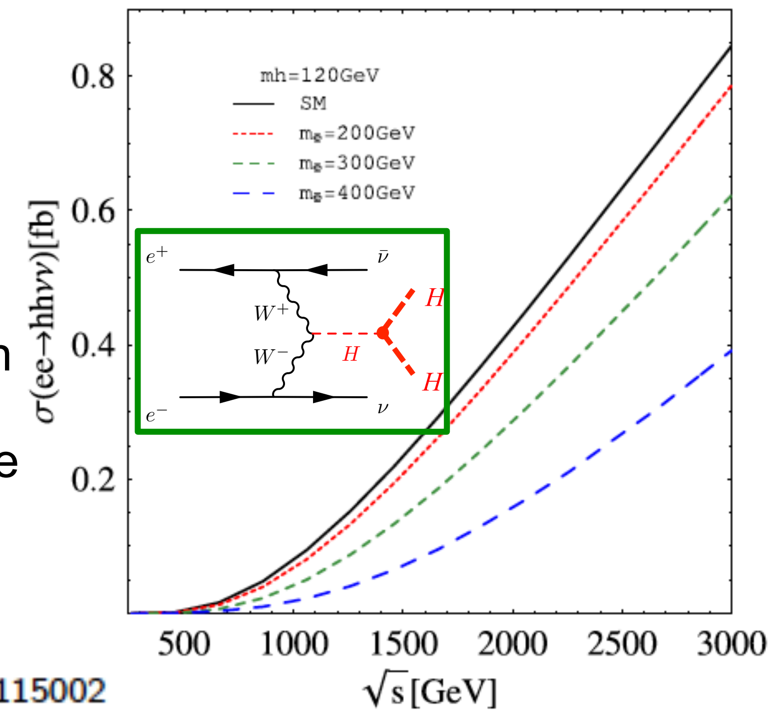

deviations in double Higgs cross-sections:

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!