Physics at ILC
Overview

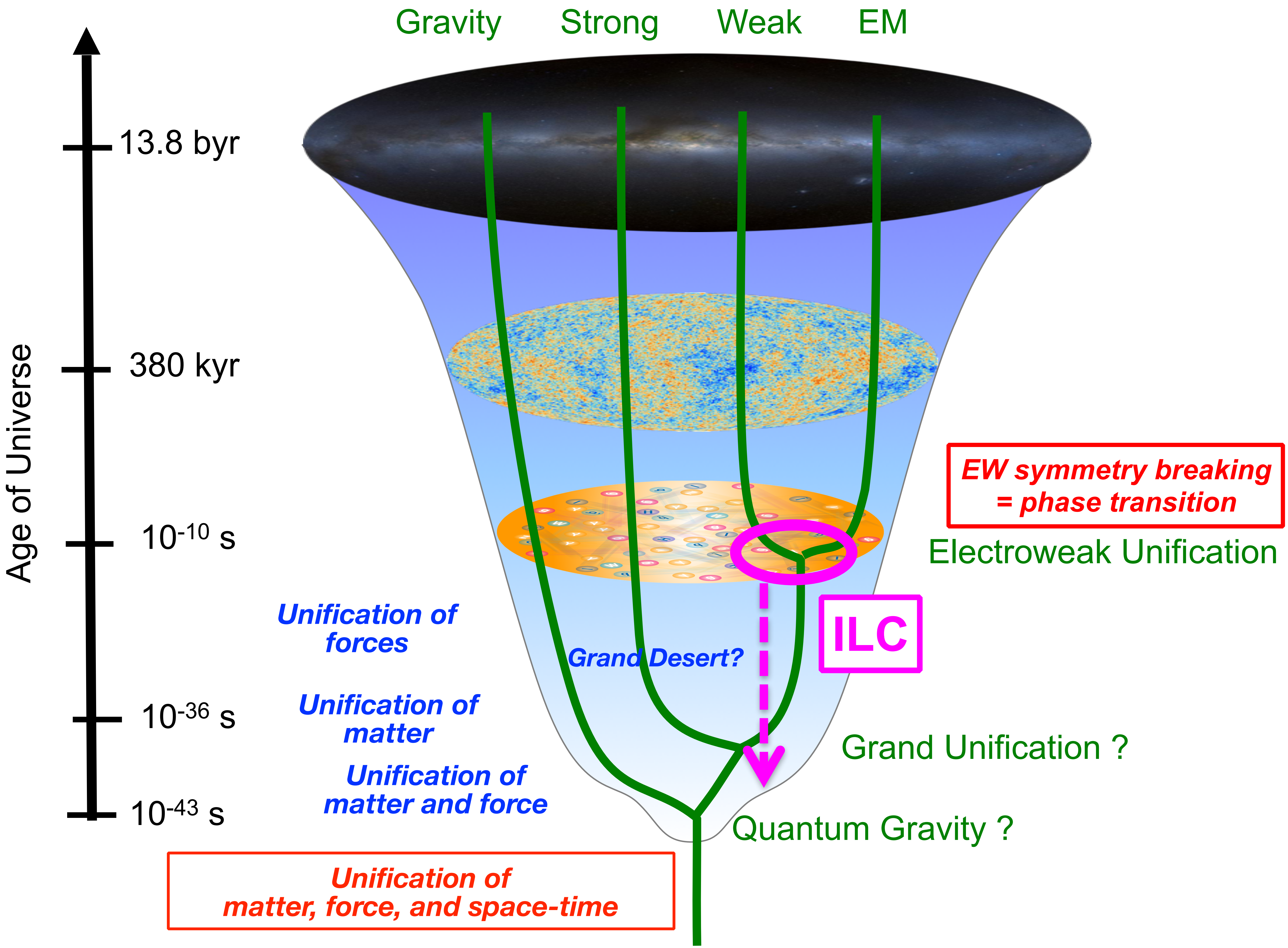
Keisuke Fujii (KEK)

March 25, 2015

KAERU Conference

Thanks to T. Tanabe for many materials

Towards ultimate unification



Why is the EW scale so important ?

Electroweak Symmetry Breaking

Mystery of something in the vacuum

- The EW symmetry forbids masses of gauge bosons and matter fermions. In order to break it without breaking that of the Lagrangian, we need ***"something" condensed in the vacuum which carries weak charge:***

$$\langle 0 \,|\, I_3, Y \,|\, 0 \rangle \neq 0 \qquad \langle 0 \,|\, I_3 + Y \,|\, 0 \rangle = 0$$

→ ***We are living in a weakly charged vacuum!***

- The discovery of H(125) provided evidence that it is an excitation of (at least part of) this "something" in the vacuum and hence the correctness of this idea of the vacuum breaking the EW symmetry.

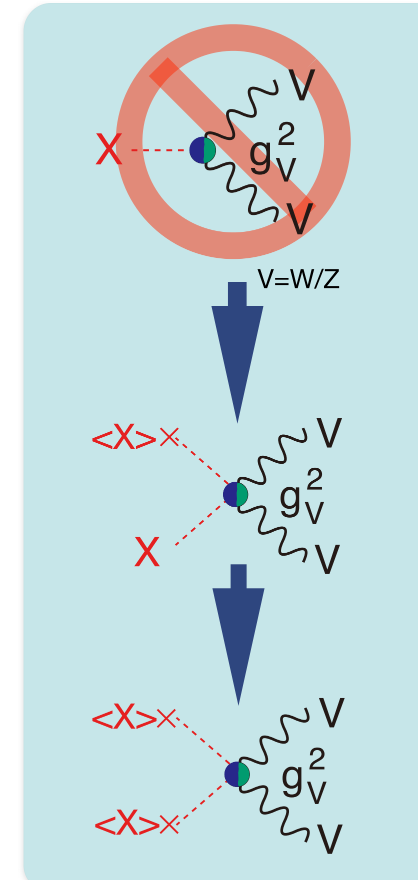
- In the SM, ***a single complex doublet scalar field*** is responsible for both gauge boson and matter fermion masses. The SM EWSB sector is the simplest, but other than that there is no reason for it.
The EWSB sector might be more complex.

→ We need to know ***the multiplet structure*** of the EWSB sector.

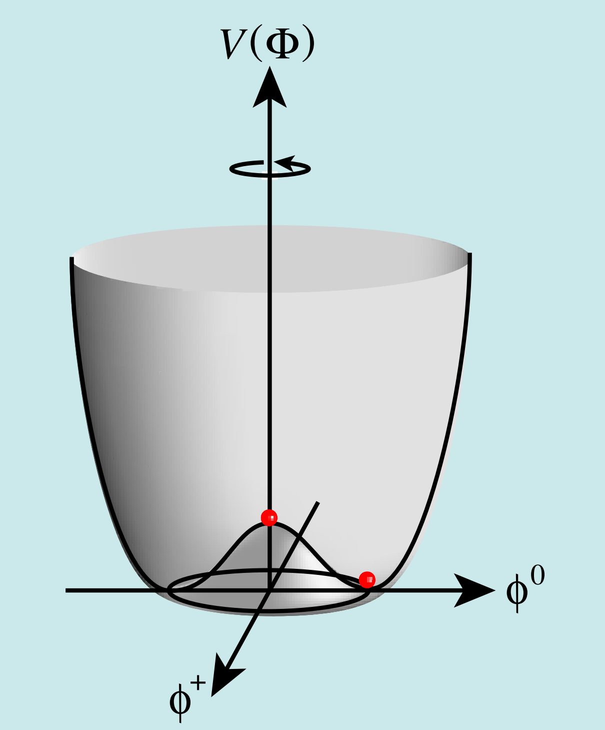
- Moreover, the SM does not explain ***why the Higgs field developed a vacuum expectation value.***

★ ***In other words the SM does not answer the question:***

Why $\mu^2 < 0$?



$$V(\phi) = \mu^2 |\phi|^2 + \lambda |\phi|^4$$



Why $\mu^2 < 0$?

To answer this question we need to go beyond the SM.

The Big Branching Point

- Concerning ***the dynamics behind the EWSB***.

  Is it ***weakly interacting or strongly interacting?***

  = Is the H(125) ***elementary or composite?***

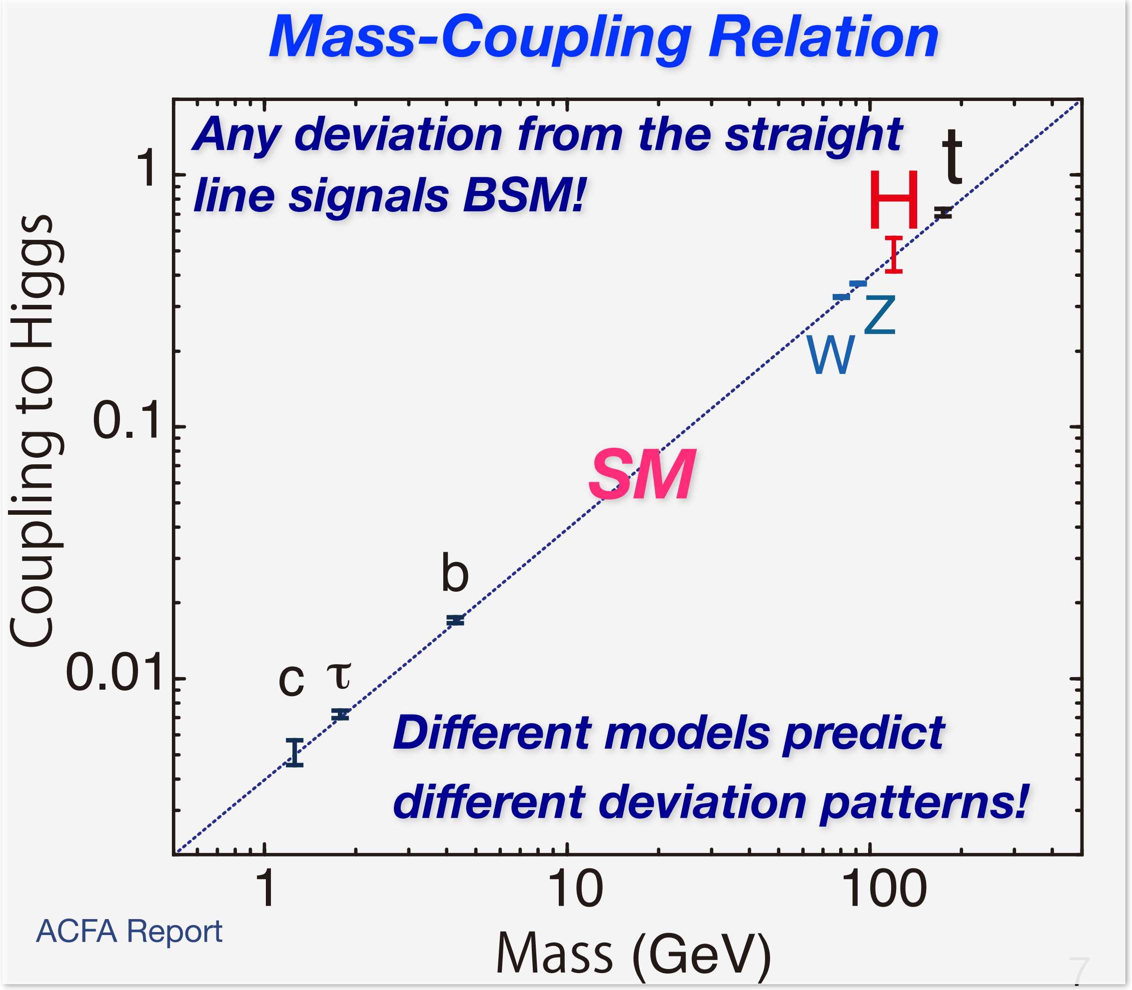
- ***SUSY***, which gives ***a raison d'être for a fundamental scalar fields***, is the most attractive scenario for the 1st branch, *where EW symmetry is broken radiatively*.
  → ***The EWSB sector is weakly interacting.***
  → ***H(125) is elementary*** and embedded in an ***extended multiplet structure*** (there must be ***at least 2 Higgs doublets***).
  → ***Possible Grand Desert*** → ***Telescope for GUT scale physics***

- ***Composite Higgs Models,*** the 2nd branch, where *a new QCD-like strong interaction makes a vacuum condensate*.
  → ***The EWSB sector is strongly interacting***.
  → ***H(125) is composite.***
  → ***Jungle of new particles in TeV(+) scale***

Elementary or Composite?
How can ILC address this question?

- If ***SUSY (elementary),***
  → ***(At least) 2 Higgs doublets → extra degrees of freedom***
    → ***Search*** for ***new particles***
      - extra Higgs bosons: ***H, A, H±***
      - uncolored SUSY particles: ***EWkinos, sleptons***
    → ***Look for specific deviation patterns*** in
      - ***various Higgs couplings***
      - gauge boson properties

- If ***Composite,***
    → ***Look for specific deviation patterns*** in
      - ***various Higgs couplings***
      - ***Top (ttZ) couplings***



The 3 major probes for BSM at ILC:

Higgs*, *Top*, and search for *New Particles

The 3 major tools to enable this endeavor

1. *Well defined initial state and controllable Ecm*

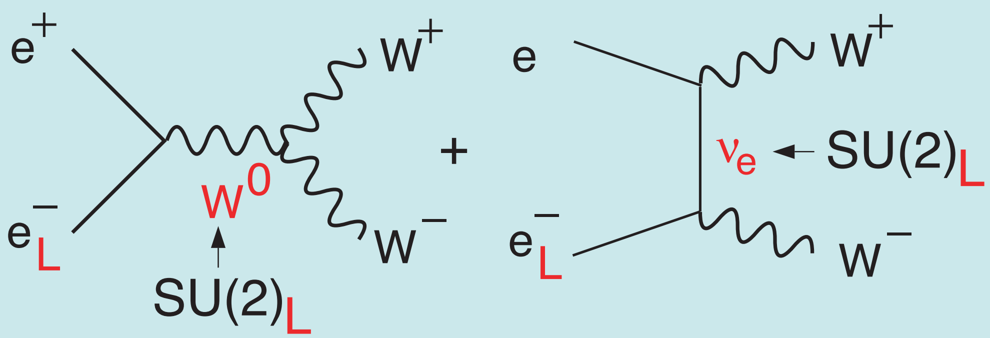
2. *Clean environment: no QCD BG, only with calculable BG from EW processes*

3. Beam polarization

Power of Beam Polarization

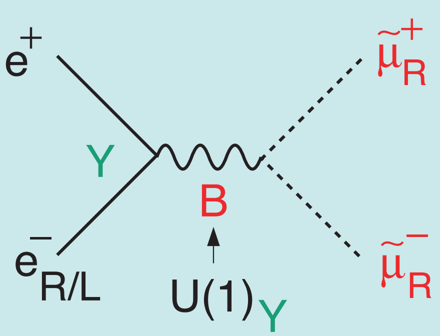
W^+W^- *(Largest SM BG in SUSY searches)*

BG Suppression



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

Slepton Pair



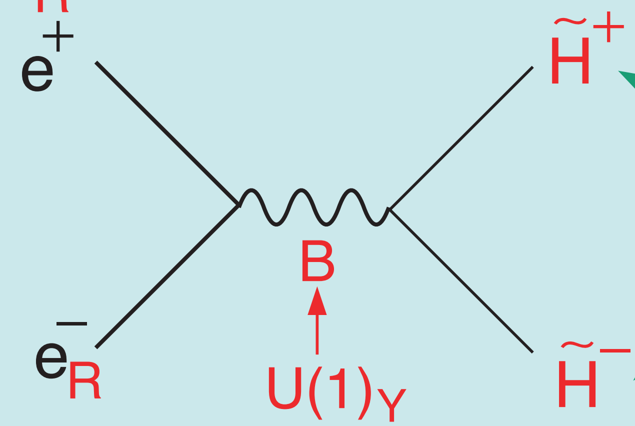
$Y_L = -1/2 : e^-_L$

$Y_R = -1 : e^-_R$

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

Chargino Pair

e^-_R Beam



Only $\tilde{H}^\pm$ components in $\tilde{\chi}^\pm_1$ contribute !

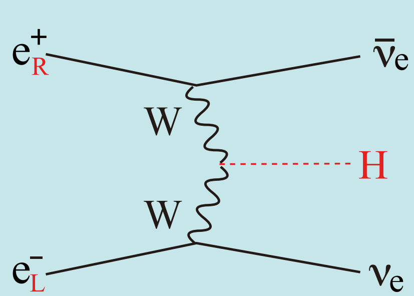
cf.) $e^+e^- \to W^+W^-$

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

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

Decomposition

WW-fusion Higgs Prod.



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

Signal Enhancement

Higgs Physics at ILC

Our mission is to understand

Multiplet Structure & Dynamics

of the EWSB sector,

and their relation to

***Other Big Questions* of High Energy Physics:**

DM, baryogenesis, …

Our strategy is to fully exploit

LHC-ILC Synergies

in

direct searches/studies of

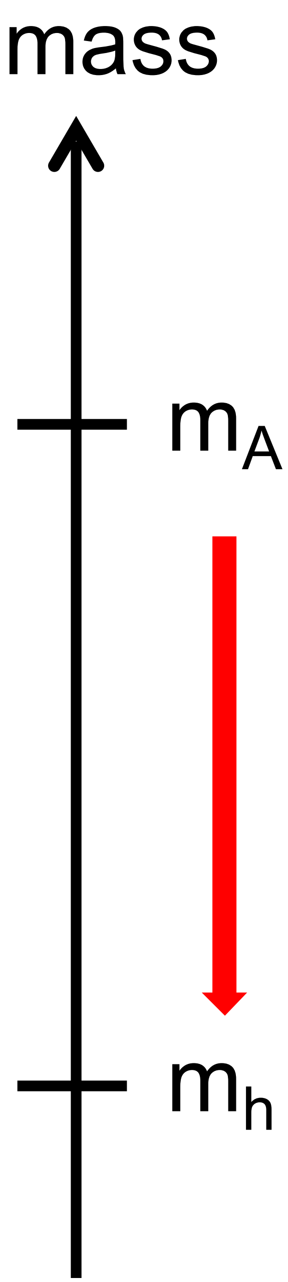
New Particles**,**

and

Precision measurements of

H(125) Properties (coupling)

Deviation in Higgs Couplings



The size of the deviation depends on the scale of new physics.

Decoupling Theorem: Λ↑ → SM

Example 1: MSSM (tanβ=5, radiative correction factor ≈ 1)

$$\frac{g_{hbb}}{g_{h_{\rm SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{\rm SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \mathrm{TeV}}{m_A}\right)^2$$

heavy Higgs mass

Example 2: Minimal Composite Higgs Model

$$\frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 8.3\% \left(\frac{1\ \mathrm{TeV}}{f}\right)^2$$

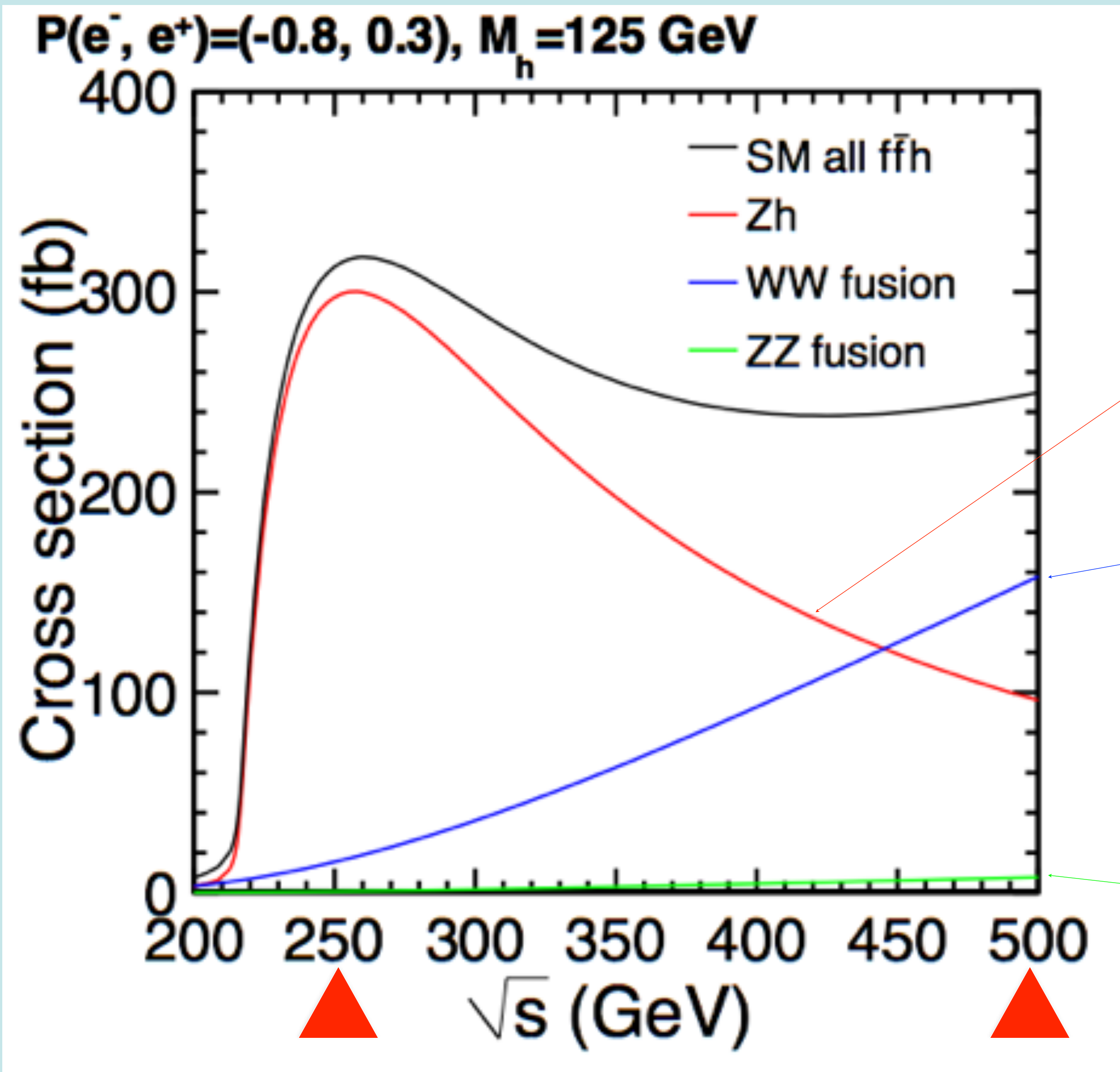
composite scale

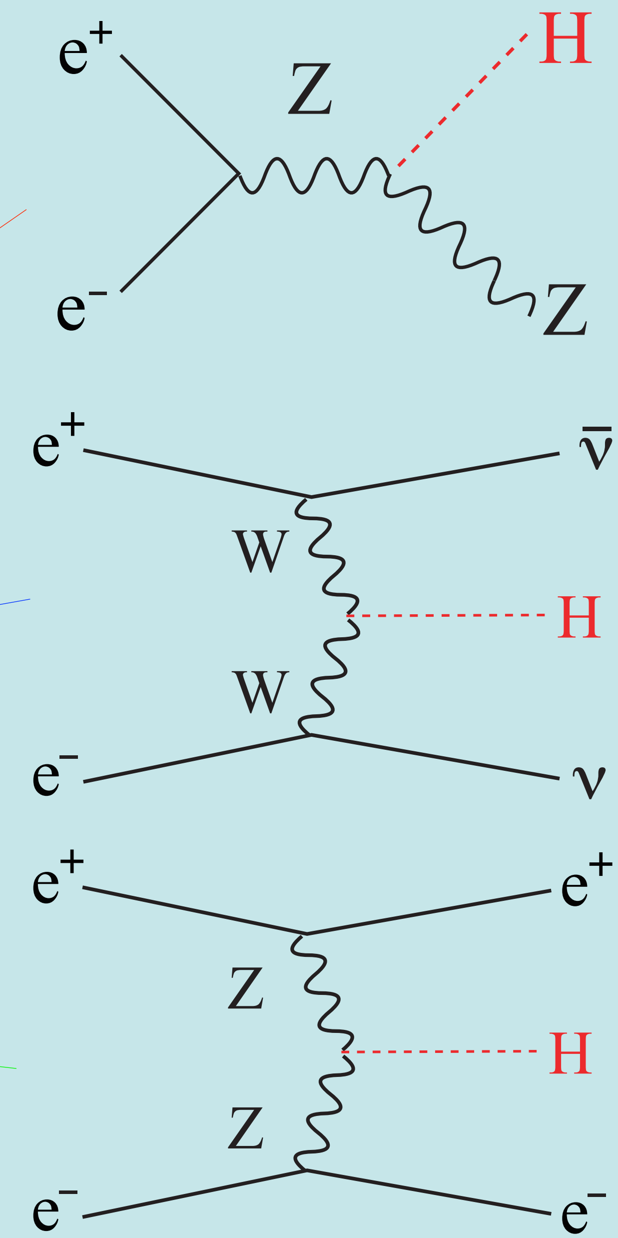
New physics at 1 TeV gives only ***a few percent*** deviation.
We ***need a %-level precision*** to see such a deviation → ***ILC***

Main Production Processes

Single Higgs Production

Production cross section





ZH dominates at 250 GeV
(~80k ev: 250 fb^{-1})

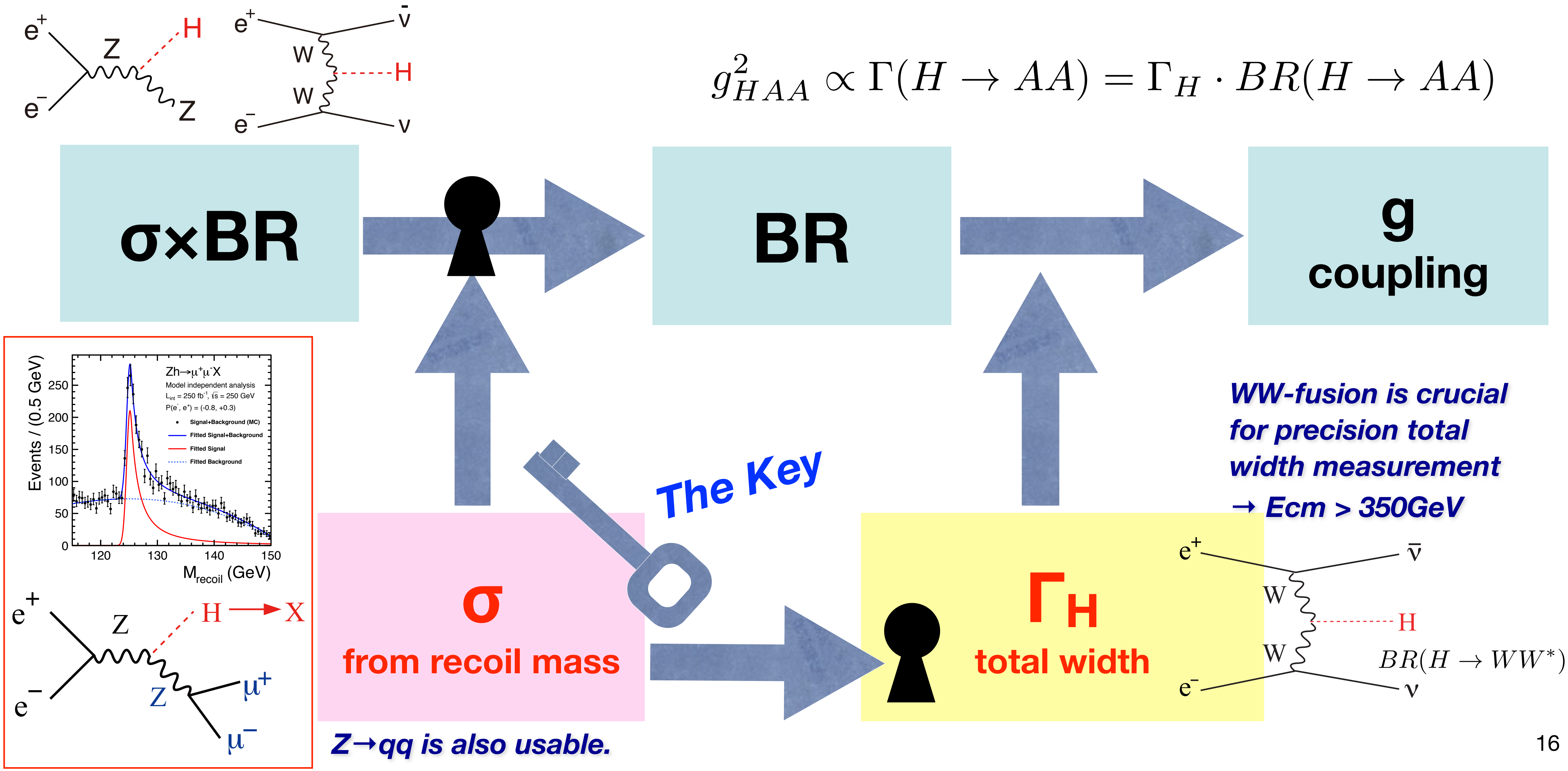
vvH takes over at 500 GeV
(~125k ev: 500 fb^{-1})

Possible to rediscover the Higgs in one day!

Key Point

At LHC all the measurements are σ×BR measurements.

At ILC all but *the σ measurement using recoil mass technique* is σ×BR measurements.



Model-independent Global Fit for Couplings

33 σxBR measurements (Y_i) and σ_{ZH} ($Y_{34,35}$)

$$\chi^2 = \sum_{i=1}^{35} \left(\frac{Y_i - Y_i'}{\Delta Y_i} \right)^2$$

$$Y_i' = F_i \cdot \frac{g^2_{HA_iA_i} \cdot g^2_{HB_iB_i}}{\Gamma_0}$$

$(i = 1, \cdots, 33)$

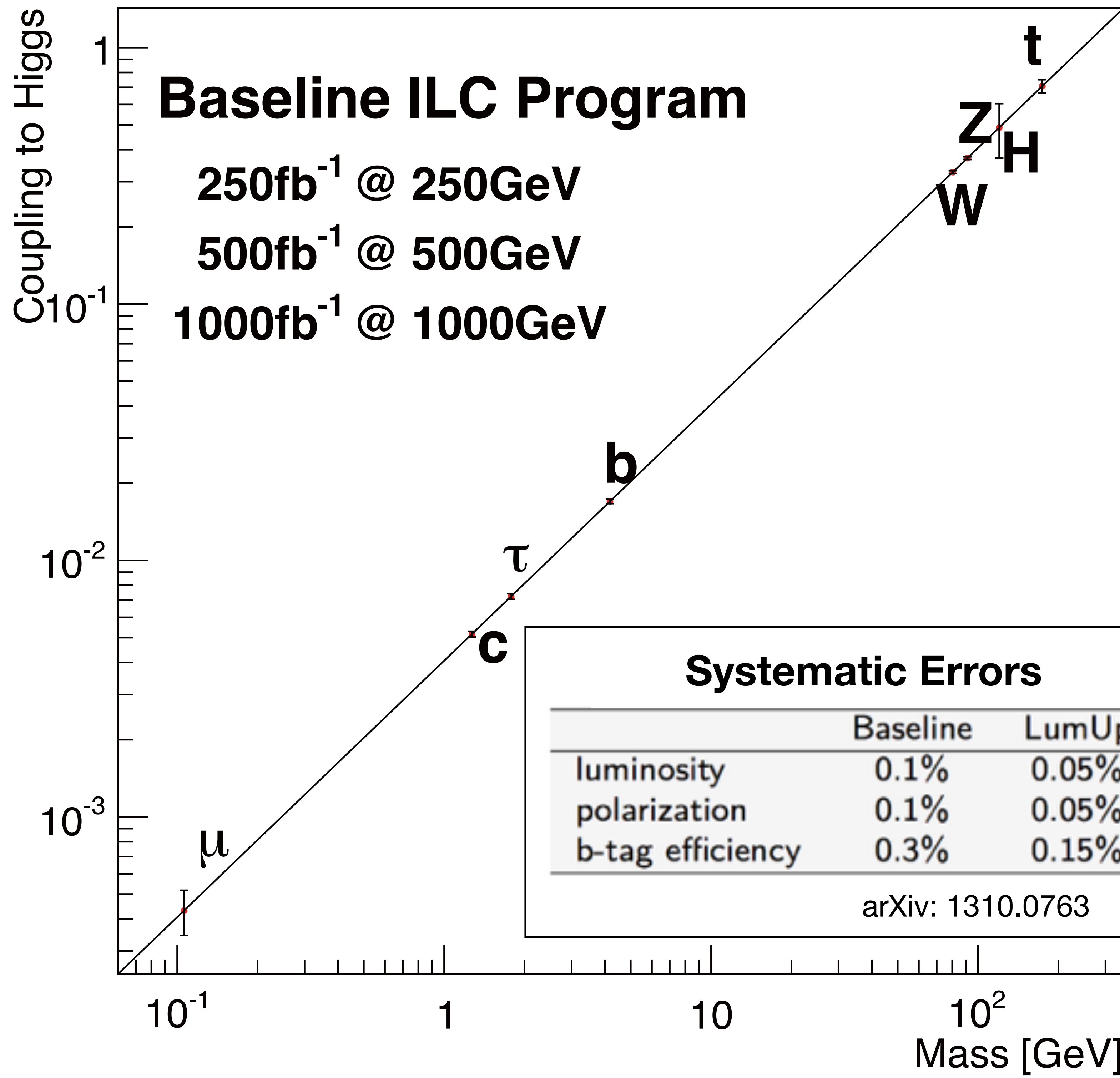
$(A_i = Z, W, t)$

$(B_i = b, c, \tau, \mu, g, \gamma, Z, W : \text{decay})$

$$F_i = S_i \, G_i$$

$$G_i = \left(\frac{\Gamma_i}{g_i^2} \right)$$

$$S_i = \left(\frac{\sigma_{ZH}}{g^2_{HZZ}} \right), \left(\frac{\sigma_{\nu\bar{\nu}H}}{g^2_{HWW}} \right), \text{ or } \left(\frac{\sigma_{t\bar{t}H}}{g^2_{Htt}} \right)$$



Systematic Errors

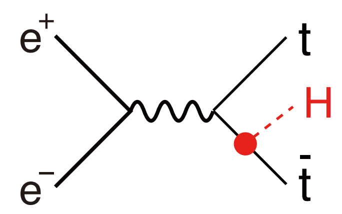
	Baseline	LumUp
luminosity	0.1%	0.05%
polarization	0.1%	0.05%
b-tag efficiency	0.3%	0.15%

arXiv: 1310.0763

ILC's precisions will eventually reach sub-% level!

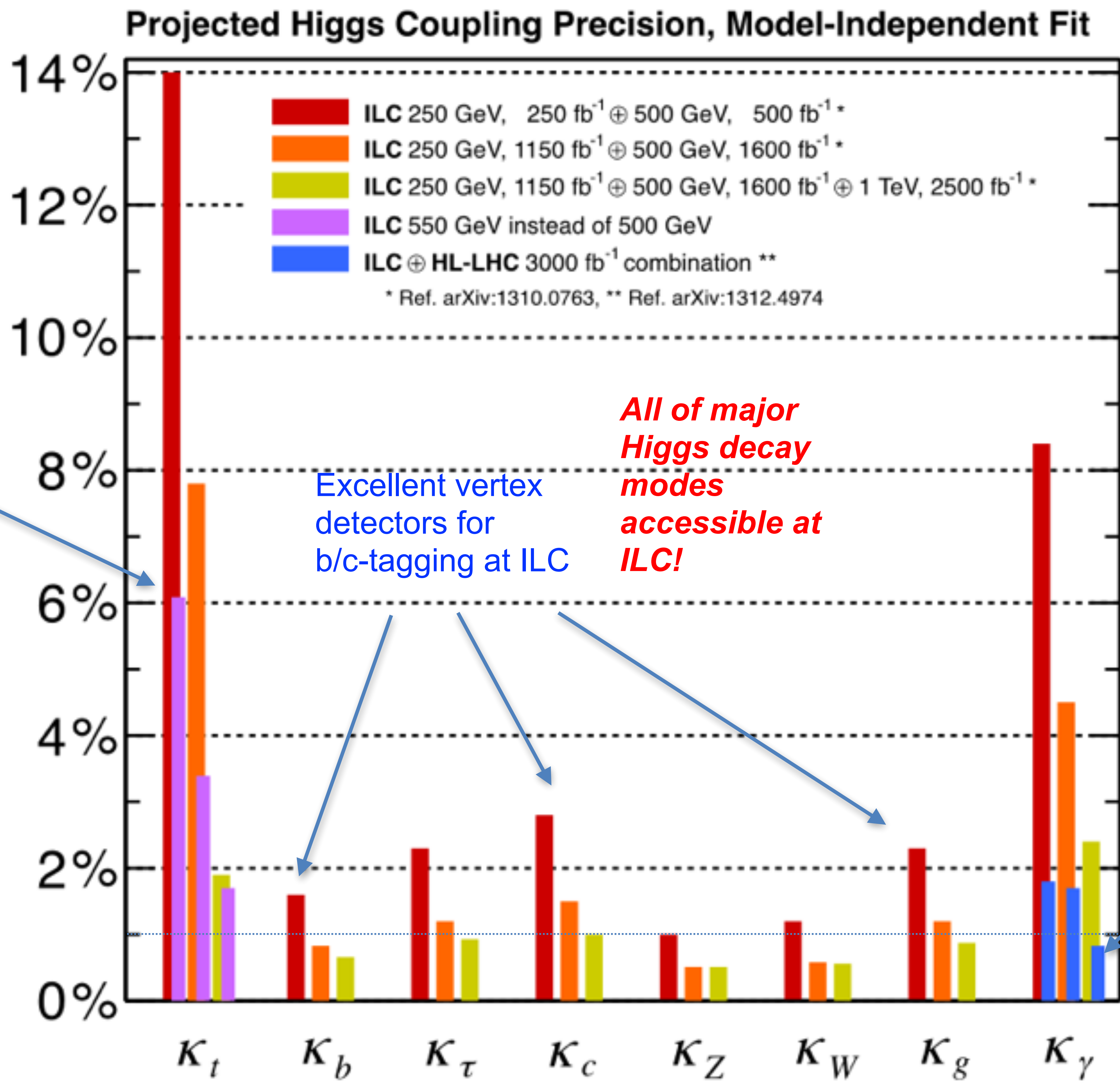
Higgs Couplings

Model-independent coupling determination, impossible at LHC



Top Yukawa improves by going to 550 GeV

Near threshold → a factor of 4 enhancement of σ_{tth} by going from 500GeV to 550 GeV



LHC can precisely measure

BR(h→γγ) / BR(h→ZZ*) = $(K_\gamma / K_Z)^2$

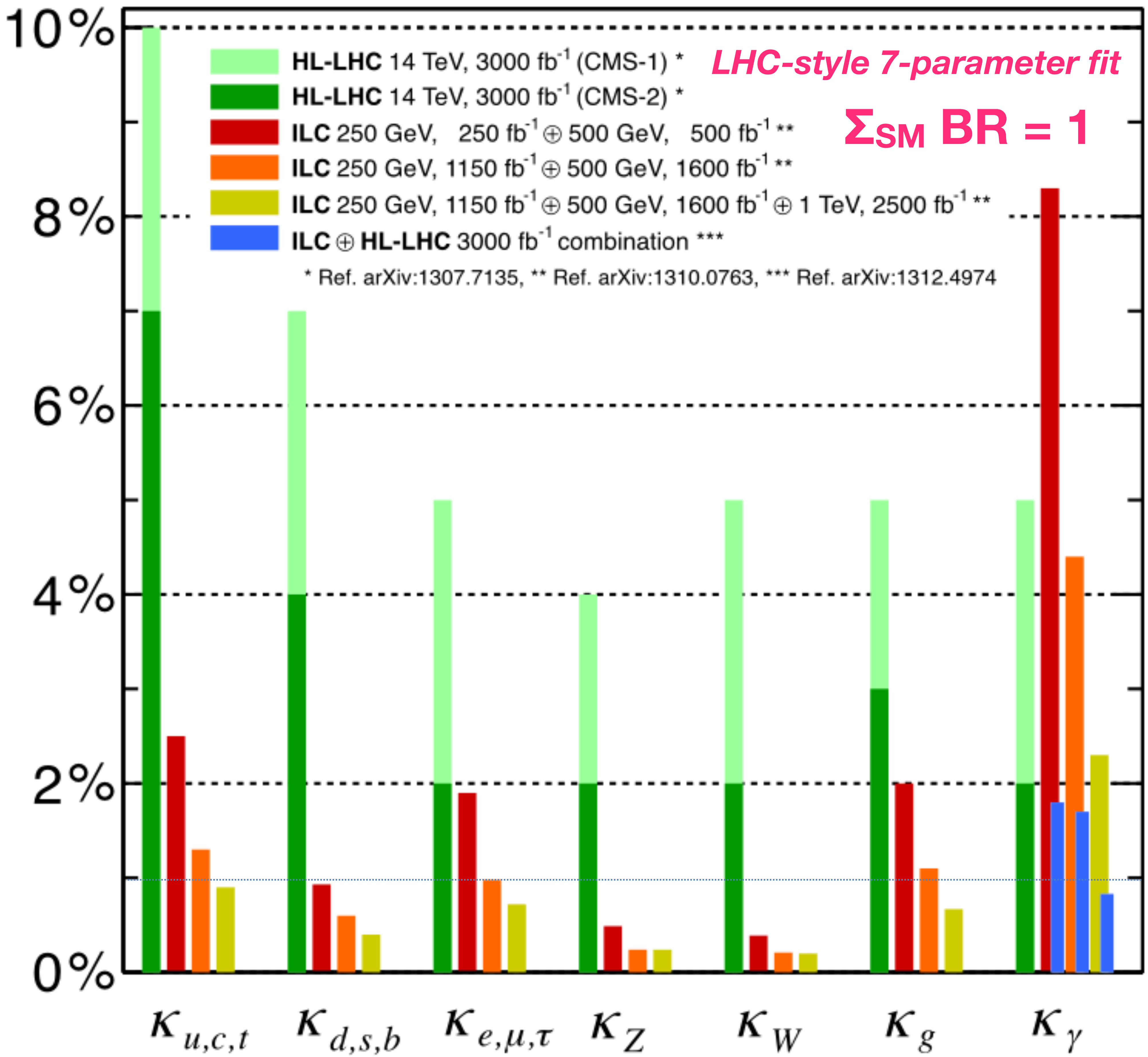
ILC can precisely measure ***K_Z***

Better hγγ with LHC/ILC synergy

500 GeV already excellent except for K_t and K_γ

~1% or better precision for most couplings!

Projected Higgs Coupling Precision, Model-Dependent Fit



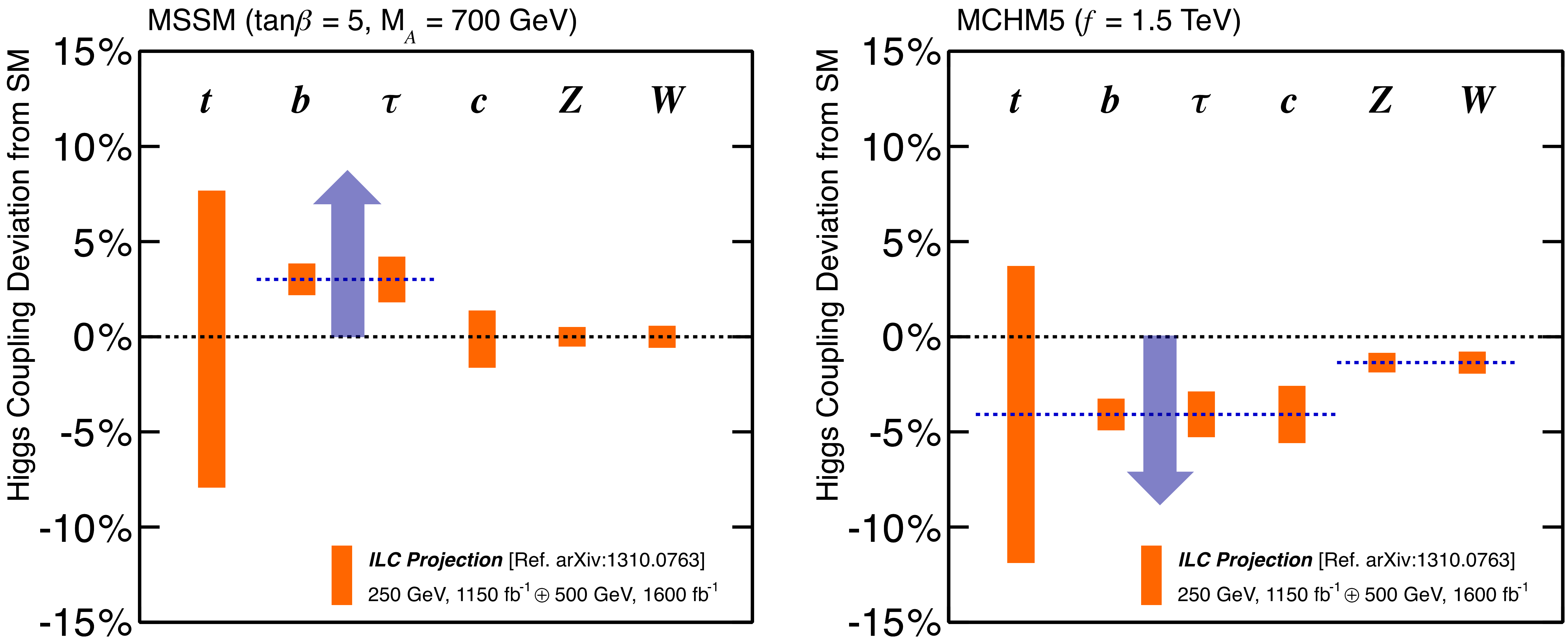
Fingerprinting

Fingerprinting

Elementary v.s. Composite

Supersymmetry
(MSSM)

Composite Higgs
(MCHM5)

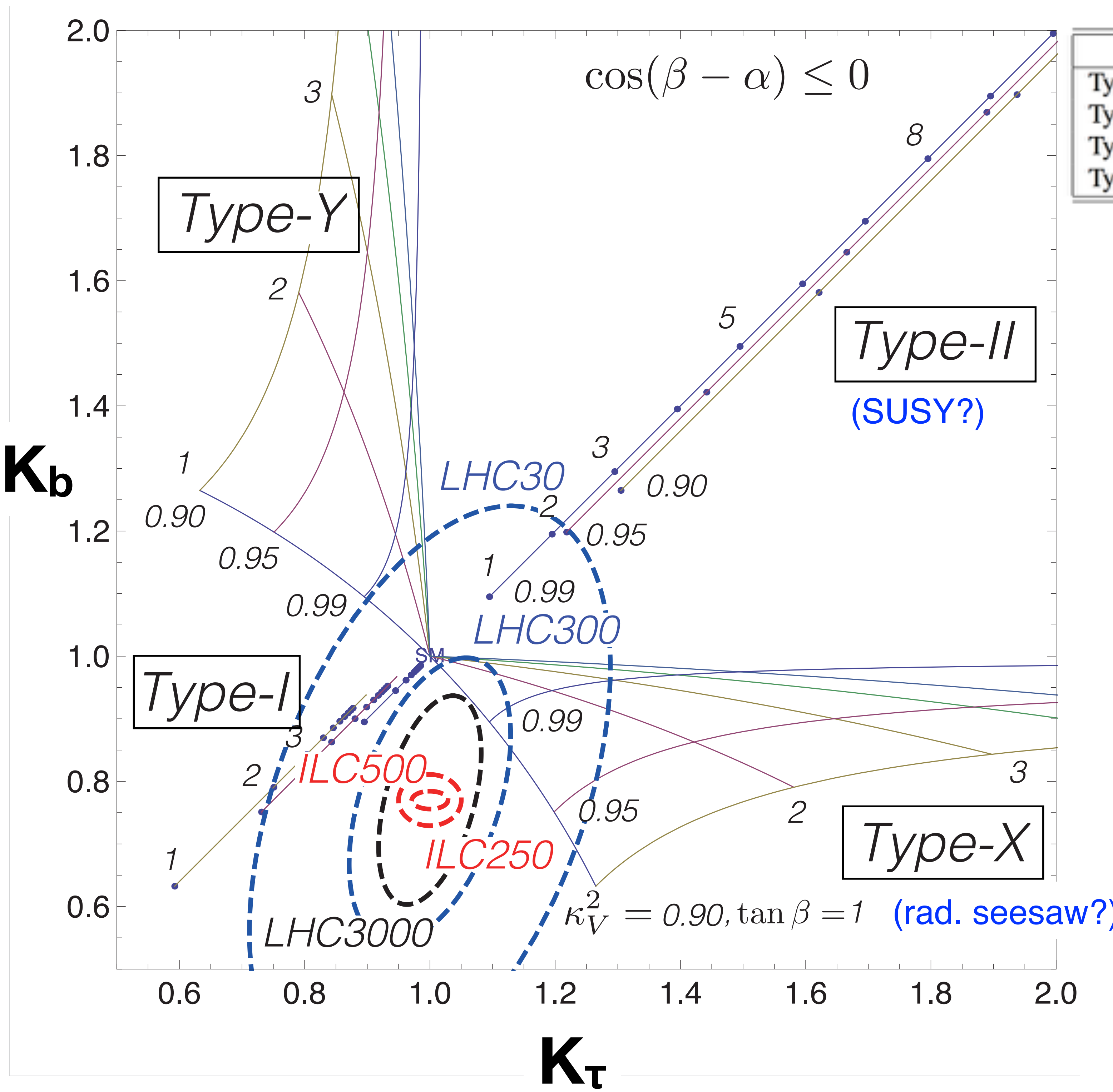


ILC 250+500 LumiUP

Fingerprinting

2HDM

Multiplet Structure



	Φ_1	Φ_2	u_R	d_R	ℓ_R	Q_L, L_L
Type I	+	−	−	−	−	+
Type II (SUSY)	+	−	−	+	+	+
Type X (Lepton-specific)	+	−	−	−	+	+
Type Y (Flipped)	+	−	−	+	−	+

4 Possible Z_2 Charge Assignments that forbids tree-level Higgs-induced FCNC

$K_V^2 = \sin(\beta-\alpha)^2 = 1 \Leftrightarrow$ SM

*Given a deviation of the Higgs to Z coupling: **$\Delta K_V^2 = 1 - K_V^2 = 0.01$** we will be able to **discriminate the 4 models!***

Model-dependent
7-parameter fit
ILC: Baseline lumi.

ILC TDR

Snowmass ILC Higgs White Paper (arXiv: 1310.0763)

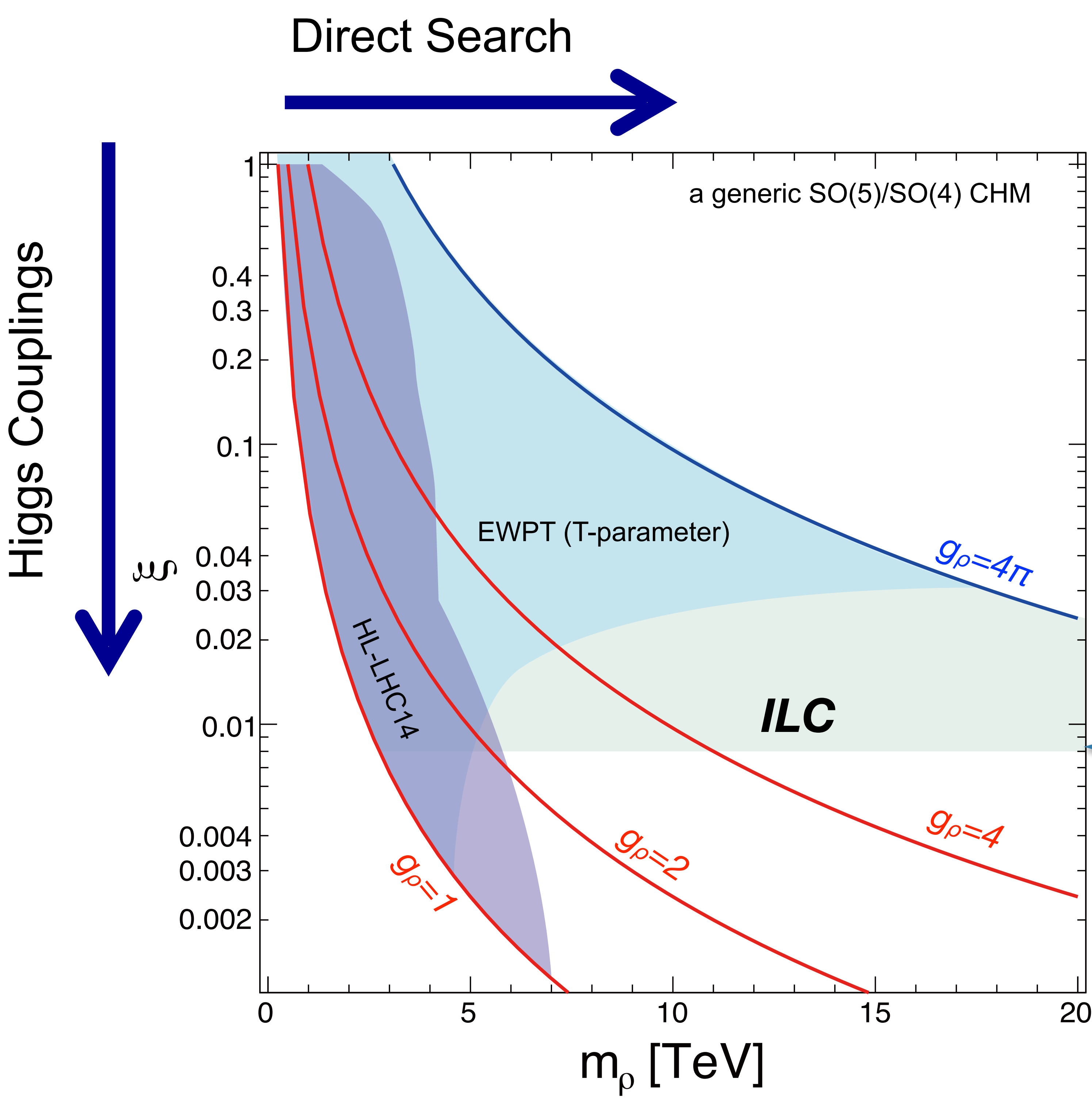
Kanemura et al (arXiv: 1406.3294)

Composite Higgs: Reach

Complementary approaches to probe composite Higgs models
- Direct search for heavy resonances at the LHC
- Indirect search via Higgs couplings at the ILC

Comparison depends on the coupling strength (g_*)

Based on Contino, et al, JHEP 1402 (2014) 006
Torre, Thamm, Wulzer 2014
Grojean @ LCWS 2014



$$\xi = \frac{g_\rho^2}{m_\rho^2} v^2 = \frac{v^2}{f^2}$$

$$\frac{g_{hVV}}{g_{h_{SM}VV}} = \sqrt{1-\xi}$$

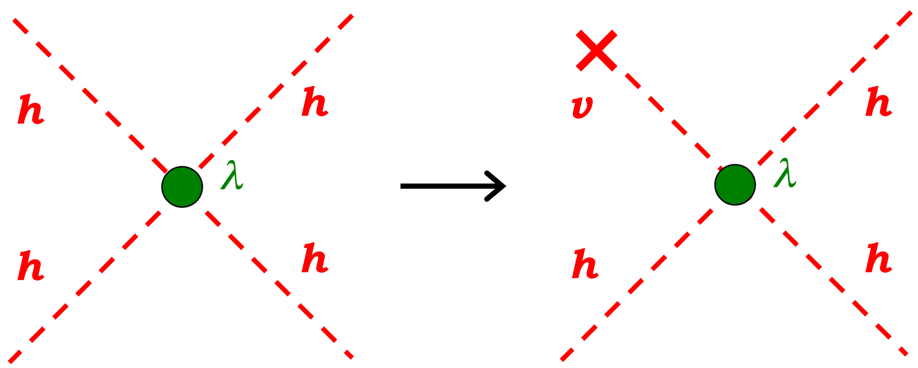
ILC (250+500 LumiUP)

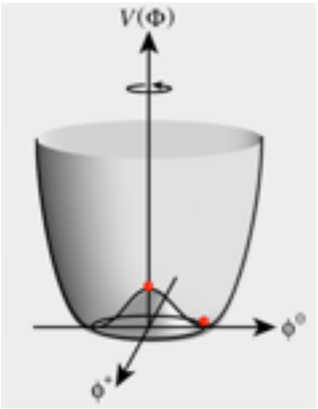
$$\Delta \frac{g_{hVV}}{g_{hVV}} = 0.4\%$$

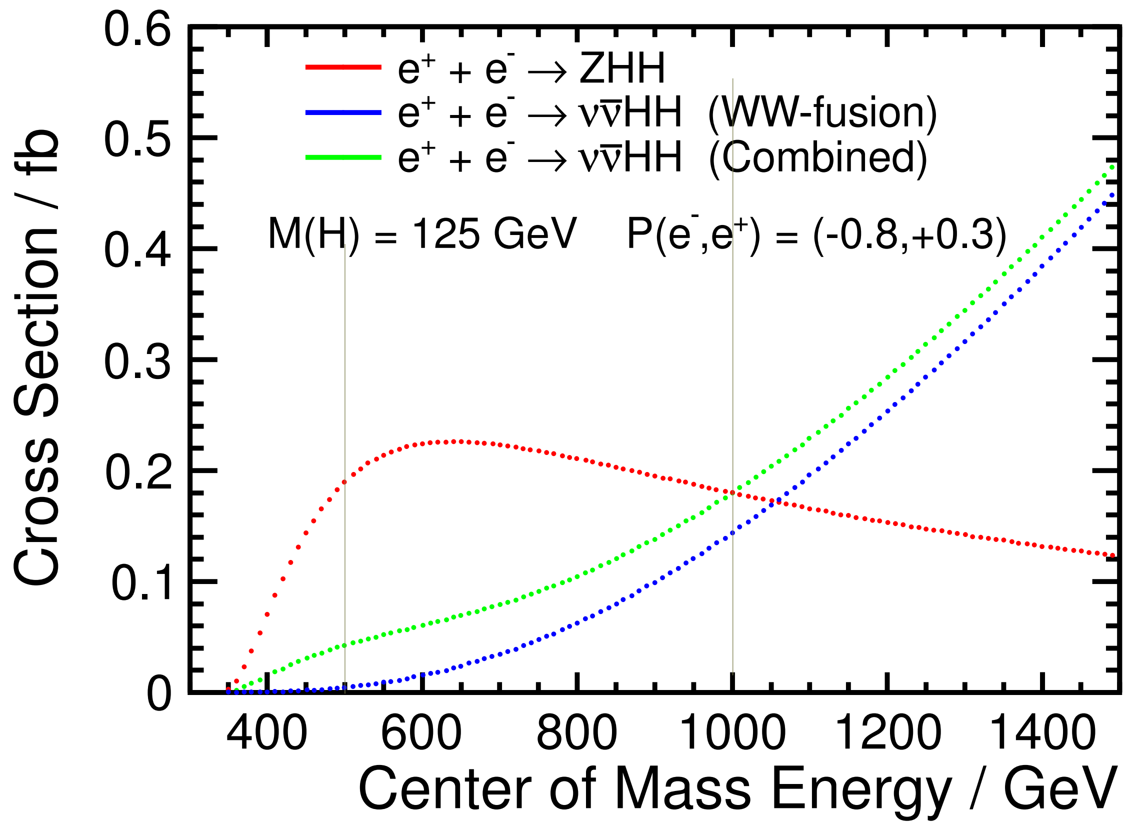
EW Phase Transition
1st order
or
2nd order ?

Higgs Self-Coupling

hhh coupling =
consequence of vacuum condensation

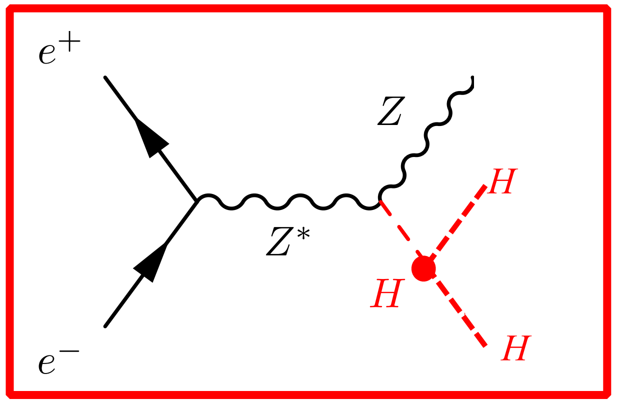


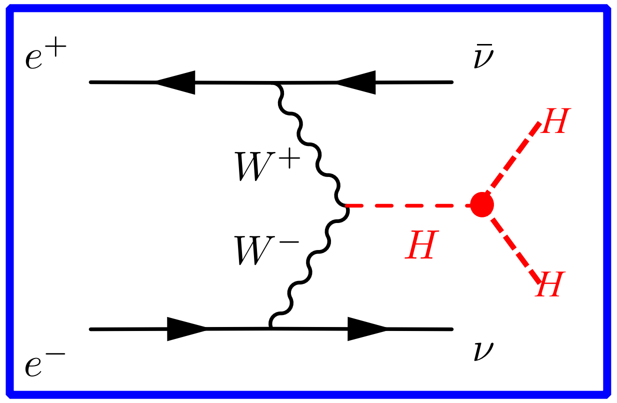




Challenging measurement because of:

- Small cross section (Zhh 0.2 fb at 500 GeV)
- Many jets in the final state
- ***Presence of irreducible BG diagrams***

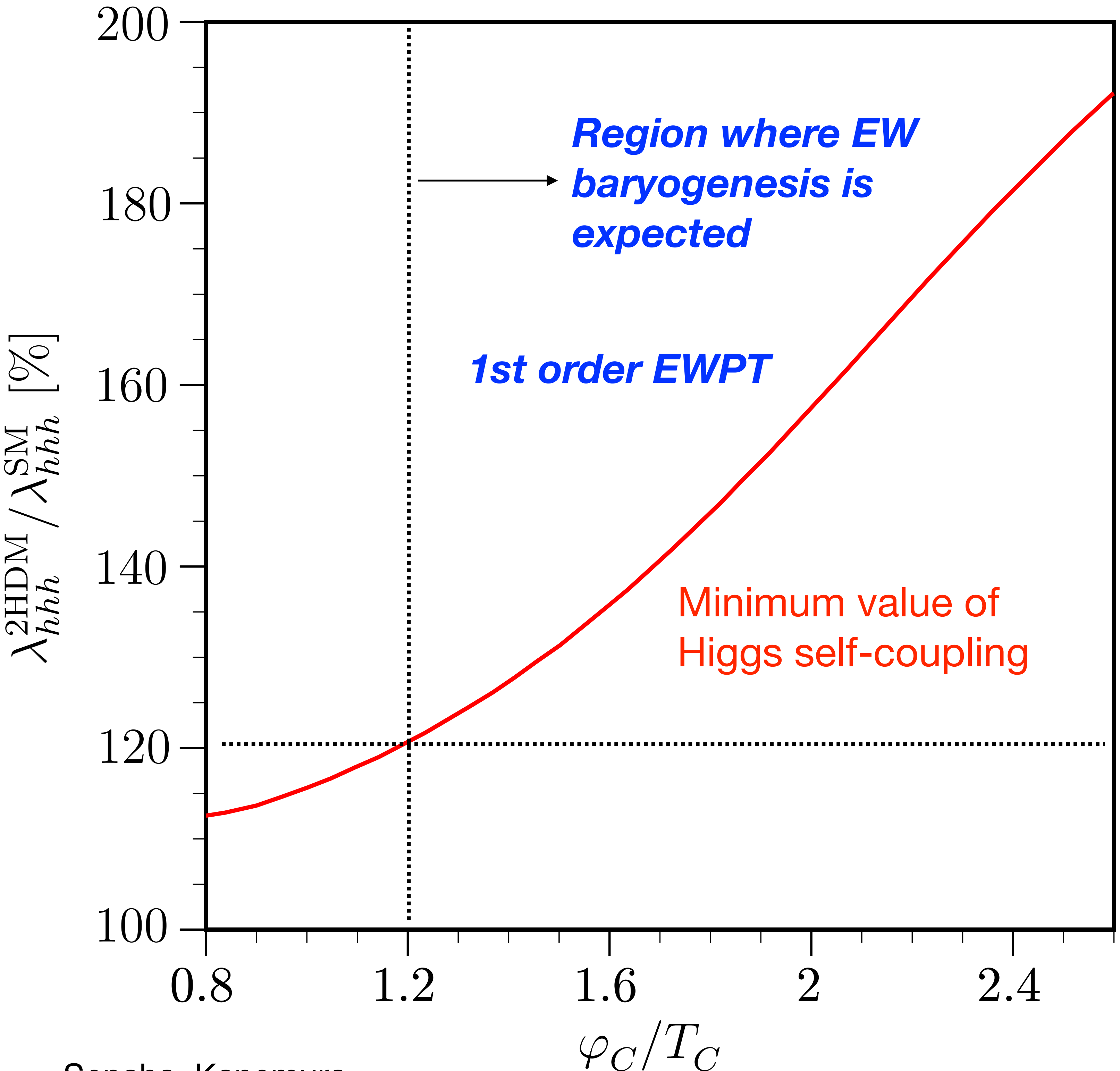




arXiv:1310.0763	ILC500	ILC500-up	ILC1000	ILC1000-up
$\sqrt{s}$ (GeV)	500	500	500/1000	500/1000
$\int \mathcal{L}dt$ (fb^{-1})	500	1600‡	500+1000	1600+2500‡
$P(e^-,e^+)$	$(-0.8, 0.3)$	$(-0.8, 0.3)$	$(-0.8, 0.3/0.2)$	$(-0.8, 0.3/0.2)$
$\sigma(ZHH)$	42.7%		42.7%	23.7%
$\sigma(\nu\bar{\nu}HH)$	–	–	26.3%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

Ongoing analysis improvements ***towards O(10)% measurement***

Electroweak Baryogenesis



Senaha, Kanemura

<u>Example:</u>

Electroweak baryogenesis in a ***Two Higgs Doublet Model***

Large deviations in Higgs self-coupling

→ ***1st order EW phase transition***

→ ***Out of equilibrium***

+ *CPV in Higgs sector*

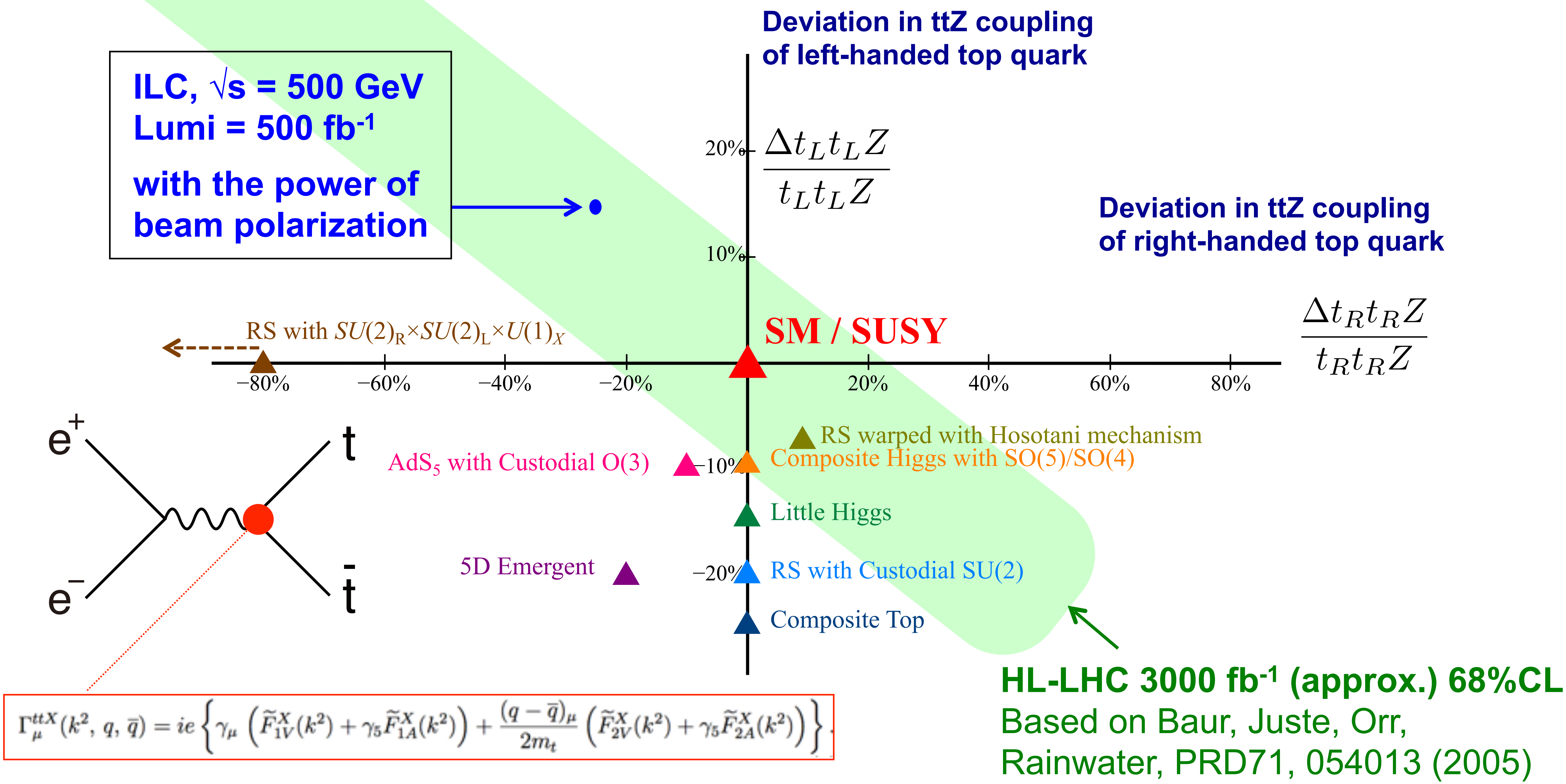
→ ***EW baryogenesis possible***

ILC can test the idea of ***baryogenesis occurring at the electroweak scale***.

Top Physics at ILC

Impact of BSM on Top Sector

In composite Higgs models, it is often said that ***the top quark is partially composite***, resulting in ***form factors in ttZ couplings***, which can be measured at ILC. ***Beam polarization is essential*** to distinguish the ***left- and right-handed couplings***.



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

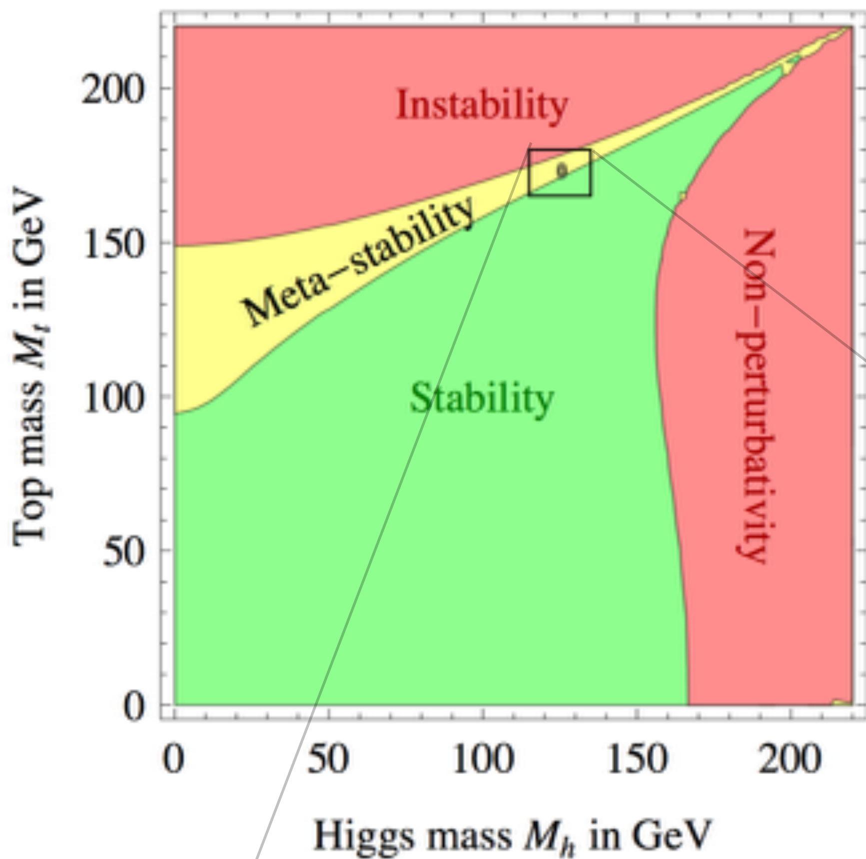
SM up to Λ_{Planck}?

What if the Higgs properties would turn out to be just like those of the SM Higgs boson, to the ILC precision, and that no BSM signal found?

We would need to question then the range of validity of the SM.

How far can the SM go?

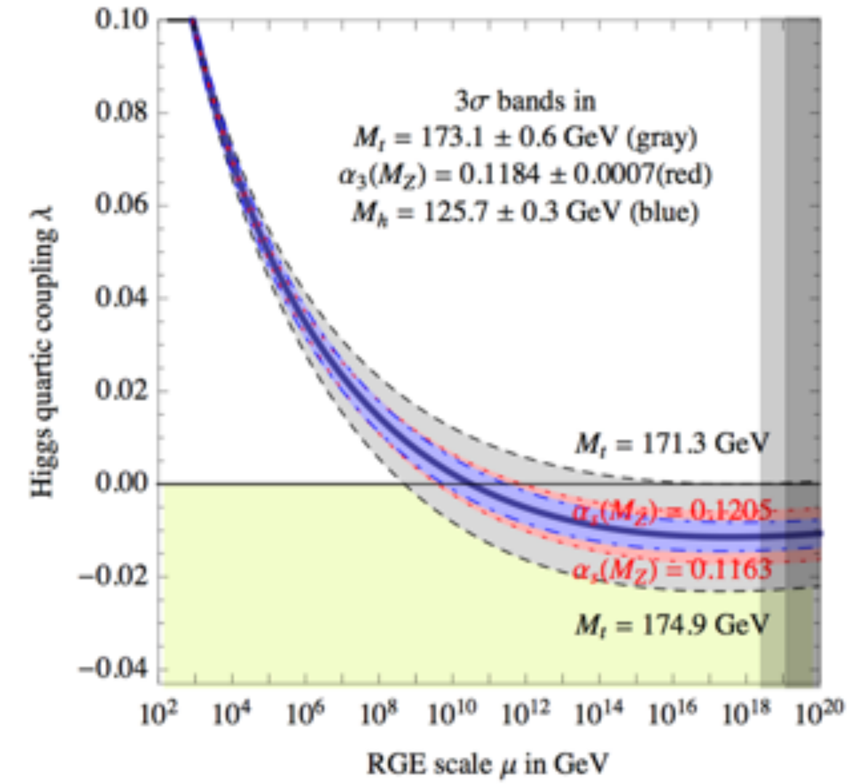
Stability of SM Vacuum



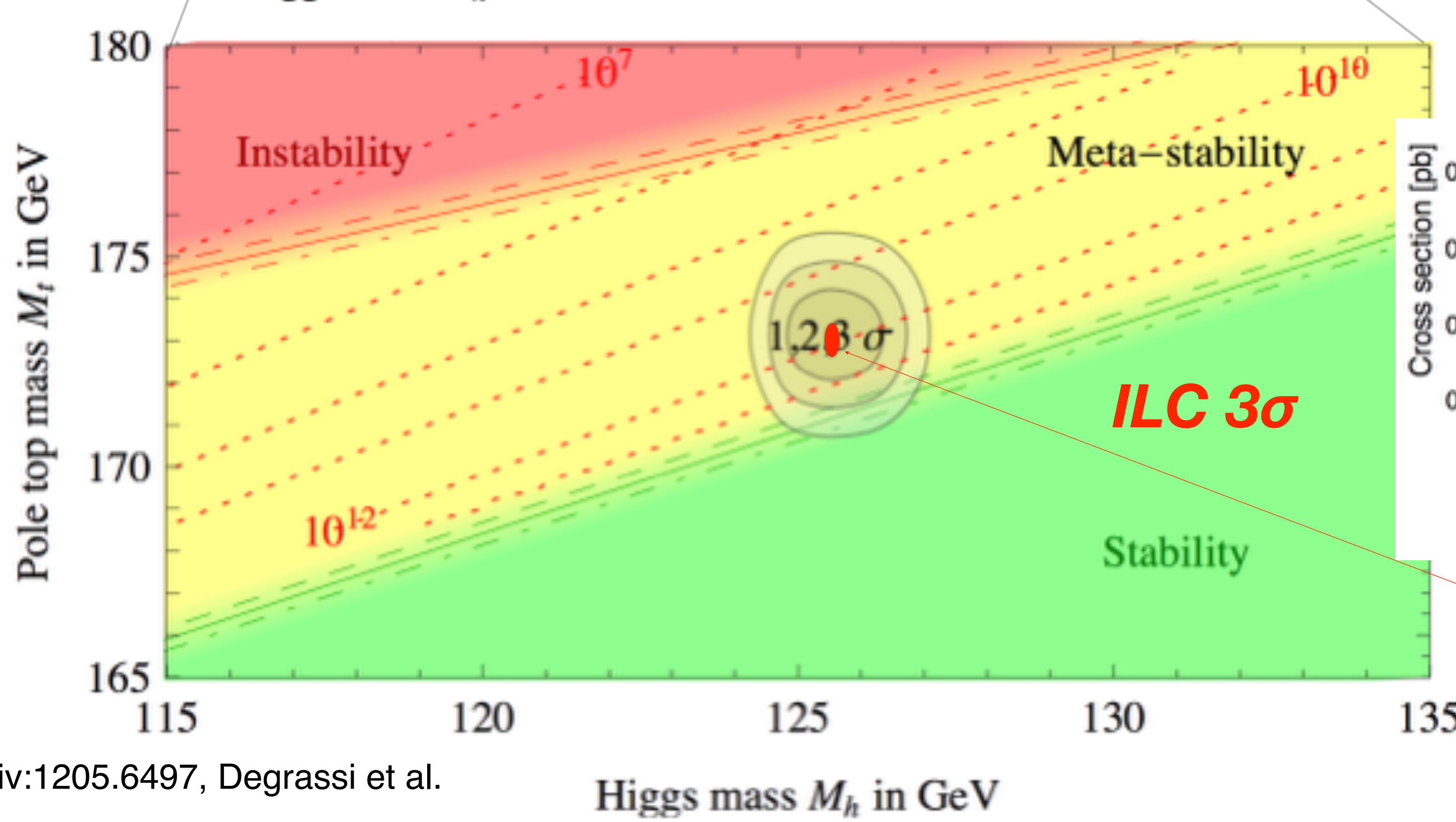
With the 125GeV Higgs boson, the SM vacuum seems to be at a subtle point of meta-stability!

Does λ really become negative below Λ_{Pl}?

or $\lambda(\Lambda_{Pl}) = 0$?

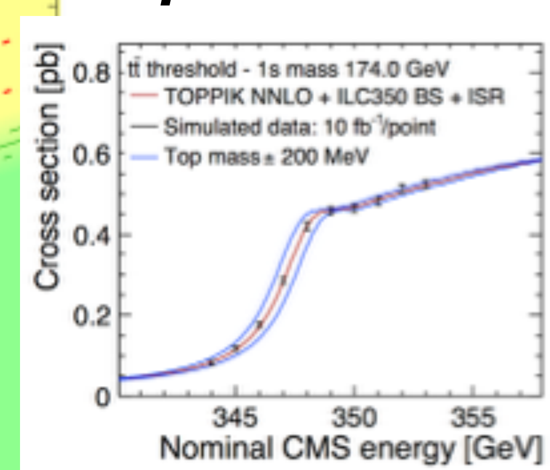


To answer this we need a precision m_t measurement!

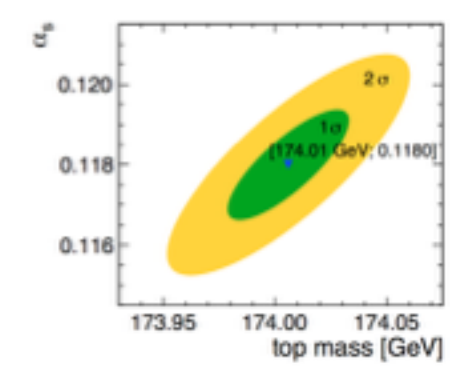


arXiv:1205.6497, Degrassi et al.

Top Pair Threshold



Theoretically very clean measurement of m_t



$$\Delta m_t(\overline{MS}) \simeq 100\,\mathrm{MeV}$$

$$\Delta m_H = 30\,\mathrm{MeV}$$

ILC pins down the location !

arXiv:hep-ph/1502.01030: Quark mass relation to 4-loop order -> <50MeV

Summary

- The primary goal for the next decades is ***to uncover the secret of the EW symmetry breaking.*** The discovery of H(125) completed the SM particle spectrum and taught us how the EW symmetry was broken. However, it does not tell us why it was broken. ***Why $\mu^2 < 0$?*** To answer this question we need to go beyond the SM.

- There is a big branching point concerning the question: ***Is H(125) elementary or composite?*** There are ***two powerful probes*** in hand: ***H(125) itself and the top quark***. Different models predict different deviation patterns in Higgs and top couplings. ***ILC will measure these couplings with unprecedented precision.***

- This will open up a window to BSM and ***fingerprint BSM models***, otherwise will set the energy scale for the E-frontier machine that will follow LHC and ILC.

- ***Cubic self-coupling measurement*** will decide whether the EWSB was strong 1st order phase transition or not. If it was, it will provide us the possibility of understanding ***baryogenesis at the EW scale***.

- ***The ILC is an ideal machine to address these questions*** (regardless of BSM scenarios) and we can do this ***model-independently***.

Last but Not Least

- In this talk I have been focusing on the case where H(125) alone would be the probe for BSM physics, but there is a good chance for LHC Run 2 to bring us more.
- It is also very important to stress that ***ILC, too, is an energy frontier machine.*** It will access the energy region never explored with any lepton collider. It is not a tiny corner of the parameter space that will be left after LHC. ***There is a wide and interesting region for ILC to explore.***

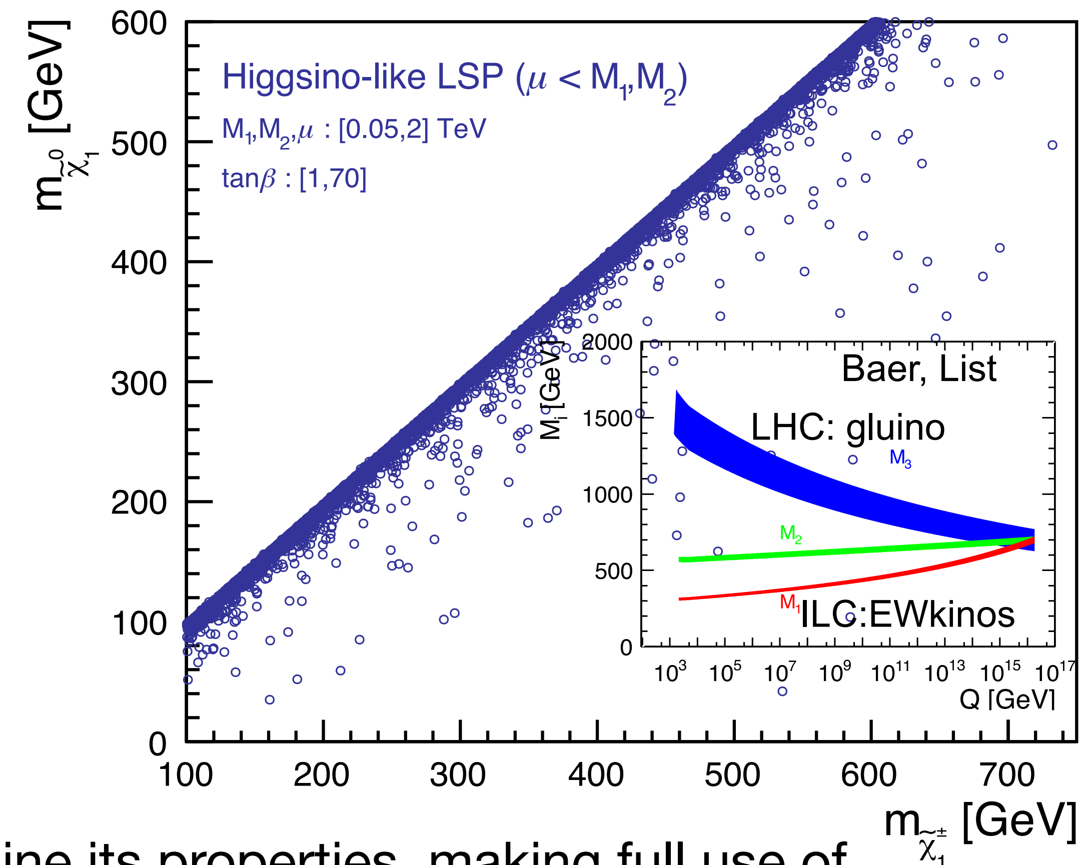
Example: Natural Radiative SUSY
Naturalness prefers ***μ not far above 100GeV*** but colored sparticles can be heavy enough to escape LHC detection

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

→ light chargino/neutralinos will be ***higgsino-dominant*** and ***nearly mass degenerate***

→ ***typically Δm of 20 GeV or less***

→ ***very difficult for LHC!***



- Once a new particle is found at ILC, we can precisely determine its properties, making full use of ***polarized beams***. In the case of natural radiative SUSY scenario, we might even probe GUT scale physics using RGE.
- If there is a DM candidate within ILC's reach, its measured mass and couplings can be used to calculate the DM relic density and will ***reveal the nature of the cosmic DM***.
- ***In this way, ILC will pave the way to BSM physics.***

Please attend ALCW 2015

The Asia region Linear Collider Workshop

April 20 ~ April 24

April 20-21: at KEK
LC Physics (mostly theory) sessions

April 22: at Univ. of Tokyo (***free admission***)
Scientific and Political
Plenary Sessions

April 23: at KEK
latest results on ILC capabilities

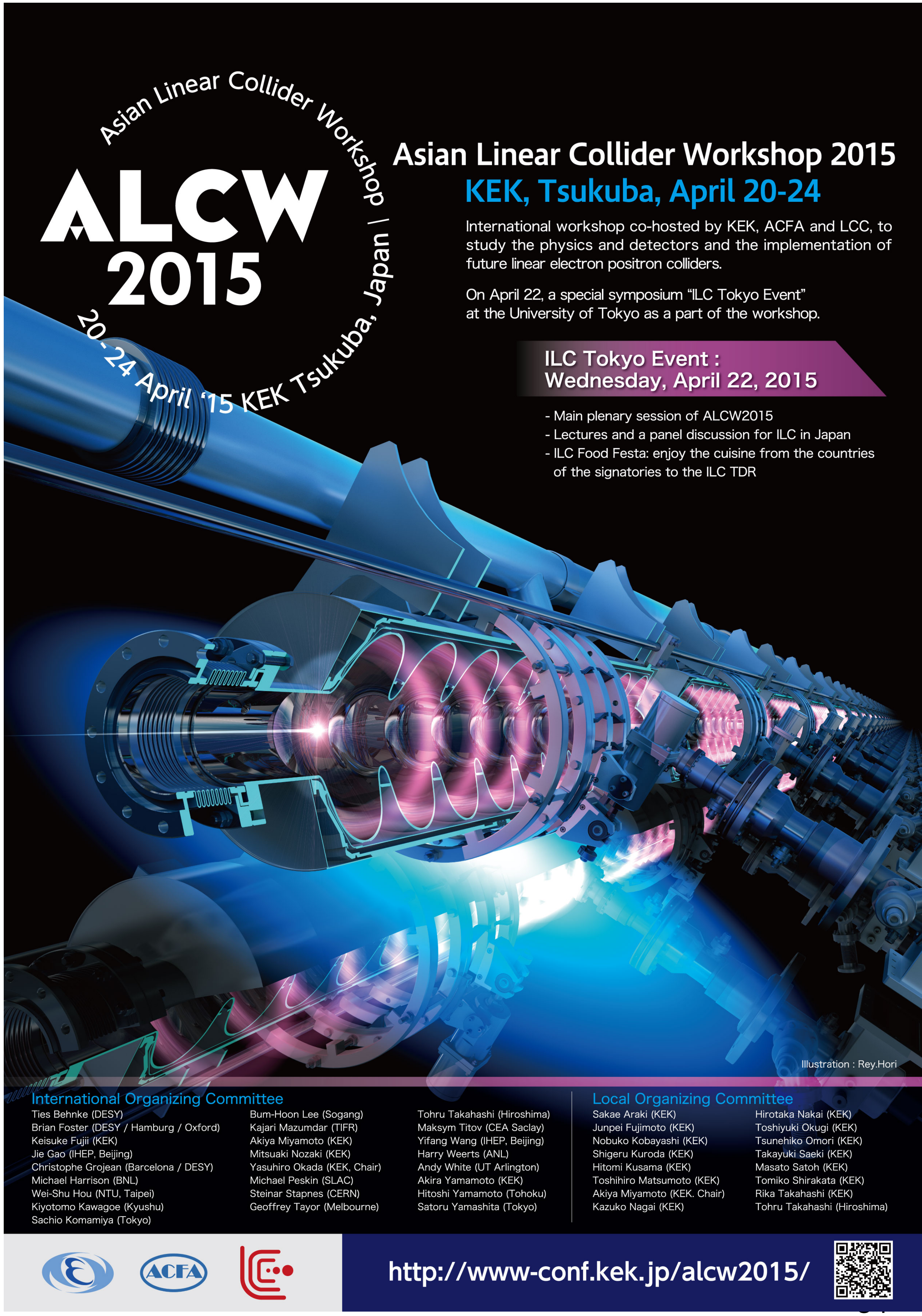
WS home:
http://www-conf.kek.jp/alcw2015

Registration:
http://www-conf.kek.jp/alcw2015/registration.html
Early registration deadline: March 29

Tokyo Event:
http://aaa-sentan.org/tokyo_event2015/en/index.html

Please send your talk proposal by March 31 to physics session conveners:

Keisuke Fujii:	keisuke.fujii@kek.jp
Christophe Grojean:	christophe.Grojean@cern.ch
Shinya Kanemura:	kanemu@sci.u-toyama.ac.jp
Mihoko Nojiri:	nojiri@post.kek.jp
Michael Peskin:	mailto:mpeskin@slac.stanford.edu



Additional Slides

Searches for direct production of SUSY / DM at the ILC

What can ILC add to HL-LHC?

SUSY: LHC vs. ILC

"LHC has excluded MSSM up to high masses"	**vs.**	"LHC leaves out holes in MSSM parameter space"
"ILC can set model-indep. limits on SUSY particles"	**vs.**	"There is nothing interesting left within the reach of ILC"

These statements are all true to a certain extent…

The Big Picture:

SUSY is only complete with SUSY breaking implemented!

The answer depends on this SUSY breaking mechanism.

An example of connecting the "high mass reach of LHC" with "model-independent reach of ILC":

Gluino @ LHC vs. **Chargino/Neutralino @ ILC**

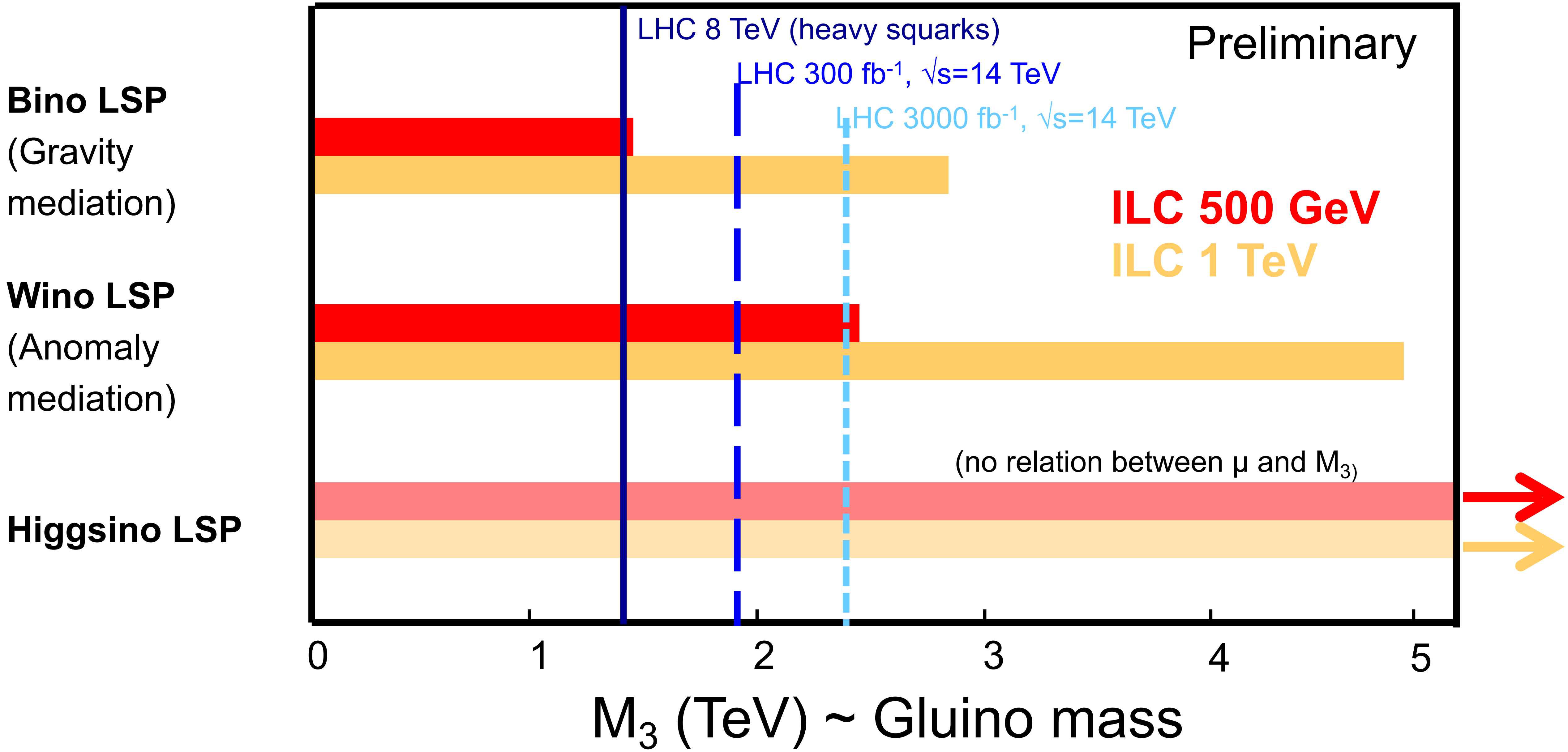
assuming various gaugino mass relations (e.g. GMSB, AMSB) and LSP types (Bino, Wino, Higgsino)

Sensitivity to SUSY

[this comparison is for illustration only; specific channels should be looked at for actual comparisons]

Examples of direct SUSY searches
- LHC: Gluino search
- ILC: EWkino (Chargino/Neutralino) search

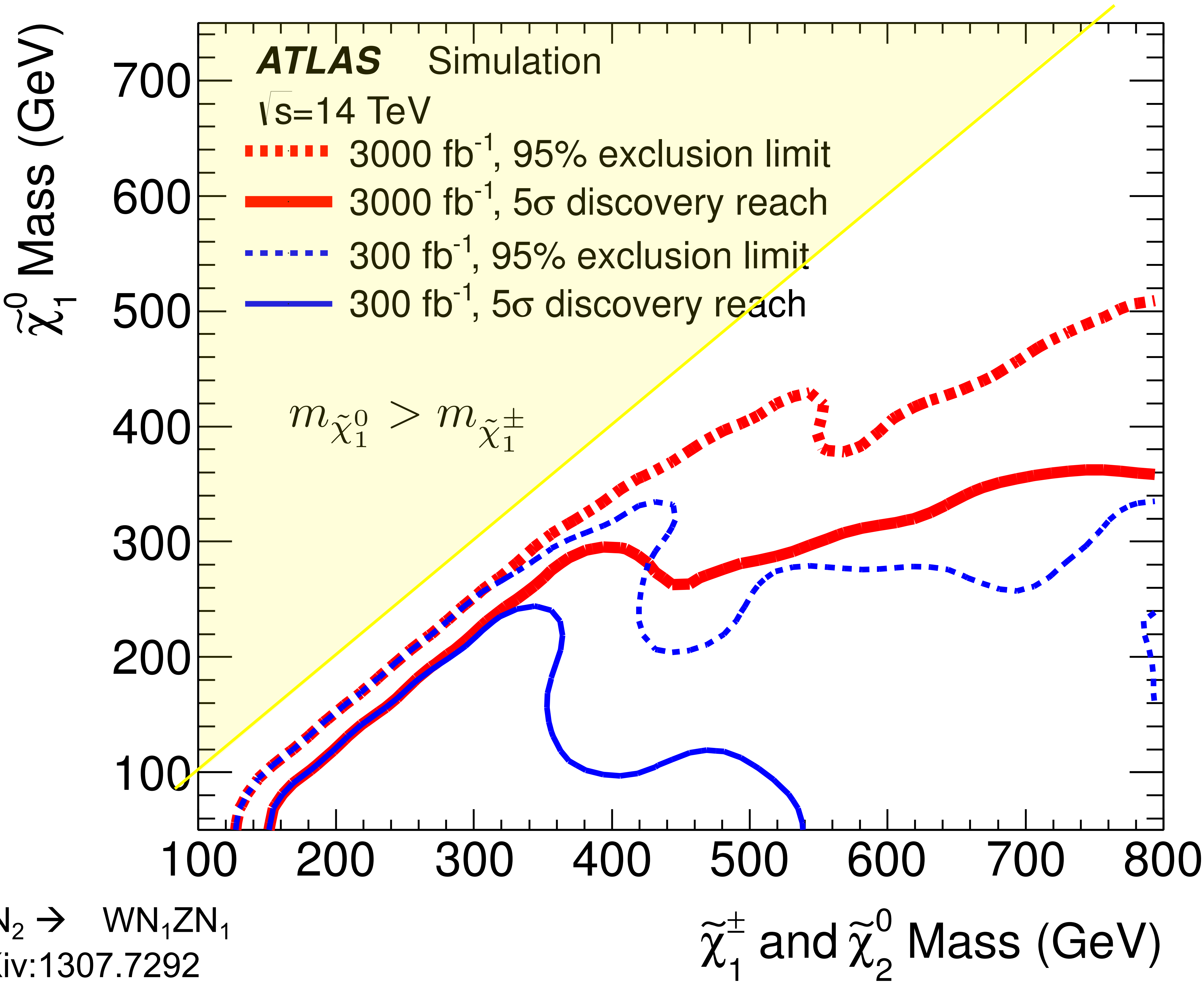
Compare using gaugino mass relations



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

But, LHC can also search for direct EWkino production

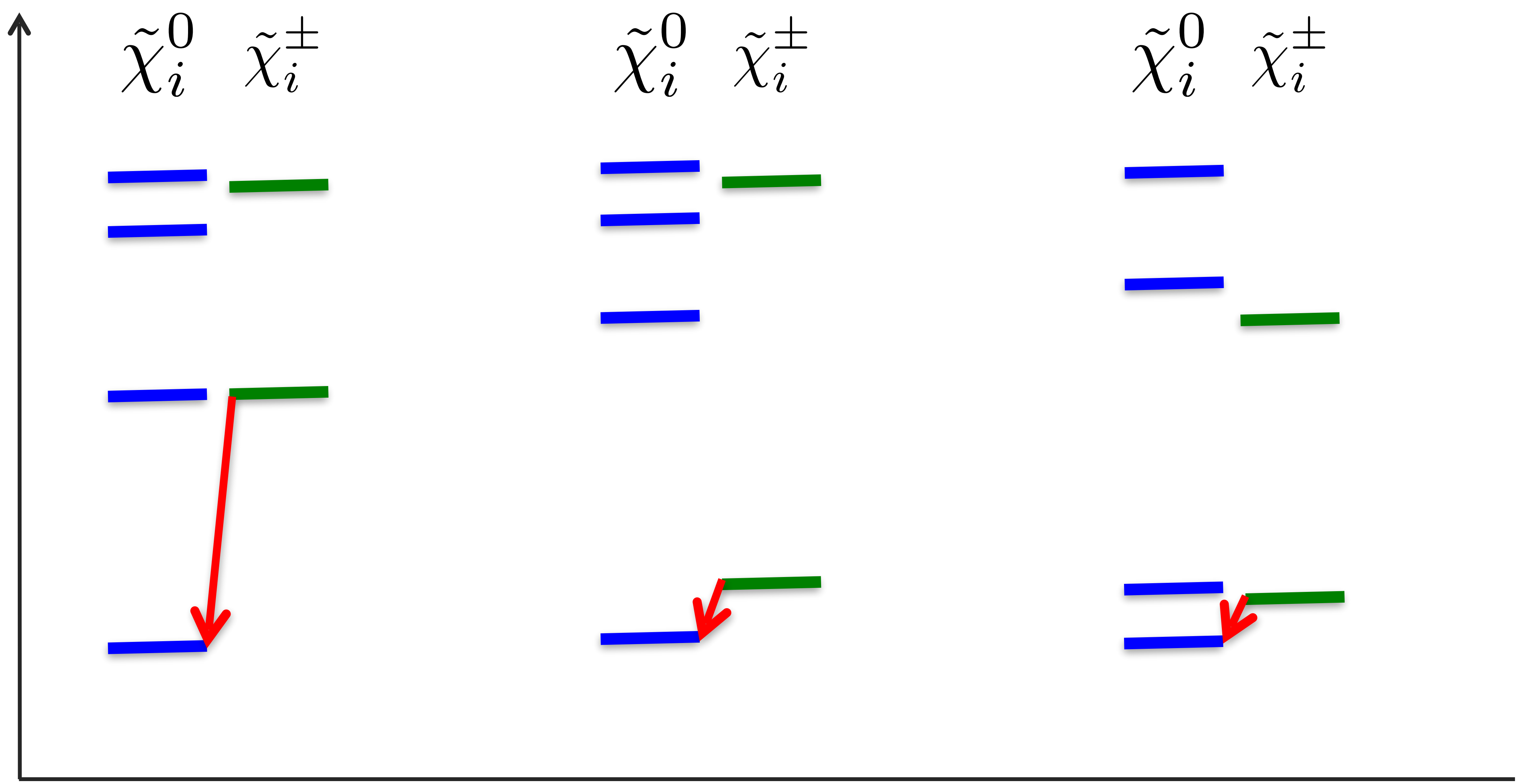
SUSY EW @ HL-LHC



$C_1N_2 \rightarrow WN_1ZN_1$
arXiv:1307.7292

Is it only a tiny corner in the parameter space that will be left? Is ILC a gleaner?

SUSY Electroweak Sector



Bino-like LSP

$M_1 \ll M_2, \mu$

Wino-like LSP

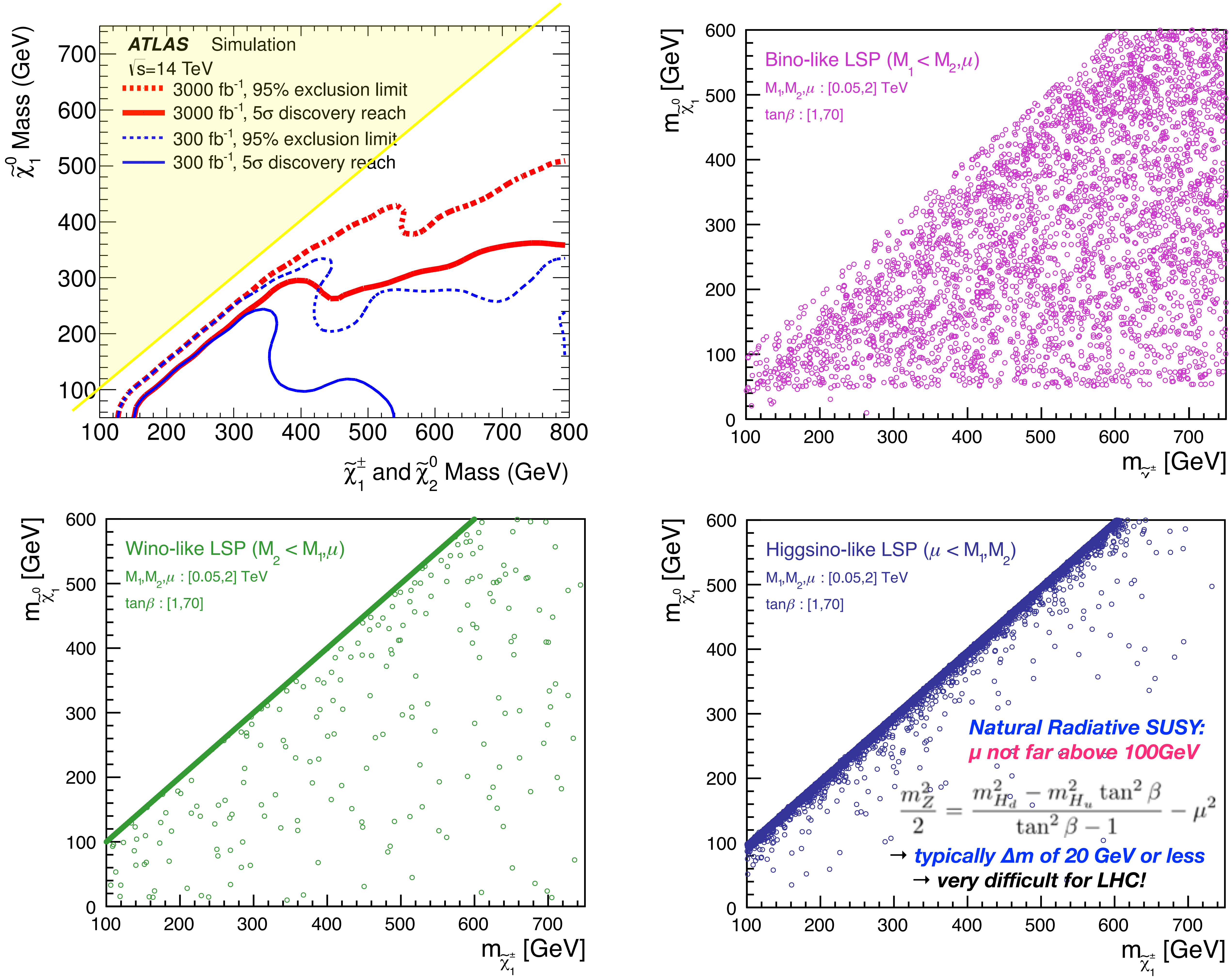
$M_2 \ll M_1, \mu$

Higgsino-like LSP

$\mu \ll M_2, M_1$

LSP/NLSP typically degenerate

(depends on mixing)


ATLAS Simulation
√s=14 TeV
3000 fb-1, 95% exclusion limit
3000 fb-1, 5σ discovery reach
300 fb-1, 95% exclusion limit
300 fb-1, 5σ discovery reach
χ̃10 Mass (GeV)
χ̃1± and χ̃20 Mass (GeV)
Bino-like LSP (M1 < M2,μ)
M1,M2,μ : [0.05,2] TeV
tanβ : [1,70]
m χ̃10 [GeV]
m χ̃± [GeV]
Wino-like LSP (M2 < M1,μ)
M1,M2,μ : [0.05,2] TeV
tanβ : [1,70]
m χ̃10 [GeV]
m χ̃1± [GeV]
Higgsino-like LSP (μ < M1,M2)
M1,M2,μ : [0.05,2] TeV
tanβ : [1,70]
m χ̃10 [GeV]
m χ̃1± [GeV]
Natural Radiative SUSY:
μ not far above 100GeV
$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu^2$
→ typically Δm of 20 GeV or less
→ very difficult for LHC!

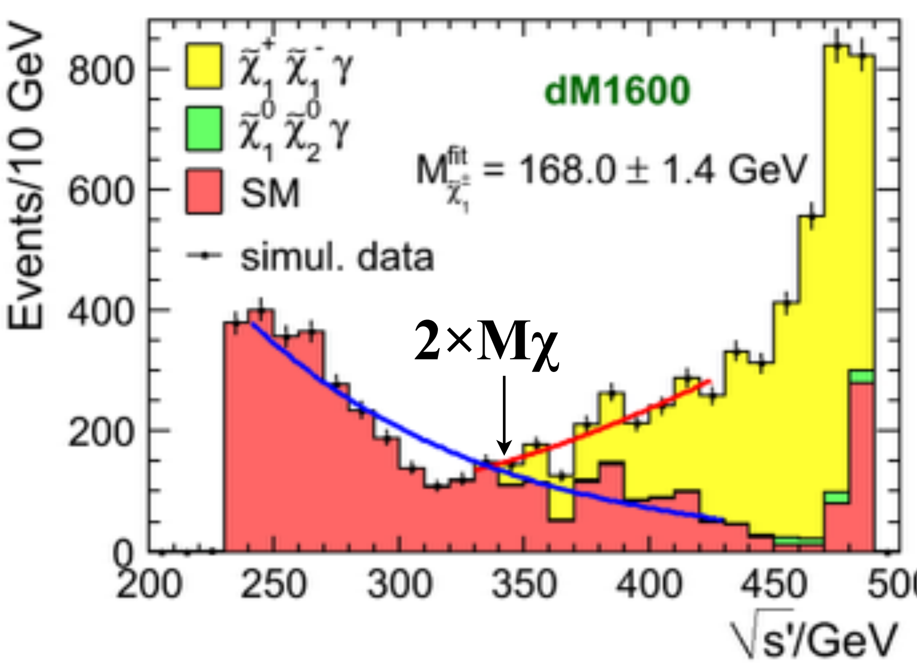
Higgsinos in Natural SUSY (ΔM<a few GeV)

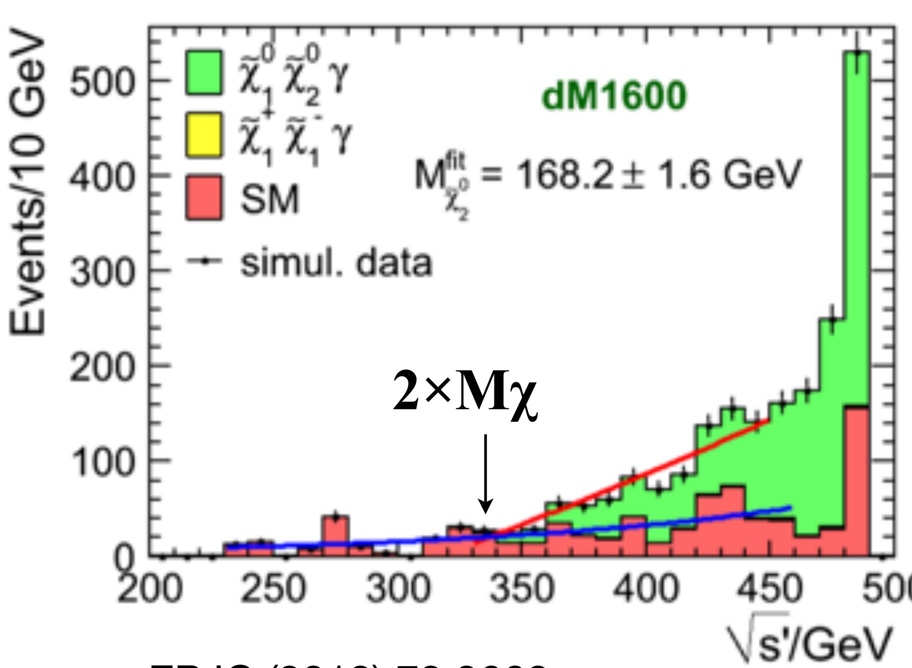
ILC as a Higgsino Factory

ISR Tagging

$$e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-\gamma$$

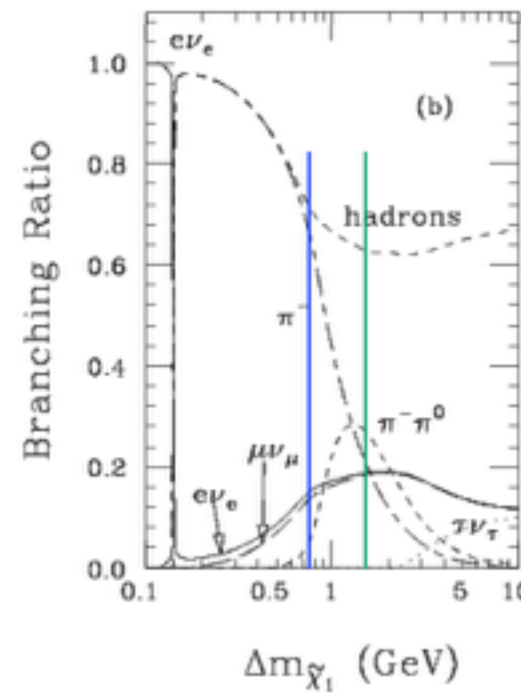
$$e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_1^0\gamma$$





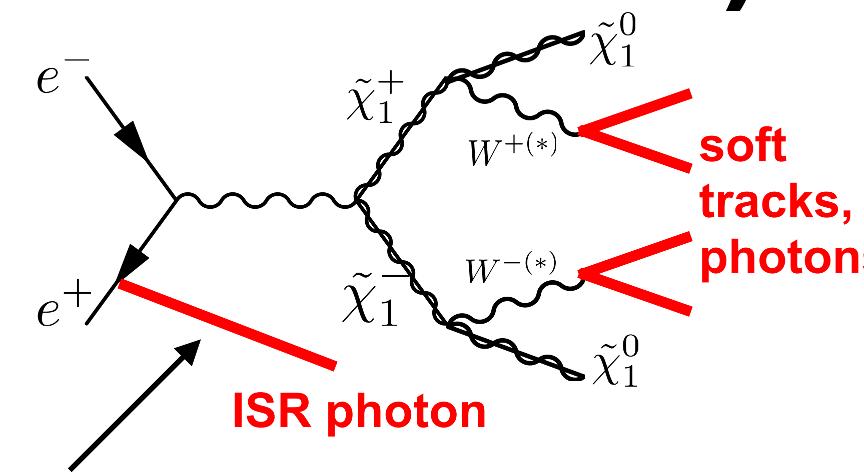
EPJC (2013) 73:2660

Ref: C.-H. Chen et al. hep-ph:9512230



mh=124 GeV
ΔM = 1.59 GeV

mh=127 GeV
ΔM = 0.77 GeV



ISR Tagging

Only very soft particles in the final states → Require a hard ISR to kill huge two-photon BG!

500fb-1 @ Ecm=500GeV
Pol (e+,e-) = (+0.3,-0.8) and (-0.3,+0.8)

dm1600

Mass Spectrum

Particle	Mass (GeV)
h	124
$\tilde{\chi}_1^0$	164.17
$\tilde{\chi}_1^\pm$	165.77
$\tilde{\chi}_2^0$	166.87
H's	$\sim 10^3$
$\tilde{\chi}$'s	$\sim 2-3\times10^3$

$\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 1.59$ GeV

$$\delta(\sigma \times BR) \simeq 3\%$$
$$\delta M_{\tilde{\chi}_1^\pm}(M_{\tilde{\chi}_1^0}) \simeq 2.1(3.7)\,\mathrm{GeV}$$
$$\delta\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \simeq 70\,\mathrm{MeV}$$

dm770

Mass Spectrum

Particle	Mass (GeV)
h	127
$\tilde{\chi}_1^0$	166.59
$\tilde{\chi}_1^\pm$	167.36
$\tilde{\chi}_2^0$	167.63
H's	$\sim 10^3$
$\tilde{\chi}$'s	$\sim 2-3\times10^3$

$\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.77$ GeV

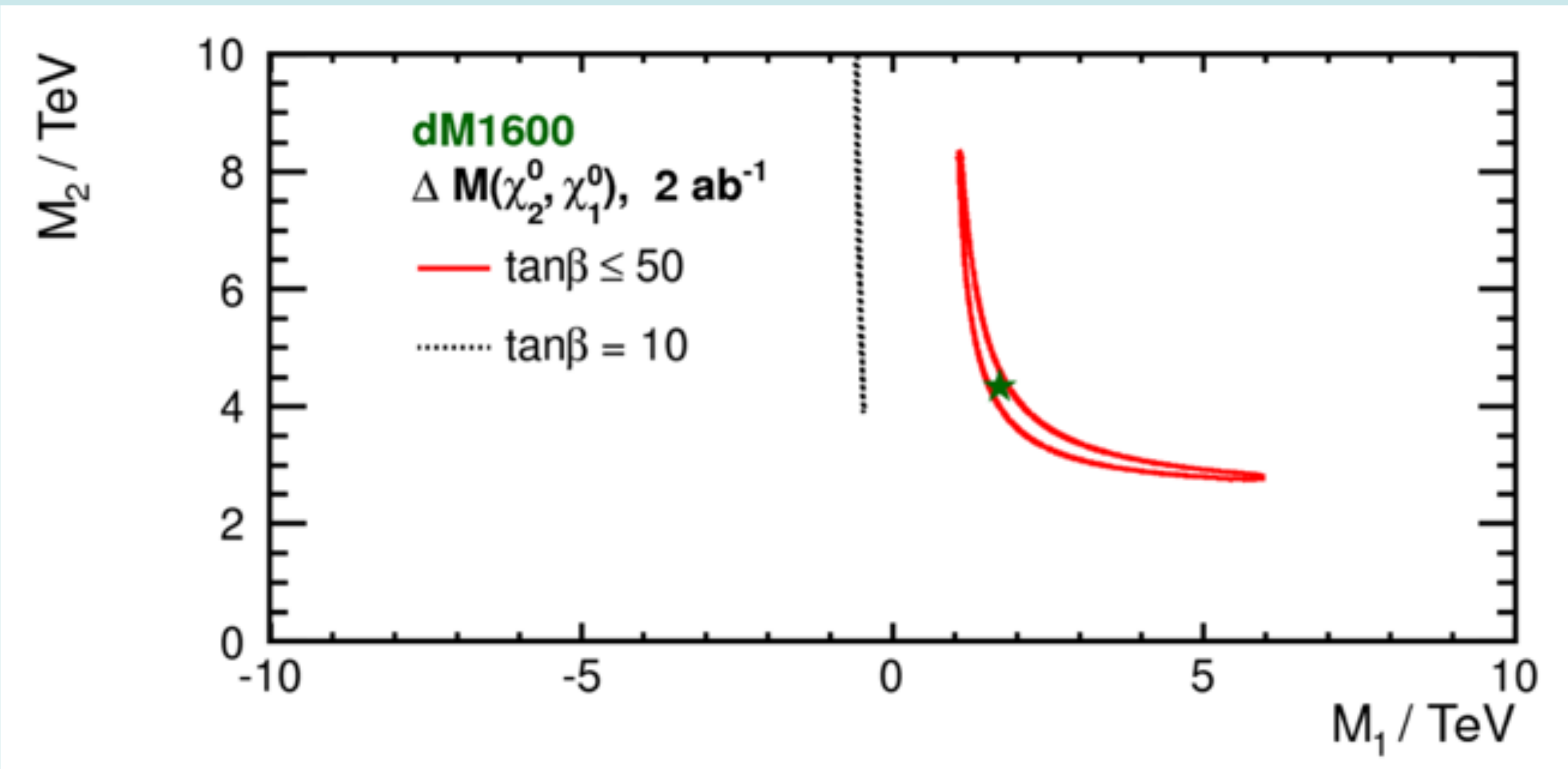
$$\delta(\sigma \times BR) \simeq 1.5\%$$
$$\delta M_{\tilde{\chi}_1^\pm}(M_{\tilde{\chi}_1^0}) \simeq 1.5(1.6)\,\mathrm{GeV}$$
$$\delta\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \simeq 20\,\mathrm{MeV}$$

Extracting M1 and M2

$$e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-\gamma$$

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

Hale Sert
ECFA LCWS 2013, DESY
Berggren et al. EPJC (2013) 73:2660

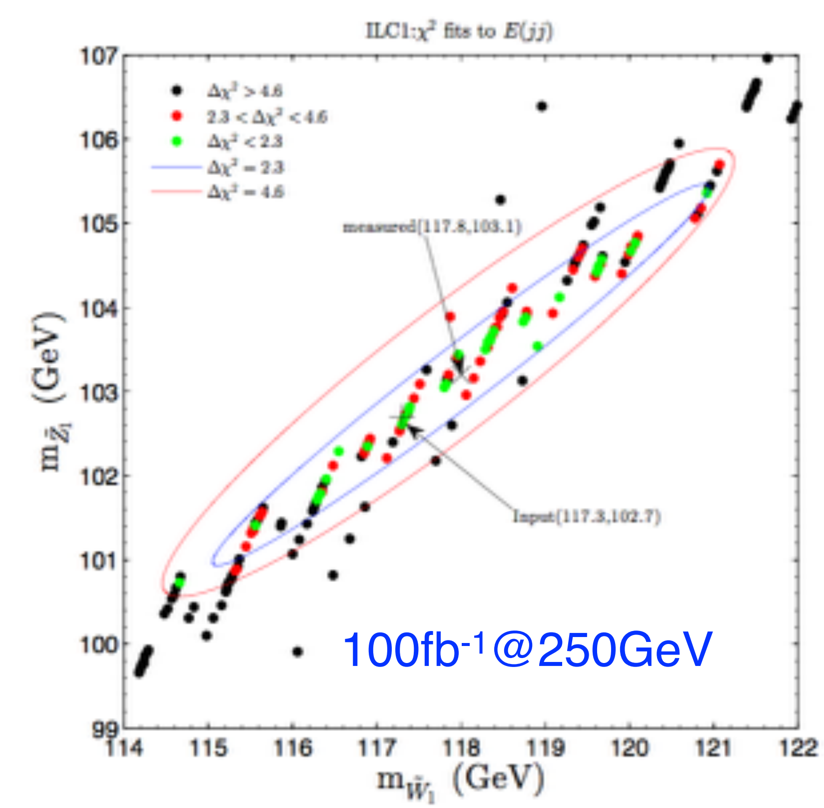


@ 2 ab^{-1}	input	lower	upper
M_1 [TeV]	1.7	~ 1.0 (-0.4)	~ 6.0
M_2 [TeV]	4.4	~ 2.5 (3.5)	~ 8.5
μ [GeV]	165.7	166.2	170.1

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

RNS: Baer et al.
arXiv: 1404.7510

ΔM=15GeV

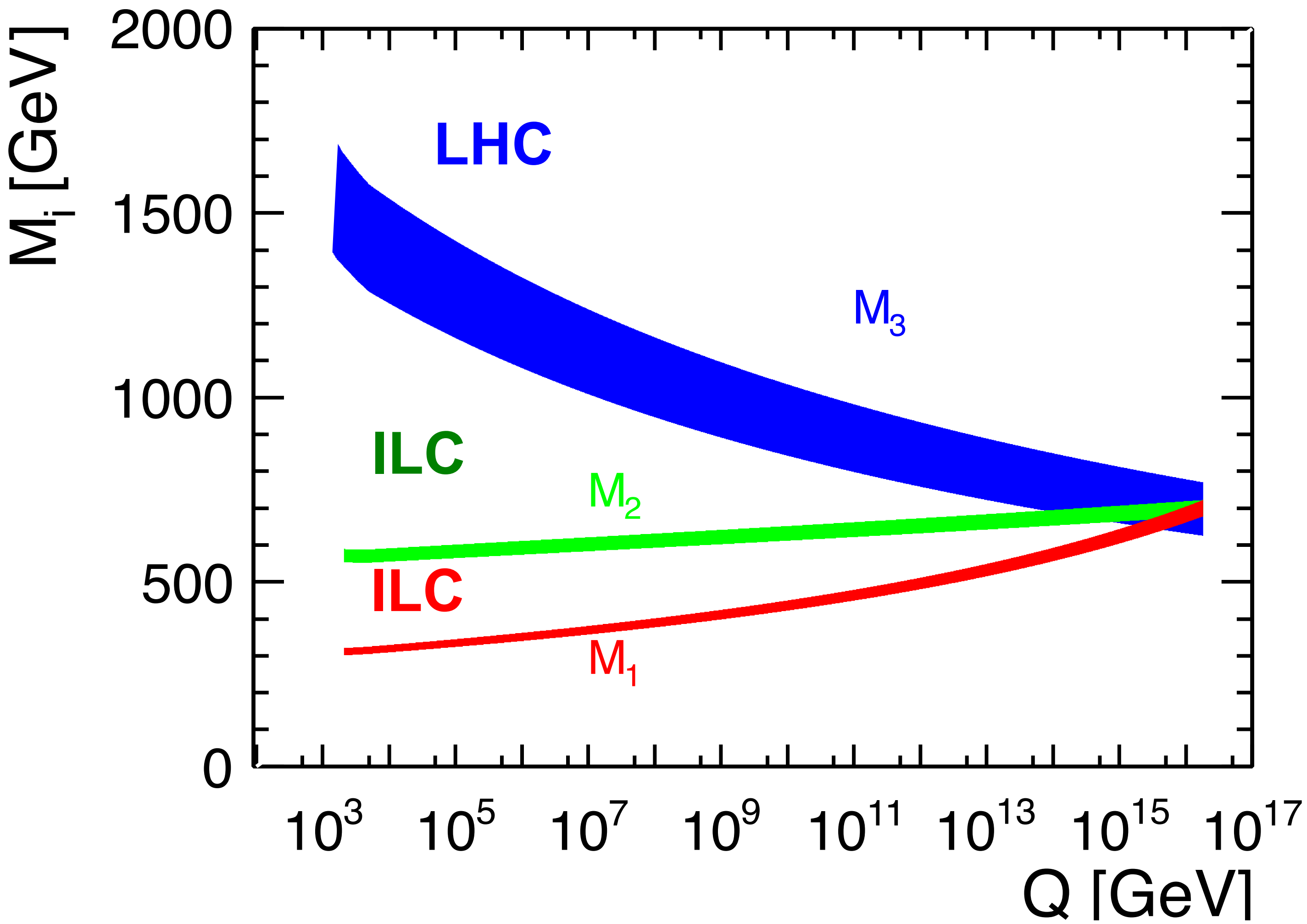


In the radiatively driven natural SUSY (RNS) scenario as in arXiv: 1404.7510, ΔM~10GeV, we can determine M1 and M2 to a few % or better, allowing us to test GUT relation!

Test gaugino mass unification

- Chargino/Neutralino @ ILC → probe M_1-M_2 gaugino mass relation
- Gluino @ LHC → test of gaugino mass relation by ILC-LHC complementarity
- Gives a prediction of the gluino mass scale
- Discrimination of SUSY spontaneous symmetry breaking scenarios

Gaugino mass unification:
Higgsino-like LSP scenario
By Baer, List



LHC: gluino discovery
→ mass determination

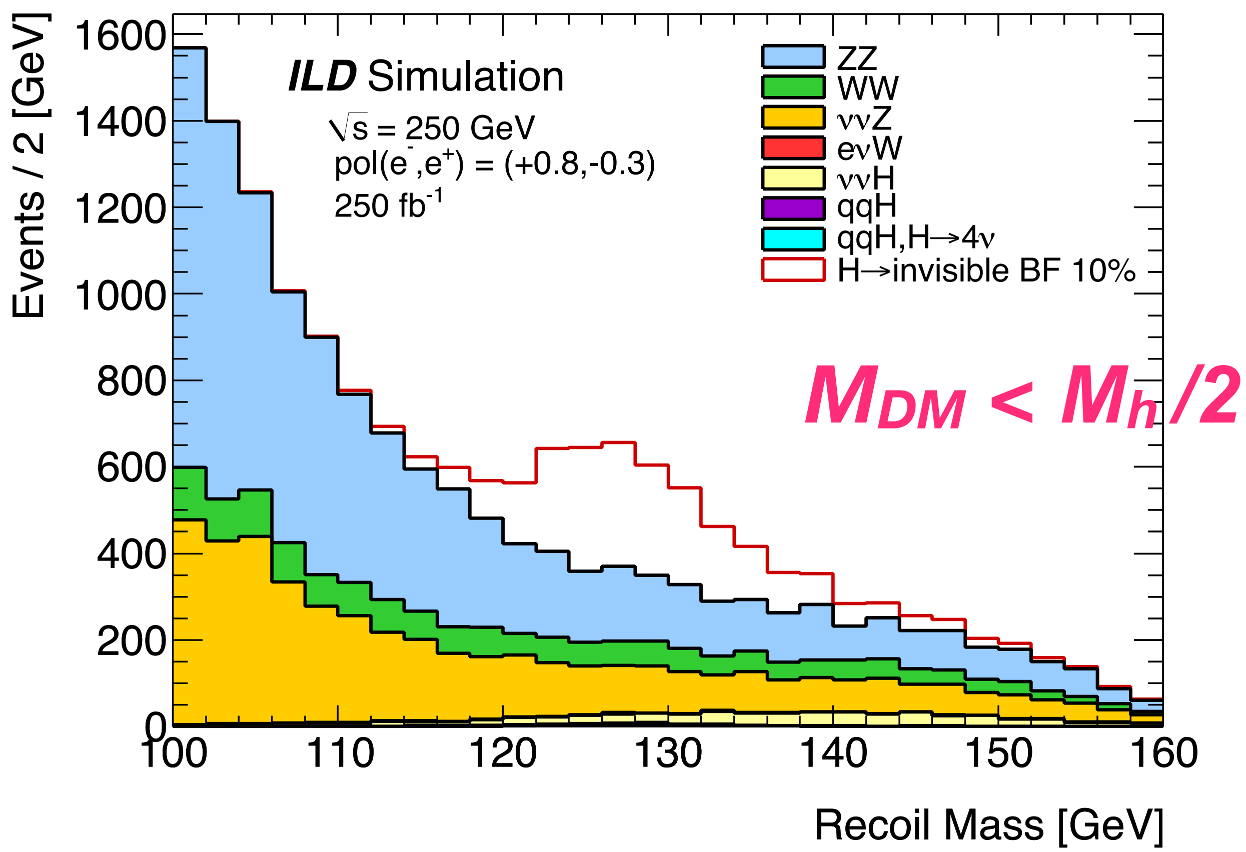
ILC: Higgsino discovery
→ M1, M2 via mixing between Higgsino and Bino/Wino

Dark Matter

WIMP Dark Matter @ ILC

WIMP searches at colliders are complementary to direct/indirect searches.
Examples at the ILC:

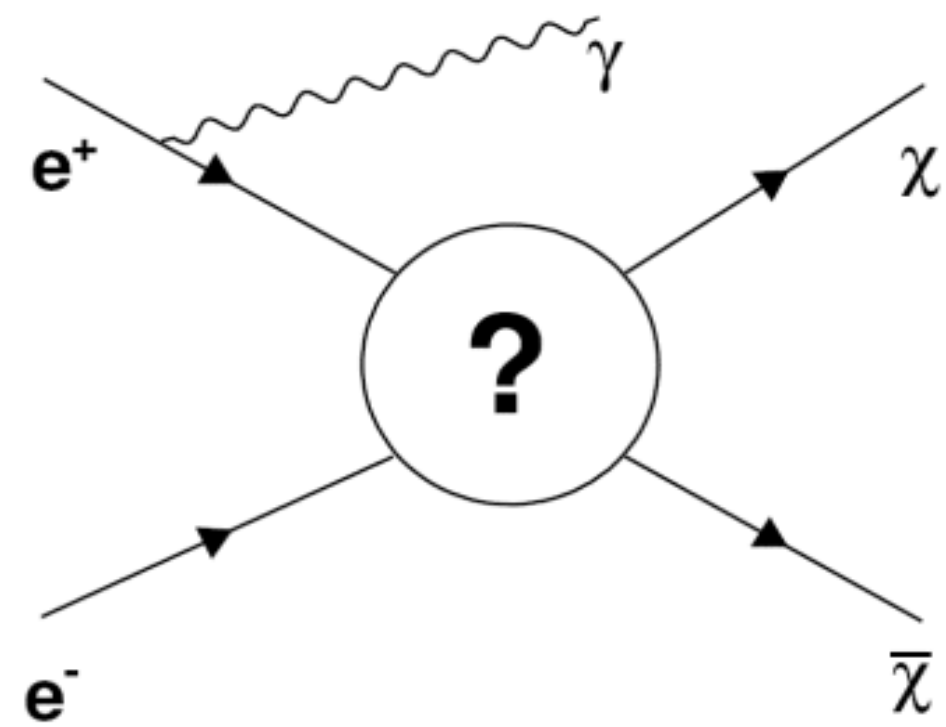
Higgs Invisible Decay



$M_{DM} < M_h/2$

BR(H→invis.) < 0.4%
at 250 GeV, 1150 fb^{-1}

Mono-photon Search



→ ***M_{DM} reach ~ Ecm/2***

In many models, DM has a charged partner as in higgsino DM case of SUSY.

SUSY-specific signatures (decays to DM)

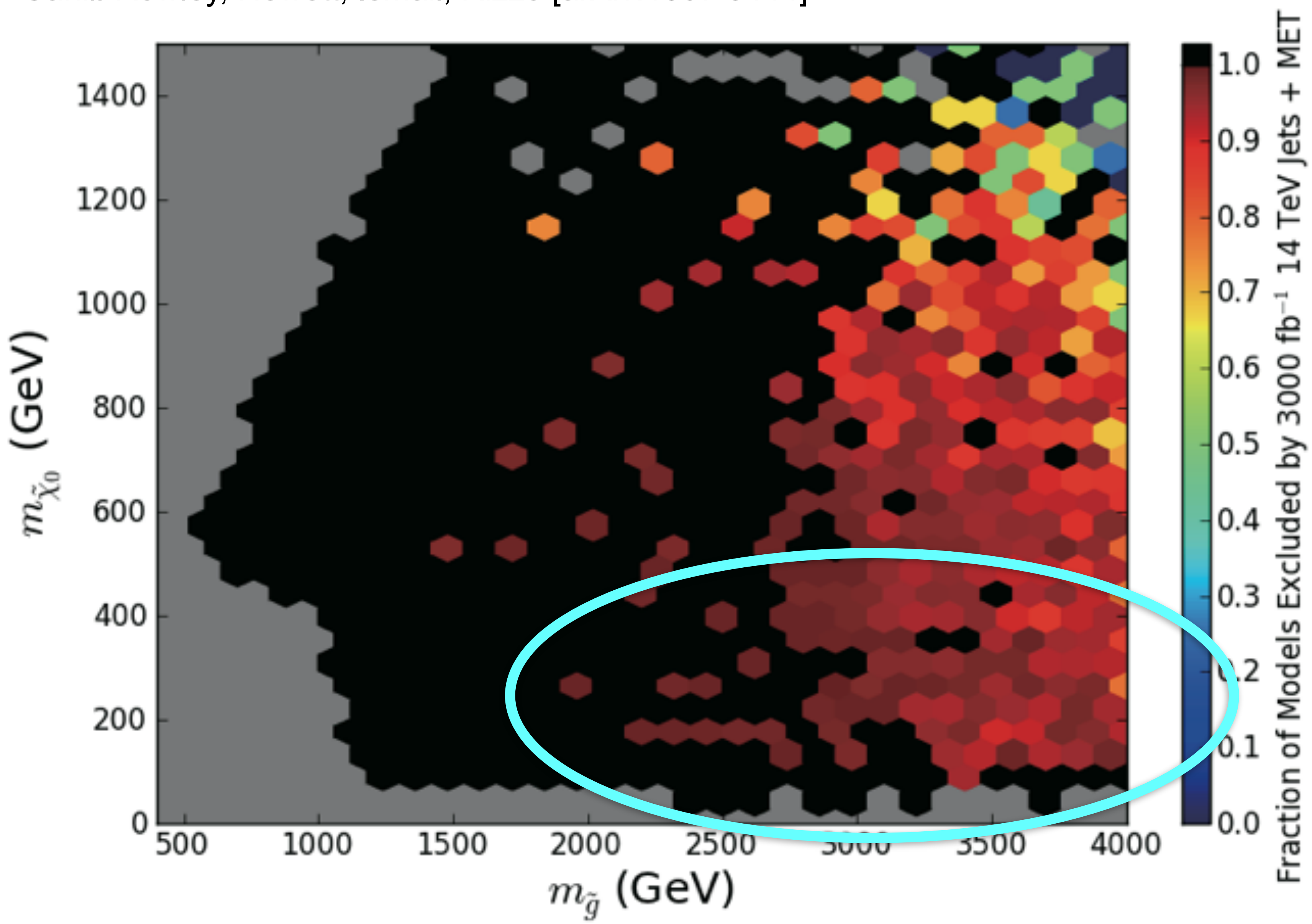
- light Higgsino, light stau, etc.

Dark Matter Search

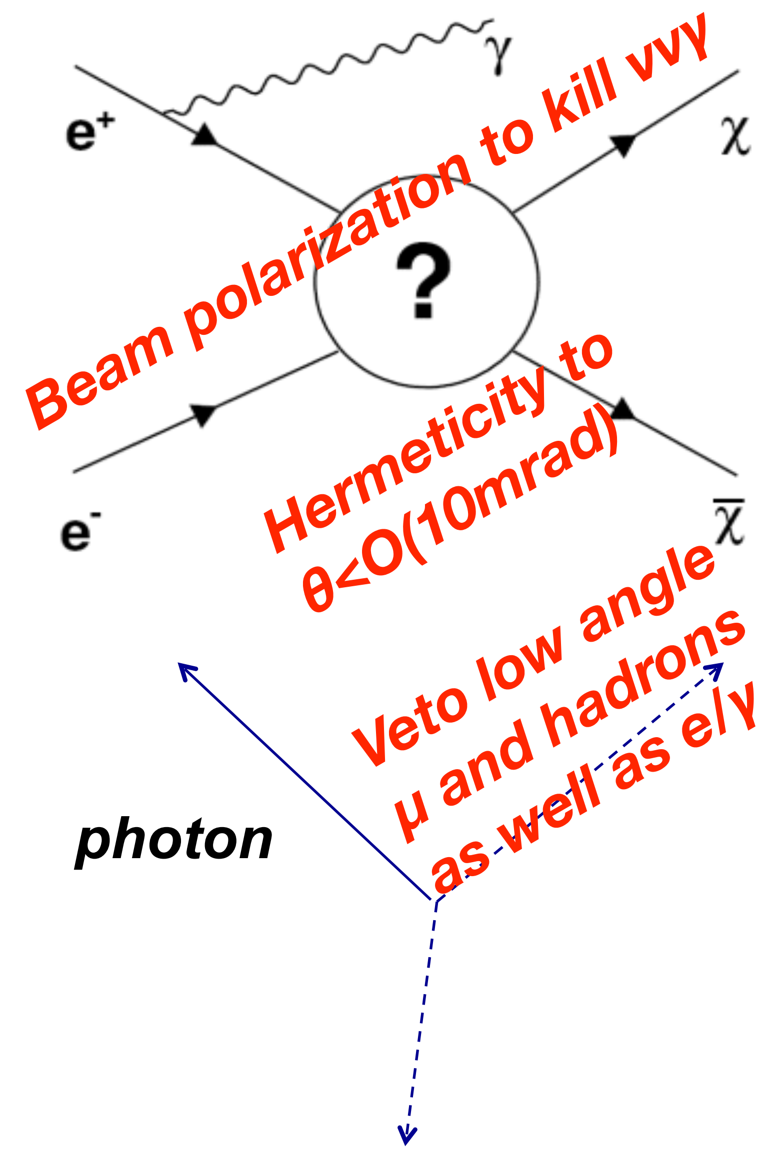
LHC 14 TeV, 3000 fb-1, *Jets+MET* analysis only
pMSSM Neutralino DM expected exclusion

may use mono-jet

Cahill-Rowley, Hewett, Ismail, Rizzo [arXiv:1307.8444]

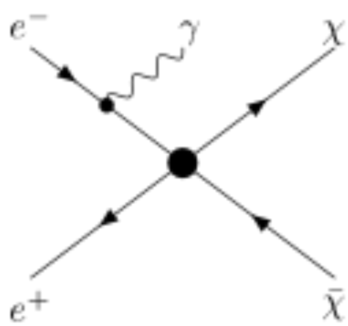


LC:
Mono photon search



Loopholes of HL-LHC → Hunting ground of ILC

DM: Effective Operator Approach

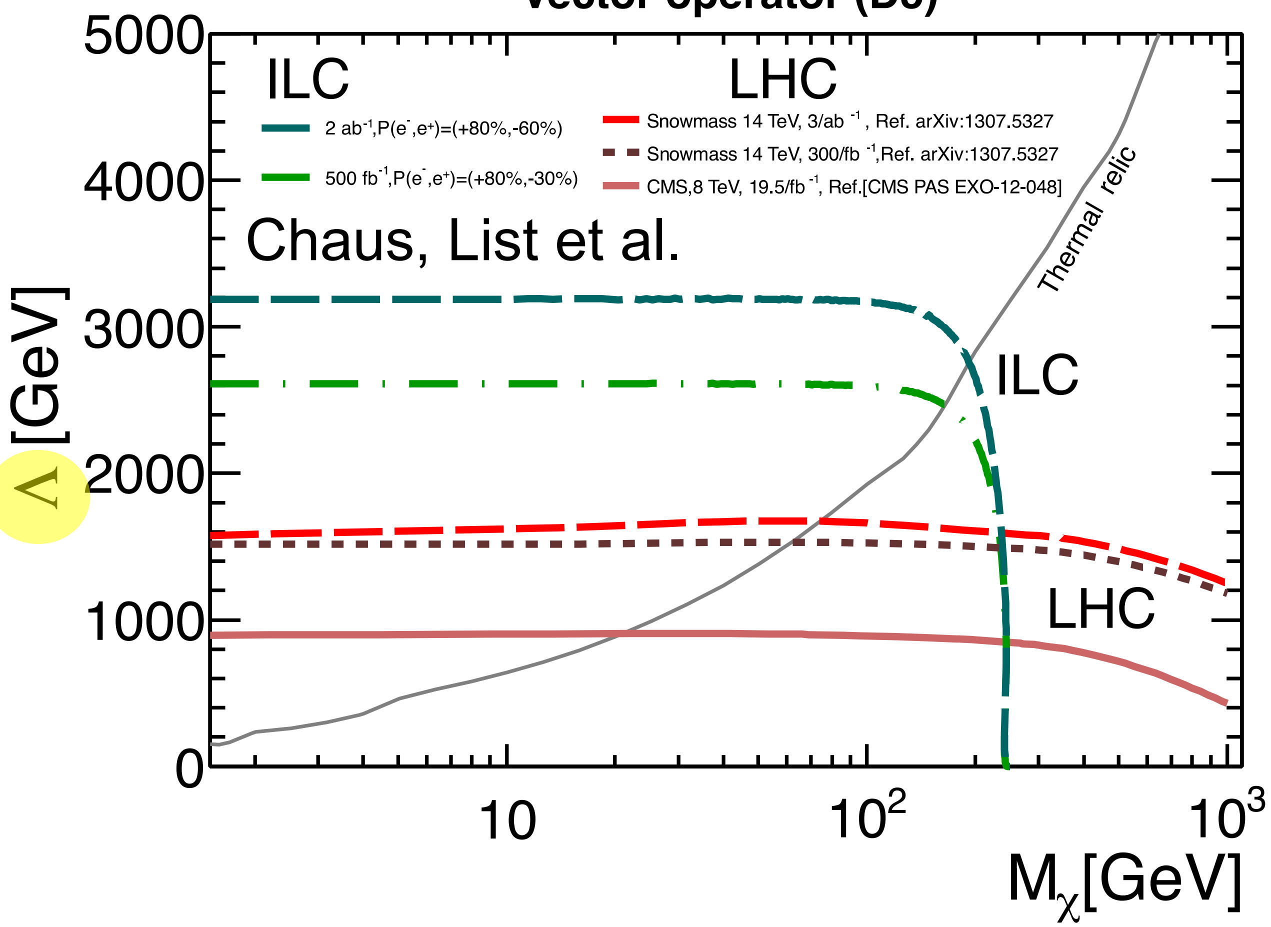


$$\mathcal{L}_{\rm int} = \frac{1}{\Lambda^2}\mathcal{O}_i$$

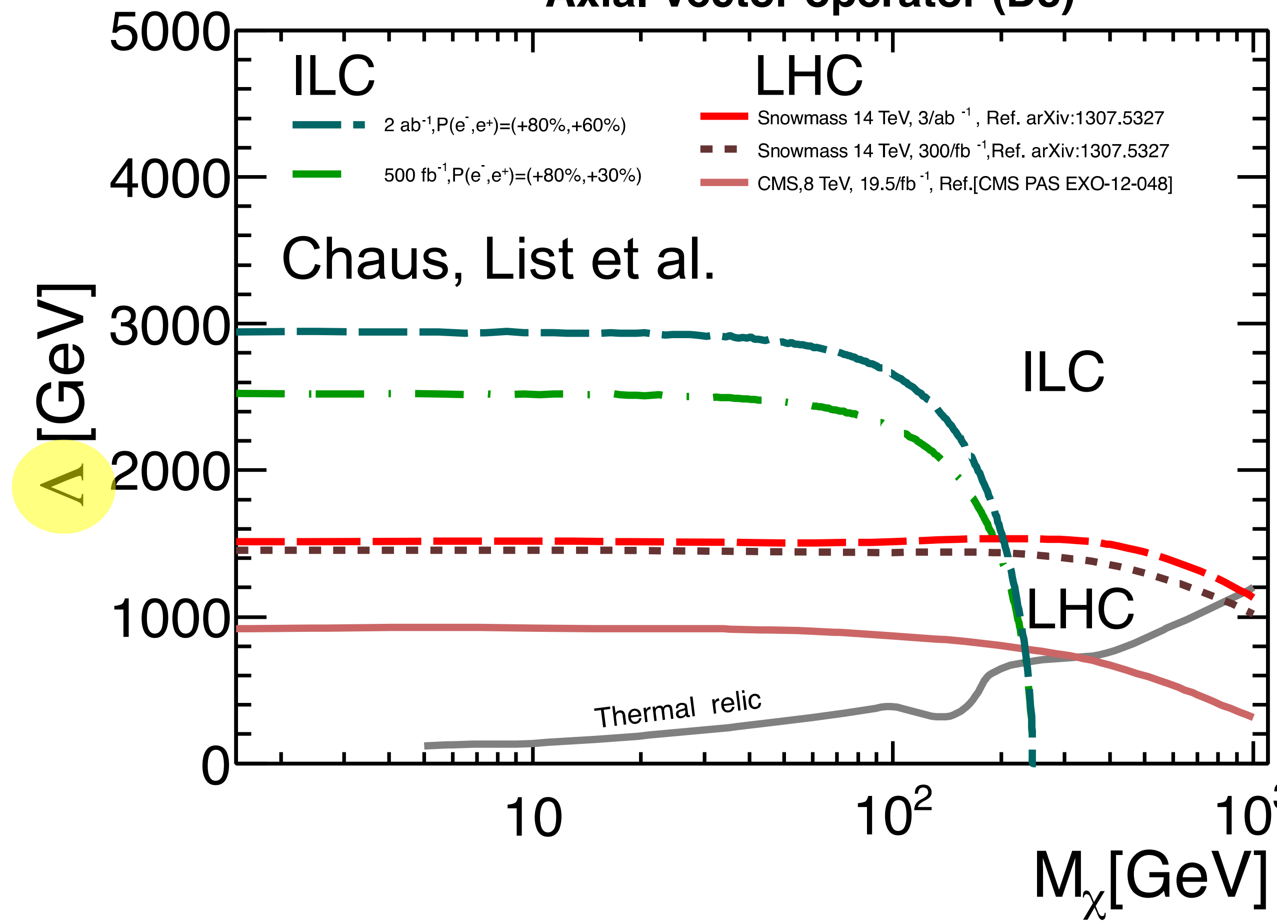
$$\mathcal{O}_V = (\bar{\chi}\gamma_\mu\chi)(\bar{\ell}\gamma^\mu\ell)$$

$$\mathcal{O}_A = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{\ell}\gamma^\mu\gamma^5\ell)$$

Vector operator (D5)



Axial-vector operator (D8)



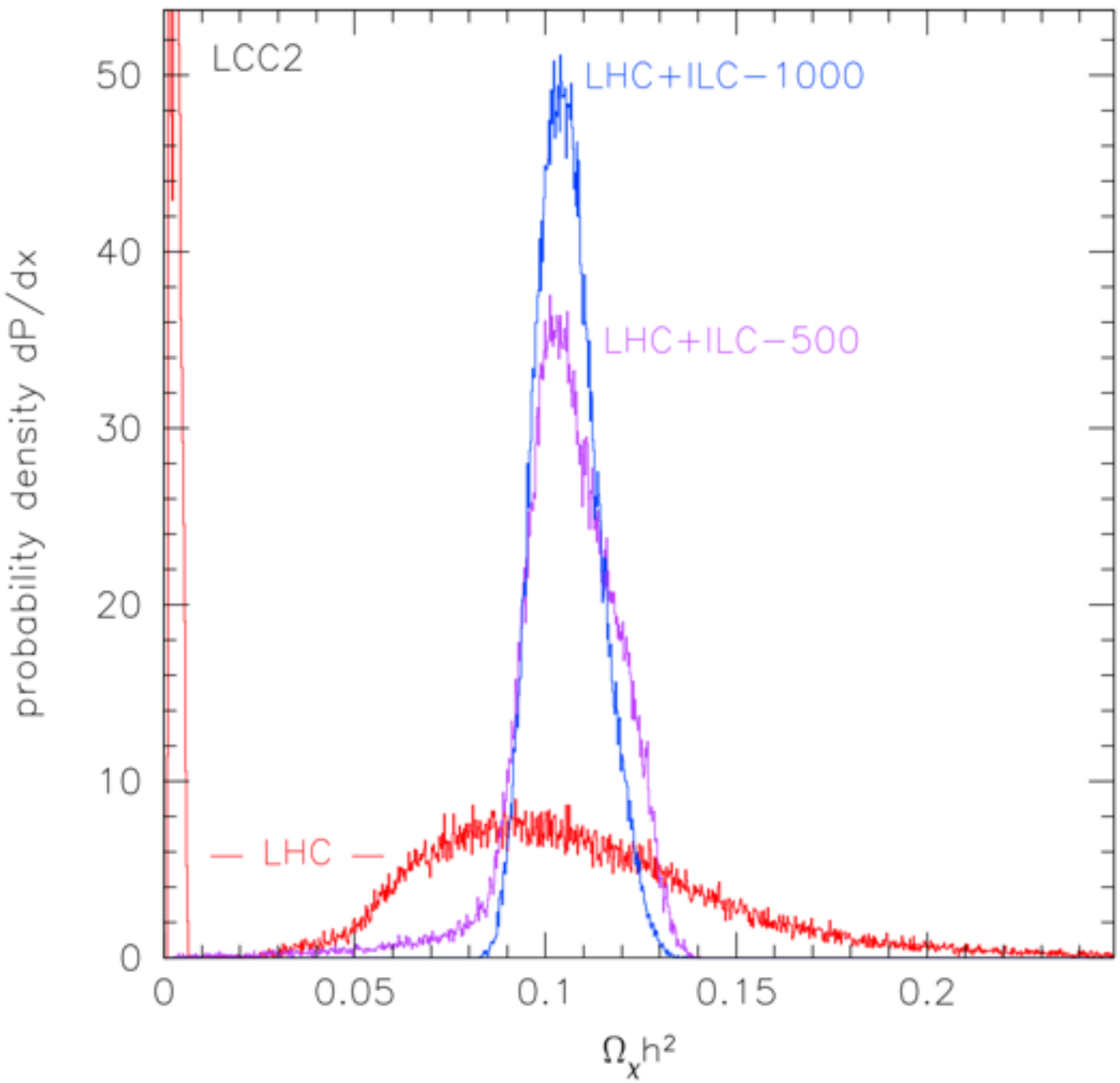
LHC sensitivity: Mediator mass up to Λ~1.5 TeV for large DM mass

ILC sensitivity: Mediator mass up to ***Λ~3 TeV*** for ***DM mass up to ~√s/2***

DM Relic Abundance

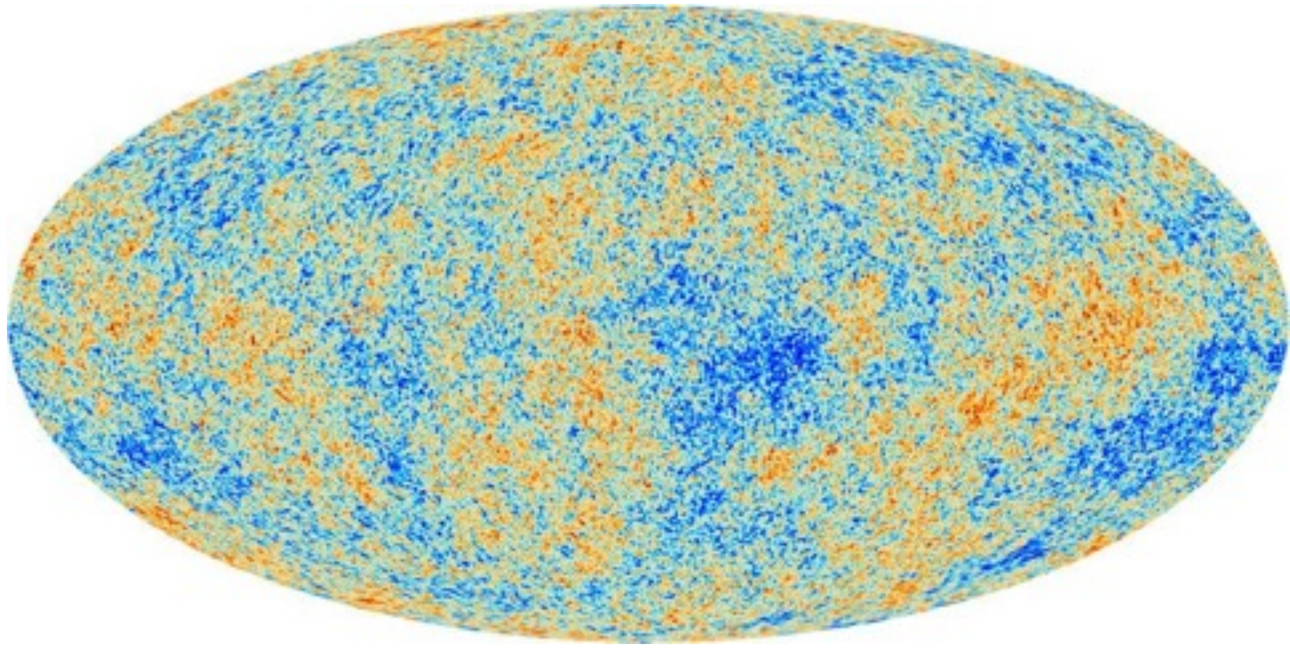
WMAP/Planck (68% CL)

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



Baltz, Battaglia, Peskin, Wizansky
PRD74 (2006) 103521, arXiv:hep-ph/0602187
**This particular benchmark point is excluded. Update is in progress.*

ESA/Planck



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

Mass and couplings measured at ILC
→ DM relic density

Backup

Higgs

Our Mission = Bottom-up Model-Independent Reconstruction of the EWSB Sector

through Precision Higgs Measurements

- **Multiplet structure :**
  - Additional singlet? $(\phi + S)$ + …?
  - Additional doublet? $(\phi + \phi')$ + …?
  - Additional triplet? $(\phi + \Delta)$ + …?
- **Underlying dynamics :**
  - ***Why did the Higgs condense in the vacuum?***
  - Weakly interacting or strongly interacting?
    = ***elementary or composite ?***
- **Relations to other questions of HEP :**
  - $\phi + S \rightarrow$ (B-L) gauge, DM, …
  - $\phi + \phi'$ → Type I : m_ν from small vev, …
    → Type II: SUSY, DM, …
    → Type X: m_ν (rad.seesaw), …
  - $\phi + \Delta \rightarrow m_\nu$ (Type II seesaw), …
  - $\lambda > \lambda_{SM} \rightarrow$ EW baryogenesis ?
  - $\lambda \downarrow 0 \rightarrow$ inflation ?

There are many possibilities!

Different models predict different deviation patterns --> Fingerprinting!

Model	μ	τ	b	c	t	g_V
Singlet mixing	↓	↓	↓	↓	↓	↓
2HDM-I	↓	↓	↓	↓	↓	↓
2HDM-II (SUSY)	↑	↑	↑	↓	↓	↓
2HDM-X (Lepton-specific)	↑	↑	↓	↓	↓	↓
2HDM-Y (Flipped)	↓	↓	↑	↓	↓	↓

Mixing with singlet

$$\frac{g_{hVV}}{g_{h_{SM}VV}} = \frac{g_{hff}}{g_{h_{SM}ff}} = \cos\theta \simeq 1 - \frac{\delta^2}{2}$$

Composite Higgs

$$\frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 3\%(1\ \mathrm{TeV}/f)^2$$

$$\frac{g_{hff}}{g_{h_{SM}ff}} \simeq \begin{cases} 1 - 3\%(1\ \mathrm{TeV}/f)^2 & \text{(MCHM4)} \\ 1 - 9\%(1\ \mathrm{TeV}/f)^2 & \text{(MCHM5)} \end{cases}$$

SUSY

$$\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \mathrm{TeV}}{m_A}\right)^2$$

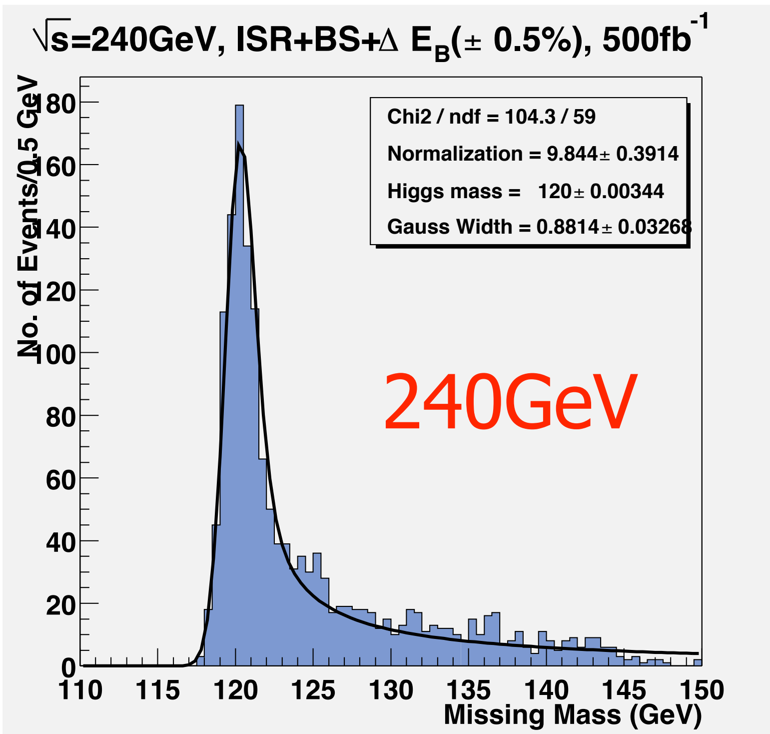
Expected deviations are small, typically a few % → ***We need a sub% precision!***

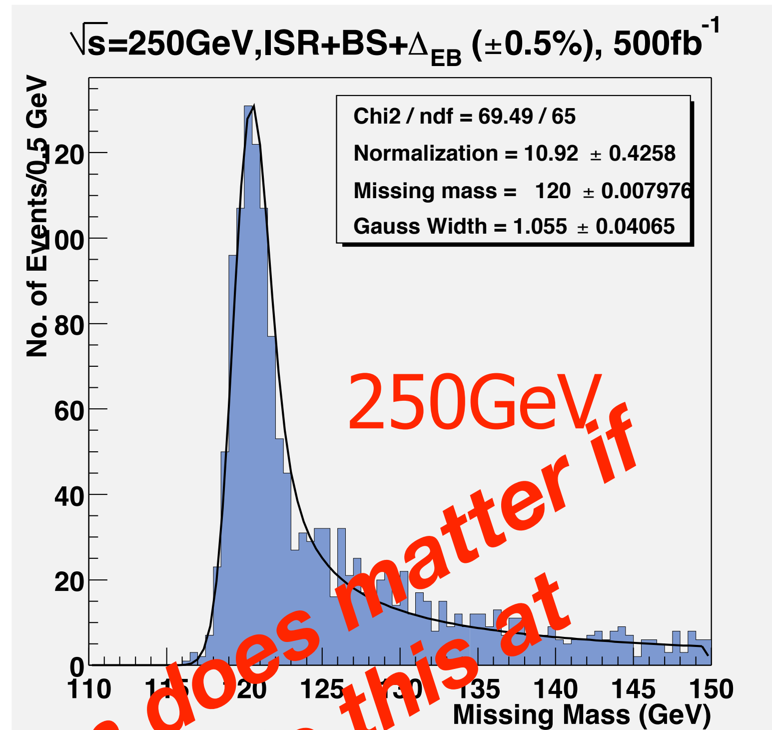
We need a LC to cover E_{cm}= 250 to 500 GeV!

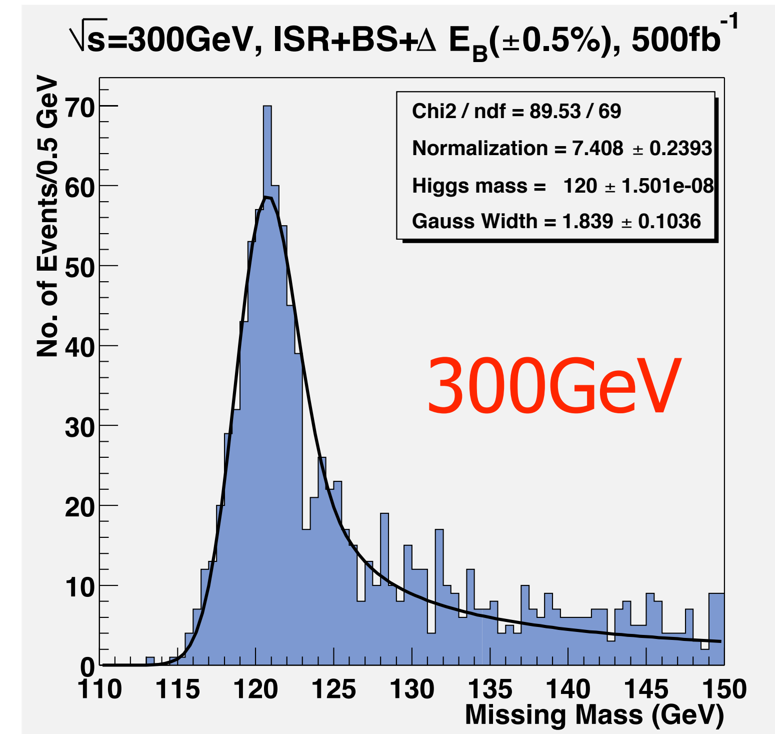
Recoil Mass Resolution

Estimation by simulation

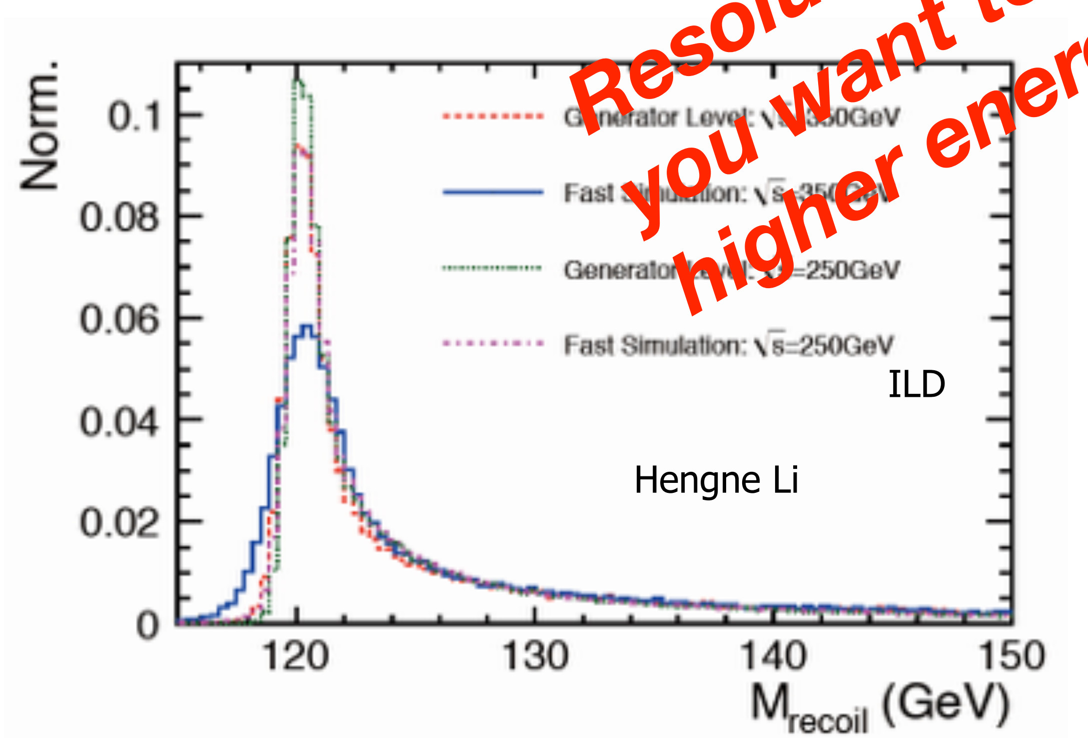
Old ACFA Study
by Akiya Miyamoto



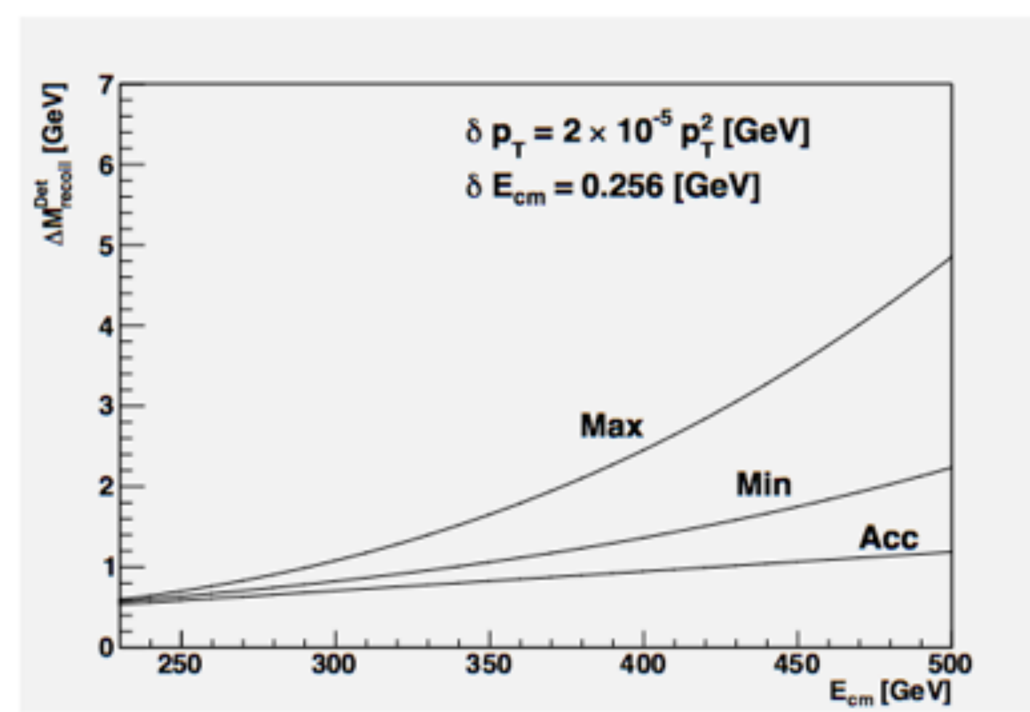




Resolution does matter if you want to do this at higher energy!



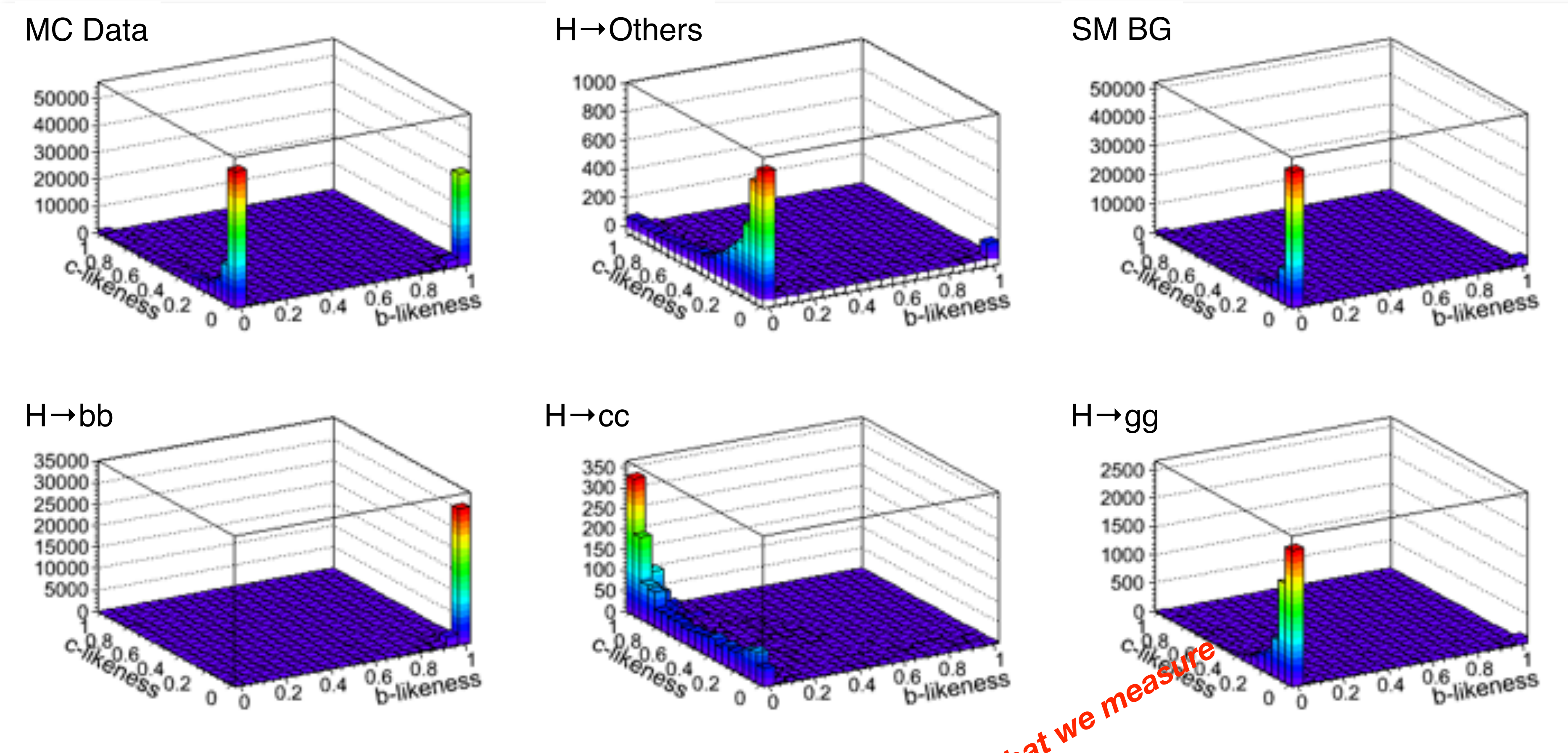
Rough analytic estimate



High Performance Flavor Tagging : The Key

*to directly access major couplings: bb, cc, ττ, gg, WW**

By template fitting, we can separate H →bb, cc, gg, others!



What we measure

What we measure here is not BR itself but σxBR.

$$BR = \boxed{(\sigma \times BR)}/\sigma$$

--> Δσ/σ=2.6% eventually limits the BR measurements.

--> luminosity upgrade and/or longer running in a later stage.

$$250\,\mathrm{fb}^{-1}@250\,\mathrm{GeV}$$
$$m_H = 125\,\mathrm{GeV}$$

scaled from mH=120 GeV

	@250GeV
process	ZH
Int. Lumi.	250
Δσ/σ	2.6%
decay mode	ΔσBr/σBr
H → bb	1.2%
H → cc	8.3%
H → gg	7%
H → WW*	6.4%
H → ττ	4.2%

DBD Physics Chap.

Clean environment and a high performance vertex detector are the two powerful weapons of the LC to directly access all of the major couplings (great advantage of the LC)

Total Width and Coupling Extraction

One of the major advantages of the LC

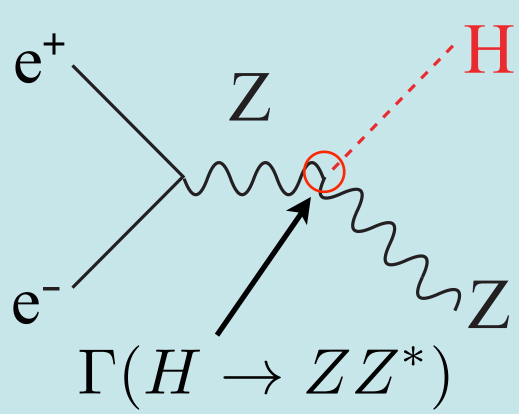
To extract couplings from BRs, we need the total width:

$$g^2_{HAA} \propto \Gamma(H \to AA) = \Gamma_H \cdot BR(H \to AA)$$

To determine the total width, we need at least one partial width and corresponding BR:

$$\Gamma_H = \Gamma(H \to AA)/BR(H \to AA)$$

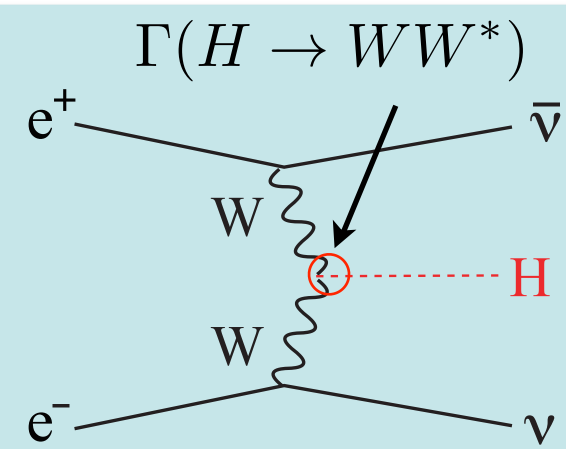
In principle, we can use A=Z, or W for which we can measure both the BRs and the couplings:



$BR(H \to ZZ^*)$

BR=O(1%): precision limited by low stat. for H->ZZ* events

$250\,\mathrm{fb}^{-1}$@$250\,\mathrm{GeV}$
$\Delta\Gamma_H/\Gamma_H \simeq 20\%$



$BR(H \to WW^*)$

More advantageous but not easy at low E

$250\,\mathrm{fb}^{-1}$@$250\,\mathrm{GeV}$
$\Delta\Gamma_H/\Gamma_H \simeq 11\%$

C.F.Durig, Helmholtz Alliance 6th WS, Dec. 2012

Independent Higgs Measurements at ILC

Baseline (=TDR) ILC program

250 GeV: 250 fb^{-1}
500 GeV: 500 fb^{-1}
1 TeV: 1000 fb^{-1}

(M_H = 125 GeV)

Ecm	250 GeV		500 GeV		1 TeV
luminosity [fb^{-1}]	250		500		1000
polarization (e^-,e^+)	(-0.8, +0.3)		(-0.8, +0.3)		(-0.8, +0.2)
process	ZH	ννH(fusion)	ZH	ννH(fusion)	ννH(fusion)
cross section	2.6%	-	3%	-	
	σ·Br	σ·Br	σ·Br	σ·Br	σ·Br
H→bb	1.2%	10.5%	1.8%	0.66%	0.32%
H→cc	8.3%		13%	6.2%	3.1%
H→gg	7%		11%	4.1%	2.3%
H→WW*	6.4%		9.2%	2.4%	1.6%
H→ττ	4.2%		5.4%	9%	3.1%
H→ZZ*	18%		25%	8.2%	4.1%
H→γγ	34%		34%	19%	7.4%
H→μμ	100%	-	-	-	31%
tth/H→bb	-		14% (6.1%@550GeV)		3.1%

Independent Higgs Measurements

Hypothetical HL-ILC

250 GeV: 250 fb^{-1}
500 GeV: 500 fb^{-1}
1 TeV: 1000 fb^{-1}

→

250 GeV: 1150 fb^{-1}
500 GeV: 1600 fb^{-1}
1 TeV: 2500 fb^{-1}

(M_H = 125 GeV)

Ecm	250 GeV		500 GeV		1 TeV
luminosity · fb	250		500		1000
polarization (e-,e+)	(-0.8, +0.3)		(-0.8, +0.3)		(-0.8, +0.2)
process	ZH	vvH(fusion)	ZH	vvH(fusion)	vvH(fusion)
cross section	1.2%	-	1.7%	-	
	σ·Br	σ·Br	σ·Br	σ·Br	σ·Br
H-->bb	0.56%	4.9%	1%	0.37%	0.3%
H-->cc	3.9%		7.2%	3.5%	2%
H-->gg	3.3%		6%	2.3%	1.4%
H-->WW*	3%		5.1%	1.3%	1%
H-->ττ	2%		3%	5%	2%
H-->ZZ*	8.4%		14%	4.6%	2.6%
H-->γγ	16%		19%	13%	5.4%
H-->μμ	46.6%	-	-	-	20%

What observables limit the coupling precisions?

The 4 most important ones

- ***Y_1: recoil mass***
- ***Y_2: WW-fusion h→bb***
- ***Y_3: higgsstrahlung h→bb***
- ***Y_4: WW-fusion h→WW****

$$Y_1 = \sigma_{ZH} \propto g^2_{HZZ}$$

$$Y_2 = \sigma_{\nu\bar{\nu}H} \cdot \mathrm{Br}(H \to b\bar{b}) \propto \frac{g^2_{HWW} g^2_{Hbb}}{\Gamma_H}$$

$$Y_3 = \sigma_{ZH} \cdot \mathrm{Br}(H \to b\bar{b}) \propto \frac{g^2_{HZZ} g^2_{Hbb}}{\Gamma_H}$$

$$Y_4 = \sigma_{\nu\bar{\nu}H} \cdot \mathrm{Br}(H \to WW^*) \propto \frac{g^4_{HWW}}{\Gamma_H}$$

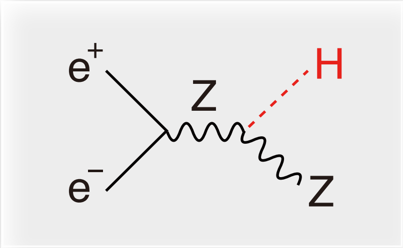
$$\Delta g_{HZZ} \sim \frac{1}{2}\Delta Y_1$$

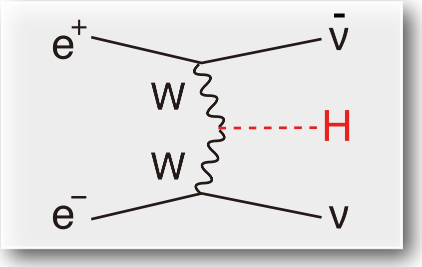
$$\Delta g_{HWW} \sim \frac{1}{2}\Delta Y_1 \oplus \frac{1}{2}\Delta Y_2 \oplus \frac{1}{2}\Delta Y_3$$

$$\Delta g_{Hbb} \sim \frac{1}{2}\Delta Y_1 \oplus \Delta Y_2 \oplus \frac{1}{2}\Delta Y_3 \oplus \frac{1}{2}\Delta Y_4$$

$$\Delta \Gamma_H \sim 2\Delta Y_1 \oplus 2\Delta Y_2 \oplus 2\Delta Y_3 \oplus \Delta Y_4$$

Both ZH and vvH productions matter!





For more details, see J.Tian @ Tokusui Workshop 2013

Model-independent Global Fit for Couplings

Luminosity Upgraded LC

(M_H = 125 GeV)

250 GeV: 250 fb^{-1}
500 GeV: 500 fb^{-1}
1 TeV: 1000 fb^{-1}

→

250 GeV: 1150 fb^{-1}
500 GeV: 1600 fb^{-1}
1 TeV: 2500 fb^{-1}

P(e-,e+)=(-0.8,+0.3) @ 250, 500 GeV   P(e-,e+)=(-0.8,+0.2) @ 1 TeV

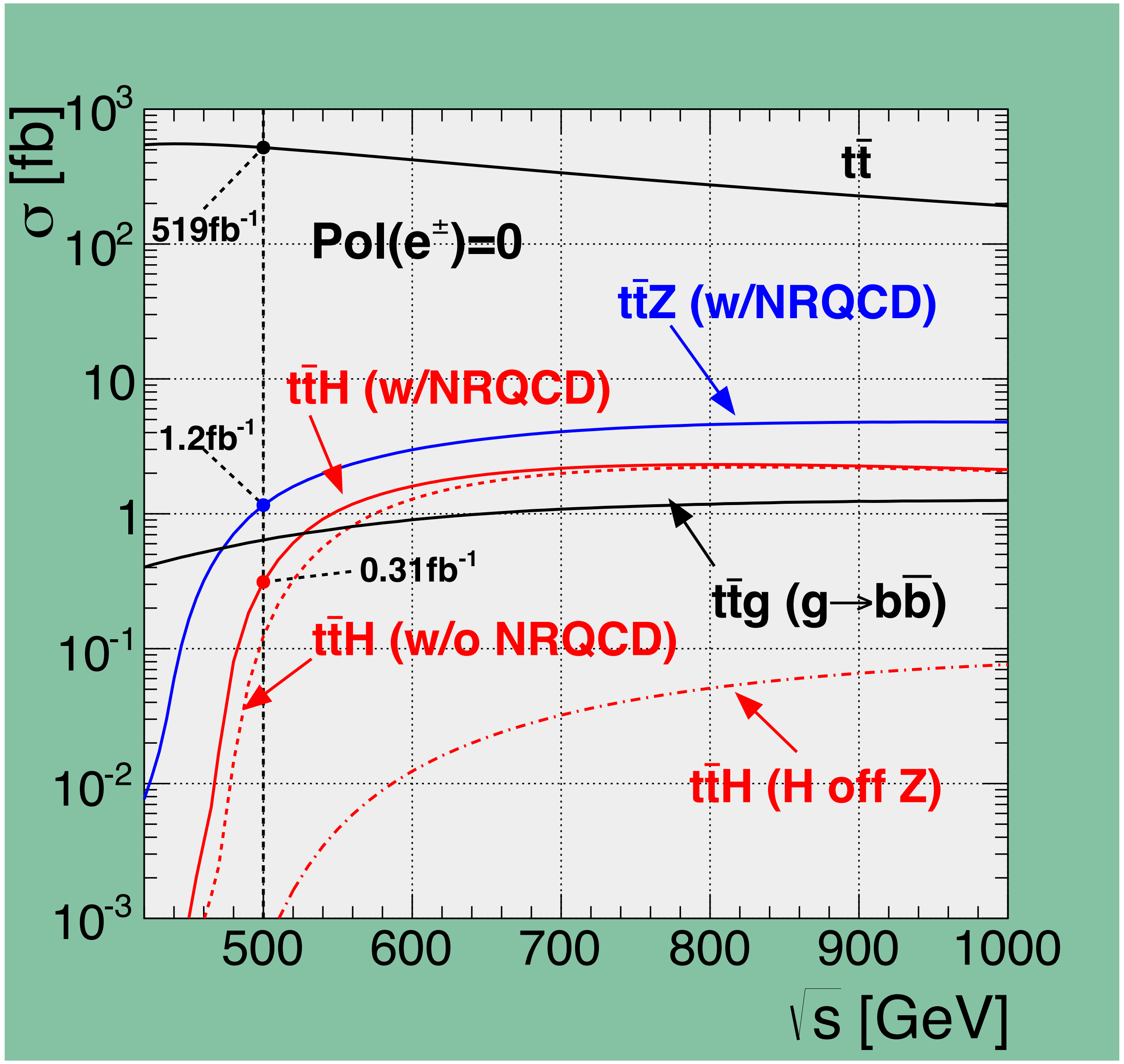
coupling	250 GeV	250 GeV + 500 GeV	250 GeV + 500 GeV + 1 TeV
HZZ	0.6%	0.5%	0.5%
HWW	2.3%	0.6%	0.6%
Hbb	2.5%	0.8%	0.7%
Hcc	3.2%	1.5%	1%
Hgg	3%	1.2%	0.93%
Hττ	2.7%	1.2%	0.9%
Hγγ	8.2%	4.5%	2.4%
Hμμ	42%	42%	10%
Γ_0	5.4%	2.5%	2.3%
Htt	-	7.8%	1.9%

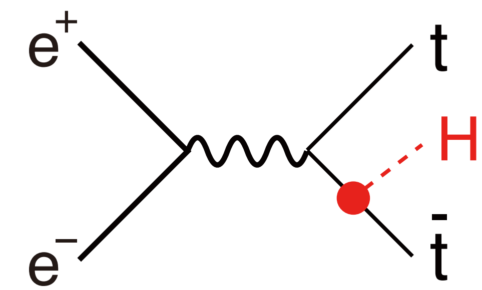
HHH	-	46%(*)	13%(*)

) With H->WW (preliminary), if we include expected improvements in jet clustering, it would become 10%!

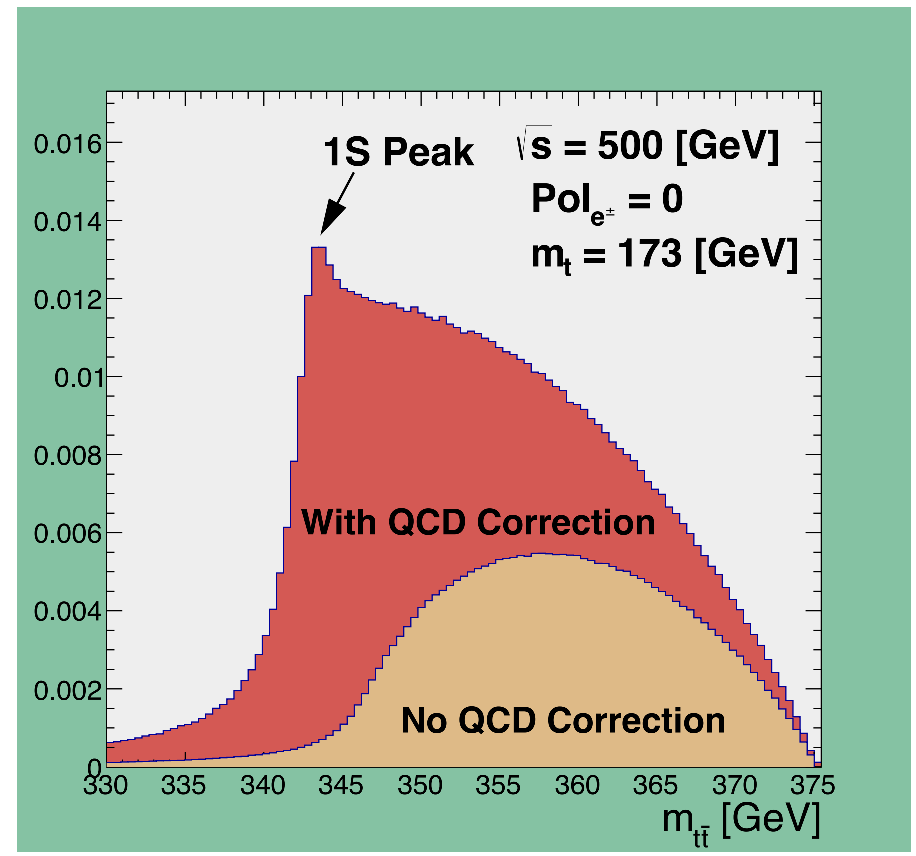
Top Yukawa Coupling

The largest among matter fermions, but not yet directly observed





H-> bb



A factor of 2 enhancement from QCD bound-state effects

Cross section maximum at around Ecm = 800GeV

Philipp Roloff, LCWS12

Tony Price, LCWS12

DBD Full Simulation

$$1\,\mathrm{ab}^{-1}@500\,\mathrm{GeV} \qquad m_H = 125\,\mathrm{GeV}$$

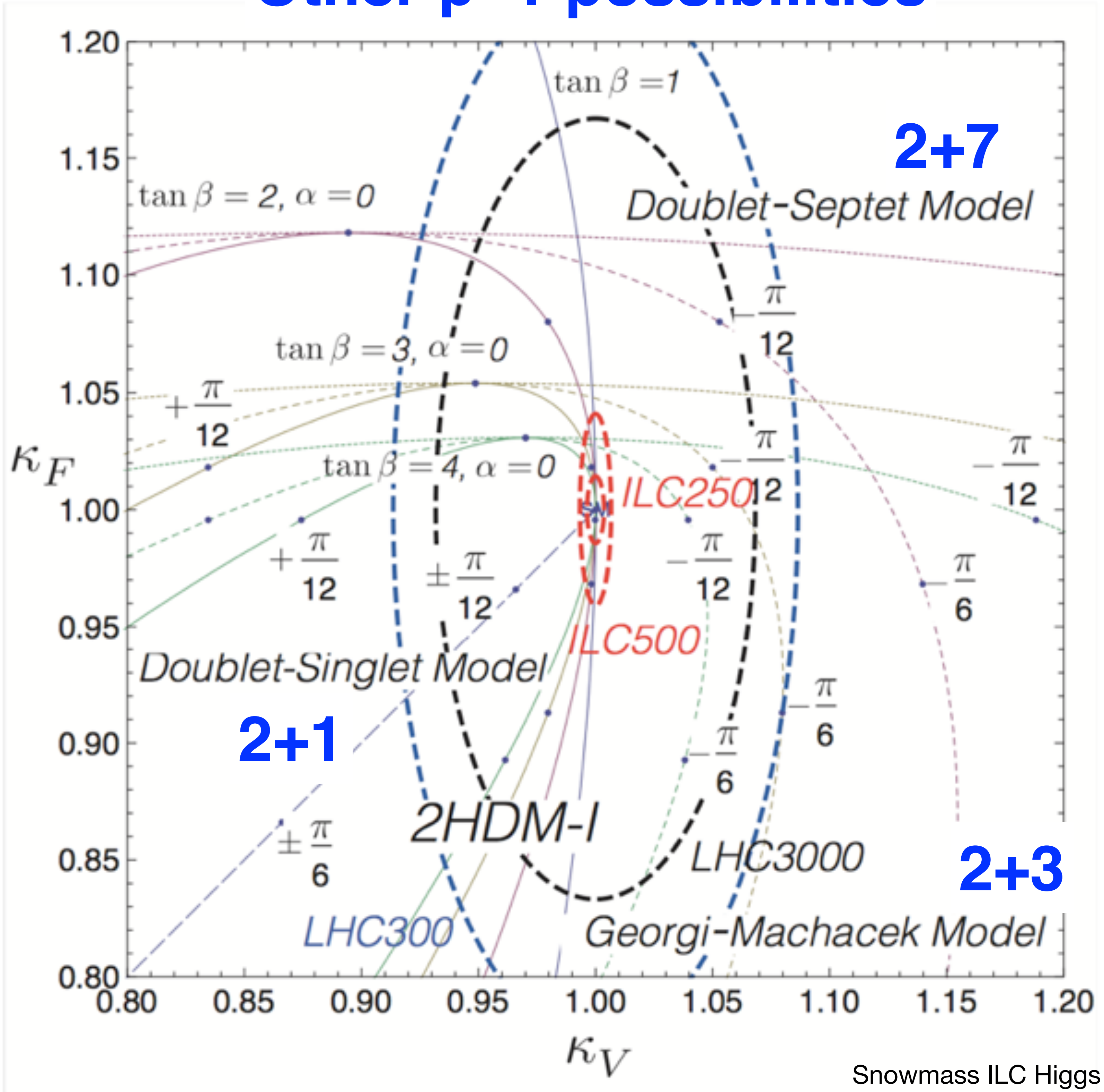
$$\Delta g_Y(t)/g_Y(t) = 9.9\%$$

Tony Price, LCWS12 scaled from mH=120 GeV

Notice σ(500+20GeV)/σ(500GeV) ~ 2
Moving up a little bit helps significantly!

Multiplet Structure

Other ρ=1 possibilities



Snowmass ILC Higgs White Paper (arXiv: 1310.0763)
Kanemura et al (arXiv: 1406.3294)

Figure 1.18. The scaling factors in models with universal Yukawa coupling constants.

SUSY

Slepton decays to DM with small mass differences

Study of stau pair production at the ILC

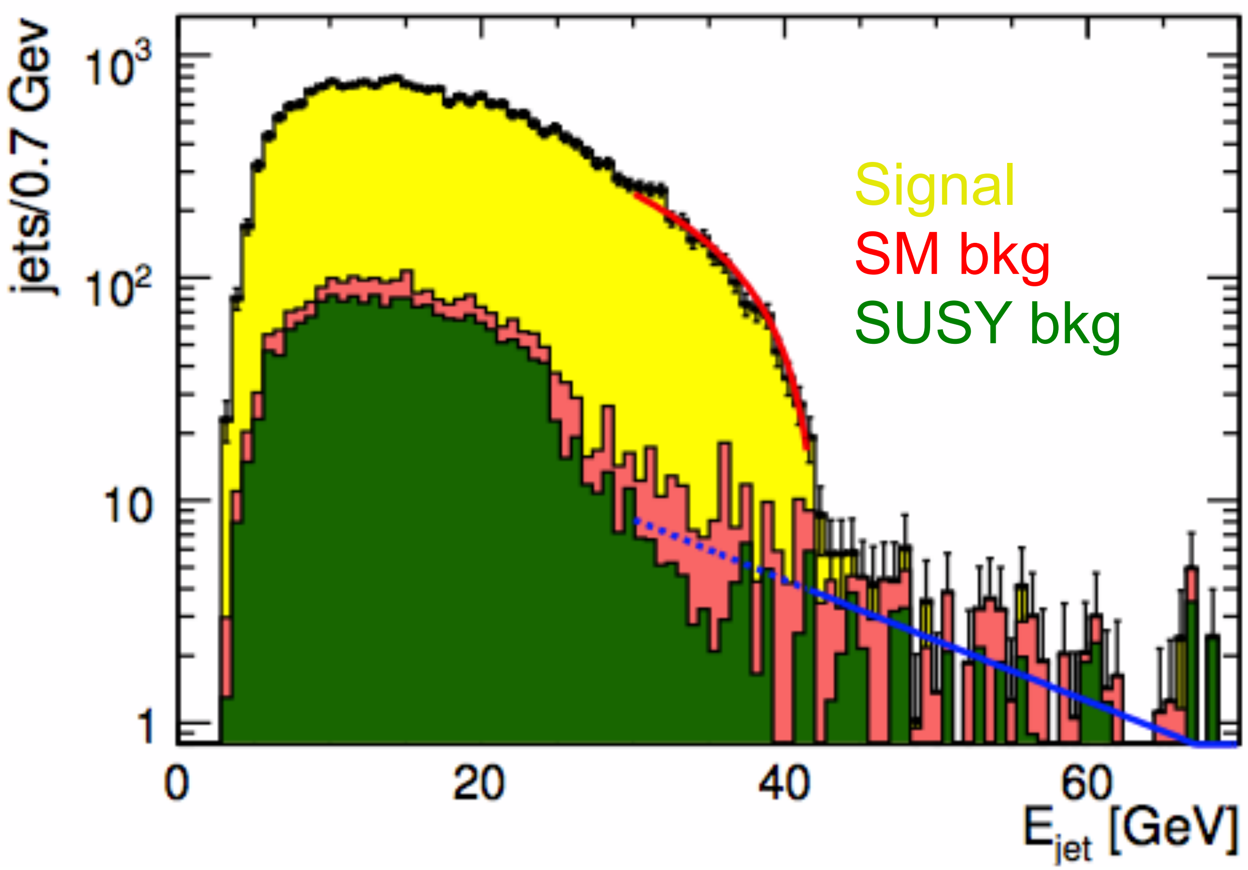
Observation of lighter and heavier stau states with decay to DM + hadronic tau

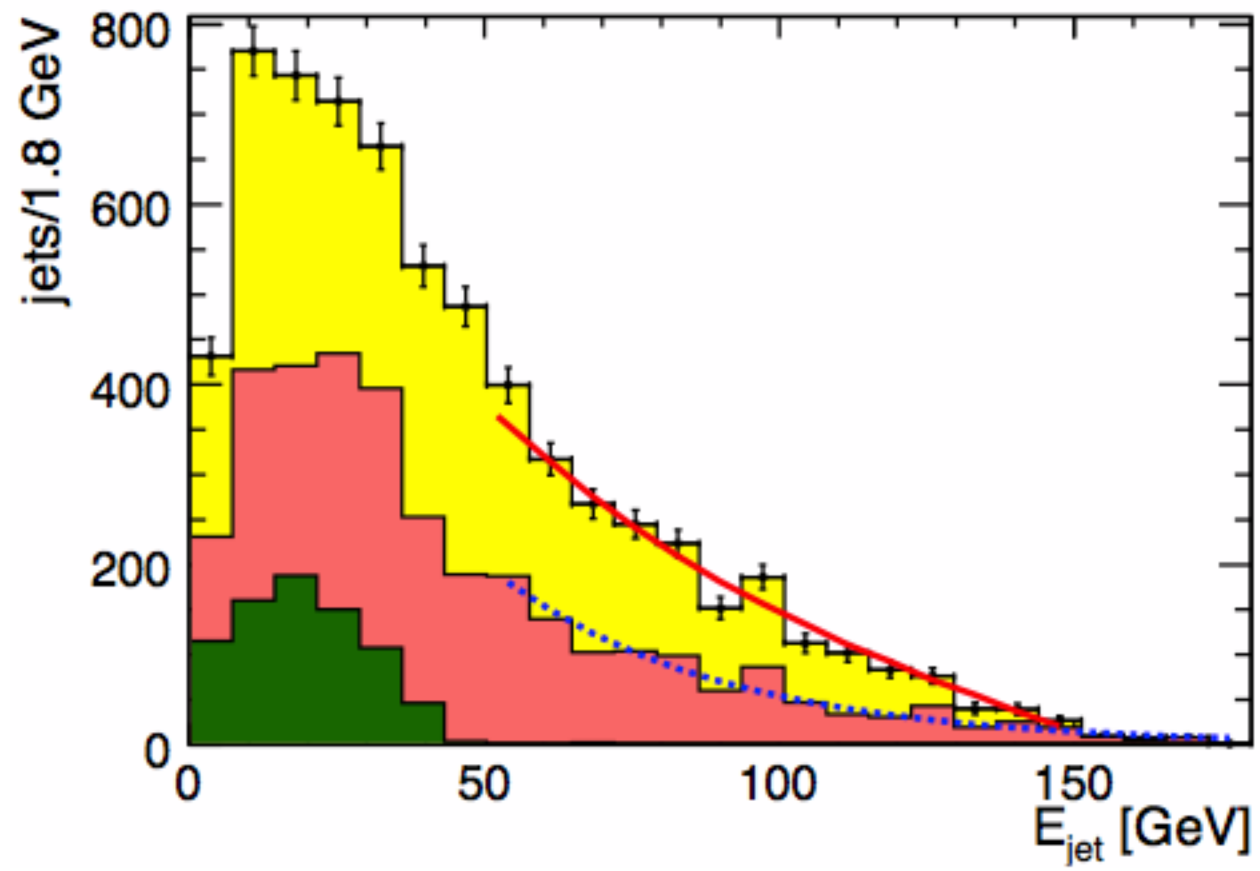
Benchmark point: m(LSP) = 98 GeV, m(stau1) = 108 GeV, m(stau2) = 195 GeV

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

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

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

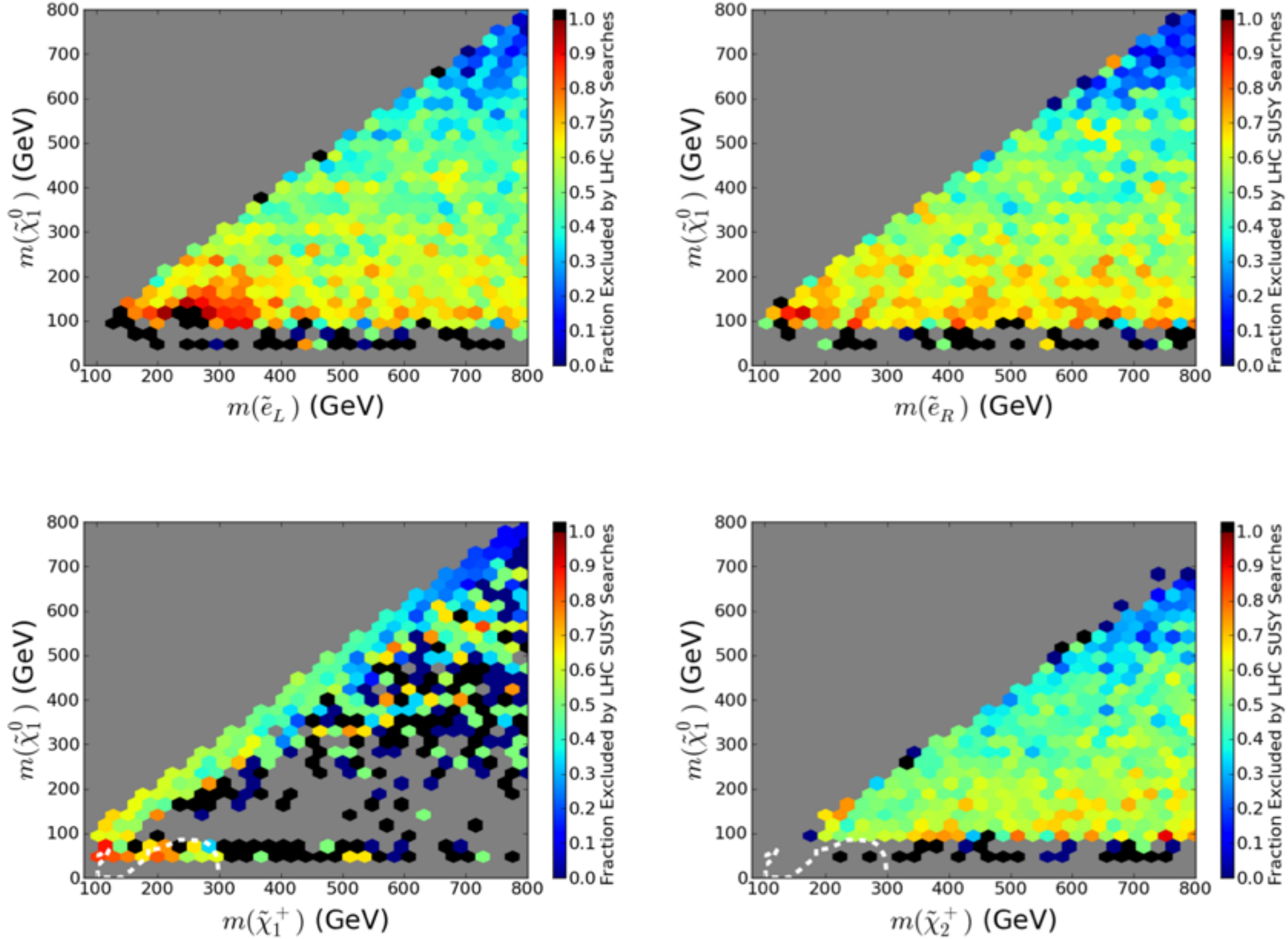




√s=500 GeV, Lumi=500 fb-1, P(e-,e+)=(+0.8,-0.3)

Stau1 mass ~0.1%, Stau2 mass ~3% → LSP mass ~1.7%

pMSSM Scan



arXiv:1407.4130

LHC constraint + no over-closing the universe

$$\text{Scalar (S):}\quad \mathscr{L} = \frac{G_S}{\sqrt{2}}\bar{\chi}\chi\bar{f}f$$

$$\text{Pseudoscalar (P):}\quad \mathscr{L} = \frac{G_P}{\sqrt{2}}\bar{\chi}\gamma^5\chi\bar{f}\gamma_5 f$$

$$\text{Vector (V):}\quad \mathscr{L} = \frac{G_V}{\sqrt{2}}\bar{\chi}\gamma^\mu\chi\bar{f}\gamma_\mu f$$

$$\text{Axial Vector (A):}\quad \mathscr{L} = \frac{G_A}{\sqrt{2}}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{f}\gamma_\mu\gamma_5 f$$

$$\text{Tensor (T):}\quad \mathscr{L} = \frac{G_T}{\sqrt{2}}\bar{\chi}\sigma^{\mu\nu}\chi\bar{f}\sigma_{\mu\nu} f.$$

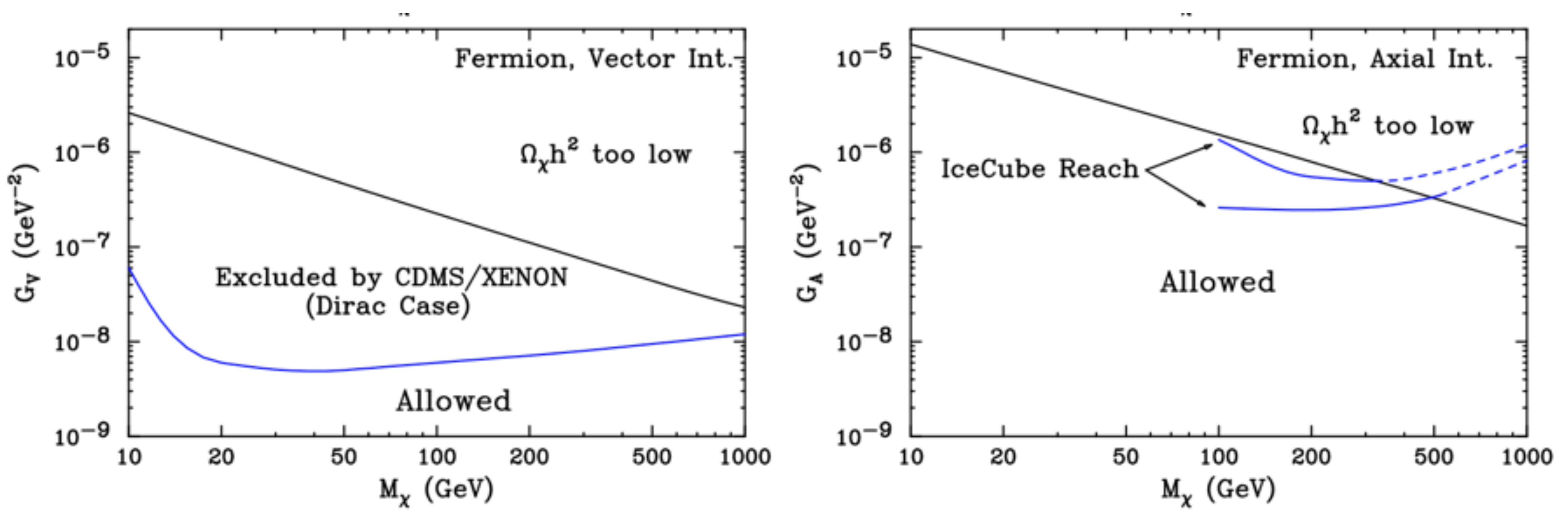


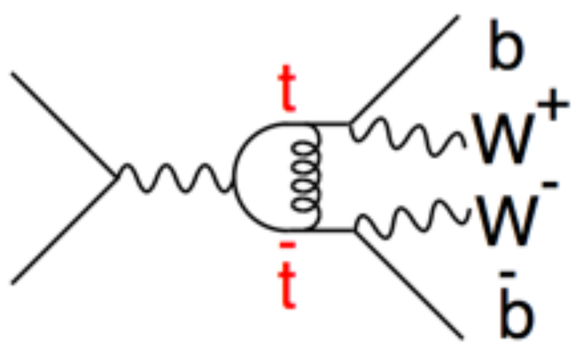
FIG. 4: A summary of the constraints on a fermionic WIMP with scalar, pseudoscalar, vector, and axial interactions, including regions excluded and allowed by direct and indirect detection experiments (note that WIMPs with pseudoscalar and axial interactions are unconstrained by direct detection experiments). If resonances, coannihilations, or annihilations to final states other than fermion-antifermion pairs are significant, smaller couplings than those shown here can lead to the measured relic abundance. See the text for more details.

Top

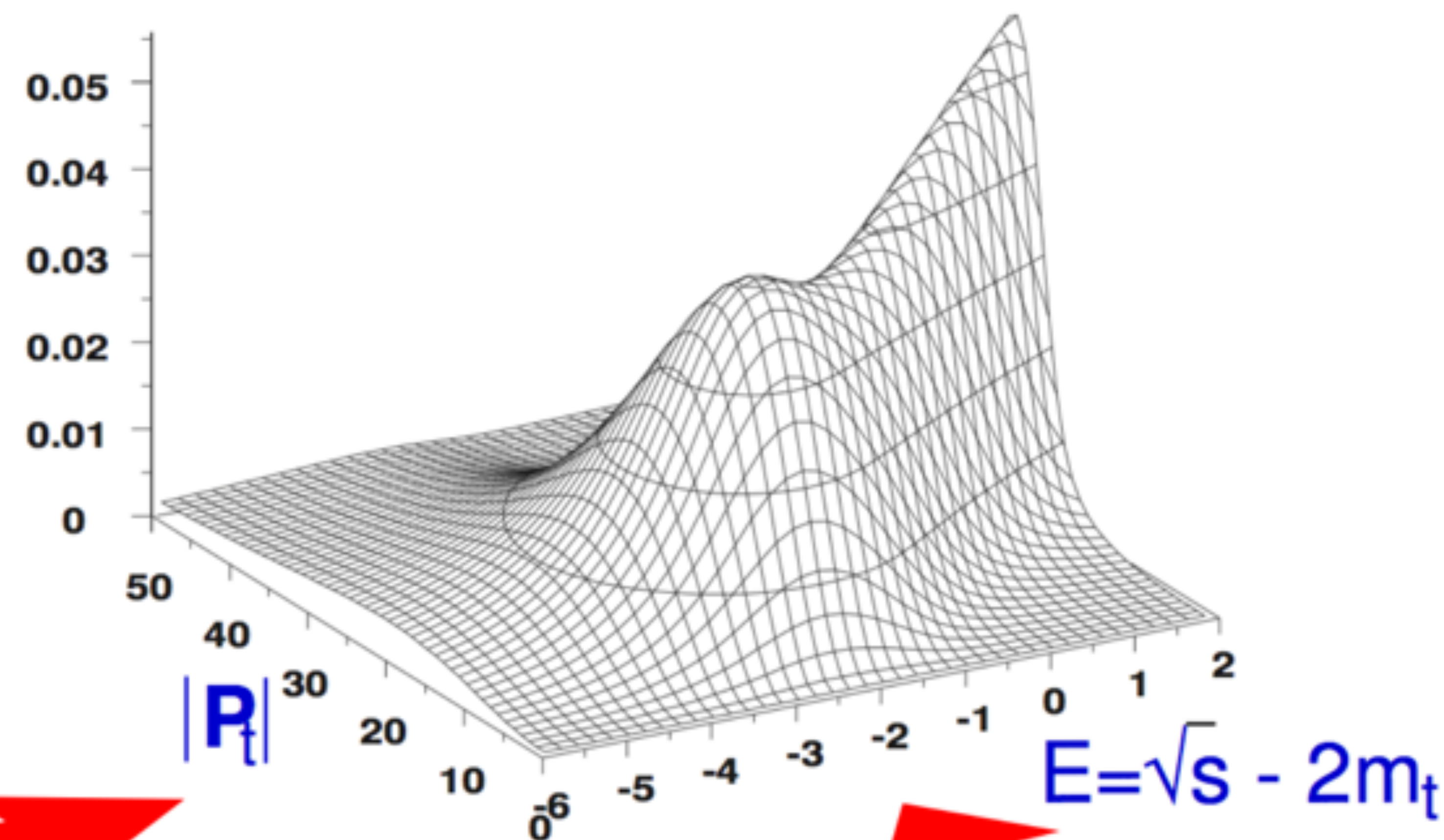
Top Quark

Threshold Region

How to access G experimentally



$p_{top} = p_{bW} = p_{3jets}$



Momentum Dist.

$$\frac{d\sigma_{t\bar{t}}}{d\,|\boldsymbol{p}|} \propto \left|\langle \boldsymbol{p}\,|\,G\,|\,\boldsymbol{x}=\boldsymbol{0}\,\rangle\right|^2 \simeq \left|\sum_n \frac{\phi_n(\boldsymbol{p})\Psi_n^*(\boldsymbol{0})}{E-E_n+i\Gamma_n/2}\right|^2$$

momentum space wave fun.

Threshold Scan

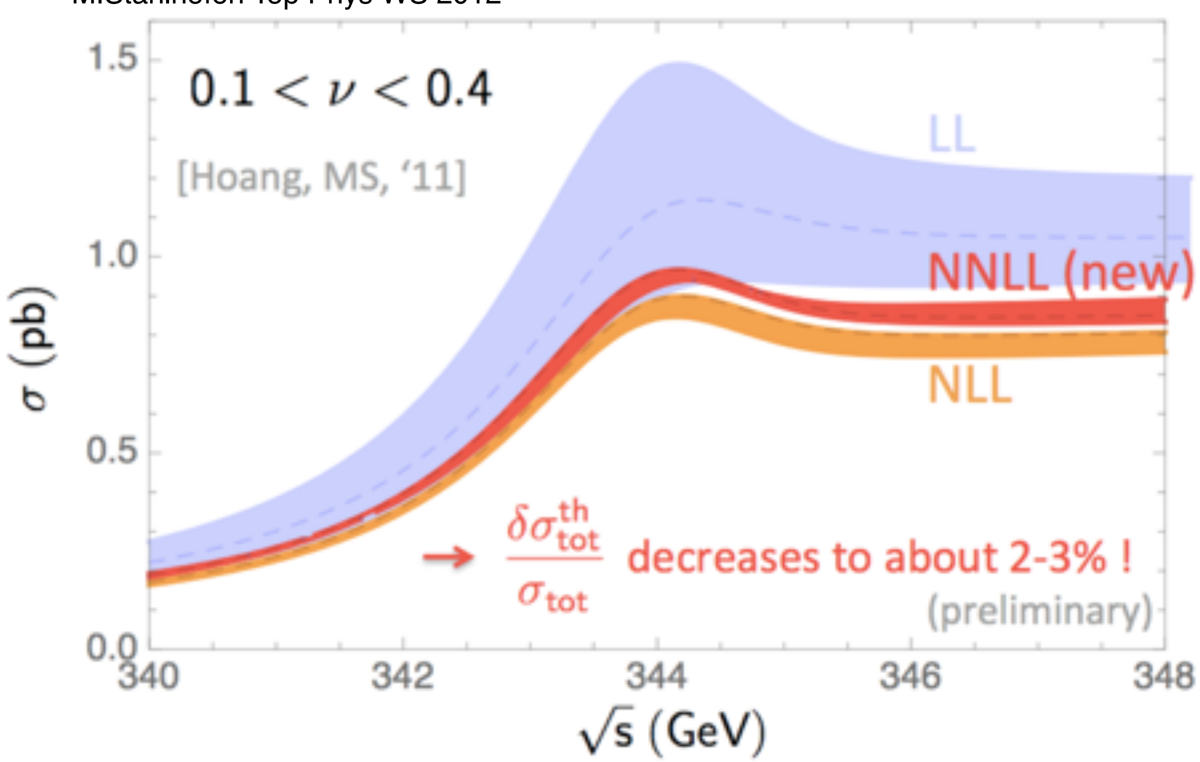
$$\sigma_{t\bar{t}} \propto Im\,\langle\,\boldsymbol{x}=\boldsymbol{0}\,|\,G\,|\,\boldsymbol{x}=\boldsymbol{0}\,\rangle \simeq Im\sum_n \frac{|\Psi_n(\boldsymbol{0})|^2}{E-E_n+i\Gamma_n/2}$$

wave function at origin

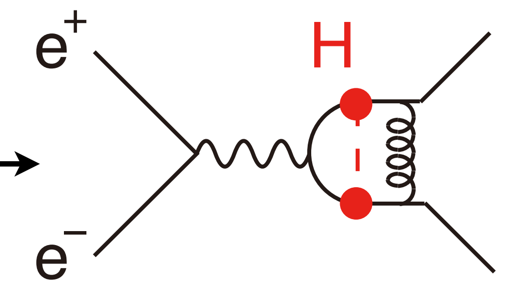
Top at Threshold

Threshold Scan

M.Stahlhofen Top Phys WS 2012



Theory improving! →

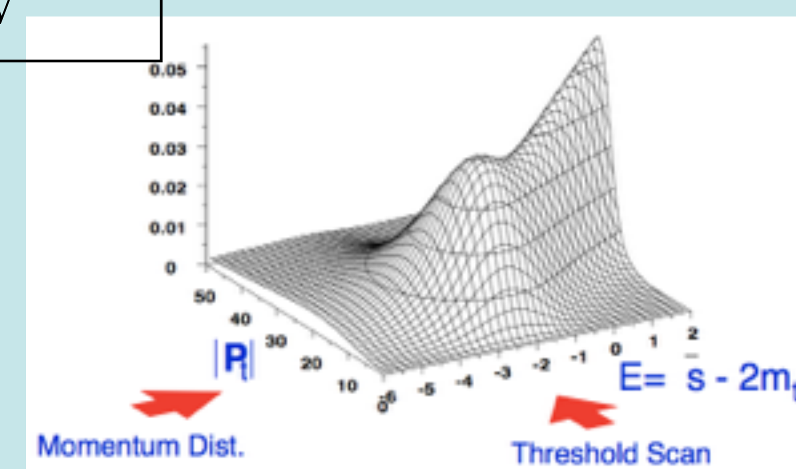


~10% effect

Expected accuracies

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

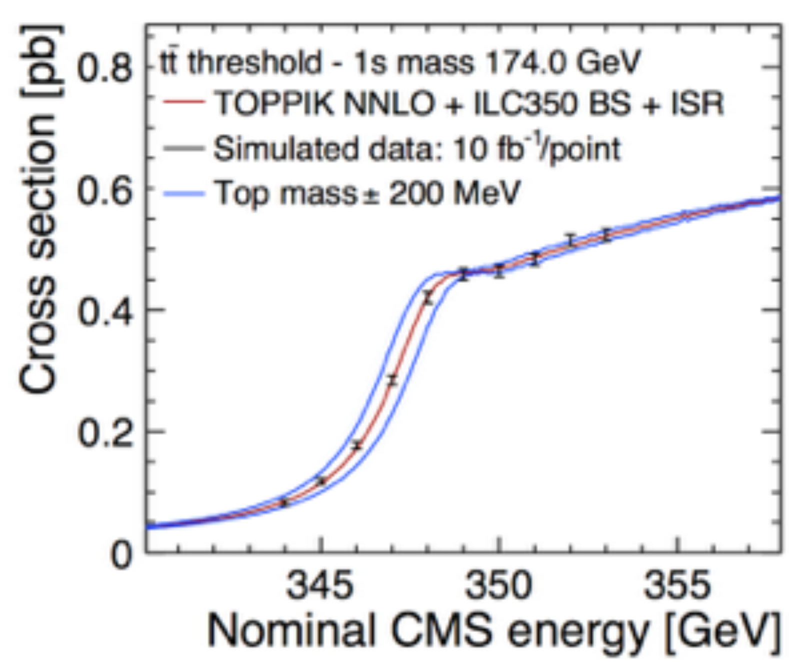
Threshold scan alone



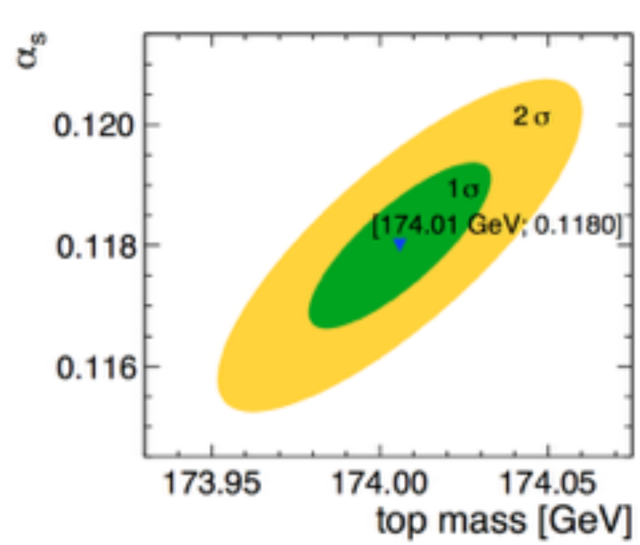
+ A_{FB} & Top Momentum

$$\Delta m_t = 19\,\mathrm{MeV}$$
$$\Delta\alpha_s(m_Z) = 0.0012$$
$$\Delta\Gamma_t = 32\,\mathrm{MeV}$$

arXiv:hep-ph/0601112v2



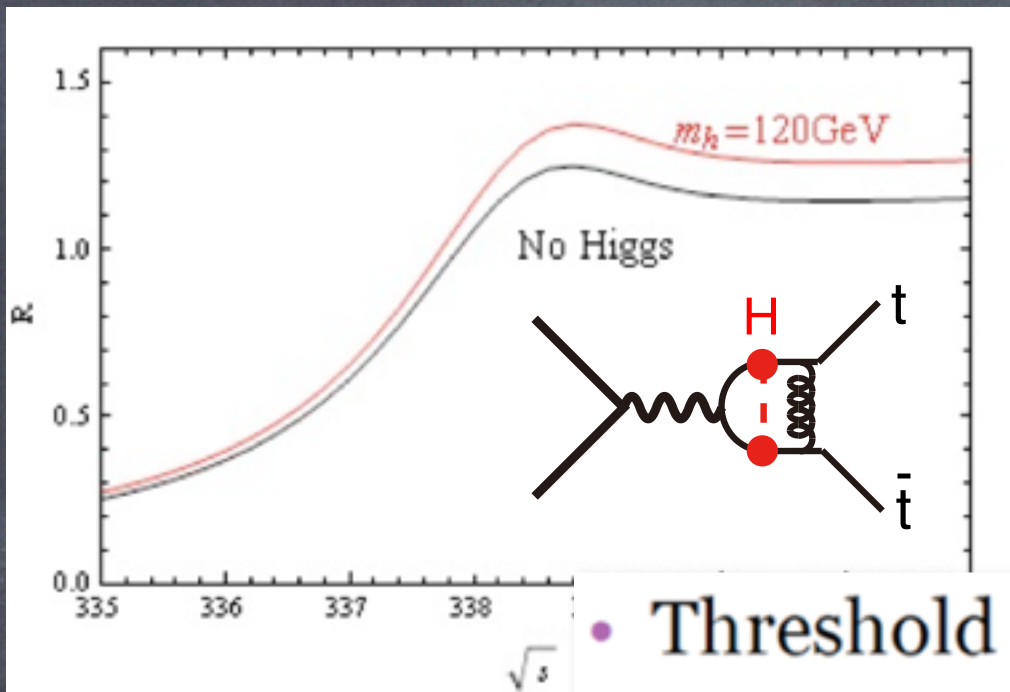
F.Simon Top Phys WS 2012



$$\Delta m_t(\overline{MS}) \simeq 100\,\mathrm{MeV}$$

arXiv:hep-ph/1502.01030: Quark mass relation to 4-loop order -> <50MeV

Reducing Theoretical Ambiguities



9% effect on the X-section

Normalization ambiguity due to the QCD enhancement has been an obstacle to do this measurement

Yuichiro Kiyo
@ LCWS10

Use of the RG improved potential can significantly improve the situation!

Still preliminary but prospect is bright!

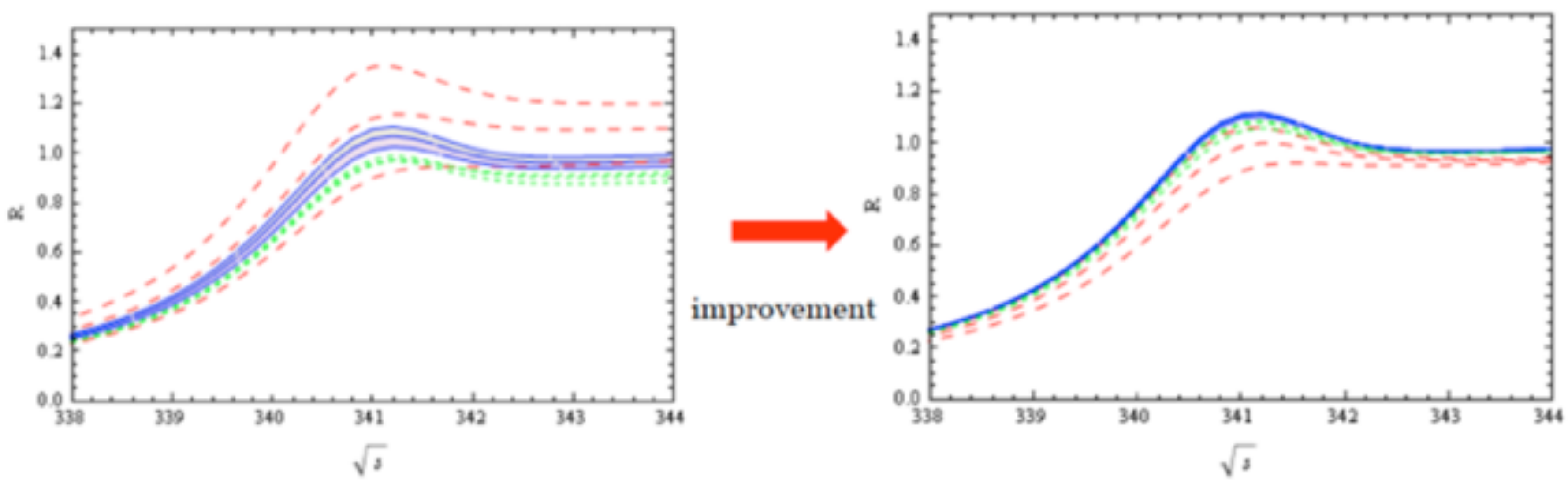
- Threshold enhancement is due to Coulomb resummation

⬇

RG improved potential to reach high accuracy

- Below RG improvement is applied to QCD static potential.

(In the plots below we neglected other corrections as a first study)



$M_{t,PS}$ =170GeV, LO(Red)/NLO(Green)/NNLO(Blue) for μ=20, 30, 40GeV

Top Quark

Open Top Region

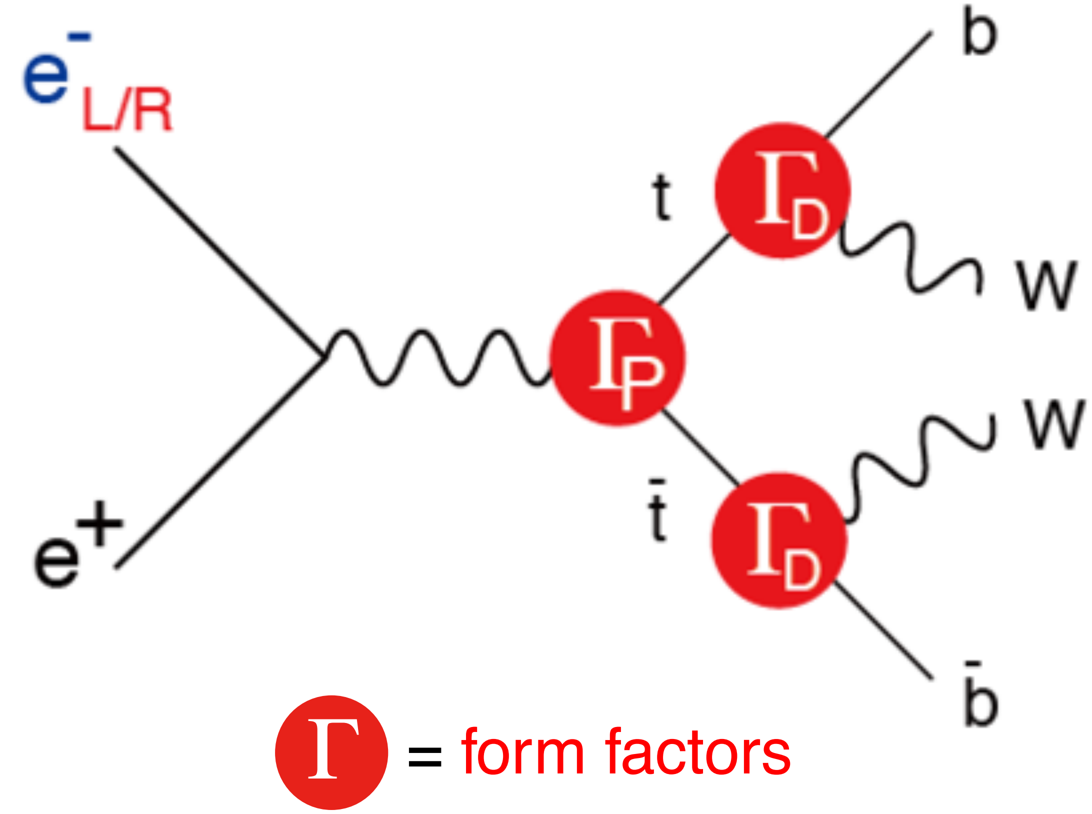
Key points

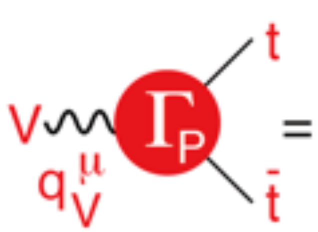
$\Gamma_t \approx 1.4$ GeV for $m_t = 175$ GeV

The top decays before forming a top hadron.

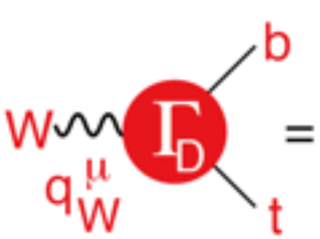
Top spin is measurable by angular analysis of decay products.

+ Polarized beams are available at ILC





$$= \mathcal{L}_{\text{int}}^{ttV} = g_W \left[V_\mu \bar{t} \gamma^\mu \left(F_{1L}^V P_L + F_{1R}^V P_R \right) t - \frac{1}{v} (\partial_\nu V_\mu) \bar{t} \sigma^{\mu\nu} \left(F_{2L}^V P_L + F_{2R}^V P_R \right) t \right] + \text{h.c.}$$



$$= \mathcal{L}_{\text{int}}^{tbW} = \frac{g_W}{\sqrt{2}} \left[W_\mu^- \bar{b} \gamma^\mu \left(F_{1L}^W P_L + F_{1R}^W P_R \right) t - \frac{1}{v} (\partial_\nu W_\mu^-) \bar{b} \sigma^{\mu\nu} \left(F_{2L}^W P_L + F_{2R}^W P_R \right) t \right] + \text{h.c.}$$

Other Probes

Z’

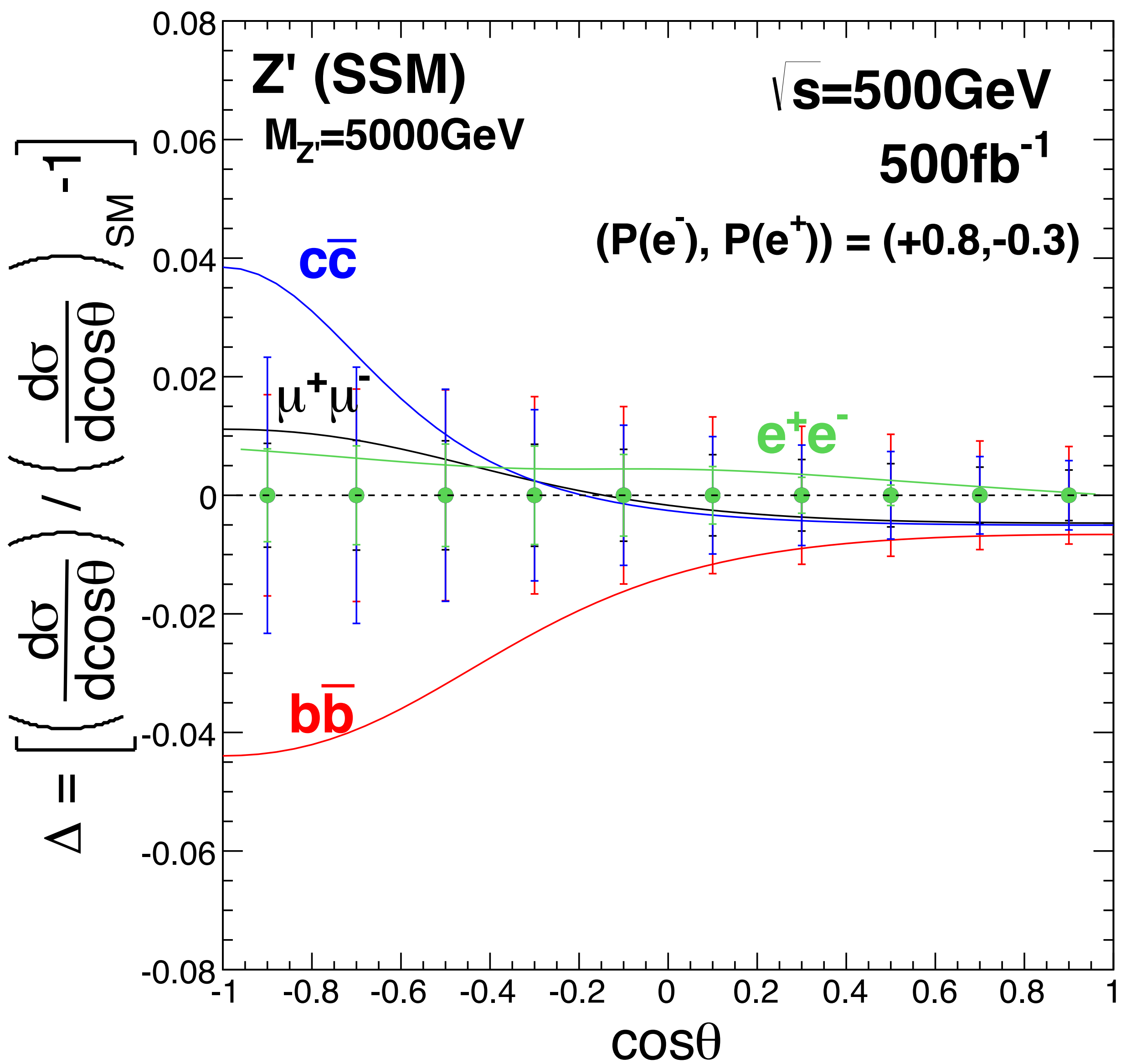
Two-Fermion Processes

Z' Search / Study

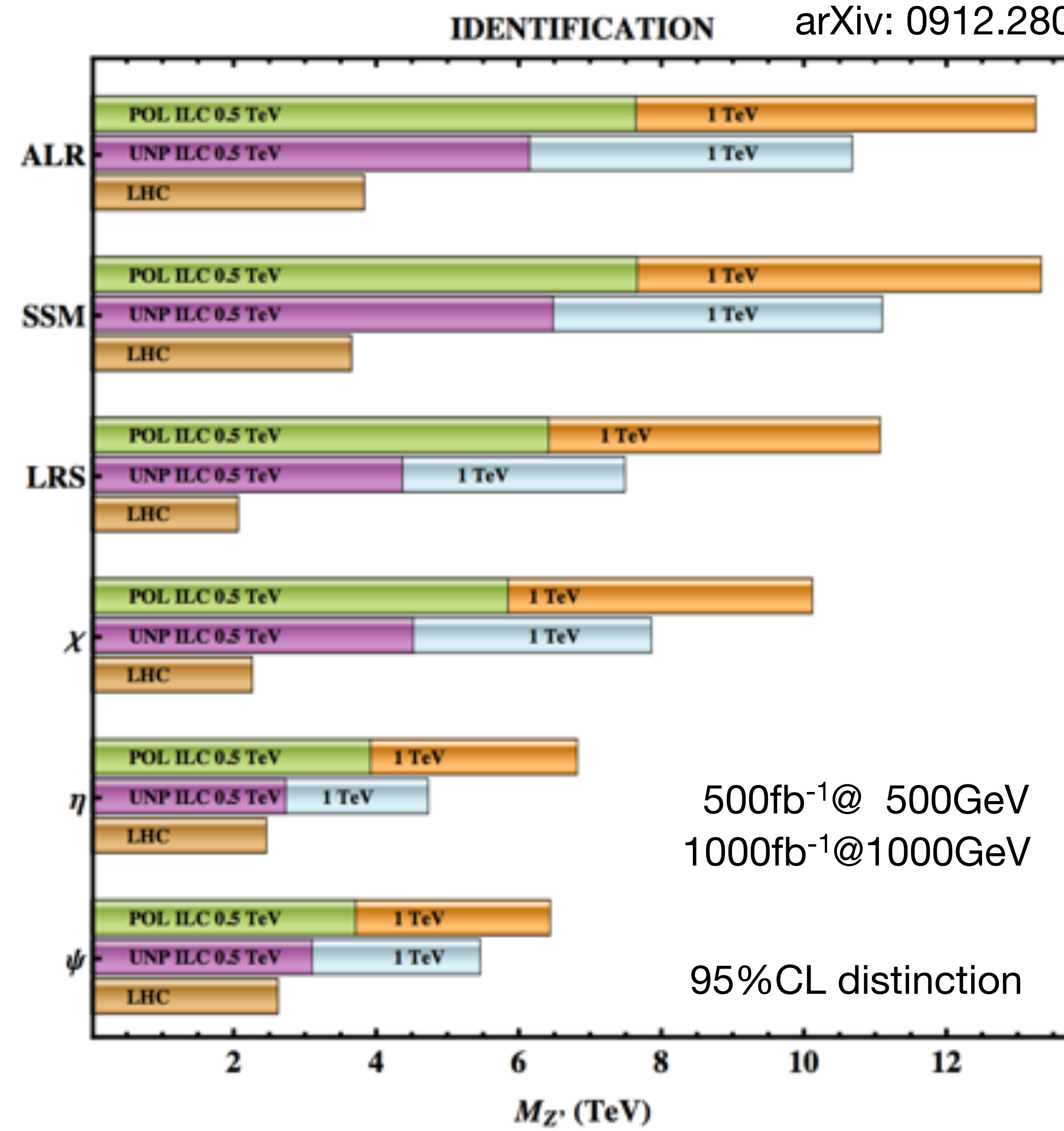
Observables: dσ(P-,P+)/d cosθ

$$\chi^2 = \sum_f \sum_{P-,P+} \sum_{i\in \mathrm{bins}} \frac{|n_i(SM+Z') - n_i(SM)|^2}{\Delta n_i} \qquad (f=e,\mu,\tau,c,b)$$

Example: Sequential SM-like Z'



arXiv: 0912.2806



Two-Fermion Processes

Z' Search / Study

arXiv:0912.2806 [hep-ph]

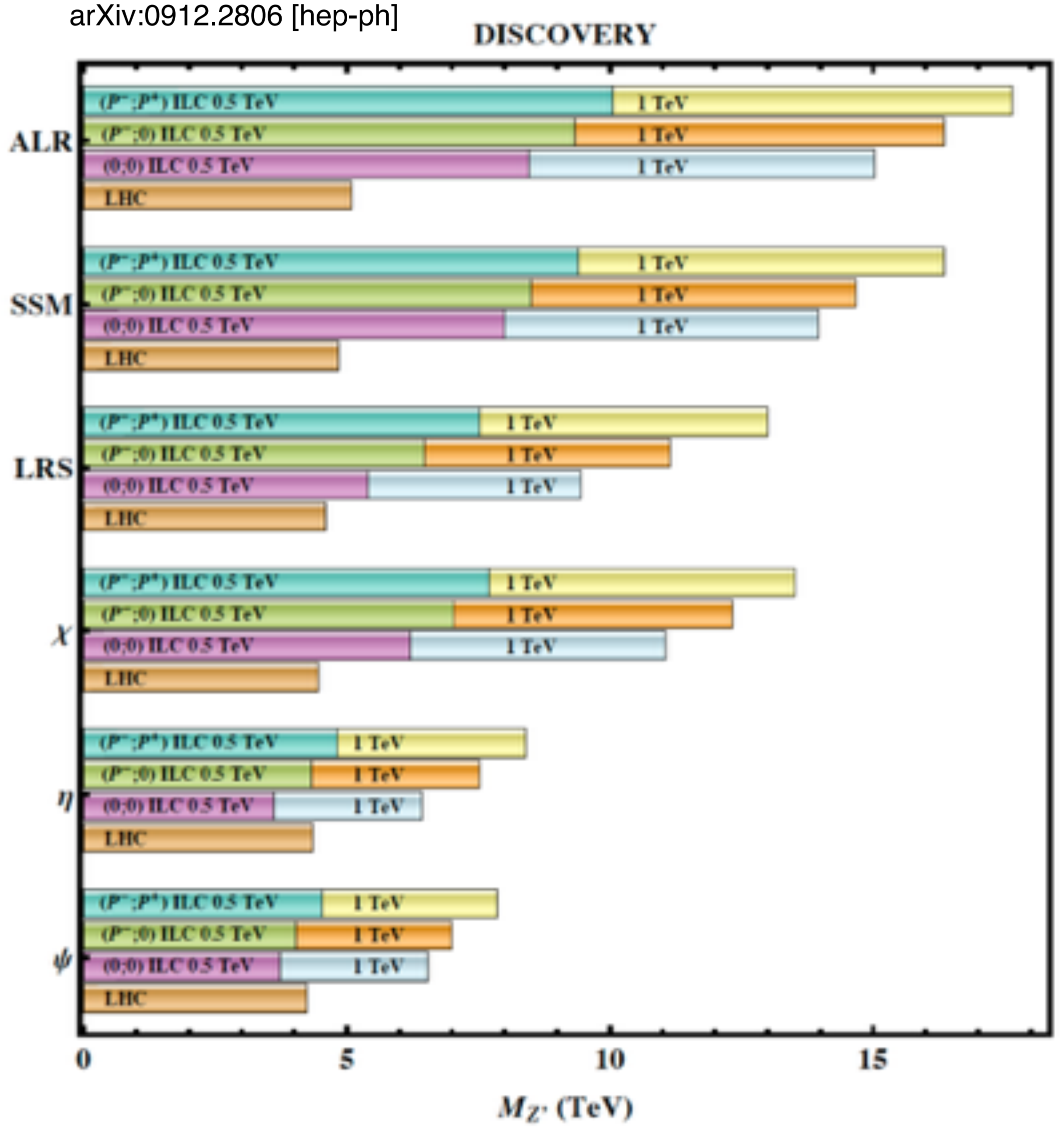
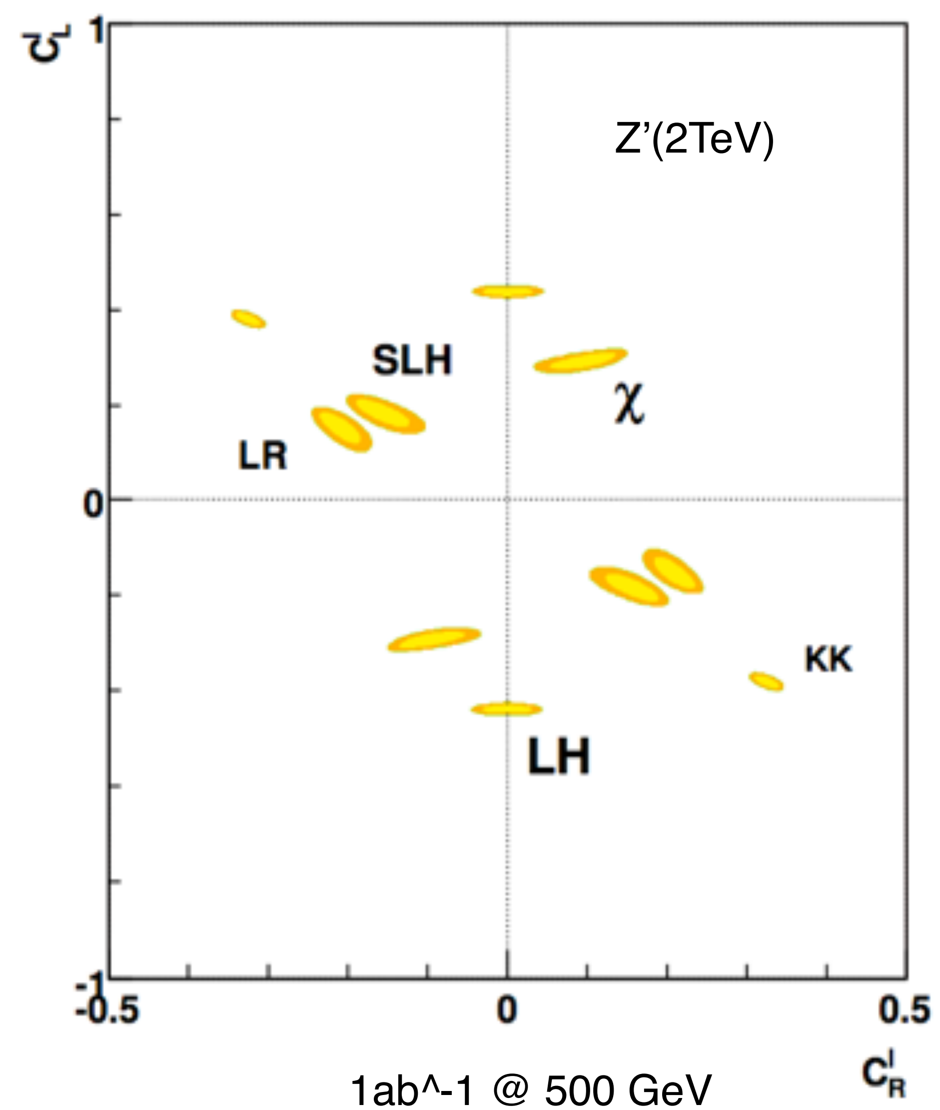


Figure 23: Sensitivity of the ILC to various candidate Z' bosons, quoted at 95% conf., with $\sqrt{s} = 0.5$ (1.0) TeV and $\mathcal{L}_{\rm int} = 500$ (1000) fb^{-1}. The sensitivity of the LHC-14 via Drell-Yan process $pp \to \ell^+\ell^- + X$ with 100 fb^{-1} of data are shown for comparison. For details, see [14].

hep-ph/0511335



ILC's Model ID capability is expected to exceed that of LHC even if we cannot hit the Z' pole.

Beam polarization is essential to sort out various possibilities.

Two-Fermion Processes

Compositeness

S. Riemann, LC-TH-2001-007

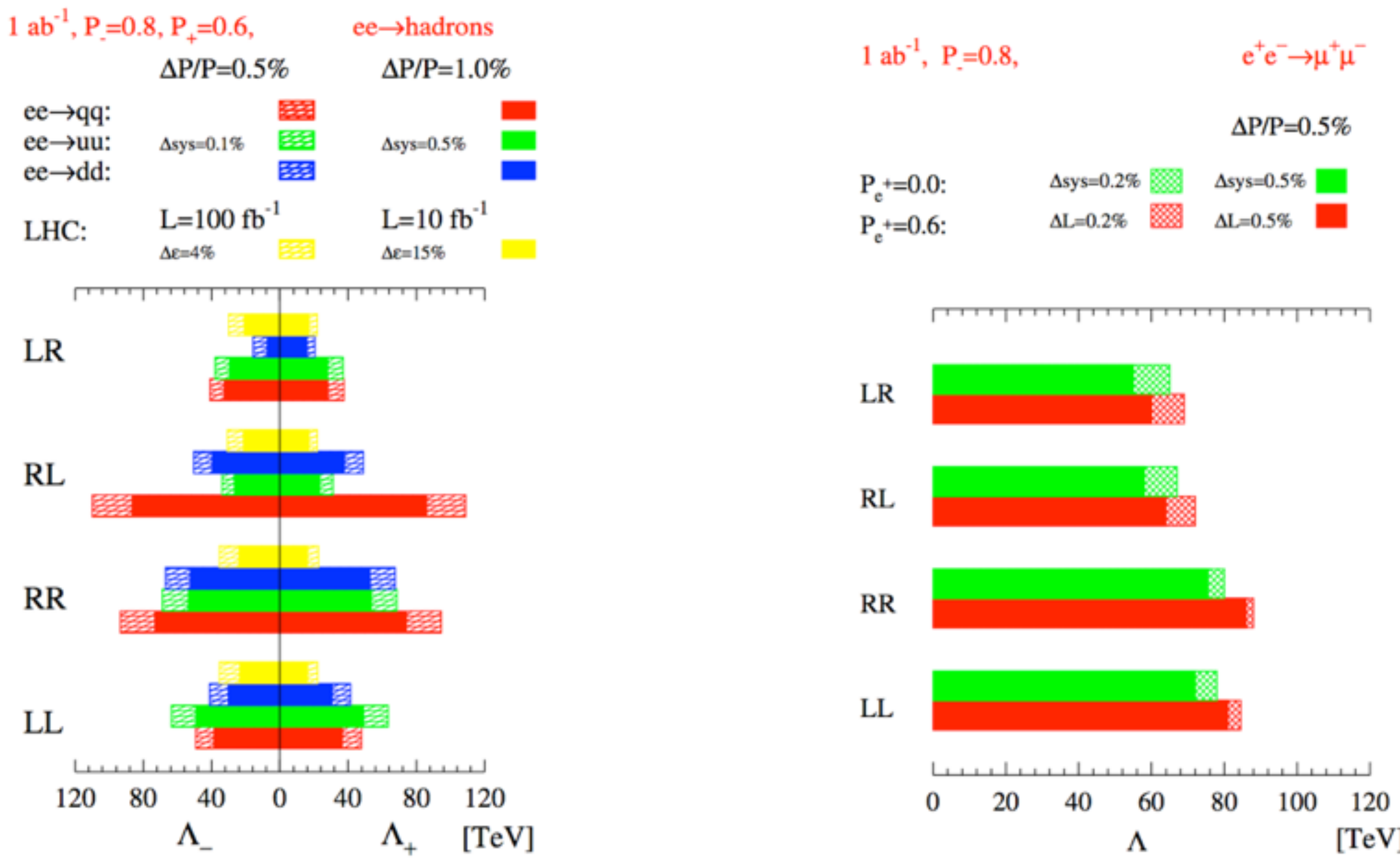
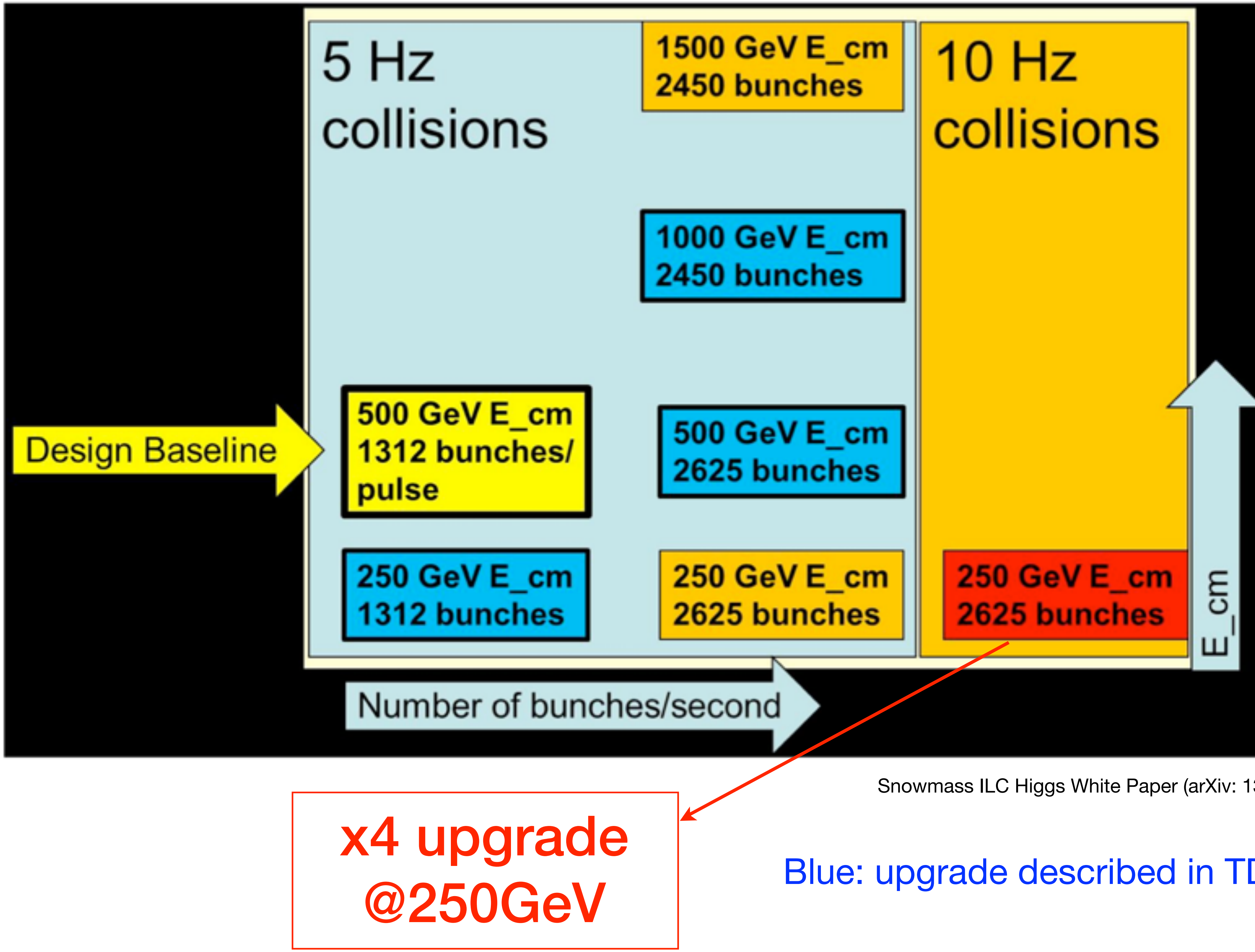


Figure 26: Sensitivities (95% c.l.) of a 500 GeV ILC to contact interaction scales Λ for different helicities in $e^+e^- \to$ hadrons (left) and $e^+e^- \to \mu^+\mu^-$ (right), including beam polarization [18].

Beam polarization is essential to sort out various possibilities.

HL-ILC ?

ILC Stages and Upgrades



Snowmass ILC Higgs White Paper (arXiv: 1310.0763)

Blue: upgrade described in TDR

The current ILC design is rather conservative!

Scalability (short-term)

Luminosity can be enhanced by increasing the number of bunches and the collision rate.

ILC TDR | Higgs Whitepaper for Snowmass (arXiv:1310.0763)

		Baseline			Luminosity Upgrade		
CM Energy	GeV	**250**	**500**	**1000**	**250**	**250**	**500**
Luminosity	10^{34} cm^{-2} s^{-1}	0.75	1.8	4.9	1.5	3.0	3.6
Collision rate	Hz	5	5	4	5	**10**	5
Number of bunches	Hz	1312	1312	2450	**2625**	**2625**	**2625**
Avg. total beam power	MW	5.9	10.5	27.2	11.8	21.0	21.0
AC power	MW	122	163	300	161	204	204
Relative cost		69%	100%	166%	74%	106%	106%

in a tunnel for 500 GeV ILC

Luminosity upgrade available at a relatively small footprint;
→ the way to go if additional funds become available

TDR

			Baseline 500 GeV Machine			1st Stage	L Upgrade	E_{CM} Upgrade	
								A	B
Center-of-mass energy	E_{CM}	GeV	250	350	500	250	500	1000	1000
Collision rate	f_{rep}	Hz	5	5	5	5	5	4	4
Electron linac rate	f_{linac}	Hz	10	5	5	10	5	4	4
Number of bunches	n_b		1312	1312	1312	1312	2625	2450	2450
Bunch population	N	$\times 10^{10}$	2.0	2.0	2.0	2.0	2.0	1.74	1.74
Bunch separation	Δt_b	ns	554	554	554	554	366	366	366
Pulse current	I_{beam}	mA	5.8	5.8	5.8	5.8	8.8	7.6	7.6
Main linac average gradient	G_a	$\mathrm{MV\,m^{-1}}$	14.7	21.4	31.5	31.5	31.5	38.2	39.2
Average total beam power	P_{beam}	MW	5.9	7.3	10.5	5.9	21.0	27.2	27.2
Estimated AC power	P_{AC}	MW	122	121	163	129	204	300	300
RMS bunch length	σ_z	mm	0.3	0.3	0.3	0.3	0.3	0.250	0.225
Electron RMS energy spread	$\Delta p/p$	%	0.190	0.158	0.124	0.190	0.124	0.083	0.085
Positron RMS energy spread	$\Delta p/p$	%	0.152	0.100	0.070	0.152	0.070	0.043	0.047
Electron polarization	P_-	%	80	80	80	80	80	80	80
Positron polarization	P_+	%	30	30	30	30	30	20	20
Horizontal emittance	$\gamma\epsilon_x$	μm	10	10	10	10	10	10	10
Vertical emittance	$\gamma\epsilon_y$	nm	35	35	35	35	35	30	30
IP horizontal beta function	β_x^*	mm	13.0	16.0	11.0	13.0	11.0	22.6	11.0
IP vertical beta function	β_y^*	mm	0.41	0.34	0.48	0.41	0.48	0.25	0.23
IP RMS horizontal beam size	σ_x^*	nm	729.0	683.5	474	729	474	481	335
IP RMS vertical beam size	σ_y^*	nm	7.7	5.9	5.9	7.7	5.9	2.8	2.7
Luminosity	L	$\times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$	0.75	1.0	1.8	0.75	3.6	3.6	4.9
Fraction of luminosity in top 1%	$L_{0.01}/L$		87.1%	77.4%	58.3%	87.1%	58.3%	59.2%	44.5%
Average energy loss	δ_{BS}		0.97%	1.9%	4.5%	0.97%	4.5%	5.6%	10.5%
Number of pairs per bunch crossing	N_{pairs}	$\times 10^3$	62.4	93.6	139.0	62.4	139.0	200.5	382.6
Total pair energy per bunch crossing	E_{pairs}	TeV	46.5	115.0	344.1	46.5	344.1	1338.0	3441.0