

ILC Physics

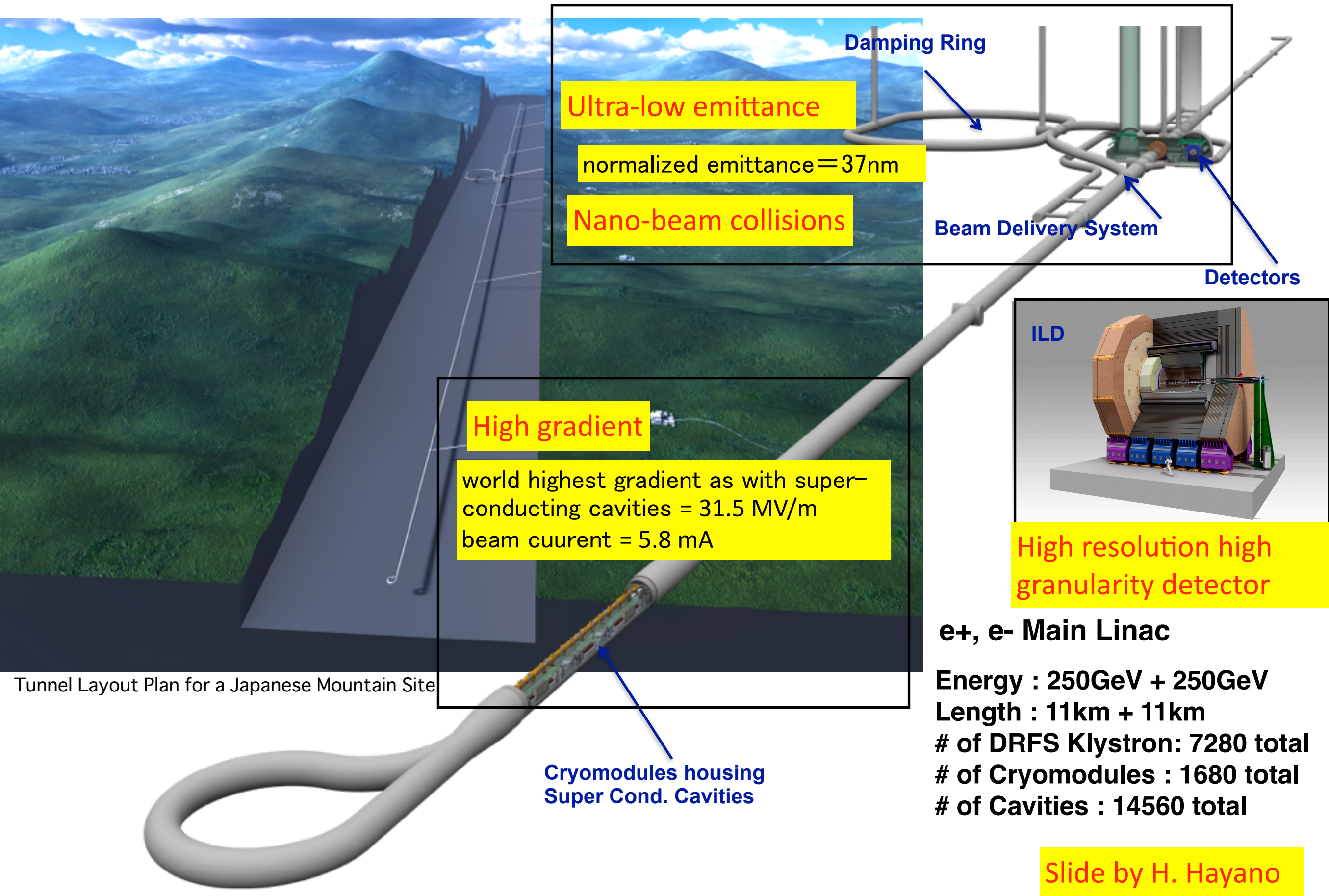
Keisuke Fujii (KEK)

February 18, 2015



Thanks to T. Tanabe
for many materials

Bird's Eye View of the ILC Accelerator

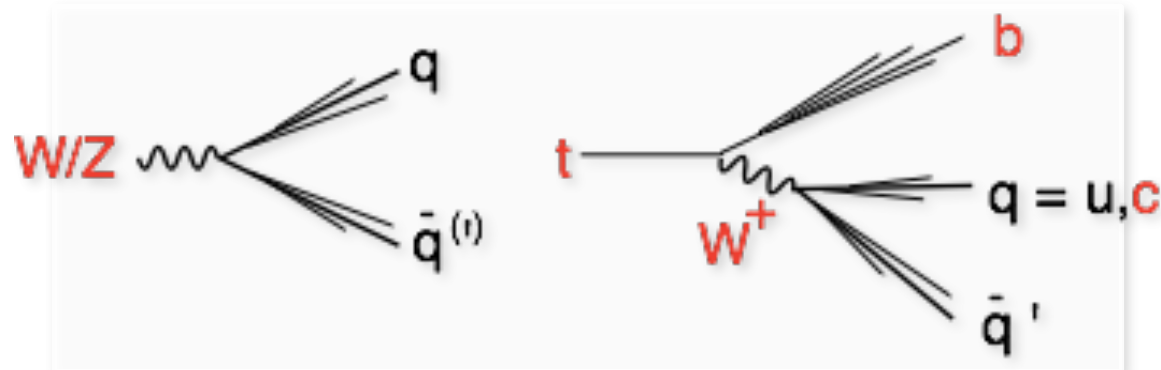


Tunnel Layout Plan for a Japanese Mountain Site

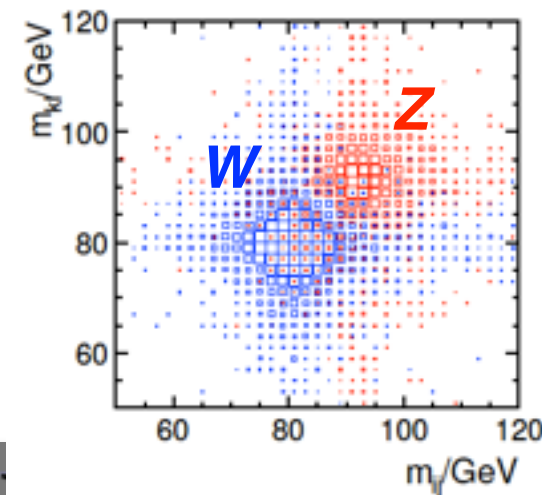
New Paradigm :

View events as viewing a Feynman diagram

Reconstruct final states in terms of fundamental particles (quarks, leptons, gauge bosons, and Higgs bosons)



Identify W/Z/top/Higgs with their jet invariant mass: M_{jets}

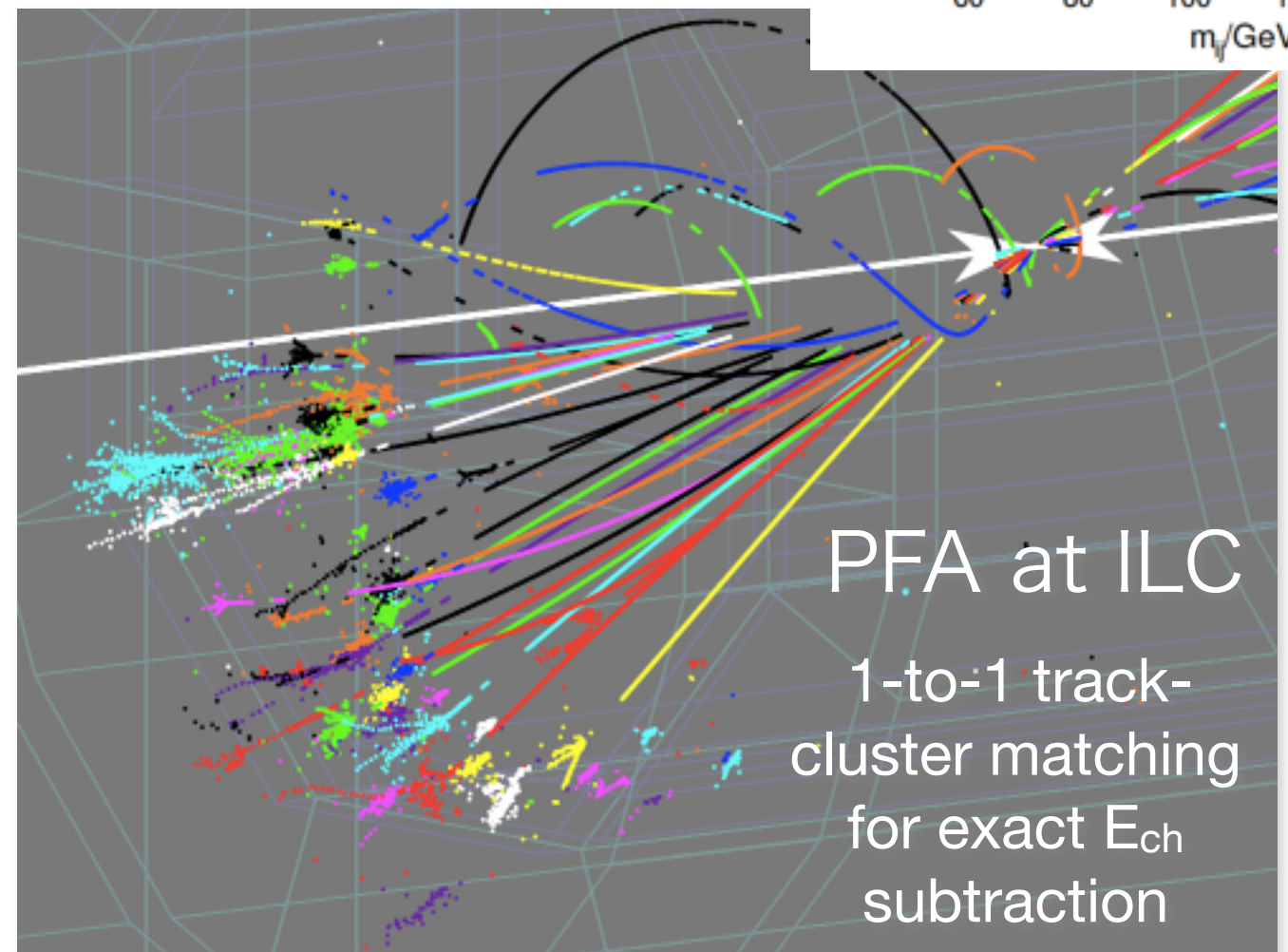


Particle Flow Analysis

PFA is the key to achieve excellent jet invariant mass resolution comparable to the natural width of the weak boson:

$$\sigma_{M_{\text{jets}}} \simeq \Gamma_Z$$

Use tracker for charged particles, **use CAL only for neutral particles**, removing energy deposits by charged particles (E_{ch}) in CAL by **1-to-1 track to CAL cluster matching**



1-to-1 matching requires
High resolution tracking
High granularity calorimetry

Detailed **B**aseline Design (TDR vol.4)

arXiv: 1306.6329

★ Large **R** with **TPC** tracker

- 32 countries, 151 institutions, ~700 members
- Most members from Asia and Europe
- **B=3.5T**, TPC + Si trackers
- ECal: **R=1.8m**

ILD

SiD

★ High **B** with **Si strip** tracker

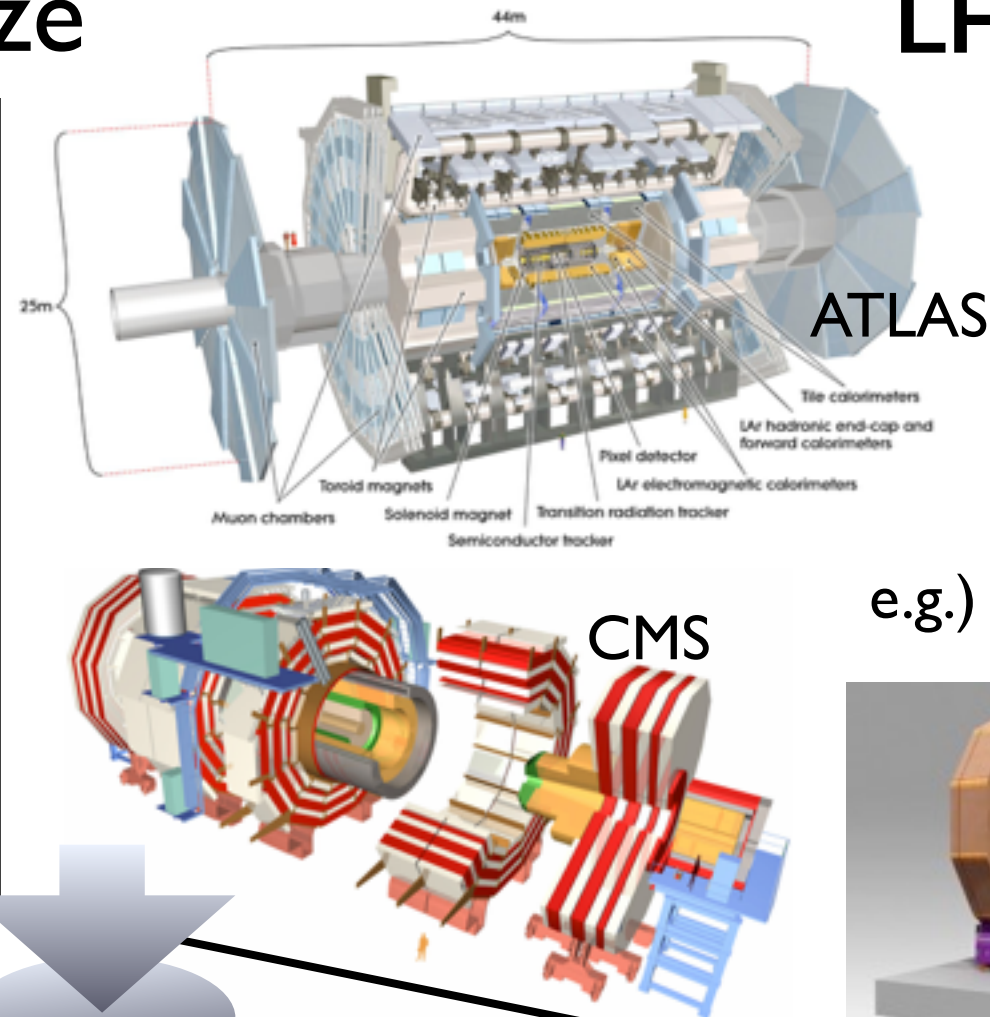
- 18 countries, 77 institutions, ~240 members
- Mostly American
- **B=5T**, Si only tracker
- ECal: **R=1.27m**

Both detector concepts are optimized for **Particle
Flow Analysis**

Comparison

LHC vs ILC

Size



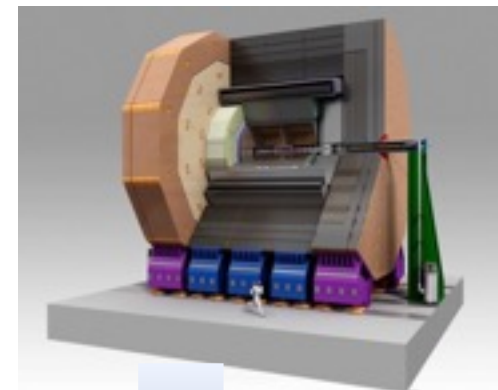
LHC : current state of the art

Use the *cleanest* modes to beat the huge QCD BG.

ILC : next generation

Use the *dominant* (jet) modes to take advantage of clean environment

e.g.) ILD



LHC : Higgs Discovery
Search for New Physics

ILC : Precision Higgs Study
Search for New Physics

Granularity

> 100 x more granular
10 x higher resolution

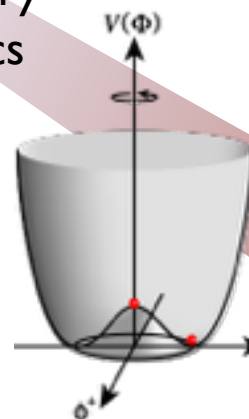
$$\sigma_p/p \simeq 2 \times 10^{-5} p(\text{GeV})$$

10 x less material budget

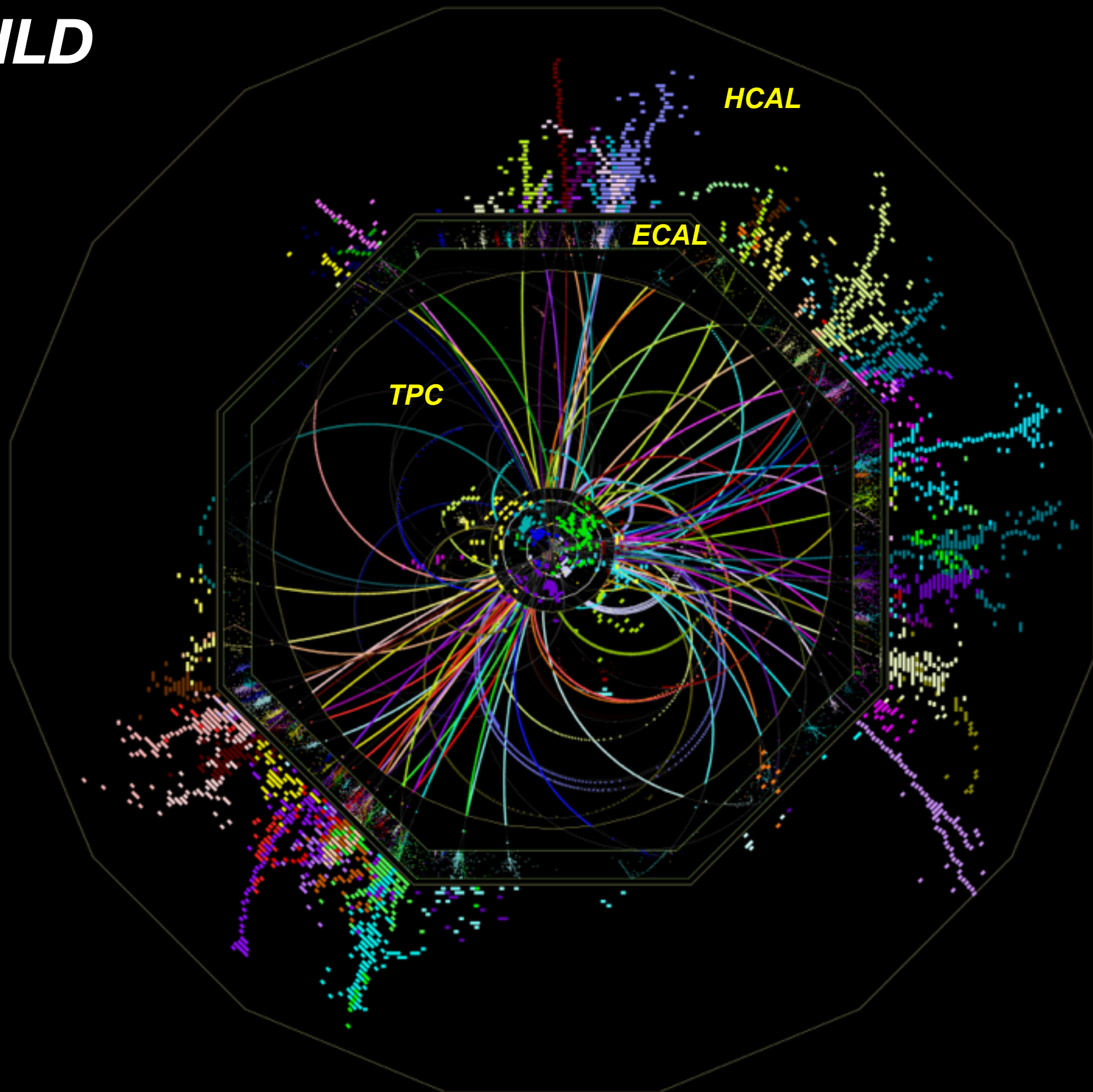
Moral

Energy Frontier
Collider Detectors
spearhead state-
of-the-art detector
technologies

Tracker
Resolution p^2/σ_p



ILD

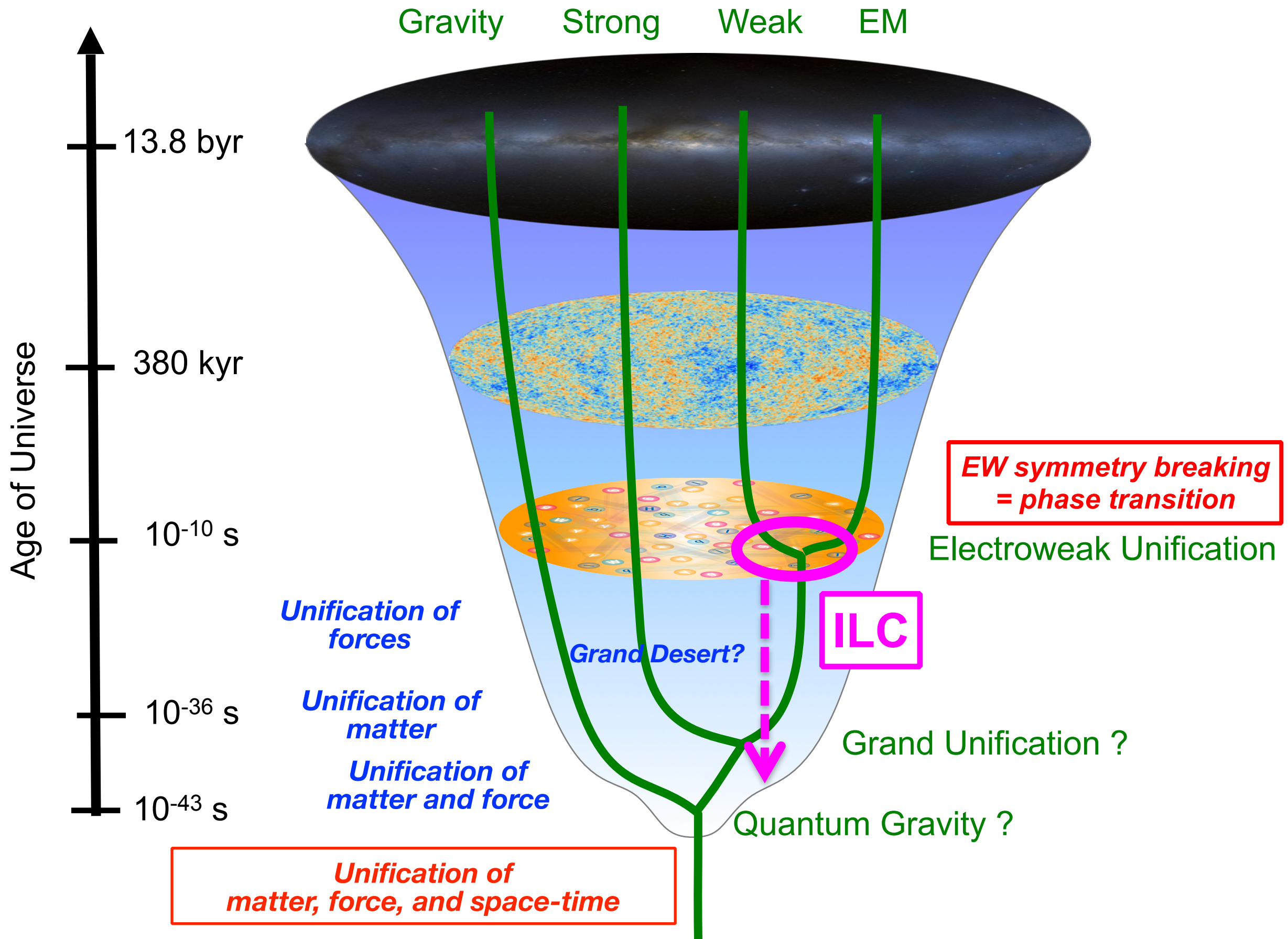


tth @ 500 GeV

Physics at ILC



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:**

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

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

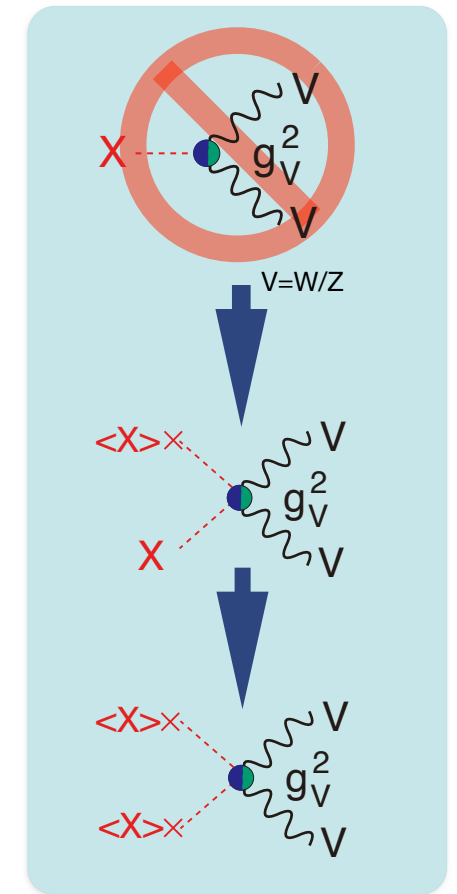
- The discovery of H(125) provided evidence that it is an excitation of (at least part of) this “something” in the vacuum and hence the correctness of this idea of the vacuum breaking the EW symmetry.
- In the SM, **a single complex doublet scalar field** is responsible for both gauge boson and matter 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.

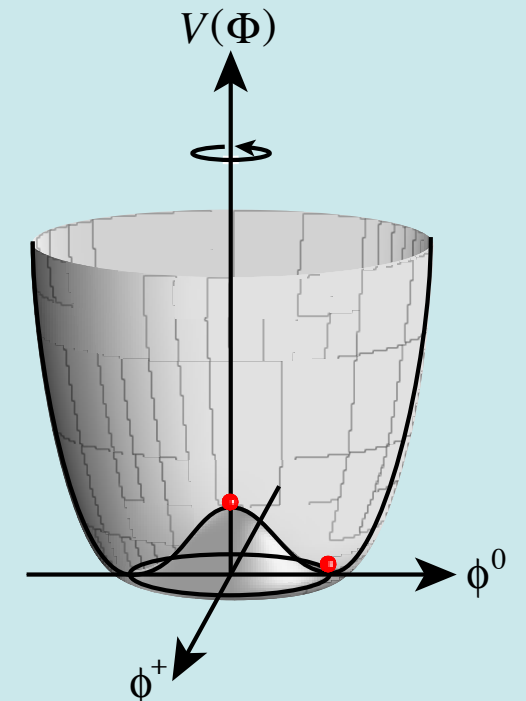
- Moreover, the SM does not explain **why the Higgs field developed a vacuum expectation value.**

★ **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?*

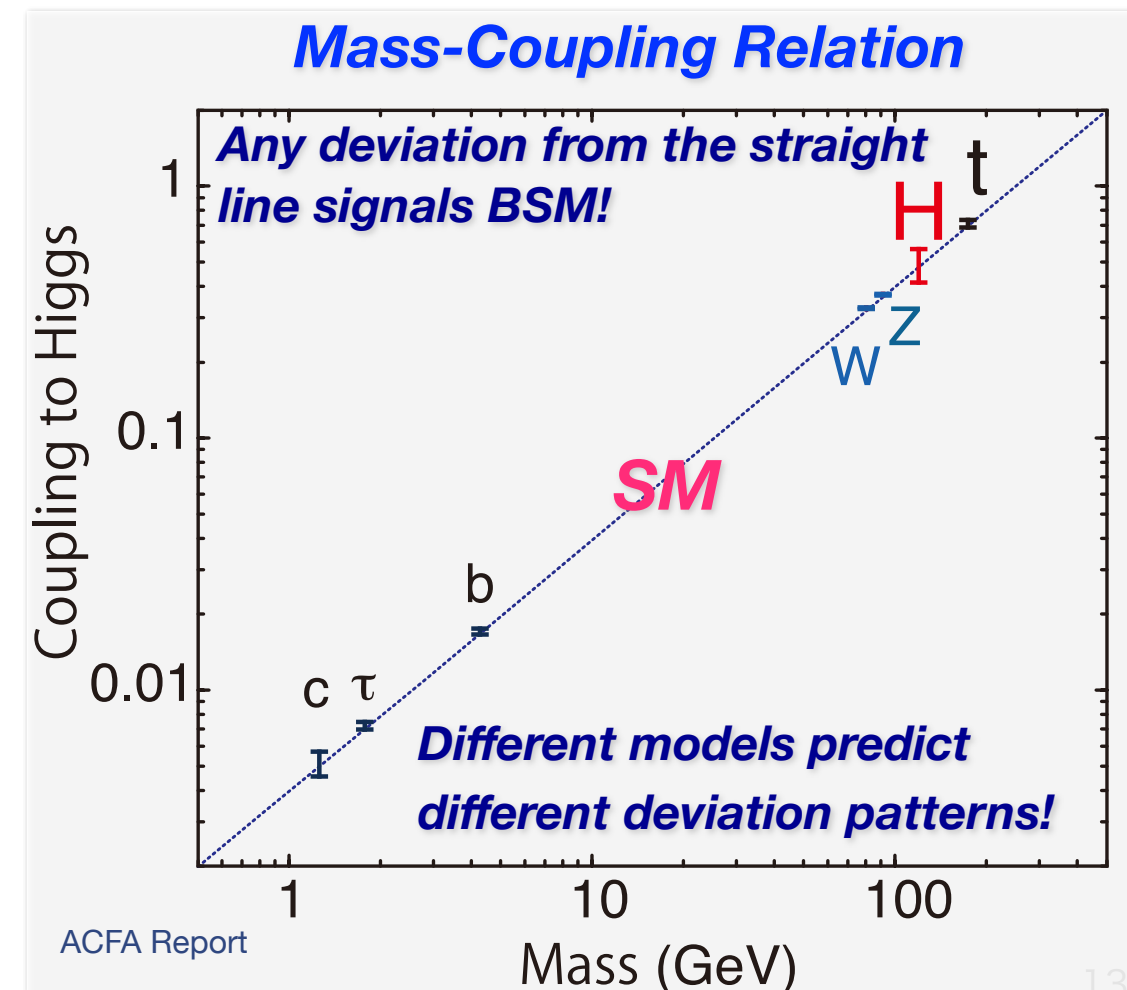
= Is the $H(125)$ *elementary or composite?*

- 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^\pm**
 - uncolored SUSY particles: **EW kinos, 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:**

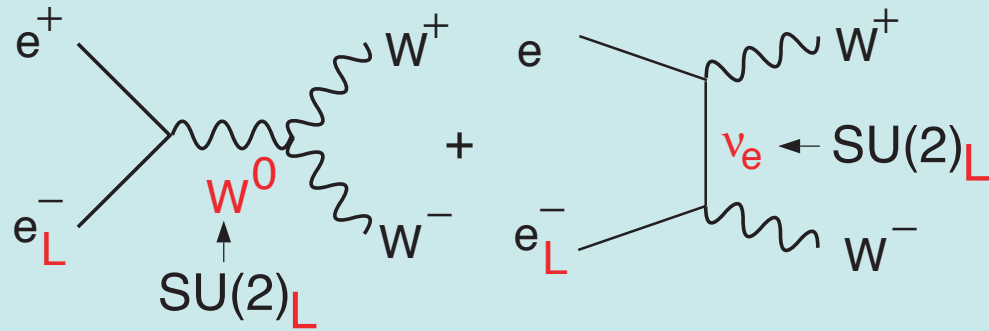
Higgs, Top, and
search for
New Particles

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***

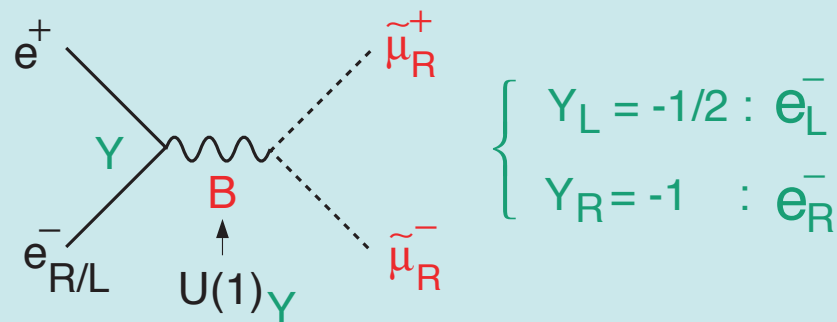
Power of Beam Polarization

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



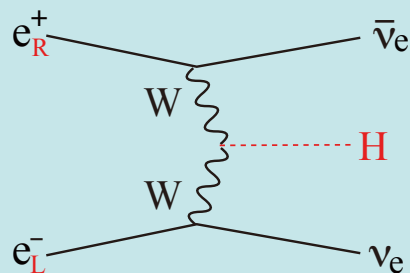
In the symmetry limit, $\sigma_{WW} \rightarrow 0$ for e_R^- !

Slepton Pair



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

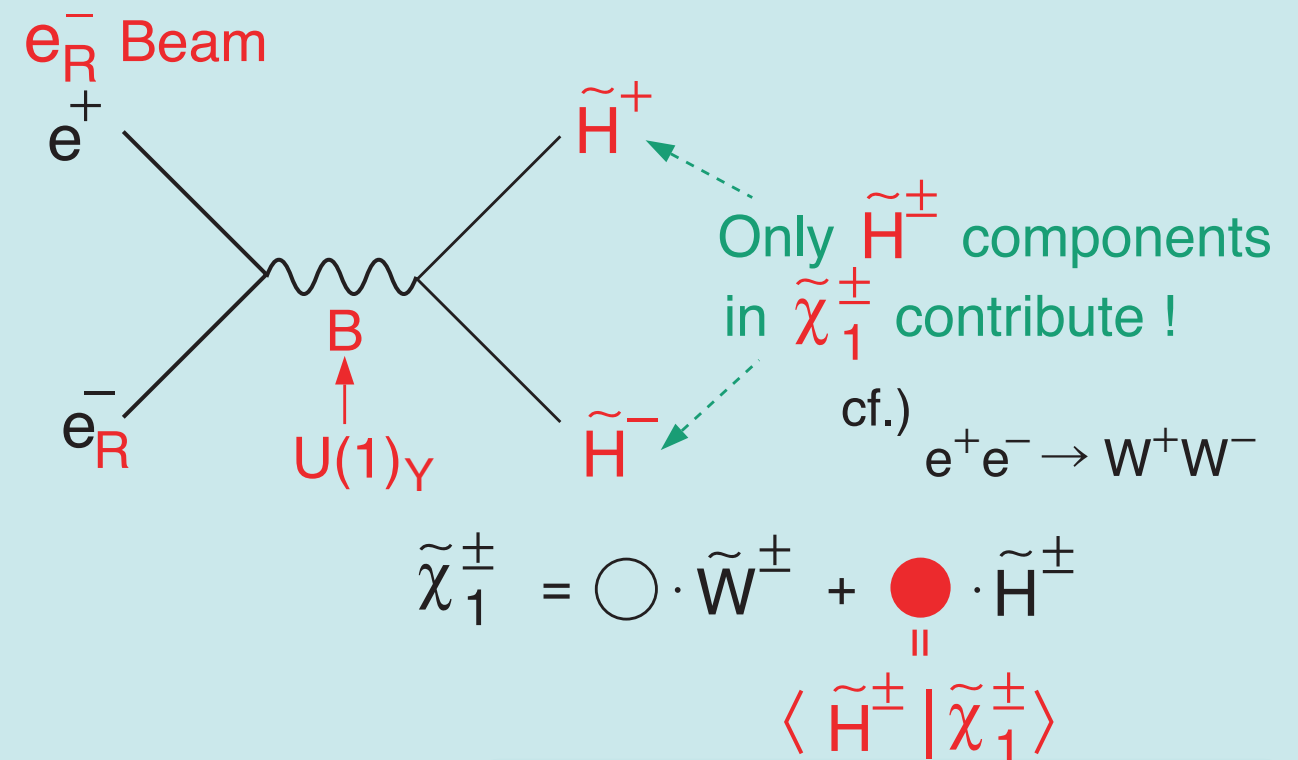
WW-fusion Higgs Prod.



	ILC
Pol (e ⁻)	-0.8
Pol (e ⁺)	+0.3
$(\sigma/\sigma_0)_{\nu\nu H}$	$1.8 \times 1.3 = 2.34$

BG Suppression

Chargino Pair



Decomposition

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: $\Lambda \uparrow \rightarrow SM$

Example 1: MSSM ($\tan\beta=5$, radiative correction factor ≈ 1)

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

heavy Higgs mass

Example 2: Minimal Composite Higgs Model

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

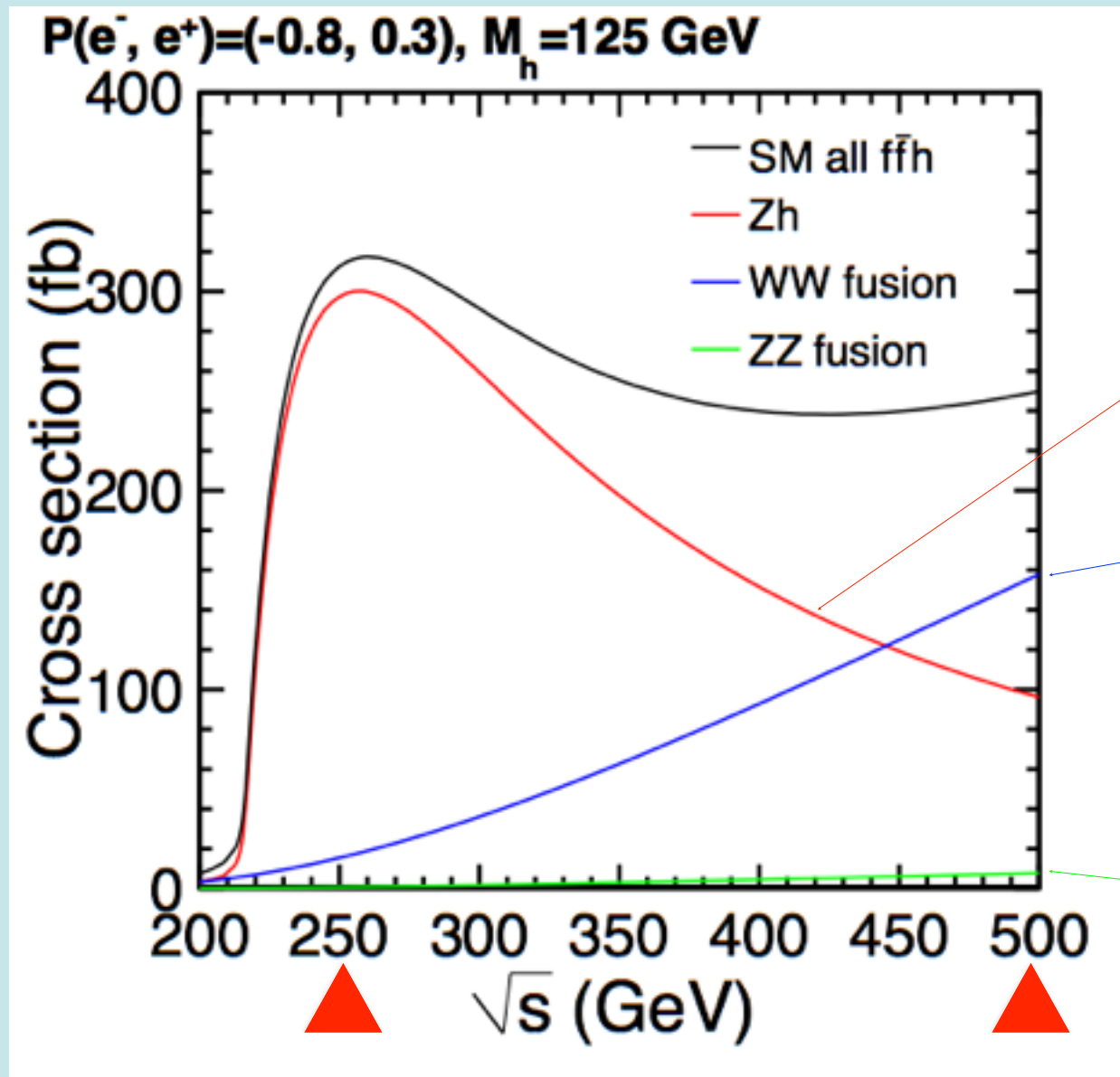
composite scale

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

Main Production Processes

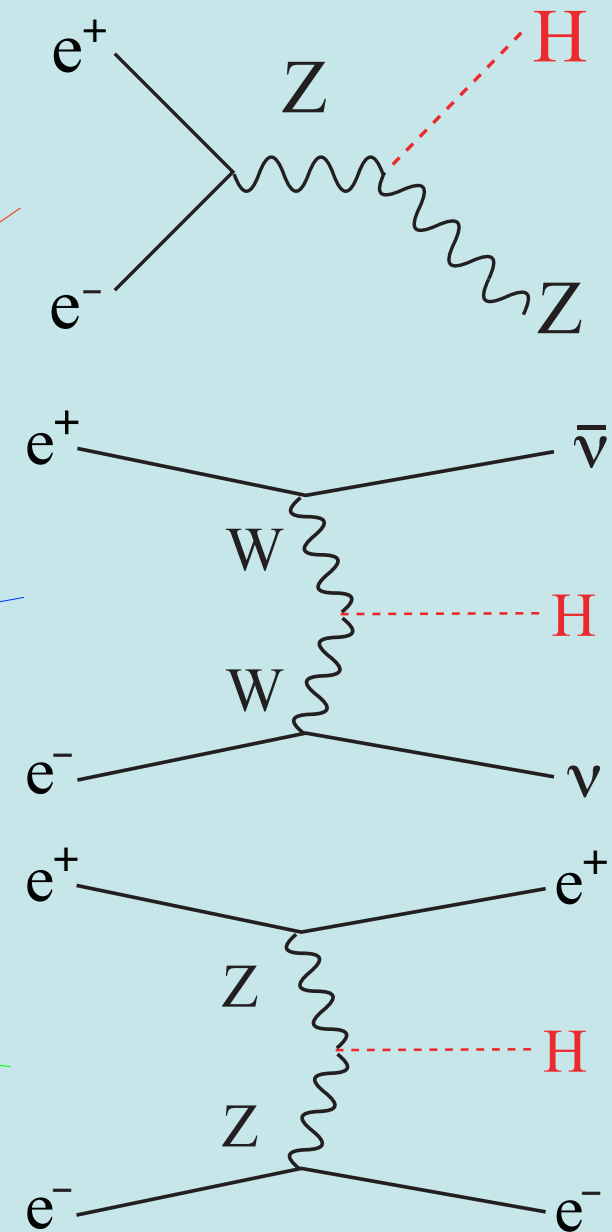
Single Higgs Production

Production cross section



ZH dominates at 250 GeV
(~80k ev: 250 fb⁻¹)

vvH takes over at 500 GeV
(~125k ev: 500 fb⁻¹)

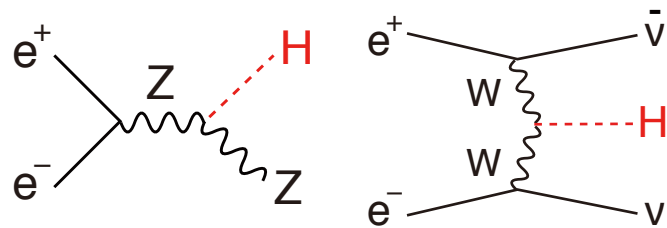


Possible to rediscover the Higgs in one day!

Key Point

At LHC all the measurements are $\sigma \times \text{BR}$ measurements.

At ILC all but *the σ measurement using recoil mass technique* is $\sigma \times \text{BR}$ measurements.

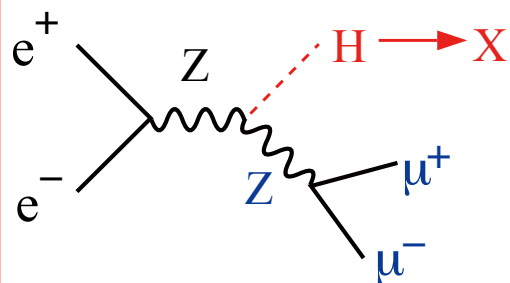
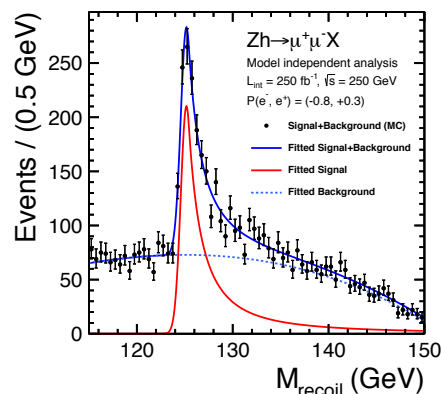


$$g_{HAA}^2 \propto \Gamma(H \rightarrow AA) = \Gamma_H \cdot \text{BR}(H \rightarrow AA)$$

$\sigma \times \text{BR}$

BR

g
coupling



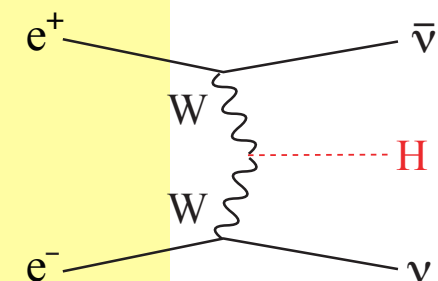
σ
from recoil mass

$Z \rightarrow qq$ is also usable.

The Key

Γ_H
total width

*WW-fusion is crucial
for precision total
width measurement
 $\rightarrow E_{\text{cm}} > 350 \text{ GeV}$*



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	vvH(fusion)	ZH	vvH(fusion)	vvH(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%

Model-independent Global Fit for Couplings

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

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

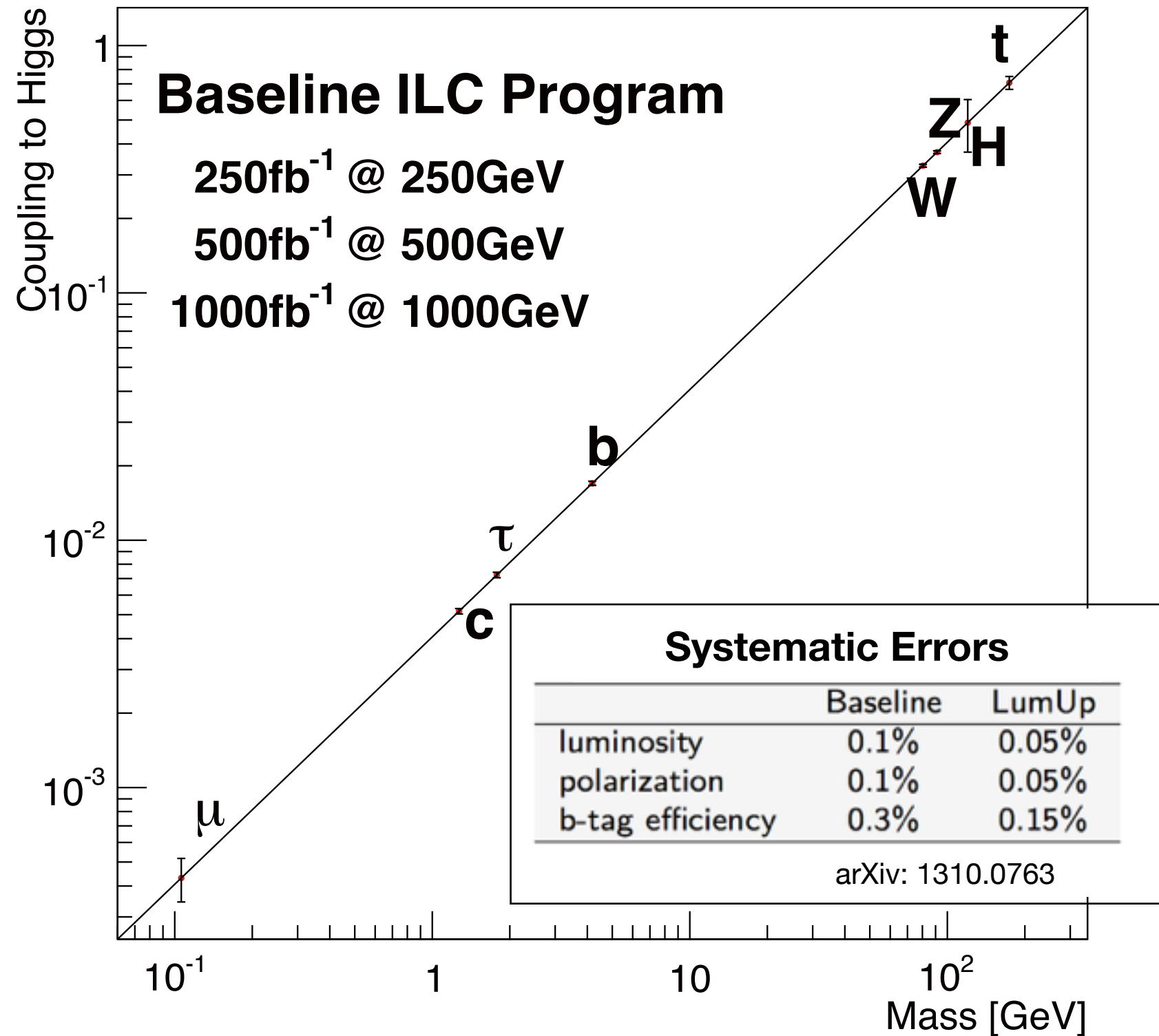
$$Y'_i = F_i \cdot \frac{g_{HA_i A_i}^2 \cdot g_{HB_i B_i}^2}{\Gamma_0}$$

($i = 1, \dots, 33$)
 ($A_i = Z, W, t$)
 ($B_i = b, c, \tau, \mu, g, \gamma, Z, W : \text{decay}$)

$$F_i = S_i G_i$$

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

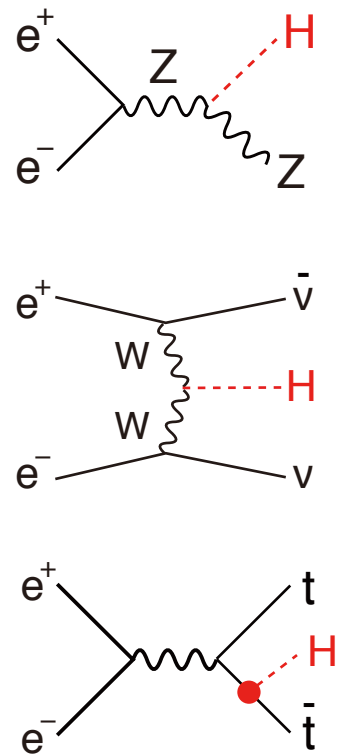
$$S_i = \left(\frac{\sigma_{ZH}}{g_{HZZ}^2} \right), \left(\frac{\sigma_{\nu\bar{\nu}H}}{g_{HWW}^2} \right), \text{ or } \left(\frac{\sigma_{t\bar{t}H}}{g_{Htt}^2} \right)$$



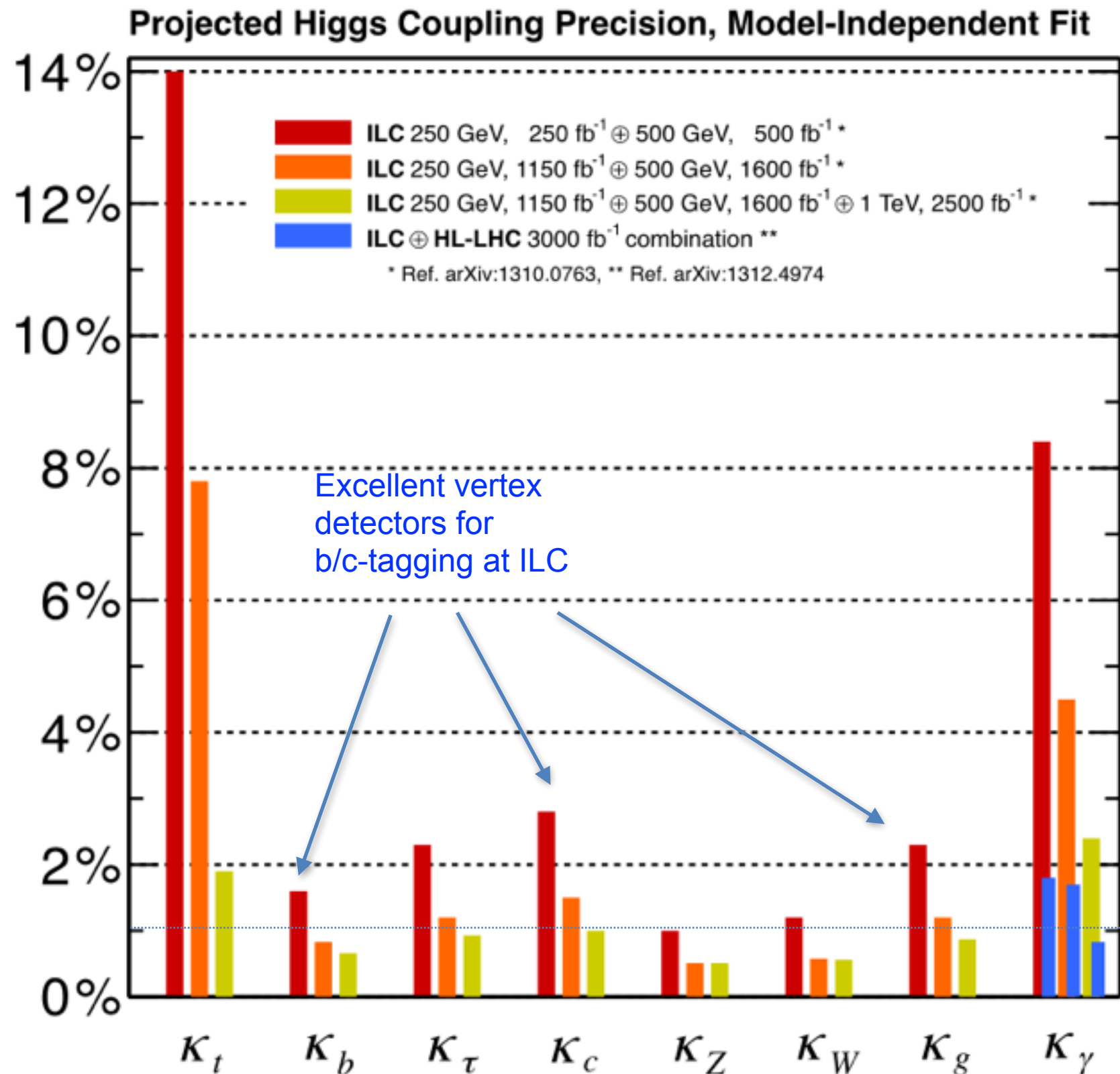
ILC's precisions will eventually reach sub-% level!

Higgs Couplings

Model-independent coupling determination, impossible at LHC



All of major Higgs decay modes accessible at ILC!

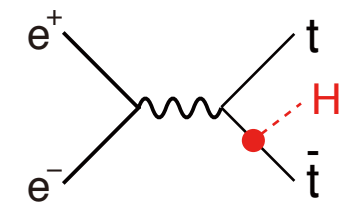
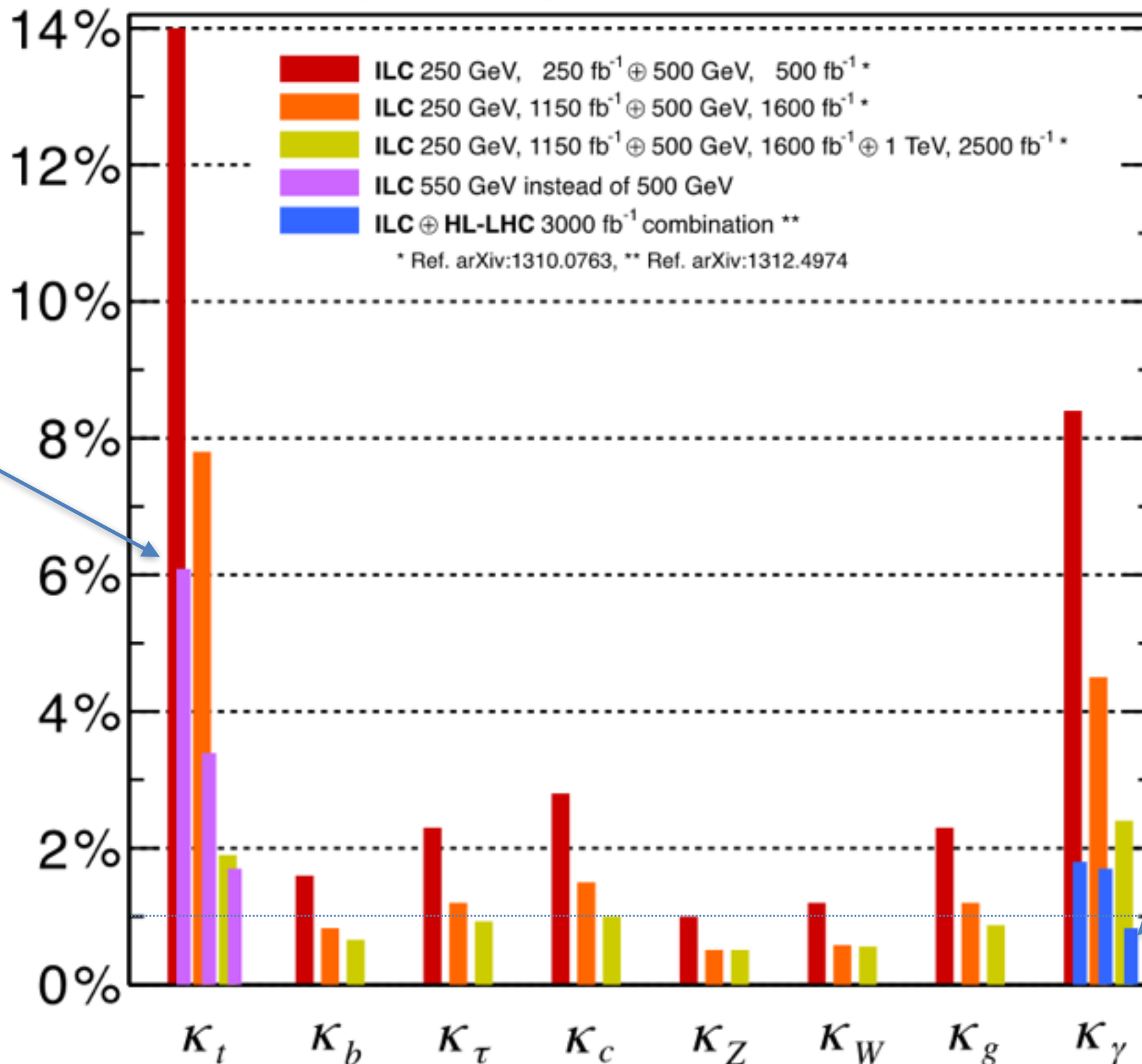


500 GeV already excellent except for K_t and K_γ

Higgs Couplings

Model-independent coupling determination, impossible at LHC

Projected Higgs Coupling Precision, Model-Independent Fit



Top Yukawa improves by going to 550 GeV

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

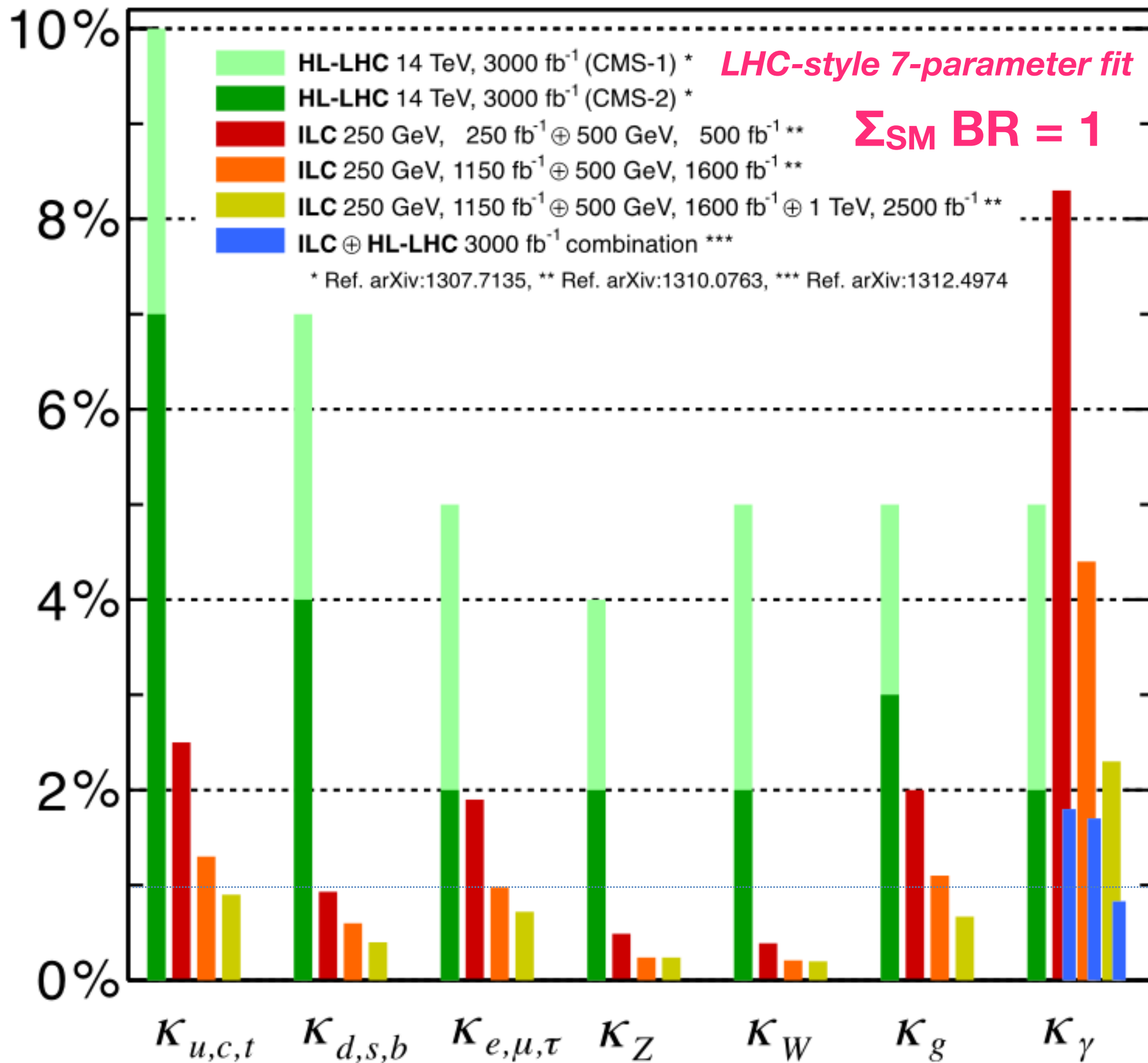
LHC can precisely measure
 $BR(h \rightarrow \gamma\gamma) / BR(h \rightarrow ZZ^*)$
 $= (K_\gamma / K_Z)^2$

ILC can precisely measure K_Z

Better hyy with LHC/ILC synergy

~1% or better precision for most couplings!

Projected Higgs Coupling Precision, Model-Dependent Fit

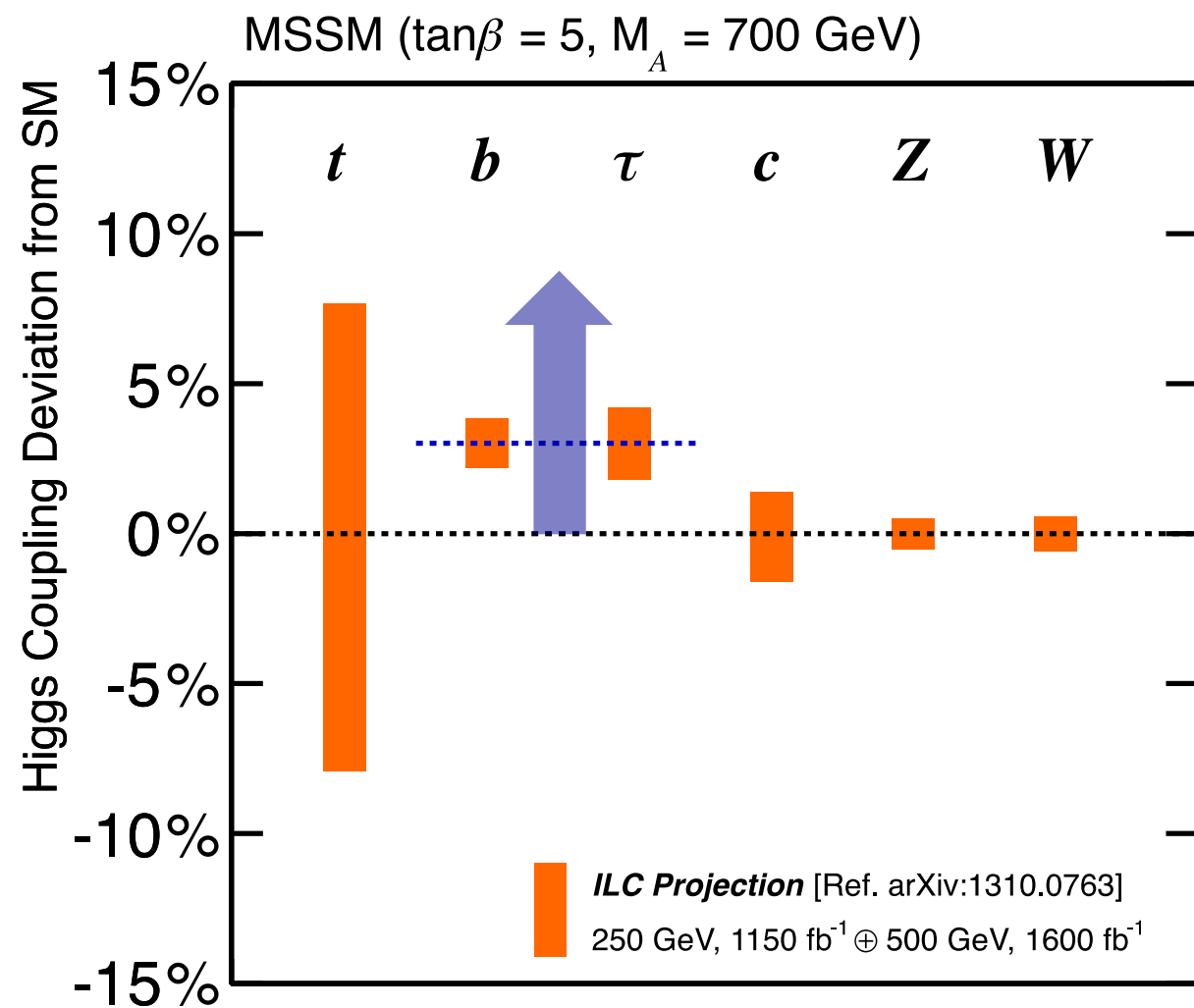


Fingerprinting

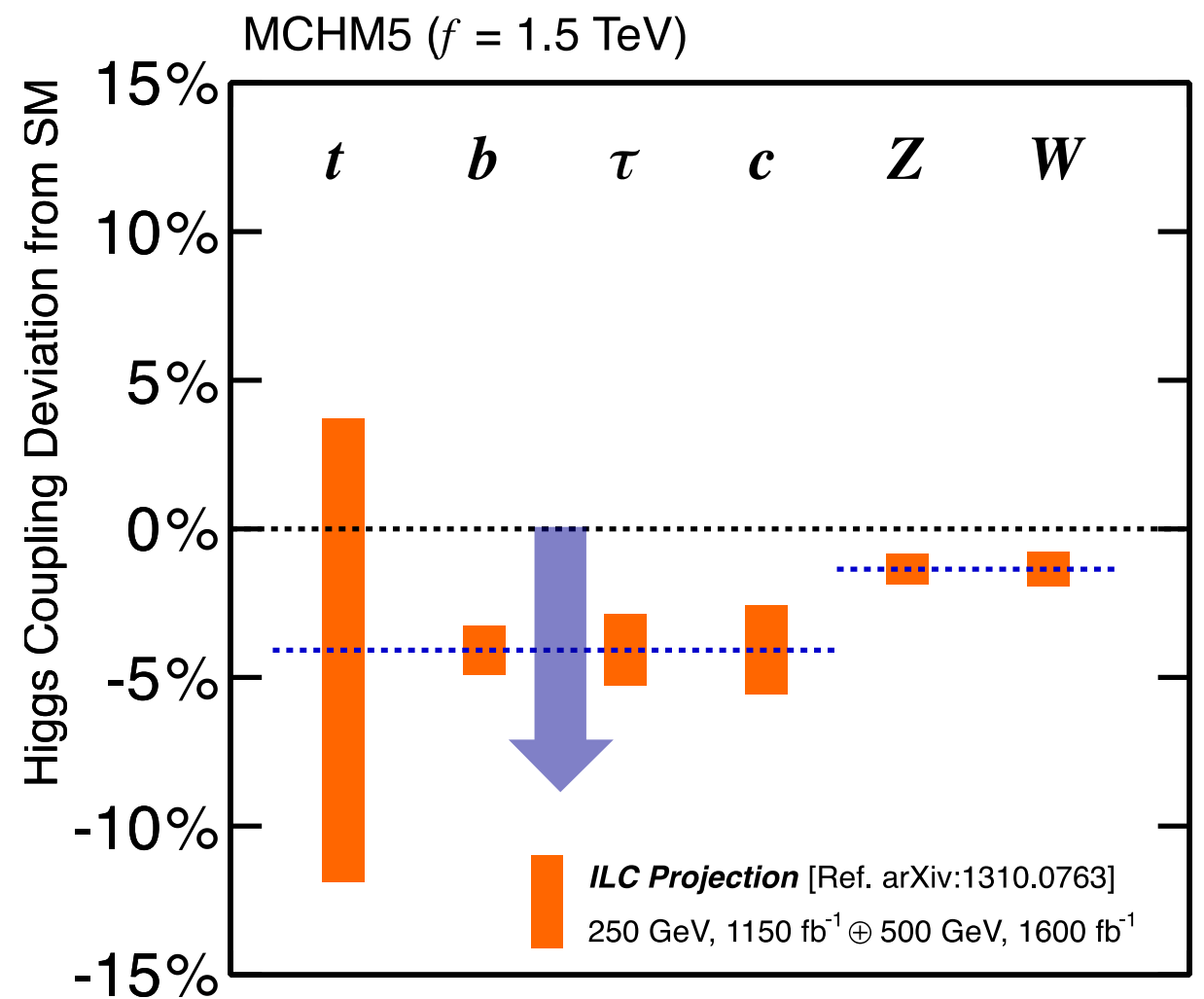
Fingerprinting

Elementary v.s. Composite

Supersymmetry (MSSM)



Composite Higgs (MCHM5)

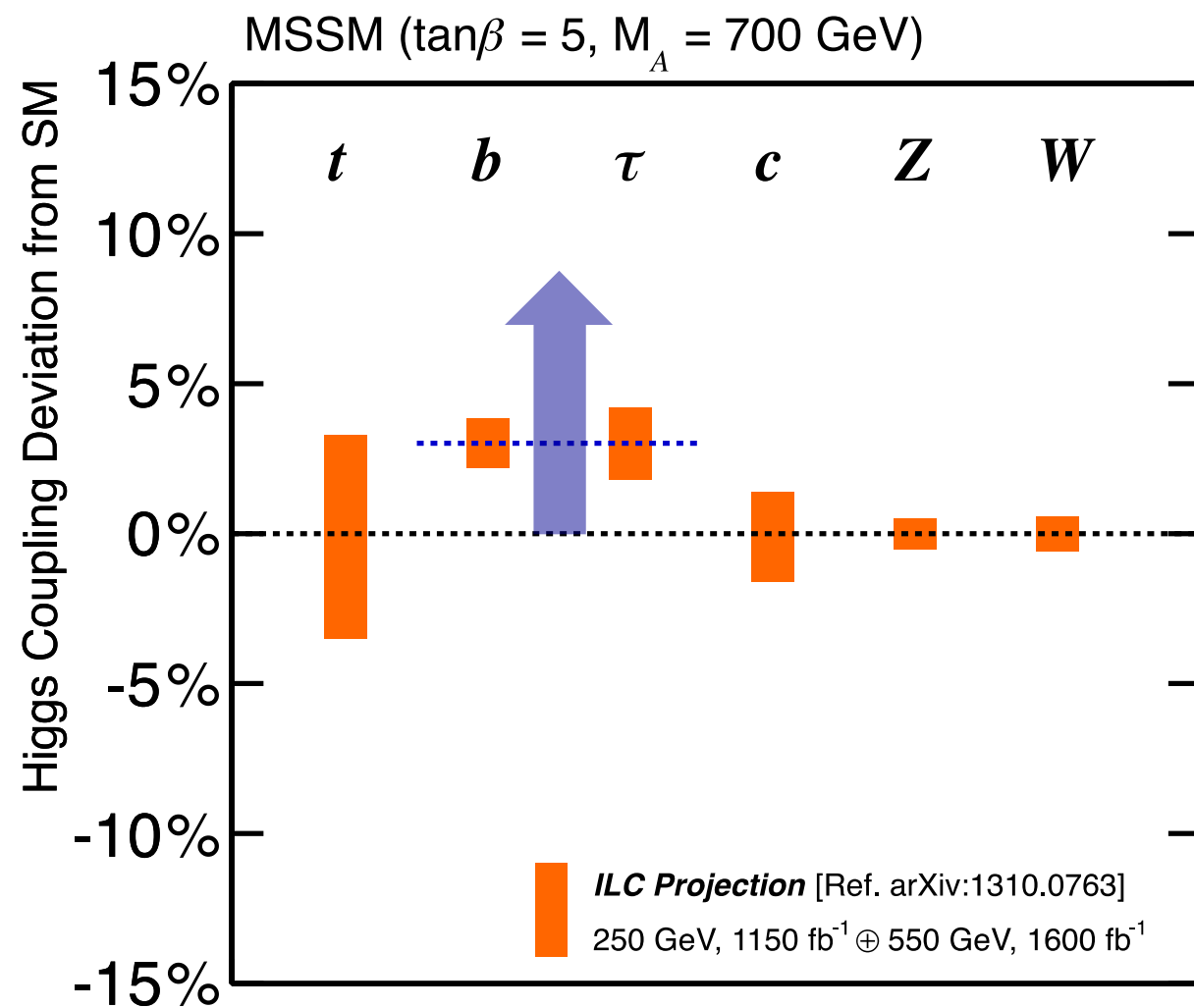


ILC 250+500 LumiUP

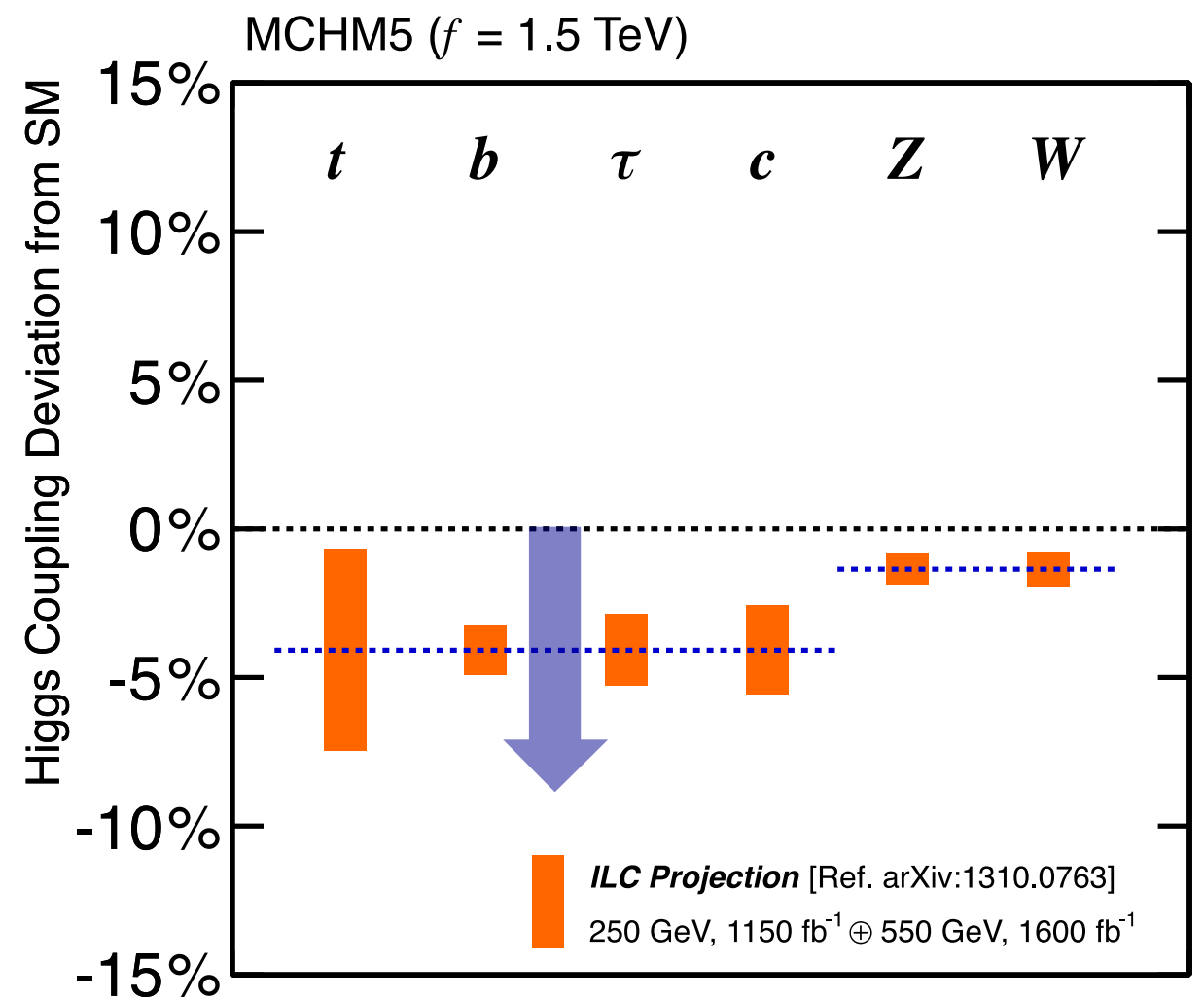
Fingerprinting

Elementary v.s. Composite

Supersymmetry (MSSM)

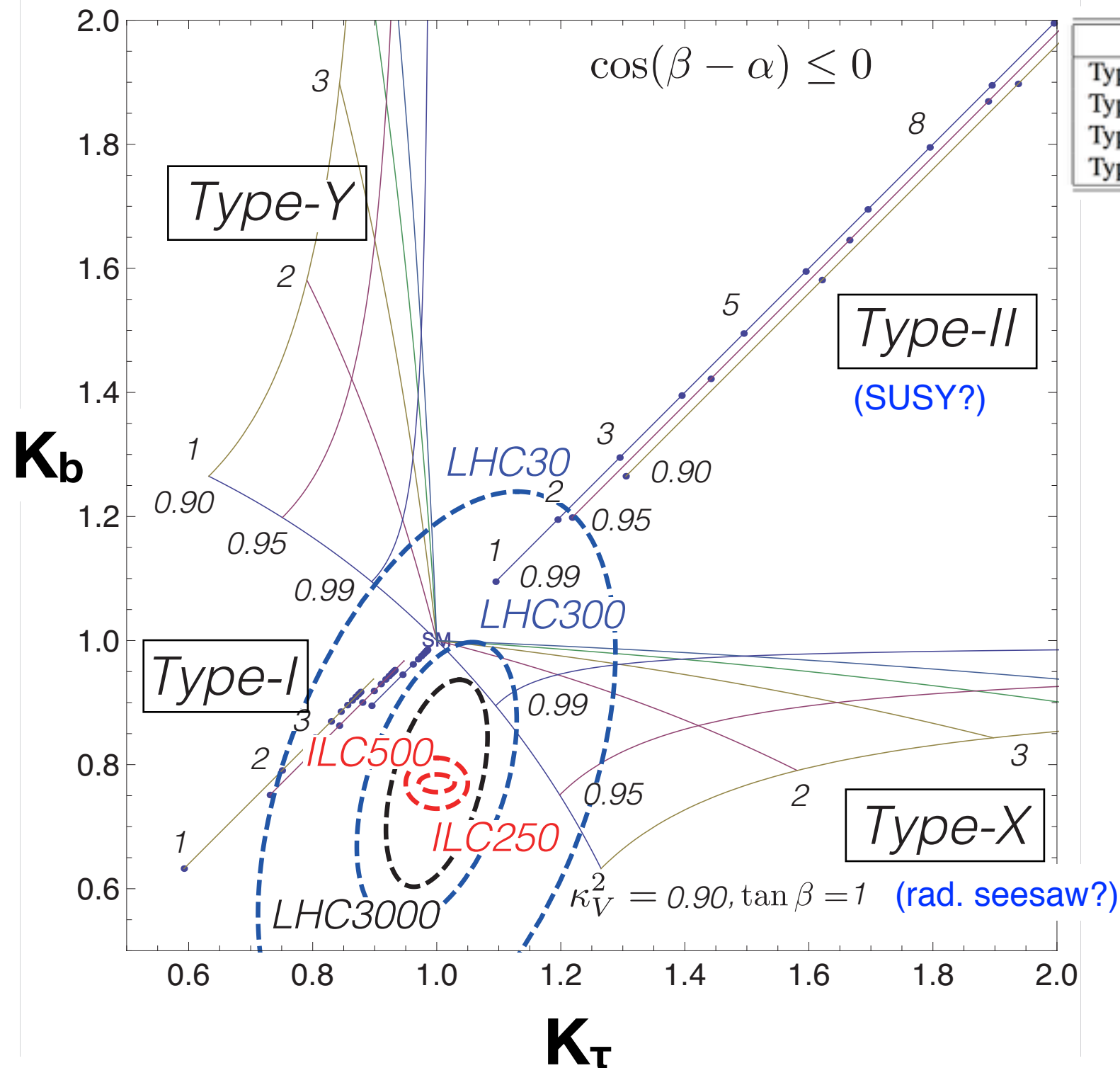


Composite Higgs (MCHM5)



Multiplet Structure

2HDM



	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

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

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)

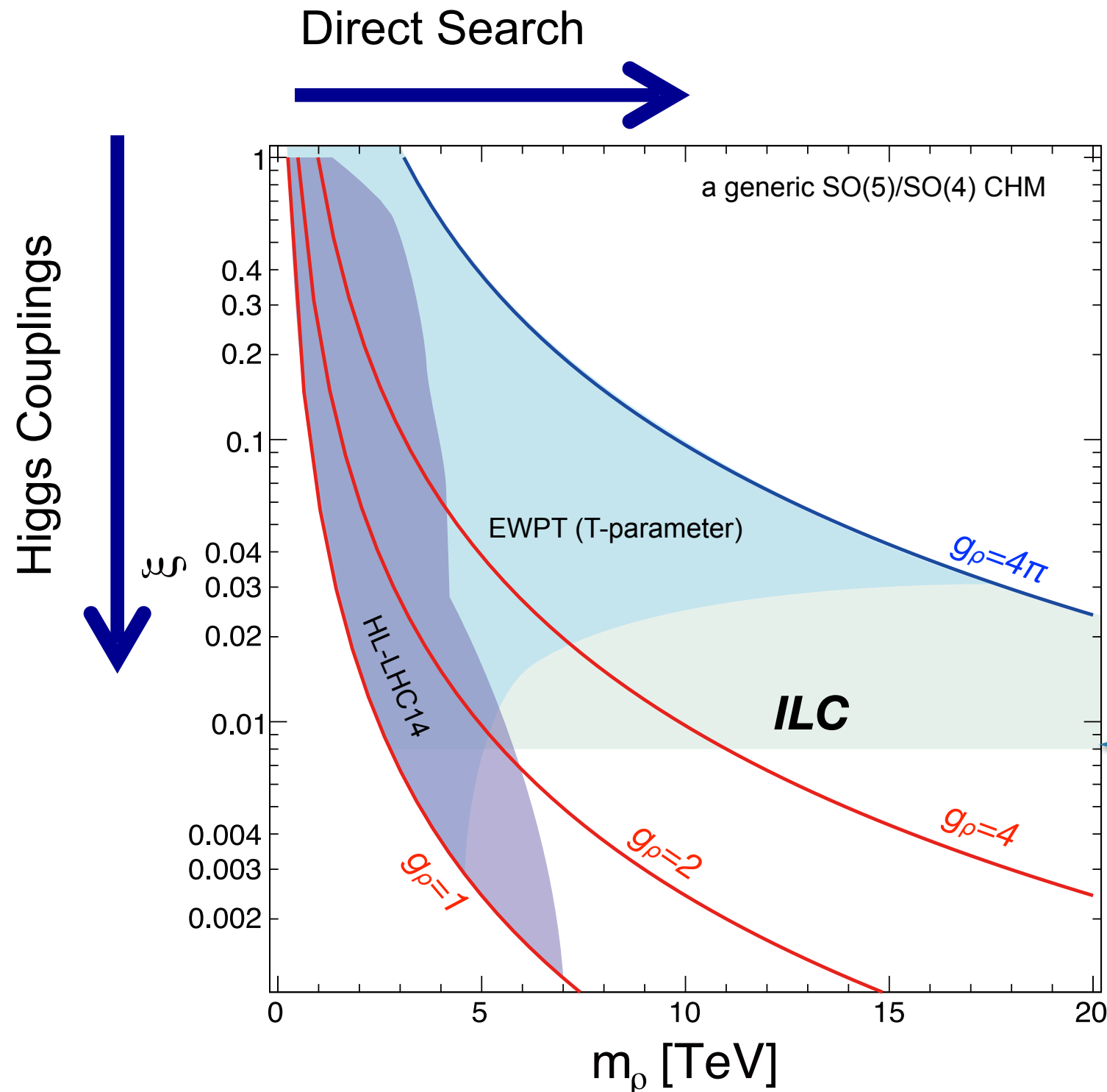
Kanemura et al (arXiv: 1406.3294)

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

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

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

ILC (250+500 LumiUP)

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

EW Phase Transition

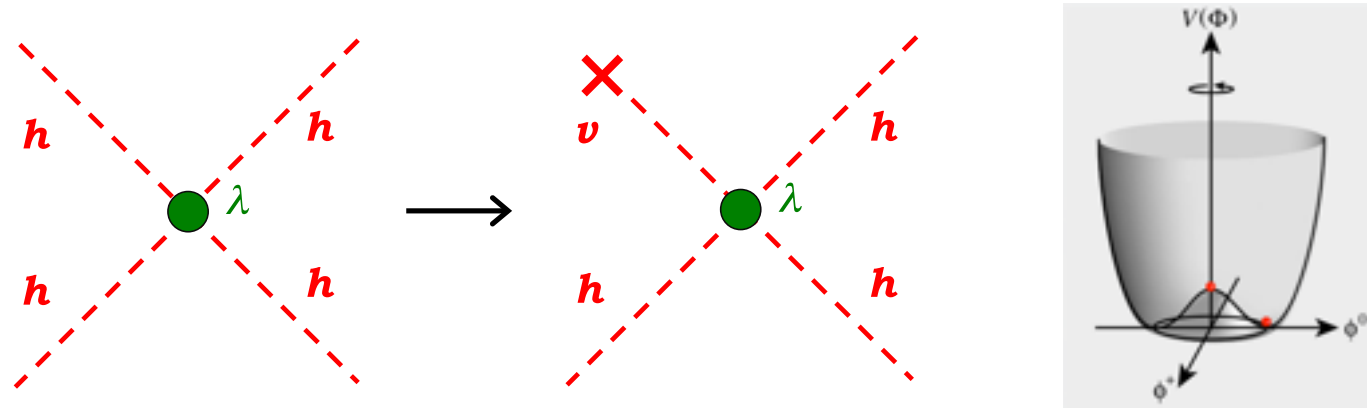
1st order

or

2nd order ?

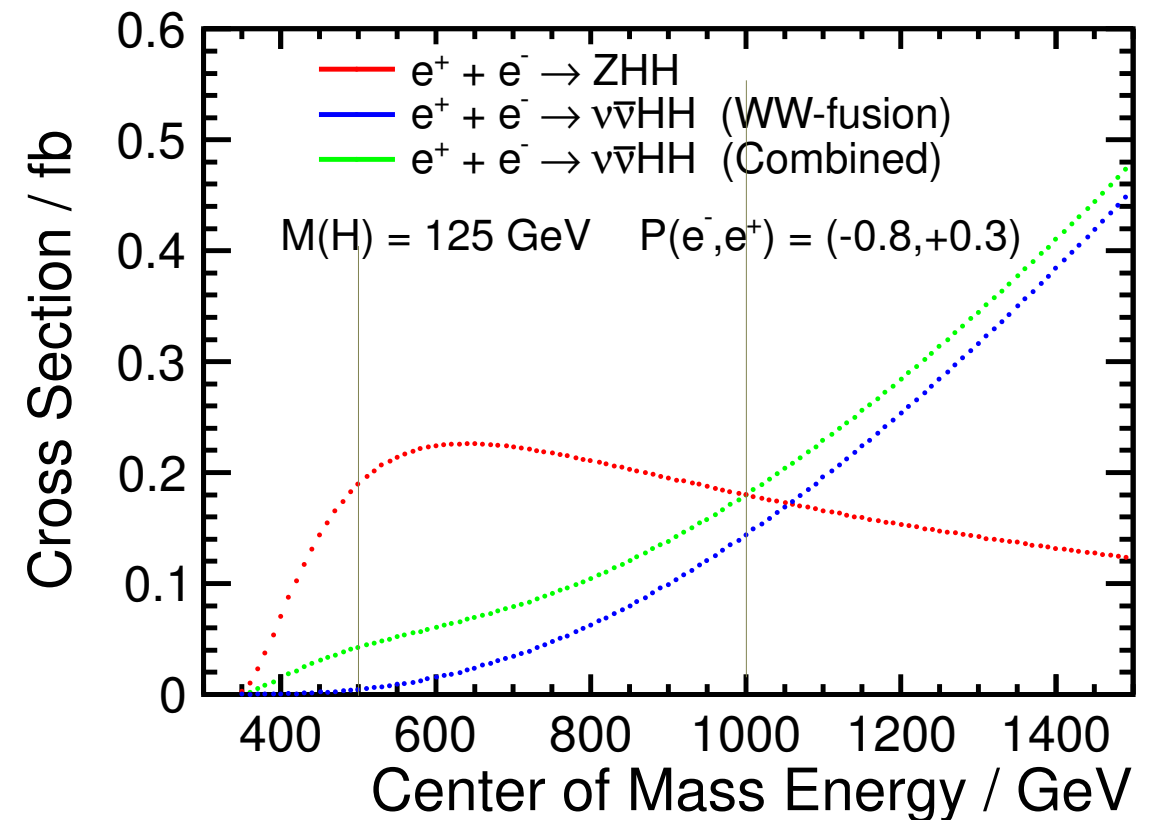
Higgs Self-Coupling

hhh coupling =
consequence of vacuum condensation

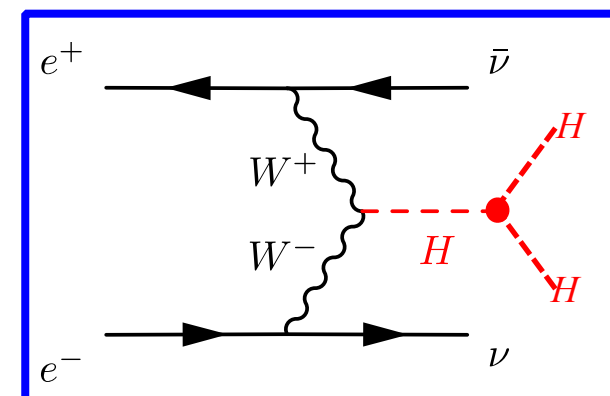
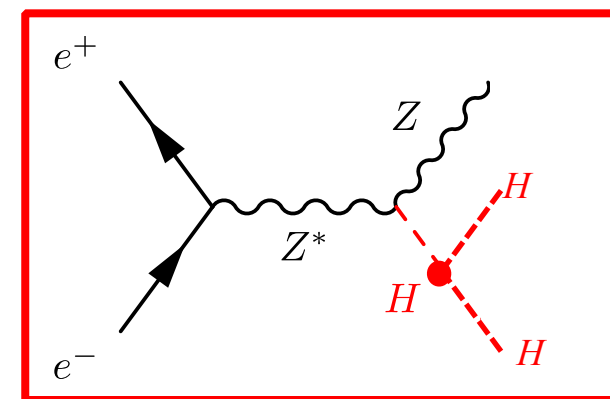


Challenging measurement because of:

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



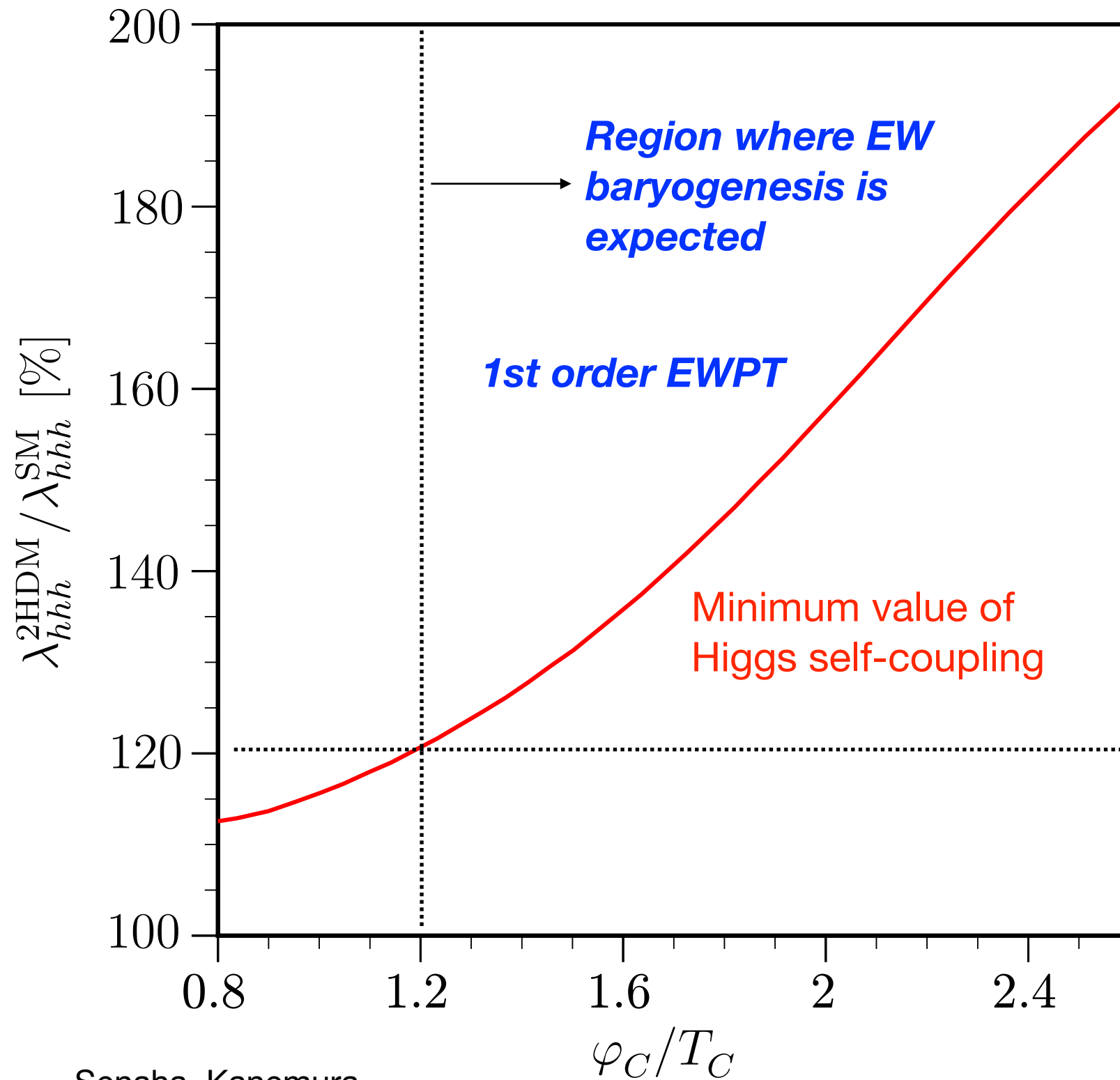
arXiv:1310.0763	ILC500	ILC500-up	ILC1000	ILC1000-up
\sqrt{s} (GeV)	500	500	500/1000	500/1000
$\int \mathcal{L} dt$ (fb $^{-1}$)	500	1600 †	500+1000	1600+2500 †
$P(e^-, e^+)$	(-0.8, 0.3)	(-0.8, 0.3)	(-0.8, 0.3/0.2)	(-0.8, 0.3/0.2)
$\sigma(ZHH)$	42.7%		42.7%	23.7%
$\sigma(\nu\bar{\nu}HH)$	—	—	26.3%	16.7%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



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

See J.Tian's Poster

Electroweak Baryogenesis



Senaha, Kanemura

Example:

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***

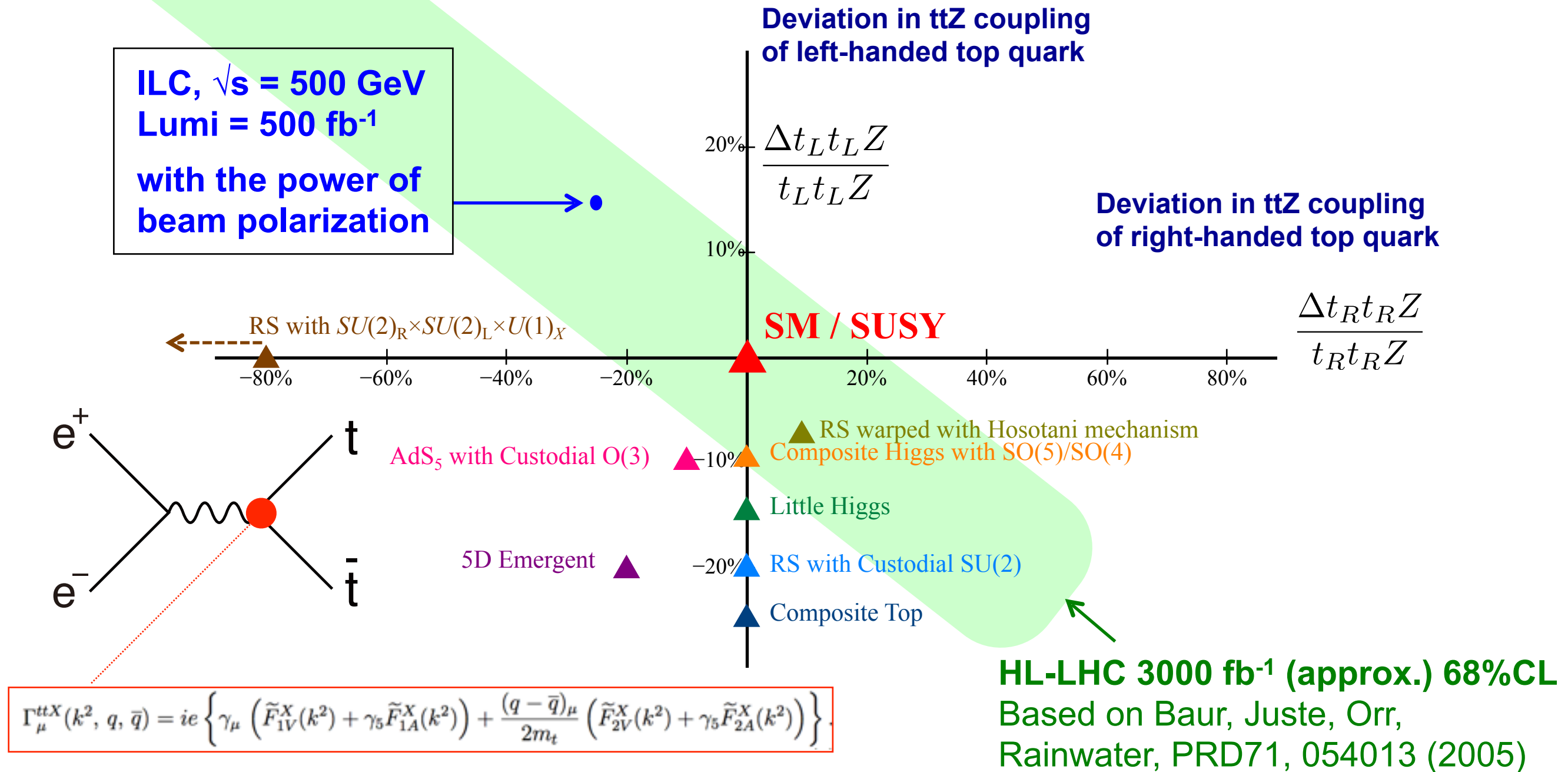
ILC can test the idea of ***baryogenesis occurring at the electroweak scale.***

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

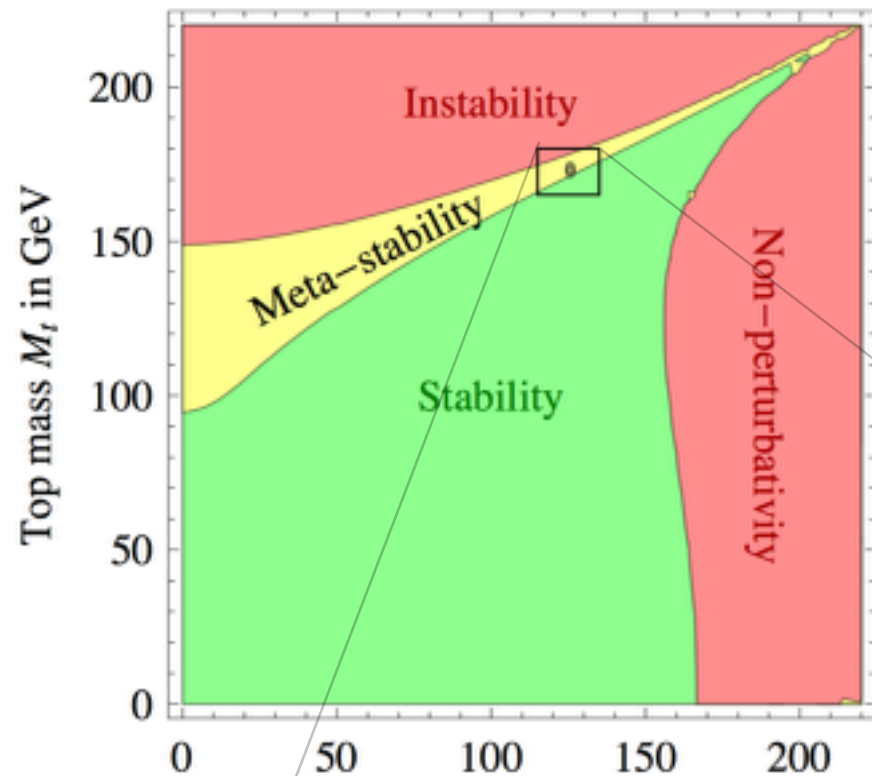
SM up to Λ_{Planck} ?

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.

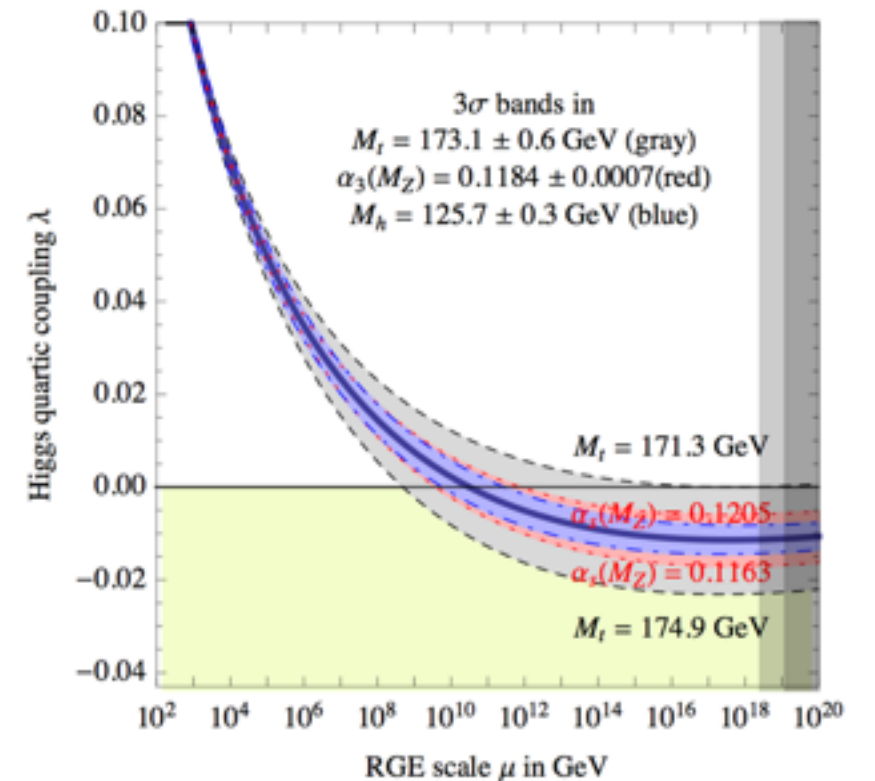
How far can the SM go?

Stability of SM Vacuum

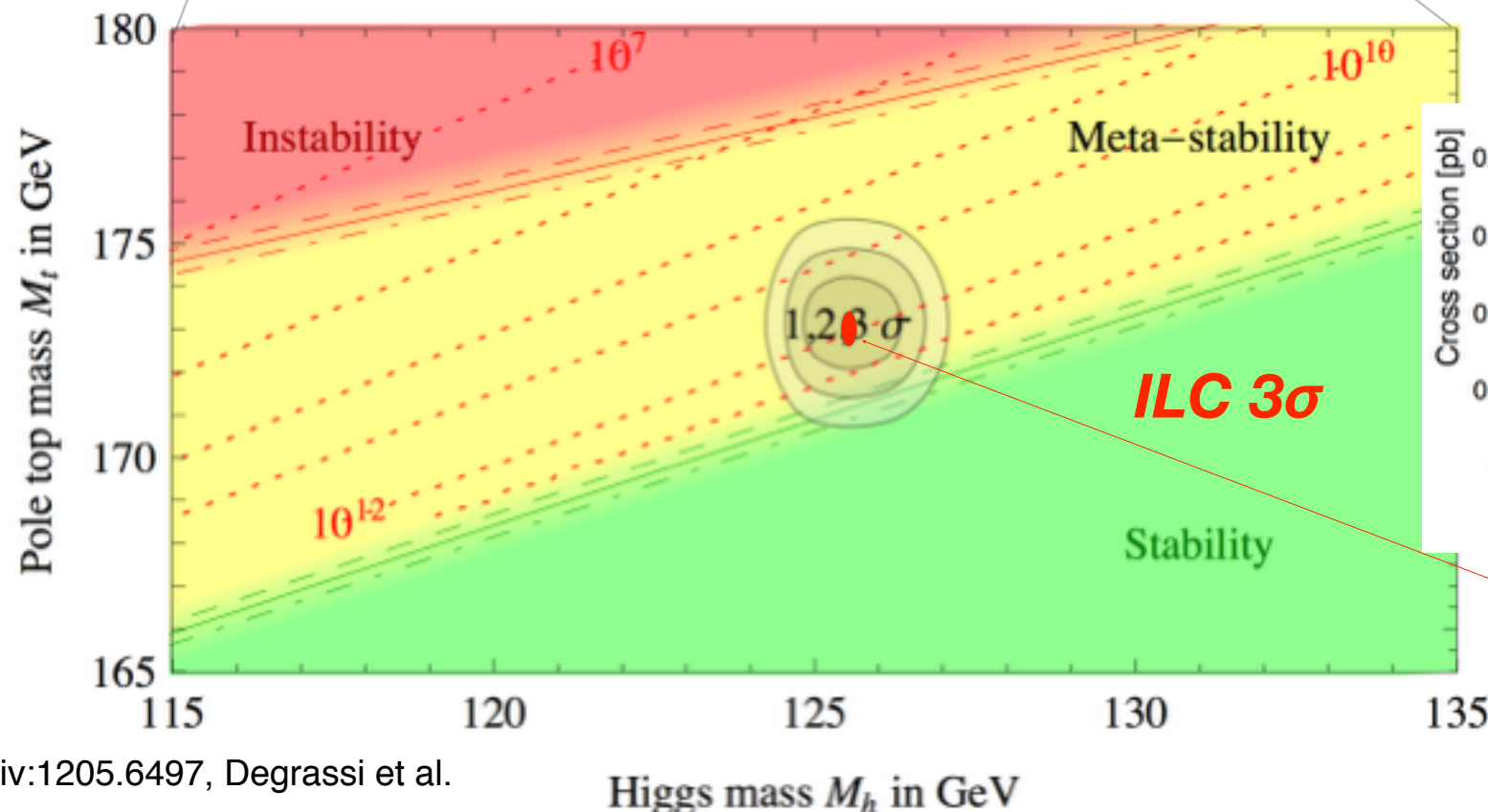


With the 125GeV Higgs boson, the SM vacuum seems to be at a subtle point of meta-stability!

Does λ really become negative below Λ_{PI} ?
or $\lambda(\Lambda_{PI}) = 0$?

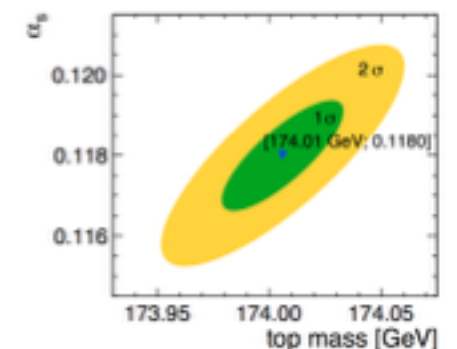
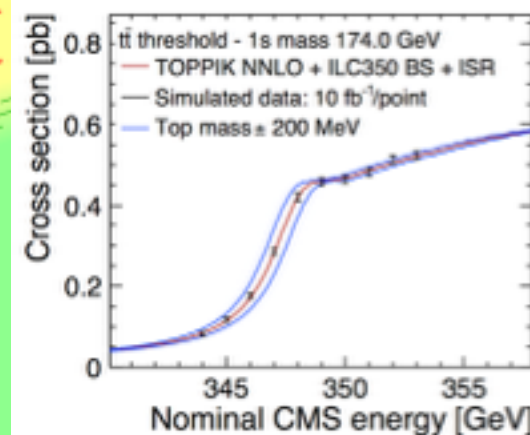


To answer this we need a precision m_t measurement!



Top Pair Threshold

Theoretically very clean measurement of m_t



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

$$\Delta m_H = 30 \text{ MeV}$$

ILC pins down the location !

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)

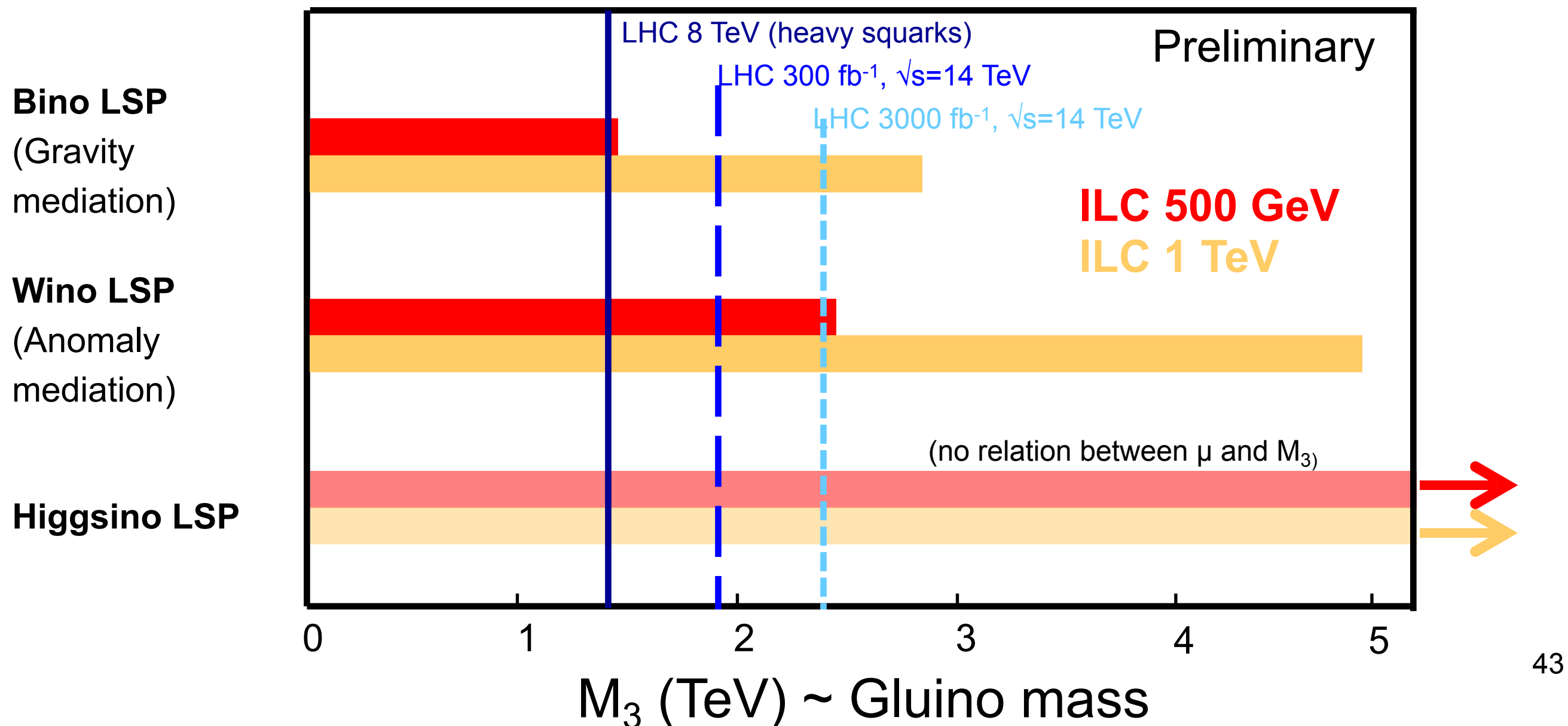
Sensitivity to SUSY

[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

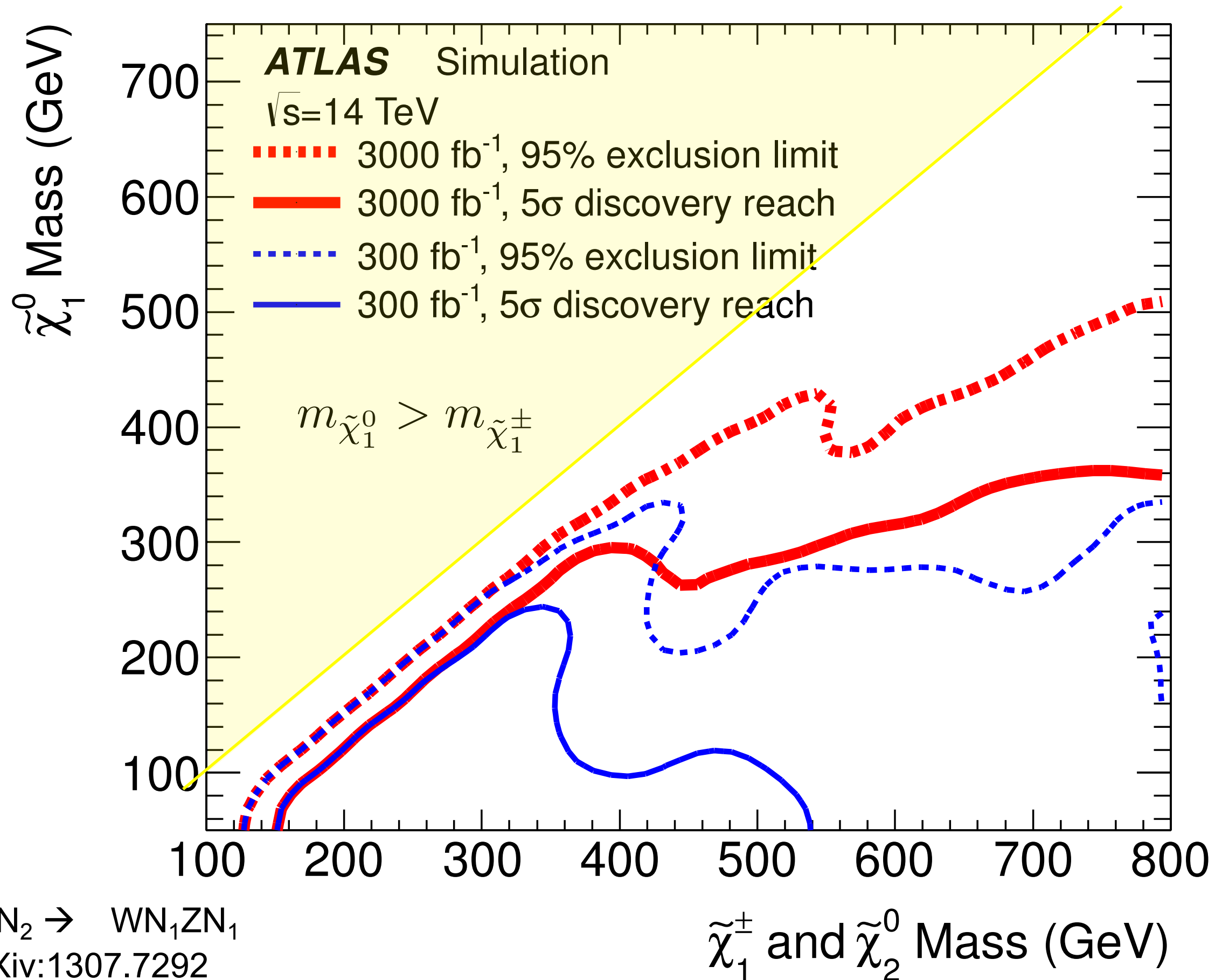
Compare using gaugino mass relations



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

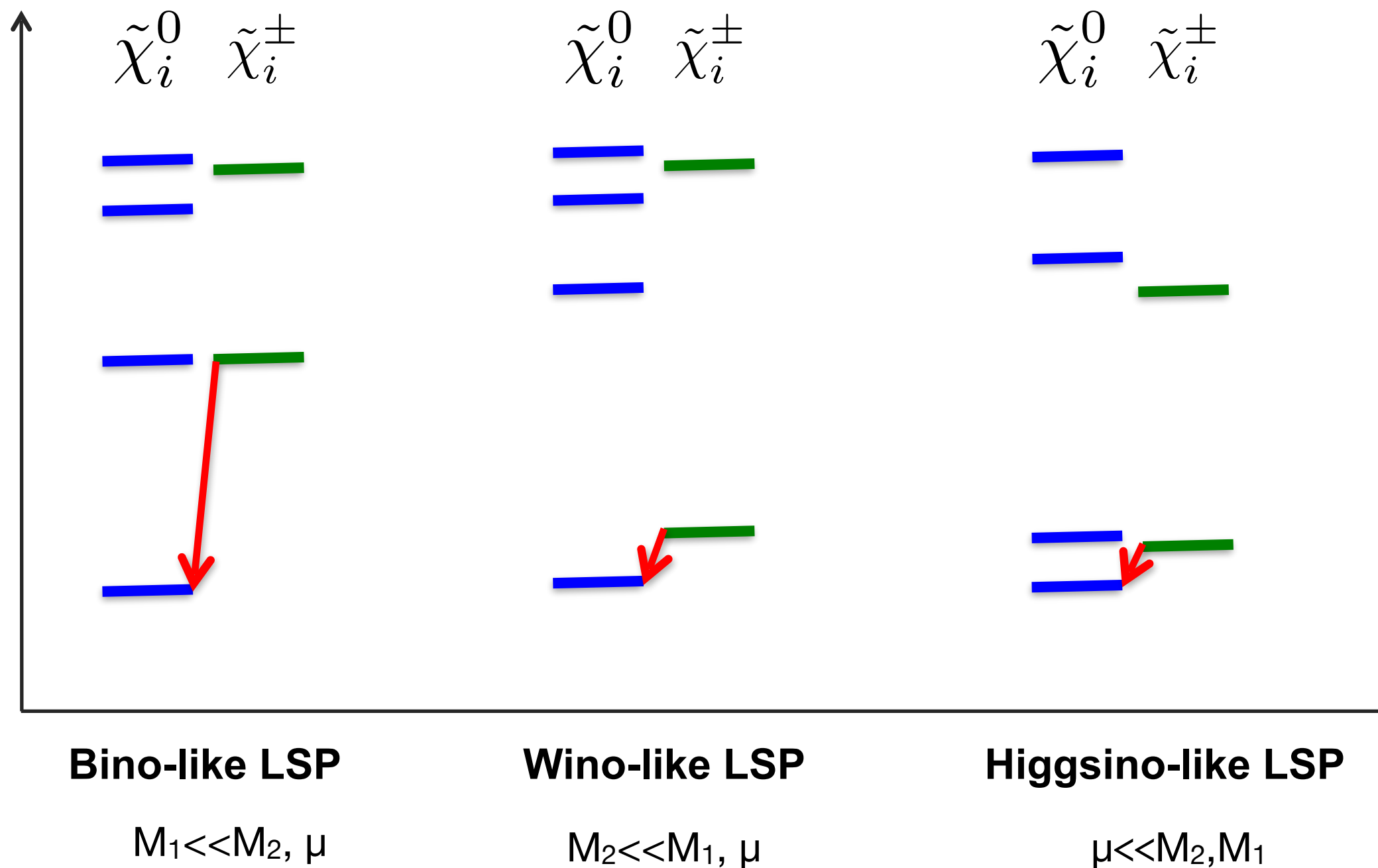
**But, LHC can also
search for direct
EWkino production**

SUSY EW @ HL-LHC

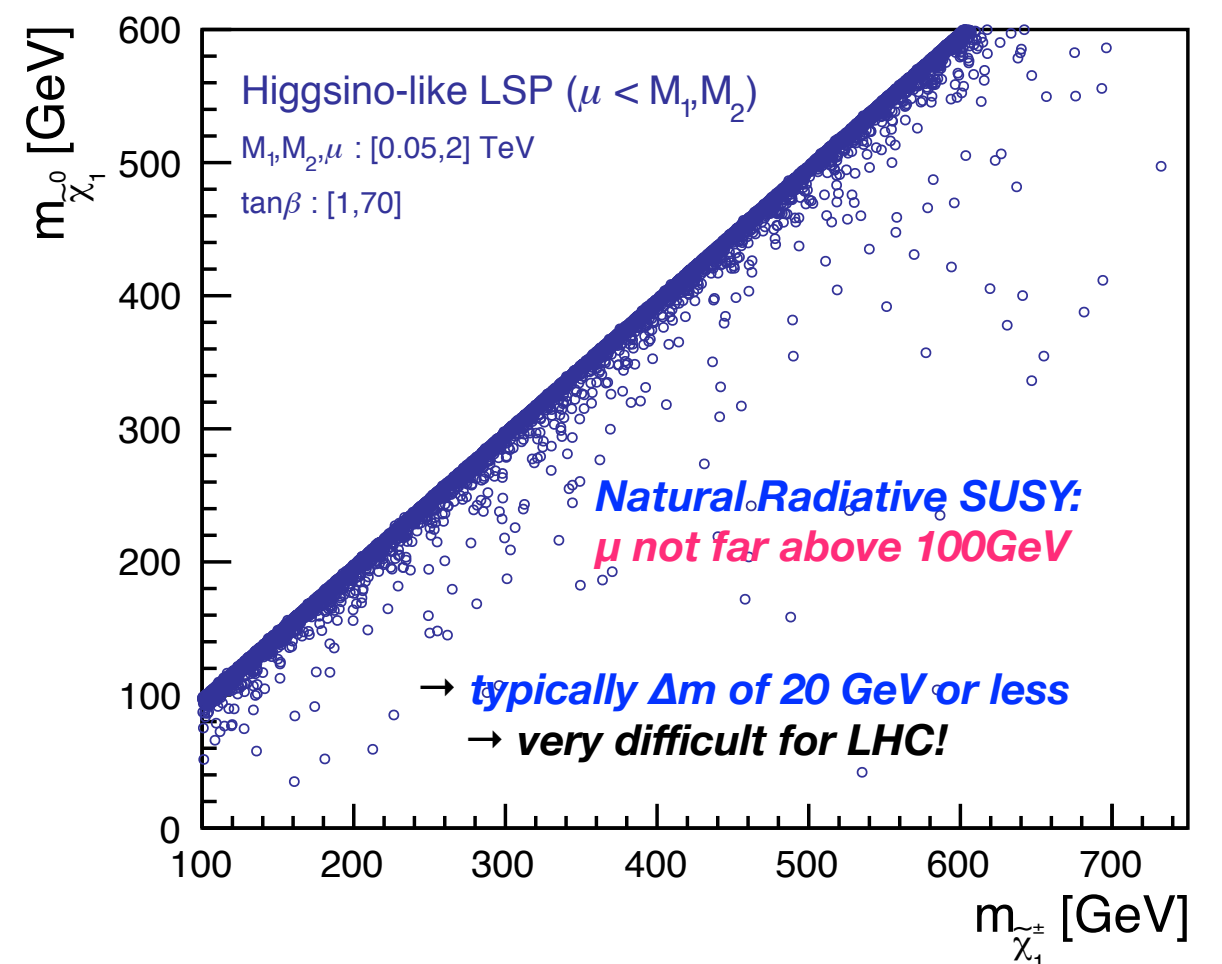
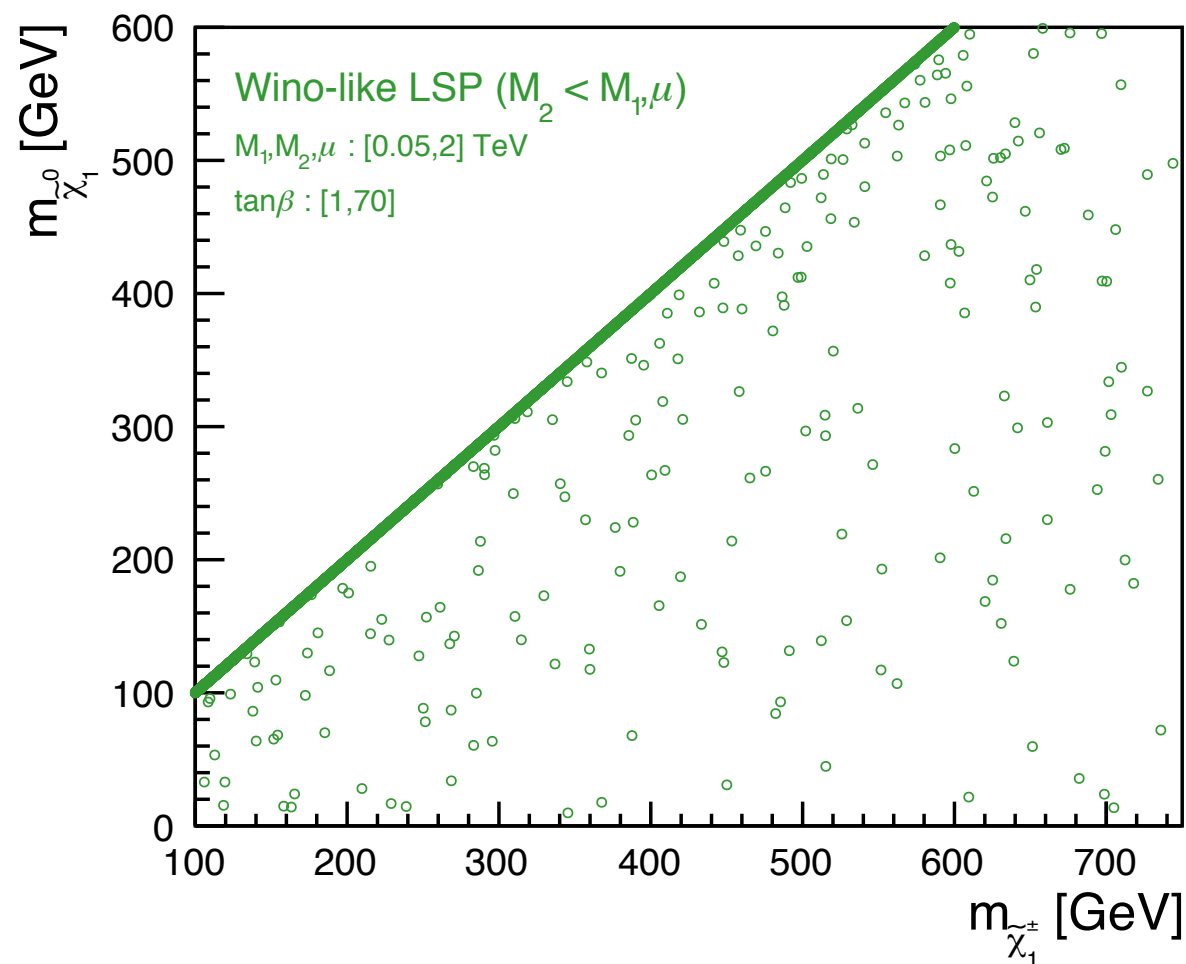
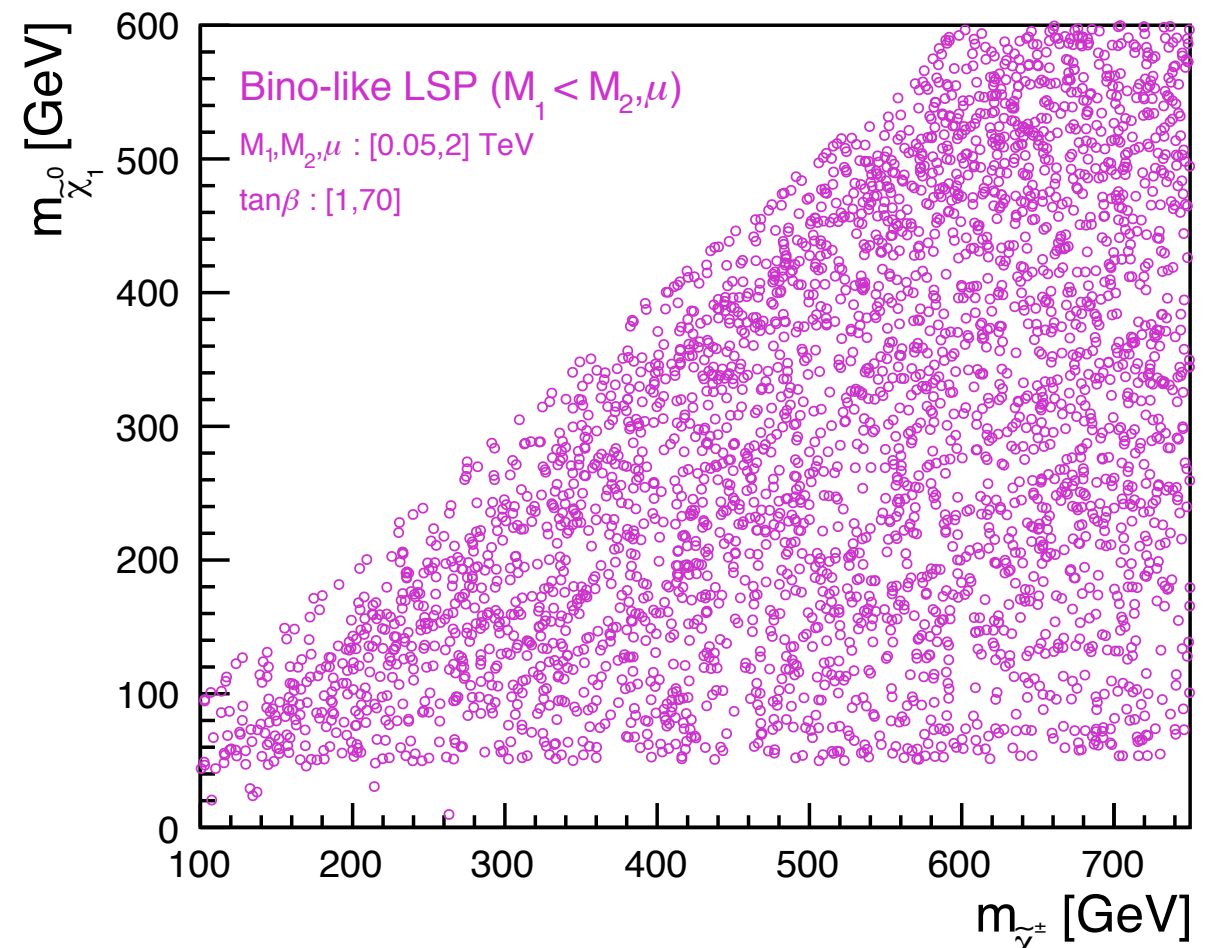
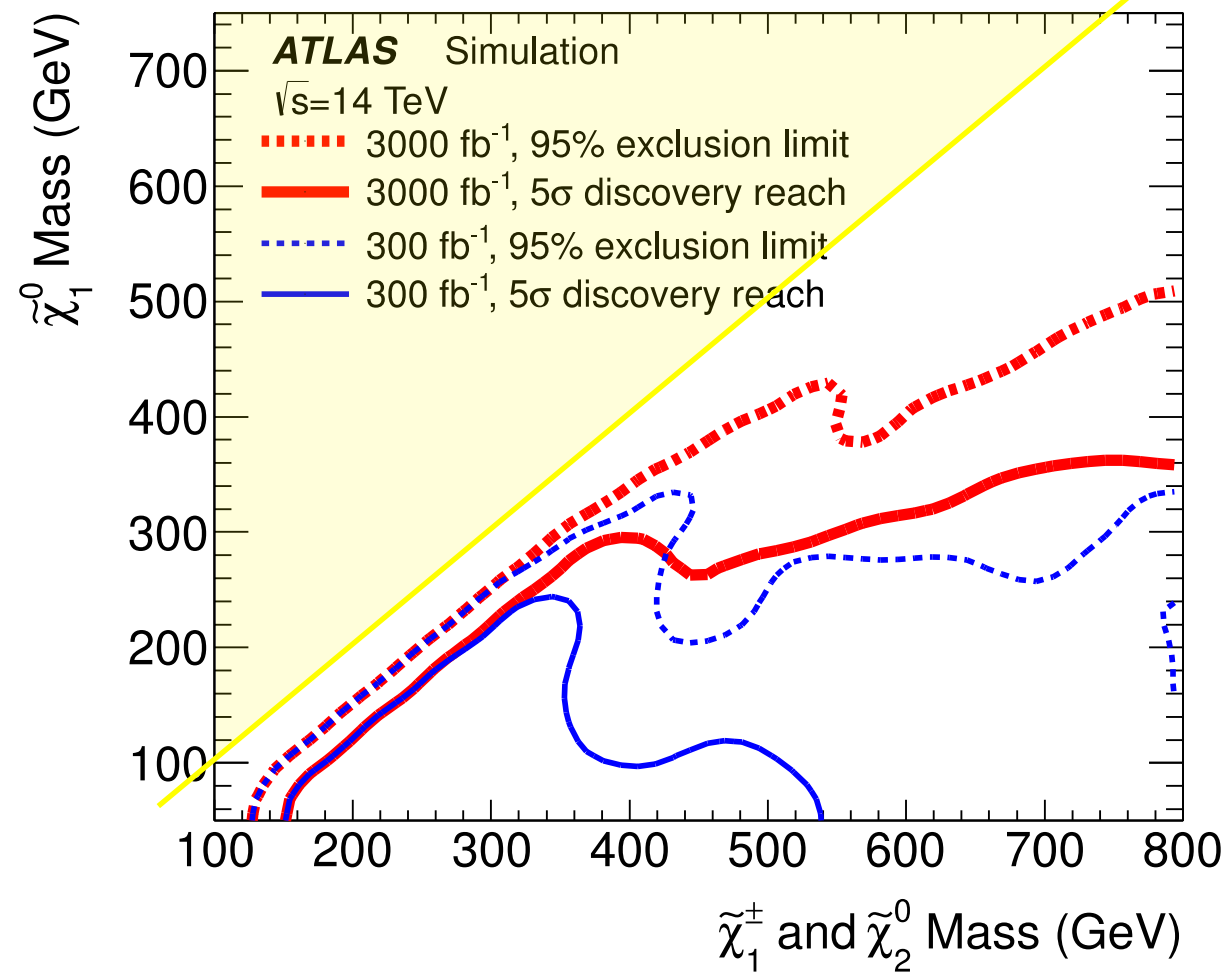


**Is it only a tiny corner
in the parameter
space
that will be left?
Is ILC a gleaner?**

SUSY Electroweak Sector



LSP/NLSP typically degenerate
(depends on mixing)



Higgsinos in Natural SUSY ($\Delta M < \text{a few GeV}$)

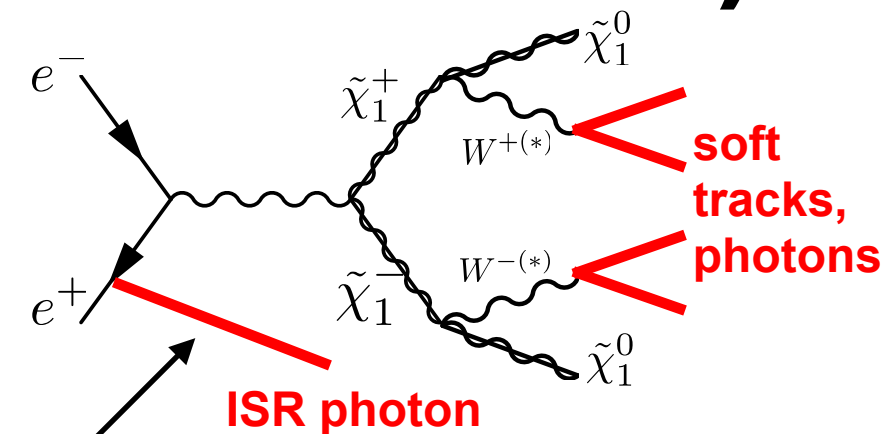
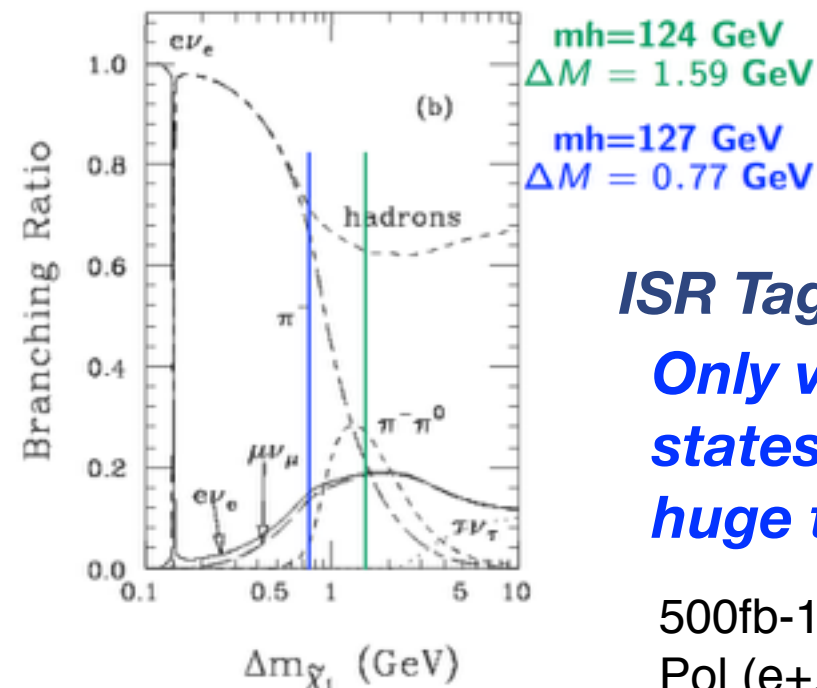
ISR Tagging

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

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

ILC as a Higgsino Factory

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

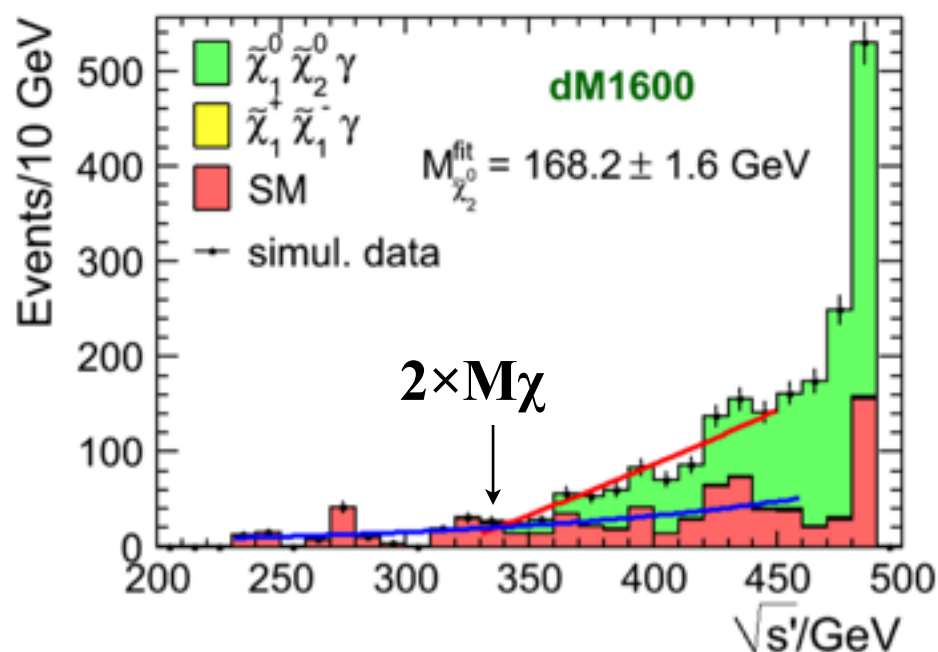
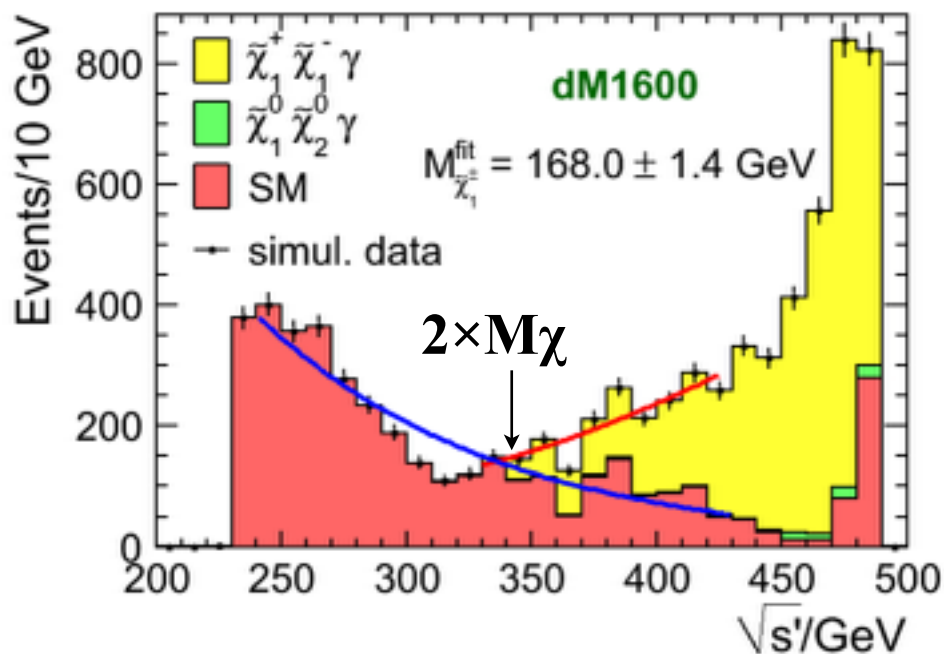


ISR Tagging

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)



EPJC (2013) 73:2660

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	$\sim 2 - 3 \times 10^3$

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

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	$\sim 2 - 3 \times 10^3$

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

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

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

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

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

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

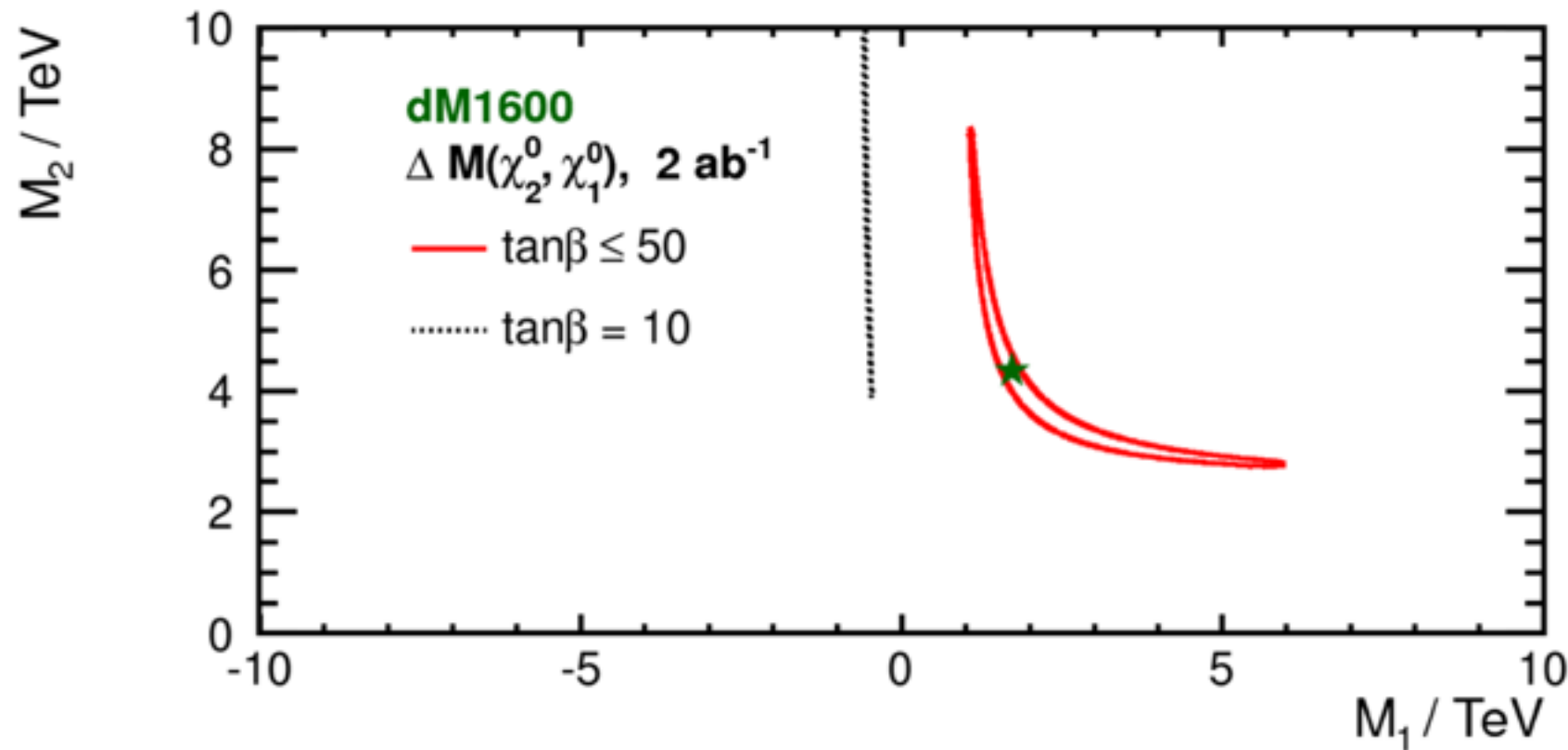
$$\delta \Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \simeq 20 \text{ MeV}$$

Extracting M1 and M2

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

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

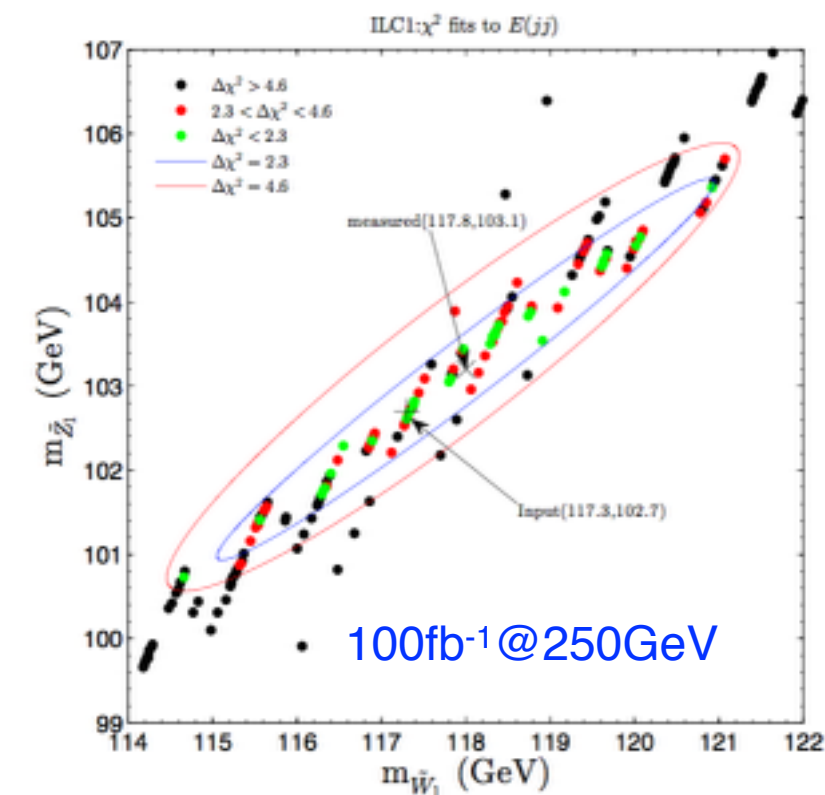
Hale Sert
ECFA LCWS 2013, DESY
Berggren et al. EPJC (2013)
73:2660



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

RNS: Baer et al.
arXiv: 1404.7510

$\Delta M = 15 \text{ GeV}$



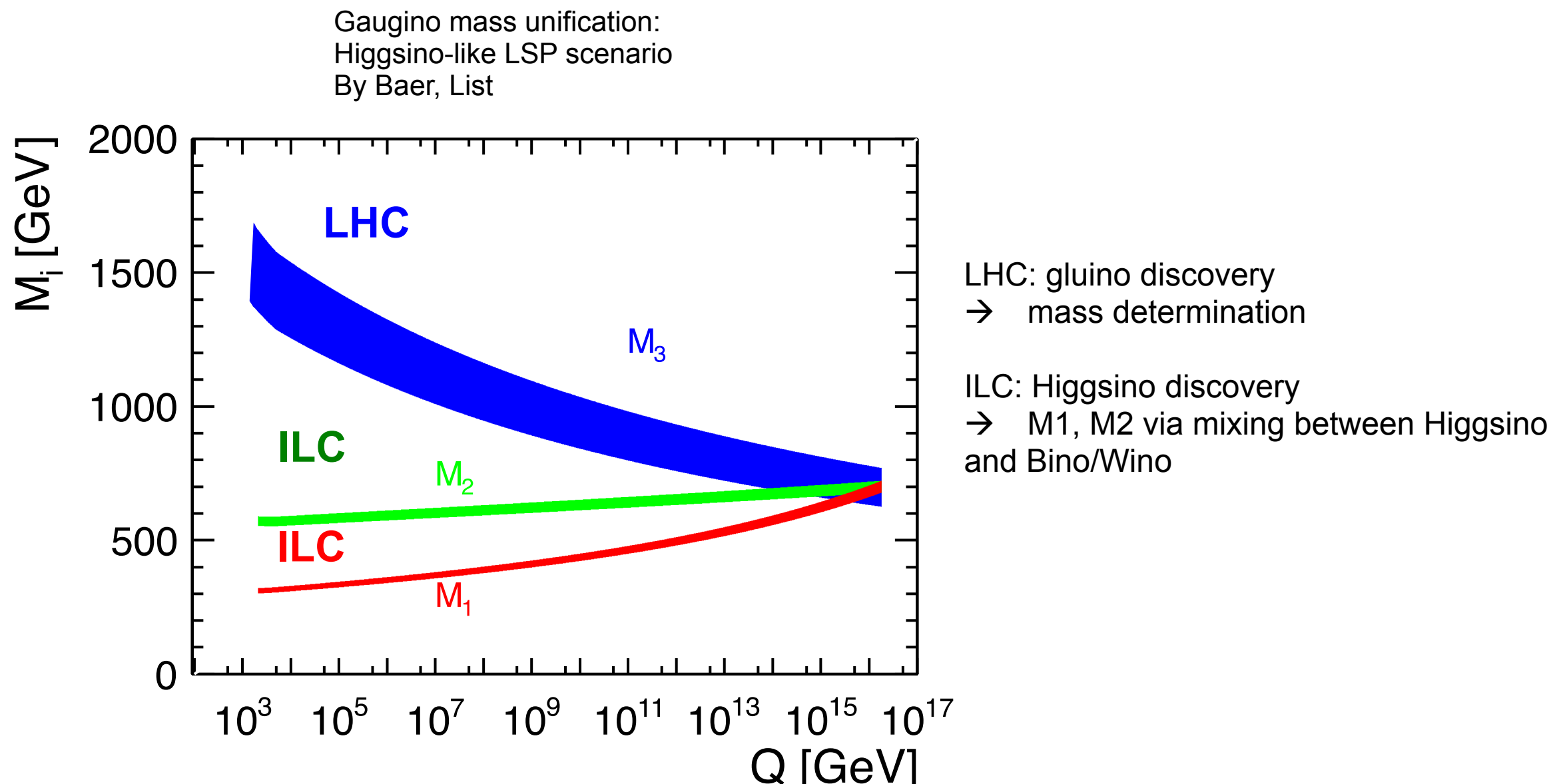
@ 2 ab^{-1}	input	lower	upper
M_1 [TeV]	1.7	~ 1.0 (-0.4)	~ 6.0
M_2 [TeV]	4.4	~ 2.5 (3.5)	~ 8.5
μ [GeV]	165.7	166.2	170.1

In the radiatively driven natural SUSY (RNS) scenario as in arXiv: 1404.7510, $\Delta M \sim 10 \text{ GeV}$, we can determine M_1 and M_2 to a few % or better, allowing us to test GUT relation!

GUT Scale Physics

Test gaugino mass unification

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

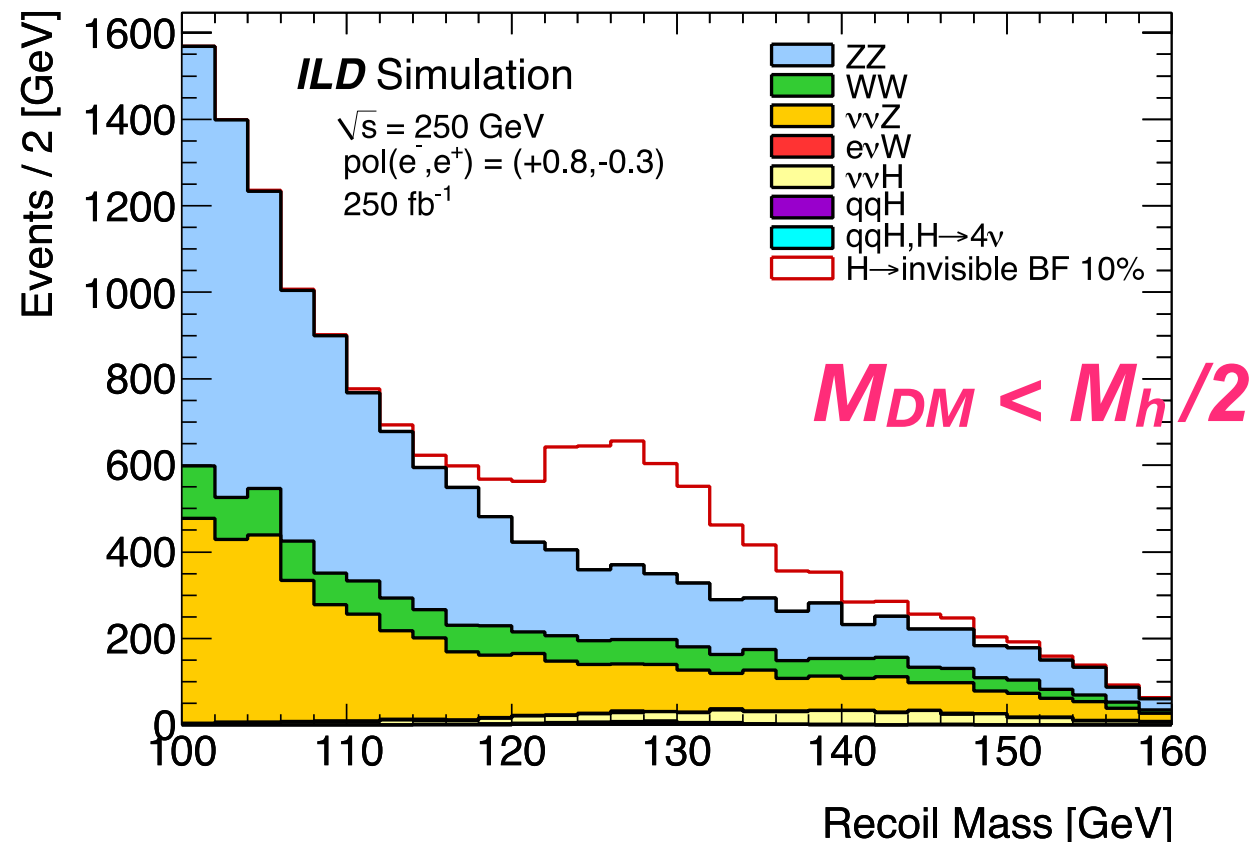


Dark Matter

WIMP Dark Matter @ ILC

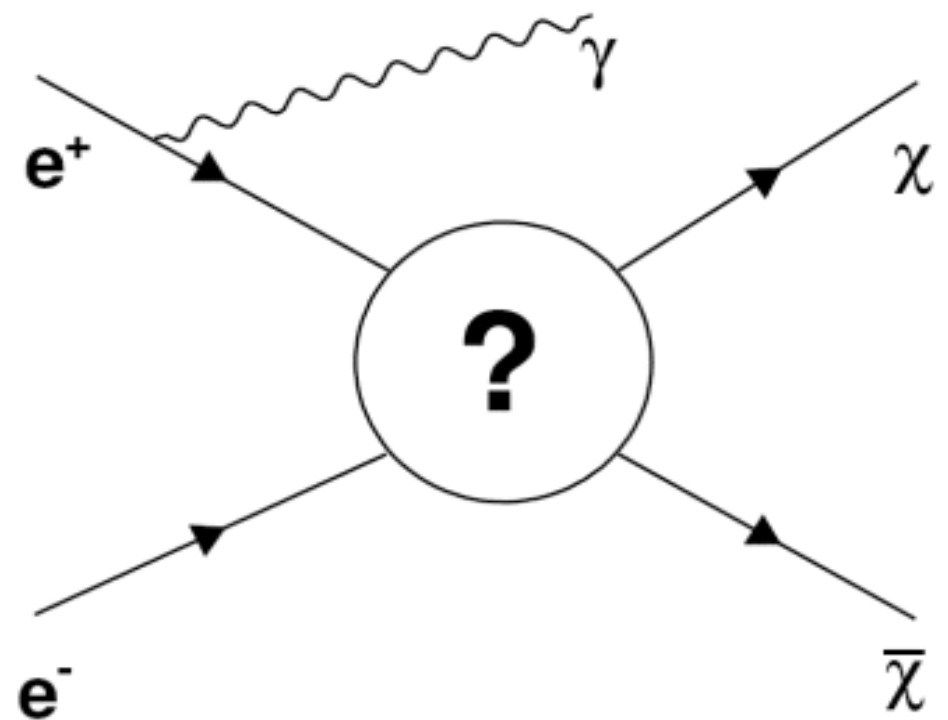
WIMP searches at colliders are complementary to direct/indirect searches.
Examples at the ILC:

Higgs Invisible Decay



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

Mono-photon Search



$\rightarrow M_{DM} \text{ reach} \sim E_{cm}/2$

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

SUSY-specific signatures (decays to DM)

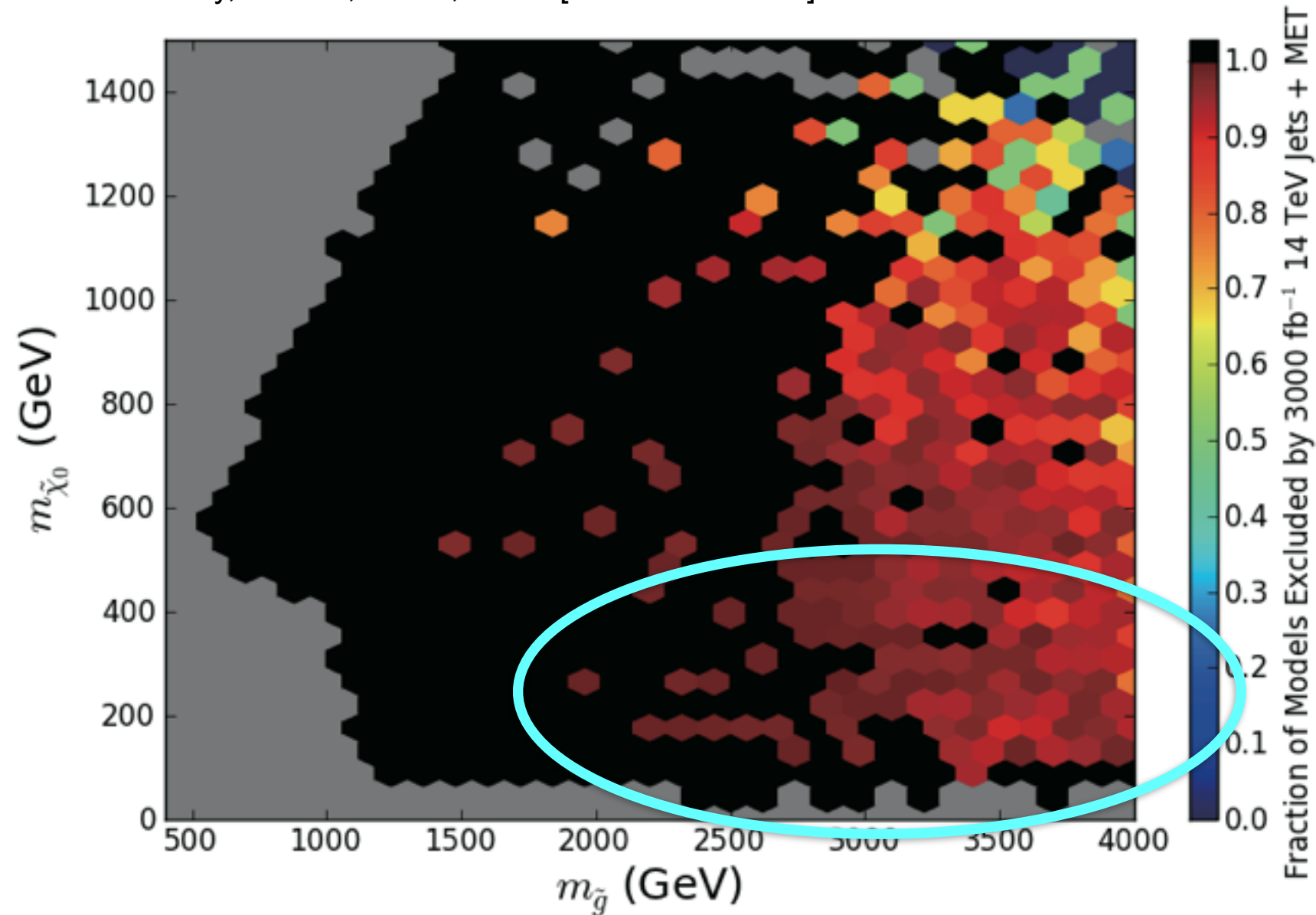
- light Higgsino, light stau, etc.

Dark Matter Search

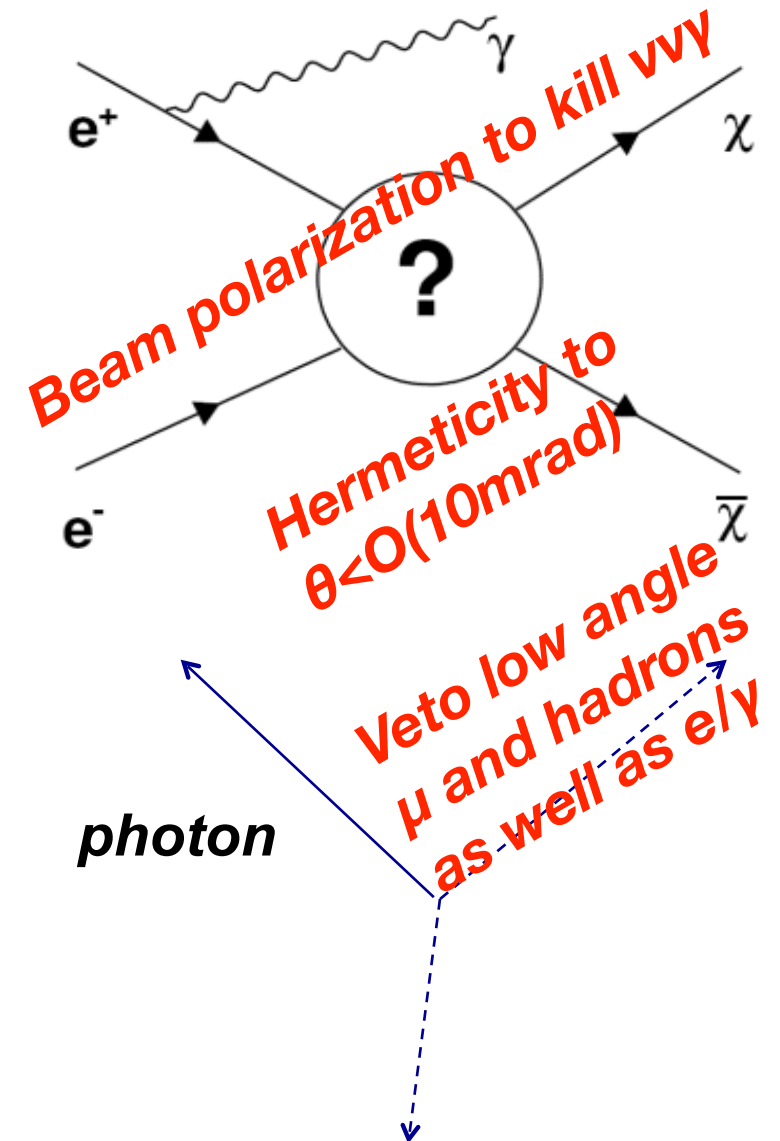
LHC 14 TeV, 3000 fb⁻¹, *Jets+MET* analysis only
pMSSM Neutralino DM expected exclusion

may use mono-jet

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

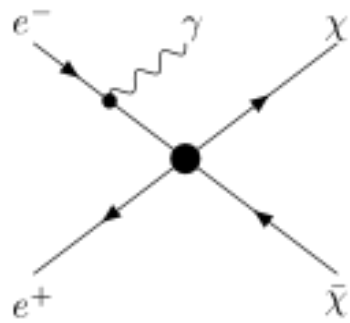


LC:
Mono photon search



Loopholes of HL-LHC → Hunting ground of ILC

DM: Effective Operator Approach

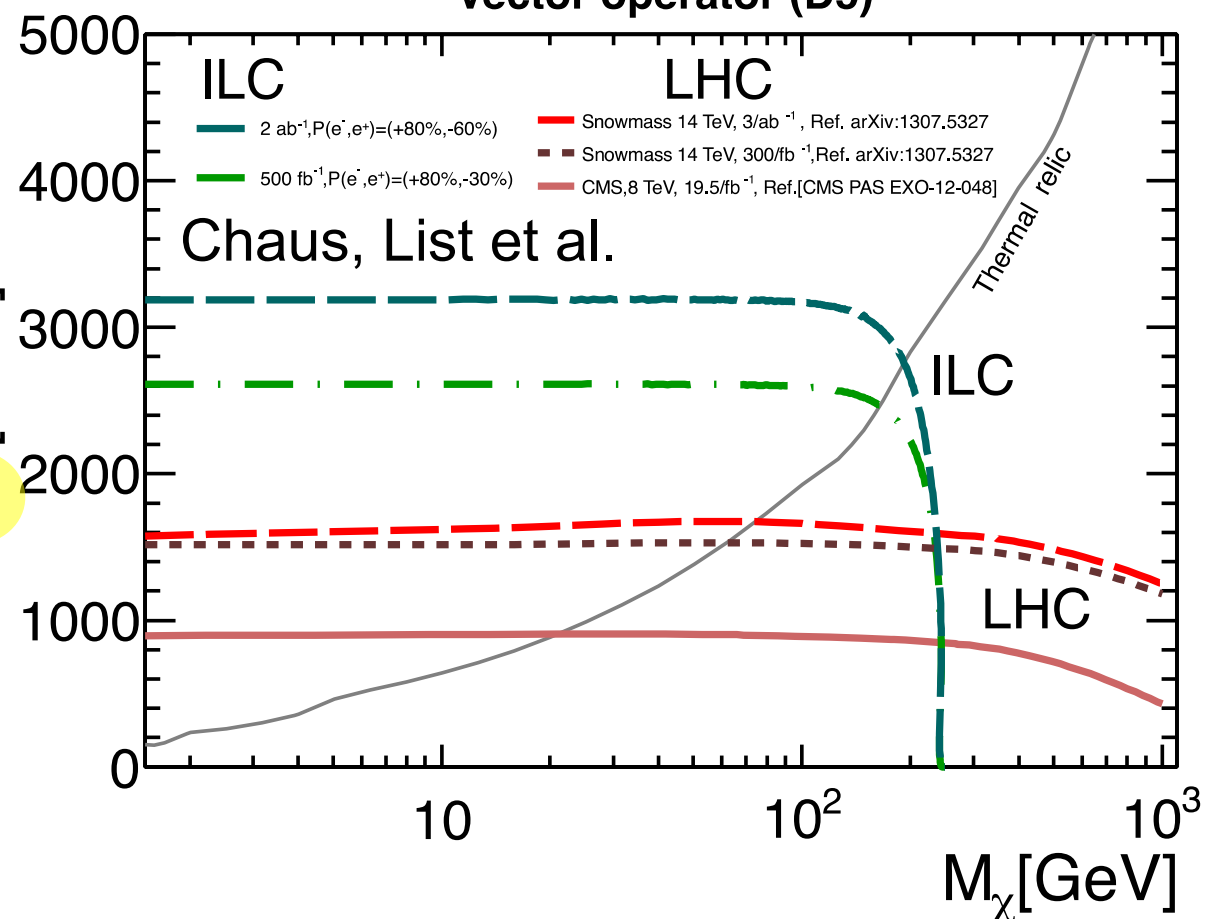


$$\mathcal{L}_{\text{int}} = \frac{1}{\Lambda^2} \mathcal{O}_i$$

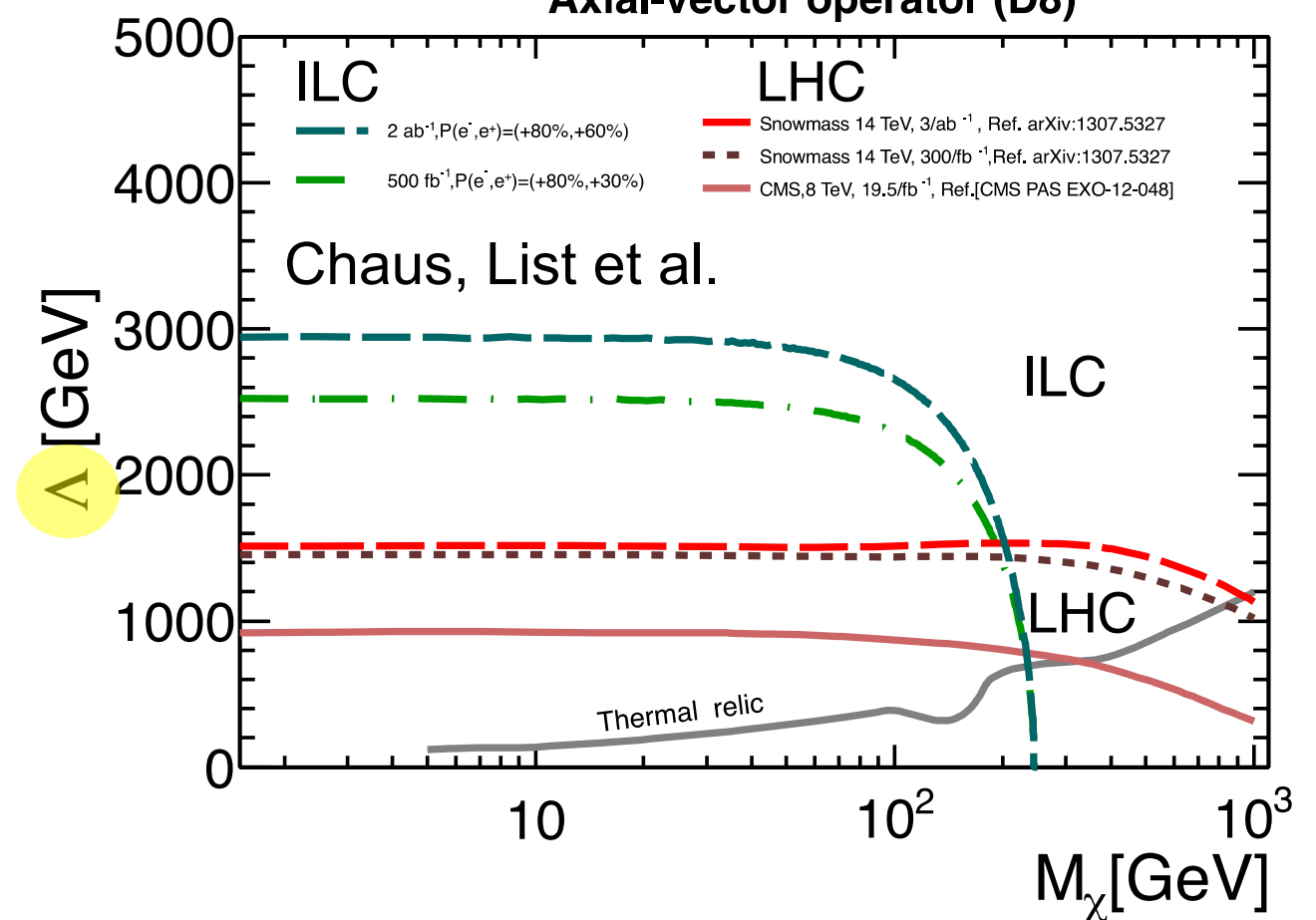
$$\mathcal{O}_V = (\bar{\chi} \gamma_\mu \chi) (\bar{\ell} \gamma^\mu \ell)$$

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

Vector operator (D5)



Axial-vector operator (D8)



LHC sensitivity: Mediator mass up to $\Lambda \sim 1.5$ TeV for large DM mass

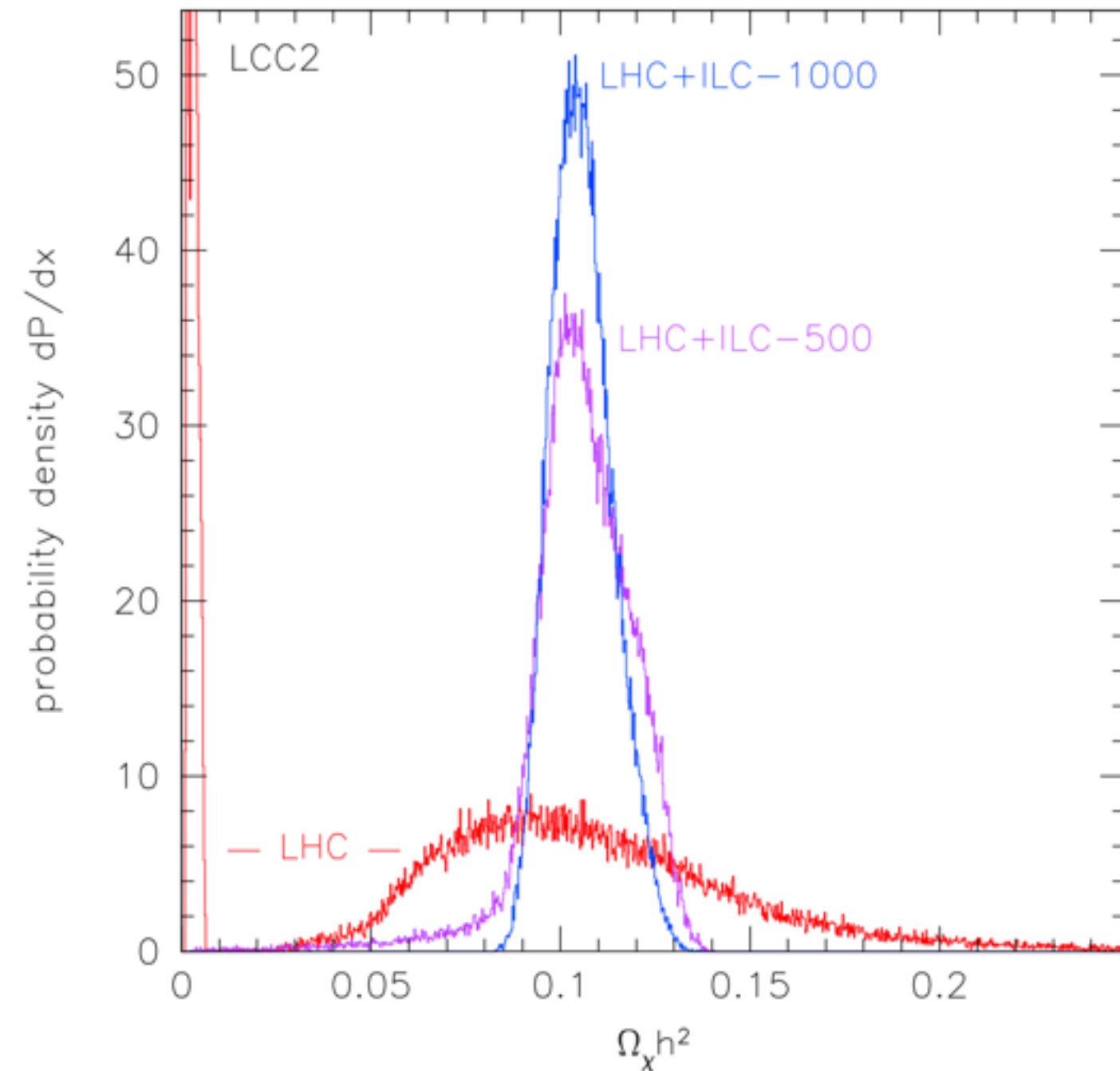
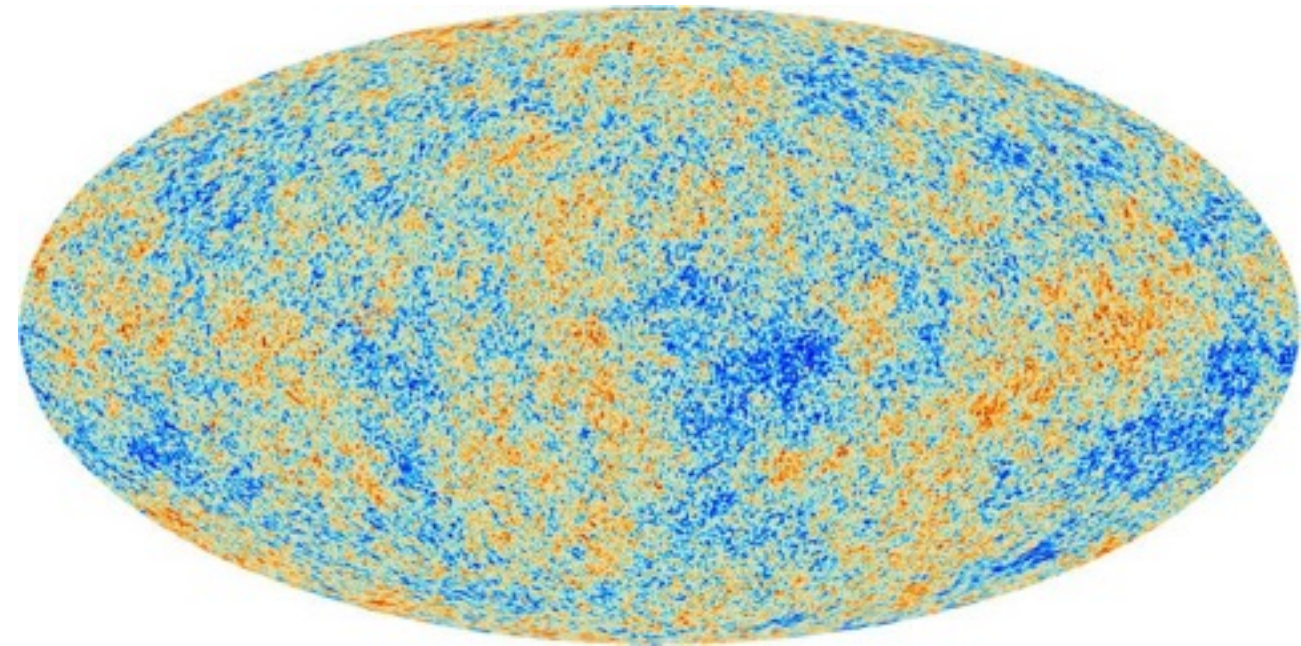
ILC sensitivity: Mediator mass up to $\Lambda \sim 3$ TeV for *DM mass up to $\sim \sqrt{s}/2$*

DM Relic Abundance

WMAP/Planck (68% CL)

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

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

Baltz, Battaglia, Peskin, Wizansky

PRD74 (2006) 103521, arXiv:hep-ph/0602187

**This particular benchmark point is excluded. Update is in progress.*

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 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 answer these questions*** (regardless of BSM scenarios) and we can do this ***model-independently.***
- 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.***
- 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.***

Additional Slides



Higgs

Our Mission = Bottom-up Model-Independent Reconstruction of the EWSB Sector through Precision Higgs Measurements

• Multiplet structure :

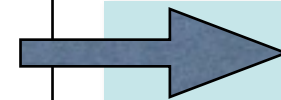
- Additional singlet? $(\phi + S) + \dots?$
- Additional doublet? $(\phi + \phi') + \dots?$
- Additional triplet? $(\phi + \Delta) + \dots?$

• 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, ...
- $\phi + \phi' \rightarrow$ 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), ...
- $\lambda > \lambda_{\text{SM}} \rightarrow$ 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

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

Composite Higgs

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

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

SUSY

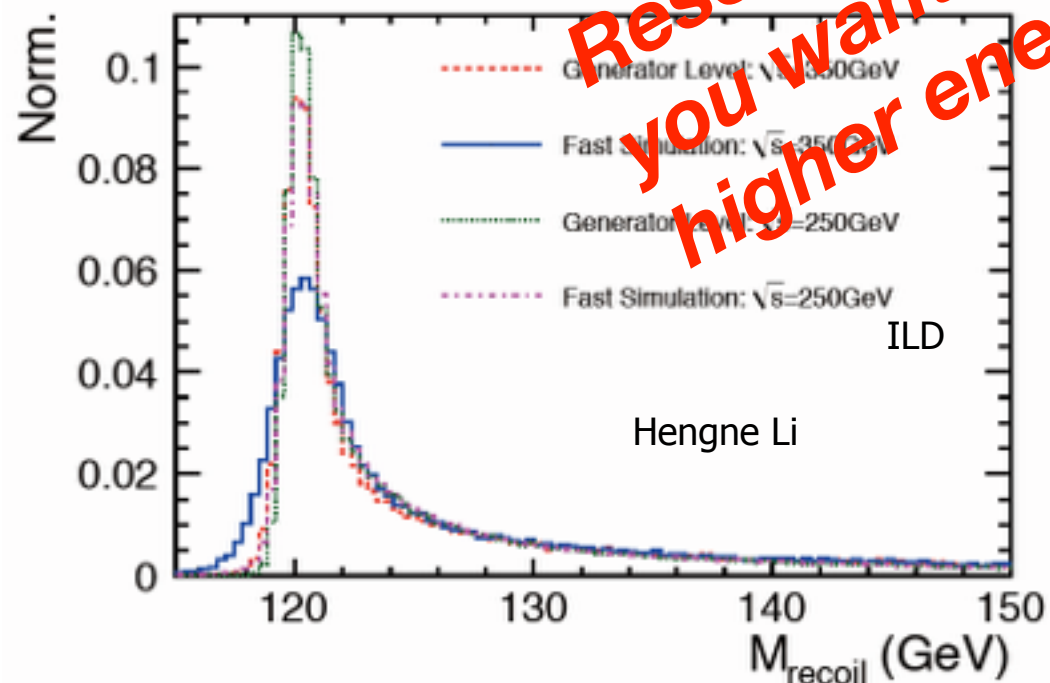
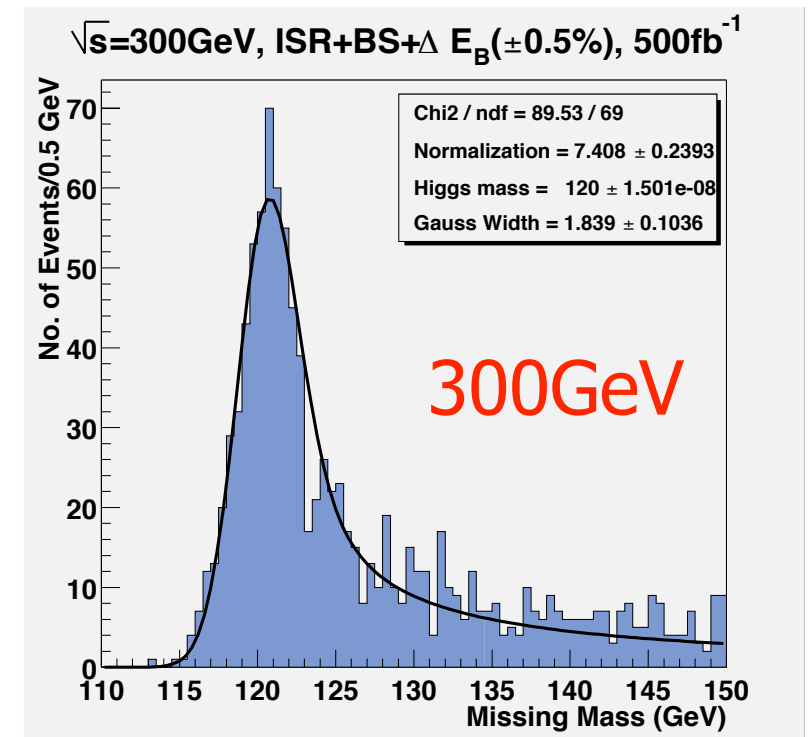
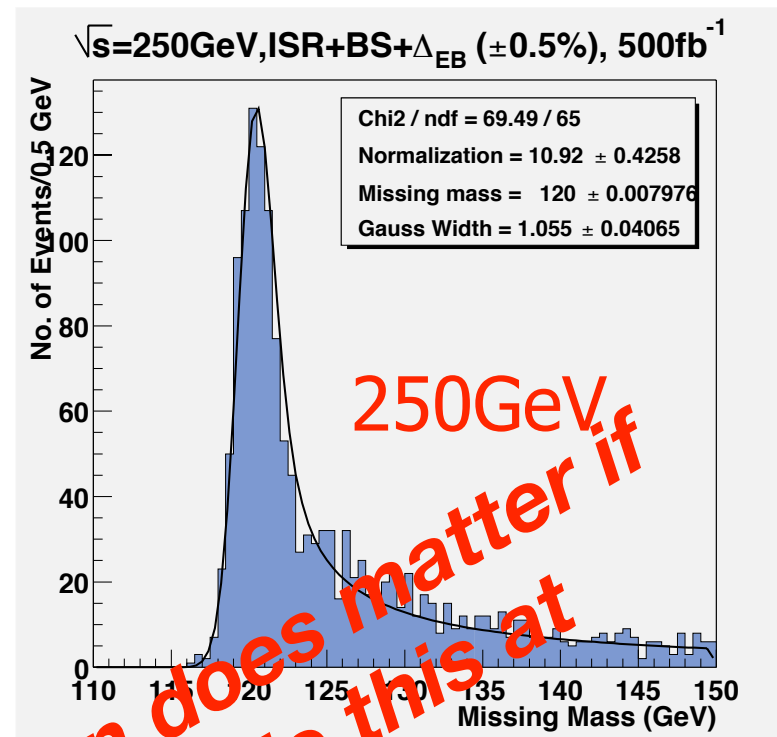
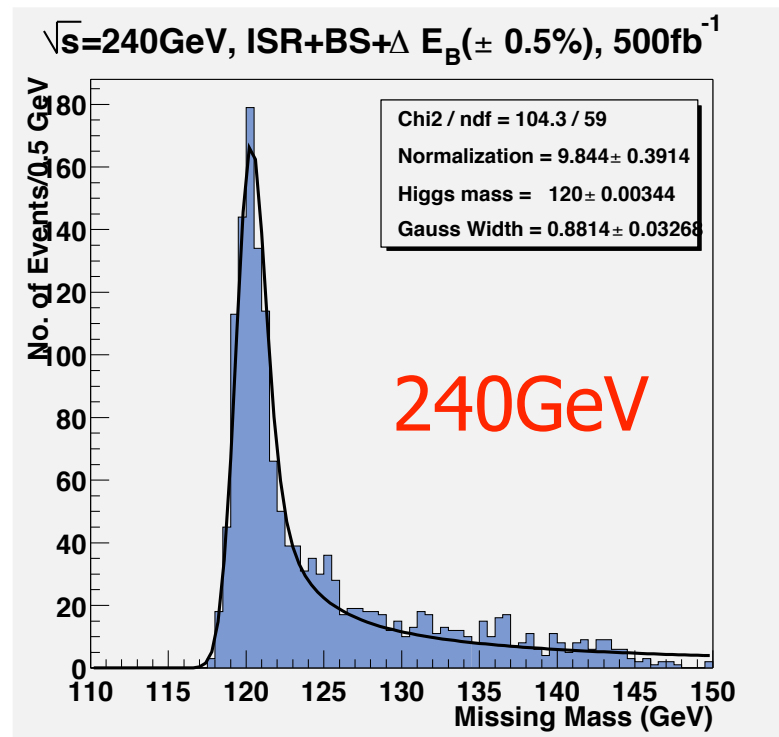
$$\frac{g_{hbb}}{g_{\text{SM}bb}} = \frac{g_{h\tau\tau}}{g_{\text{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1 \text{ TeV}}{m_A} \right)^2$$

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

Recoil Mass Resolution

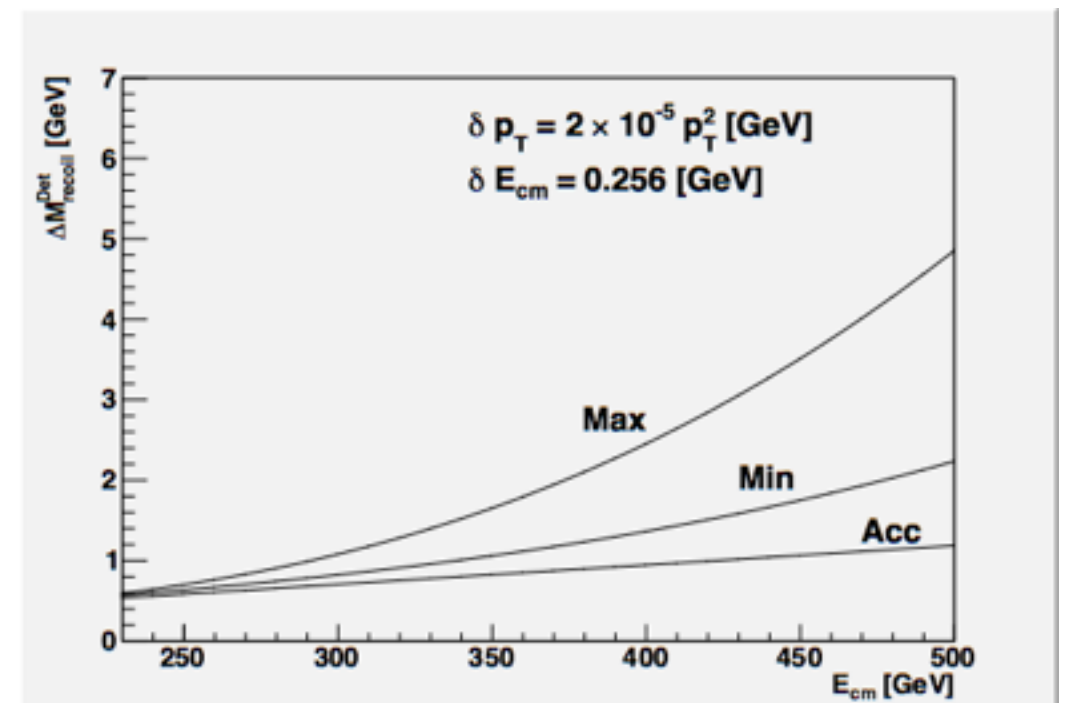
Estimation by simulation

Old ACFA Study
by Akiya Miyamoto



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

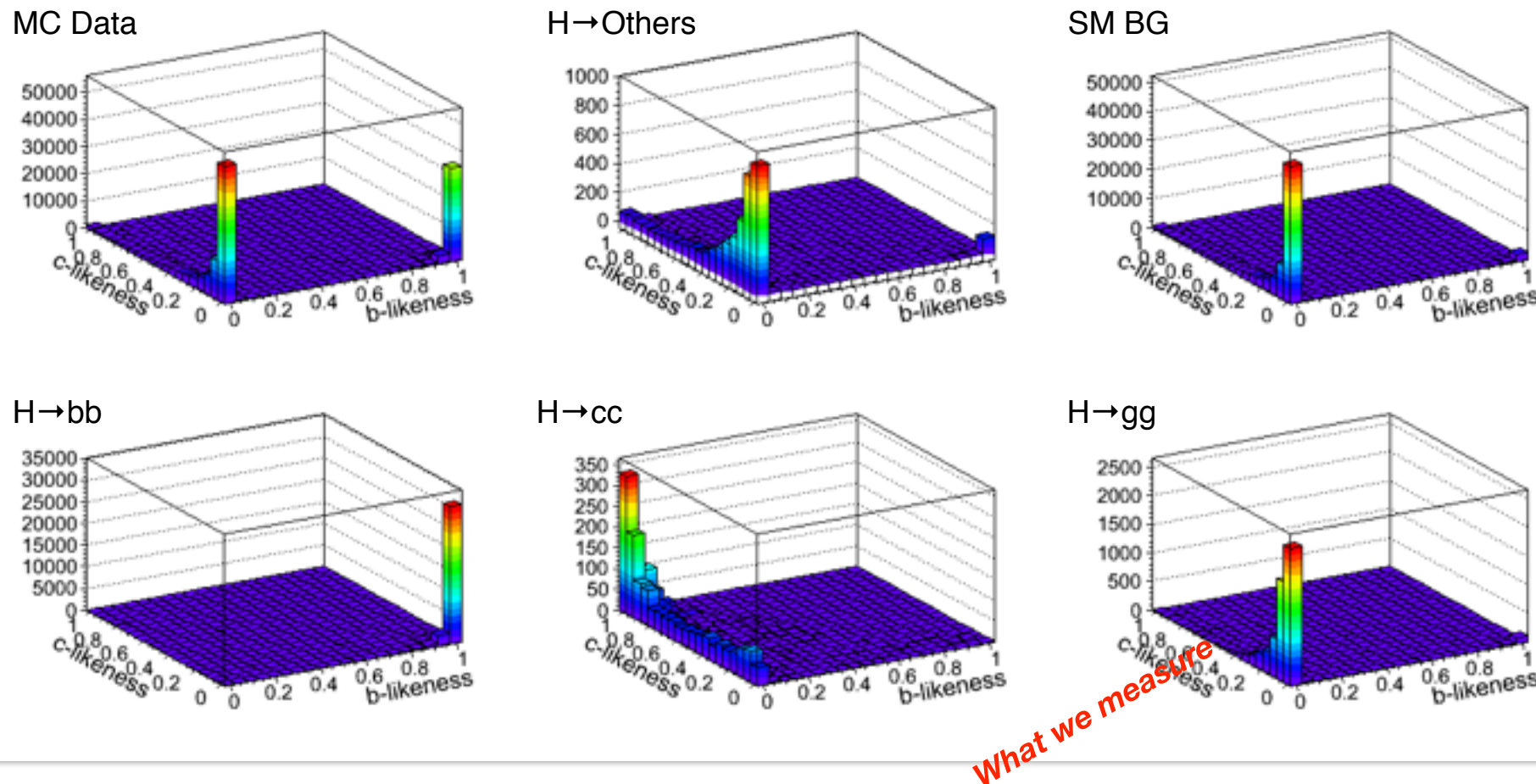
Rough analytic estimate



High Performance Flavor Tagging : The Key

*to directly access major couplings: bb , cc , $\tau\tau$, gg , WW^**

By template fitting, we can separate $H \rightarrow bb$, cc , gg , others!



$250 \text{ fb}^{-1} @ 250 \text{ GeV}$
 $m_H = 125 \text{ GeV}$
 scaled from $m_H = 120 \text{ GeV}$

	@250GeV
process	ZH
Int. Lumi.	250
$\Delta\sigma/\sigma$	2.6%
decay mode	$\Delta\sigma\text{Br}/\sigma\text{Br}$
$H \rightarrow bb$	1.2%
$H \rightarrow cc$	8.3%
$H \rightarrow gg$	7%
$H \rightarrow WW^*$	6.4%
$H \rightarrow \tau\tau$	4.2%

What we measure here is not BR itself but σBR .

$$BR = (\sigma \times BR) / \sigma$$

--> $\Delta\sigma/\sigma=2.6\%$ eventually limits the BR measurements.

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

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)

DBD Physics Chap.

Total Width and Coupling Extraction

One of the major advantages of the LC

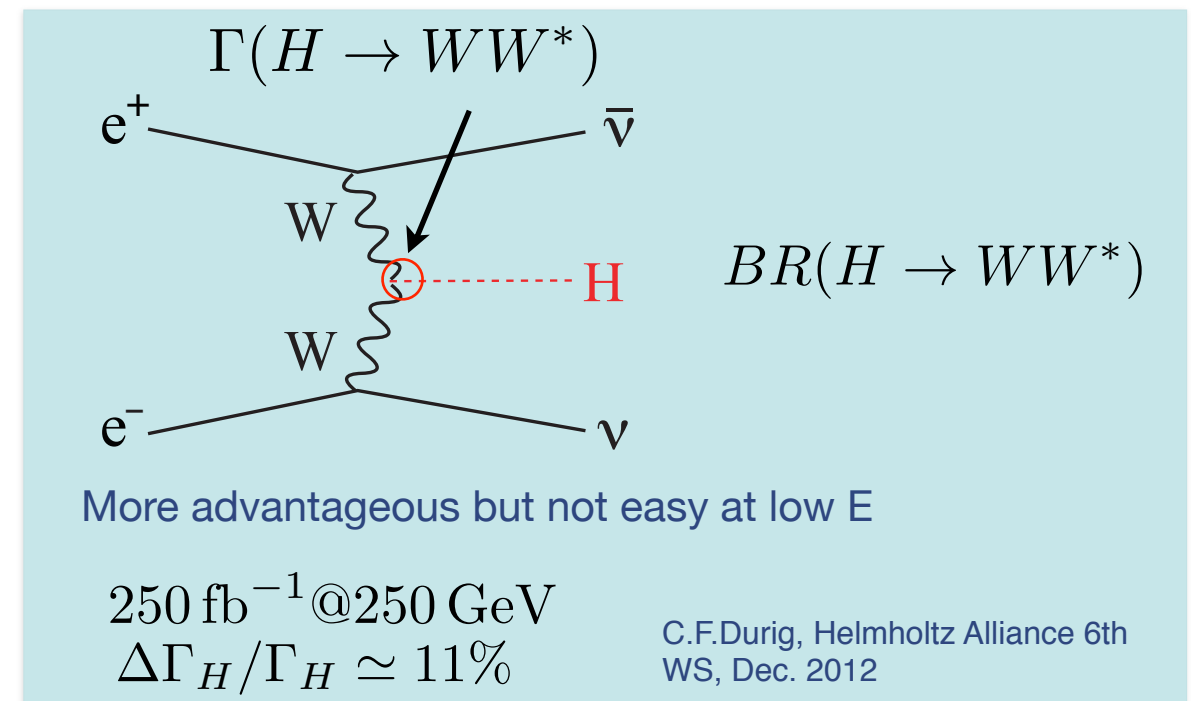
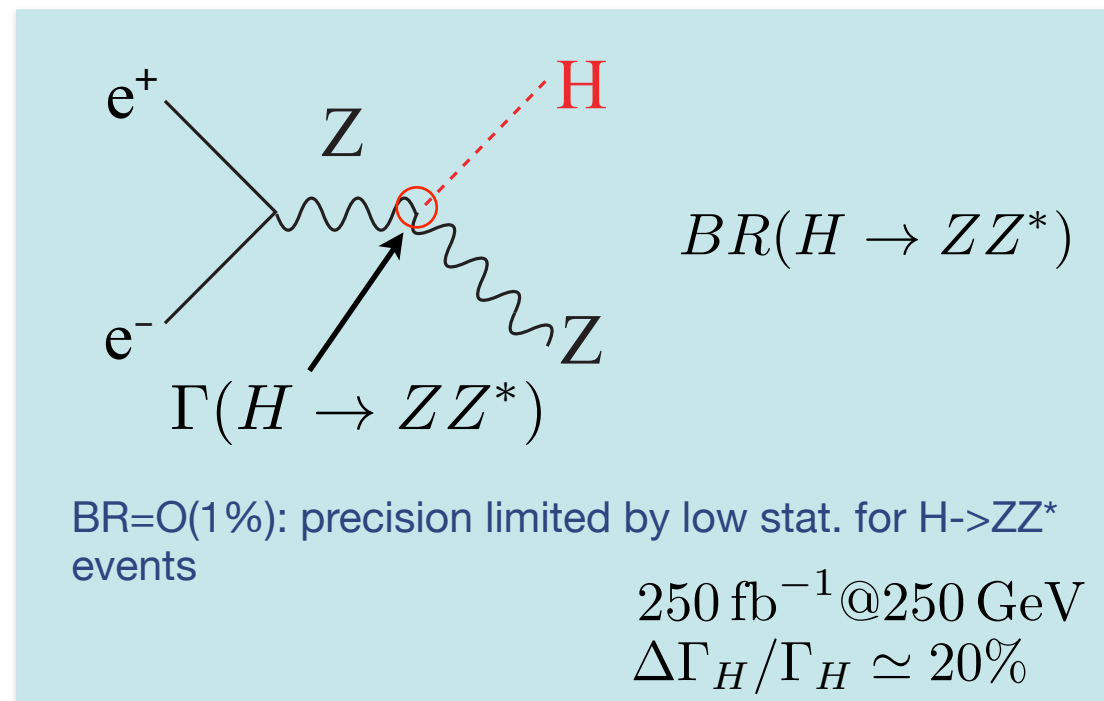
To extract couplings from BRs, we need the total width:

$$g_{HAA}^2 \propto \Gamma(H \rightarrow AA) = \Gamma_H \cdot BR(H \rightarrow AA)$$

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

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

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



What observables limit the coupling precisions?

The 4 most important ones

Y_1 : recoil mass

Y_2 : WW-fusion $h \rightarrow bb$

Y_3 : higgsstrahlung $h \rightarrow bb$

Y_4 : WW-fusion $h \rightarrow WW^$*

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

$$Y_2 = \sigma_{\nu\bar{\nu}H} \cdot \text{Br}(H \rightarrow b\bar{b}) \propto \frac{g_{HWW}^2 g_{Hbb}^2}{\Gamma_H}$$

$$Y_3 = \sigma_{ZH} \cdot \text{Br}(H \rightarrow b\bar{b}) \propto \frac{g_{HZZ}^2 g_{Hbb}^2}{\Gamma_H}$$

$$Y_4 = \sigma_{\nu\bar{\nu}H} \cdot \text{Br}(H \rightarrow WW^*) \propto \frac{g_{HWW}^4}{\Gamma_H}$$

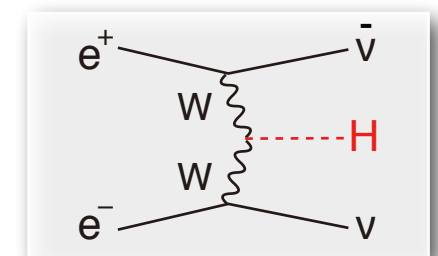
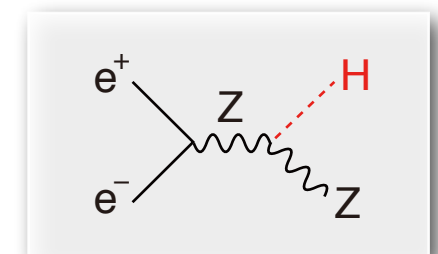
$$\Delta g_{HZZ} \sim \frac{1}{2} \Delta Y_1$$

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

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

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

Both ZH and $\nu\bar{\nu}H$ productions matter!



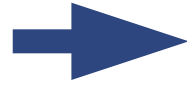
For more details, see J.Tian @ Tokusui Workshop 2013

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

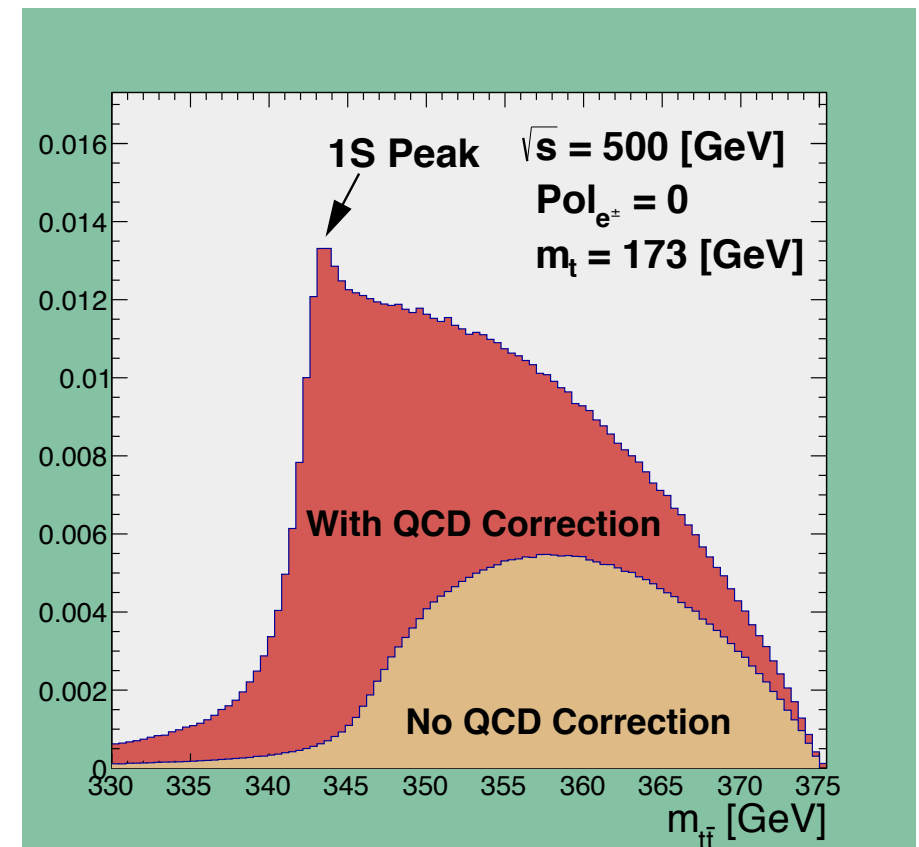
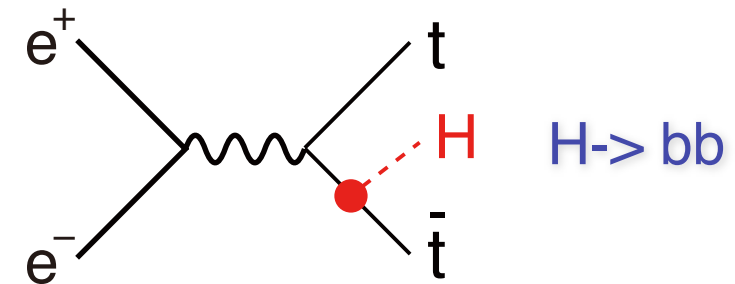
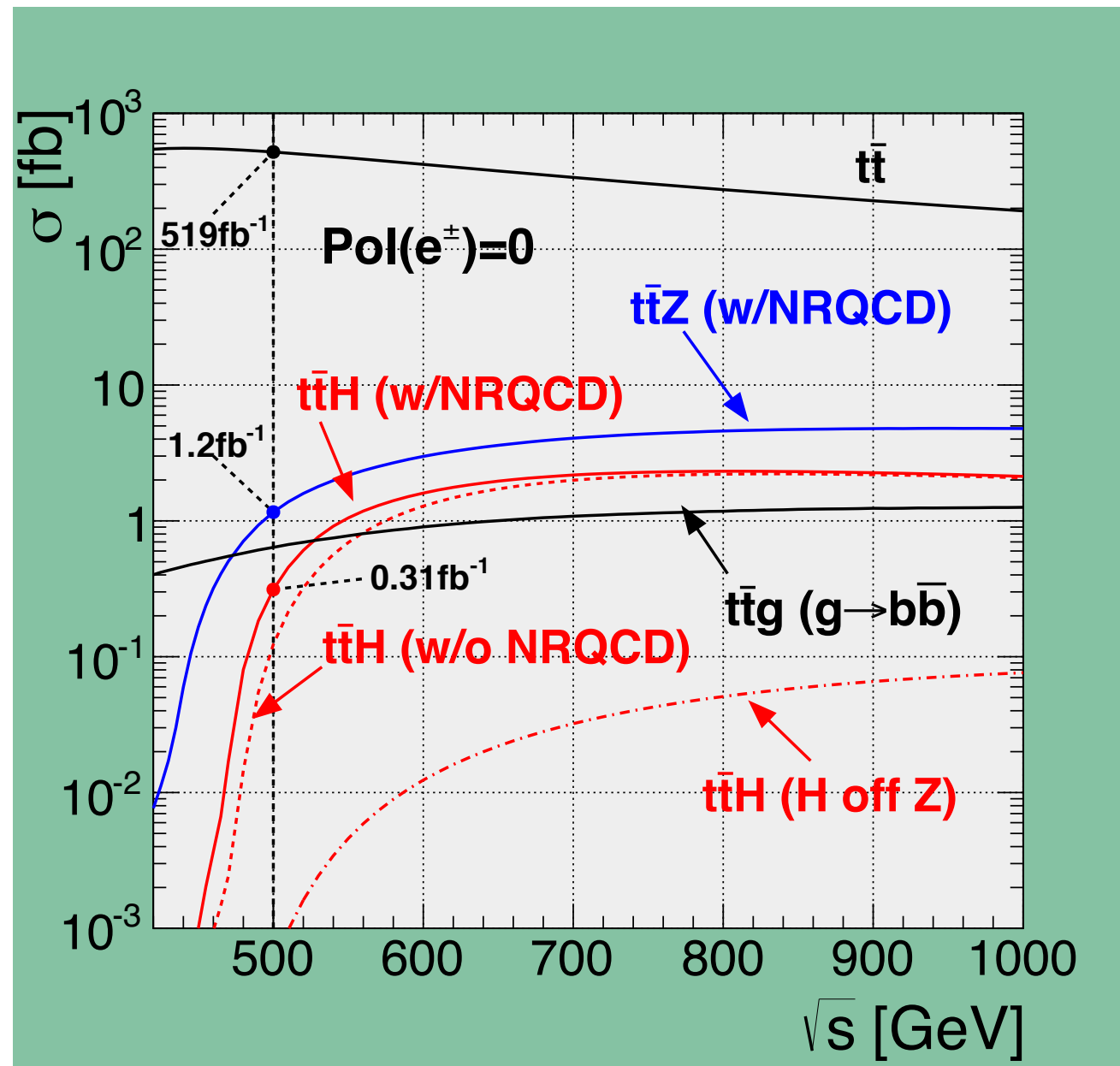
coupling	250 GeV	250 GeV + 500 GeV	250 GeV + 500 GeV + 1 TeV
HZZ	0.6%	0.5%	0.5%
HWW	2.3%	0.6%	0.6%
Hbb	2.5%	0.8%	0.7%
Hcc	3.2%	1.5%	1%
Hgg	3%	1.2%	0.93%
H $\tau\tau$	2.7%	1.2%	0.9%
H $\gamma\gamma$	8.2%	4.5%	2.4%
H $\mu\mu$	42%	42%	10%
Γ_0	5.4%	2.5%	2.3%
Htt	-	7.8%	1.9%

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

) With $H \rightarrow WW^$ (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



A factor of 2 enhancement from QCD bound-state effects

Cross section maximum at around $E_{cm} = 800 \text{ GeV}$

Philipp Roloff, LCWS12

Tony Price, LCWS12

DBD Full Simulation

$$1 \text{ ab}^{-1} @ 500 \text{ GeV} \quad m_H = 125 \text{ GeV}$$

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

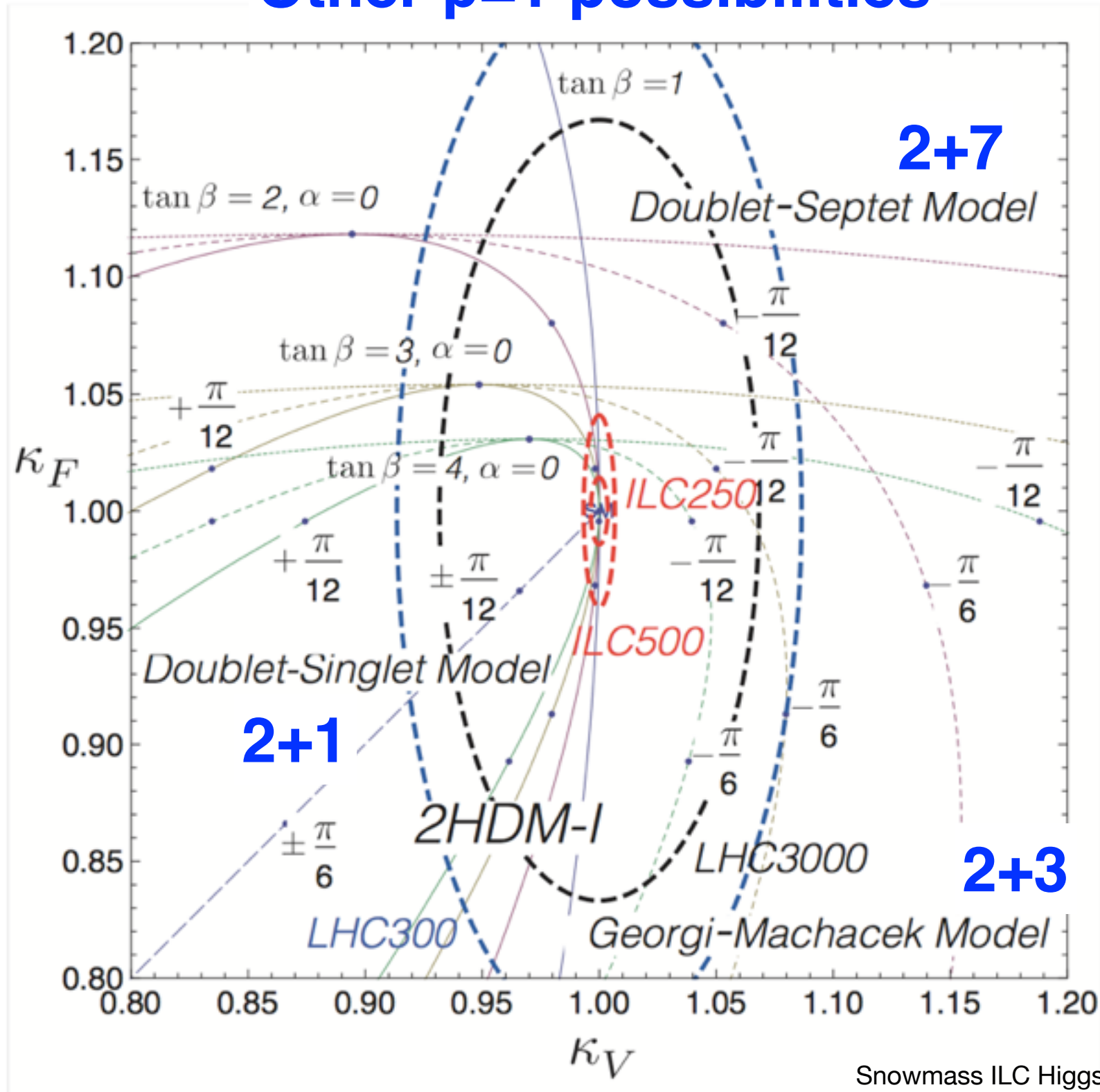
Tony Price, LCWS12

scaled from $m_H = 120 \text{ GeV}$

Notice $\sigma(500+20 \text{ GeV})/\sigma(500 \text{ GeV}) \sim 2$
Moving up a little bit helps significantly!

Multiplet Structure

Other $\rho=1$ possibilities



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

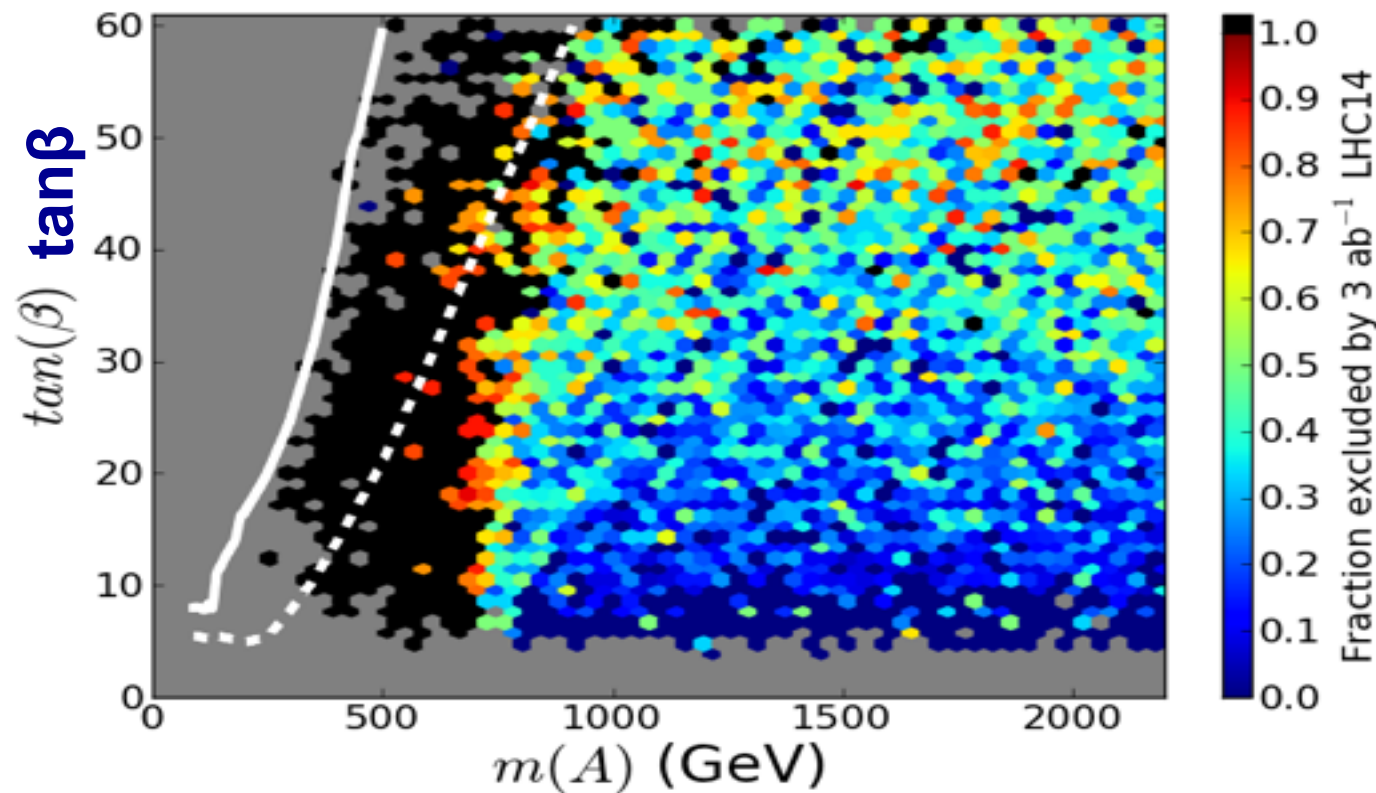
Figure 1.18. The scaling factors in models with universal Yukawa coupling constants.

MSSM Heavy Higgs Bosons

Exclusions of pMSSM points via Higgs couplings (combining $h\gamma\gamma$, $h\tau\tau$, hbb)

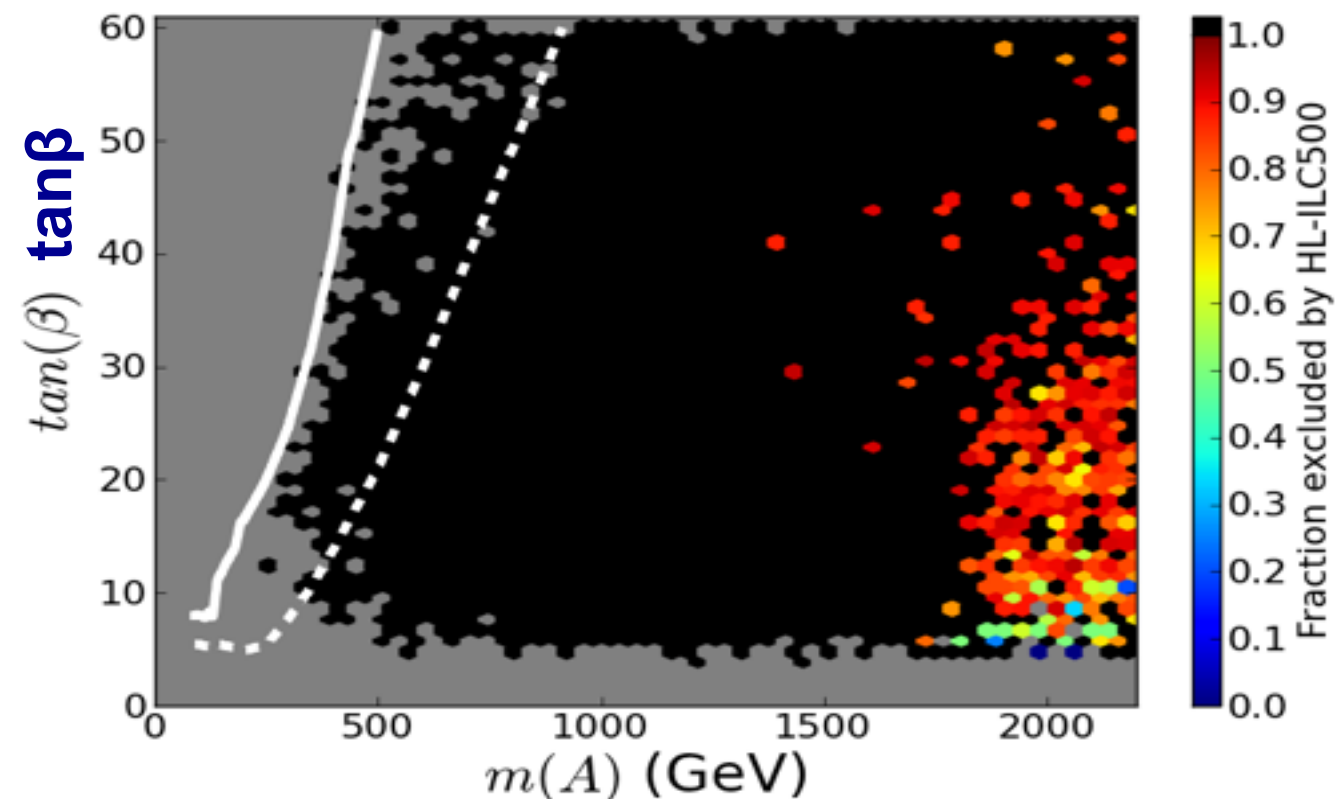
Cahill-Rowley, Hewett, Ismail, Rizzo, arXiv:1407.7021 [hep-ph]

HL-LHC 3000 fb⁻¹



Heavy Higgs mass

ILC (1150 fb⁻¹@250 GeV & 1600 fb⁻¹@500 GeV)

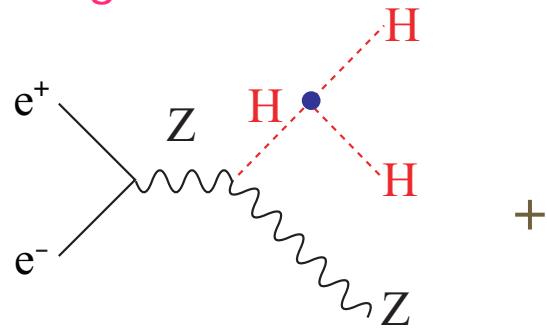


Heavy Higgs mass

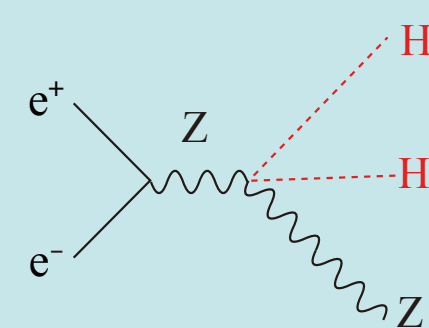
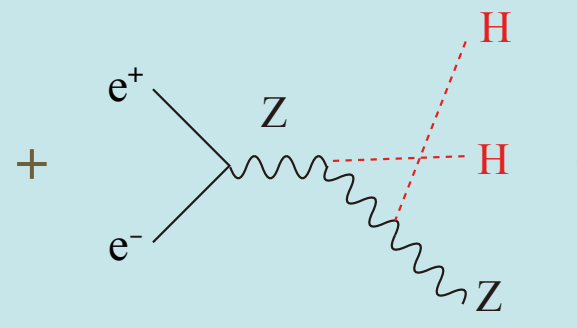
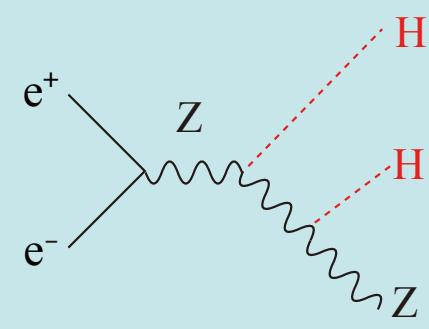
Precision Higgs coupling measurements
sensitive probe for heavy Higgs bosons
 $m_A \sim 2$ TeV reach for any $\tan\beta$ at the ILC

The Problem : BG diagrams dilute self-coupling contribution

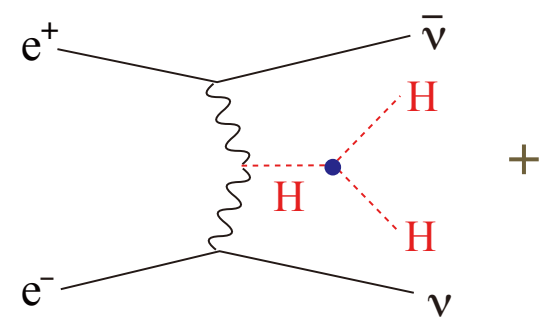
Signal diagram



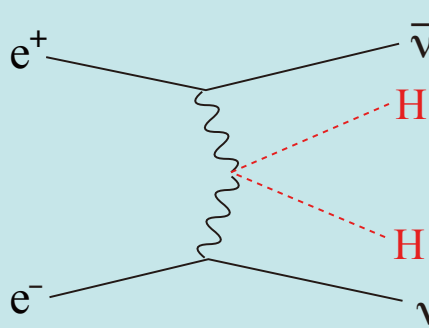
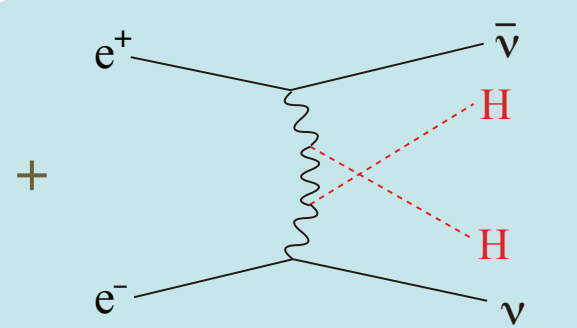
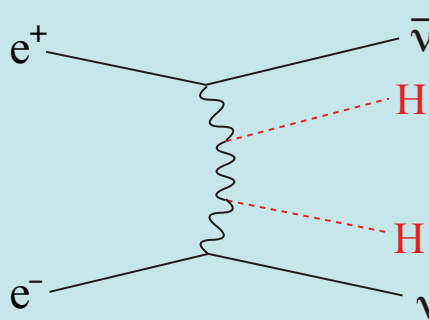
Irreducible BG diagrams



Signal diagram



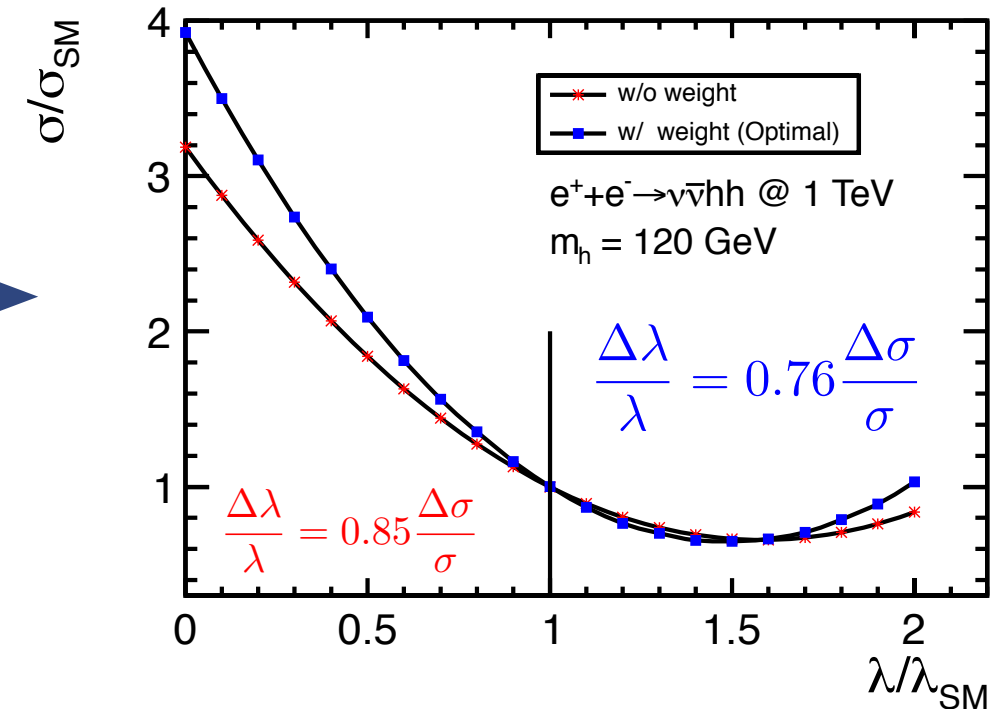
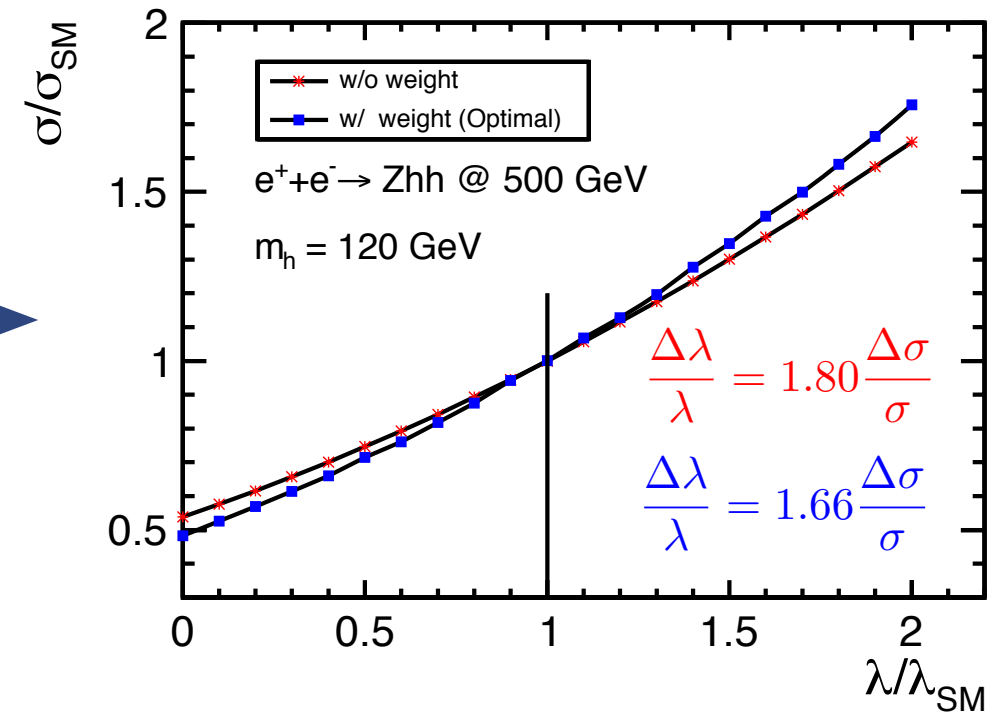
Irreducible BG diagrams



$$\sigma = \lambda^2 S + \lambda I + B$$

$$\frac{\Delta\lambda}{\lambda} = F \cdot \frac{\Delta\sigma}{\sigma}$$

F=0.5 if no BG diagrams



Junping Tian LC-REP-2013-003

SUSY

Slepton decays to DM with small mass differences

Study of stau pair production at the ILC

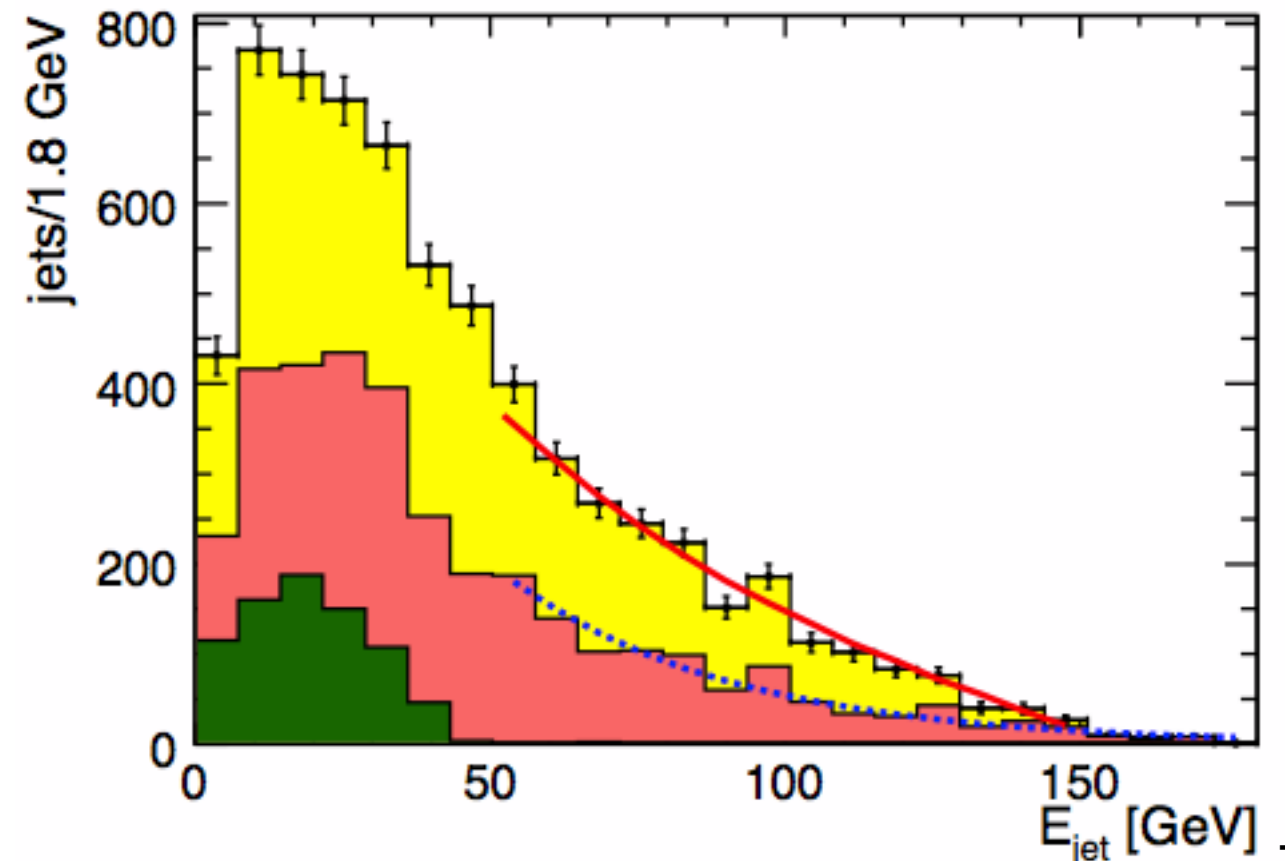
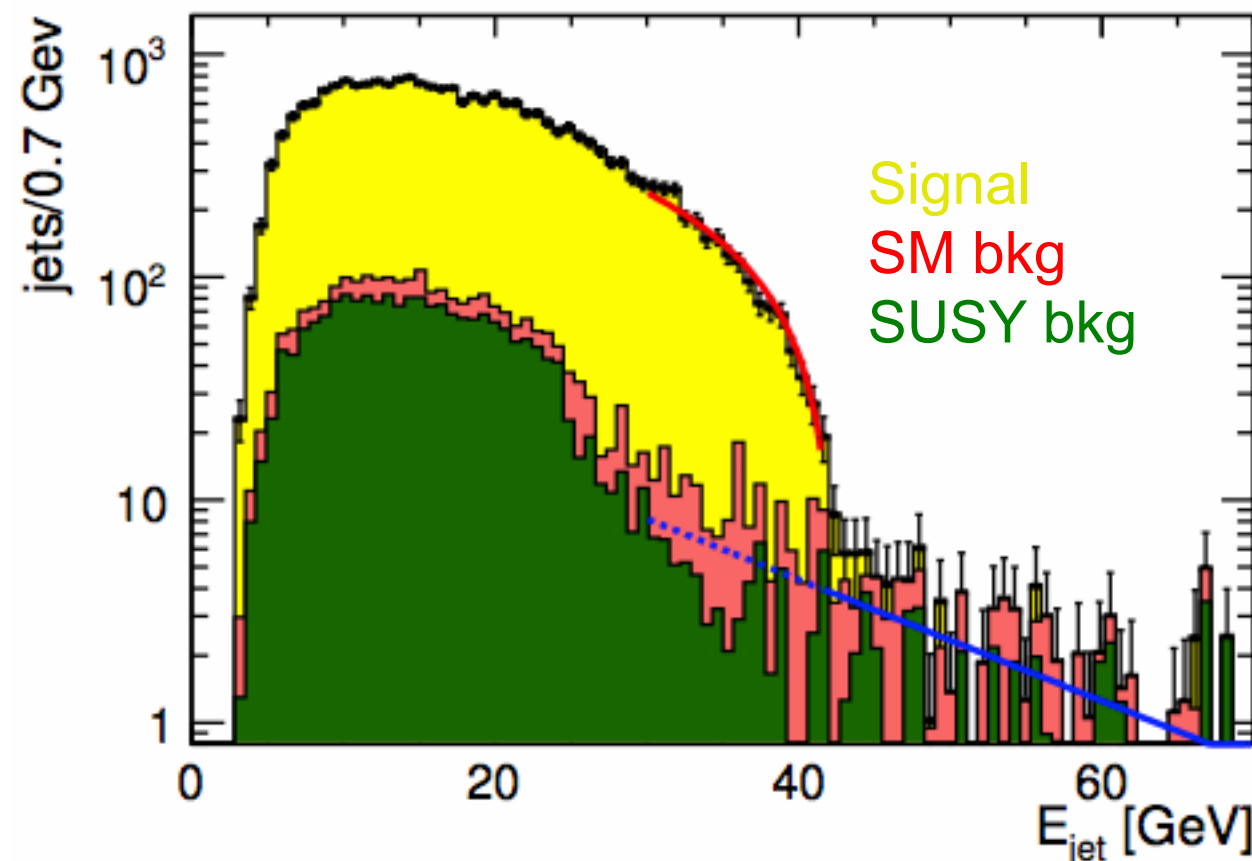
Observation of lighter and heavier stau states with decay to DM + hadronic tau

Benchmark point: $m(\text{LSP}) = 98 \text{ GeV}$, $m(\text{stau1}) = 108 \text{ GeV}$, $m(\text{stau2}) = 195 \text{ GeV}$

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

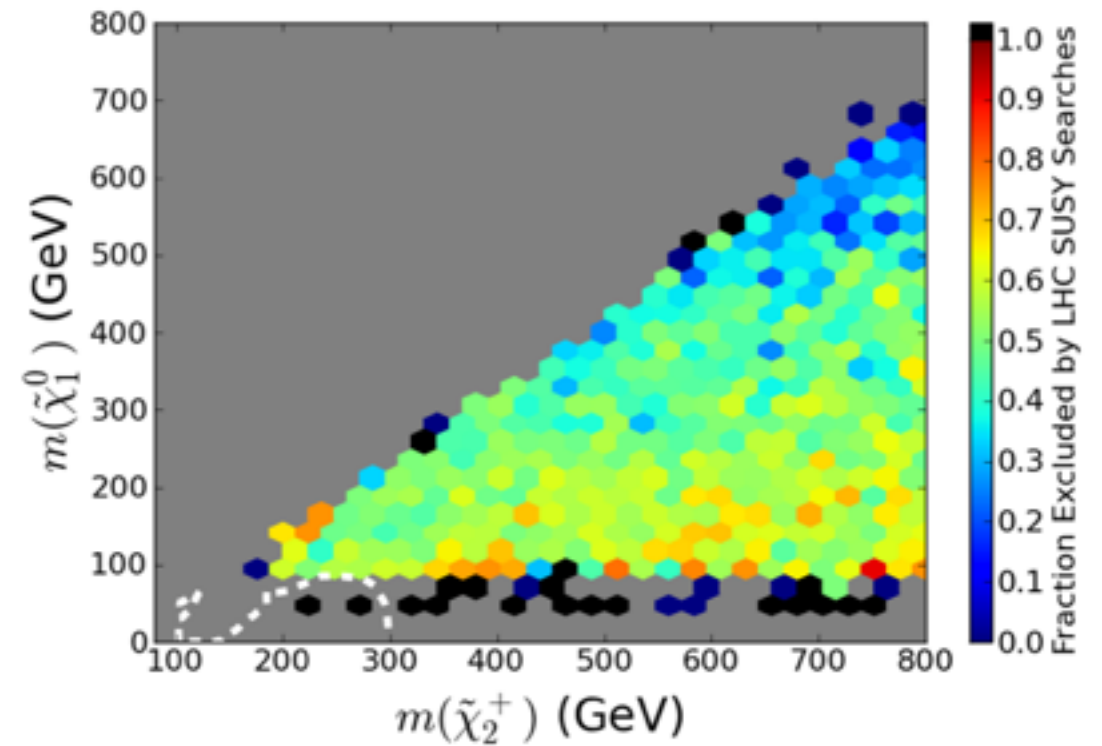
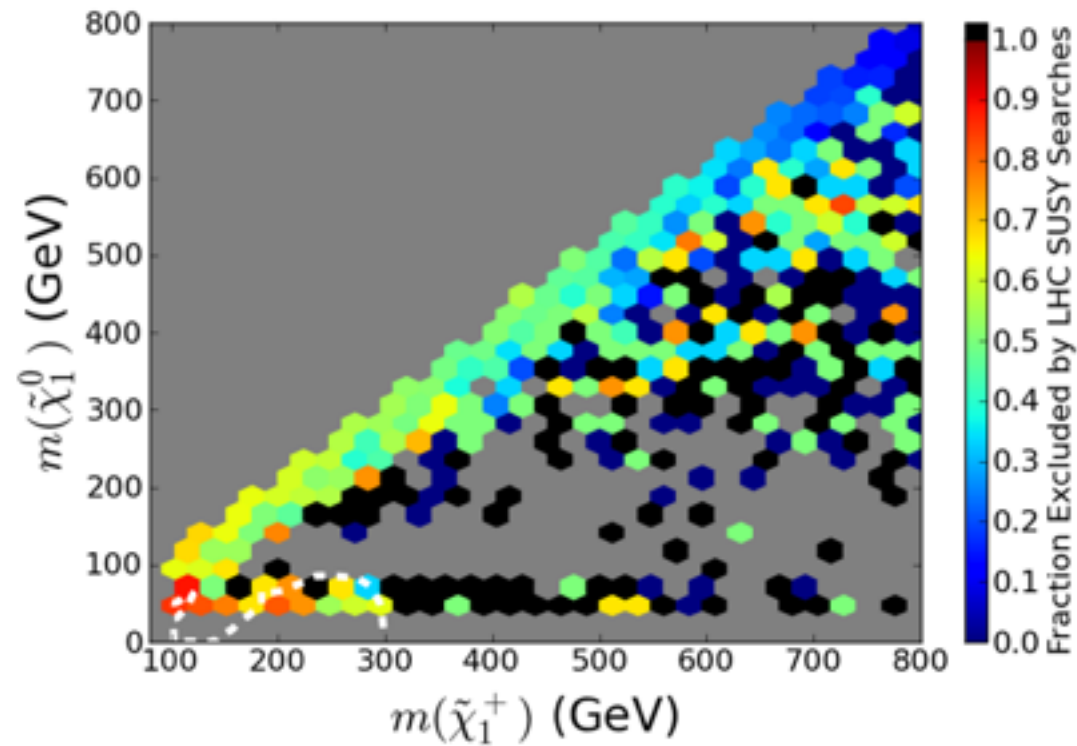
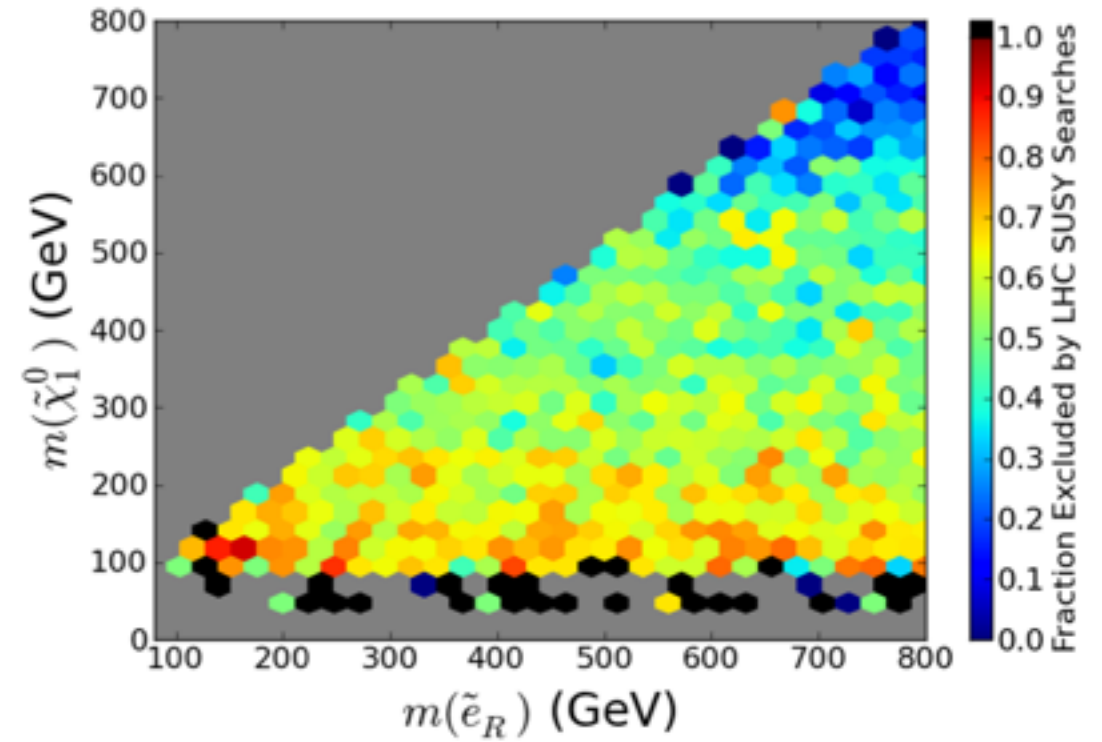
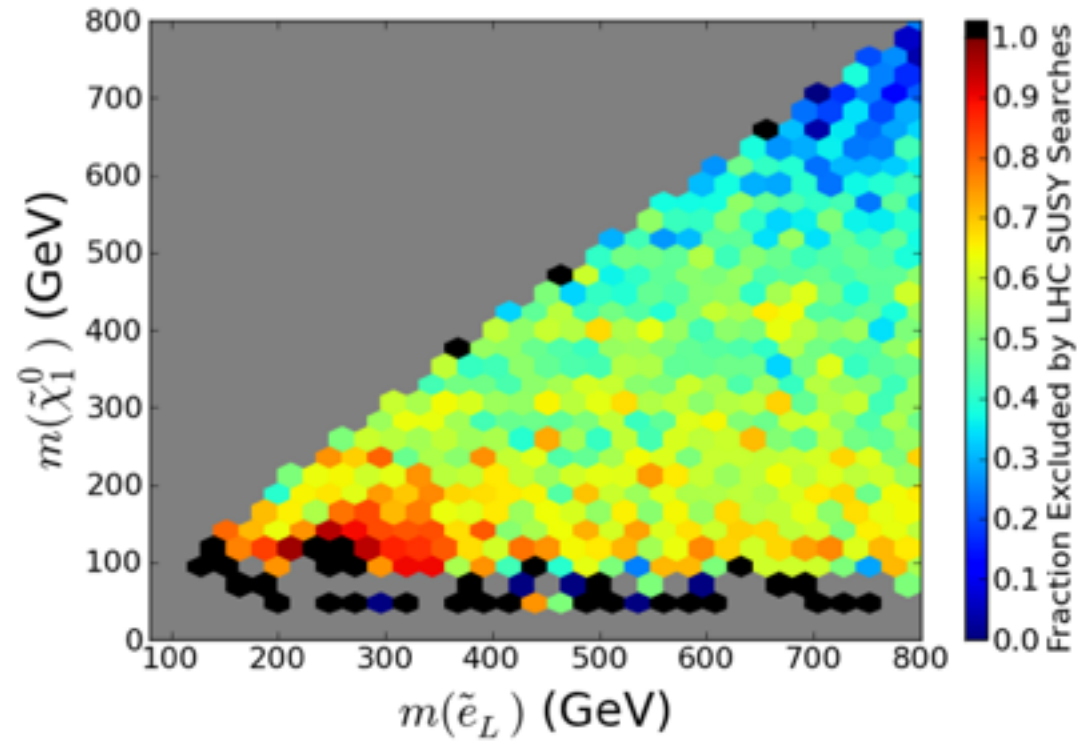
$$\sigma(e^+e^- \rightarrow \tilde{\tau}_2^+ \tilde{\tau}_2^-) = 18 \text{ fb}$$

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



$\sqrt{s}=500 \text{ GeV}$, $\text{Lumi}=500 \text{ fb}^{-1}$, $P(e^-,e^+)=(+0.8,-0.3)$
Stau1 mass $\sim 0.1\%$, Stau2 mass $\sim 3\%$ \rightarrow LSP mass $\sim 1.7\%$

pMSSM Scan



$$\begin{aligned}
\text{Scalar (S): } \mathcal{L} &= \frac{G_S}{\sqrt{2}} \bar{\chi} \chi \bar{f} f \\
\text{Pseudoscalar (P): } \mathcal{L} &= \frac{G_P}{\sqrt{2}} \bar{\chi} \gamma^5 \chi \bar{f} \gamma^5 f \\
\text{Vector (V): } \mathcal{L} &= \frac{G_V}{\sqrt{2}} \bar{\chi} \gamma^\mu \chi \bar{f} \gamma_\mu f \\
\text{Axial Vector (A): } \mathcal{L} &= \frac{G_A}{\sqrt{2}} \bar{\chi} \gamma^\mu \gamma^5 \chi \bar{f} \gamma_\mu \gamma^5 f \\
\text{Tensor (T): } \mathcal{L} &= \frac{G_T}{\sqrt{2}} \bar{\chi} \sigma^{\mu\nu} \chi \bar{f} \sigma_{\mu\nu} f.
\end{aligned}$$

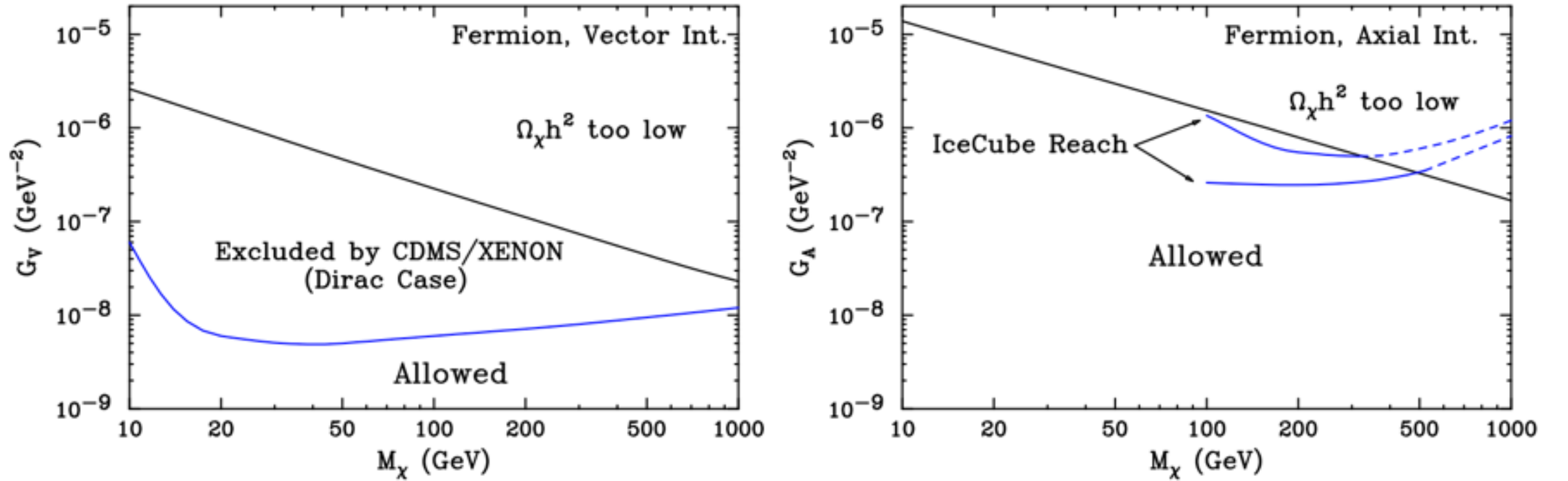


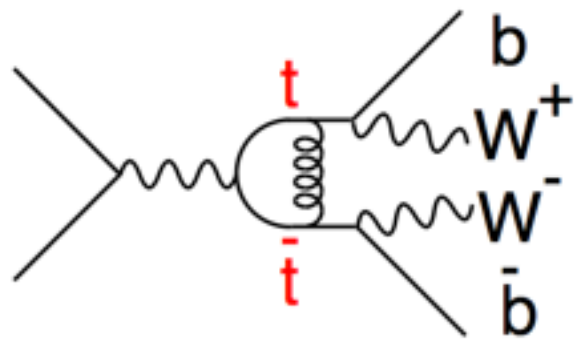
FIG. 4: A summary of the constraints on a fermionic WIMP with scalar, pseudoscalar, vector, and axial interactions, including regions excluded and allowed by direct and indirect detection experiments (note that WIMPs with pseudoscalar and axial interactions are unconstrained by direct detection experiments). 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

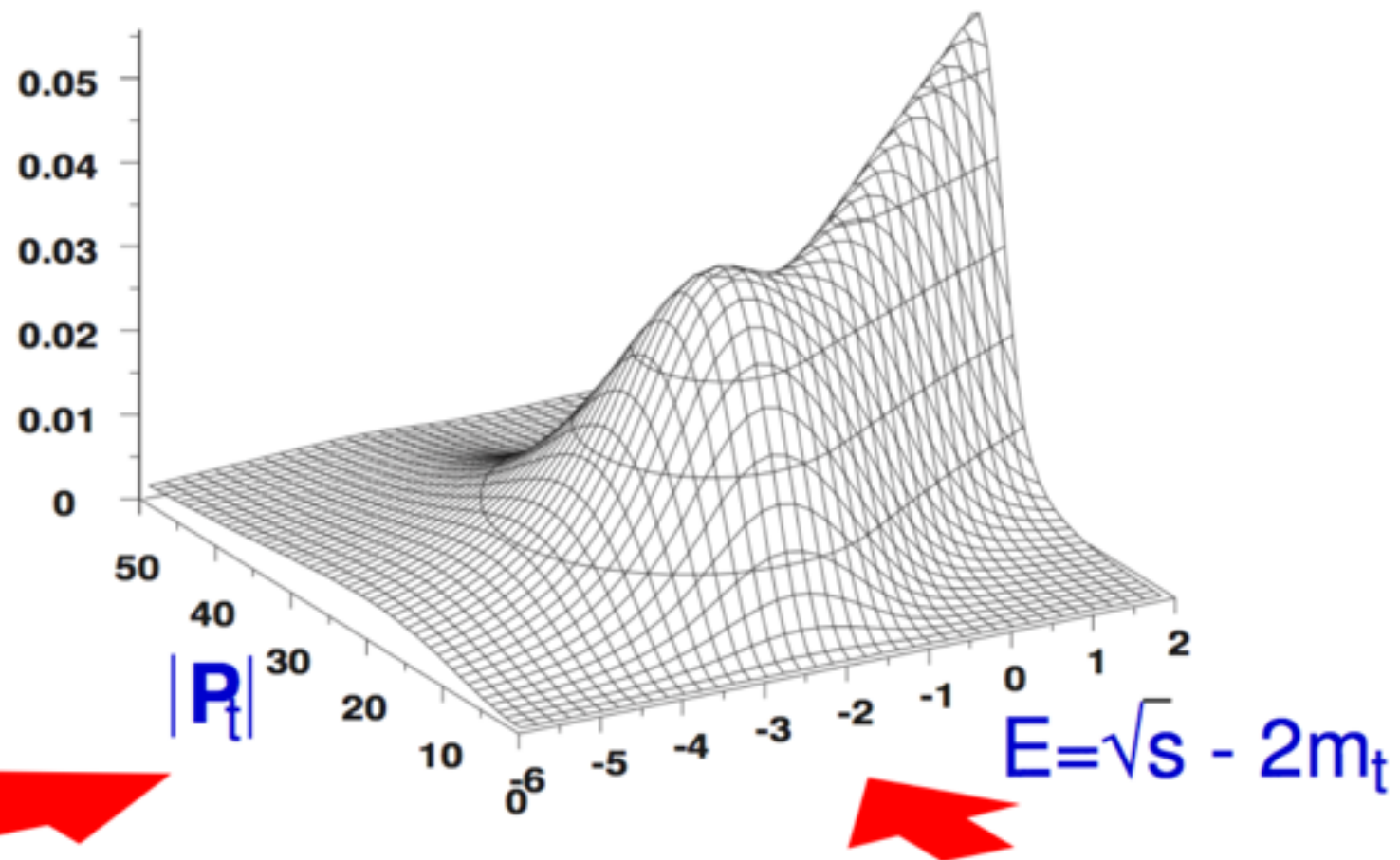
Top Quark

Threshold Region

How to access G experimentally



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



Momentum Dist.

$$\frac{d\sigma_{t\bar{t}}}{d|p|} \propto |\langle p | G | x = 0 \rangle|^2$$

$$\simeq \left| \sum_n \frac{\phi_n(p) \Psi_n^*(0)}{E - E_n + i\Gamma_n/2} \right|^2$$

momentum space wave fun.

Threshold Scan

$$\sigma_{t\bar{t}} \propto \text{Im} \langle x = 0 | G | x = 0 \rangle$$

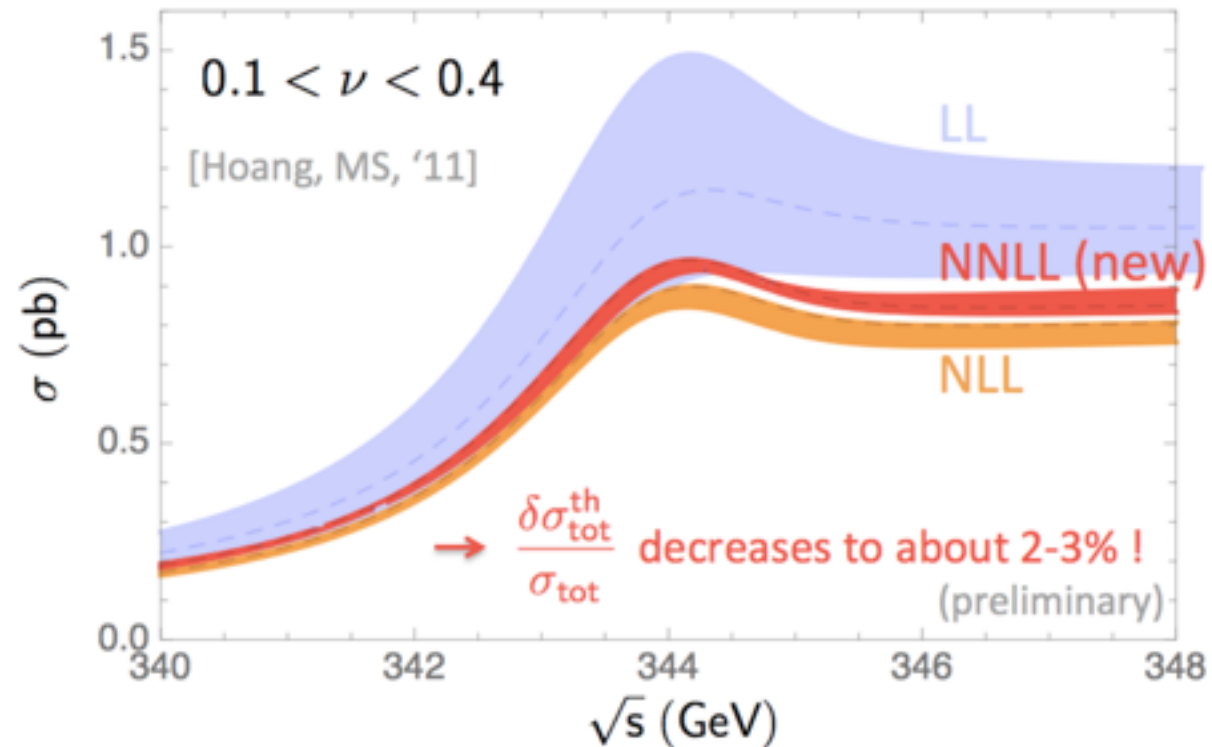
$$\simeq \text{Im} \sum_n \frac{|\Psi_n(0)|^2}{E - E_n + i\Gamma_n/2}$$

wave function at origin

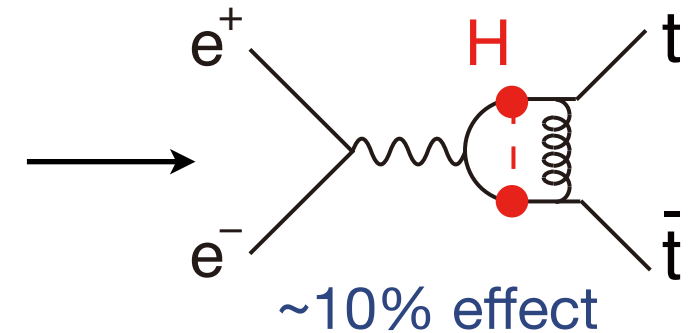
Top at Threshold

Threshold Scan

M.Stahlhofen Top Phys WS 2012



Theory improving!



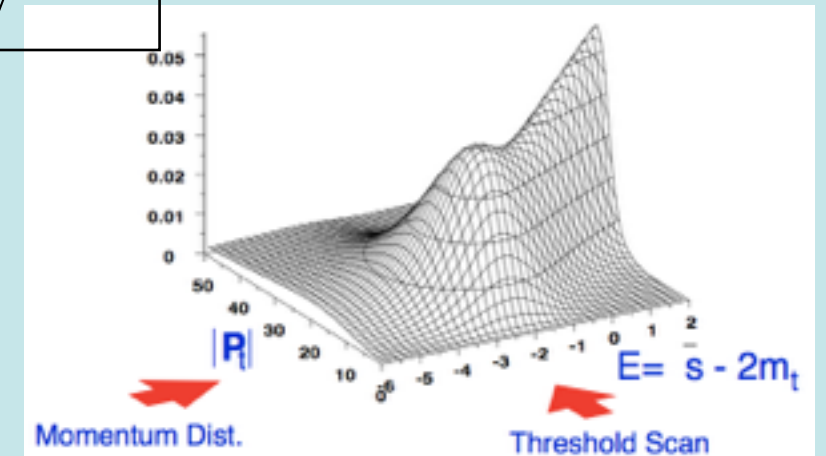
Expected accuracies

$$\Delta m_t = 34 \text{ MeV}$$

$$\Delta \alpha_s(m_Z) = 0.0023$$

$$\Delta \Gamma_t = 42 \text{ MeV}$$

Threshold scan alone



+ A_{FB} & Top Momentum

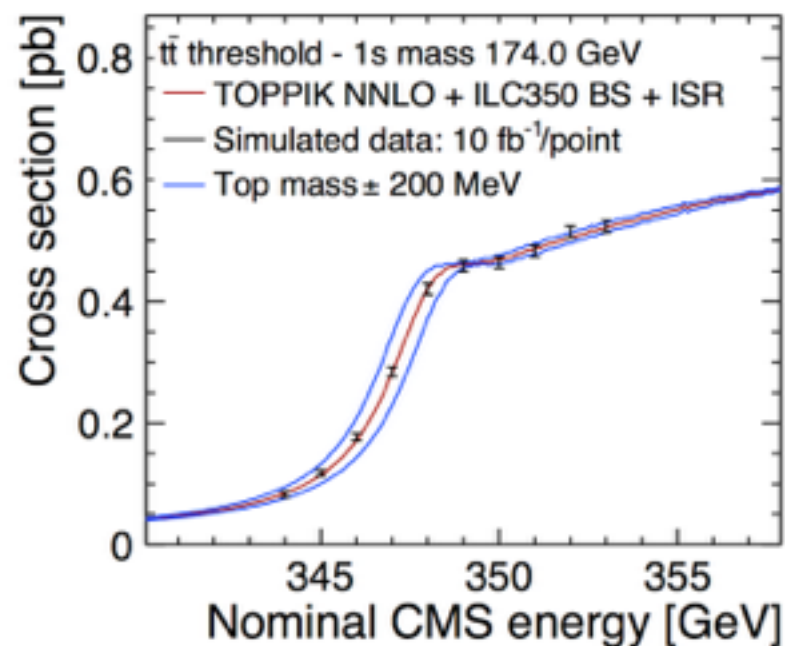
$$\Delta m_t = 19 \text{ MeV}$$

$$\Delta \alpha_s(m_Z) = 0.0012$$

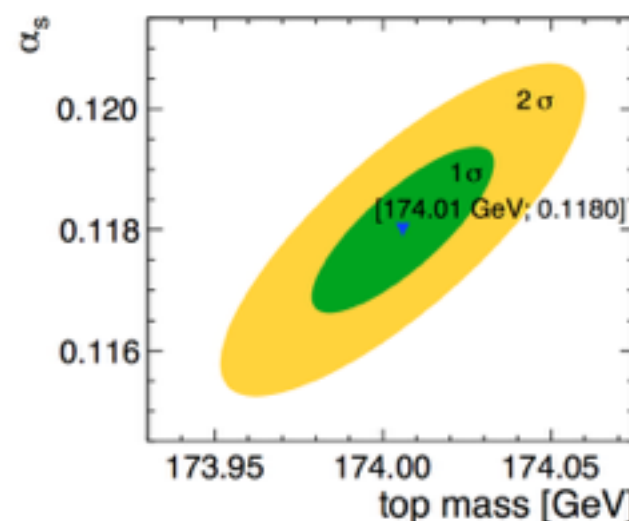
$$\Delta \Gamma_t = 32 \text{ MeV}$$

arXiv:hep-ph/0601112v2

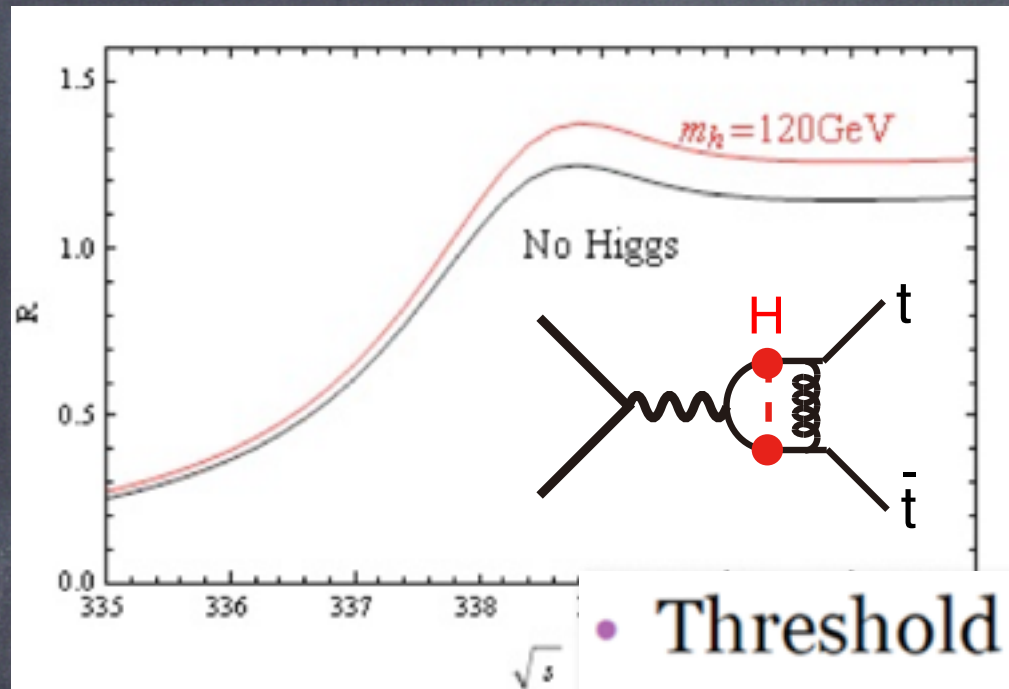
$$\Delta m_t(\overline{MS}) \simeq 100 \text{ MeV}$$



F.Simon Top Phys WS 2012



Reducing Theoretical Ambiguities



9% effect on the X-section

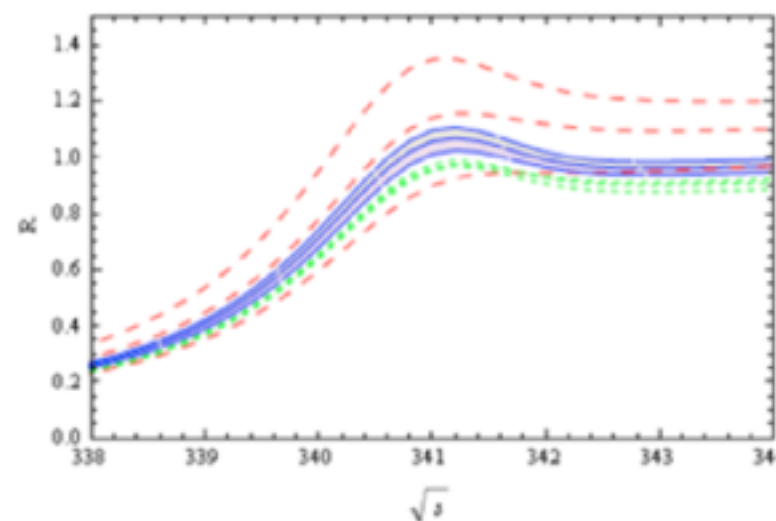
Normalization ambiguity due to the QCD enhancement has been an obstacle to do this measurement

- Threshold enhancement is due to Coulomb resummation

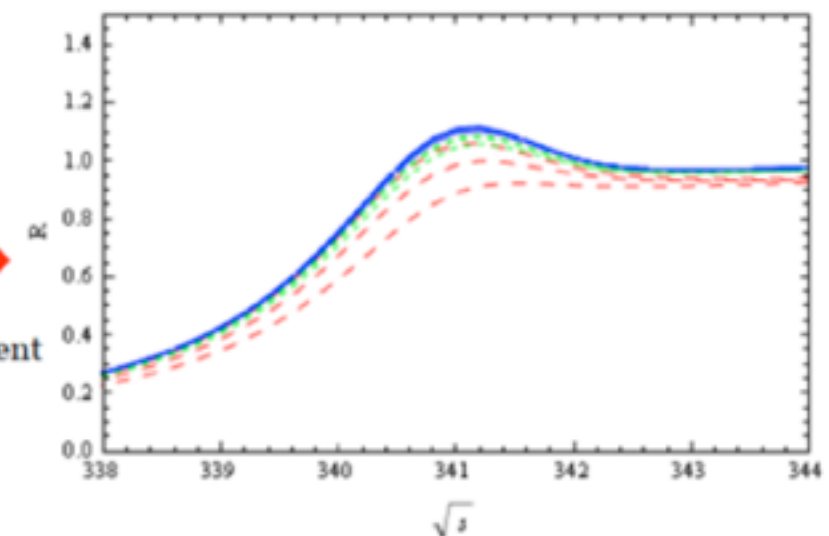


RG improved potential to reach high accuracy

- Below RG improvement is applied to QCD static potential. (In the plots below we neglected other corrections as a first study)



improvement



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

Yuichiro Kiyo
@ LCWS10

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

Still preliminary but prospect is bright!

Top Quark

Open Top Region

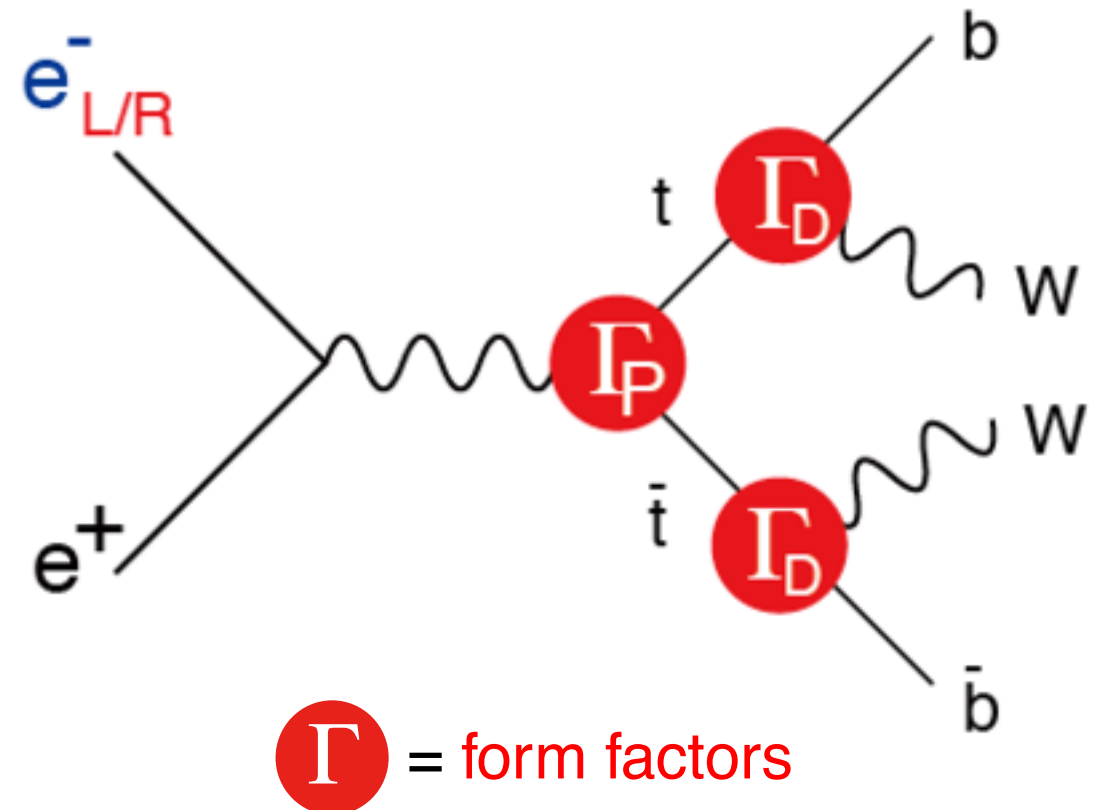
Key points

$\Gamma_t \approx 1.4 \text{ GeV}$ for $m_t = 175 \text{ GeV}$

The top decays before forming a top hadron.

Top spin is measurable by angular analysis of decay products.

+ Polarized beams are available at ILC



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

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

Other Probes

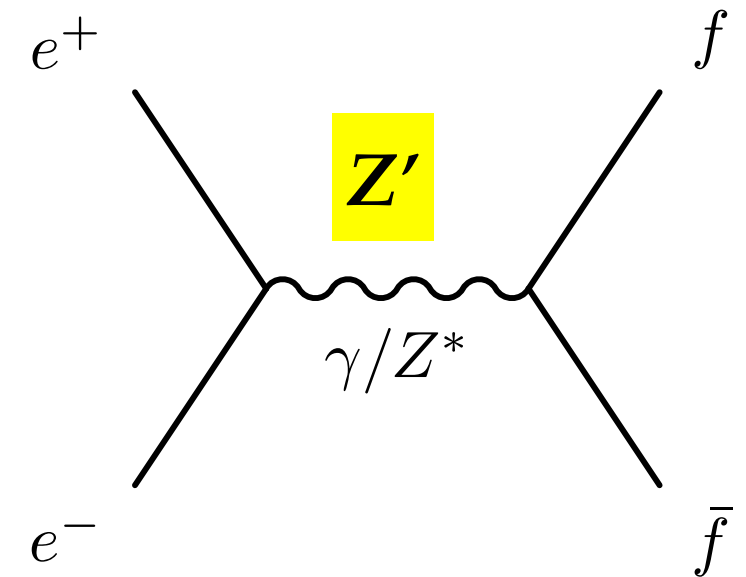
z'

Z' : Heavy Neutral Gauge Bosons

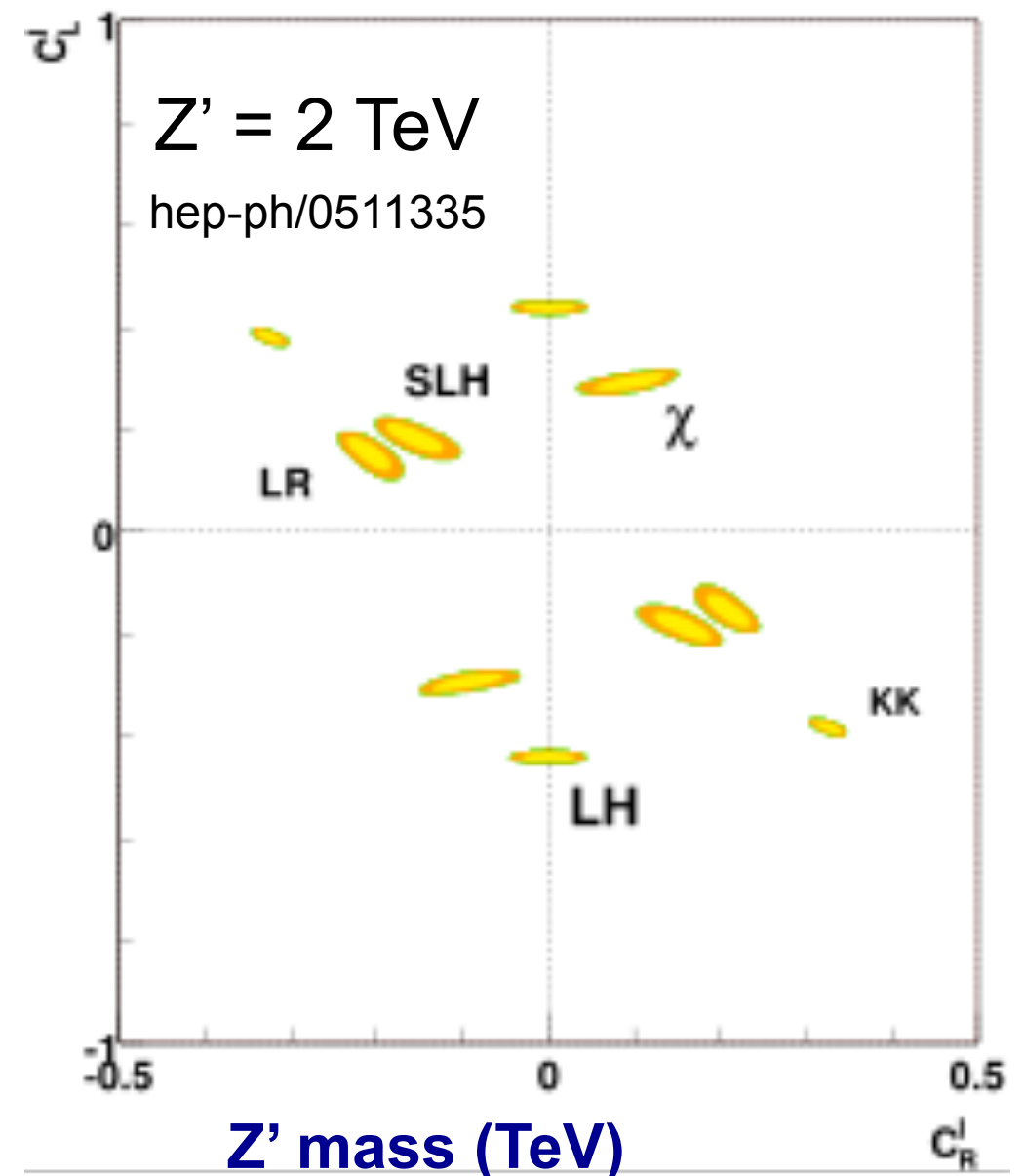
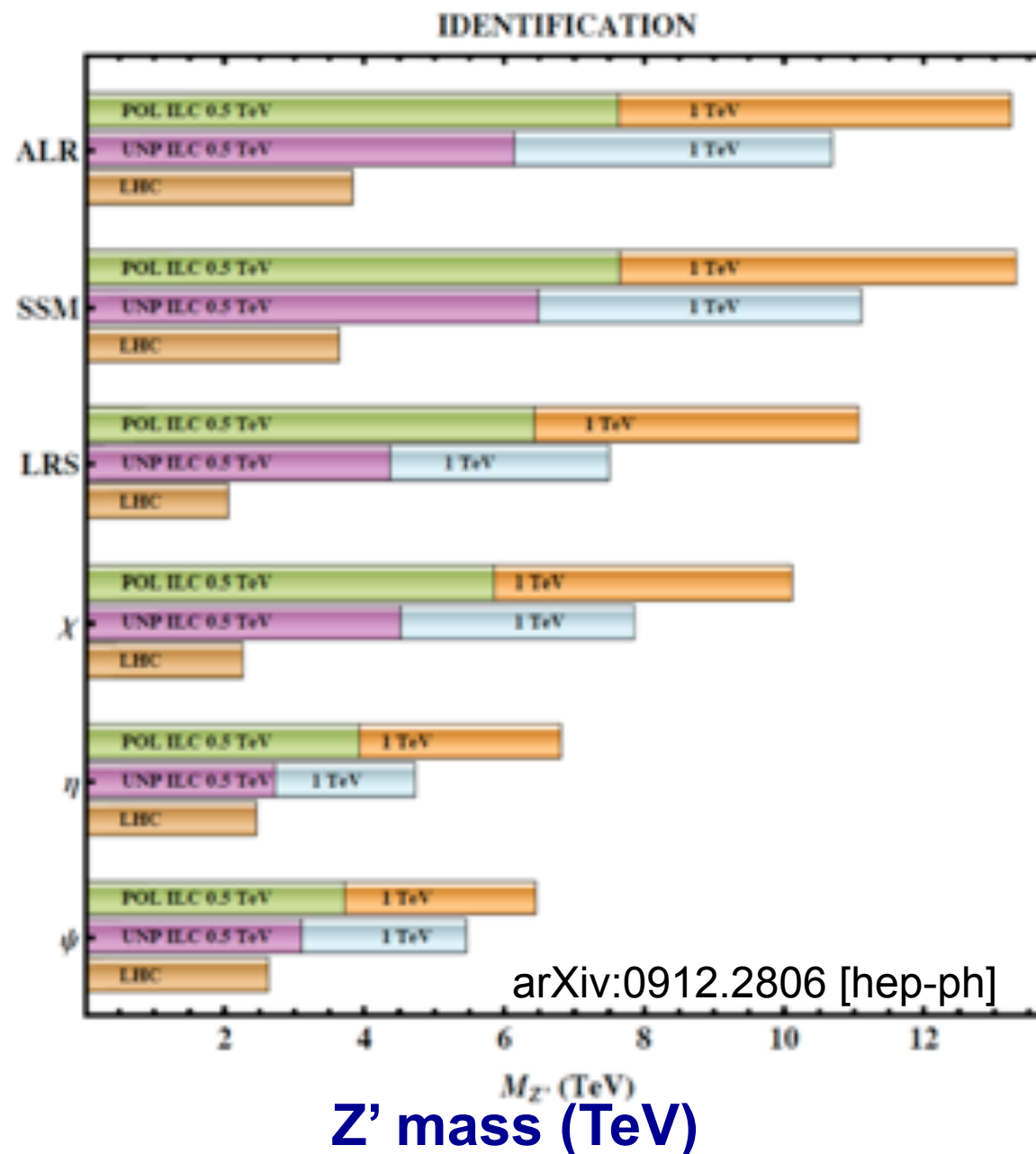
New gauge forces imply existence of heavy gauge bosons (Z')

Complementary approaches LHC/ILC

- LHC: Direct searches for Z' (mass determination)
- ILC: Indirect searches via interference effects (coupling measurements and model discrimination) – beam polarizations improve reach and discrimination power



Models with Z' boson



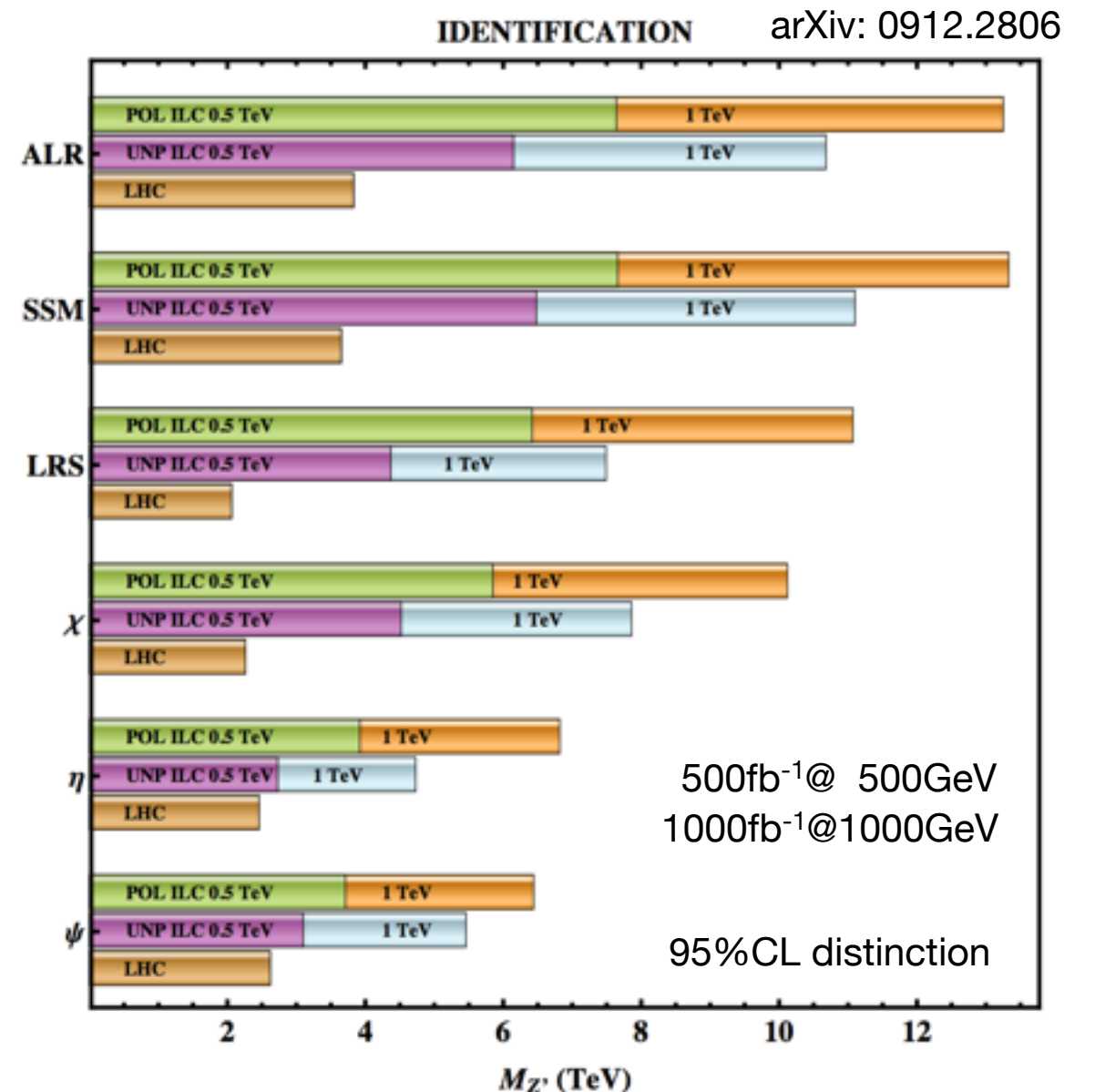
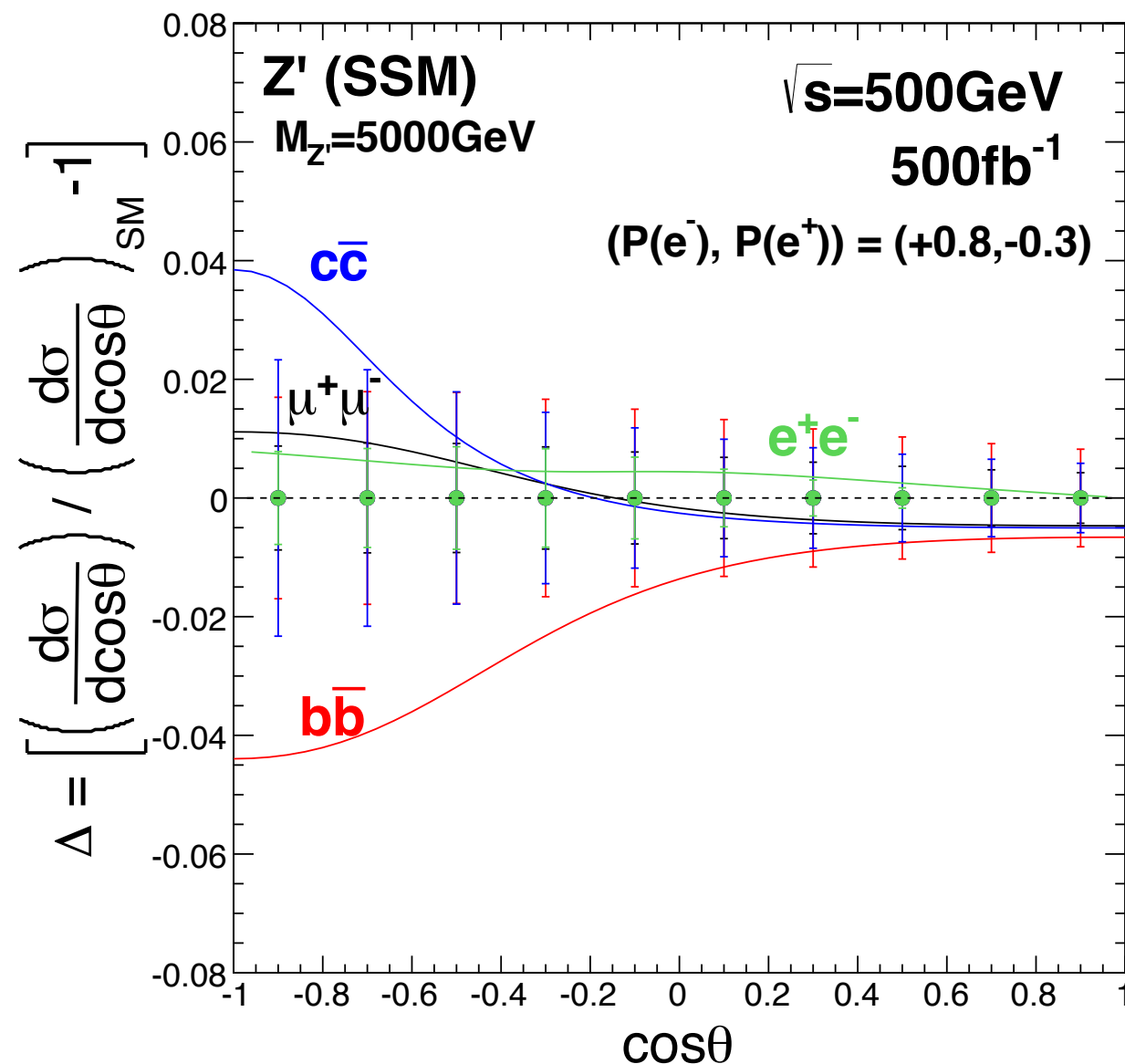
Two-Fermion Processes

Z' Search / Study

Observables: $d\sigma(P-,P+)/d \cos\theta$

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

Example: Sequential SM-like *Z'*



Two-Fermion Processes

Z' Search / Study

arXiv:0912.2806 [hep-ph]

hep-ph/0511335

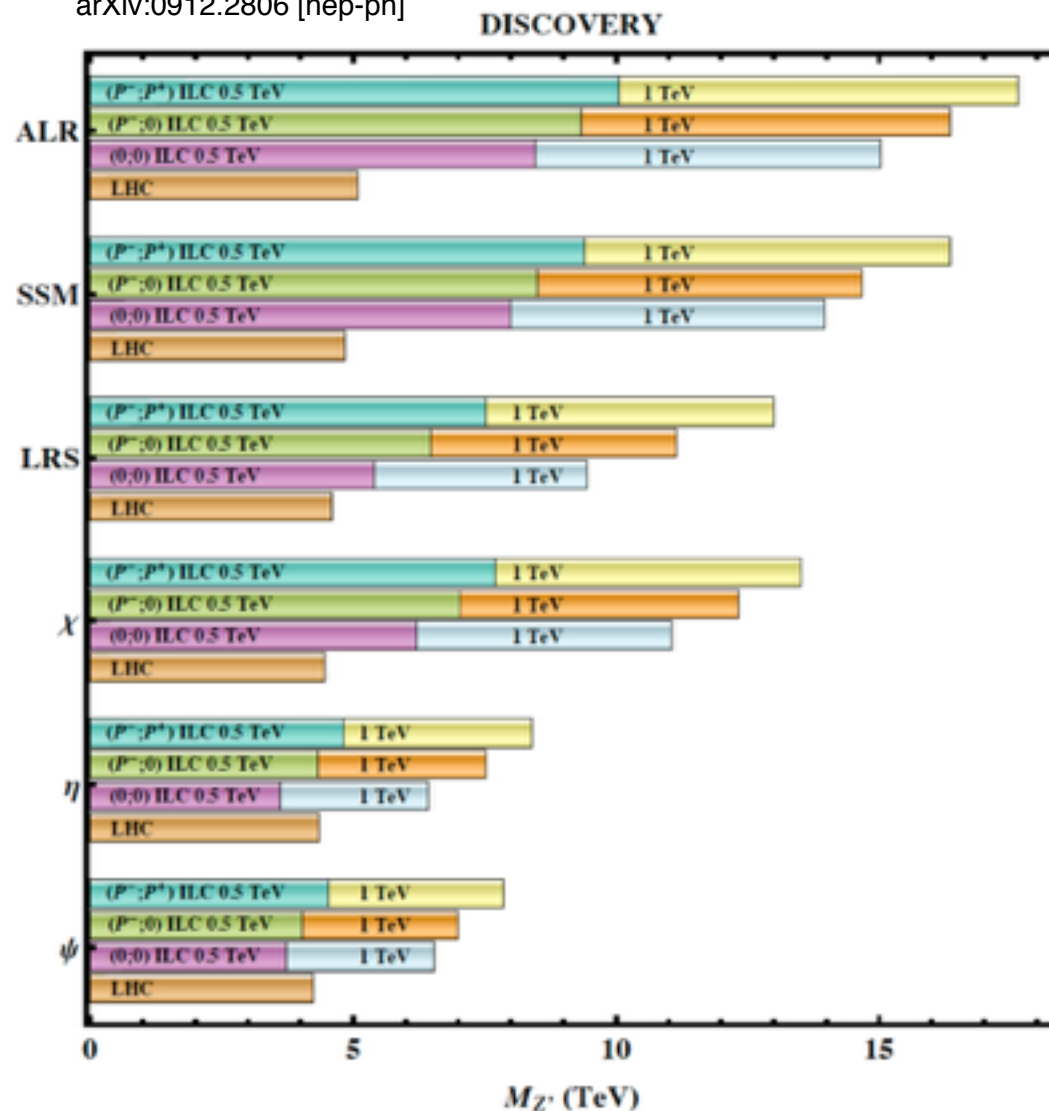
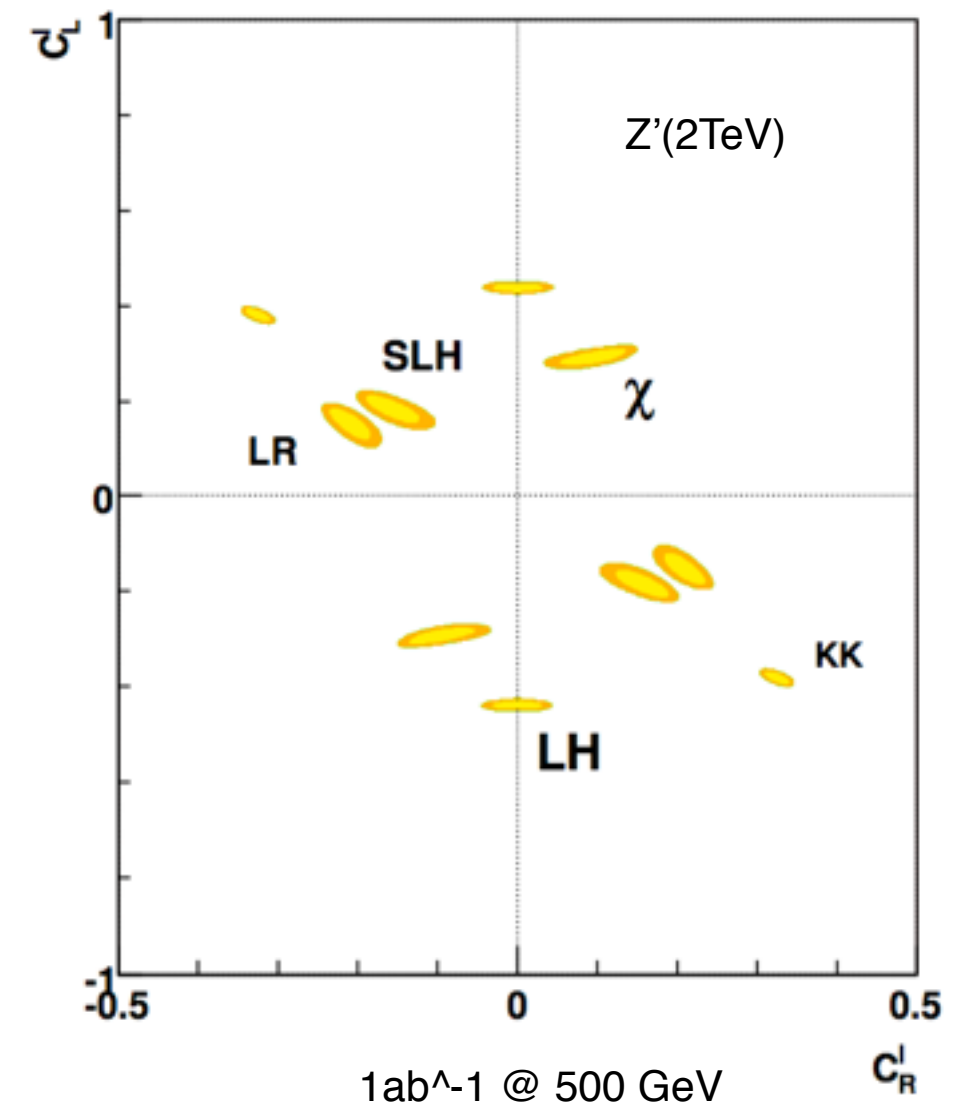


Figure 23: Sensitivity of the ILC to various candidate Z' bosons, quoted at 95% conf., with $\sqrt{s} = 0.5$ (1.0) TeV and $\mathcal{L}_{\text{int}} = 500$ (1000) fb^{-1} . The sensitivity of the LHC-14 via Drell-Yan process $pp \rightarrow \ell^+ \ell^- + X$ with 100 fb^{-1} of data are shown for comparison.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



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

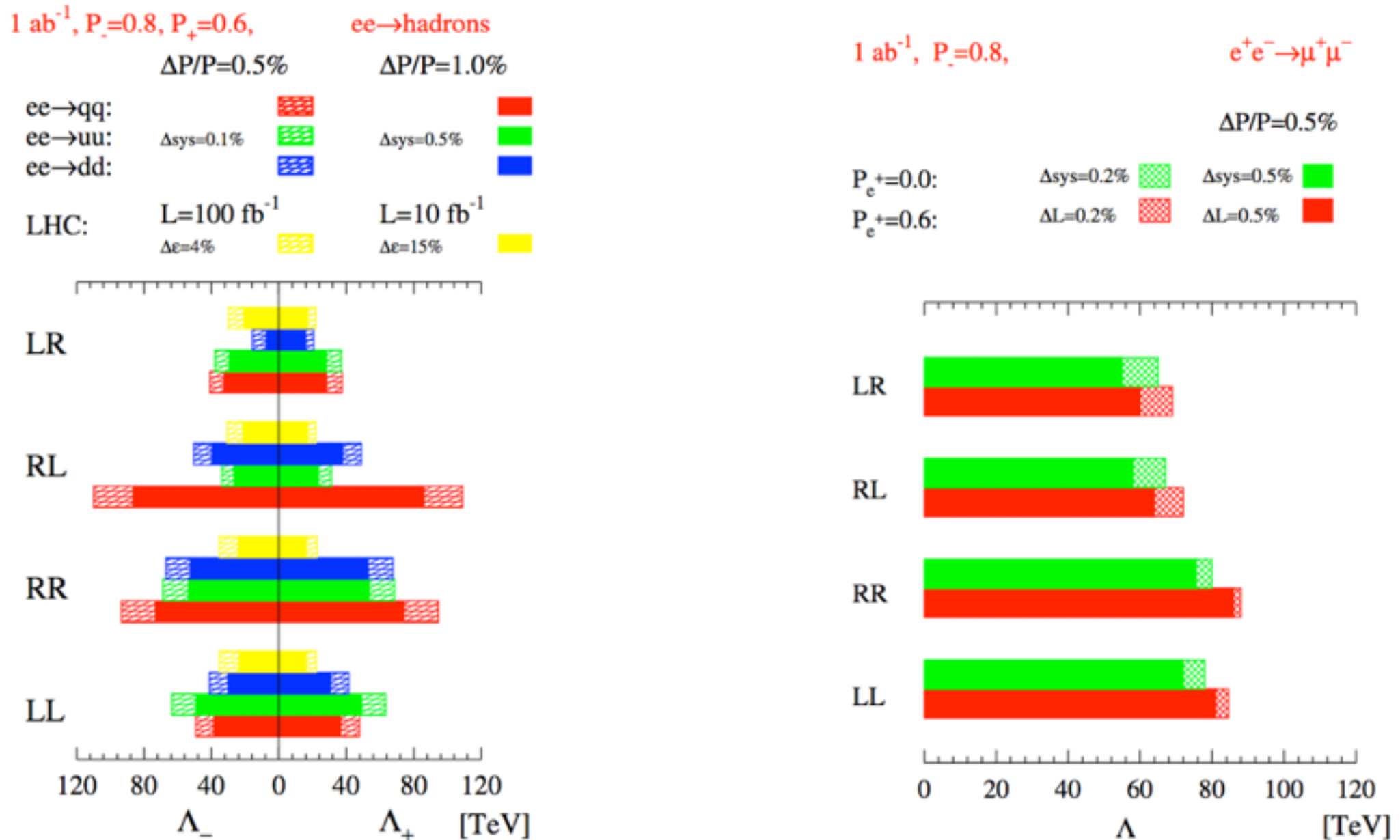
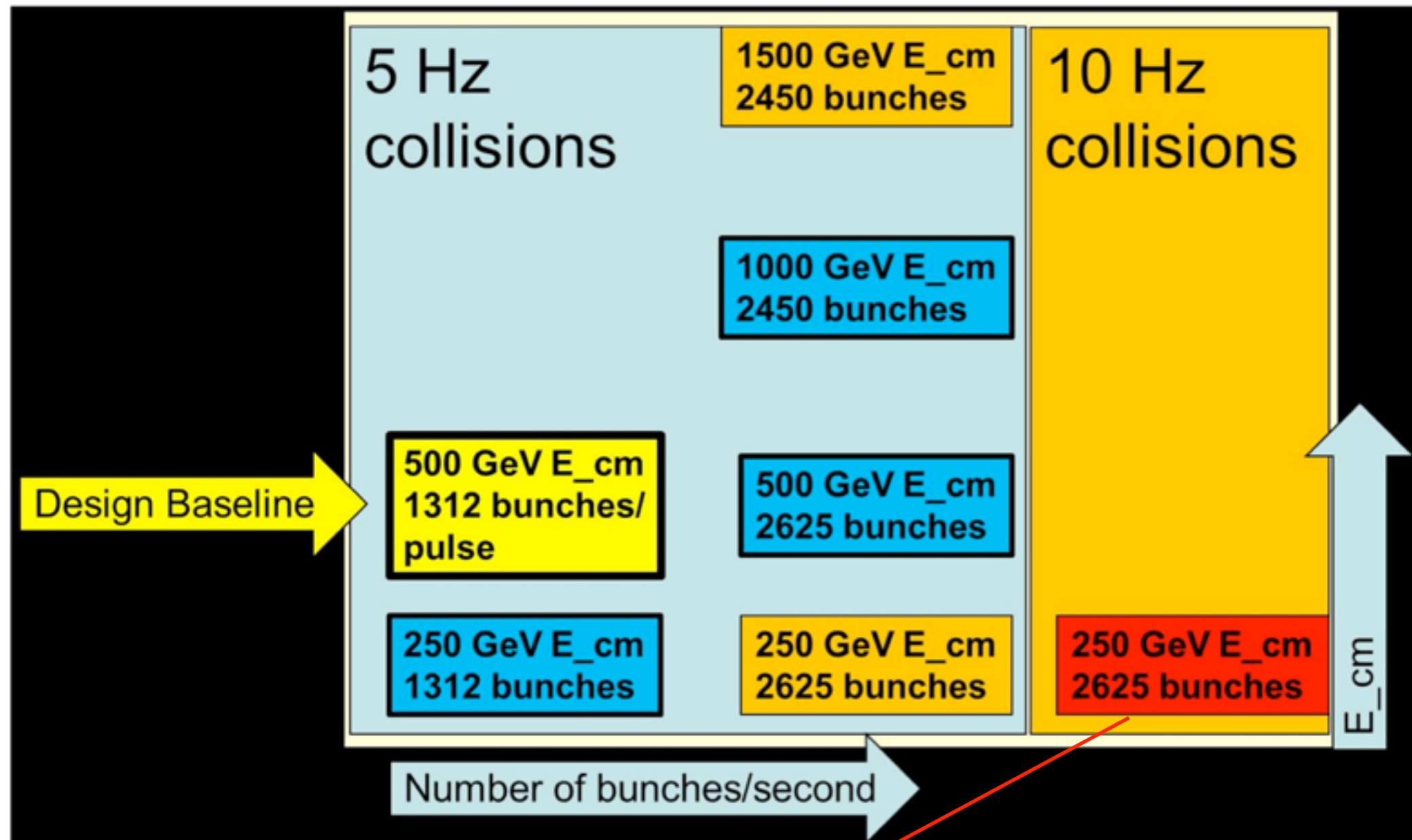


Figure 26: Sensitivities (95% c.l.) of a 500 GeV ILC to contact interaction scales Λ for different helicities in $e^+e^- \rightarrow \text{hadrons}$ (left) and $e^+e^- \rightarrow \mu^+\mu^-$ (right), including beam polarization [18].

Beam polarization is essential to sort out various possibilities.

HL-ILC ?

ILC Stages and Upgrades



Snowmass ILC Higgs White Paper (arXiv: 1310.0763)

**x4 upgrade
@250GeV**

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	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$	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**