Physics at ILC

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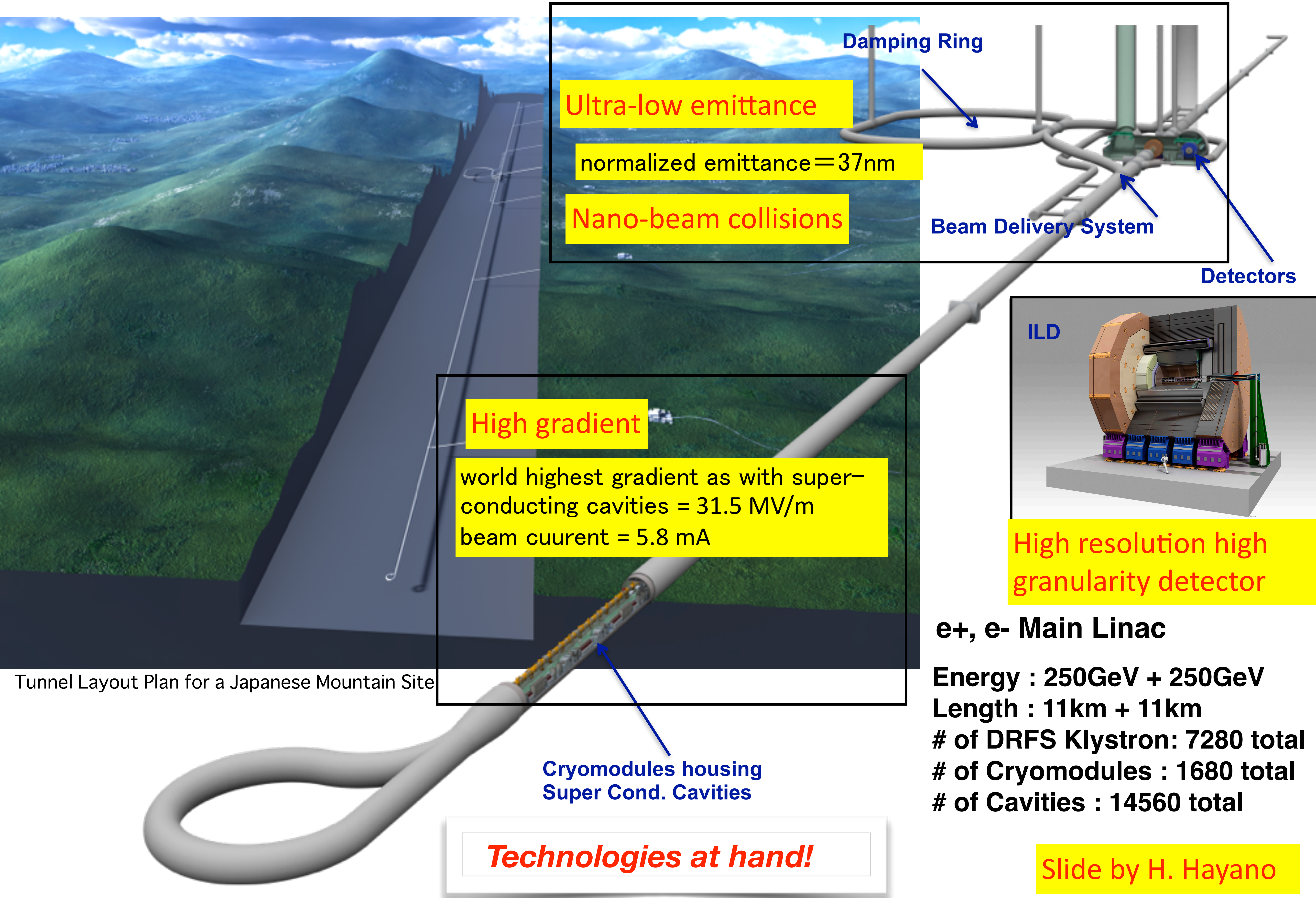
MadGraph School 2015

Thanks to T. Tanabe for many materials

Bird's Eye View of the ILC Accelerator



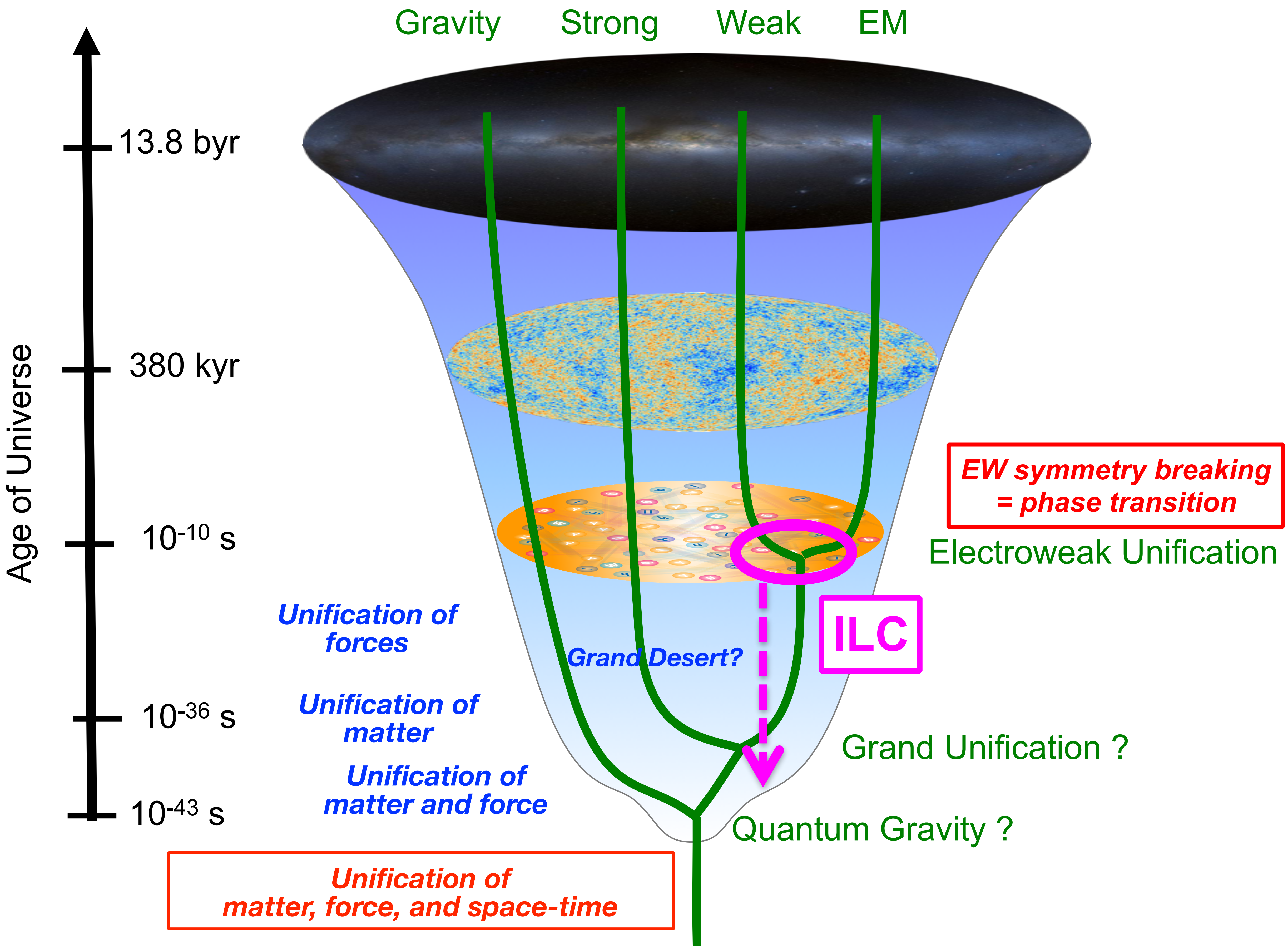
Technologies at hand!

e+, e- Main Linac

Energy : 250GeV + 250GeV
Length : 11km + 11km
# of DRFS Klystron: 7280 total
# of Cryomodules : 1680 total
# of Cavities : 14560 total

Slide by H. Hayano

Towards ultimate unification



Why is the EW scale so important ?

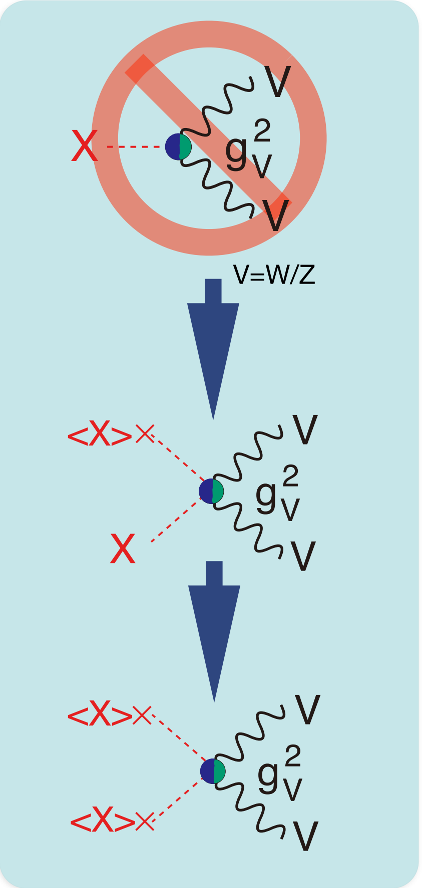
Electroweak Symmetry Breaking

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.

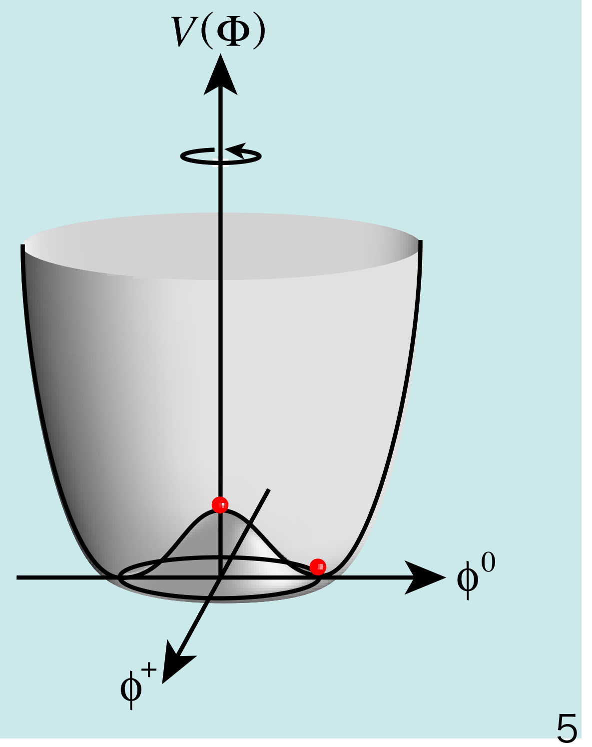
→ We need to know ***the multiplet structure*** of the EWSB sector.

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

★ ***In other words the SM does not tell us:***

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*** (with ***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***

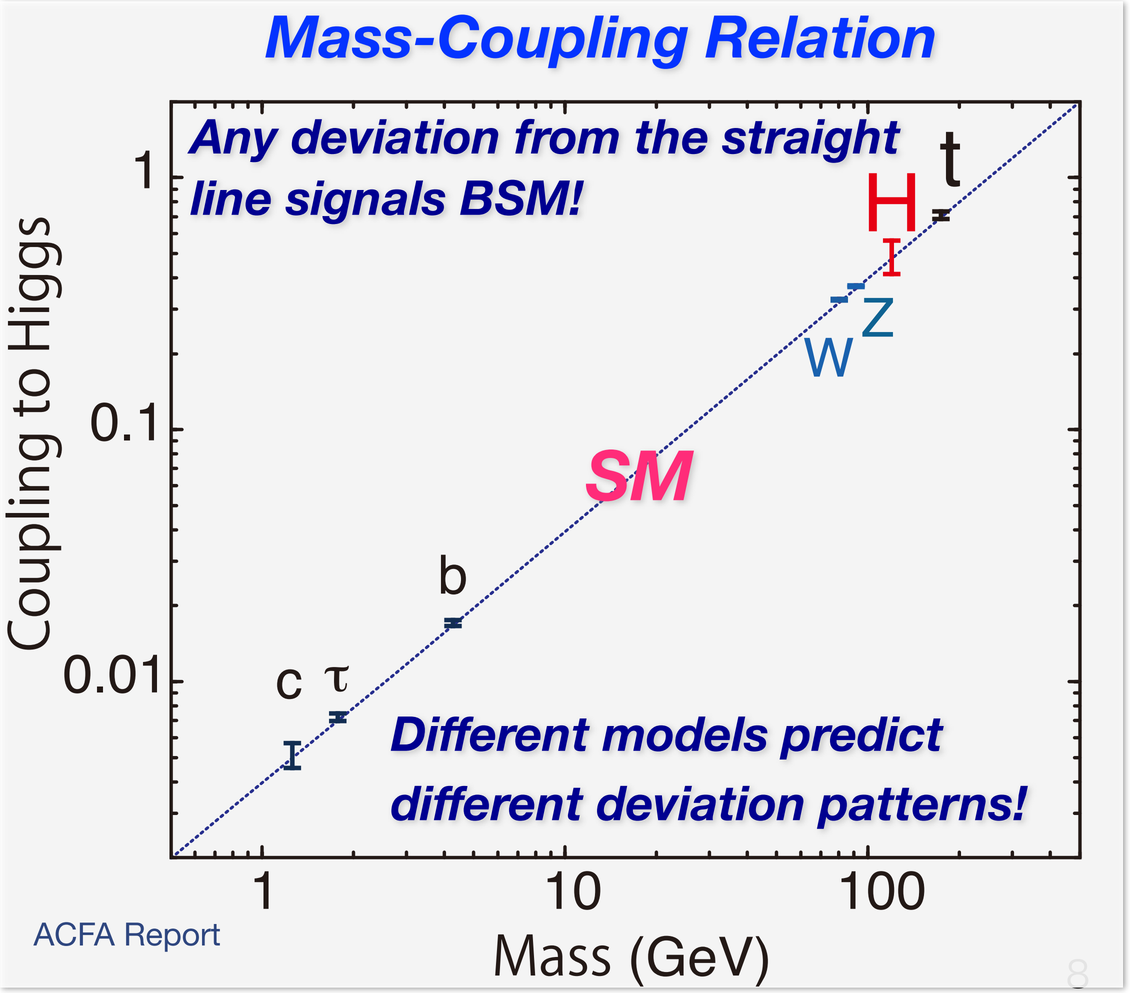
Elementary or Composite?

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: ***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*

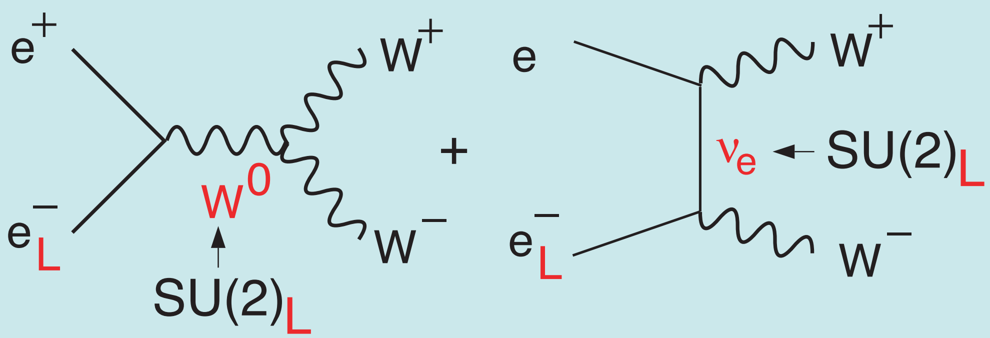
2. *Clean environment: no QCD BG, only with calculable BG from EW processes*

3. *Beam polarization*

Power of Beam Polarization

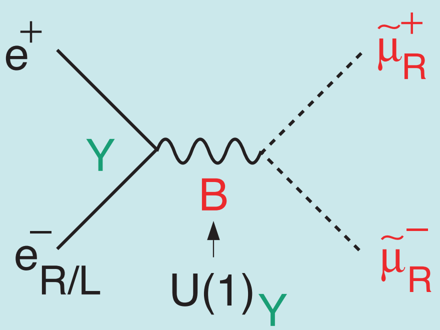
W^+W^- *(Largest SM BG in SUSY searches)*

BG Suppression



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

Slepton Pair

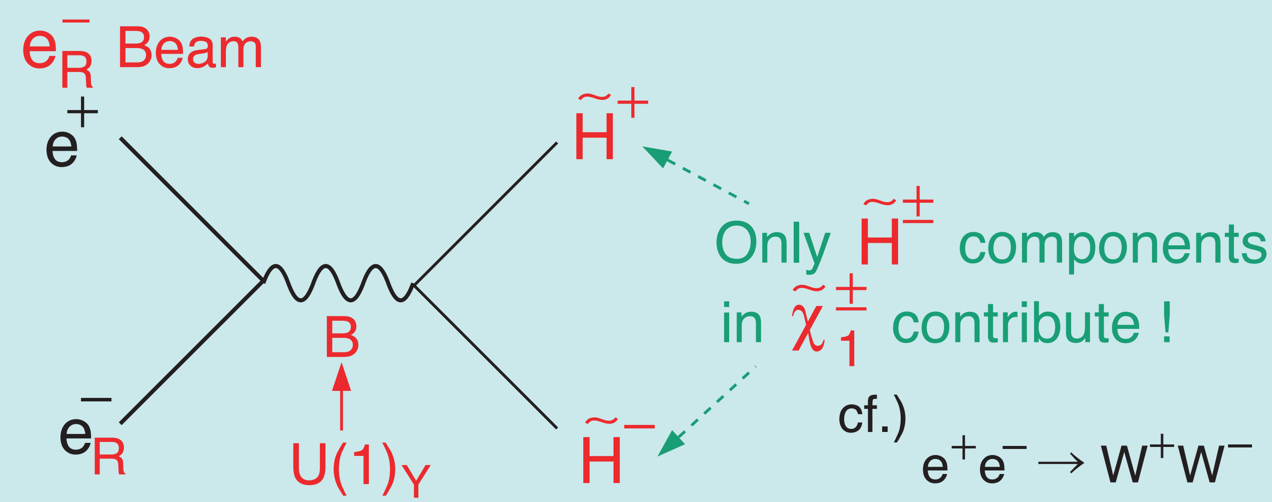


$Y_L = -1/2$: e^-_L

$Y_R = -1$: e^-_R

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

Chargino Pair

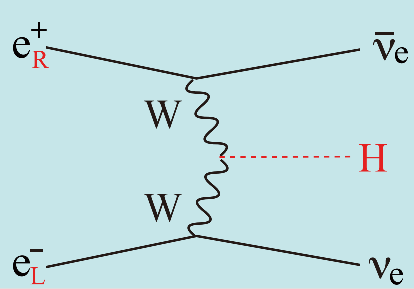


$$\tilde{\chi}^\pm_1 = \bigcirc \cdot \tilde{W}^\pm + \bullet \cdot \tilde{H}^\pm$$

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

Decomposition

WW-fusion Higgs Prod.



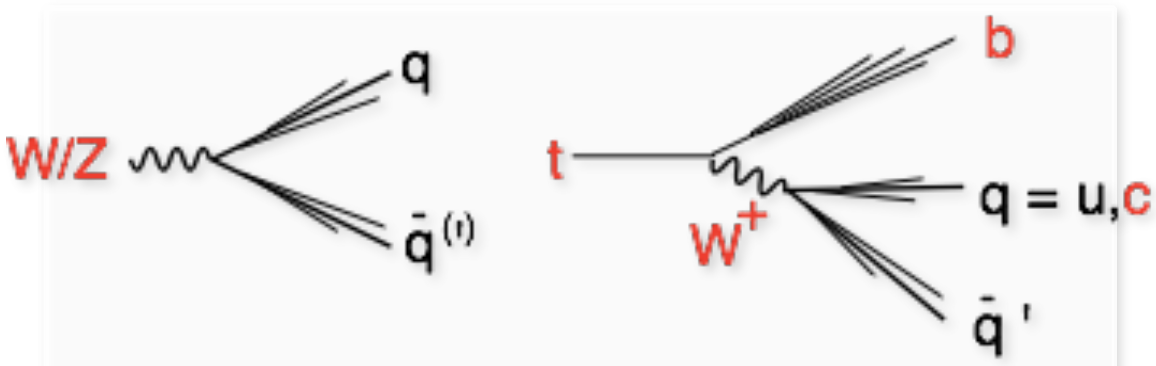
	ILC
Pol (e$^-$)	-0.8
Pol (e$^+$)	+0.3
$(\sigma/\sigma_0)_{\nu\nu H}$	1.8x1.3=2.34

Signal Enhancement

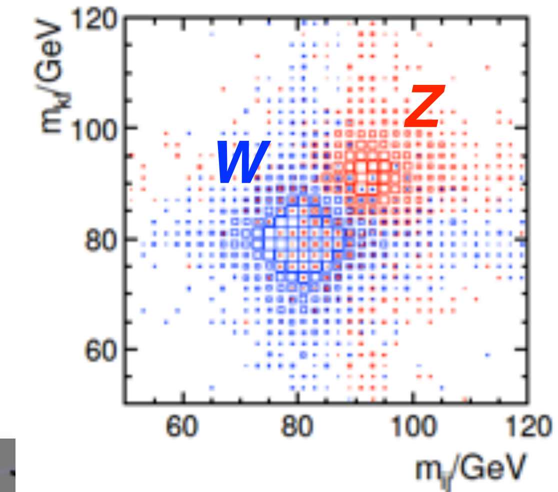
New Paradigm :

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}

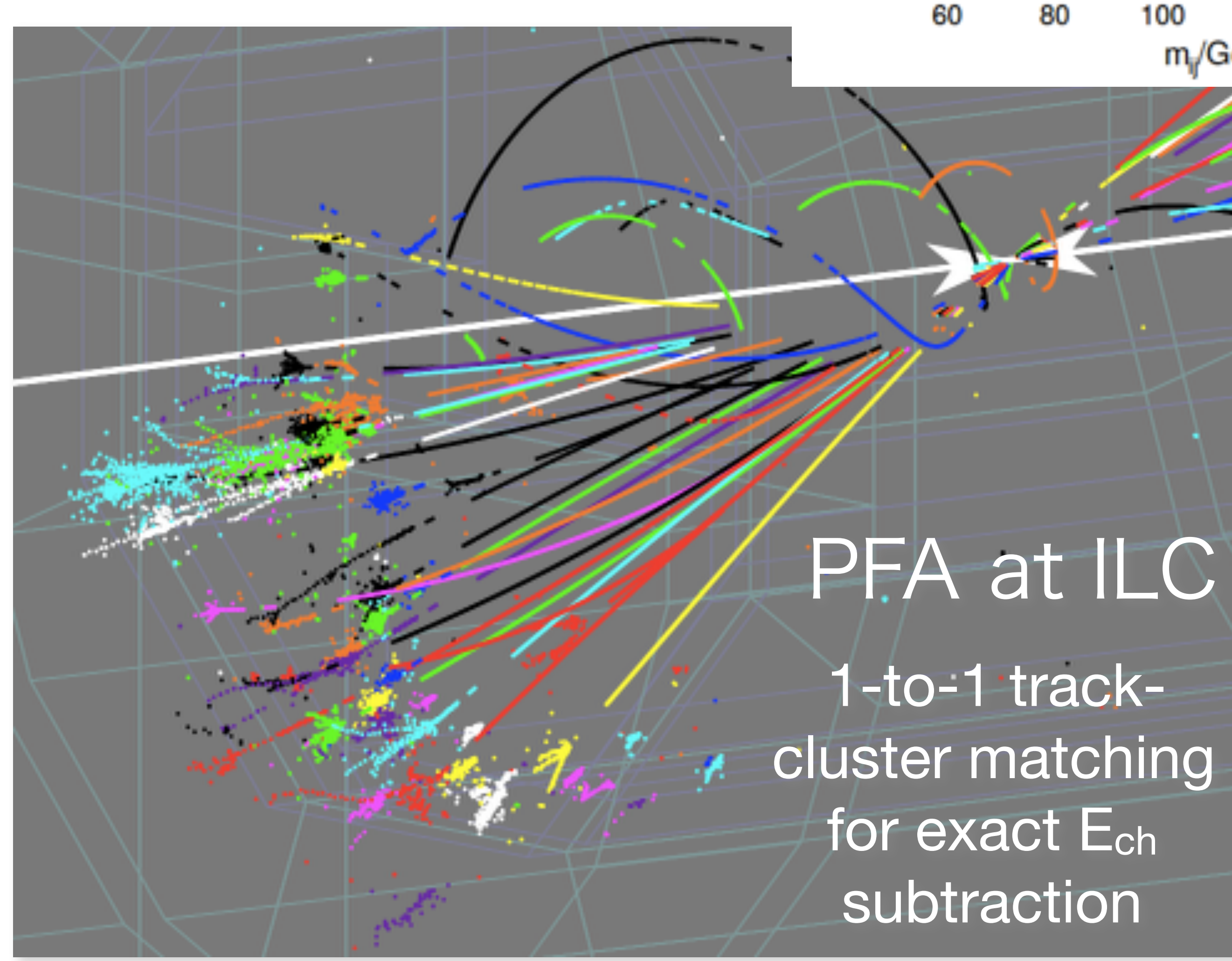


Particle Flow Analysis

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

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

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 Baseline Design (TDR vol.4)

arXiv: 1306.6329

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

ILD

SiD

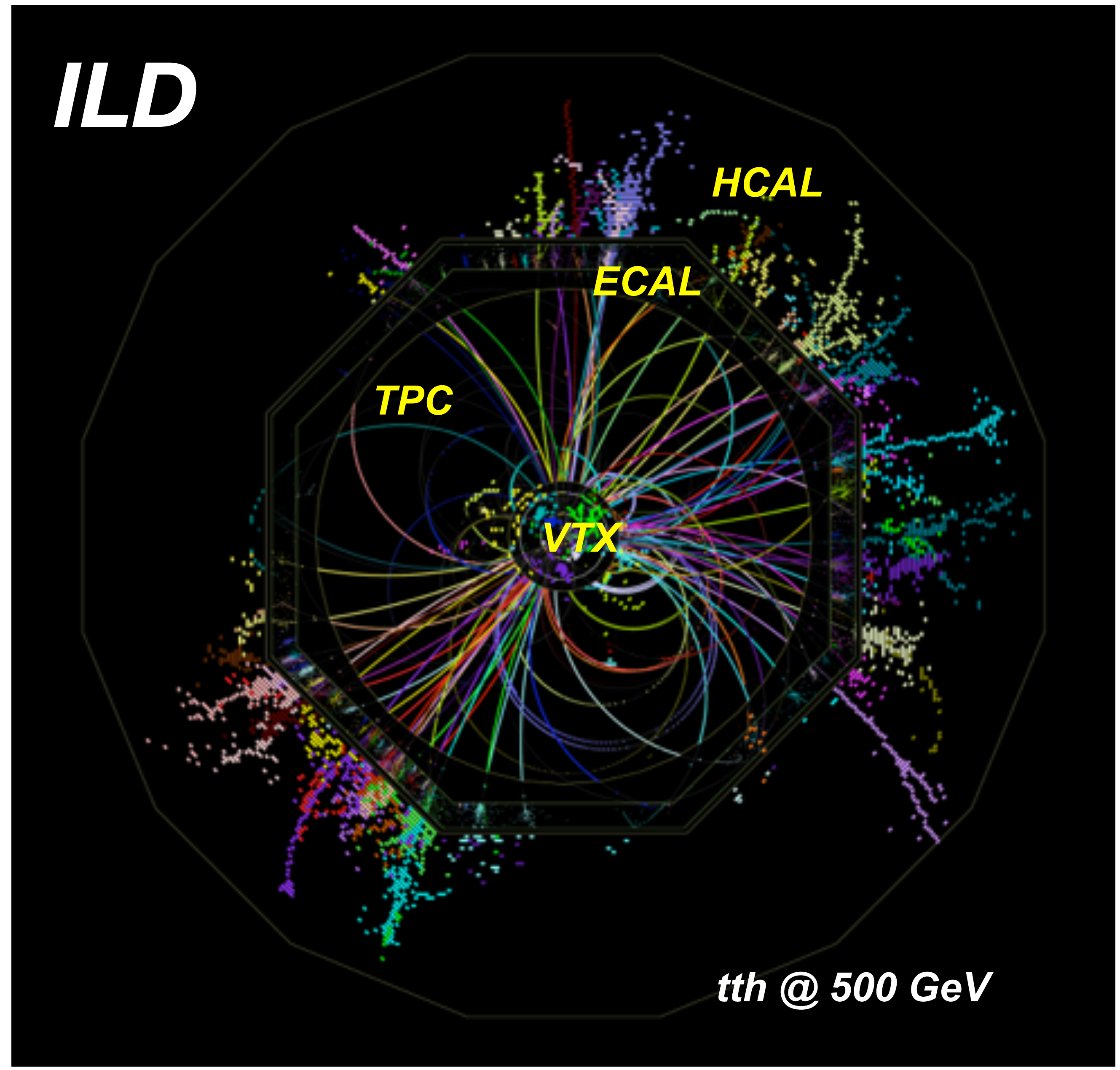
- High B with *Si strip tracker*
  - *LOI signatories:* 18 countries, 77 institutions, ~240 members
  - Mostly American
  - B=5T, Si only tracker
  - ECal : R=1.27m

Both detector concepts are optimized for

Particle Flow Analysis

Features of ILC Detectors

- Compared with LHC detectors, ILC detectors have **~10 times better momentum resolution and 100~1000 times finer granularity.**
- This performance **can be achieved only in the clean environment of the ILC**, and cannot be achieved in the LHC environment.



Higgs

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

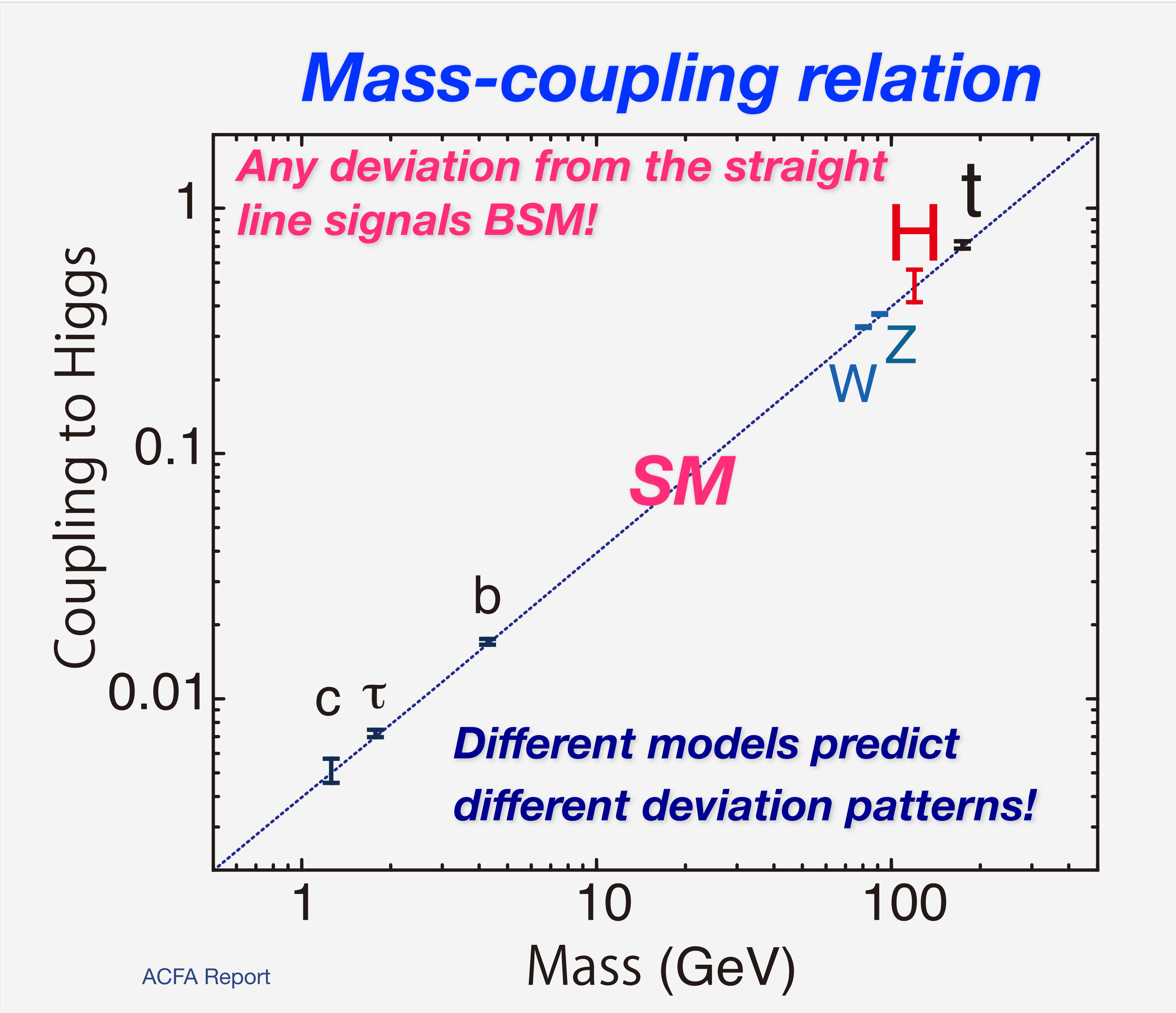
***New Particles*,**

and

Precision measurements of

H(125) Properties (couplings)

Deviation in Higgs Couplings



The size of the deviation depends on the new physics scale (Λ)!

Decoupling Theorem:
Λ↑ → SM

example 1: **Minimal SUSY**

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

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

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 → **deviation is at most ~10%**
We ***need a %-level precision*** → LHC is not enough → ***ILC at 500 GeV***

Why 500 GeV?

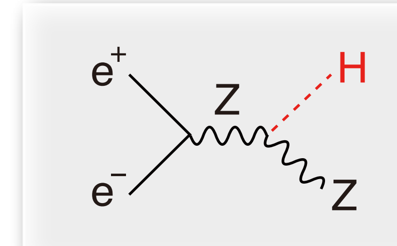
Higgs-related Physics at Ecm ≲ 500 GeV

Three well know thresholds

ZH @ 250 GeV (~M_Z+M_H+20GeV) :

- Higgs mass, width, J^{PC}
- Gauge quantum numbers
- Absolute measurement of HZZ coupling (***recoil mass***)
- BR(h->VV,qq,ll,invisible) : V=W/Z(direct), g, γ (loop)

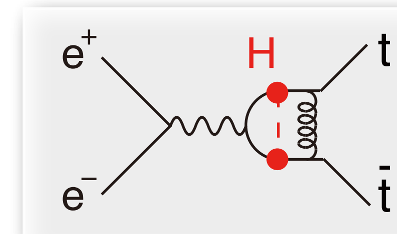
→Higgs couplings (other than top)



ttbar @ 340-350GeV (~2mt) : ZH meas. Is also possible

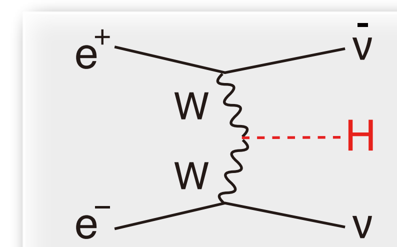
- Threshold scan --> theoretically clean ***mt*** measurement: $\Delta m_t(\overline{MS}) \simeq 100\,\mathrm{MeV}$
  --> test stability of the SM vacuum
  --> indirect meas. of ***top Yukawa*** coupling
- A_{FB}, Top momentum measurements
- Form factor measurements

γ γ → HH @ 350GeV possibility



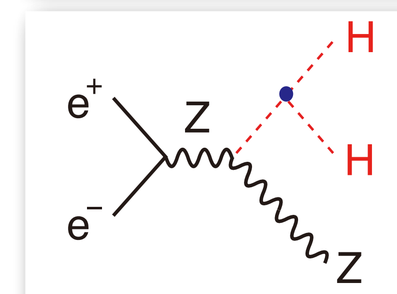
vvH @ 350 - 500GeV :

- ***HWW coupling*** -> ***total width*** --> absolute normalization of Higgs couplings



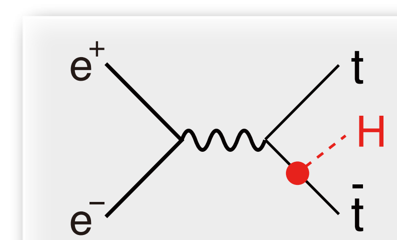
ZHH @ 500GeV (~M_Z+2M_H+170GeV) :

- Prod. cross section attains its maximum at around 500GeV -> ***Higgs self-coupling***



ttbarH @ 500GeV (~2mt+M_H+30GeV) :

- Prod. cross section becomes maximum at around 800GeV.
- QCD threshold correction enhances the cross section -> ***top Yukawa*** measurable at 500GeV concurrently with the self-coupling

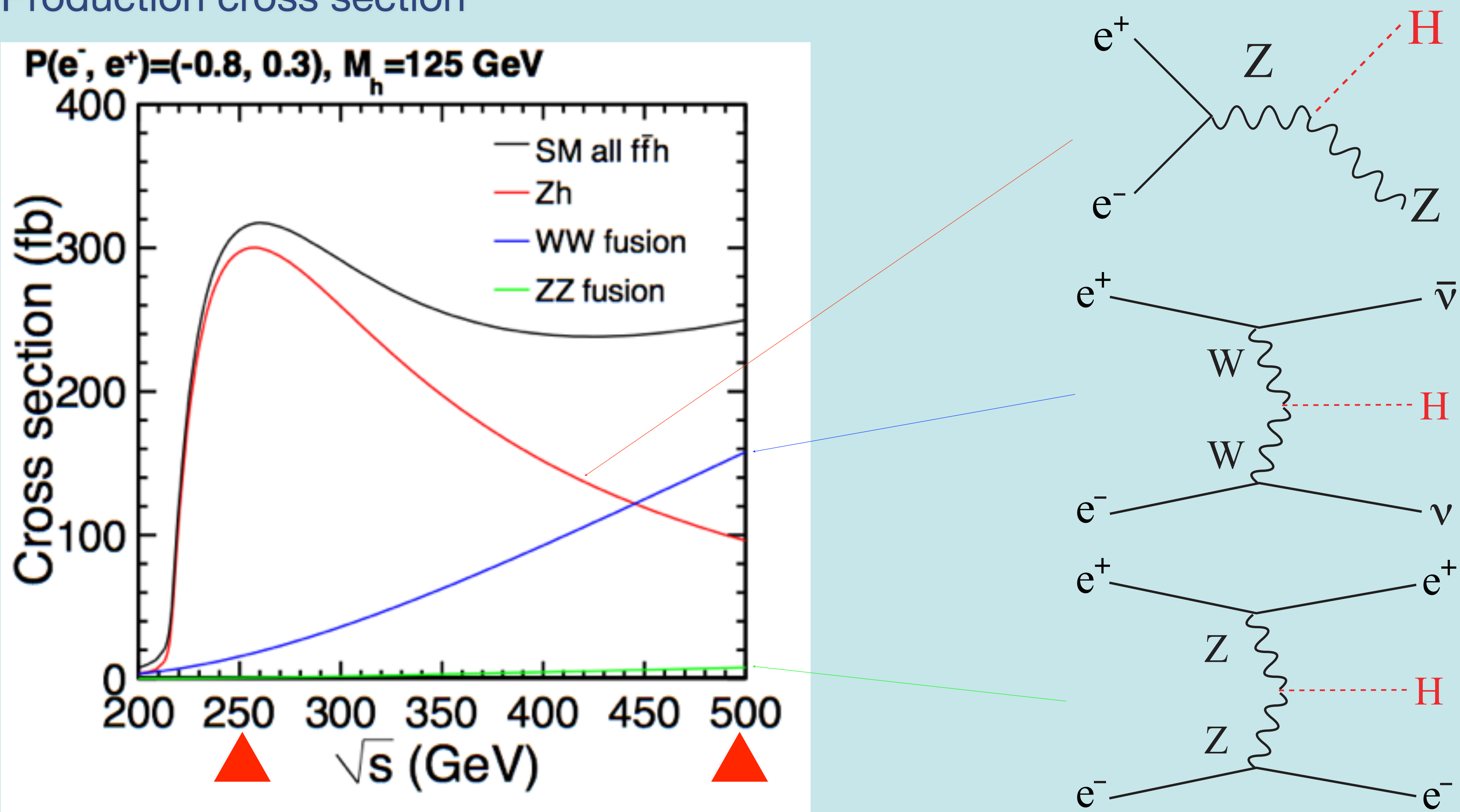


We can access all the relevant Higgs couplings at ~500GeV for the mass-coupling plot!

Main Production Processes

Single Higgs Production

Production cross section



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

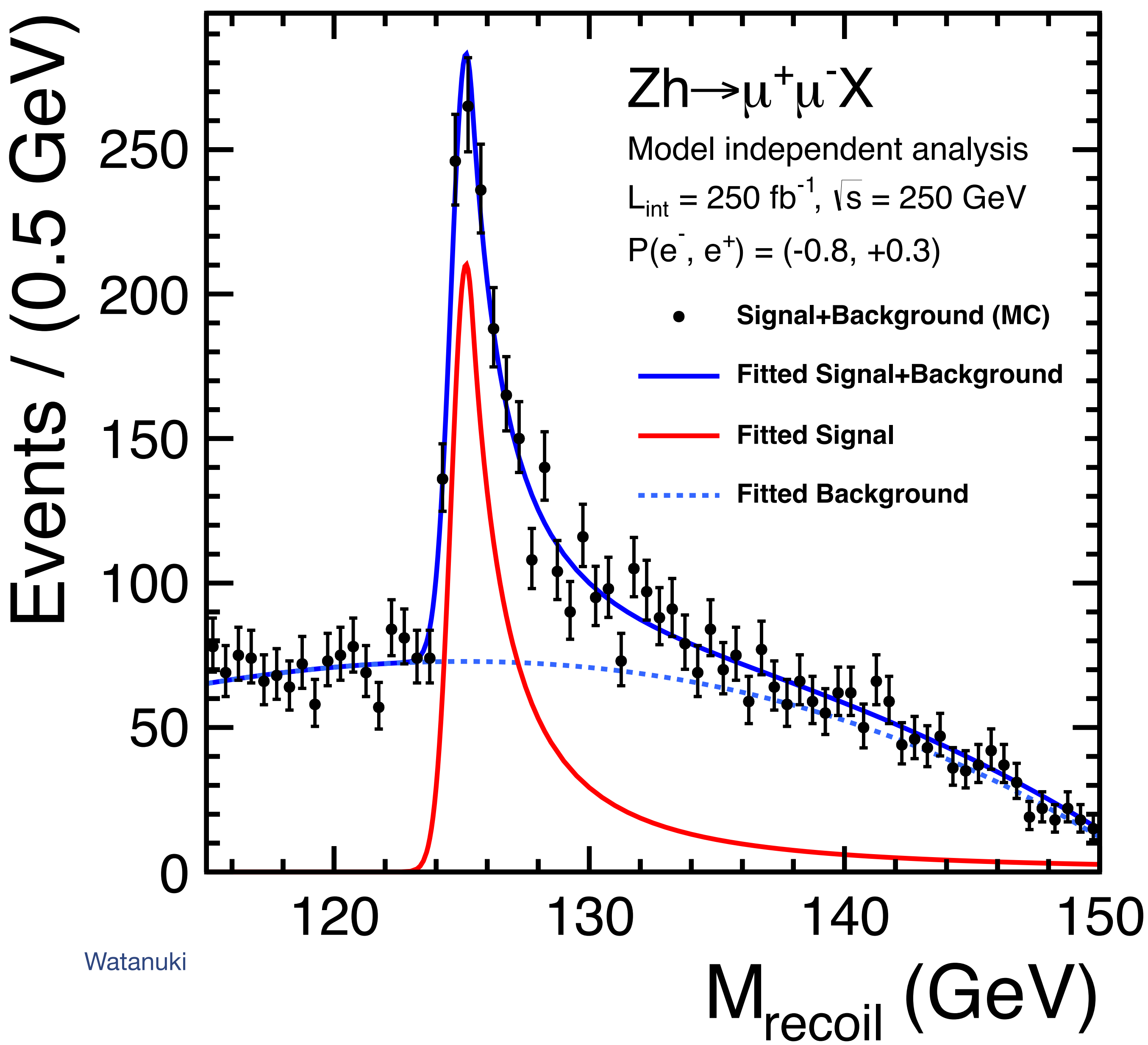
vvH takes over at 500 GeV
(~125k ev: 500 fb^{-1})

200k w/ TDR baseline, eventually >1M Higgs events!

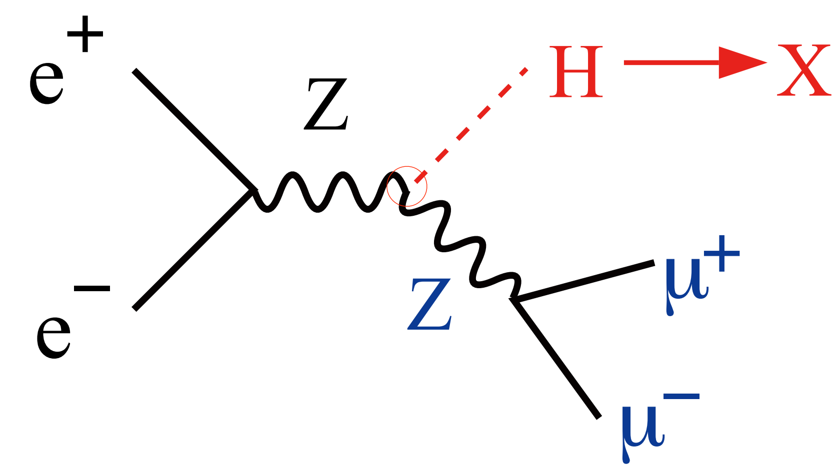
Recoil Mass Measurement: The Key

to unlock the door to fully model-independent determinations of various BRs, Higgs couplings, and total widths

Recoil Mass



Watanuki



$$M_X^2 = \left(p_{CM} - (p_{\mu^+} + p_{\mu^-})\right)^2$$

Invisible decay detectable!

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

$$\Delta\sigma_H/\sigma_H = 2.6\%$$

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

$$BR(\text{invisible}) < 1\%\,@\,95\%\,\text{C.L.}$$

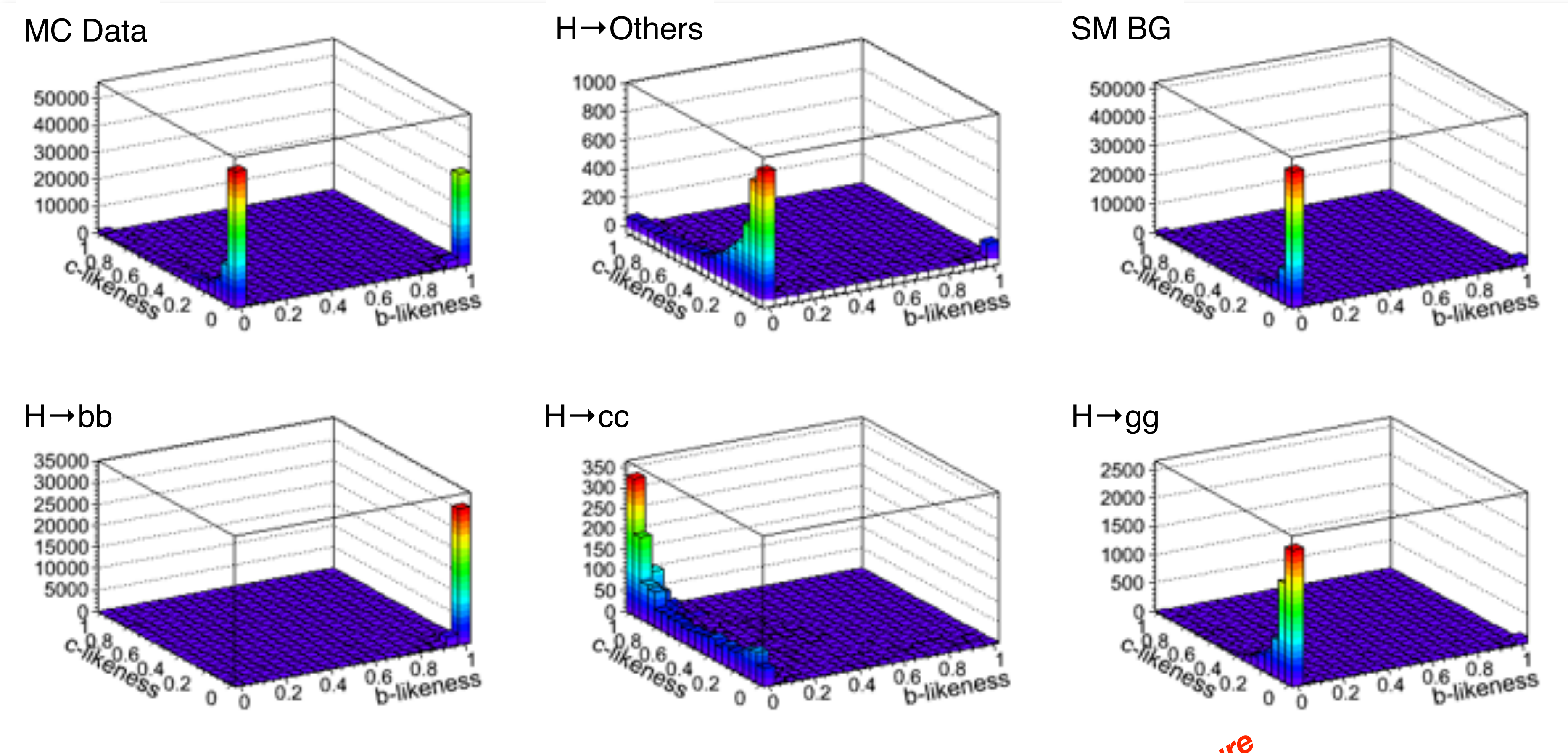
scaled from mH=120 GeV

Model-independent absolute measurement of the σ(HZ) → HZZ coupling

High Performance Flavor Tagging

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

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



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

What we measure here is not BR itself but σxBR

What we measure

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

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

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

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

Total Width and Coupling Extraction

One of the major advantages of the LC

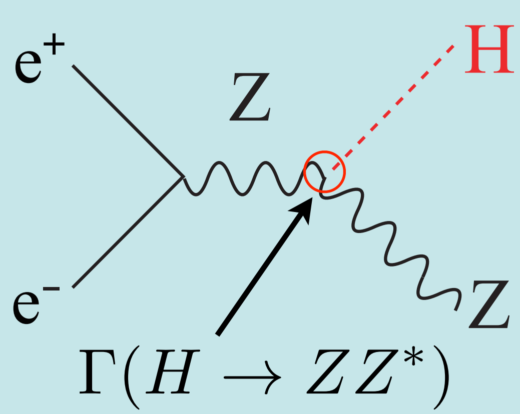
To extract couplings from BRs, we need the total width:

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

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

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

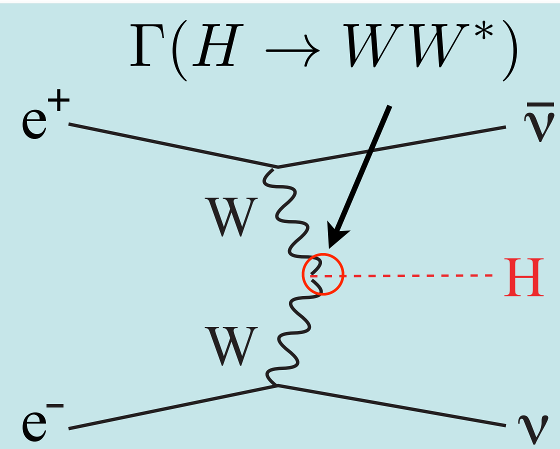
In principle, we can use A=Z, or W for which we can measure both the BRs and the couplings:



$BR(H \to ZZ^*)$

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

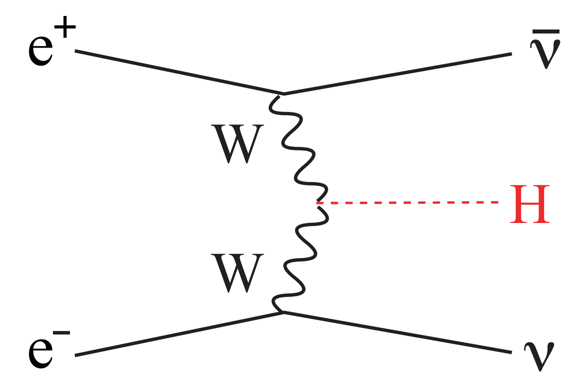
Width and BR Measurements at 500 GeV

Addition of 500GeV data to 250GeV data

E_{cm} [GeV]	independent measurements	relative error
250	σ_{ZH}	2.6%
	$\sigma_{ZH} \cdot Br(H \to b\bar{b})$	1.2%
	$\sigma_{ZH} \cdot Br(H \to c\bar{c})$	8.3%
	$\sigma_{ZH} \cdot Br(H \to gg)$	7%
	$\sigma_{ZH} \cdot Br(H \to WW^*)$	6.4%
	$\sigma_{ZH} \cdot Br(H \to \tau^+\tau^-)$	4.2%
	$\sigma_{\nu\bar{\nu}H} \cdot Br(H \to b\bar{b})$	10.5%
500	σ_{ZH}	3%
	$\sigma_{ZH} \cdot Br(H \to b\bar{b})$	1.8%
	$\sigma_{ZH} \cdot Br(H \to c\bar{c})$	13%
	$\sigma_{ZH} \cdot Br(H \to gg)$	11%
	$\sigma_{ZH} \cdot Br(H \to WW^*)$	9.2%
	$\sigma_{ZH} \cdot Br(H \to \tau^+\tau^-)$	5.4%
	$\sigma_{\nu\bar{\nu}H} \cdot Br(H \to b\bar{b})$	0.66%
	$\sigma_{\nu\bar{\nu}H} \cdot Br(H \to c\bar{c})$	6.2%
	$\sigma_{\nu\bar{\nu}H} \cdot Br(H \to gg)$	4.1%
	$\sigma_{\nu\bar{\nu}H} \cdot Br(H \to WW^*)$	2.4%

$$250\,\text{fb}^{-1}@250\,\text{GeV}$$
$$+500\,\text{fb}^{-1}@500\,\text{GeV}$$
$$m_H = 125\,\text{GeV}$$

ILD DBD Full Simulation Study



comes in as a powerful tool!

$$\Delta\Gamma_H/\Gamma_H \simeq 5\%$$

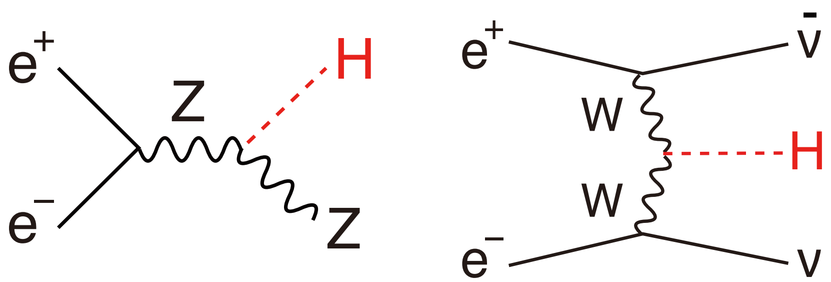
Mode	ΔBR/BR
bb	2.2 (2.9)%
cc	5.1 (8.7)%
gg	4.0 (7.5)%
WW*	3.1 (6.9)%
τ τ	3.7 (4.9)%

The numbers in the parentheses are as of $250\,\text{fb}^{-1}@250\,\text{GeV}$

Key Point

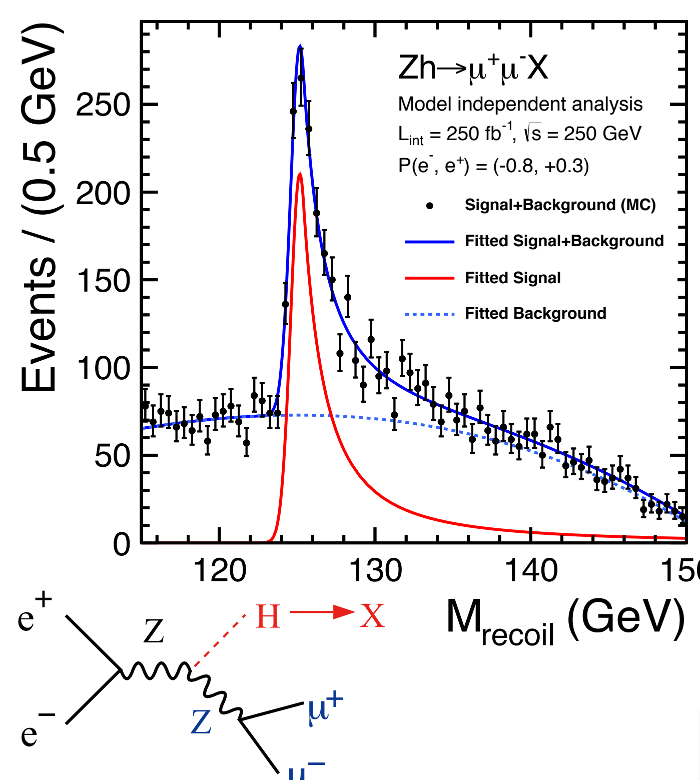
At LHC all the measurements are σ×BR measurements.

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



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

σ×BR → **BR** → **g coupling**

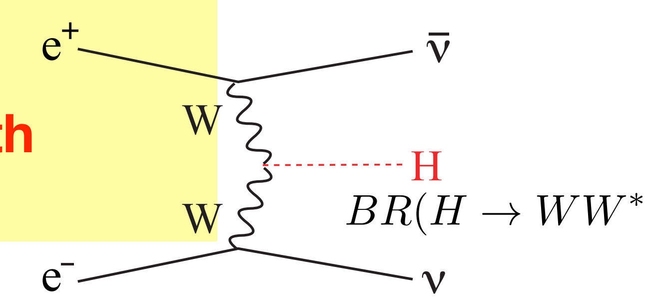


$$M_X^2 = \left(p_{CM} - (p_{\mu^+} + p_{\mu^-})\right)^2$$

The Key

σ from recoil mass → **Γ_H Total Width**

WW-fusion is crucial for precision total width measurement
→ Ecm > 350GeV



Can detect even if Higgs decays invisibly!

Higgs Physics at Higher Energy

Self-coupling with WBF, top Yukawa at xsection max., other higgses, ...

vvH @ at >1TeV : > 1ab^{-1} (pol e$^+$, e$^-$)=(+0.2,-0.8)

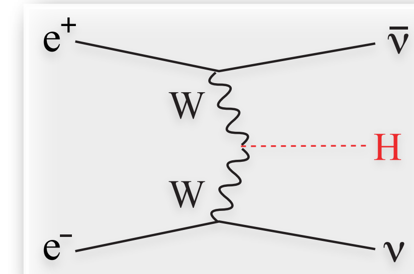
- allows us to measure rare decays such as H -> $\mu^+ \mu^-$, ...
- further improvements of coupling measurements

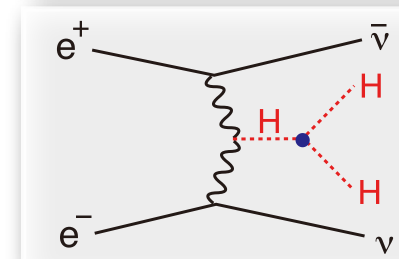
vvHH @ 1TeV or higher : 2ab^{-1} (pol e$^+$, e$^-$)=(+0.2,-0.8)

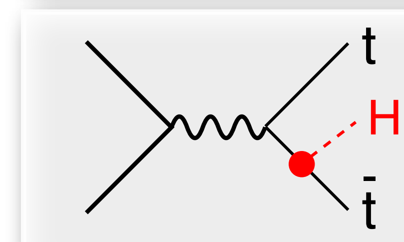
- cross section increases with Ecm, which compensates the dominance of the background diagrams at higher energies, thereby giving a better precision for the self-coupling.
- If possible, we want to see the running of the self-coupling (very very challenging).

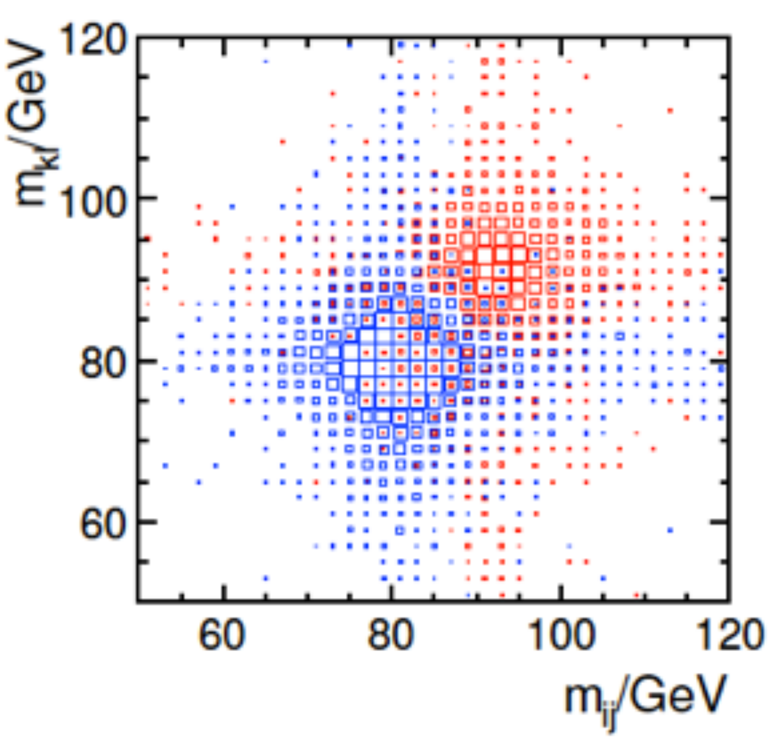
ttbarH @ 1TeV : 1ab^{-1}

- Prod. cross section becomes maximum at around 800GeV.
- CP mixing of Higgs can be unambiguously studied.









Obvious but most important advantage of higher energies in terms of Higgs physics is, however, its higher mass reach to other Higgs bosons expected in extended Higgs sectors and higher sensitivity to $W_L W_L$ scattering to decide whether the Higgs sector is strongly interacting or not.

In any case we can improve the mass-coupling plot by including the data at 1TeV!

Independent Higgs Measurements at ILC

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

Baseline (=TDR) ILC program

(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	3.2%		5.4%	9%	3.1%
H→ZZ*	19%		25%	8.2%	4.1%
H→γγ	34%		34%	19%	7.4%
H→μμ	72%	-	88%	72%	31%
tth/H→bb	-		28% (12%@550GeV)		6.2%

Model-independent Global Fit for Couplings

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

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

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

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

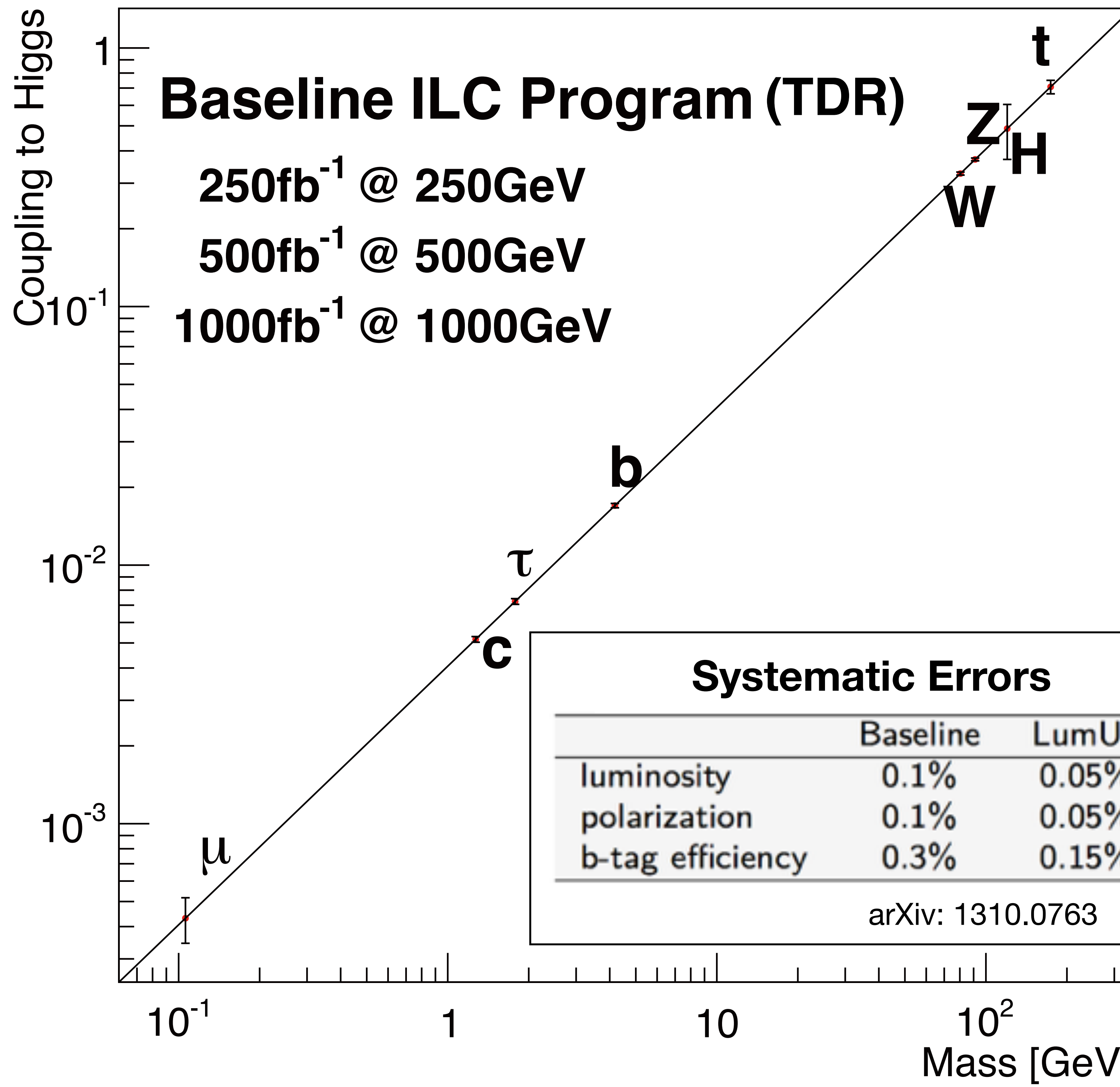
$(A_i = Z, W, t)$

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

$$F_i = S_i\, G_i$$

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

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



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 fit, impossible at LHC***

H20 Scenario

arXiv: 1506.05992

arXiv: 1506.07830

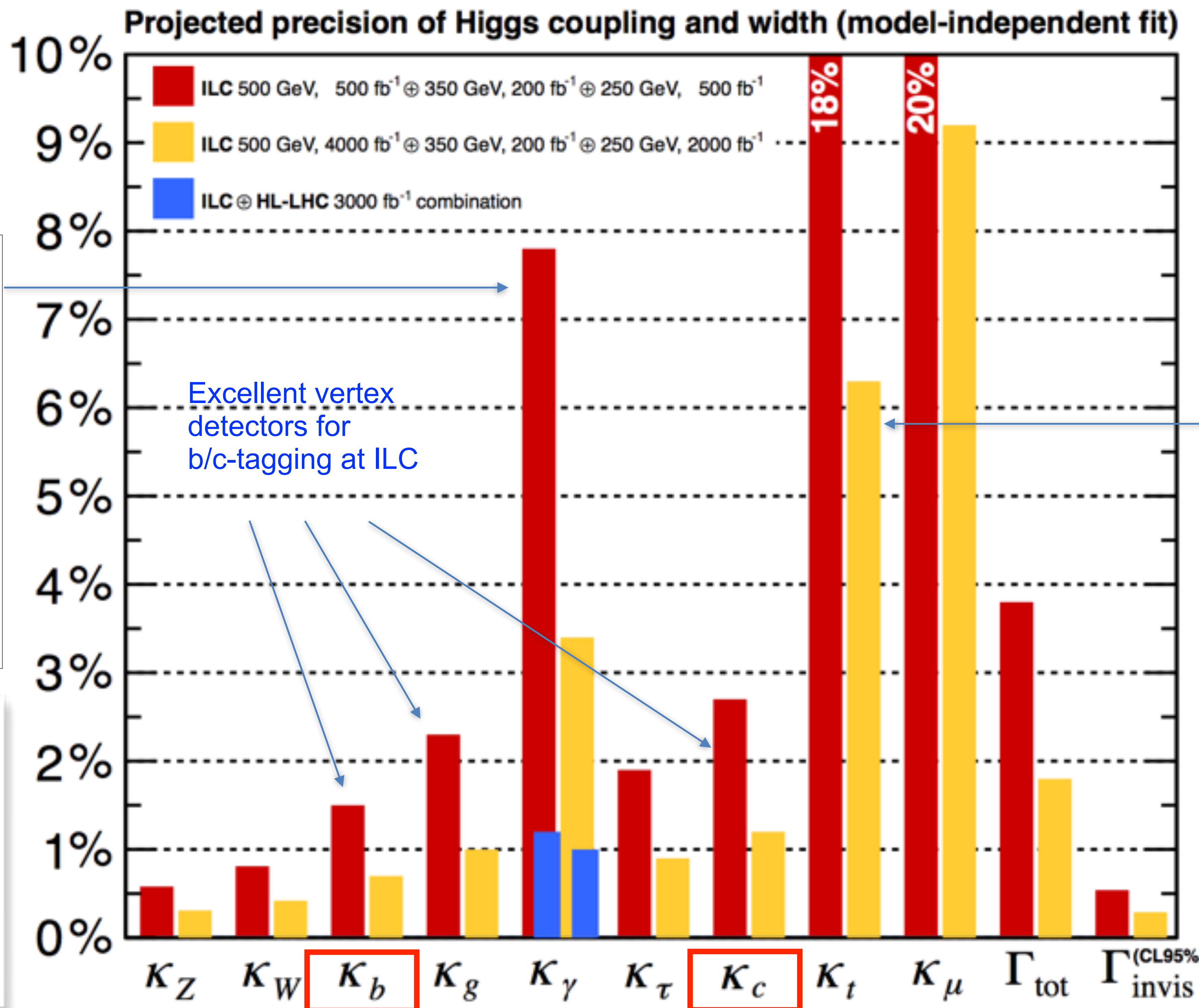
Better hγγ with LHC/ILC synergy

LHC can precisely measure

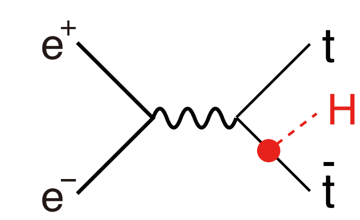
$BR(h \to \gamma\gamma) / BR(h \to ZZ^*)$
$= (K_\gamma / K_Z)^2$

ILC can precisely measure K_Z

All of major Higgs decay modes accessible at ILC with 250-500GeV!



Top Yukawa improves by going to 550 GeV

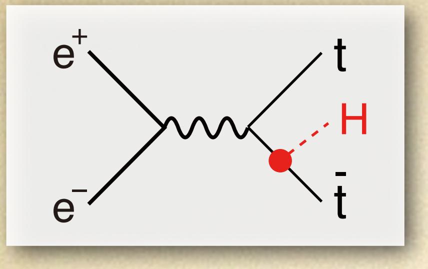


Near threshold → a factor of 4 enhancement of σ_{tth} by going from 500GeV to 550 GeV

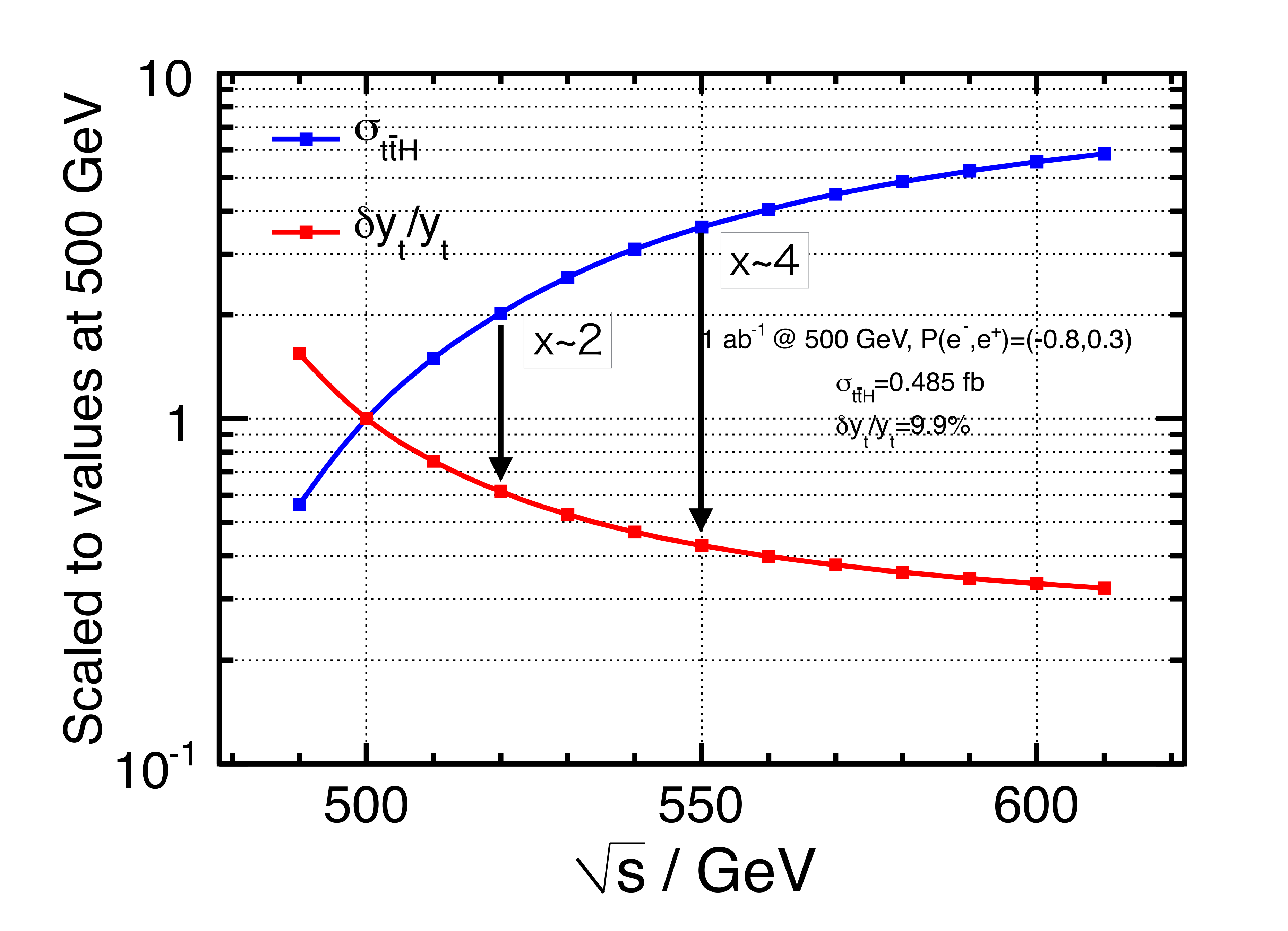
→ 3%

500 GeV already excellent except for K_t, K_μ, and K_γ

~1% or better for most couplings!



Top Yukawa coupling



Y. Sudo

Slight increase of E_{max} is very beneficial!

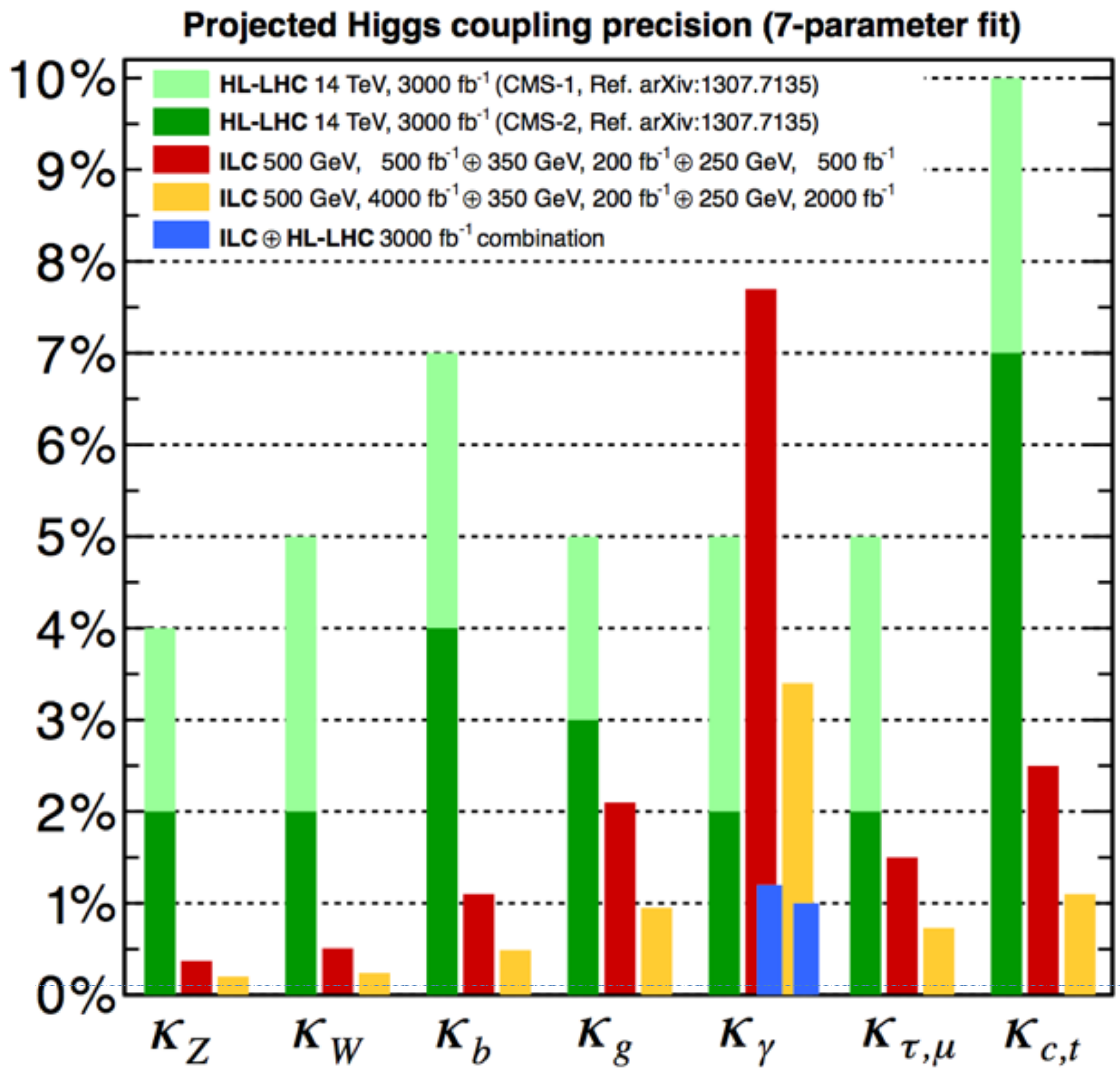
Model-dependent ***coupling fit*** *(LHC-style 7-parameter fit)*

H20 Scenario

arXiv: 1506.05992

arXiv: 1506.07830

Σ_{SM} BR = 1



Possible to achieve precision far exceeding LHC!

Fingerprinting

H20 Scenario

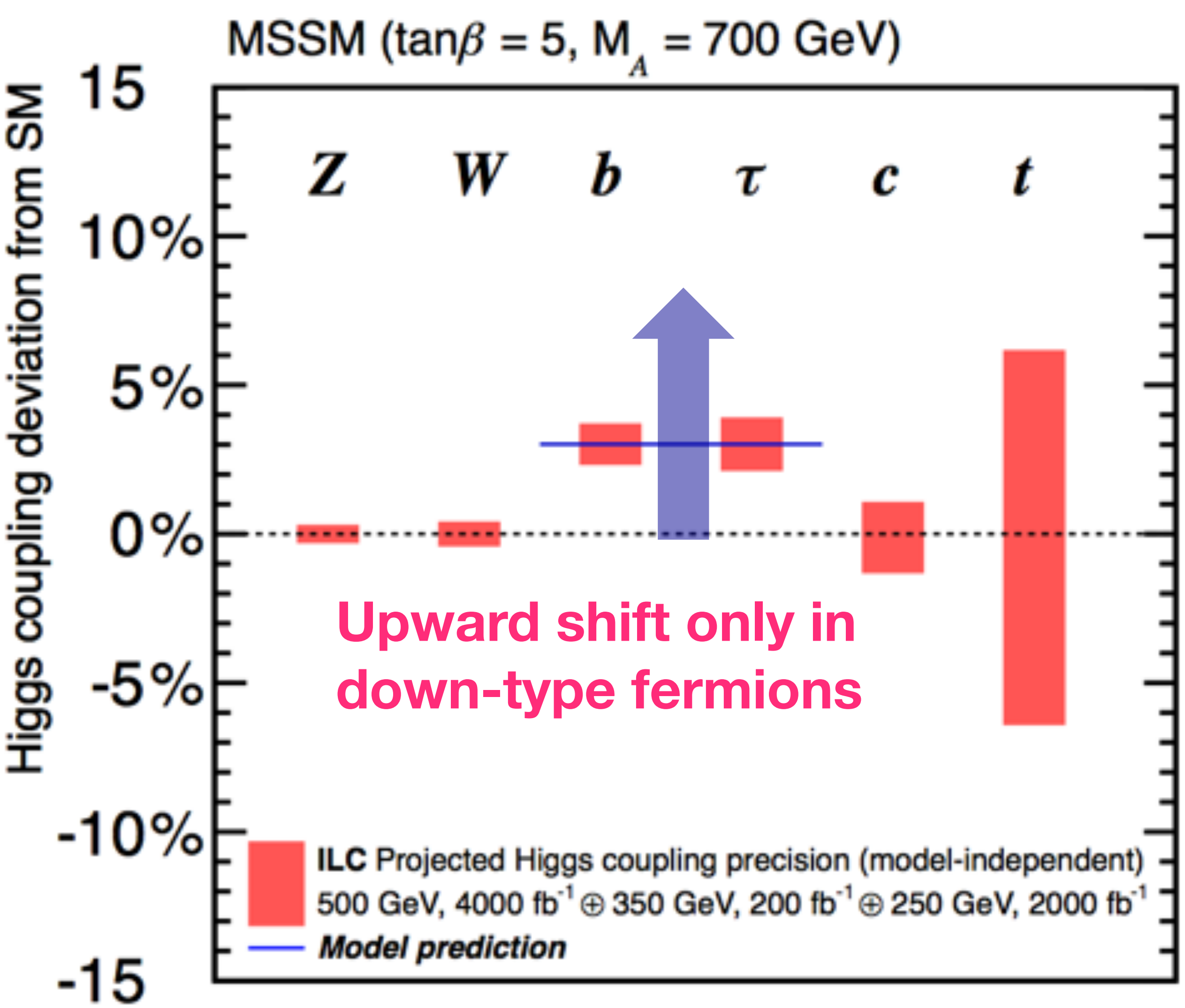
arXiv: 1506.05992

arXiv: 1506.07830

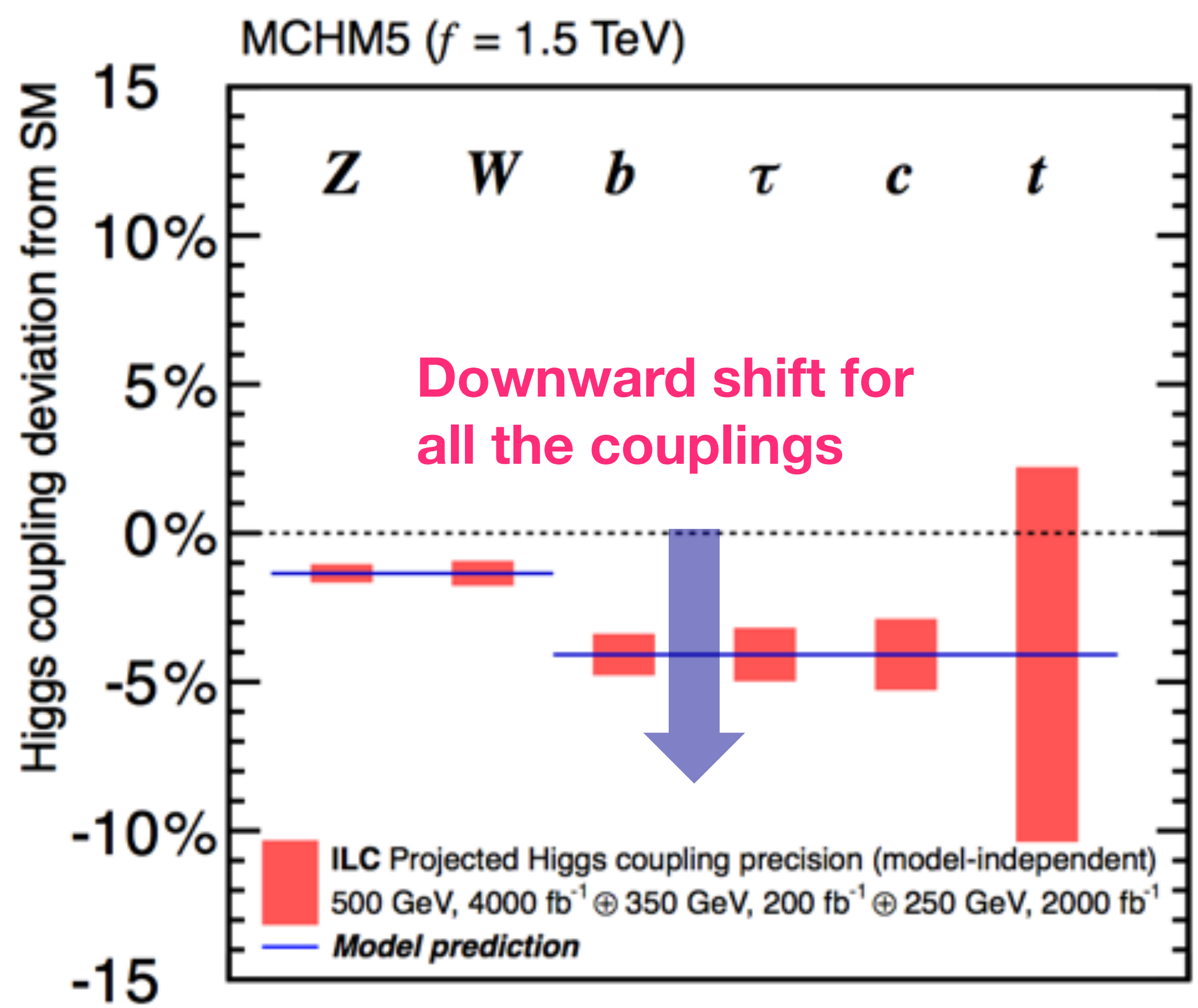
Fingerprinting

Elementary v.s. Composite?

Supersymmetry
(MSSM)



Composite Higgs
(MCHM5)



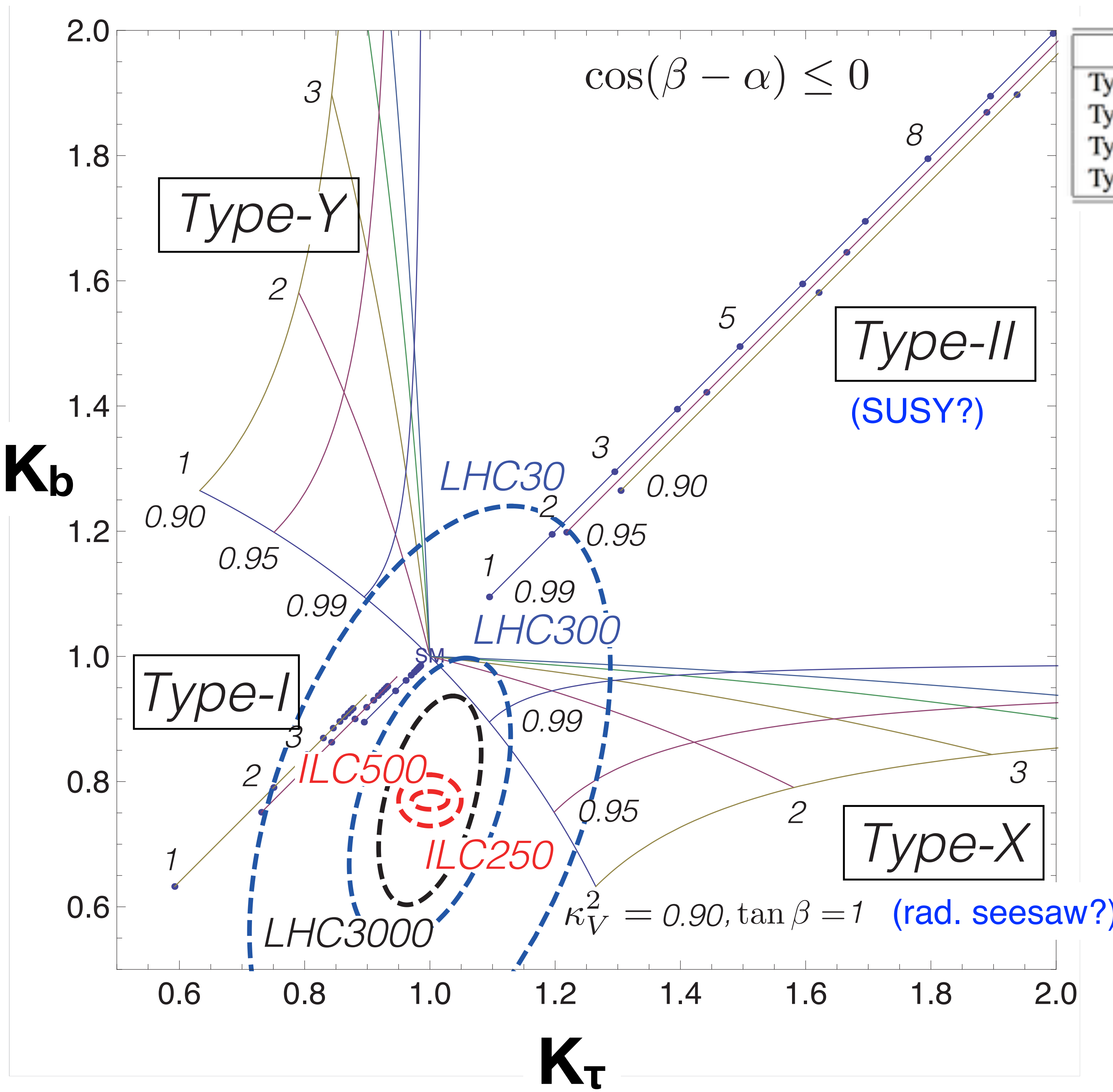
ILC 250+500 LumiUP

Complementary to direct searches at LHC: Depending on parameters, ILC's sensitivity far exceeds that of LHC!

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.

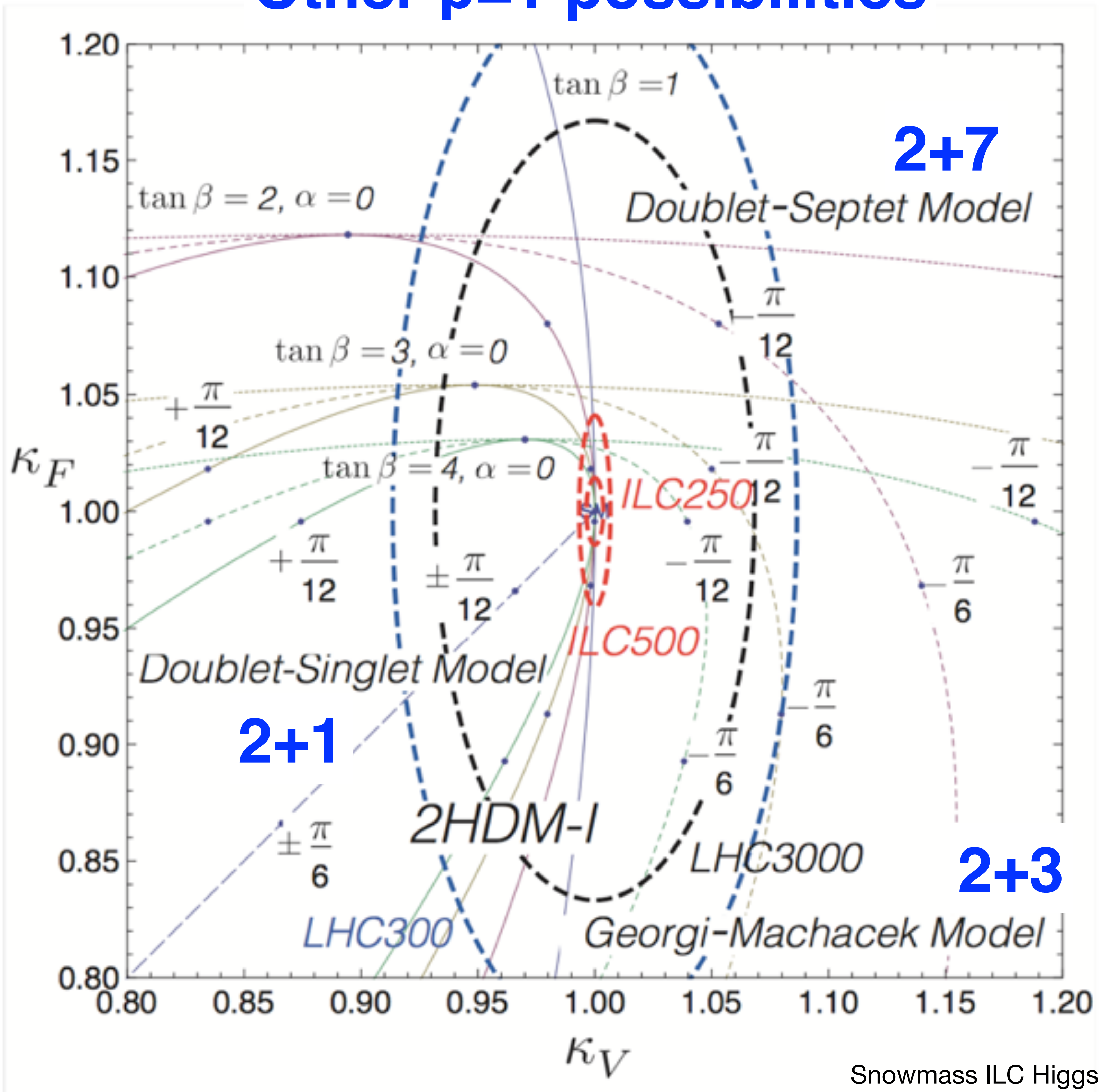
ILC TDR

Snowmass ILC Higgs White Paper (arXiv: 1310.0763)

Kanemura et al (arXiv: 1406.3294)

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.

arXiv 1502.03959

Footprints of Supersymmetry on Higgs Decay

Motoi Endo[a,b], Takeo Moroi[a,b], and Mihoko M. Nojiri[b,c,d]

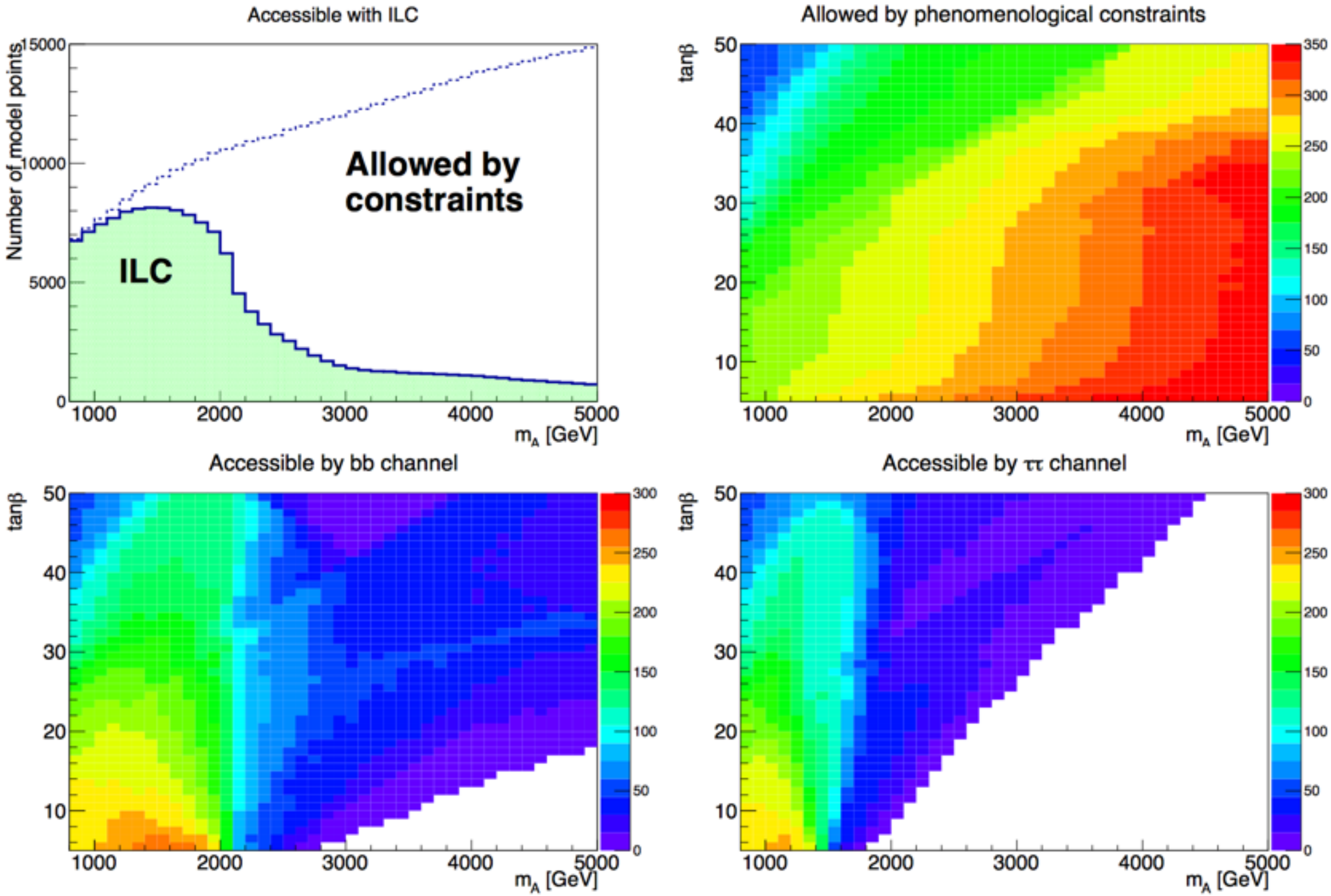


Figure 8: Upper-left: The number of model points accessible with ILC by at least one decay mode of h as a function of m_A (green histogram), as well as that of model points allowed by the phenomenological constraints (dotted histogram). Upper-right: The number of model points allowed by the phenomenological constraints on m_A vs. $\tan\beta$ plane. Lower-left: The number of model points accessible with ILC by $h \to \bar{b}b$. Lower-right: The number of model points accessible with ILC by $h \to \bar{\tau}\tau$.

Composite Higgs: Reach

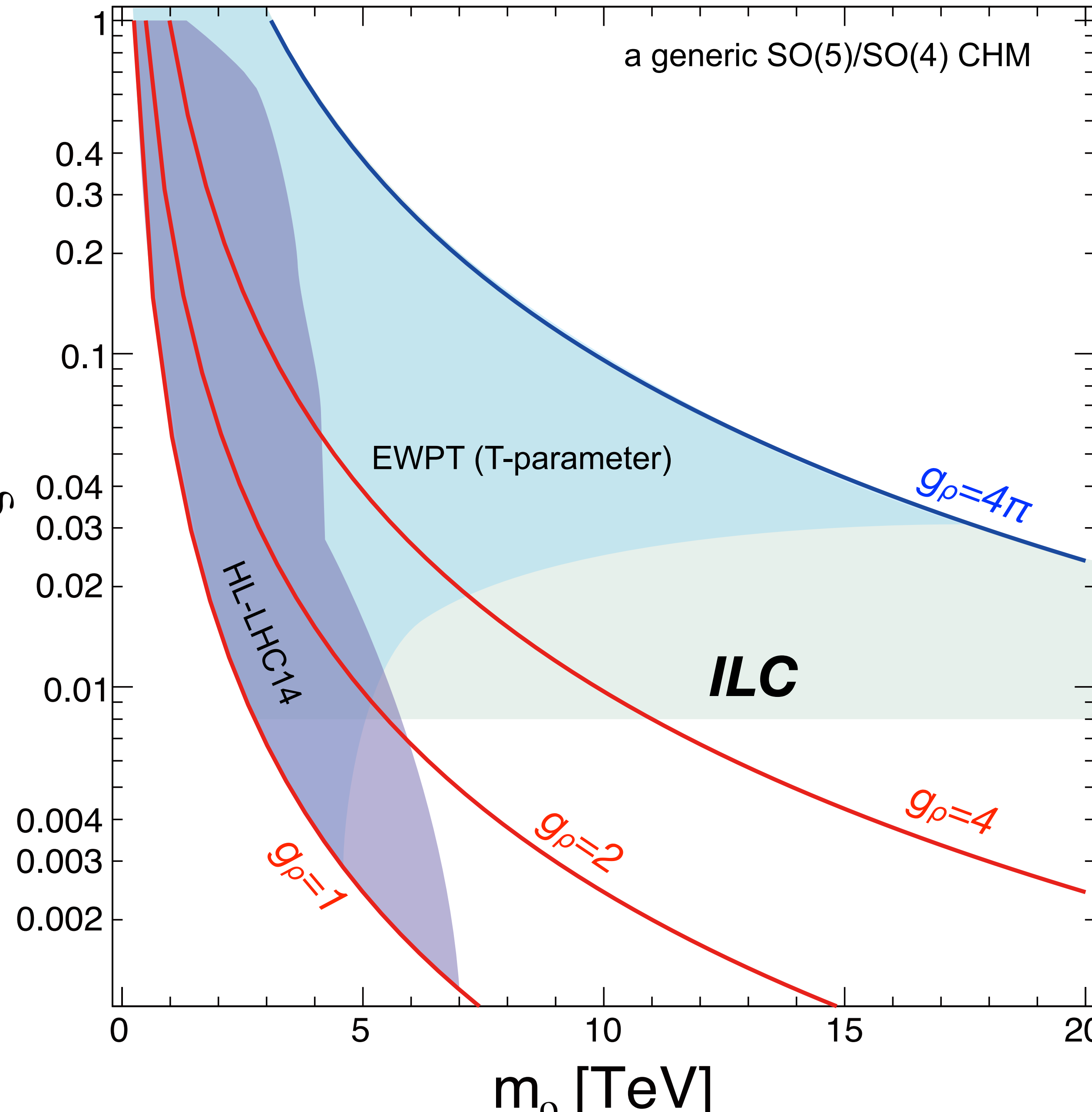
Complementary approaches to probe composite Higgs models
- Direct search for heavy resonances at the LHC
- Indirect search via Higgs couplings at the ILC

Comparison depends on the coupling strength (g_*)

Direct Search

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

Higgs Couplings



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

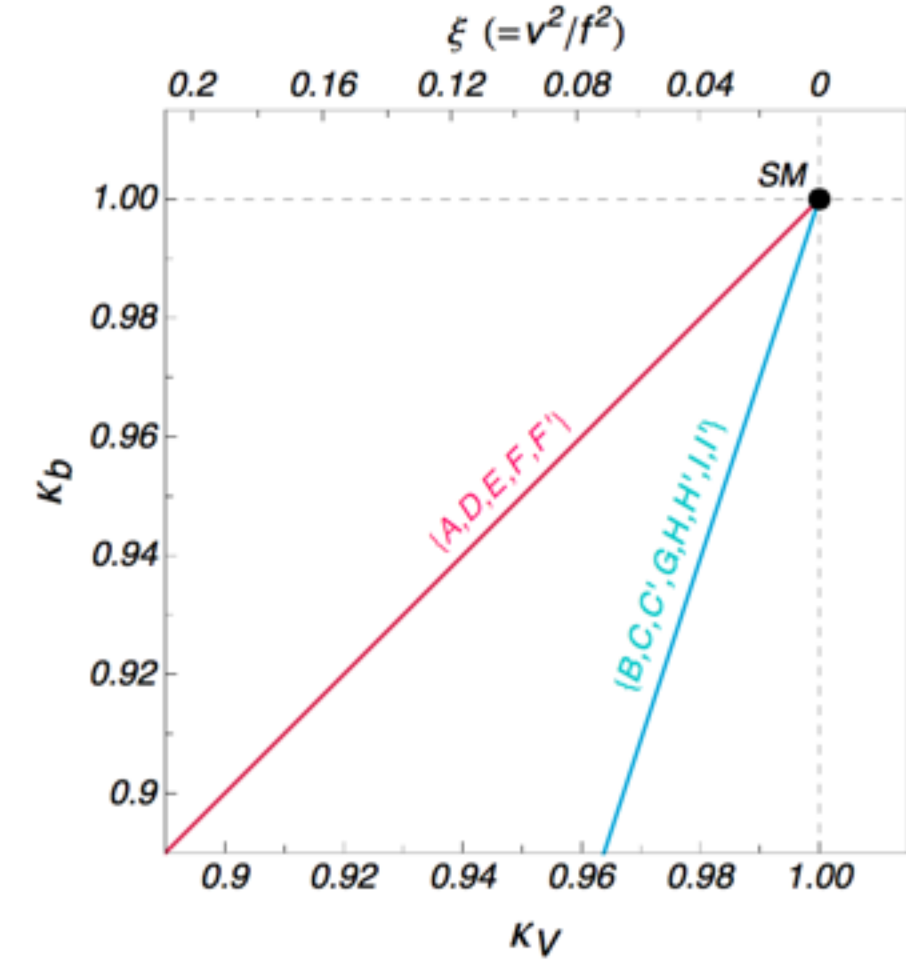
$$\frac{g_{hVV}}{g_{h_{SM}VV}} = \sqrt{1-\xi}$$

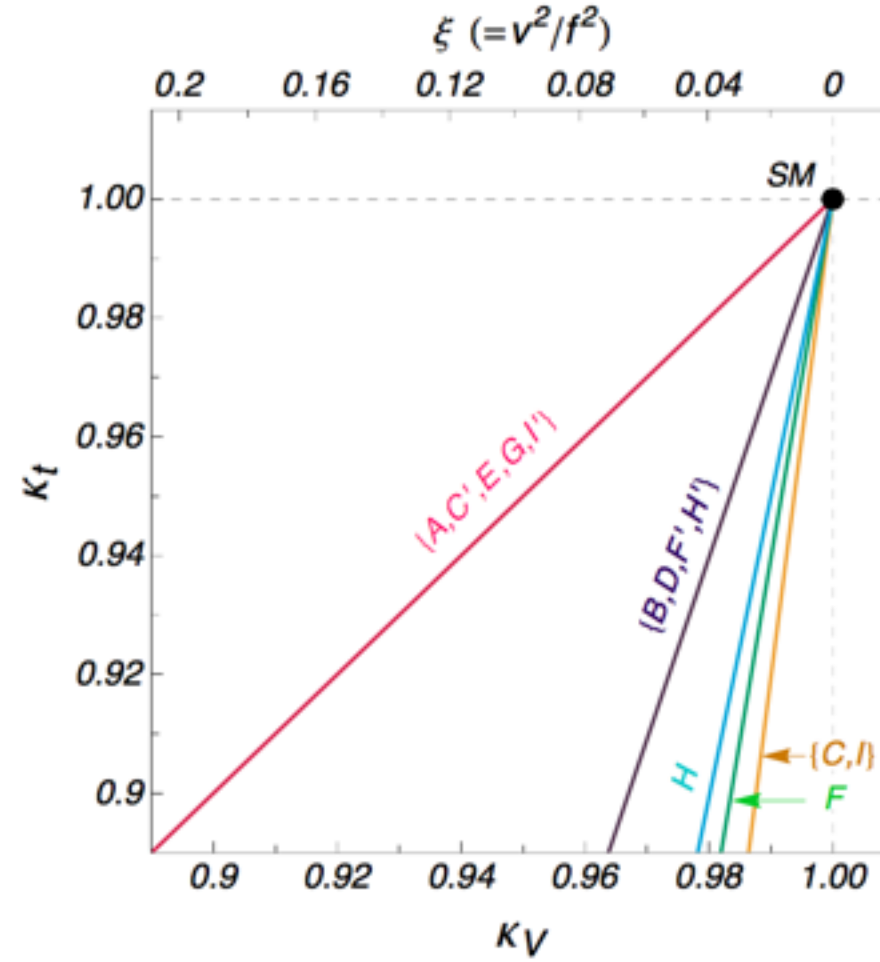
ILC (250+500 LumiUP)

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

New resonance scale and fingerprint identification in minimal composite Higgs models

Shinya Kanemura,[1] Kunio Kaneta,[2] Naoki Machida,[1] and Tetsuo Shindou[3]





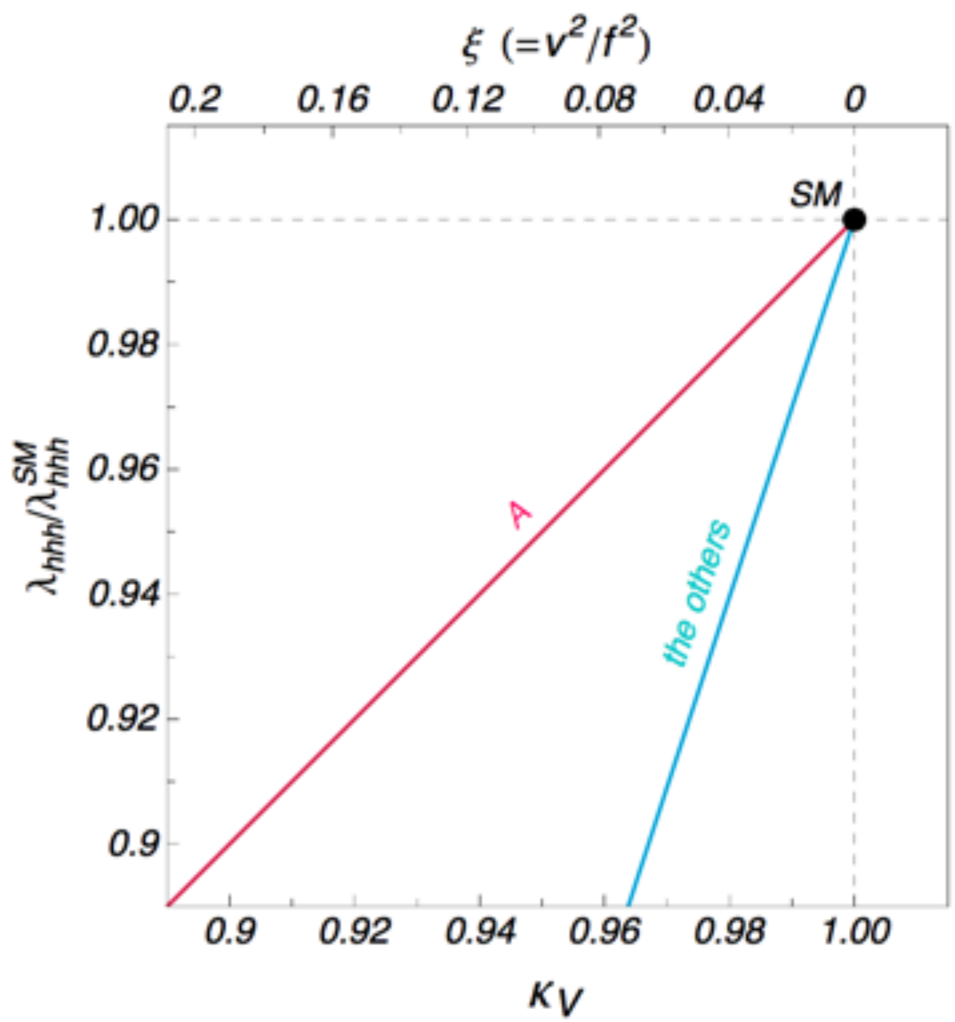


TABLE I: Scale factors for MCHMs with various matter representations. The labels are used in Fig. 7, where C, H and I are the case of $M_1^t \to 0$, and C', H' and I' are the case of $M_2^t \to 0$.

Label	Model	κ_V	c_{hhVV}	κ_{hhh}	c_{hhhh}	κ_t	κ_b	c_{hhtt}	c_{hhbb}
A	$MCHM_4$	$\sqrt{1-\xi}$	$1-2\xi$	$\sqrt{1-\xi}$	$1-\frac{7}{3}\xi$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$	$-\xi$	$-\xi$
B	$MCHM_5$	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	-4ξ
B	$MCHM_{10}$	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	-4ξ
C, C'	$MCHM_{14}$	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	F_3	$\frac{1-2\xi}{\sqrt{1-\xi}}$	F_6	-4ξ
D	$MCHM_{5\text{-}5\text{-}10}$	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\sqrt{1-\xi}$	-4ξ	$-\xi$
E	$MCHM_{5\text{-}10\text{-}10}$	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$	$-\xi$	$-\xi$
F, F'	$MCHM_{5\text{-}14\text{-}10}$	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	F_5	$\sqrt{1-\xi}$	F_8	$-\xi$
G	$MCHM_{10\text{-}5\text{-}10}$	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\sqrt{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$-\xi$	-4ξ
B	$MCHM_{10\text{-}14\text{-}10}$	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	-4ξ
B	$MCHM_{14\text{-}1\text{-}10}$	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	-4ξ
H, H'	$MCHM_{14\text{-}5\text{-}10}$	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	F_4	$\frac{1-2\xi}{\sqrt{1-\xi}}$	F_7	-4ξ
B	$MCHM_{14\text{-}10\text{-}10}$	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	-4ξ
I, I'	$MCHM_{14\text{-}14\text{-}10}$	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	F_3	$\frac{1-2\xi}{\sqrt{1-\xi}}$	F_6	-4ξ

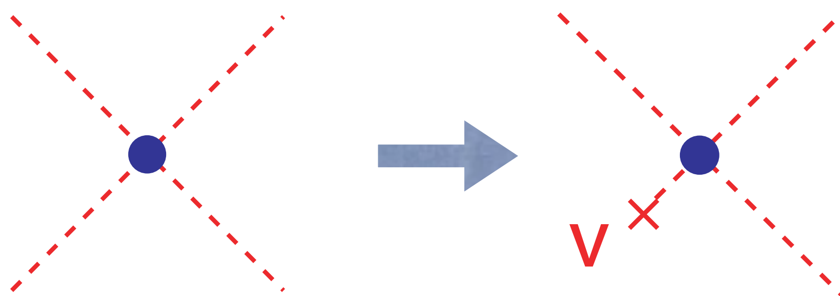
arXiv 1410.8413

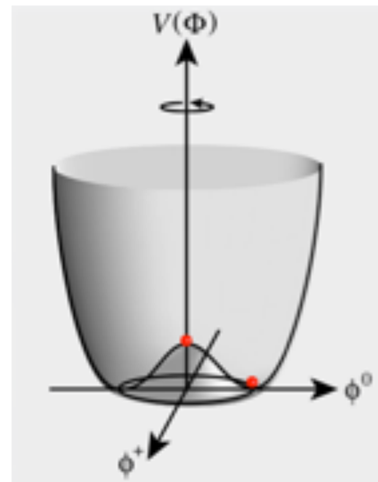
Higgs Self-coupling

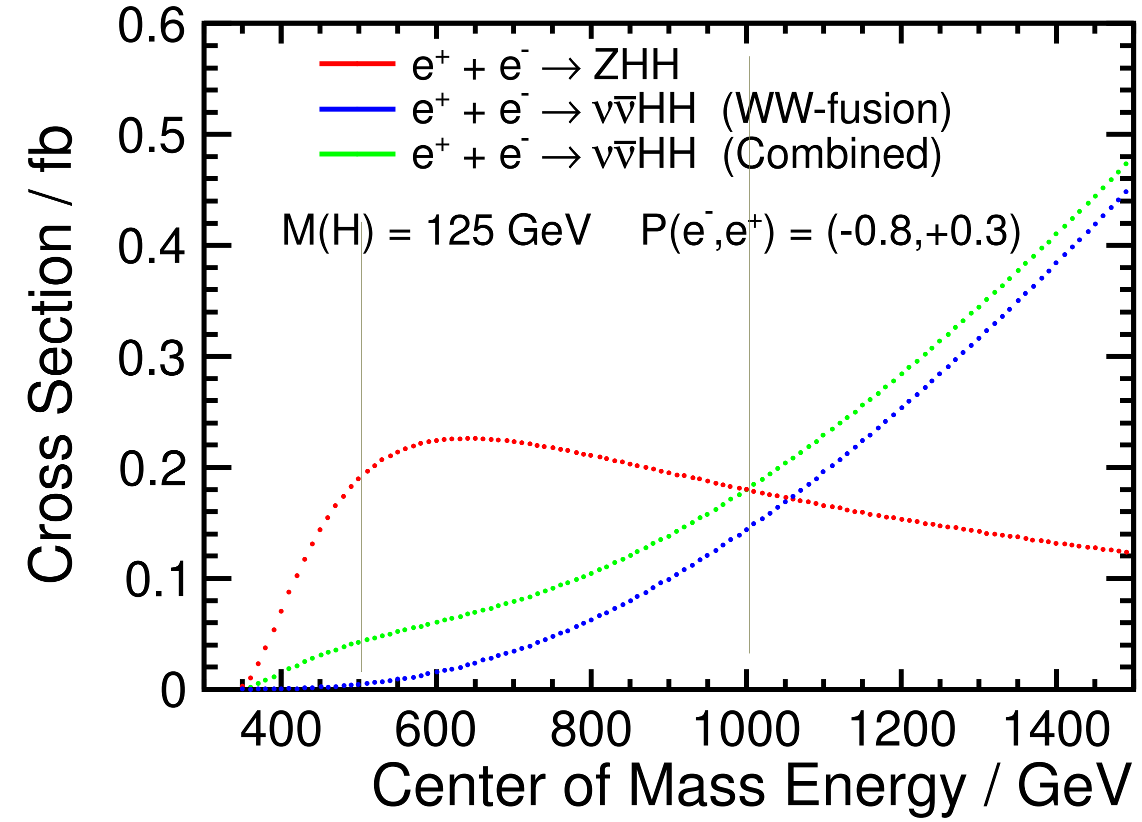
EW phase transition:
1st order
or
2nd order?

Higgs Self-Coupling

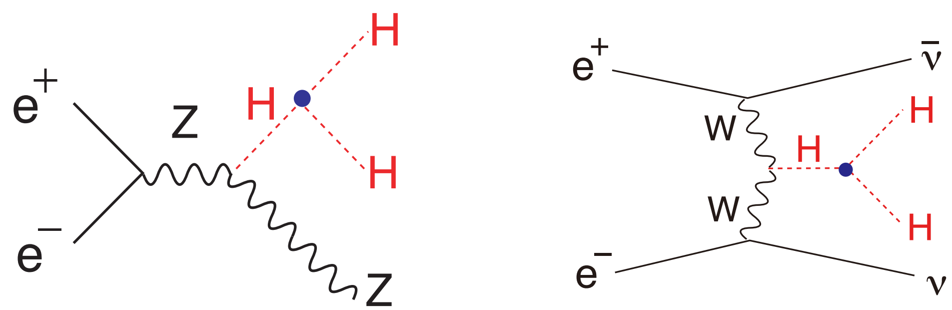
The ***Higgs 3-point self-coupling*** is at the heart of EWSB!







There are ***two ways to measure it*** at ILC



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%

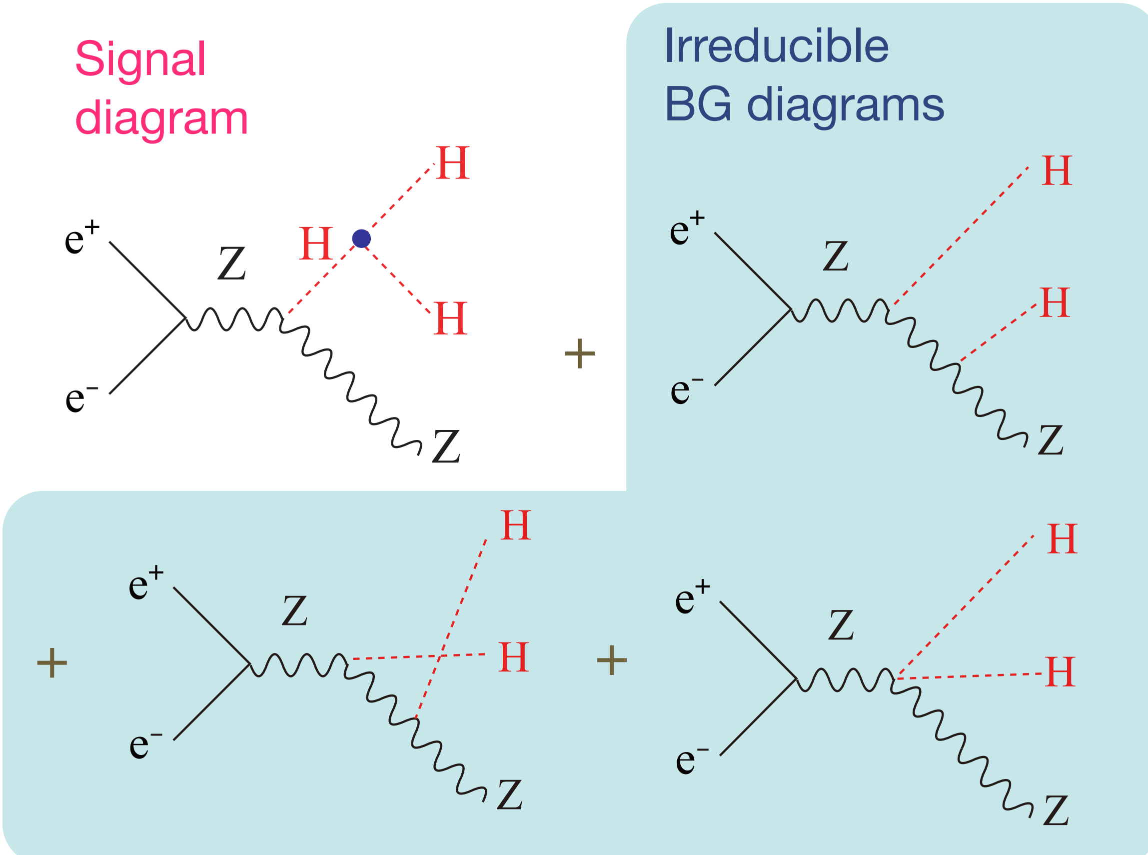
27% (H20)

Challenging even at ILC because of

- Small cross section
- ***Presence of irreducible BG diagrams***

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

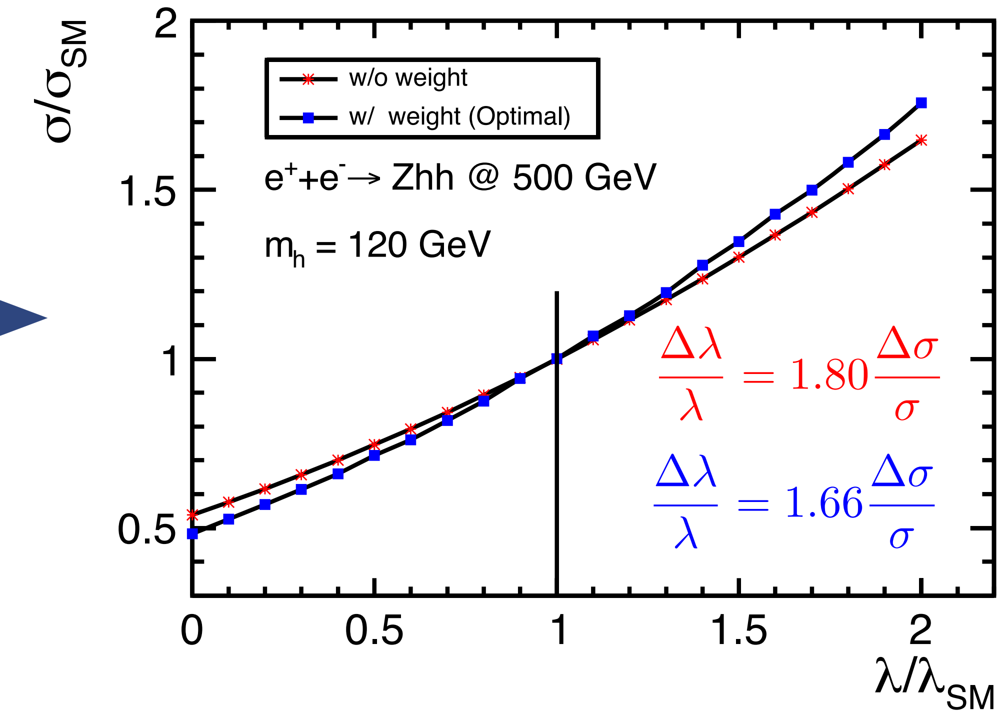
The Problem : BG diagrams dilute self-coupling contribution

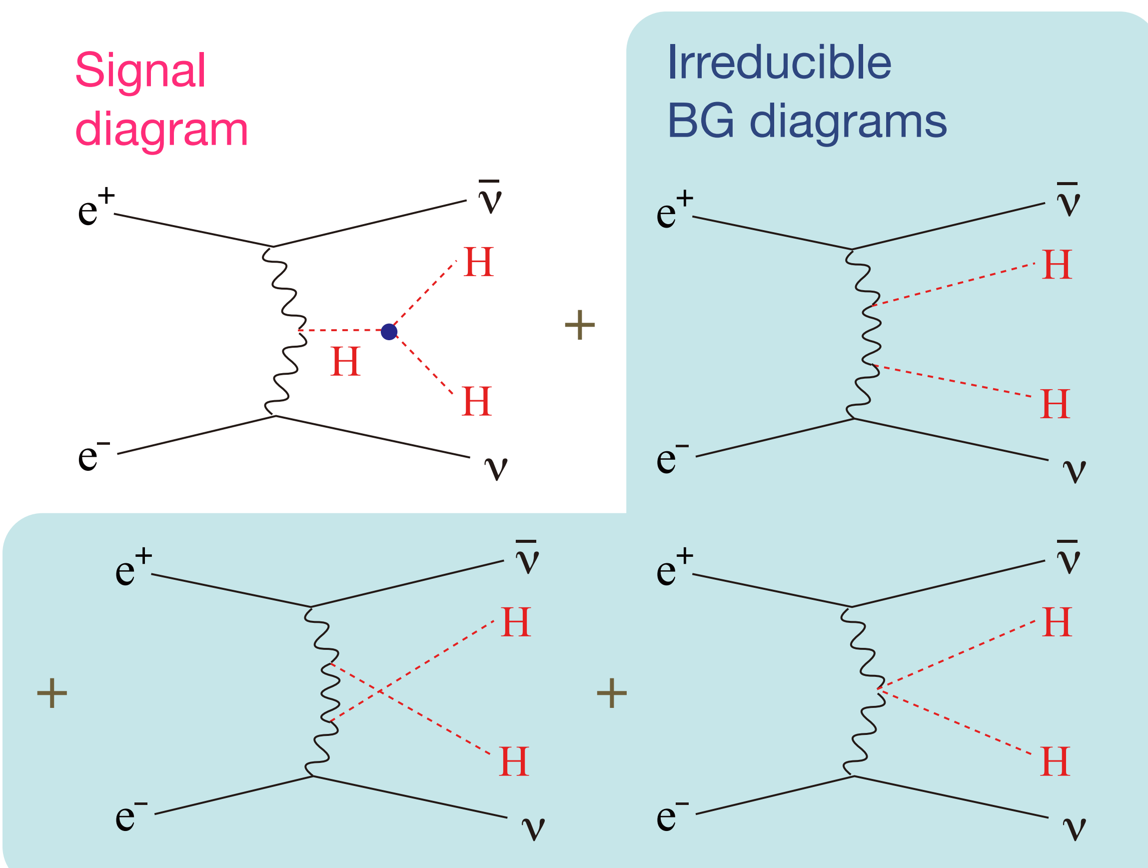


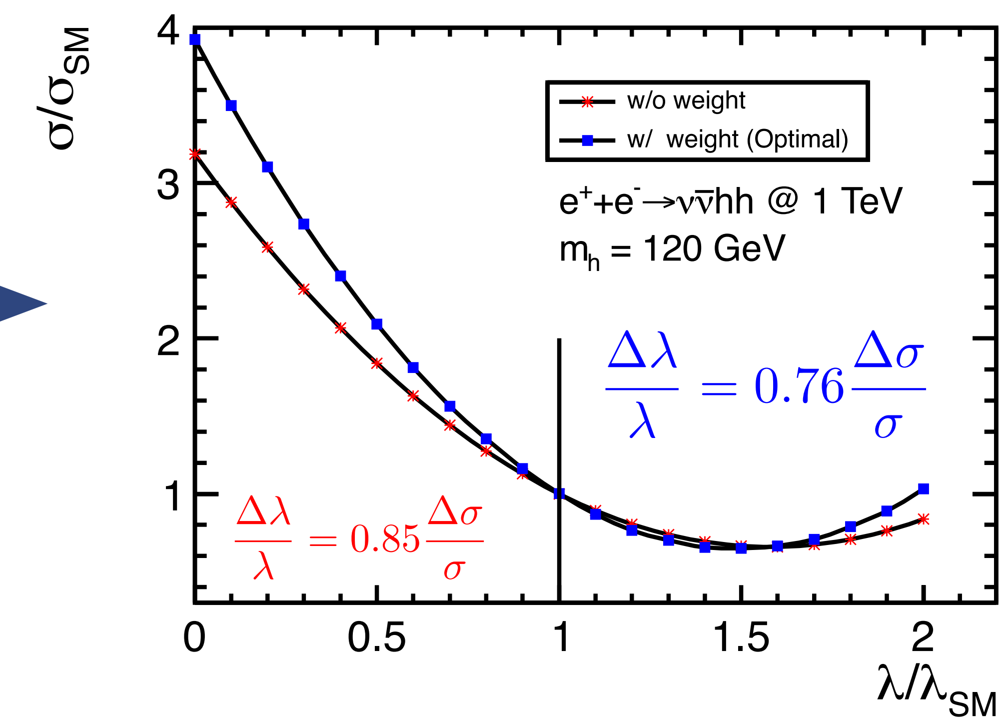
$$\sigma = \lambda^2 S + \lambda I + B$$

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

F=0.5 if no BG diagrams

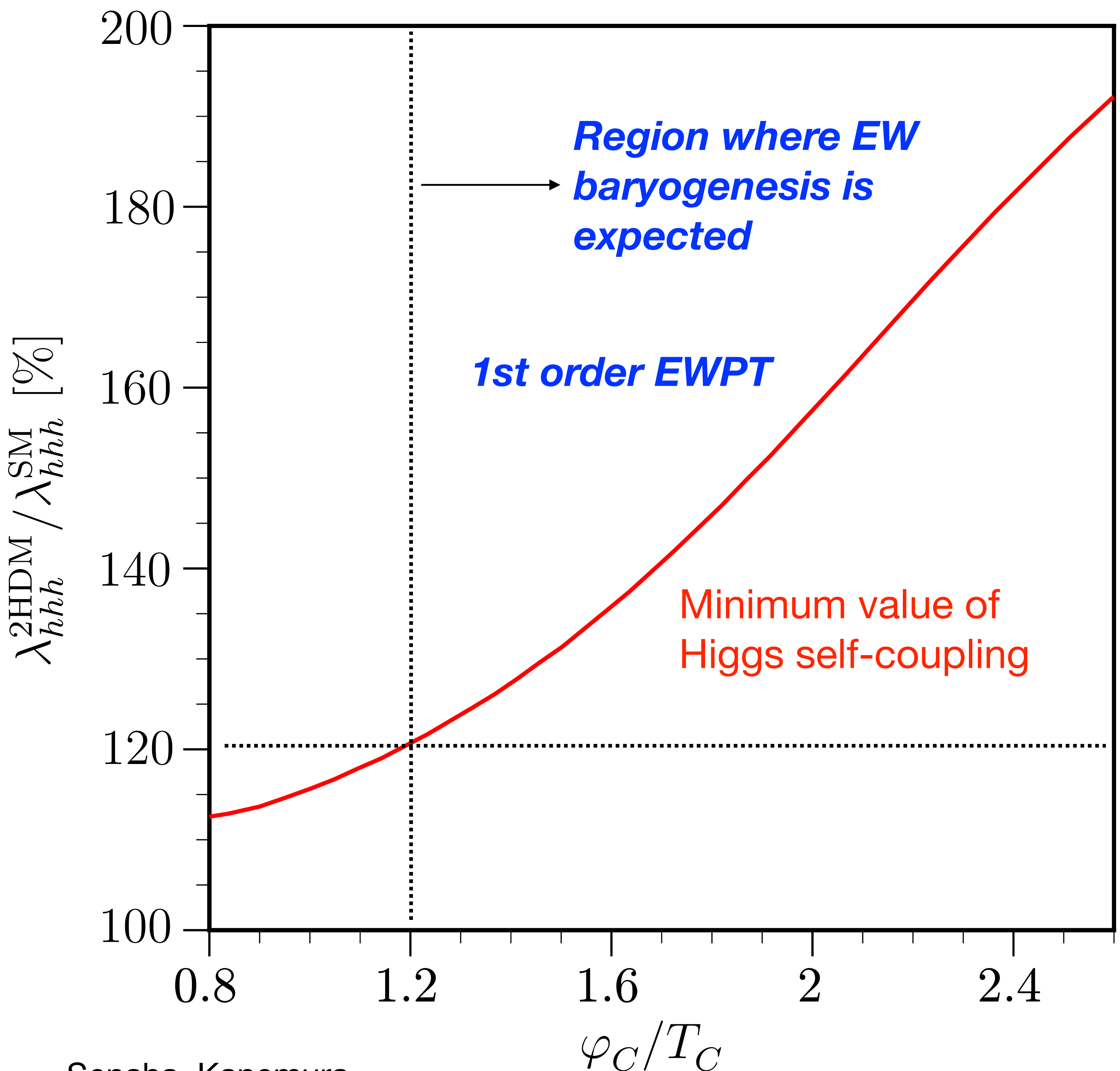






Junping Tian LC-REP-2013-003

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***

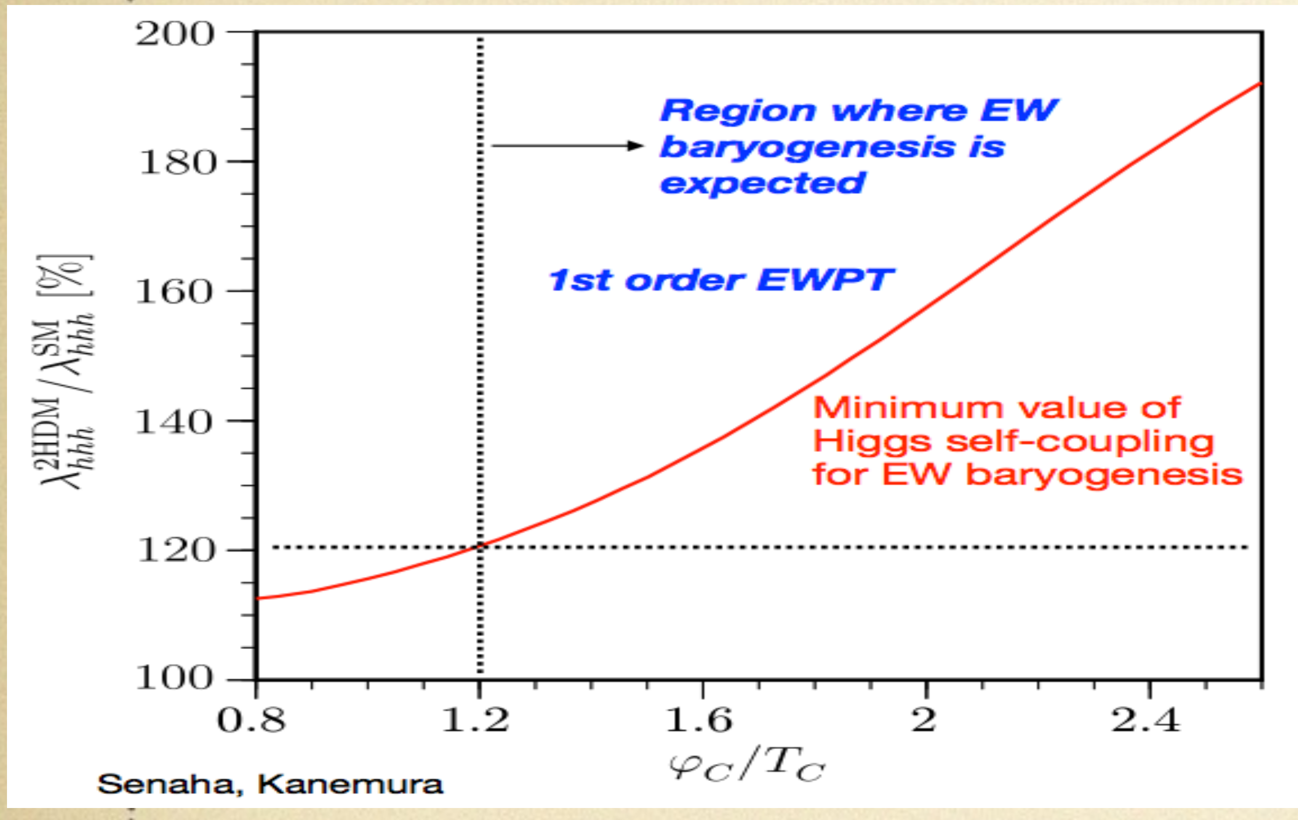
+ CPV in Higgs sector
→ ***EW baryogenesis possible***

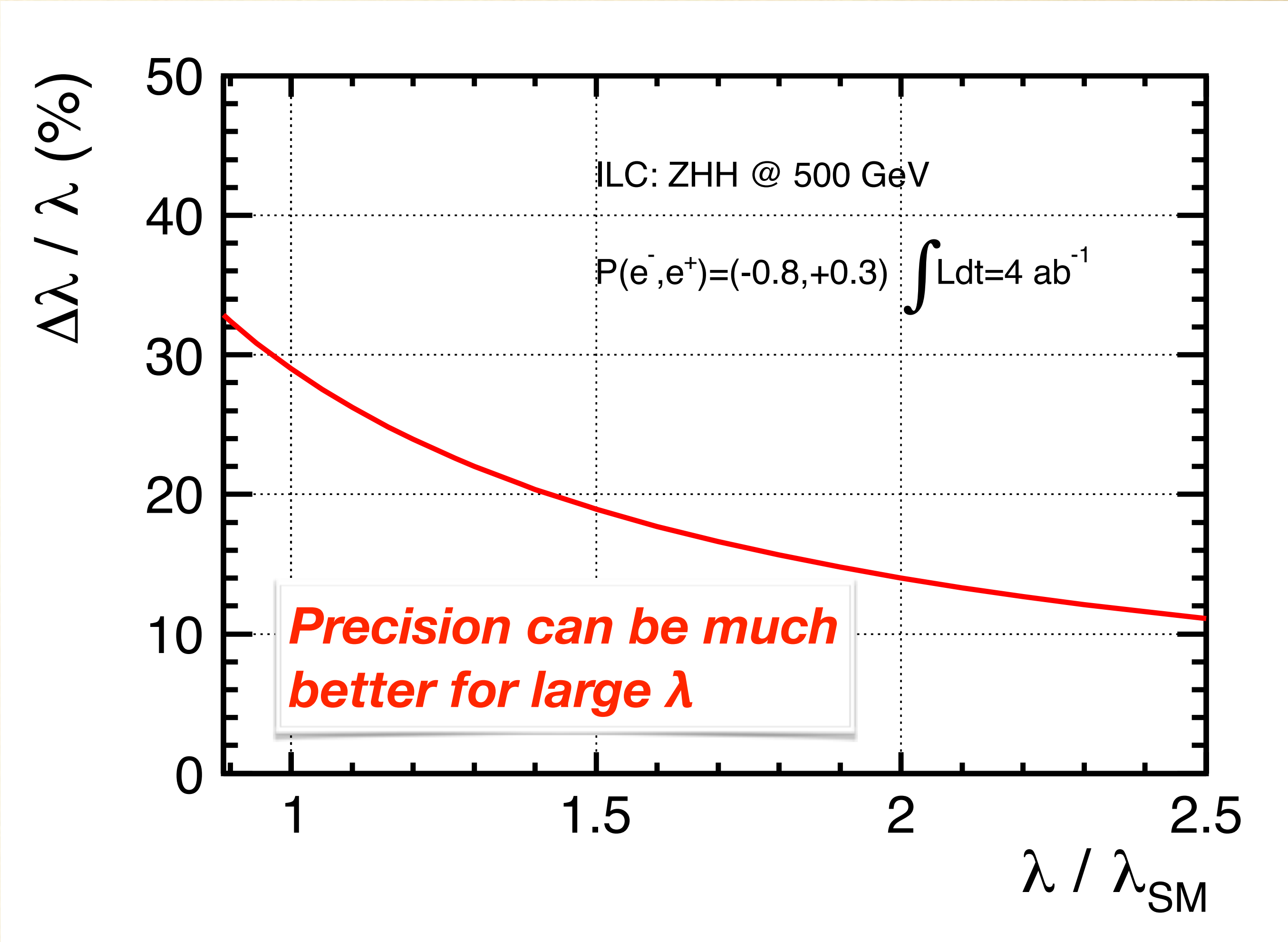
Constructive interference between signal and BG diagrams:
→ ***if +100% deviation, then 14% precision expected on λ*** at 500GeV.

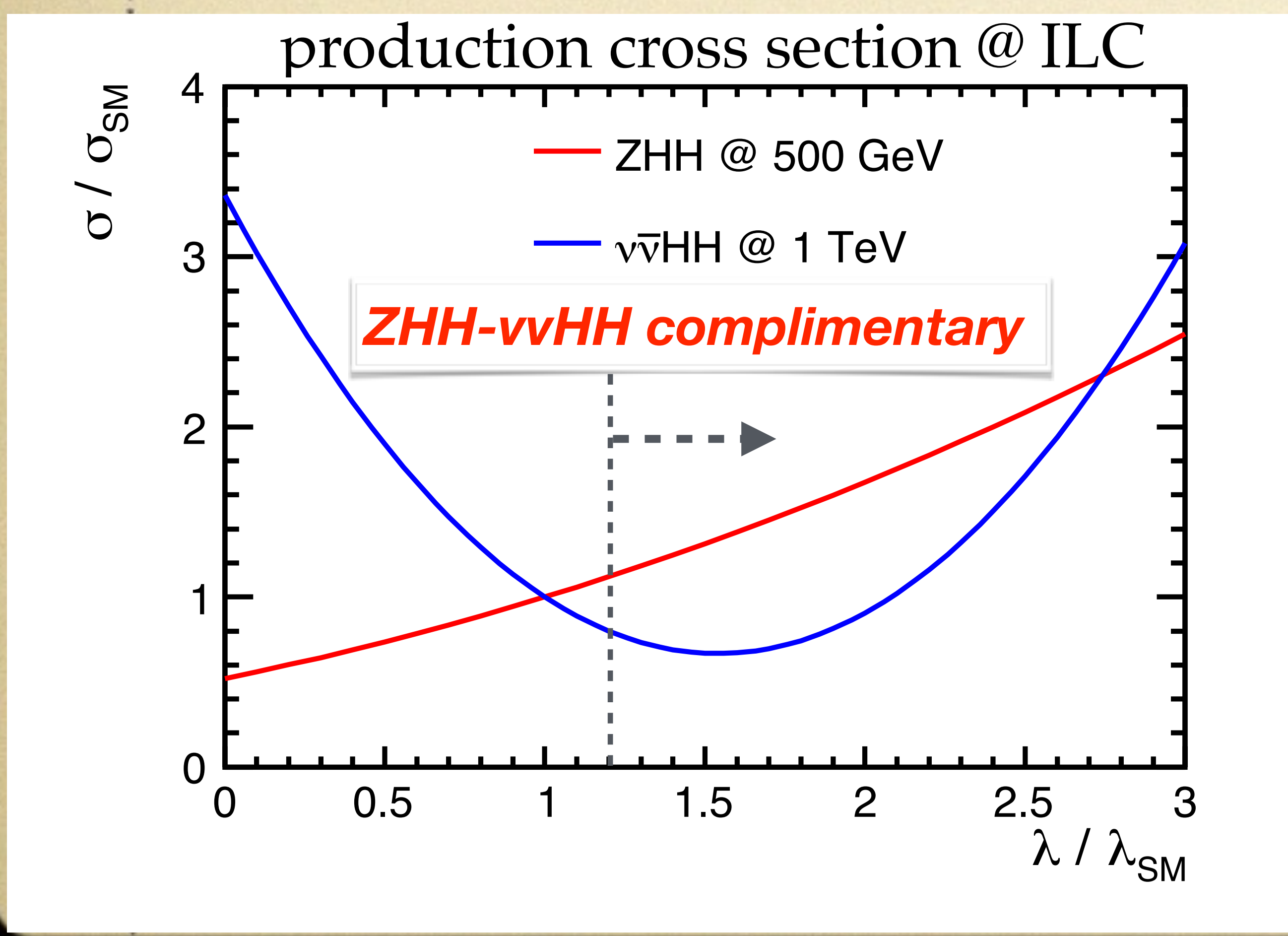
ILC can address the idea of ***baryogenesis occurring at the electroweak scale***.

λ_{HHH} in Electroweak Baryongenesis

can be significantly enhanced — good for measurement using ZHH @ 500 GeV







example: if $\lambda_{HHH} = 2\lambda_{SM}$

σ_{ZHH} enhanced by 60%; λ_{HHH} and interference diagram become more dominant comparing irreducible diagram; $\Delta\lambda/\lambda$ improved by a factor of 2

λ_{HHH} will be measured to 14% —> 7σ discovery —> more than 3σ deviation from SM

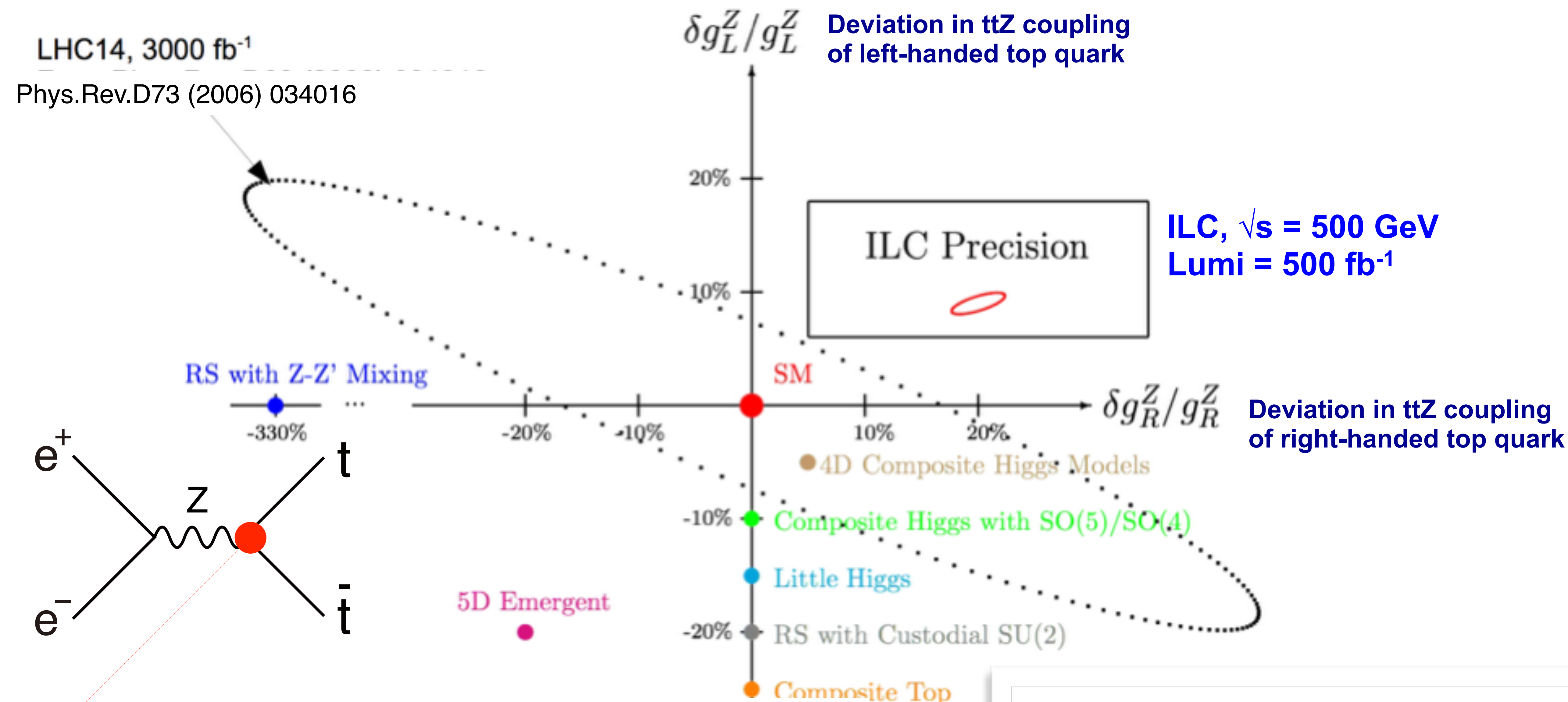
Top

Search for Anomalous tZZ Couplings

Top: **Heaviest in SM**→Must couples **strongly to EW breaking sector (source of $\mu^2<0$)!**

→ ***Specific deviation pattern*** *expected in* ***ttZ form factors*** *depending on new physics.*

→ ***Beam polarization essential*** ***to separate L- and R-couplings (Strength of ILC)***



$$\Gamma_\mu^{ttX}(k^2, q, \bar{q}) = ie\left\{\gamma_\mu\left(\widetilde{F}_{1V}^X(k^2) + \gamma_5 \widetilde{F}_{1A}^X(k^2)\right) + \frac{(q-\bar{q})_\mu}{2m_t}\left(\widetilde{F}_{2V}^X(k^2) + \gamma_5 \widetilde{F}_{2A}^X(k^2)\right)\right\}.$$

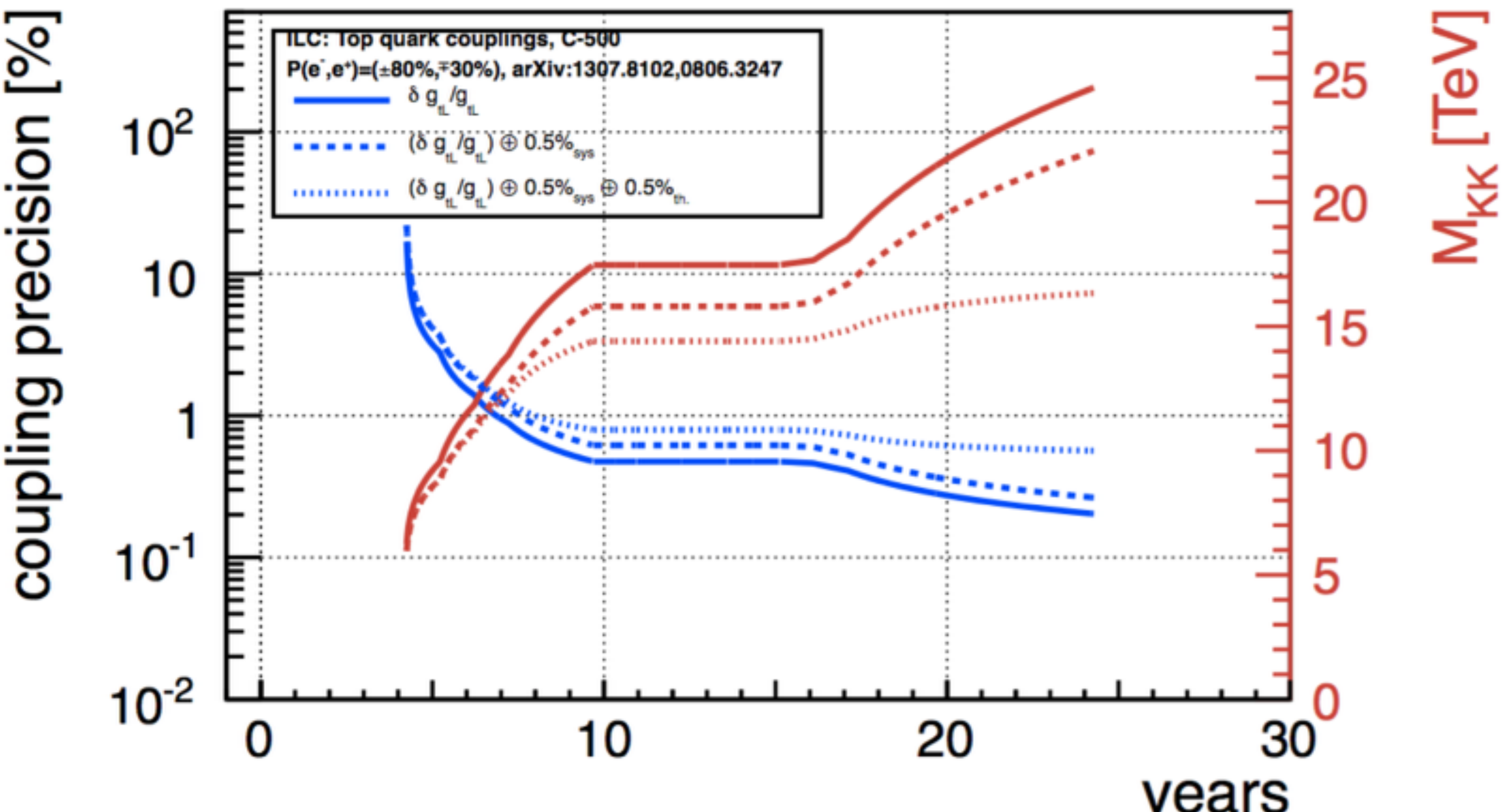
Deviation expected for various new physics models (new physics scale ~1 TeV)
arXiv:1505.06020

ILC is sensitive to ***M_{KK} up to ~25TeV*** for typical RS scenarios (even up to ~80 TeV in extreme cases)!

Example for physics reach

New physics reach for typical BSM scenarios with composite Higgs/Top and or extra dimensions

Based on phenomenology described in Pomerol et al. arXiv:0806.3247



Can probe scales of ~25 TeV in typical scenarios

(… and up tp 80 GeV for extreme scenarios)

=> Important guidance for e.g. 100 TeV pp-collider

Comparison to FCC-ee

Recent publication assesses potential of FCC-ee

P. Janot, arXiv:1503.01325, arXiv:1510.09056

- run right above threshold; study assumes 2.4 ab^{-1} at $\sqrt{s}$ = 365 GeV

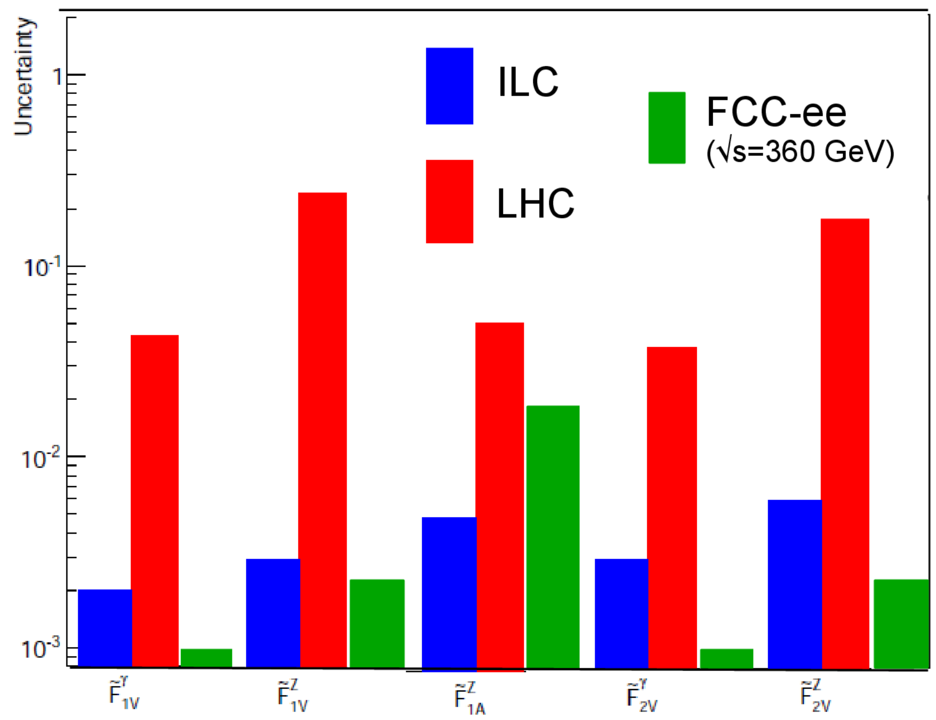
  (theory systematics close to threshold to be evaluated)
- no beam polarization, use final-state polarization instead

  (ILC beam polarization expected to be known to 10^{-3}, can one understand final state polarization to that level?)

Fast simulation analysis based on lepton energy and angle yields:

- similar precision to ILC for Z couplings, except F1AZ
- significantly better than ILC for photon couplings

Complementarity

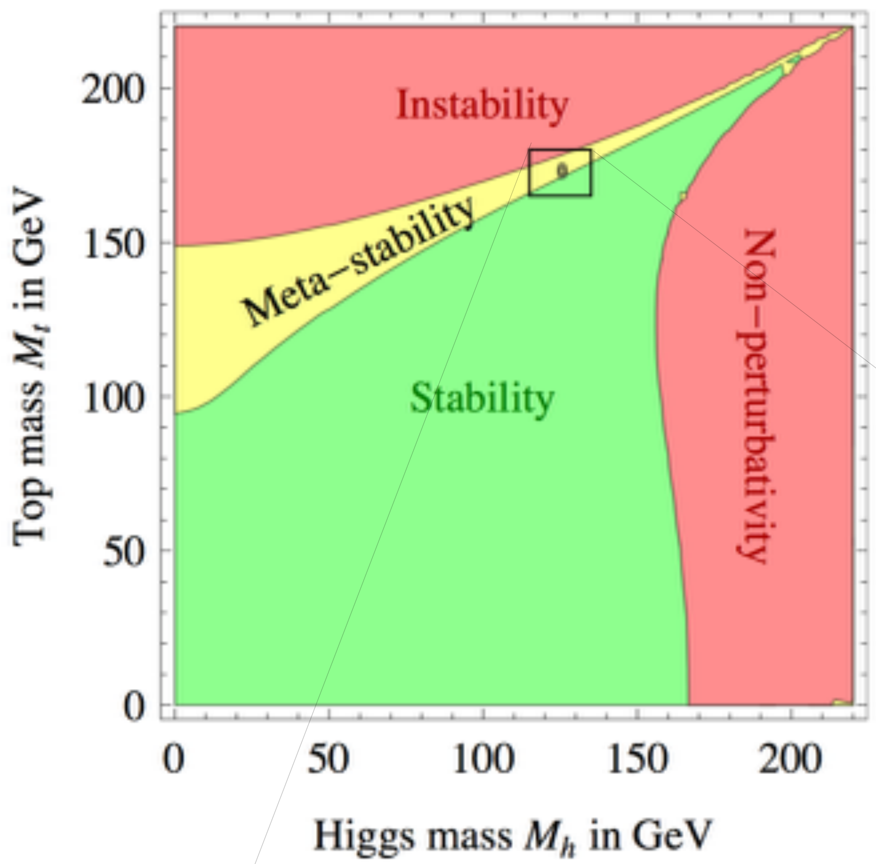


Good to see interest in this measurement
Full study needed to understand systematics

What if no deviation from the SM would be seen?

Clarify the Range of Validity of SM

Stability of SM Vacuum

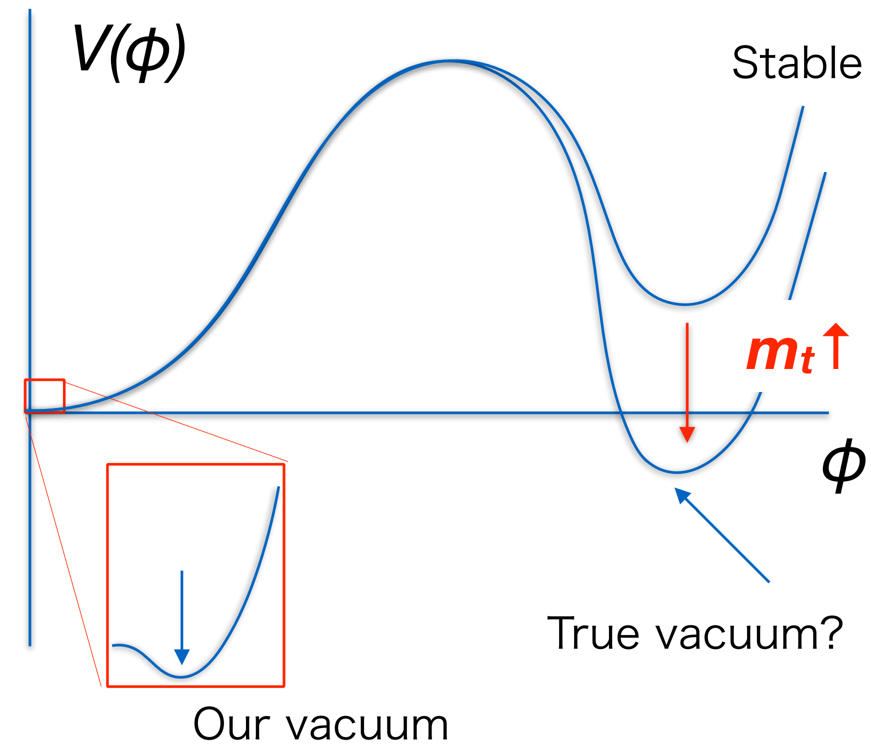


Top Yukawa coupling drives the 4-point Higgs couplint (λ) to negative!

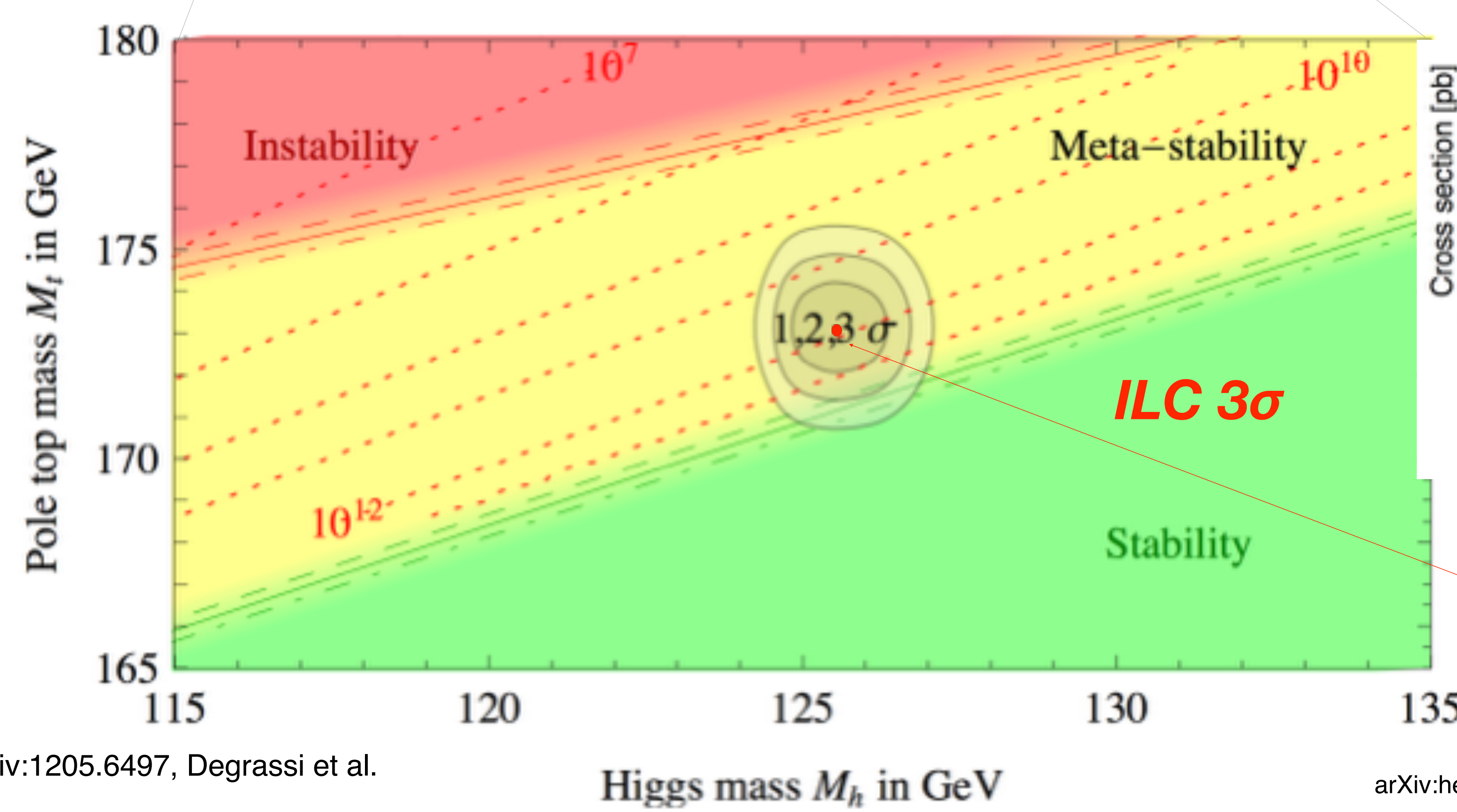
The current values of mt and mh:
Subtle point of meta-stability!

λ goes to negative below Λ_P?
or $\lambda(\Lambda_{Pl}) = 0$?

To anser this, we need precision m_t measurement!

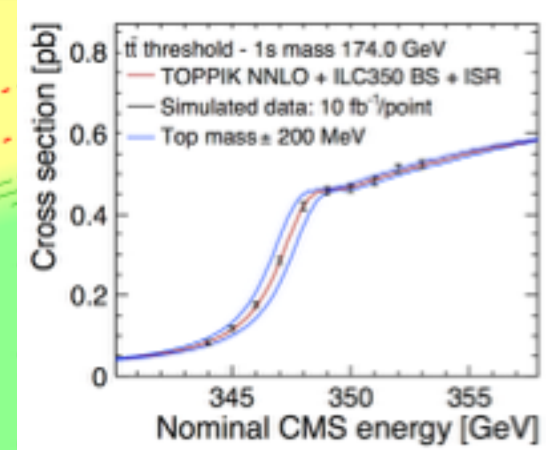


At LHC, theory error limits the precision to ~500MeV.

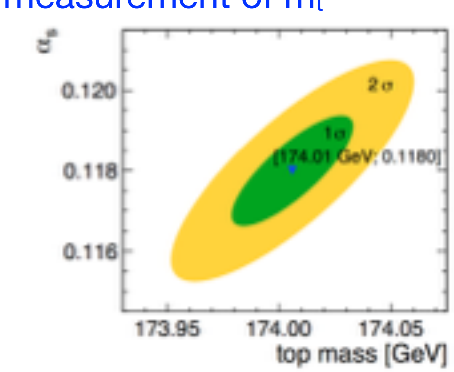


arXiv:1205.6497, Degrassi et al.

TTbar Threshold Scan @ILC



Theoretically very clean measurement of m_t



$$\Delta m_t(\overline{MS}) \lesssim 50\,\mathrm{MeV}$$
$$\Delta m_H = 30\,\mathrm{MeV}$$

ILC pinpoints the vacuum location

arXiv:hep-ph/1502.01030: Quark mass relation to 4-loop order
arXiv:hep-ph/1506.06864: NNNLO QCD
arXiv:hep-ph/1506.06542: possibility of MSbar mass to 20MeV

Direct Searches for New Particles

ILC, too, is an energy frontier machine!

It will enter ***an uncharted region never explored by any e^+e^- collider!***

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**

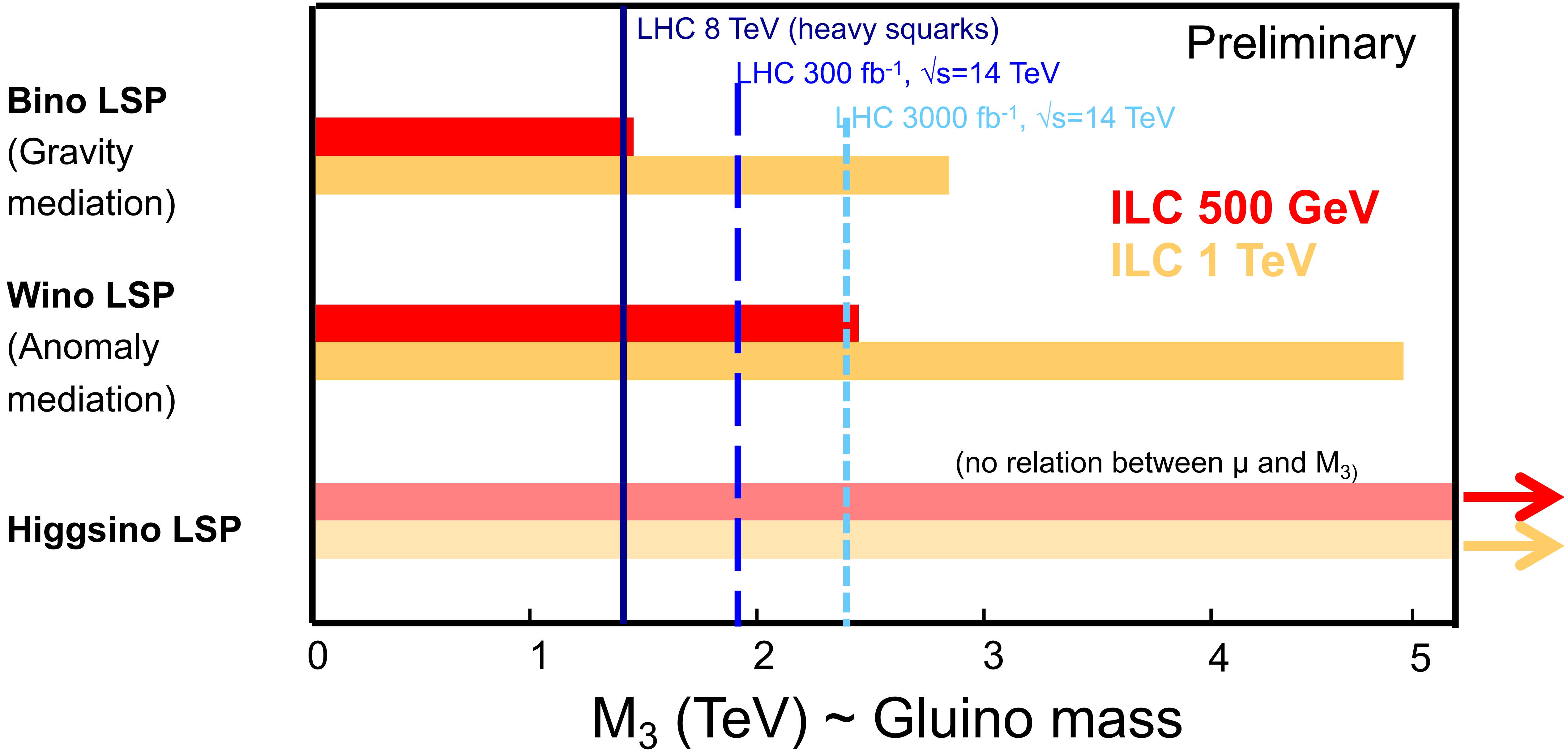
assuming various gaugino mass relations (e.g. GMSB, AMSB) and LSP types (Bino, Wino, Higgsino)

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

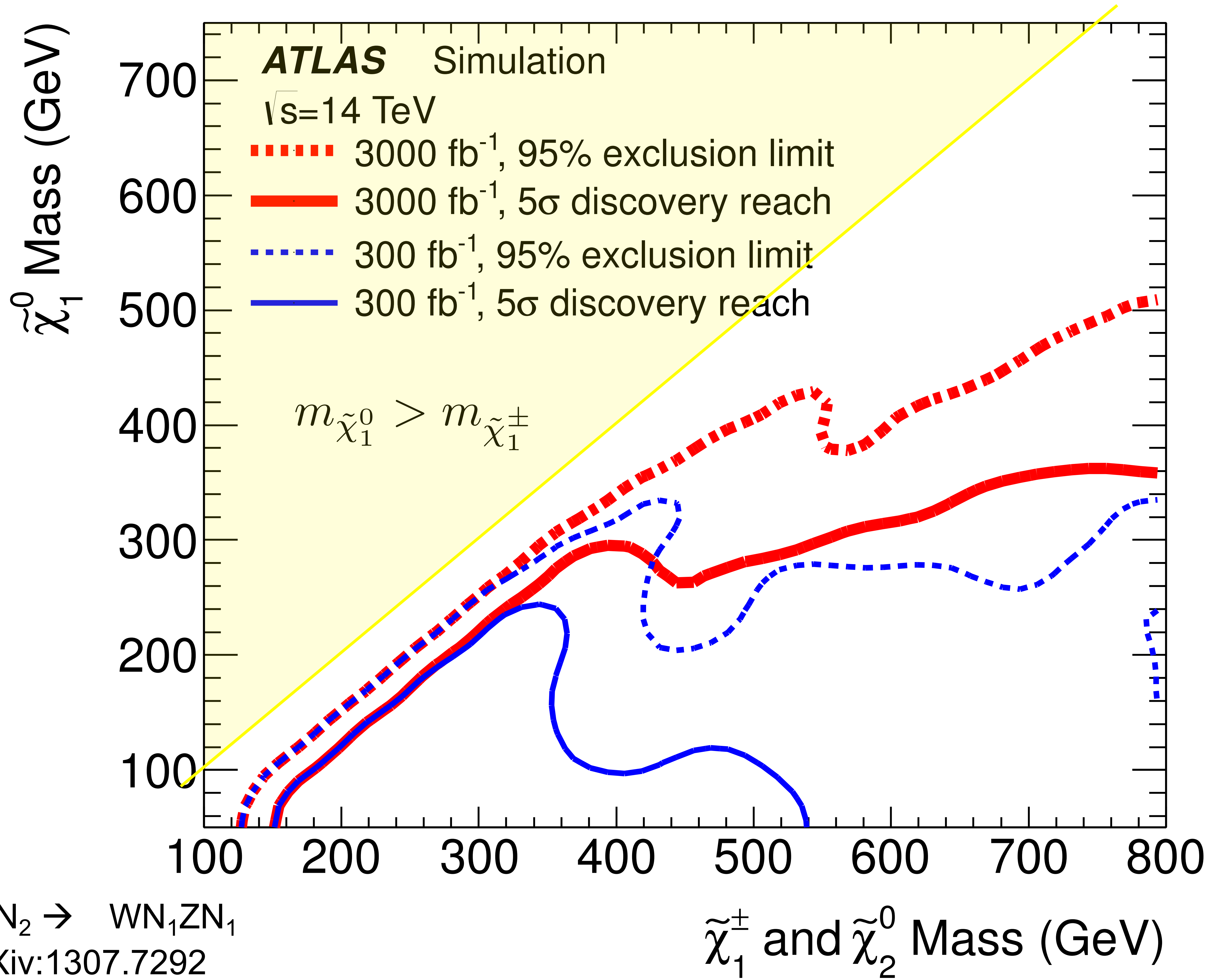
Compare using gaugino mass relations



[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

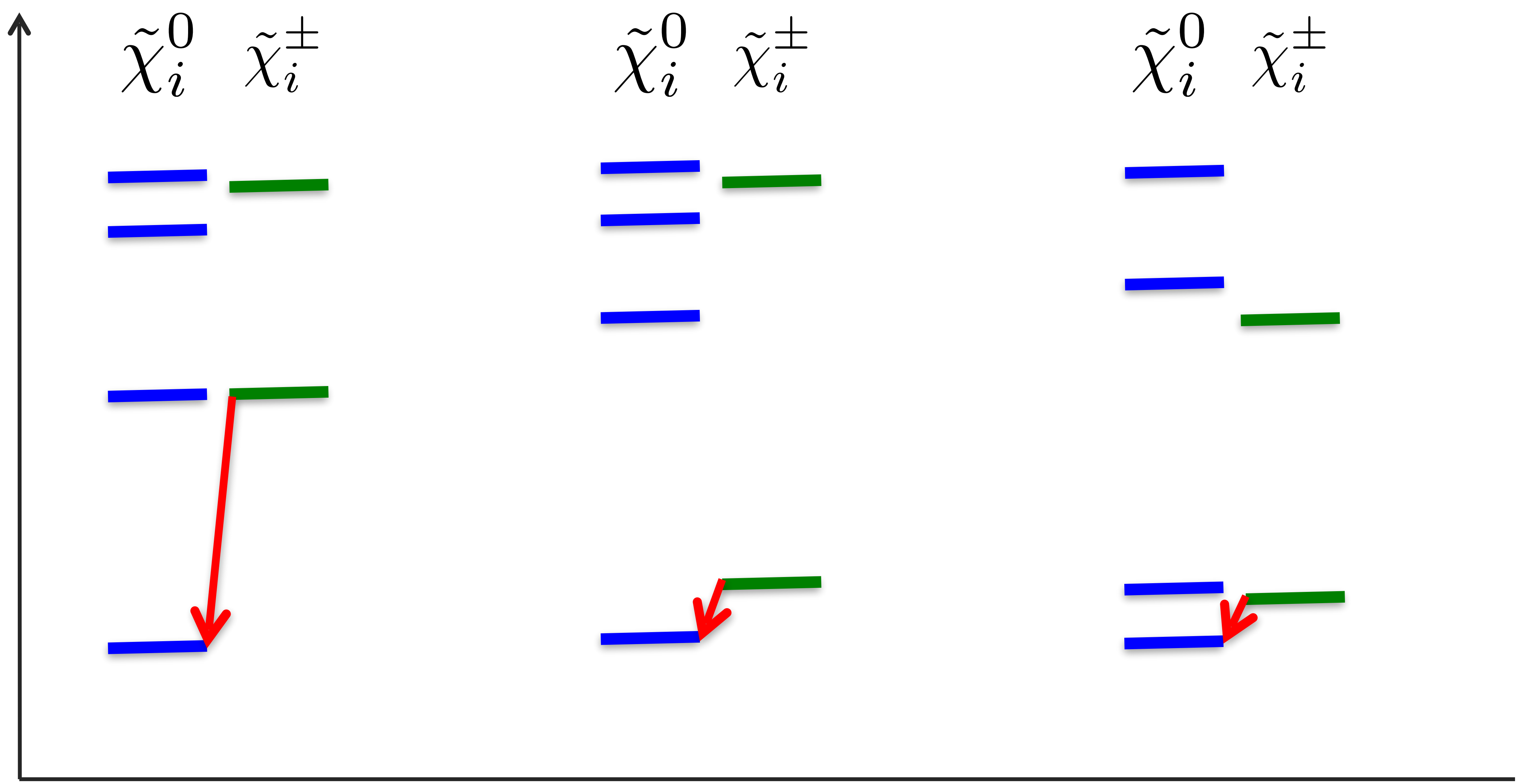


$C_1N_2 \rightarrow WN_1ZN_1$

arXiv:1307.7292

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

SUSY Electroweak Sector

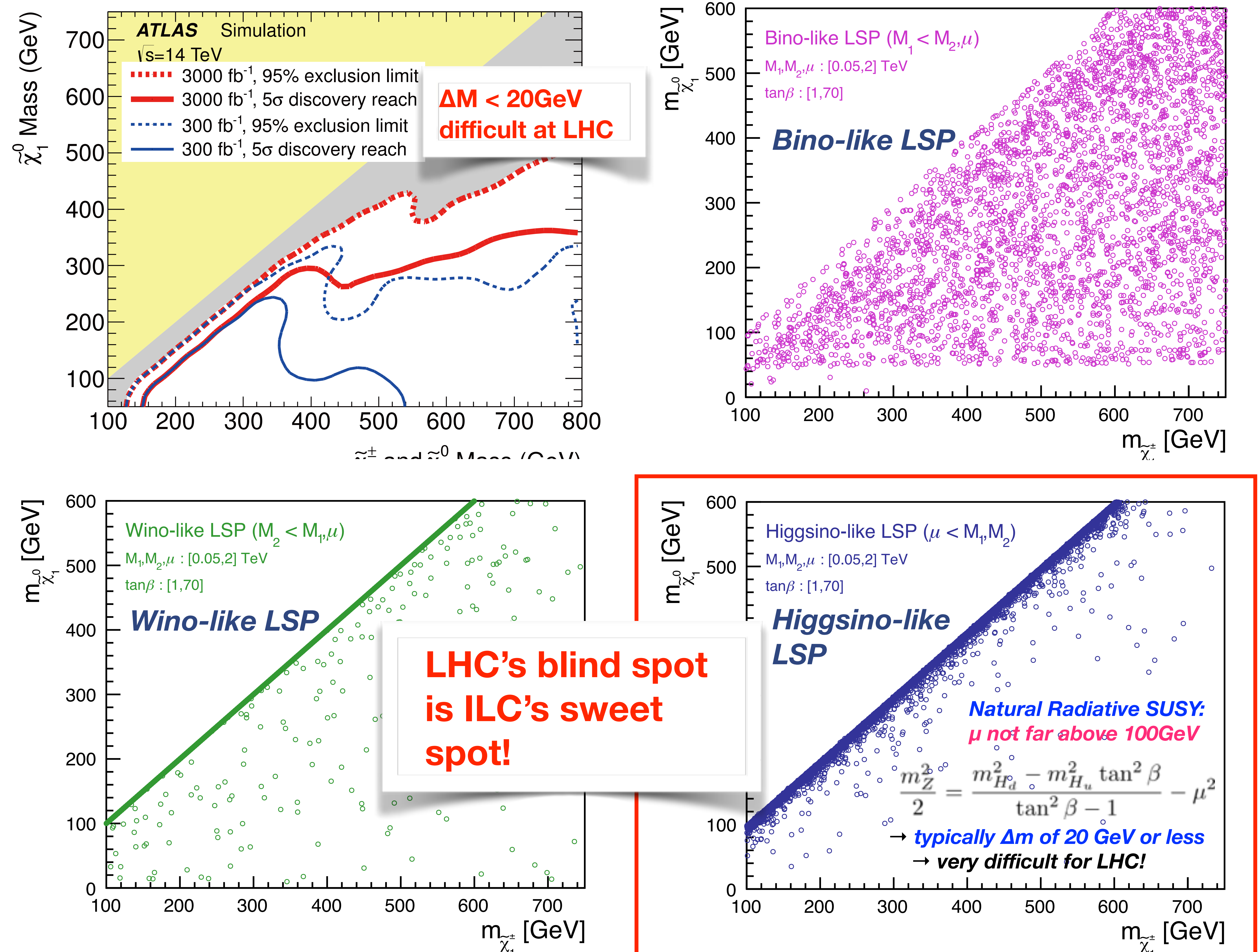


Bino-like LSP — $M_1 << M_2, \mu$

Wino-like LSP — $M_2 << M_1, \mu$

Higgsino-like LSP — $\mu << M_2, M_1$

LSP/NLSP typically degenerate
(depends on mixing)

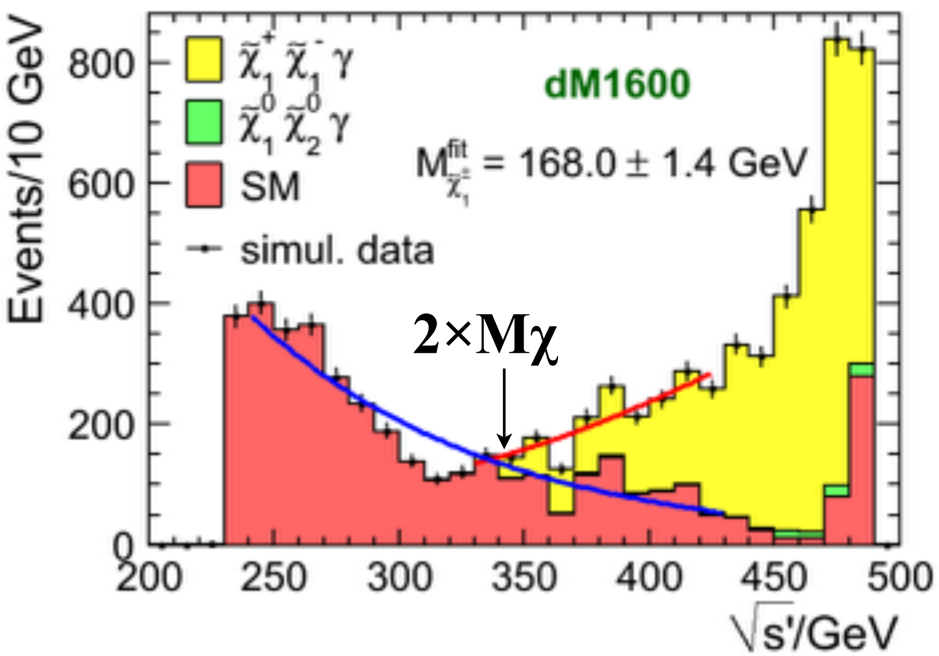

ATLAS Simulation
√s=14 TeV
3000 fb-1, 95% exclusion limit
3000 fb-1, 5σ discovery reach
300 fb-1, 95% exclusion limit
300 fb-1, 5σ discovery reach
ΔM < 20GeV
difficult at LHC
χ̃⁰₁ Mass (GeV)
χ̃± and χ̃⁰ Mass (GeV)
Bino-like LSP (M1 < M2,μ)
M1,M2,μ : [0.05,2] TeV
tanβ : [1,70]
Bino-like LSP
Wino-like LSP (M2 < M1,μ)
M1,M2,μ : [0.05,2] TeV
tanβ : [1,70]
Wino-like LSP
LHC's blind spot
is ILC's sweet
spot!
Higgsino-like LSP (μ < M1,M2)
M1,M2,μ : [0.05,2] TeV
tanβ : [1,70]
Higgsino-like
LSP
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!
m χ̃⁰₁ [GeV]
m χ̃±₁ [GeV]

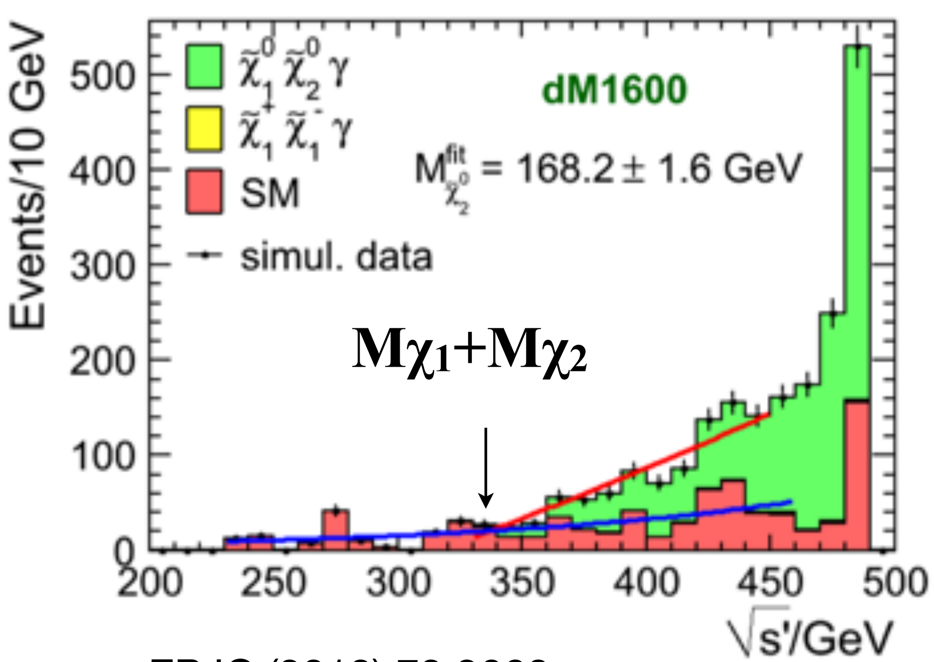
Higgsinos in Natural SUSY (ΔM<a few GeV)

ILC as a Higgsino Factory

ISR Tagging

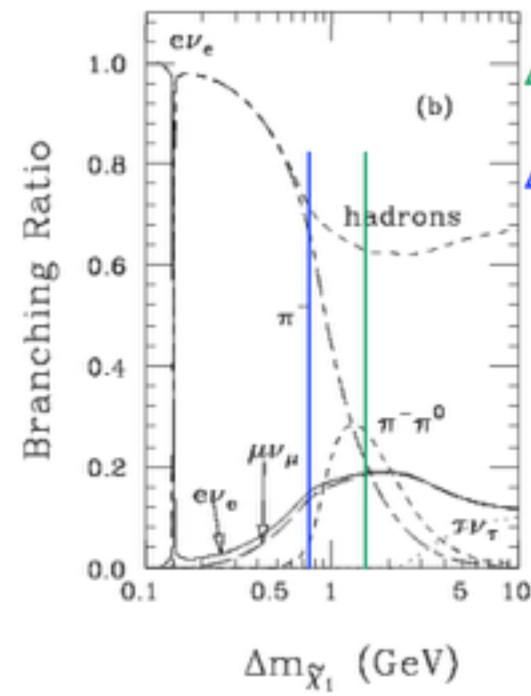
$$e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-\gamma$$
$$e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_1^0\gamma$$

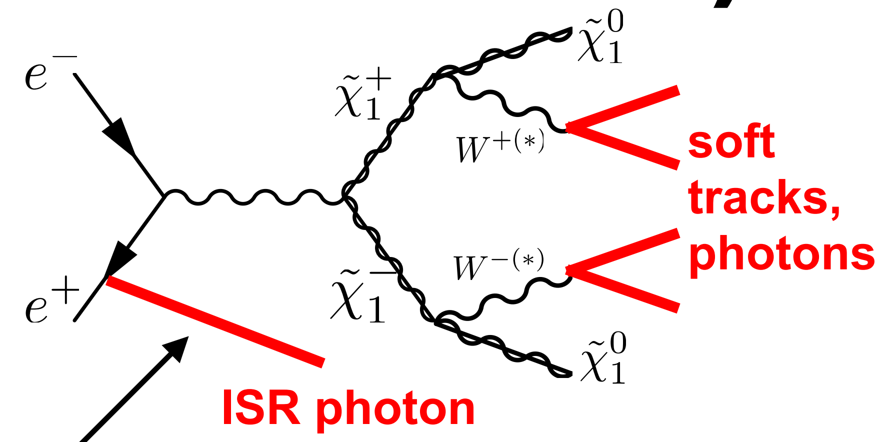




EPJC (2013) 73:2660

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





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

$\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 1.59$ 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	$\sim 2-3\times 10^3$

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

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

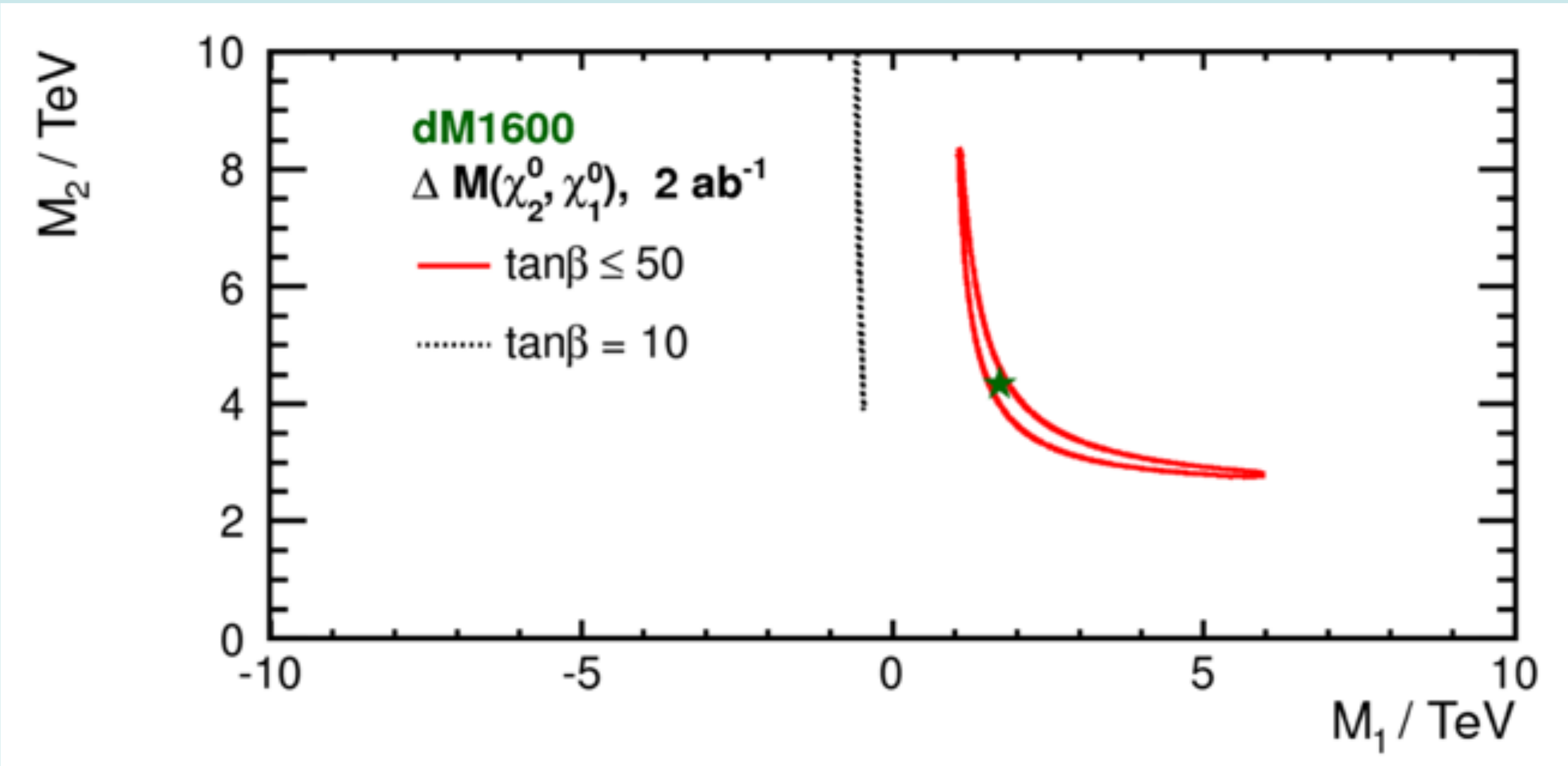
Extracting M1 and M2

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

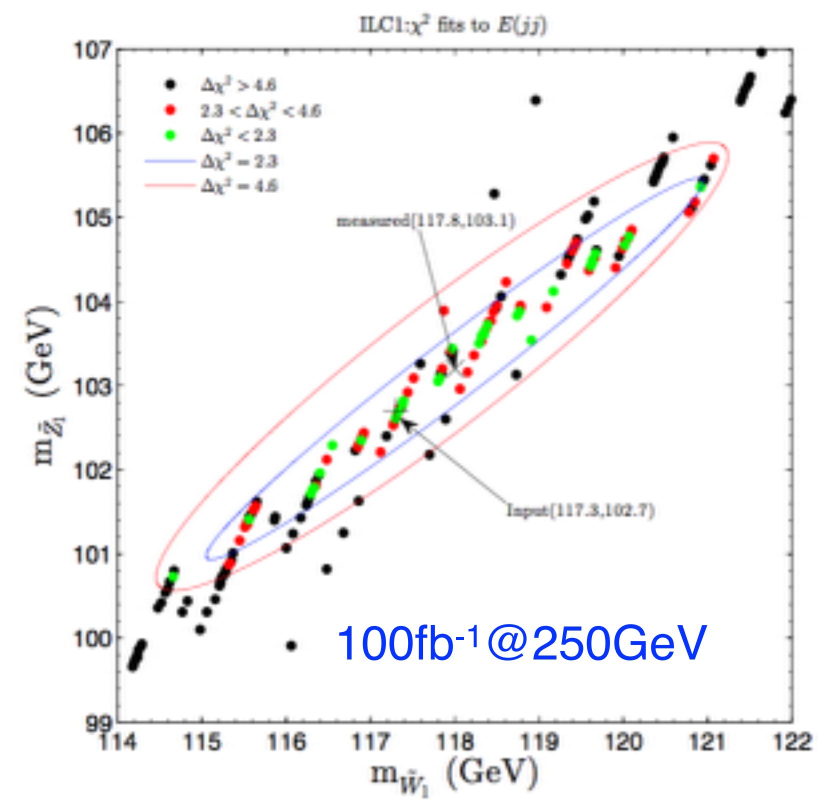
Hale Sert
ECFA LCWS 2013, DESY
Berggren et al. EPJC (2013) 73:2660

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

RNS: Baer et al.
arXiv: 1404.7510



ΔM=15GeV



@ 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, ΔM~10GeV, we can determine M1 and M2 to a few % or better, allowing us to test GUT relation!

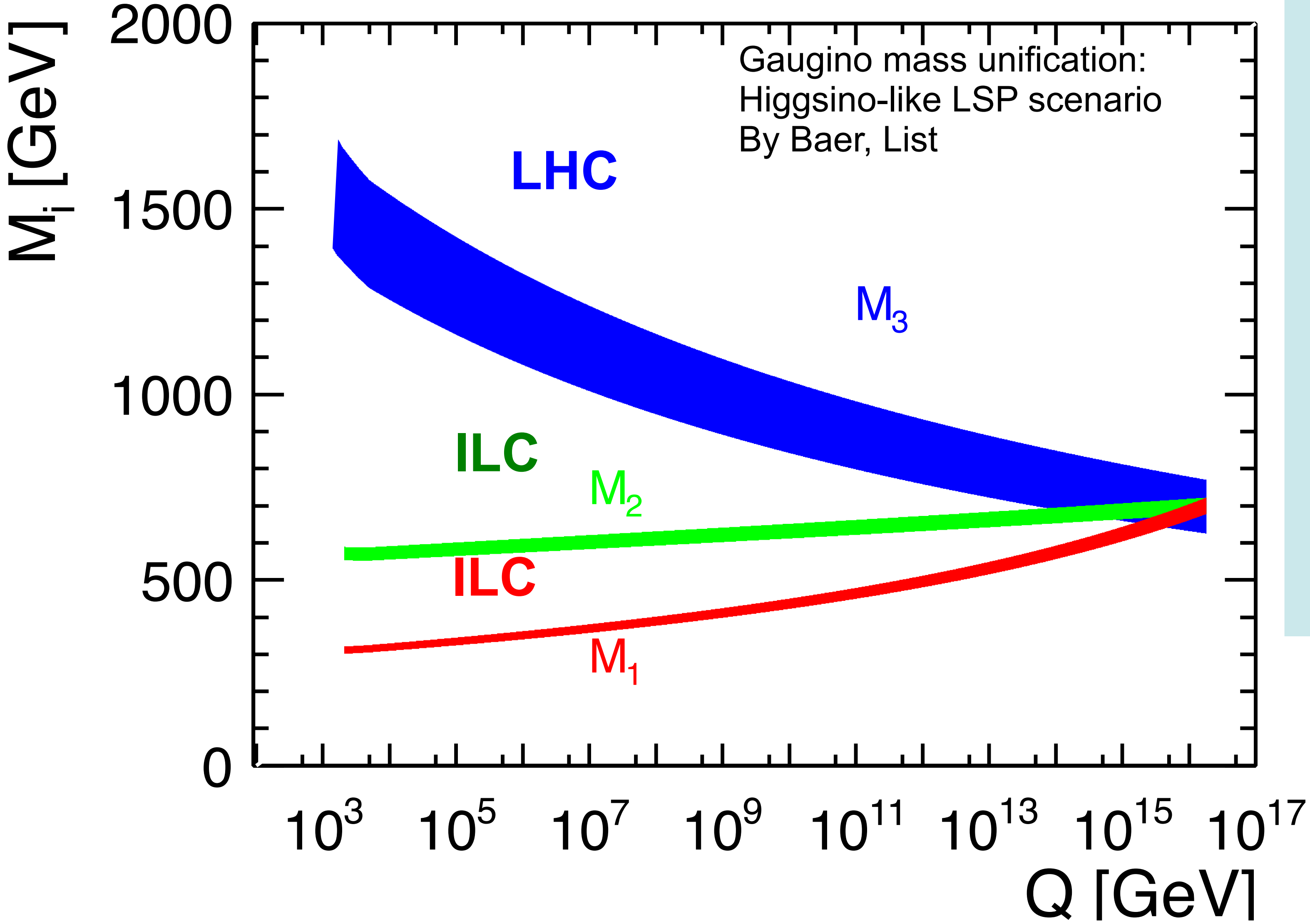
GUT Scale Physics

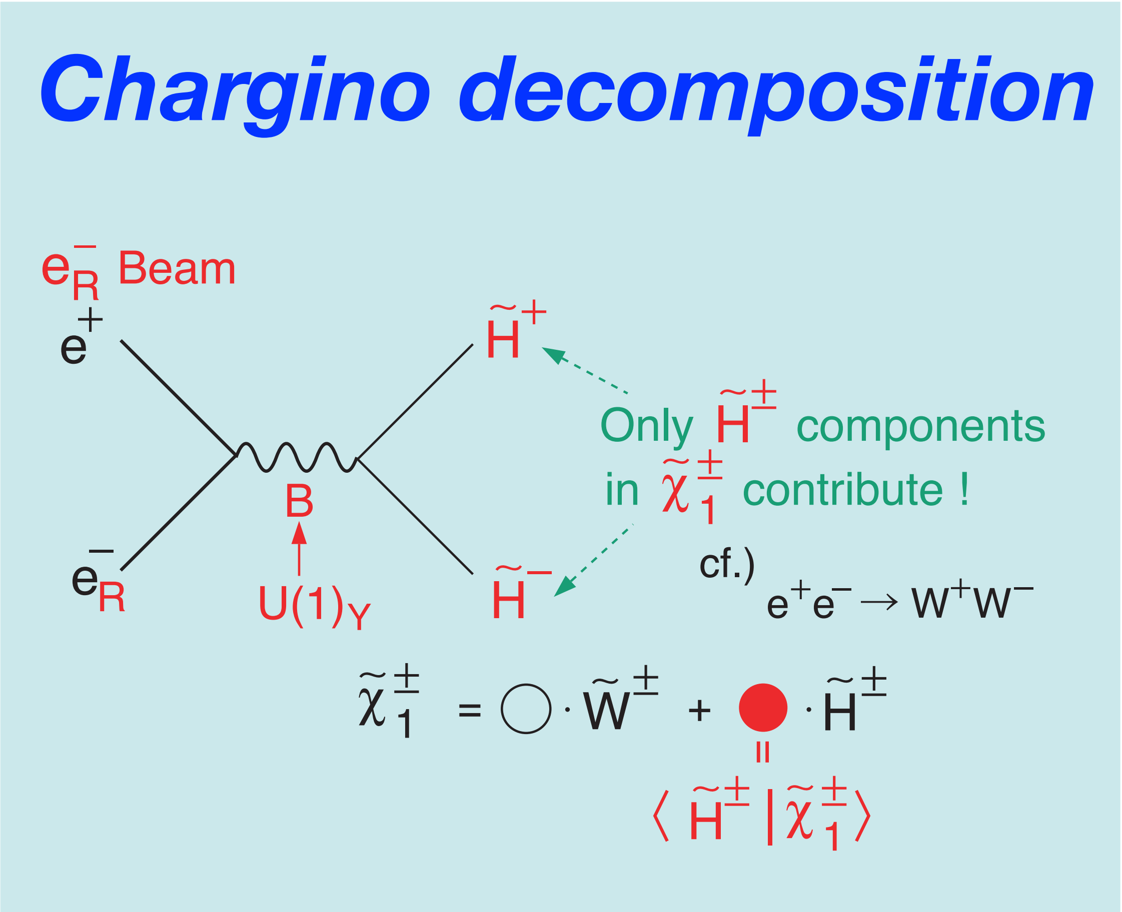
GUT Scale Physics

If we are lucky and the gluino is in LHC's mass reach and the lighter chargino and the neutralinos are in ILC's mass reach, ***we will be able to test the gaugino mass unification!***

LHC: gluino discovery
→ mass determination

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





Beam polarization is essential *to decompose the EWkinos to bino, wino, and higgsino and extract* M_1 *and* M_2.

Dark Matter

WIMP Dark Matter Search @ ILC

Weakly Interacting Massive Particle 探索

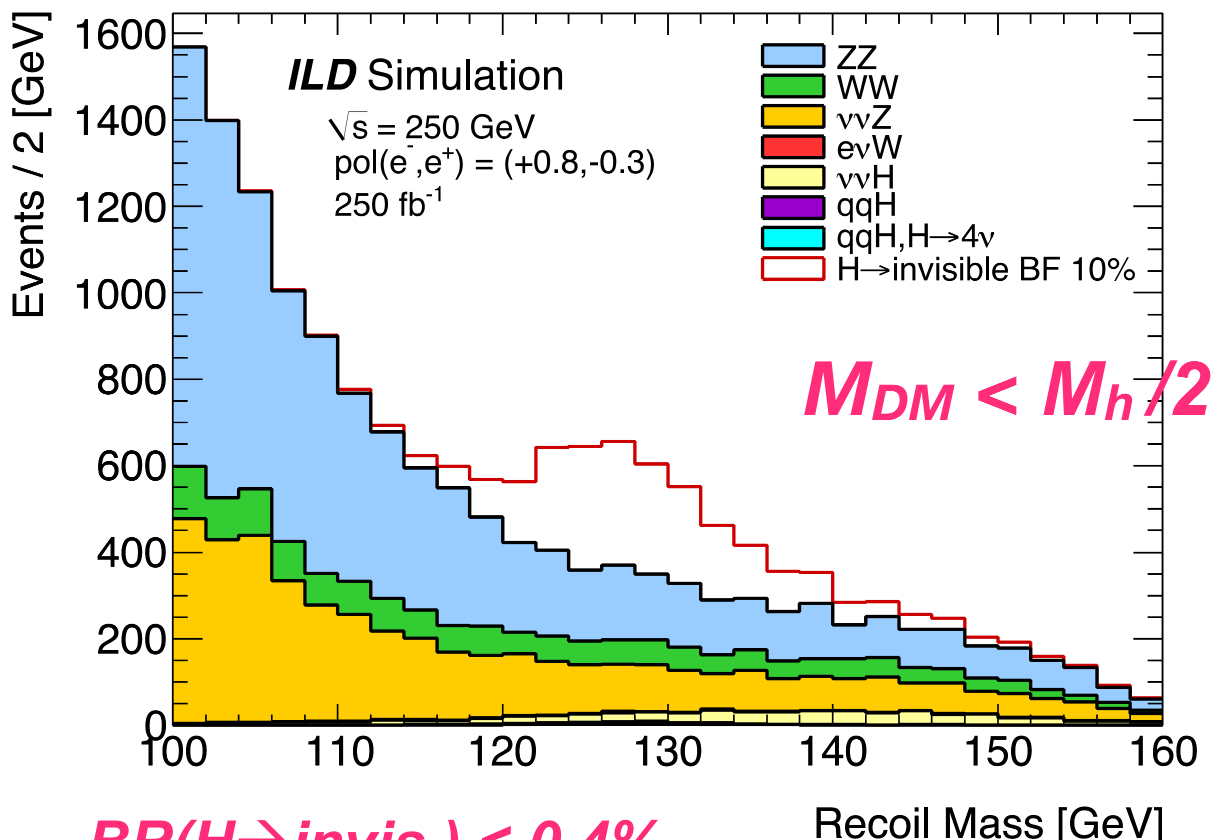
Decay of a new particle to Dark Matter (DM)

DM has a charged partner in many new physics models.

SUSY: The Lightest SUSY Particle (LSP) = DM → Its partner decays to a DM.

- Events with missing Pt (example: light chargino: see the previous page)

Higgs Invisible Decay



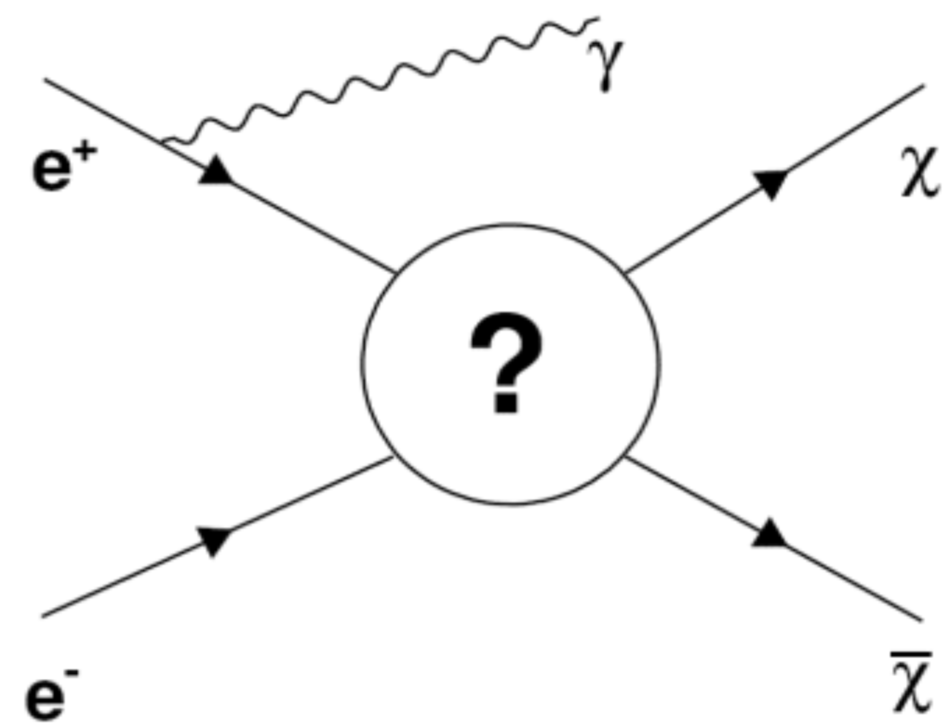
$M_{DM} < M_h/2$

BR(H→invis.) < 0.4%

at 250 GeV, 1150 fb^{-1}

Possible to access BR_{inv} to 0.4%!

Mono-photon Search



→ M_{DM} reach ~ $E_{cm}/2$

Possible to access DM to ~E_{cm}/2!

Slepton decays to DM with small mass differences

Study of stau pair production at the ILC

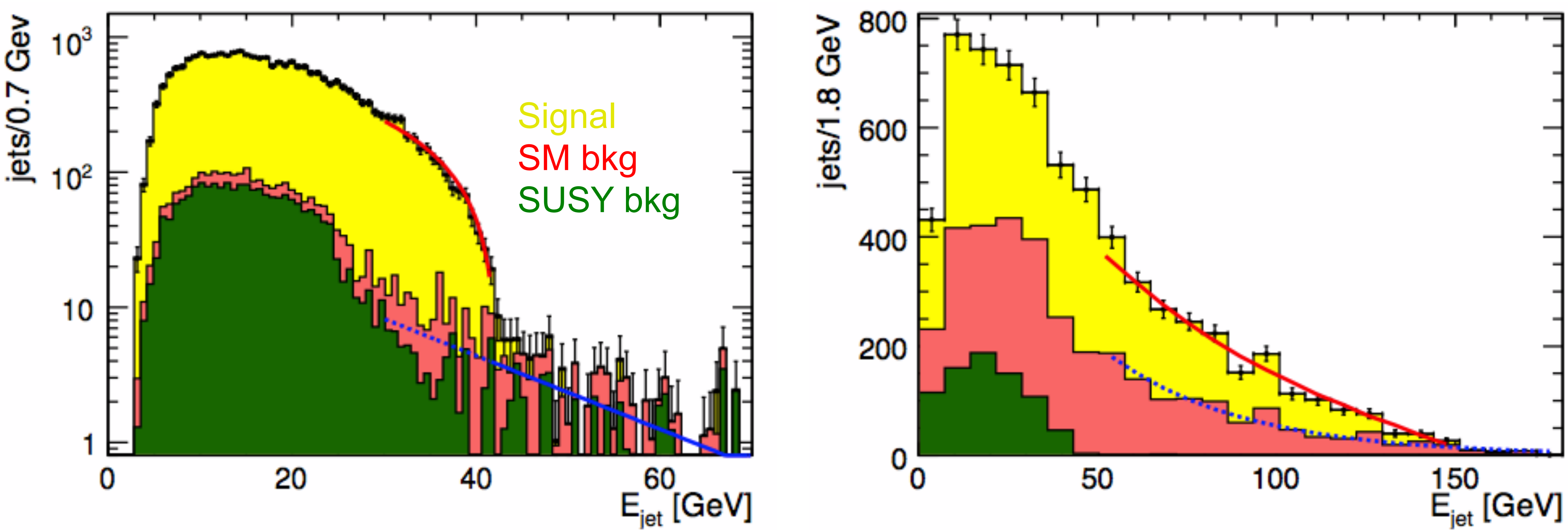
Observation of lighter and heavier stau states with decay to DM + hadronic tau

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

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

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

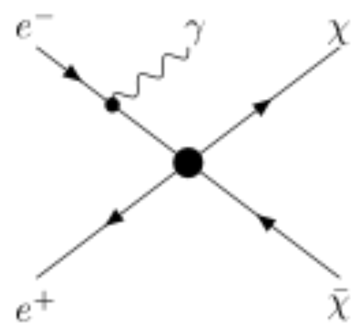
Bechtle, Berggren, List, Schade, Stempel, arXiv:0908.0876, PRD82, 055016 (2010)



√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%

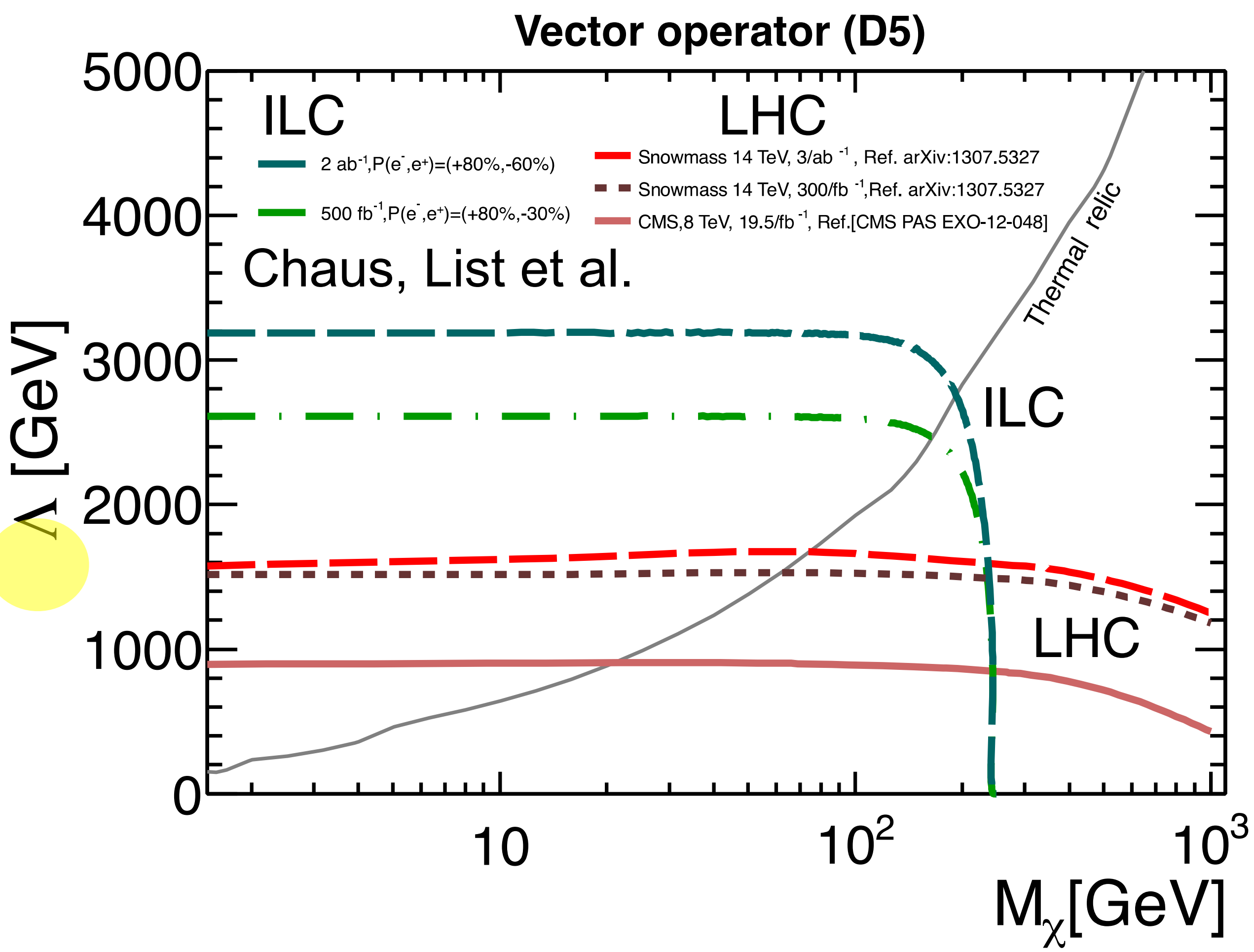
DM: Effective Operator Approach

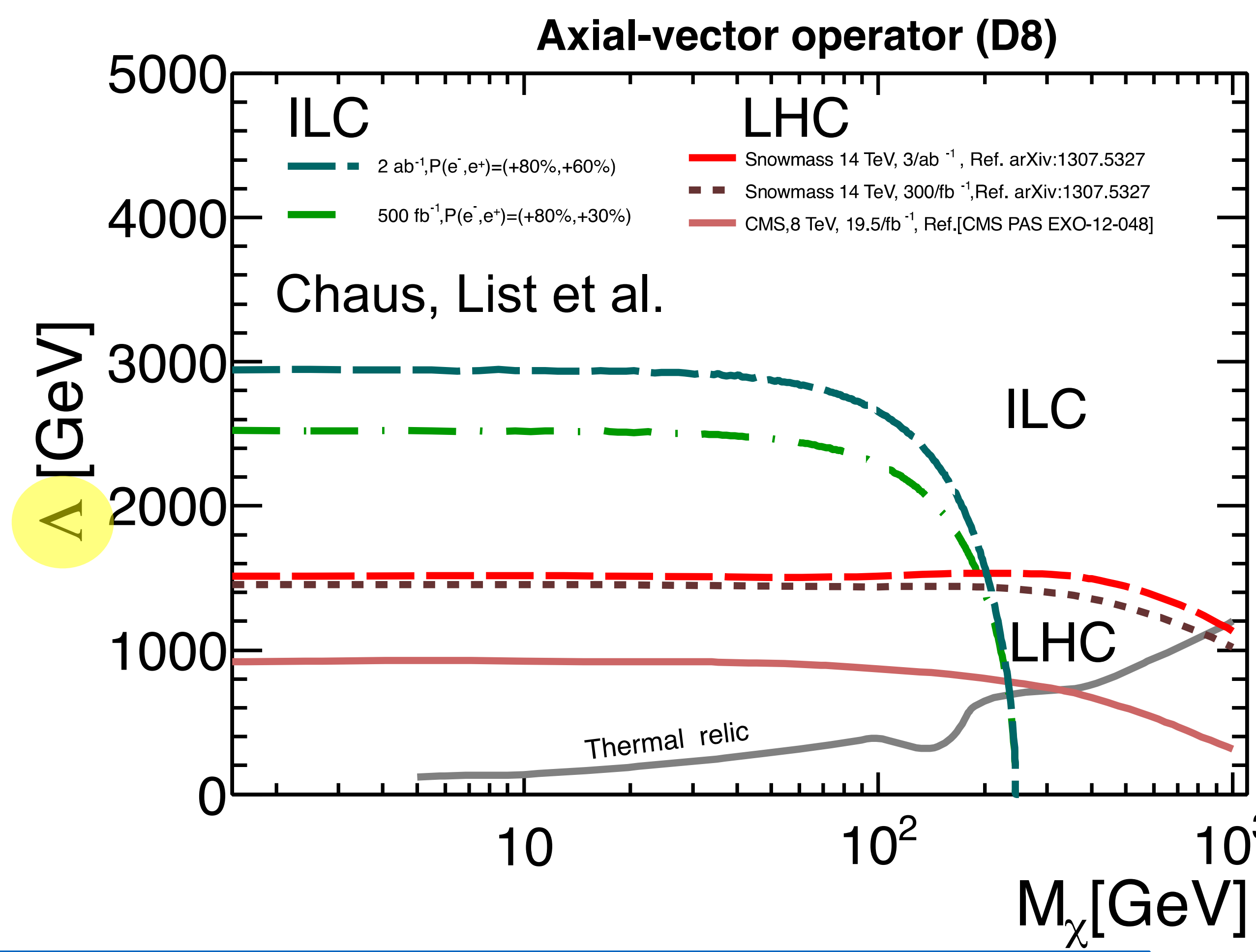


$$\mathcal{L}_{\text{int}} = \frac{1}{\Lambda^2}\mathcal{O}_i$$

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

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





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

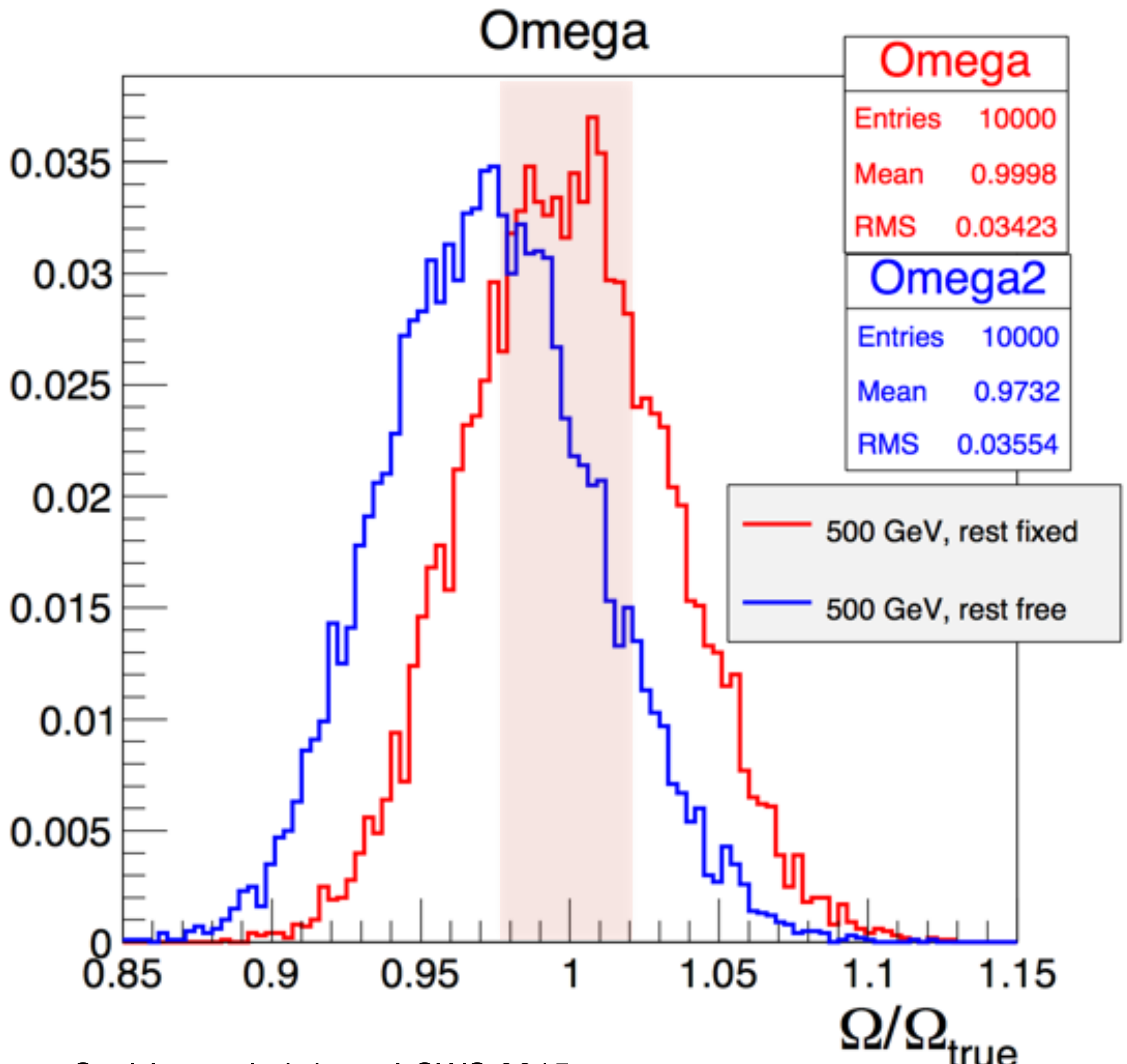
ILC sensitivity: Mediator mass up to ***Λ~3 TeV*** for ***DM mass up to ~√s/2***

LHC-ILC synergy!

DM Relic Abundance

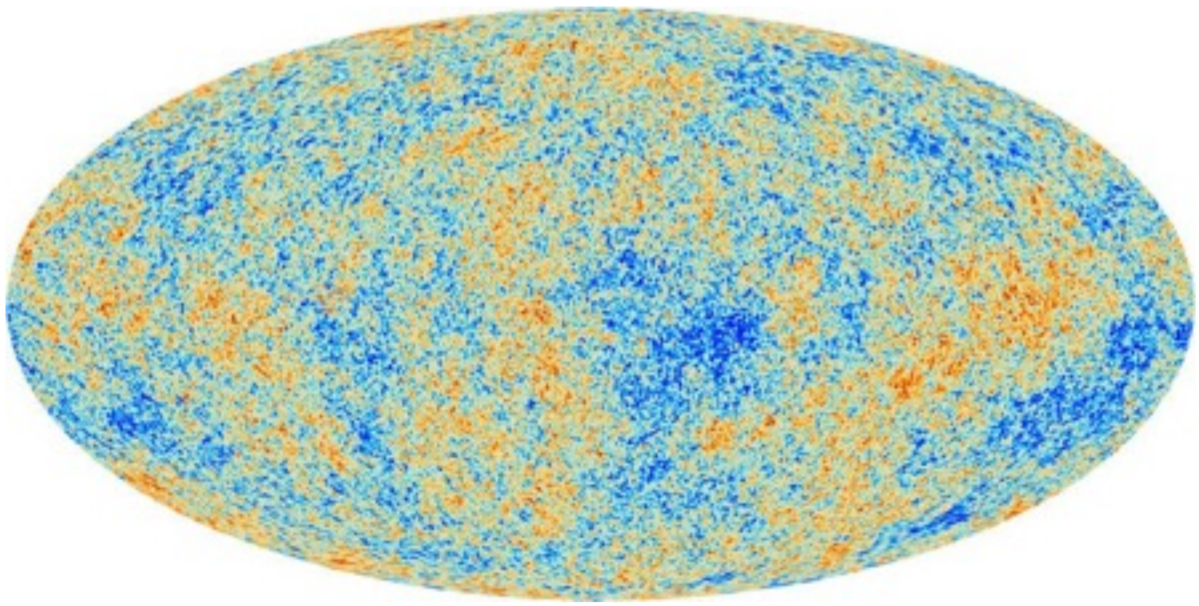
WMAP/Planck (68% CL)

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



Suvi-Leena Lehtinen, LCWS 2015

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 to compare with the CMB data

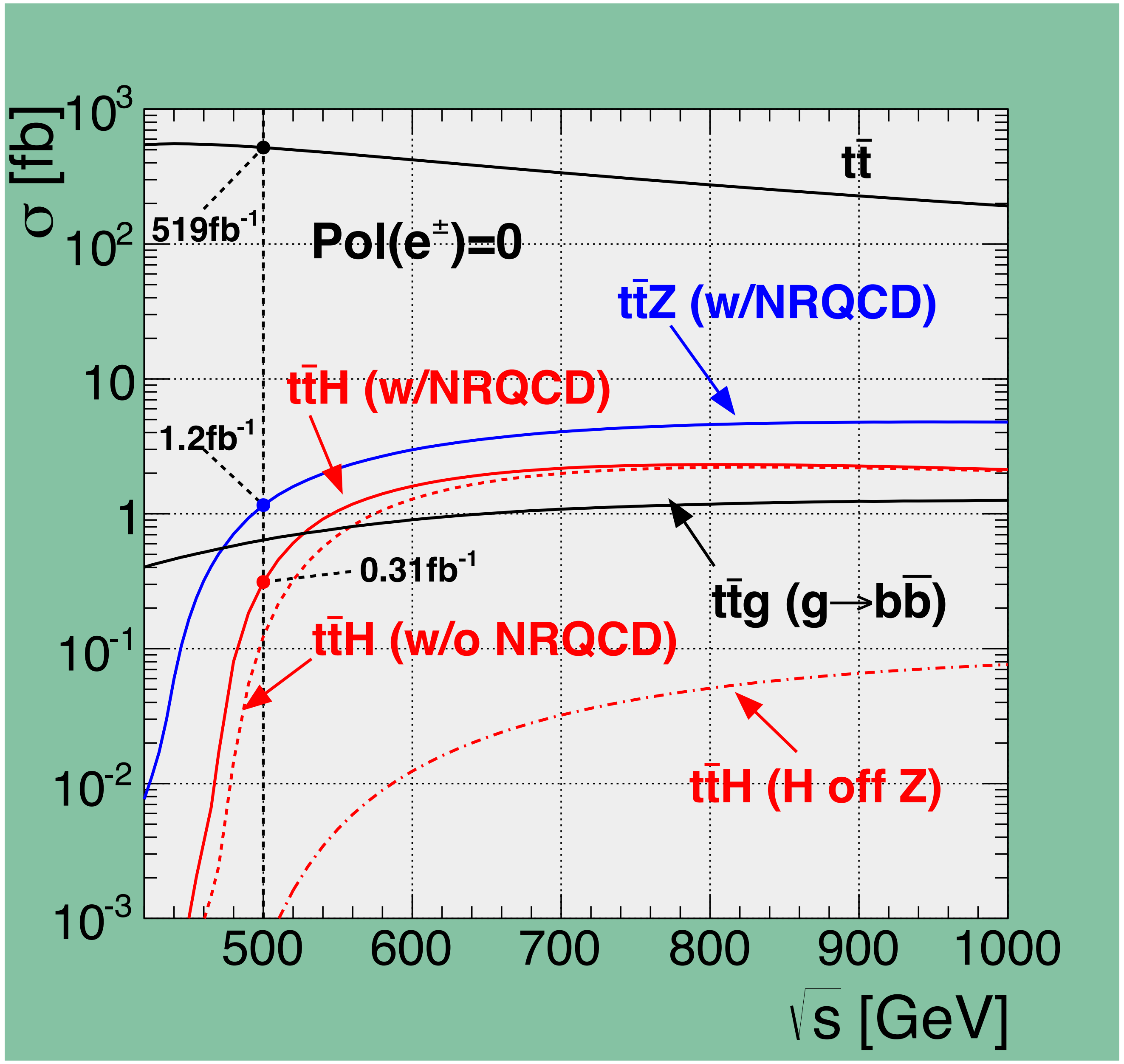
Summary

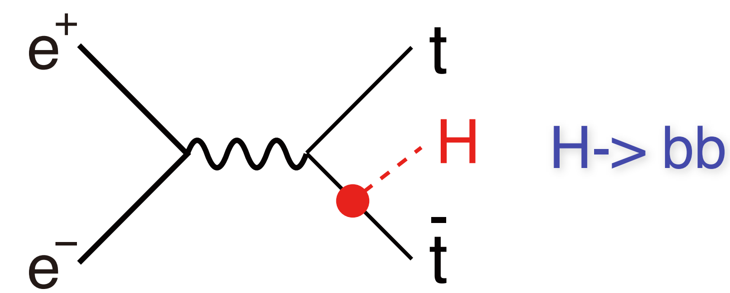
- The primary goal for the next decades is ***to uncover the secret of the EW symmetry breaking.*** The discovery of H(125) completed the SM particle spectrum and taught us how the EW symmetry was broken. However, it does not tell us why it was broken. ***Why $\mu^2 < 0$?*** To answer this question we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

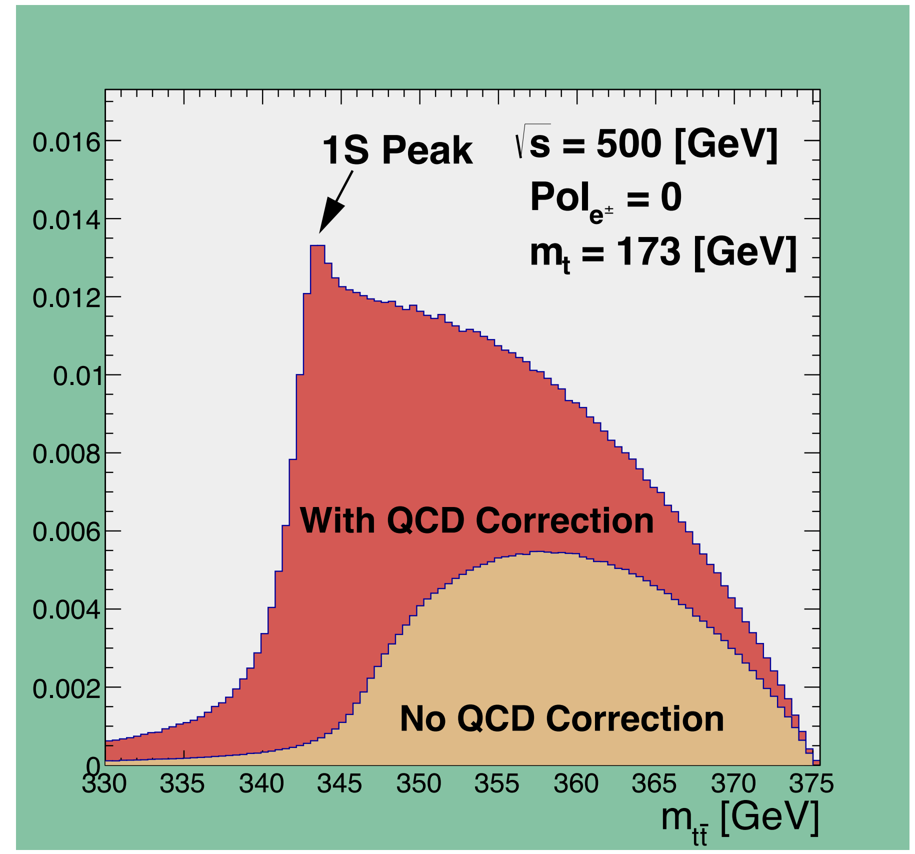
Backup

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 Ecm = 800GeV

Philipp Roloff, LCWS12

Tony Price, LCWS12

DBD Full Simulation

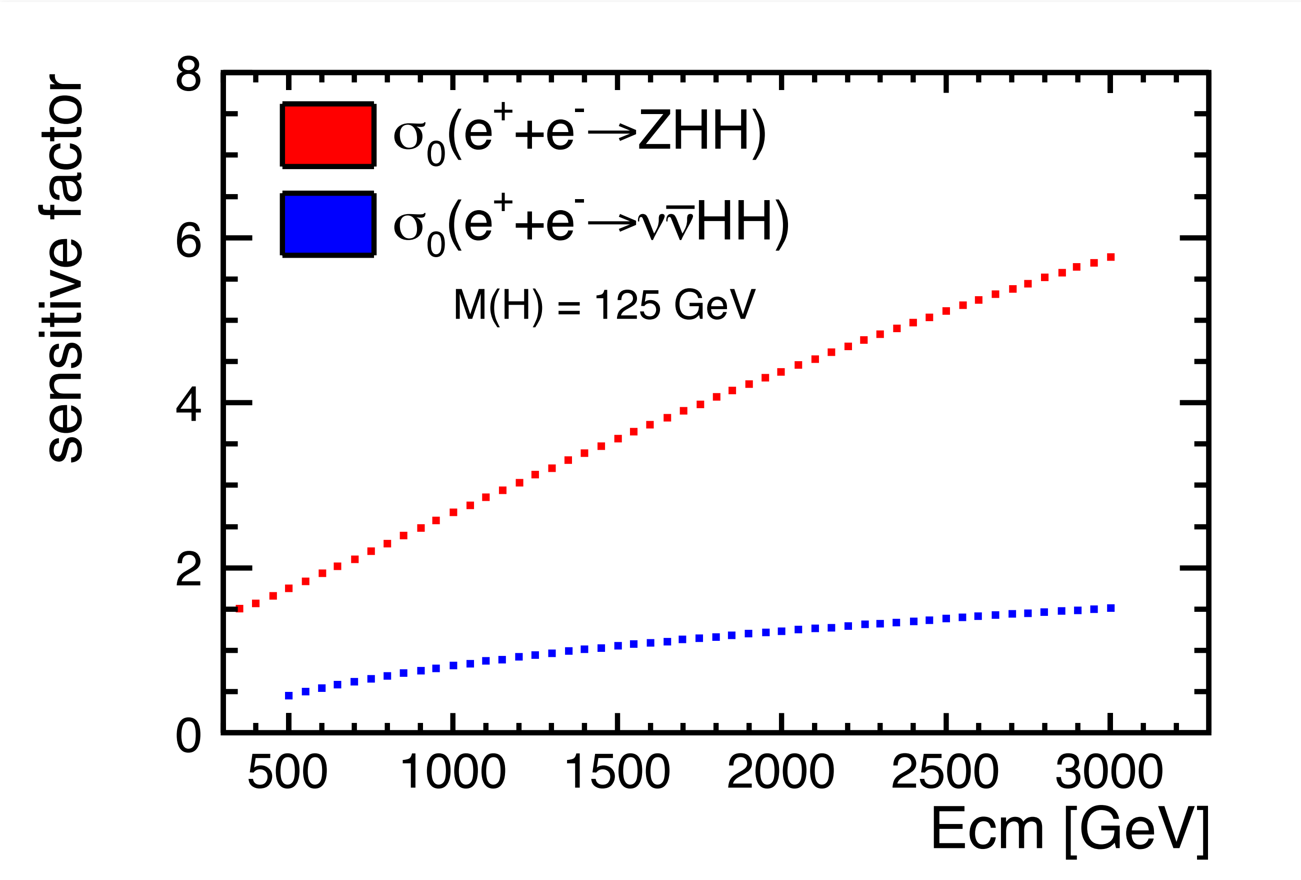
$$1\,\mathrm{ab}^{-1}@500\,\mathrm{GeV} \qquad m_H = 125\,\mathrm{GeV}$$

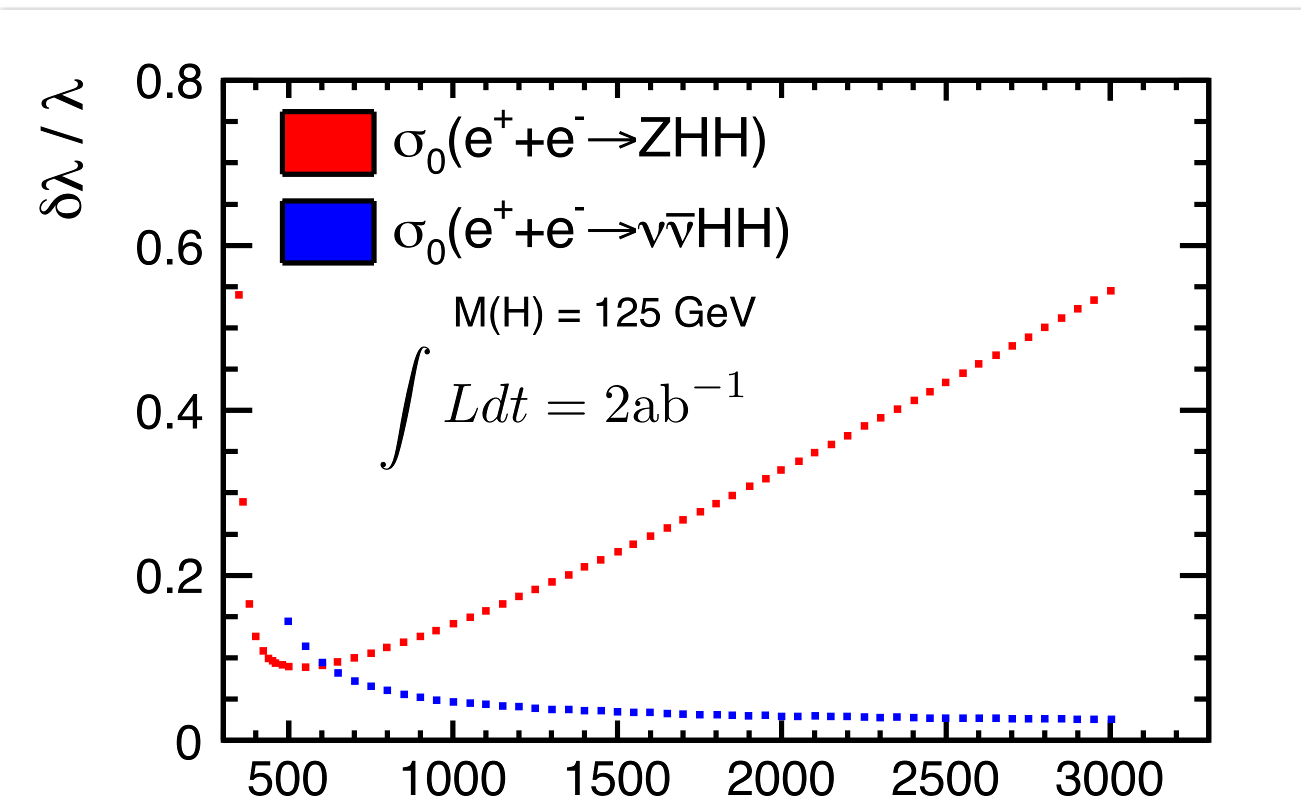
$$\Delta g_Y(t)/g_Y(t) = 9.9\%$$

Tony Price, LCWS12 scaled from mH=120 GeV

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

Expected Coupling Precision as a Function of Ecm





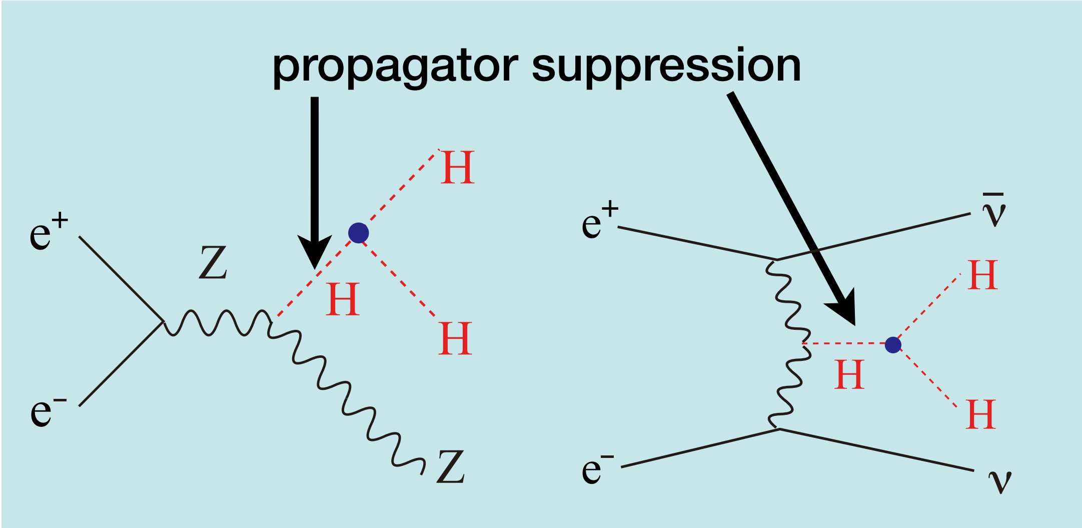
ILD DBD Study (Junping Tian)

Sensitivity Factor

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

F=0.5 if no BG diagrams there

BG diagrams dominate at high E_{cm}



⇒ F grows quickly with Ecm !

Coupling Precision

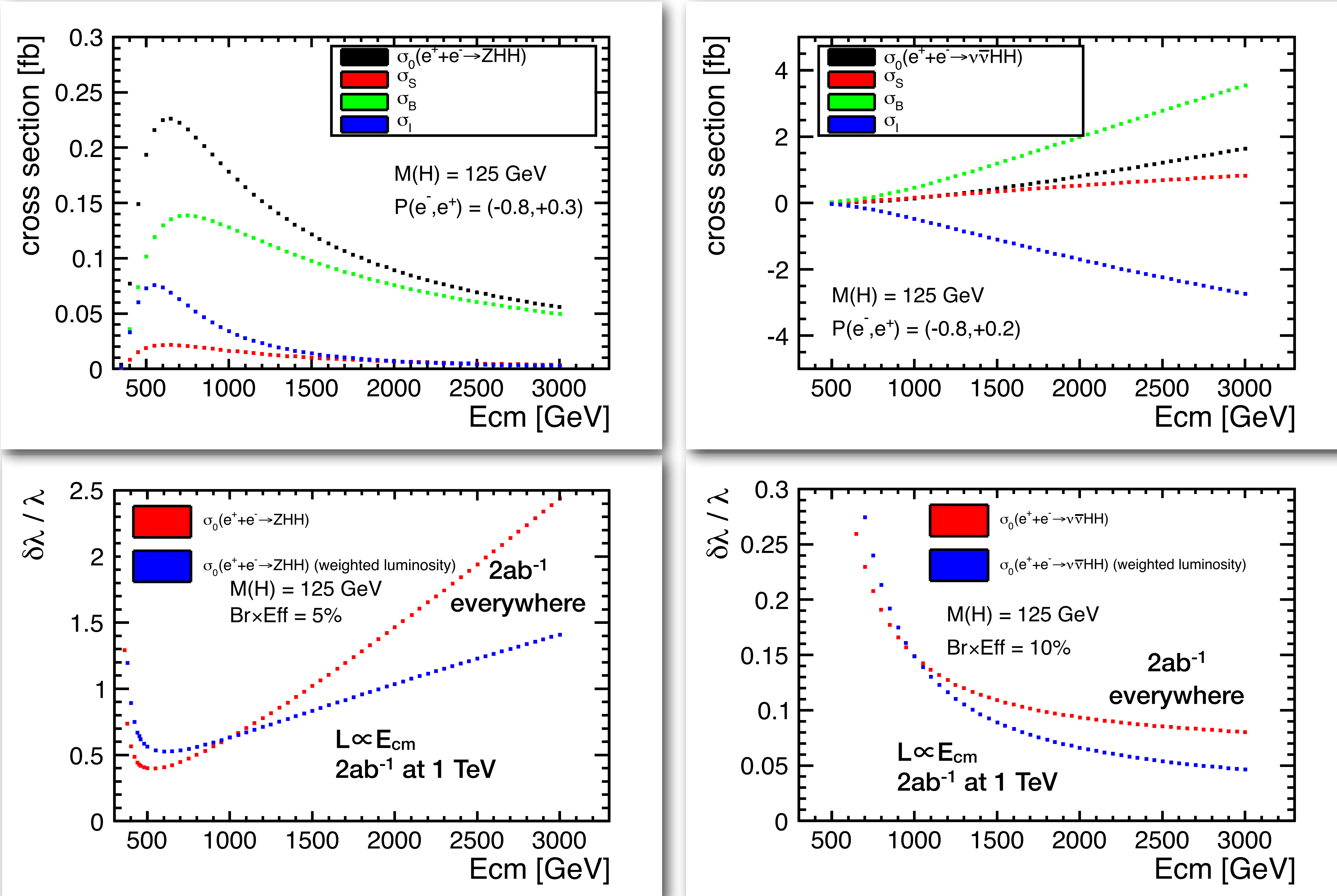
ZHH : **optimal Ecm ~ 500 GeV**

though the cross section maximum is at around Ecm = 600 GeV

vvHH :

Precision slowly improves with Ecm

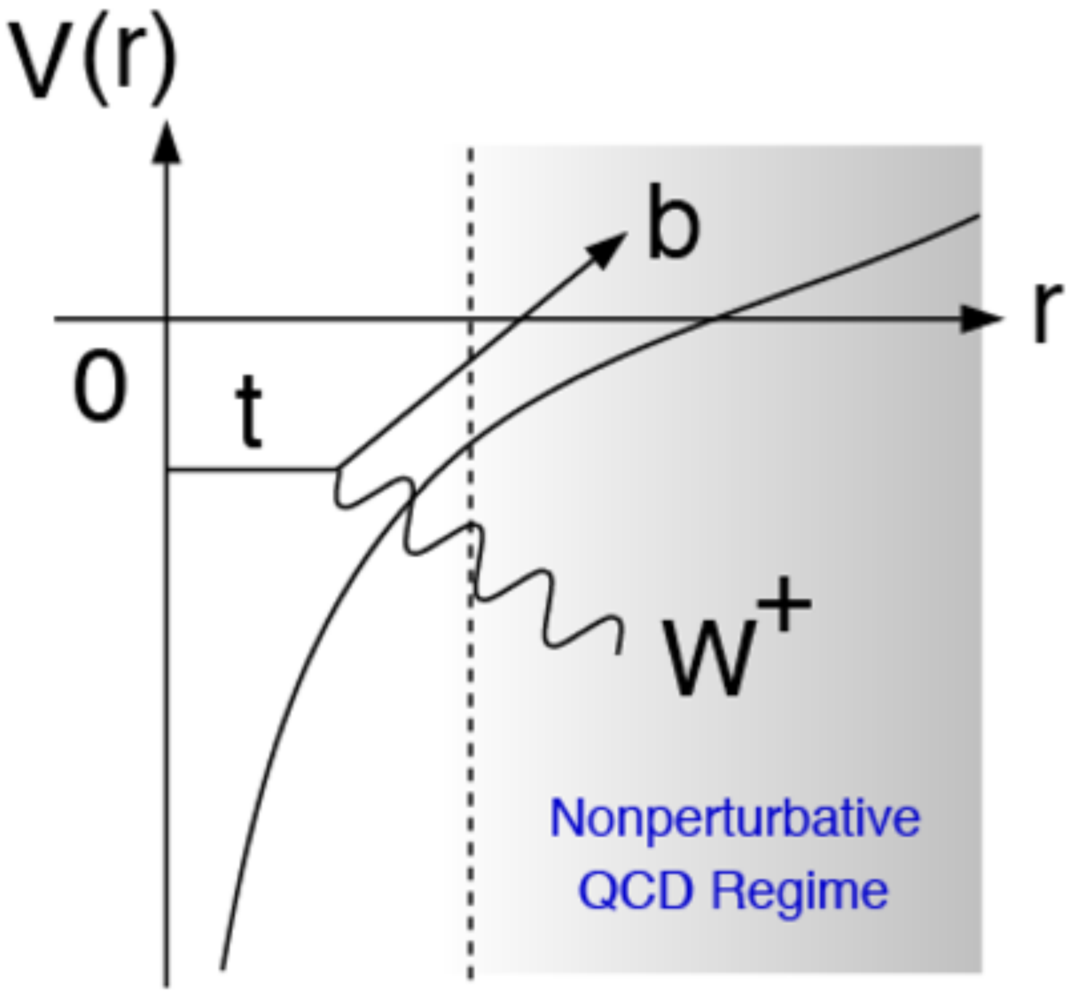
Expected Coupling Precision as a Function of Ecm



Top

Top Quark

The heaviest in the SM particles



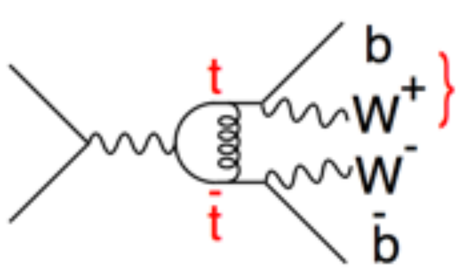
$\Gamma_t \approx 1.4$ GeV for $m_t = 175$ GeV

Because of this large width, the top and the anti-top pair created at r=0 decay before entering the non-perturbative QCD regime.

Γ_t acts as an infrared cutoff

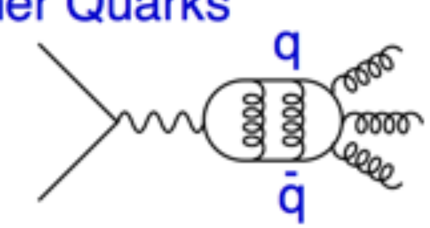
Reliable cross section calculation from first principle (perturbative QCD) as first shown by Fadin-Khoze!

Top



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

Other Quarks

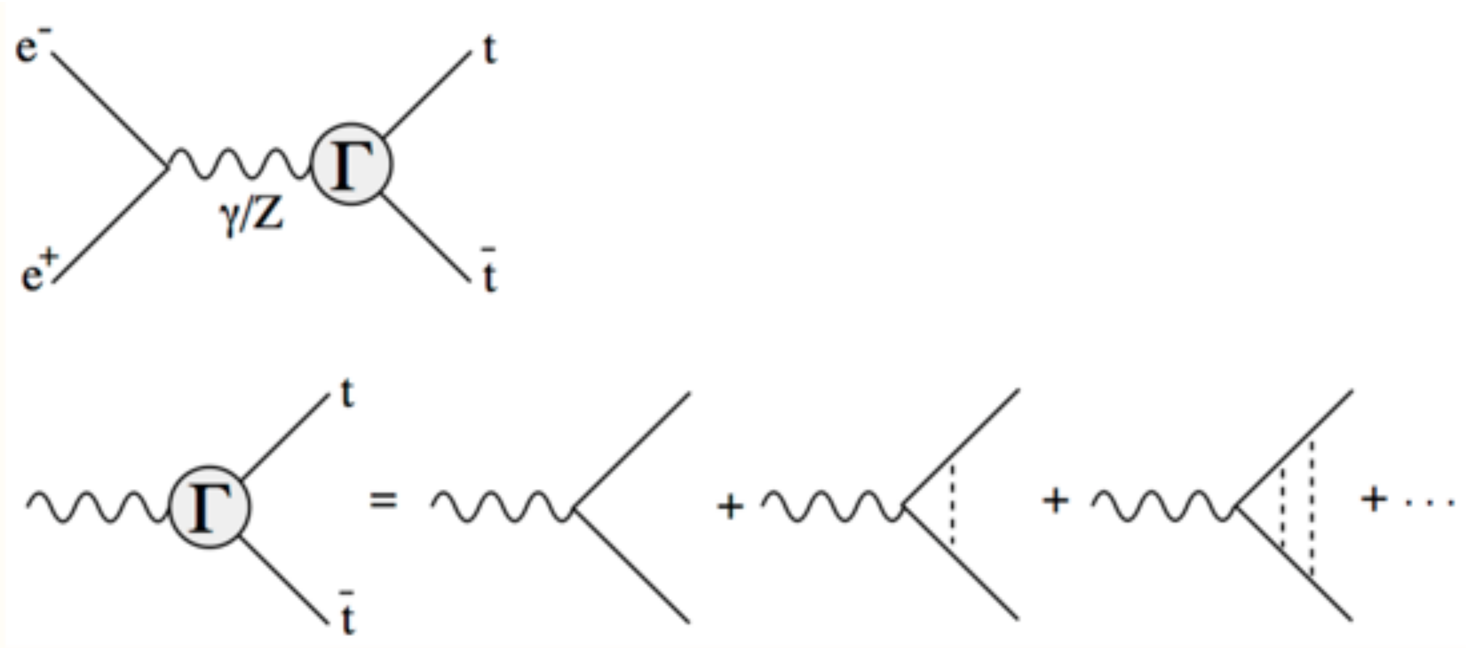


We cannot measure p_q in the onium!

The first chance to measure momentum space wave function of a (remnant of) quarkonium state.

Top Quark

Threshold Region



At threshold both the top quark and the anti-top quark are slow and stay close to each other, allowing multiple exchange of Coulombic gluons.

⇒ Leading contribution

The threshold correction factor (bound-state effect) denoted by Γ satisfies the Bethe-Salpeter equation which reduces to Schroedinger's equation:

$$\left[H-\left(E+\frac{i}{2}\Gamma_{\ominus}\right)\right]G=1$$

in the non-relativistic limit. The operator G is related to Γ through

$$\Gamma_V^k \simeq -\left(\frac{1}{D_t}+\frac{1}{D_{\bar{t}}}\right)\cdot\tilde{G}(\boldsymbol{p};E)\cdot\gamma^k$$

$$\tilde{G}(\boldsymbol{p};E)\equiv\langle\,\boldsymbol{p}\,|\,G\,|\,\boldsymbol{x}=\boldsymbol{0}\,\rangle$$

for vector part

$$\Gamma_A^k \simeq -\left(\frac{1}{D_t}+\frac{1}{D_{\bar{t}}}\right)\cdot\left(\frac{\tilde{F}^l(\boldsymbol{p};E)}{m_t}\right)\cdot\sigma^{kl}\gamma^5$$

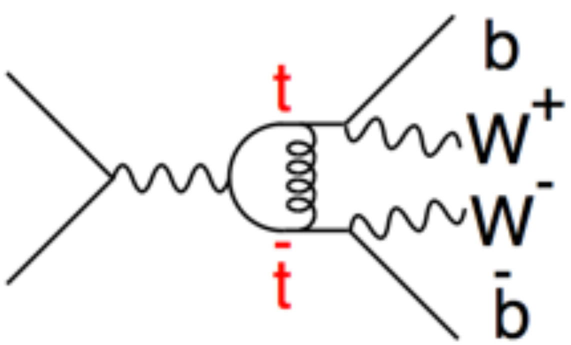
$$\tilde{F}^l(\boldsymbol{p};E)\equiv\langle\,\boldsymbol{p}\,|\,G\cdot\hat{p}^l\,|\,\boldsymbol{x}=\boldsymbol{0}\,\rangle$$

for axial vector part

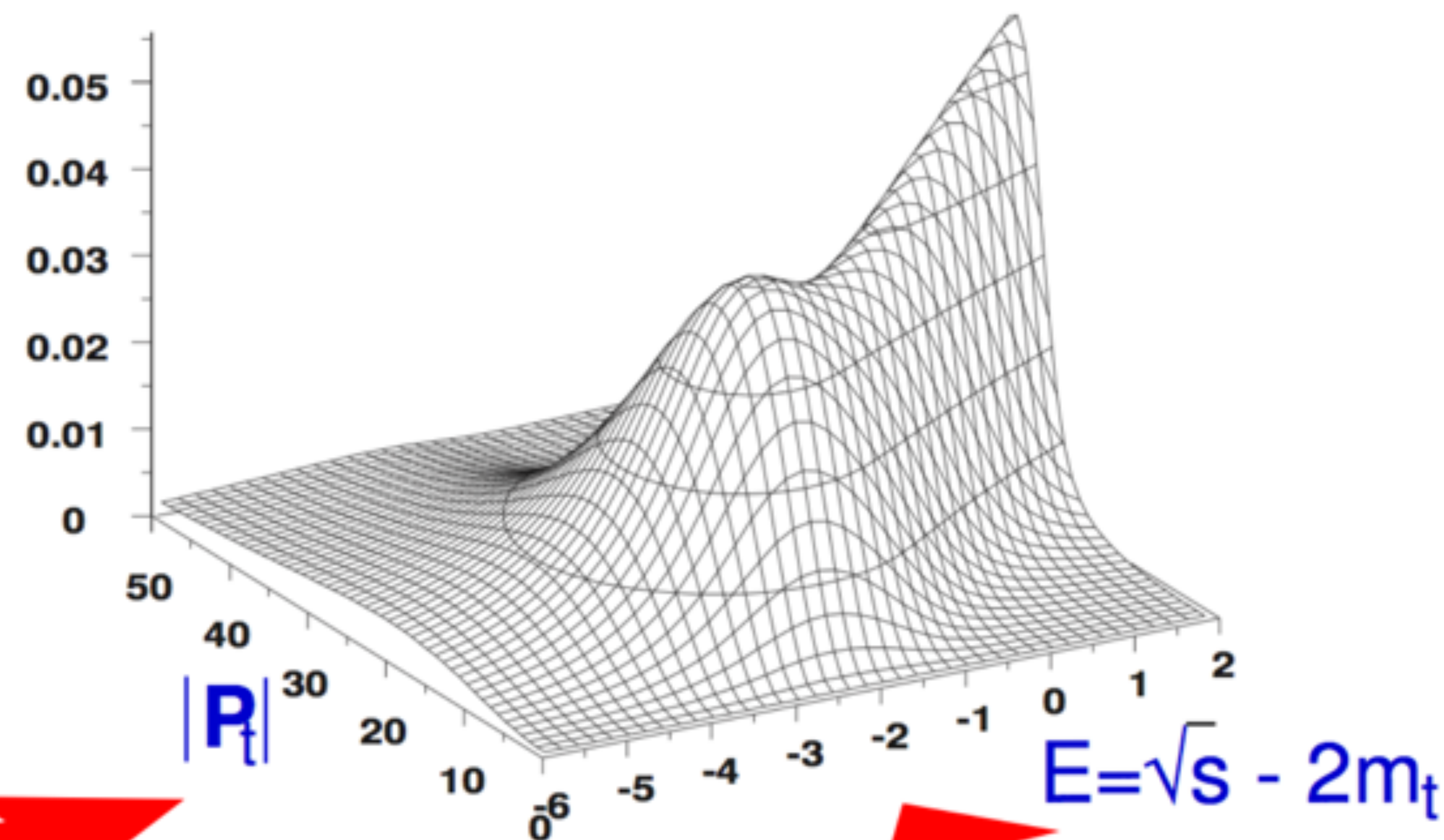
Top Quark

Threshold Region

How to access G experimentally



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



Momentum Dist.

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

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

momentum space wave fun.

Threshold Scan

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

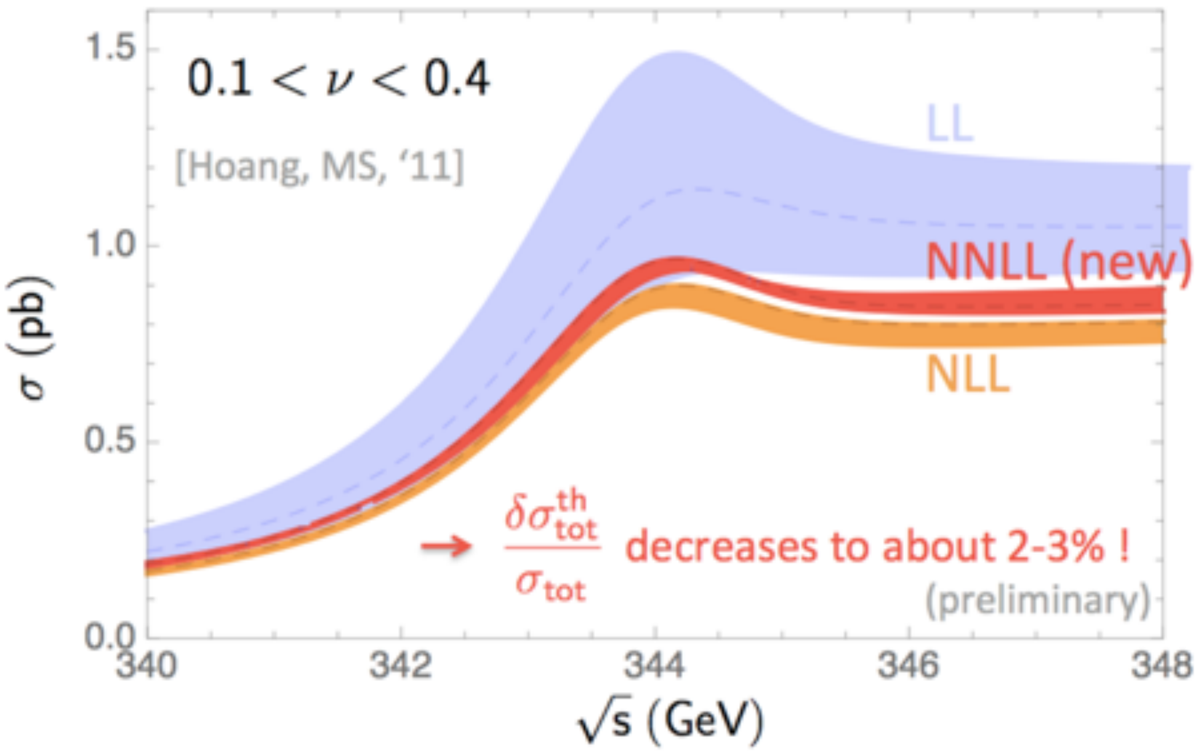
$$\simeq Im \sum_n \frac{|\Psi_n(\boldsymbol{0})|^2}{E - E_n + i\Gamma_n/2}$$

wave function at origin

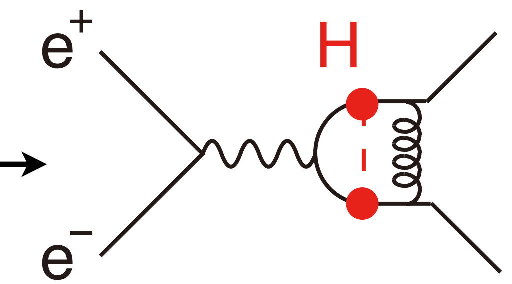
Top at Threshold

Threshold Scan

M.Stahlhofen Top Phys WS 2012



Theory improving! →

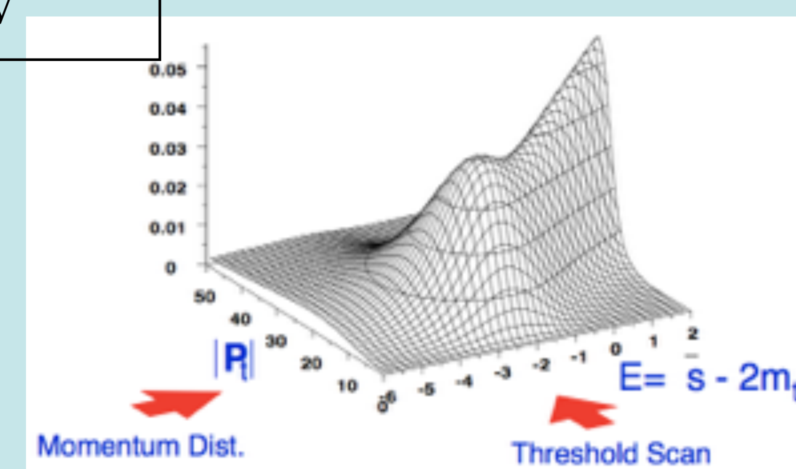


~10% effect

Expected accuracies

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

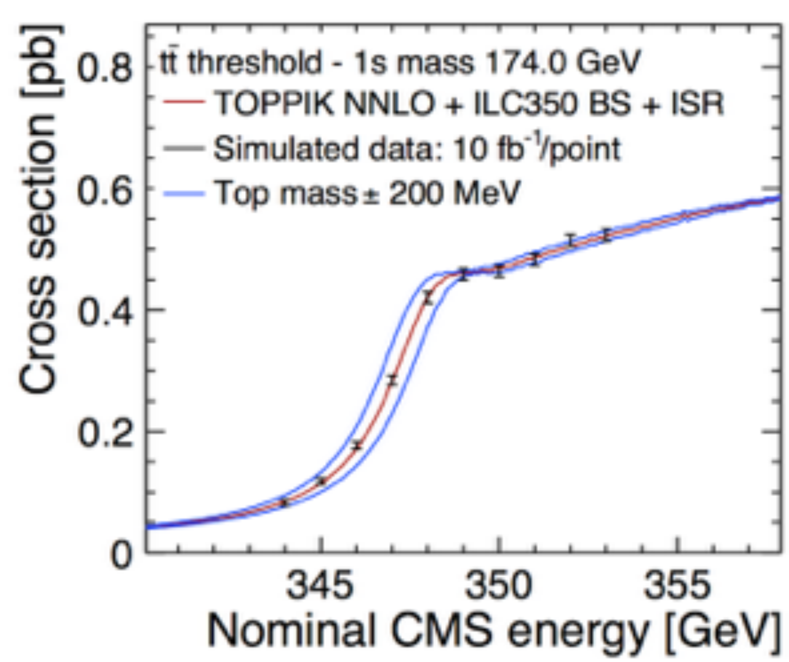
Threshold scan alone



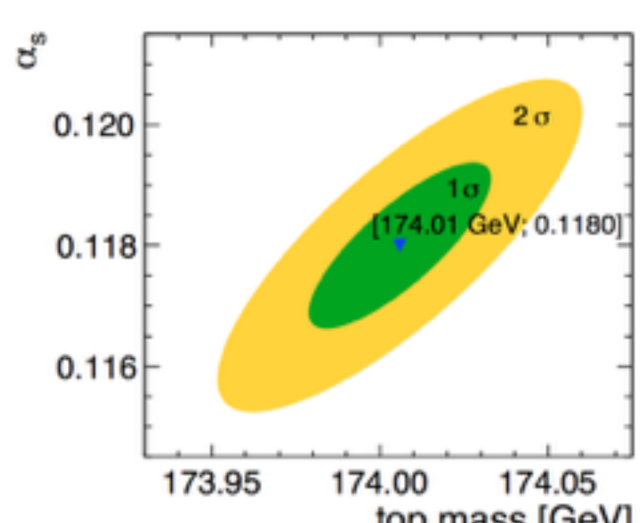
+ A_{FB} & Top Momentum

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

arXiv:hep-ph/0601112v2



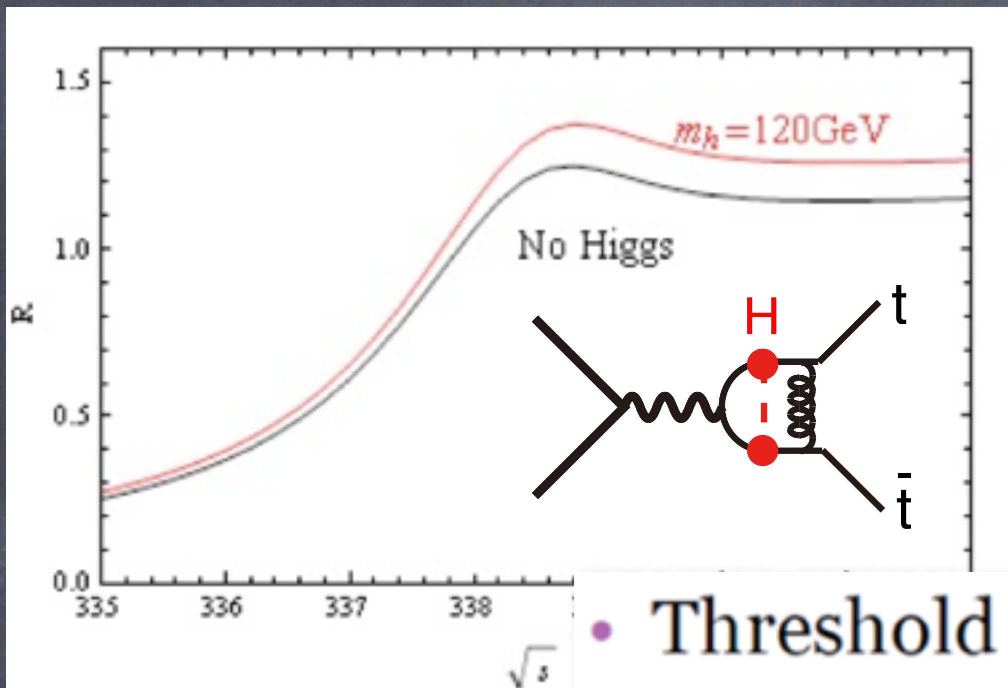
F.Simon Top Phys WS 2012



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

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

Reducing Theoretical Ambiguities



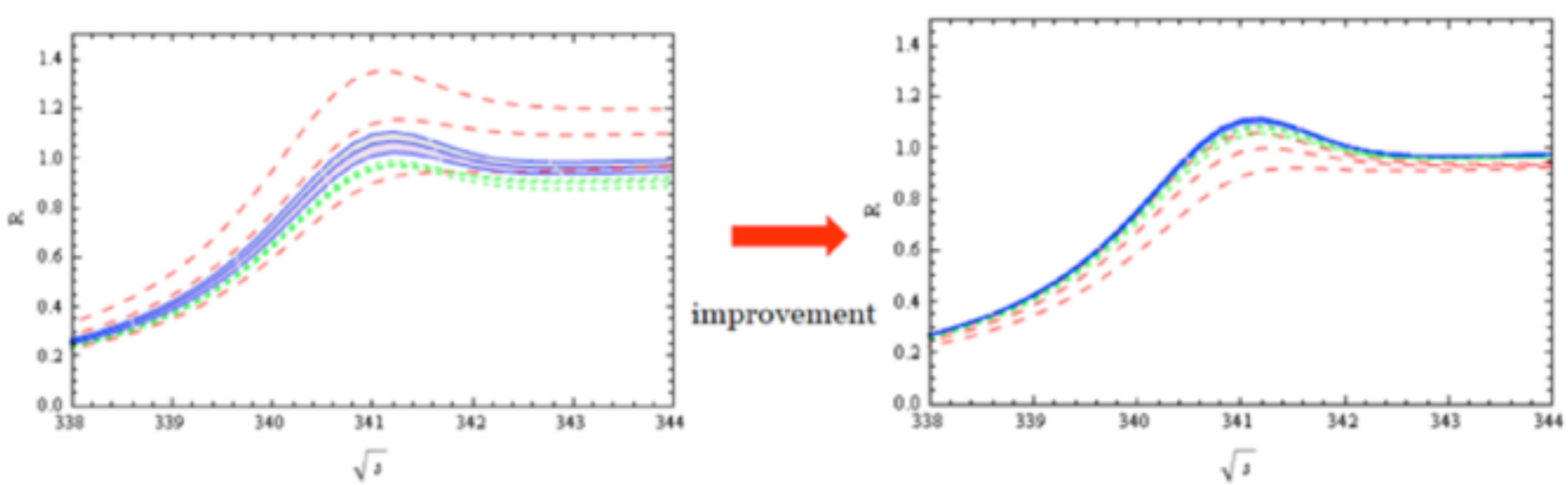
9% effect on the X-section

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

- 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

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

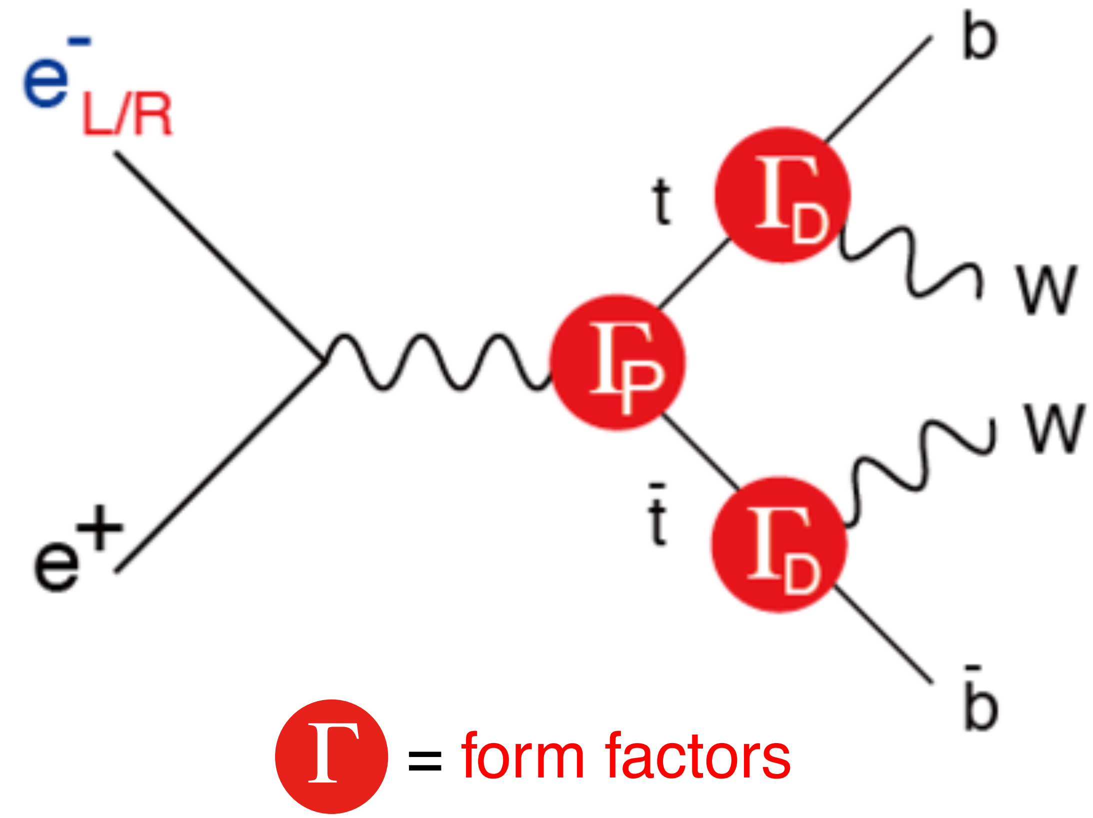
Key points

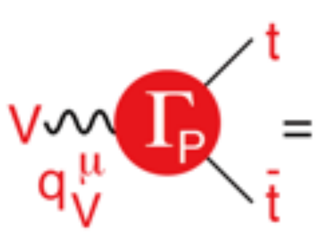
$\Gamma_t \approx 1.4$ GeV for $m_t = 175$ GeV

The top decays before forming a top hadron.

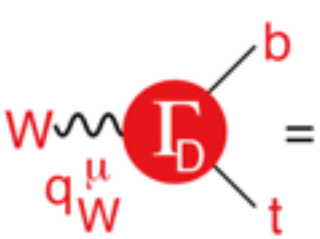
Top spin is measurable by angular analysis of decay products.

+ 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

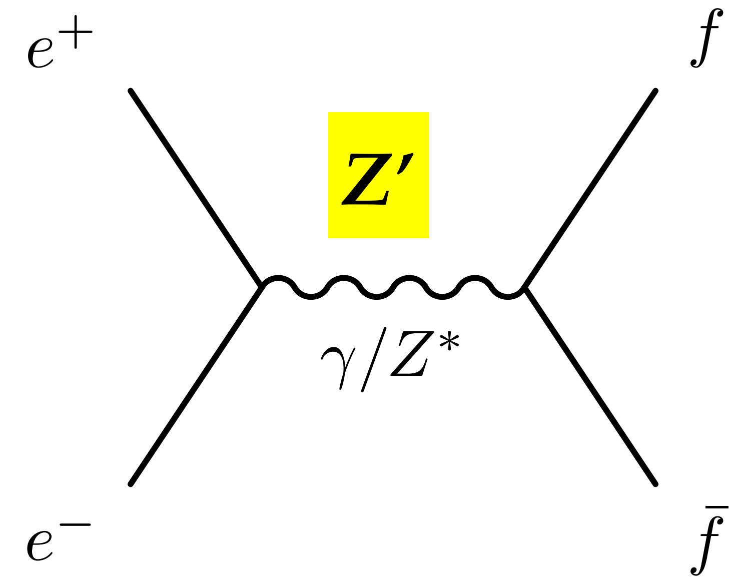
Z’

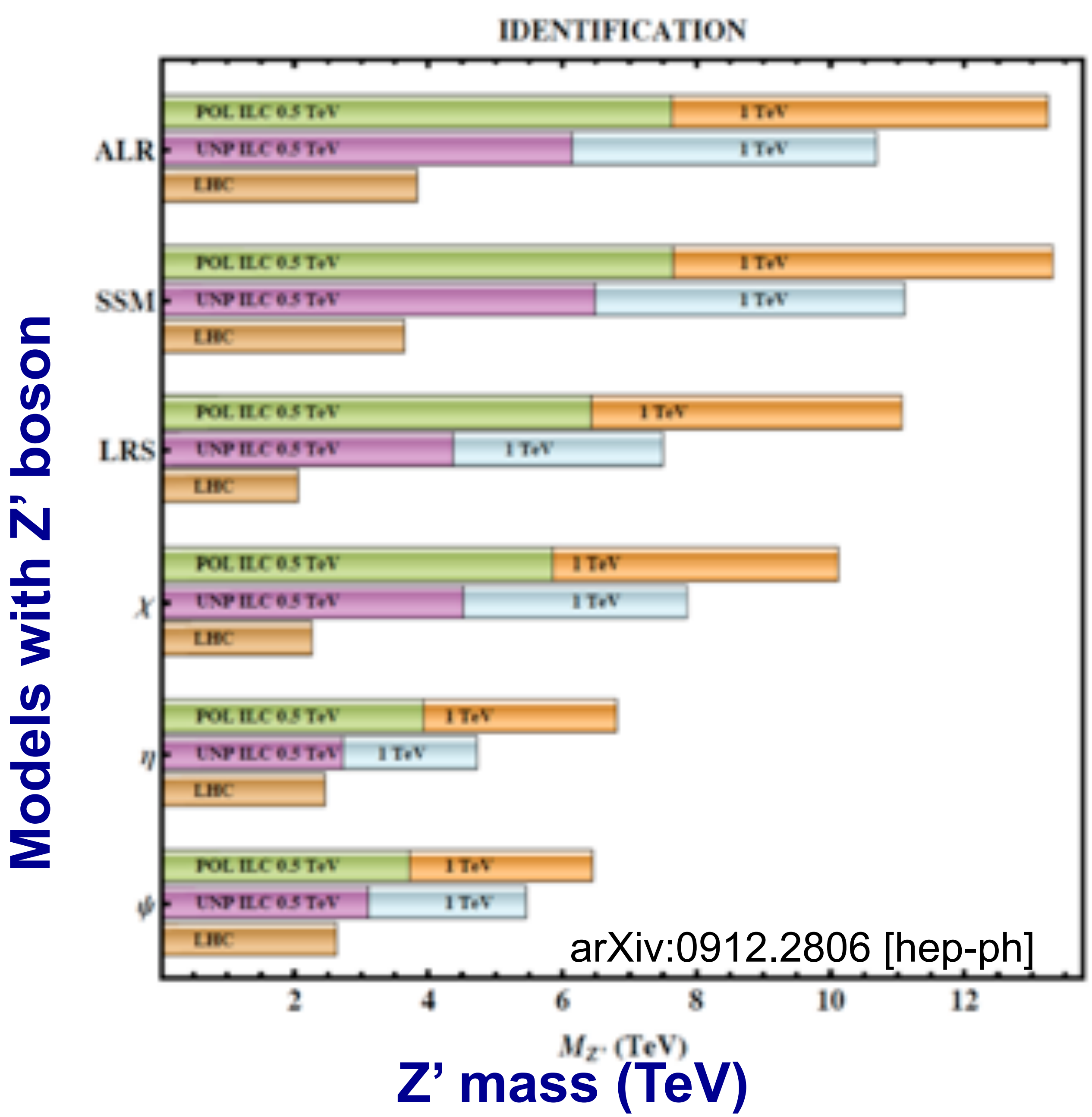
Z’ : Heavy Neutral Gauge Bosons

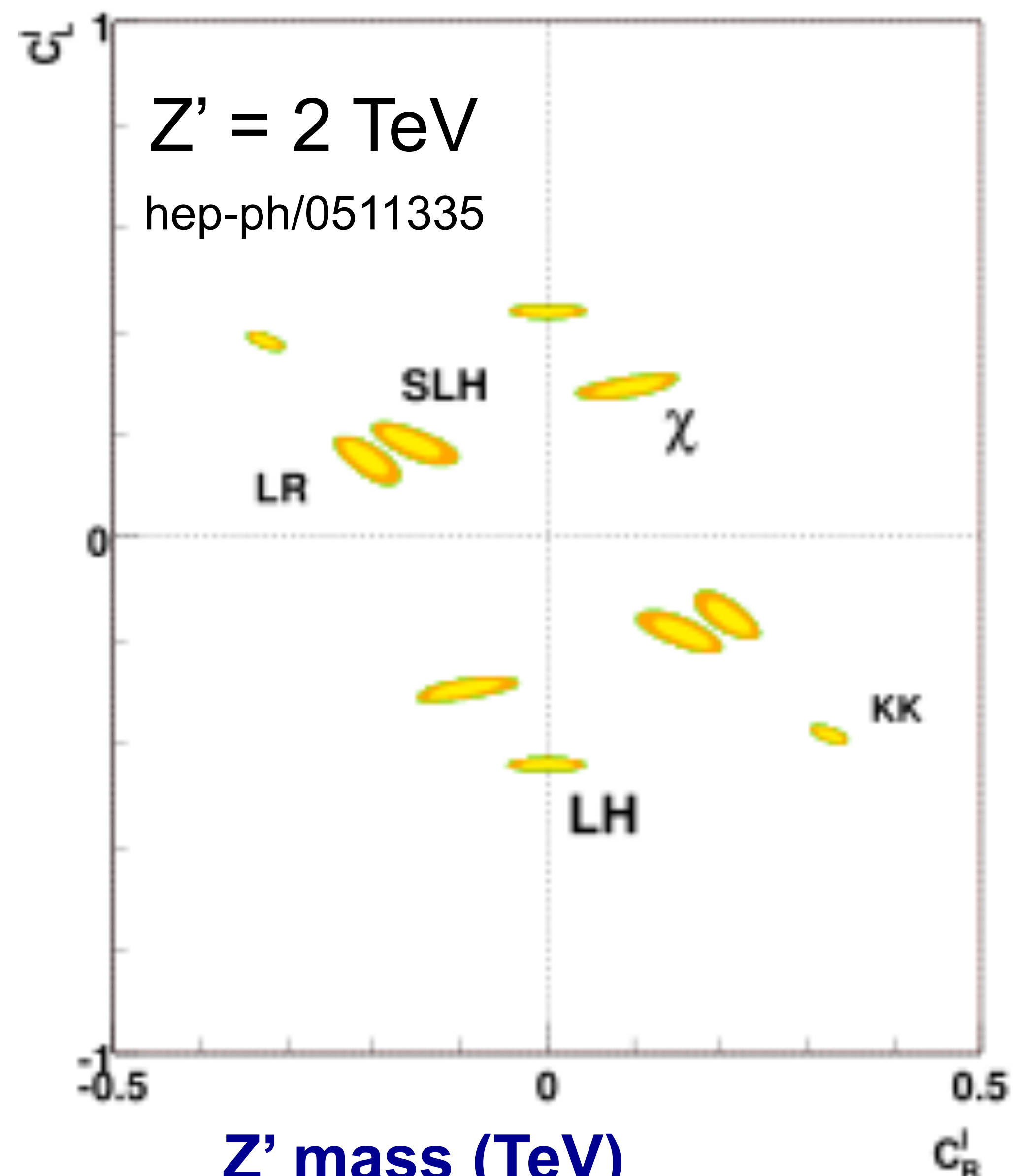
New gauge forces imply existence of heavy gauge bosons (Z’)

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







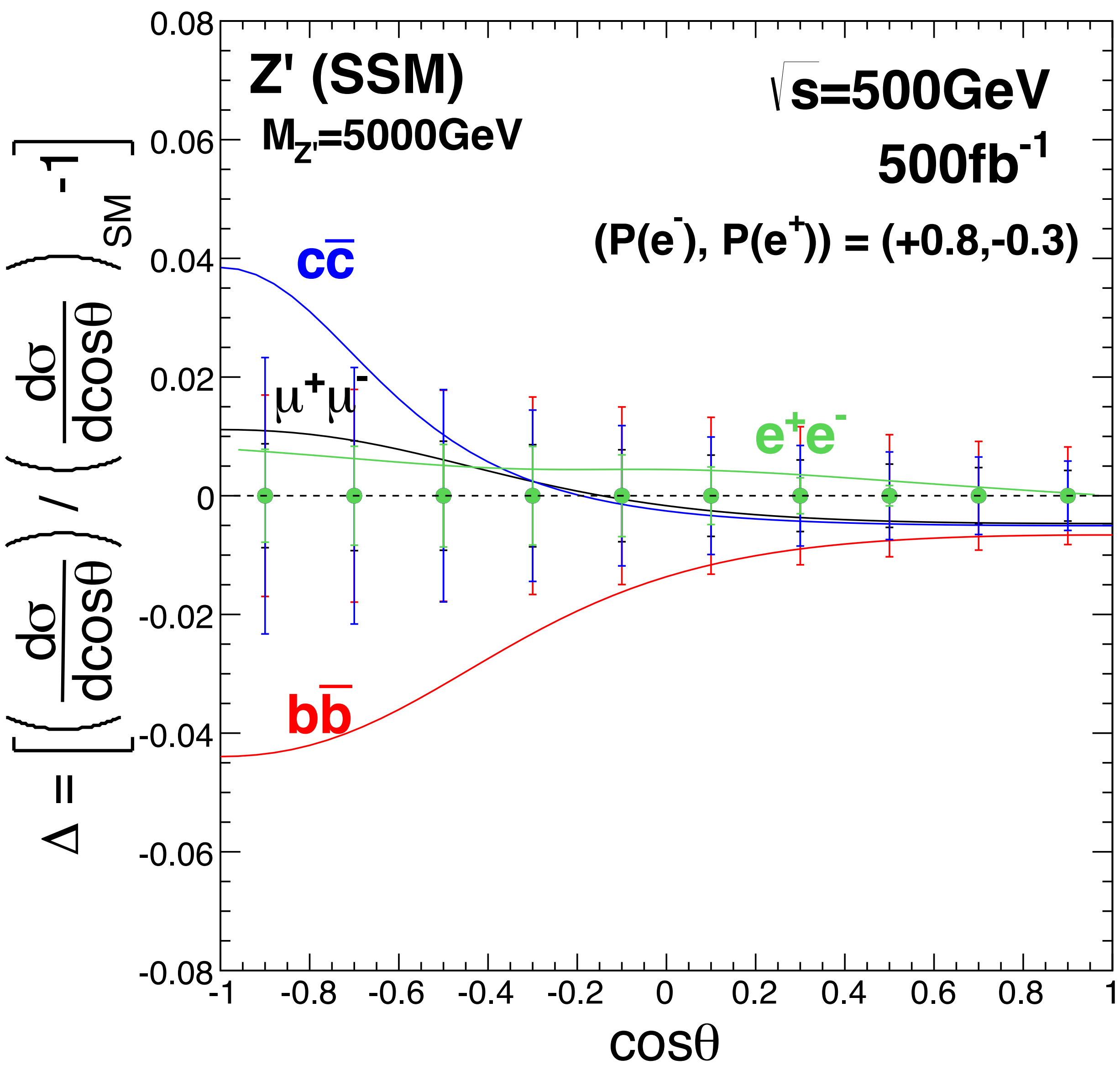
Two-Fermion Processes

Z' Search / Study

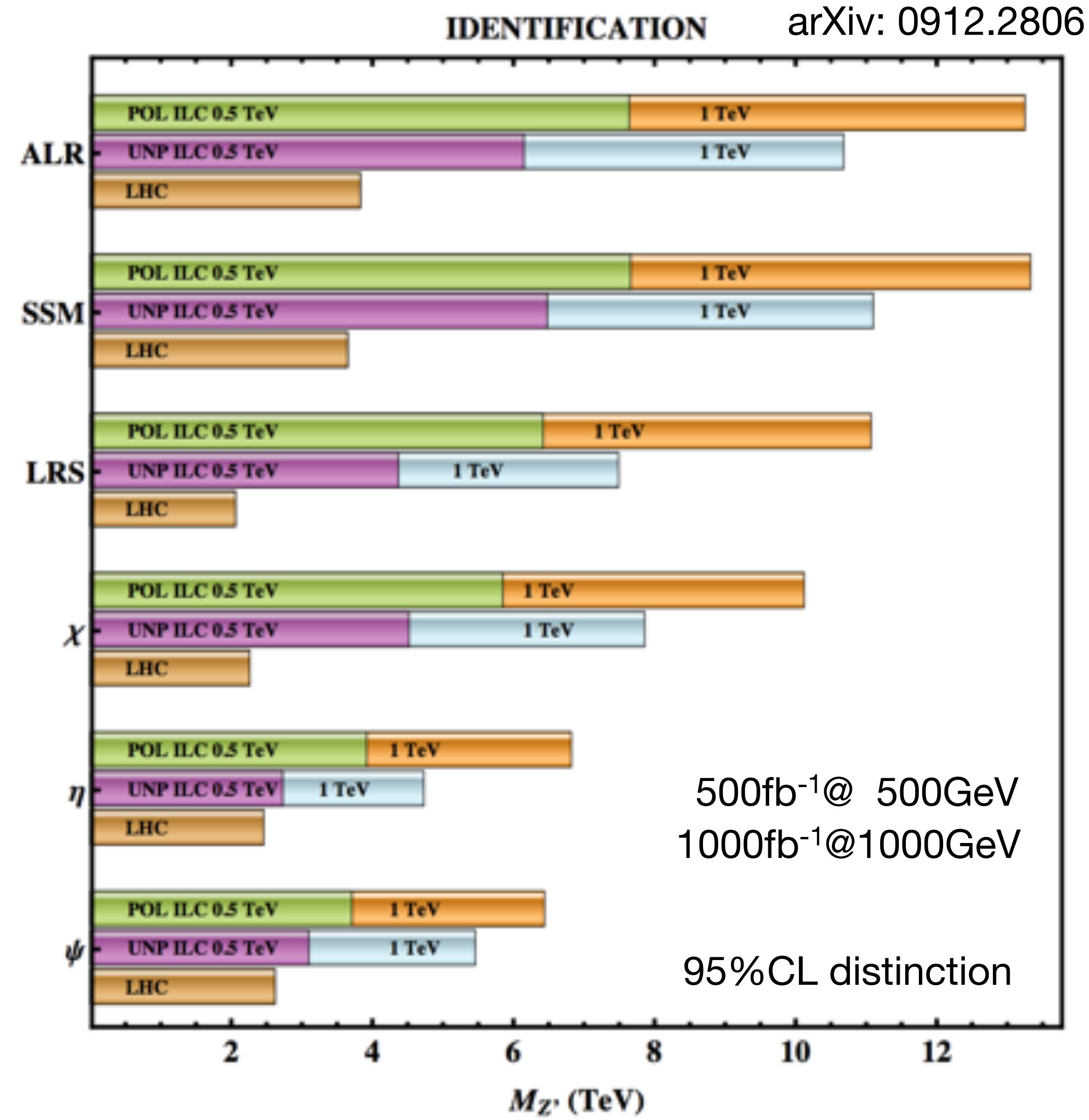
Observables: dσ(P-,P+)/d cosθ

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

Example: Sequential SM-like Z'



arXiv: 0912.2806



Two-Fermion Processes

Z' Search / Study

arXiv:0912.2806 [hep-ph]

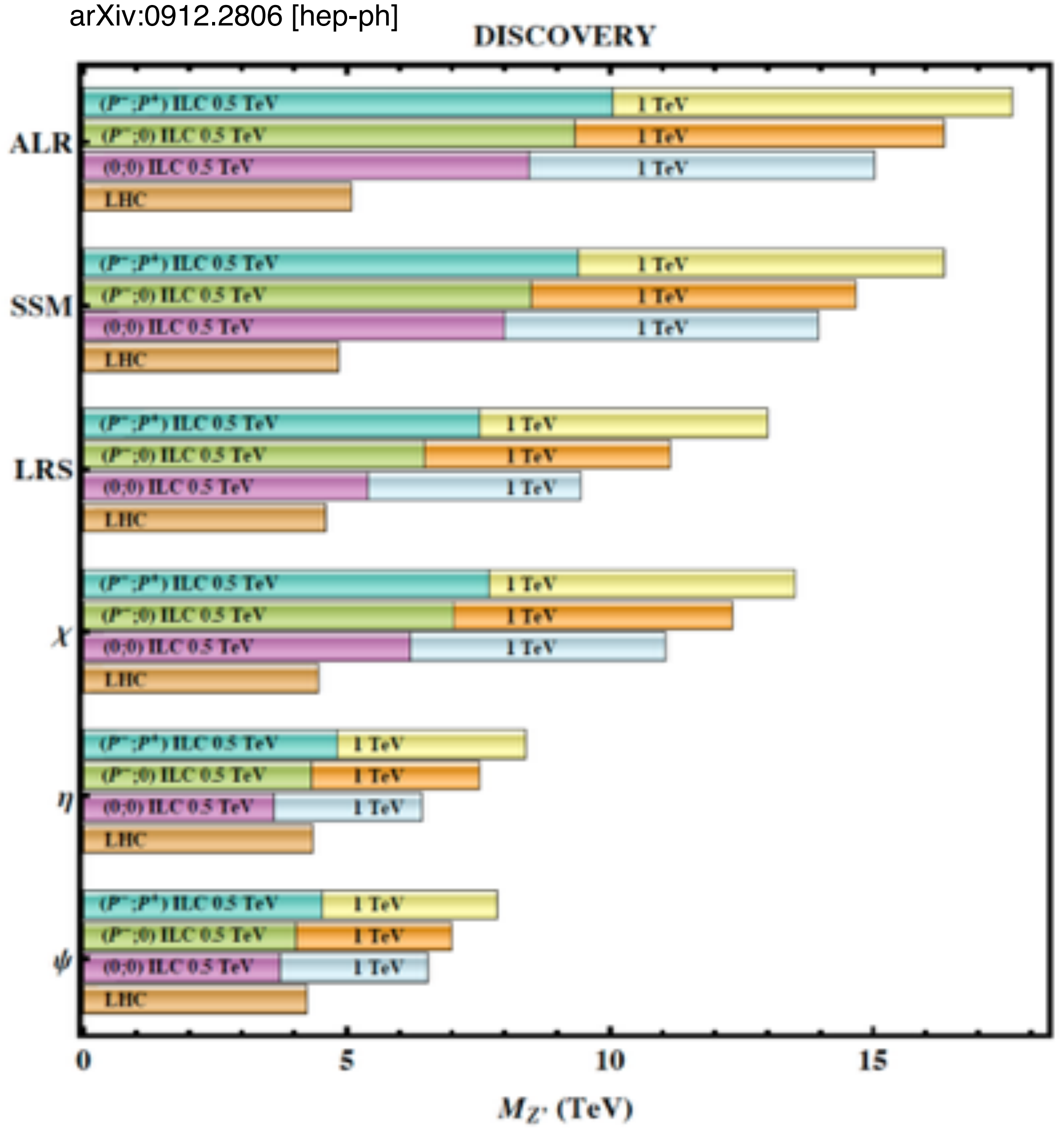
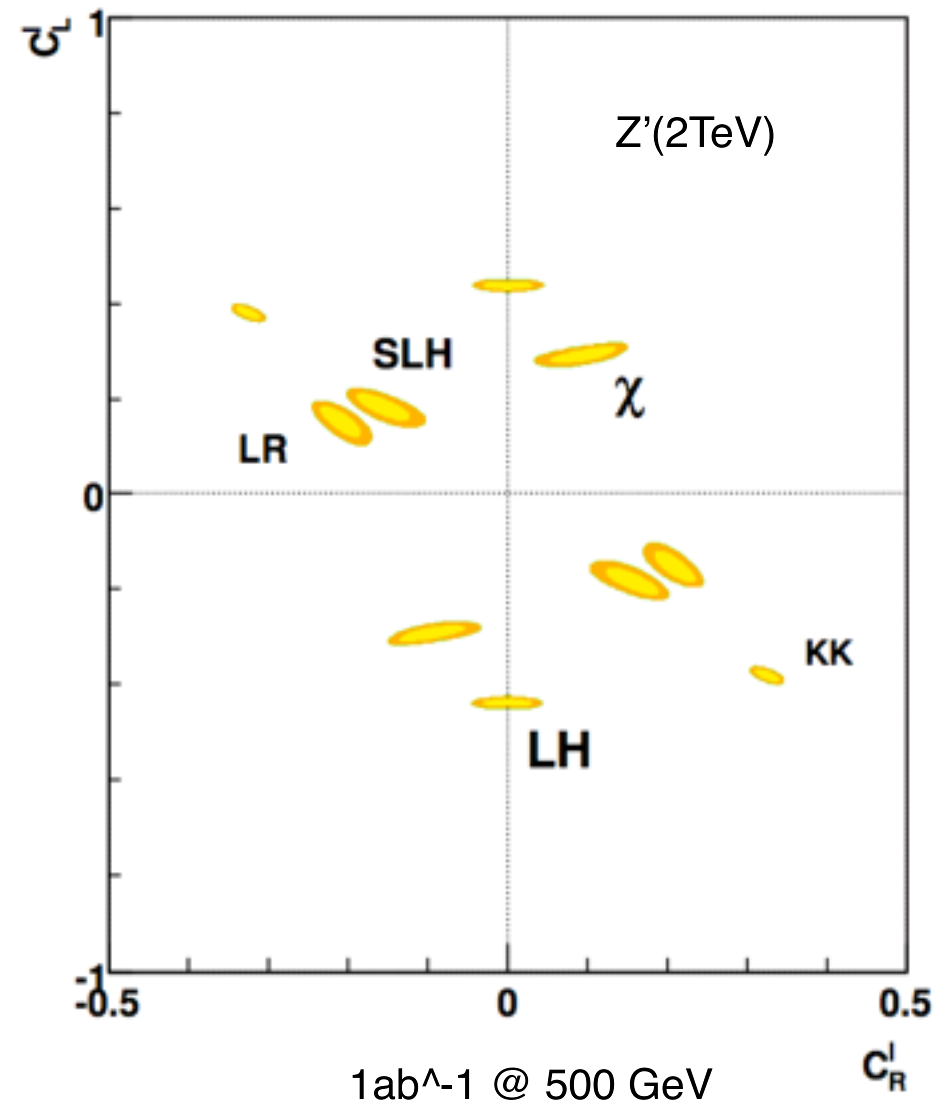


Figure 23: Sensitivity of the ILC to various candidate Z' bosons, quoted at 95% conf., with $\sqrt{s} = 0.5$ (1.0) TeV and $\mathcal{L}_{\rm int} = 500$ (1000) fb^{-1}. The sensitivity of the LHC-14 via Drell-Yan process $pp \to \ell^+\ell^- + X$ with 100 fb^{-1} of data are shown for comparison. For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

hep-ph/0511335



1ab^-1 @ 500 GeV

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

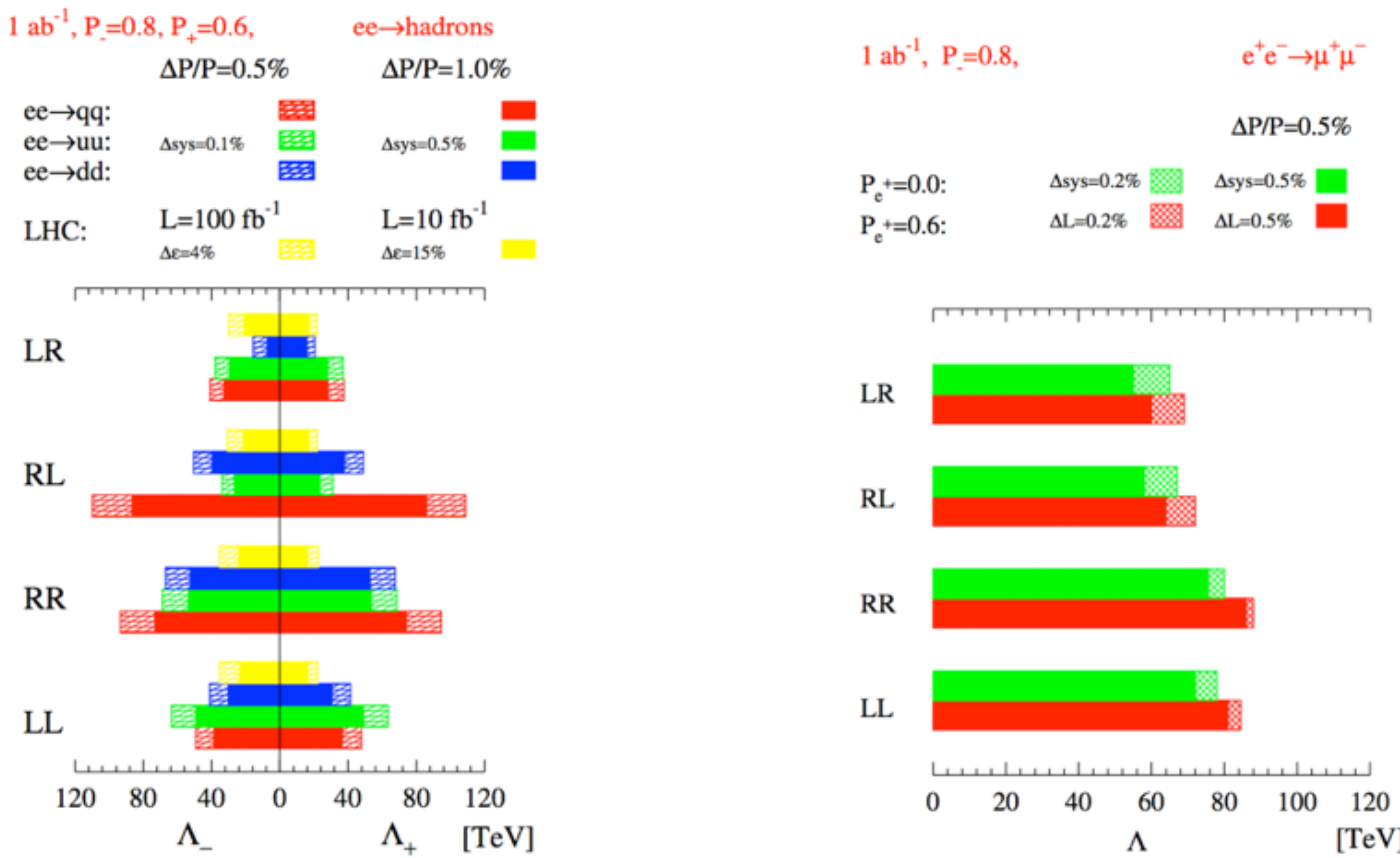


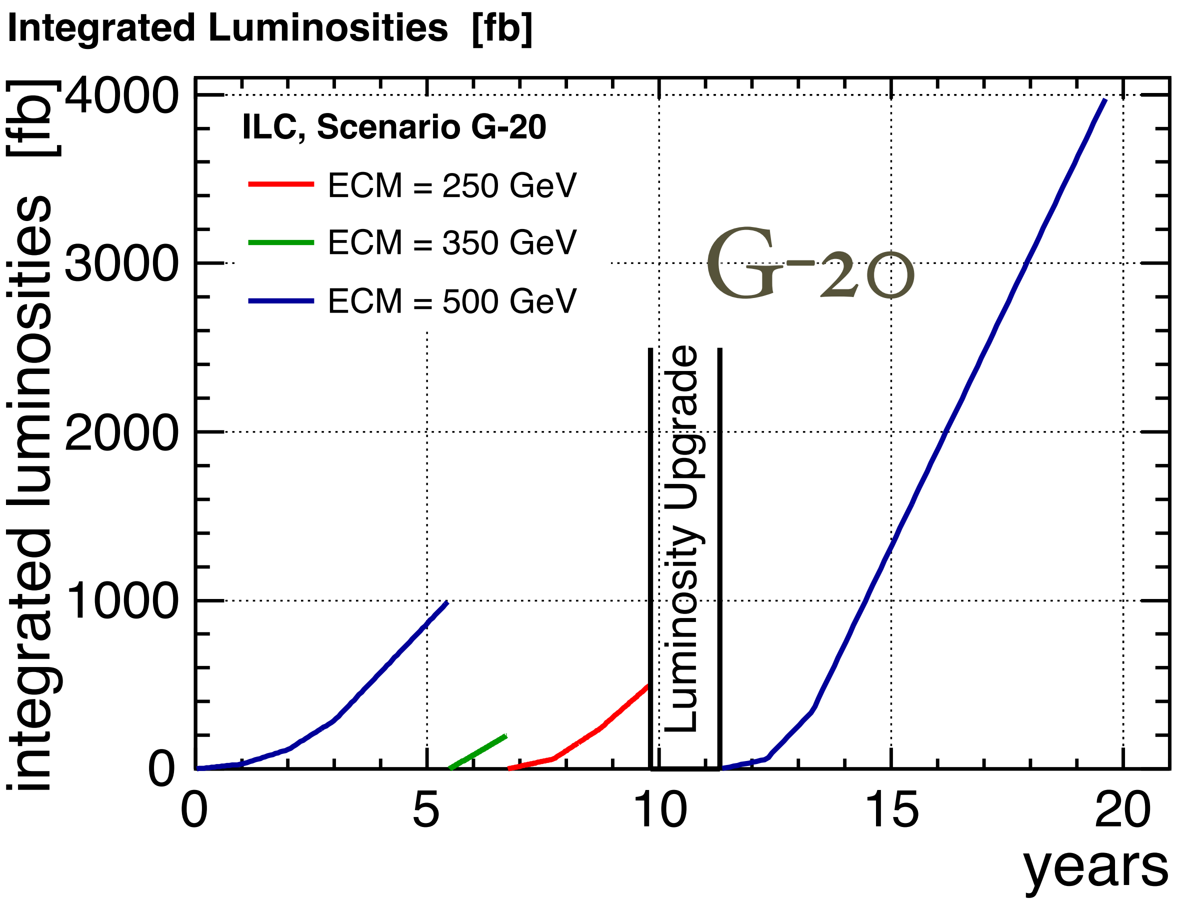
Figure 26: Sensitivities (95% c.l.) of a 500 GeV ILC to contact interaction scales Λ for different helicities in $e^+e^- \to$ hadrons (left) and $e^+e^- \to \mu^+\mu^-$ (right), including beam polarization [18].

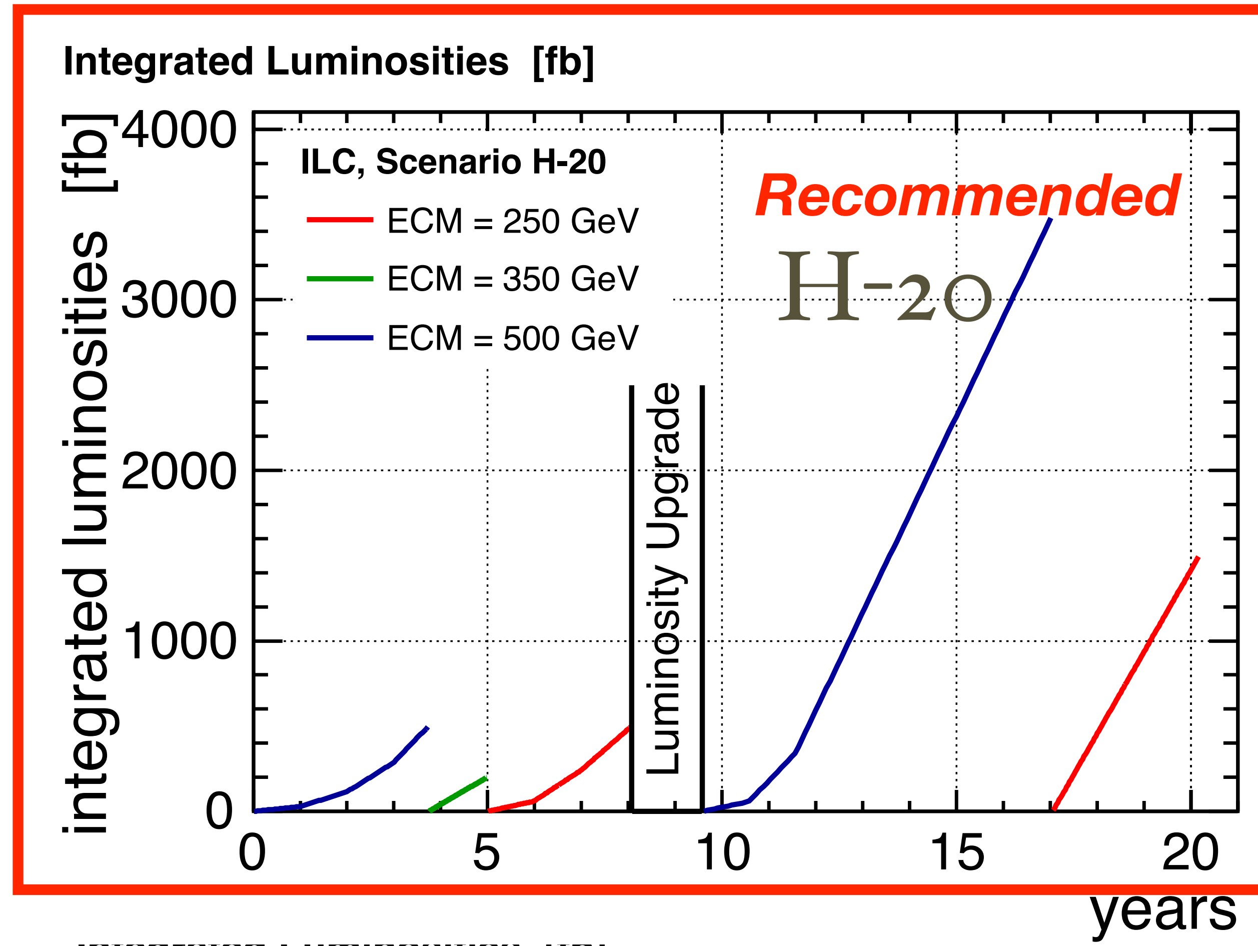
Beam polarization is essential to sort out various possibilities.

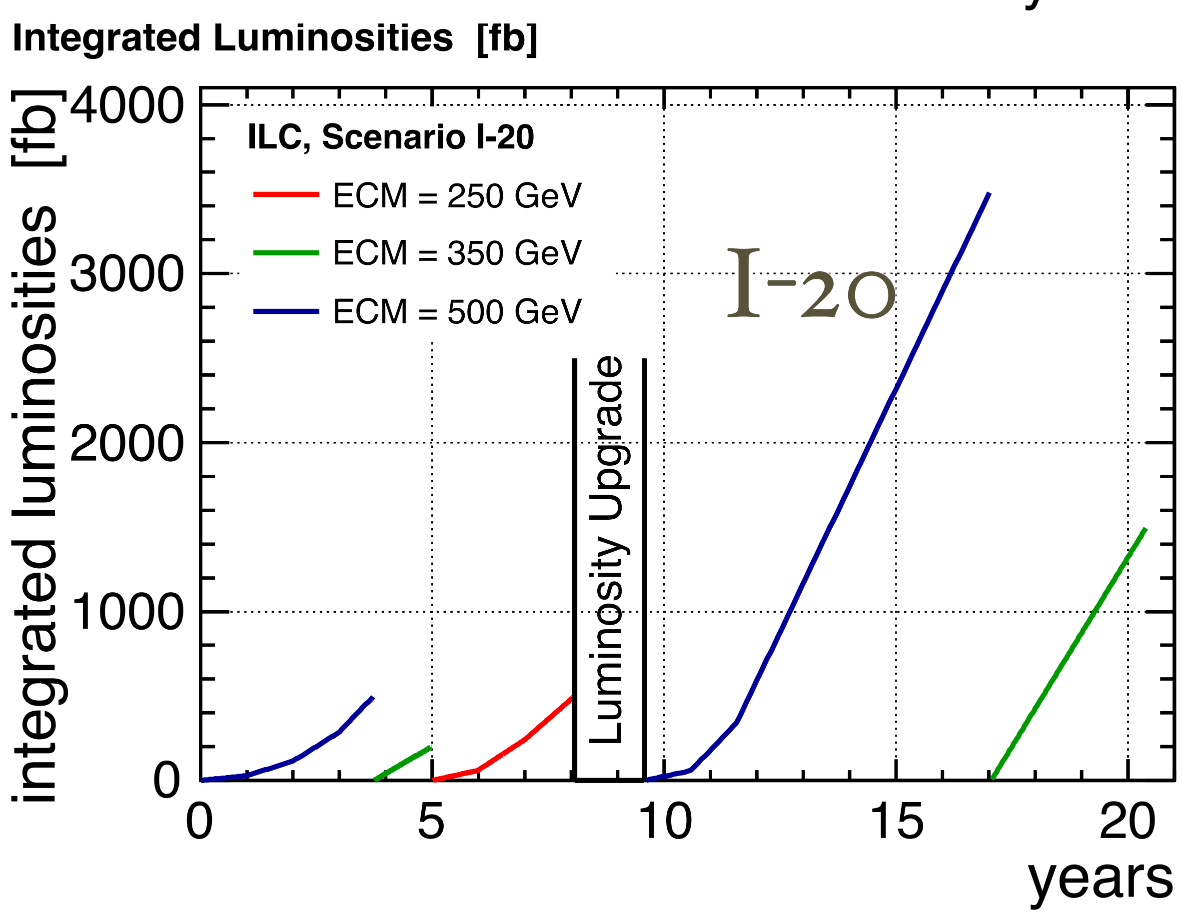
More Extra Slides

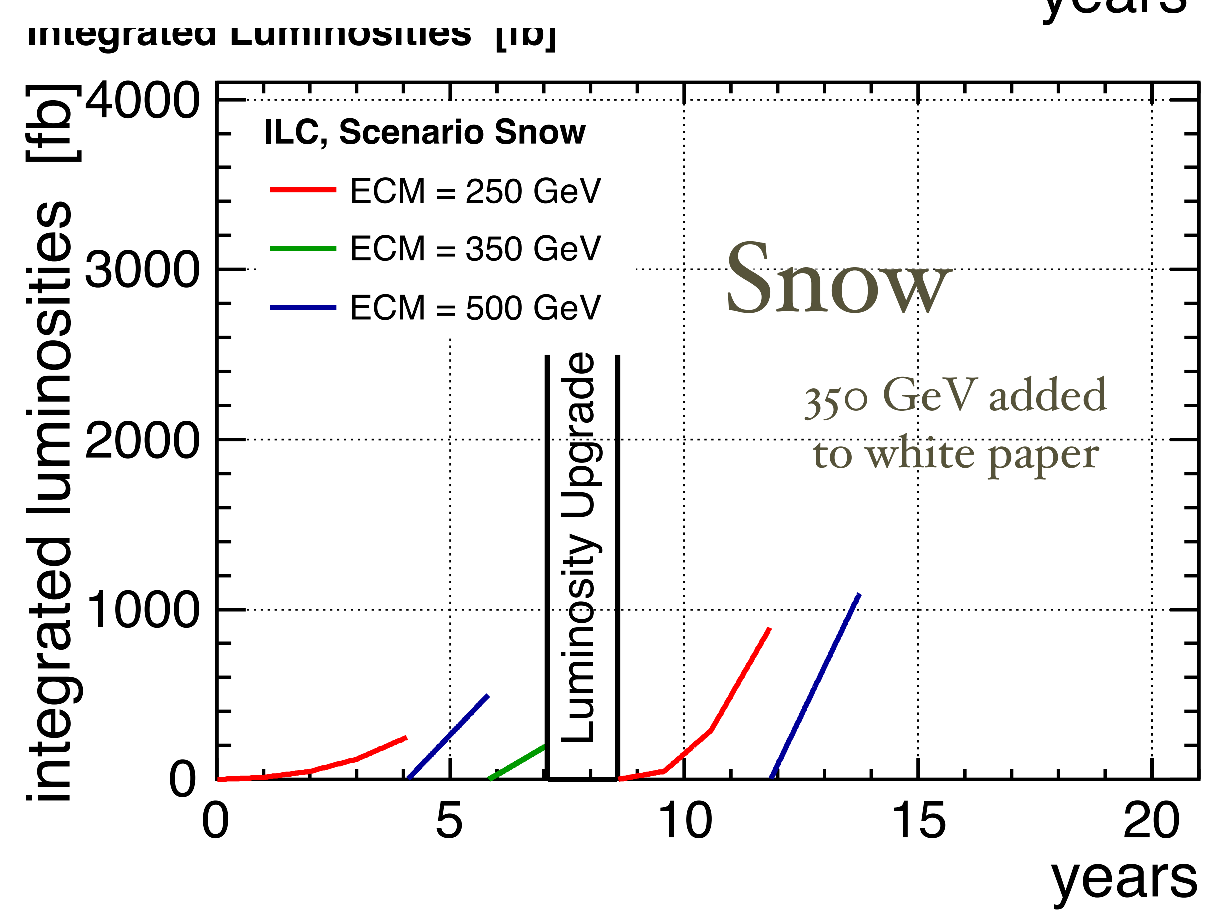
Running Scenario

See arXiv: 1506.07830


Integrated Luminosities [fb]
ILC, Scenario G-20
ECM = 250 GeV
ECM = 350 GeV
ECM = 500 GeV
G-20
Luminosity Upgrade
integrated luminosities [fb]
years


Integrated Luminosities [fb]
ILC, Scenario H-20
ECM = 250 GeV
ECM = 350 GeV
ECM = 500 GeV
Recommended
H-20
Luminosity Upgrade
integrated luminosities [fb]
years


Integrated Luminosities [fb]
ILC, Scenario I-20
ECM = 250 GeV
ECM = 350 GeV
ECM = 500 GeV
I-20
Luminosity Upgrade
integrated luminosities [fb]
years


ILC, Scenario Snow
ECM = 250 GeV
ECM = 350 GeV
ECM = 500 GeV
Snow
350 GeV added
to white paper
Luminosity Upgrade
integrated luminosities [fb]
years

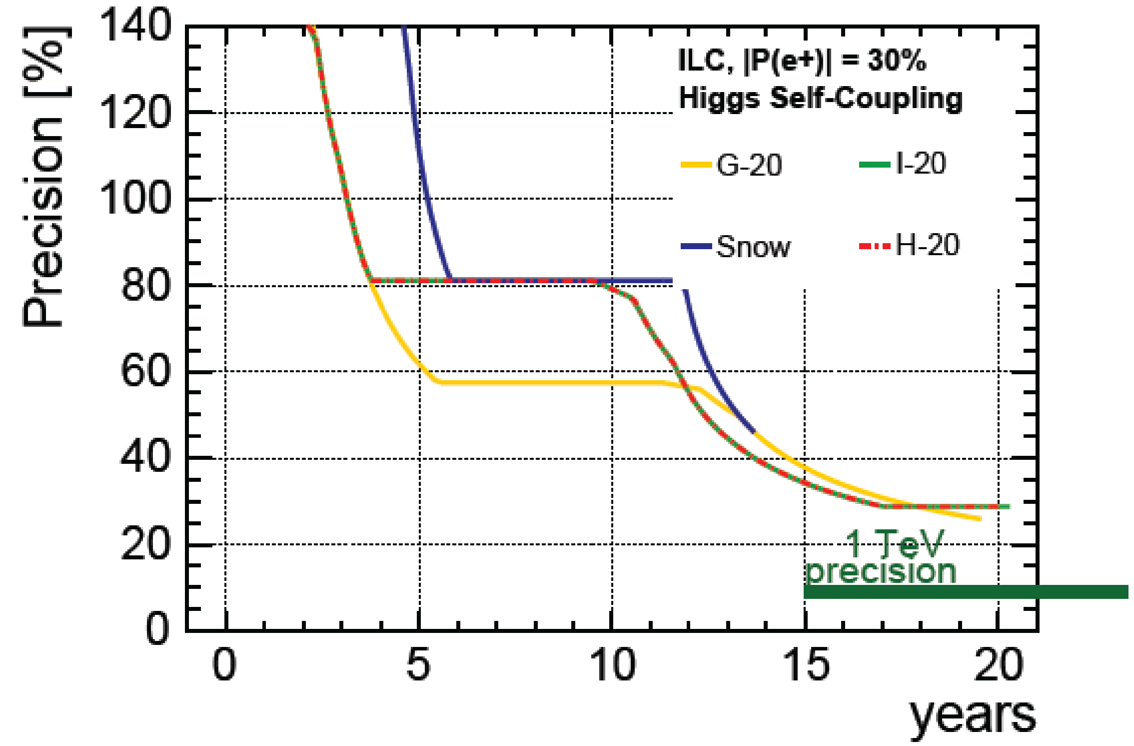
	Stage	500			500 LumiUP		
Scenario	$\sqrt{s}$ [GeV]	500	350	250	500	350	250
G-20	$\int \mathcal{L} dt$ [fb^{-1}]	1000	200	500	4000	-	-
	time [years]	5.5	1.3	3.1	8.3	-	-
H-20	$\int \mathcal{L} dt$ [fb^{-1}]	500	200	500	3500	-	1500
	time [years]	3.7	1.3	3.1	7.5	-	3.1
I-20	$\int \mathcal{L} dt$ [fb^{-1}]	500	200	500	3500	1500	-
	time [years]	3.7	1.3	3.1	7.5	3.4	-

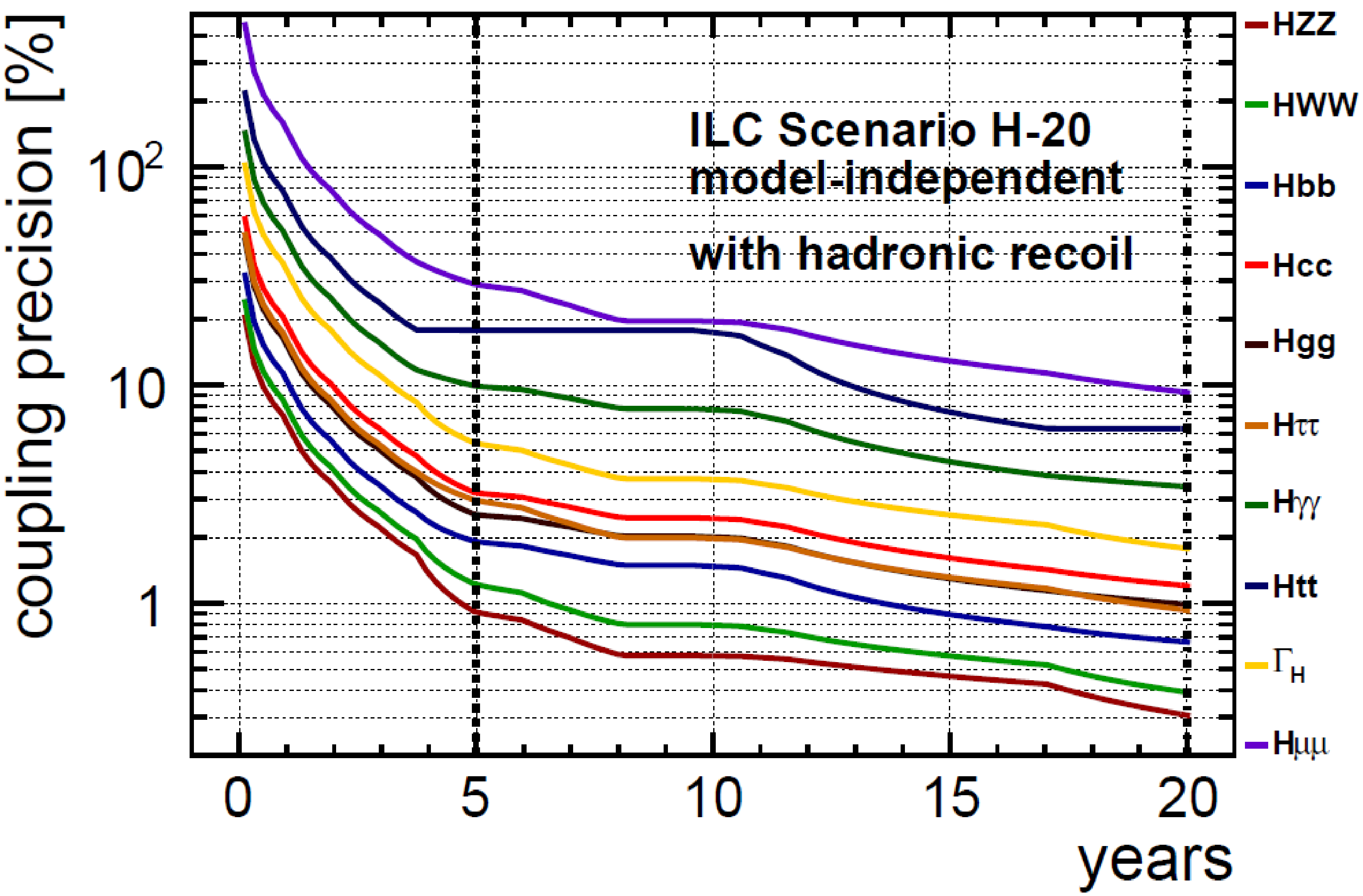
	Stage	500			500 LumiUP		
Scenario	$\sqrt{s}$ [GeV]	250	500	350	250	350	500
Snow	$\int \mathcal{L} dt$ [fb^{-1}]	250	500	200	900	-	1100
	time [years]	4.1	1.8	1.3	3.3	-	1.9

Higgs Measurements

H-20

	first phase	lumi upgrade	total
250 GeV	500 fb^{-1}	1500 fb^{-1}	2 ab^{-1}
350 GeV	200 fb^{-1}		0.2 ab^{-1}
500 GeV	500 fb^{-1}	3500 fb^{-1}	4 ab^{-1}
time	8.1 yrs	10.6 yrs	20.2 yrs*





Self-coupling reaches <30% for SM case.
<15% if lamda=2xSM

ILC parameter WG report *Jim BRAU*

Most couplings reach <1%