JCL2016 March 24, 2016

(I)LC Physics Case

Keisuke Fujii

KEK

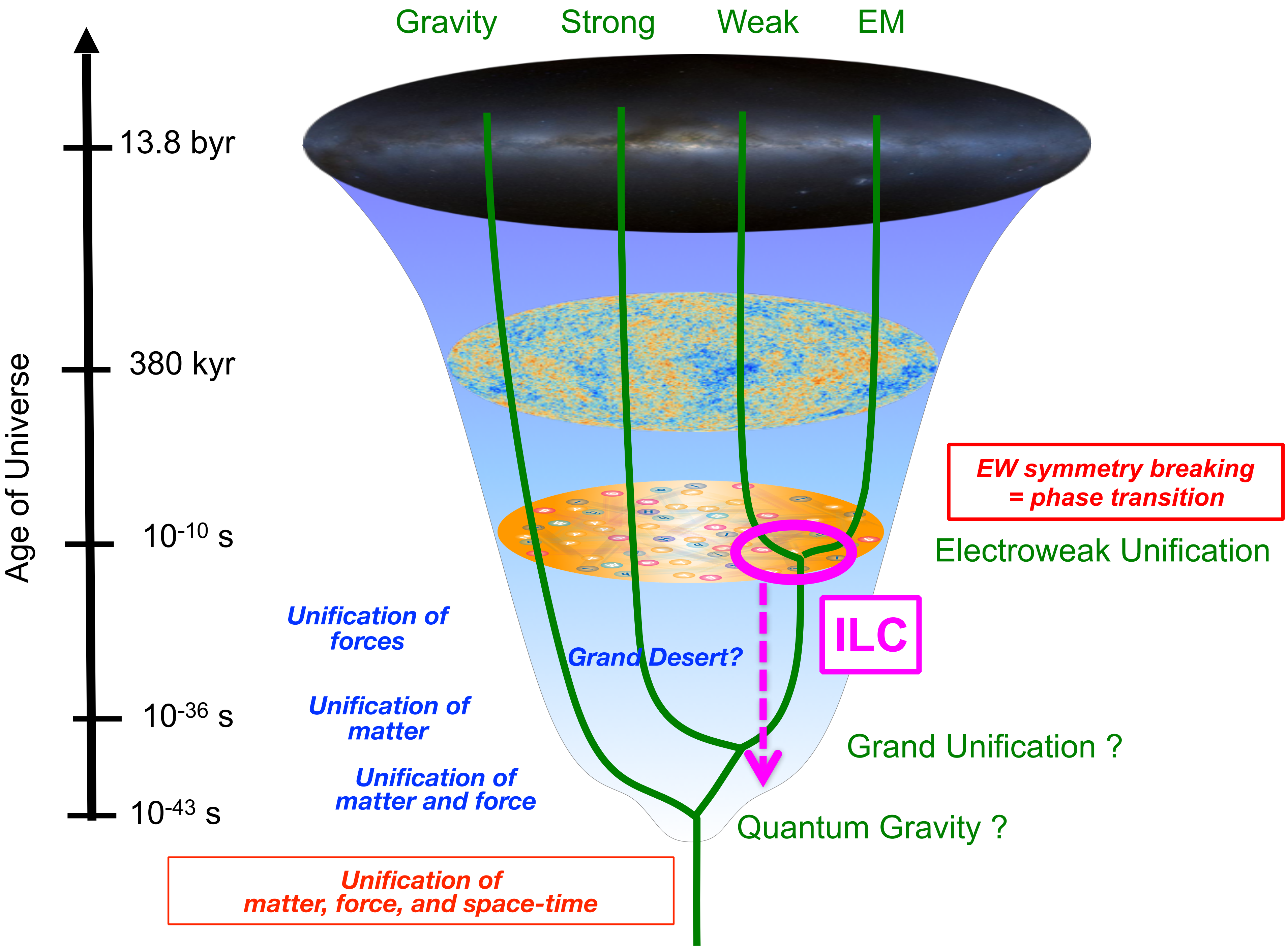
arXiv: 1506.05992 (ILC Physics Case)

arXiv: 1506.07830 (ILC Run Scenarios)

arXiv: 1306.6352 (ILC TDR: Physics)

EPJC (2015) 75:371 (LC Physics)

Towards ultimate unification

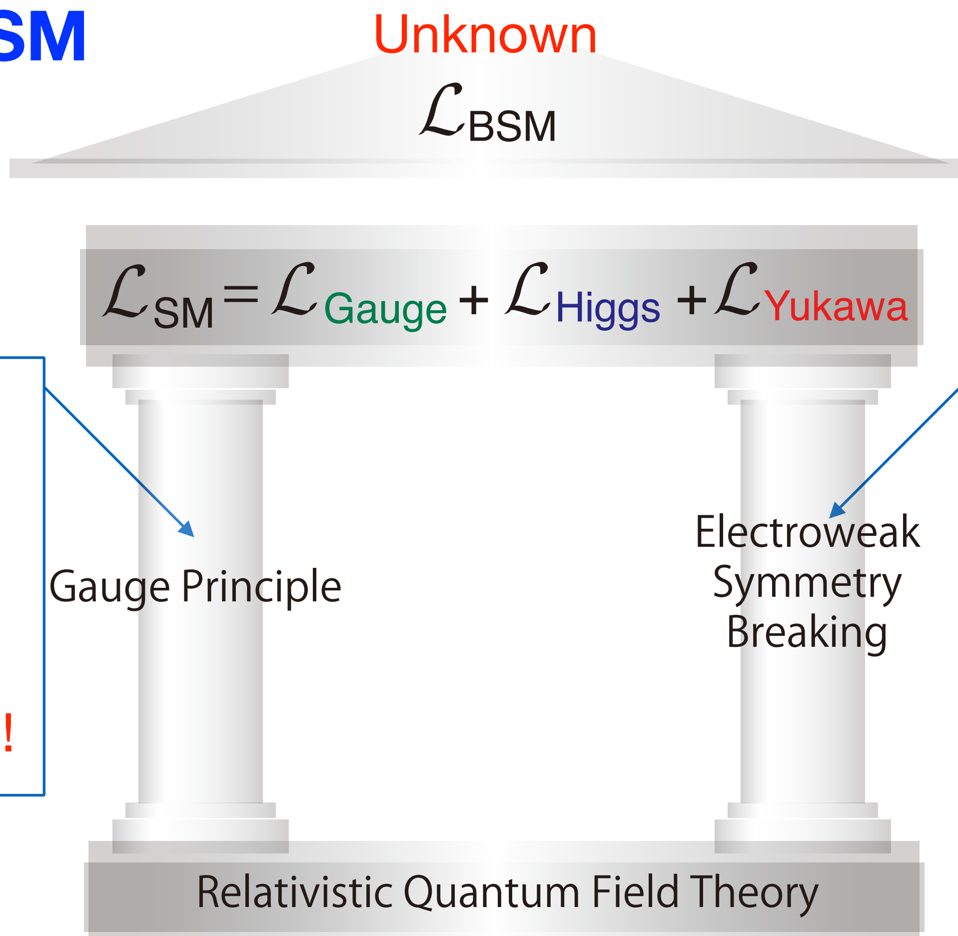


Why is the EW scale so important ?

Why is the EW scale so important?

Mystery of something in the vacuum

2 Pillars of SM

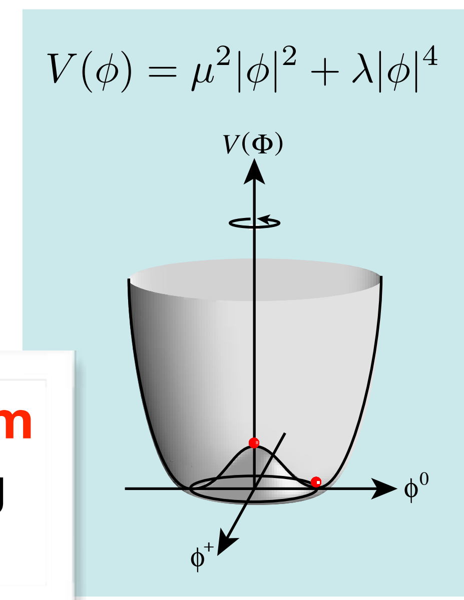


Success of SM
= success of
gauge theory
(left pillar)

Precisely tested!

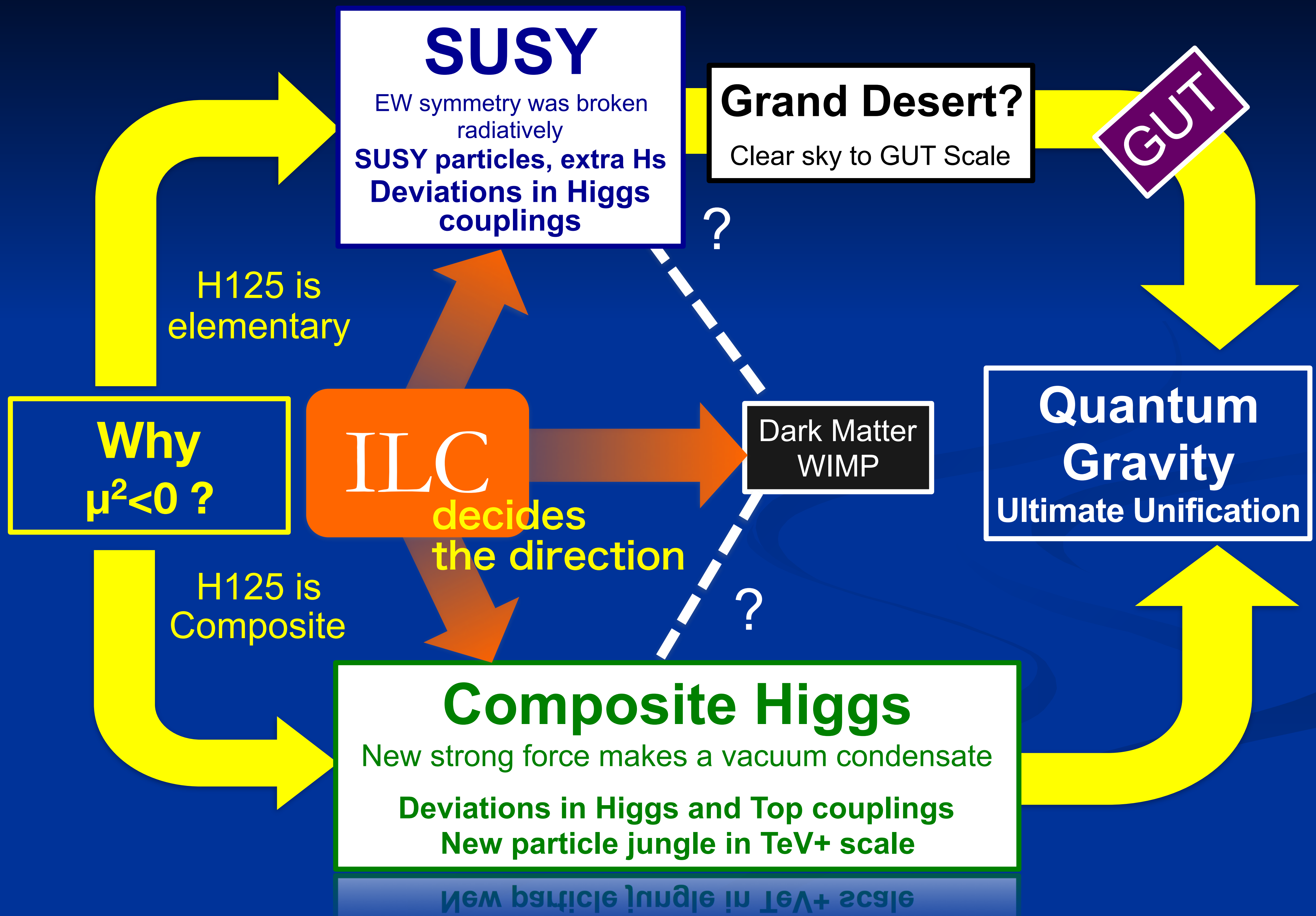
Vacuum filled with weak charge (evidence: H125)

The nature of the Higgs field - its multiplet structure & dynamics behind it - is all unknown!



The SM does not explain **why the Higgs field developed a vacuum expectation value** (***Why $\mu^2 < 0$?***)**! The answer forks depending on whether H125 is elementary or composite!**

Big Branching Point at the EW Scale

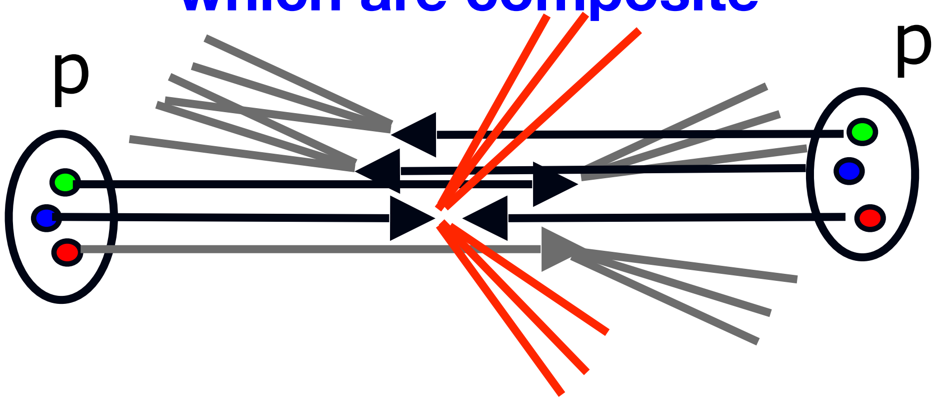


The 3 major probes for BSM at ILC:

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

3 Powerful Tools

LHC: Collision of protons which are composite

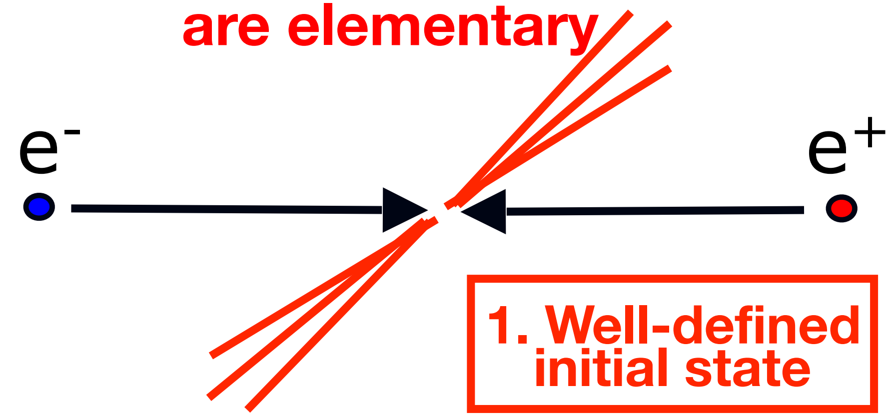


Ecm 7-14 TeV

Pileup

Initial state not very well defined

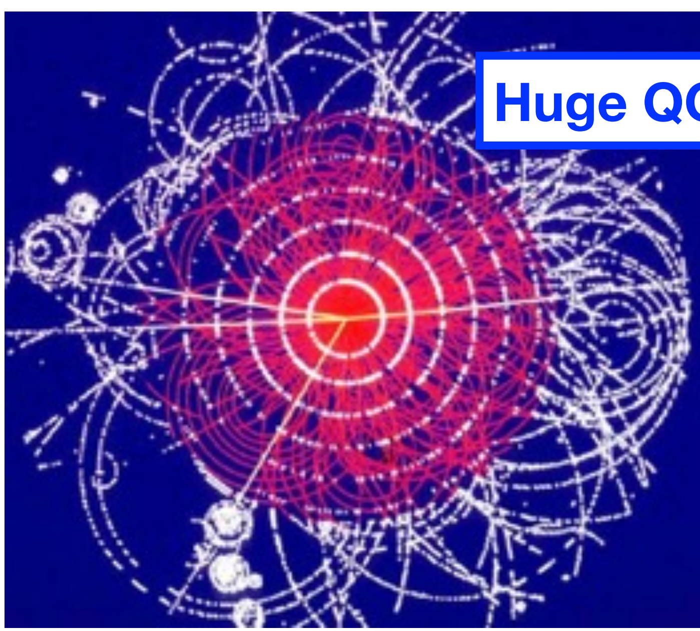
ILC: Collision of e+e- which are elementary



1. Well-defined initial state

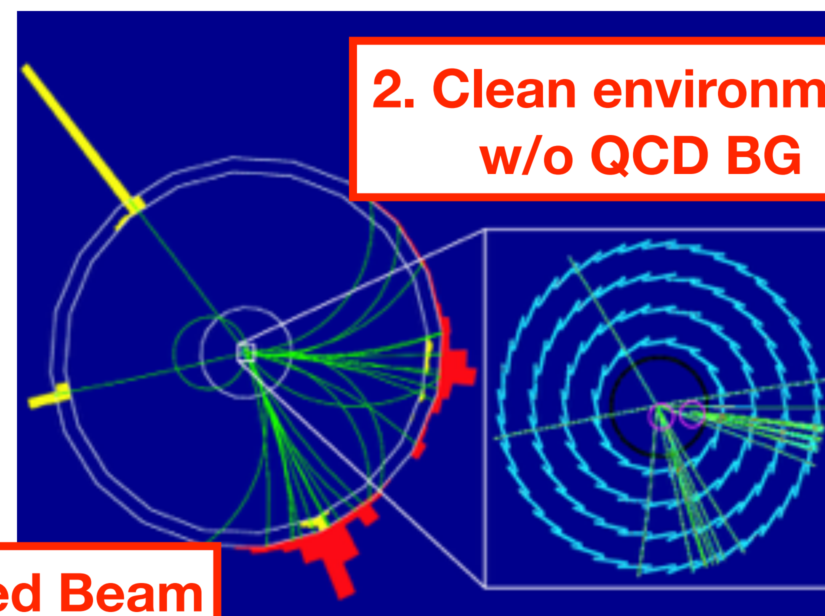
Ecm 0.25-1 TeV

Lab. frame = CM frame



Huge QCD BG

proton is composite ⇒ events are complicated but maximum reachable energy is high.!



2. Clean environment w/o QCD BG

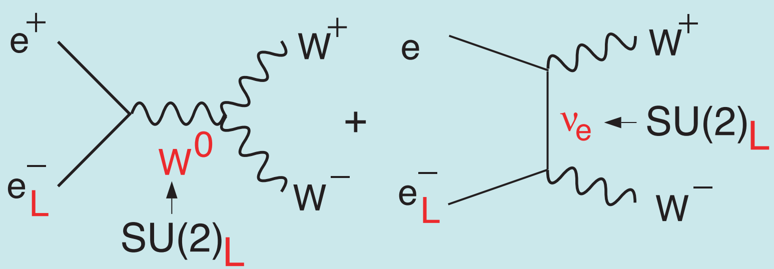
3. Polarized Beam

clean and and able to detect everything produced!

Power of Beam Polarization

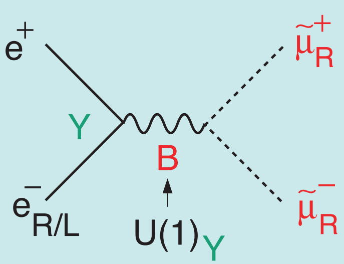
BG Suppression

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



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

Slepton Pair



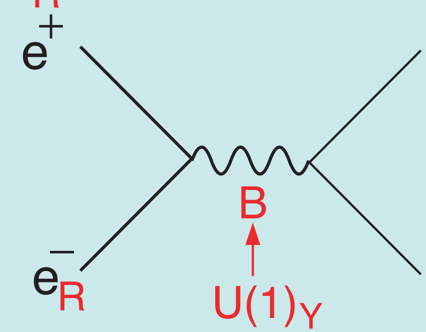
$Y_L = -1/2 : e^-_L$

$Y_R = -1 : e^-_R$

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

Chargino Pair

e^-_R Beam



Only $\tilde{H}^{\pm}$ components in $\tilde{\chi}^{\pm}_1$ contribute !

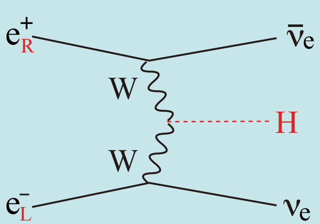
cf.) $e^+e^- \to W^+W^-$

$$\tilde{\chi}^{\pm}_1 = \bigcirc \cdot \tilde{W}^{\pm} + \bullet \cdot \tilde{H}^{\pm}$$

$$\bullet = \langle \tilde{H}^{\pm} | \tilde{\chi}^{\pm}_1 \rangle$$

Decomposition

WW-fusion Higgs Prod.

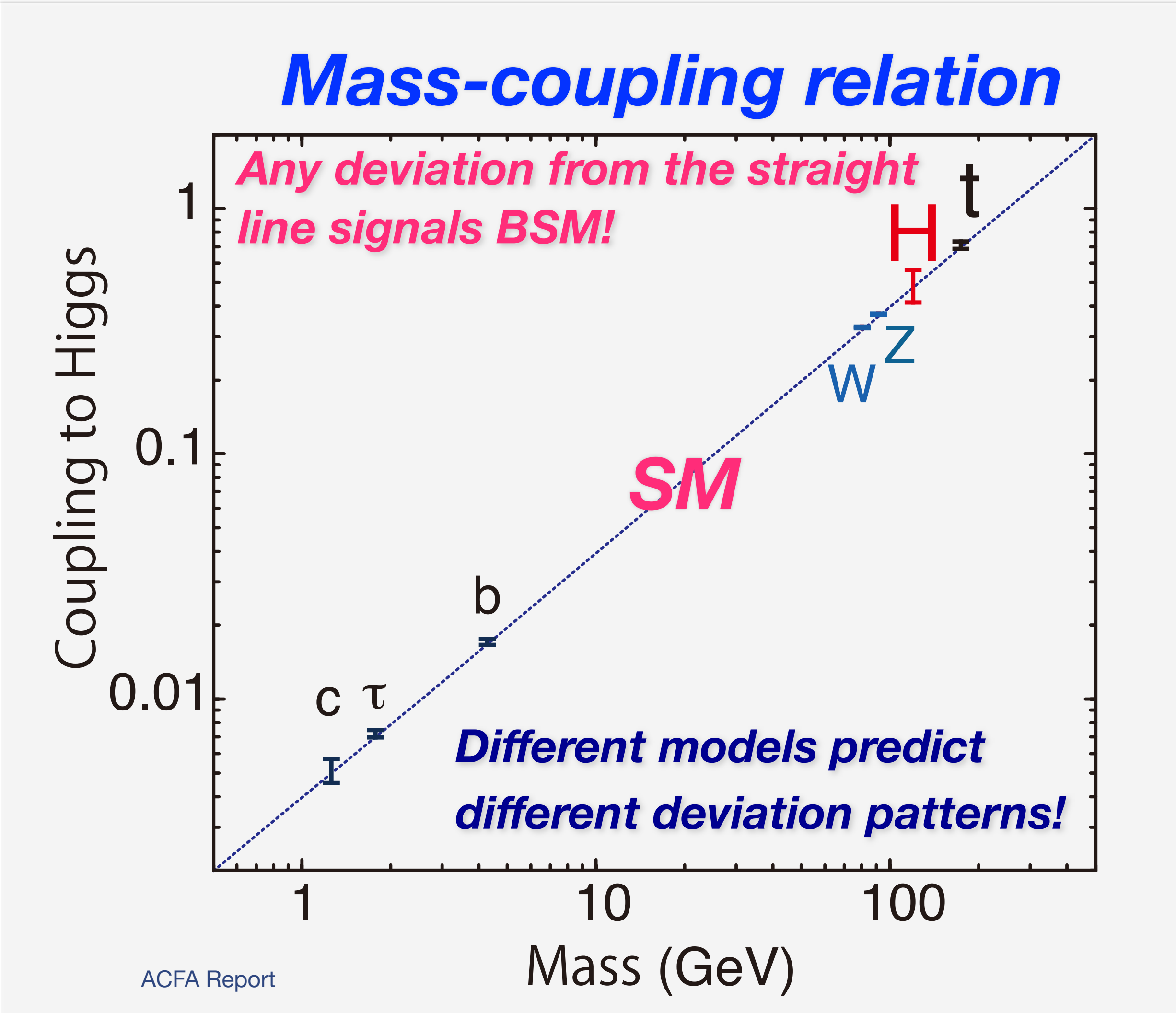


	ILC
Pol (e-)	-0.8
Pol (e+)	+0.3
$(\sigma/\sigma_0)_{\nu\nu H}$	1.8x1.3=2.34

Signal Enhancement

Higgs

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**

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

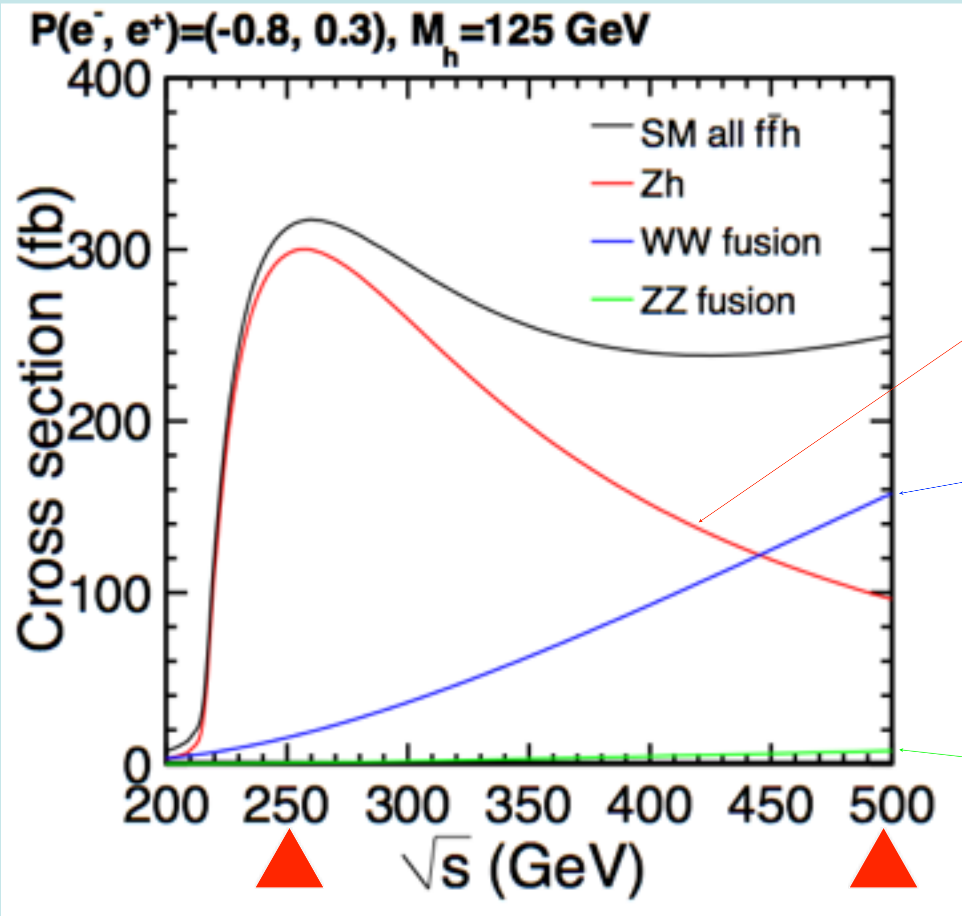
composite scale

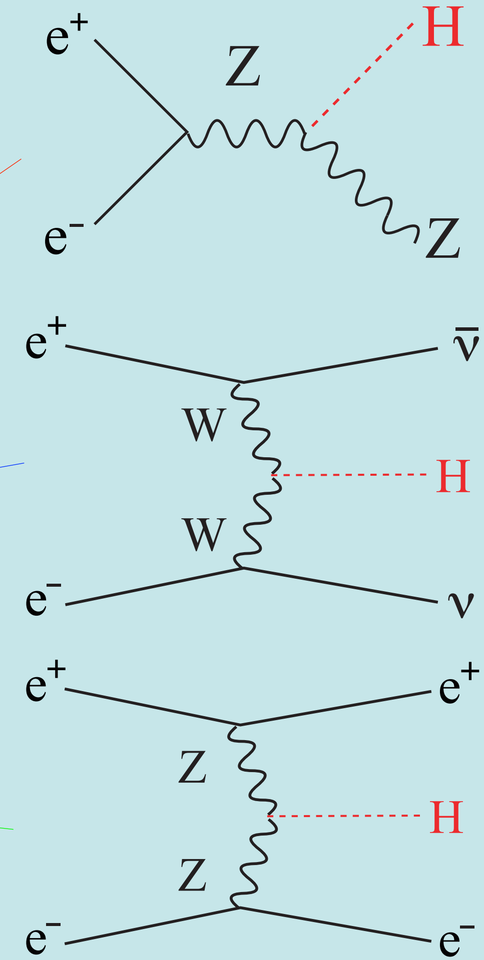
New physics at 1 TeV → **deviation is at most ~10%**
We ***need a %-level precision*** → LHC is not enough → ***ILC***

Main Production Processes

Single Higgs Production

Production cross section





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

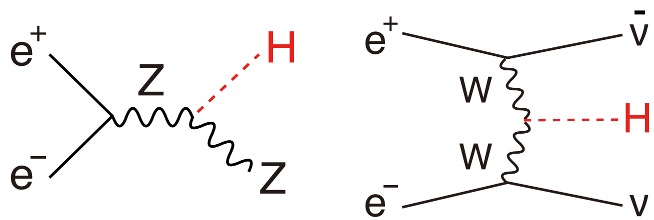
vvH takes over at 500 GeV
(~125k ev: 500 fb^{-1})

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

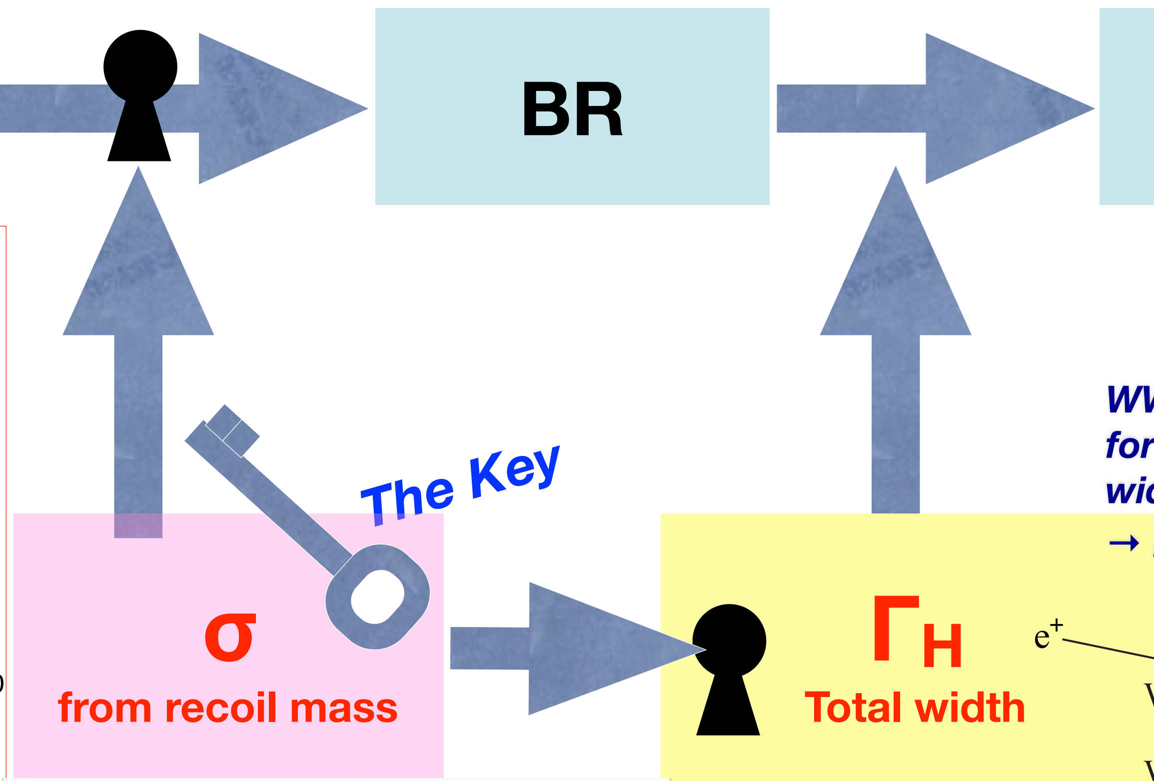
Key Point

At LHC all the measurements are σ×BR measurements.

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

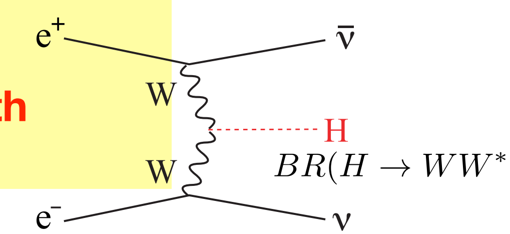


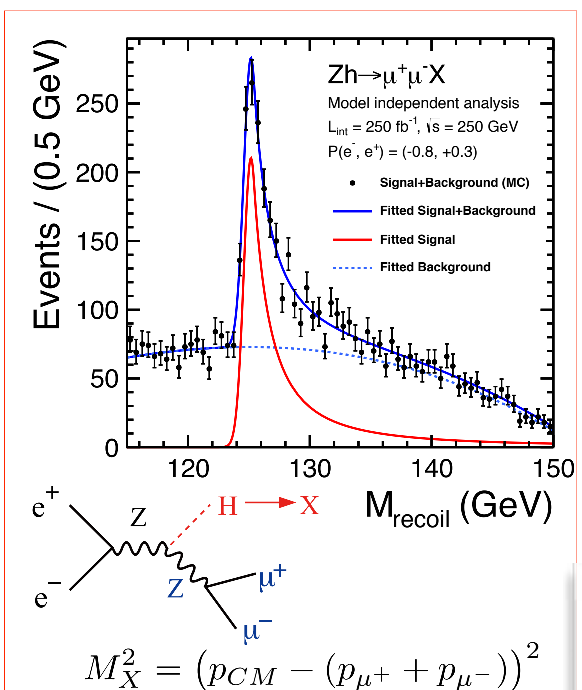
$$g_{HAA}^2 \propto \Gamma(H \to AA) = \Gamma_H \cdot BR(H \to AA)$$



WW-fusion is crucial for precision total width measurement

→ Ecm > 350GeV





Can detect even if Higgs decays invisibly!

Higgs Couplings

***Model-independent* coupling fit, impossible at LHC**

H20 Scenario

arXiv: 1506.05992
arXiv: 1506.07830

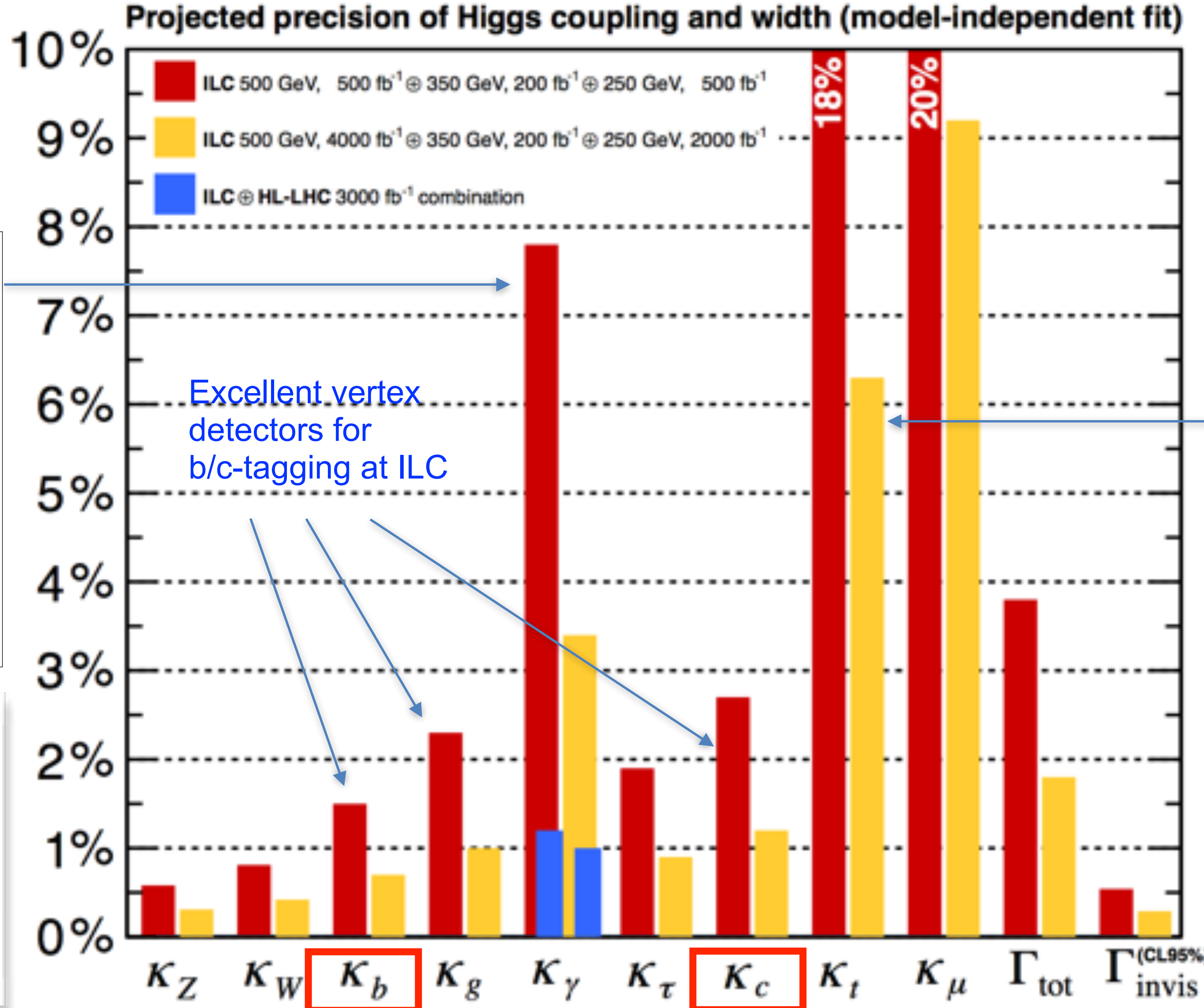
Better $h\gamma\gamma$ with LHC/ILC synergy

LHC can precisely measure

$BR(h \to \gamma\gamma) / BR(h \to ZZ^*)$ $= (\kappa_\gamma / \kappa_Z)^2$

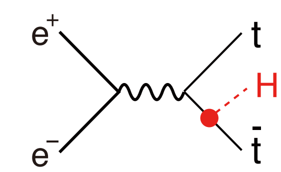
ILC can precisely measure κ_Z

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



Excellent vertex detectors for b/c-tagging at ILC

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 κ_t, κ_μ, and κ_γ

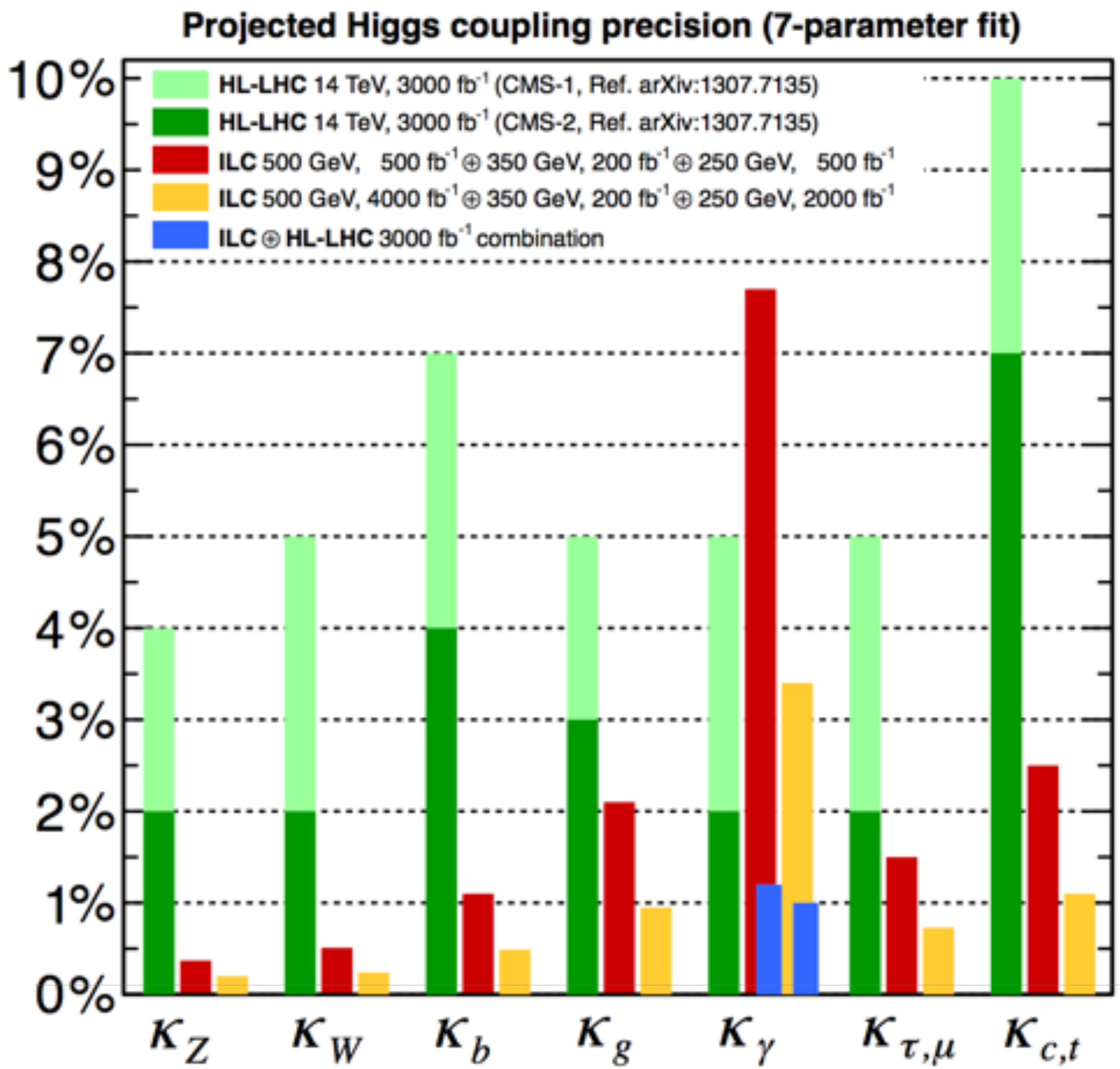
~1% or better for most couplings!

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

H20 Scenario

arXiv: 1506.05992
arXiv: 1506.07830

Σ_{SM} **BR = 1**



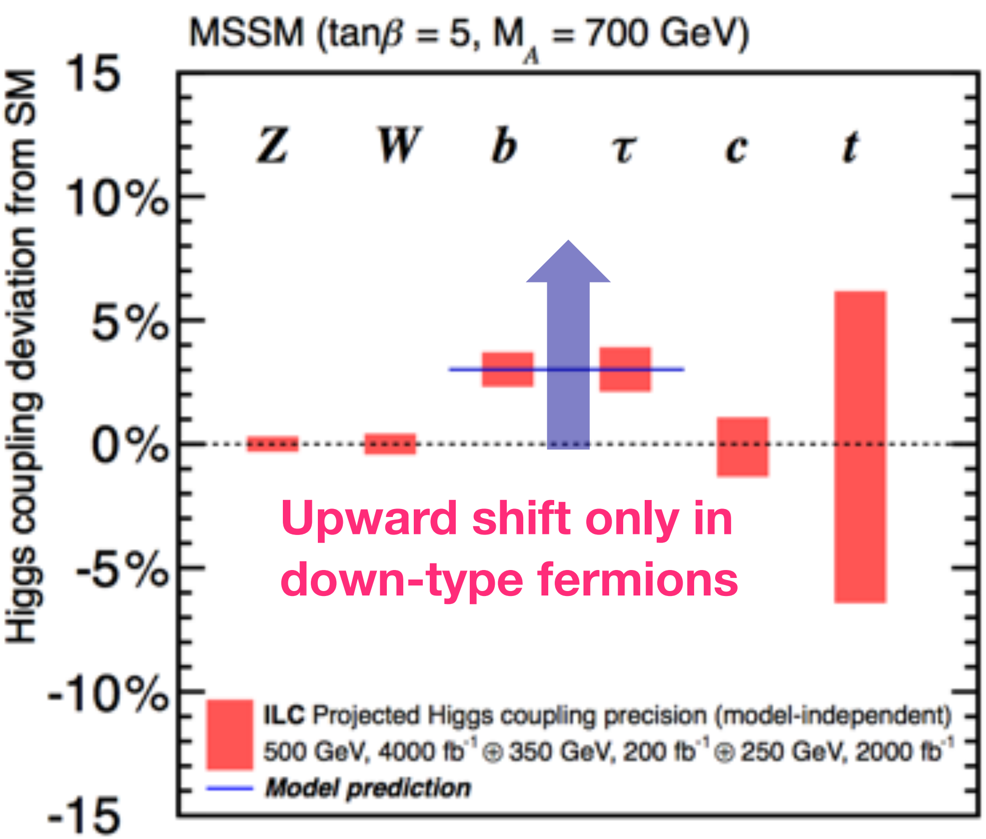
Possible to achieve precision far exceeding LHC!

H20 Scenario
arXiv: 1506.05992
arXiv: 1506.07830

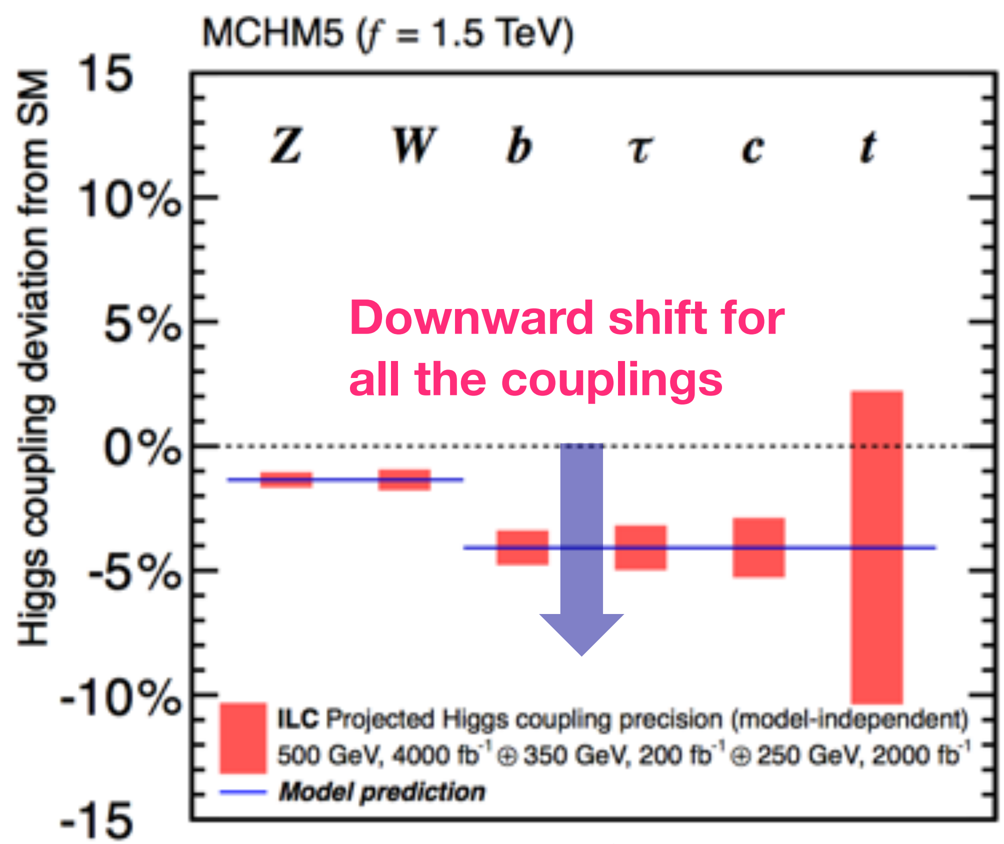
Fingerprinting

Elementary v.s. Composite?

Supersymmetry
(MSSM)



Composite Higgs
(MCHM5)



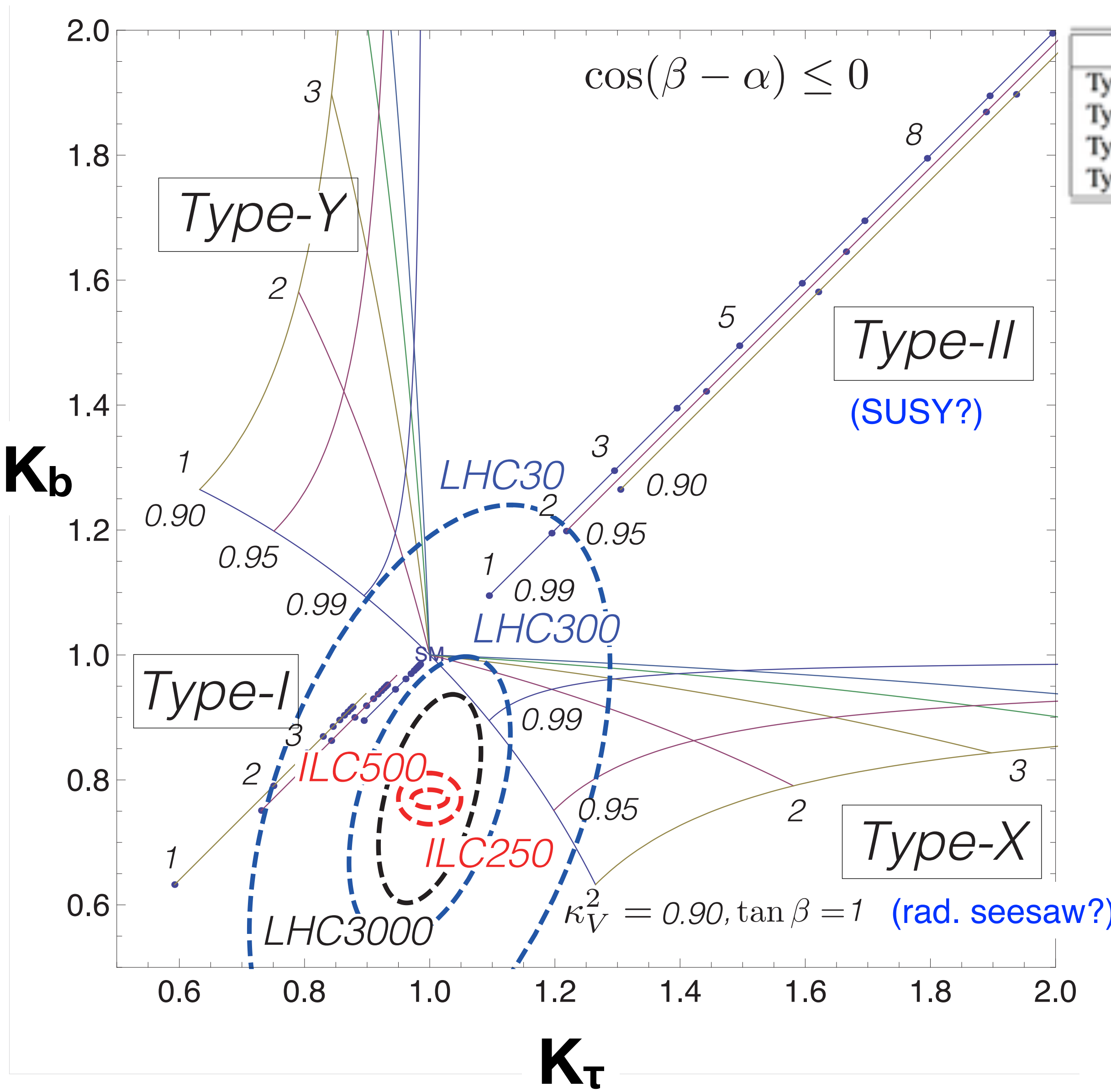
ILC 250+500 LumiUP

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

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

*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)

arXiv 1502.03959

Footprints of Supersymmetry on Higgs Decay

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

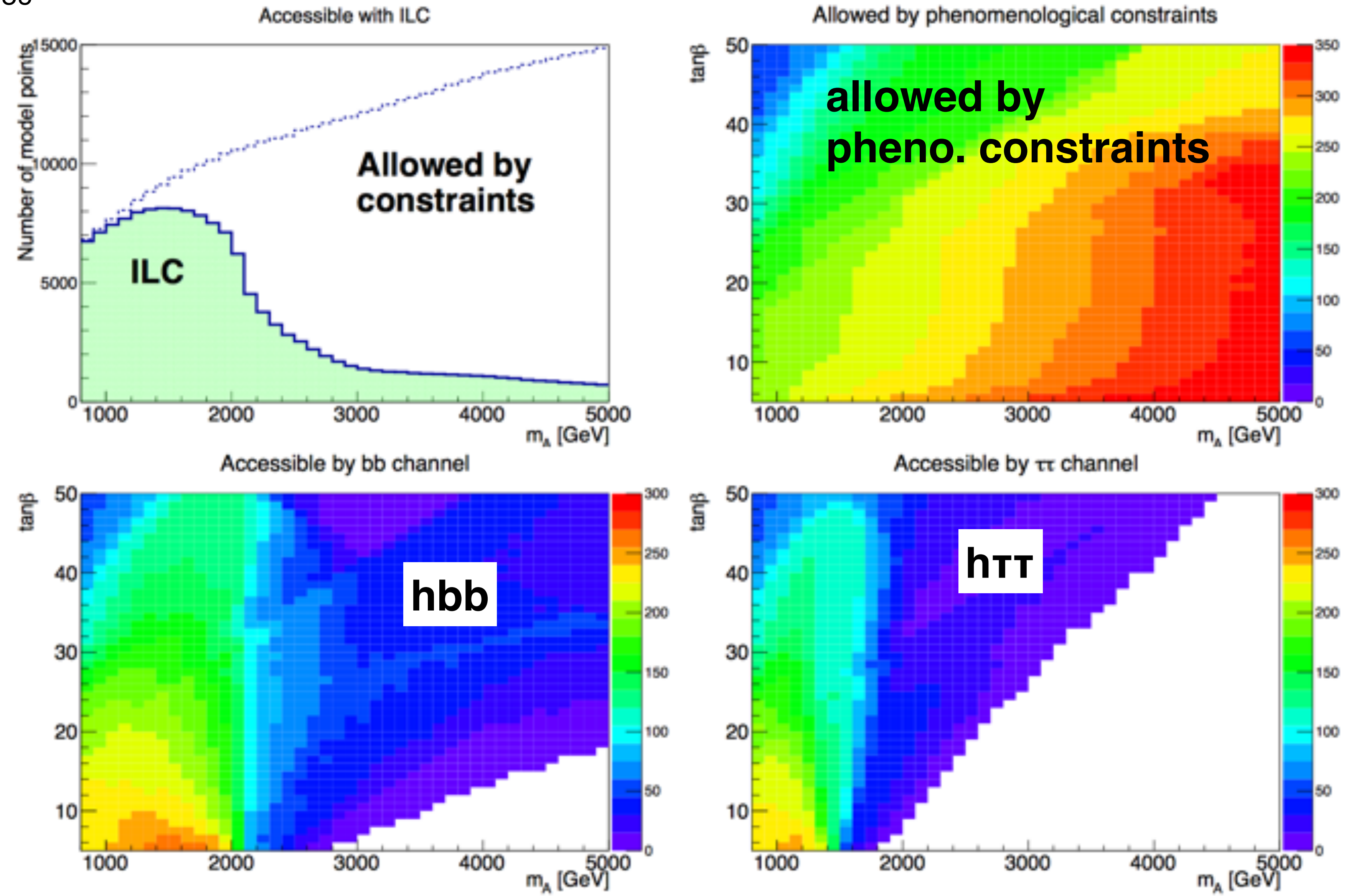


Figure 8: Upper-left: The number of model points accessible with ILC by at least one decay mode of h as a function of m_A (green histogram), as well as that of model points allowed by the phenomenological constraints (dotted histogram). Upper-right: The number of model points allowed by the phenomenological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

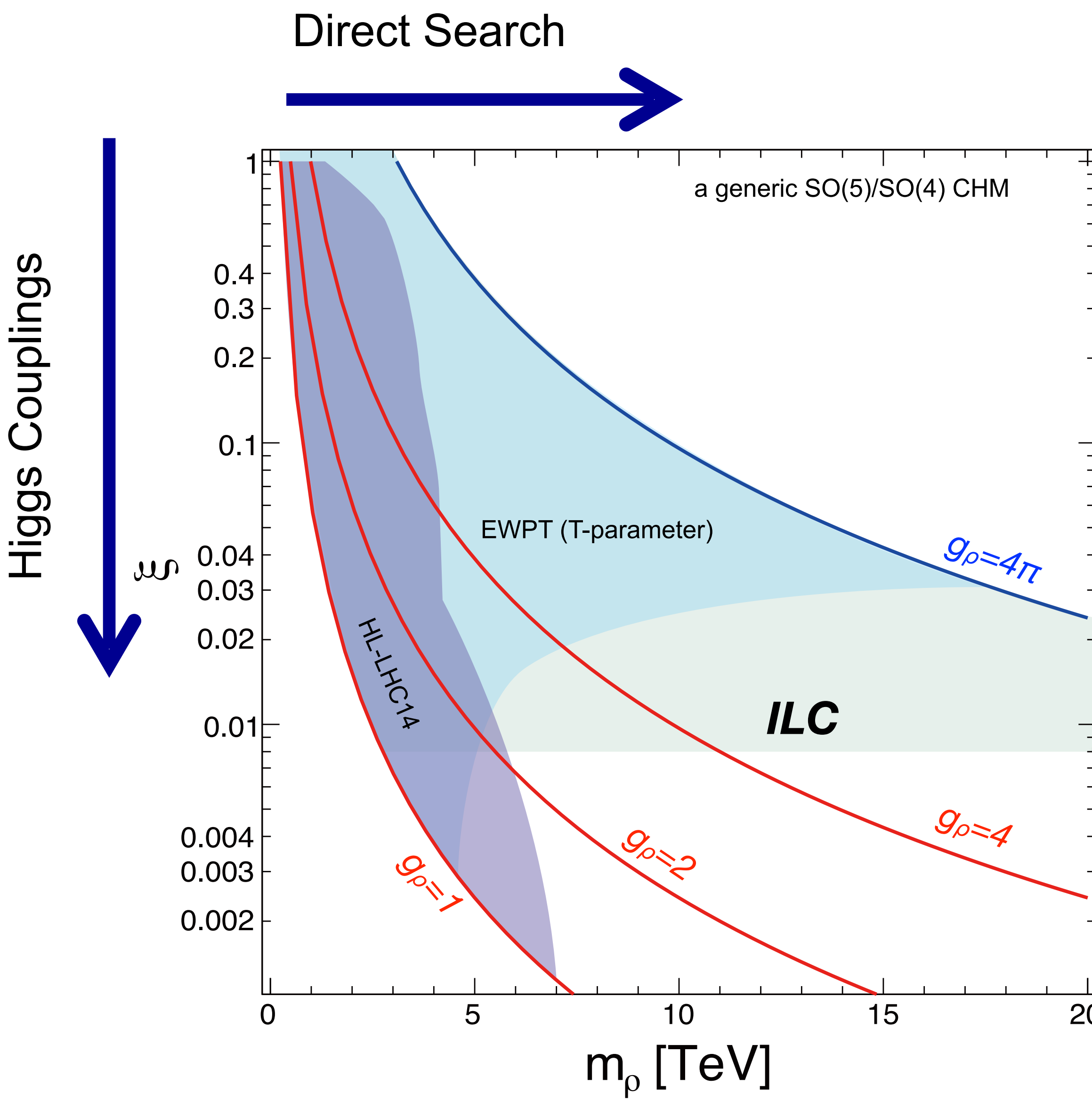
Composite Higgs: Reach

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_*)

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



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

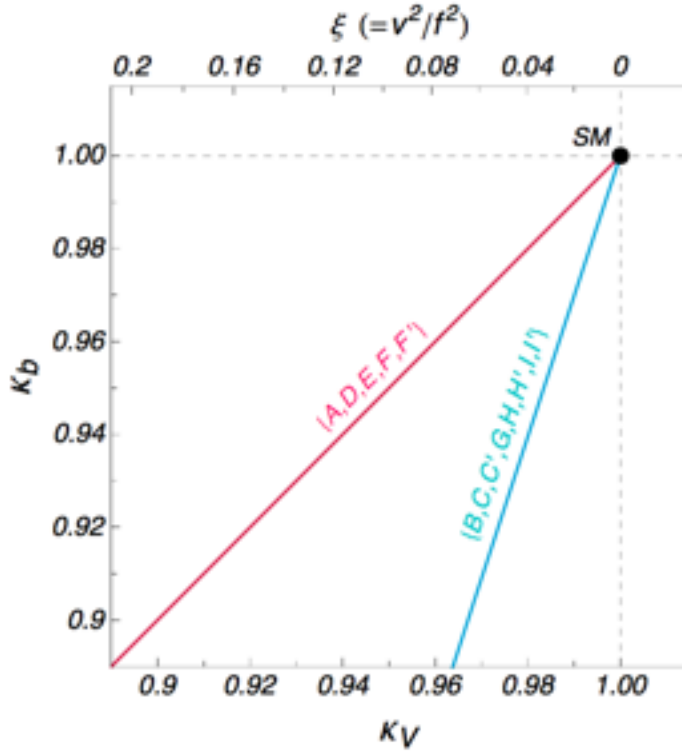
$$\frac{g_{hVV}}{g_{h_{SM}VV}} = \sqrt{1 - \xi}$$

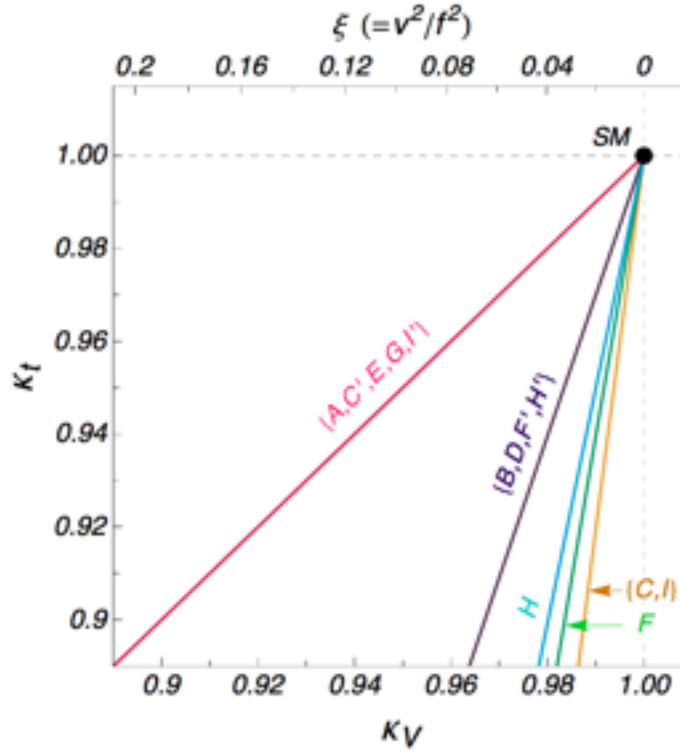
ILC (250+500 LumiUP)

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

New resonance scale and fingerprint identification in minimal composite Higgs models

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





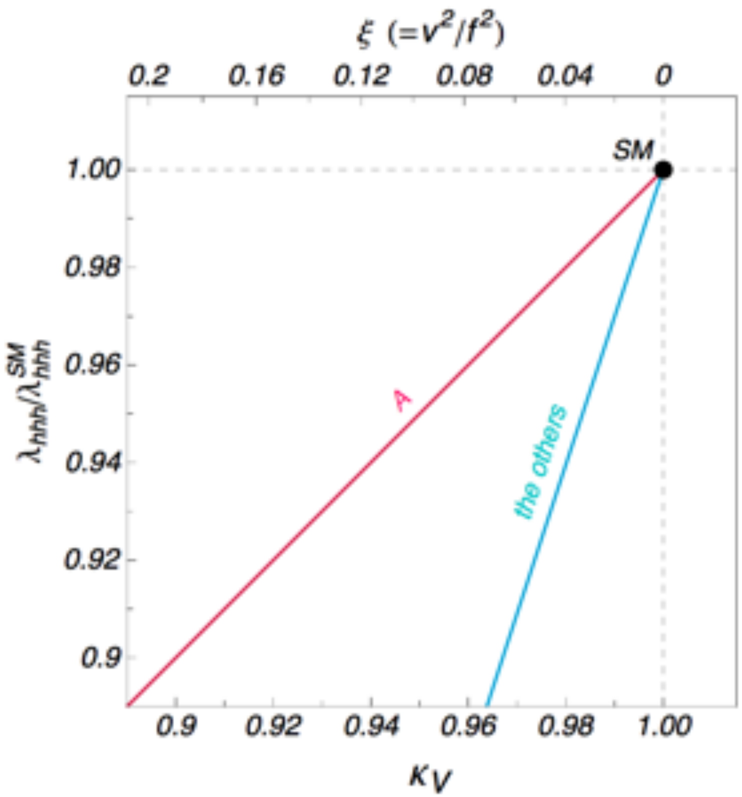


TABLE I: Scale factors for MCHMs with various matter representations. The labels are used in Fig. 7, where C, H and I are the case of $M_1^t \to 0$, and C', H' and I' are the case of $M_2^t \to 0$.

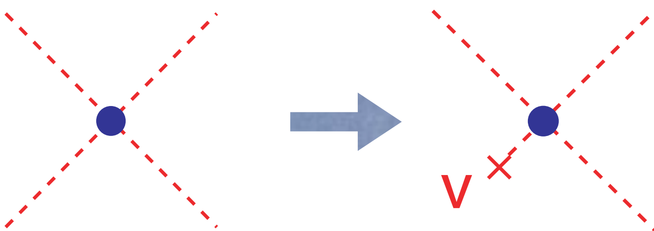
Label	Model	κ_V	c_{hhVV}	κ_{hhh}	c_{hhhh}	κ_t	κ_b	c_{hhtt}	c_{hhbb}
A	MCHM_4	$\sqrt{1-\xi}$	$1-2\xi$	$\sqrt{1-\xi}$	$1-\frac{7}{3}\xi$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$	$-\xi$	$-\xi$
B	MCHM_5	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$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

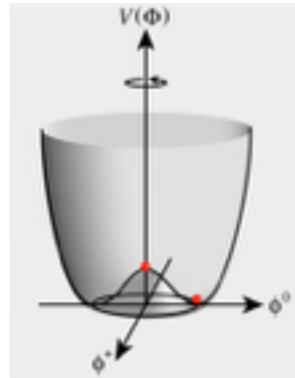
arXiv 1410.8413

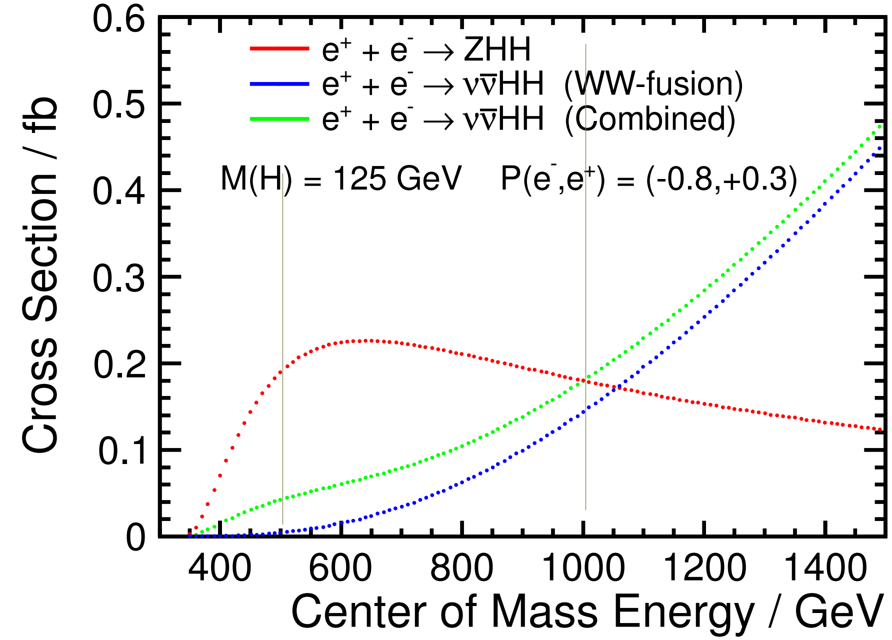
EW Phase Transition
1st order
or
2nd order ?

Higgs Self-Coupling

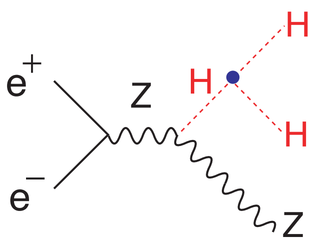
The ***Higgs 3-point self-coupling*** is at the heart of EWSB!

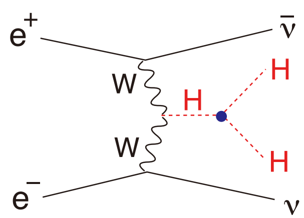






There are ***two ways to measure it*** at ILC





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

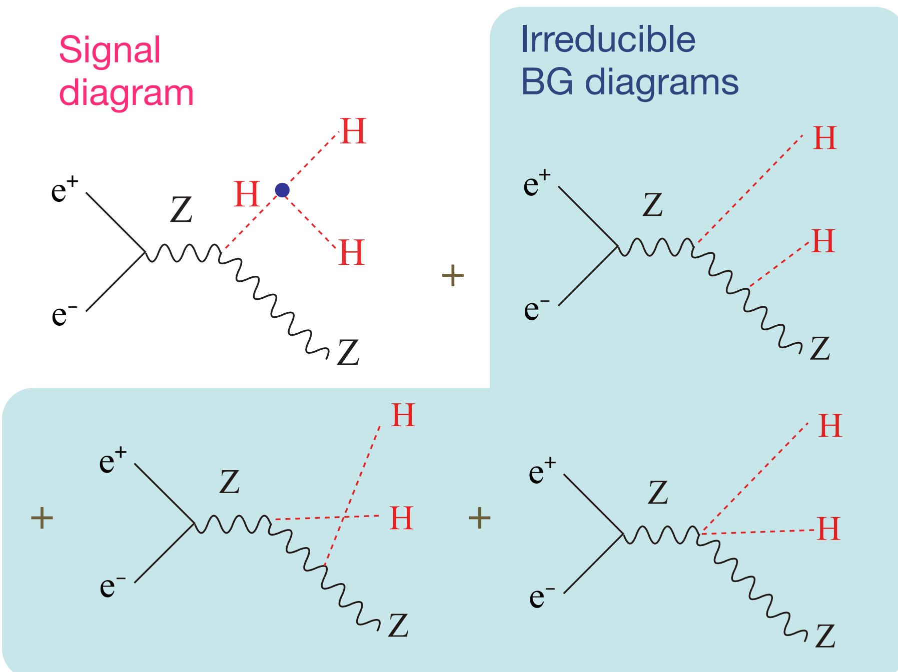
- Small cross section
- ***Presence of irreducible BG diagrams***

CLIC (arXiv: 1307.5288)

1.4 TeV (1.5 ab^{-1})	+3 TeV (2 ab^{-1})
21%	10%

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

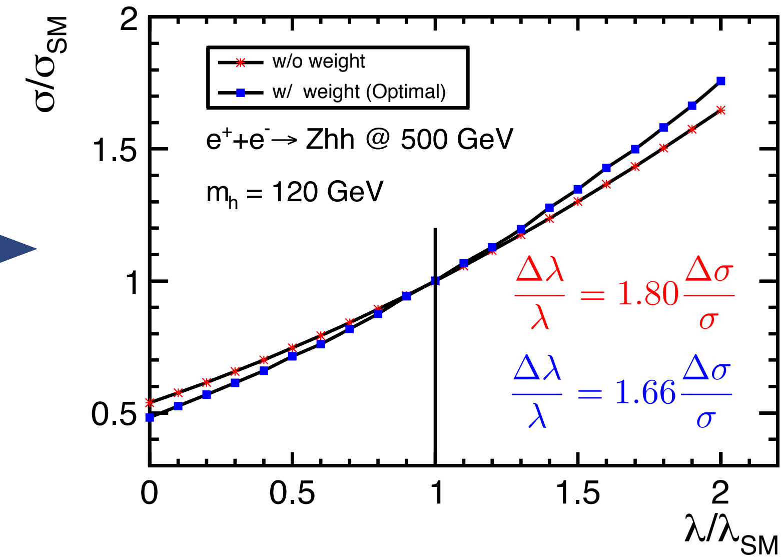
The Problem : BG diagrams dilute self-coupling contribution

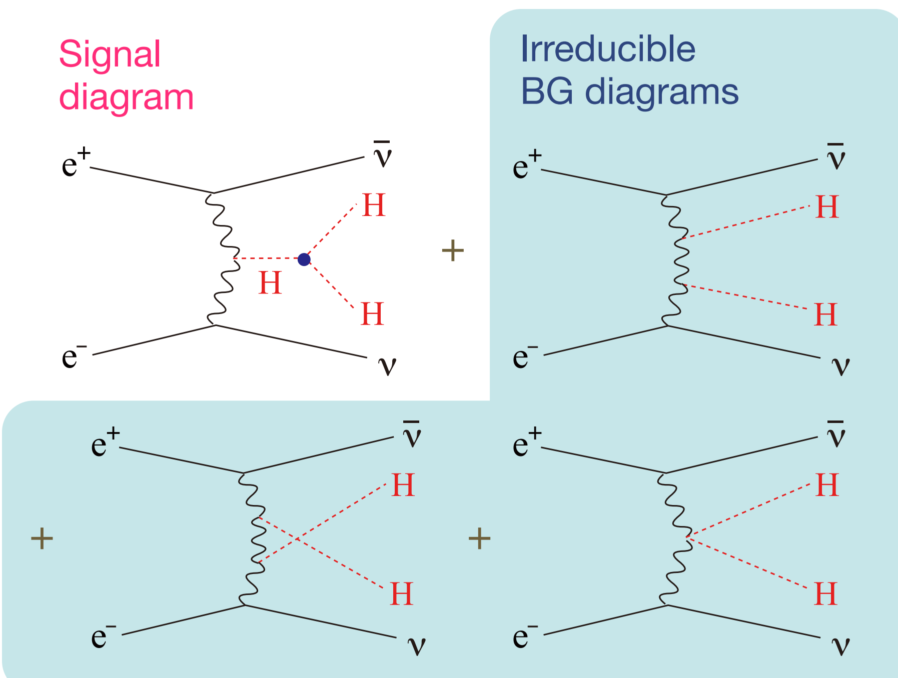


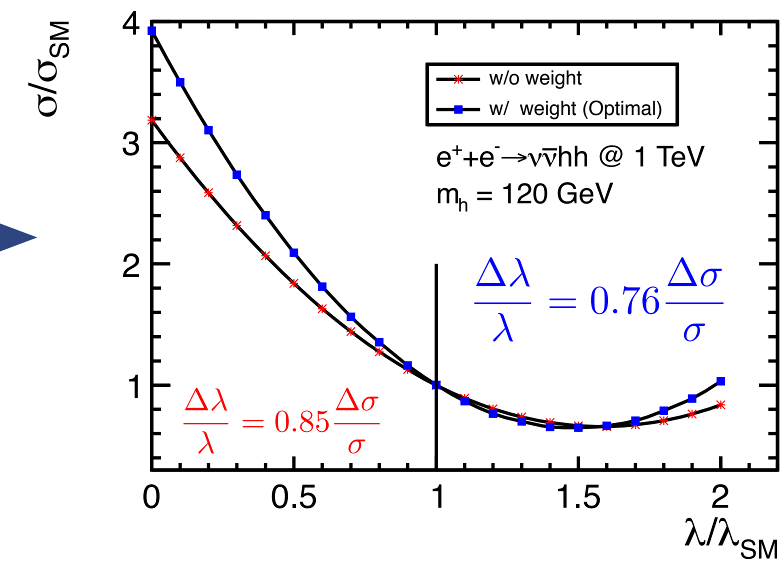
$$\sigma = \lambda^2 S + \lambda I + B$$

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

F=0.5 if no BG diagrams

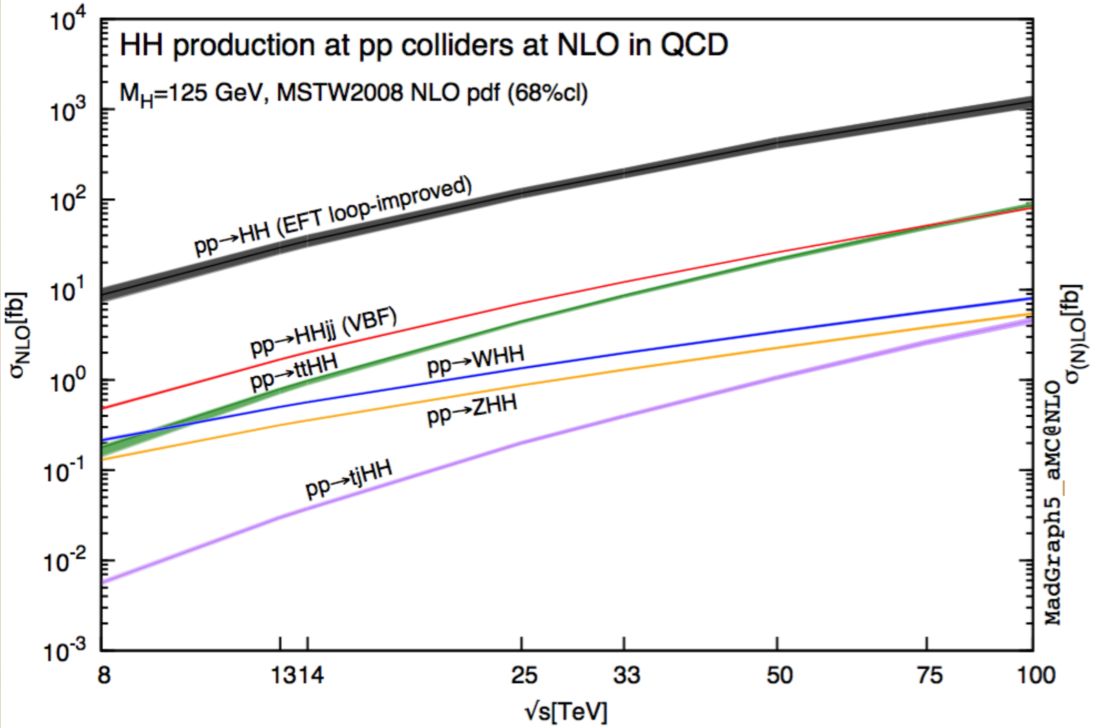


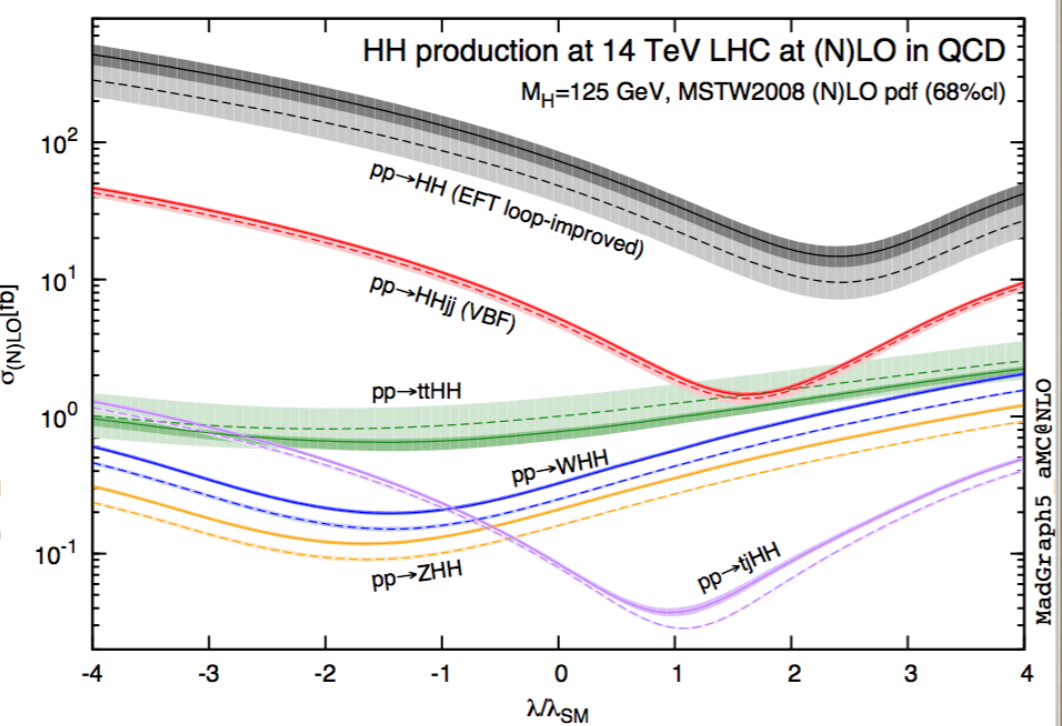




Junping Tian LC-REP-2013-003

What if $\lambda \neq \lambda_{SM}$? @ LHC

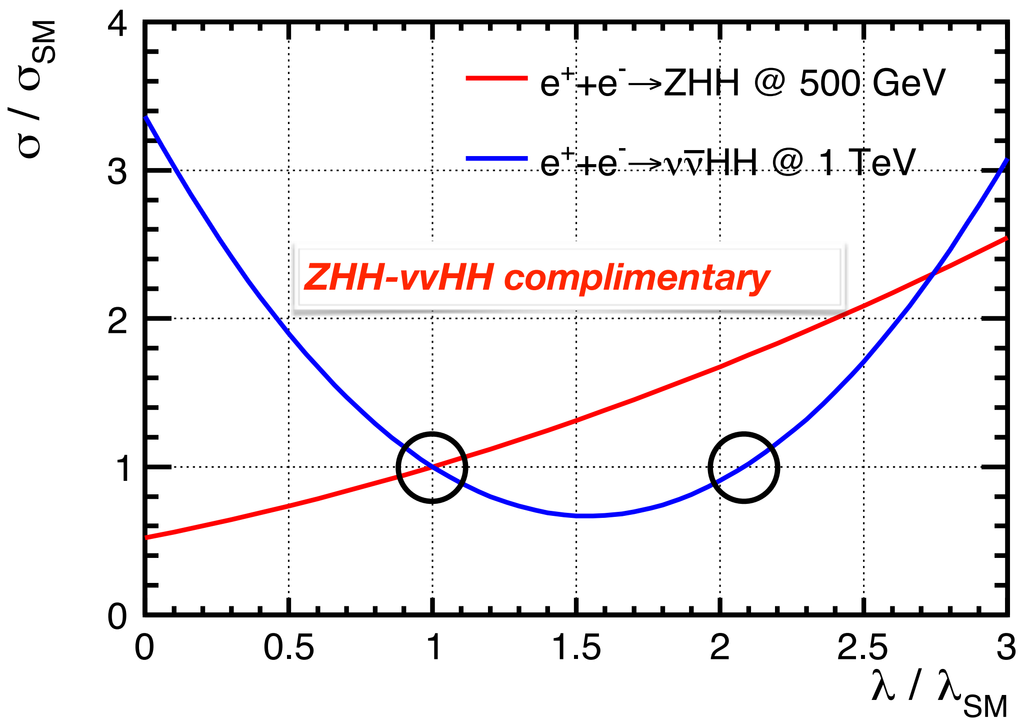


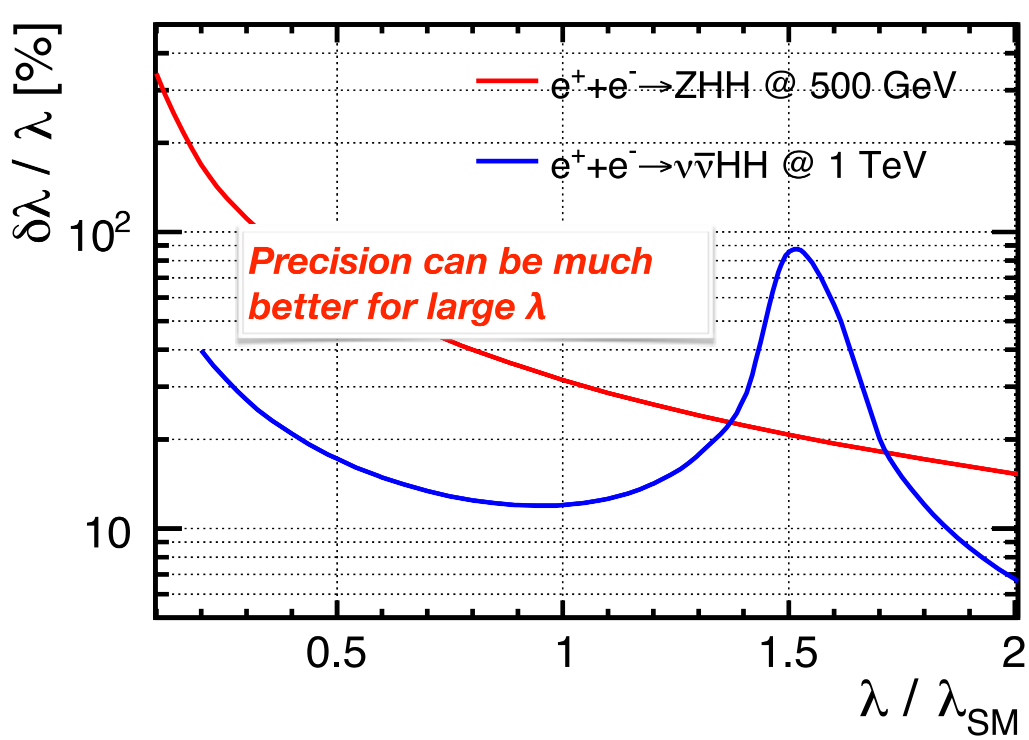


arXiv:1401.7304

- interference is destructive, σ minimum at $\lambda \sim 2.5\lambda_{SM}$; if λ is enhanced, it's going to be very difficult (from snowmass study by 3000 fb-1 @ 14 TeV, significance of double Higgs production is only ~ 2σ, if cross section decreases by a fact of 2~3, very challenging to observe pp—>HH)

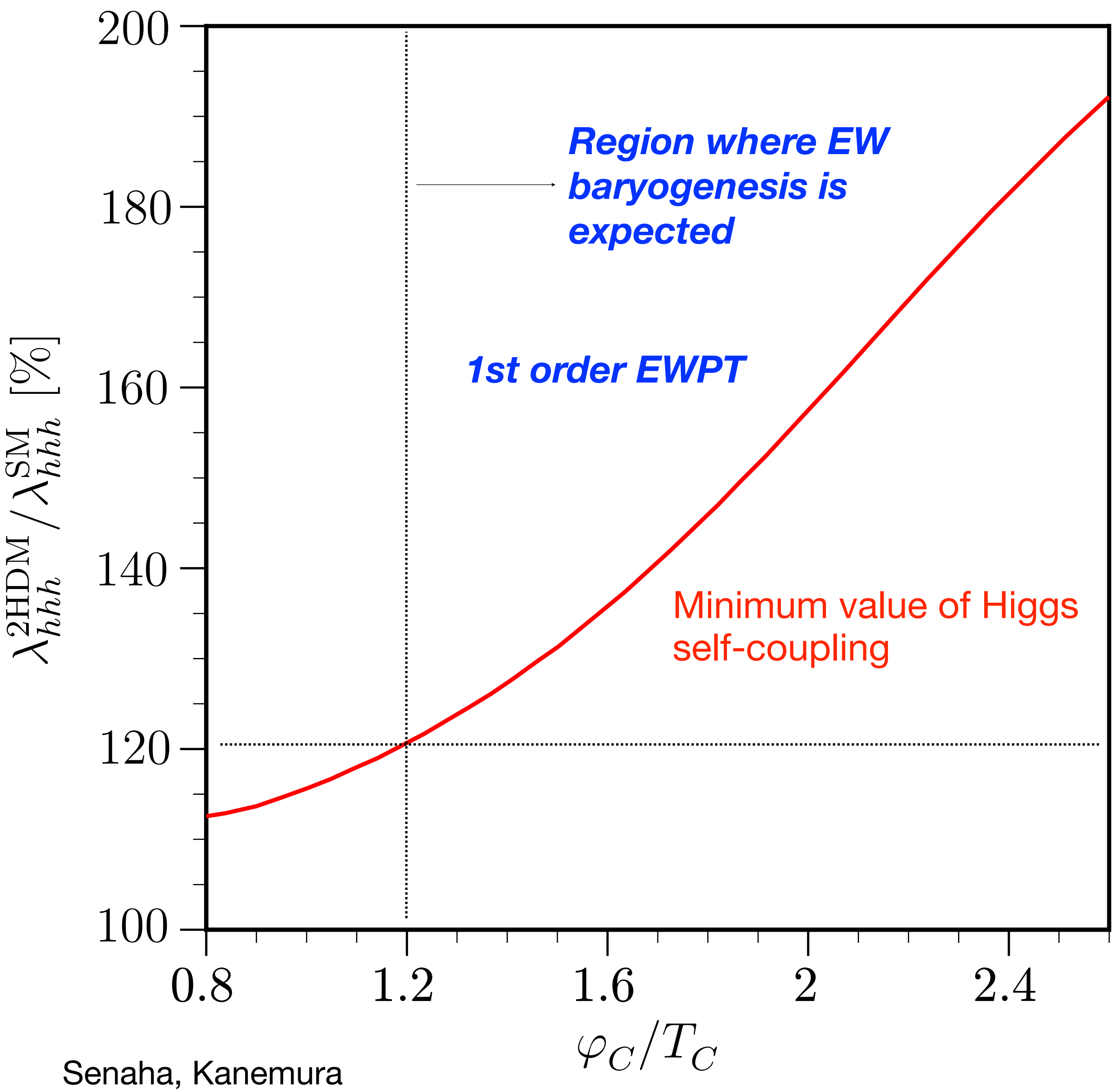
What if $\lambda \neq \lambda_{SM}$? @ LCs





- for ZHH, interference is constructive, enhanced λ will increase σ, and improve sensitivity factor as well, e.g. if $\lambda = 2\lambda_{SM}$, σ increases by 60%, F reduced by 1/2, $\delta\lambda/\lambda$ ~15%
  → we may finish the λ story at 500 GeV ILC !
  In EWSB models with classical conformal symmetry (Hashino,Kanemura,Orikasa, arXiv:1508.03245)
  $$\Gamma_{hhh}^{\rm CSI} = \frac{5m_h^2}{v} = \frac{5}{3} \times \Gamma_{hhh}^{\rm SMtree}.$$
- for ννHH, interference is destructive, enhanced λ will decrease σ, minimum when λ~$1.5\lambda_{SM}$, $\delta\lambda/\lambda$ degrades significantly if $\lambda/\lambda_{SM} \in (1.3, 1.7)$
- but if $\lambda < \lambda_{SM}$, more difficult to use ZHH, have to rely more on ννHH
- two channels are complementary in terms of λ measurement in BSM

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***.

Top

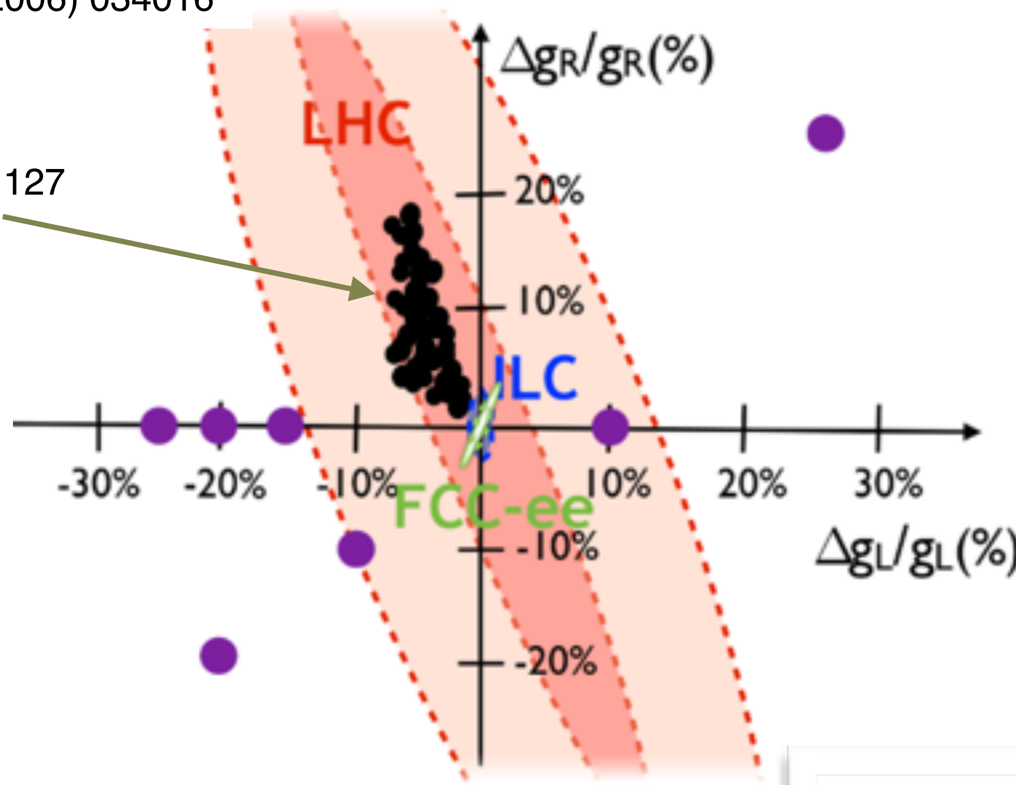
Search for Anomalous tZZ Couplings

Top: **Heaviest in SM**→Must couple **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)***

Deviation in ttZ coupling of right-handed top quark

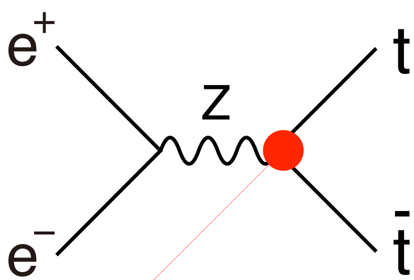
Phys.Rev.D73 (2006) 034016

4DCHM JHEP08 (2015) 127



ILC, $\sqrt{s}$ = 500 GeV
Lumi = 500 fb^{-1}

Deviation in ttZ coupling of left-handed top quark



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

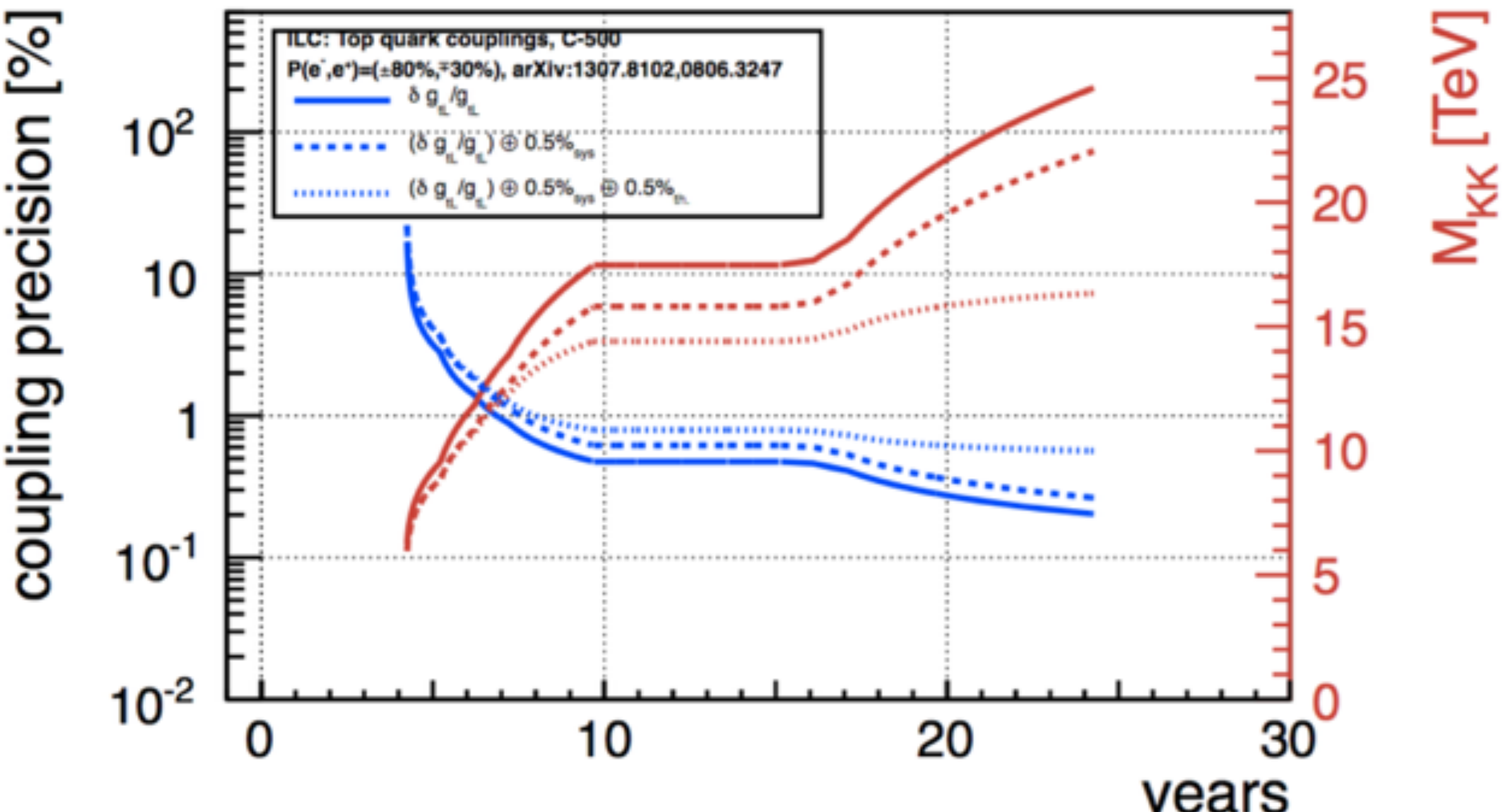
Purple points: deviations expected for various new physics models (new physics scale ~1 TeV) compiled in arXiv:1505.06020

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



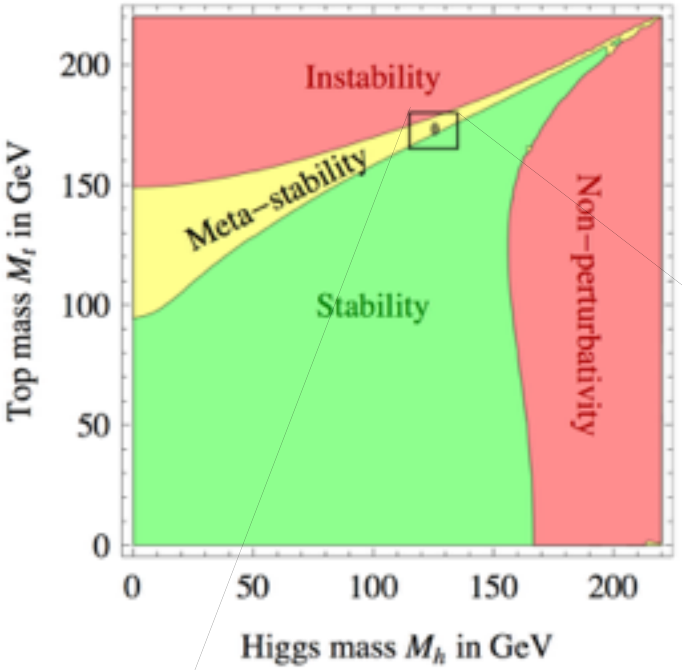
Can probe scales of ~25 TeV in typical scenarios

(… and up tp 80 GeV for extreme scenarios)

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

What if no deviation from the SM would be seen?

Clarify the Range of Validity of SM



Stability of SM Vacuum

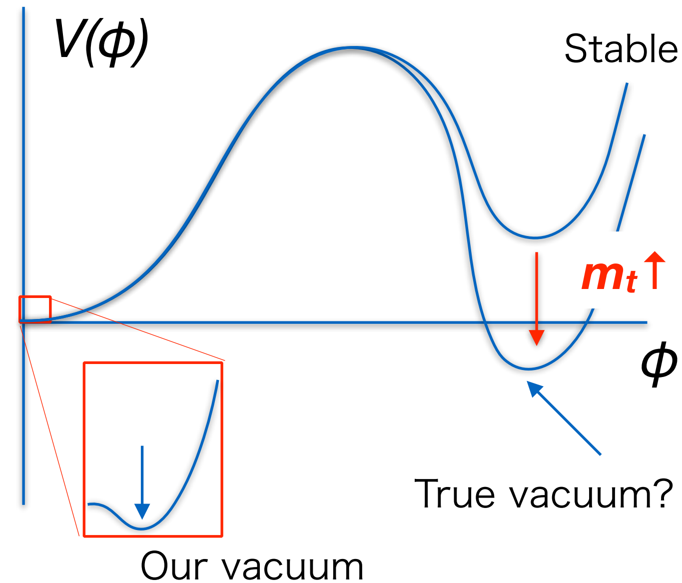
Top Yukawa coupling drives the 4-point Higgs couplint (λ) to negative!

The current values of mt and mh:

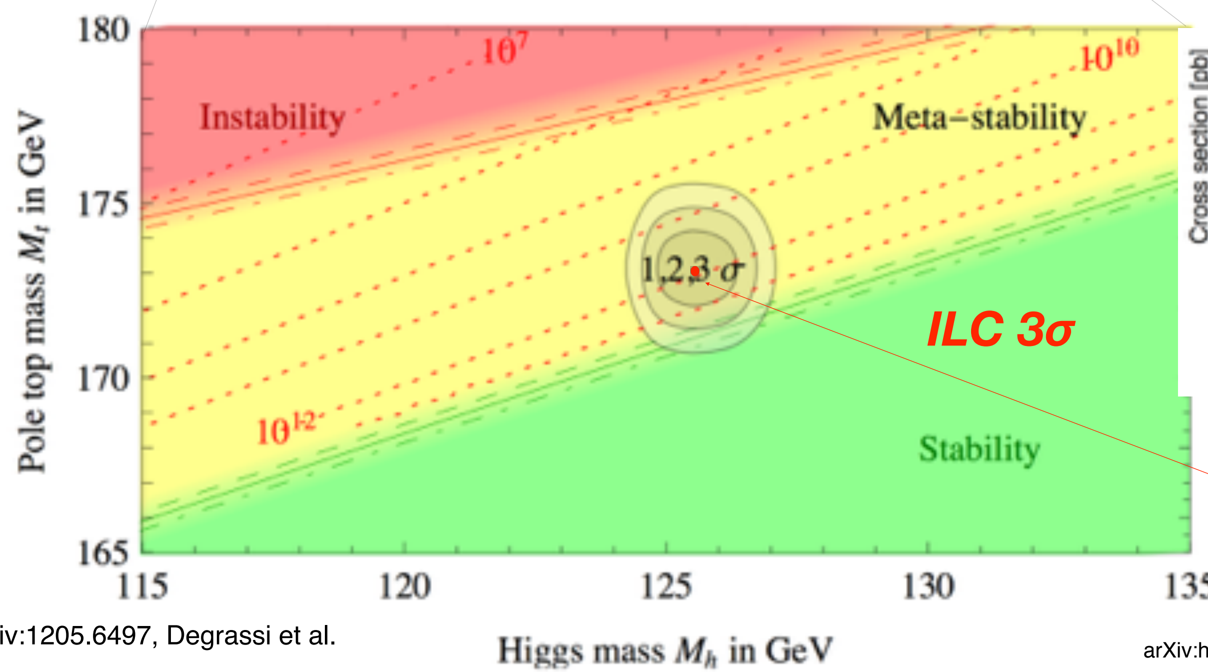
Subtle point of meta-stability!

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

To anser this, we need precision m_t measurement!

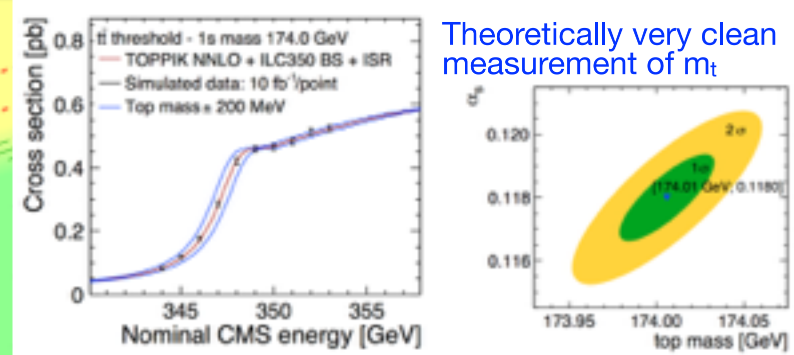


At LHC, theory error limits the precision to ~500MeV.



arXiv:1205.6497, Degrassi et al.

TTbar Threshold Scan @ILC



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

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

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

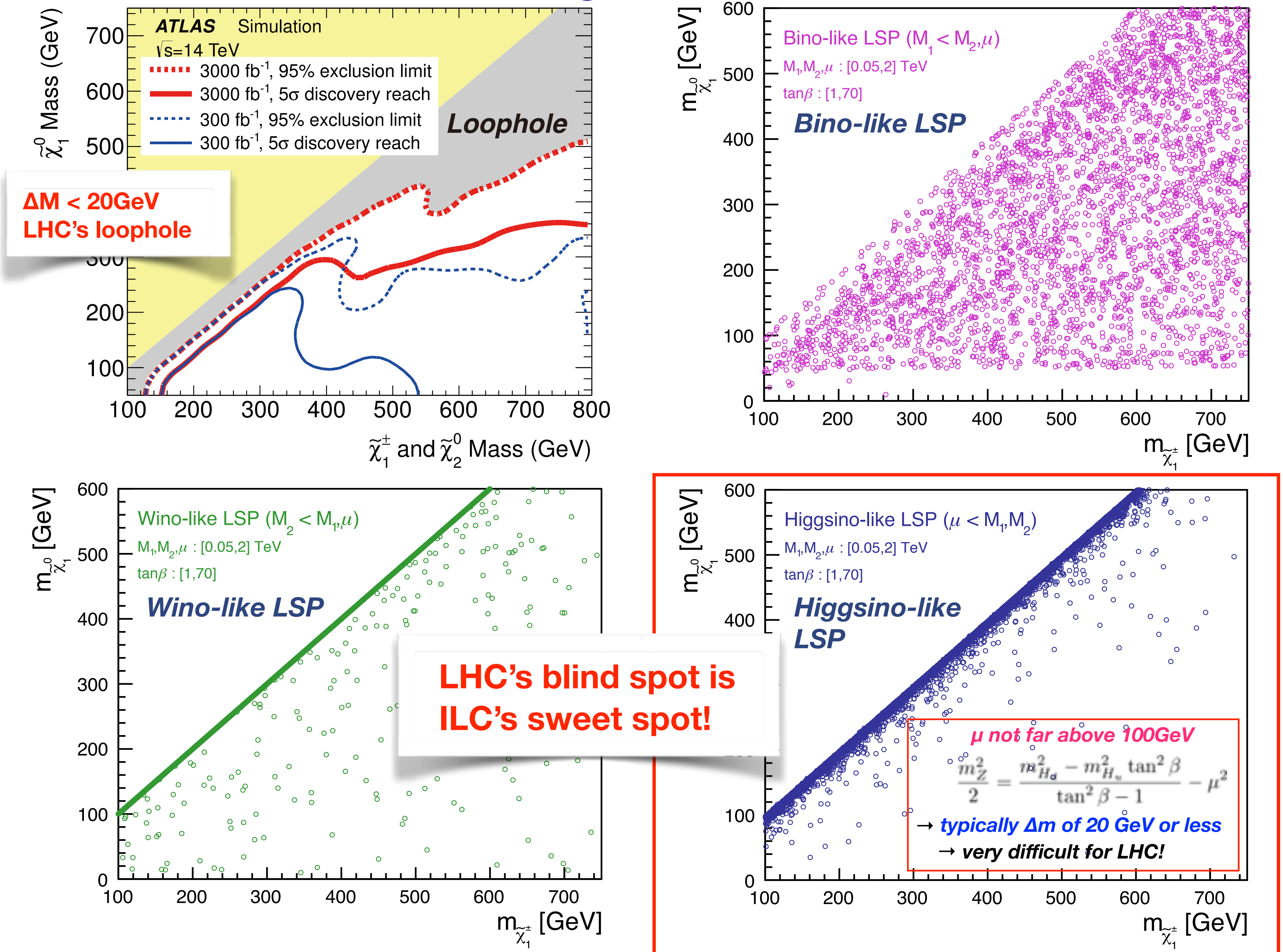
Direct Searches for New Particles

ILC, too, is an energy frontier machine!

It will enter ***an uncharted water of e^+e^- collisions***

Thanks to well-defined initial states,
clean environment w/o QCD BG, and polarized beams
ILC can cover blind spots of LHC

Chargino Search

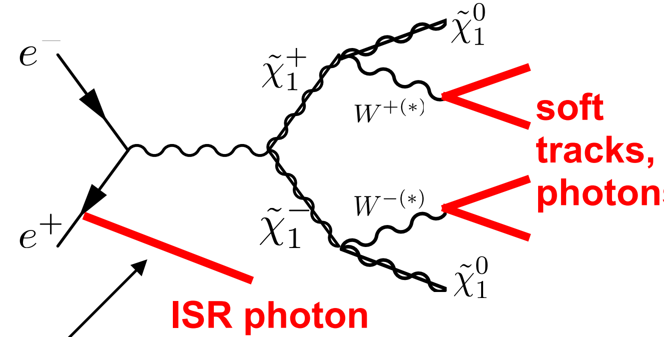


Higgsinos in Natural SUSY (ΔM<a few GeV)

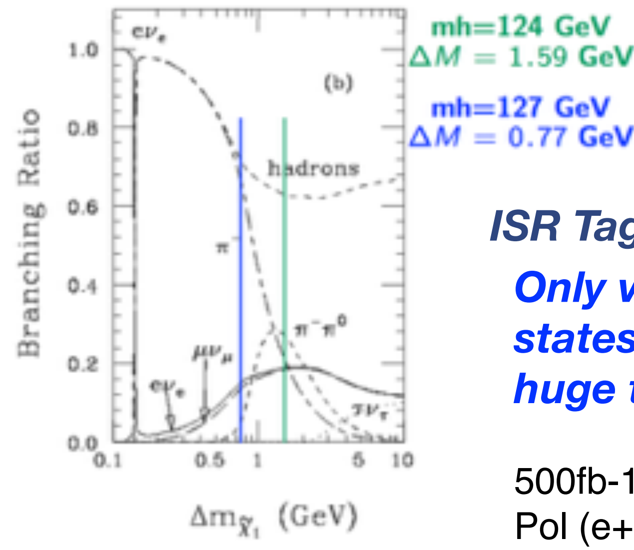
ISR Tagging

ILC as a Higgsino Factory

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

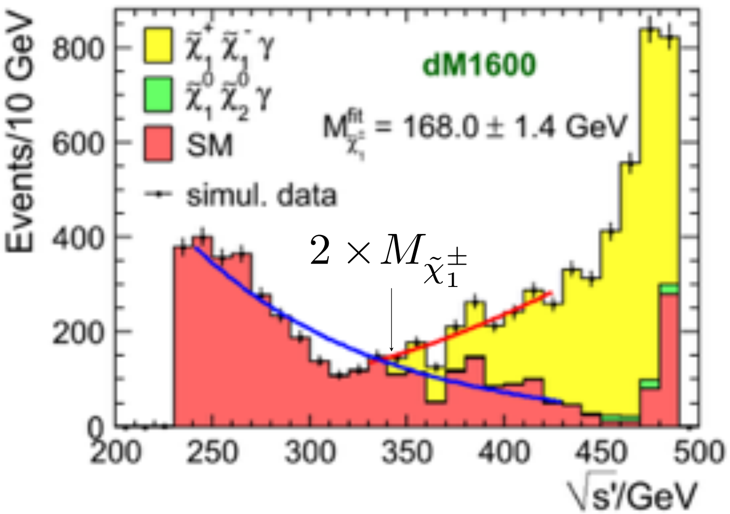


Ref: C.-H. Chen et al. hep-ph:9512230



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)

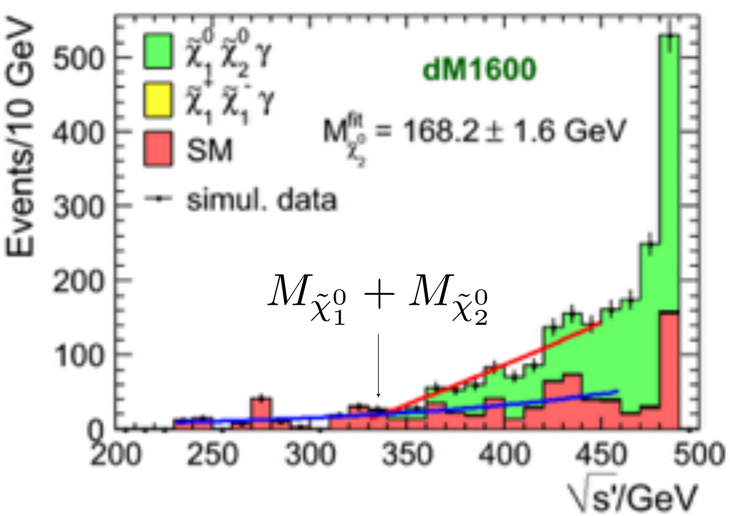
dm1600

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
$\tilde{H}$'s	$\sim 10^3$
$\tilde{X}$'s	$\sim 2-3\times 10^3$

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

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



EPJC (2013) 73:2660

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
$\tilde{H}$'s	$\sim 10^3$
$\tilde{X}$'s	$\sim 2-3\times 10^3$

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

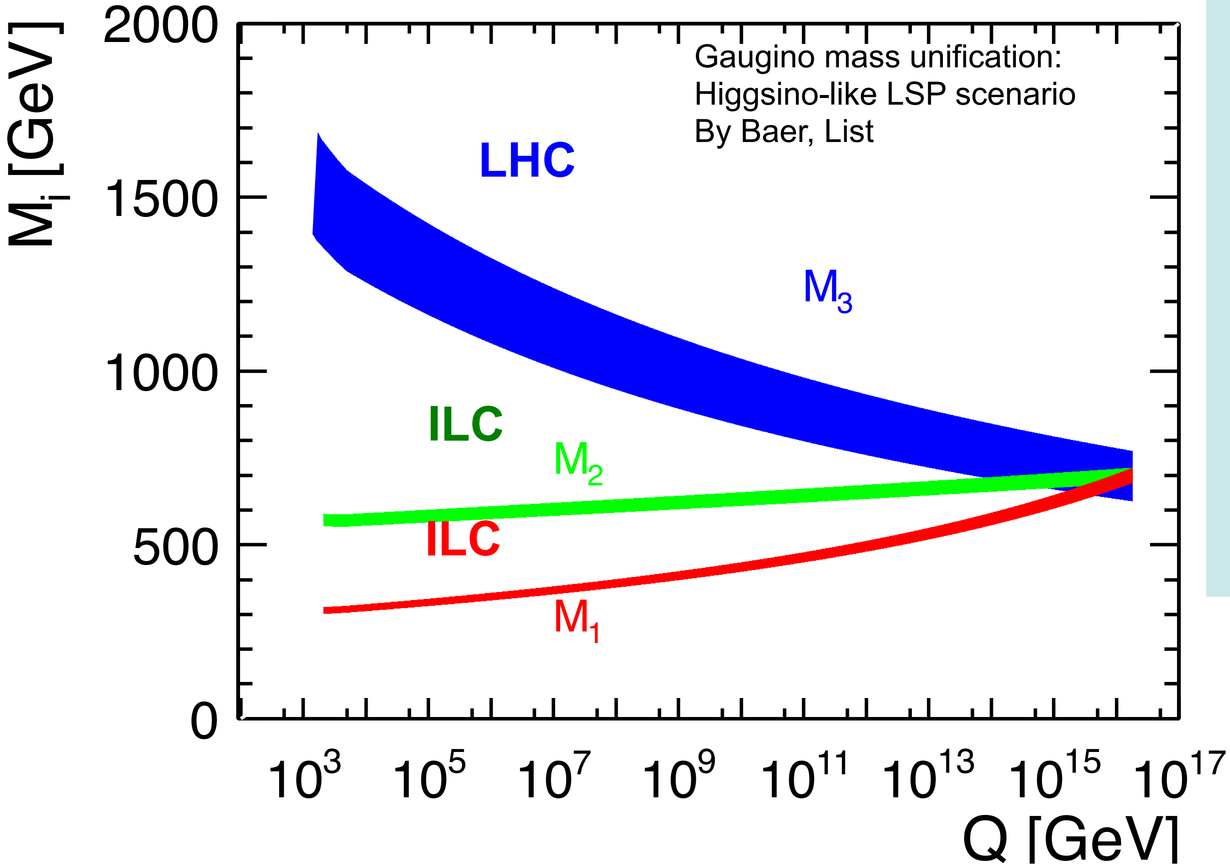
$$\delta(\sigma \times BR) \simeq 1.5\%$$
$$\delta M_{\tilde{\chi}_1^\pm}(M_{\tilde{\chi}_1^0}) \simeq 1.5(1.6)\,\text{GeV}$$
$$\delta\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \simeq 20\,\text{MeV}$$

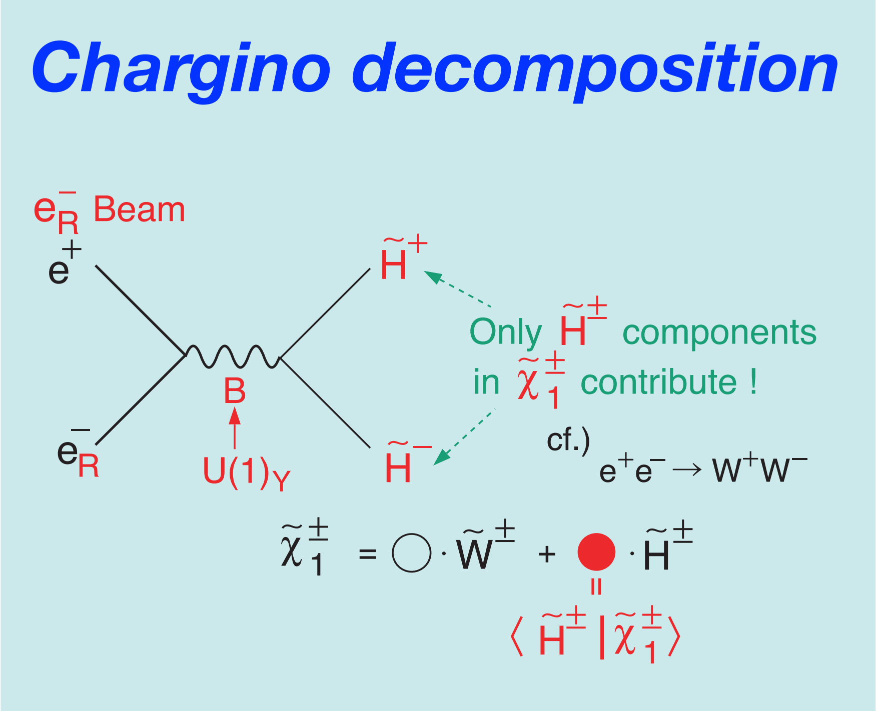
GUT Scale Physics

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.*

WIMP Dark Matter Search @ ILC

Weakly Interacting Massive Particle 探索

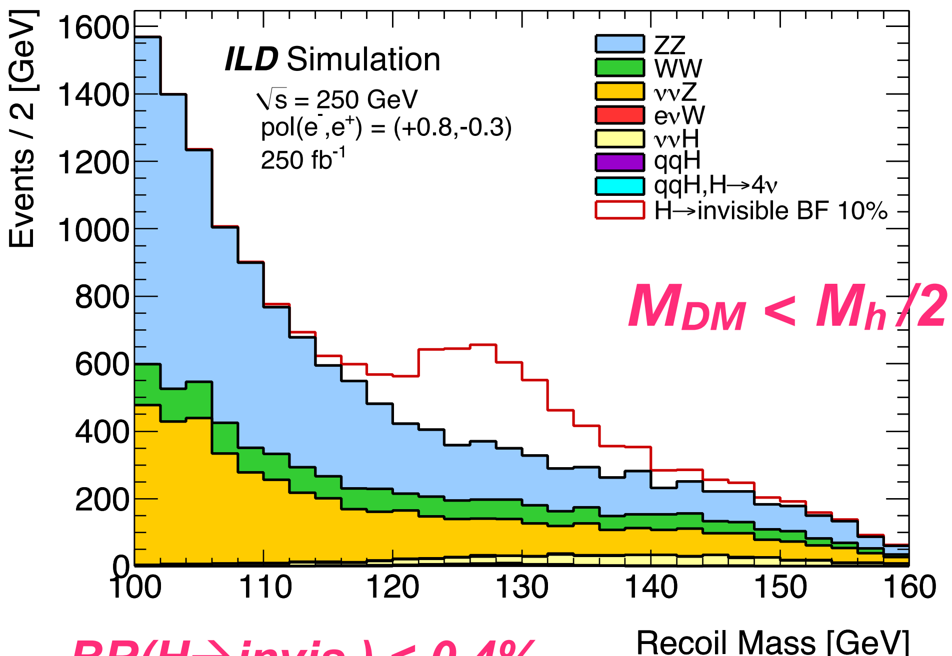
Decay of a new particle to Dark Matter (DM)

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

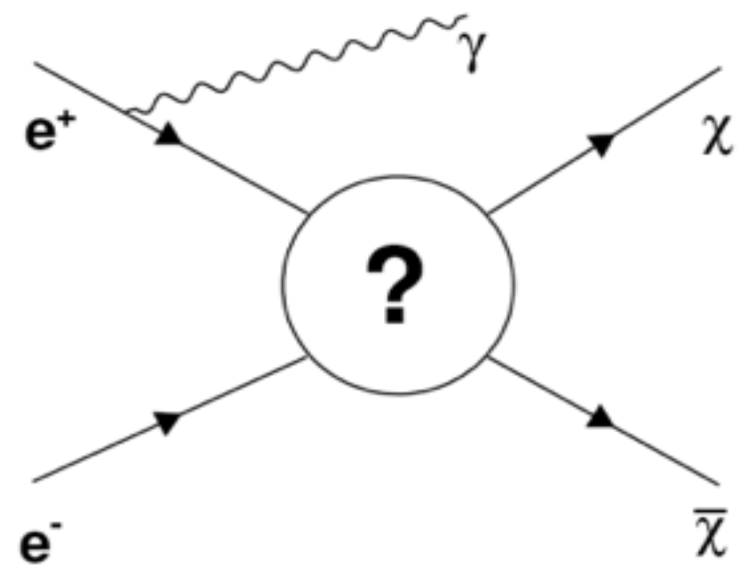


BR(H→invis.) < 0.4%

at 250 GeV, 1150 fb^{-1}

Possible to access BR_{inv} to 0.4%!

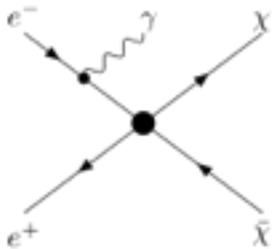
Mono-photon Search



→ ***M_{DM} reach ~ $E_{cm}/2$***

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

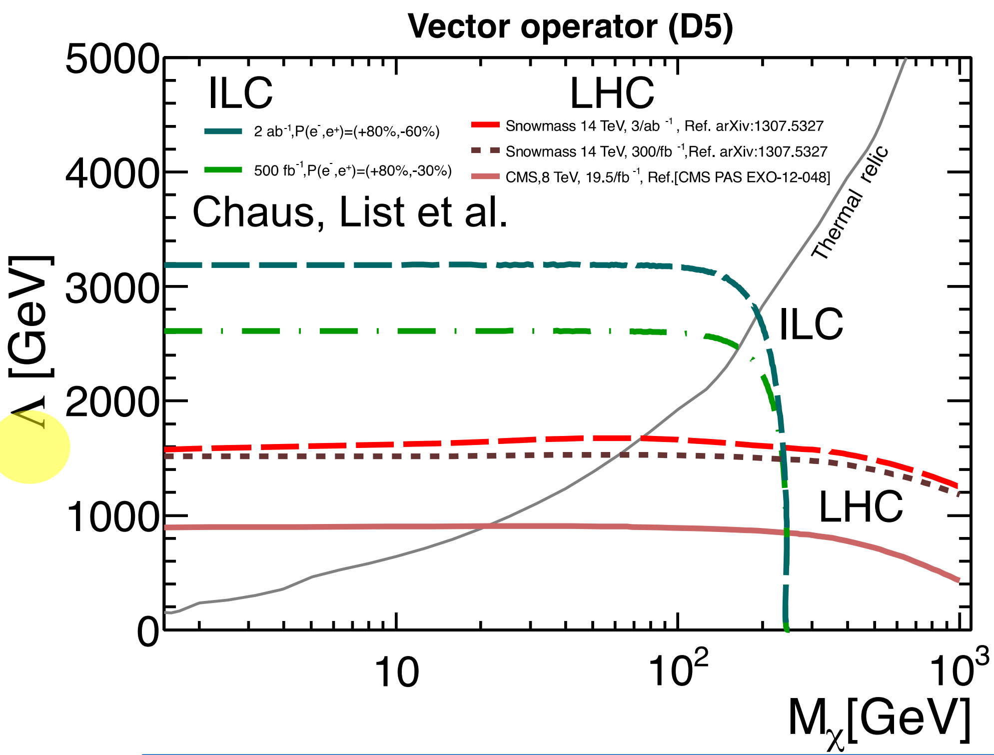
DM: Effective Operator Approach

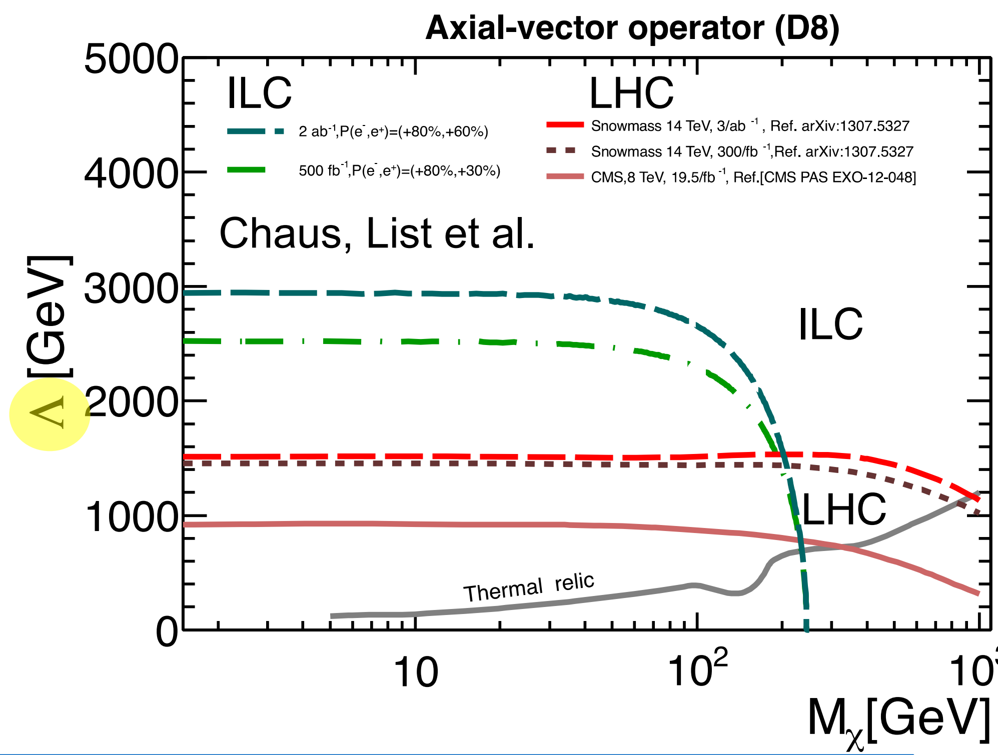


$$\mathcal{L}_{\rm int} = \frac{1}{\Lambda^2}\mathcal{O}_i$$

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

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





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***

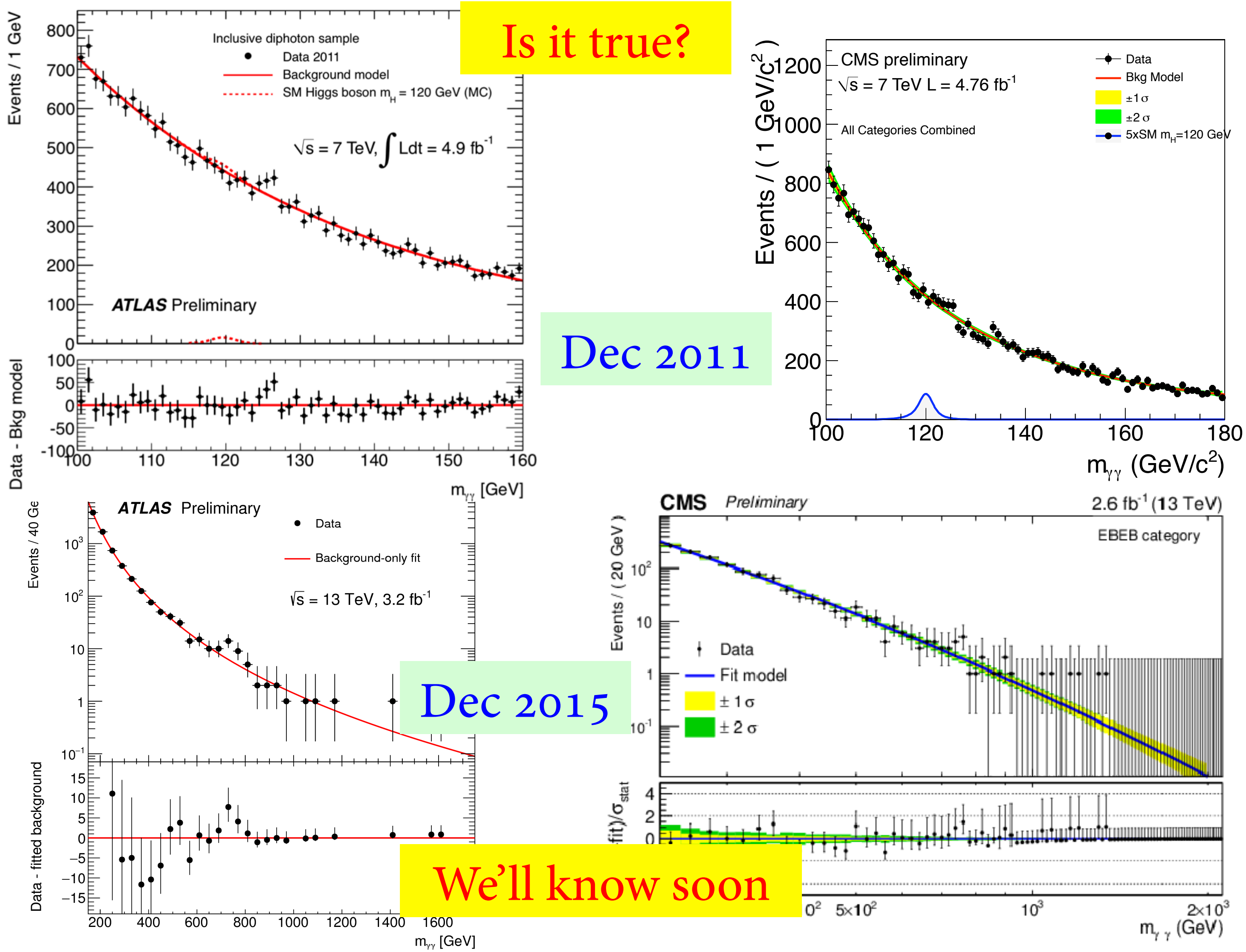
LHC-ILC synergy!

I strongly believe that **ILC is worth building regardless of what LHC is going to discover.**

But the MEXT ILC Advisory Panel recommended **to closely monitor, analyze, and examine the development of LHC experiments.**

X750

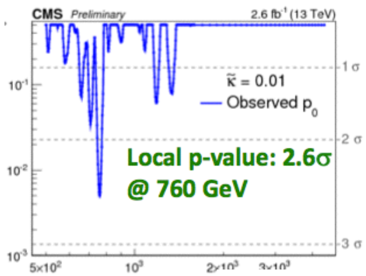
Bis repetita placent



What ATLAS and CMS say

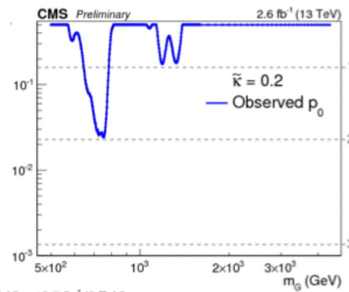
CMS Significance

Narrow

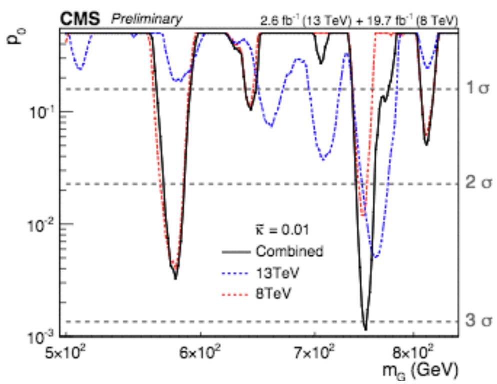


Equally plausible

Wide

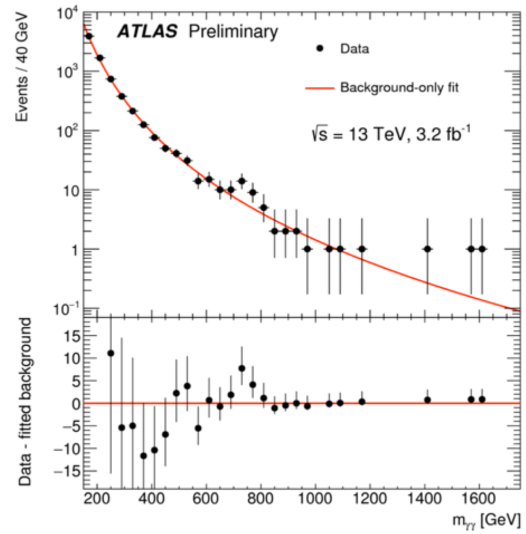


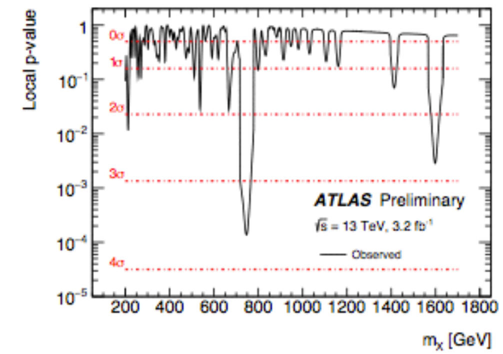
Combined with 8 TeV



3σ local

ATLAS data





narrow: 3.6 σ local
wide: 3.9 σ local
(equally plausible)

total signal rate: 5 - 10 fb

2.6 σ local excess at 760 GeV
1.2 σ with LEE (500 GeV - 4.5 TeV)

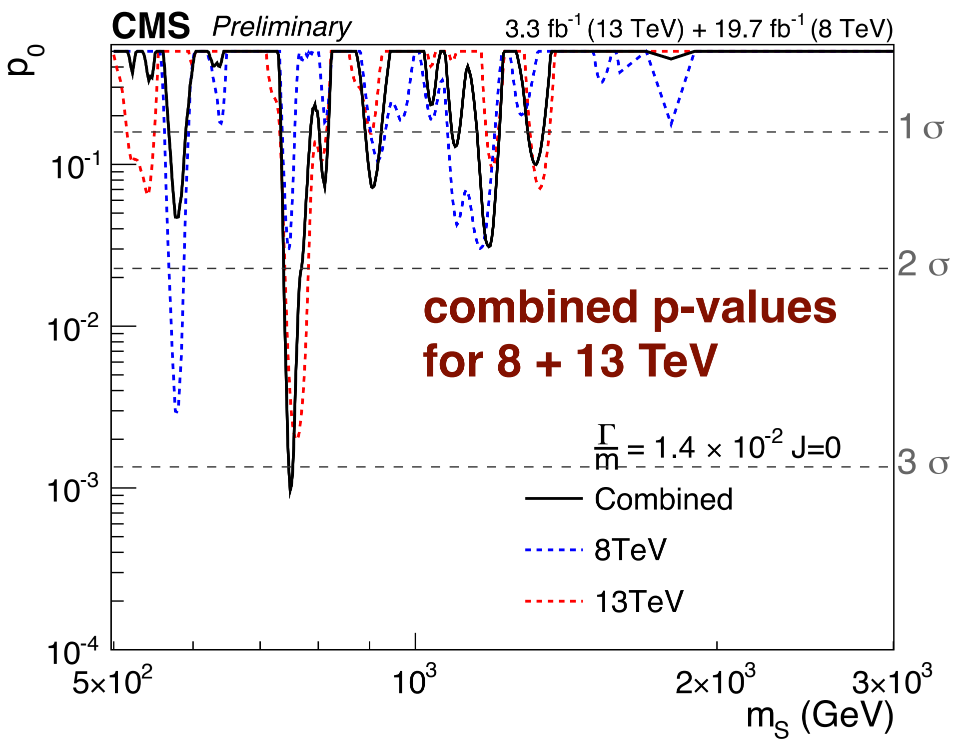
3.6 σ local excess at 750 GeV
2.0 σ with LEE (200 GeV - 2 TeV)

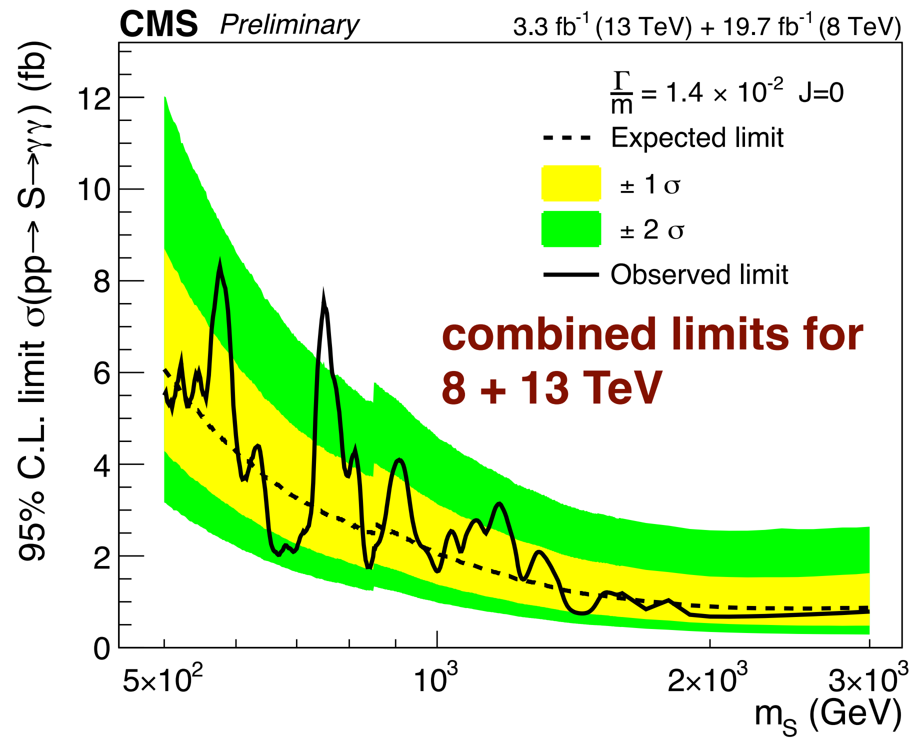
$\sigma(pp \to \gamma\gamma)$	8 TeV	13 TeV
CMS	(0.5 ± 0.6) fb	(6 ± 3) fb
ATLAS	(0.4 ± 0.8) fb	(10 ± 3) fb

Diphoton Resonances

[EXO-16-018]

- Combined 8 TeV + 13 TeV results
  - Largest excess is observed for **750 GeV, spin-0, narrow width**
    - local significance of 3.4σ, 1.6σ after look-elsewhere effect





- Dec '15 result: largest excess at 760 GeV for $\Gamma/M=1.4\text{x}10^{-2}$
  - local significance of ~3σ, <1.7σ after look-elsewhere effect

A violent reaction of HEP community

- violation of unitarity: more papers than the number of events
- violation of causality: first papers posted to the arXiv before the end of the CERN seminars

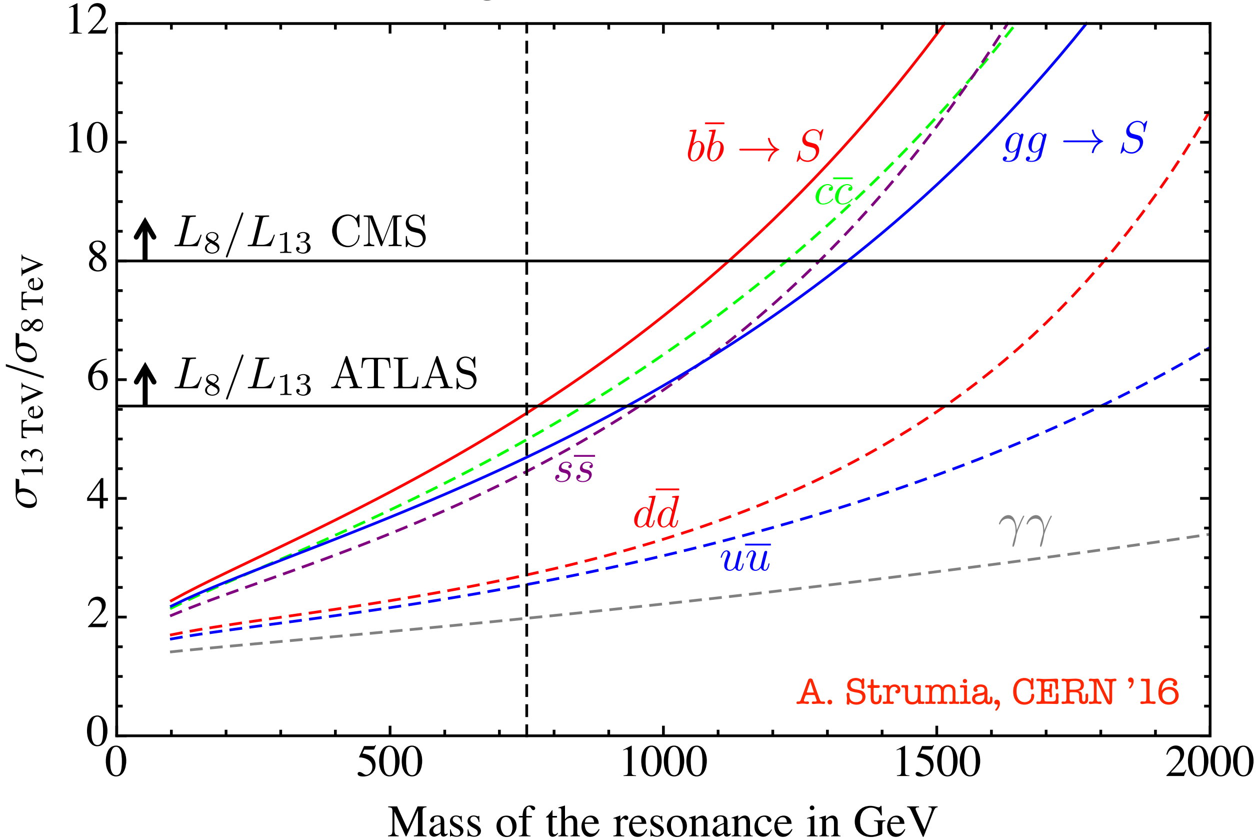
~~ raises many interesting questions ~~

- new scalar? is it natural?
- how is it produced?
- what is its width?
- is there other particles accompanying it?
- what are its SM quantum numbers?
- is it second heavy Higgs?

Learning about X(750): production?

seeing an excess at 13TeV without seeing anything at 8TeV

" Looking and not finding is different than not looking "



$$\frac{\mathcal{L}_{gg}^{(13)}}{\mathcal{L}_{gg}^{(8)}} \sim 4.6$$

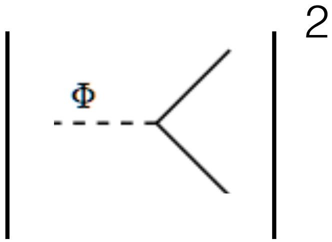
Run 1 compatible with Run 2 if X is produced as gg, $b\bar{b}$, $c\bar{c}$, $s\bar{s}$.

strong prejudice for gg fusion production (like the Higgs)

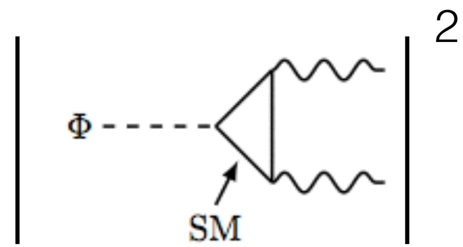
despite the fact that X doesn't carry color charge

Learning about X(750): lonely BSM?

if the X decay to photons is mediated by SM particles, many other decay channels would be open and they haven't been found



$\sim 10^5$



"Looking and not finding is different than not looking"

final state f	σ at $\sqrt{s} = 8$ TeV observed	expected	implied bound on $\Gamma(S \to f)/\Gamma(S \to \gamma\gamma)_{\text{obs}}$
$\gamma\gamma$	< 1.5 fb	< 1.1 fb	$< 0.8\ (r/5)$
$e^+e^-, \mu^+\mu^-$	< 1.2 fb	< 1.2 fb	$< 0.6\ (r/5)$
$\tau^+\tau^-$	< 12 fb	< 15 fb	$< 6\ (r/5)$
$Z\gamma$	< 11 fb	< 12 fb	$< 6\ (r/5)$
ZZ	< 12 fb	< 20 fb	$< 6\ (r/5)$
Zh	< 19 fb	< 28 fb	$< 10\ (r/5)$
hh	< 39 fb	< 42 fb	$< 20\ (r/5)$
W^+W^-	< 40 fb	< 70 fb	$< 20\ (r/5)$
$t\bar{t}$	< 450 fb	< 600 fb	$< 300\ (r/5)$
invisible	< 0.8 pb	-	$< 400\ (r/5)$
$b\bar{b}$	$\lesssim 1$ pb	$\lesssim 1$ pb	$< 500\ (r/5)$
jj	$\lesssim 2.5$ pb	-	$< 1300\ (r/5)$

$r = \sigma_{13\,\text{TeV}}/\sigma_{8\,\text{TeV}}$

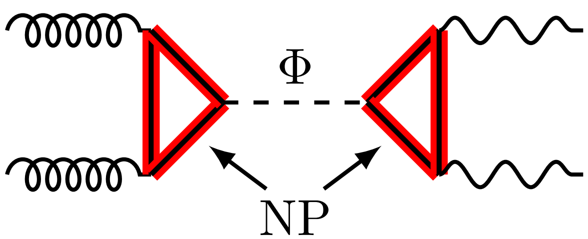
New 13TeV searches are much waited to confirm these results

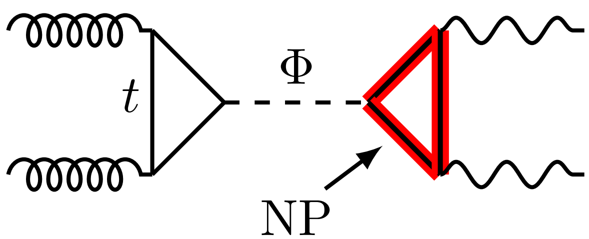
The loops are mediated by new other particles!

Learning about X(750): new color BSM?

Are these new fermions accompanying the X decay also contributing to the X production, i.e. are they colored particles?

S. Knapen, LHC forum '16





$$R_{\gamma\gamma} \sim \frac{\Gamma_{\gamma\gamma}}{m_\Phi} \mathcal{L}_{gg} \sim \frac{\Gamma_{\gamma\gamma}}{\text{MeV}}\,\text{fb}$$

$$R_{\gamma\gamma} \sim \frac{\Gamma_{gg}}{\Gamma_{tt}} \frac{\Gamma_{\gamma\gamma}}{m_\Phi} \mathcal{L}_{gg} \sim \frac{\Gamma_{\gamma\gamma}}{\text{GeV}}\,\text{fb}$$

easier to accommodate in perturbative models

requires a large width to di-photon

not easy!

NP with large multiplicity, large Q,

non MVF-suppressed couplings to X

nearby Landau pole/strong coupling?

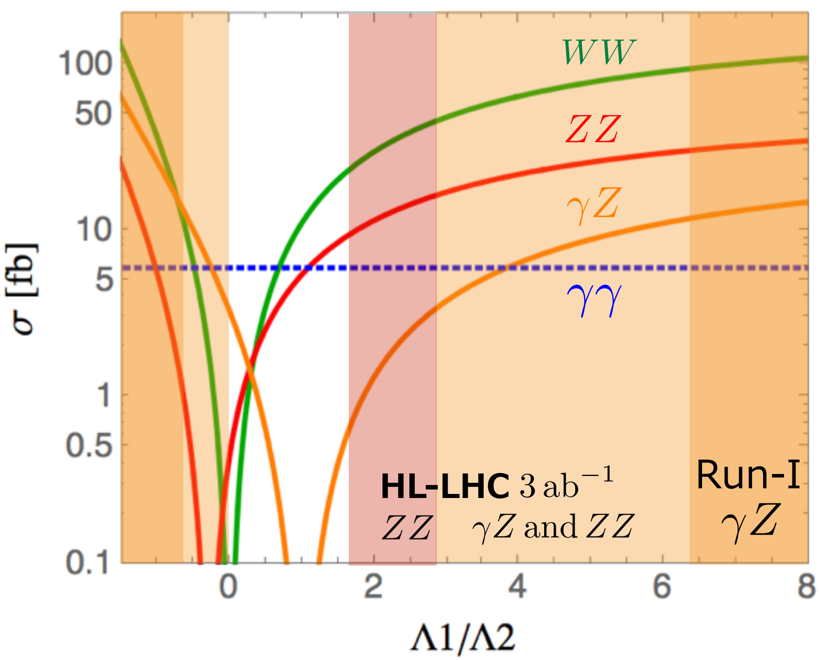
X(750) and the LHC

$$\mathcal{L}_{\text{eff}} = \frac{\Phi}{\Lambda_1} B_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{\Phi}{\Lambda_2} W^i_{\mu\nu}\tilde{W}^{i\mu\nu} + \frac{\Phi}{\Lambda_3} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

EW decay modes may not be detected at the LHC

if $0 < \Lambda1/\Lambda2 < 1.5$.

Y. Takaesu, Okinawa '16

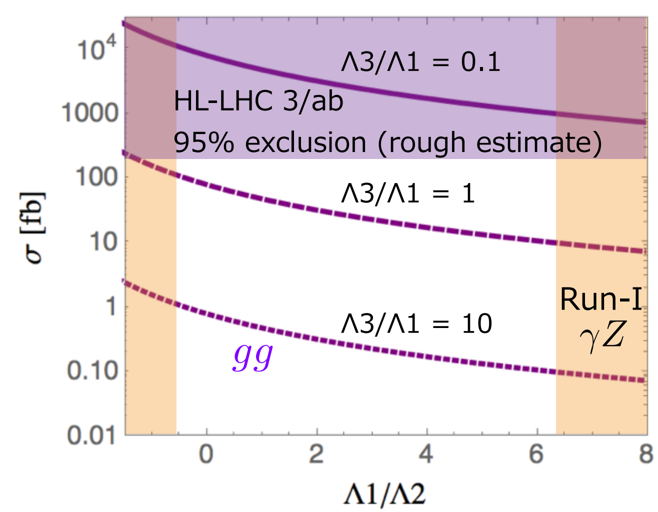


95% C.L. exclusion

ATL-PHYS-PUB-2013-016 (ZZ)

1512.05542 (γZ)

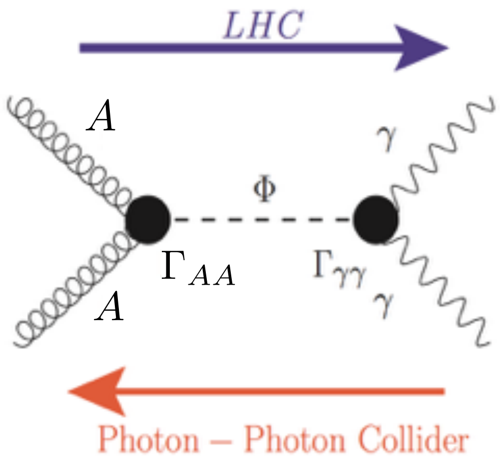
gg decay mode may not be detected if $\Lambda3/\Lambda1 > 1$.



ATL-PHYS-PUB-2015-004: di-jet limit QBH (750 GeV) with 50% acceptance

X(750) and the ILC

A. Djouadi et al, '16



Y. Takaesu, Okinawa '16

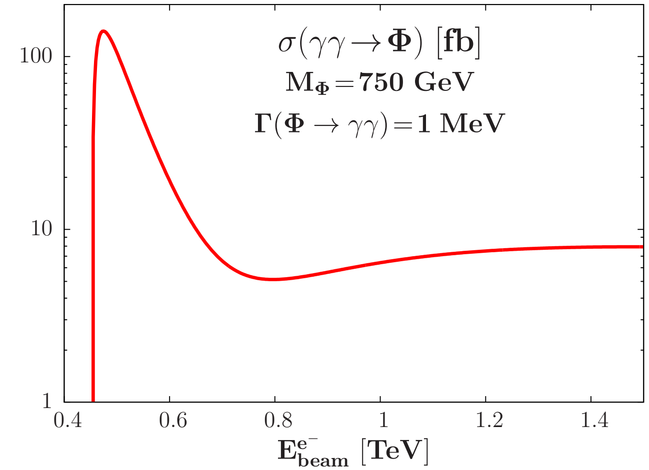


Figure 4: *Cross section for producing a singlet Φ boson with mass 750 GeV via $\gamma\gamma$ fusion at an e^+e^- collider as a function of the e^+e^- centre-of-mass energy in the range from $\sqrt{s} = 0.8$ TeV to 3 TeV. The $\Phi \to \gamma\gamma$ partial width is assumed to be 1 MeV as can be inferred from $\sigma(gg \to \Phi) \approx 6$ fb at $\sqrt{s} = 13$ TeV when the decay $\Phi \to gg$ is dominant.*

Given a $\gamma\gamma$ collider based on a 1 TeV ILC, we can estimate the Φ event sample, the expectation of a 3 ab^{-1} luminosity sample in e^+e^-, and decrement of about 1/3 for the $\gamma\gamma$ luminosity. This leads to a total sample of 20,000 Φ events at the minimal value of the $\gamma\gamma$ width ($\Gamma(\Phi \to \gamma\gamma)/m_\Phi \geq 4 \times 10^{-7}$).

LCC physics WG, to appear

X(750) and the Higgs

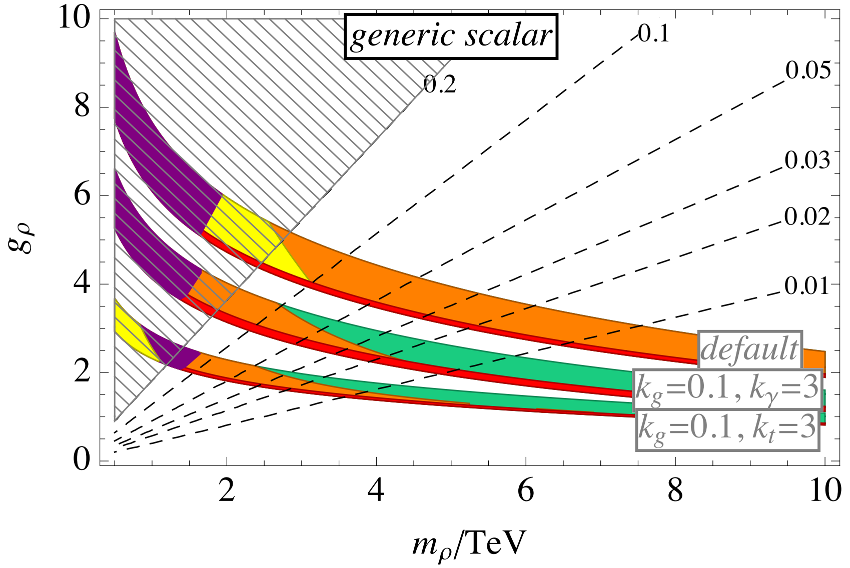
M. Chala, G. Durieux, L. de Lima, C. Grojean, O. Matsedonsky , 'to appear

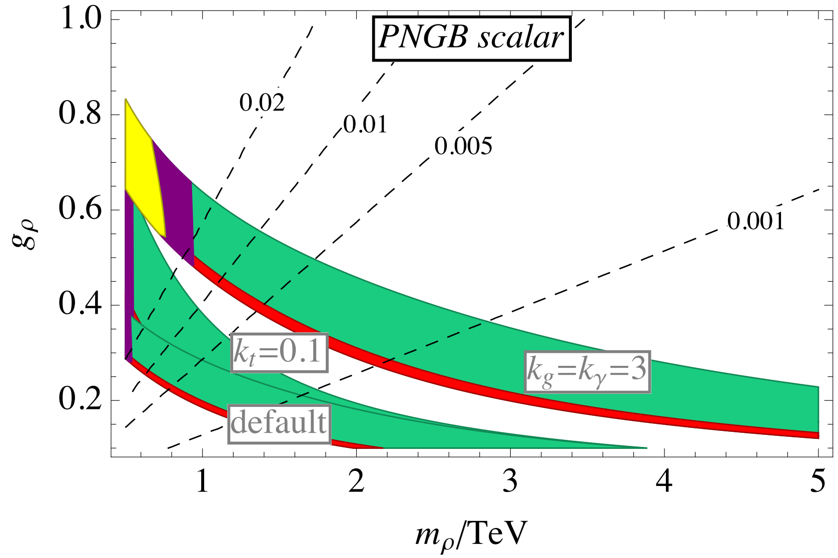
Under the assumption that new physics in the gg and loops for X(750) is characterized by a single scale m_ρ and a single coupling g_ρ

we can infer the implications on Higgs physics under simple dynamical assumptions

Contour lines for the expected deviations in Higgs couplings

green regions = X(750) signal compatible with all other constraints





moral #1: data prefer X(750) as pseudo-Goldstone boson

(hence new approximate global symmetries spontaneously broken)

moral #2: typical Higgs coupling deviations O(1%)

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 address 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.
- ***In this way, ILC will pave the way to BSM physics.***

Backup

Higgs

Why 500 GeV?

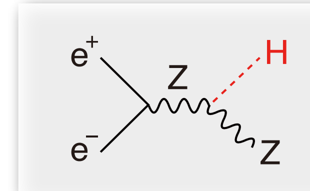
Higgs-related Physics at Ecm ≲ 500 GeV

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)

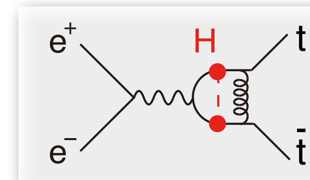
→Higgs couplings (other than top)



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

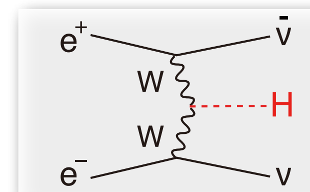
- Threshold scan --> theoretically clean ***mt*** measurement: $\Delta m_t(\overline{MS}) \simeq 100\,\mathrm{MeV}$
  --> test stability of the SM vacuum
  --> indirect meas. of ***top Yukawa*** coupling
- A_{FB}, Top momentum measurements
- Form factor measurements

γ γ → HH @ 350GeV possibility



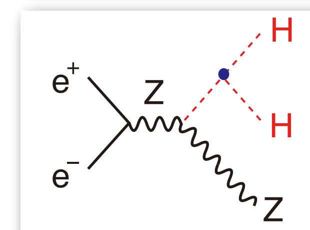
vvH @ 350 - 500GeV :

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



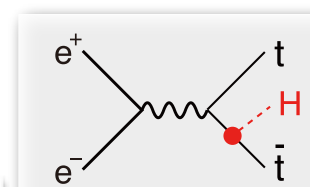
ZHH @ 500GeV (~M_Z+2M_H+170GeV) :

- 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!

Higgs Physics at Higher Energy

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

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

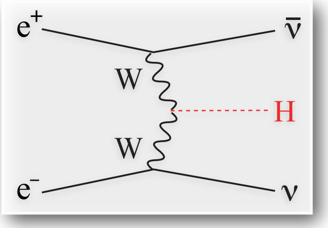
- allows us to measure rare decays such as H -> $\mu^+ \mu^-$, ...
- further improvements of coupling measurements

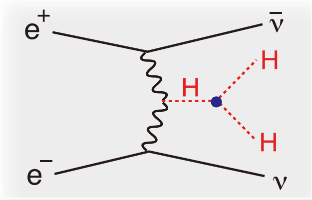
$\nu\nu HH$ @ 1TeV or higher : 2ab^{-1} (pol e$^+$, e$^-$)=(+0.2,-0.8)

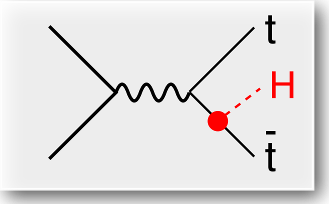
- cross section increases with Ecm, which compensates the dominance of the background diagrams at higher energies, thereby giving a better precision for the self-coupling.
- If possible, we want to see the running of the self-coupling (very very challenging).

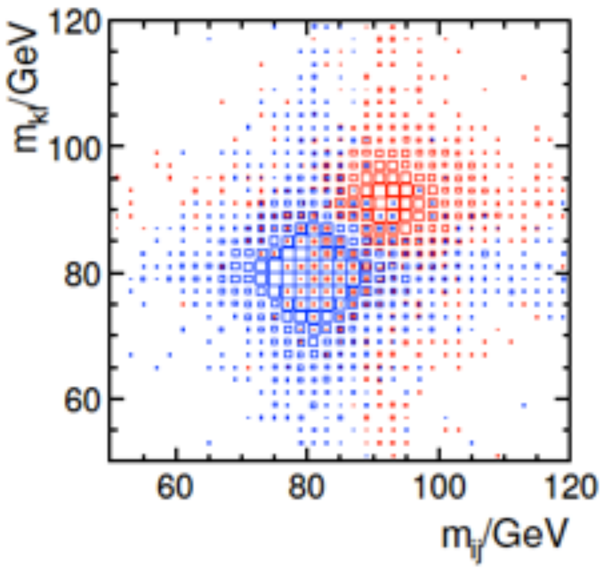
ttbarH @ 1TeV : 1ab^{-1}

- 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!

Model-independent Global Fit for Couplings

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

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

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

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

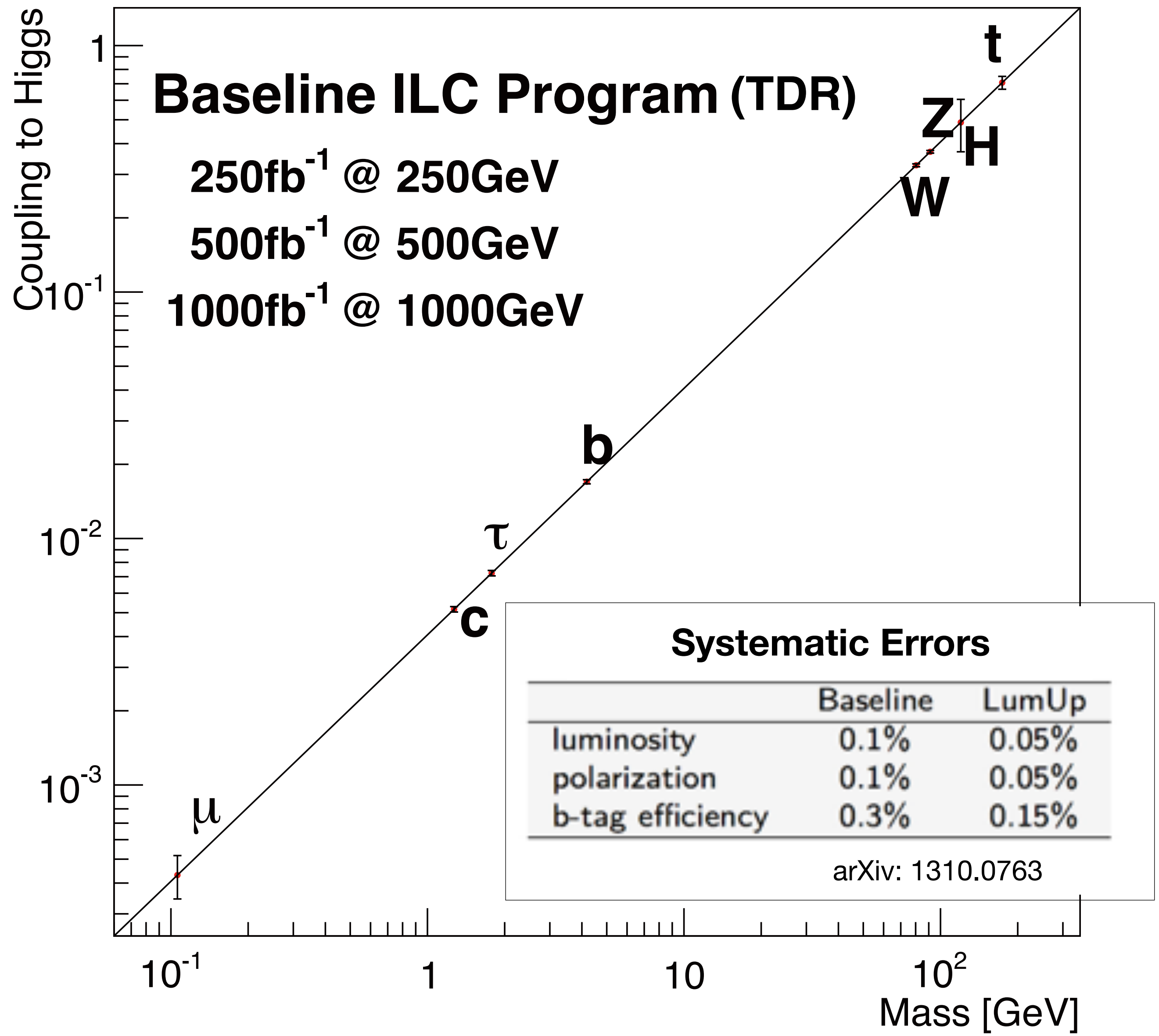
$$(A_i = Z, W, t)$$

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

$$F_i = S_i \, G_i$$

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

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



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!

Independent Higgs Measurements at ILC

Baseline (=TDR) ILC program

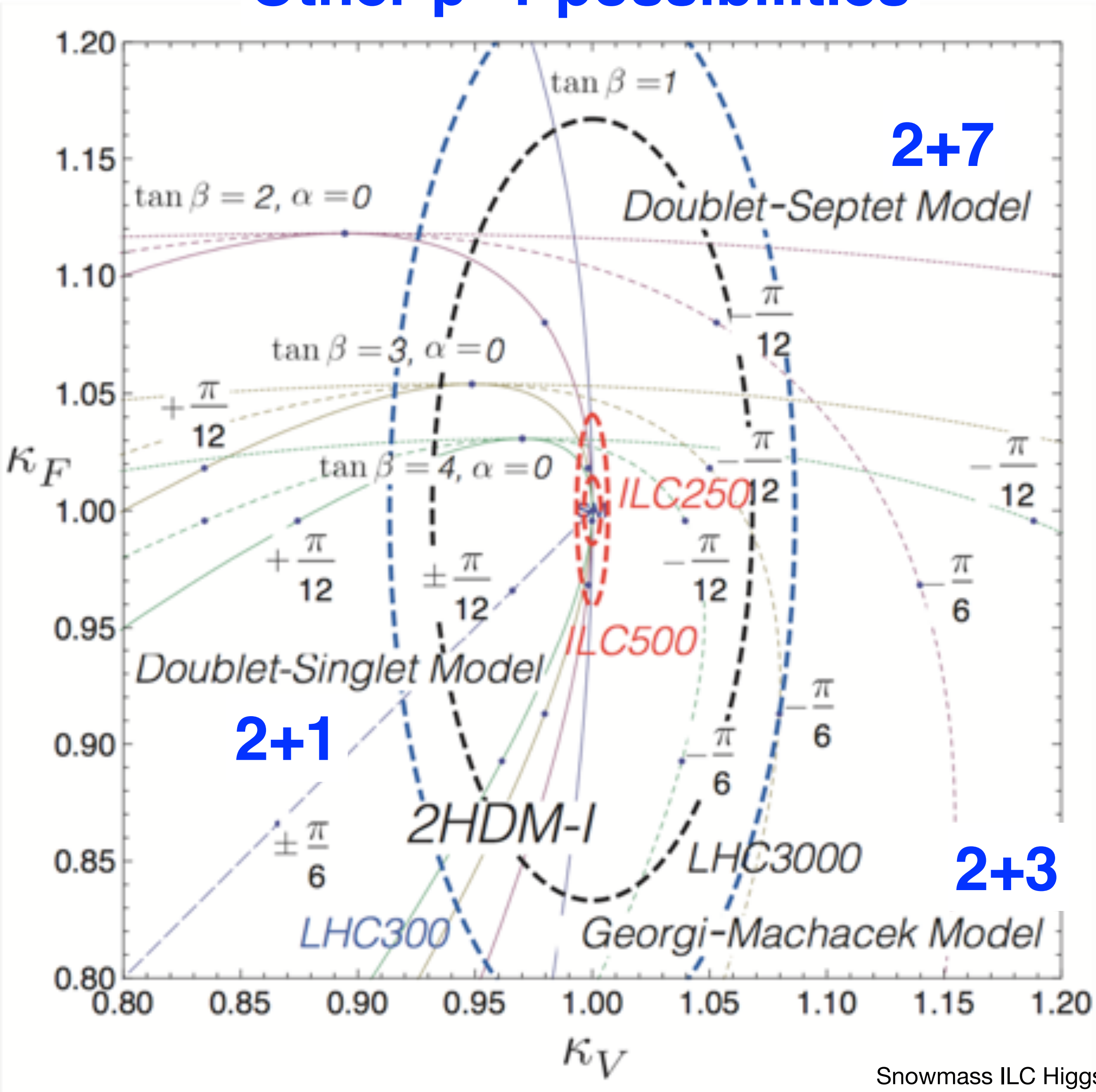
250 GeV: 250 fb^{-1}
500 GeV: 500 fb^{-1}
1 TeV: 1000 fb^{-1}

(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	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%

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]

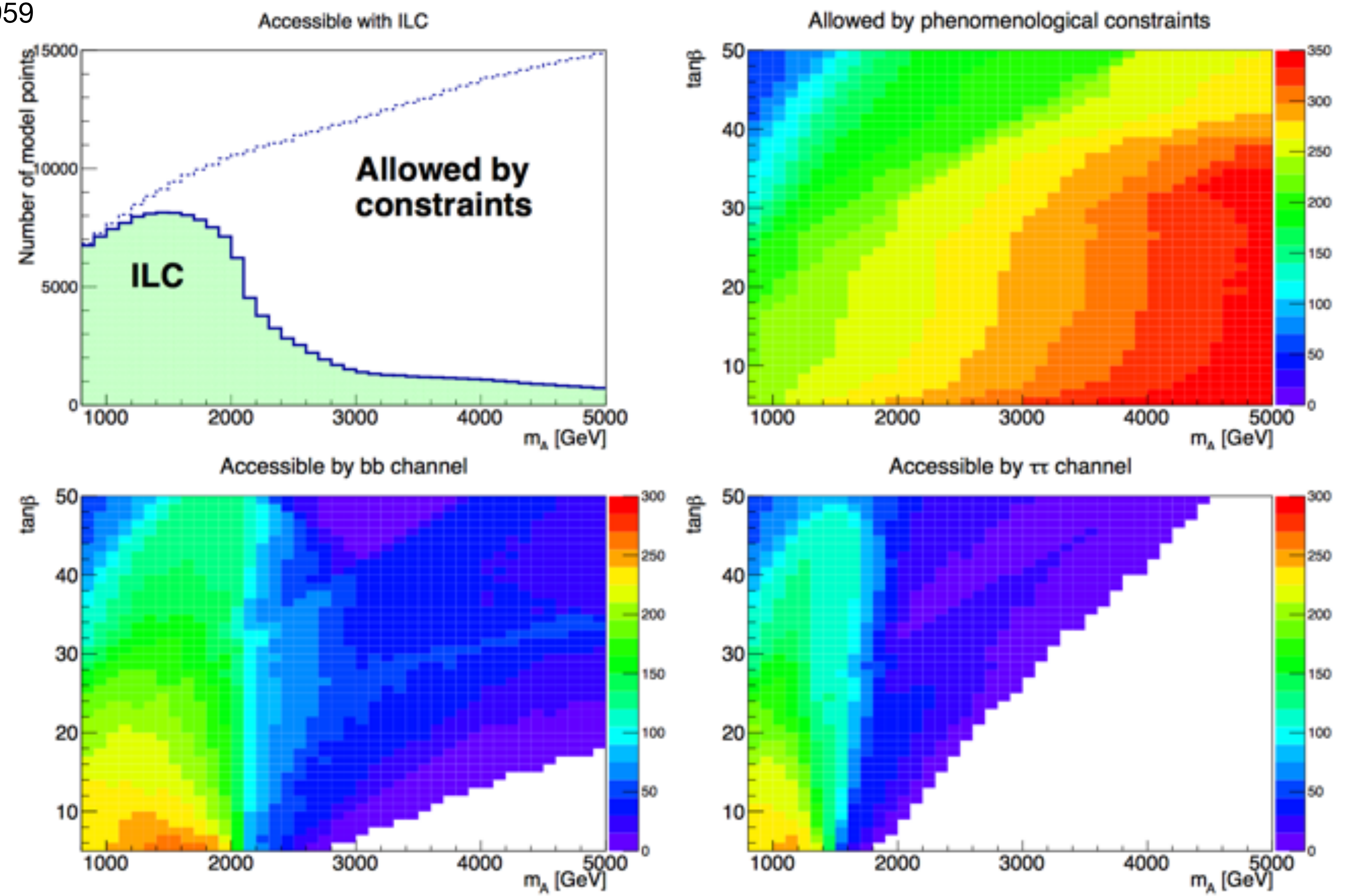


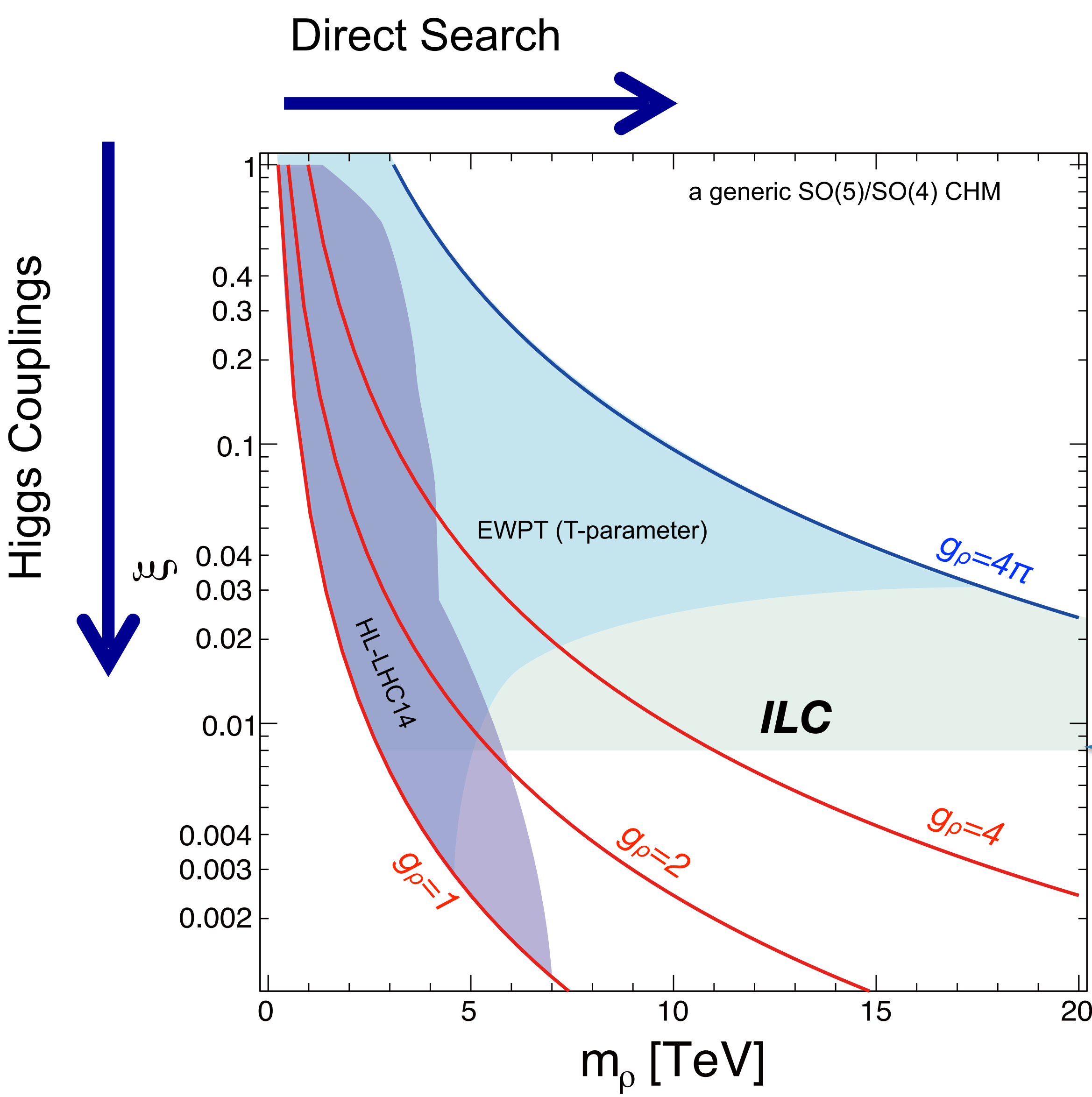
Figure 8: Upper-left: The number of model points accessible with ILC by at least one decay mode of h as a function of m_A (green histogram), as well as that of model points allowed by the phenomenological constraints (dotted histogram). Upper-right: The number of model points allowed by the phenomenological 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_*)



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

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

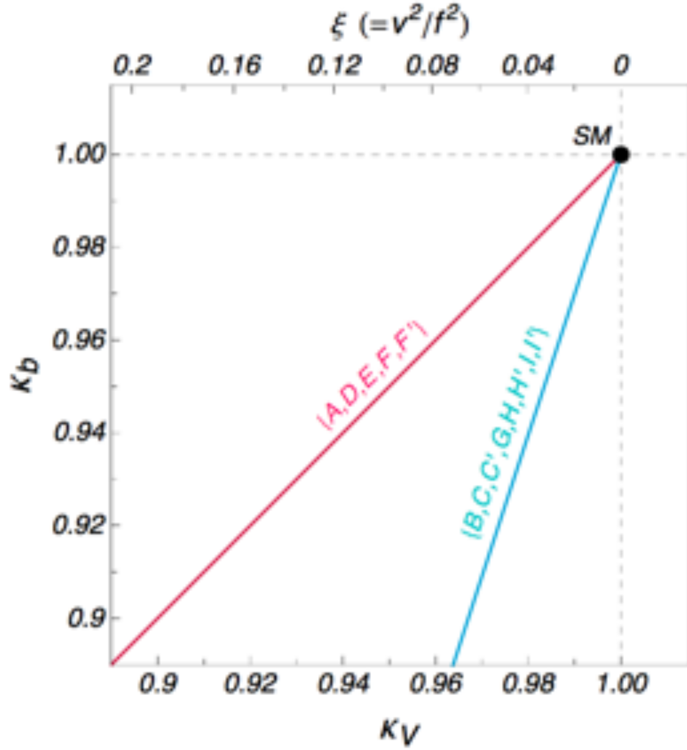
$$\frac{g_{hVV}}{g_{h_{SM}VV}} = \sqrt{1-\xi}$$

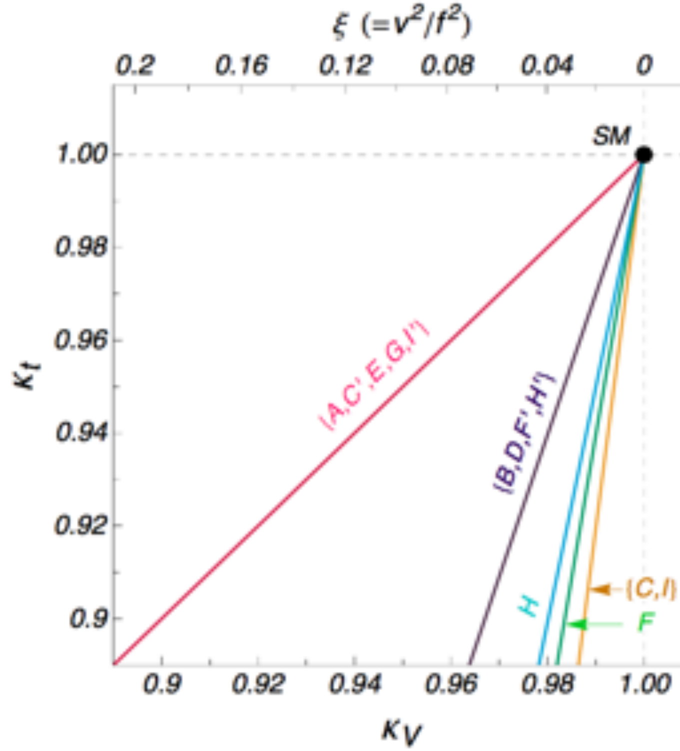
ILC (250+500 LumiUP)

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

New resonance scale and fingerprint identification in minimal composite Higgs models

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





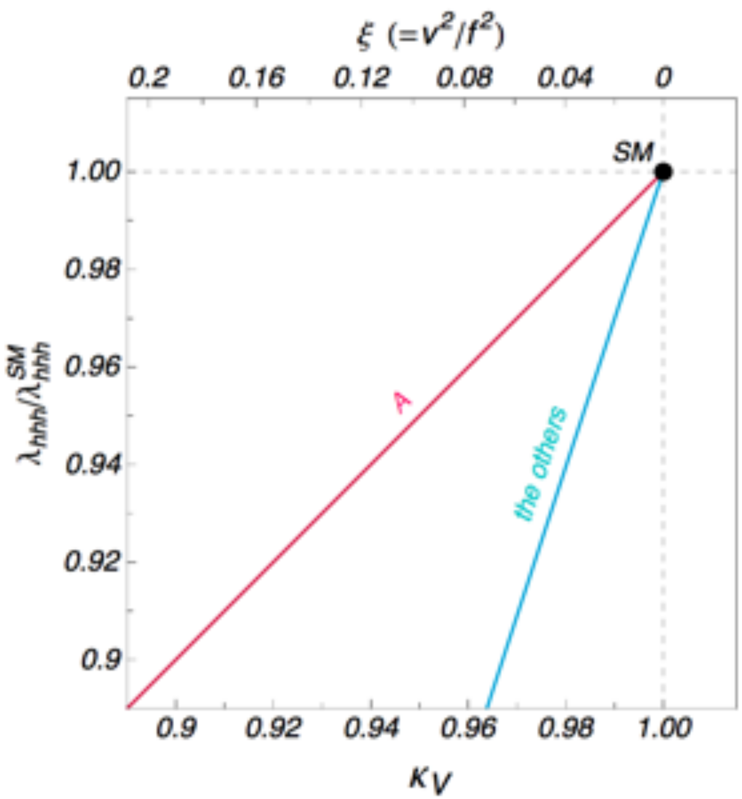


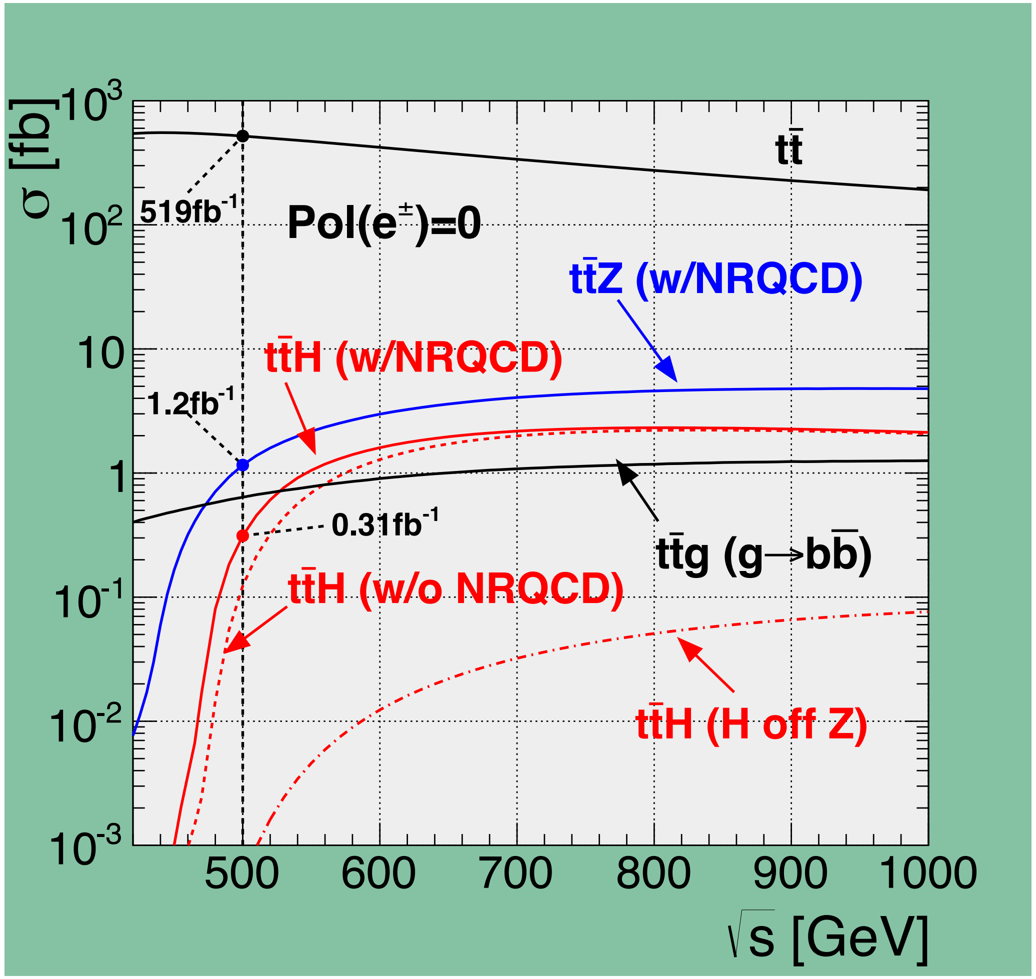
TABLE I: Scale factors for MCHMs with various matter representations. The labels are used in Fig. 7, where C, H and I are the case of $M_1^t \to 0$, and C', H' and I' are the case of $M_2^t \to 0$.

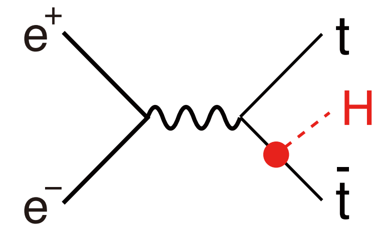
Label	Model	κ_V	c_{hhVV}	κ_{hhh}	c_{hhhh}	κ_t	κ_b	c_{hhtt}	c_{hhbb}
A	$MCHM_4$	$\sqrt{1-\xi}$	$1-2\xi$	$\sqrt{1-\xi}$	$1-\frac{7}{3}\xi$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$	$-\xi$	$-\xi$
B	$MCHM_5$	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-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

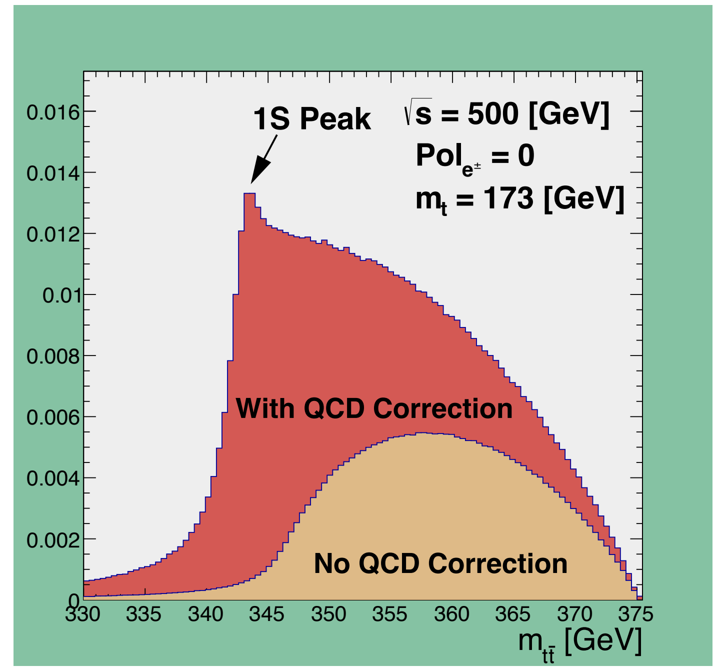
Top Yukawa Coupling

The largest among matter fermions, but not yet directly observed





H-> bb



A factor of 2 enhancement from QCD bound-state effects

Cross section maximum at around Ecm = 800GeV

Philipp Roloff, LCWS12

Tony Price, LCWS12

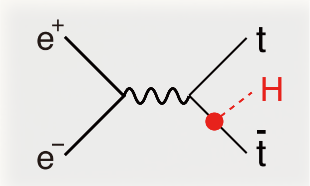
DBD Full Simulation

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

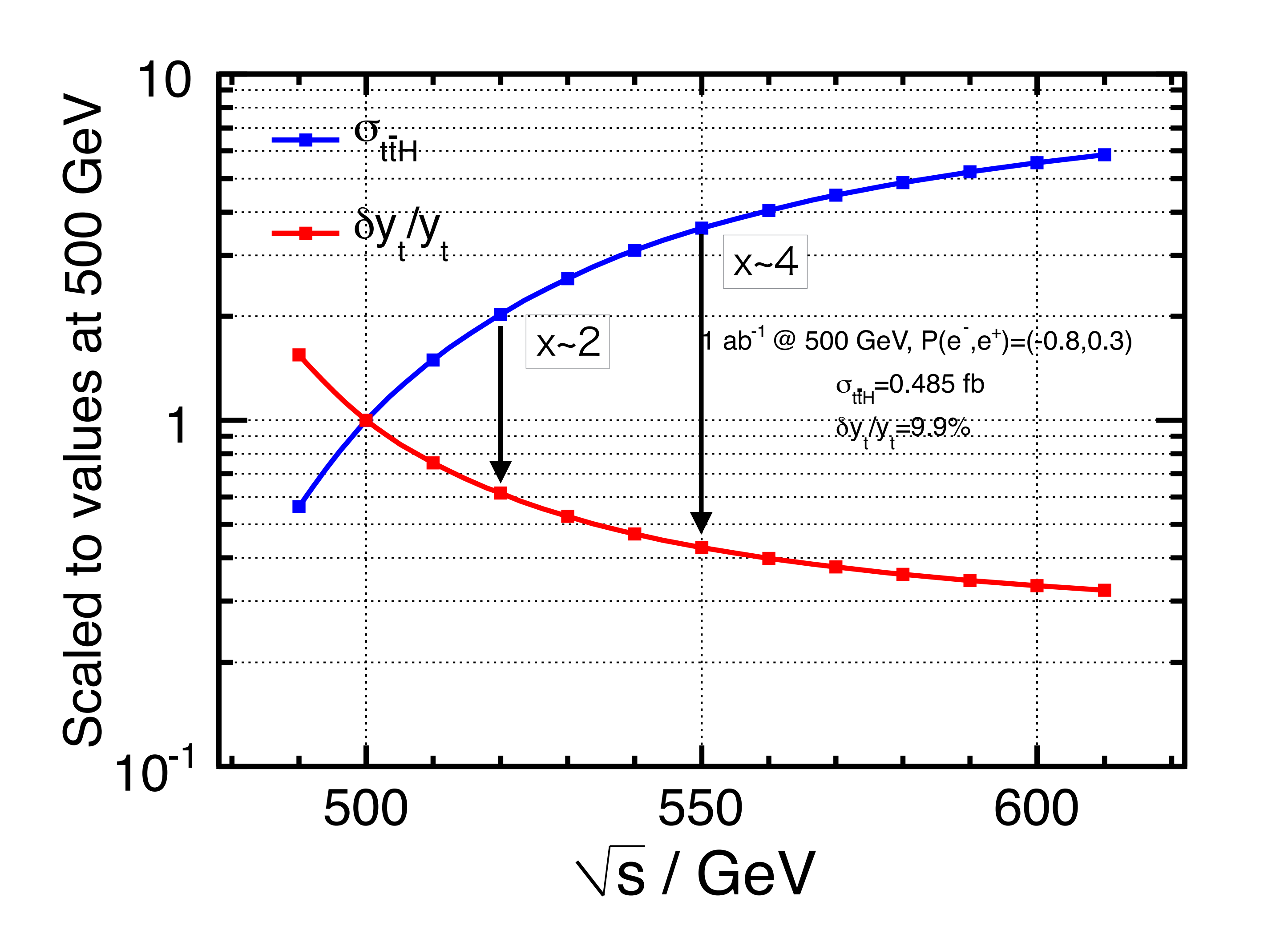
$$\Delta g_Y(t)/g_Y(t) = 9.9\%$$

Tony Price, LCWS12 scaled from mH=120 GeV

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



Top Yukawa coupling



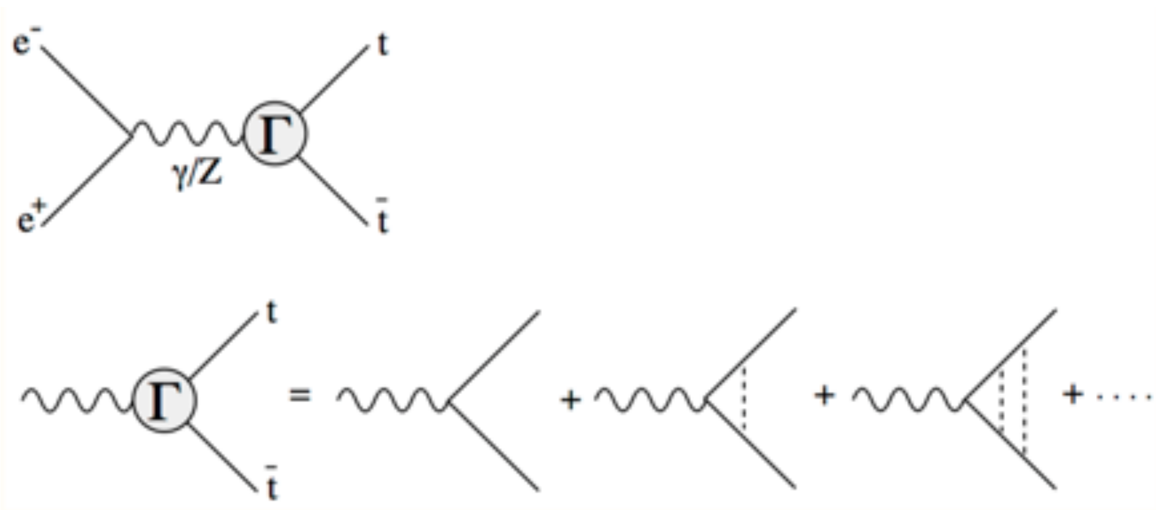
Y. Sudo

Slight increase of E_{max} is very beneficial!

Top

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:

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

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

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

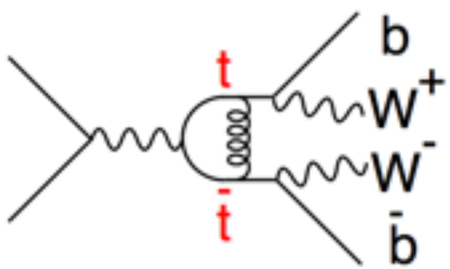
$$\tilde{F}^l(\boldsymbol{p}; E) \equiv \langle\, \boldsymbol{p} \,|\, G \cdot \hat{p}^l \,|\, \boldsymbol{x} = \boldsymbol{0} \,\rangle$$

for axial vector part

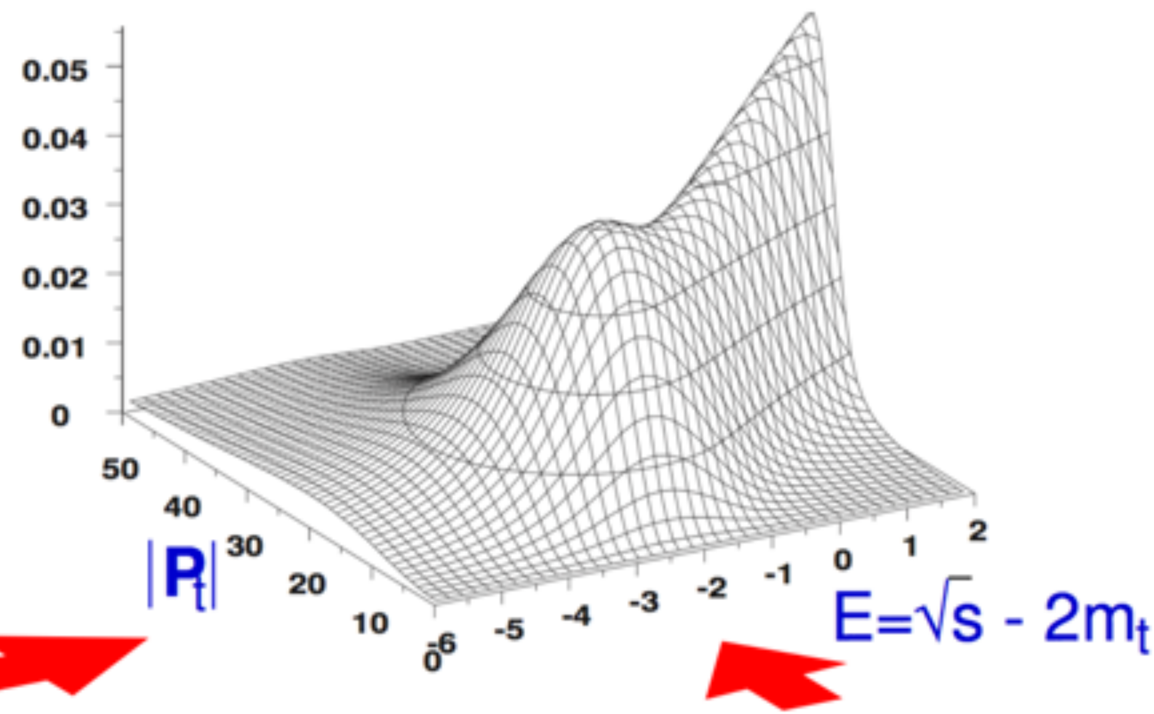
Top Quark

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

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)

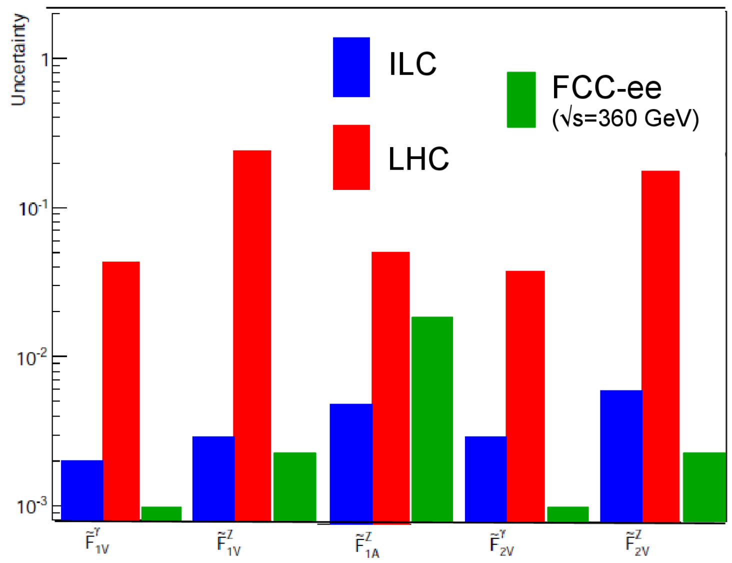
- no beam polarization, use final-state polarization instead

  (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

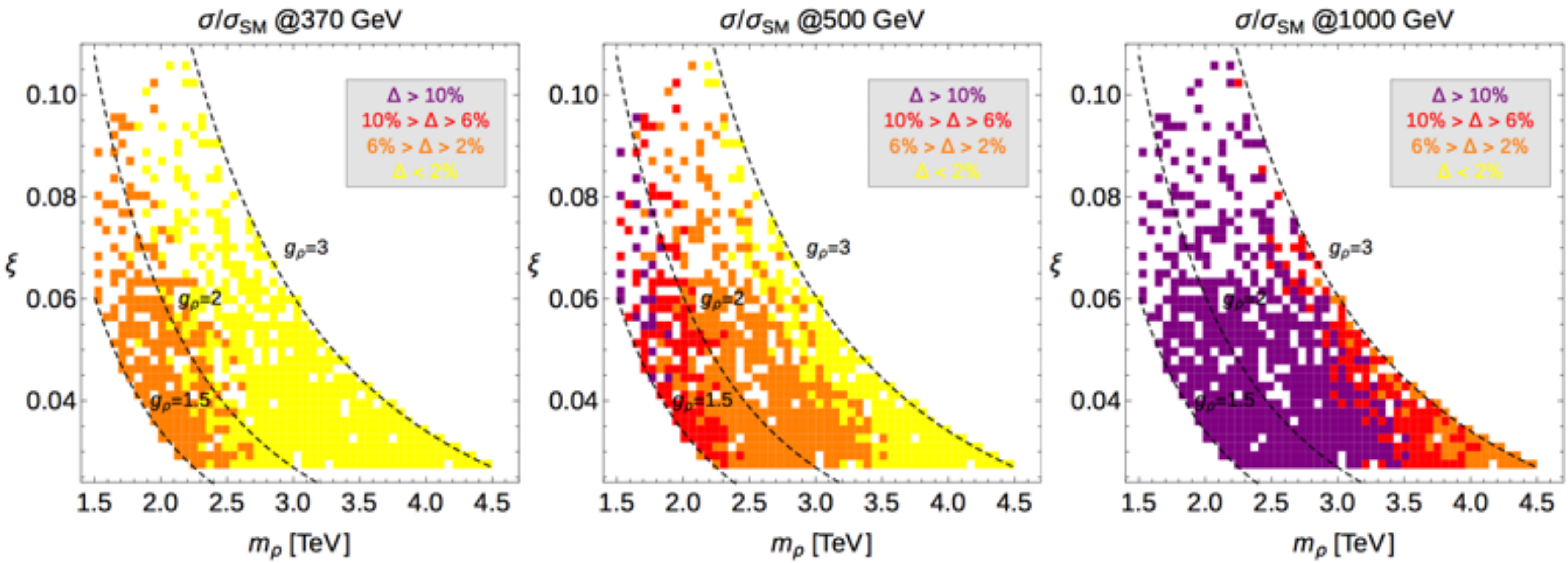


Figure 5. Predicted deviations for the cross section of the process $e^+e^- \to t\bar{t}$ at 370, 500, 1000 GeV in the 4DCHM compared with the SM as functions of $m_\rho = fg_\rho$ and $\xi = v^2/f^2$. For each point we have selected the configuration yielding the maximal deviation defined as $\Delta = (\sigma^{4DCHM} - \sigma^{SM})/\sigma^{SM}$. The points correspond to $f = 0.75 - 1.5\,\text{TeV}$, $g_\rho = 1.5 - 3$. Bounds on the masses of the extra fermions are the same as in figure 2.

Cosme, Lopes, Penedones: JHEP08 (2015) 127

DM

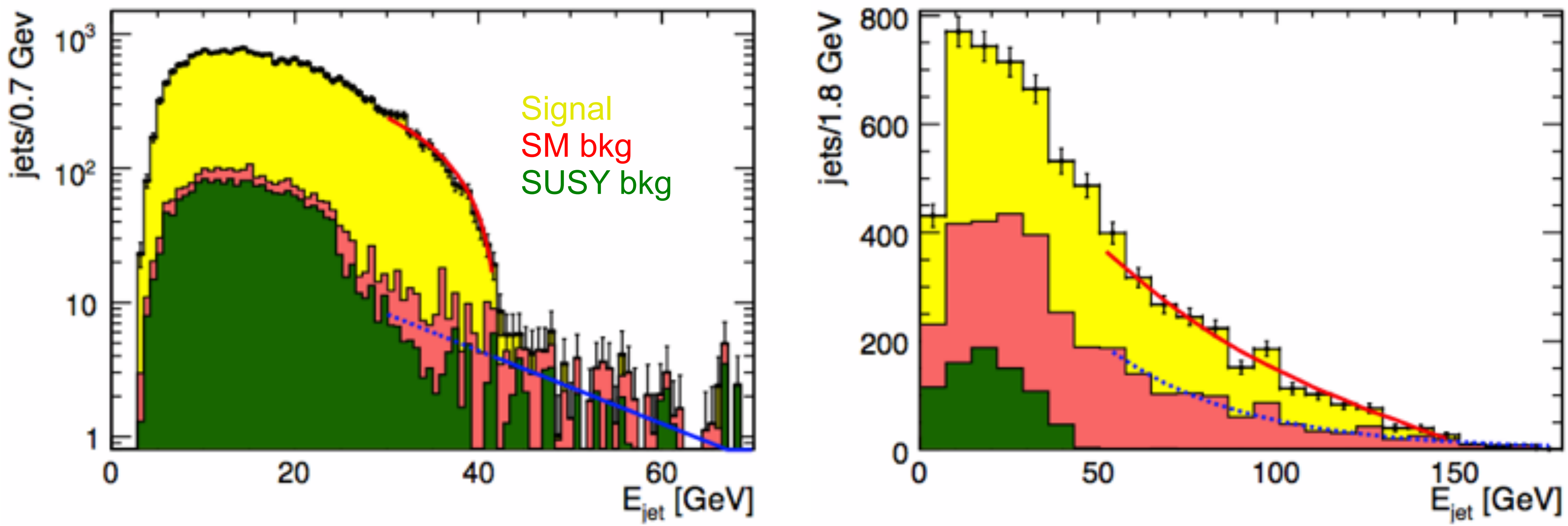
Slepton decays to DM with small mass differences

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)

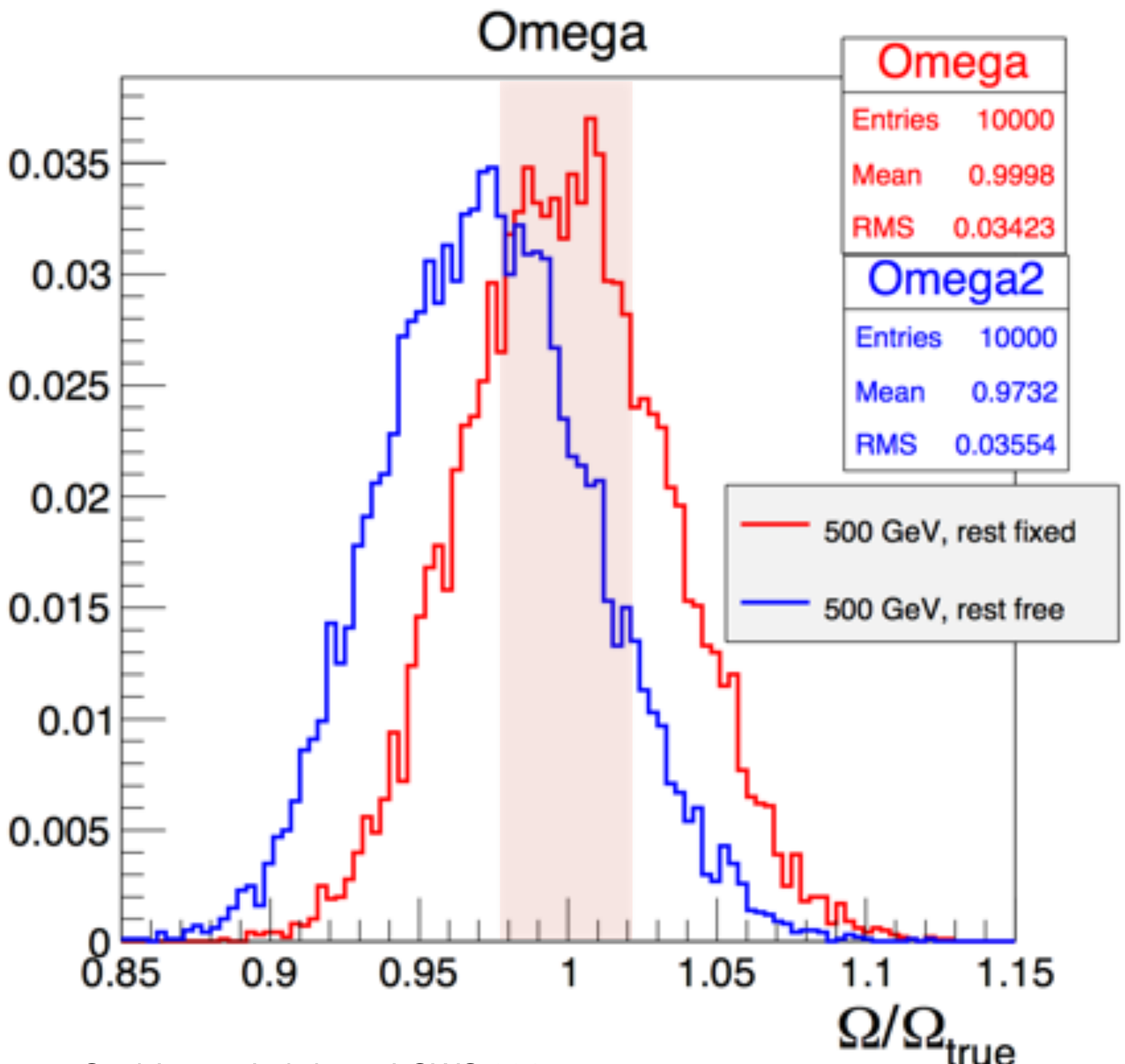


√s=500 GeV, Lumi=500 fb-1, P(e-,e+)=(+0.8,-0.3)
Stau1 mass ~0.1%, Stau2 mass ~3% → LSP mass ~1.7%

DM Relic Abundance

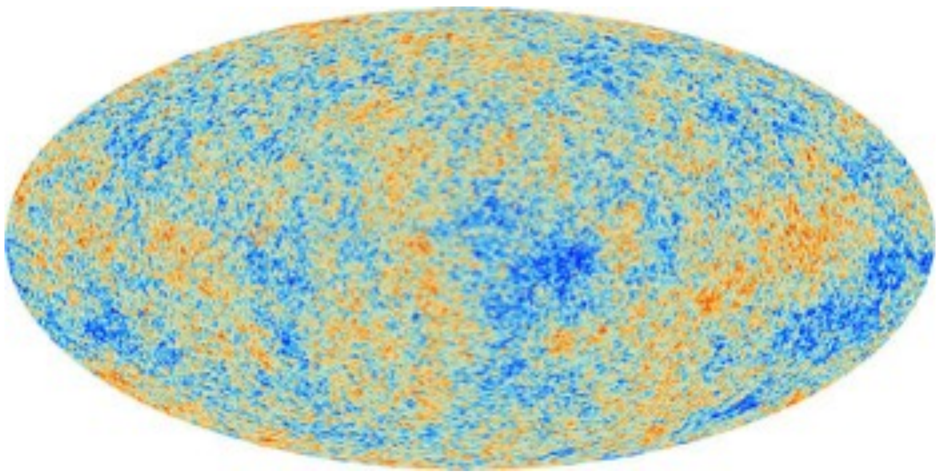
WMAP/Planck (68% CL)

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



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

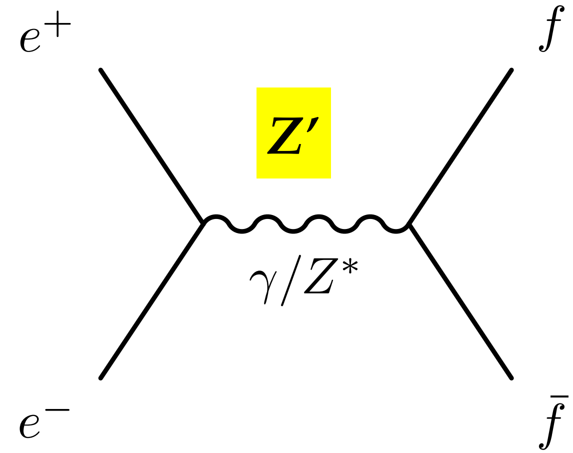
Other Probes

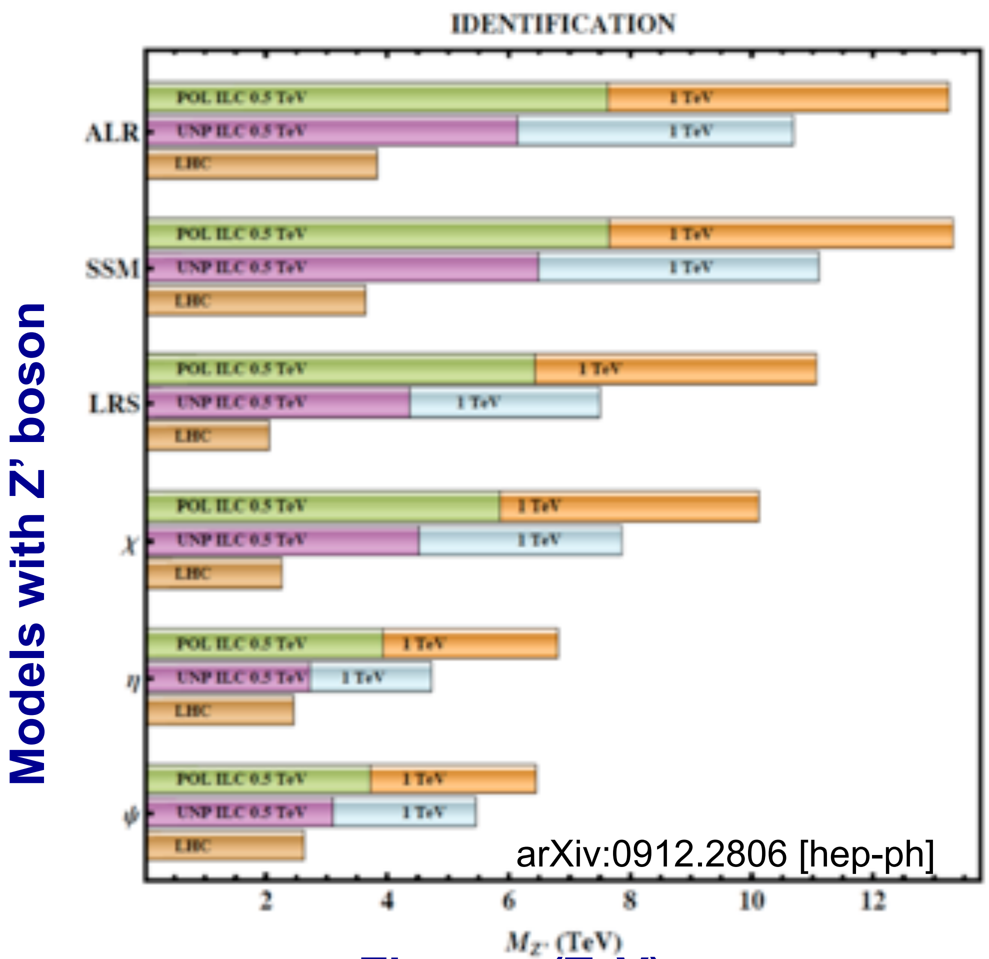
Z’

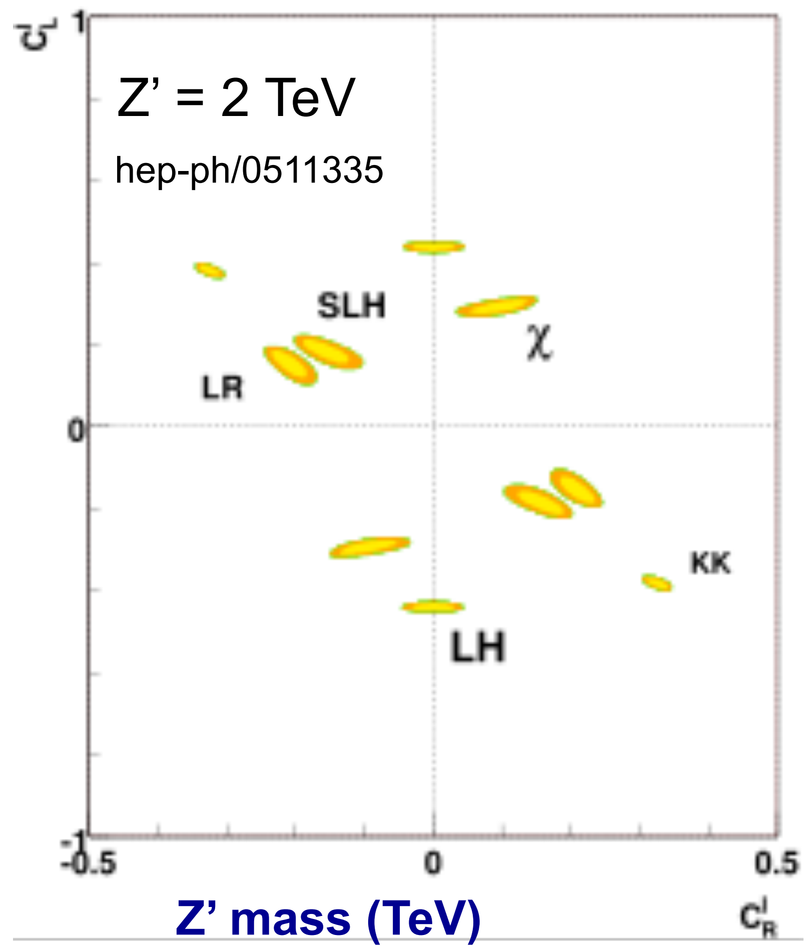
Z' : Heavy Neutral Gauge Bosons

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







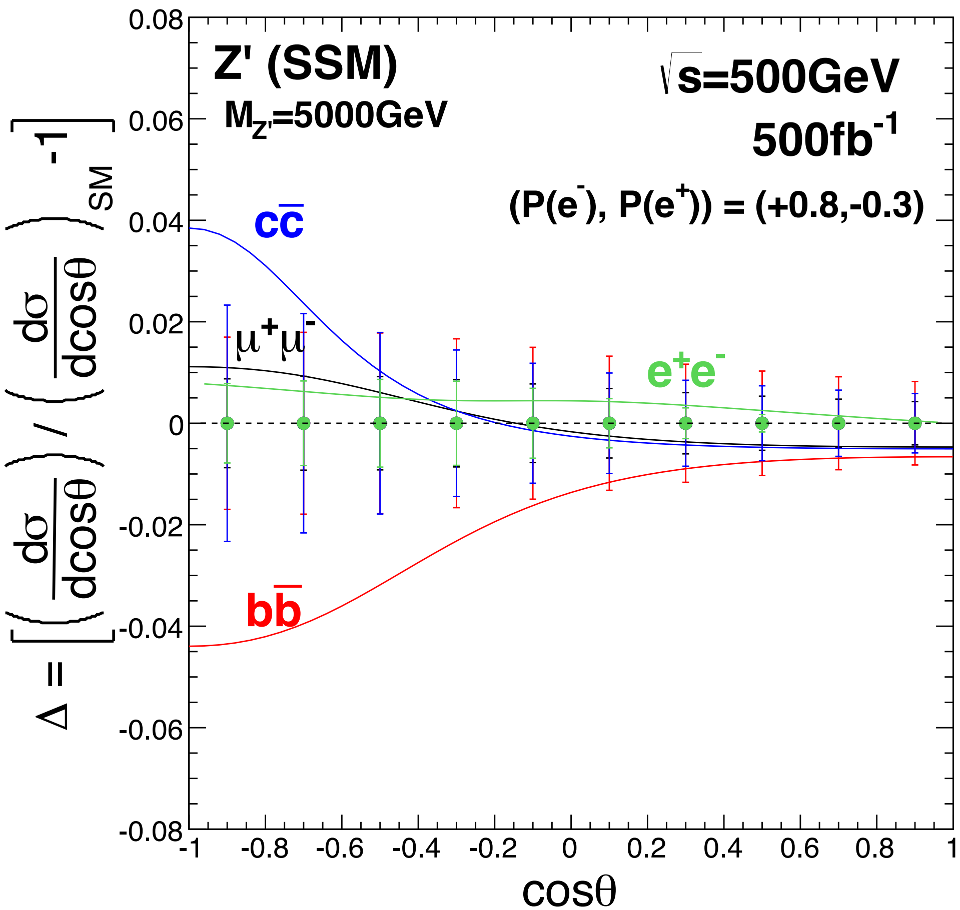
Two-Fermion Processes

Z' Search / Study

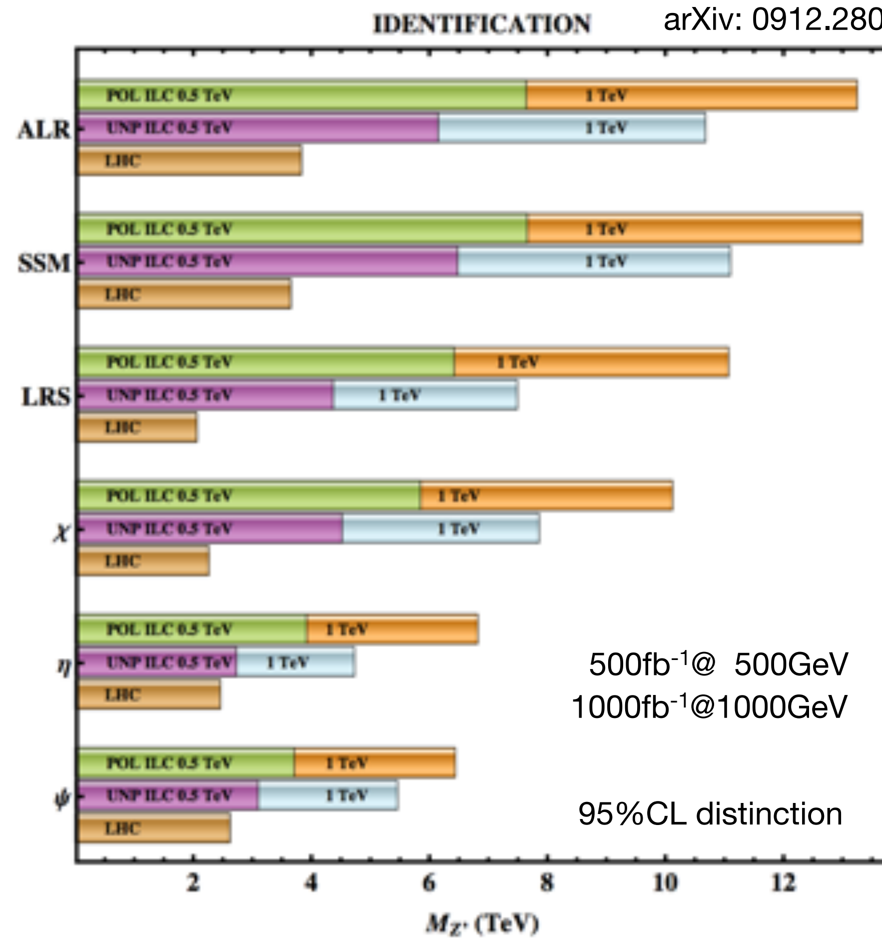
Observables: dσ(P-,P+)/d cosθ

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

Example: Sequential SM-like Z'



arXiv: 0912.2806



Two-Fermion Processes

Z' Search / Study

arXiv:0912.2806 [hep-ph]

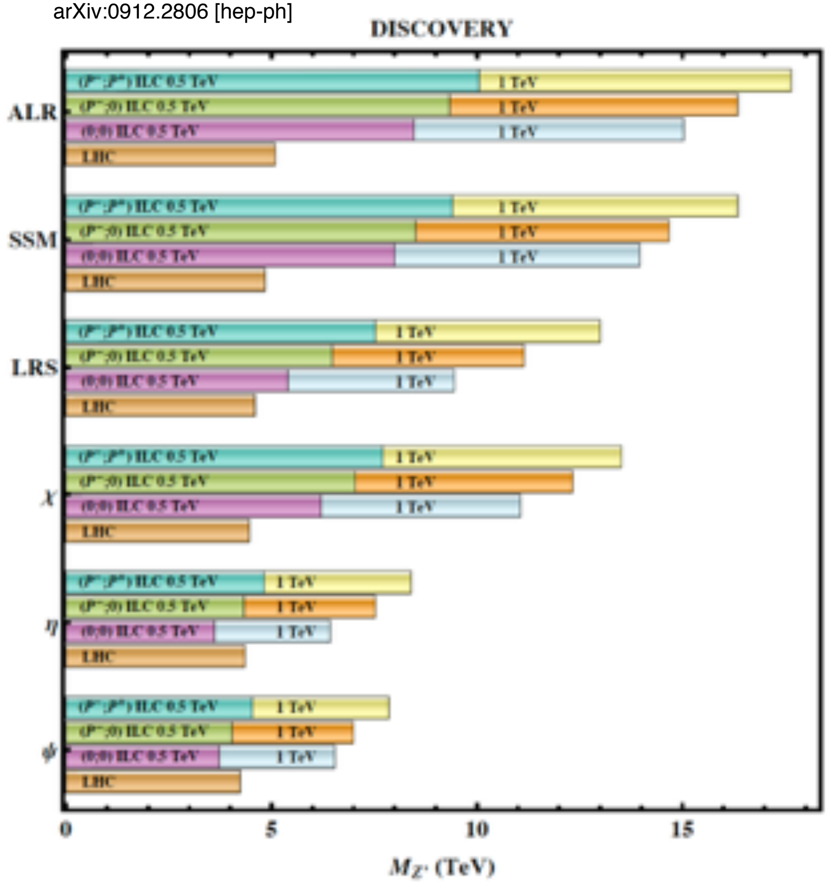
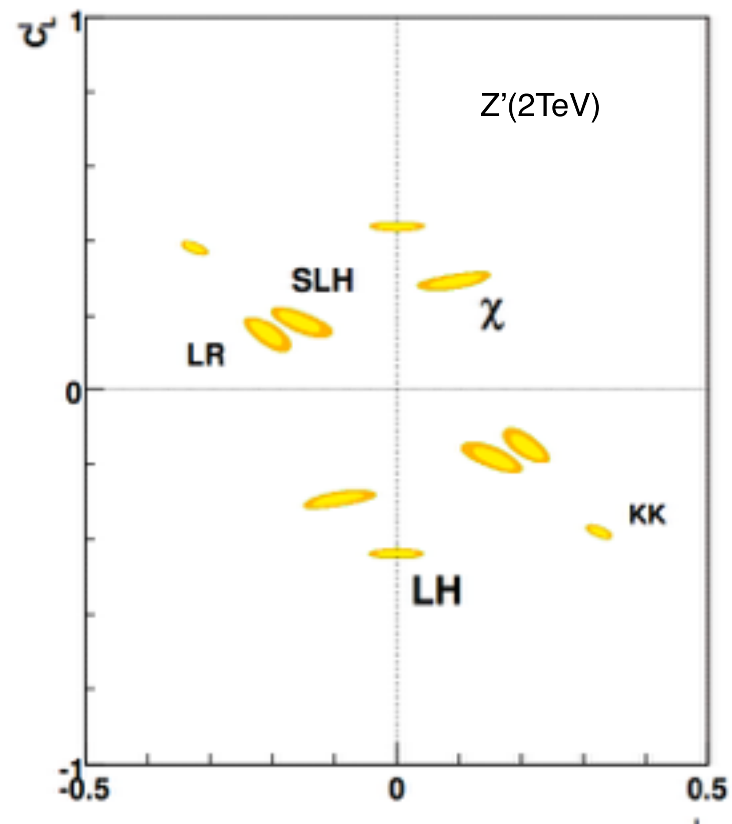


Figure 23: Sensitivity of the ILC to various candidate Z' bosons, quoted at 95% conf., with $\sqrt{s} = 0.5$ (1.0) TeV and $\mathcal{L}_{\rm int} = 500$ (1000) fb^{-1}. The sensitivity of the LHC-14 via Drell-Yan process $pp \to \ell^+\ell^- + X$ with 100 fb^{-1} of data are shown for comparison. For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

hep-ph/0511335



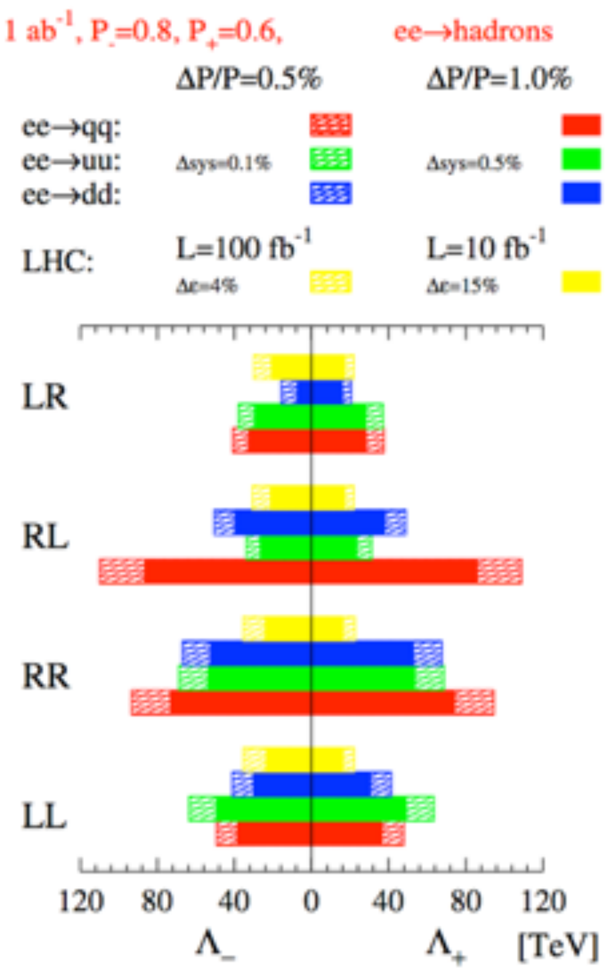
ILC's Model ID capability is expected to exceed that of LHC even if we cannot hit the Z' pole.

Beam polarization is essential to sort out various possibilities.

Two-Fermion Processes

Compositeness

S. Riemann, LC-TH-2001-007



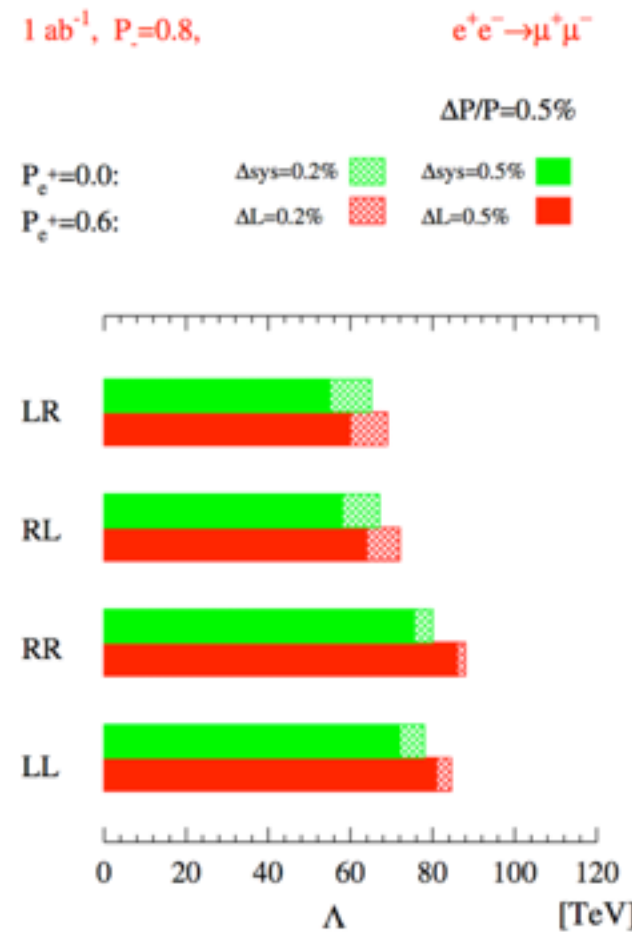


Figure 26: Sensitivities (95% c.l.) of a 500 GeV ILC to contact interaction scales Λ for different helicities in $e^+e^- \to$ hadrons (left) and $e^+e^- \to \mu^+\mu^-$ (right), including beam polarization [18].

Beam polarization is essential to sort out various possibilities.