Big Questions in Particle Physics and the ILC Project

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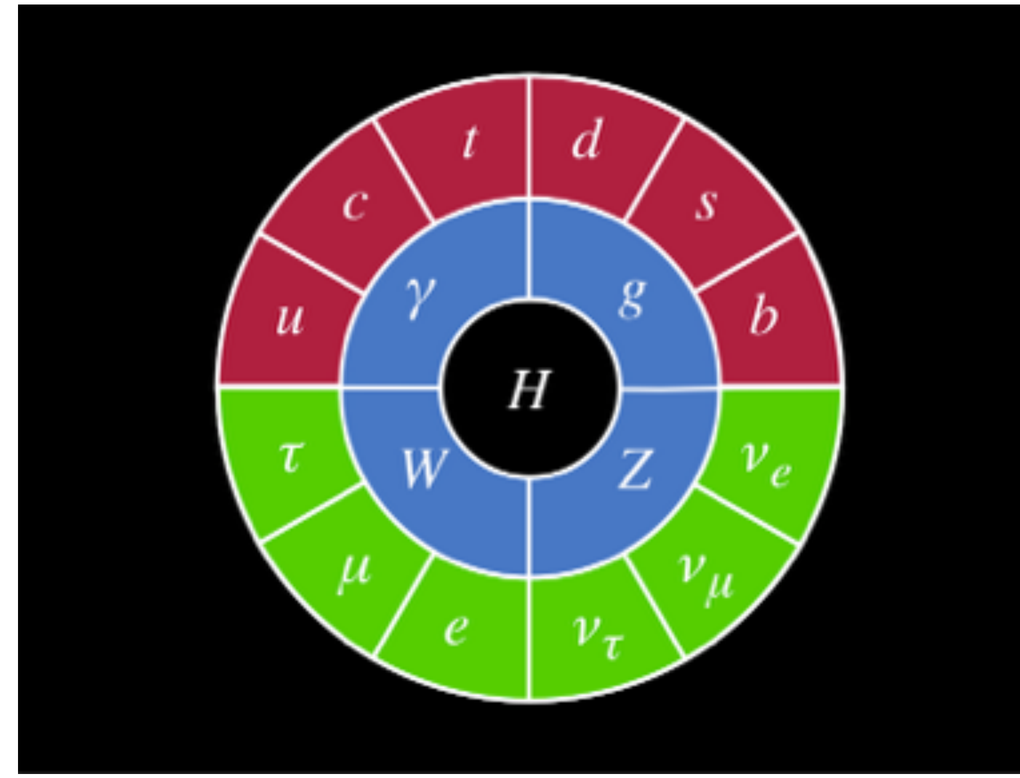
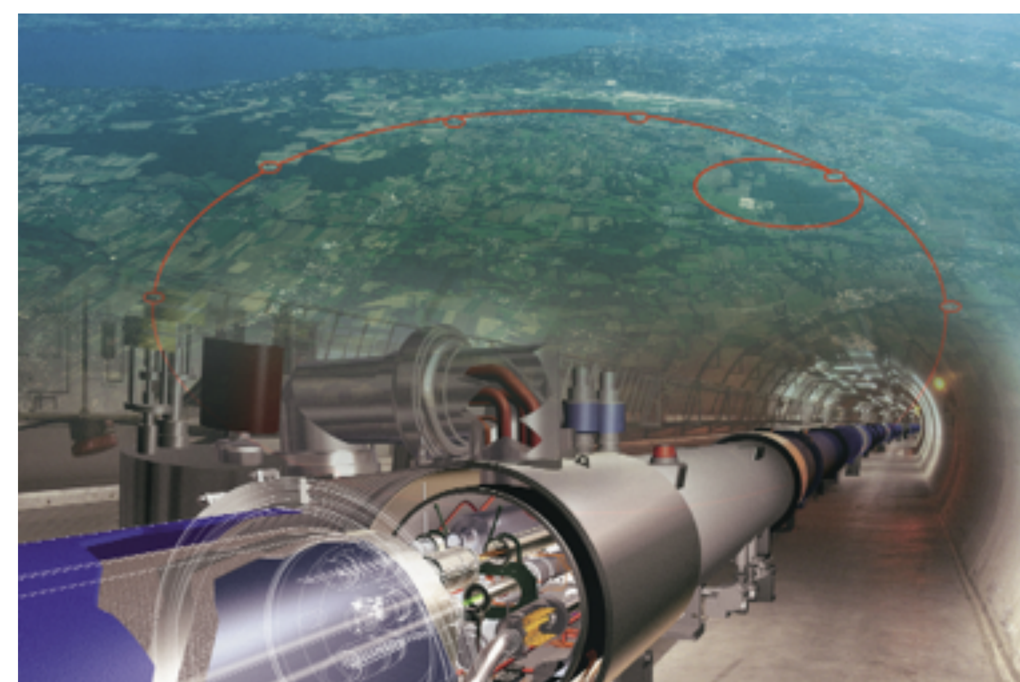
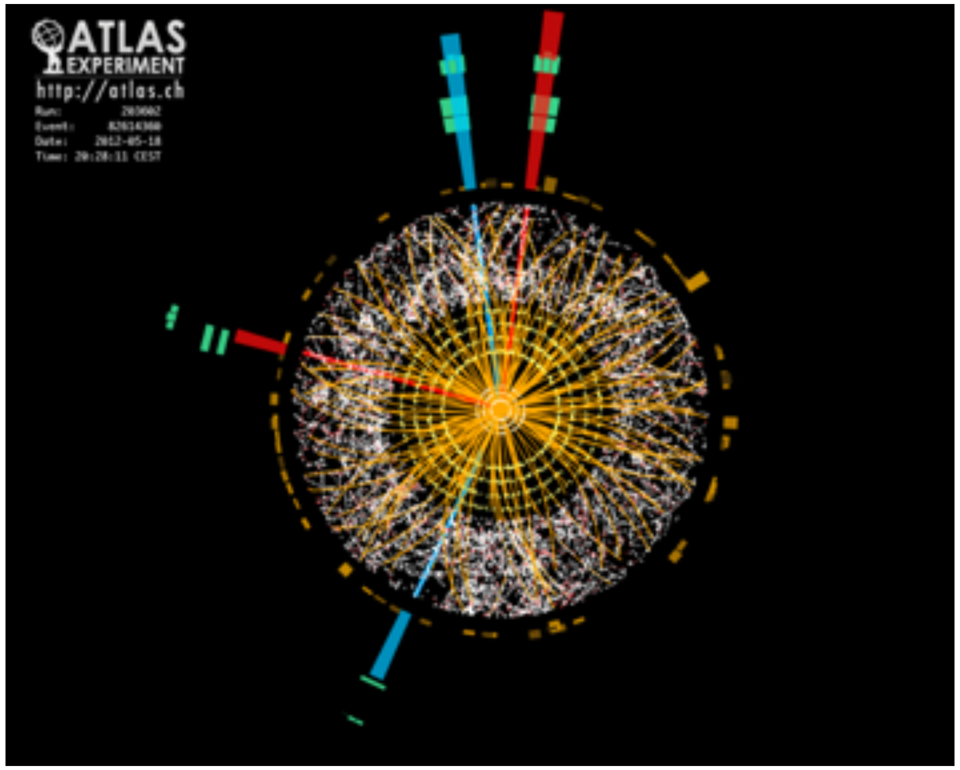
Where We Are Now

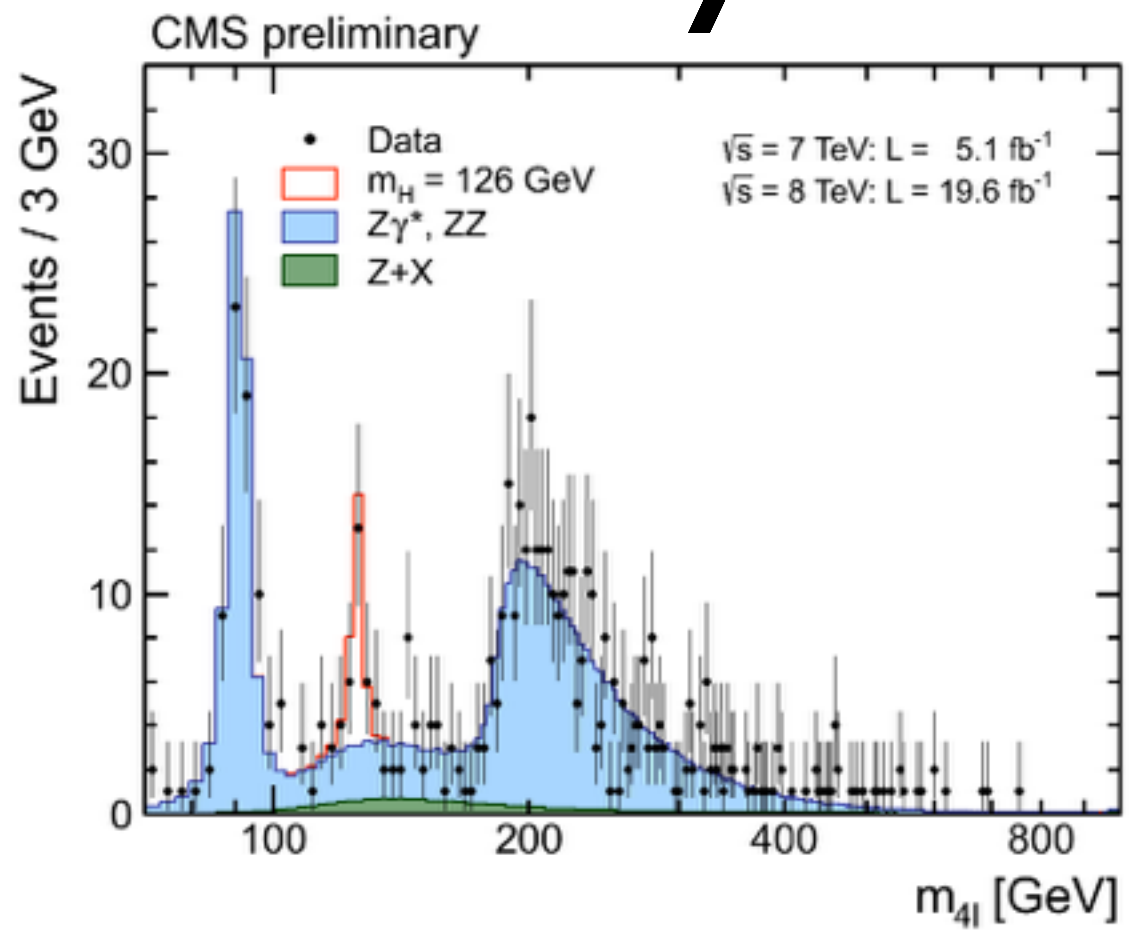
- The Standard Model (SM) has been the undisputed queen of particle physics since (at least) the late 1970’s
- Aspects of SM have been probed with increasing degree of precision by LEP, SLC/SLD, Tevatron, CLEO, Belle, BaBar, etc.
- Since 2010, experiments at the Large Hadron Collider (LHC) at CERN are pushing the high-energy frontier
- Higgs discovery completes the verification of SM particle content





Higgs Discovery!





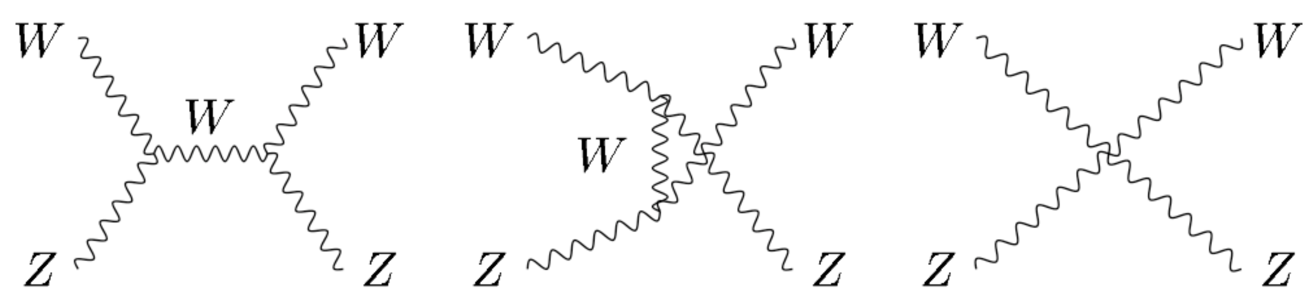
Why is the Higgs Special?

- Higgs boson is the only spin-0 particle in the SM
- Constant and uniform Higgs field is predicted to exist everywhere in space, even in the "vacuum" (i.e. lowest energy state of the universe)
- Masses of all other SM particles arise from their interactions with the "vacuum" Higgs field. Prediction: Higgs coupling to X proportional to mass of X.
- Existence of the Higgs and the structure of its interactions allows the SM to be extrapolated to very high energies, without entering strong-coupling regime

Higgs and Unitarity

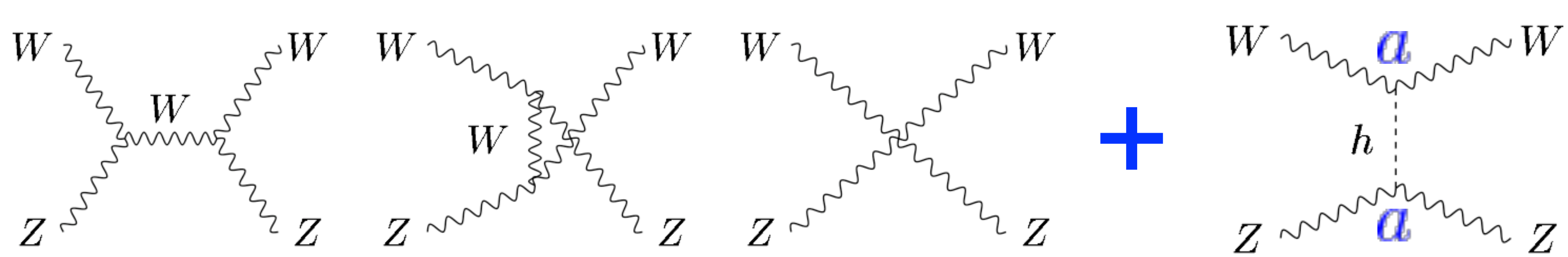
- As an example, consider the process $W + Z \to W + Z$

- In the SM without the Higgs, perturbative amplitude grows with energy, eventually predict Prob>1- nonsense!



$\mathcal{M} \propto E^2$

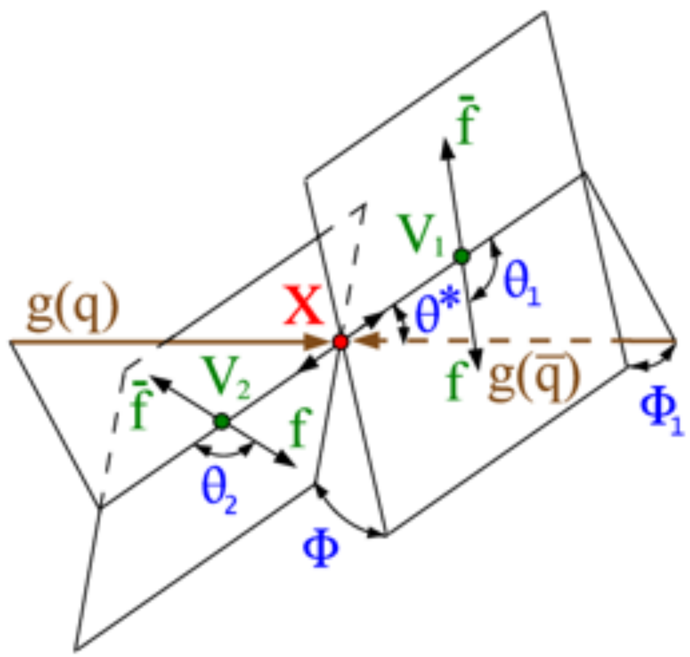
- In the SM with the Higgs, the problem is fixed - theory can be valid up to arbitrarily high scale (until Planck)



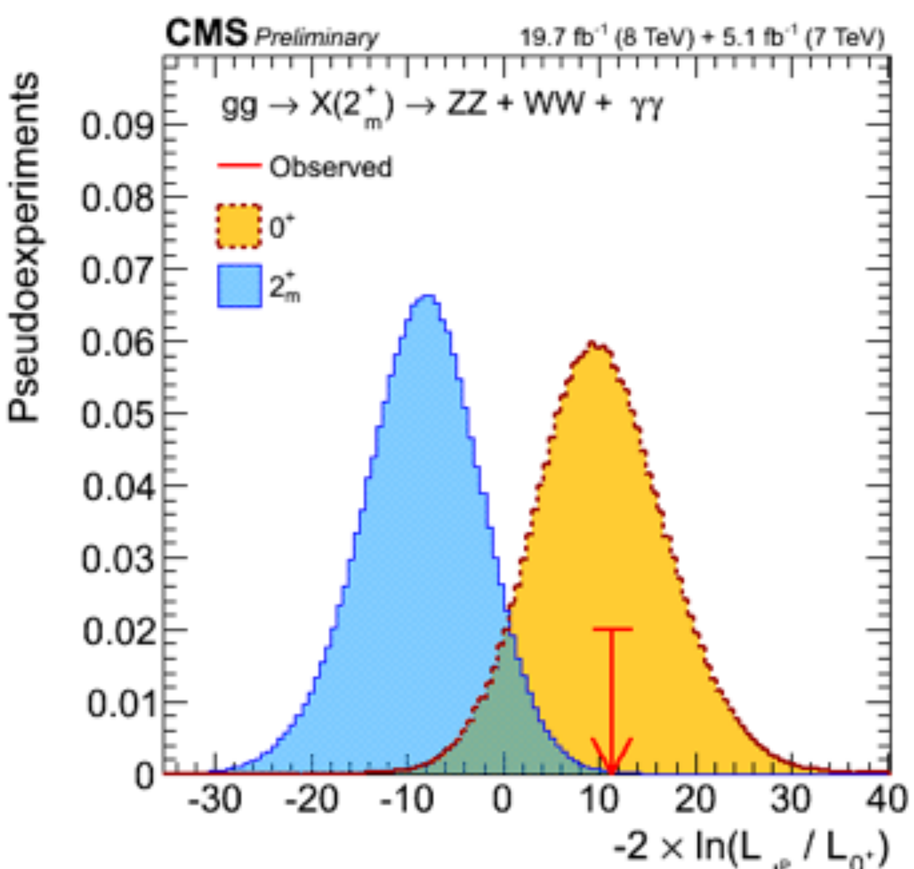
$\mathcal{M} \propto E^0$!

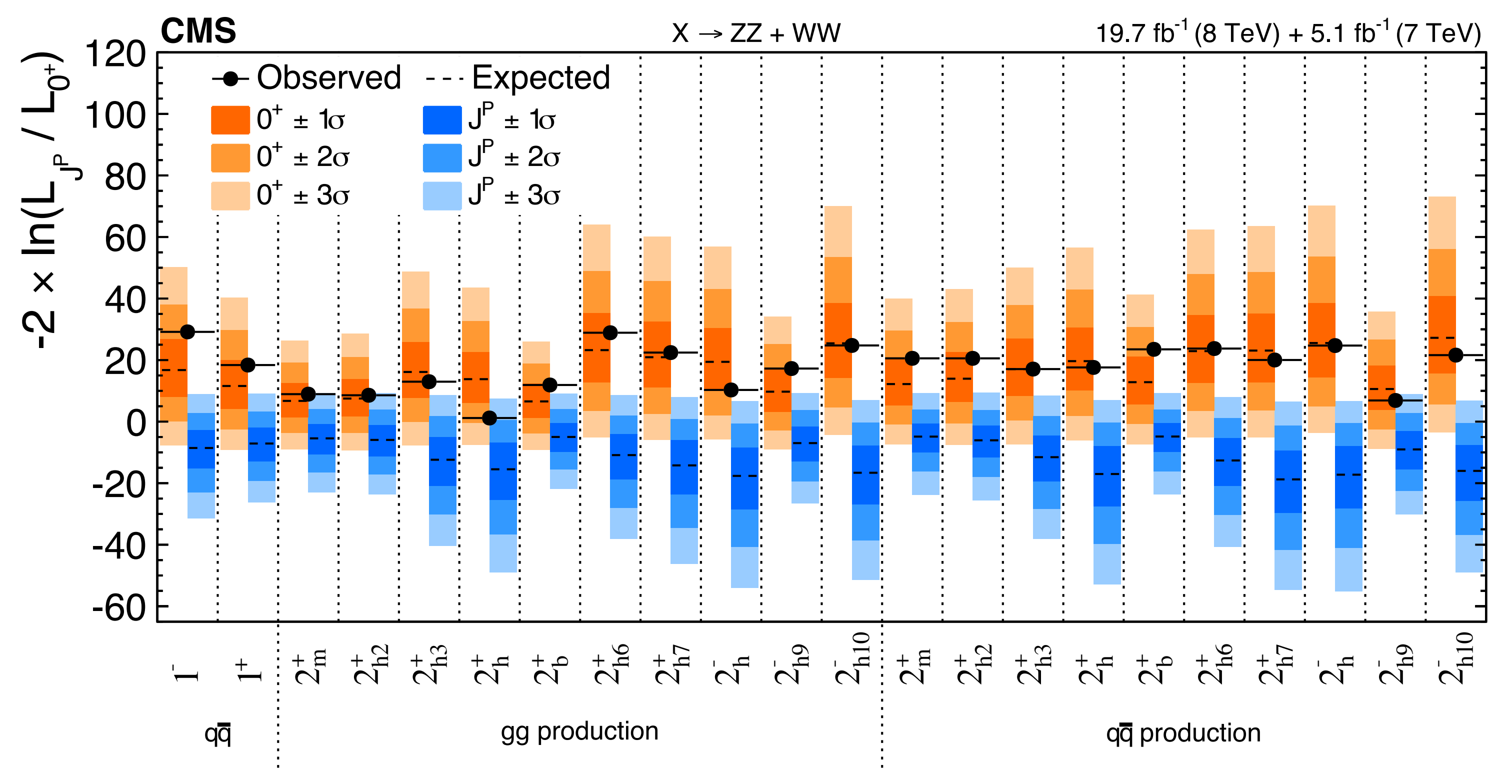
- If the HWW coupling is not exactly SM, cancellation is spoiled, the theory "predicts its own demise": $\Lambda \sim \dfrac{4\pi v}{\sqrt{1-a^2}}$

Higgs Spin: LHC Data

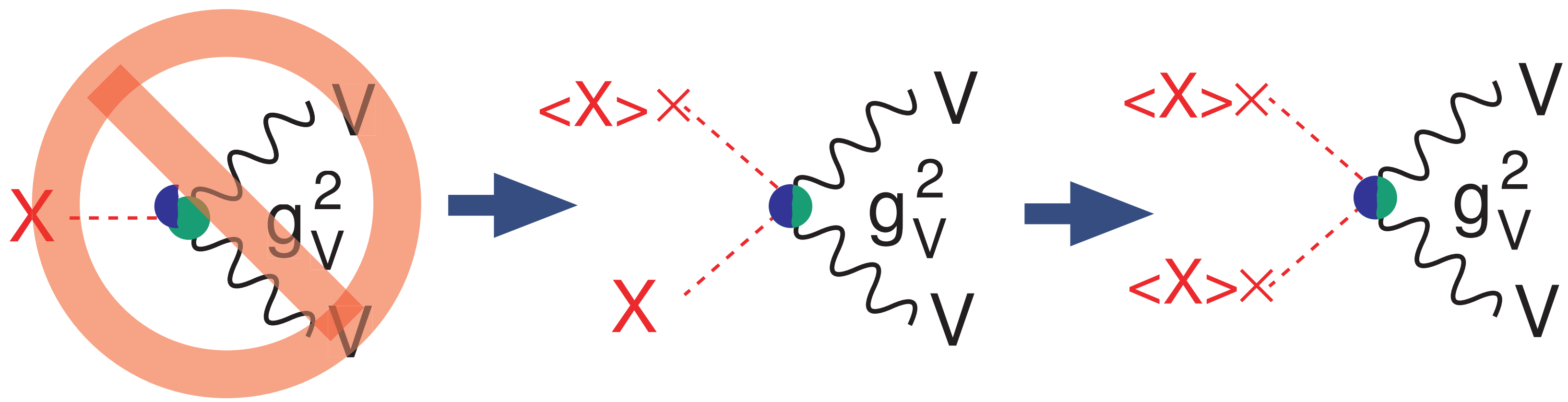


Angular distributions in $h \to ZZ^*$ consistent with $S^P = 0^+$, inconsistent with S=1, 2 at 99% c.l.

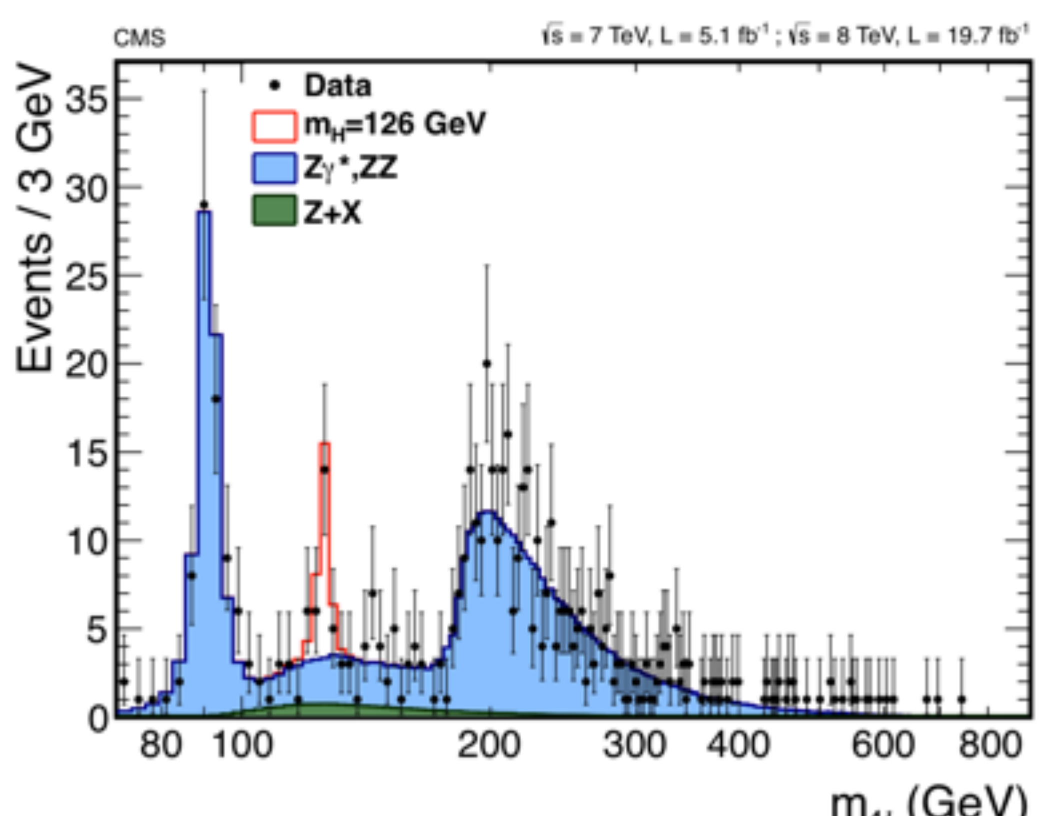


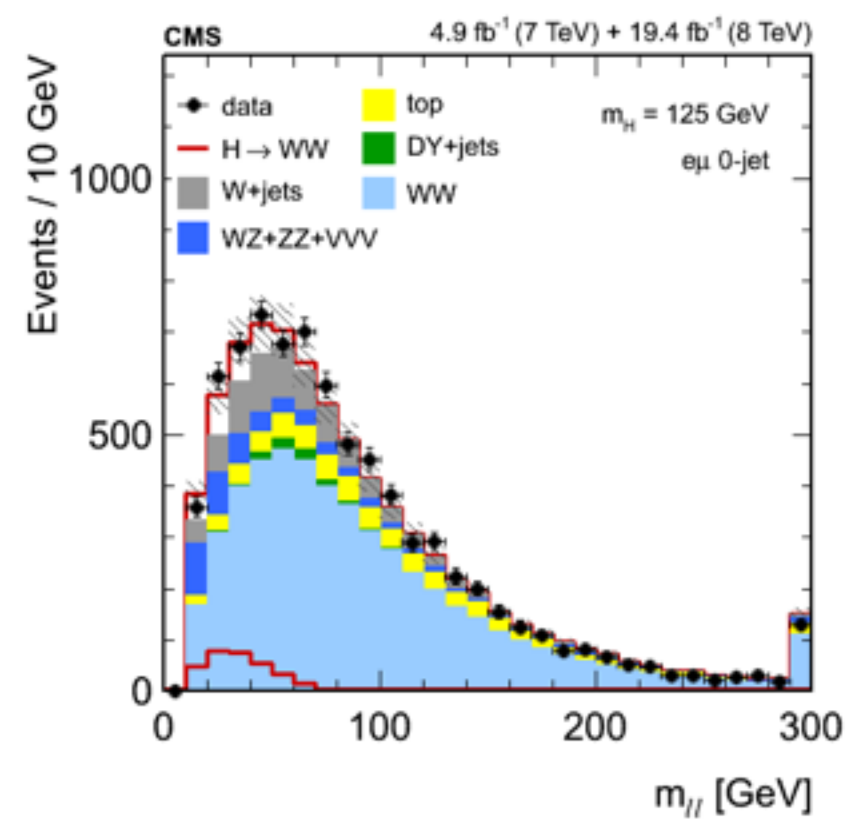


Higgs in Vacuum: LHC Data



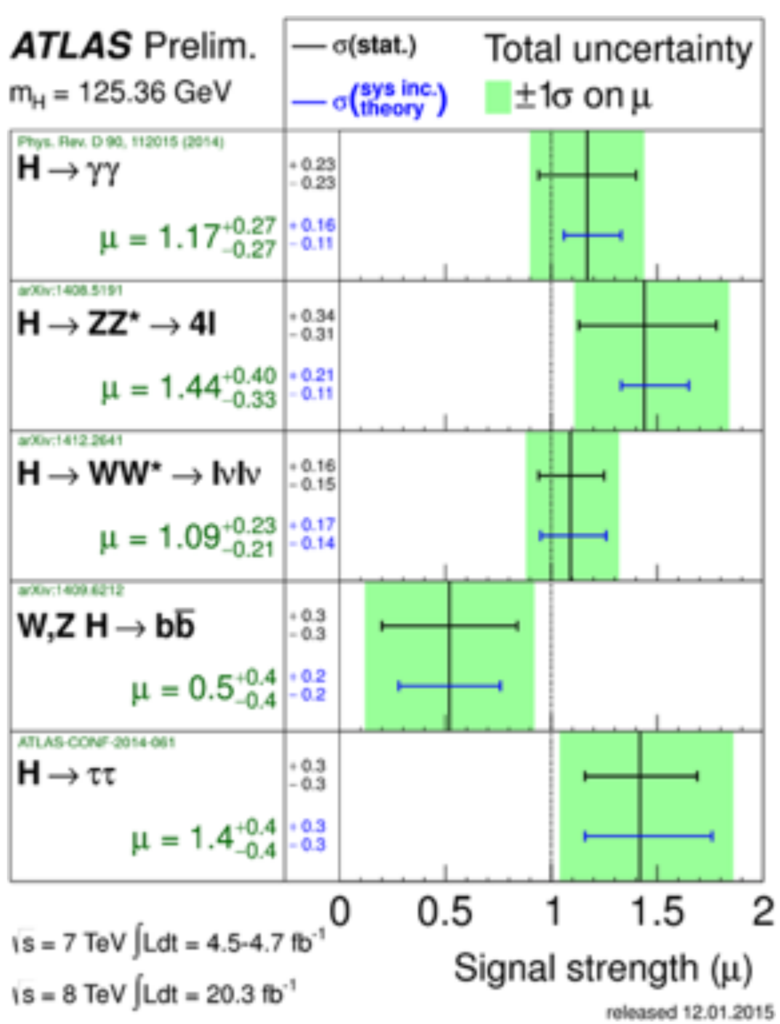
Observation of decays $h \to WW^*, ZZ$ provides strong evidence for Higgs in vacuum ("v.e.v.")

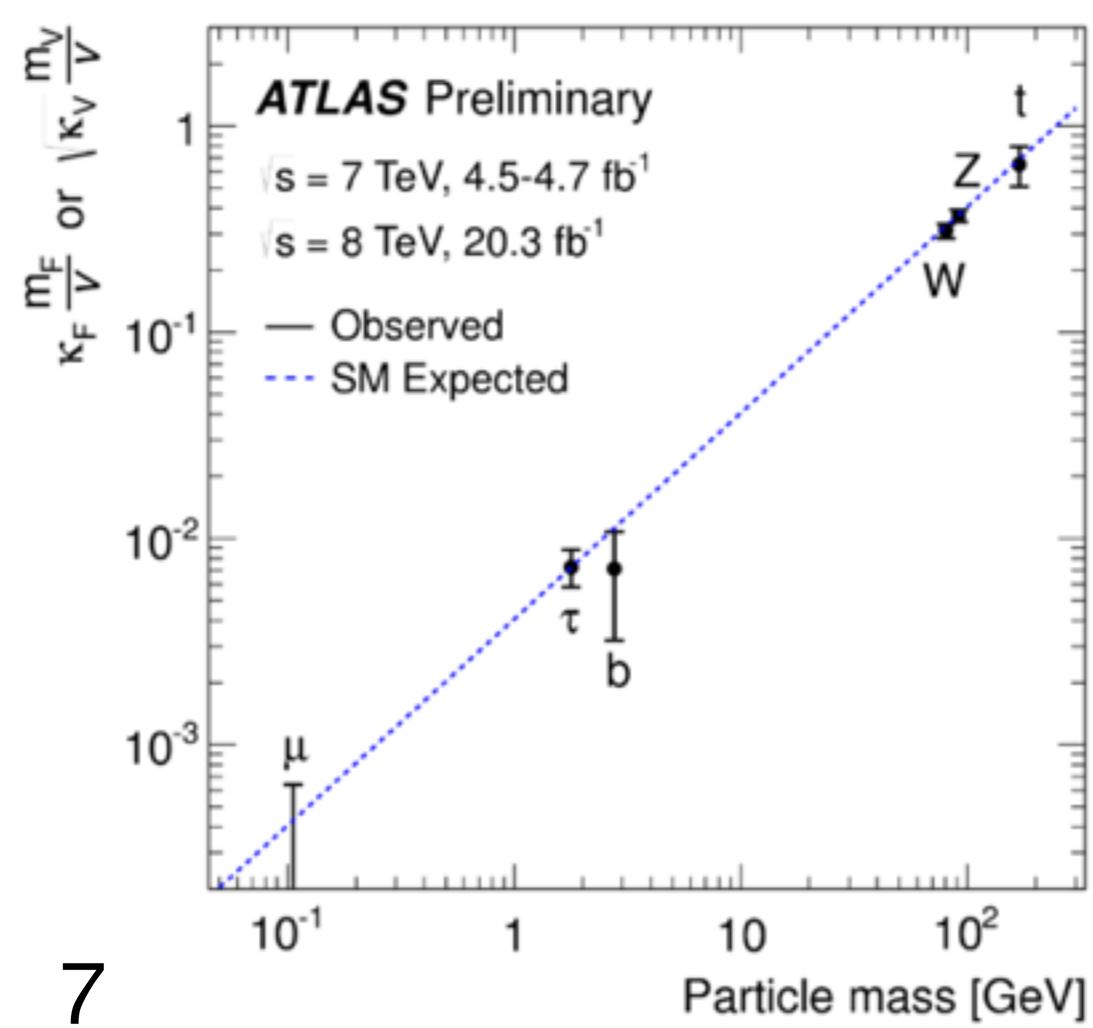




Higgs and Mass: LHC Data

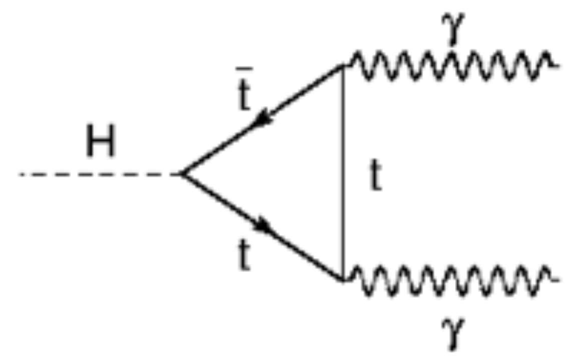
- SM predicts: tree-level Higgs couplings to all particles are linearly proportional to their masses
- Couplings determine production cross-section and decay branching ratios → rates*





*Higgs and Mass: Caveats

- Top quark coupling is not measured directly: inferred from loops



- New particles in loops can affect the inferred value. Should a deviation from SM be observed, its interpretation would be uncertain.

- Rate-to-coupling conversion assumes SM total width:

$$R \propto \frac{\sigma \times \Gamma_{H \to X\bar{X}}}{\Gamma_{\text{tot}}}$$

- No direct measurement of Γ_{tot} (it's too small); unobserved non-SM Higgs decay modes can affect the overall scale of the couplings

LHC Higgs Scorecard

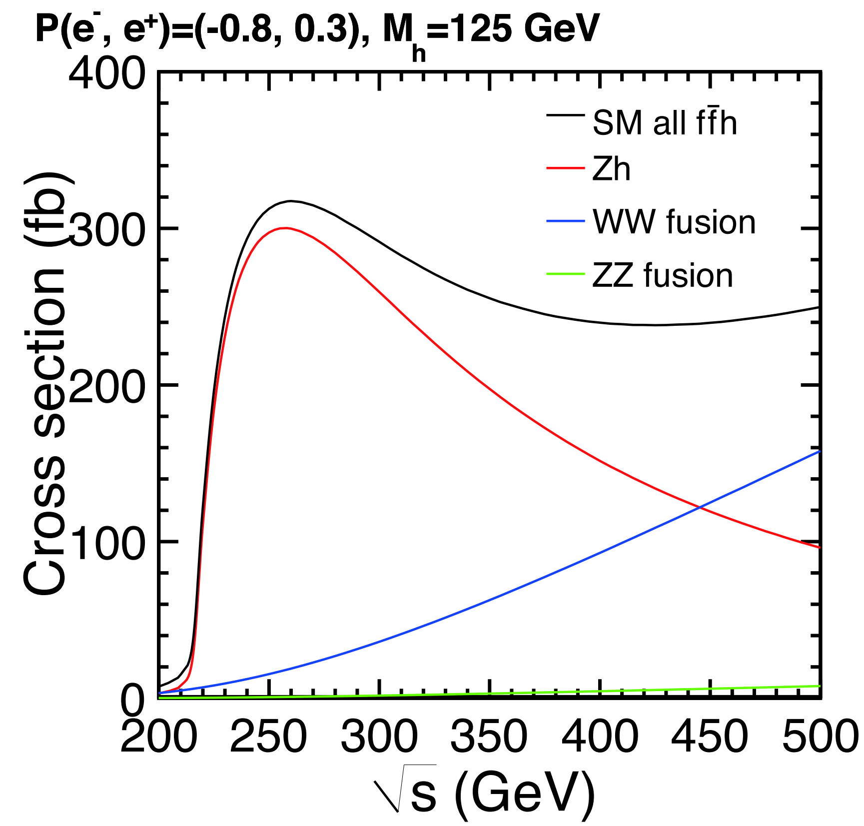
- The existence of a 125 GeV particle has been established with overwhelming certainty
- Very strong evidence for $S^P = 0^+$
- Overwhelming evidence for the existence of interactions that are only possible if the Higgs field has a vev
- Some evidence for the linear mass-coupling relationship, but precision is only 10-20% in the best cases, and some caveats apply

ILC Physics Case, Part 1: Precision Higgs Program

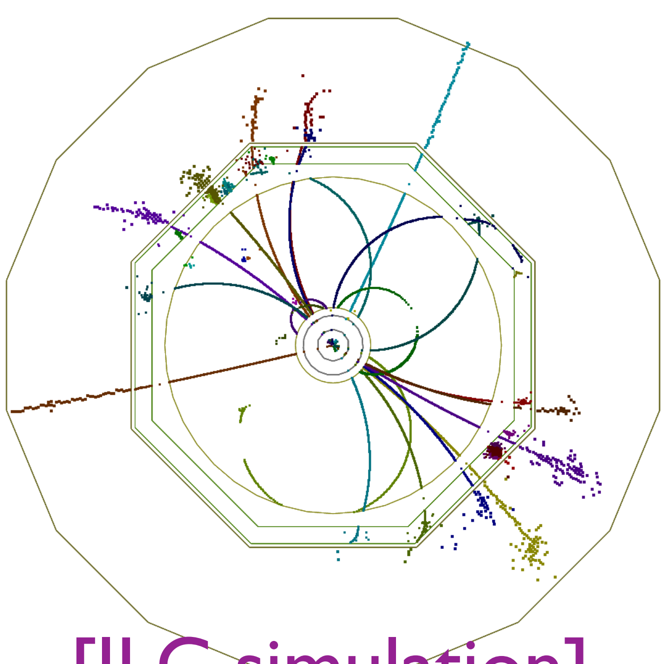
Higgs at the ILC

- Copious Higgs production in e+e- collisions at energies above ~230 GeV

- Collisions of elementary, weakly-interacting particles, (e+e-), can be interpreted with more precision than those of composite, strongly-interacting ones (pp at the LHC)

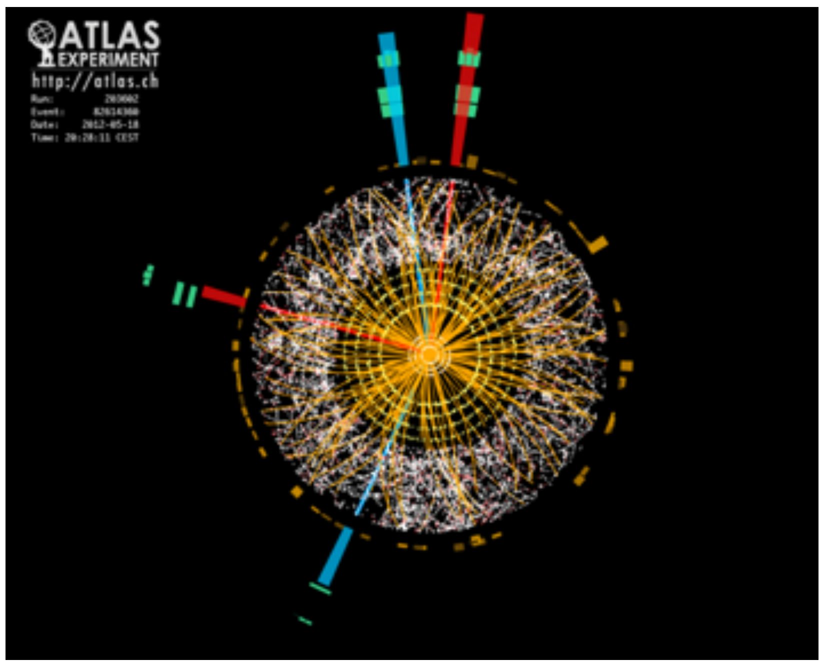


ILC plan: $\sim 10^6$ Higgses!



[ILC simulation]

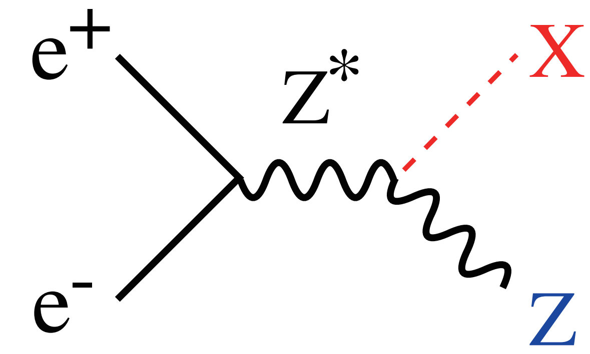
vs.

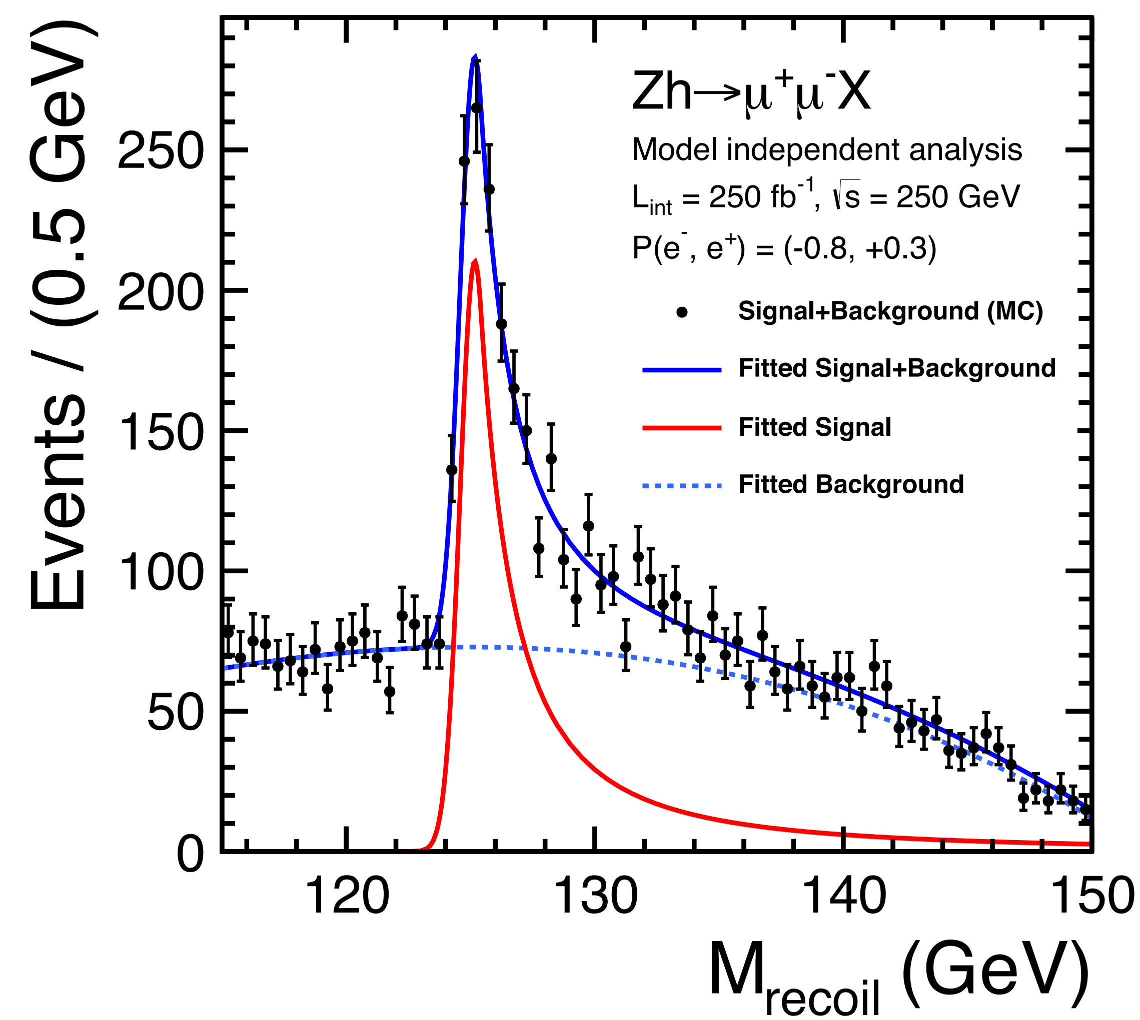


"Higgsstrahlung" @ ILC250

- Dominant Higgs production at 250 GeV
- Cross section measurement: with 250 fb-1
- Model-independent: no Higgs reconstruction required first measurement of κ_Z with no total width assumption!
- Fixes the overall scale for all couplings

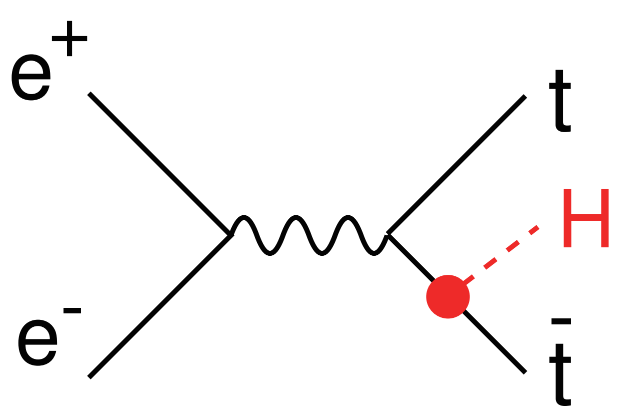
$$M_X^2 = (p_{CM} - (p_{\ell^+} + p_{\ell^-}))^2$$



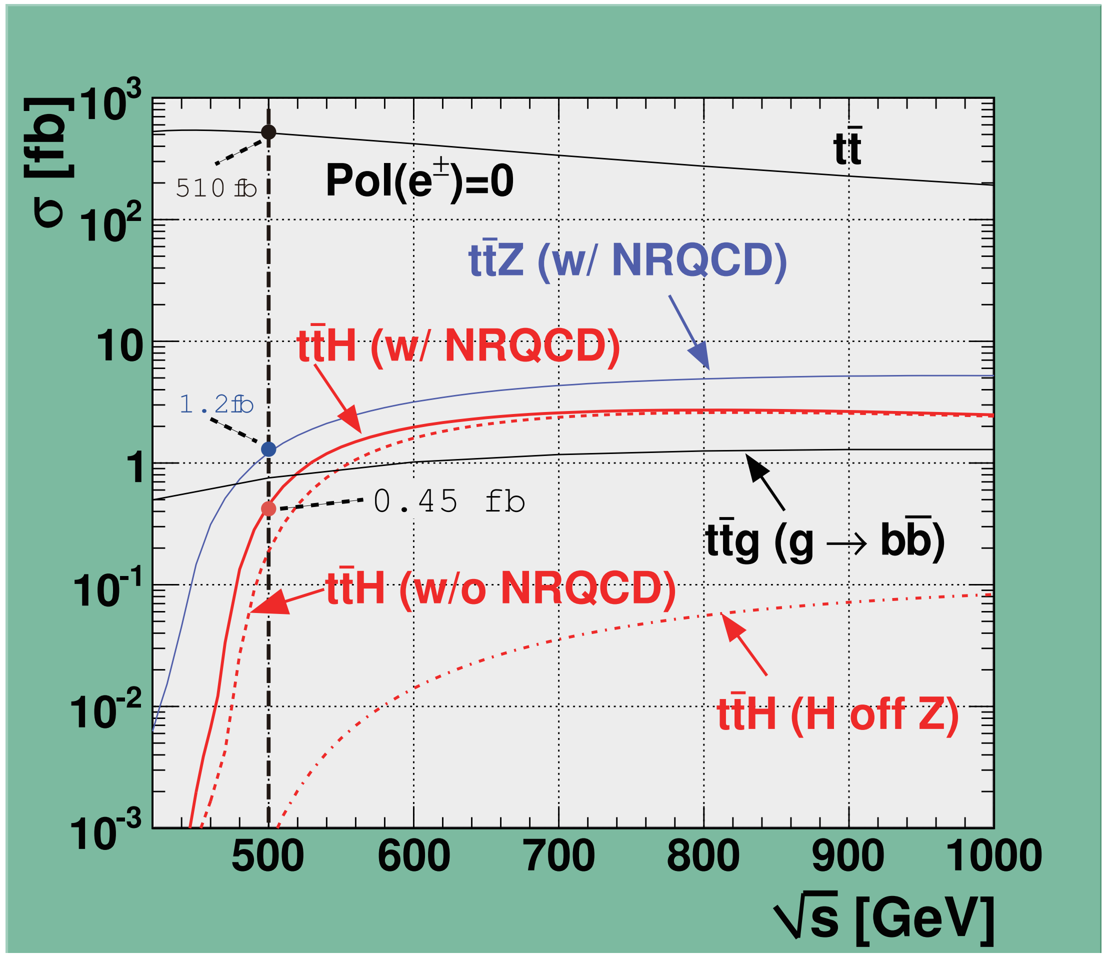


Top Yukawa @ ILC500

- The process $e^+e^- \to t\bar{t}h$ gives a direct measurement of the Higgs-top coupling
- LHC direct measurement in $pp \to t\bar{t}h$ is limited to ~10%
- For new physics searches, important to get into the ~1% range

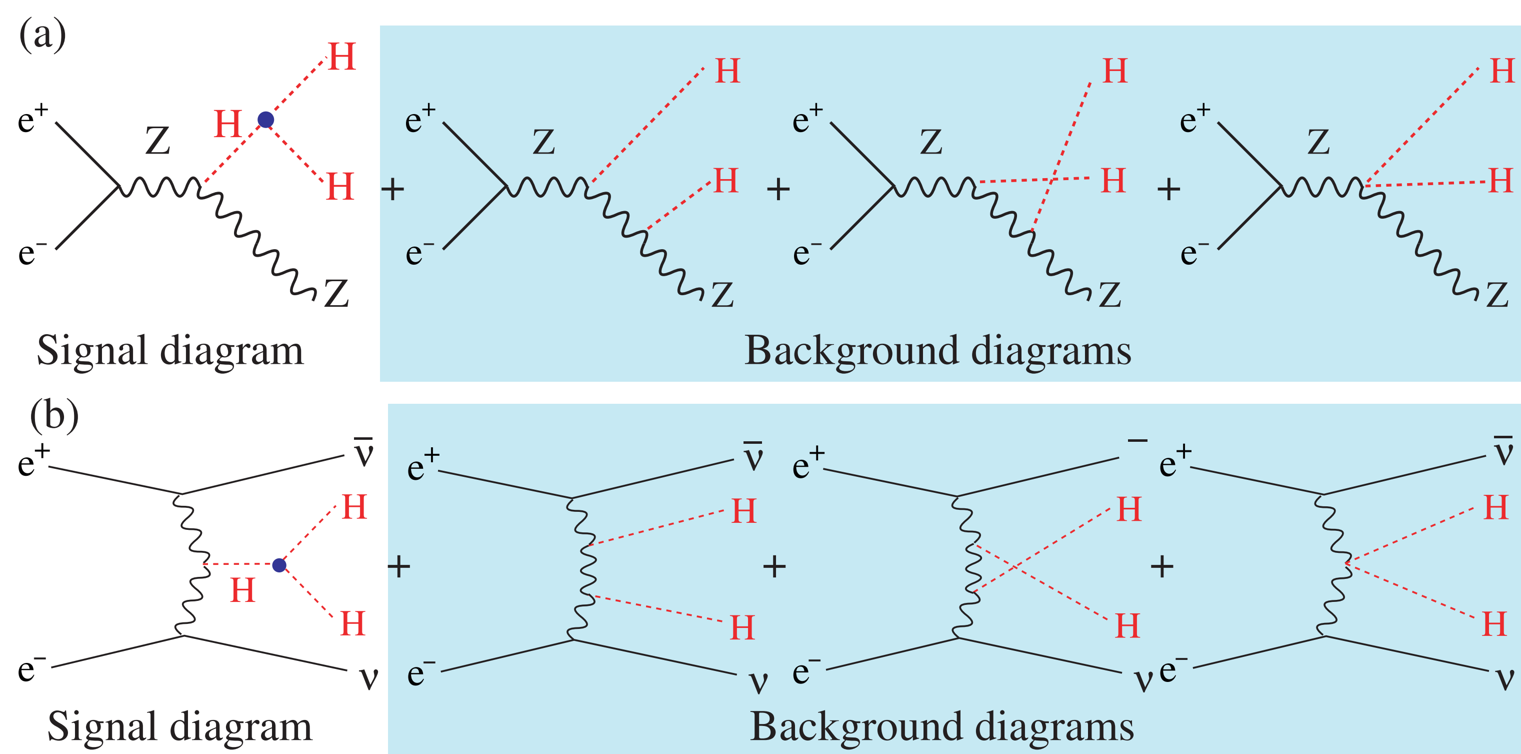


$$\frac{\Delta y_t}{y_t} \approx 10\%, \ \sqrt{s} = 500 \text{ GeV}$$
$$\to 5\%, \ \sqrt{s} = 550 \text{ GeV}$$



Higgs^3 @ ILC-1000

- SM predicts Higgs "self-coupling": $\lambda_3 = \frac{m_h^2}{2v} \approx 32\ \mathrm{GeV}$
- ILC-1000 will provide the first ~10% measurement of this crucially important quantity*

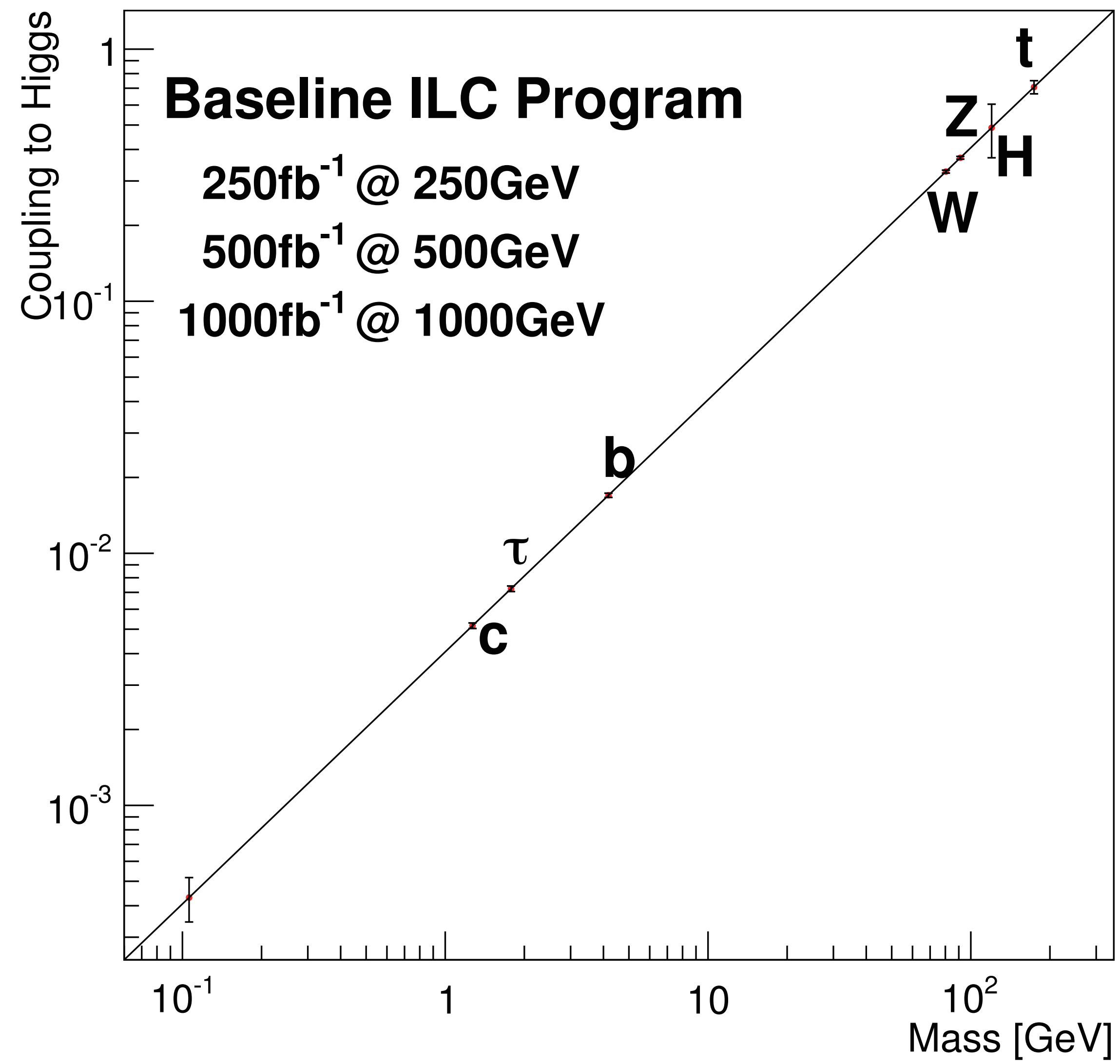


* ILC-500 can get to ~30% with the "H-20" running scenario [J. Brau's talk yesterday]

Precision Higgs @ ILC

Table 13 Expected precisions for various couplings of the Higgs boson with $m_h = 125\,\mathrm{GeV}$ from a model-independent fit to observables listed in Table 12 at three energies: $\sqrt{s} = 250\,\mathrm{GeV}$ with $250\,\mathrm{fb}^{-1}$, $500\,\mathrm{GeV}$ with $500\,\mathrm{fb}^{-1}$ both with $(e^-, e^+) = (-0.8, +0.3)$ beam polarization, $\sqrt{s} = 1\,\mathrm{TeV}$ with $2\,\mathrm{ab}^{-1}$ and $(e^-, e^+) = (-0.8, +0.2)$ beam polarization. Values with (*) assume inclusion of $hh \to WW^* b\bar{b}$ decays.

coupling	$\sqrt{s}$ (GeV) 250	250+500	250 + 500 + 1000
hZZ	1.3%	1.0%	1.0%
hWW	4.8%	1.1%	1.1%
hbb	5.3%	1.6%	1.3%
hcc	6.8%	2.8%	1.8%
hgg	6.4%	2.3%	1.6%
$h\tau\tau$	5.7%	2.3%	1.6%
$h\gamma\gamma$	18%	8.4%	4.0%
$h\mu\mu$	91%	91%	16%
Γ_0	12%	4.9%	4.5%
htt	-	14%	3.1%
hhh	-	83%(*)	21%(*)



- ILC will achieve 1-2% level model-independent determination of many Higgs couplings, impossible at the LHC

Precision Higgs @ ILC

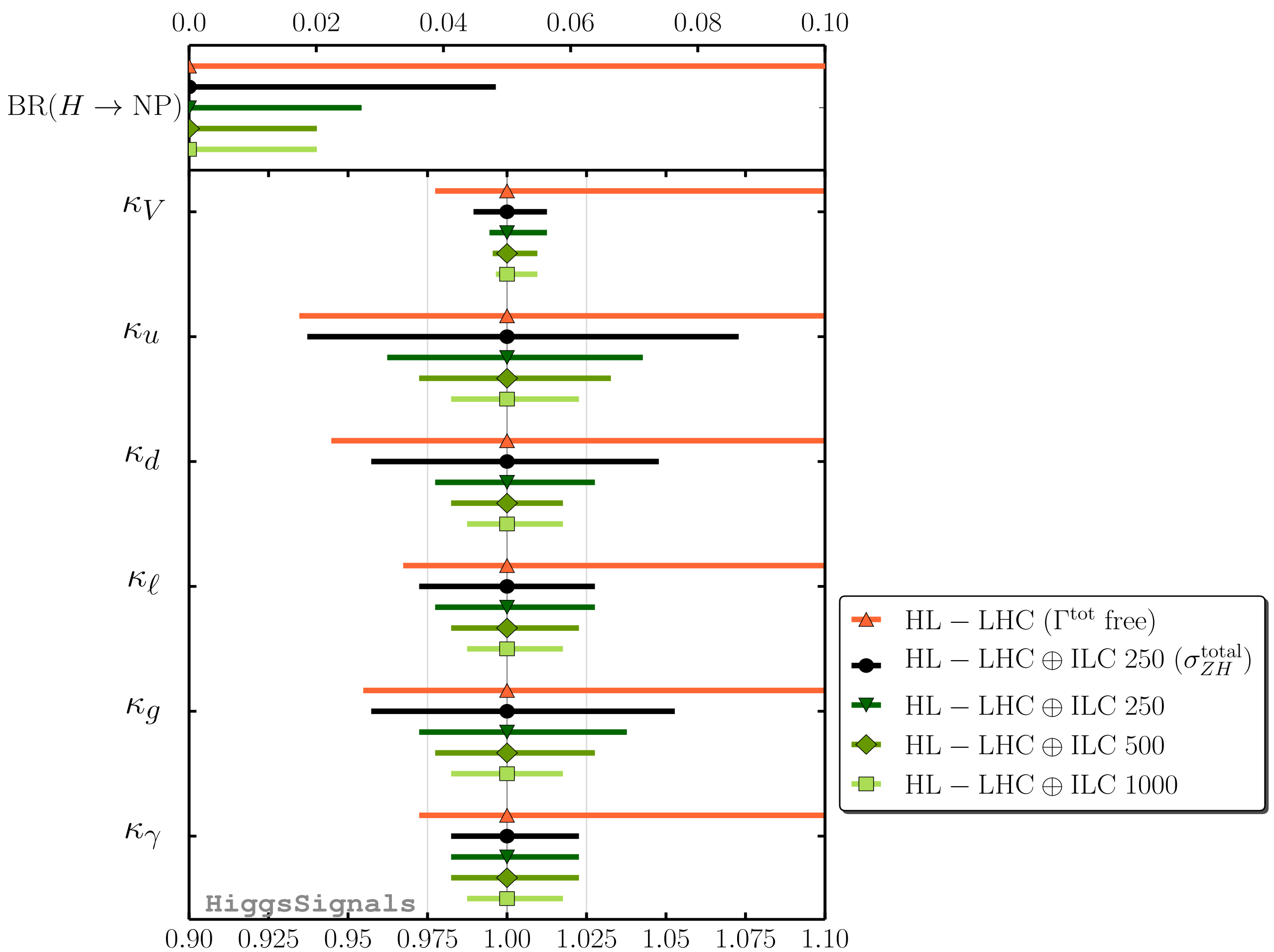


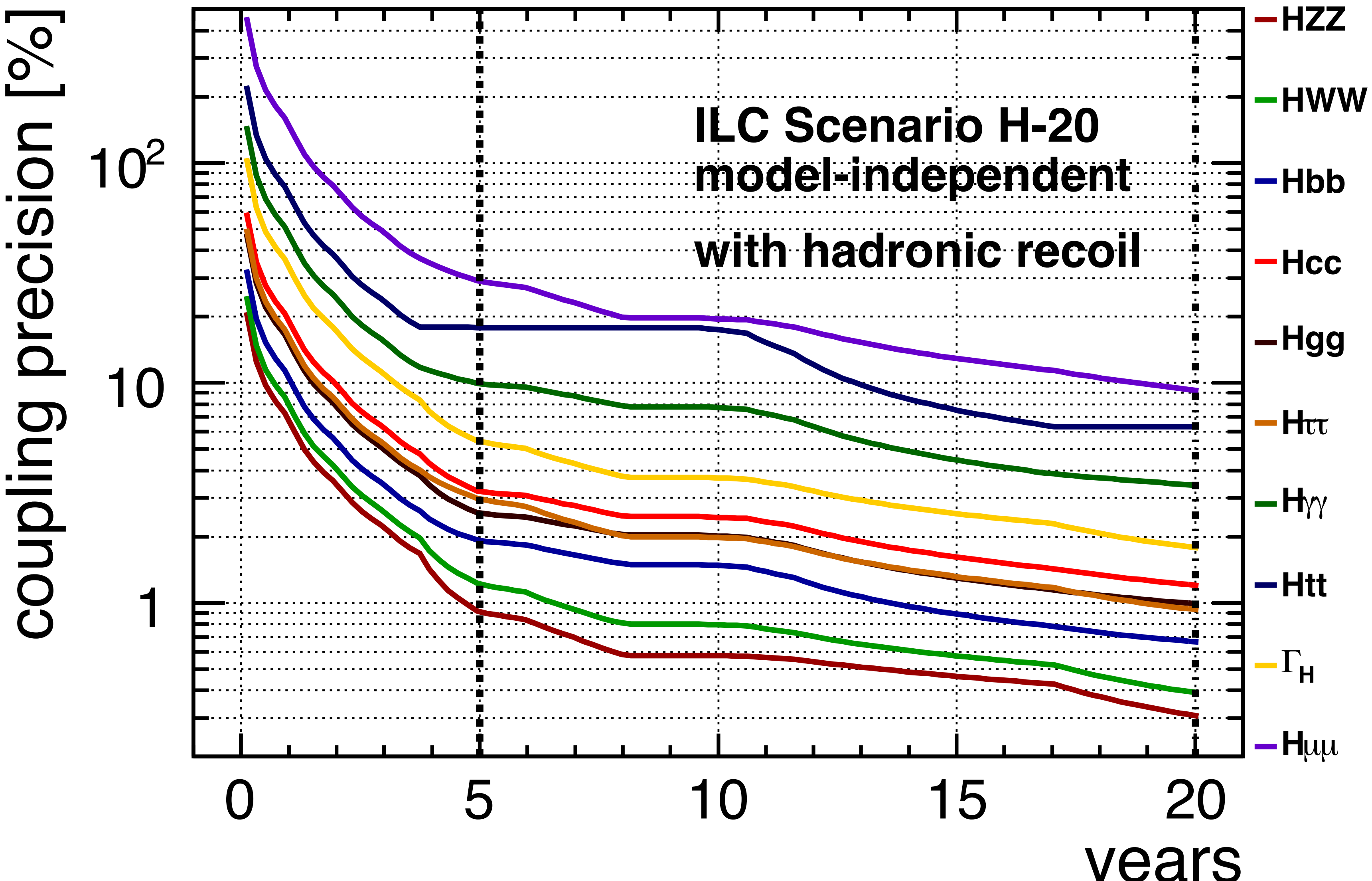
Table 15 Expected Higgs precisions on normalized Higgs couplings ($\kappa_i := g_i/g_i(\mathrm{SM})$) for $m_h = 125\,\mathrm{GeV}$ from model-dependent 7-parameter fits for the LHC and the ILC, where $\kappa_c = \kappa_t =: \kappa_u$, $\kappa_s = \kappa_b =: \kappa_d$, $\kappa_\mu = \kappa_\tau =: \kappa_\ell$, and $\Gamma_{\mathrm{tot}} = \sum \Gamma_i^{\mathrm{SM}} \kappa_i^2$ are assumed.

Facility	LHC	HL-LHC	ILC500	ILC1000
$\sqrt{s}$ (GeV)	1,400	14,000	250/500	250/500/1000
$\int \mathscr{L} dt$ (fb^{-1})	300/exp	3000/exp	250+500	250+500+1000
κ_γ	5-7%	2-5%	8.3%	3.8%
κ_g	6-8%	3-5%	2.0%	1.1%
κ_W	4-6%	2-5%	0.39%	0.21%
κ_Z	4-6%	2-4%	0.49%	0.50%
κ_ℓ	6-8%	2-5%	1.9%	1.3%
κ_d	10-13%	4-7%	0.93%	0.51%
κ_u	14-15%	7-10%	2.5%	1.3%

$\Lambda \sim 50$ TeV!

- With mild model assumptions, ILC will achieve 0.2-0.5% determination of several Higgs couplings, vs. 2-5% ultimate precision at HL-LHC

Update on Higgs Couplings



Better precision with 250/350/500 GeV only, H-20 scenario (20 years)

[J. Brau's talk yesterday]

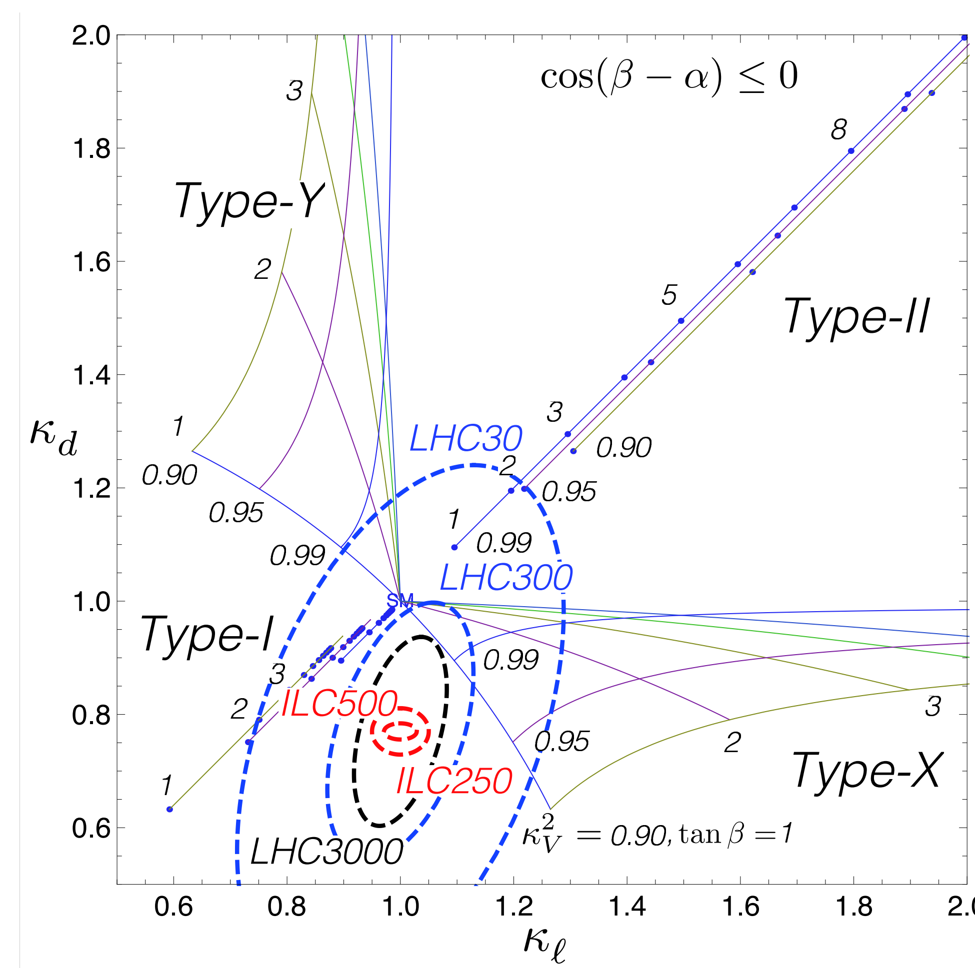
Physics Implications of Precision Higgs

- Exquisite precision of the ILC Higgs program allows to address a new layer of fundamental questions:
  - Are there other scalar fields?
  - Is the Higgs elementary or composite particle?
  - Why is the Higgs field non-zero in the vacuum?
  - Are there "top partners"?
  - What was the order of electroweak phase transition? Could matter-antimatter asymmetry arise during this transition?

Other Scalar Fields?

- Many extensions of the SM contain scalar fields beyond the Higgs: e.g. supersymmetry
- The 125 GeV Higgs can be a "mixed" state, composed of >1 fundamental fields
- Mixing results in deviation of couplings from the SM, pattern of deviations is model-dependent
- Precision Higgs program can distinguish between models if a deviation is observed

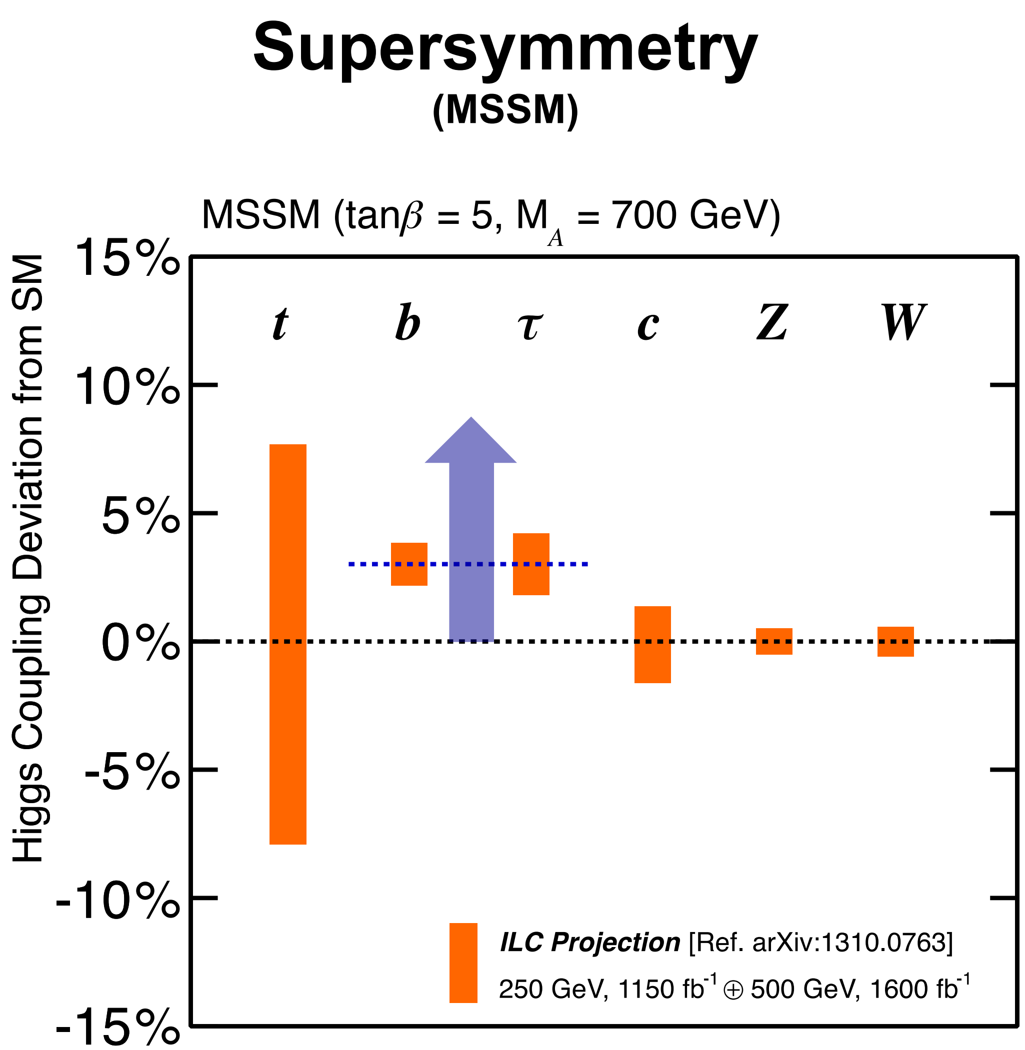
Model	μ	τ	b	c	t	g_V
Singlet mixing	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$
2HDM-I	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$
2HDM-II (SUSY)	$\uparrow$	$\uparrow$	$\uparrow$	$\downarrow$	$\downarrow$	$\downarrow$
2HDM-X (Lepton-specific)	$\uparrow$	$\uparrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$
2HDM-Y (Flipped)	$\downarrow$	$\downarrow$	$\uparrow$	$\downarrow$	$\downarrow$	$\downarrow$

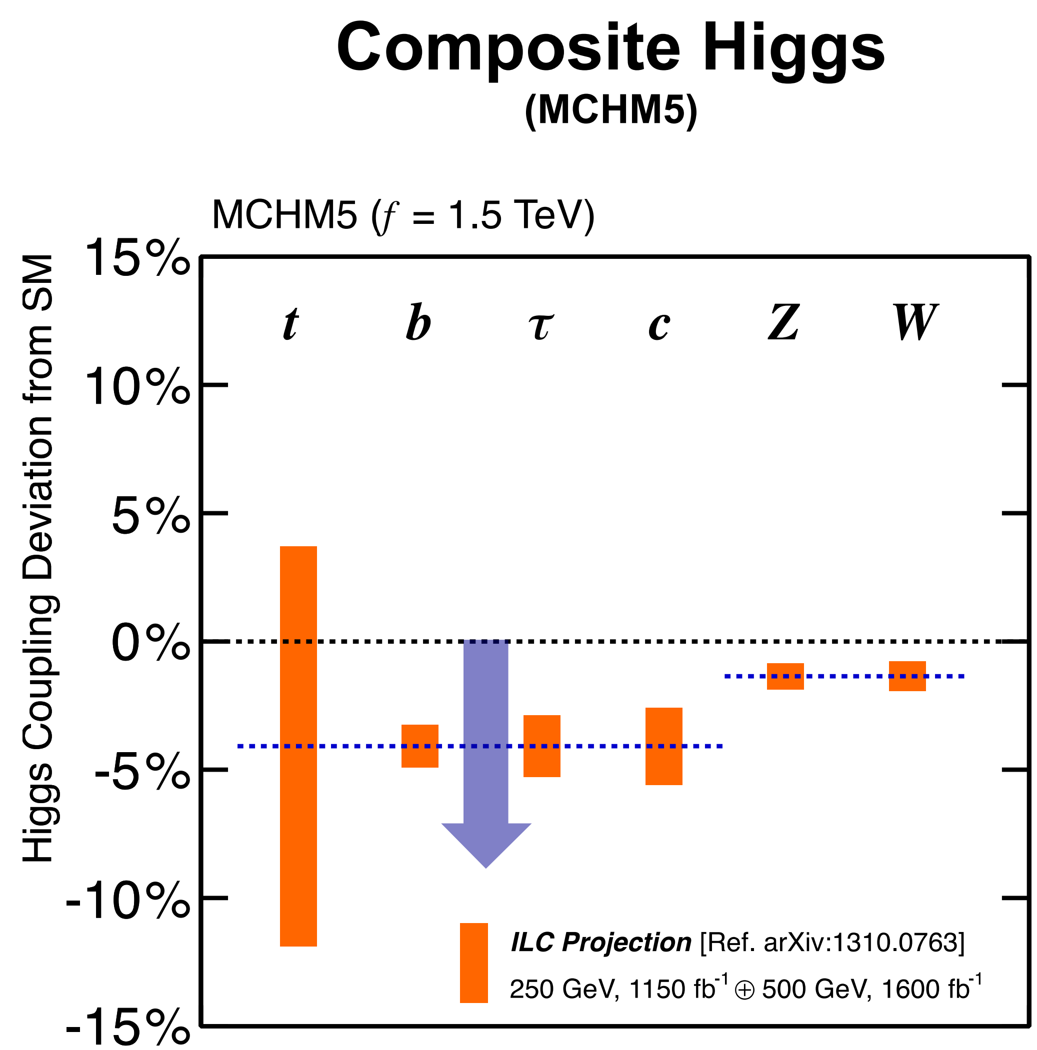


[Kanemura, Tsumura, Yagyu, Yokoya'14]

Model Discrimination

- Should a deviation from the SM Higgs couplings be observed, precise measurements can distinguish between competing model interpretations

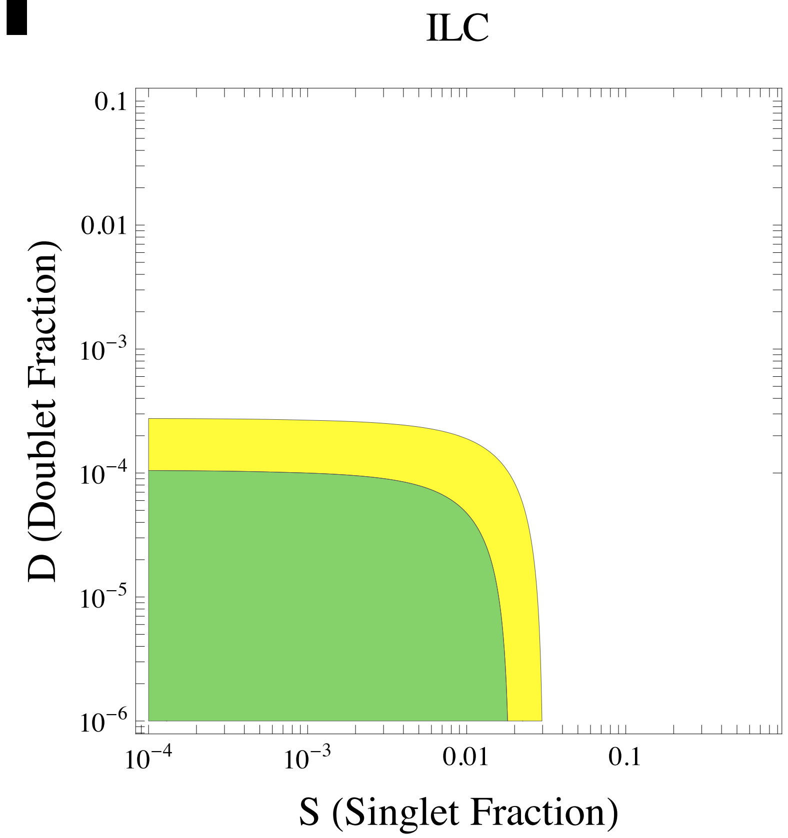


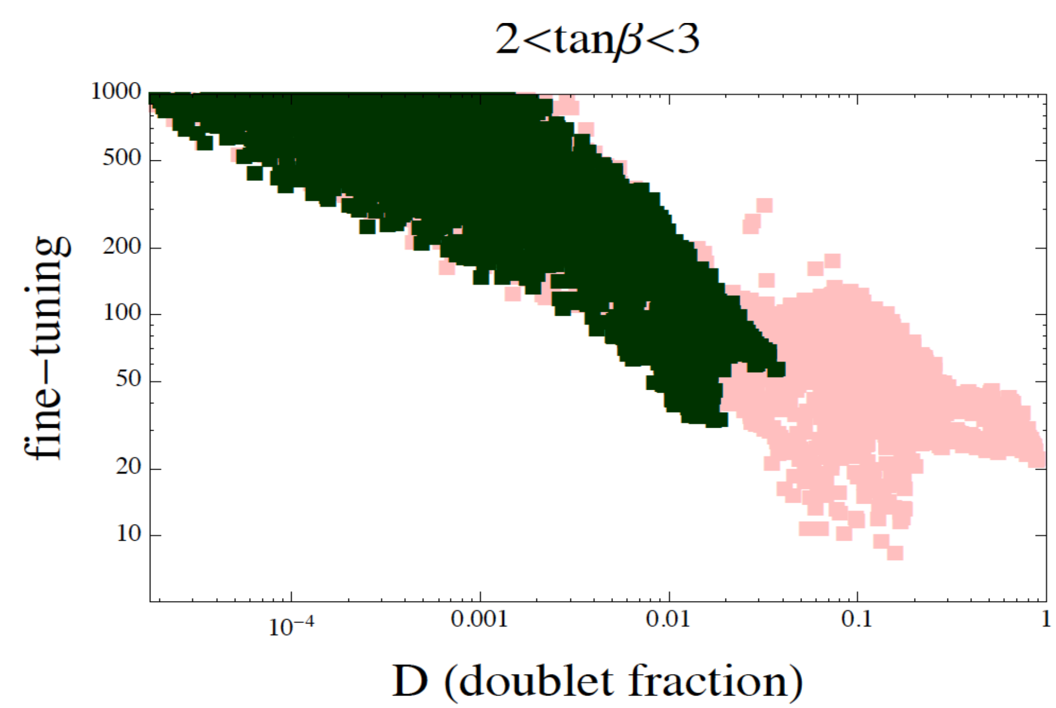


[Asner, Barklow, et.al. '13]

Higgs Mixing: Implications

- 125 GeV Higgs is difficult to accommodate in the Minimal SUSY Model (MSSM)
- Popular solution: Introduce an extra singlet scalar field (NMSSM, or λ-SUSY)
- Size of non-SM components in the 125 Higgs is inversely correlated with fine-tuning
- Precision Higgs program at the ILC will definitively test this proposal





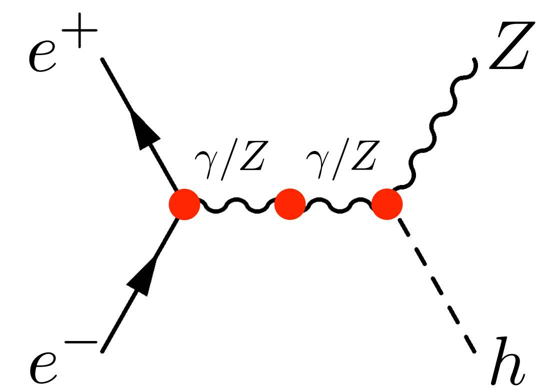
[Farina, MP, Shakya'13]

Is the Higgs a Bound State?

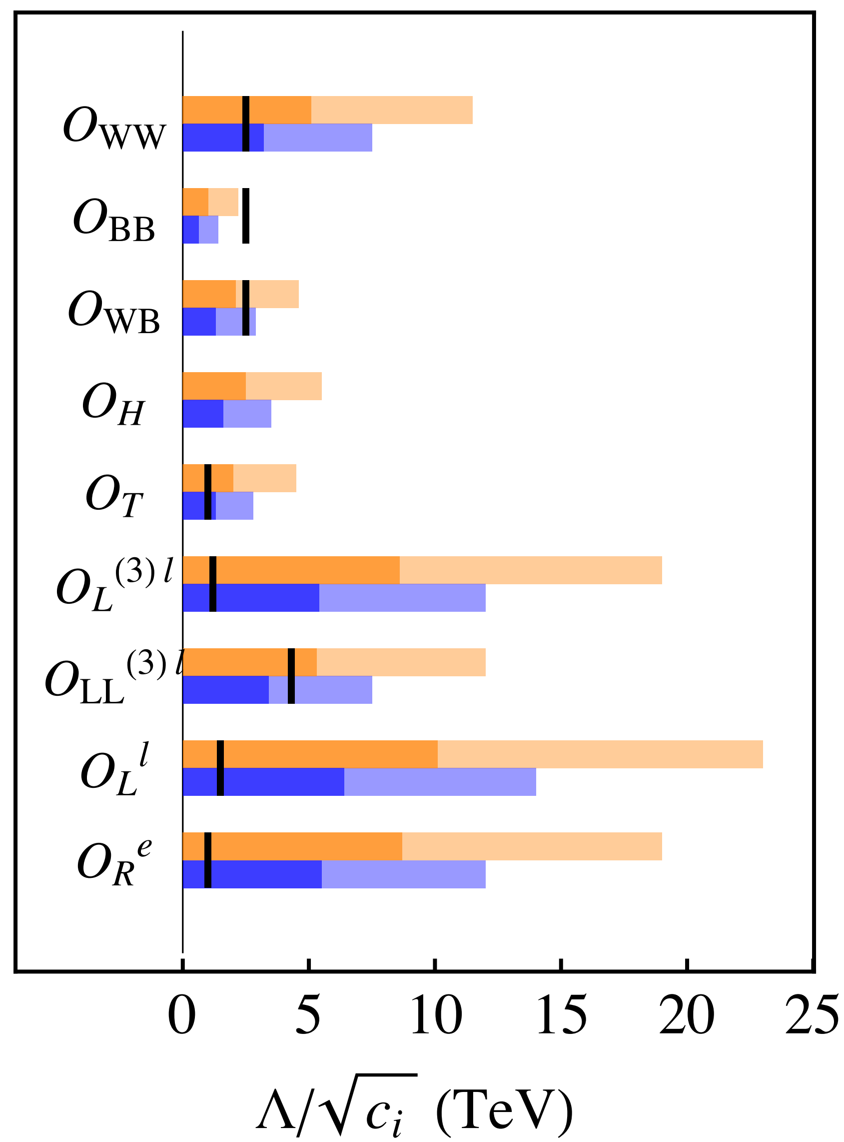
- Is the Higgs an Elementary or Composite Particle?
- All other known spin-0 particles are composite: pions, kaons, etc. are bound states of spin-1/2 quarks
- Might Higgs be made out of some new fermions?
- Characteristic energy scale of compositeness:
- At lower energy, compositeness manifests itself as "form-factors", modifying Higgs interactions with SM particles
- Estimates indicate ~1-5% deviations from SM couplings are plausible, given current precision electroweak and direct bounds

Higgs Form-factors @ ILC

$$\mathcal{L}_{\text{pre-EWSB}} = \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$



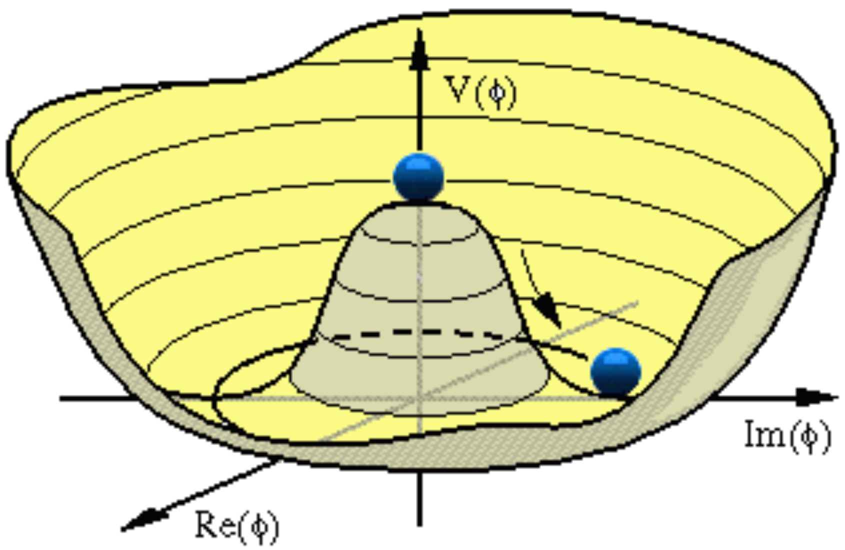
$$\begin{aligned}
\mathcal{O}_{WW} &= g^2|H|^2 W^a_{\mu\nu}W^{a,\mu\nu} \\
\mathcal{O}_{BB} &= g'^2|H|^2 B_{\mu\nu}B^{\mu\nu} \\
\mathcal{O}_{WB} &= gg' H^\dagger\sigma^a H W^a_{\mu\nu}B^{\mu\nu} \\
\mathcal{O}_{H} &= \tfrac{1}{2}(\partial_\mu|H|^2)^2 \\
\mathcal{O}_{T} &= \tfrac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2 \\
\mathcal{O}_{L}^{(3)\ell} &= (iH^\dagger\sigma^a\overleftrightarrow{D}_\mu H)(\bar{L}_L\gamma^\mu\sigma^a L_L) \\
\mathcal{O}_{LL}^{(3)\ell} &= (\bar{L}_L\gamma_\mu\sigma^a L_L)(\bar{L}_L\gamma^\mu\sigma^a L_L) \\
\mathcal{O}_{L}^{\ell} &= (iH^\dagger\overleftrightarrow{D}_\mu H)(\bar{L}_L\gamma^\mu L_L) \\
\mathcal{O}_{R}^{e} &= (iH^\dagger\overleftrightarrow{D}_\mu H)(\bar{e}_R\gamma^\mu e_R)
\end{aligned}$$



[Craig, Farina, McCullough, MP, '14]

Why Is the Higgs Everywhere?

- The SM postulates the "Mexican Hat" shape for Higgs potential energy function



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

- Testing the shape of the Higgs potential requires measuring mass, vev, and cubic self-coupling:

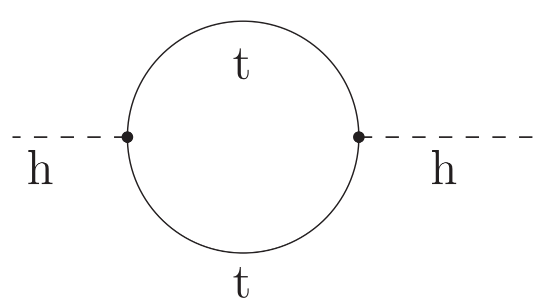
$$\lambda_3 = \frac{m_h^2}{2v} \approx 32\ \mathrm{GeV}$$

Why Mexican Hat?

- The structure of our Universe depend crucially on a single minus sign in the SM Lagrangian:

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

- The SM contains a tempting hint: Radiative corrections associated with the top quark make a negative contribution to the coefficient of $|H|^2$



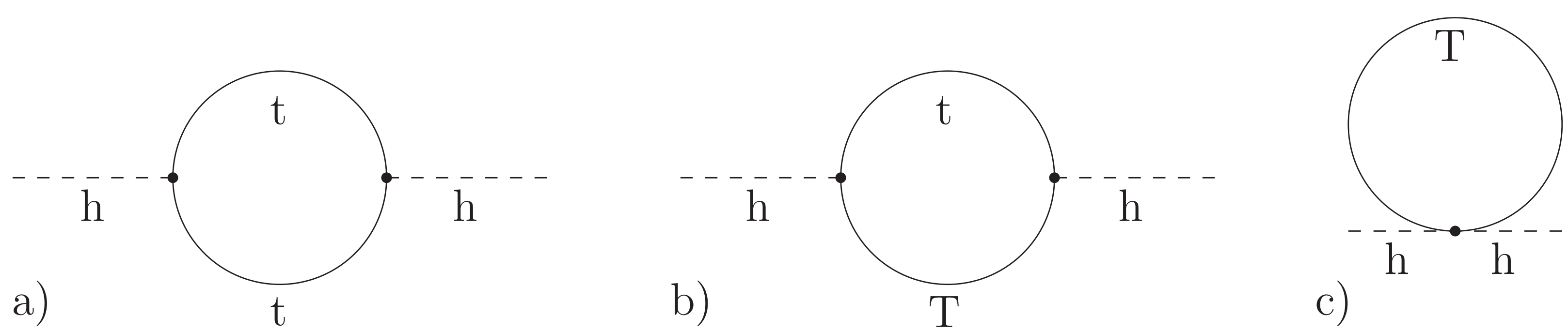
$$= -6\lambda_t^2 \int \frac{d^4k}{(2\pi)^4}\frac{1}{k^2}$$

- However, in the SM, there are other additive, and incalculable, contributions to this coefficient: hence, no prediction is possible

Beyond the SM: Top Partners

- Some SM extensions solve this problem (and the closely related "hierarchy problem"), predict electroweak symmetry breaking
- Examples are: Supersymmetry, "Little Higgs", 5D "Goldstone Higgs", "Twin Higgs", …
- Common feature: all contain "top partners", new particles with specific pattern of Higgs couplings

Example:
"Littlest Higgs"

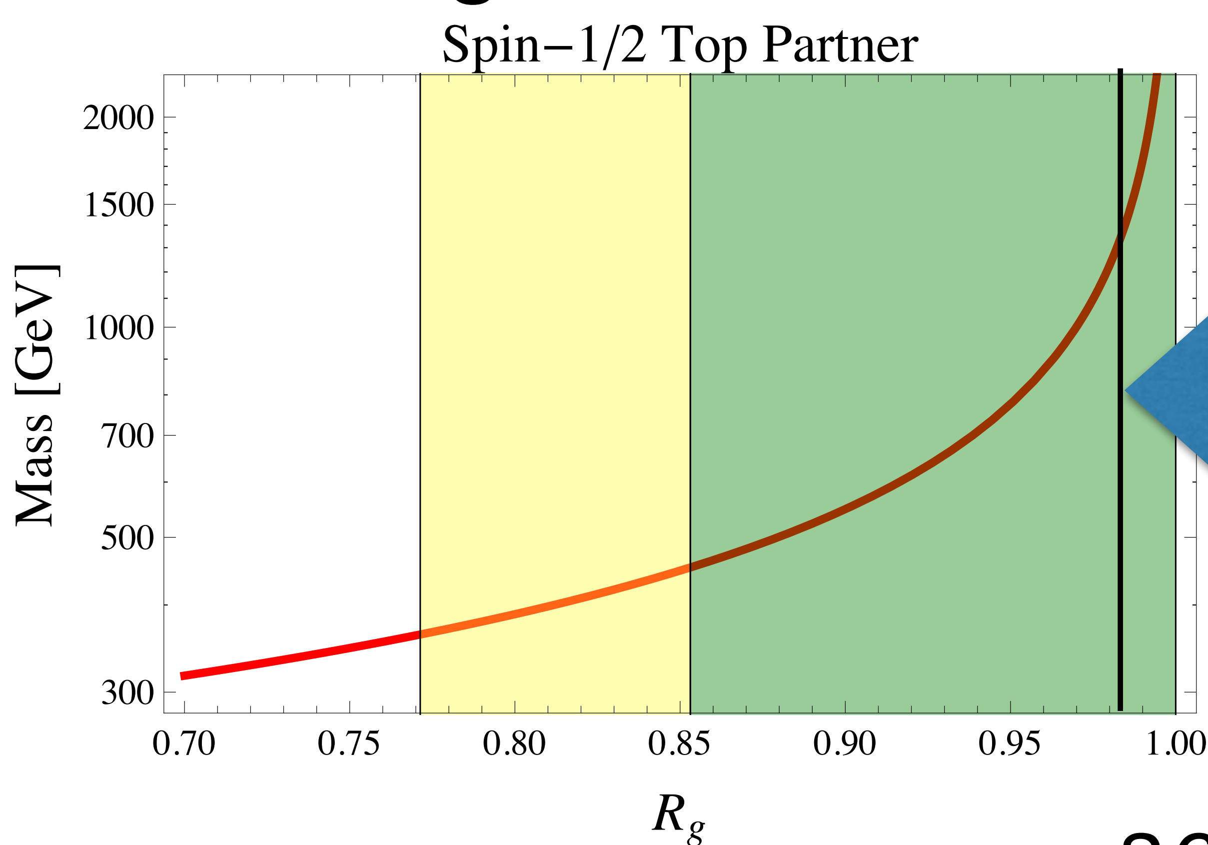


Sum Rule: $\frac{m_T}{f} = \frac{\lambda_t^2 + \lambda_T^2}{\lambda_T}$

[MP, Peskin, Pierce,'03]

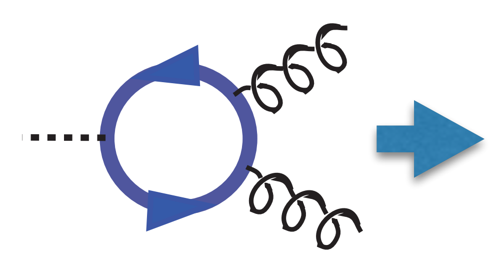
TP and Higgs Couplings

- Top partners must be not too heavy, otherwise theory is “fine-tuned”: too much EWSB
- In most models, TP loops contribute to Higgs couplings to gluons, photons, at 1-loop (i.e. same level as SM)*
- Robust correlation between TP mass, degree of fine-tuning and deviations of Higgs couplings from the SM



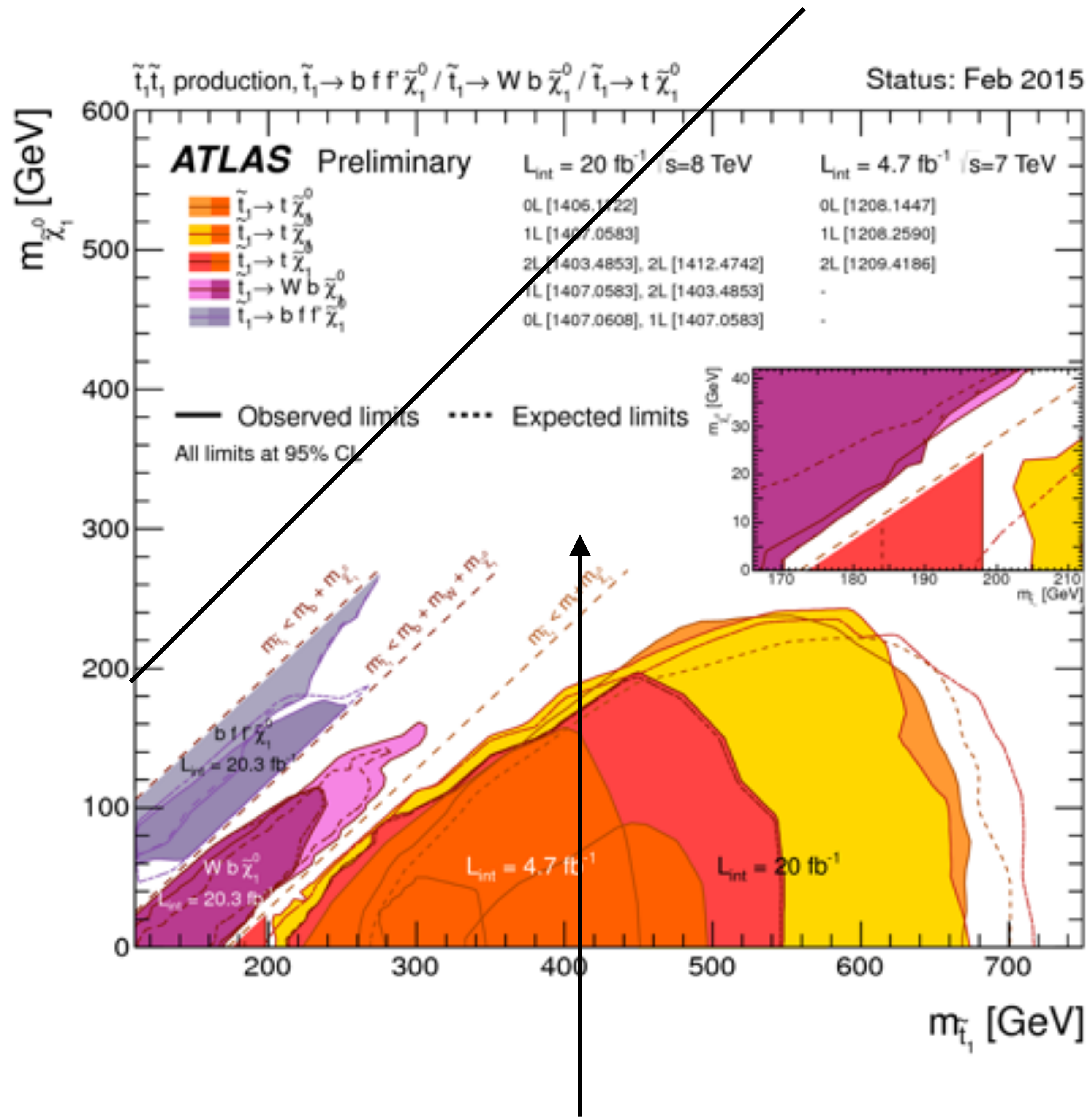
[Carmi, Falkowski, Kuflik, Volansky, ’12; Farina, MP, Rey-Le Lorier, ‘13]

ILC 95% c.l. sensitivity: $m_T \approx 1.3$ TeV, FT ~ 3%

*  need an independent top Yukawa measurement @ ILC-500!

Top Partners @ LHC

- LHC searches for top partners directly, with strong bounds already in place from run-1
- However, there are model parameter regions where LHC searches are difficult or impossible, due to small S/B
- Gaps in coverage will likely persist even at HL-LHC
- ILC Precision Higgs program will close the gaps



All this space is currently allowed!

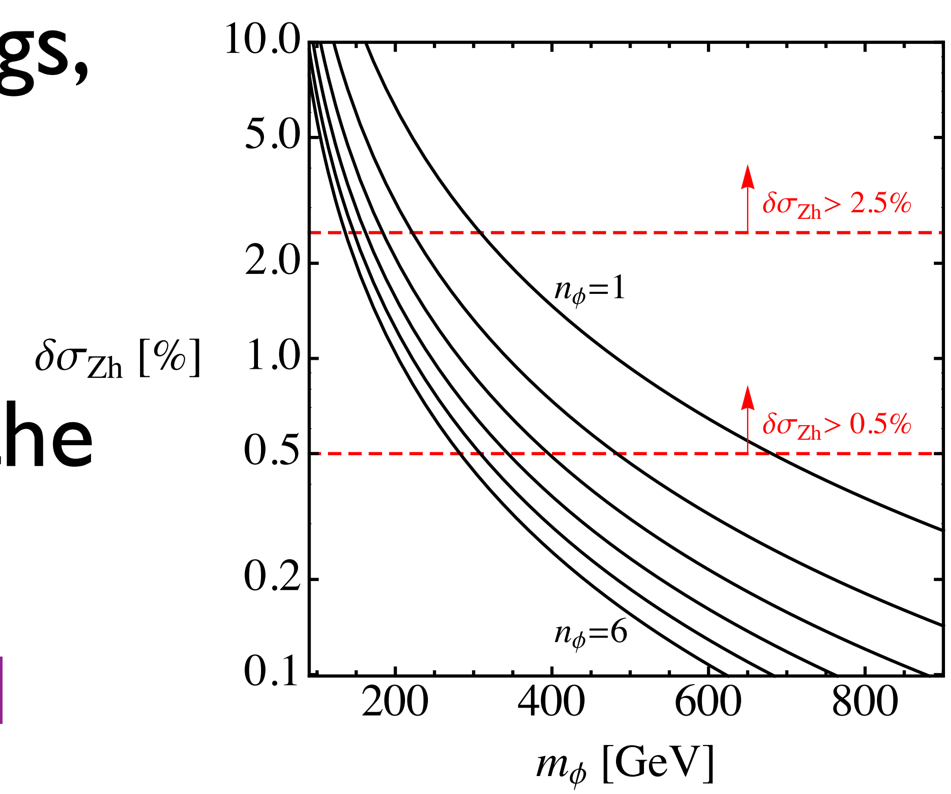
Colorless Top Partners

- "Twin Higgs" models contain top partners that do not have SM color and electric charges - "Tazakis"

- Tazakis cannot be searched for at the LHC, due to tiny production cross sections

- However, Tazakis must couple to Higgs, and their loops will modify cross sections such as $e^+e^- \to hZ$

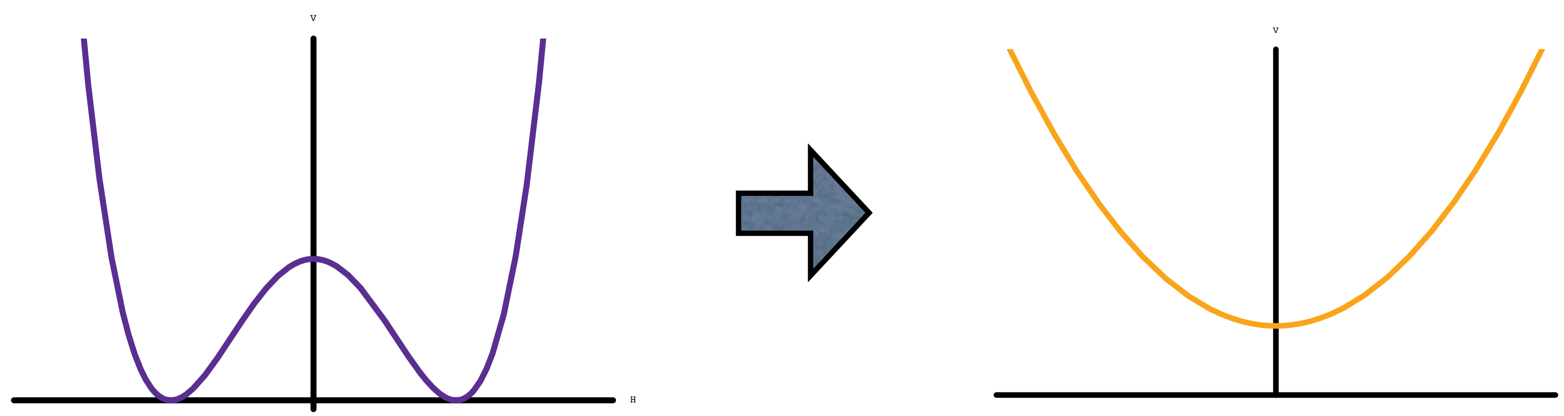
- Precision e+e- Higgs factories offer the only chance to look for Tazakis



[Craig, Englert, McCullough, '13]

Electroweak Phase Transition

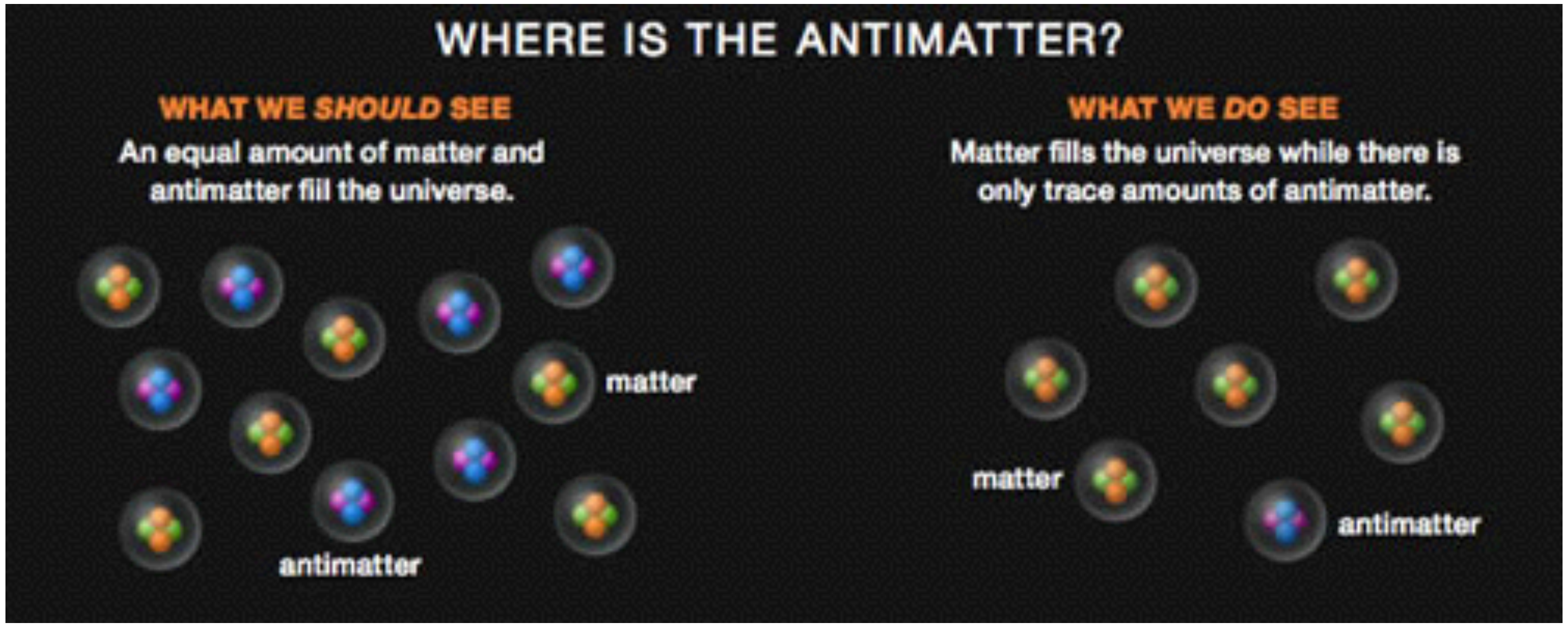
- Higgs boson moving through a plasma of quarks acquires a "thermal mass" (much like photon "plasma mass")
- At high plasma densities, EW symmetry is unbroken!



- Right after the Big Bang, the Universe was filled with dense quark plasma, was in unbroken EW phase
- As the Universe expanded and cooled, phase transition to current phase with broken symmetry - EWPT

$kT \sim 100 - 1000 \text{ GeV}, \quad T \sim 10^{15} \text{ K}, \quad t \sim 10^{-10} \text{ sec}$

EWPT and "Baryogenesis"

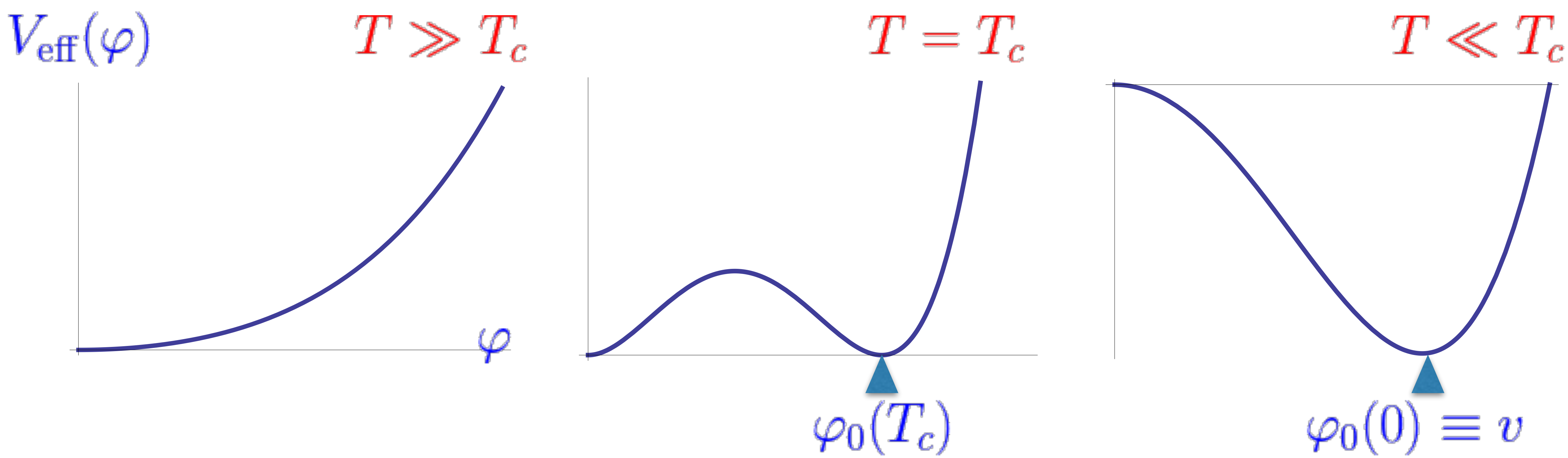


- It is believed that the observed matter-antimatter asymmetry arose dynamically, very soon (<1 sec) after the Big Bang

- Many mechanisms proposed; one of the most theoretically attractive is "Electroweak Baryogenesis", in which the asymmetry is generated during the EWPT

- It only works if transition is 1-st order (out-of-equlibrium)

First-Order EWPT



- In a 1st-order transition, bubbles of broken ("our") phase are nucleated inside the unbroken-EW phase

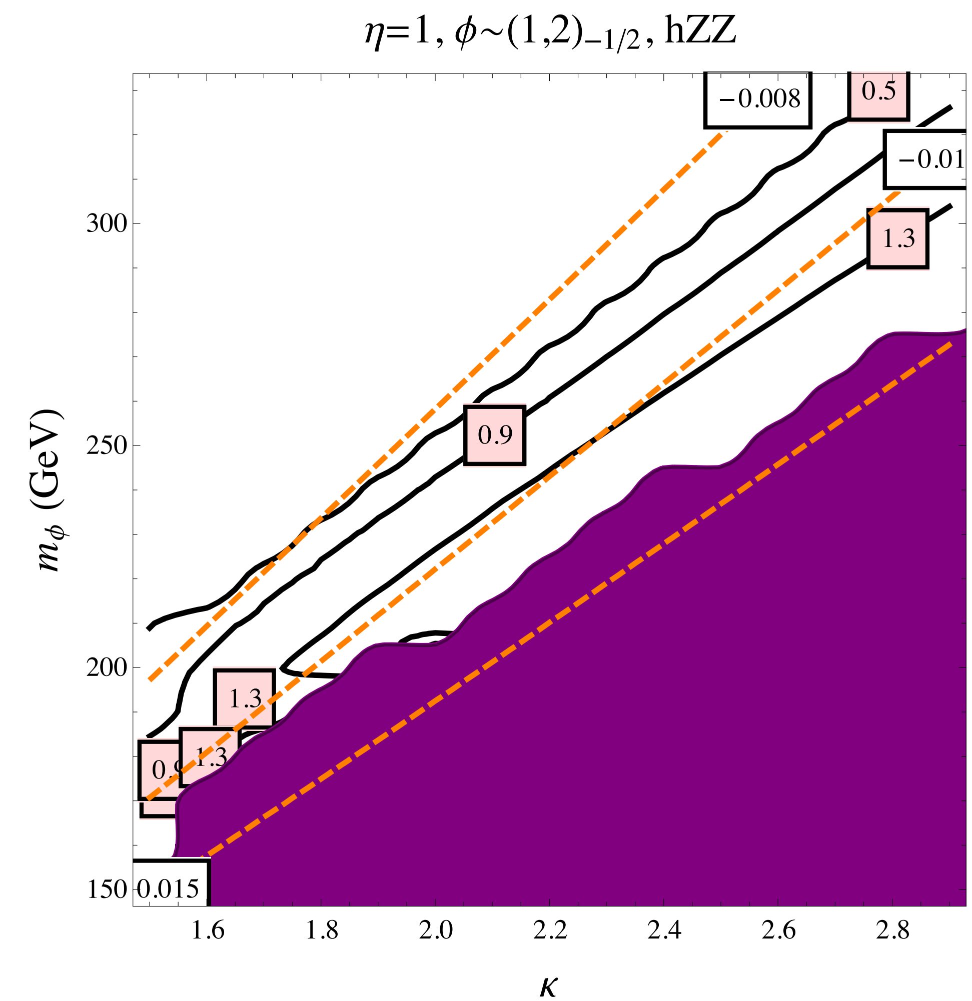
- Non-equilibrium process → satisfies one of the famous "Sakharov conditions" for generating matter-antimatter asymmetry

EWPT and Higgs Couplings

[A. Katz, MP, '14]

- In the SM, EWPT is 2nd-order no EW Baryogenesis
- New particles, coupled to Higgs, may change the dynamics and re-open the window for EW Baryogenesis
- However, they will also change the Higgs couplings to gluons, photon, W/Z, and self-coupling
- In most models, ILC can probe most or all of parameter space with a 1st order EWPT!

Example: "LH Stau" model



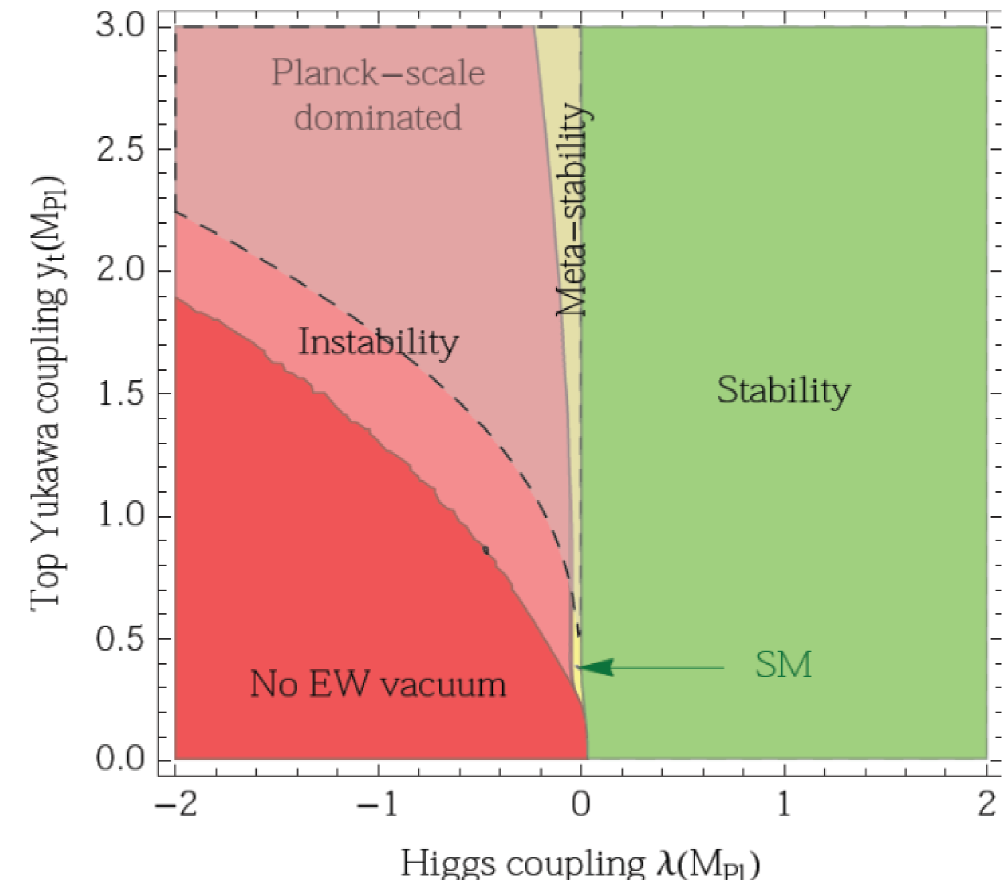
$$\Delta\kappa_V = 0.8 - 1.2\%$$

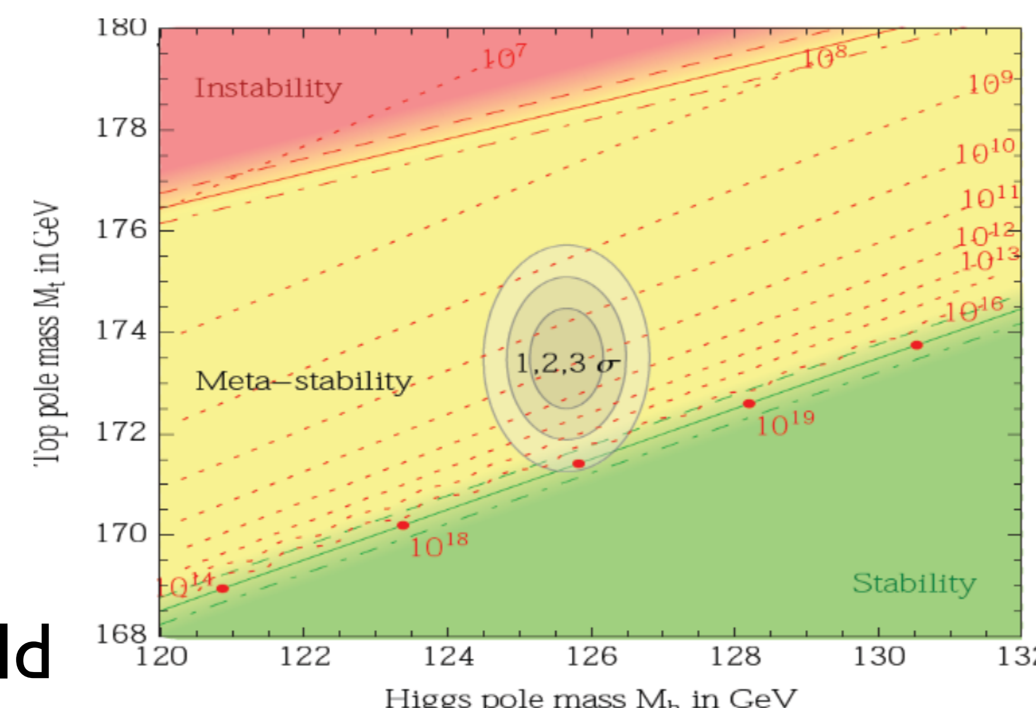
cf. ILC precision 0.2-0.4%

ILC Physics Case, Part 2: Precision Top

SM Vacuum Stability

- Our vacuum is a local minimum of the Higgs potential, but it may not be the global minimum
- Even in the SM, radiative corrections may induce new minima
- If such a new minimum exist, bubbles of that phase may be nucleated in our Universe, "destroy" it!
- SM is posed precariously between stability and instability*; depends very sensitively on the top quark mass

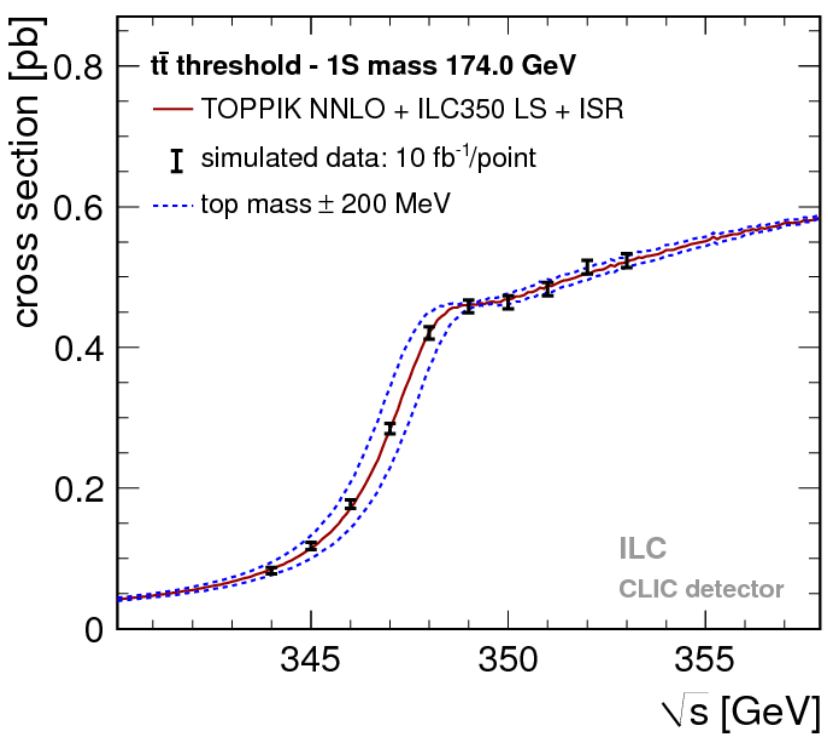


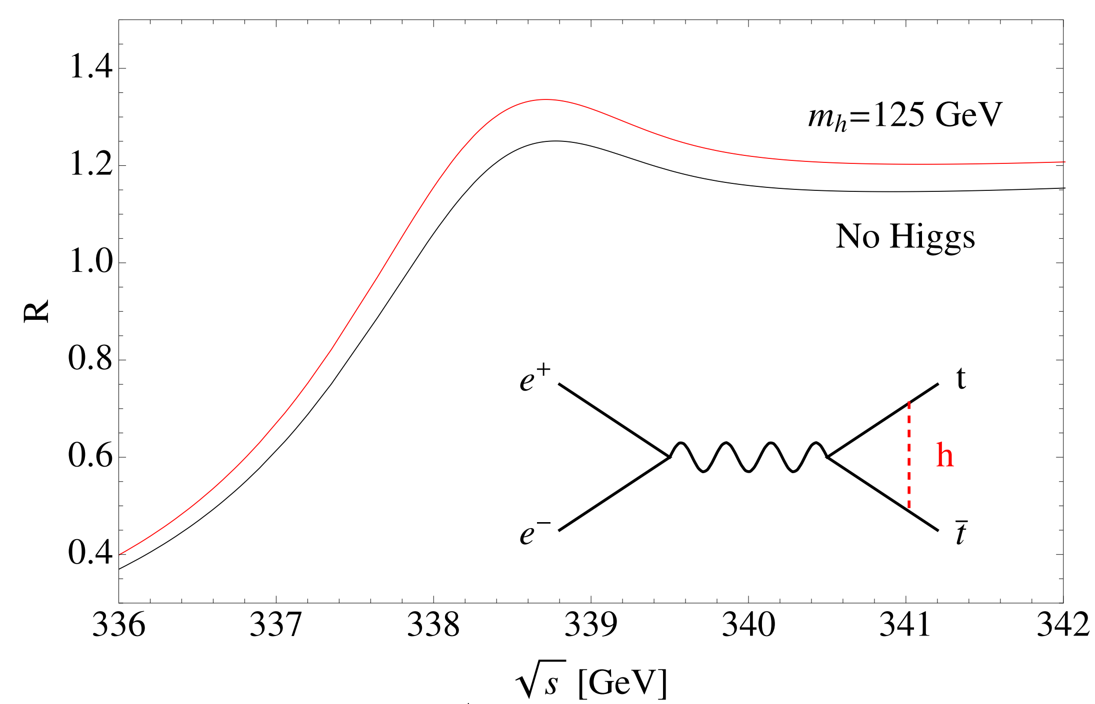


* - This assumes no new physics. Conclusion would be different e.g. if there are top partners.

Top Mass @ ILC-350

- ILC can perform a very precise measurement of the top mass via a threshold scan:
- Projected error 50-100 MeV (a factor of 5-10 better than HL-LHC projection)
- An alternative (albeit indirect) determination of the top Yukawa





Top Couplings @ ILC-500

- Many SM extensions predict shifts in top couplings to W, Z, photon
- Example: in models of composite Higgs, top quark is typically also composite, form factors are induced
- ILC will be able to greatly improve on the LHC measurements of these couplings
- Polarization is important to disentangle various contributions

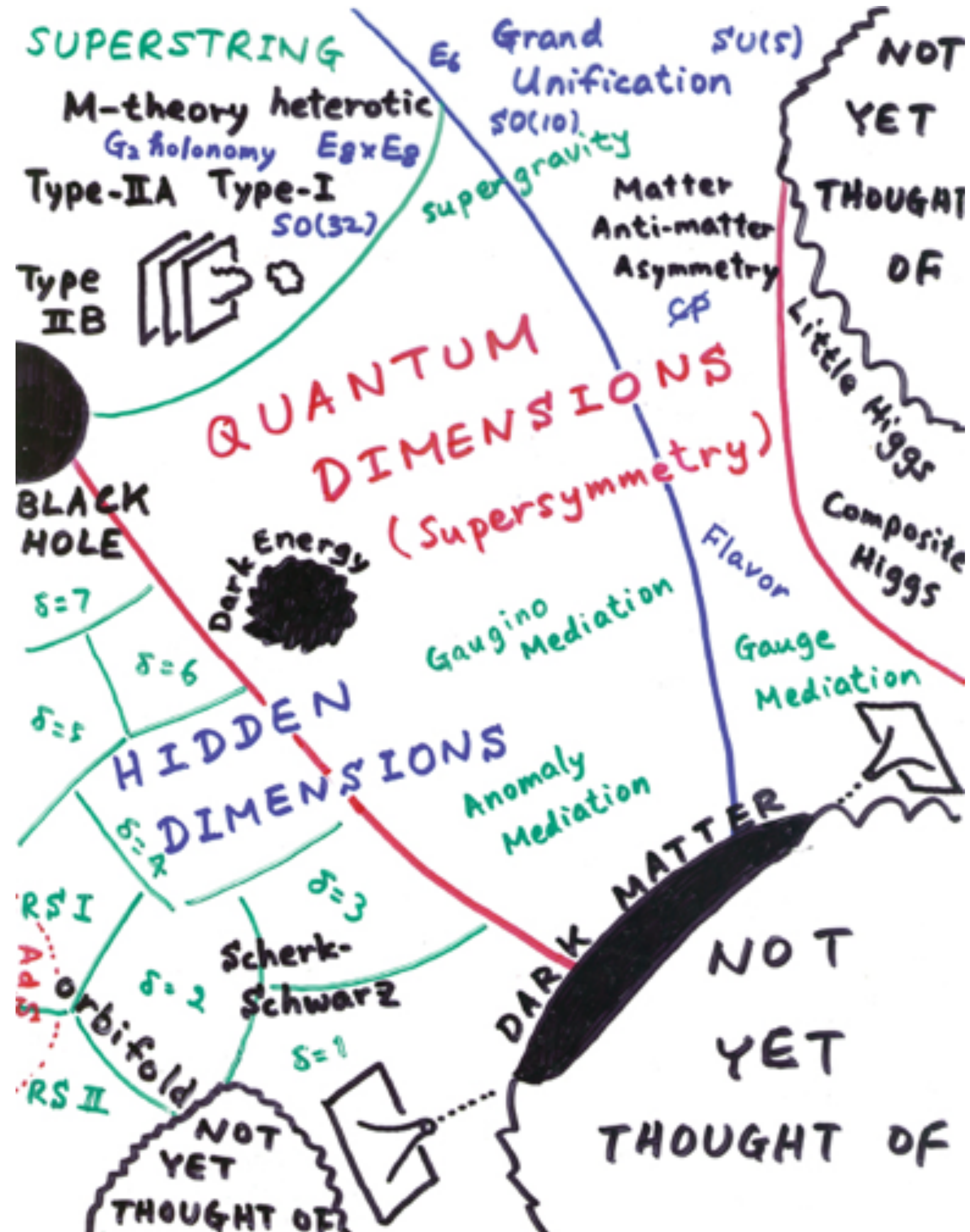
Collider	LHC		ILC/CLIC
CM Energy [TeV]	14	14	0.5
Luminosity [fb^{-1}]	300	3000	500
SM Couplings			
photon, F_{1V}^{γ} (0.666)	0.042	0.014	0.002
Z boson, F_{1V}^{Z} (0.24)	0.50	0.17	0.003
Z boson, F_{1A}^{Z} (0.6)	0.058	–	0.005
Non-SM couplings			
photon, F_{1A}^{γ}	0.05	–	–
photon, F_{2V}^{γ}	0.037	0.025	0.003
photon, F_{2A}^{γ}	0.017	0.011	0.007
Z boson, F_{2V}^{Z}	0.25	0.17	0.006
Z boson, ReF_{2A}^{Z}	0.35	0.25	0.008
Z boson, ImF_{2A}^{Z}	0.035	0.025	0.015

[Snowmass Top Quark WG]

ILC Physics Case, Part 3: Direct Search for New Physics

Beyond the Standard Model

- Many extensions of the SM at ~weak scale have been proposed
- All contain new particles that can be produced in colliders
- Extensive searches at the LHC, nothing found yet, to be continued at Run-2, HL, …
- Despite lower energy of the ILC, it can discover particles missed at the LHC



[figure credit: H. Murayama]

Direct Search: ILC vs LHC

pp colliders

- High Energy, BUT
- Hierarchical cross sections: colored final states >> uncolored final states
- Backgrounds: >>1 soft QCD jets in each event

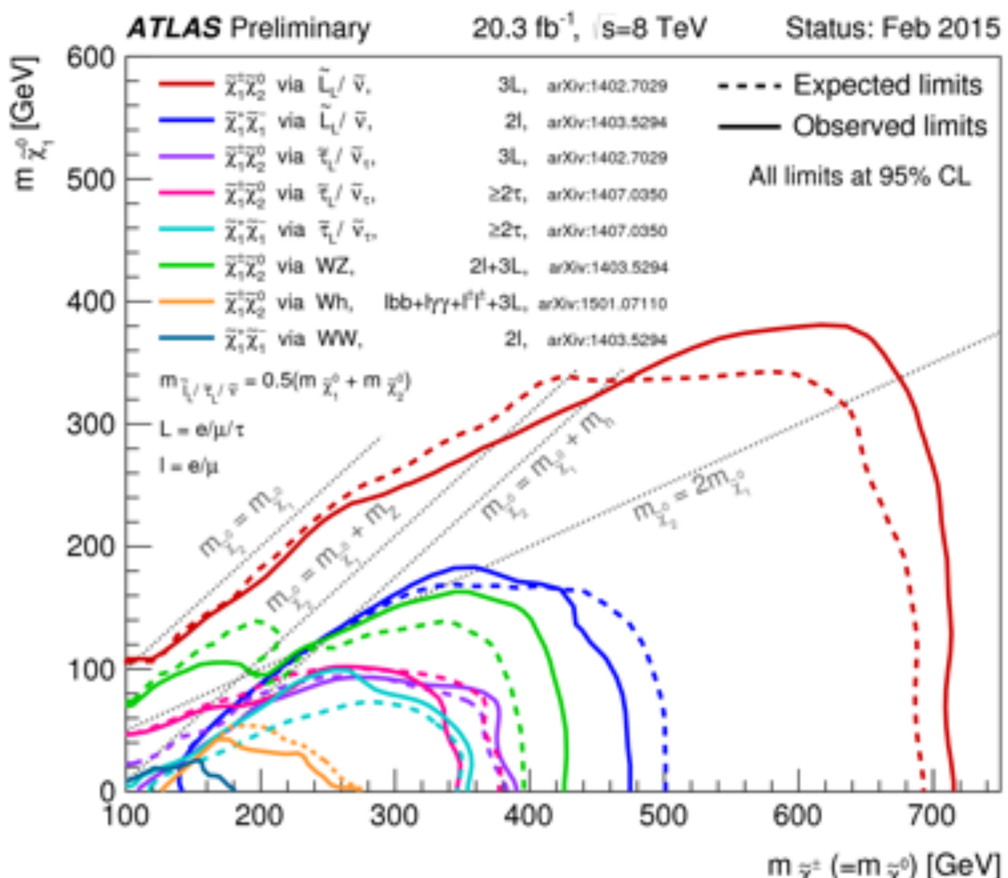
➡ Gaps in coverage: weakly interacting states, purely hadronic signatures, soft jet signatures

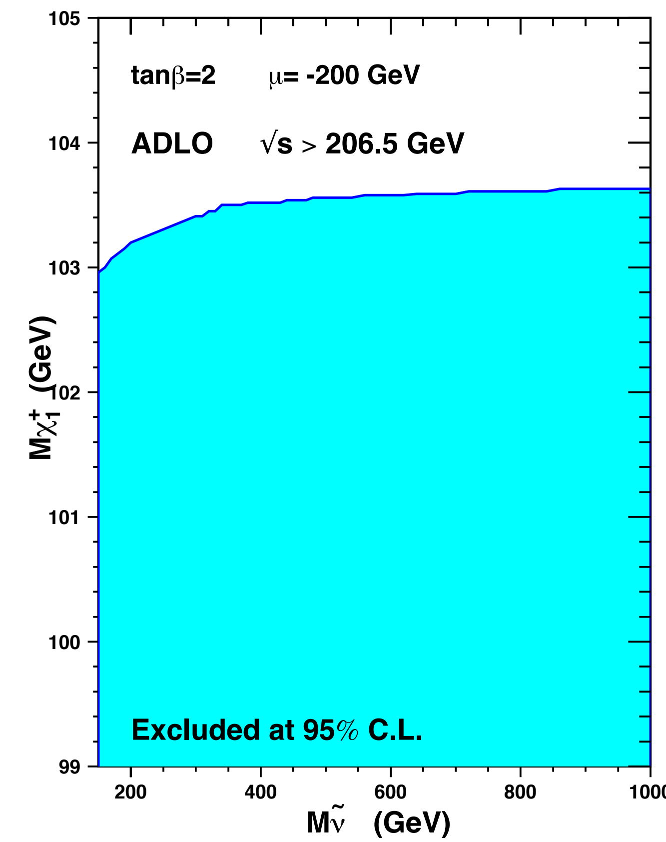
e+e- colliders

- Lower energy, BUT
- Democratic cross sections: just need to couple to photon or Z
- Low, well-understood backgrounds

➡ "Hermetic" coverage of particles with mass up to the kinematic limit, $\sqrt{s}$ or $\frac{\sqrt{s}}{2}$

Example: Chargino Search





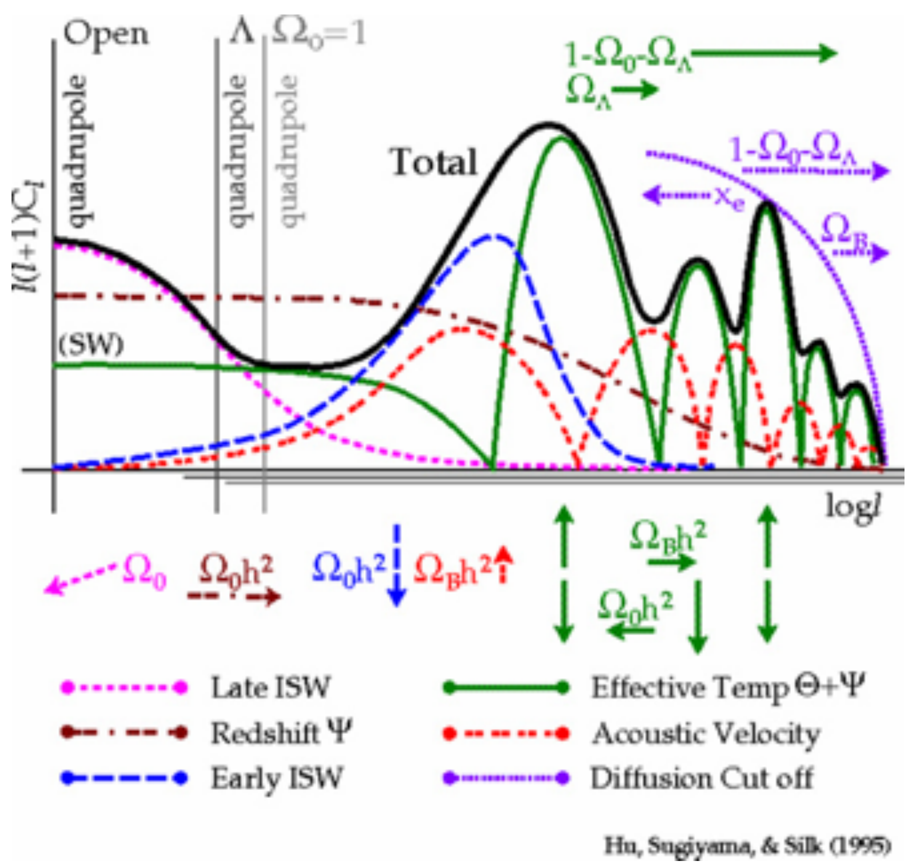
- LHC: Model-dependent bounds, 700 GeV in some cases, but could be ~200 GeV in others.

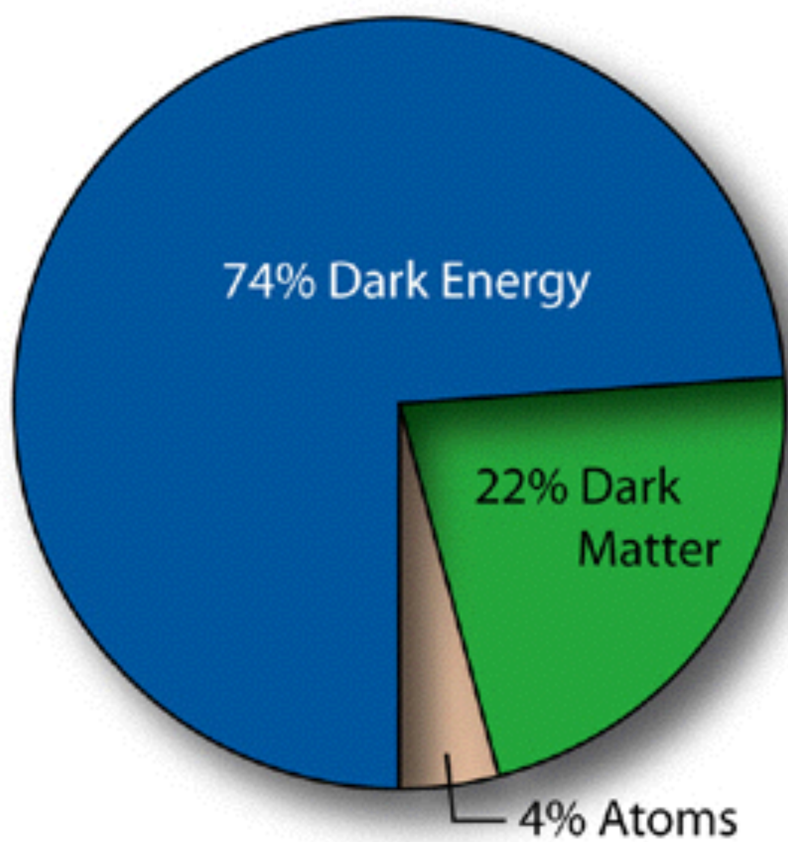
- LEP-2: $m_{\chi^{\pm}} \geq 103$ GeV. No gaps or caveats. Applies to all charged particles.

- ILC will extend such robust bound to 250 GeV

Dark Matter

- Existence of dark matter from galactic to cosmological scales has been firmly established by observations
- DM makes up about 25% of the Universe by mass, ~5 times more than ordinary matter
- Standard Model has no particle with right properties to account for dark matter

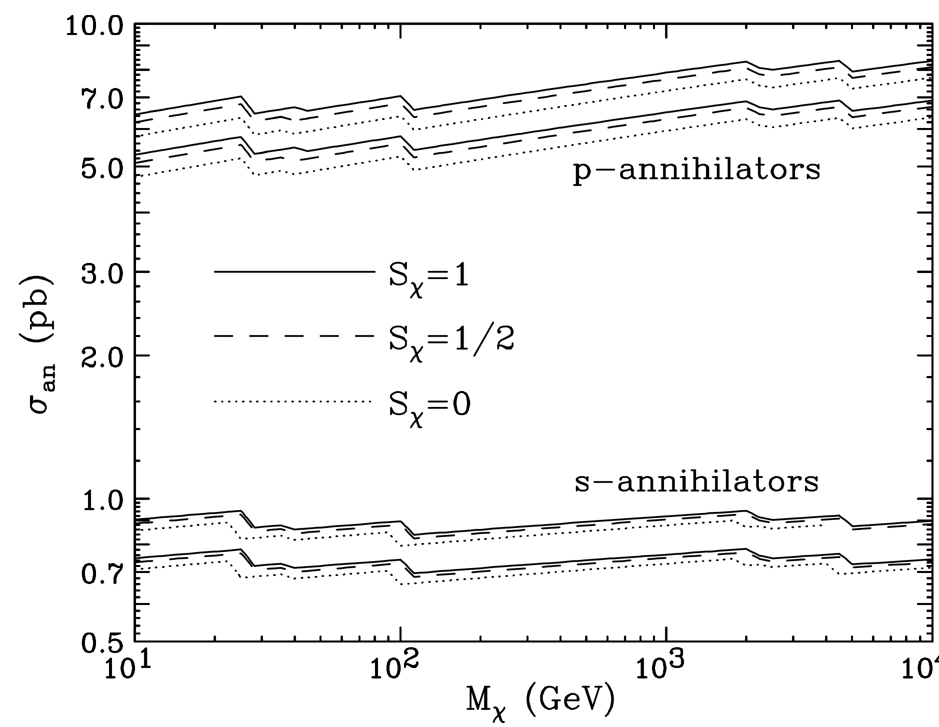




WIMP Dark Matter

- First firm "experimental" evidence for physics beyond the SM!
- There are (too) many particle physics models of DM; a useful classification is by cosmological history: "thermal" vs "non-thermal"
- In the thermal case, present DM density implies annihilation cross section* of ~1 pb, typical scale for weak interactions → "Weakly-Interacting Massive Particle" (WIMP)

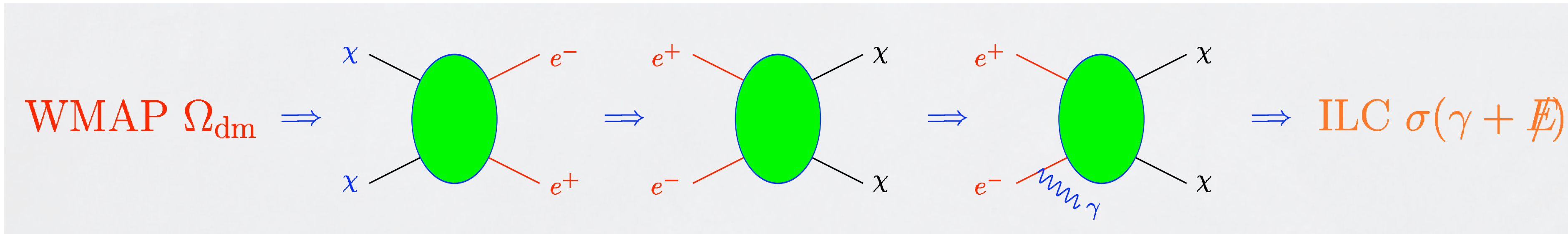
$$\Omega_{\rm dm} \approx 0.22$$



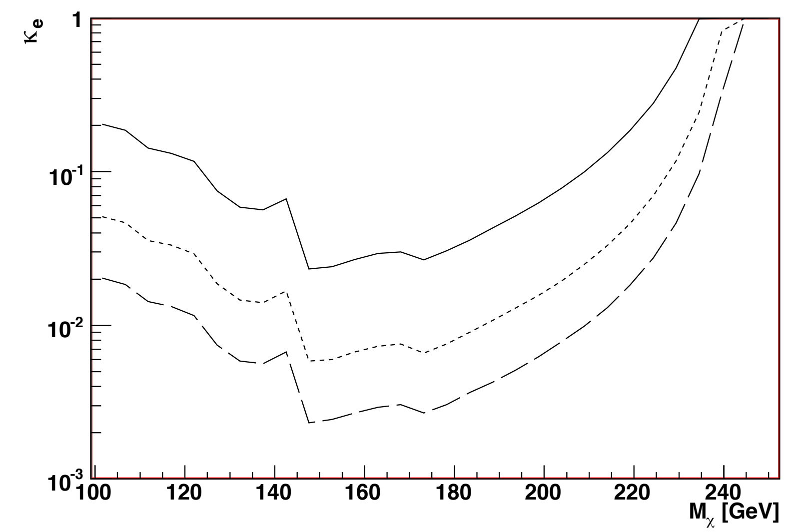
* total, into all SM states:

$$\sigma_{\rm an} = \sum_{X \in {\rm SM}} \sigma(\chi\chi \to X\bar{X})$$

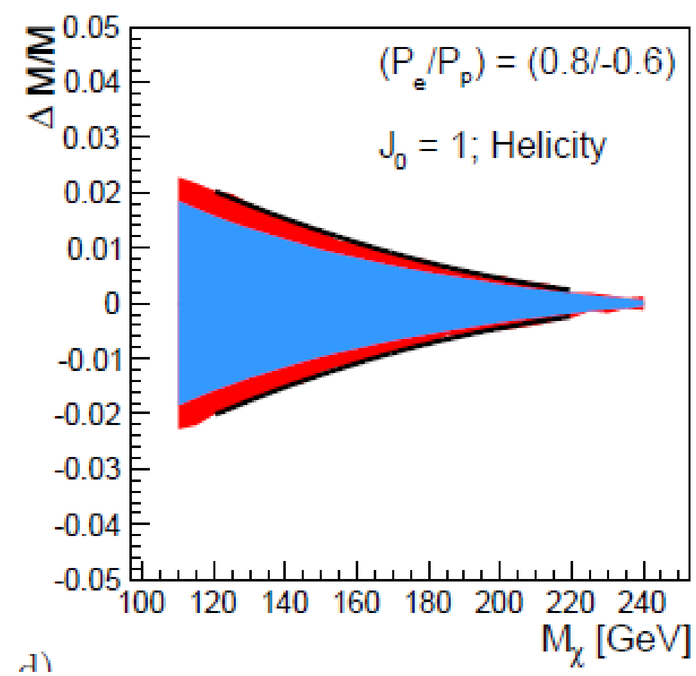
Dark Matter @ ILC



- WIMP hypothesis yields a simple, robust prediction for rate of "mono-photon" DM signature at the ILC:



- At the ILC, WIMPs can be discovered if at least ~1% of their annihilations in the early universe are into e^+e^-

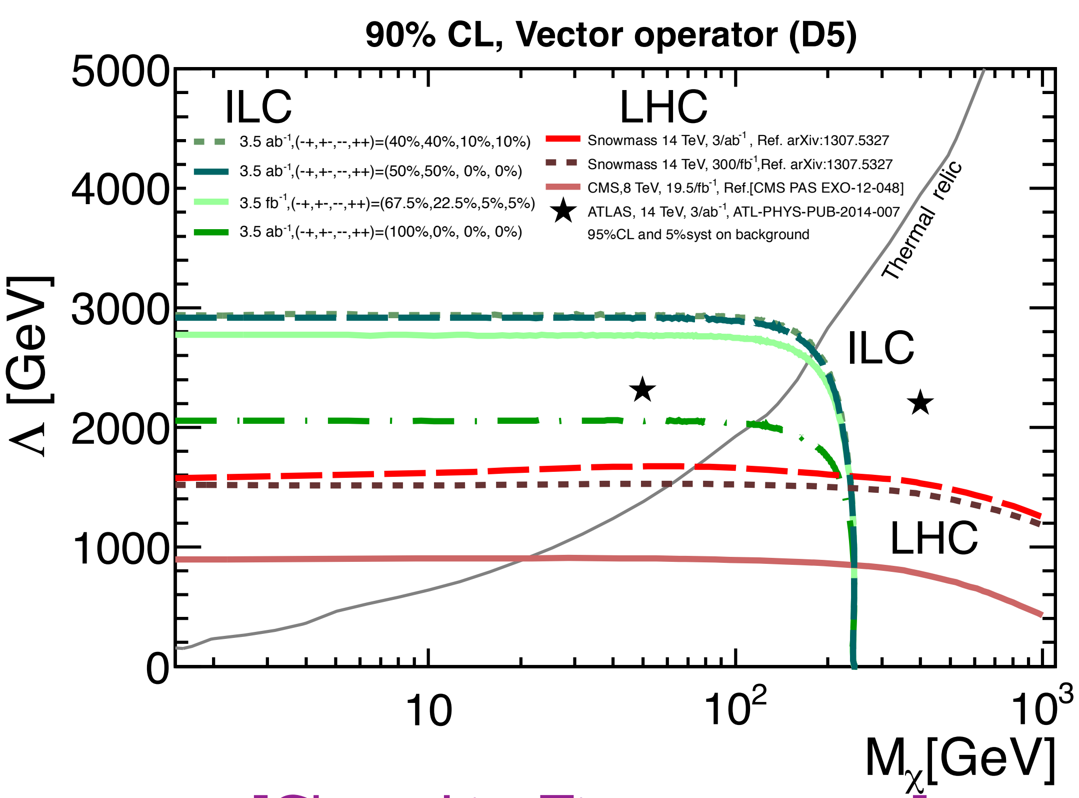


- If discovered, WIMP mass and spin can be measured

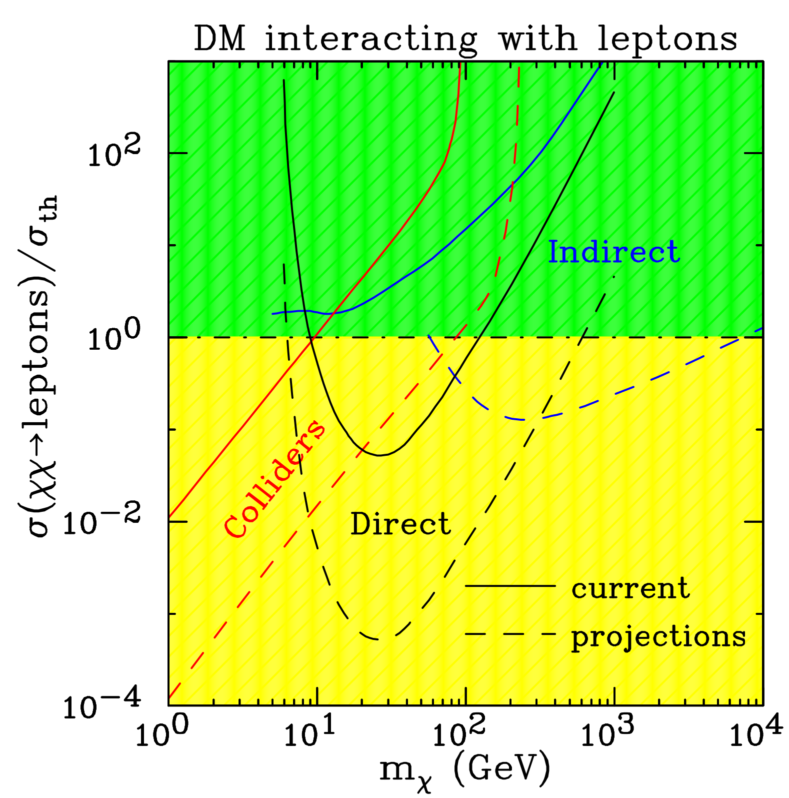
[Birkedal, Matchev, MP, '04; Bartels, List, '12]

DM Complementarity

- DM search at the ILC complements the LHC searches: probe DM-electron vs. DM-quark couplings
- If DM couples to both equally, ILC probes smaller couplings in the accessible mass range, while LHC probes higher mass
- ILC also complements direct and indirect DM searches



[Chaus, List, Titov, to appear]



[Snowmass DM Complementarity WG, '13]

Beyond This Talk

- In this talk, I was not able to cover all of the exciting physics measurements can be performed at the ILC
- Some prominent examples include:
  - Precision electroweak program $\sqrt{s} = 92 \ldots 160\ \mathrm{GeV}$
  - Indirect (non-Higgs) new physics searches, e.g. Z'
- Suggested further reading:
  - ILC Technical Design Report, vol. 2: Physics [1306.6352]
  - "Physics at the e+e- Linear Collider" [1504.01726]
  - Snowmass '13 WG Reports and White papers

Conclusions

- Today, particle physics is confronted with a number of fundamental questions:
  - What is the nature of the Higgs? Is it elementary or composite? Are there other scalar fields?
  - Why is the electroweak symmetry broken?
  - What happened during the electroweak phase transition? Can this transition produce matter-antimatter asymmetry?
  - Is our vacuum stable, or only meta-stable?
  - Are there new particles at the weak/TeV scale?
  - What is the nature of dark matter?
- ILC is a crucial tool to address these questions. Let's build it!