Physics at Future e+e- Colliders

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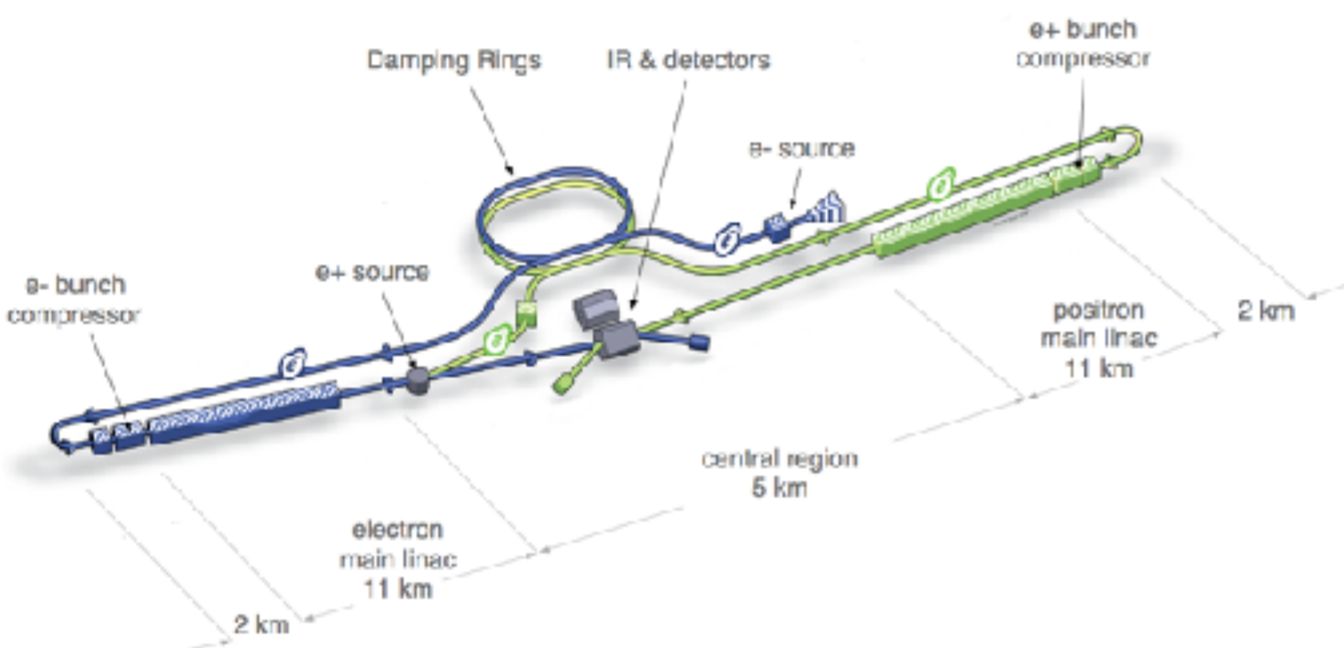
outline

- introduction
- Higgs sector at linear colliders
- top physics at linear colliders
- potential of discovering new particles
- summary

proposals of future linear colliders

ILC



0.1-1 TeV

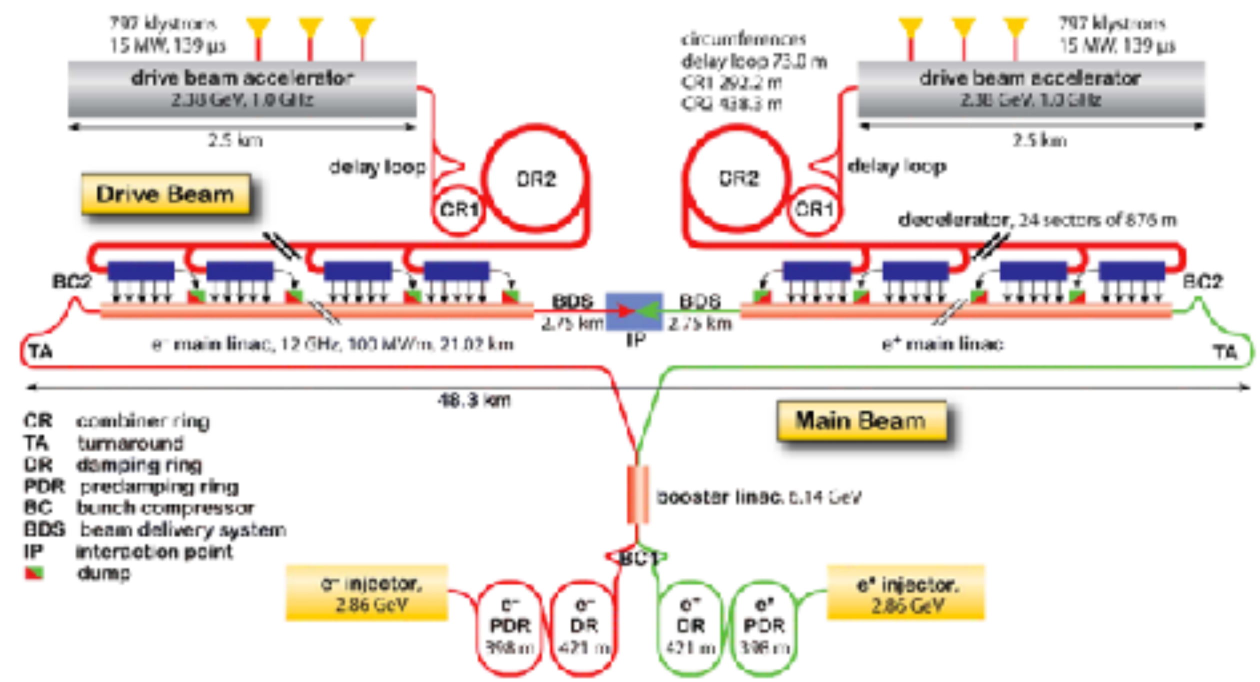
P_{e-}: 80%; P_{e+}: 30%

1.8 x 10^{34} $cm^{-2}s^{-1}$ @ 500 GeV

TDR in 2013

1506.05992; 1506.07830

CLIC



0.35-3 TeV

P_{e-}: 0%(80%); P_{e+}: 0%

5.9 x 10^{34} $cm^{-2}s^{-1}$ @ 3 TeV

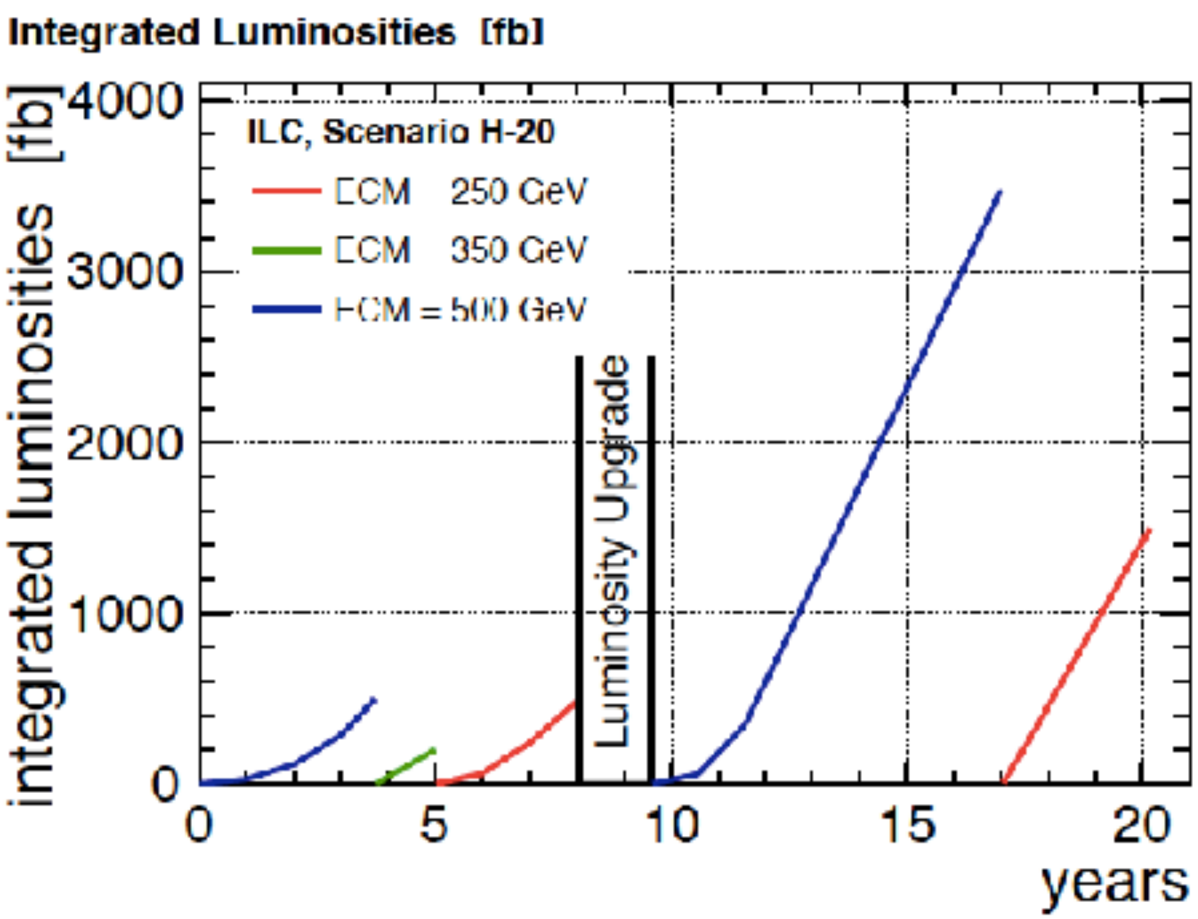
CDR in 2012

1202.5940; 1608.07537

20+ years of running

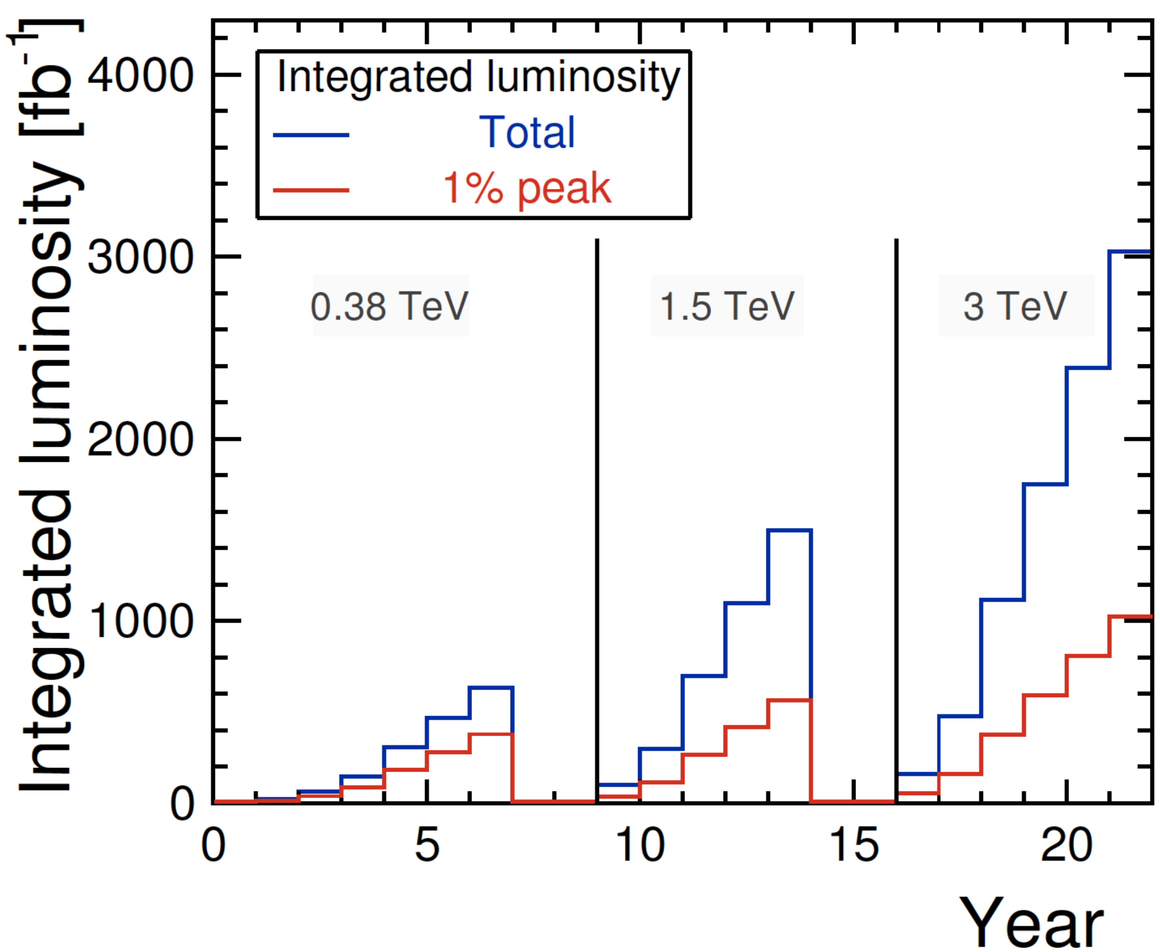
ILC H-20 running scenario

Total
250GeV 1500fb-1
350GeV 200fb-1
500GeV 4000fb-1



CLIC staging scenario

Stage	$\sqrt{s}$ (GeV)	$\mathscr{L}_{int}$ (fb^{-1})
1	380	500
	350	100
2	1500	1500
3	3000	3000

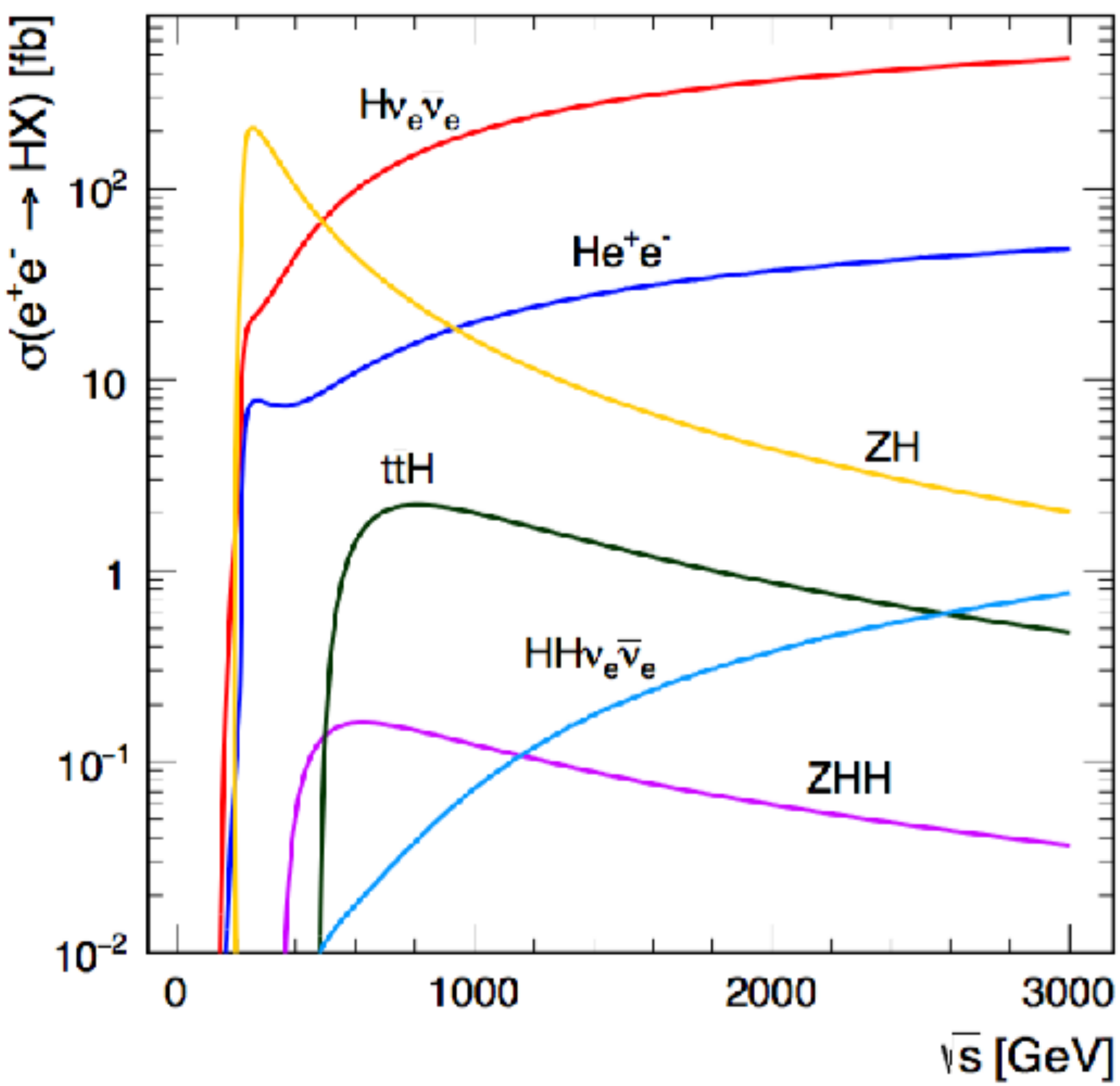


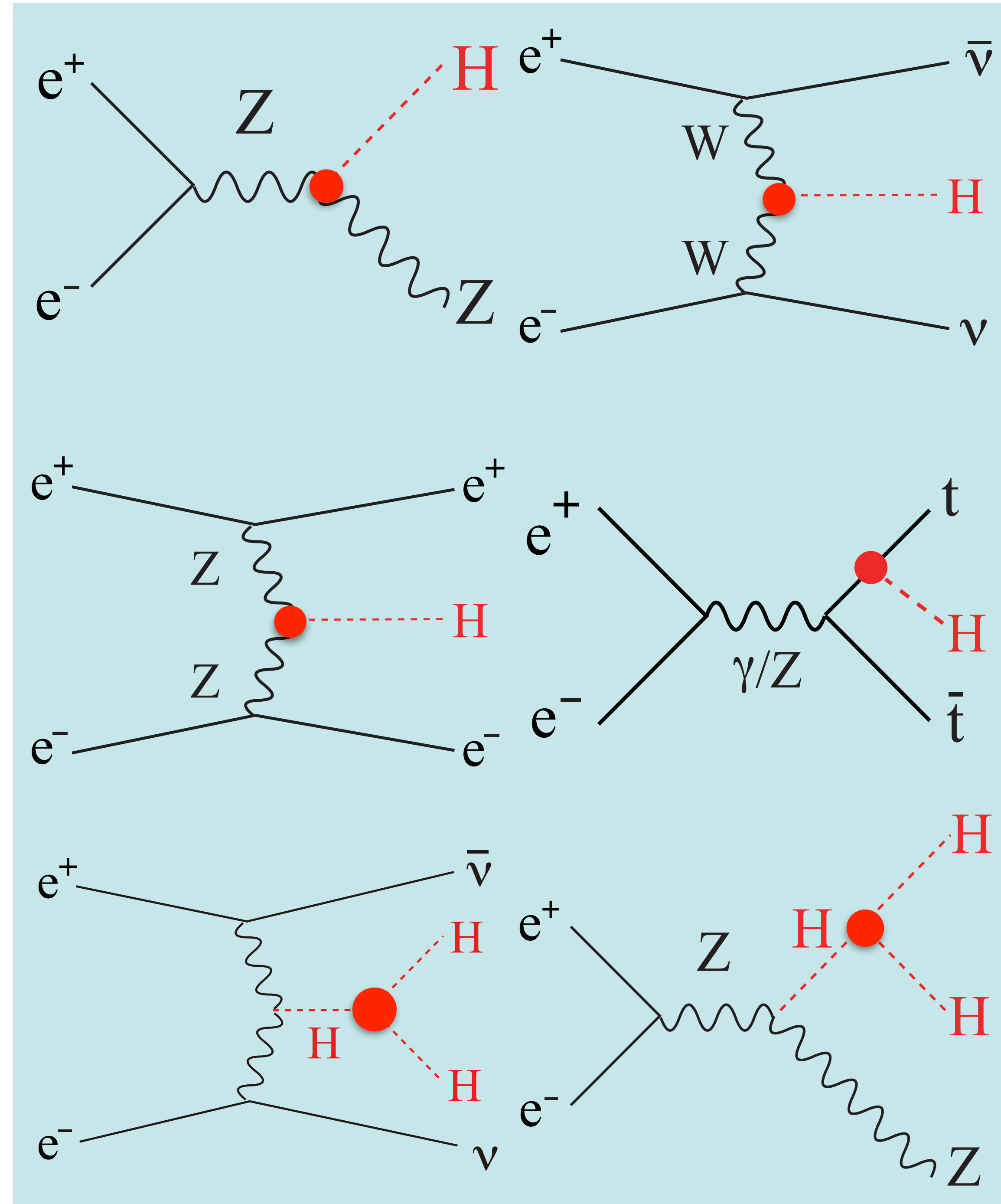
three major probes for BSM at future linear colliders

- Higgs
- top
- new particles

with emphasis on complementarity with LHC

Higgs production at e⁺e⁻ collisions





two important thresholds: √s ~ 250 GeV for ZH,
~500 GeV for ZHH and ttH

nail down Higgs sector at future lepton colliders

bottom-up and model independent way

Mass & J^{CP} $\quad M_h \quad \Gamma_h \quad J^{\rm CP}$

new CP violating source?

$L_{\rm Higgs}$ $\quad hhh: \; -6i\lambda v = -3i\frac{m_h^2}{v}, \quad hhhh: \; -6i\lambda = -3i\frac{m_h^2}{v^2}$

probe Higgs potential, EWBG?

$L_{\rm Gauge}$

$$W_\mu^+ W_\nu^- h: \; i\frac{g^2 v}{2} g_{\mu\nu} = 2i\frac{M_W^2}{v} g_{\mu\nu}, \quad W_\mu^+ W_\nu^- hh: \; i\frac{g^2}{2} g_{\mu\nu} = 2i\frac{M_W^2}{v^2} g_{\mu\nu},$$

$$Z_\mu Z_\nu h: \; i\frac{g^2+g'^2 v}{2} g_{\mu\nu} = 2i\frac{M_Z^2}{v} g_{\mu\nu}, \quad Z_\mu Z_\nu hh: \; i\frac{g^2+g'^2}{2} g_{\mu\nu} = 2i\frac{M_Z^2}{v^2} g_{\mu\nu}$$

SU(2) nature? m_V from SSB?

$L_{\rm Yukawa}$ $\quad h\bar{f}f: \; -i\frac{y^f}{\sqrt{2}} = -i\frac{m_f}{v}$

m_f from Yukawa coupling? 2HDM?

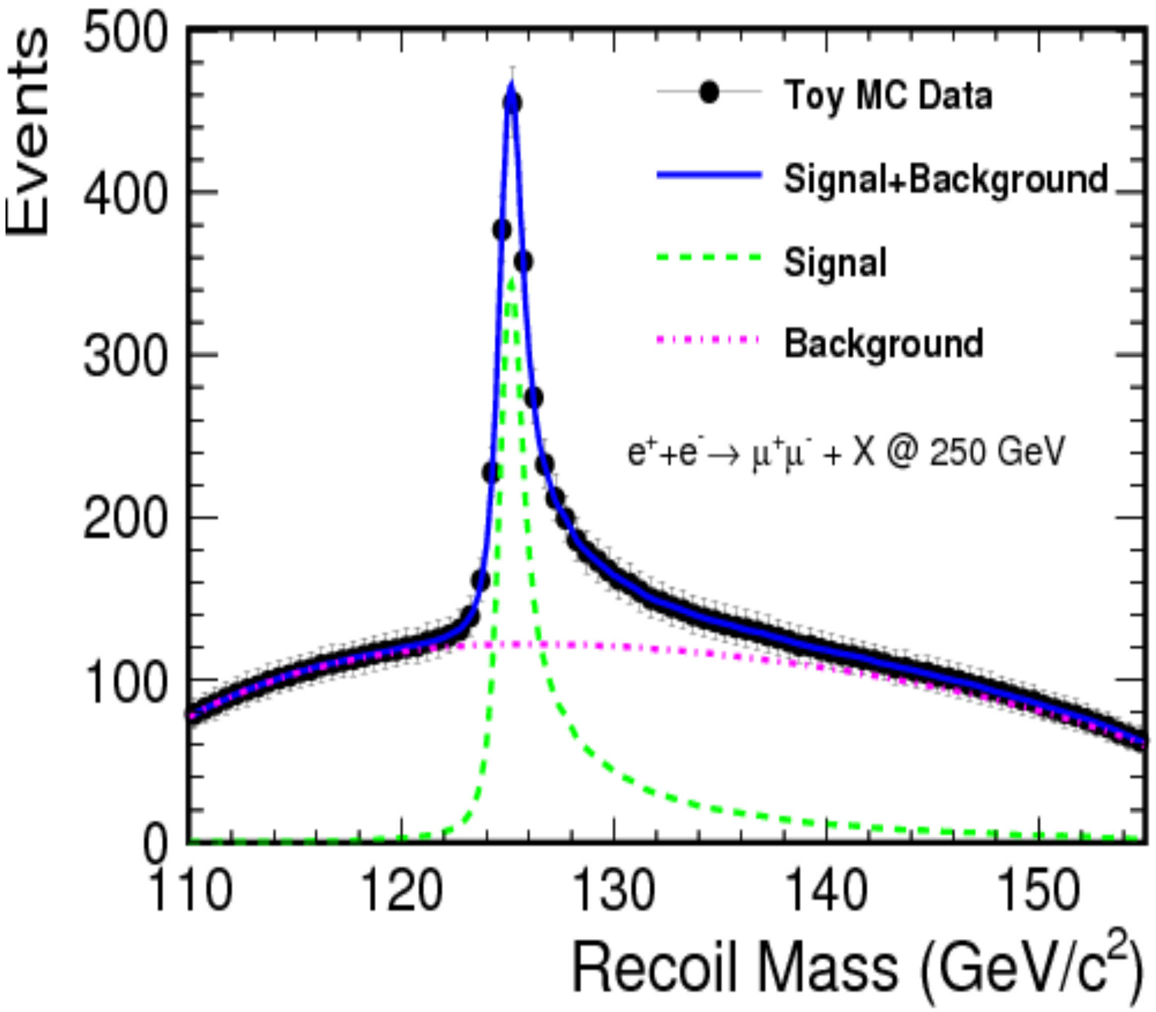
$L_{\rm Loop}$ $\quad h\gamma\gamma \quad hgg \quad h\gamma Z$

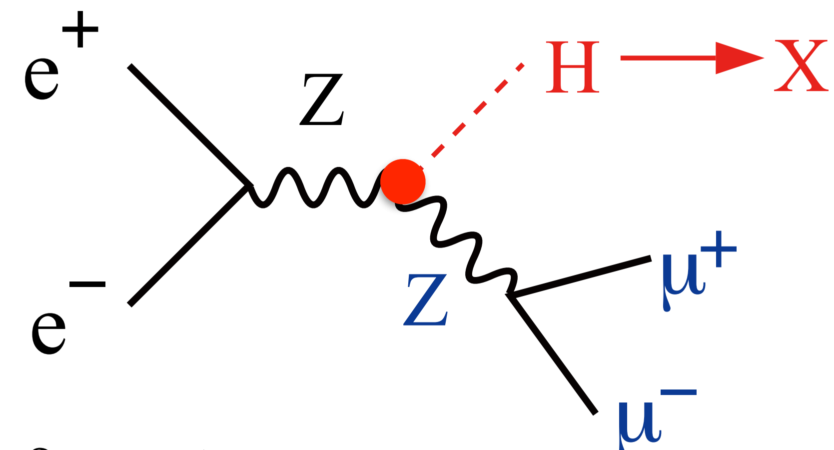
new particles in the loop?

+ possible exotic interactions of Higgs, e.g. H—>dark matter?

the key of model independence: absolute σ_{ZH}

Yan, et al, Phys.Rev. D94 (2016) 113002;
Thomson, Eur.Phys.J. C76 (2016) 72





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

$$Y_1 = \sigma_{ZH} \propto g_{HZZ}^2$$
$$\delta g_{HZZ} \sim 0.38\%$$

- meas. of σ_{ZH} doesn't depend on how Higgs decays
- meas. of σ_{ZH} doesn't depend on underlying models on HZZ vertex

importance of absolute coupling determination

- in some BSM, only Higgs wave function gets modified
- Higgs BR, and ratio of Higgs couplings could stay unchanged

$$\mathcal{O}_H = \frac{1}{2}\left(\partial_\mu |H|^2\right)^2$$

N. Craig @ LCWS16
arXiv: 1702.06079

Appears in Lagrangian as $\mathcal{L} \supset \frac{c_H}{\Lambda^2}\mathcal{O}_H$ and after EWSB $H \to v + \frac{1}{\sqrt{2}}h$

$$\frac{c_H}{\Lambda^2}\cdot\frac{1}{2}\left(\partial_\mu |H|^2\right)^2 \to \left(\frac{2c_H v^2}{\Lambda^2}\right)\cdot\frac{1}{2}(\partial_\mu h)^2$$

Correction to Higgs wavefunction in broken phase

Canonically normalizing $h \to \left(1 - c_H v^2/\Lambda^2\right) h$

shifts all Higgs couplings uniformly, e.g.

$$\frac{m_Z^2}{v} h Z_\mu Z^\mu \to \frac{m_Z^2}{v}\left(1 - c_H v^2/\Lambda^2\right) h Z_\mu Z^\mu$$

$\delta g_{HZZ} \sim 0.38\%$ —> $\Lambda > 2.8$ TeV

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HWW coupling & Higgs total width Γ_H

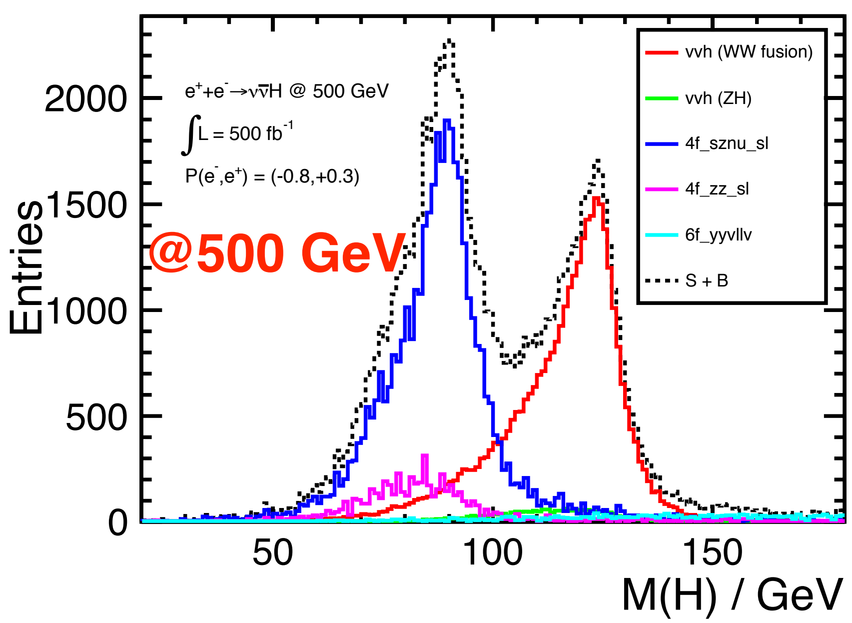
$$\Gamma_H = \frac{\Gamma_{HZZ}}{\mathrm{Br}(H \to ZZ^*)} \propto \frac{g^2_{HZZ}}{\mathrm{Br}(H \to ZZ^*)}$$

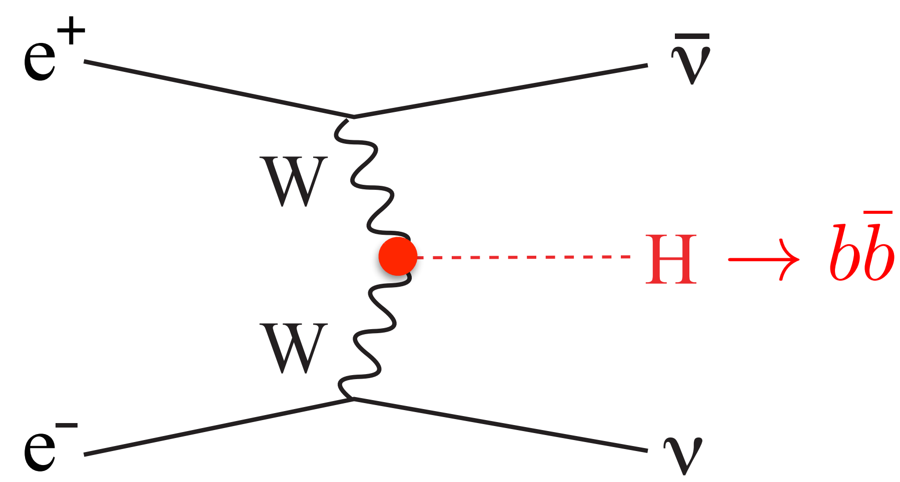
—>Br(H->ZZ*) very small

★ $$\Gamma_H = \frac{\Gamma_{HWW}}{\mathrm{Br}(H \to WW^*)} \propto \frac{g^2_{HWW}}{\mathrm{Br}(H \to WW^*)}$$

—> better option!

$\delta\Gamma_H$=1.8%



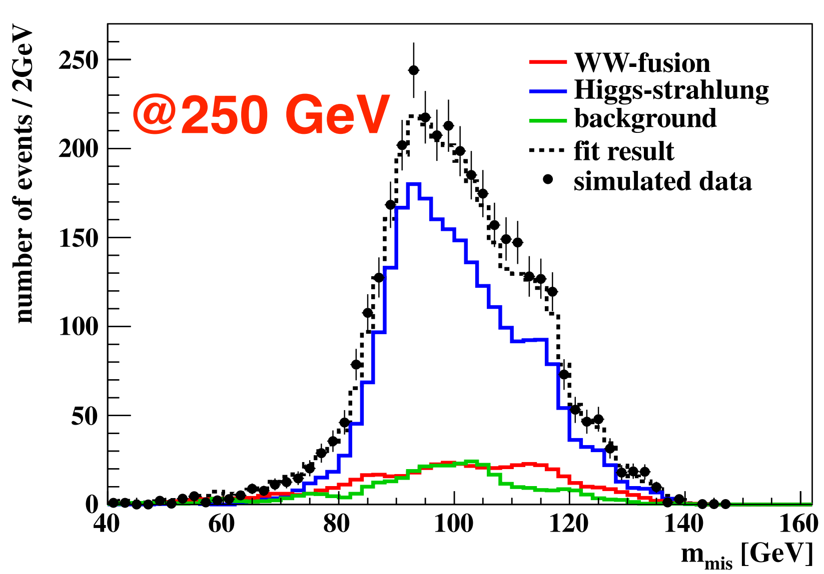


$$Y_2 = \sigma_{\nu\bar{\nu}H} \cdot \mathrm{Br}(H \to b\bar{b}) \propto g^2_{HWW} \cdot \mathrm{Br}(H \to b\bar{b})$$

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

$$g_{HWW} \propto \sqrt{\frac{Y_2}{Y_3}} \cdot g_{HZZ} \propto \sqrt{\frac{Y_1 Y_2}{Y_3}}$$

—>0.4%



Duerig, et al., arXiv:1403.7734

- δg_{HWW} is a limiting factor for Γ_H & all other couplings (other than g_{HZZ})
- higher √s, much larger $\sigma_{\nu\nu H}$

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determine Higgs CP admixture

- find CP-violating source in Higgs sector —> baryongenesis
- essential to understand structures of all Higgs couplings

through H—>$\tau^+\tau^-$

$$L_{Hff} = -\frac{m_f}{v} H \bar{f} (\cos\Phi_{CP} + i\gamma^5 \sin\Phi_{CP}) f$$

$$\Delta\Phi_{CP} \sim 3.8^\circ$$

D.Jeans @ LCWS16

through HZZ/HWW

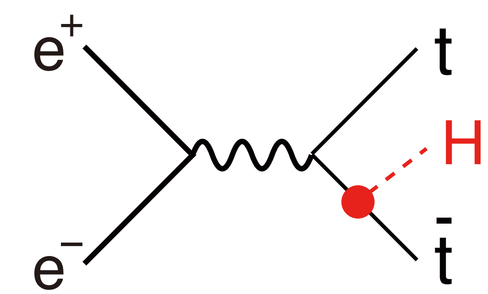
$$L_{HVV} = 2C_V M_V^2 (\frac{1}{v} + \frac{a}{\Lambda}) H V_\mu V^\mu + C_V \frac{b}{\Lambda} H V_{\mu\nu} V^{\mu\nu} + C_V \frac{\tilde{b}}{\Lambda} H V_{\mu\nu} \tilde{V}_{\mu\nu}$$

(CP-odd)

$\Delta\tilde{b} \sim 0.016$ (for Λ=1TeV) T.Ogawa @ LCWS16

Top-Yukawa coupling

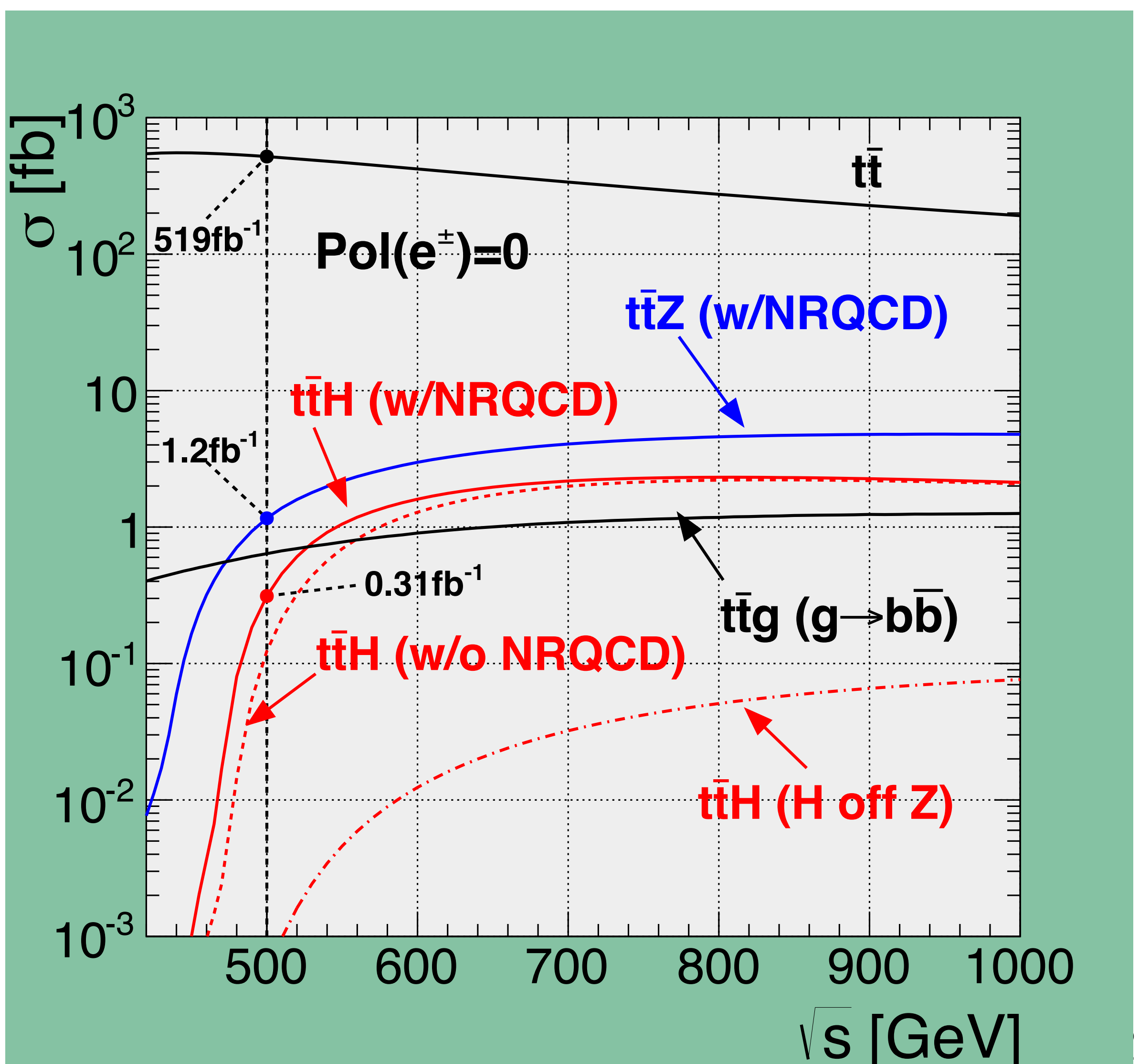
- largest Yukawa coupling; crucial role in theory
- non-relativistic tt-bar bound state correction: enhancement by ~2 at 500 GeV
- cross section increases by ~4 if √s goes from 500 to 550 GeV
- Higgs CP measurement

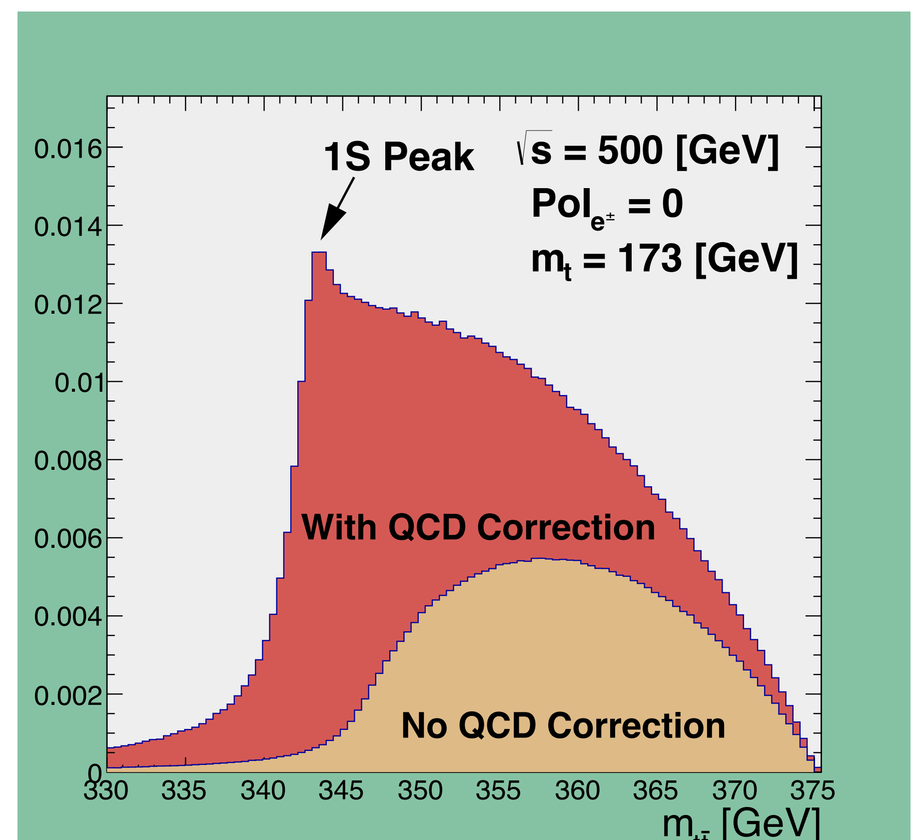


H-> bb

$\Delta g_{ttH}/g_{ttH}$	500 GeV	+ 1 TeV
Snowmass	7.8%	2.0%
H20	6.3%	1.5%

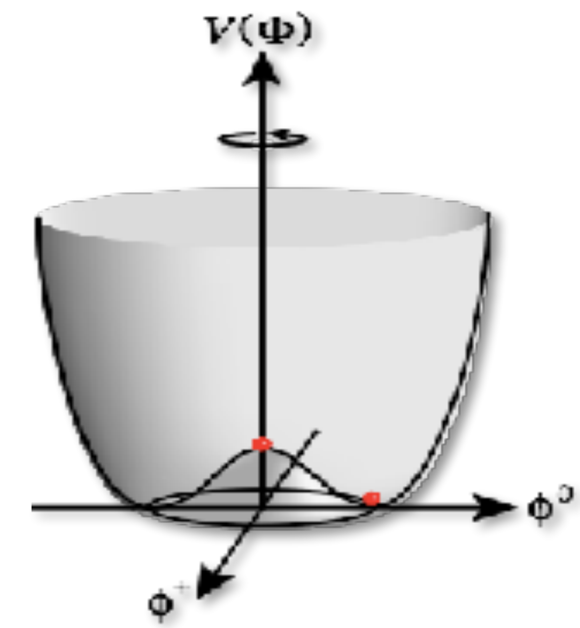
Yonamine, et al., PRD84, 014033;
Price, et al., Eur. Phys. J. C75 (2015) 309





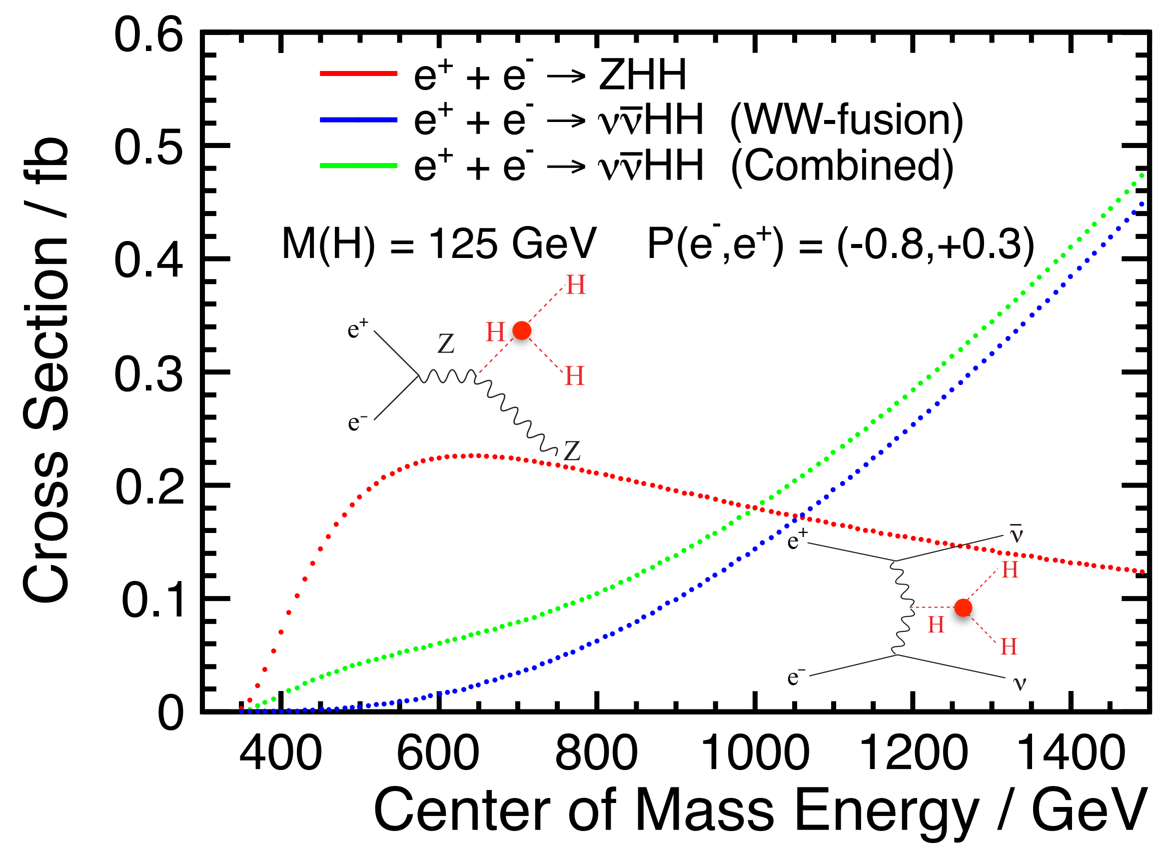
Higgs self-coupling

- direct probe of the Higgs potential
- large deviation (> 20%) motivated by electroweak baryongenesis, could be ~100%
- √s>=500 GeV, e+e- —> ZHH
- √s>=1 TeV, e+e- —> vvHH (WW-fusion)



	$\Delta\lambda_{HHH}/\lambda_{HHH}$	500 GeV	+ 1 TeV
ILC	Snowmass	46%	13%
	H20	27%	10%

	1.4 TeV	+3 TeV
CLIC	24%	11%



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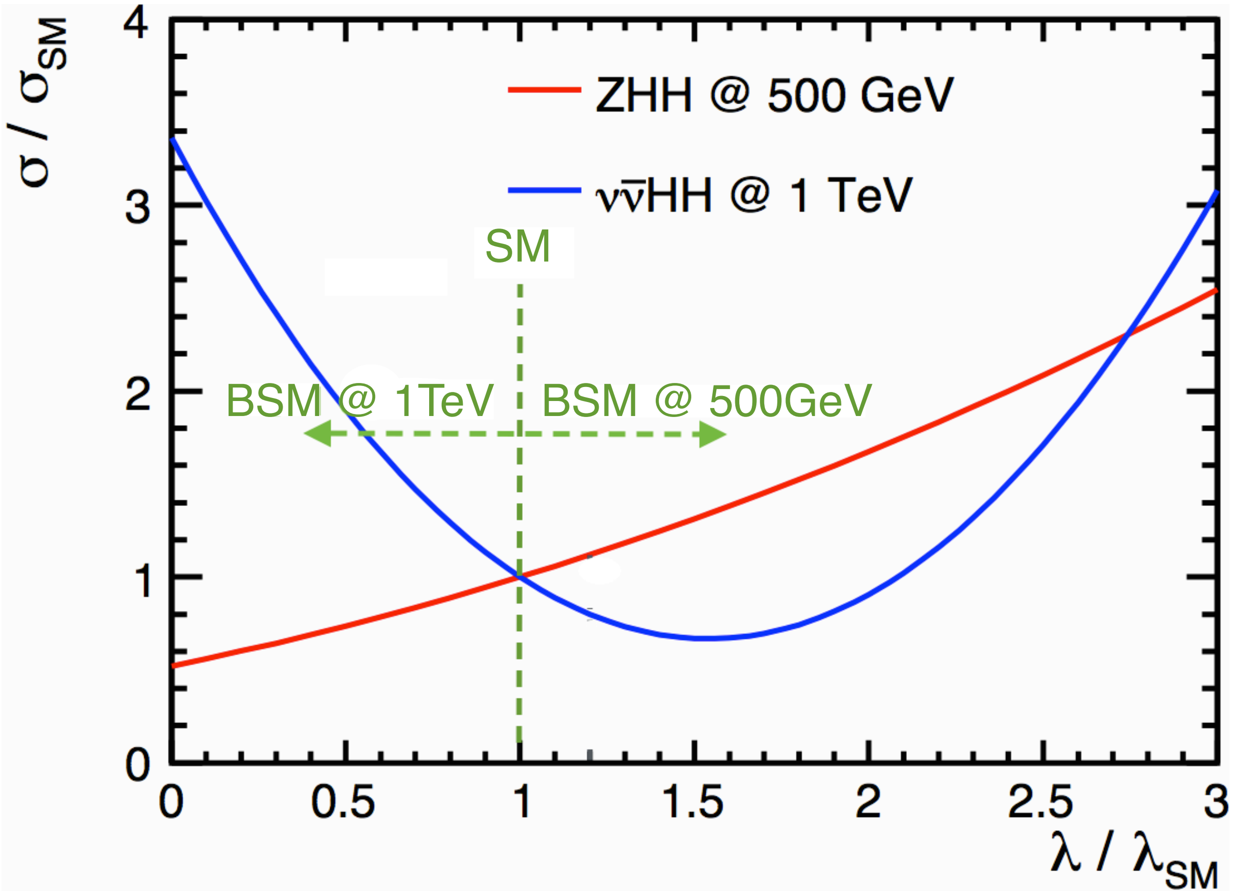
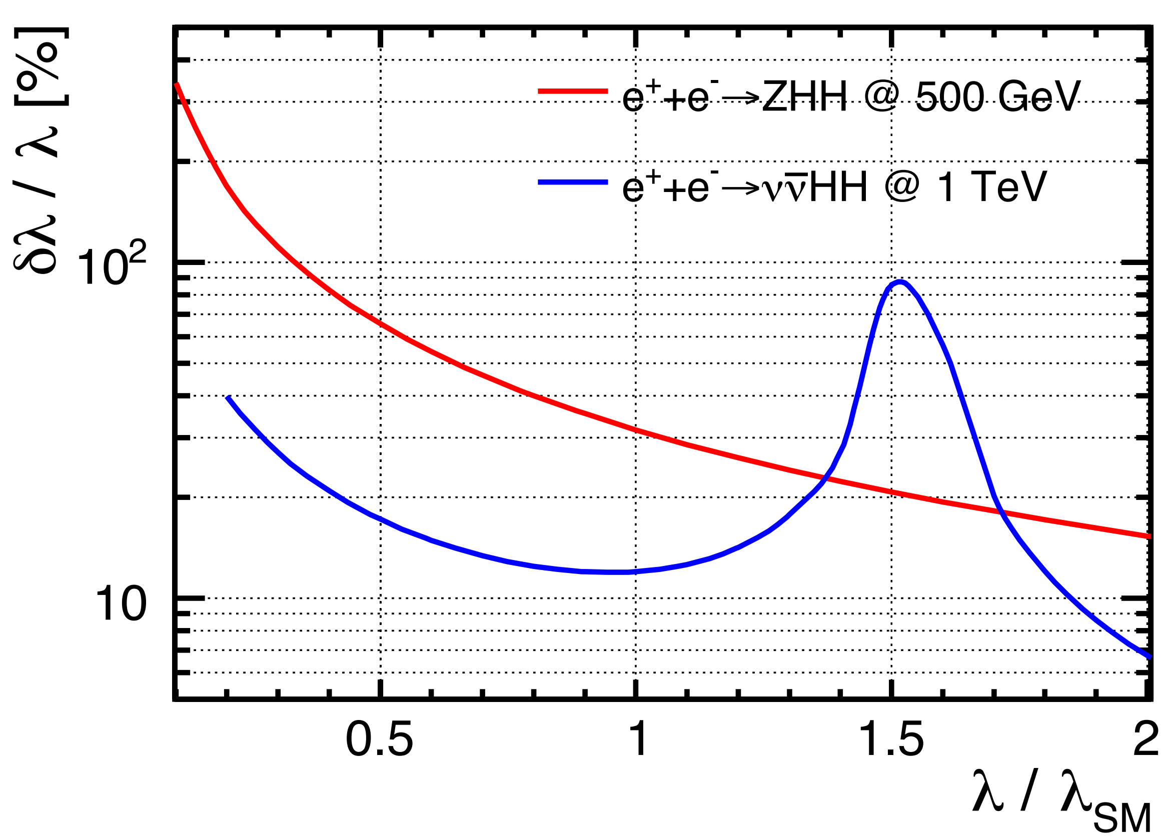
Higgs self-coupling: when $\lambda_{HHH} \neq \lambda_{SM}$?

- constructive interference in ZHH, while destructive in vvHH (& LHC) —> complementarity between ILC & LHC, between √s ~500 GeV and >1TeV
- if $\lambda_{HHH} / \lambda_{SM} = 2$, Higgs self-coupling can be measured to ~15% using ZHH at 500 GeV e+e-

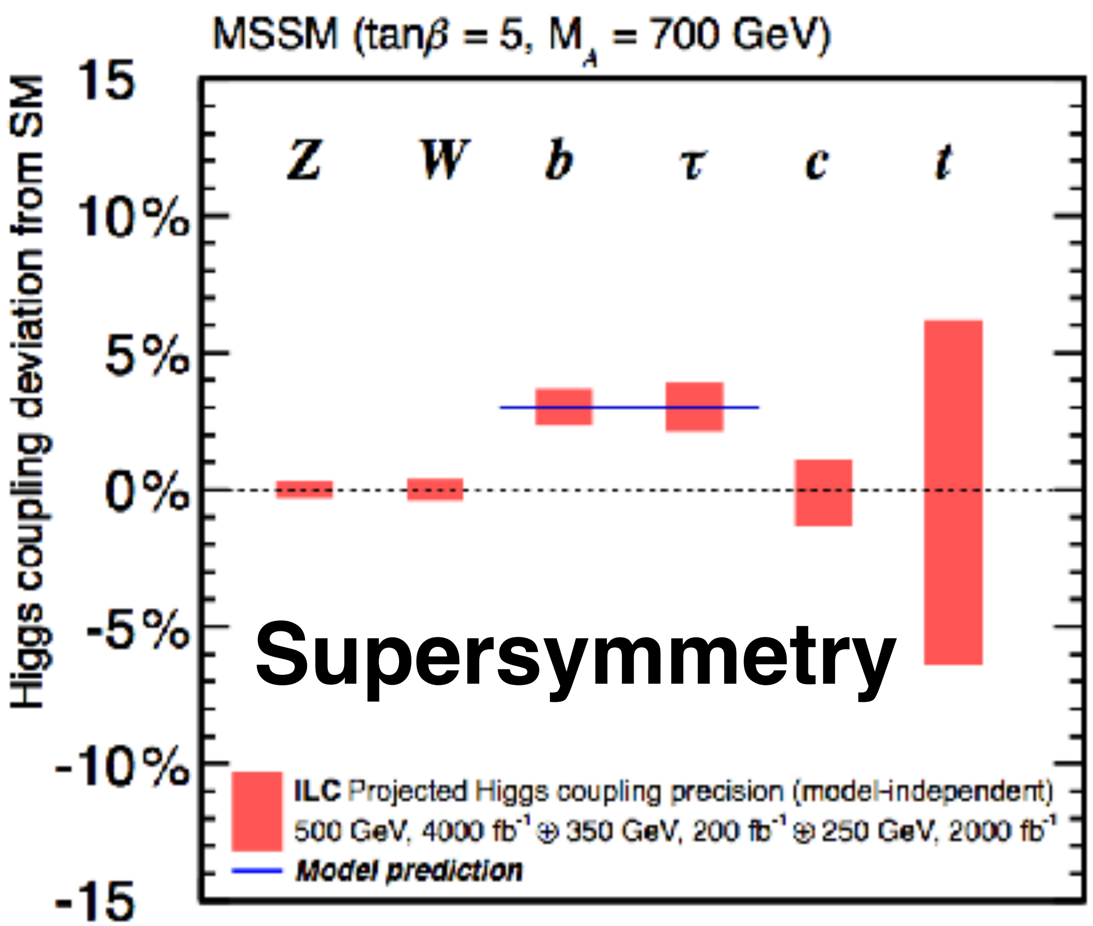
Duerig, Tian, et al, paper in preparation

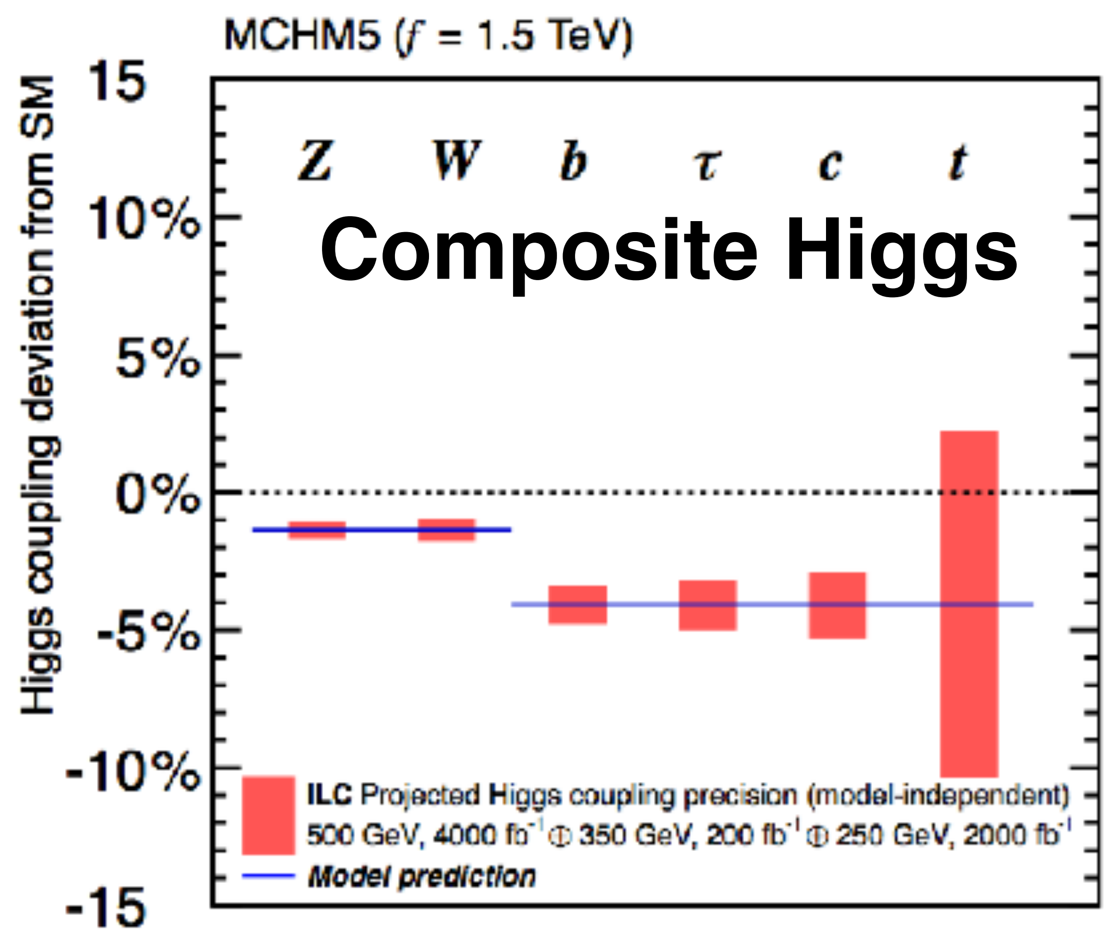




references for large deviations e.g. Grojean, et al., PRD71, 036001; Kanemura, et al., 1508.03245; Kaori, Senaha, PHLTA,B747,152; Perelstein, et al., JHEP 1407, 108

precision Higgs couplings: probe/fingerprint BSM





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

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

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

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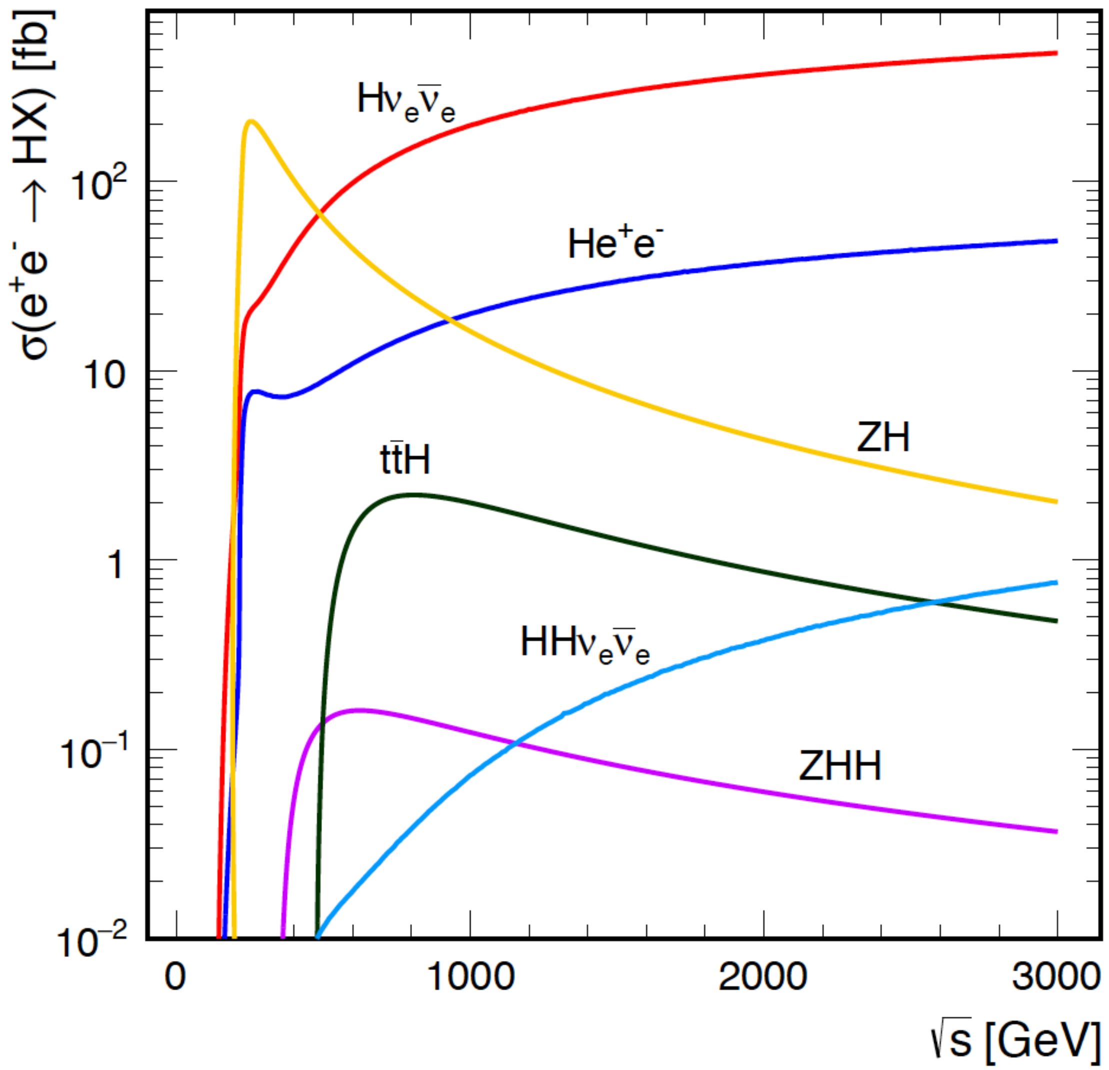
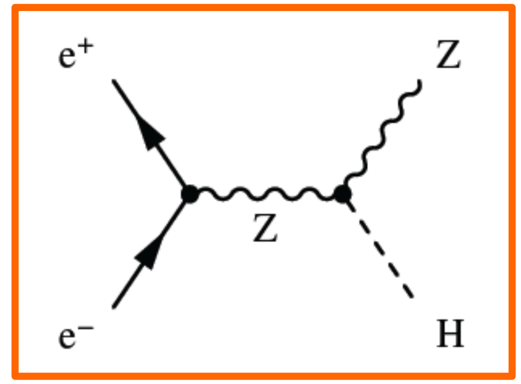
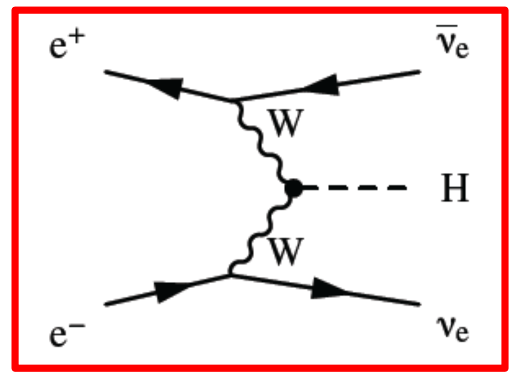
Higgs physics at CLIC





Higgsstrahlung
σ ~ 1/s
Higgs id. from Z recoil



WW(ZZ) - fusion
σ ~ log(s)
Large stat. at high E

	350 GeV	1.4 TeV	3 TeV
$\mathcal{L}_{int}$	500 fb^{-1}	1.5 ab^{-1}	2 ab^{-1}
# ZH events	68 000	20 000	11 000
# $H\nu_e\bar{\nu}_e$ events	17 000	370 000	830 000
# He^+e^- events	3 700	37 000	84 000

For unpolarised beams. Hνν increases ×1.8 for -80% e- polarisation (CLIC baseline)

high selection efficiencies !

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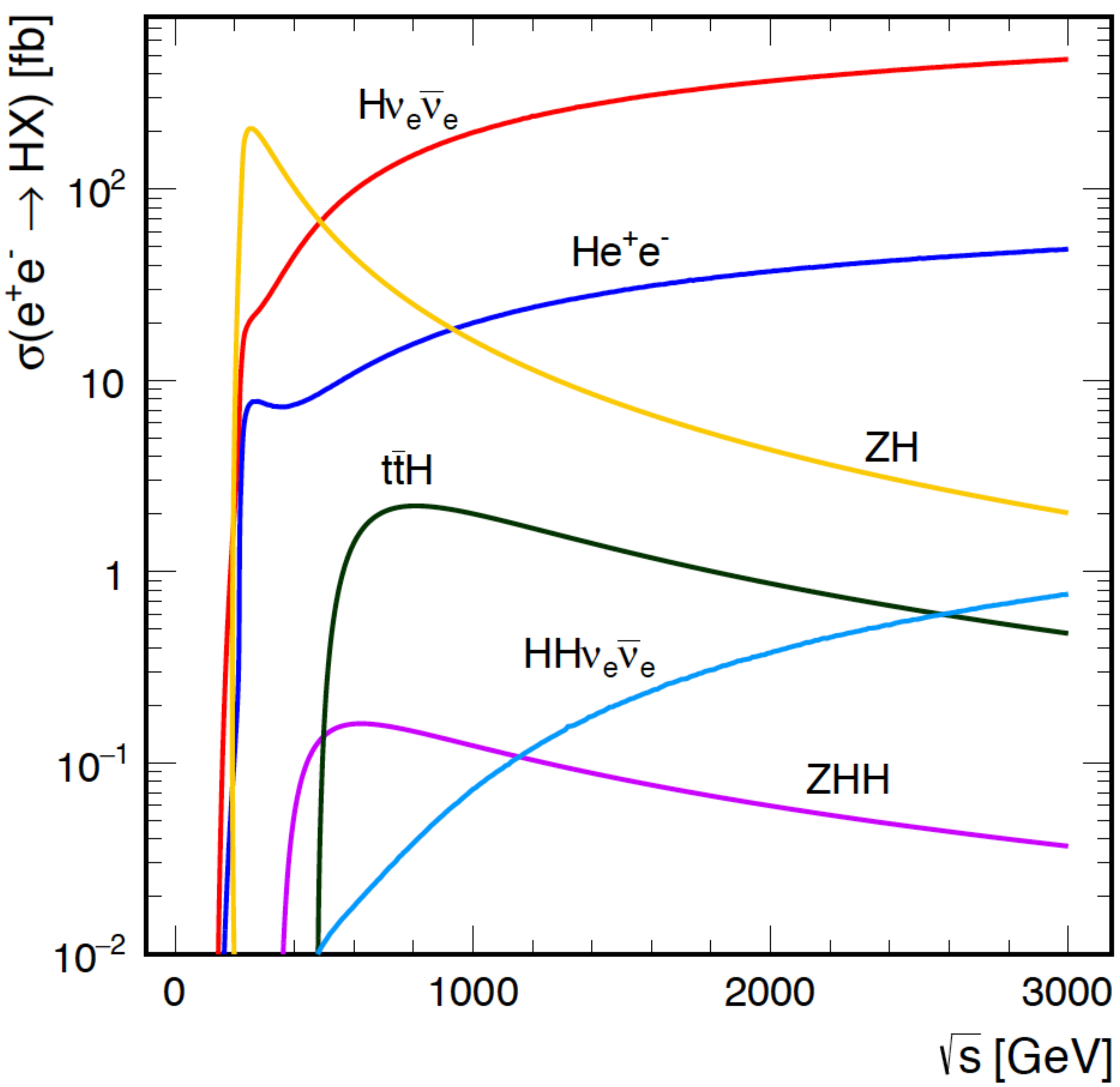
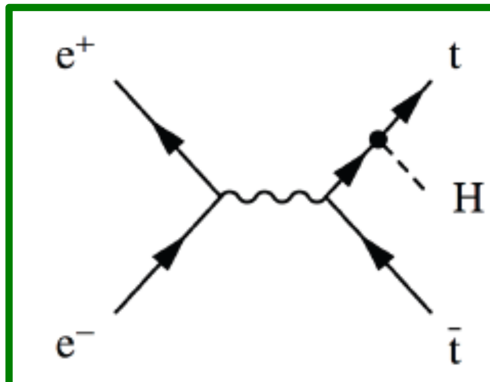
Higgs physics above 1 TeV



Vector boson fusion:
$e^+e^- \rightarrow H\nu\nu$, $e^+e^- \rightarrow He^+e^-$
High σ + increased luminosity
Gives access to rare Higgs decays



$t\bar{t}H$ production:

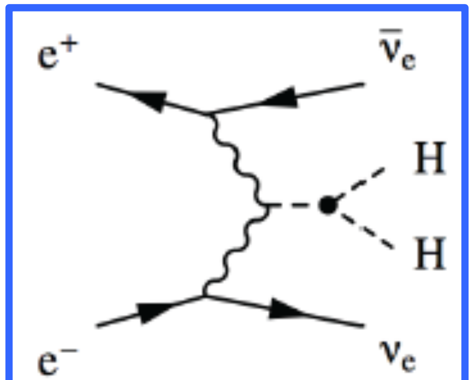
- Extraction of Yukawa coupling y_t
- Best at √s above 700 GeV

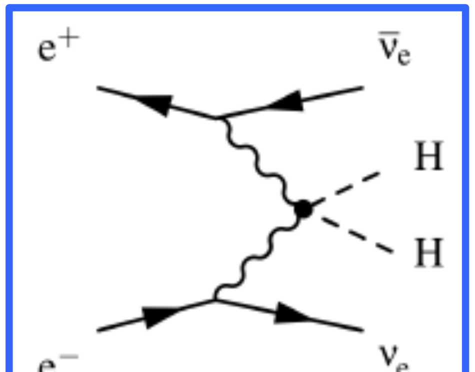
Studied at 1.4 TeV, 1.5 ab^{-1}

- Fully hadronic (8 jets)
- Semi-leptonic (6 jets + lepton + ν)

Statistical accuracy:

- **$\Delta(g_{Htt})$ = ±4.4%** at 1.4 TeV





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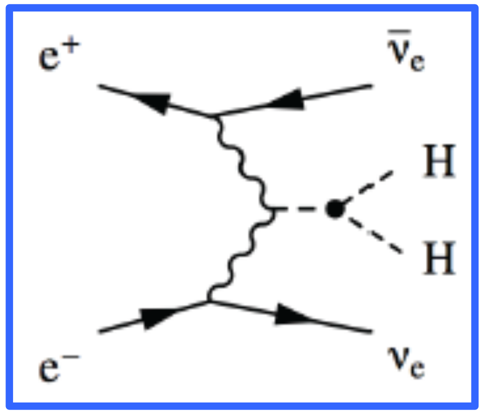
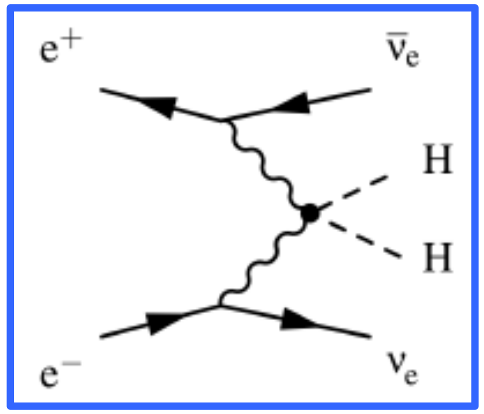
double Higgs production

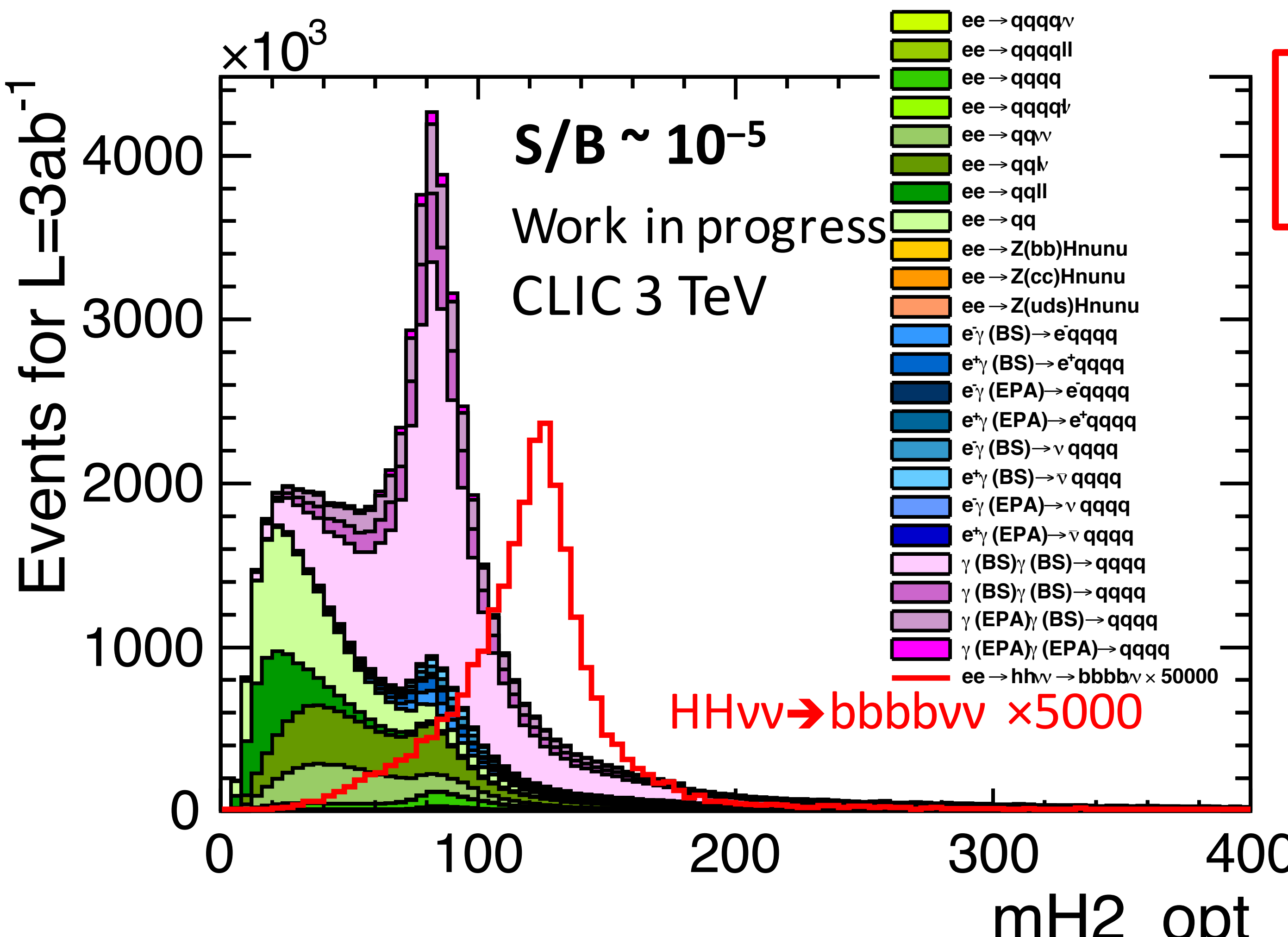




- Cross section sensitive to g_{HHH} and g_{WWHH}
- Small cross section (225/1200 evts @ 1.4/3 TeV)
- Large backgrounds

$\Rightarrow$ **Requires high energy and high luminosity**

Most promising final states:
*bbbbνν and bbWW*νν*



$\Rightarrow$ **$\Delta g_{HHH}/g_{HHH} \approx \pm 10\%$**

for operation at 1.4 TeV + 3 TeV with polarisation

Process with strong sensitivity to BSM

Model	$\Delta g_{hhh}/g_{hhh}^{SM}$
Mixed-in Singlet	$-18\,\%$
Composite Higgs	tens of %
Minimal Supersymmetry	$-2\,\%^a$ $-15\,\%^b$
NMSSM	$-25\,\%$

arXiv:1305.6397

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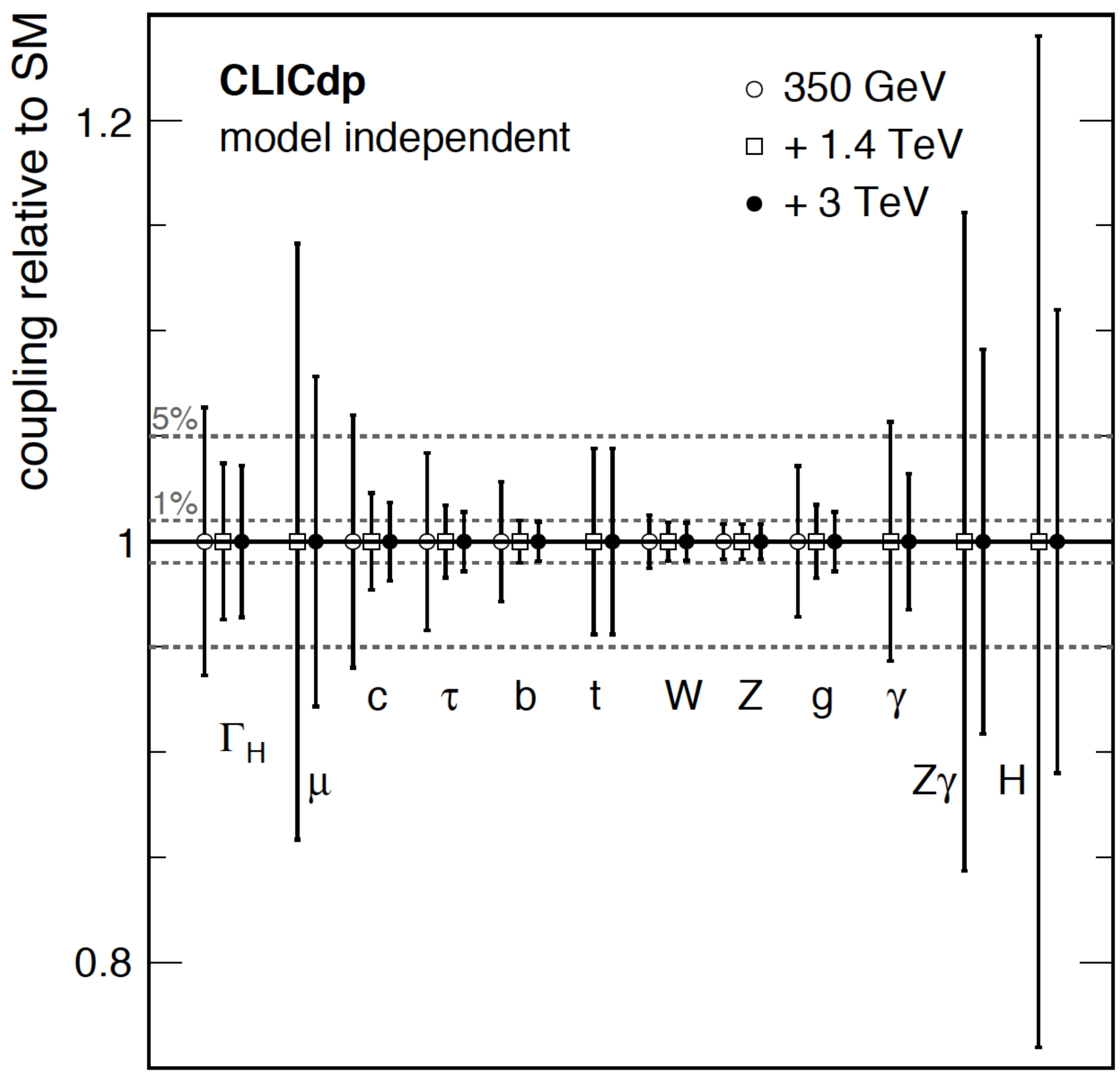
combined CLIC Higgs results

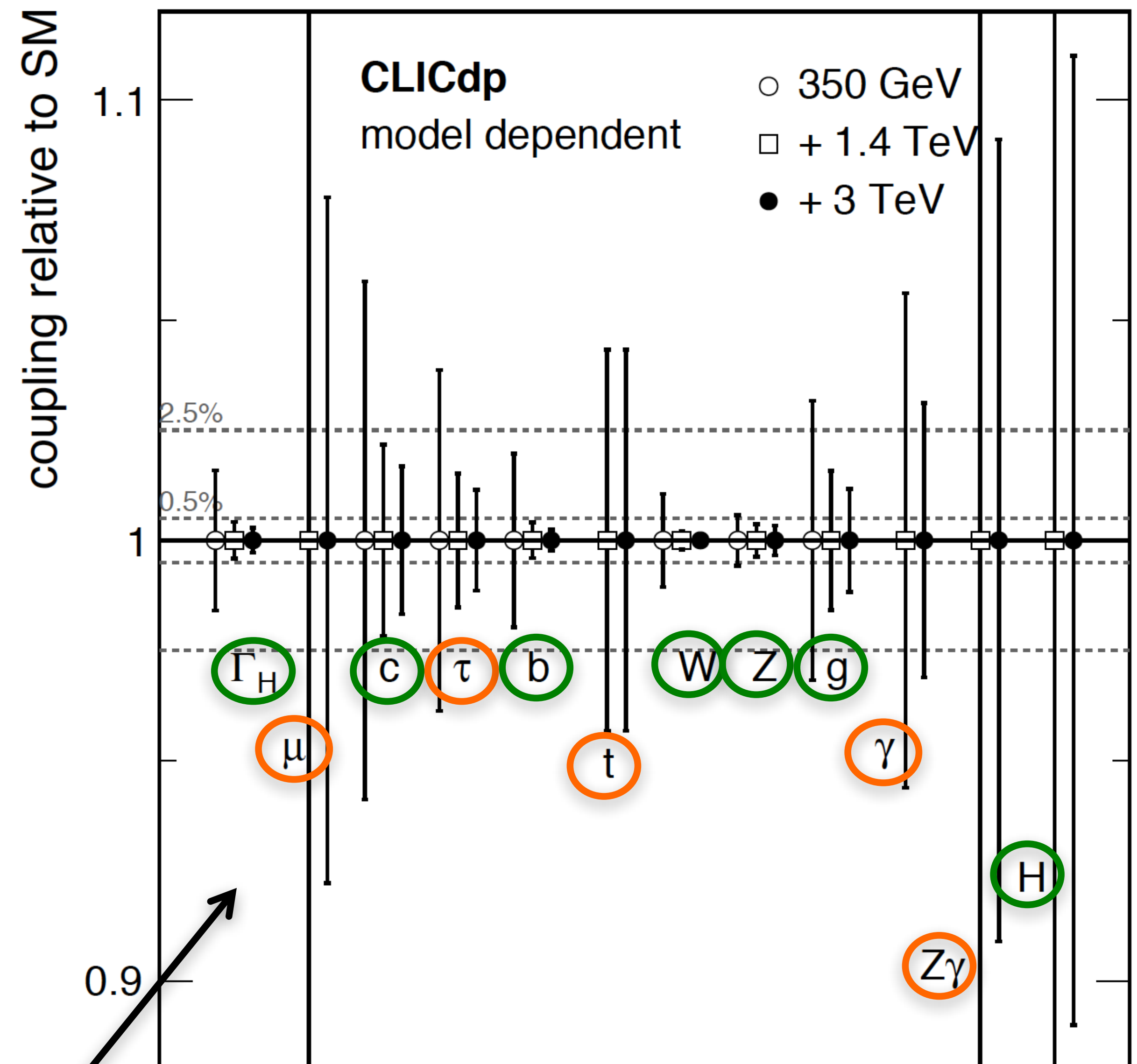
indicative comparison with HL-LHC capabilities

Model-independent



CLIC (and other e^+e^- colliders) can do model-independent measurements

Model-dependent



LHC-like fit, assuming SM decays only.
Fit to deviations from SM BR's

Accuracy significantly better than HL-LHC (green circle)
Accuracy comparable to HL-LHC (orange circle)

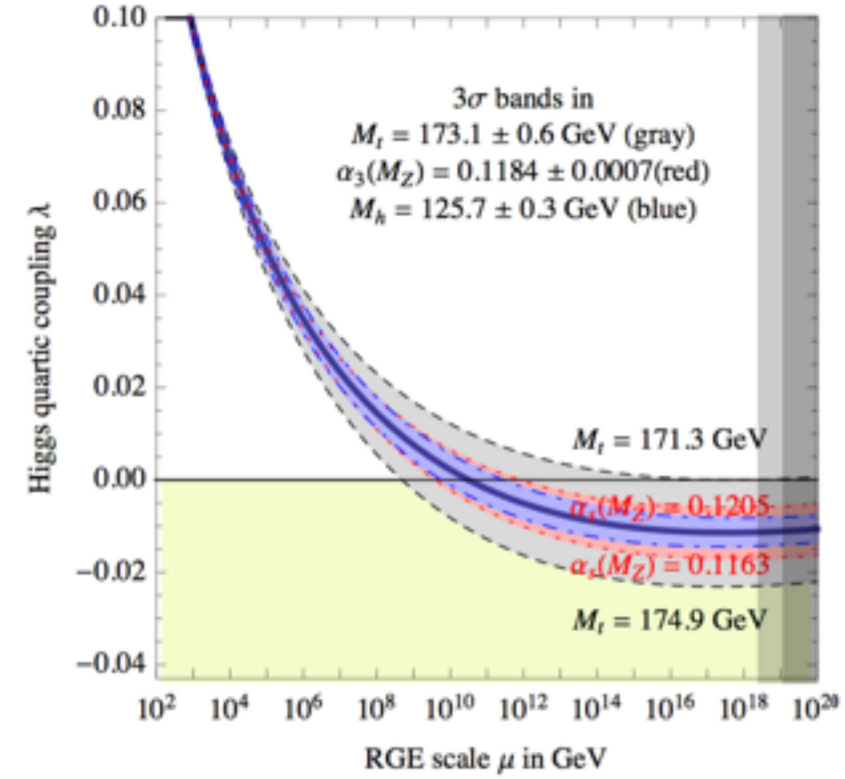
three major probes for BSM at e+e- colliders

- Higgs
- top
- new particles

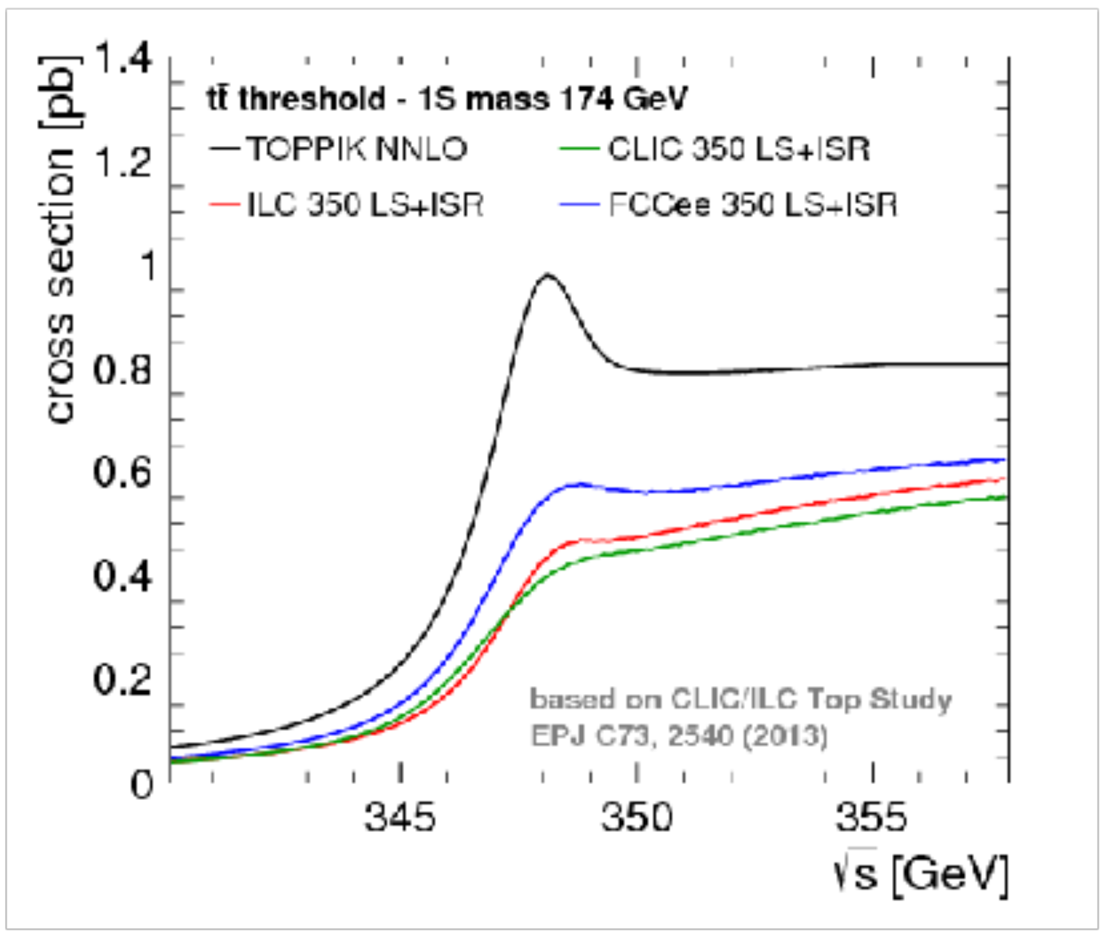
with emphasis on complementarity with LHC

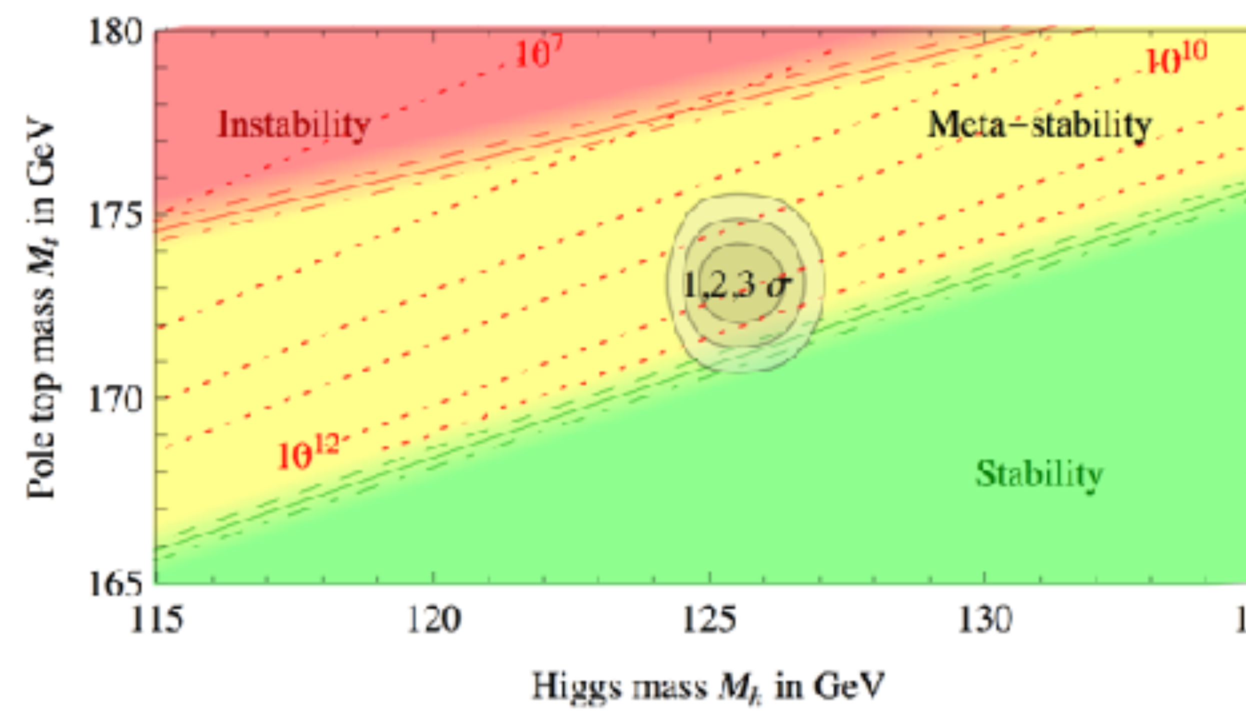
top mass: vacuum stability

- λ runs < 0? top mass precision crucial for vacuum stability
- at e+e-: top-pair threshold scan to measure m_t, much lower theory error
- Δm_t(MS-bar) < 100 MeV (Δm_H=14MeV)



Degrassi et al, JHEP 1208 (2012) 098





top mass at LCs: systematic errors

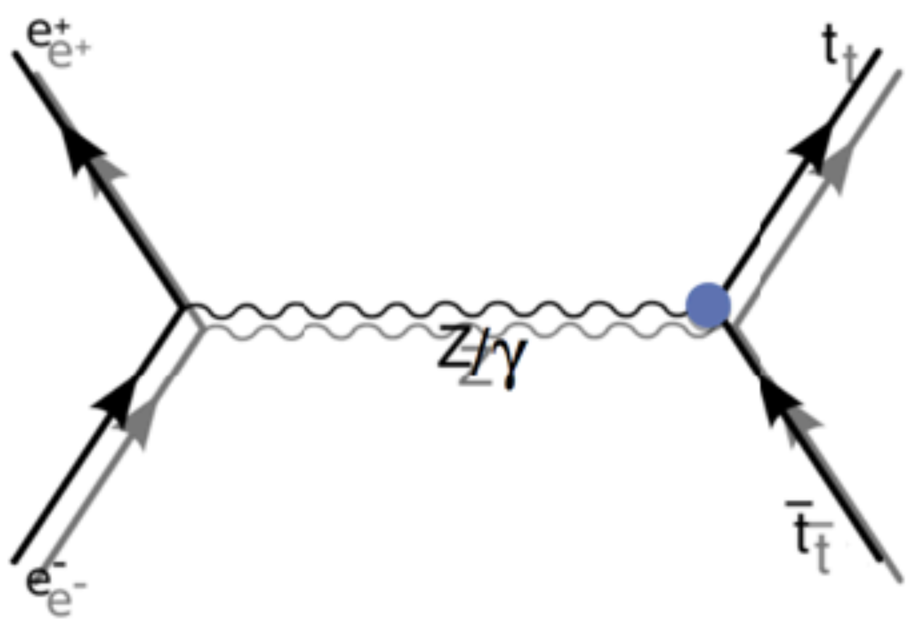
error source	Δm_t^{PS} [MeV]	references
stat. error (200 fb^{-1})	13	[63, 66]
theory (NNNLO scale variations, PS scheme)	40	[65, 66]
parametric (α_s, current WA)	35	[65]
non-resonant contributions (such as single top)	< 40	[67]
residual background / selection efficiency	10 – 20	[63]
luminosity spectrum uncertainty	< 10	[68]
beam energy uncertainty	< 17	[63]
combined theory & parametric	30 – 50	
combined experimental & backgrounds	25 - 50	
total (stat. + syst.)	40 – 75	

top EW chiral couplings

M.Vos @ LCWS16

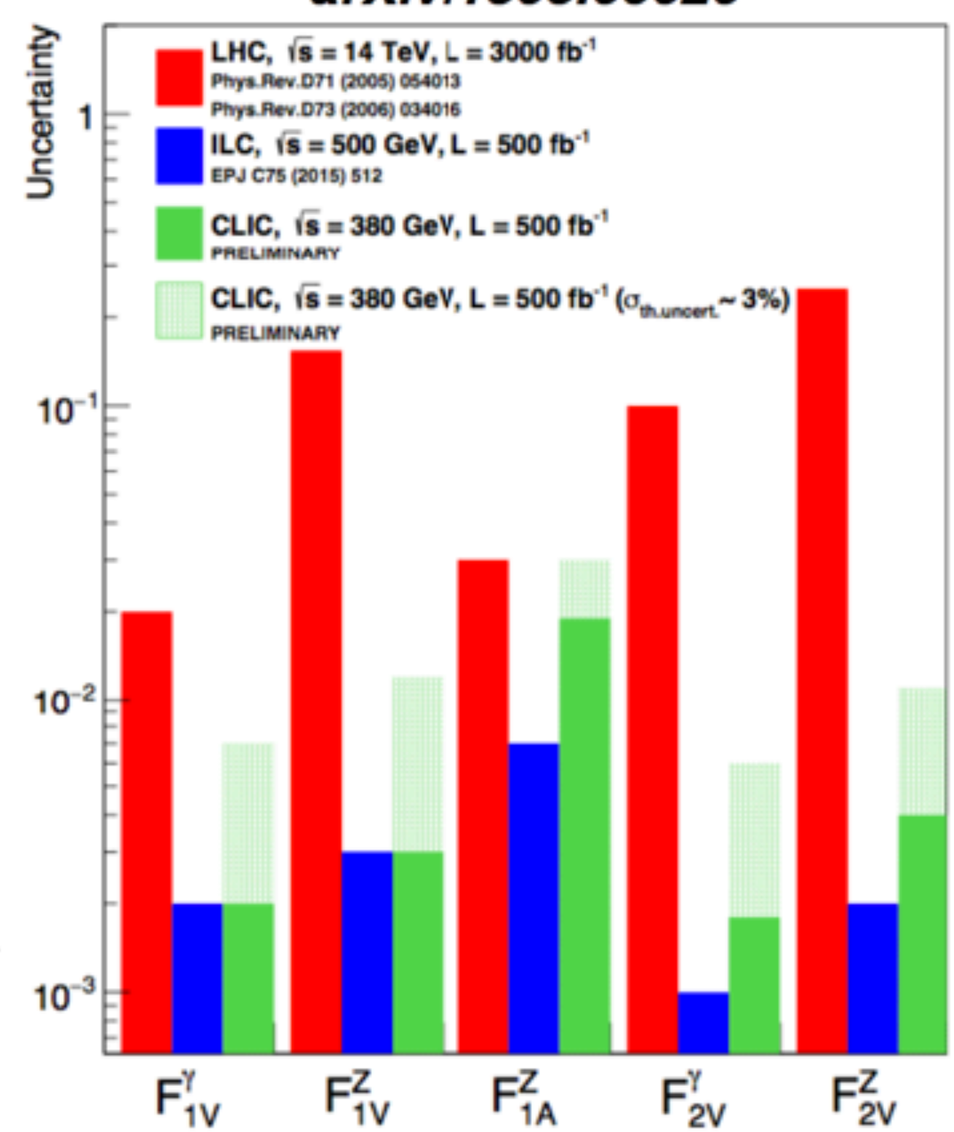
Assume production is dominated by SM and NP scale is beyond direct reach.

$$\Gamma_{\mu}^{t\bar{t}X}(k^2, q, \bar{q}) = ie\left\{\gamma_\mu\left(\underline{F_{1V}^X}(k^2) + \gamma_5 \underline{F_{1A}^X}(k^2)\right) - \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu\left(i\underline{F_{2V}^X}(k^2) + \gamma_5 F_{2A}^X(k^2)\right)\right\}$$



IFIC - LAL Collaboration

arXiv:1505.06020



Measure 2 observables for 2 beam polarizations at ILC500 and CLIC380 (full-simulation):

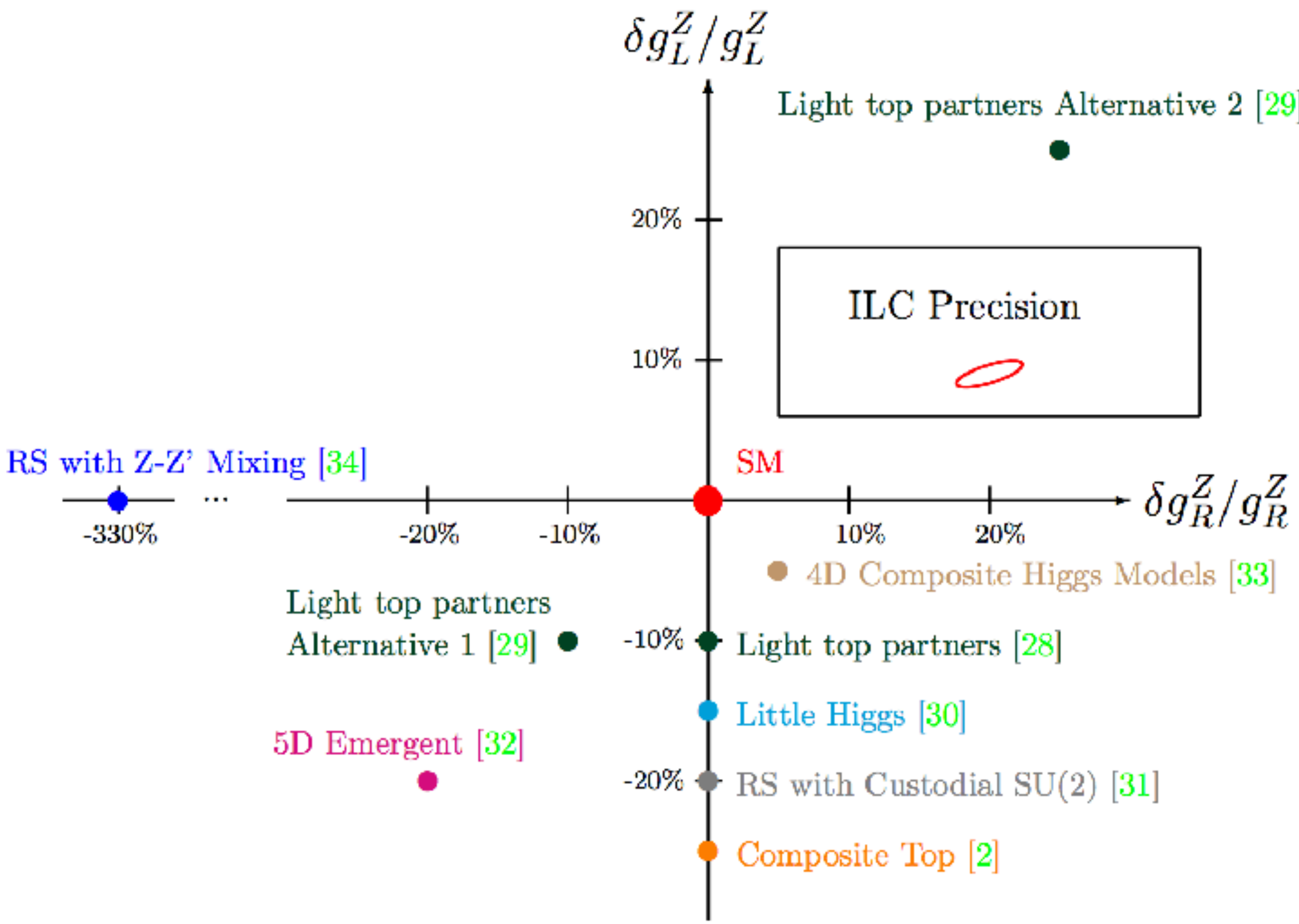
$F_{1A}^{\gamma,\mathrm{SM}} = 0$ always because of the gauge invariance

$$\begin{matrix} \sigma(+) & A_{FB}(+) \\ \sigma(-) & A_{FB}(-) \end{matrix} \qquad \left.\begin{matrix} (+ = e_R^-) \\ (- = e_L^-) \end{matrix}\right\} \Rightarrow \left\{\begin{matrix} F_{1V}^\gamma & * & F_{2V}^\gamma \\ F_{1V}^Z & F_{1A}^Z & F_{2V}^Z \end{matrix}\right\} \longrightarrow$$

Measure **Extract**

top EW chiral couplings

Eur.Phys.J. C75 (2015) no.10, 512



- great sensitivities to discover/distinguish various composite models

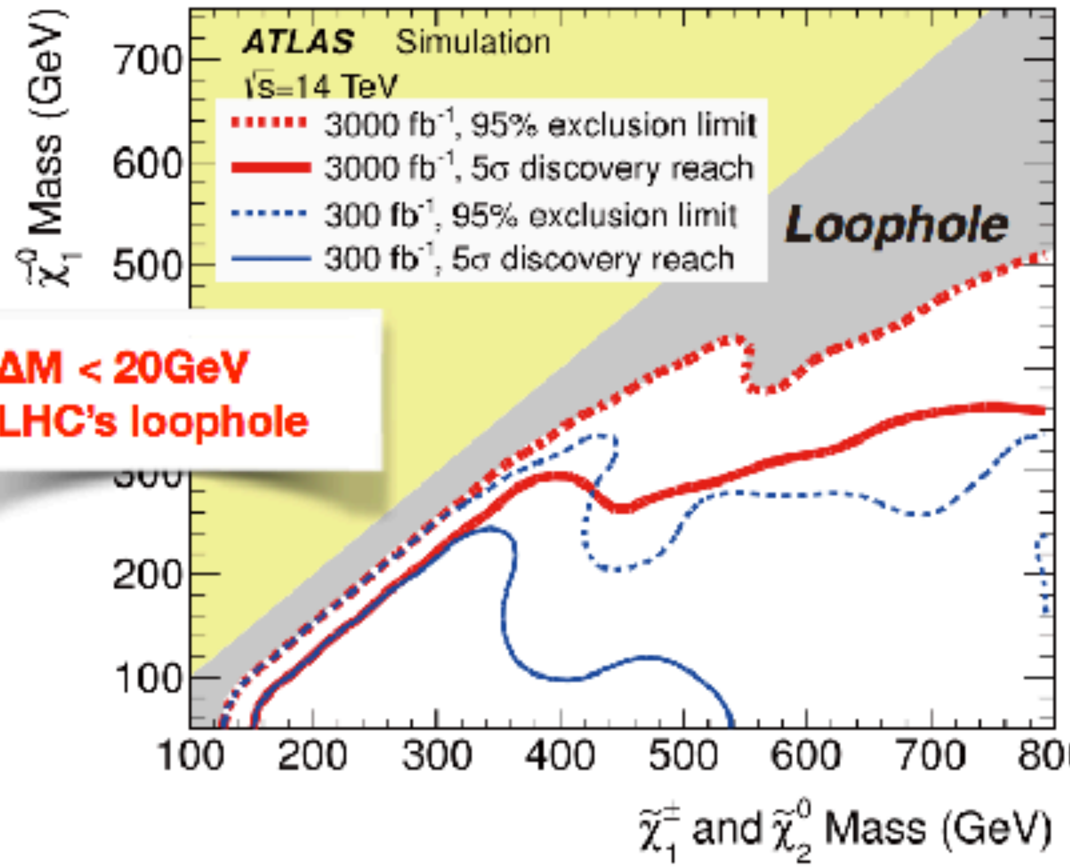
three major probes for BSM at e+e- colliders

- Higgs
- top
- new particles

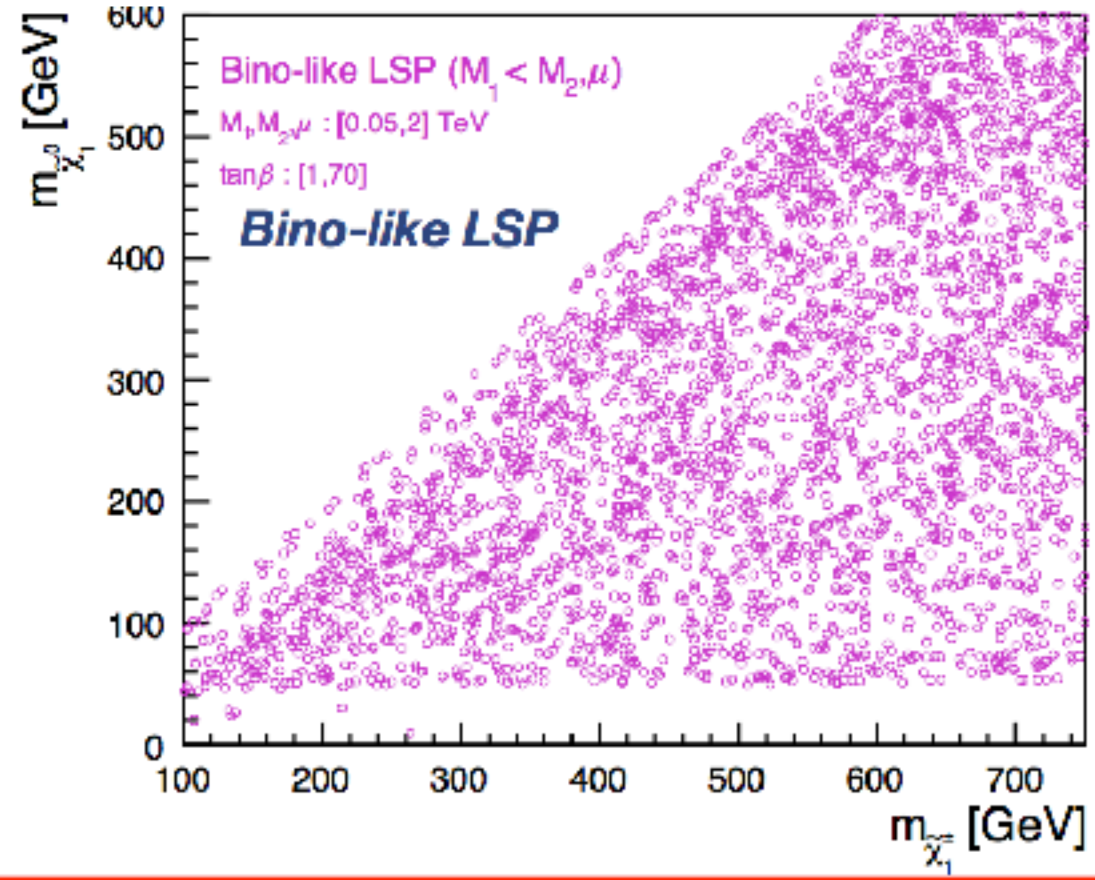
with emphasis on complementarity with LHC

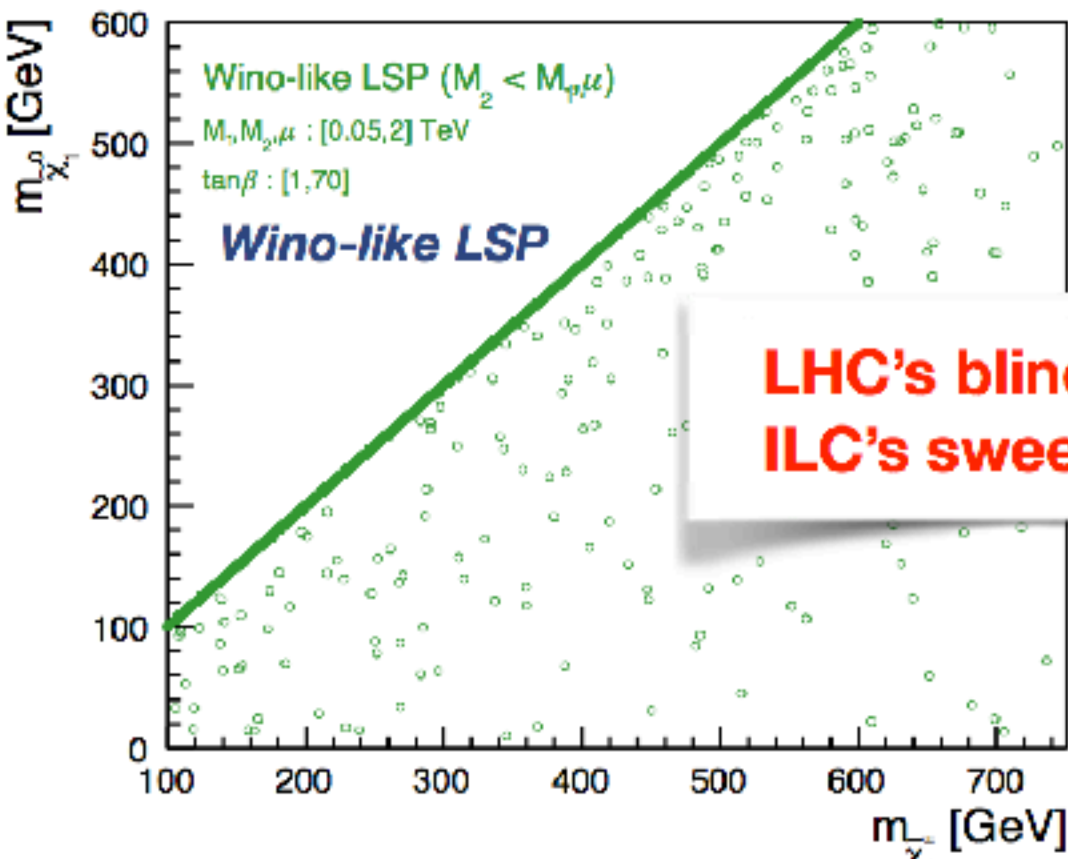
Chargino search

K.Fujii@HPNP2017

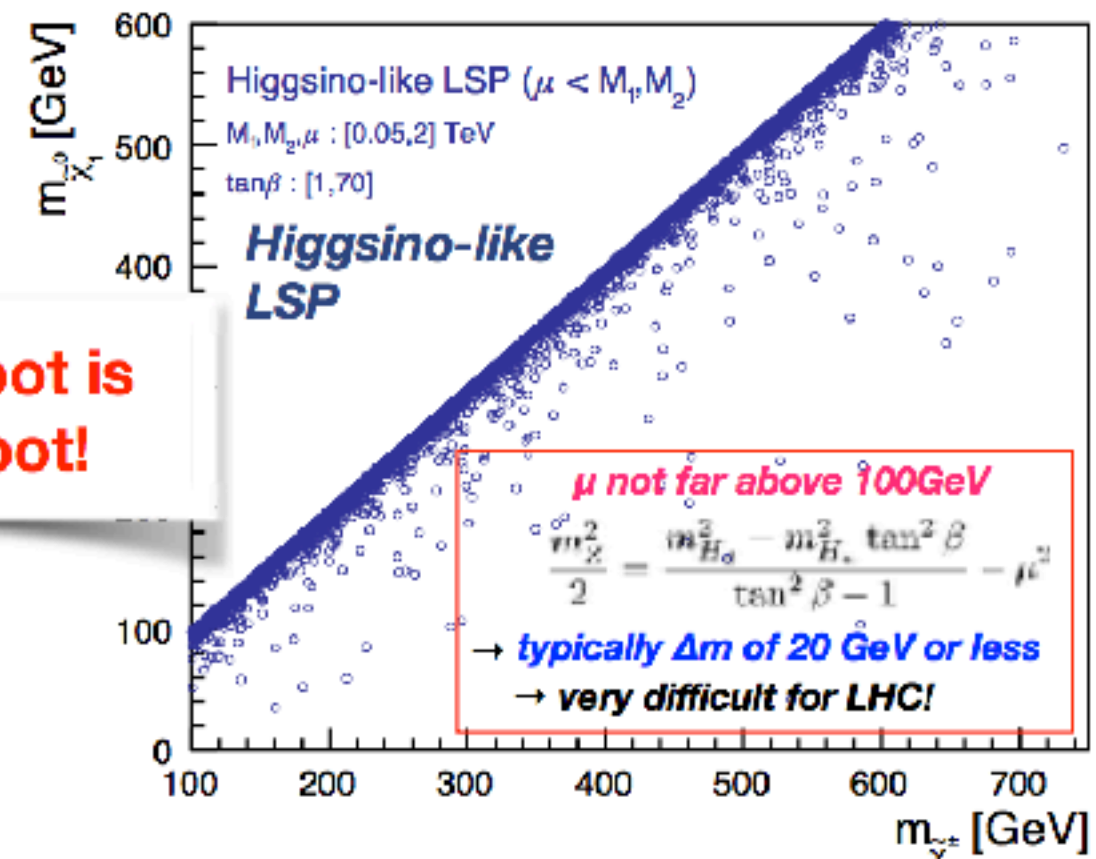


ΔM < 20GeV
LHC's loophole





LHC's blind spot is ILC's sweet spot!



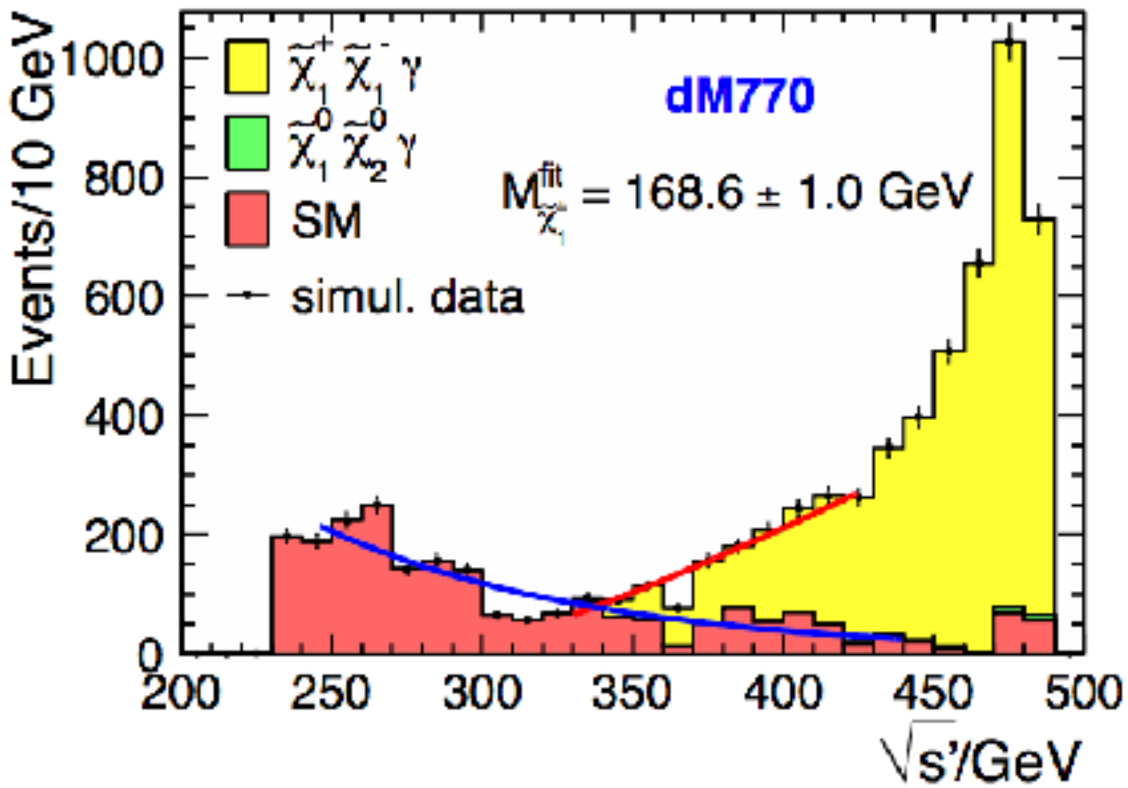
μ not far above 100GeV

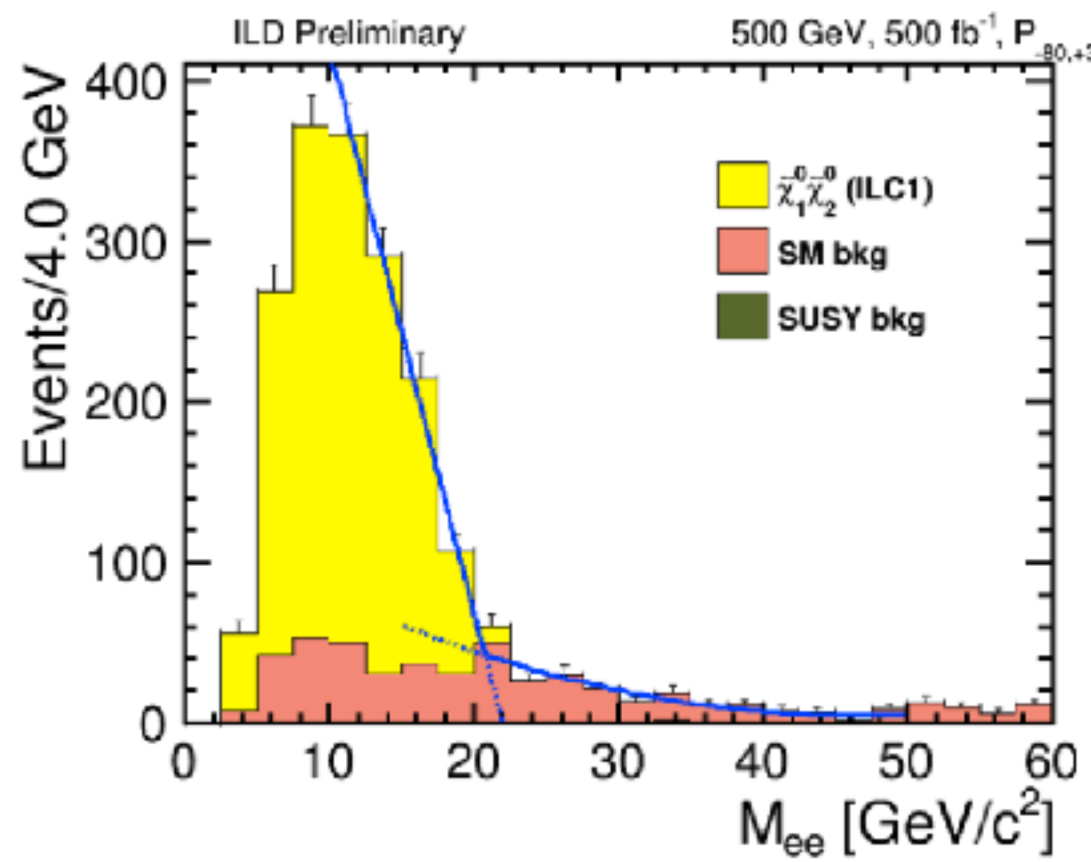
$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

→ *typically Δm of 20 GeV or less*
→ *very difficult for LHC!*

Natural SUSY: light Higgsinos

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2 \simeq -m_{H_u}^2 - \Sigma_u^u - \mu^2$$





$$M_{\widetilde{\chi_1}^{\pm}} - M_{\widetilde{\chi_1}^0} = 770\mathrm{MeV}$$

$$M_{\widetilde{\chi_2}^0} - M_{\widetilde{\chi_1}^0} = 20\mathrm{GeV}$$

arXiv:1307.3566

arXiv:1611.02846

WIMP Dark Matter search

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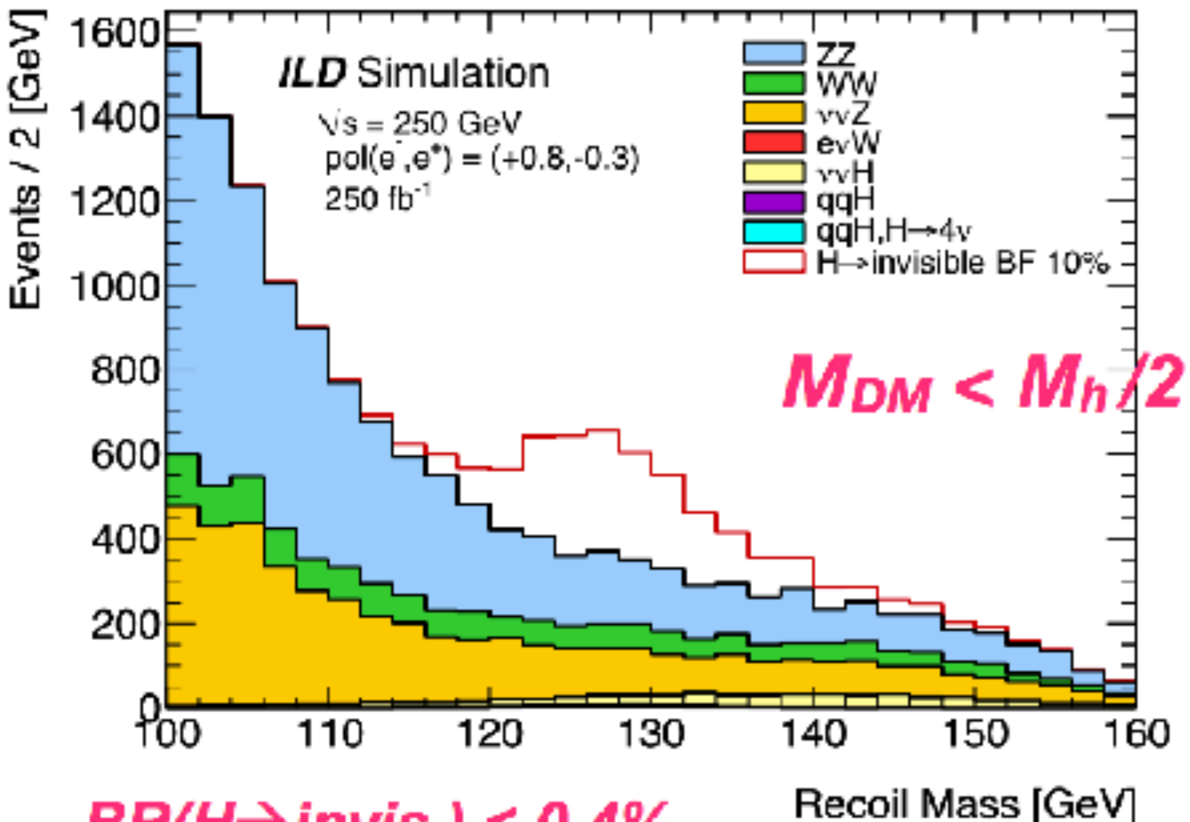
***Decay of a new particle to Dark Matter* (DM)**

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

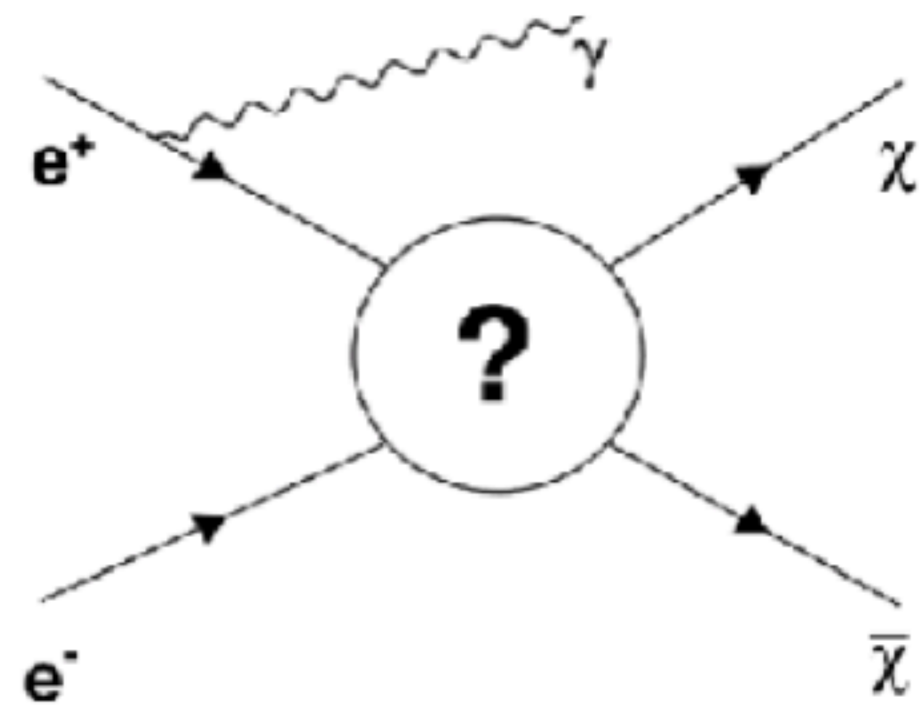


BR(H→invis.) < 0.4%

at 250 GeV, 1150 fb^{-1} ***(<0.3% at 95%CL: H20)***

Possible to access BR$_{inv}$ to 0.4%!

Mono-photon Search

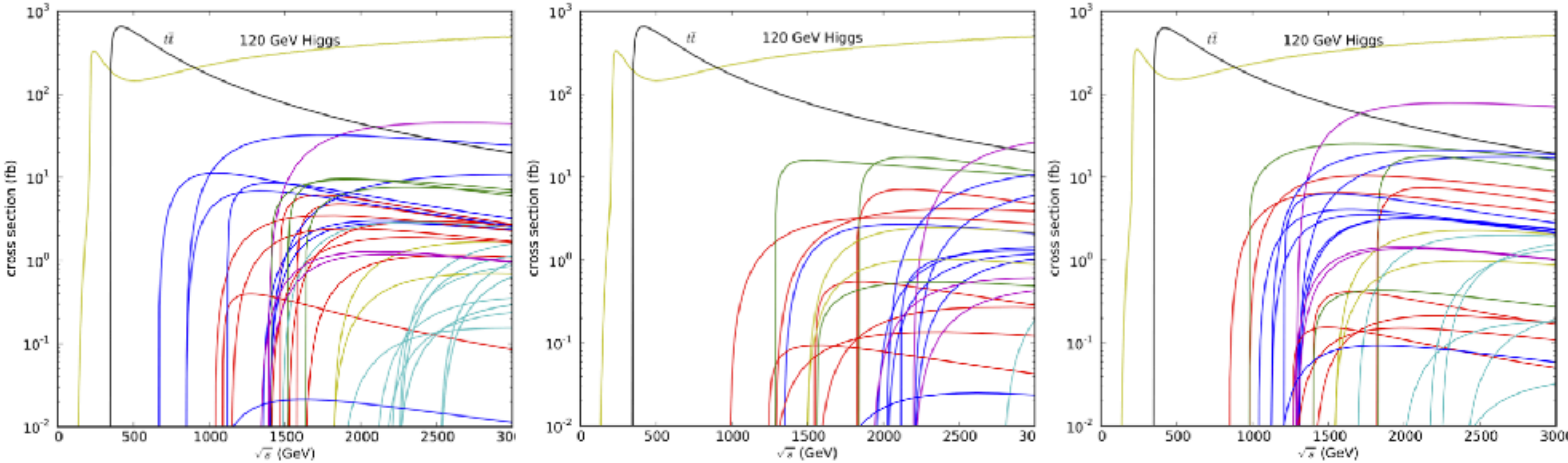


→ ***M_{DM} reach ~ $E_{cm}/2$***

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

SUSY search at CLIC

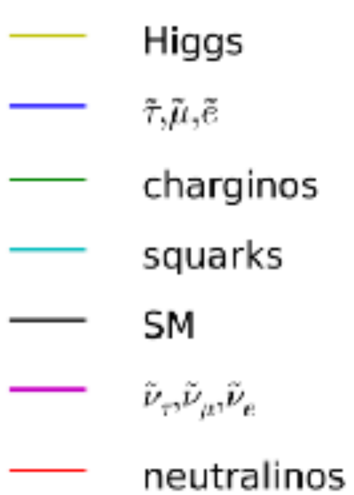
P.Roloff@LCWS16



CDR Model I, 3 TeV:
- Squarks
- Heavy Higgs

CDR Model II, 3 TeV:
- Smuons, selectrons
- Gauginos

CDR Model III, 1.4 TeV:
- Smuons, selectrons
- Staus
- Gauginos



In general, O(1%) precision on masses and pair production cross sections found

Wider applicability than only SUSY: Reconstructed particles can be classified simply as states of given mass, spin and quantum numbers

Summary

- future linear colliders are able to comprehensively reveal the mysteries at electroweak scale
- main probes for BSM: precision measurements of Higgs and Top properties, direct search of new particles
- precision top mass requires $\sqrt{s}$ >= 350 GeV
- direct measurements of Higgs self-coupling and top-Yukawa couplings requires $\sqrt{s}$ >= 500 GeV
- one of the greatest advantage is energy extendability, once next energy scale is found by precision measurements
- apologies that many interesting physics couldn't be covered

backup

towards ultimate unification

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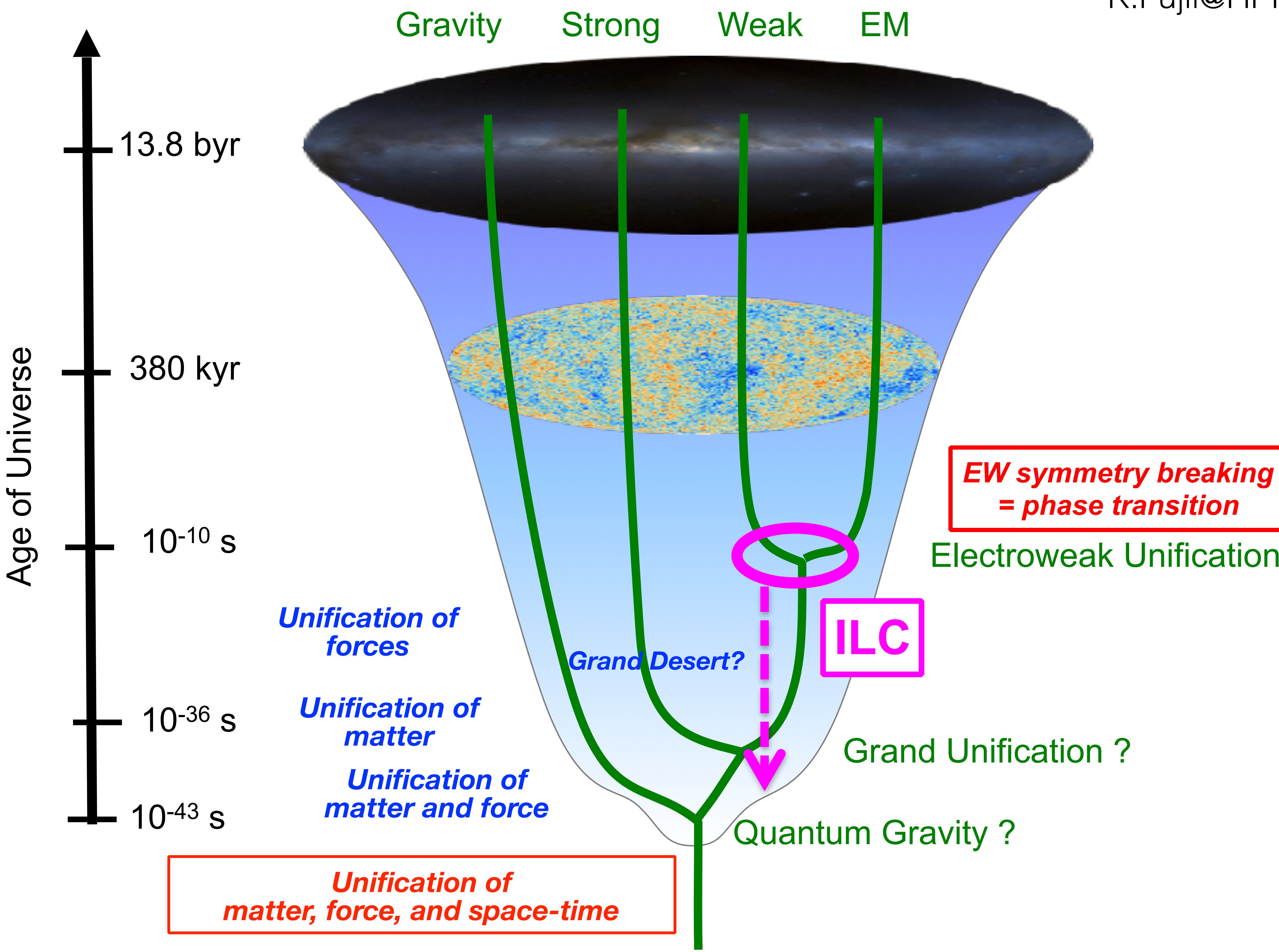
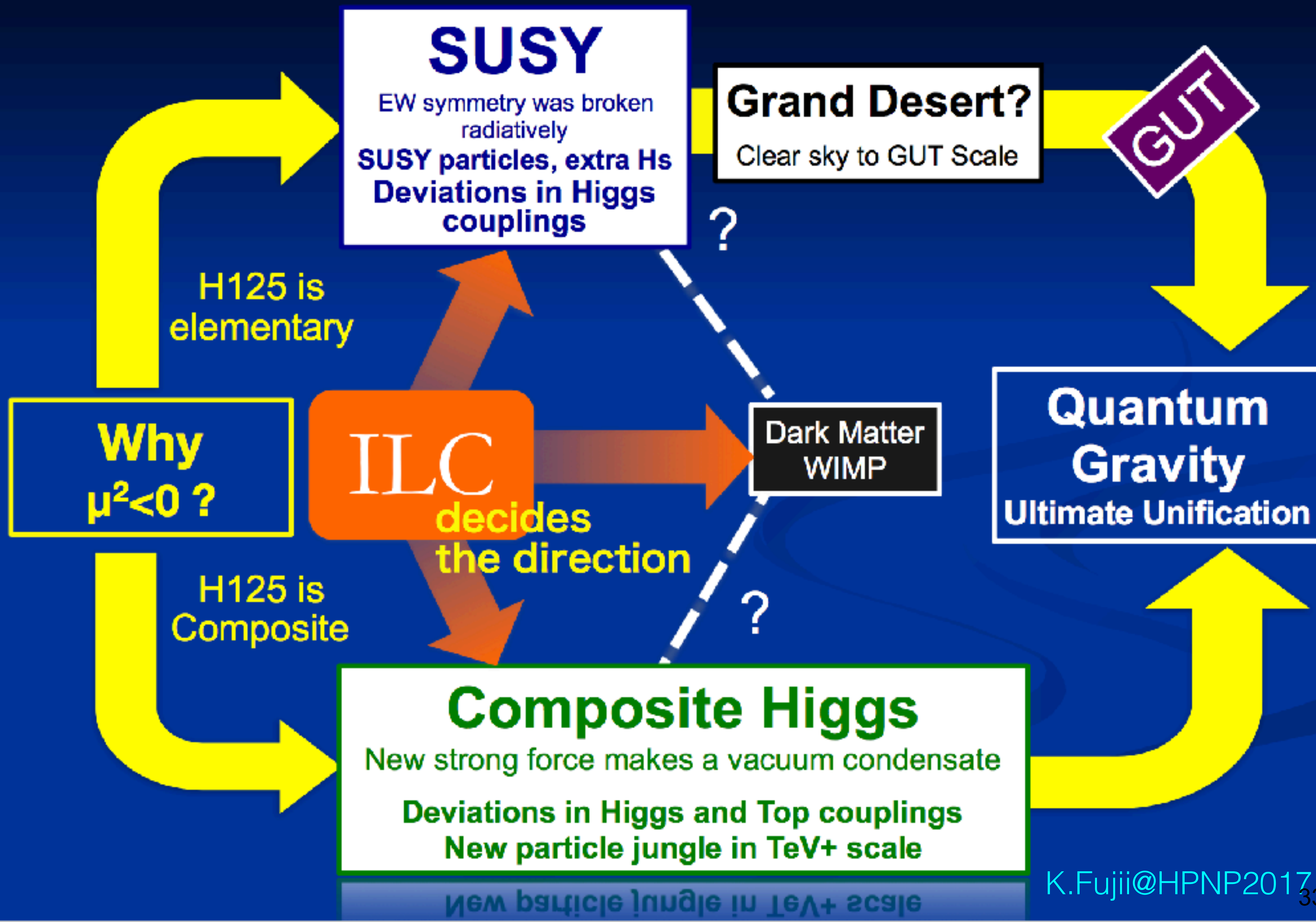


Big Branching Point at the EW Scale



Why is the EW scale so important?

Mystery of something in the vacuum

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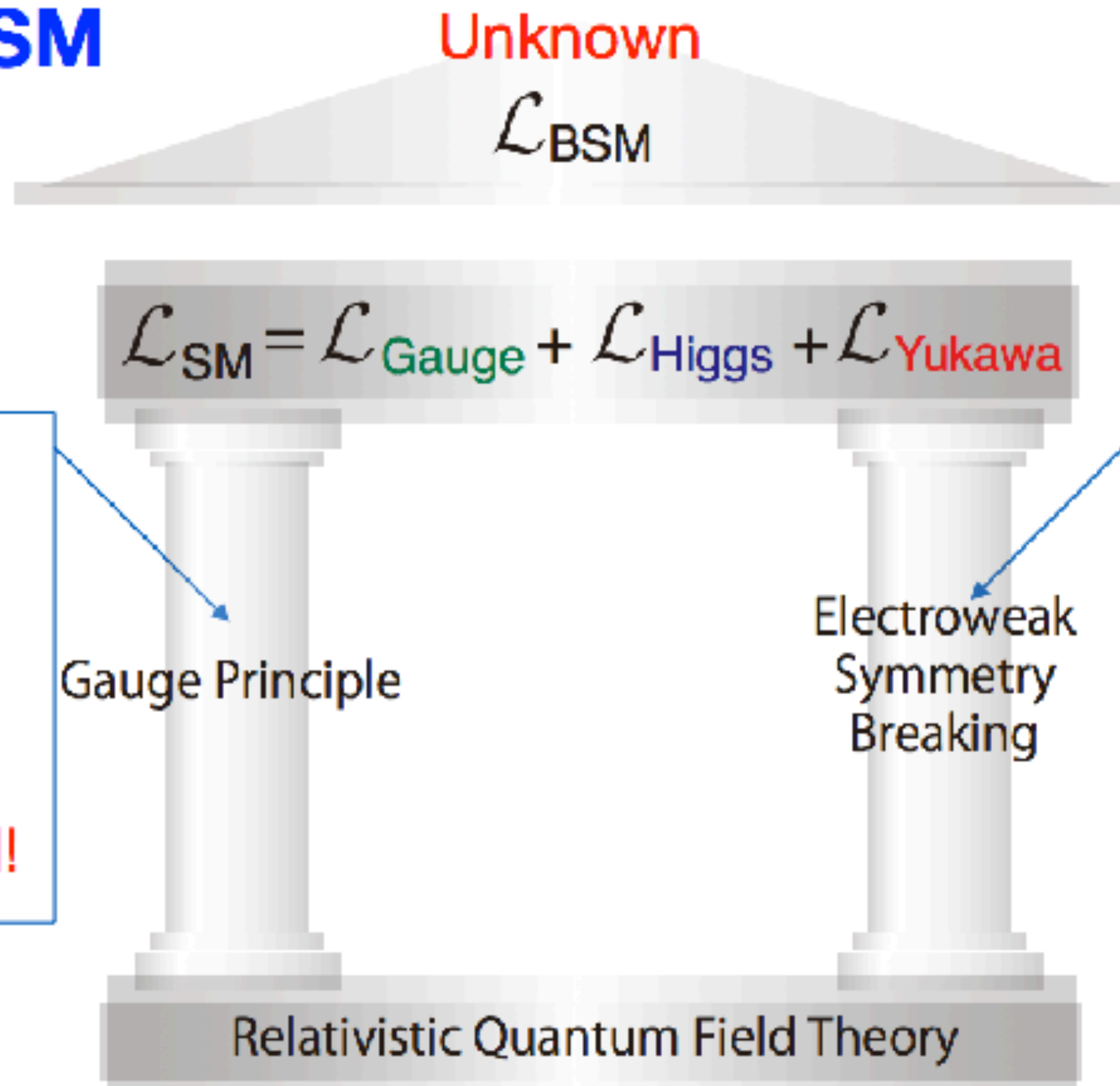
2 Pillars of SM



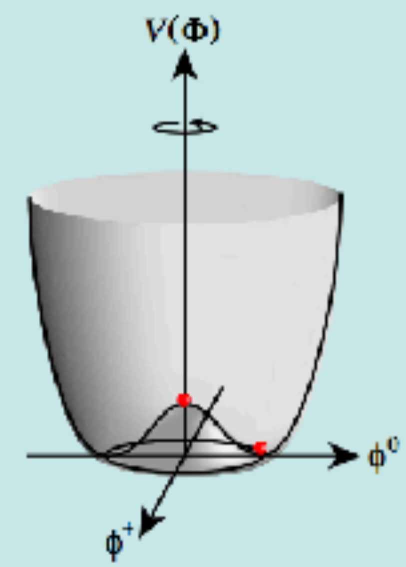
Success of SM
= success of gauge theory (left pillar)

Precisely tested!

Vacuum filled with weak charge (evidence: H125)

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

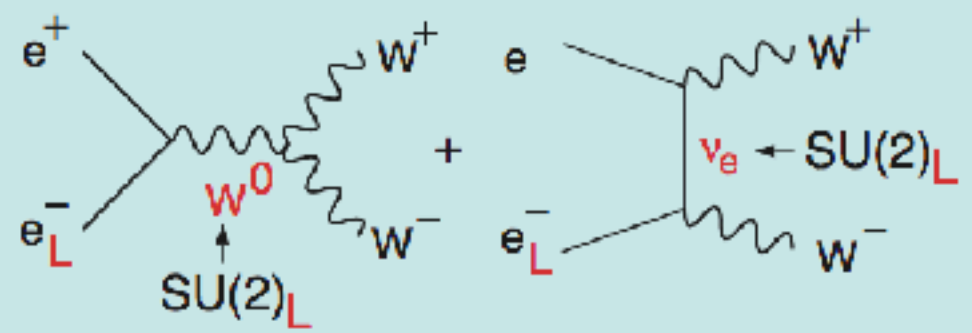
$V(\phi) = \mu^2|\phi|^2 + \lambda|\phi|^4$



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!**

Power of Beam Polarization

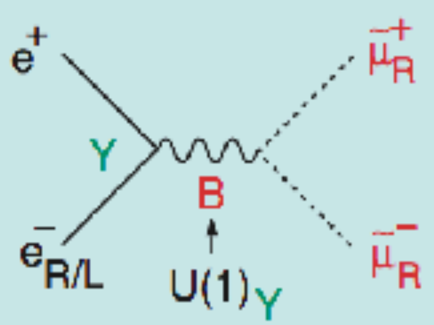
W^+W^- *(Largest SM BG in SUSY searches)*



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

BG Suppression

Slepton Pair

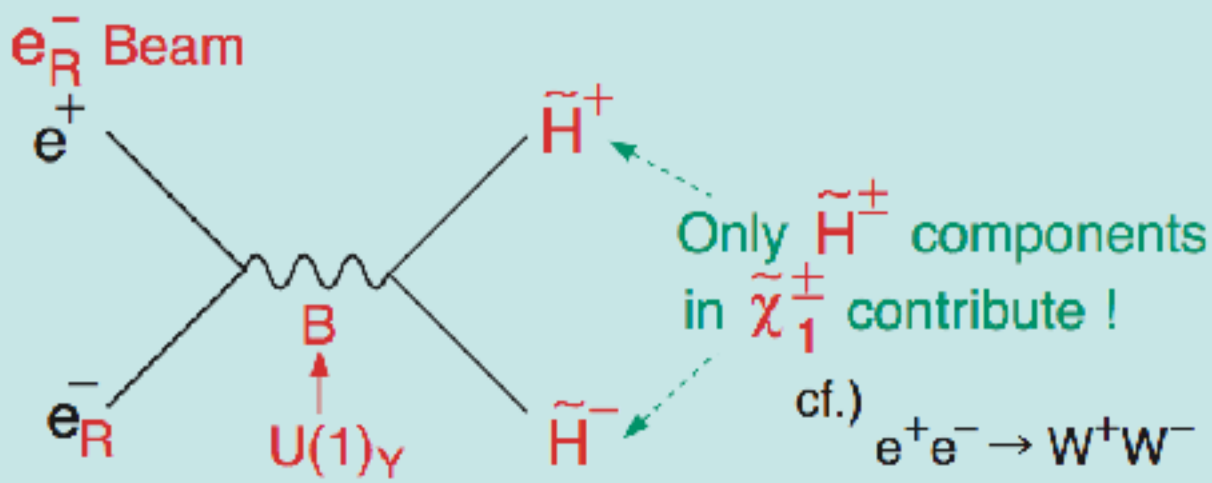


$Y_L = -1/2 : e^-_L$

$Y_R = -1 \quad : e^-_R$

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

Chargino Pair

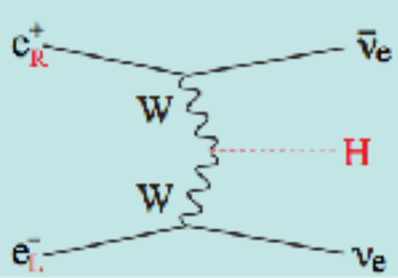


$$\tilde{\chi}^\pm_1 = \bigcirc \cdot \tilde{W}^\pm + \bullet \cdot \tilde{H}^\pm$$

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

Decomposition

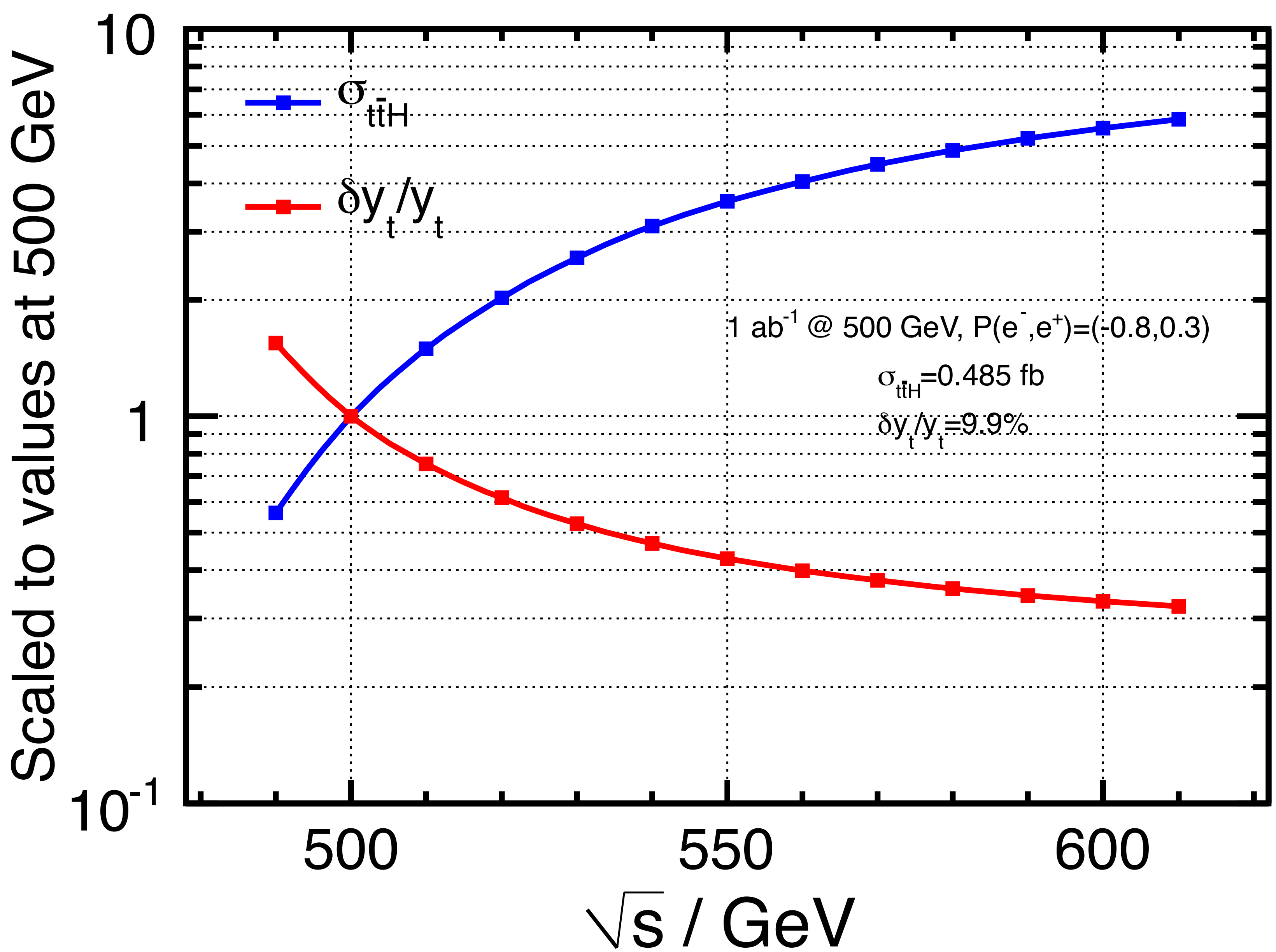
WW-fusion Higgs Prod.



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

Signal Enhancement

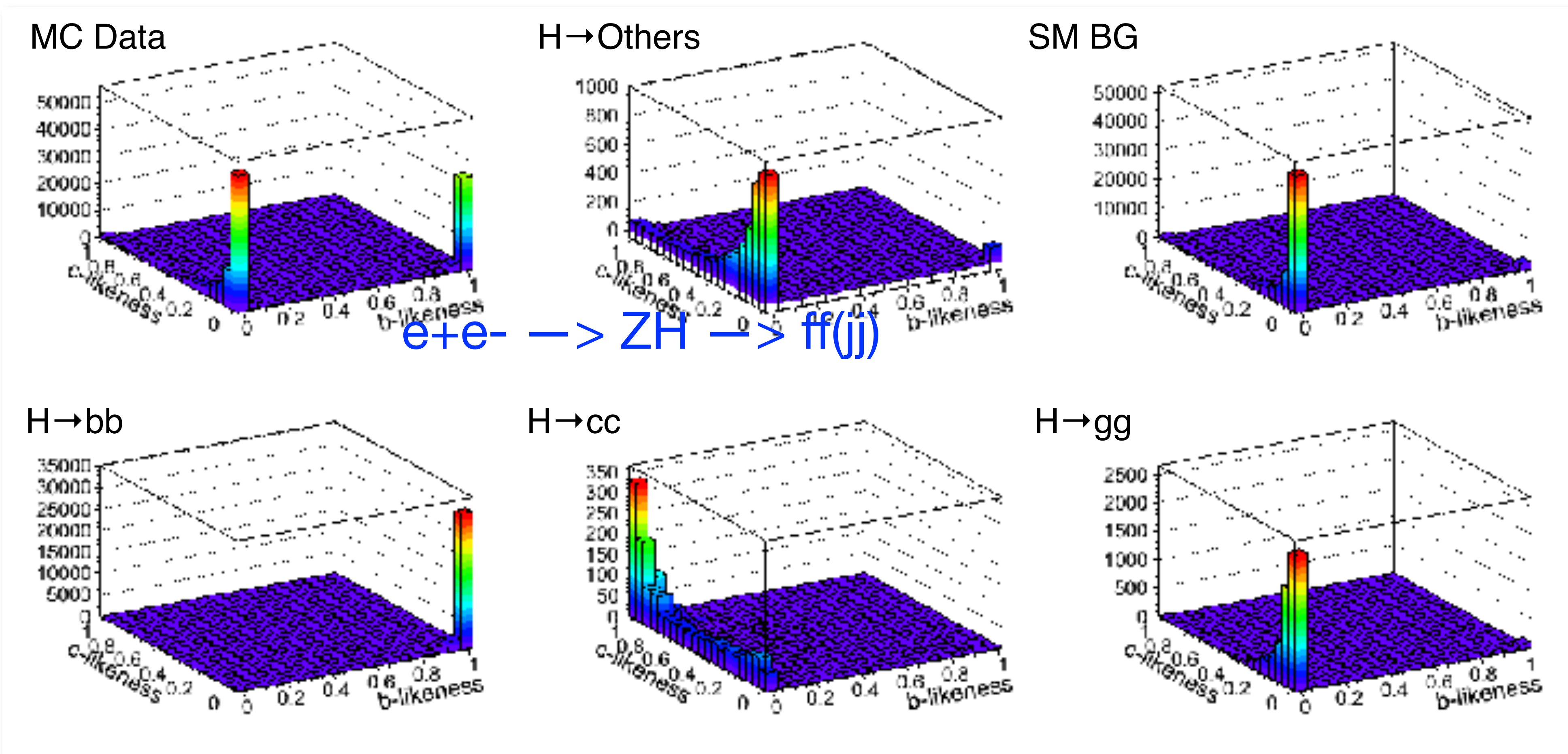
top-Yukawa coupling: dependence on ECM



Y. Sudo

Higgs direct couplings to bb, cc and gg

- clean environment at e+e-; excellent b- and c-tagging performance
- bb/cc/gg modes can be separated simultaneously by template fitting



e+e- —> ZH —> ff(jj)

directly measured →

$$\sigma_{ZH} \cdot \mathrm{Br}(H \to b\bar{b}) \propto g^2_{HZZ} g^2_{Hbb} / \Gamma_H$$
$$\sigma_{ZH} \cdot \mathrm{Br}(H \to c\bar{c}) \propto g^2_{HZZ} g^2_{Hcc} / \Gamma_H$$
$$\sigma_{ZH} \cdot \mathrm{Br}(H \to gg) \propto g^2_{HZZ} g^2_{Hgg} / \Gamma_H$$

with Γ_H → g_{HZZ}

g_{Hbb}

g_{Hcc}

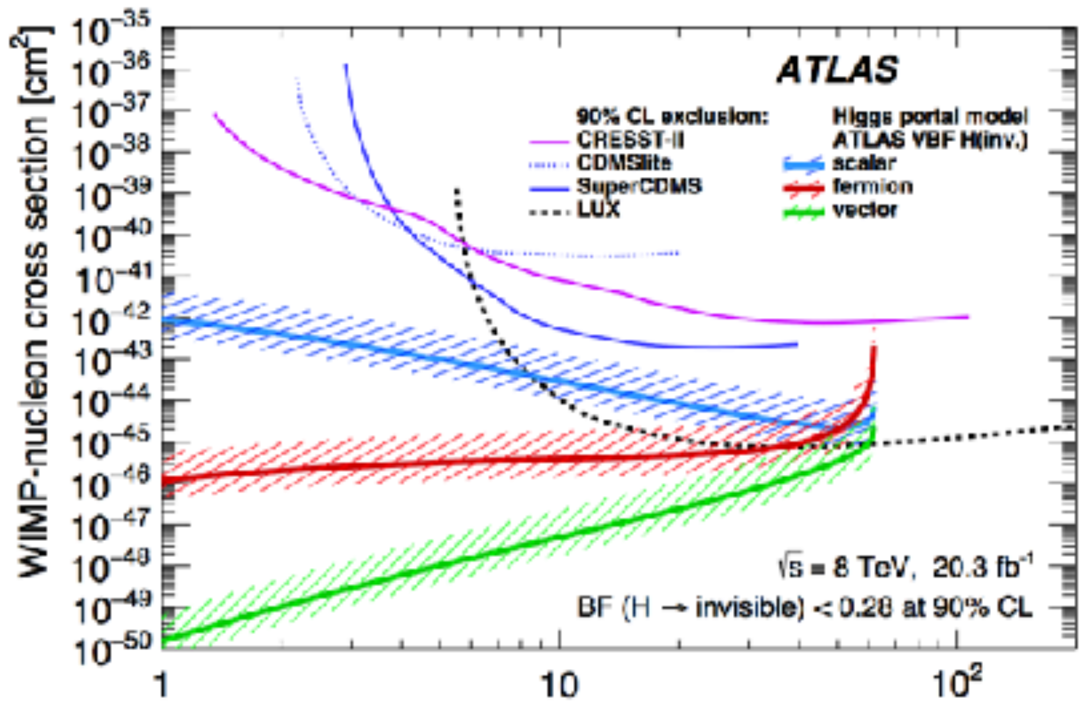
g_{Hgg}

Ono, et. al, Euro. Phys. J. C73, 2343; F.Mueller, PhD thesis (DESY)

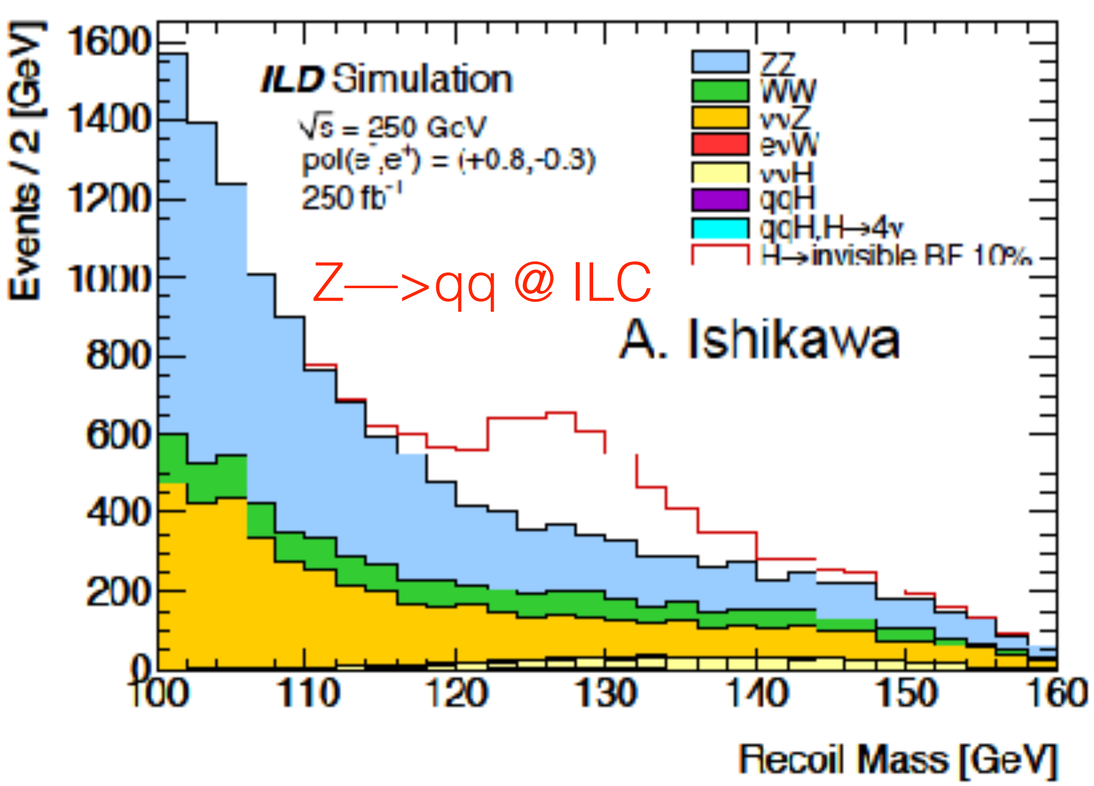
exotic decay: search of Higgs to invisible

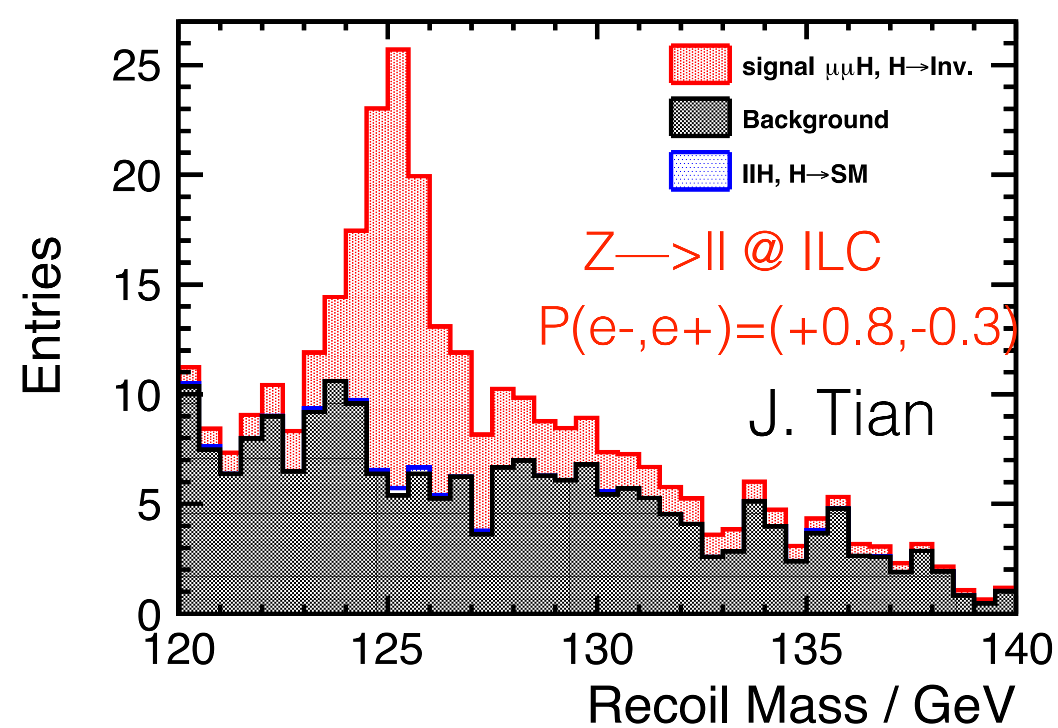
$$e^+ + e^- \to ZH \to l^+l^-/q\bar{q} + \text{Missing}$$

- BR(H—>inv.) < 0.3% (CL95%)
- a sensitive test for Higgs portal dark mater model —> complementary for low mass
- beam polarisation does help

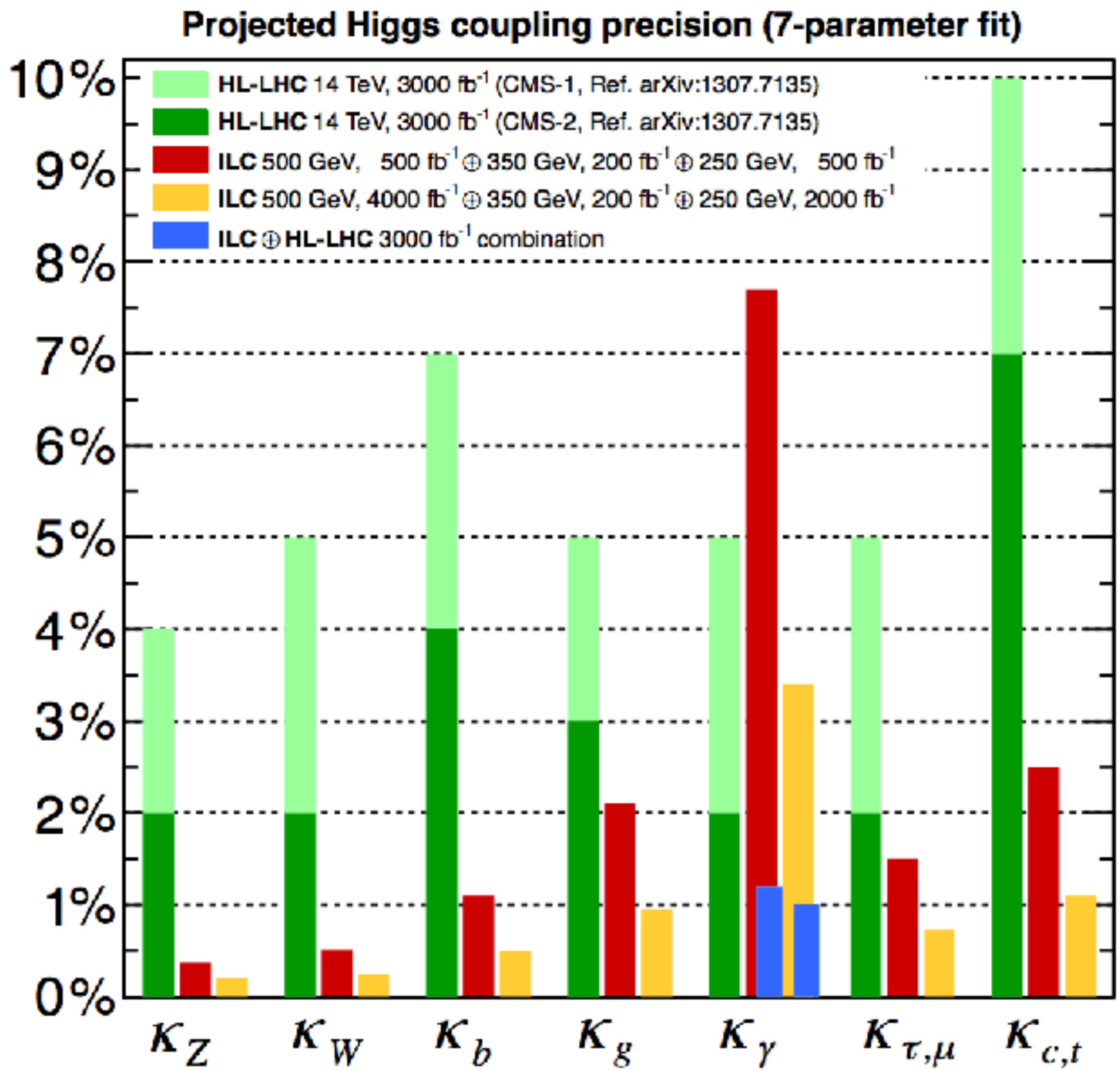


JHEP 1601 (2016) 172





expected precisions of Higgs couplings



Two-Fermion Processes

Z' Search / Study

arXiv:0912.2806 [hep-ph]

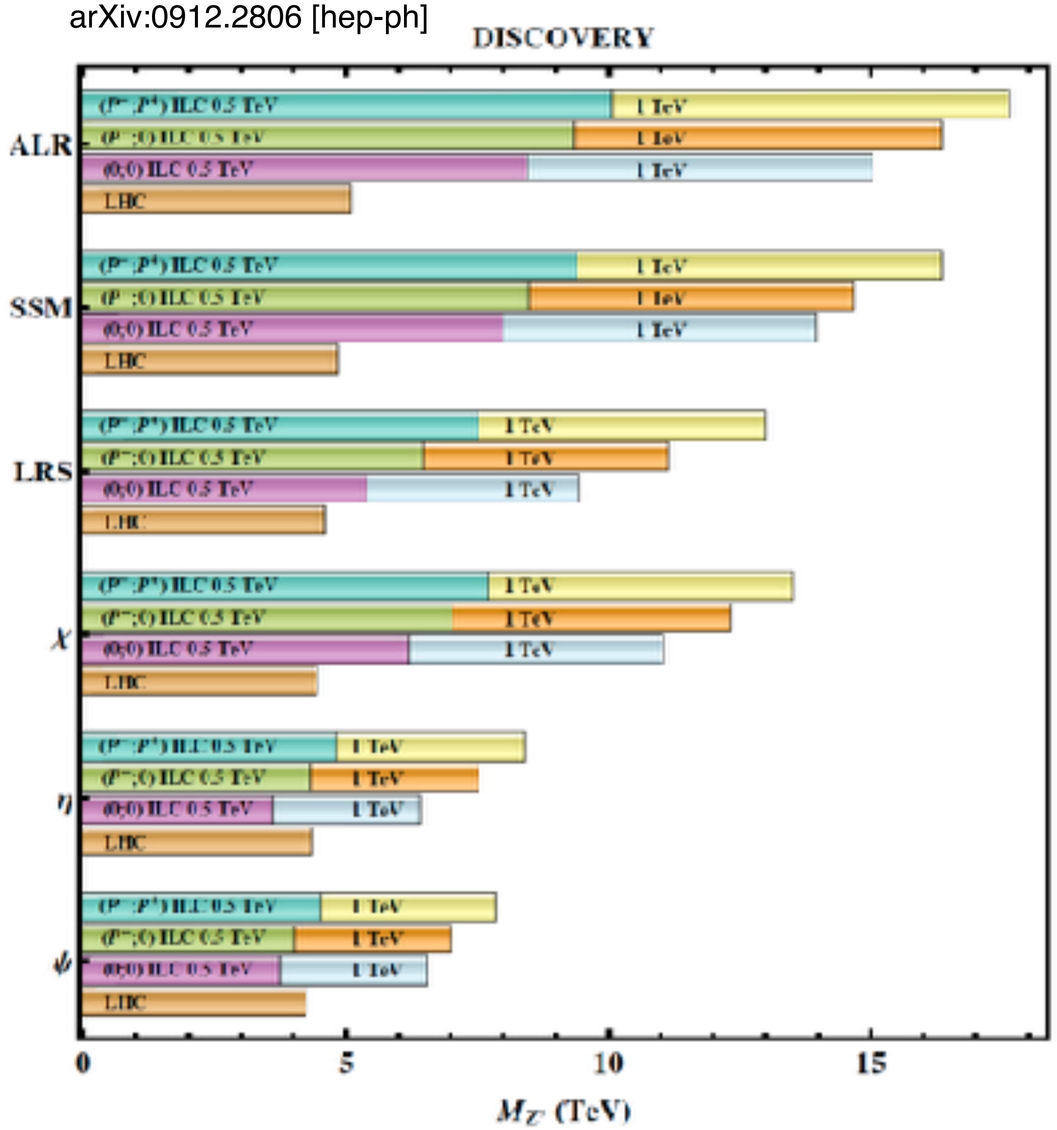
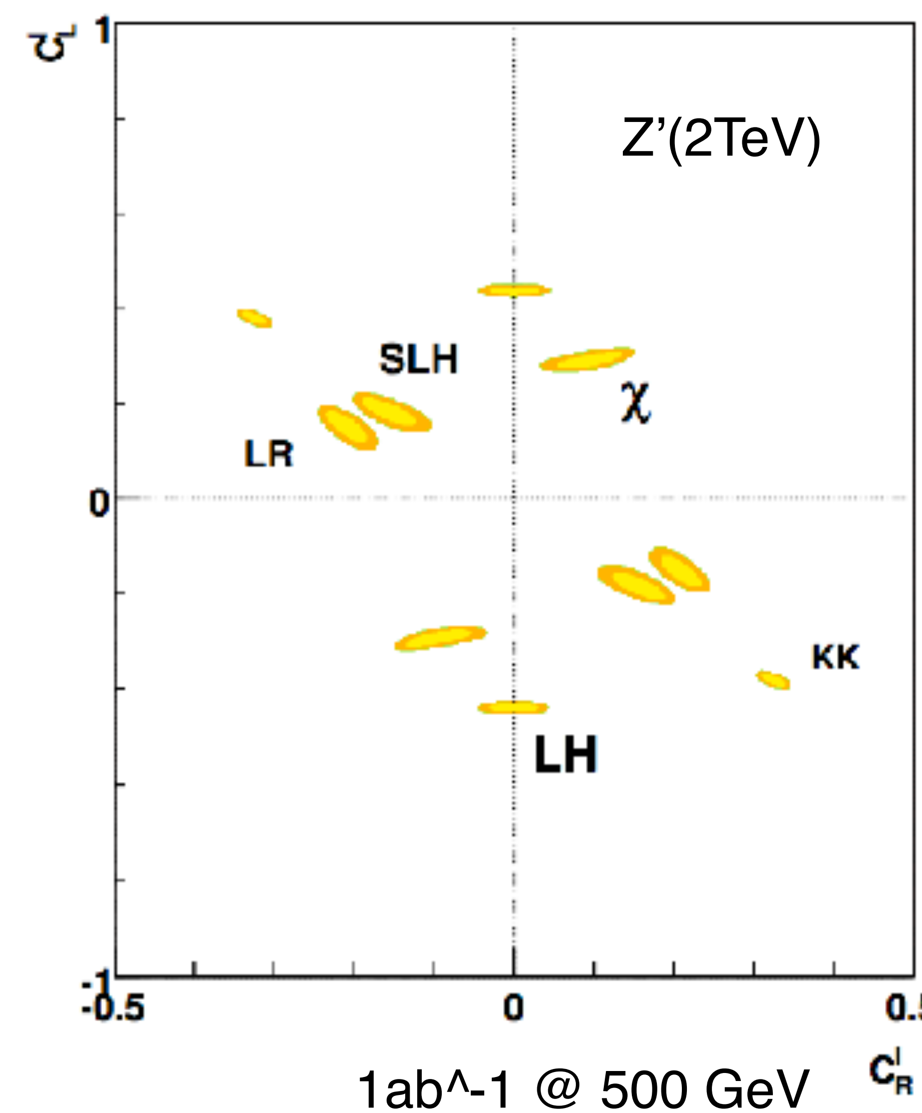


Figure 23: Sensitivity of the ILC to various candidate Z' bosons, quoted at 95% conf., with $\sqrt{s} = 0.5$ (1.0) TeV and $\mathcal{L}_{\rm int} = 500$ (1000) fb^{-1}. The sensitivity of the LHC-14 via Drell-Yan process $pp \to \ell^+\ell^- + X$ with 100 fb^{-1} of data are shown for comparison. For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