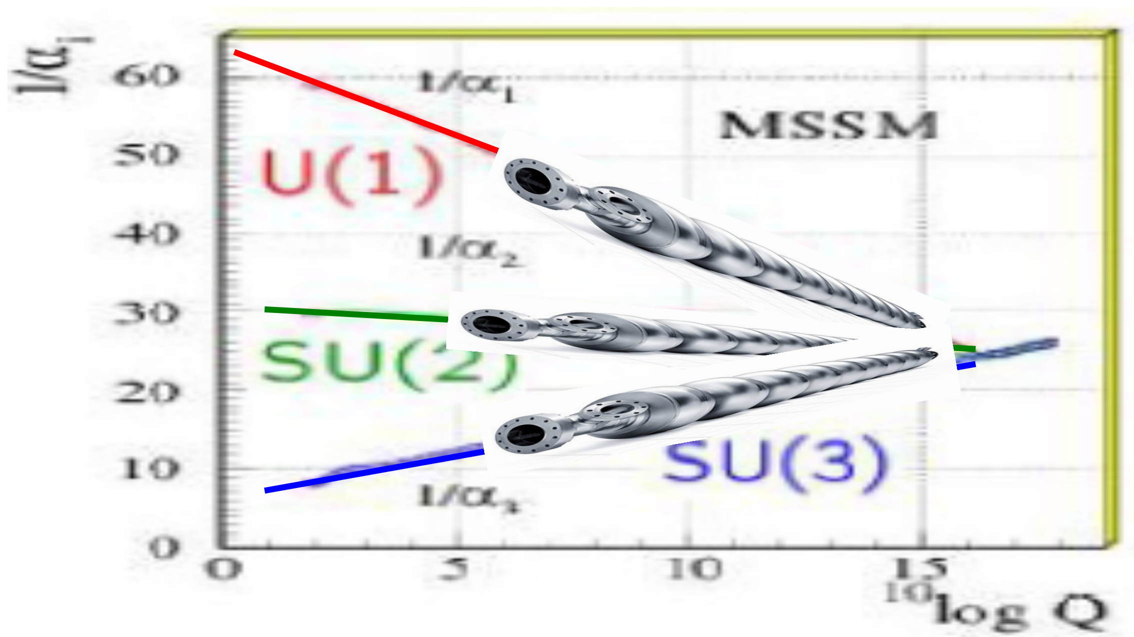
Physics at future Lepton Colliders

G. Moortgat-Pick
(Uni Hamburg/DESY)



LINEAR COLLIDER COLLABORATION

Lecture 2

The LC offers and challenges

- **Staged energy approach:**
  - $\sqrt{s}$~240 GeV, `Higgs frontier‘
  - $\sqrt{s}$~350 GeV, `Top threshold‘
  - $\sqrt{s}$~500 GeV, `Top Yukawa‘ , ‘Higgs potential’
  - ($\sqrt{s}$=91 GeV, `EW Precision frontier‘)
  - $\sqrt{s}$~1000 GeV, `Higgs potential‘
- **Polarized beams and threshold scans:**
  - impact on ‘quality’ (and quantity)
  - Something ‘new’ comp. to LHC analyses
- **Further option: γγ-option (…H, DM,…)**

➡ **Highest precision measurements !**

Polarization basics

- **Applicable for V,A processes (most SM, some BSM)**

$$\sigma\,(Pe-,Pe+)=(1-Pe-\ Pe+)\ \sigma_{unpol}\ [1-P_{eff}\ A_{LR}]$$

- **With both beams polarized we gain in**
  - **Higher effective polarization (higher effect of polarization)**
  - **Higher effective luminosity (higher fraction of collisions)**

$\sqrt{s}$	$P(e^-)$	$P(e^+)$	P_{eff}	$\mathcal{L}_{eff}/L$	$\Delta A_{LR}/A_{LR}$
total range	∓80%	0%	∓80%	0.5	1
250 GeV	∓80%	±40%	∓91%	0.65	0.43
≥350 GeV	∓80%	±55%	∓94%	0.7	0.30

L_{eff} and P_{eff}

- More concrete: If only LR and RL contributions: only 50 % of collisions useful

effective luminosity: $L_{eff}/L = \frac{1}{2}(1 - P_{e-}P_{e+})$

This quantity = the effective number of collisions, can only be changed with P_{e-} and P_{e+}:

ILC baseline:	With $\mp 80\%$, $\pm 30\%$, the increase is 24%	P_{eff}~89%
	With $\mp 80\%$, $\pm 60\%$, the increase is 48%	P_{eff}~95%
	With $\mp 90\%$, $\pm 60\%$, the increase is 54%	P_{eff}~97%

In other words: *no P_{e+} means 24% more running time (!)*

and

10% loss in P_{eff} ≙ 10% loss in analyzing power!

Quite substantial in Higgsstrahlung and electroweak 2f production !

- allows model-independent access!
- Absolute measurement of Higgs cross section σ(HZ) and g_{HZZ}: crucial input for all further Higgs measurement!
- Allows access to H-> invisible/exotic
- Allows with measurement of Γ^h_{tot} absolute measurement of BRs!

L_{eff} and P_{eff}: further example

- Charged currents, i.e. t-channel W- or ν-exchange (A_{LR}=1):

$$\sigma(\mathcal{P}_{e^-}, \mathcal{P}_{e^+}) = 2\sigma_0(\mathcal{L}_{\text{eff}}/\mathcal{L})[1 - \mathcal{P}_{\text{eff}}]$$

In other words: ***no P_{e+} means 30% more running time needed !***

Quite substantial in Higgs production via WW-fusion!

Statistics Suppression of WW and ZZ production

WW, ZZ production = large background for NP searches!

W^- couples only left–handed:
$\rightarrow WW$ background strongly suppressed with right polarized beams!

Scaling factor= $\sigma^{pol}/\sigma^{unpol}$ for WW and ZZ:

$P_{e^-} = \mp 80\%$, $P_{e^+} = \pm 60\%$	$e^+e^- \rightarrow W^+W^-$	$e^+e^- \rightarrow ZZ$
(+0)	0.2	0.76
(−0)	1.8	1.25
(+−)	0.1	1.05
(−+)	2.85	1.91

'No lose theorem': scaling factors for signals&background

	S	B	S/B	$S/\sqrt{B}$
Example 1	$\times 2$	$\times 0.5$	$\times 4$	$\times 2\sqrt{2}$
Example 2	$\times 2$	$\times 2$	Unchanged	$\times\sqrt{2}$

Transversely polarized beams

Transversely polarized beams

➙ enables to exploit azimuthal asymmetries in fermion production !

- the process $e^+e^- \to W^+W^-$:
  $\Rightarrow$ azimuthal asymmetry projects out $W_L^+W_L^-$ *e.g. Fleischer et al,*
- the process e+e- ⟶ tt:
  ➡ probe leptoquark models *e.g. Rindani, Poulose, et al.*
- the process e+e- ⟶ ff:
  ➡ probe extra dimensions *e.g. Hewett, Rizzo et al.*

- the construction of CP violating oservables:
  $\Rightarrow$ matrix elements $|M|^2 \sim \mathcal{C} \times \Delta(\alpha)\Delta^*(\beta) \times \mathcal{S}$ ($\mathcal{C}$=coupl., Δ=prop., $\mathcal{S}$=momenta)

  if CP violation: contributions of $Im(\mathcal{C}) \times Im(\mathcal{S})$ (e.g. contributions of ϵ tensors!)

  $\Rightarrow$ azimuthal dependence ('not only in scattering plane')

  $\Rightarrow$ observables are e.g. asymmetries of CP-odd quantities: $\vec{p}_a(\vec{p}_b \times \vec{p}_c)$

  $\vec{s}^{2\mu} := \vec{p}_1 \times \vec{p}_3$ perpendicular scattering plane, CP even

  $\vec{s}^{1\mu} := \vec{p}_1 \times \vec{s}^2(p_1)$ transverse in plane, CP odd

e.g. Cheng Li et al.

In general: Interactions and Polarization

- **Different Interaction structures:** $\sigma \sim T_k \, T_l^*$ *hep-ph/0507011*

S=scalar-, P=pseudoscalar-, V=vector-, A=axial-vector-, T=tensor- like interactions

Interaction structure		Longitudinal		Transverse		Longitudinal/Transverse
Γ_k	$\bar{\Gamma}_\ell$	Bilinear	Linear	Bilinear	Linear	Interference
S	S	$\sim P_{e^-}P_{e^+}$	–	$\sim P^T_{e^-}P^T_{e^+}$	–	–
S	P	–	$\sim P_{e^\pm}$	$\sim P^T_{e^-}P^T_{e^+}$	–	–
S	V,A	–	–	–	$\sim P^T_{e^\pm}$	$\sim P_{e^\pm}P^T_{e^\mp}$
S	T	$\sim P_{e^-}P_{e^+}$	$\sim P_{e^\pm}$	$\sim P^T_{e^-}P^T_{e^+}$		–
P	P	$\sim P_{e^-}P_{e^+}$	–	$\sim P^T_{e^-}P^T_{e^+}$	–	–
P	V,A	$\sim P_{e^-}P_{e^+}$	$\sim P_{e^\pm}$	$\sim P^T_{e^-}P^T_{e^+}$	$\sim P^T_{e^\pm}$	$\sim P_{e^\pm}P^T_{e^\mp}$
P	T	$\sim P_{e^-}P_{e^+}$	$\sim P_{e^\pm}$	$\sim P^T_{e^-}P^T_{e^+}$		–
V,A	V,A	$\sim P_{e^-}P_{e^+}$	$\sim P_{e^\pm}$	$\sim P^T_{e^-}P^T_{e^+}$	–	–
V,A	T	–	–	–	$\sim P^T_{e^\pm}$	$\sim P_{e^\pm}P^T_{e^\mp}$
T	T	$\sim P_{e^-}P_{e^+}$	$\sim P_{e^\pm}$	$\sim P^T_{e^-}P^T_{e^+}$	–	–

‣ **dependence on polarization provides information on kind of interaction**

What is the current status?

* 29.5.1929 † 8.4.2024

- One Higgs particle discovery on 4.7.2012
  - strongly consistent with Standard Model (SM) predictions
- Few excesses around…..(e.g. a light scalar at about 95 GeV)
  - but not (yet) confirmed discoveries
- Still strong motivation for Beyond SM (BSM) physics
  - Dark Matter, Gravitational Waves, Baryon-Asymmetry, etc.
- However, scale of new physics window still unclear
  - …..the research field might be in great danger

➡Therefore, high precision and/or high energy in specific areas needed and additional tools complementary to (HL)LHC analyses required to identify the promising windows

LLParticles,2203.05502, Aiko, Endo, 2302.11377

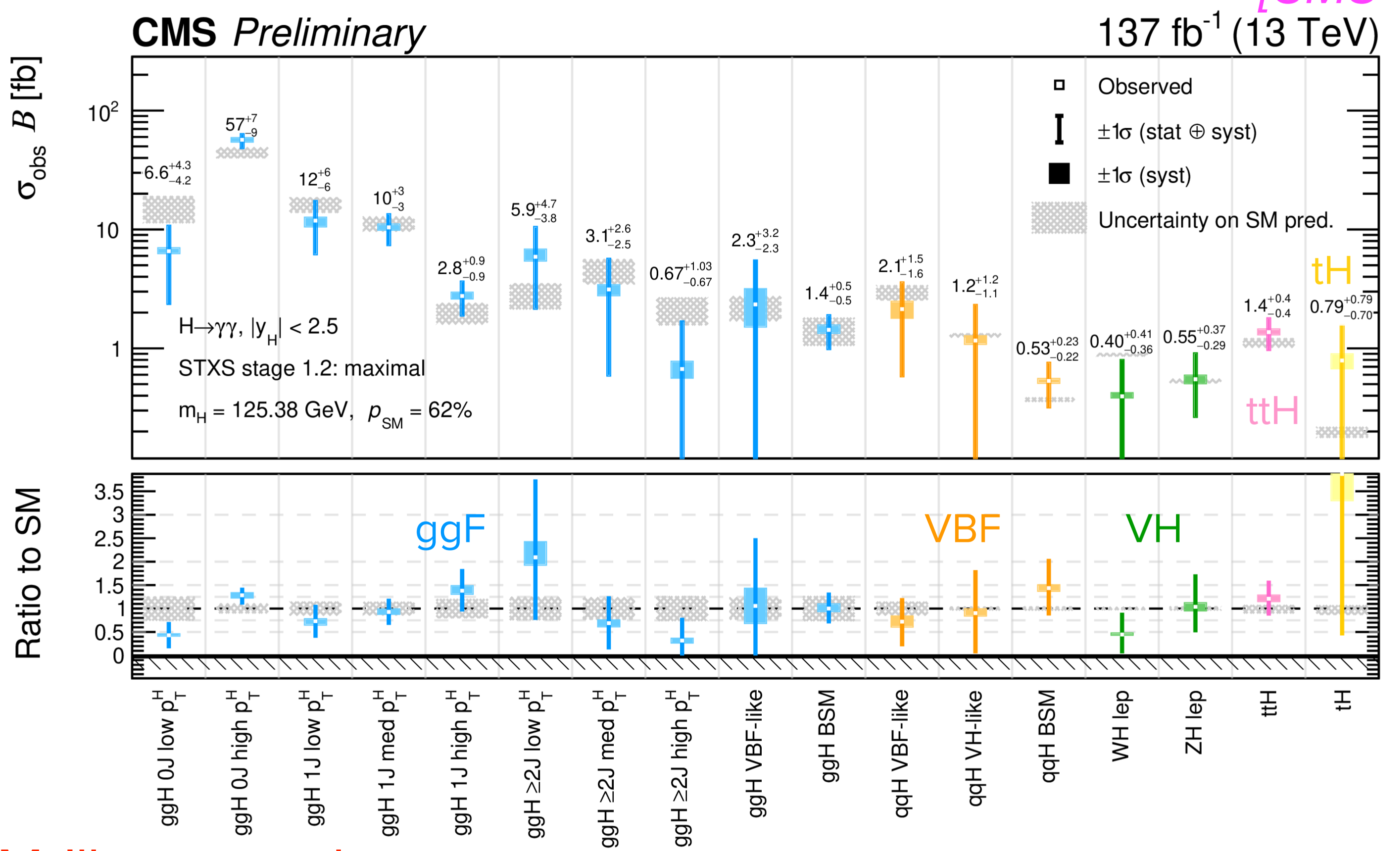
➡ stageable, tuneable lepton colliders required

➡e+e- collider designs with sane beam polarization crucial!

Status Higgs……

A bit more than 11 years after the discovery of the boson at 125 GeV (h125): high-precision measurement of the mass, detailed investigations of inclusive and differential rates

[CMS Collaboration '22]

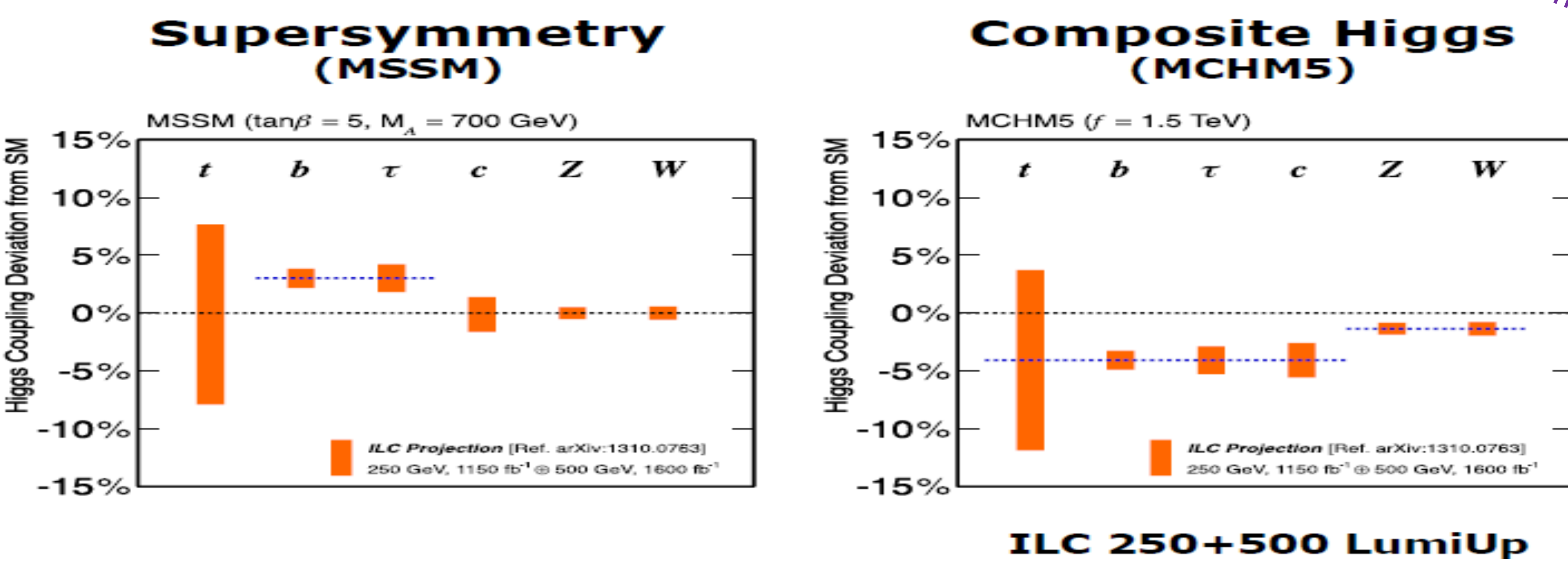


⇒ SM-like properties

Back to the Higgs……

- **Higgs within achievable accuracy at LHC: SM-like**
  - Could be the only SM Higgs (what's about DM? gauge unification?)
  - Could be a SUSY Higgs (one has to be close to a SM-like one)
  - Could be a composite state

S. Komamiya, LP15



courtesy of G. Weiglein

Higgs coupling determination at the LHC

Problem: no absolute measurement of total production cross section (no recoil method like LEP, ILC: $e^+e^- \to ZH$, $Z \to e^+e^-, \mu^+\mu^-$)

Production $\times$ decay at the LHC yields combinations of Higgs couplings ($\Gamma_{\text{prod, decay}} \sim g^2_{\text{prod, decay}}$):

$$\sigma(H) \times \text{BR}(H \to a + b) \sim \frac{\Gamma_{\text{prod}} \Gamma_{\text{decay}}}{\Gamma_{\text{tot}}},$$

Total Higgs width cannot be determined without further assumptions

⇒ LHC can directly determine only ratios of couplings, e.g. $g^2_{H\tau\tau}/g^2_{HWW}$

``$\varkappa$ framework" and EFT approach for coupling analyses

Simplified framework for coupling analyses: deviations from SM parametrised by ``scale factors" $\varkappa_i$, where $\varkappa_i \equiv g_{Hii}/g^{SM,\,(0)}{}_{Hii}$

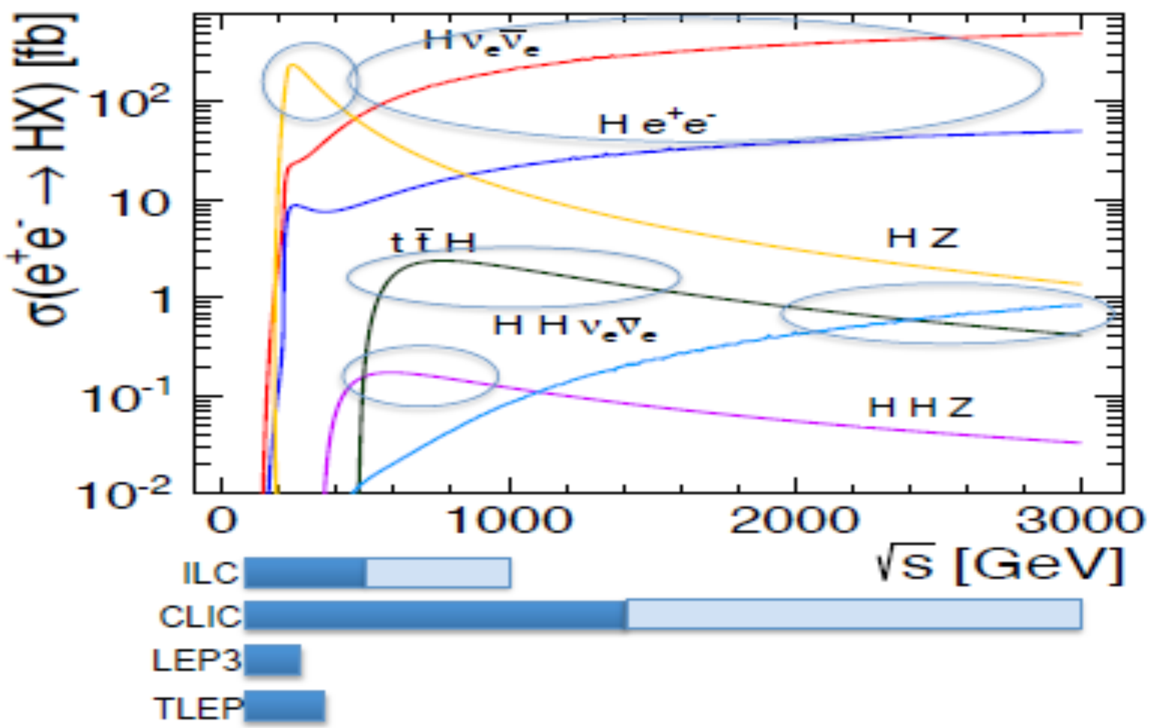
Assumptions inherent in the $\varkappa$ framework: signal corresponds to only one state, no overlapping resonances, etc., zero-width approximation, only modifications of coupling strengths (absolute values of the couplings) are considered
⇒ Assume that the observed state is a CP-even scalar

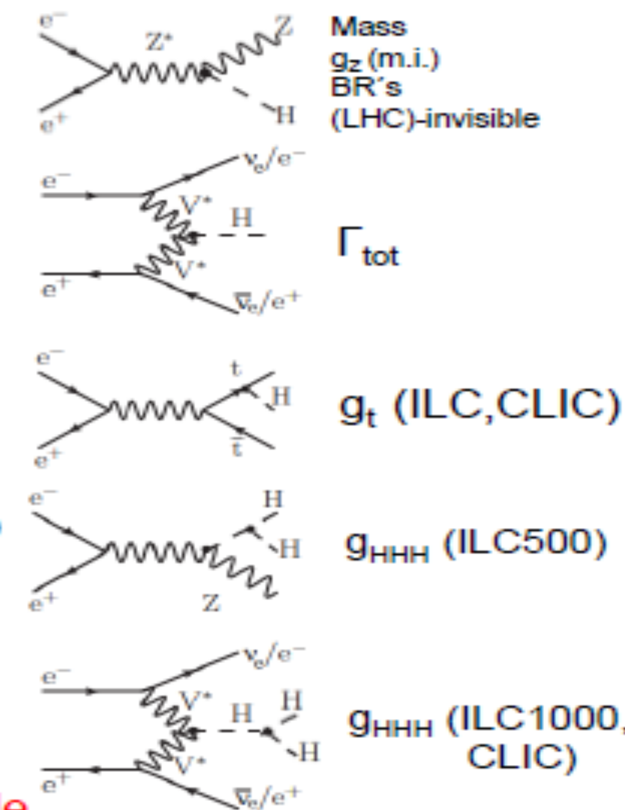
Theoretical assumptions in determination of the $\varkappa_i$:
$\varkappa_V \leqq 1$, no invisible / undetectable decay modes, …

EFT: fits for Wilson coefficients of higher-dimensional operators in SMEFT Lagrangian, …

Higgs @ LC

Many processes at different √s needed & accessible





- Many processes at different √s needed & accessible

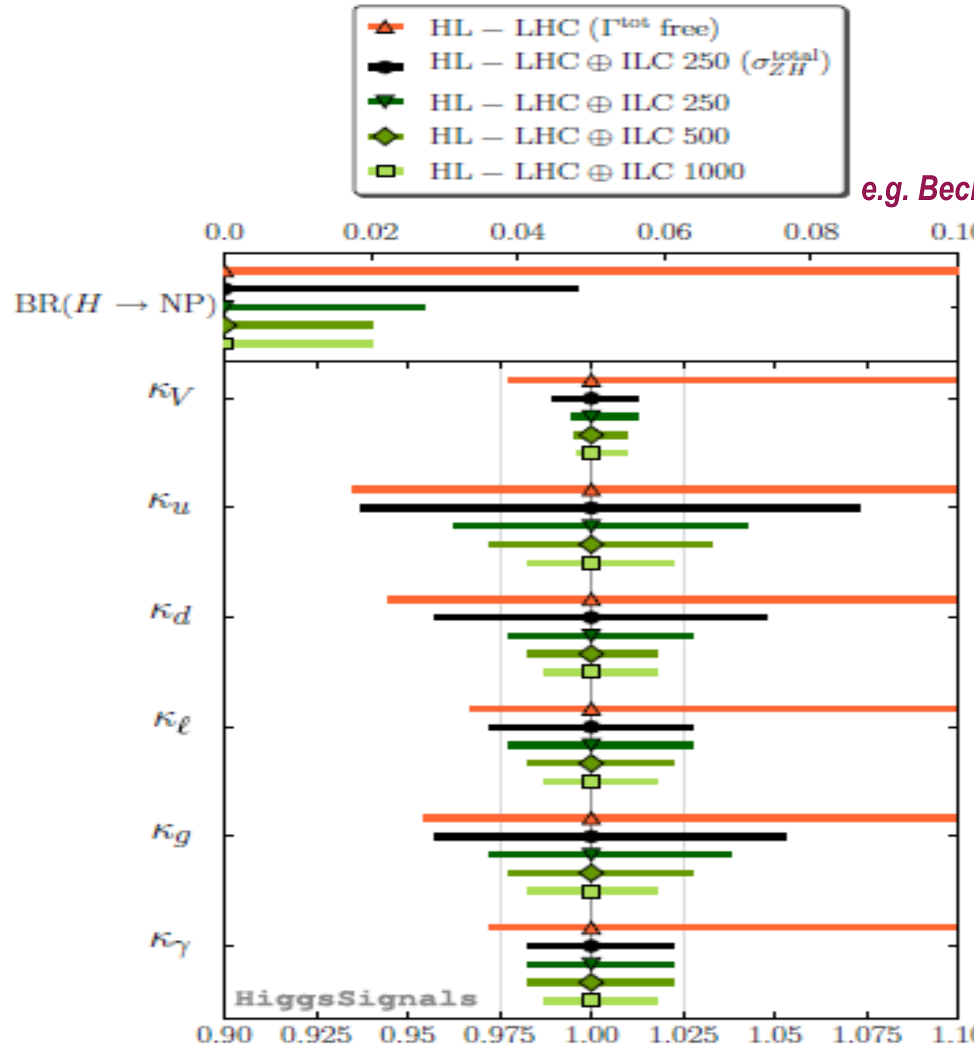
The Linear Collider is crucial in this regard!

Great thanks to LHC&(I)LC….

- **Precision of 1-2% achievable in Higgs couplings !!!**

- **Crucial input from ILC**
  - **total cross section σ(HZ)**
  - **Has to be measured at √s=250GeV**
  - **Input parameter for all further Higgs studies (Higgs width etrc.) !**

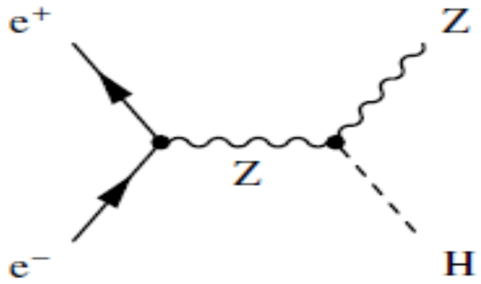
- **Lots of improvement if only σ(HZ) from ILC is added**



e.g. Bechtle et al.

Process: Higgs Strahlung

$\sqrt{s}$=250 GeV



- $\sqrt{s}$=250 GeV: dominant process
- Why crucial?
  - allows model-independent access!
  - Absolute measurement of Higgs cross section $\sigma(HZ)$ and g_{HZZ}:

    crucial input for all further Higgs measurement!

  - Allows access to H-> invisible/exotic
  - Allows with measurement of Γ^h_{tot} absolute measurement of BRs!

Higgs sector@250 GeV

- **What if no polarization / no P_{e+} available?**
  - Higgsstrahlung dominant $\sigma_{pol}/\sigma_{unpol} \sim (1-0.151\, P_{eff}) * L_{eff}/L$

    With P_{e+}=0%: $\sigma_{pol}/\sigma_{unpol} \sim 1.13$

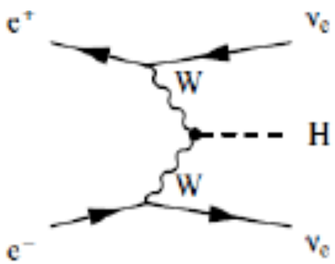
    With P_{e+}=40%: $\sigma_{pol}/\sigma_{unpol} \sim 1.55$ (about 37% increase comp. to 0%)
  - Background: mainly ZZ (if leptonic), WW (if hadronic)

– S/B:	1.14 (+,0)	4.35 (+,0)
	1.20 (+,-)	12.6 (+,-)
– S/√B:	0.99 (+,0)	1.95 (+,0)
	1.22 (+,-)	3.98 (+,-)
➢ *Loss if no P_{e+} :*	~20%	~ factor 2

  - **If no P(e+): 20% longer running time!…..** *~few years and less precision!*

Crucial: *Higgs width* at the LC $\sqrt{s}$=350 GeV

- **Already at $\sqrt{s}$=350 GeV:**
- Access to Higgs total width :
  - Total width for mH=125 GeV: T_h^{tot} ~4 MeV!
  - Does need WW-fusion in addition to HZ



	$\Delta T_h^{tot}/T_h^{tot}$
250 GeV:	13%
350 GeV:	~7%
500 GeV:	~5-6%
1 TeV:	~ 4%

$$\sigma_{tot} = \sigma_{prod} \times \Gamma_{part}/\Gamma_{tot}$$

- Higgs width crucial for absolute BR's, couplings and model discrimination!

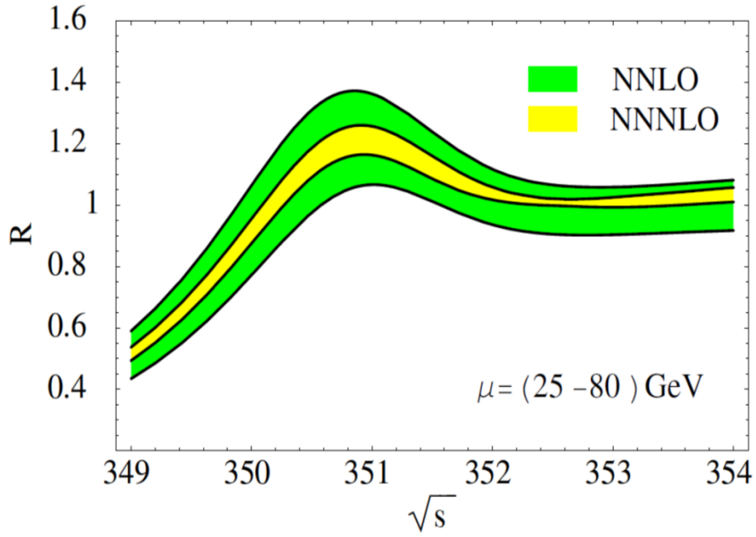
Top production at the LC

- **Top very special role: heaviest fundamental fermion**
  - most strongly coupled to EWSB sector,
  - Intimately related to the dynamics behind the SB mechanism
  - M_{top} affects M_H, M_W, M_Z via radiative corrections
- **At LHC/Tevatron: Δm_{top}~1 GeV**
  - Crucial: relation between measured mass to a well-defined parameter that is a suitable theoretical input, as $\overline{\text{MS}}$ mass
  - Relation affected by non-perturbative contr. = limiting factor
- **At the LC, e+e- -> t t: measure 'threshold mass'**
  - Relation to well-defined m_{top}, theoretically well under control
  - Threshold scan: Δm_{top}~100 MeV

Top mass

$\sqrt{s}$=350 GeV

- **Threshold scan:**



Important shift due to non-logarithmic NNNLO terms

- **LC: Peak position remains stable: m_t=100 MeV**
- **includ. exp uncertainty of ~30 MeV + theo. uncertainty ~70 MeV**
- **expected accuracy confirmed by full simulation studies!**
- **Dedicated threshold scan required with about ~100fb^{-1}**

Top Yukawa coupling

$\sqrt{s} \geq 500$ GeV

- **Crucial quantity!**
  - Key role in dynamics of ew symmetry breaking
- **At $\sqrt{s}$=500 GeV: first measurements of ttH-coupling**
  - At this energy: ttH is close to threshold
  - But thanks to threshold effects: σ enhancement by a factor 2!
    - Yukawa couplings $\Delta g_{ttH} / g_{ttH} \sim 5.5\%$ based on 3ab^{-1} and polarized beams (-80%,+30%)

      LHC estimates: $\Delta g_{ttH} / g_{ttH} \sim 10\%$ at HL-LHC at 14 TeV and 3000 fb^{-1}
- **At $\sqrt{s}$=1 TeV:**

  $\Delta g_{ttH} / g_{ttH} \sim 4.3\%$ based on 1ab^{-1} and polarized beams (-80%,+20%)

  - Exploiting both hadronic+semi-leptonic ttH in decay angle distributions

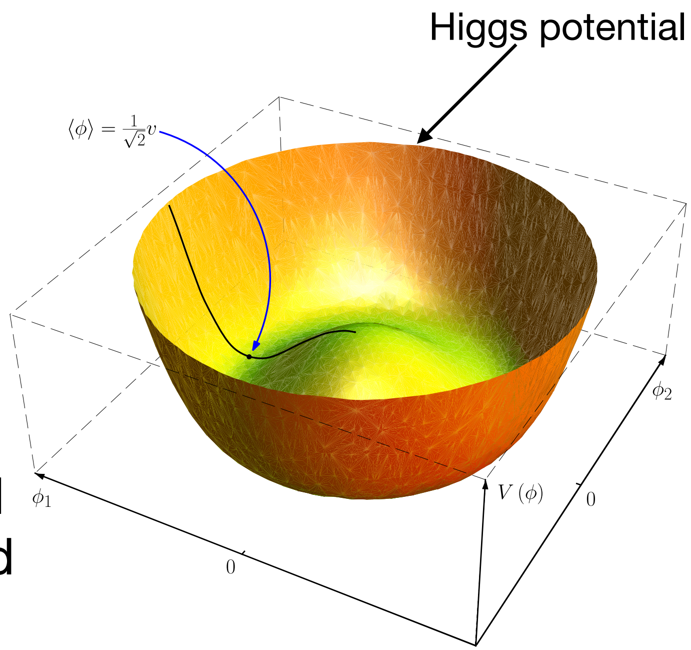
Back to the Higgs again……

√s=500 GeV

What is the underlying dynamics of electroweak symmetry breaking?

courtesy of G. Weiglein

The vacuum structure is caused by the Higgs field through the Higgs potential. We lack a deeper understanding of this!



We do not know where the Higgs potential that causes the structure of the vacuum actually comes from and which form of the potential is realised in nature. Experimental input is needed to clarify this!

Single doublet or extended Higgs sector? (new symmetry?)

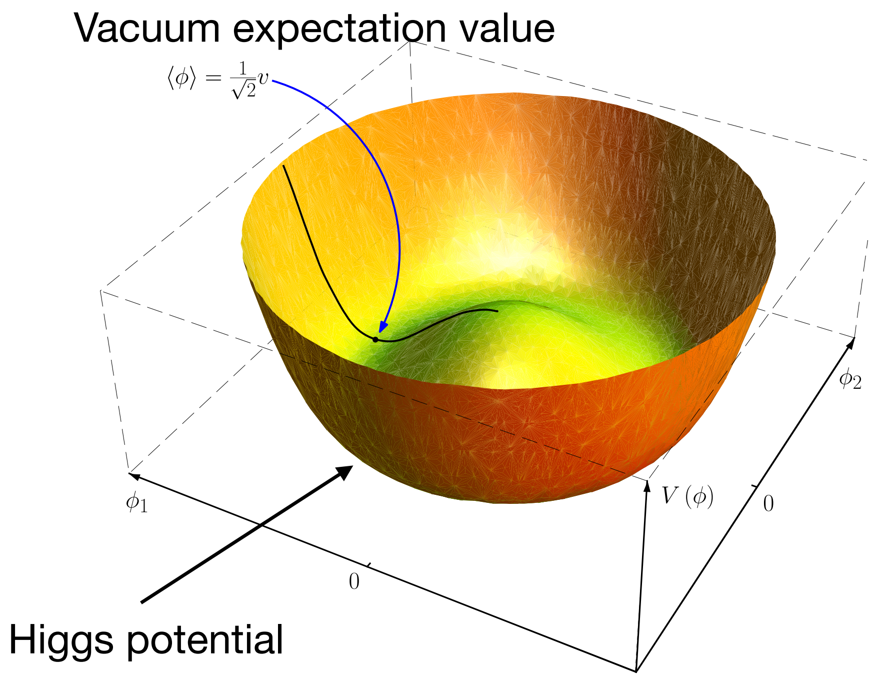
Fundamental scalar or compositeness? (new interaction?)

11

courtesy of G. Weiglein

Higgs potential: the "holy grail" of particle physics

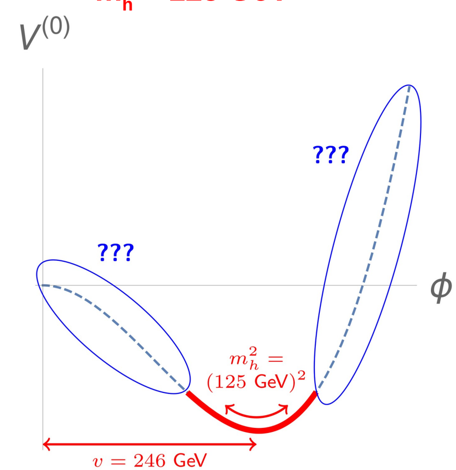
Crucial questions related to electroweak symmetry breaking: what is the form of the Higgs potential and how does it arise?



Only known so far:

→ the location of the EW minimum:
v = 246 GeV

→ the curvature of the potential around the EW minimum:
m_h = 125 GeV



Information can be obtained from the trilinear and quartic Higgs self-couplings, which will be a main focus of the experimental and theoretical activities in particle physics during the coming years

12

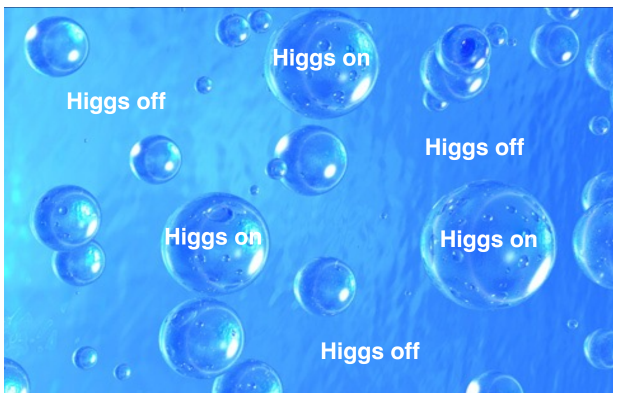
courtesy of G. Weiglein

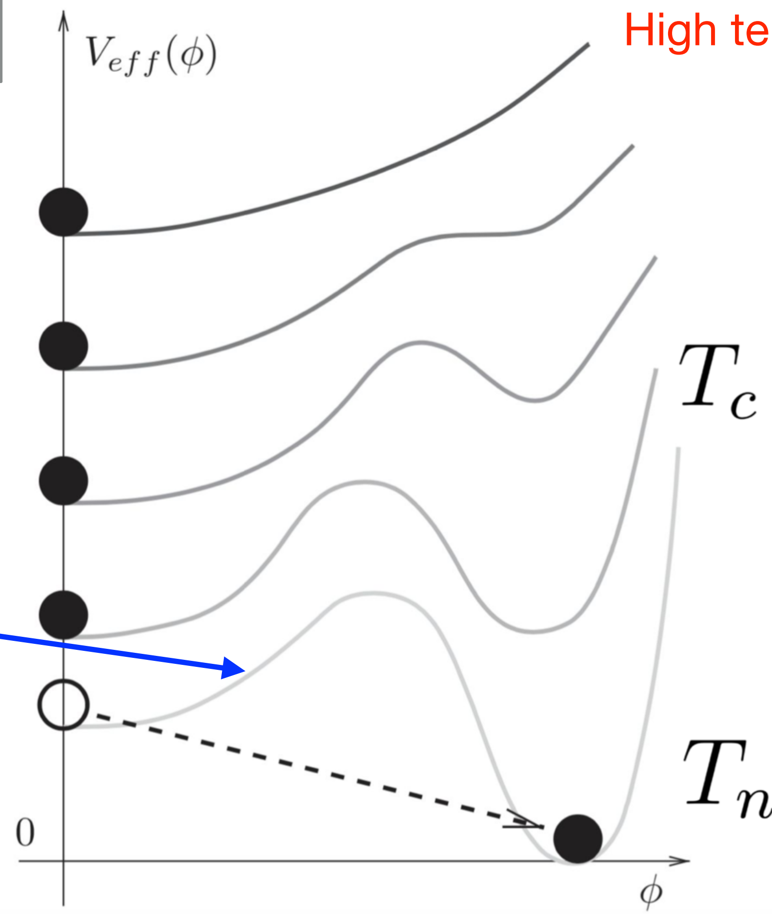
The Higgs potential and the electroweak phase transition (EWPT)

[D. Gorbunov, V. Rubakov]

Temperature evolution of the Higgs potential in the early universe:

$$V(\phi,T) = V_0(\phi) + V^{loop}(\phi,T)$$





High temperature

Critical temperature (degenerate minima)

Transition temperature (strong first-order EWPT)

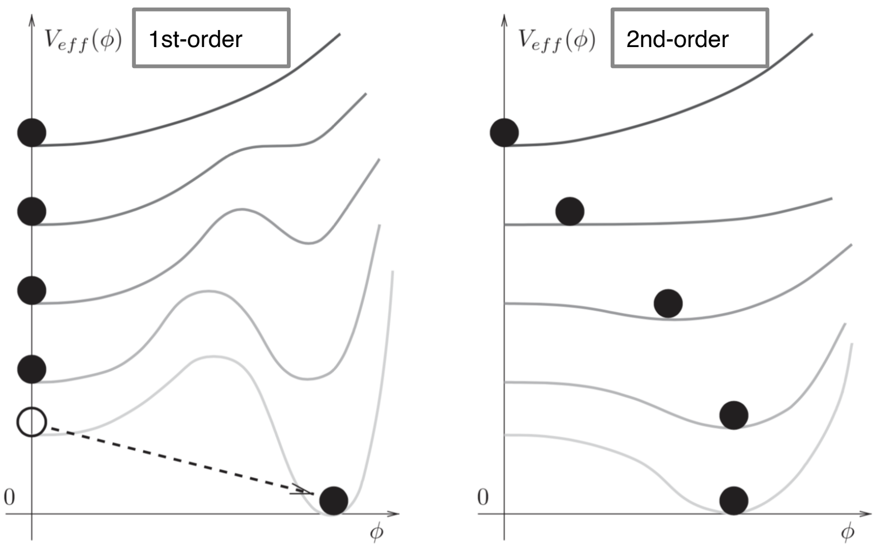
Potential barrier depends on trilinear Higgs coupling(s)

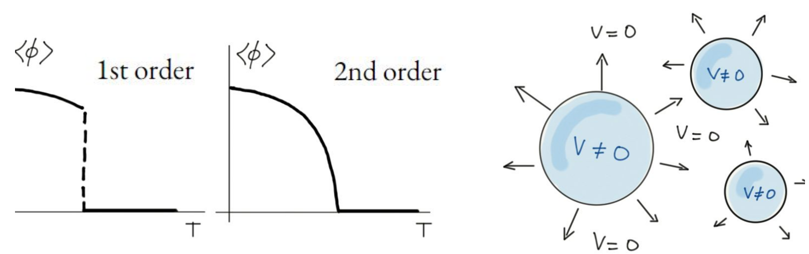
Baryogenesis: creation of the asymmetry between matter and antimatter in the universe requires strong first-order EWPT

courtesy of G. Weiglein

First-order vs. second order EWPT

[D. Gorbunov, V. Rubakov]





[K. Radchenko '23]

Potential barrier needed for first-order EWPT, depends on trilinear Higgs coupling(s)

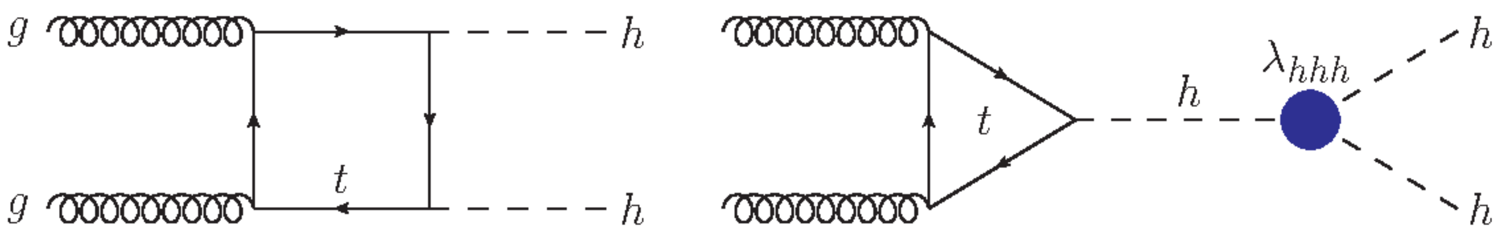
Deviation of trilinear Higgs coupling from SM value is a typical feature of a strong first-order EWPT

14

Trilinear Higgs self-coupling and the Higgs pair production process

Sensitivity to the trilinear Higgs self-coupling from Higgs pair production:

- **Double-Higgs production** → λ_{hhh} enters at LO → **most direct probe of λ_{hhh}**



[Note: Single-Higgs production (EW precision observables) → λ_{hhh} enters at NLO (NNLO)]

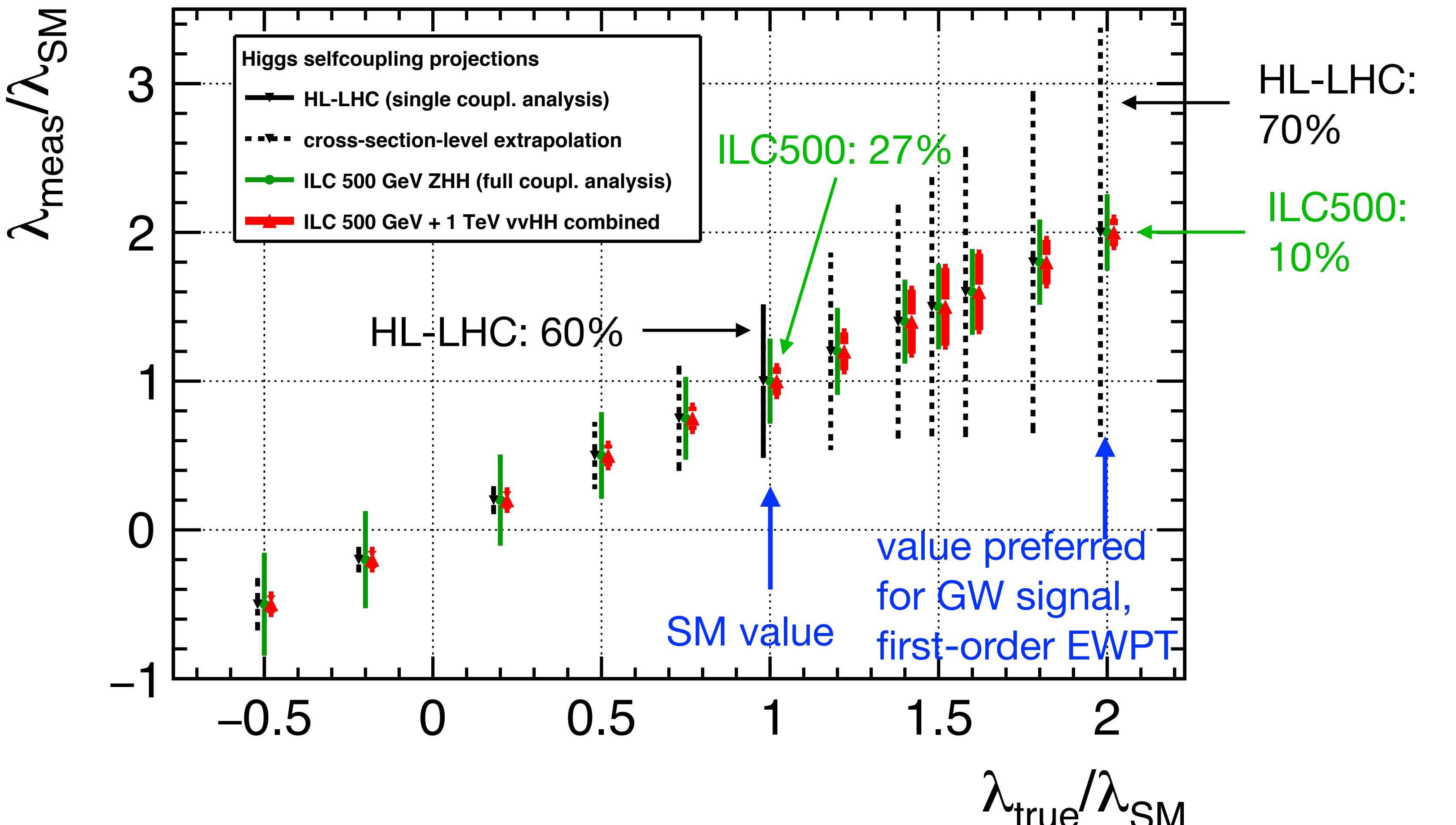
e^+e^- Higgs factory:
Indirect constraints from measurements of single Higgs production and electroweak precision observables at lower energies are not competitive!
Direct measurement of trilinear Higgs self-coupling at lepton collider with at least 500 GeV c.m. energy will be crucial!

Note: the ``non-resonant” experimental limit on Higgs pair production obtained by ATLAS and CMS depends on $\varkappa_\lambda = \lambda_{hhh} / \lambda_{hhh}^{SM, 0}$

47

Prospects for measuring the trilinear Higgs coupling: HL-LHC vs. ILC (500 GeV, Higgs pair production)

[J. List et al. '21]



⇒ For $\varkappa_\lambda \approx 2$: much better prospects for ILC500 than for HL-LHC

Reason: different interference contributions

CP properties of h125

$\mathcal{CP}$ properties: more difficult than spin, observed state can be any admixture of $\mathcal{CP}$-even and $\mathcal{CP}$-odd components

Observables mainly used for investigaton of $\mathcal{CP}$-properties ($H \to ZZ^*, WW^*$ and H production in weak boson fusion) involve HVV coupling

General structure of HVV coupling (from Lorentz invariance):

$$a_1(q_1, q_2) g^{\mu\nu} + a_2(q_1, q_2) \left[(q_1 q_2)\, g^{\mu\nu} - q_1^\mu q_2^\nu \right] + a_3(q_1, q_2) \epsilon^{\mu\nu\rho\sigma} q_{1\rho} q_{2\sigma}$$

SM, pure $\mathcal{CP}$-even state: $a_1 = 1, a_2 = 0, a_3 = 0$,

Pure $\mathcal{CP}$-odd state: $a_1 = 0, a_2 = 0, a_3 = 1$

However: in many models (example: SUSY, 2HDM, ...) a_3 is loop-induced and heavily suppressed

CP-violating admixtures in the Higgs sector

Sensitivity at the LHC and e⁺e⁻ Higgs factories

[C. Li, G. Moortgat-Pick '24]

$e^+e^- \to HZ \to H\mu^-\mu^+$ with transverse and longitudinal beam pol.

Experiments	ATLAS[24]	CMS[19]	HL-LHC[25]	CEPC[29]	CLIC[30]	CLIC [31, 40]	ILC
Processes	$H \to 4\ell$	$H \to 4\ell$	$H \to 4\ell$	HZ	W-fusion	Z-fusion	$HZ,\ Z \to \mu^+\mu^-$
$\sqrt{s}$ [GeV]	13000	13000	14000	240	3000	1000	250
Luminosity [fb^{-1}]	139	137	3000	5600	5000	8000	5000
$(\lvert P_-\rvert, \lvert P_+\rvert)$							$(90\%, 40\%)$
$\widetilde{c}_{HZZ}$ $(\times 10^{-2})$ 95% C.L. (2σ)limit	[-16.4, 24.0]	[-9.0, 7.0]	[-9.1, 9.1]	[-1.6, 1.6]	[-3.3, 3.3]	[-1.1, 1.1]	[-1.1, 1.0]

$\widetilde{c}_{HZZ} = a_3$

Possible scenarios of new physics

- New physics model
  - Valid up to high scales (Standard Model up to $\Lambda < M_{PL} = 10^{19}$ GeV)
  - May be treated as effective theory
- Supersymmetry (SUSY) = NP with high predictive power
  - renormalizable
  - provides, for instance, dark matter candidates
- Extra Dimension Models = we live on a 3+1 dim brane in higher-dim space time
  - Fundamental Planck scale is ~TeV (ADD model)
  - Hierachy of scales is related to a 'warp factor'
  - Dark matter: lightest KK particle
- In the following:

Concentrate on deviations of SM, SUSY as one example, the challenges and on LC-relevant features

SUSY solutions

- **Impose new symmetry: SUSY=symmetry between fermions and baryons:same quantum numbers wo spin**
  - Solves the hierarchy problem
  - Provides dark matter candidate: lightest stable particle
  - Recovers the SM: same gauge group SU(3)xSU(2)xU(1)
  - Provides gauge coupling unification
  - Potential to solve baryon asymmetry: new sources for CP violation
  - Fully renormalizable up to the Planck scale (as the SM)
- **Unconvenient features:**
  - Has to be a broken symmetry: many new parameters
  - 'No' hints at LHC ….so far
- **Nevertheless SUSY=most mature candidate**

Polarization: chiral quantum numbers at LC

- **Unique feature: polarized e- and e+ beams available**

Test of SUSY assumption: SM $\leftrightarrow$ SUSY have same quantum numbers!

$\Rightarrow e^-_{L,R} \leftrightarrow \tilde{e}^-_{L,R}$ and $e^+_{L,R} \leftrightarrow \tilde{e}^+_{R,L}$

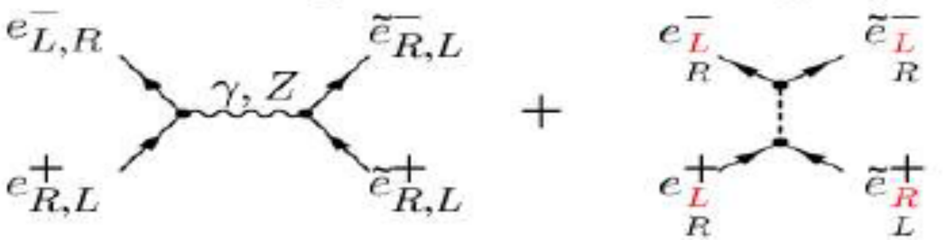
Scalar partners $\leftrightarrow$ chiral quantum numbers!

How to test this association?

Strategy: $\sigma(e^+e^- \to \tilde{e}^+_{L,R}\tilde{e}^-_{L,R})$ with polarised beams

annihilation diagram

scattering diagram



$\Rightarrow$ 2nd diagram: unique relation between chiral fermion $\longleftrightarrow$ scalar partner

Use e.g. $e^+_L e^-_L$

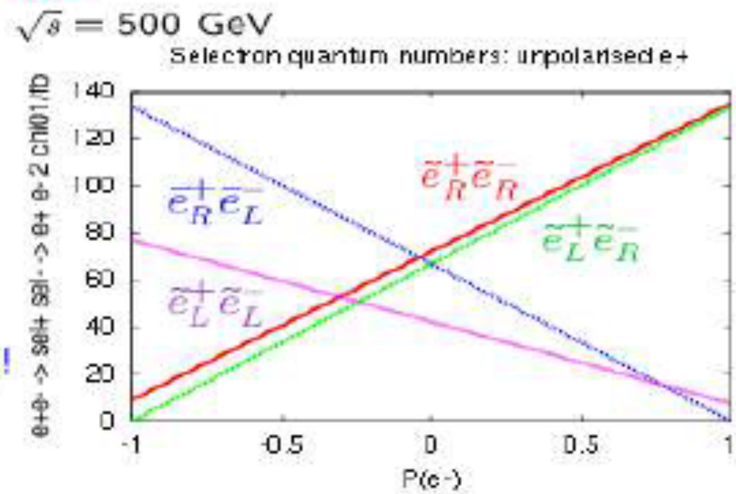
$\to$ scattering diagram: $\tilde{e}^+_R \tilde{e}^-_L \longrightarrow \tilde{e}^+_R \leftrightarrow \tilde{e}^-_L$

$\to$ no annihilation diagram

Polarization: Test of new quantum numbers

$\sqrt{s}$=500 GeV

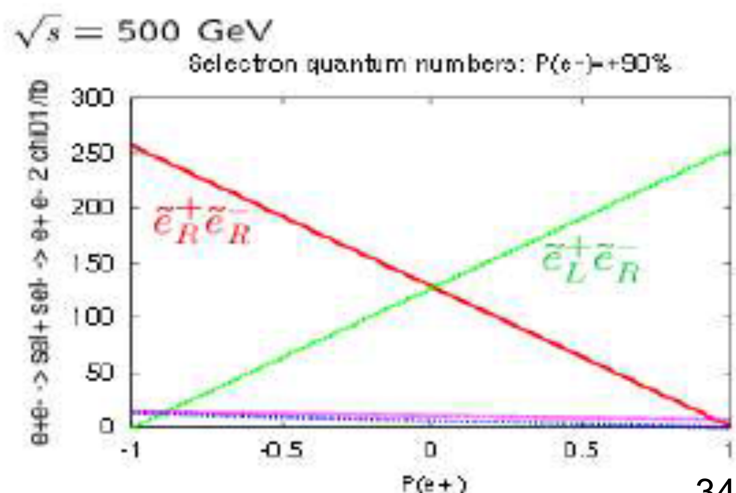
- precise analysis of non–standard couplings



Polarised cross sections: $\sigma(e^+e^- \to \tilde{e}^+_{L,R}\tilde{e}^-_{L,R})$

⇒ No separation of $\tilde{e}^+_R\tilde{e}^-_R$, $\tilde{e}^+_L\tilde{e}^-_R$ even for high $P(e^-)$!

- could additional $P(e^+)$ help?



$P(e^-) = +90\%$, $P(e^+) = +60\%$:
excellent separation of $\tilde{e}^+_R\tilde{e}^-_R$, $\tilde{e}^+_L\tilde{e}^-_R$!

⇒ Test of association of chiral quantum numbers to $\tilde{e}$!

⇒ $P(e^+)$ absolutely needed!

Be prepared for the 'Unexpected'…

- the LC +LHC are mandatory………!

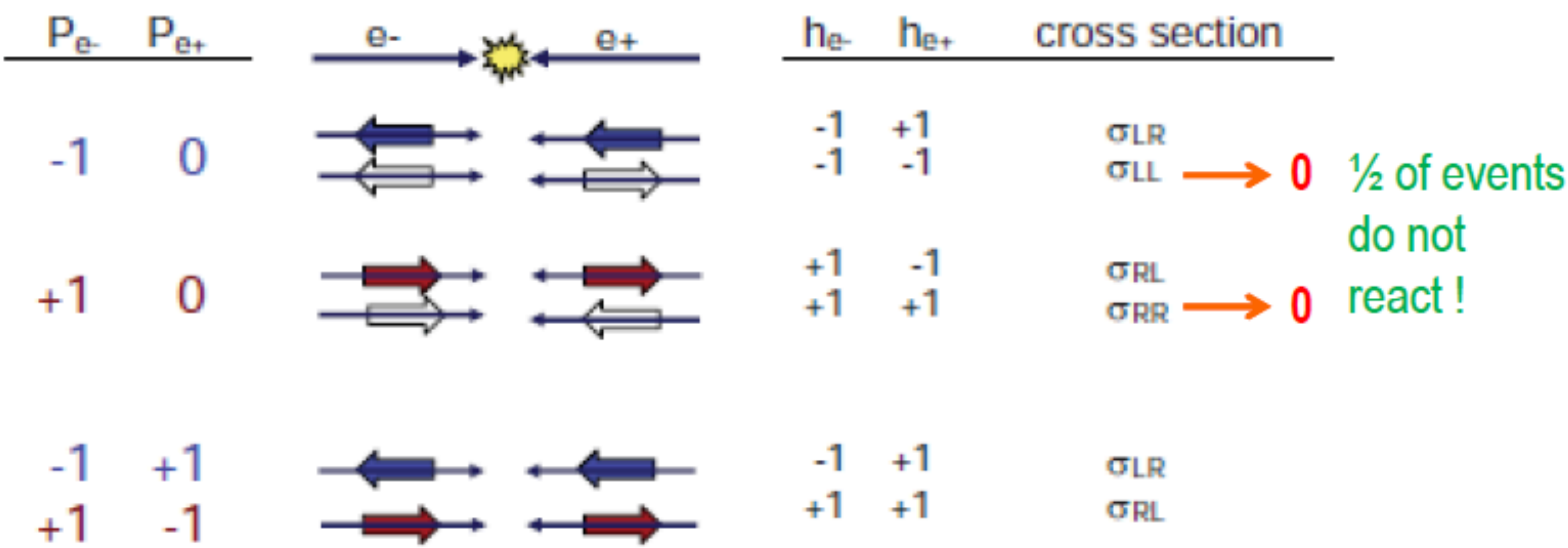
Statistical arguments

- Effective polarization

$$P_{eff} := (P_{e^-} - P_{e^+})/(1 - P_{e^-}P_{e^+})$$
$$= (\#LR - \#RL)/(\#LR + \#RL)$$

- Fraction of colliding particles

$$\mathcal{L}_{eff}/\mathcal{L} := \tfrac{1}{2}(1 - P_{e^-}P_{e^+}) = (\#LR + \#RL)/(\#all)$$



⇒ Enhancing of $\mathcal{L}_{eff}$ with $P(e^-)$ and $P(e^+)$!

Polarization basics

- **Longitudinal polarization:** $\mathcal{P} = \frac{N_R - N_L}{N_R + N_L}$

- **Cross section:**

$$\sigma(\mathcal{P}_{e^-}, \mathcal{P}_{e^+}) = \frac{1}{4}\{(1+\mathcal{P}_{e^-})(1+\mathcal{P}_{e^+})\sigma_{\mathrm{RR}} + (1-\mathcal{P}_{e^-})(1-\mathcal{P}_{e^+})\sigma_{\mathrm{LL}} + (1+\mathcal{P}_{e^-})(1-\mathcal{P}_{e^+})\sigma_{\mathrm{RL}} + (1-\mathcal{P}_{e^-})(1+\mathcal{P}_{e^+})\sigma_{\mathrm{LR}}\}$$

- **Unpolarized cross section:**

$$\sigma_0 = \frac{1}{4}\{\sigma_{\mathrm{RR}} + \sigma_{\mathrm{LL}} + \sigma_{\mathrm{RL}} + \sigma_{\mathrm{LR}}\}$$

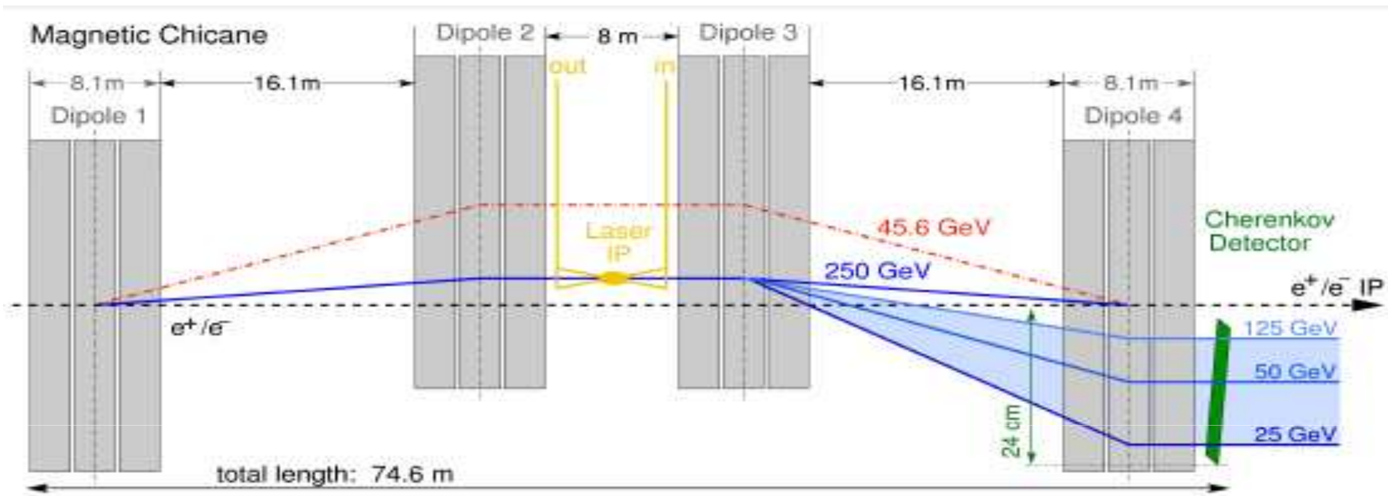
- **Left-right asymmetry:** $A_{\mathrm{LR}} = \frac{(\sigma_{\mathrm{LR}} - \sigma_{\mathrm{RL}})}{(\sigma_{\mathrm{LR}} + \sigma_{\mathrm{RL}})}$

- **Effective polarization and luminosity:**

$$\mathcal{P}_{\mathrm{eff}} = \frac{\mathcal{P}_{e^-} - \mathcal{P}_{e^+}}{1 - \mathcal{P}_{e^-}\mathcal{P}_{e^+}} \qquad \mathcal{L}_{\mathrm{eff}} = \frac{1}{2}(1 - \mathcal{P}_{e^-}\mathcal{P}_{e^+})\mathcal{L}$$

Compton polarimetry at ILC

- Upstream polarimeter: use chicane system



  - Can measure individual e± bunches
  - Prototype Cherenkov detector tested at ELSA!
- Downstream polarimeter: crossing angle required
  - Lumi-weighted polarization (via w/o collision)
  - Spin-tracking simulations required

Polarimetry requirements

- **SLC experience: measured ΔP/P=0.5%**
  - **Compton scattered e- measured in magnetic spectrometer**
- **Goal at ILC: measure ΔP/P≤0.25%**
  - **Dedicated Compton polarimeters and Cherenkov detectors**
  - **Use upstream and downstream polarimeters**
    - ➢ **Machine feedback and access to luminosity-weighted polarization**

  - **Use also annihilation data:** **`average polarization'**
    - ➢ **Longterm absolute calibration scale, up to ΔP/P=0.1%**