Linear Collider Facility

Roman Pöschl
Many slides taken from Jenny List

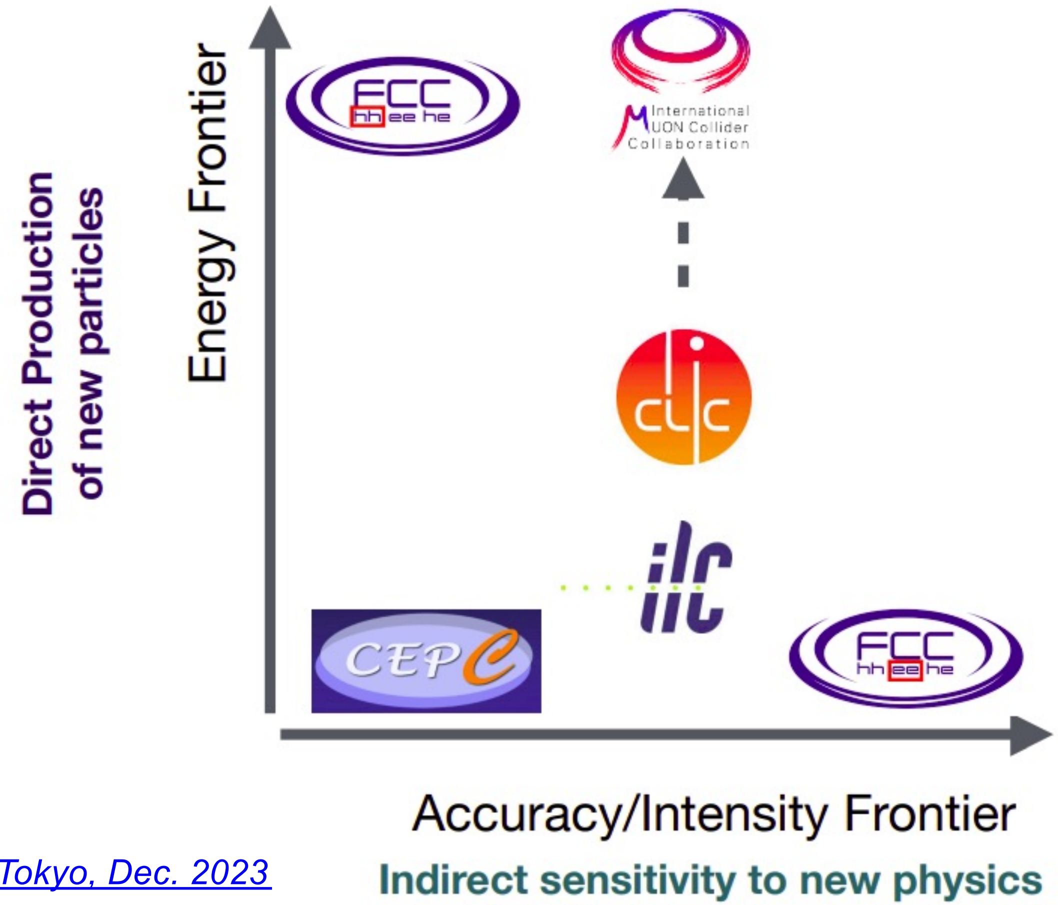
Linear Collider Vision

See also https://agenda.linearcollider.org/event/10624/program

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis
CNRS NUCLÉAIRE & PARTICULES
université PARIS-SACLAY GRADUATE SCHOOL Physique
P2I Physique des deux Infinis

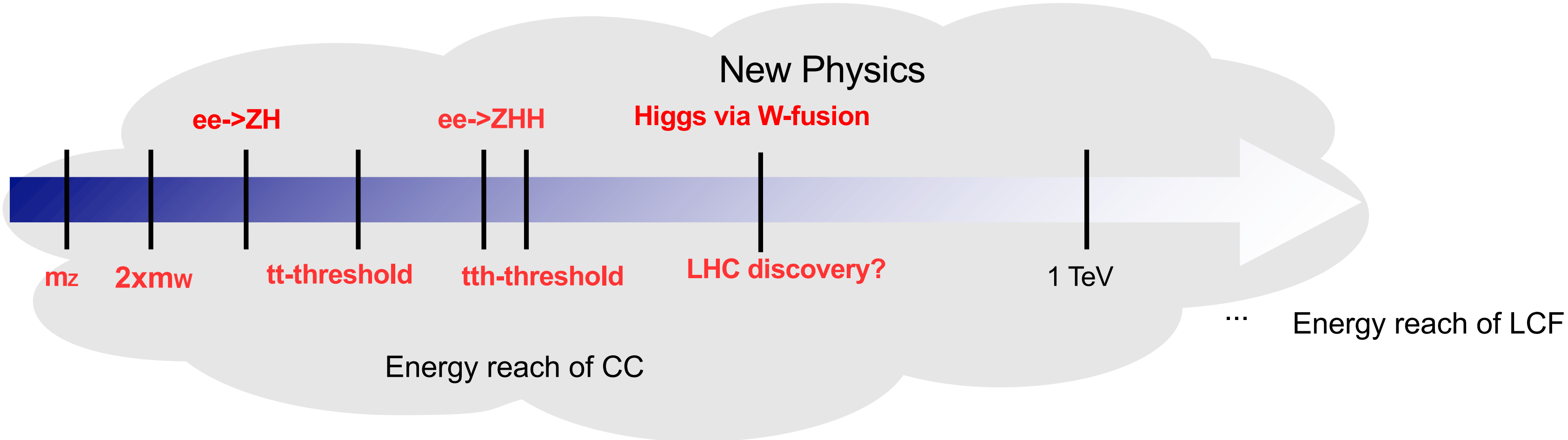
IRN Terascale Meeting – Strasbourg May 2025

Future Projects – “The Frontiers”



[Cartoon J. de Blas, ICEPP Tokyo, Dec. 2023]

e+e- Physics program



- All Standard Model particles within reach of planned e+e- colliders
- High prec… ct onset of New Physics

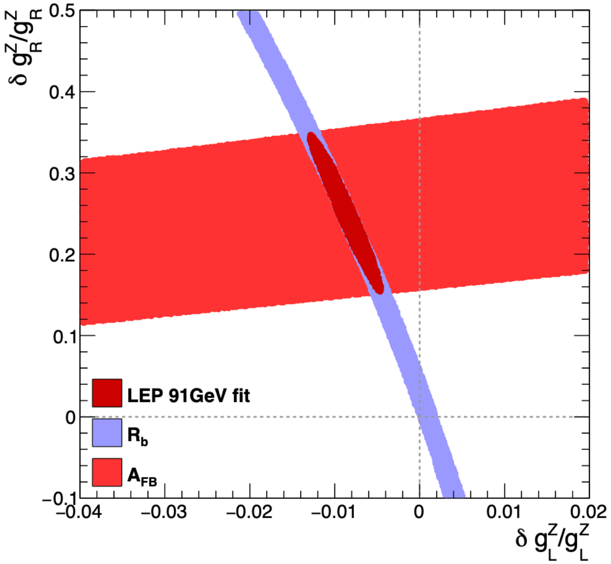
the full Higgs / top / electroweak program requires polarised beams & E_{CM} up to at least 1 TeV

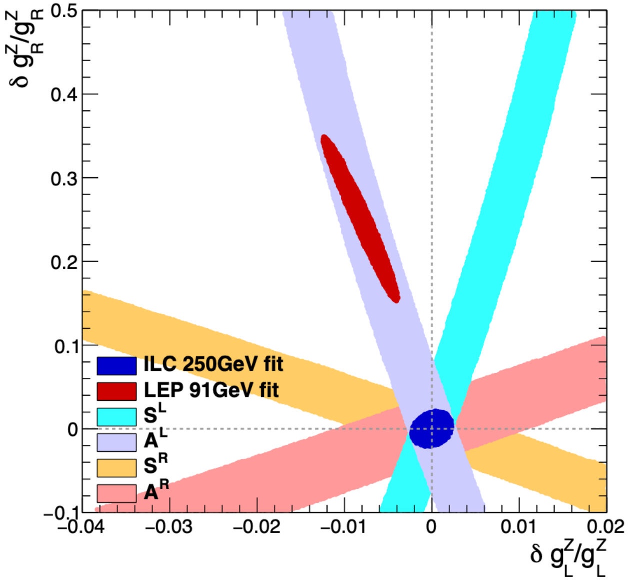
- Machine s… for specific processes
  - Centre-of-Mass energy
  - Beam polarisation (straightforward at linear colliders)

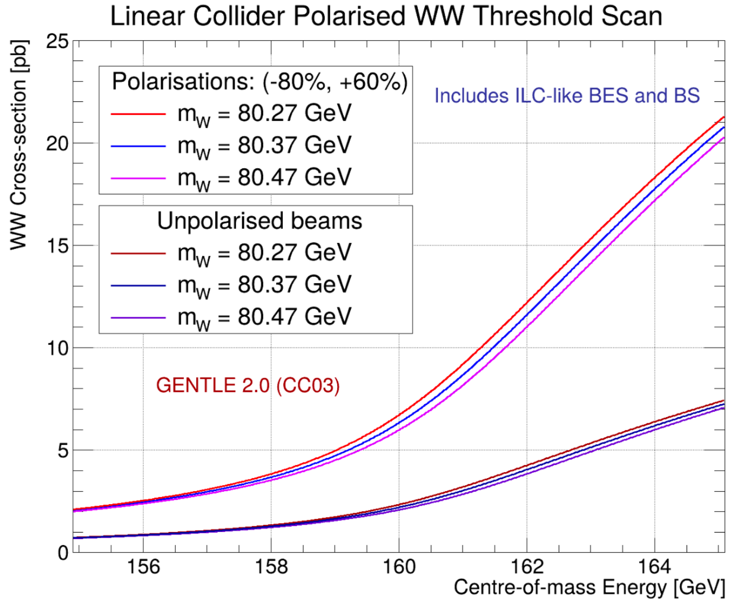
$$\sigma_{P,P'} = \frac{1}{4}\left[(1 - PP')(\sigma_{LR} + \sigma_{RL}) + (P - P')(\sigma_{RL} - \sigma_{LR})\right]$$

- **Drastic reduction of background through beam polarisation** → facilitates BSM searches

Beam Polarisation







- Example electroweak couplings
  - More observables for constraints
  - “Four machines in one”
- Example WW threshold
  - Much sharper rise at threshold
  - Enhanced sensitivity to W mass

Future Projects – Linear Colliders

Linear Collider Vision

HALHF and PWA

Linear Collider Facility - LCF

- Linear Colliders would cover in a staged approach centre-of-mass energies between the Z-pole until multi-TeV
- Polarised beams
- Documents for all proposals see backup

LCVision – A Unified approach

Linear Collider Vision

LCWS2024: Linear Colliders teaming up in view of the upcoming EPSSU

- **all linear colliders share the same scientific goals:**
  - formulate a coherent physics program
  - define energy stages etc science-driven
- **beyond an individual technology:**
  - design a linear collider *facility*
  - infrastructure compatible with various technologies
  - plus beam-dump / fixed-target exp's / R&D facilities
- **study the Higgs now - but maintain flexibility for the future:**
  - start now with an *affordable* project
    - maintain scientific diversity
    - strengthen accelerator R&D towards 10 TeV pCoM collider
  - decide on upgrades / new projects based on future developments - or even break-throughs:
    - scientifically: HL-LHC could still discover new particles
    - technologically: higher gradients / muon cooling / high-field magnets

LCVision and the ESPPU

from [the remit of the European Strategy Group]

- The aim of the Strategy update should be
  - to develop a visionary and concrete plan
  - that greatly advances human knowledge in fundamental physics
  - through the realisation of the next flagship project at CERN.
- The Strategy update should include
  - the preferred option for the next collider at CERN
  - and prioritised alternative options to be pursued if the chosen preferred plan turns out not to be feasible or competitive.

In order to receive full attention for the LCVision idea:
complement a generic, site-independent concept with
a concrete proposal for a
Linear Collider Facility (LCF) @ CERN

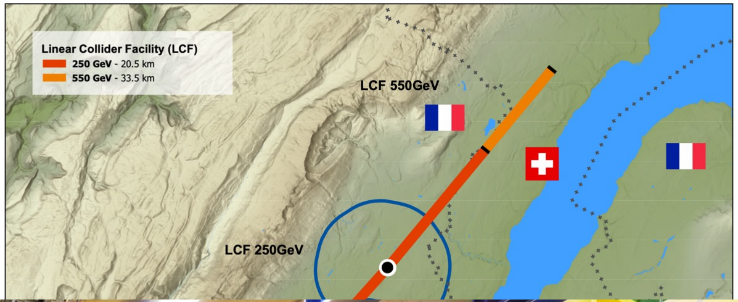
General Considerations

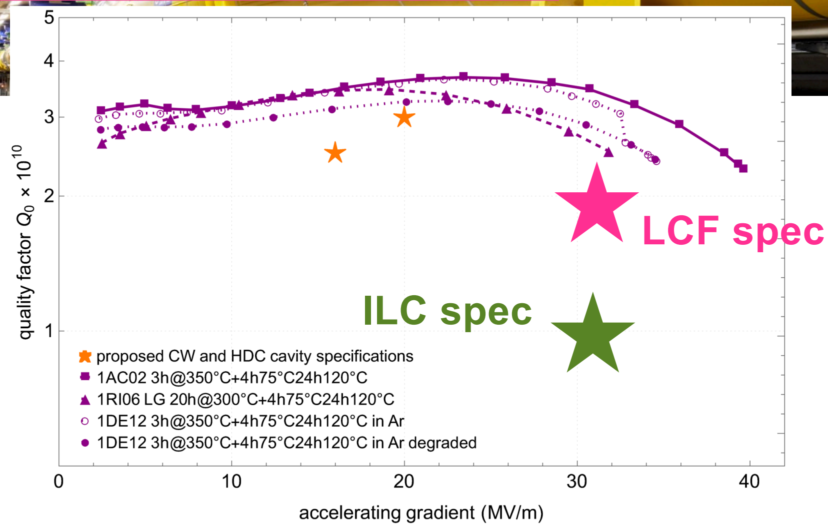
for the LCF@CERN

- Philosophy:
  - leverage all the excellent work done for ILC & CLIC in the past
    - reliable costing etc
    - “ready to build”
  - gently modernize to turn into true flagship project for CERN
- Superconducting RF technology (like ILC)

The LCF in 2025 is NOT the ILC as planned in Japan in 2016

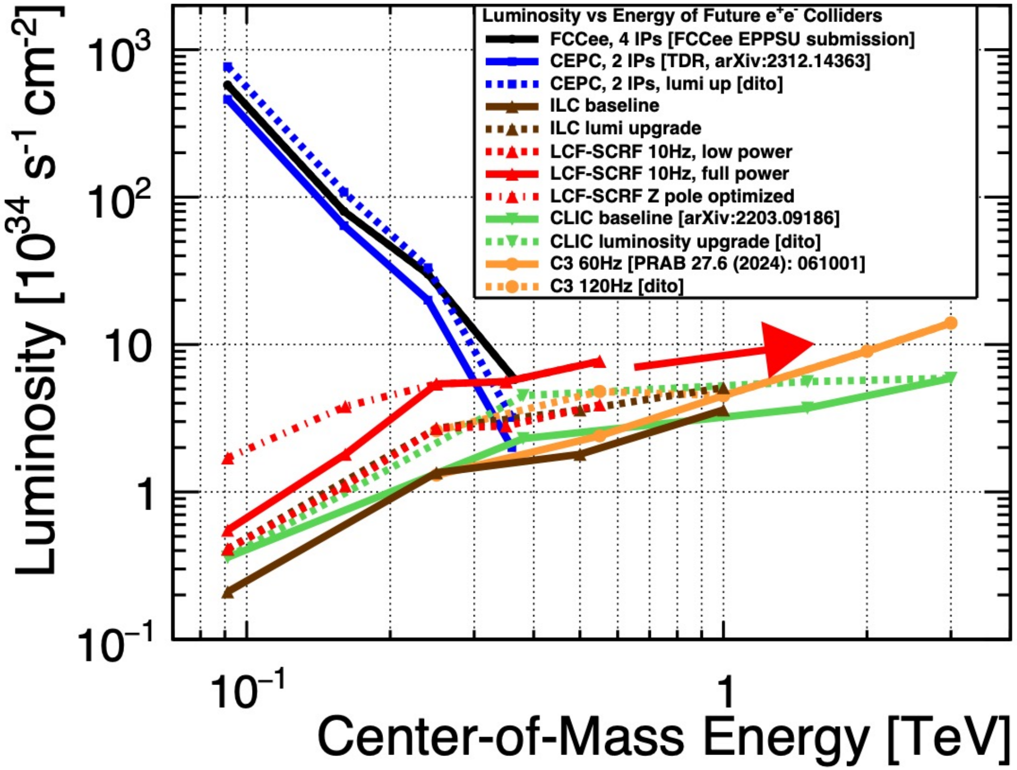
  - lab experience and production capacities in industry globally => opportunity to take burden off CERN’s shoulders
  - choice for fastest implementation
- Scope project to be a flagship project for CERN
  - **2 interaction regions**
  - higher luminosity than ILC (possible due to Q_0=**2**E10)
  - add-on facilities (Beyond Collider, R&D / irradiation facilities)
  - attaractive upgrade perspectives with advanced technologies
  - but stay affordable, wrt to CERN budget

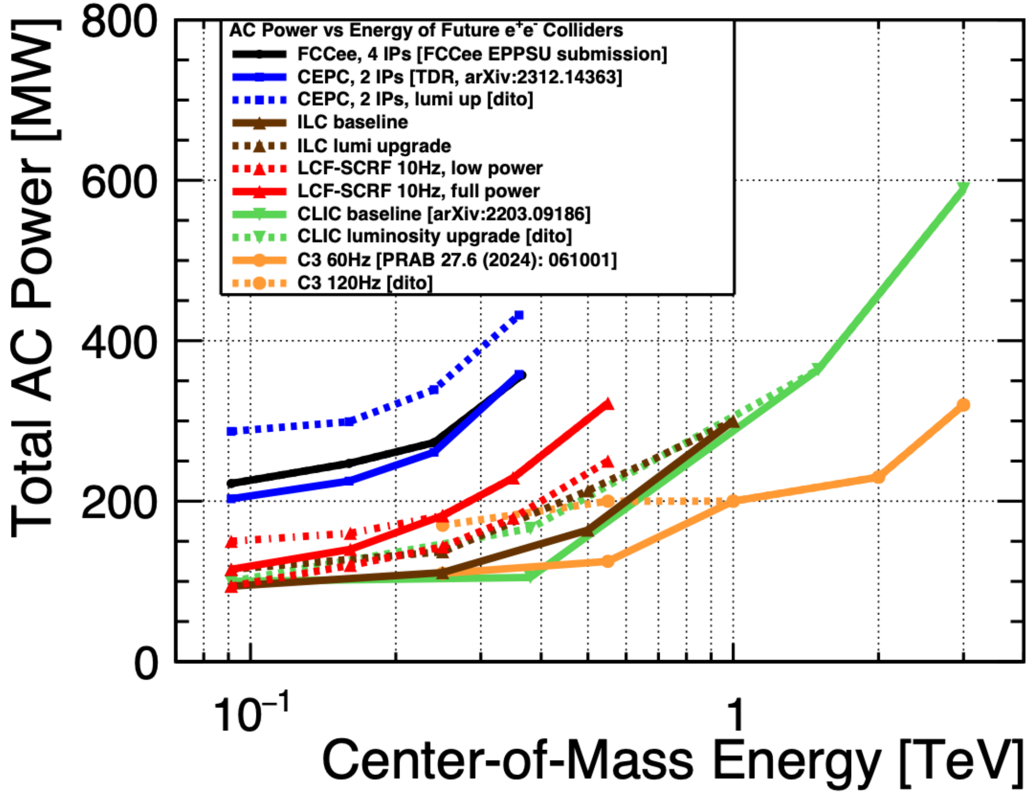




Linear Collider Vision

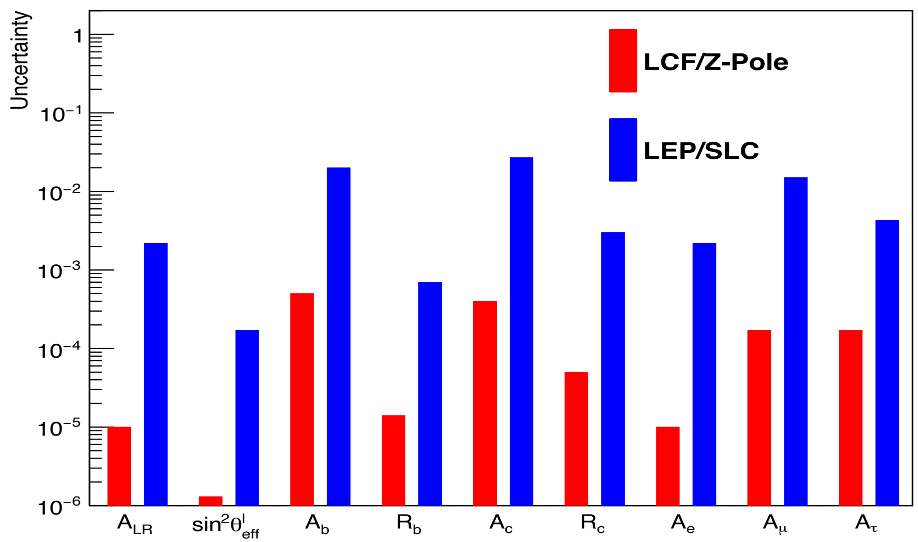
For LCF-SCRF and other e+e- colliders





Linear Collider Vision

Electroweak Precision Observables

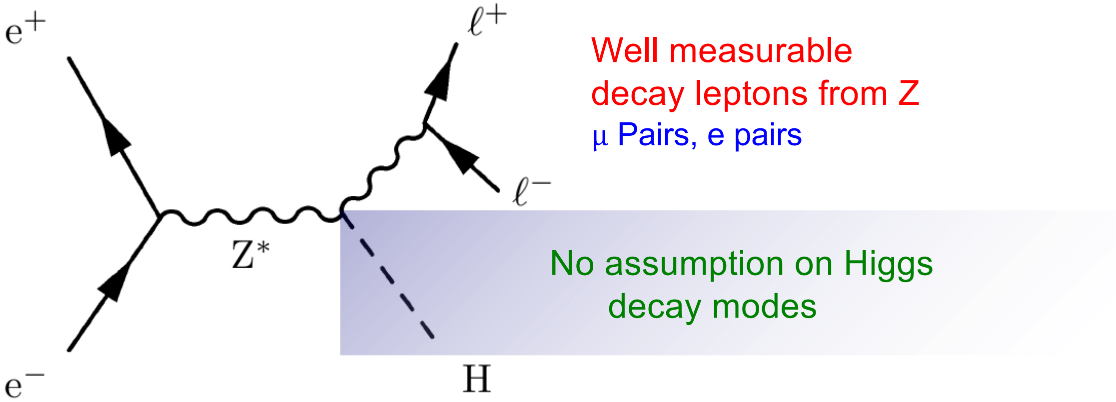


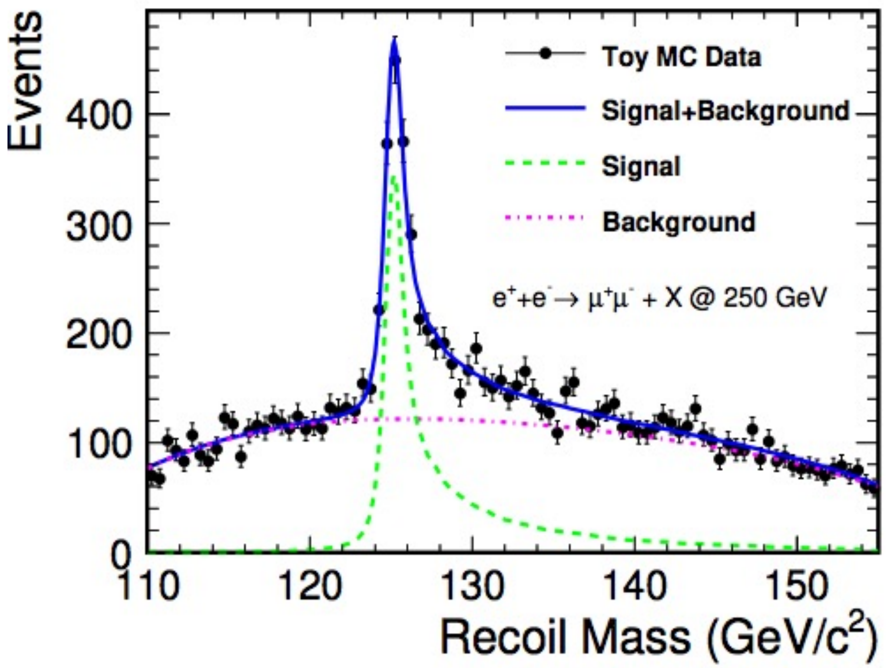
- LCF foresees a running on the Z Pole
  - Necessary for interpretation of results above pole
- A WW threshold run is possible if needed
- Baseline for Z-Pole running is 100 fb-1 = 5×10^9 Z
  - 800 fb^{-1} in a reasonable time seem to be feasible
- Significant improvement compared with LEP and SLC
  - e.g. $\Delta\sin^2\theta_{eff} \sim 10^{-6}$
- For asymmetries error on polarisation limits precision
  - Possible to overcome but requires work (experts at IJCLab)
- In general treament of systematics is important topic for ESPPU

Quantity	SM Value	Current Precision	Prospect Snowmass 2021		Prospect ESPPU 2026	
		$\delta[10^{-4}]$	$\delta_{stat.}[10^{-4}]$	$\delta_{sys.}[10^{-4}]$	$\delta_{stat.}[10^{-4}]$	$\delta_{sys.}[10^{-4}]$
M_W[GeV]	80.379	1.5	-	-	<0.1	0.2
M_Z[GeV]	91.1876	0.23		0.022	0.016	
Γ_Z[GeV]	2.4952	9.4	0.5	-	0.07	
Γ_Z (had.)[GeV]	1.7444	11.5		4.		

Higgs-strahlung at lepton colliders

- Powerful channel for unbiased tagging of Higgs Events
- Absolute normalisation of Higgs couplings
- Sensitivity to invisible Higgs decays



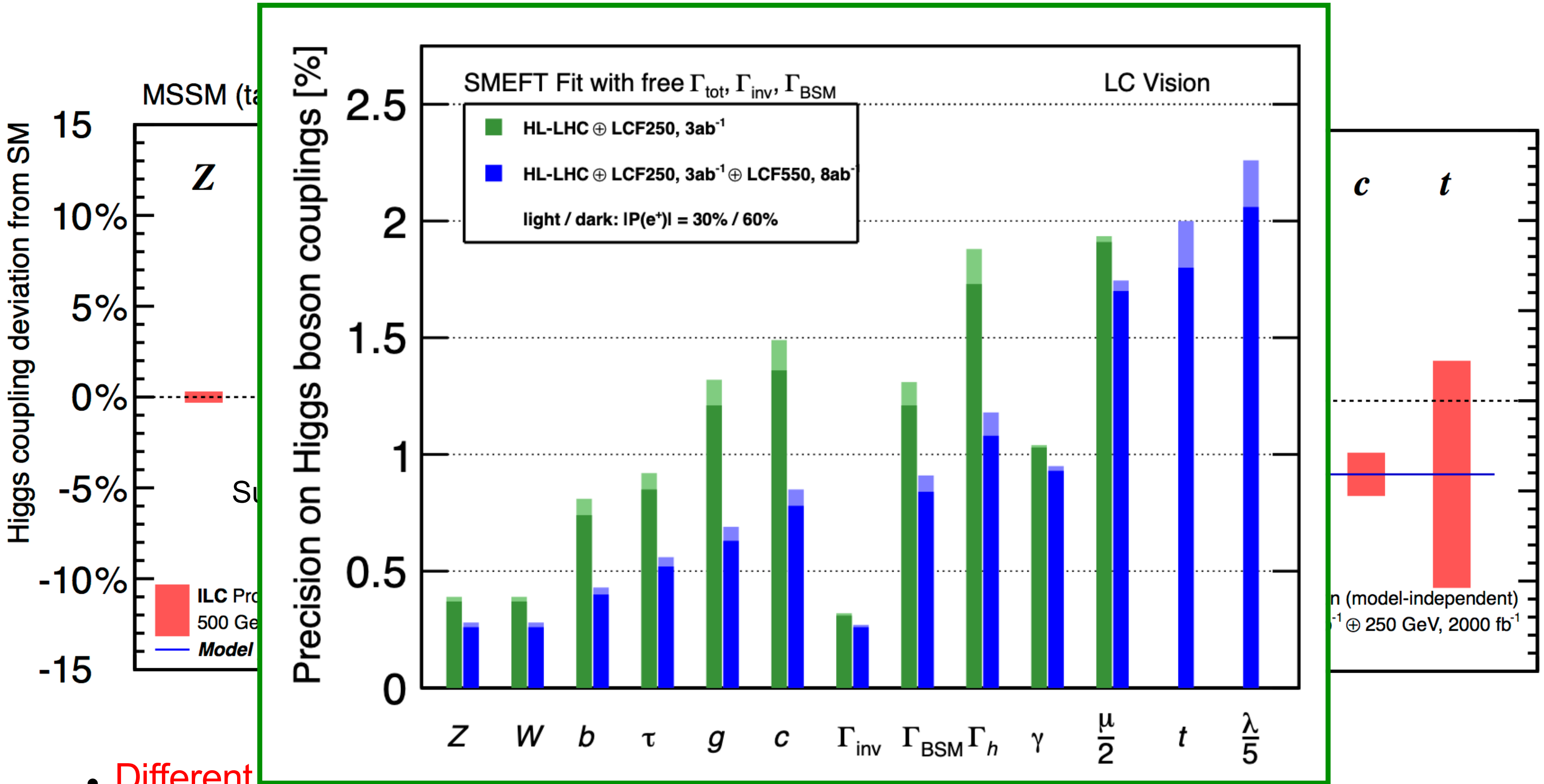


Higgs Recoil Mass: $M_h^2 = M_{recoil}^2 = s + M_Z^2 - 2E_Z\sqrt{s}$

- Clean and sharp peak in Z recoil spectrum
- Illustrates precision that can be expected from e+e- colliders

Precision matters ...

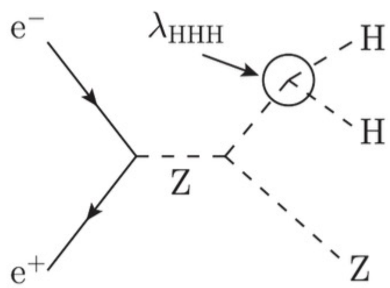
- Example for illustration: Coupling precision after full LCF programme



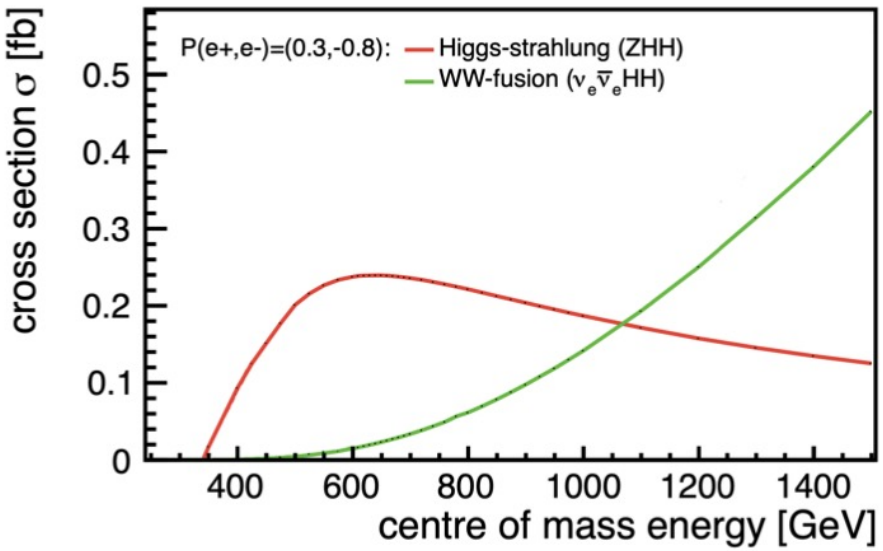
- Different new physics models lead to different patterns

Higgs Self Coupling measurement - Ingredients to cross section

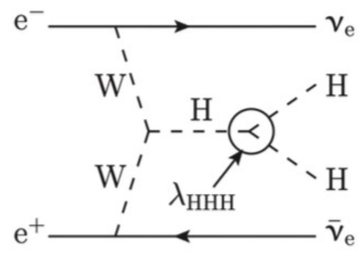
Di-Higgsstrahlung



Dominates below 1 TeV

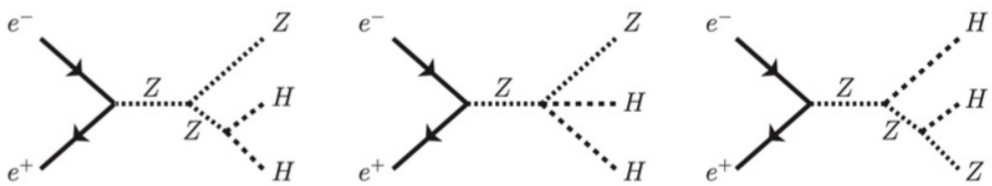


WW Fusion

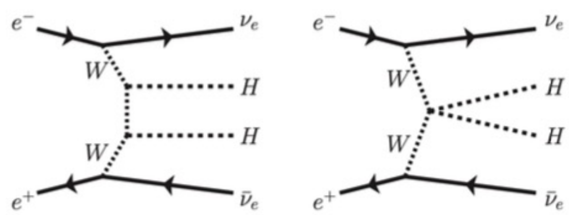


Dominates above 1 TeV

Constructive Interference



Destructive Interference



[Slide from Julie Munch Torndal]

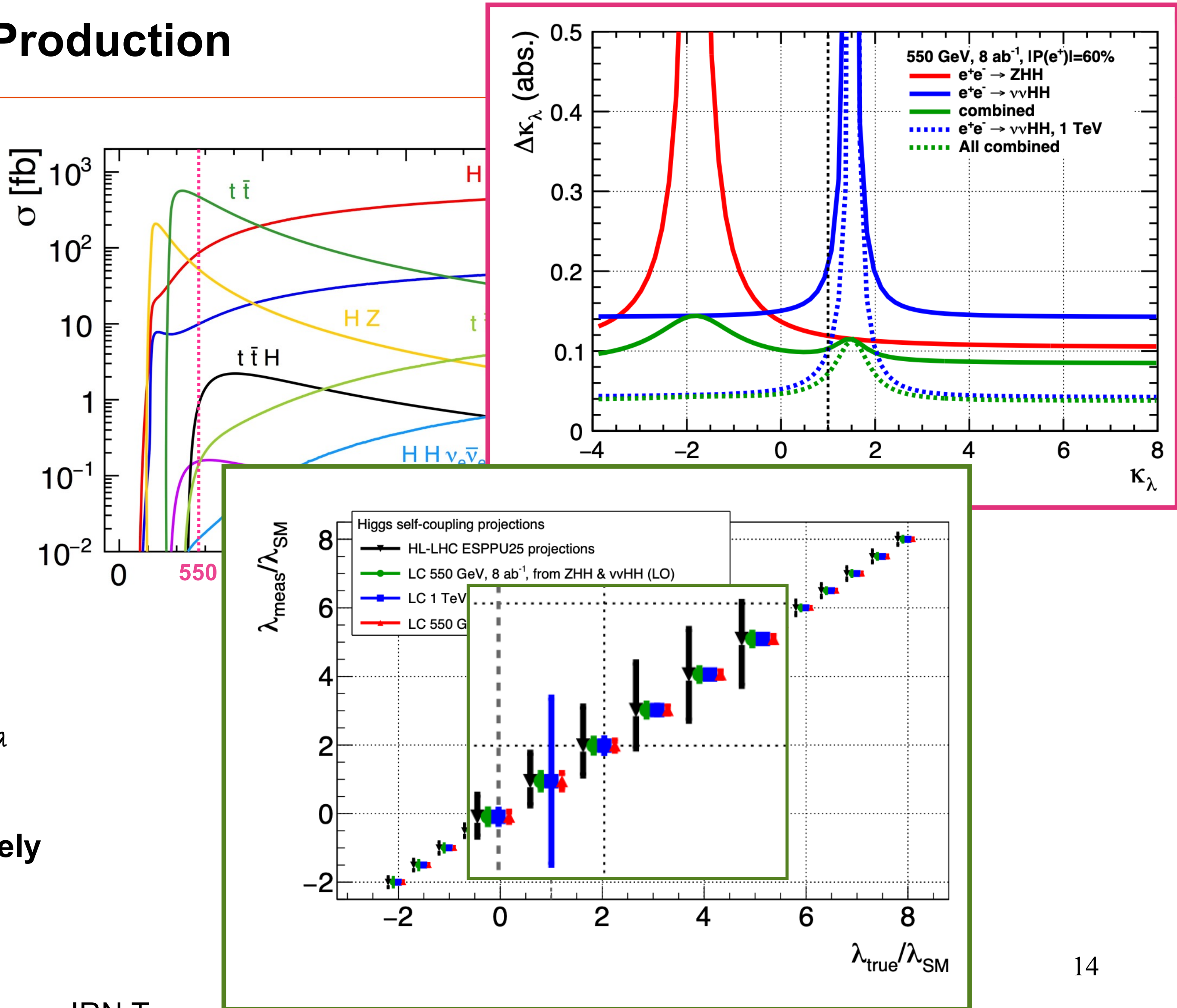
Di Higgs Production

- tree-level access to self-coupling
  - **550 GeV**
    - ~ peak of ZHH cross-section
    - vvHH becomes just about visible

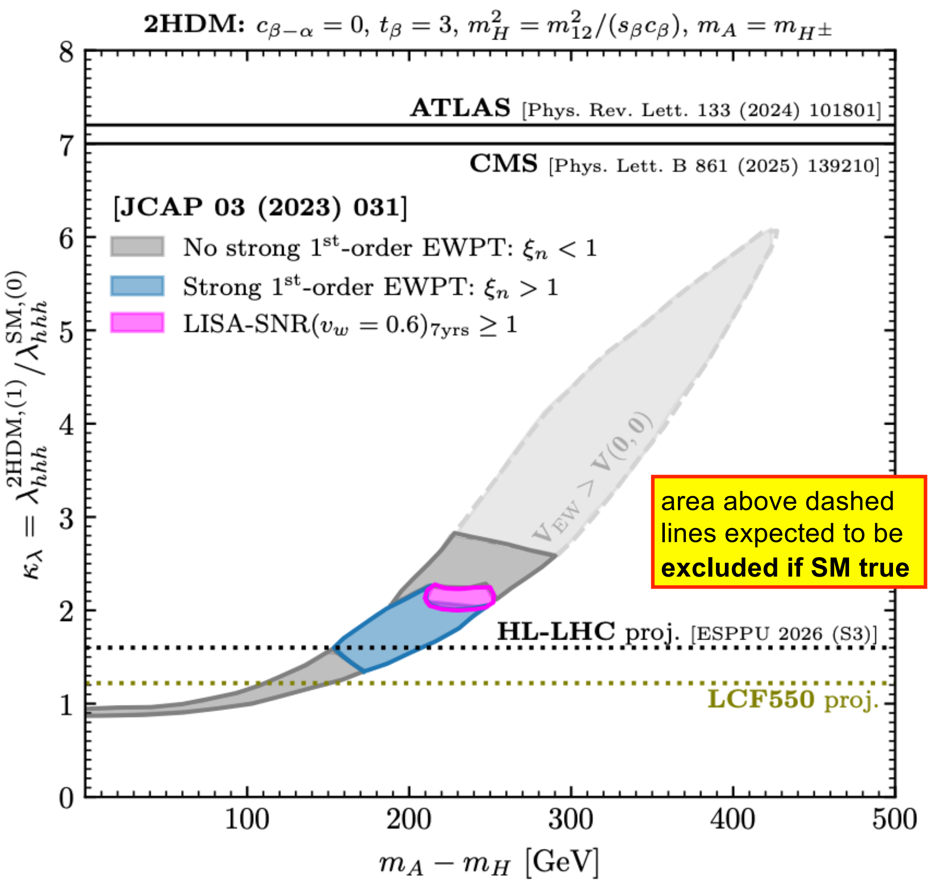
    - together for SM case:
      $\Delta\kappa_\lambda$ = 11% (15%) for **8ab^{-1}** (4ab^{-1})
  - **dependence on λ:**
    - ZHH: **constructive** interference
    - vvHH: **destructive** interference
    - **together**: ~const absolute precision as function of λ
  - **1-3 TeV:** vvHH becoming dominant

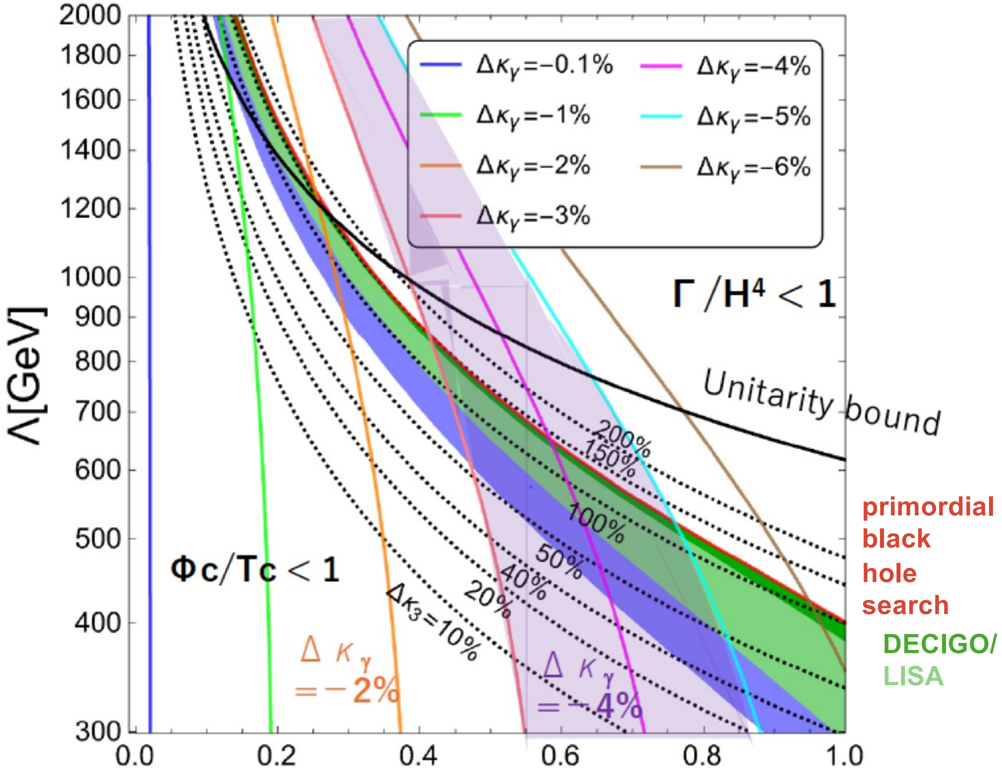
    - $\Delta\kappa_\lambda$ = 0.04 (8ab-1) over wide range of κ_λ (except κ_λ ~ 1.5)

  - **quantitative improvement and qualitatively new information wrt HL-LHC**



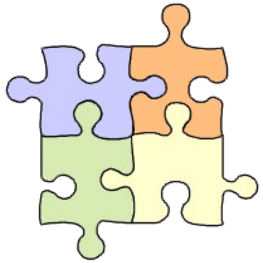
Interplay with gravitational waves





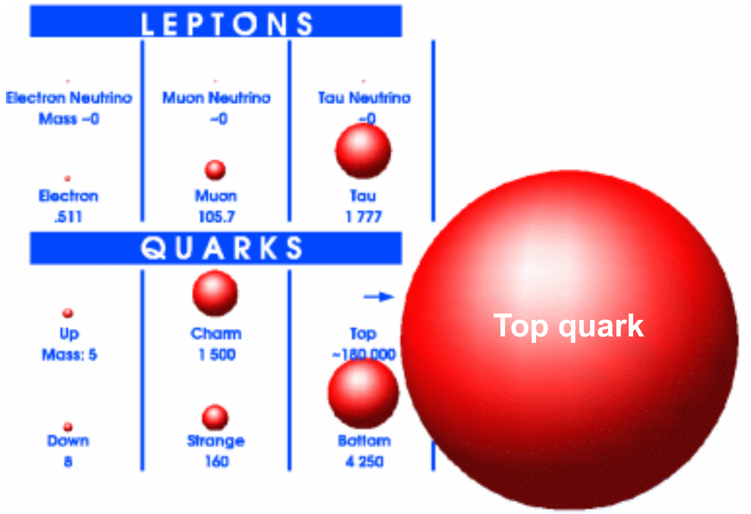
Phys.Lett.B 856 (2024) 138940

An enigmatic couple



Elementary Scalar?

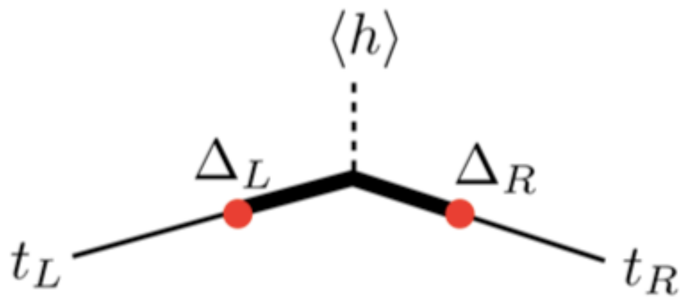
Composite object?



- Higgs and top quark are intimately coupled!
  Top Yukawa coupling O(1) !
  => Top mass important SM Parameter (-> backup)

- New physics by compositeness?
  Higgs <u>and</u> top composite objects?

- Future colliders perfectly suited to decipher both particles

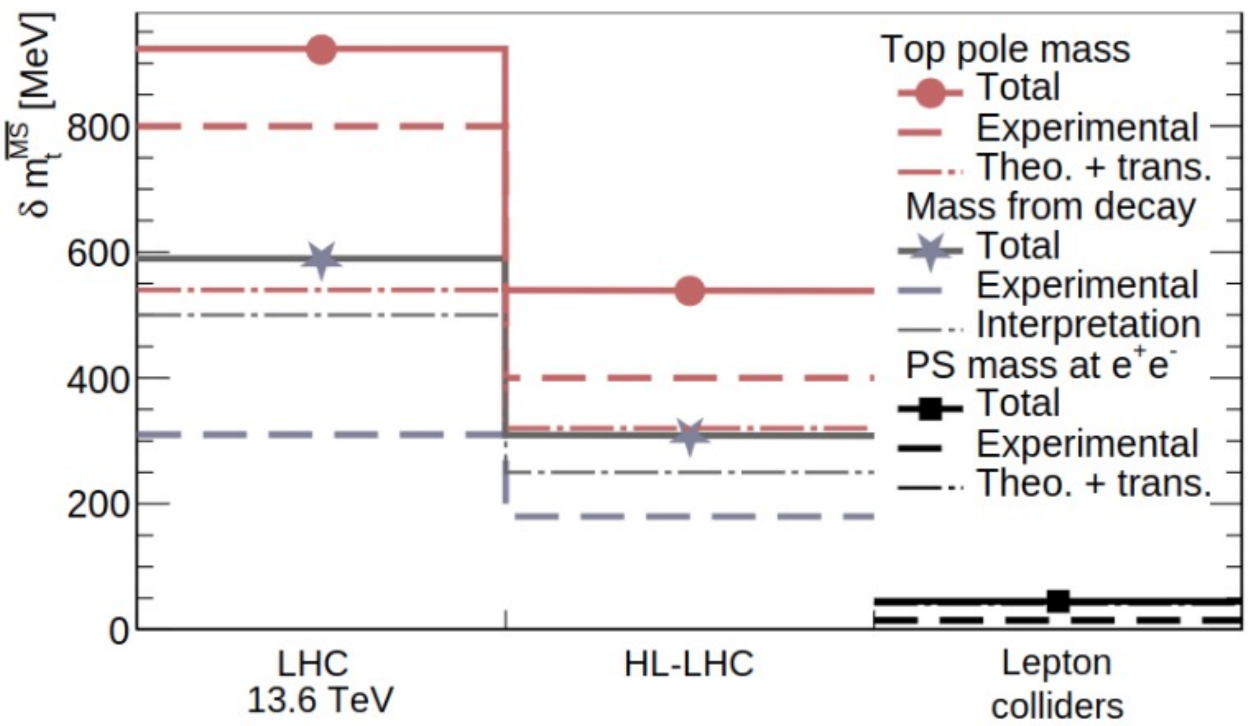


Courtesy of S. Rychkov

Top Mass Summary

Linear Collider Vision

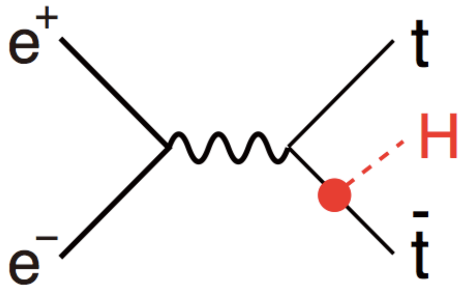
Snowmass report, arXiv:2209.11267



All future lepton (e+e- colliders) will improve considerably the precision on m_{top}

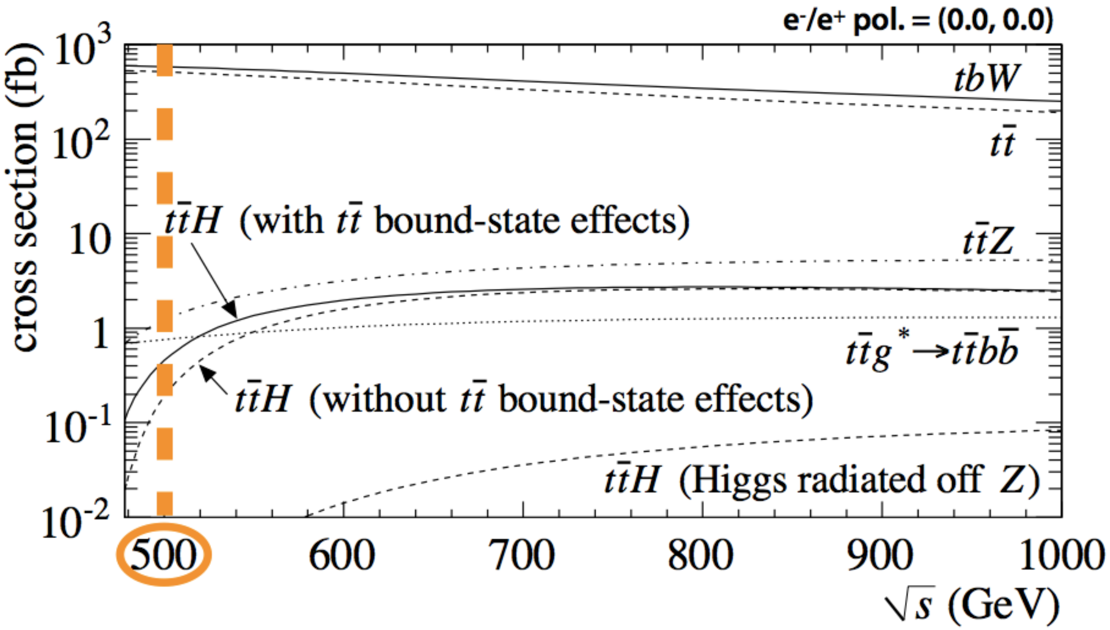
Marcel Vos@Top23

Top Yukawa Coupling – e+e-



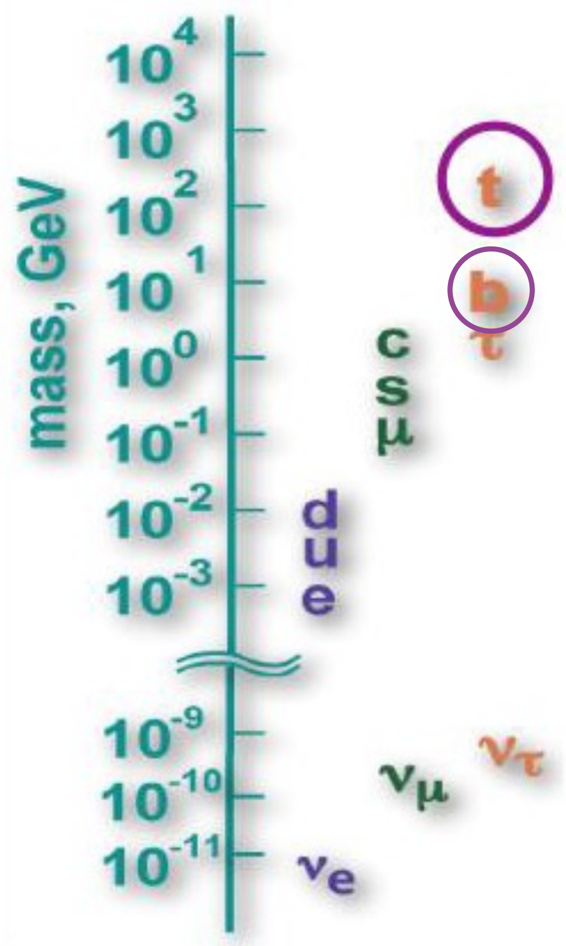
- Coupling of Higgs to heaviest particle known today

- Up to eight final state jets



√s[GeV]	550	1000	1400
L[ab-1]	4	8	2
δyt/yt[%]	2.8	1.0	2.7

Fermion Hierarchy



- SM does not provides no explanation for mass spectrum of fermions (and gauge bosons)

- Fermion mass generation closely related to the origin electroweak symmetry breaking

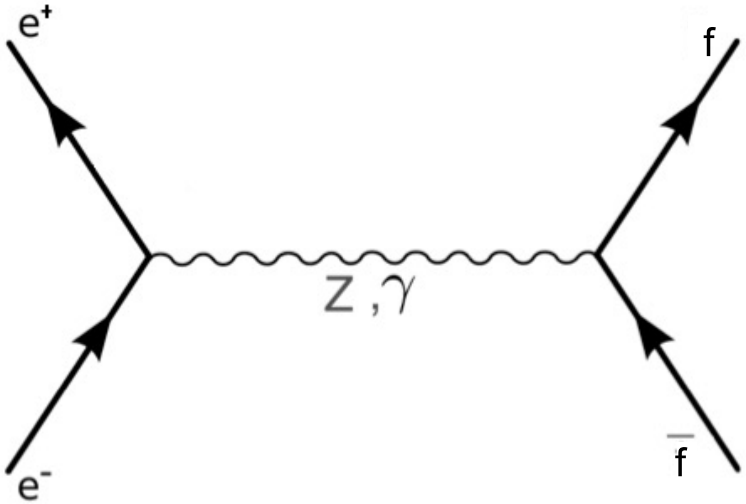
- Expect residual effects for particles with masses closest to symmetry breaking scale

$$\begin{pmatrix} t \\ b \end{pmatrix}_L$$

- Heavy quark effect or effect on all fermions?

Strong motivation to study chiral structure of (heavy) quark vertices

Two fermion processes



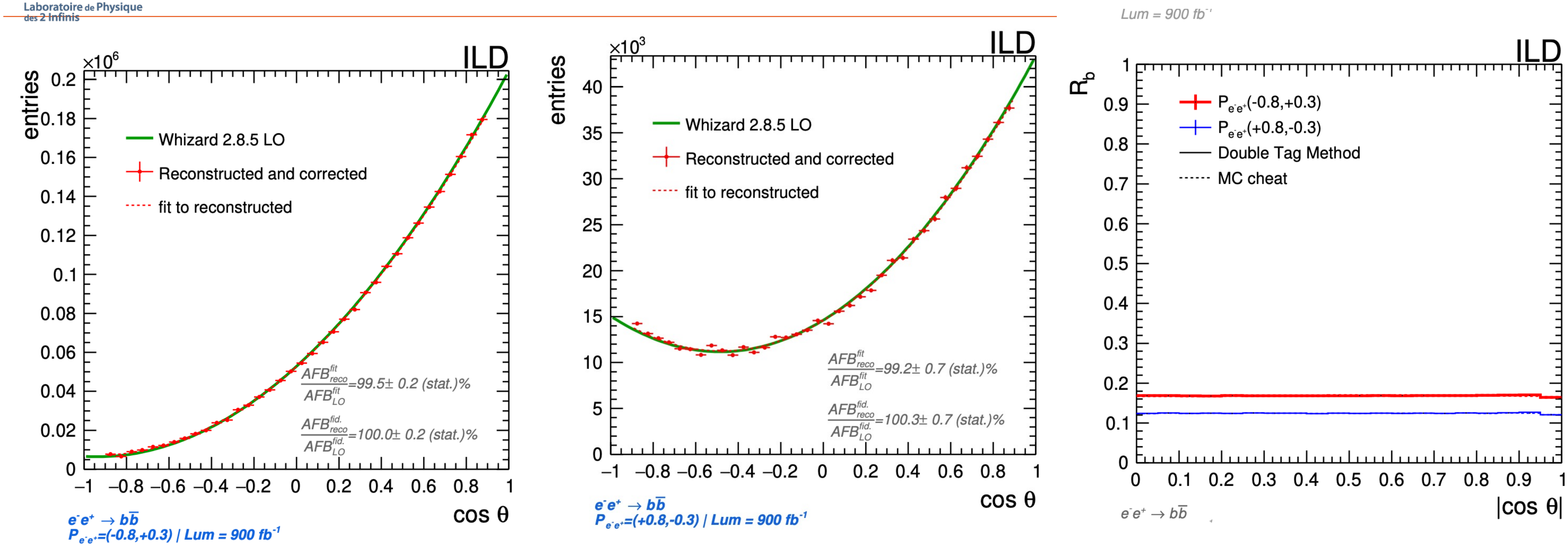
$$\frac{d\sigma}{d\cos\theta}(e^-_L e^+_R \to f\bar{f}) = \Sigma_{LL}(1+\cos\theta)^2 + \Sigma_{LR}(1-\cos\theta)^2$$

$$\frac{d\sigma}{d\cos\theta}(e^-_R e^+_L \to f\bar{f}) = \Sigma_{RL}(1-\cos\theta)^2 + \Sigma_{RR}(1+\cos\theta)$$

*add term ~$\sin^2\theta$ in case of non-relativistic fermions e.g. top close to threshold

- Σ_{IJ} are helicity amplitudes that contain couplings g_L, g_R (or F_V, F_A)
- $\Sigma_{IJ} \neq \Sigma_{I'J'}$ => (characteristic) asymmetries for each fermion
- Forward-backward in angle, general left-right in cross section
- **All four** helicity amplitudes for all fermions **only available with polarised beams**
- **LC would be four colliders in one!**

ee→bb at 250 GeV



- Powerful tool to study onset and amplification of new physics effects
- Full simulation study at 250 GeV is solid basis for estimations on Z pole (A_b, R_b)
- Interpretation in terms of new physics (Z' up to 19 TeV in case of GHU) require precise input from Z pole
- Study has been extended to 500 GeV, 1 TeV

A. Irles et al.
https://arxiv.org/pdf/2306.11413

Interpretation of two fermion processes

Separation power in GHU Models

J. P. Marquez et al. (arxiv:2403.09144)

ILD

GHU vs SM discrimination power (σ-level)

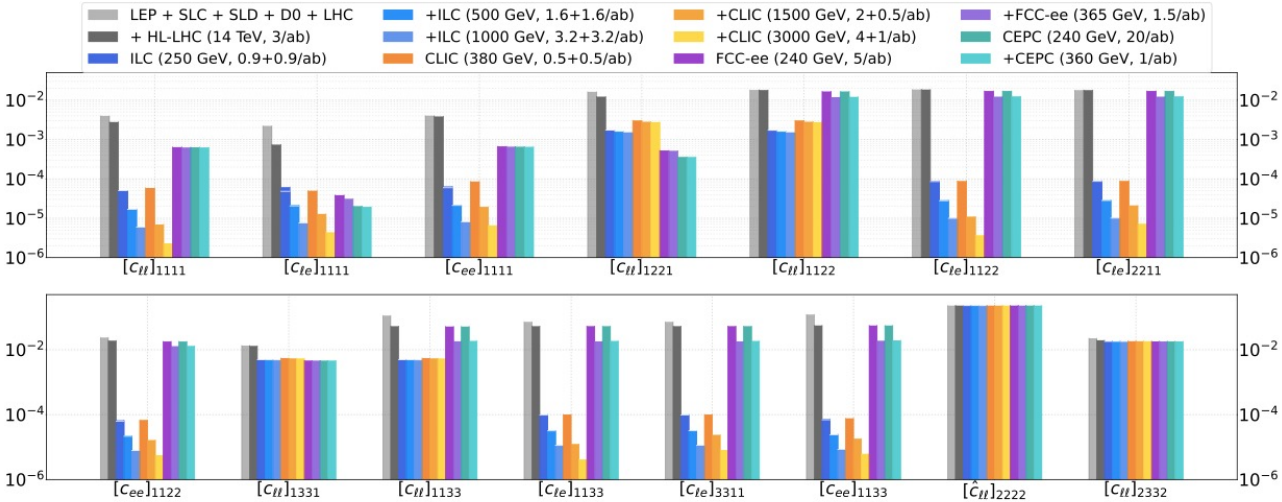
$m_{Z_1'}$ [TeV]		ILC250♦ (no pol.) C	R	Z	ILC250 C	R	Z	ILC250 +500 C	R	Z	ILC250 +500 +1000* C	R	Z
19.6	B_3^+	0.1	0.5	0.5	0.1	0.7	0.8	0.5	1.3	1.3	1.6	2.5	2.5
19.6	B_3^-	0.1	0.5	0.5	0.3	0.9	0.9	0.9	2.7	2.7	3.3	6.7	6.8
14.9	B_2^+	0.2	0.8	0.8	0.3	1.5	1.6	0.9	2.2	2.3	3.0	4.4	4.5
14.9	B_2^-	0.2	0.7	0.7	0.5	1.4	1.5	1.7	4.6	4.8	6.3	>10	>10
10.2	B_1^+	0.3	1.7	1.7	0.7	3.2	3.5	1.5	4.4	4.7	4.3	6.8	7.0
10.2	B_1^-	0.5	1.4	1.4	0.9	2.7	2.8	3.3	9.6	9.9	>10	>10	>10
8.5	A_2	0.6	3.5	3.6	0.9	4.8	5.3	4.3	>10	>10	>10	>10	>10
7.2	A_1	0.8	4.1	4.3	1.0	5.0	5.5	5.3	>10	>10	>10	>10	>10

Z-fermion couplings
- *C: Current precision*
- *R: ILC250 (Rad. Ret.)*
- *Z: Giga-Z*

< 3 σ | 3-4 σ | 4-5 σ | > 5 σ

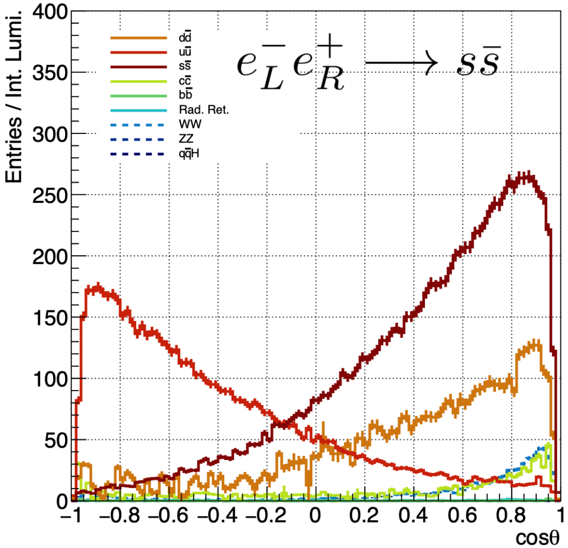
Probed mass scale: 9-25 TeV

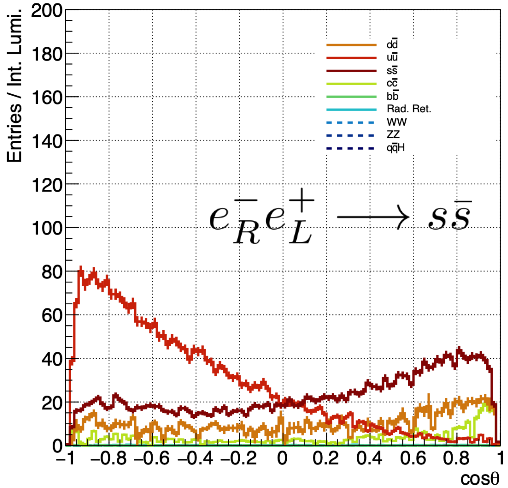
4-fermion operators in EFT (arxiv:2209.08078)



- Interpretation of 2f results bears discovery potential
  - Will benefit from polarisation and higher energies
- Has to be vetted regularly against (HL-)LHC results

Interpretation of two fermion processes

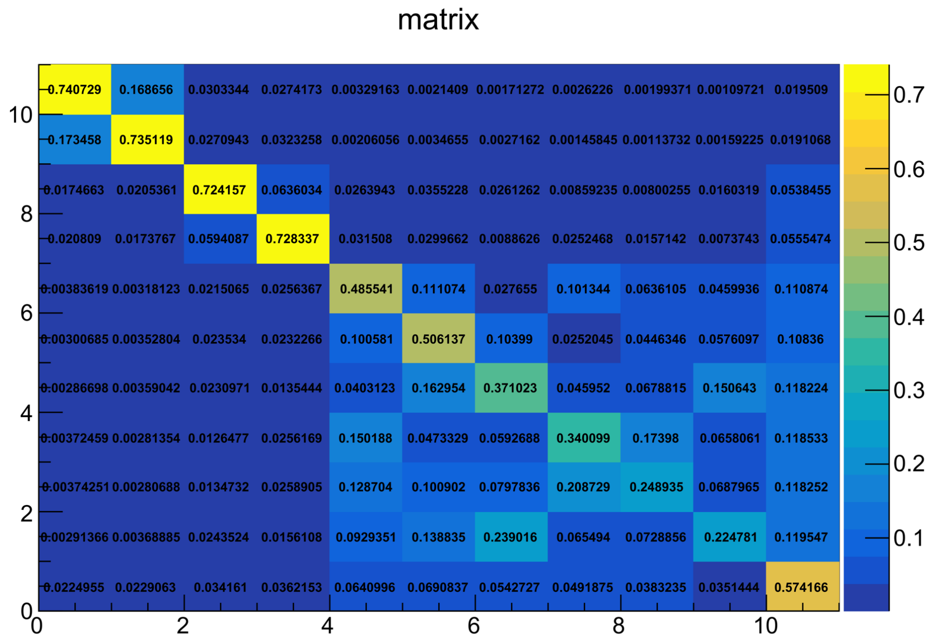


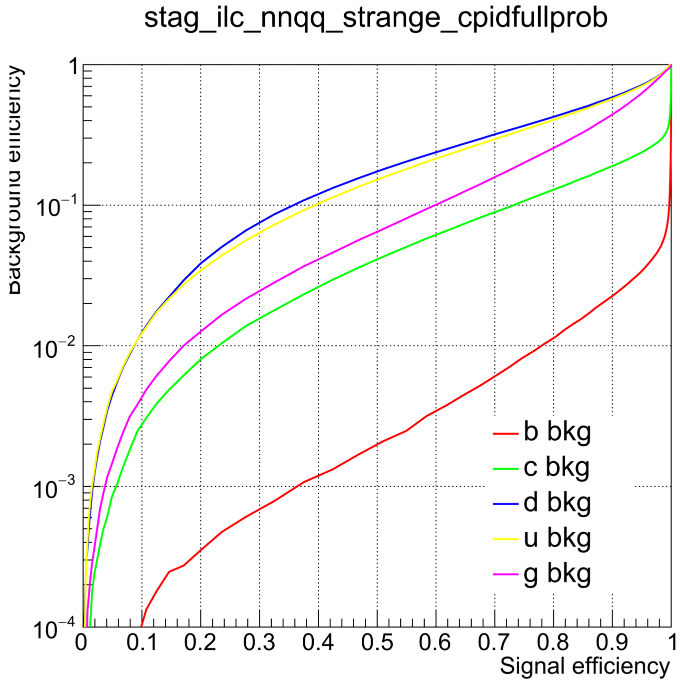


- PhD thesis of Yuichi Okugawa (IJCLab/Tohoku U, 2021-2024)
  - Polarisation (-80,+30): ΔR_s = 0.9%, $\Delta A_{fb,s}$ = 0.9%
  - Polarisation (+80,-30): ΔRs = 1.6%, $\Delta A_{fb,s}$ = 5.9%
  - Statistical error only
  - Systematic error sensitive to knowledge of background
- Analysis based on leading particle
  - "hand made cuts" to understand effect of potential selection criteria
  - Some cuts are very harsh
  - Therefore selection effiency is low (0.6%) and S/B ~ 1
    - u,d final states with Kaons cannot be well suppressed

- Analysis needs revision

Interpretation of two fermion processes

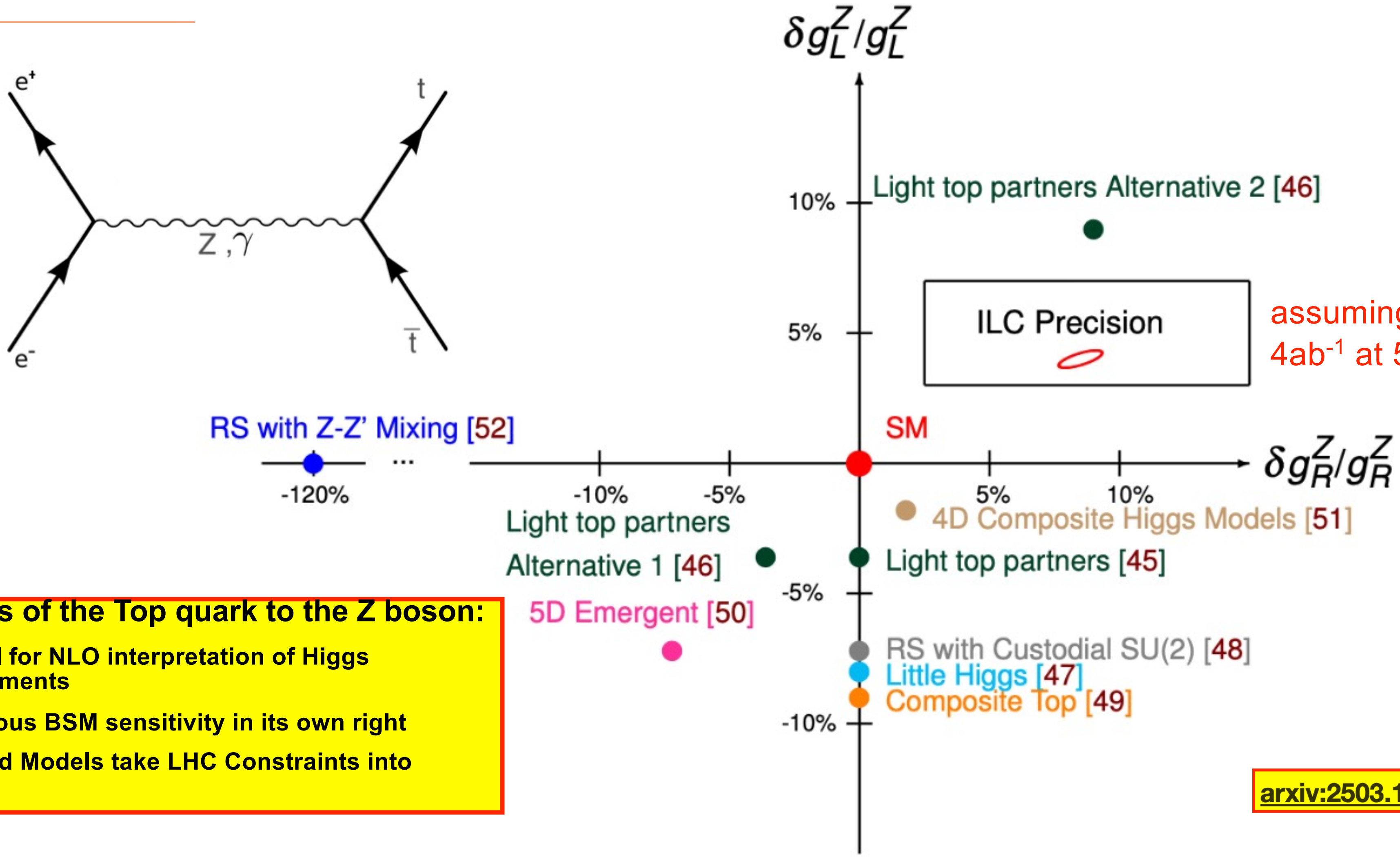




- Considerable progress in flavor tagging in recent years ...
- Mouthwatering opportunities for light quarks
- e.g. Background down to 10^{-2} at 10% efficiency
- For this working point statistical error would go down to
  - Polarisation (-80,+30): ΔR_s = 0.22%, $\Delta A_{fb,s}$ = 0.22%
  - Polarisation (+80,-30): ΔR_s = 0.4%, $\Delta A_{fb,s}$ = 1.5%
- Systematics due to background could be ~statistical error
- Remains to be shown, other systematics may set in -> TYL/FJPPN project!

T. Suehara

Top quark and new physics



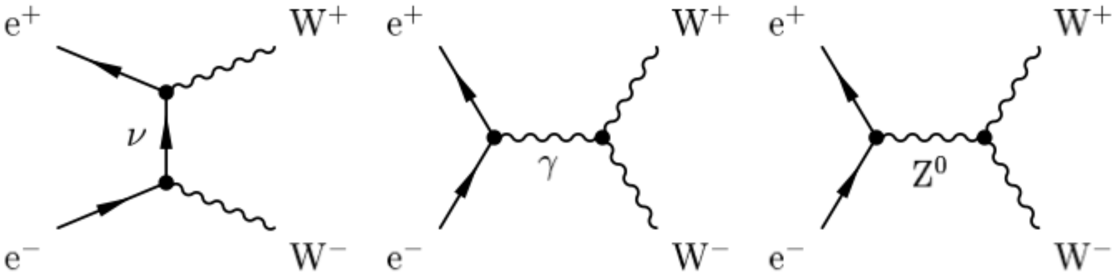
assuming only
$4ab^{-1}$ at 500 GeV

Couplings of the Top quark to the Z boson:

- **essential for NLO interpretation of Higgs measurements**
- **tremendous BSM sensitivity in its own right**
- **Displayed Models take LHC Constraints into account**

arxiv:2503.19983

WW Production at 250 GeV (and above)?

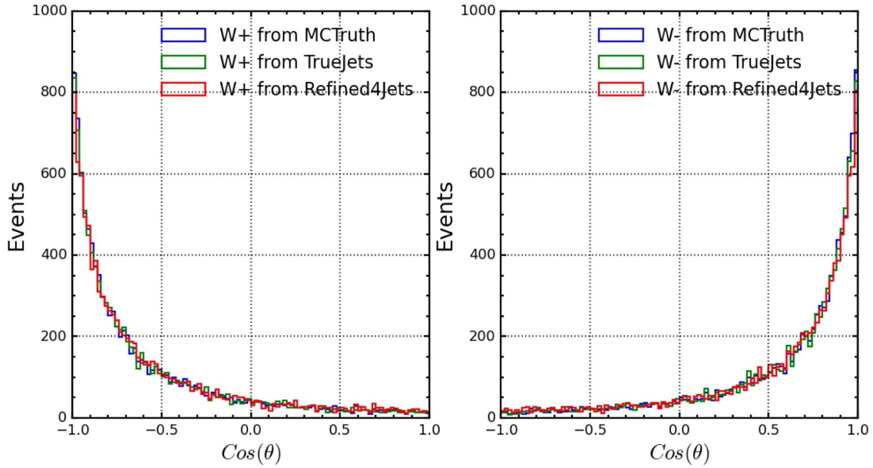


- Sensitivity to triple and quartic gauge Boson couplings (TGC and QGC)
- Observables depend strongly on beam polarisation

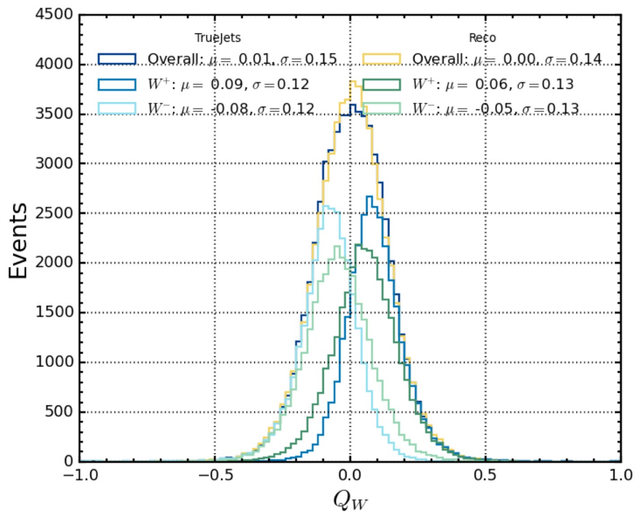
=> Enrich different helicity modes of W
=> Disentangling of couplings to Z and γ
=> in situ measurement of beam polarisation (and luminosity)

Analysis of fully hadronic final state (first steps)

The goal



W charges (true jets and measured)



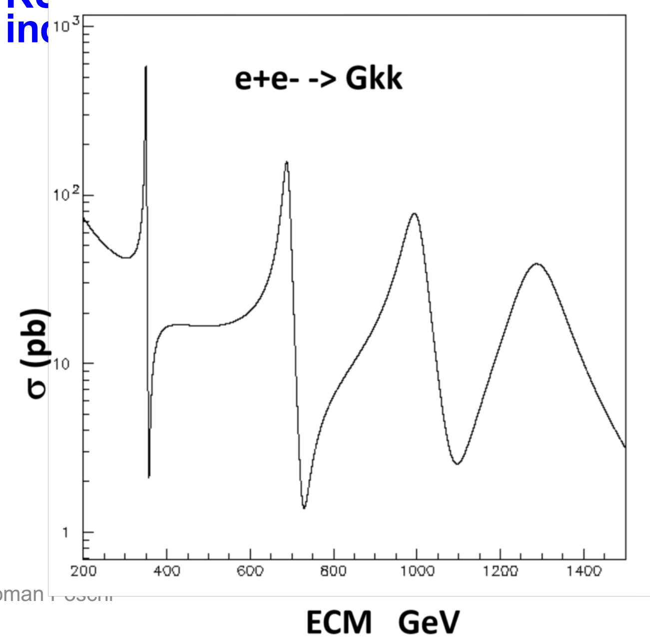
- Overlap leads to charge flips
- Correction compromised by correlation introduced by jet algorithm
- Improvement by Machine learning?

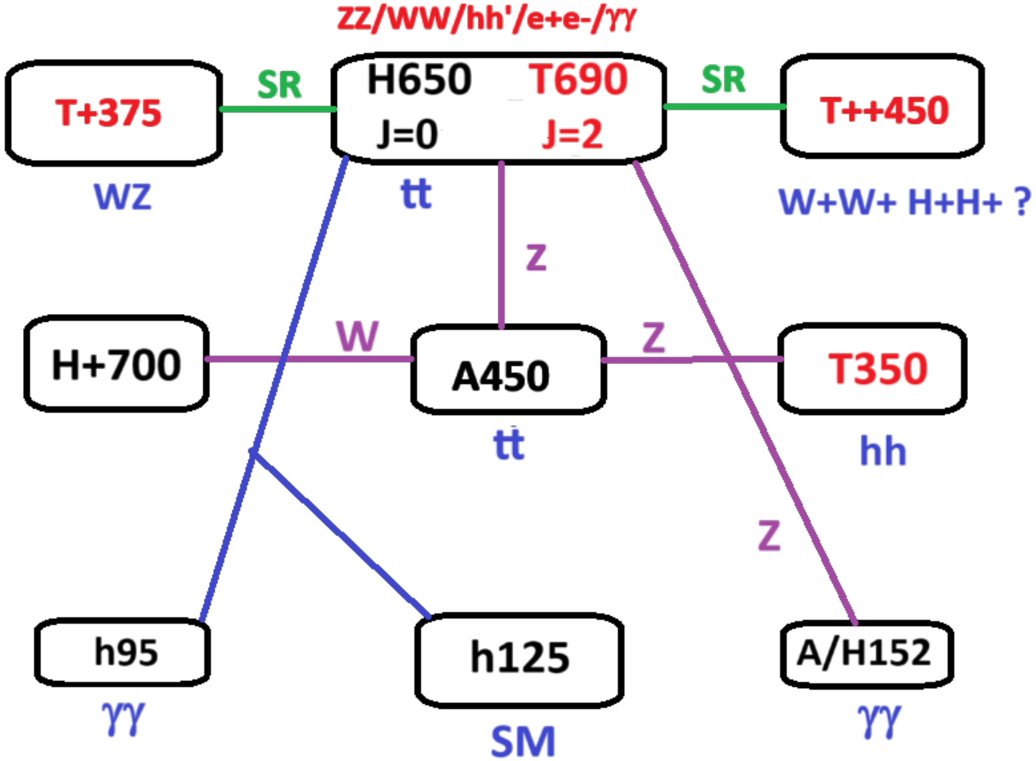
X. Xia, PhD Student

What if … LHC makes a discovery I?

- >> 5 sd Narrow resonance seen in top pairs by CMS
- Candidates: A(365), CP-odd toponium, KK graviton T(350) seen in hh
- T(690) a narrow resonance, 20 GeV wide, seen in ZZ/WW/h125h95/γγ/e+e- which could also be a KK graviton
- Combined significance > 5 sd
- A(450) indicated in ttZ, tt and T(350)Z->hhZ
- RU … these in…

Series of KK resonances at LCF?

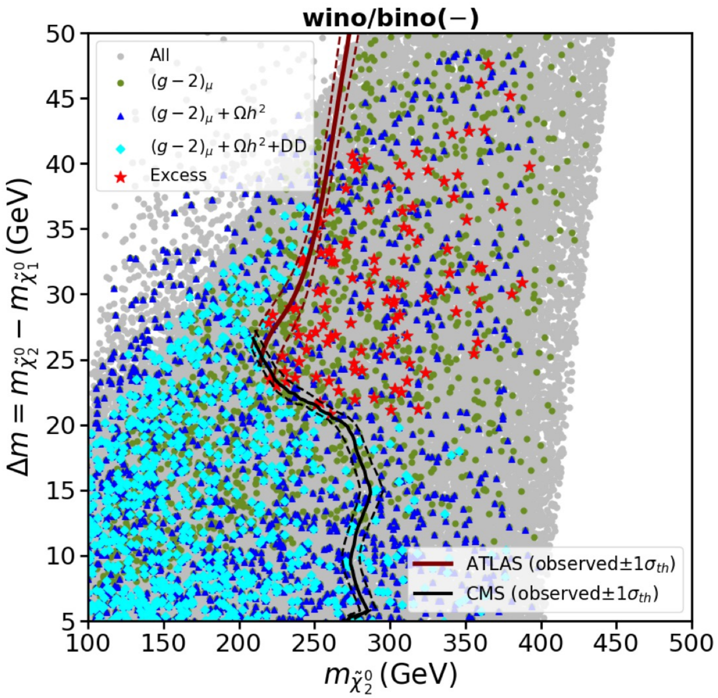


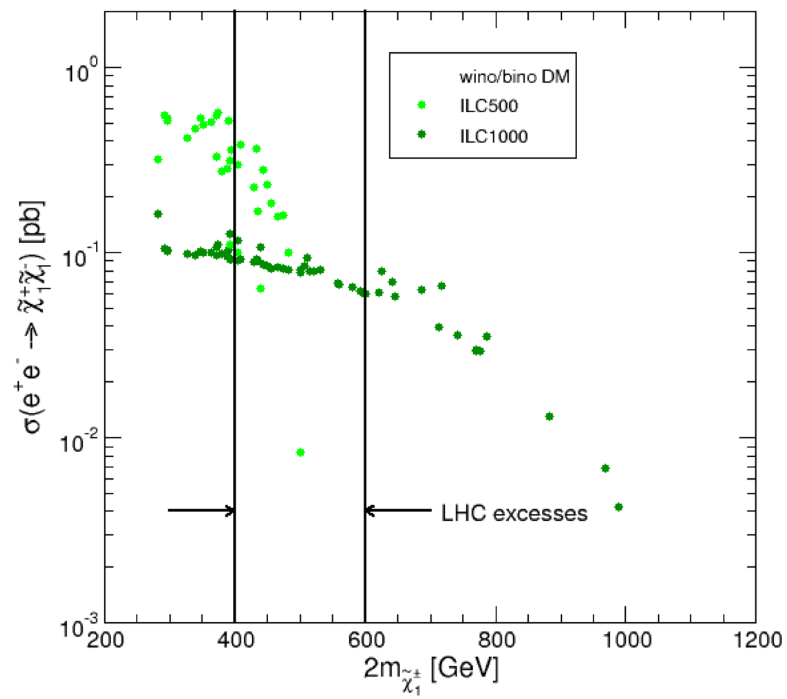


Slide provided by F. Richard

What if … LHC makes a discovery II?

Some excesses in "golden" EWino Channel at LHC $pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 Z^{(*)} \tilde{\chi}_1^0 W^{(*)}$





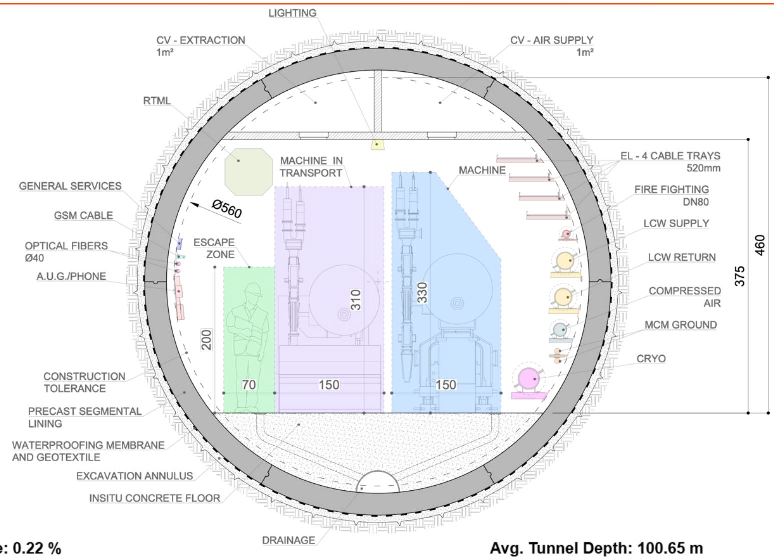
Parameter scan for Wino/Bino DM scenario
$\tilde{\chi}_1^0$ would be dark matter candidate

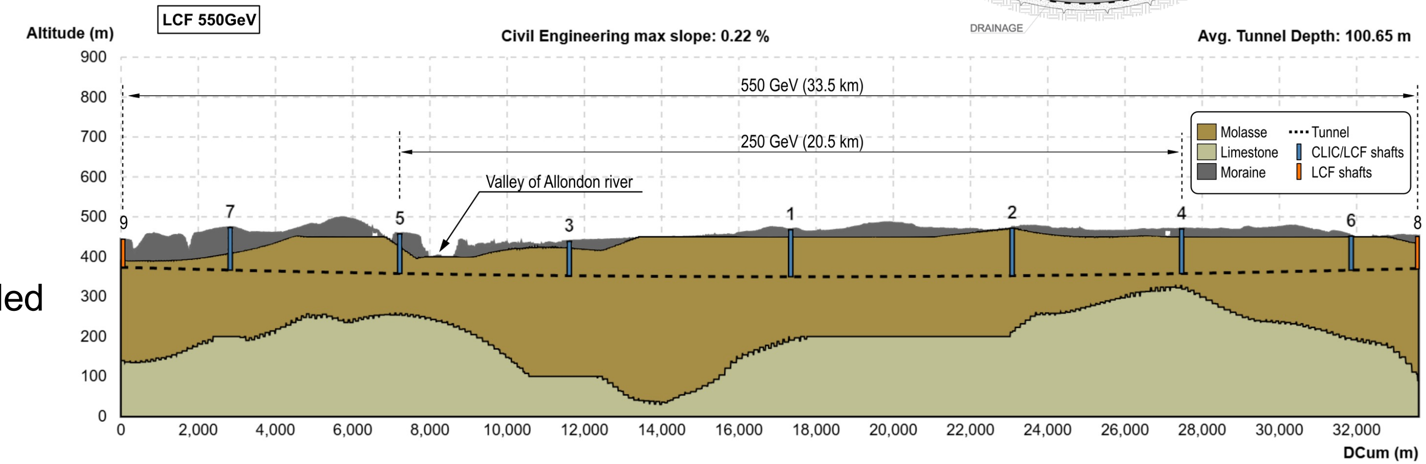
e^+e^- cross section for EWino production
LCF would cover phase space of excesses

Staging I

250 GeV incl Z pole - facility

- **33.5km long tunnel => reach 550 GeV with 31.5 MV/m SCRF**
- **ø 5.6m, two IPs**
- **equipped with SCRF for 250 GeV**
- **10Hz trains of 1312 bunches => L = 2.7 x 10^{34} / cm^2 / s**
- **construction cost: 8.29 BCHF**
- **AC power: 143 MW**
- optionally: beam-dump / fixed-target
- upgrade: double luminosity 2625 bunches / train: +0.77 BCHF + 39MW
- **both beams polarised:**
  - **e-: 80%**
  - **e+: 30%**
- **3ab-1 @ 250 GeV**
- operation at Z pole (eg $100fb^{-1}$) WW theshold (eg $500fb^{-1}$) as needed





Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

Staging II

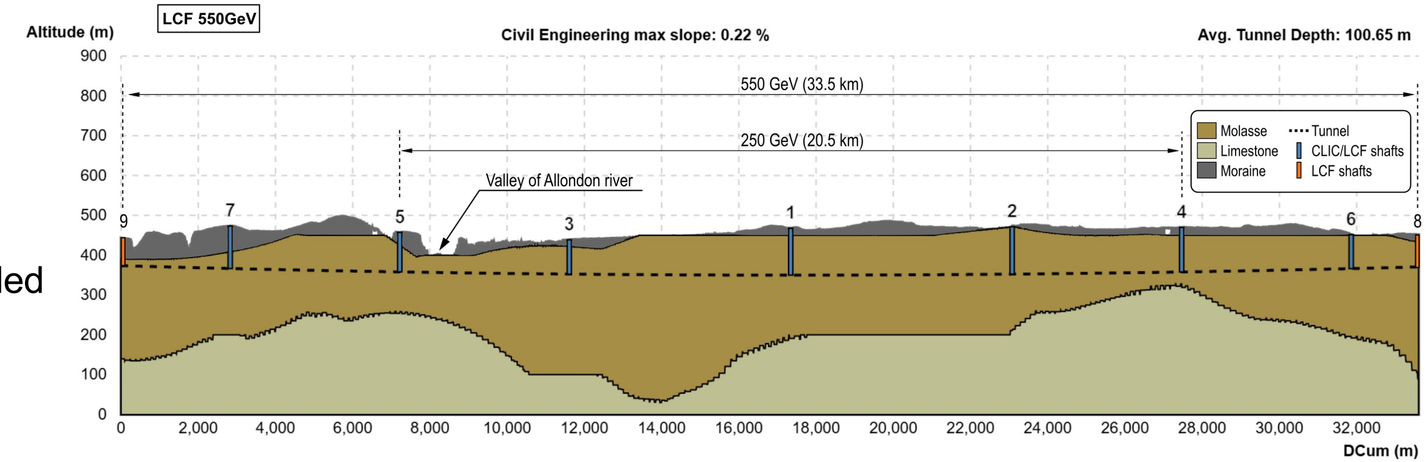
Linear Collider Vision

250 GeV incl Z pole - facility

- **33.5km long tunnel => reach 550 GeV with 31.5 MV/m SCRF**
- **ø 5.6m, two IPs**
- **equipped with SCRF for 250 GeV**
- **10Hz trains of 1312 bunches => L = 2.7 x 10^{34} / cm^2 / s**
- **construction cost: 8.29 BCHF**
- **AC power: 143 MW**
- optionally: beam-dump / fixed-target
- upgrade: double luminosity 2625 bunches / train: +0.77 BCHF + 39MW
- **both beams polarised:**
  - **e-: 80%**
  - **e+: 30%**
- **3ab-1 @ 250 GeV**
- operation at Z pole (eg 100fb^{-1}) WW theshold (eg 500fb^{-1}) as needed

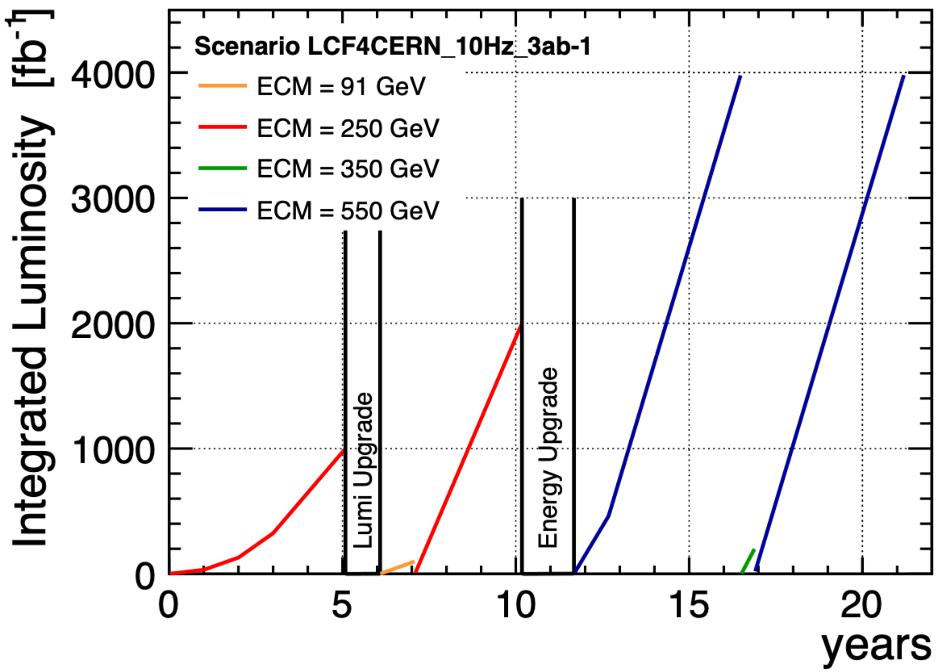
550 GeV incl ttbar theshold

- Upgrade
  - equipping the additional tunnel with SCRF
  - **+ 5.46 BCHF**
  - 10 Hz trains of 2625 bunches => 7.7 x 10^{34} / cm^2 / s
  - **AC power 322 MW**
  - target 8 ab^{-1}

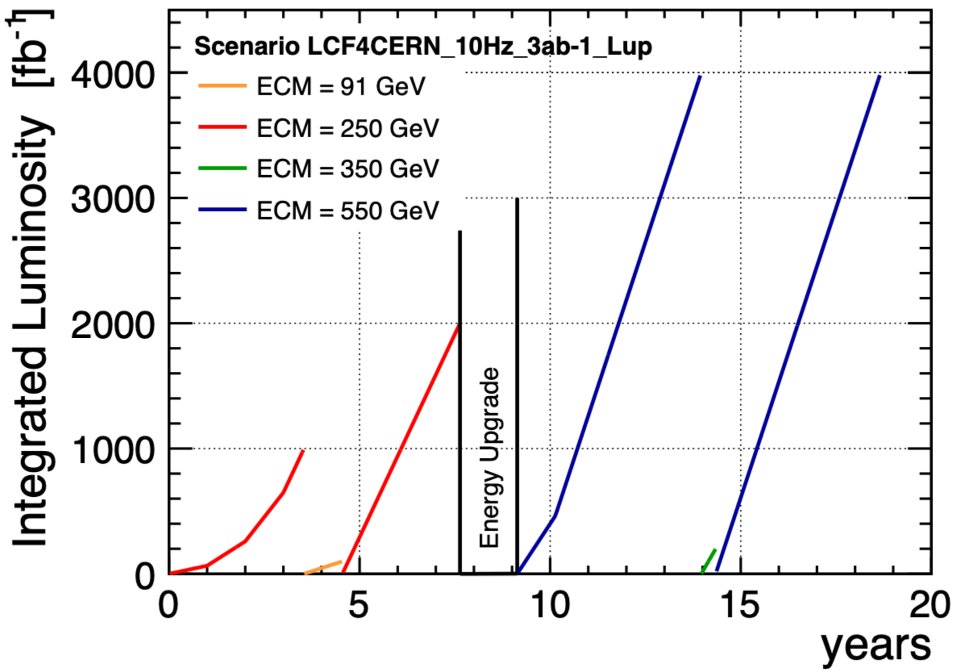


Running Scenarios up to 550 GeV

baseline



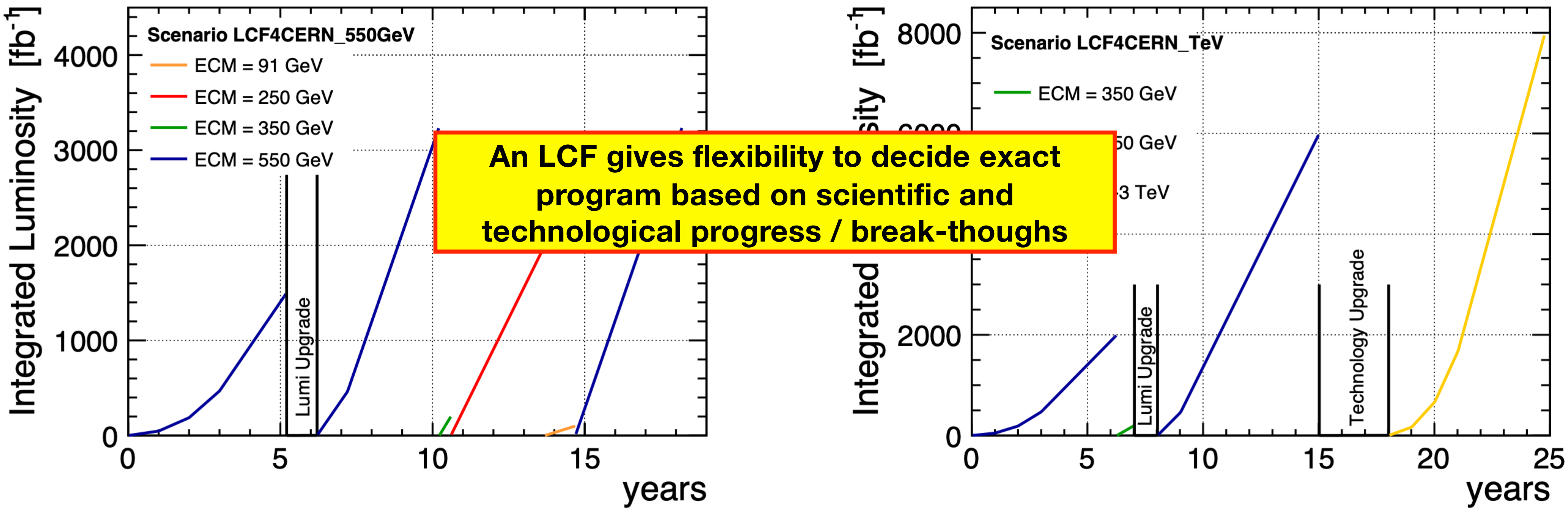
start immediately with full power



Running Scenarios starting at 550 GeV

Linear Collider Vision

take some polarised data at lower energies | **or go more quickly to TeV range**



An LCF gives flexibility to decide exact program based on scientific and technological progress / break-thoughs

Summary and Conclusion

- e+e- colliders are indispensable tools to understand and/or discover the nature of new physics
  - Precision on Higgs couplings at or below 1% level
  - Indrect and direct discovery potential at all centre-of-mass energies
  - Light scalars or vector bosons with different gauge symmetry

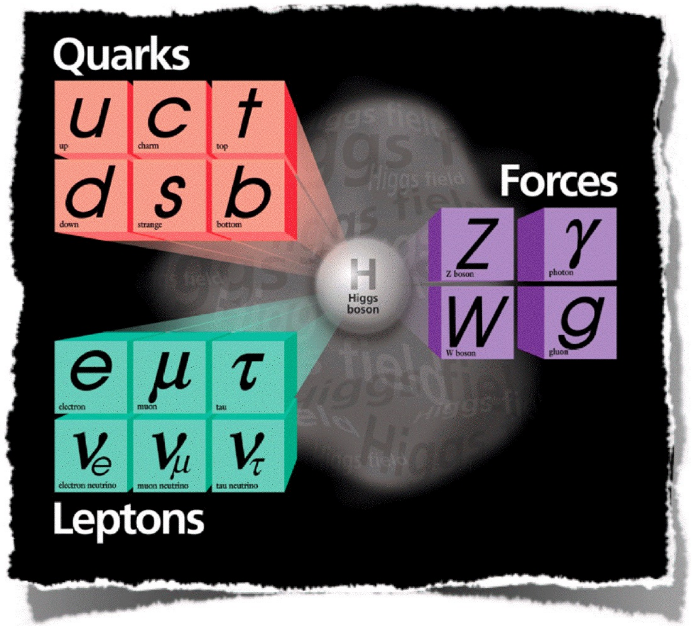
- Full exploitation of physics potential requires large energy coverage and polarised beams
  - Effects at HZ threshold and below are expected to become more prominent at higher energies
  - New physics signals and relevant operators depend on chiral state of initial and final state fermions
  - (“Early”) direct measurement of the Higgs-selfcoupling
  - Sufficient lever arm to react to HL-LHC results
    - Remember also the “LEP disaster”, Higgs missed by 30 GeV in centre-of-mass

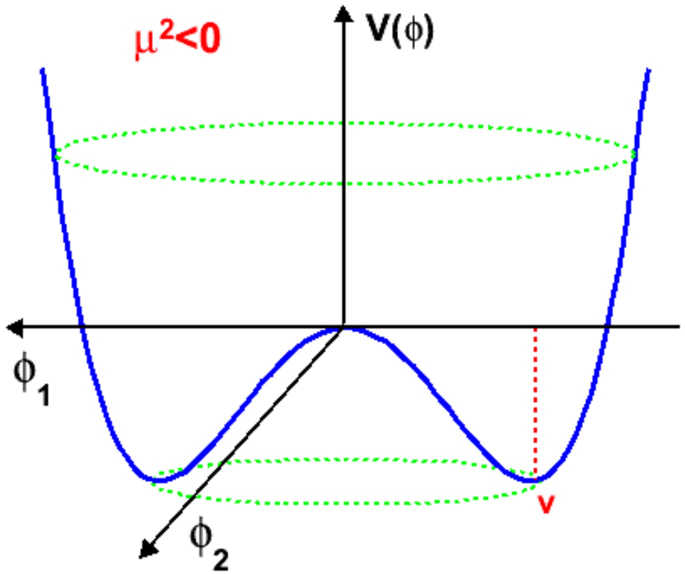
- A clear pattern of anomalies would be an excellent (and maybe the only) motivation for a large hadron machine

- Linear Collider Facility based on SCRF is close at hand
  - Attractive options for innovative accelerator (and detector) concepts
  - LCVision effort to coordinate the different proposals
  - Require close collaboration between Physics and Detector and Accelerator Experts!

Backup

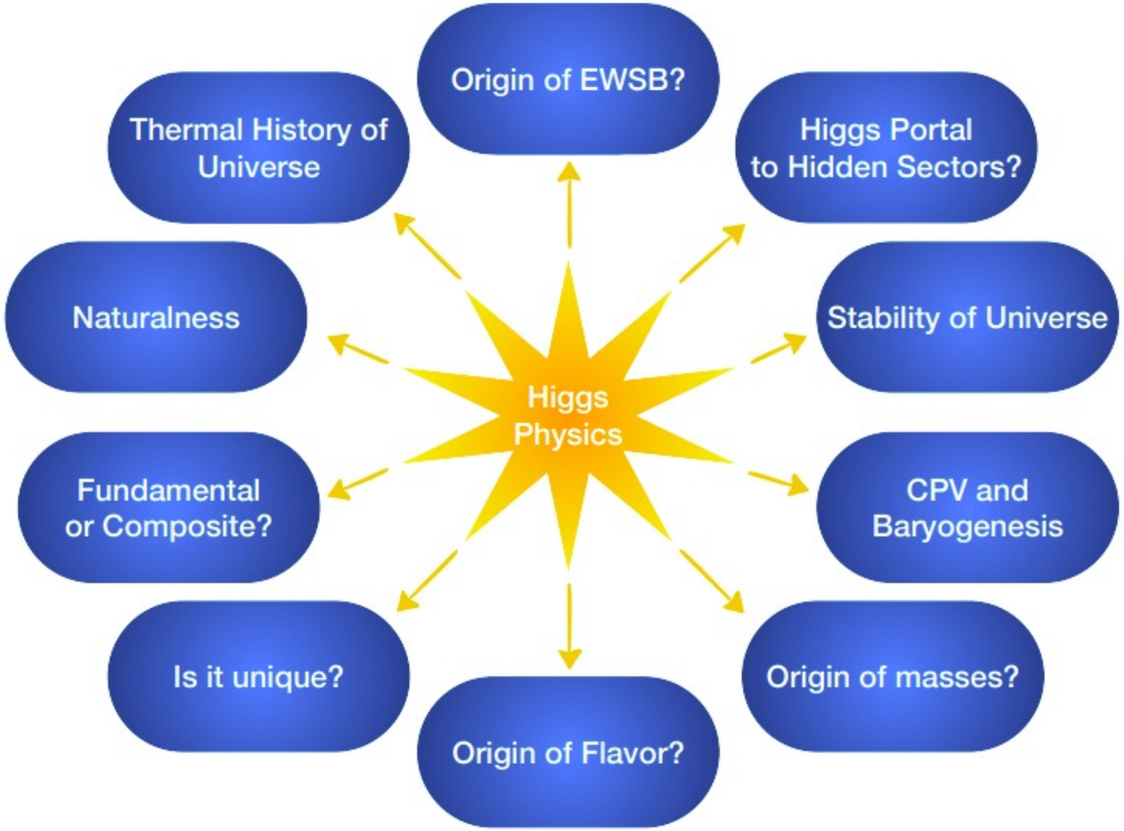
The Standard Model is complete





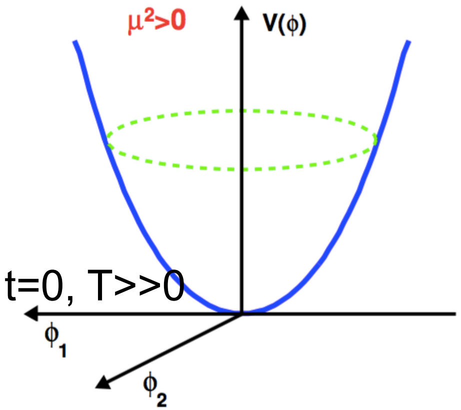
- We know that there exists at least one fundamental scalar with a non-vanishing expectation value
- We don't know what shapes the potential and whether the potential is the footprint of a larger mass scale

Science Driver Higgs Boson

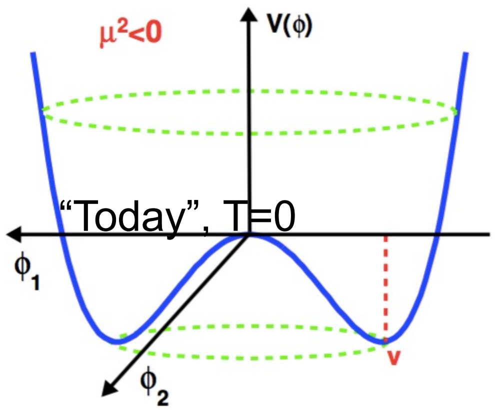


The Higgs Potential

Linear Collider Vision



Perfect (electroweak) symmetry
and massless particles

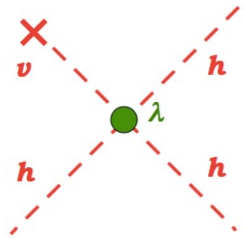


Broken (electroweak) symmetry
and massive particles

Two questions:

- Shape of "today's" Higgs Potential?

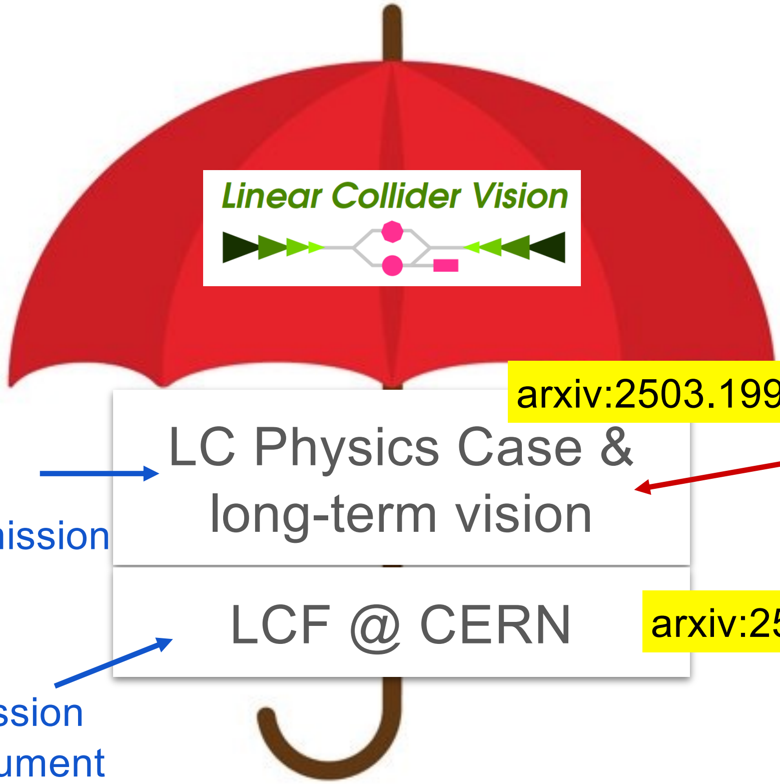
$$V(\eta) = \frac{1}{2}m^2\eta^2 + \lambda v\eta^3 + \frac{1}{4}\lambda\eta^4$$ => Triple Higgs-self coupling



- Transition from symmetric, unbroken to broken phase?

LCVision EPPSU documents

… and relation to other inputs



arxiv paper & EPPSU submission → LC Physics Case & long-term vision — arxiv:2503.19983

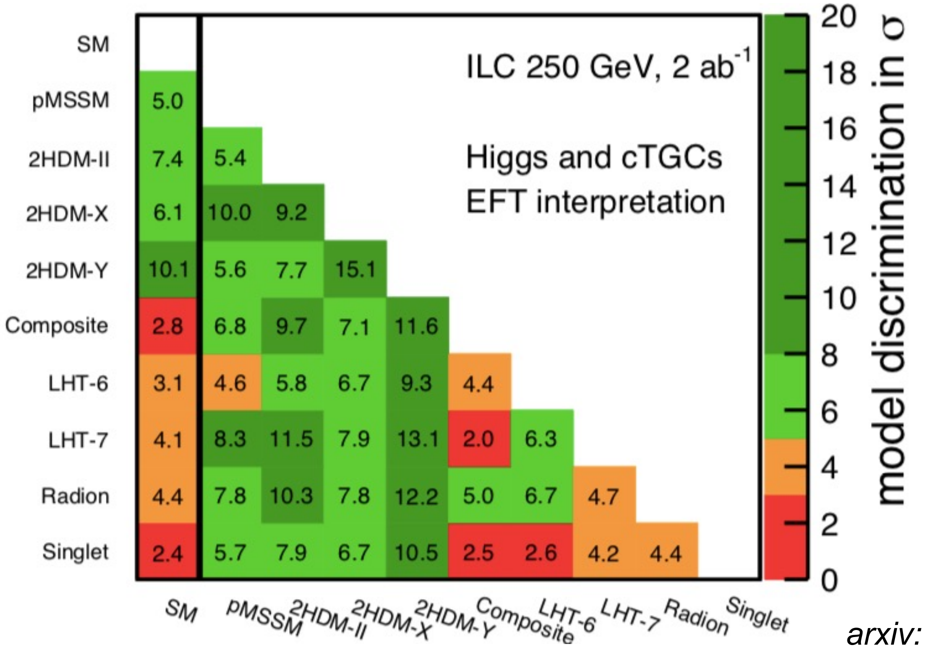
EPPSU submission & back-up document → LCF @ CERN — arxiv:2503.24049

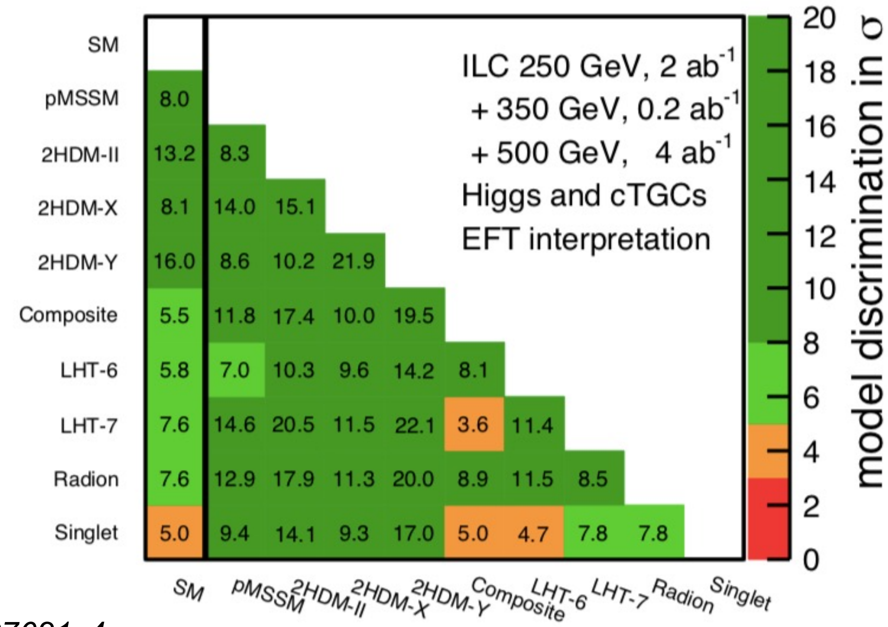
Technologies and upgrades:

- ILC in Japan (IDT) — arxiv:2504.XXX
- CLIC at CERN — arxiv:2503.24168, arxiv:2503.21857
- C^3 — arxiv:2503.20829
- HALHF — arxiv:2503.23489, arxiv:2503.19880
- 10 TeV Wakefield — arxiv:2503.20214, arxiv:2504.01434
- Beyond Collider — https://cds.cern.ch/record/2927631

Open questions

Higgs – Discovery by precision



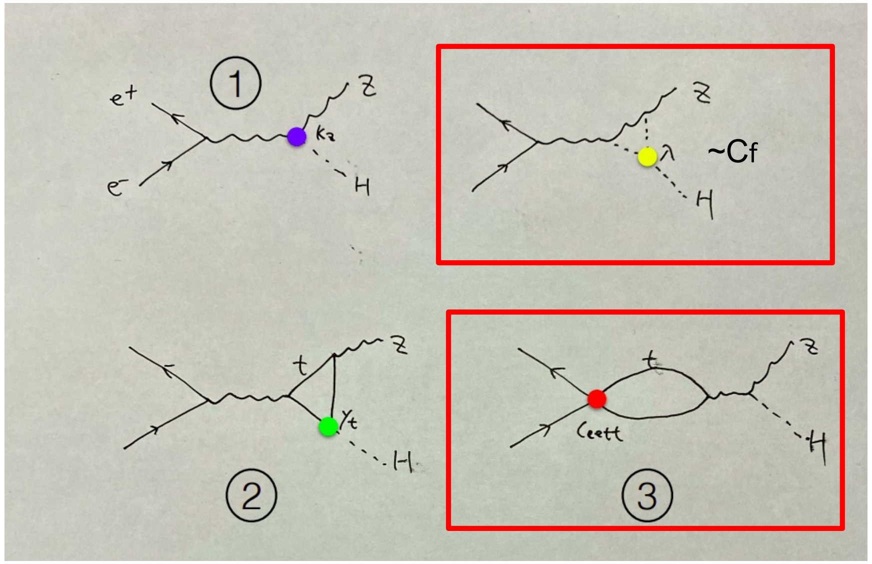


arxiv: 1710.07621v4

- Already large discriminative power at 250 GeV
- Full discovery potential developed at higher energies (e.g. 500 GeV)
- Observed “Anomalies” could be followed up by future hadron or muon colliders

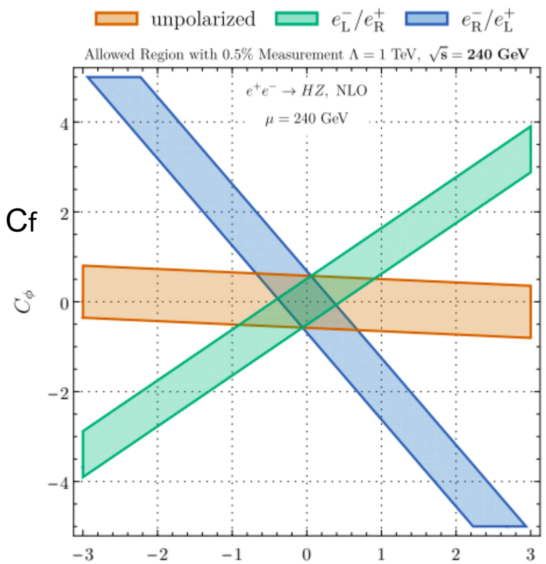
Entanglement SMEFT NLO

NLO Contributions to ee->HZ



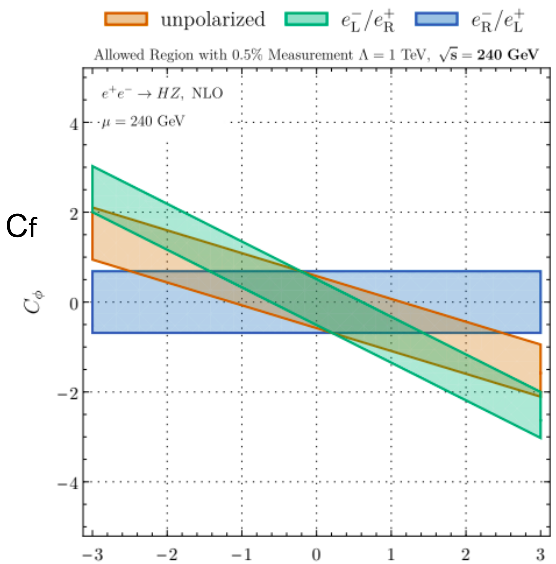
One important contribution is eett Vertex

Correlation Cf to tt-Vertices arxiv:2409.11466



Cf

Cfu=f(Ztt)



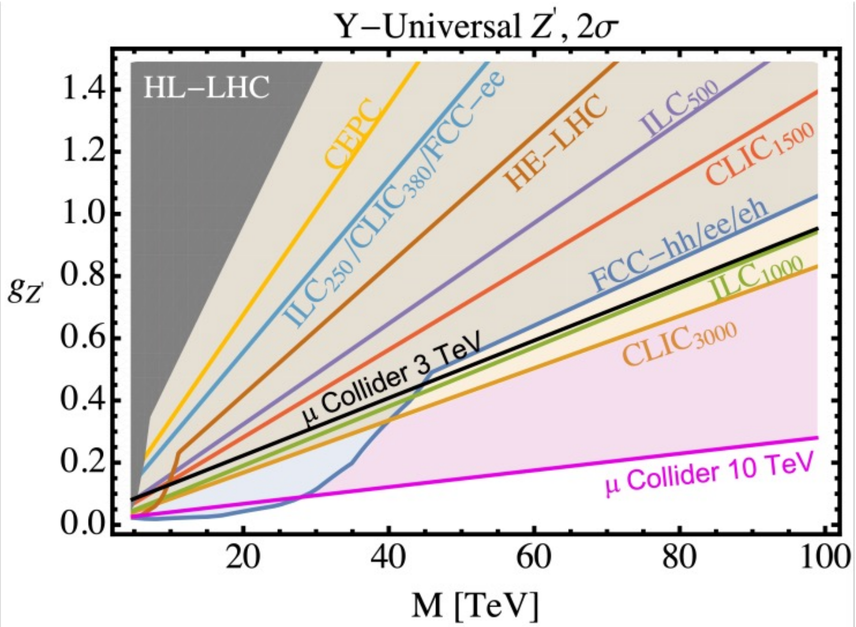
Cf

Clq=f(eett)

- NLO SMEFT introduces sensitivity to and constrains Cf and operators involving top vertices
- Disentangling of constraints using beam polarisation
- Final word would come from higher energy measurements
- Note that Clq is strongly energy dependent (-> would benefit from higher energies)

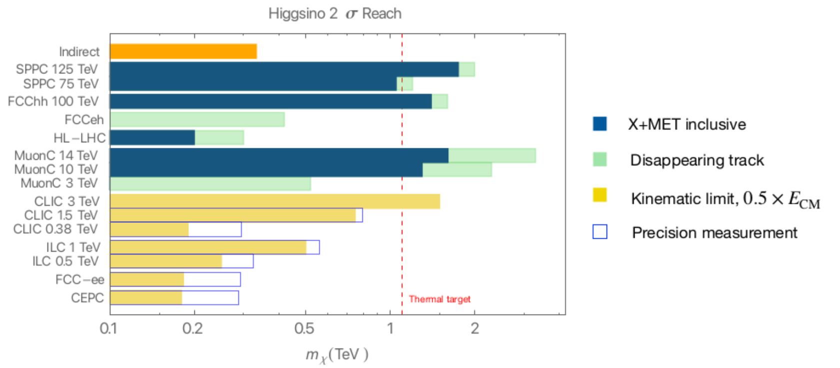
Mass reaches of future colliders (from Snowmass EF Report)

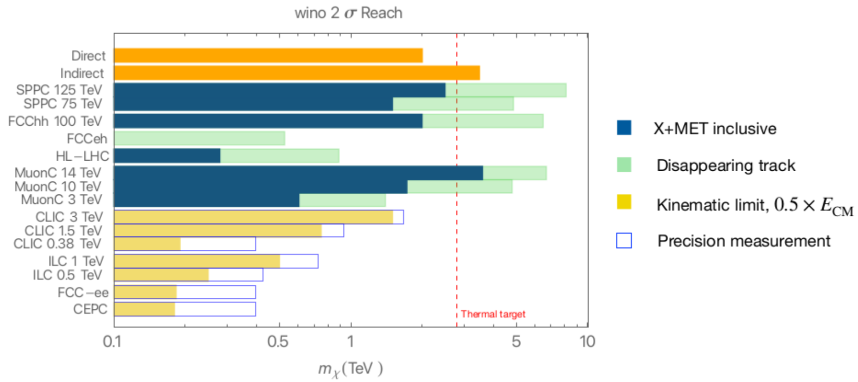
Generic Z' Model



Z' are expected for in compositeness models or in (dual) models with extra dimensions

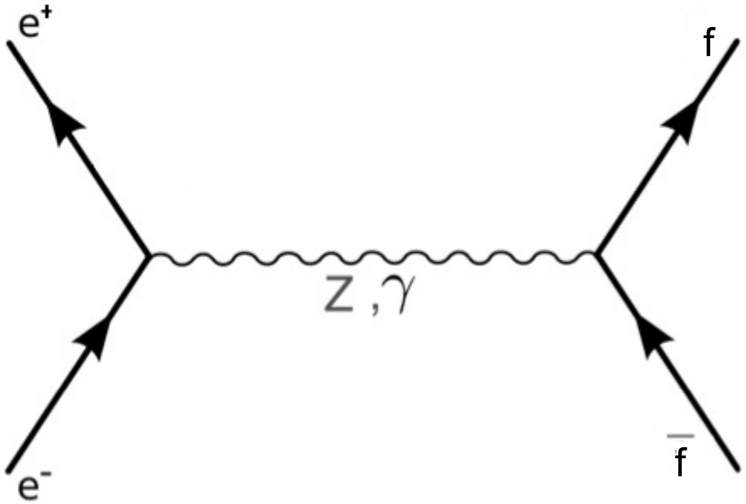
Dark Matter 2σ exclusion limits





- Example for light Higgsino search in backup
- High centre-of-mass energy helps (here)
- Don't forget light states (see backup)

Two fermion processes



Differential cross sections for (relativistic) di-fermion production*:

$$\frac{d\sigma}{d\cos\theta}(e^-_L e^+_R \to f\bar{f}) = \Sigma_{LL}(1+\cos\theta)^2 + \Sigma_{LR}(1-\cos\theta)^2$$

$$\frac{d\sigma}{d\cos\theta}(e^-_R e^+_L \to f\bar{f}) = \Sigma_{RL}(1-\cos\theta)^2 + \Sigma_{RR}(1+\cos\theta)$$

*add term ~$sin^2\theta$ in case of non-relativistic fermions e.g. top close to threshold

- Σ_{IJ} are helicity amplitudes that contain couplings g_L, g_R *(or F_V, F_A)*
- $\Sigma_{IJ} \neq \Sigma_{I'J'}$ => (characteristic) asymmetries for each fermion
- Forward-backward in angle, general left-right in cross section
- **All four** helicity amplitudes for all fermions **only available with polarised beams**

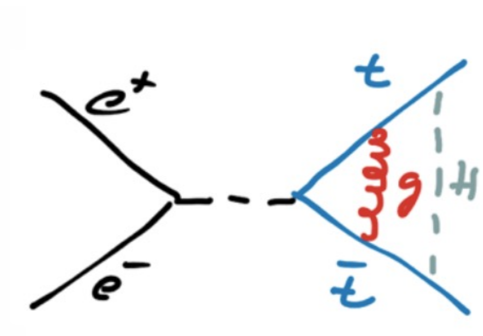
- **tt production see above**

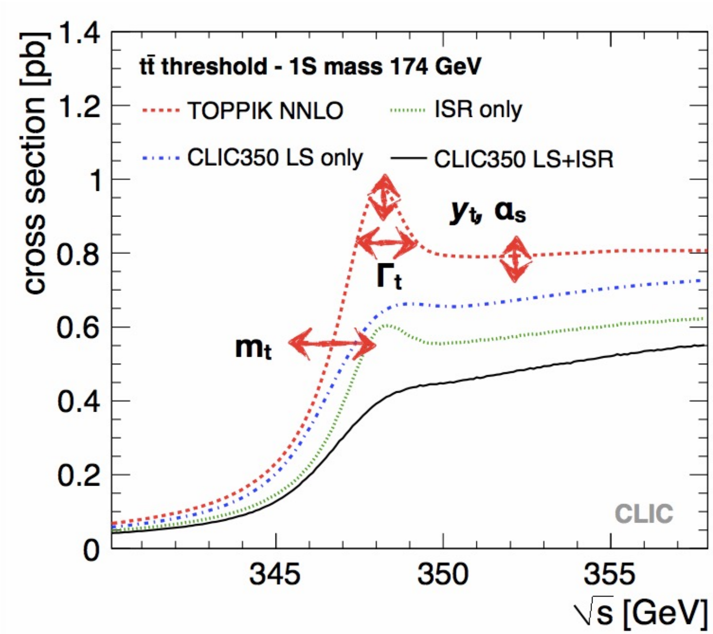
e+e- - Top quark production at threshold

Small size of ttbar “bound state” at threshold ideal premise for precision physics

Cross section around threshold is affected by several properties of the top quark and by QCD

- Top mass, width Yukawa coupling
- Strong coupling constant



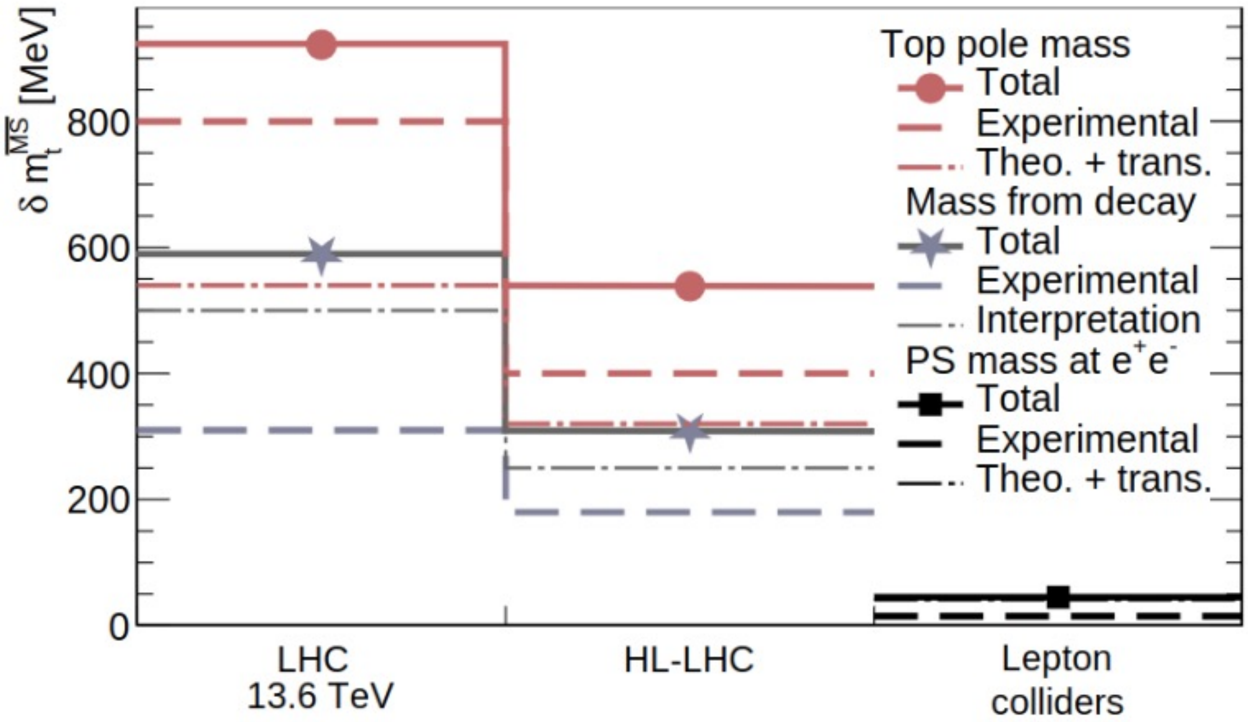


- Effects of some parameters are correlated:
- Dependence on Yukawa coupling rather weak,
- Precise external α_s helps

F. Simon, Top@LC15 Valencia

Top Mass Summary

Snowmass report, arXiv:2209.11267

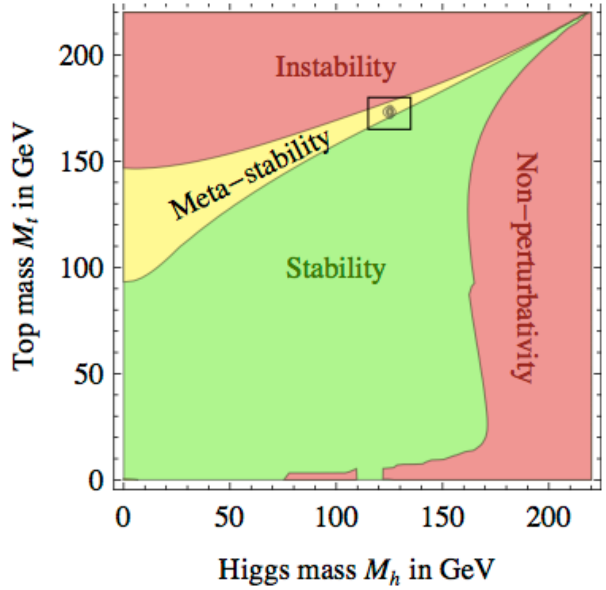


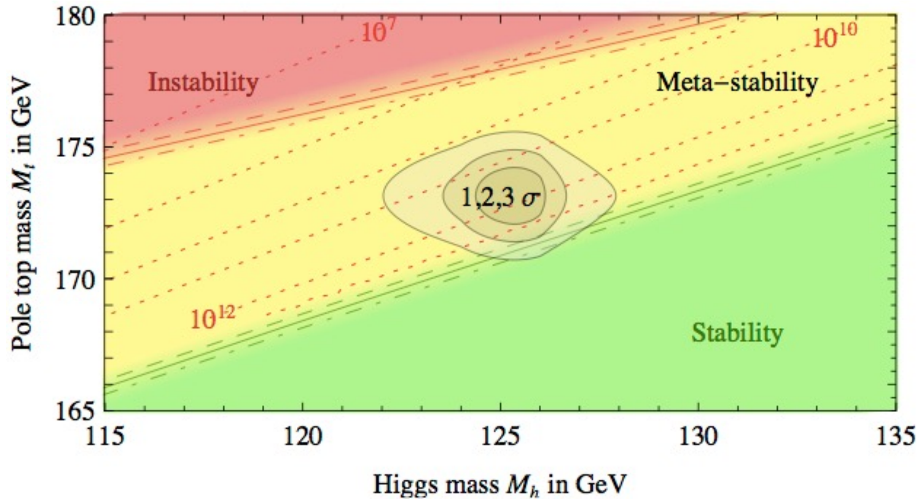
All future lepton (e+e- colliders) will improve considerably the precision on m_{top}

Marcel Vos@Top23

Vacuum Stability and Top Quark Mass

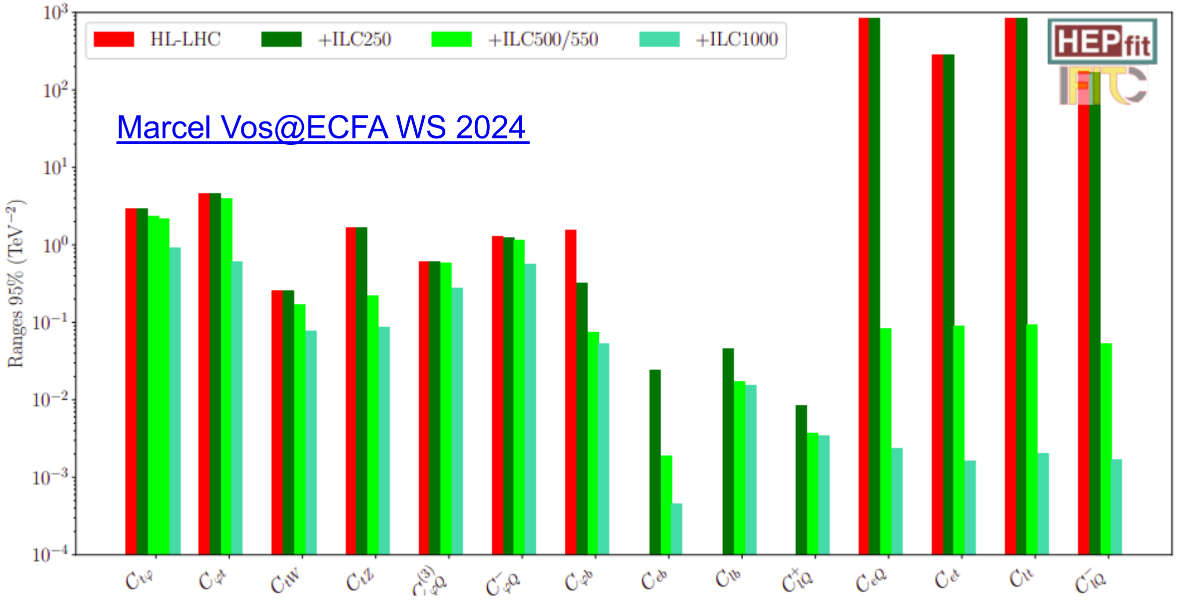
$$M_h \text{ [GeV]} > 129.4 + 1.4\left(\frac{M_t \text{ [GeV]} - 173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{\text{th}}\,.$$

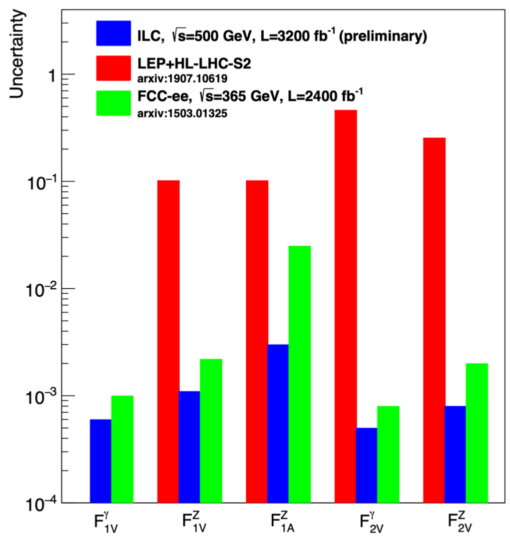




Uncertainty on (pole) top quark mass determines uncertainty on stability conditions

Precision on electroweak form factors and couplings

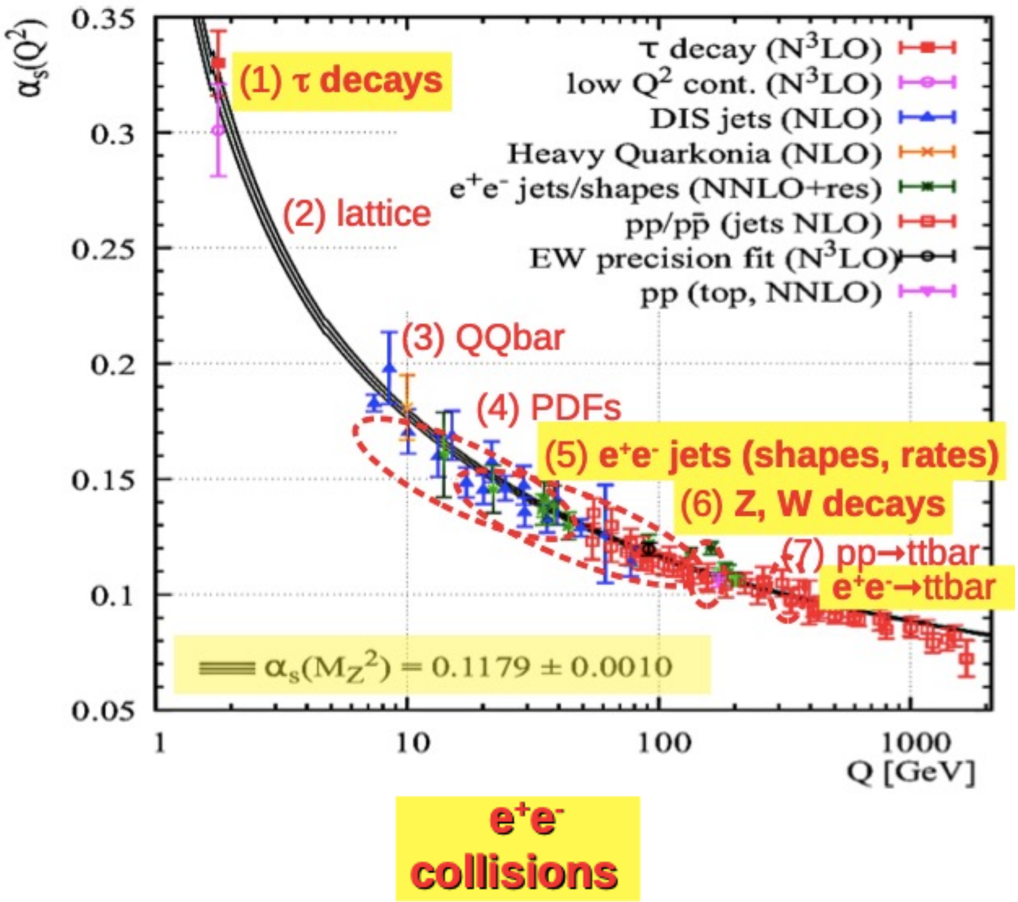




- e+e- collider way superior to LHC (√s = 14 TeV)
  - True for both, analysis in terms of Form Factors and Wilson Coefficients
- Polarised beams at ILC, final state analysis at FCCee
  - Final stat analysis also possible at LC => Redundancy
  - should be checked again (see arxiv 1503.04247)
- :500 GeV is nicely away from QCD matching regime (see backup)
  - Less systematic uncertainties
- Axial form factors are ~β and benefit therefore from higher energies

The 250 GeV run provides some information (interplay bottom-top)
Top production at an e+e- collider yields dramatic improvement
The fit benefits from a 2nd top run at high energy (2-vs-4 fermion operators)

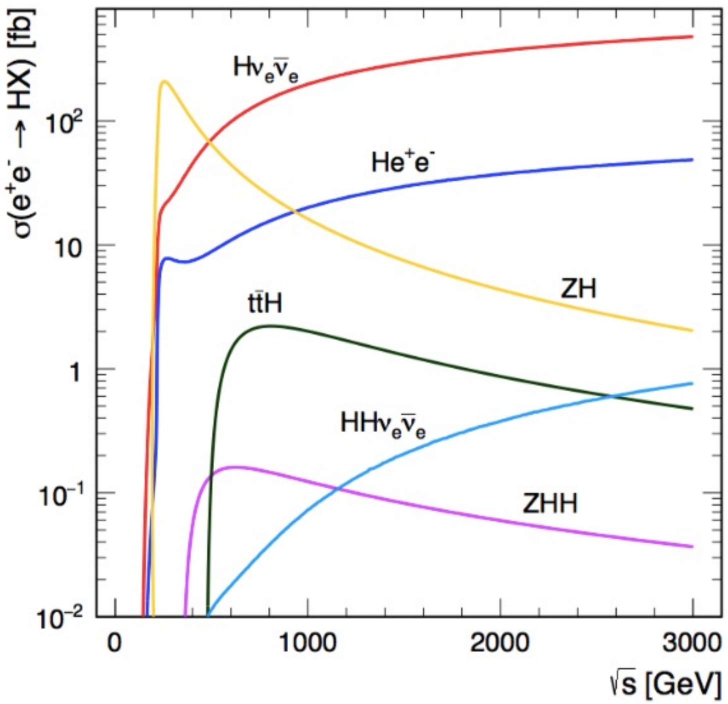
Uncertainty driver α_s

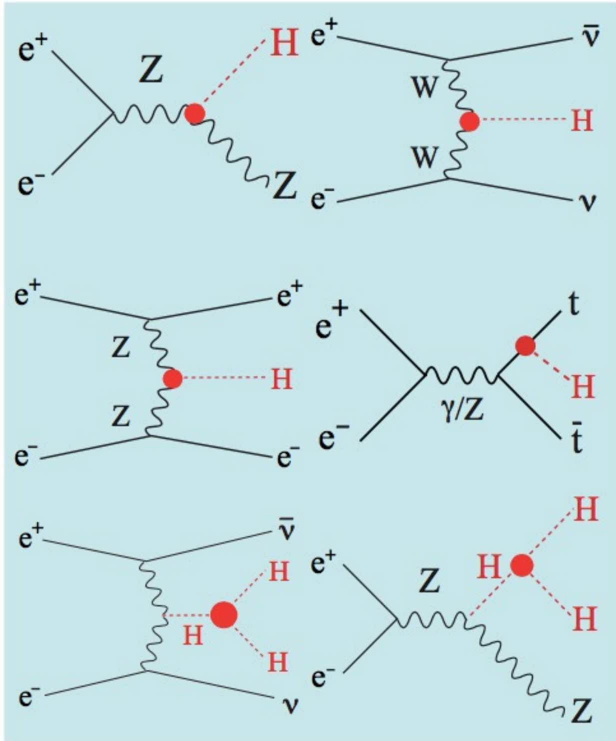


- See talk by Francesco Giuli LCF2022
  - https://indico.ectstar.eu/event/149/contributions
  - /3058/attachments/1919/2513/FCC_LFC_FGiuli_2022.pdf
- Best prospects from e+e- collisions
  - $\Delta\alpha/\alpha$ ~0.1% for FCCee hadronic Z-decays
    - Comparable with QCD Lattice Results
  - Status for ILC $\Delta\alpha/\alpha$ ~0.6% (arXiv:1512.05194)
    - Worth another look ?!

Higgs production at e+e- colliders

Associated and t-channel production



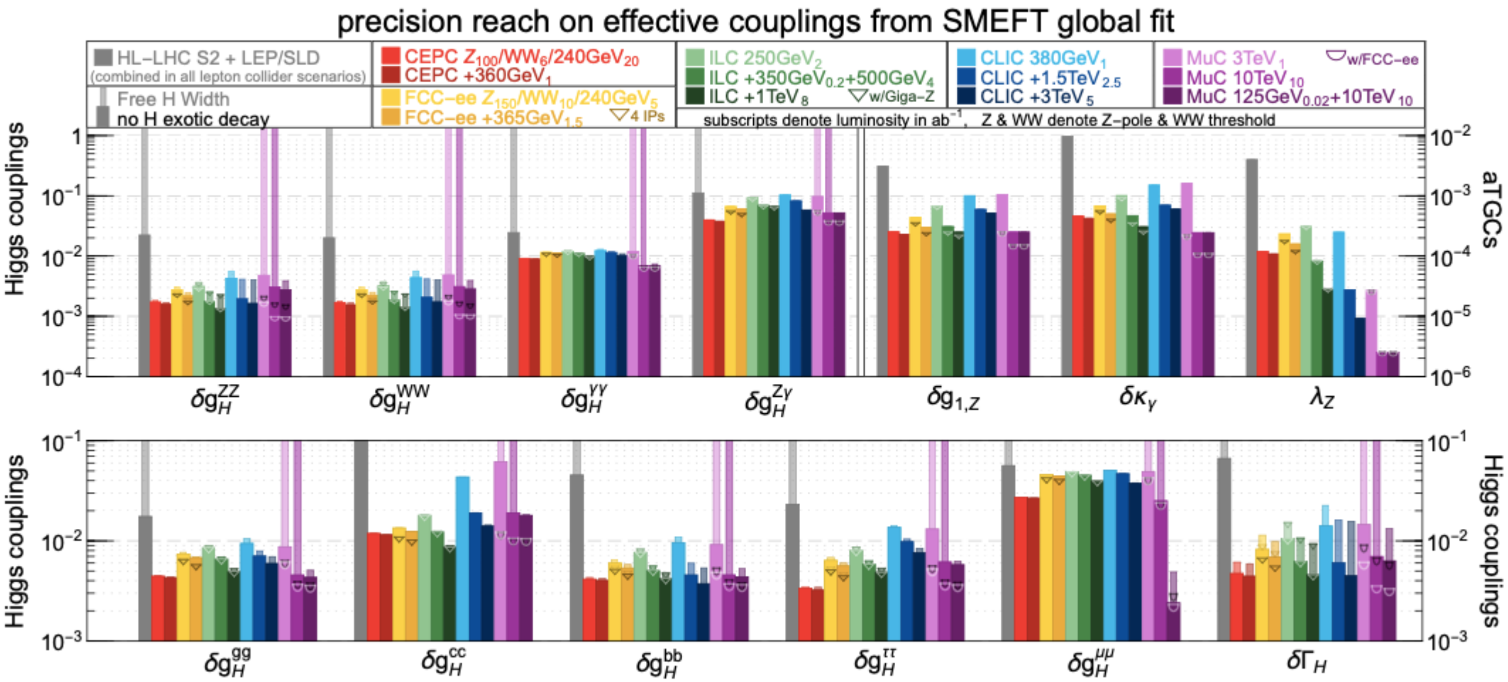


two important thresholds:
√s ~ 250 GeV for ZH, ~500 GeV for ZHH and ttH

Expected precision at future lepton colliders

Arxiv: 2206.08326

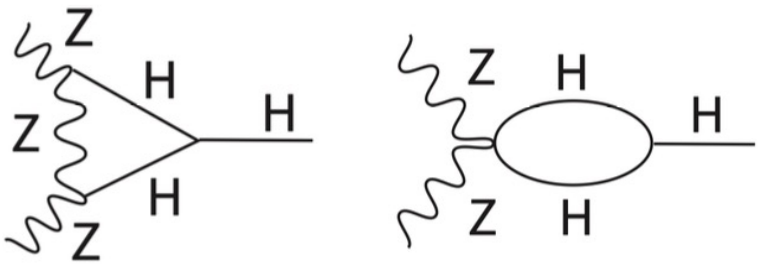
Higgs interactions



- All planned e+e- machines will deliver O(1%) precision on Higgs couplings
  - Beam polarisation at LC catches up for smaller luminosity
- Muon Collider makes excellent job on trilinear couplings and Hμμ coupling
-

Higgs Selfcoupling measurement in e+e- (μ+μ-)

- Indirect access
  - Through loop order corrections in EFT fits
  - Single Higgs measurements in e+e-
  - at or better than 1%
  - Large number of independent observables
  - Running at two different centre-of-mass
  - energies

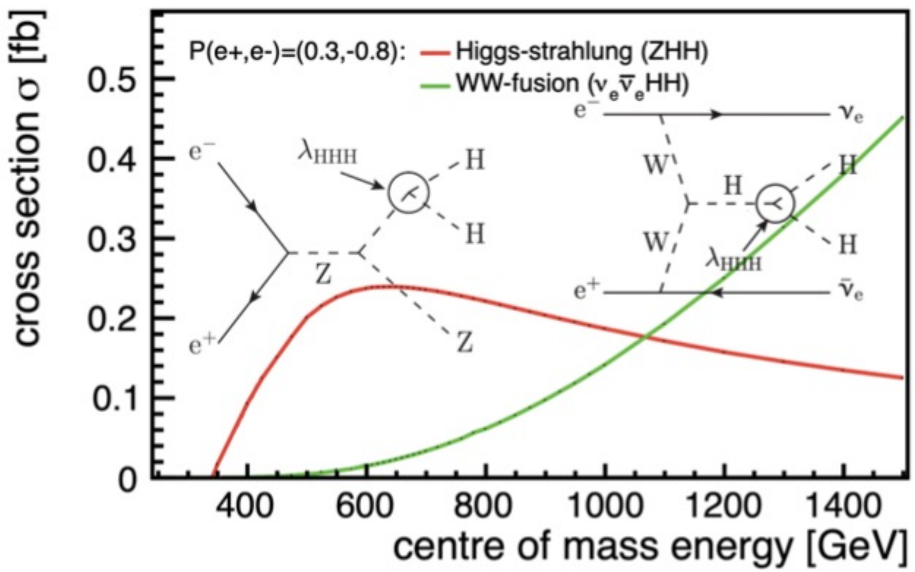


[Details see M. Peskin, 12/1/23]

[Slide from Julie Munch Torndal]

- Direct access
  - Through double-Higgs Production

$$\frac{\Delta\lambda_{HHH}}{\lambda_{HHH}} = c \cdot \frac{\Delta\sigma_{HHx}}{\sigma_{HHs}}$$



e+e- Colliders – Uncertainties and their drivers

	experimental accuracy			intrinsic theory uncertainty		
	current	ILC	FCC-ee	current	current source	prospect
ΔM_Z[MeV]	2.1	0.2	0.1			
$\Delta\Gamma_Z$[MeV]	2.3	0.1	0.03	0.4	$\alpha^3, \alpha^2\alpha_s, \alpha\alpha_s^2$	0.15
$\Delta \sin^2\theta^\ell_{eff}[10^{-5}]$	23	1.3	0.2	4.5	$\alpha^3, \alpha^2\alpha_s$	1.5
$\Delta R_b[10^{-5}]$	66	14	6	11	$\alpha^3, \alpha^2\alpha_s$	5
$\Delta R_\ell[10^{-3}]$	25	3	1	6	$\alpha^3, \alpha^2\alpha_s$	1.5

FCCee: 2203.06520 ILC: 2203.07622

Theory requires 3-loop calculations

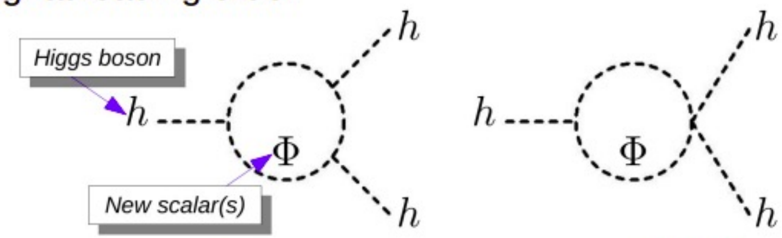
Experimental uncertainty drivers:

- M_Z, Γ_Z: Beam energy, detector calibration and acceptance
  - Would require a reduction of a factor 20-25 to match FCCee statistics w.r.t current estimates
- $\sin^2\theta^\ell_{eff}$: Beam energy (FCCee, CEPC), beam polarisation (ILC)
- R_b: Detector acceptance, QCD (gluon radiation?)
  - Difficult to judge on “the error source”, it's rather a sum of many
- R_l: Detector acceptance

Probing New Physics with the trilinear Higgs Coupling

J. Braathen, IDT-WG3 Physics Meeting

- **Large effects from New Physics possible in λ_{hhh}** due to radiative corrections from extra scalars, e.g. at leading order



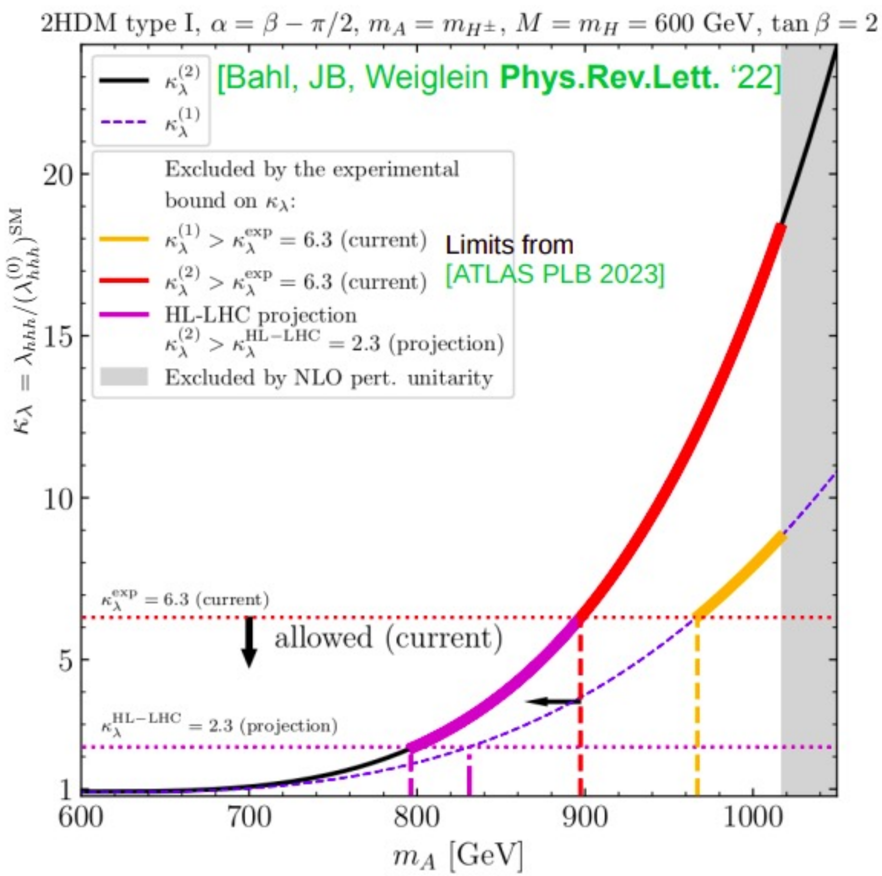
$$m_\Phi^2 = M^2 + \frac{1}{2} g_{hh\Phi\Phi} v^2 \Leftrightarrow g_{hh\Phi\Phi} = -\frac{2(M^2 - m_\Phi^2)}{v^2}$$

- Comparing latest exp. bounds

$$-1.2 < \kappa_\lambda = \frac{\lambda_{hhh}}{(\lambda_{hhh}^{(0)})^{\mathrm{SM}}} < 7.2$$

[ATLAS 2024]

with precise theory predictions for λ_{hhh} provides a **powerful new tool to constrain BSM models**
[Bahl, JB, Weiglein **Phys.Rev.Lett.** '22]



New physics?

EFT: Two distinct observations

Observables at fixed mass m
(e.g. Z pole of Higgs decays)

$$\frac{\sigma}{\sigma_{SM}} \approx |1 + \frac{c_6 m^2}{\Lambda^2}|^2$$

Increasing UV scales probed in EFT achieved solely by increasing the measurement precision

$c_6 \sim (g^*)^2$

Typical experimental precision 0.1-1%

High energy tails of distributions
(e.g. Drell-Yan Productions)

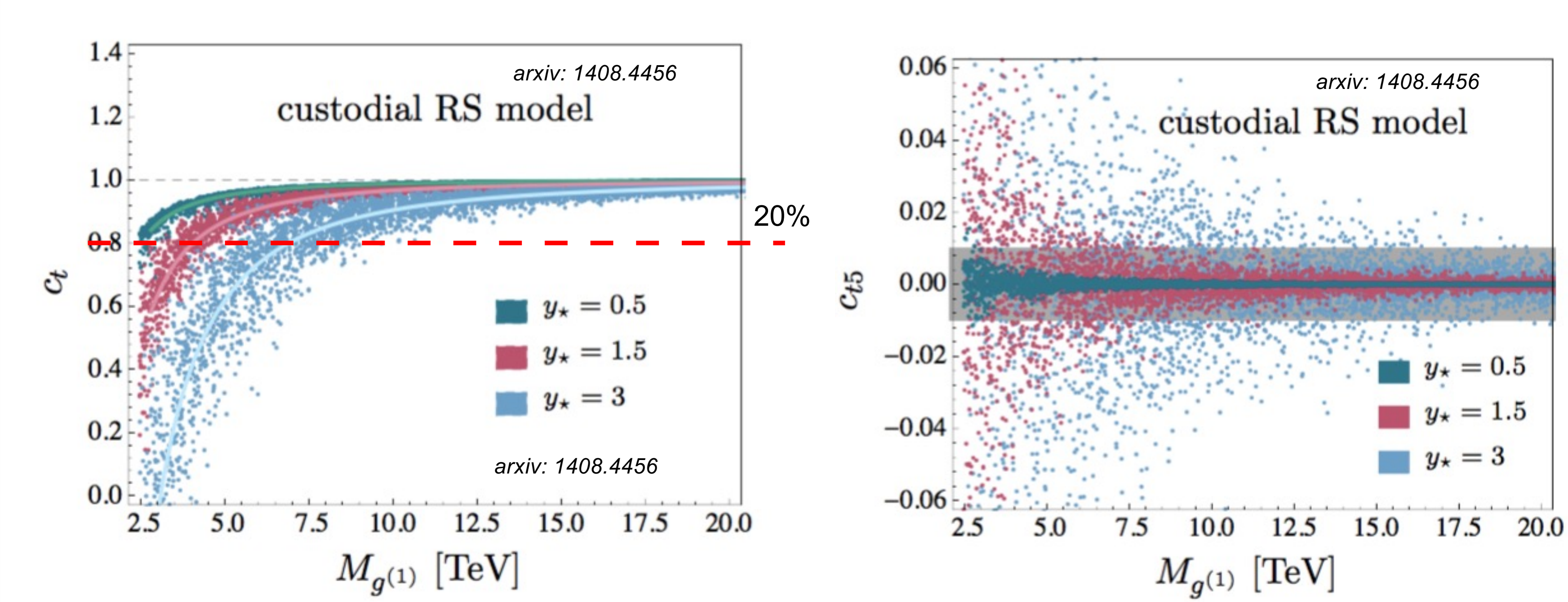
$$\frac{\sigma}{\sigma_{SM}} \approx |1 + \frac{c_6 E^2}{\Lambda^2}|^2$$

Increasing UV scales probed in EFT achieved solely by increasing the energy scale of measurement precision

Typical experimental precision 10%

Top Yukawa Coupling and New Physics

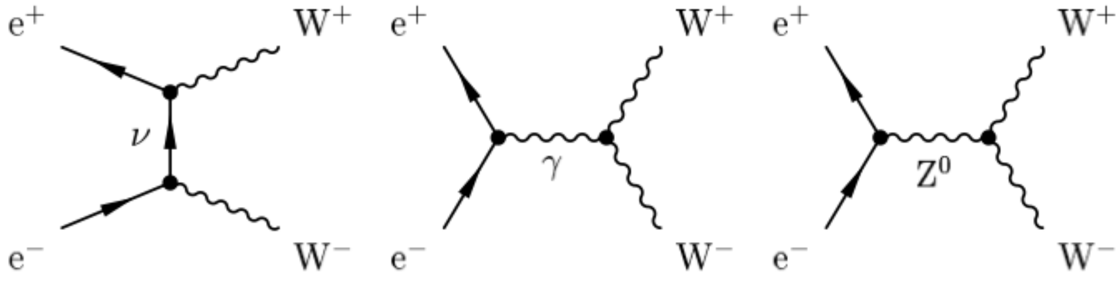
Top-Higgs couplings in “presence” of heavy particles



- Heavy particles, e.g. (Kaluza Klein) “duplicas” of SM particles provoke sizable effects
- Sensitivity to CP Violation !?
- Caveat: R.P. did not check against current LHC constraints!

Anomalous Triple Gauge Couplings

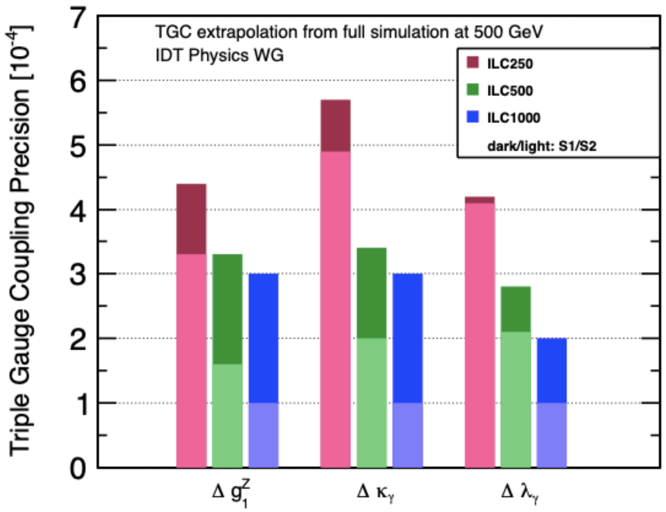
Linear Collider Vision

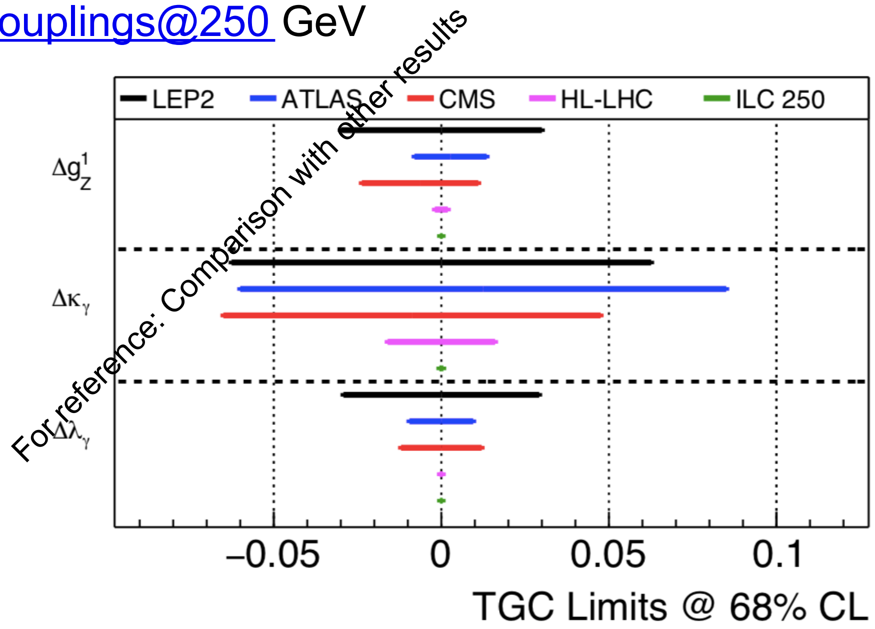


- Sensitivity to triple and quartic gauge Boson couplings (TGC and QGC)
- Observables depend strongly on beam polarisation

=> Enrich different helicity modes of W
=> Disentangling of couplings to Z and γ
=> in situ measurement of beam polarisation (and luminosity)

Limits on Triple Gauge Couplings@250 GeV





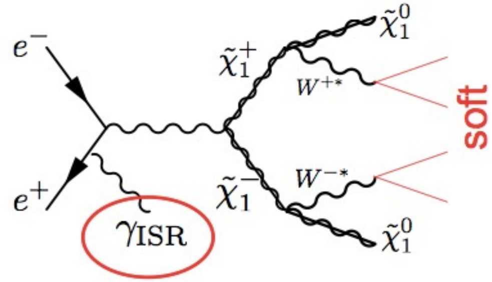
Light Higgsinons- Event Display

Study of Higgsino pair production, with ISR tag

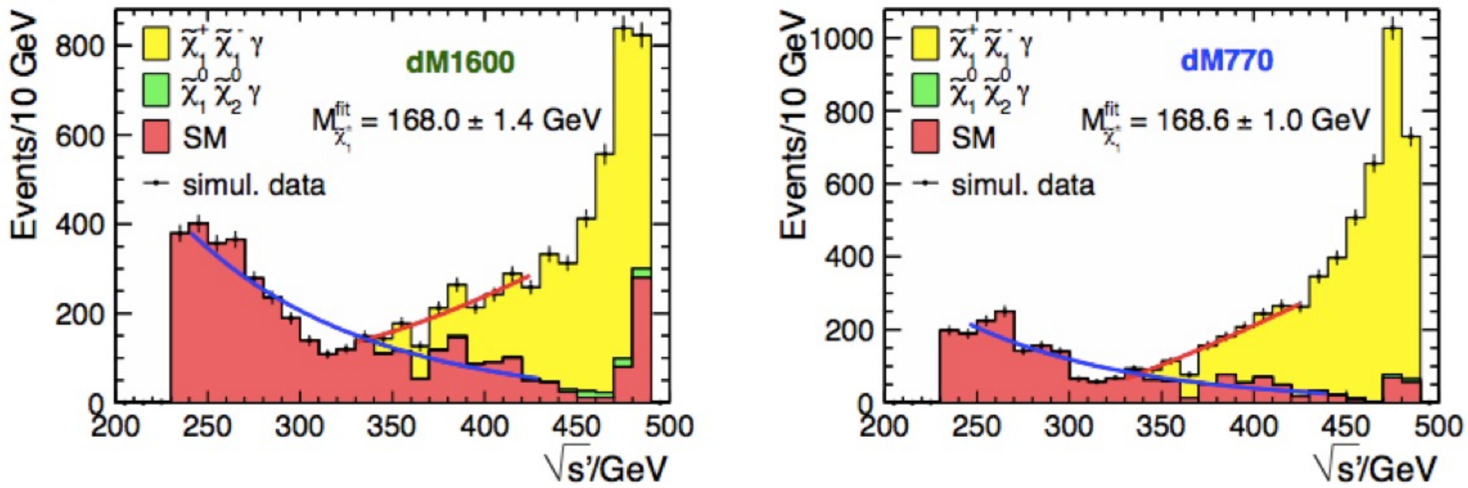
Benchmark models with

m(NLSP) – M(LSP) = 1.6 GeV and 0.8 GeV

$$\sigma(e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-) = 78.7\ (77.0)\ \text{fb}$$
$$\Delta M = 1.60\ (0.77)\ \text{GeV}$$



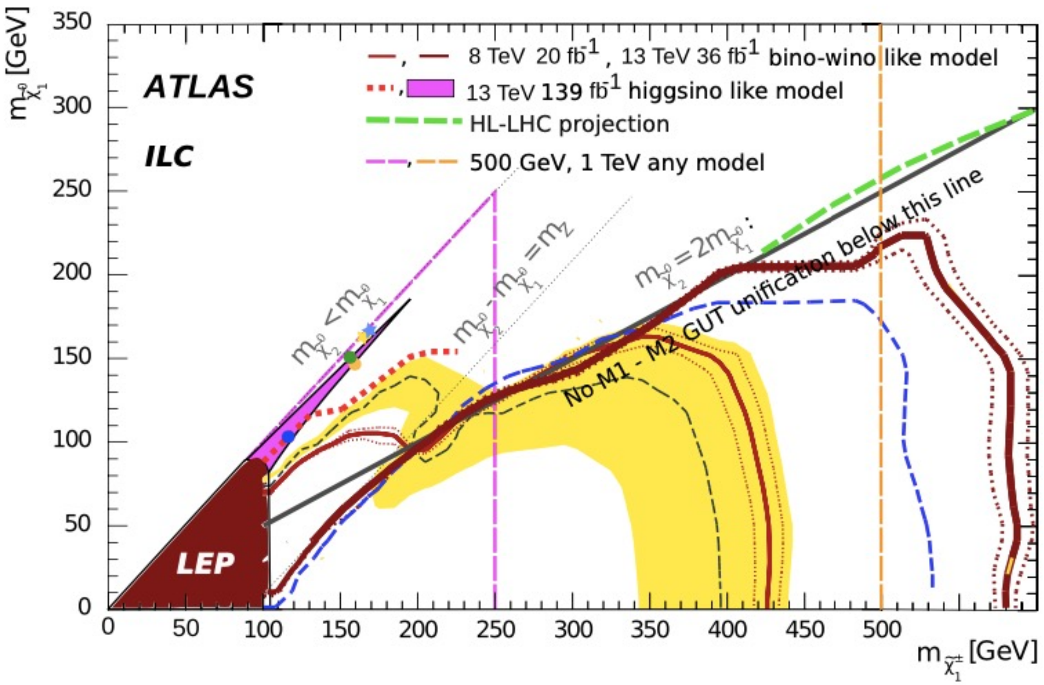
Berggren, Bruemmer, List, Moortgat-Pick, Robens, Rolbiecki, Sert, EPJ C73 (2013) 2660 [arXiv:1307.3566]



√s=500 GeV, Lumi=500 fb^{-1}, P(e-,e+)=(-0.8,+0.3) → LSP mass resolution ~1%

Clear signal => ILC covers important corner of phase space for SUSY Searches

Direct Searches for New Particles - SUSY

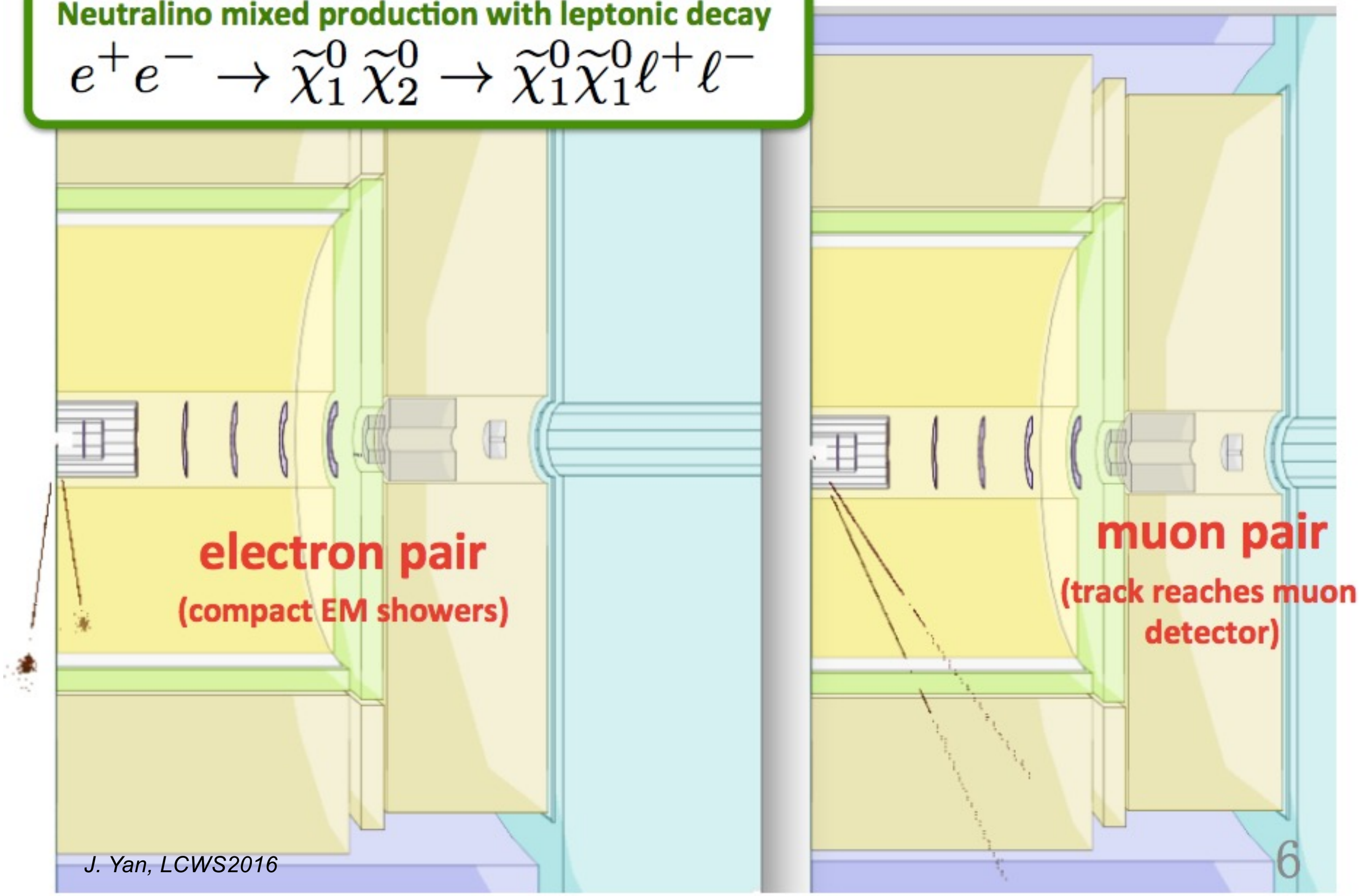


- Hadron Colliders have a great potential to discover supersymmetric particles
- Hadron Colliders cannot exclude low mass SUSY with light neutralinos and charginos
  - … that are degenerated in mass

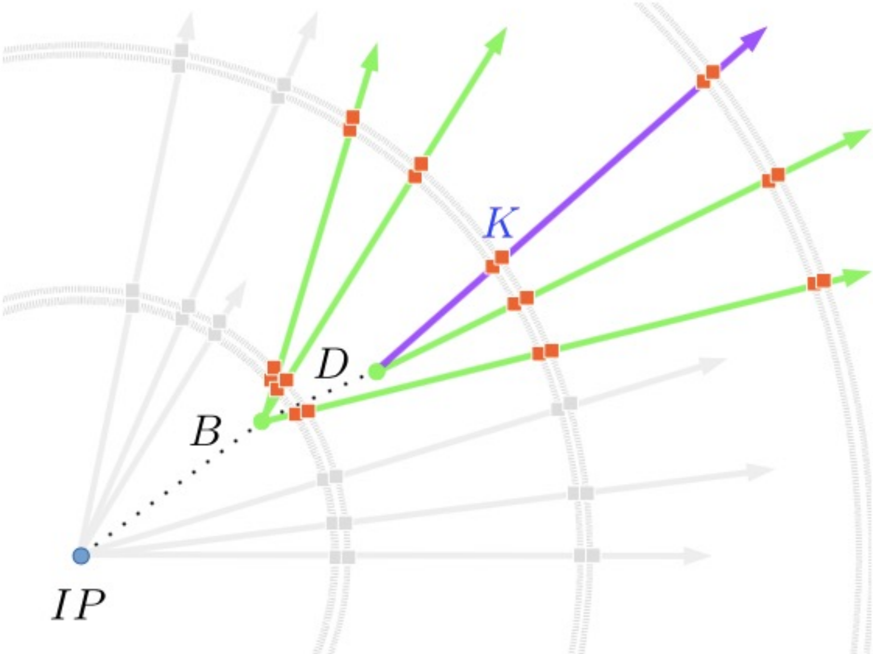
Light Higgsinons- Event Display

Neutralino mixed production with leptonic decay

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



Experimental challenges - Flavor tagging and charge measurement



PhD thesis: S. Bilokin
A. Irles

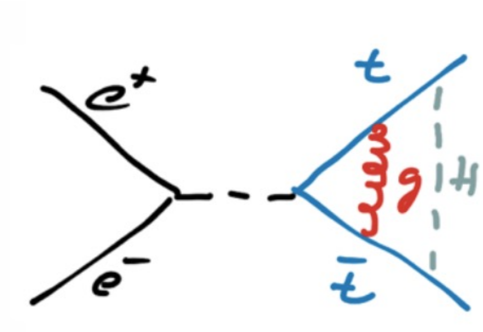
- Flavor tagging
  - Indispensable for analyses with final state quarks
- Quark charge measurement
  - Important for top quark studies,
  - indispensable for ee->bb, cc, ss, ...
- Control of migrations:
  - Correct measurement of vertex charge
  - Kaon identification by dE/dx (and more)
- Future detectors can base the entire measurements on
- double Tagging and vertex charge
  - LEP/SLC had to include single tags and
  - Semi-leptonic events

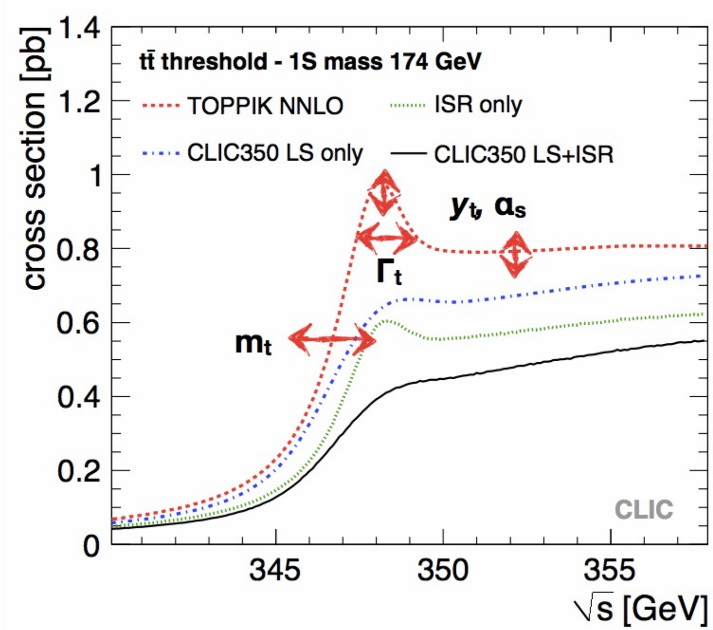
Top pair production at threshold

Small size of ttbar “bound state” at threshold ideal premise for precision physics

Cross section around threshold is affected by several properties of the top quark and by QCD

- Top mass, width Yukawa coupling
- Strong coupling constant





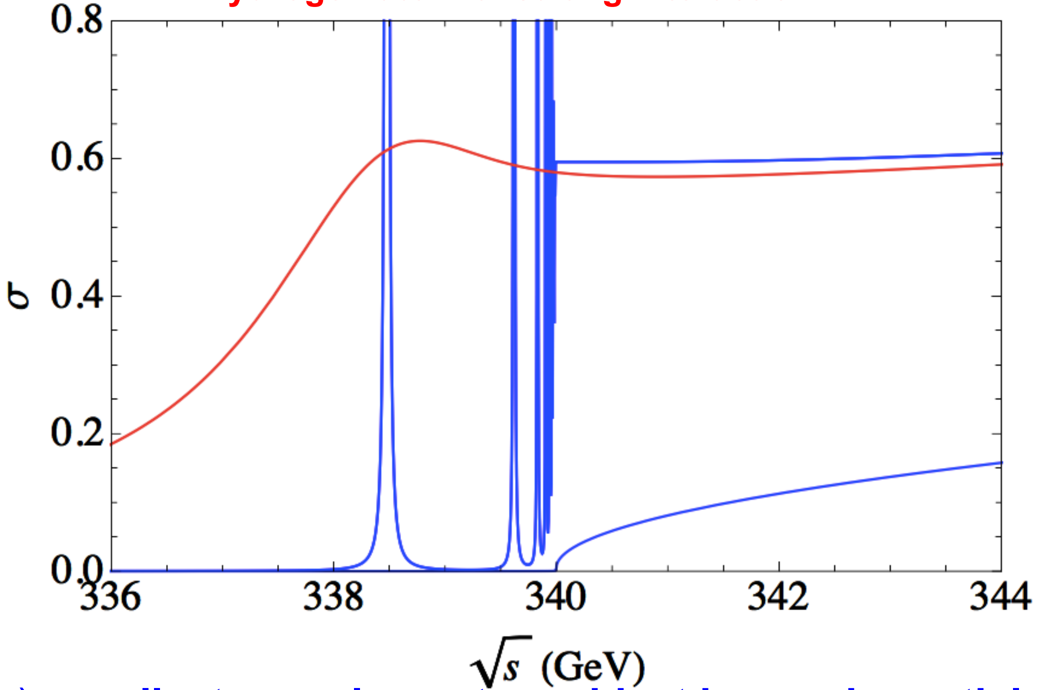
- Effects of some parameters are correlated:
- Dependence on Yukawa coupling rather weak,
- Precise external α_s helps

Top pair production at threshold

Linear Collider Vision

“Bound states” at tt threshold

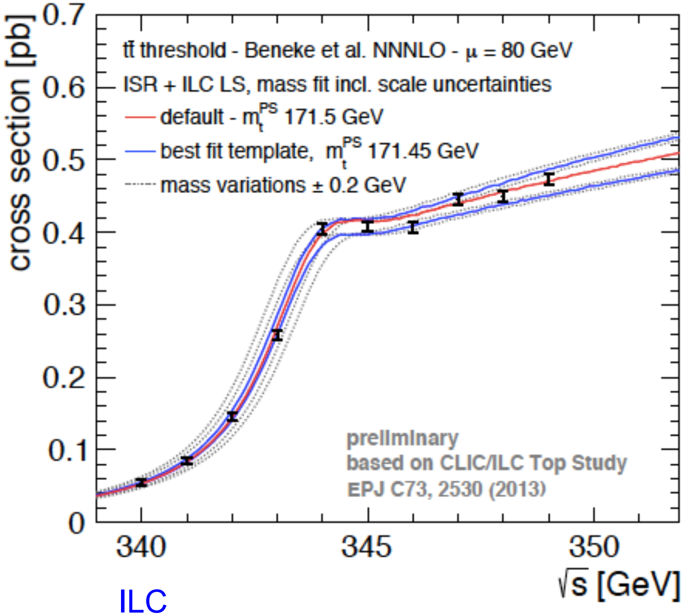
Hydrogen atom of strong interaction



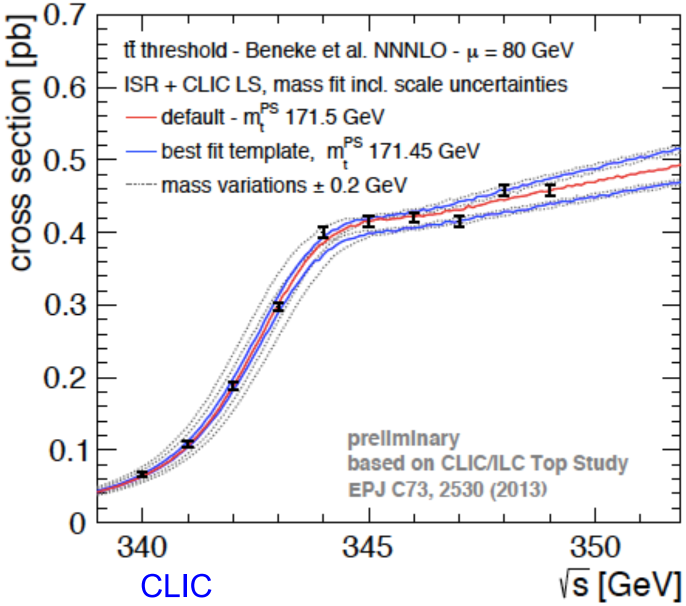
- Size O(10^{-17}m), **smallest non-elementary object known in particle physics**
  Small scale => Free of confinement effects => Ideal premise for precision calculations
  Measurement of (a hypothetical) 1^3S_1 State

- Decay of top quark smears out resonances in a well defined way

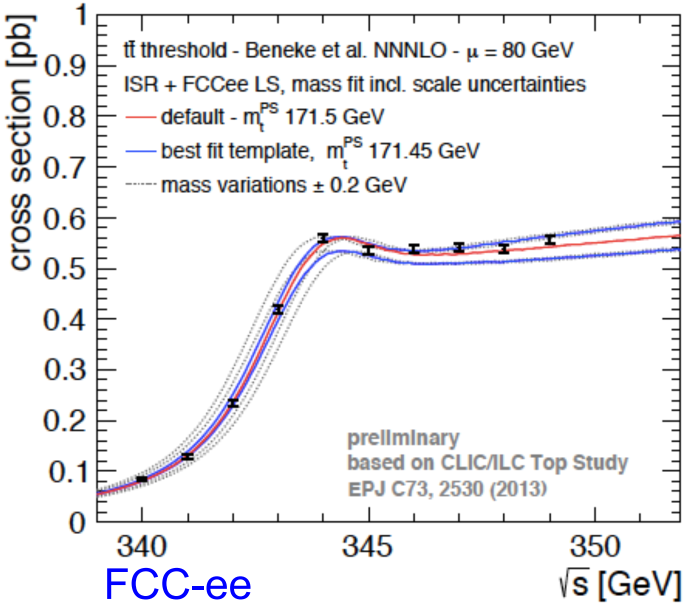
Top threshold scans at different e+e- colliders



ILC



CLIC



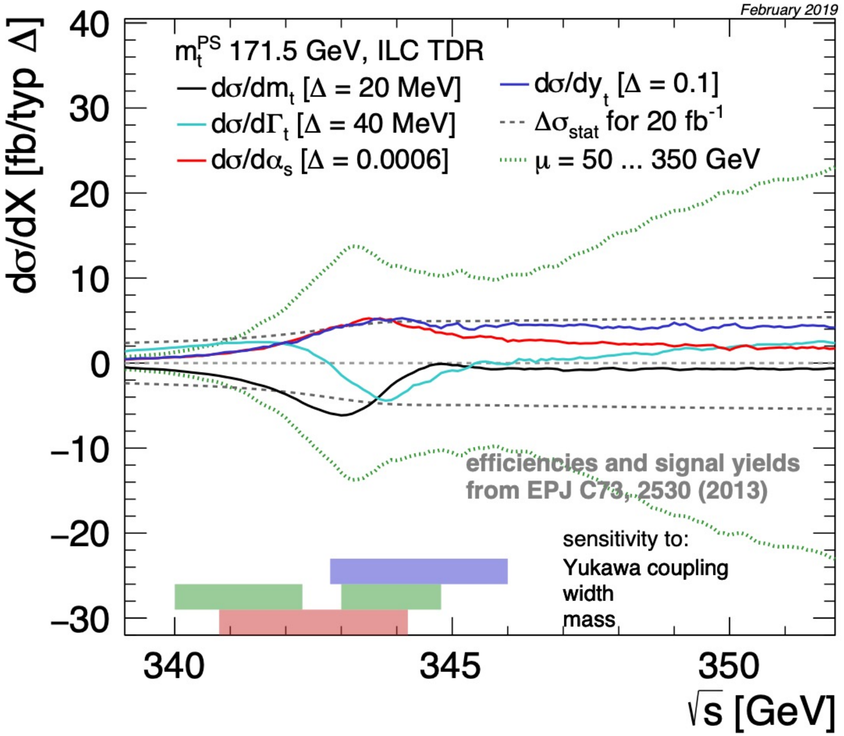
FCC-ee

Fit uncertainty:
28.5 MeV (18 MeV stat)

Fit uncertainty:
31 MeV (21 MeV stat)

Fit uncertainty:
27 MeV (15 MeV stat)

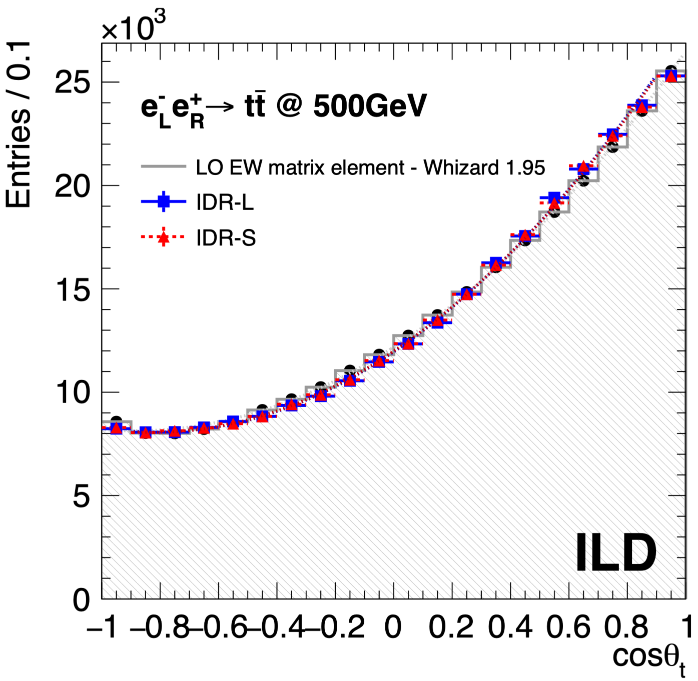
Sensitivity and error breakdown



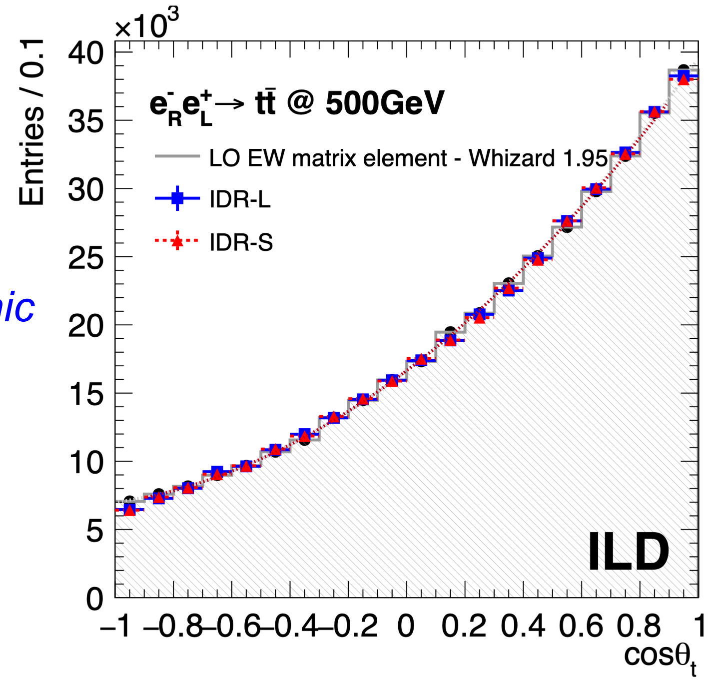
error source	Δm_t^{PS} [MeV]
stat. error (200 fb^{-1})	13
theory (NNNLO scale variations, PS scheme)	40
parametric (α_s, current WA)	35
non-resonant contributions (such as single top)	< 40
residual background / selection efficiency	10 – 20
luminosity spectrum uncertainty	< 10
beam energy uncertainty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

- Numbers for ILC/CLIC, some numbers get better for FCCee
  - e.g. Beam energy uncertainty < 3 [MeV]
- Uncertainty driver α_s
  - $\Delta m \sim 2.6$ per 10^{-4} in α_s

Top quark polar angle spectrum at 500 GeV



Semi-leptonic channel



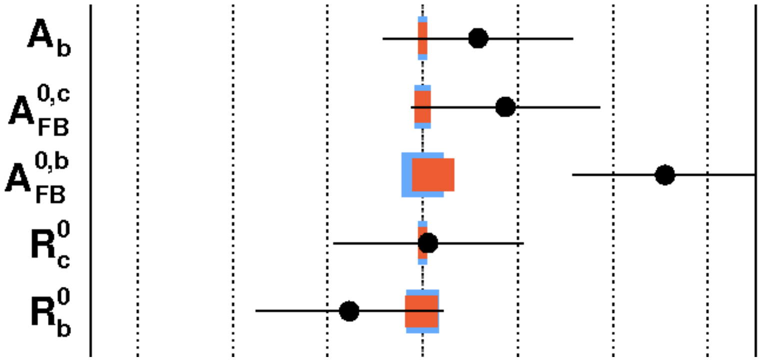
ILD-Note-2019-007

- Integrated Luminosity 4 fb^{-1}
- Exact reproduction of generated spectra
- Statistical precision on cross section: ~0.1%
- Statistical precision on A_{FB}: ~0.5%
  - Can expect that systematic errors will match statistical precision (but needs to be shown)
-

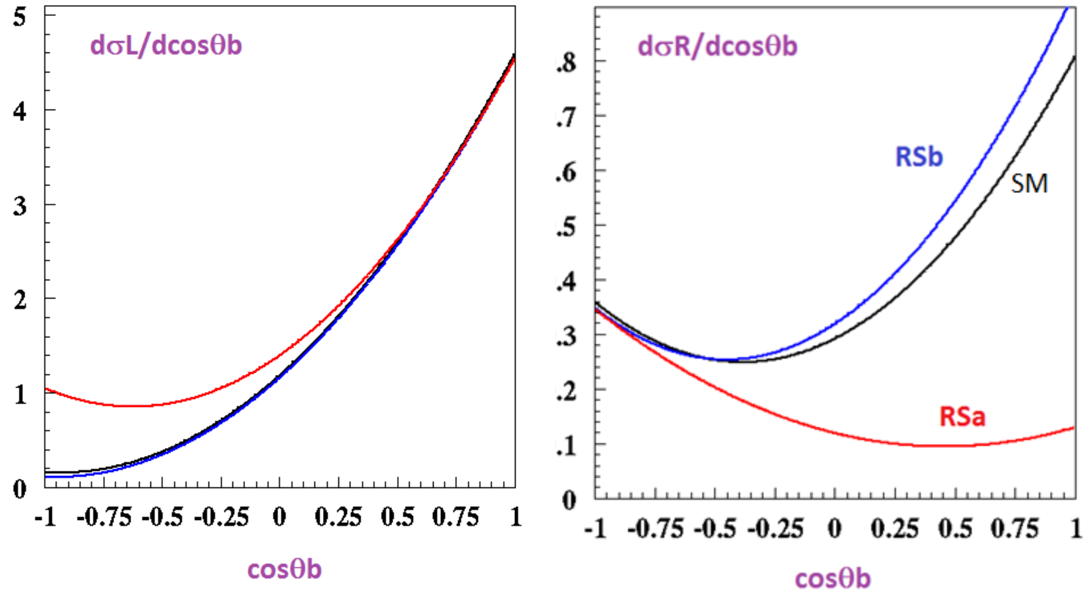
New physics below tt threshold? - Example b quark couplings

Linear Collider Vision

~3σ in heavy quark observable A^b_{FB}



ee->bb@250 GeV



Randall Sundrum Models Djouadi/Richard '06

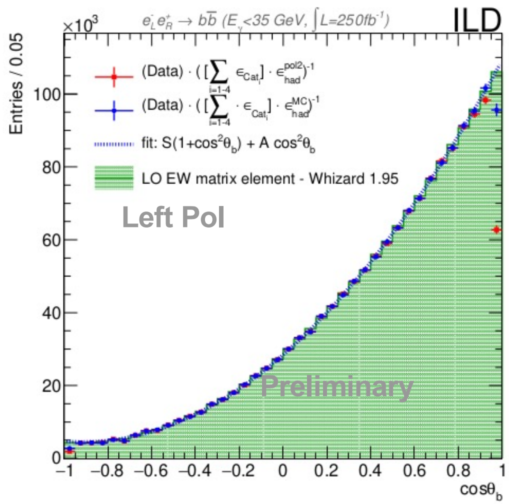
- Is tension due to underestimation of errors or
- due to new physics?

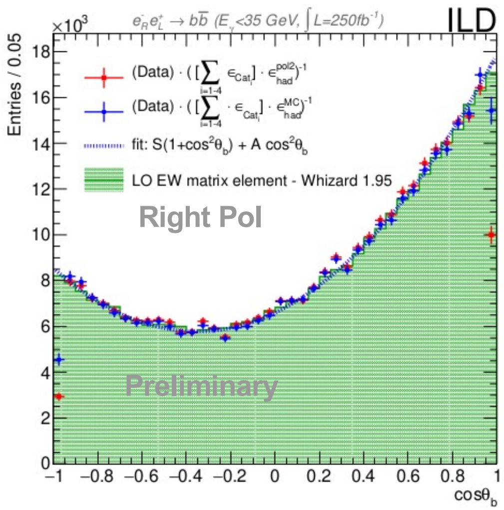
- High precision e+e- collider will give final word on anomaly

- In case it will persist polarised beams will allow for discrimination between effects on left and right handed couplings
- Randall Sundrum Models generate basically automatically a symmetry group of type $SU(2)_R$

Decomposing ee->bb – Differential cross section

Full simulation study within ILD Concept allows for educated guess on uncertainties on Z-Pole





Arxiv:1709.04289, ILD Paper in progress
A. Irles, SUSY2021

Excellent agreement between predicted and reconstructed distributions

- Gap between red dots and green histogram = acceptance drop.
- Blue dots = corrected acceptance
- The fit is restricted to |costheta|<0.8
  - *Minimal impact of the corrections*

Systematic uncertainties under scrutiny:

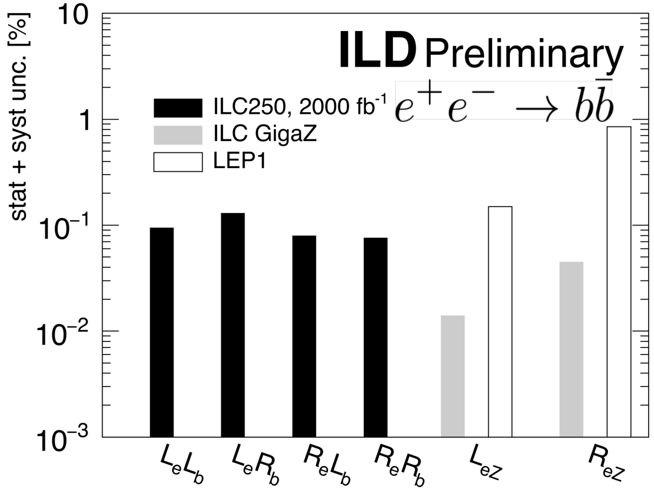
- Selection and background rejection
- quark tagging/mistagging (modelisation, QCD, correlations)
- Luminosity
- Polarisation

Additional complication in continuum: Rejection of ISR events – Uncertainty ~5x10^{-4} (doesn't apply on Z-pole)

Precision on electroweak form factors and couplings

Linear Collider Vision

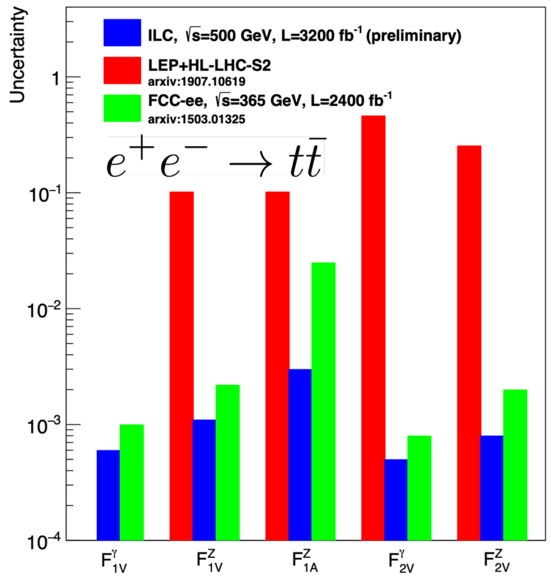
Arxiv:1709.04289, ILD Paper in progress



- Couplings are order of magnitude better than at LEP

$$\mathrm{LeLb} = QeQb + \frac{LeZLbZ}{s^2wc^2w}BWZ + \sum_{Z'}\frac{LeZ'LbZ'}{s^2wc^2w}BWZ'$$

ILC250 SM GigaZ New resonances



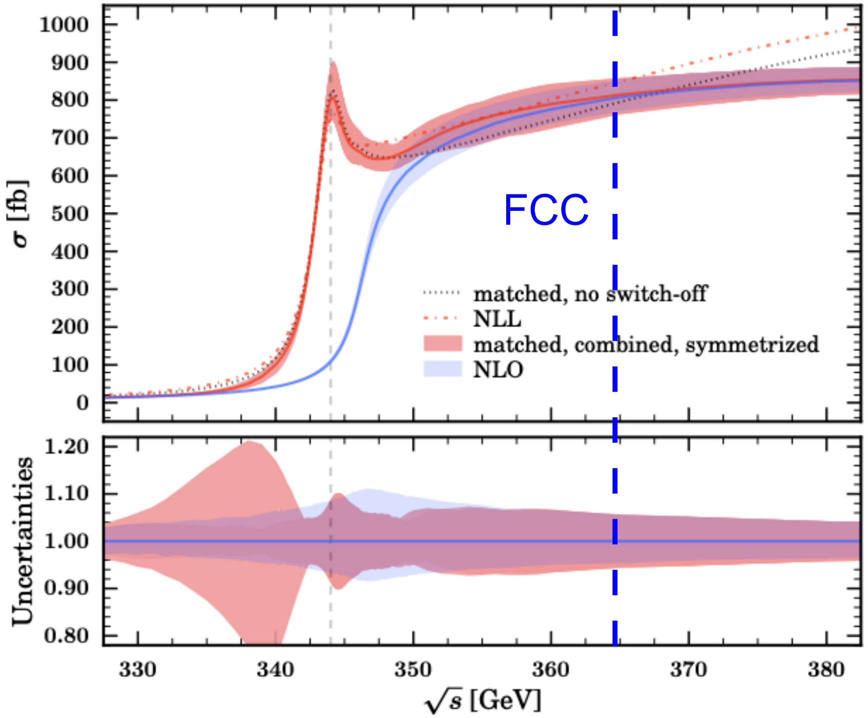
- e+e- collider way superior to LHC (√s = 14 TeV)
- Final state analysis at FCCee
  - Also possible at LC => Redundancy
- Two remarks:
  - 500 GeV is nicely away from QCD Matching regime
    - Less systematic uncertainties
  - Axial form factors are ~β and benefit therefore from higher energies

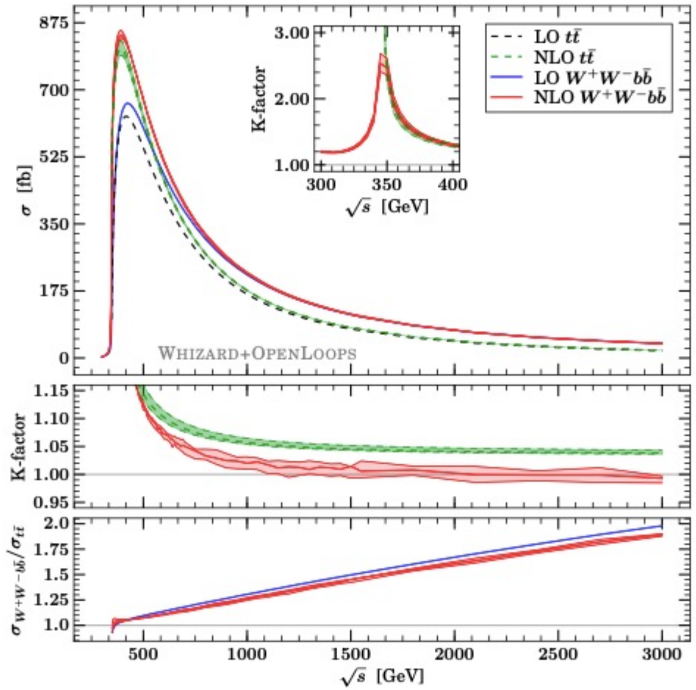
- Full disentangling of helicity structure for all fermions only possible with polarised beams!!

QCD uncertainties on ee->tt cross section

$e^+e^- \to W^+bW^-\bar{b}$

Linear Colliders →





- Marching non-relativistic calculations in threshold region with tt-continuum is theoretical challenge
- QCD uncertainties shrink as energy increases
- Non resonant contributions are important (i.e. ee->tt --> ee->WbWb)

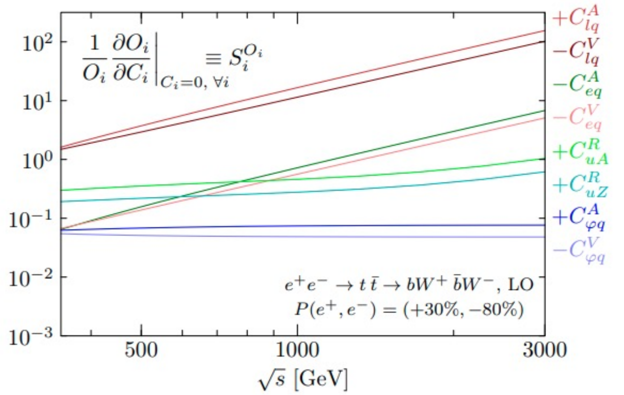
J. Reuter, FCCee-France Workshop, Annecy and arXiv 1609.03390

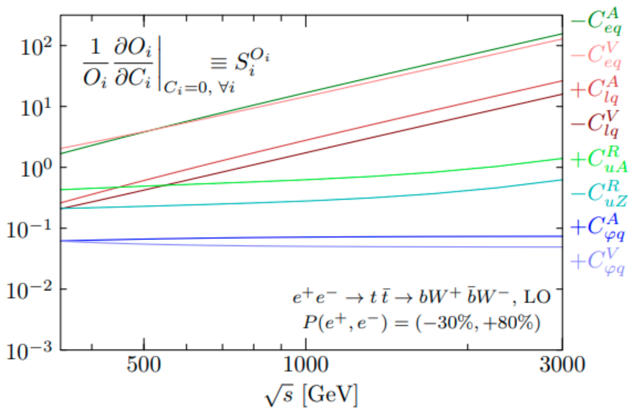
Effects at higher energies

Linear Collider Vision

Development of EFT Operators

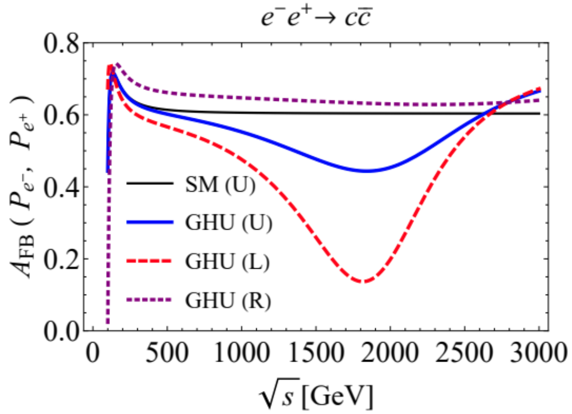
arxiv:1807.02121

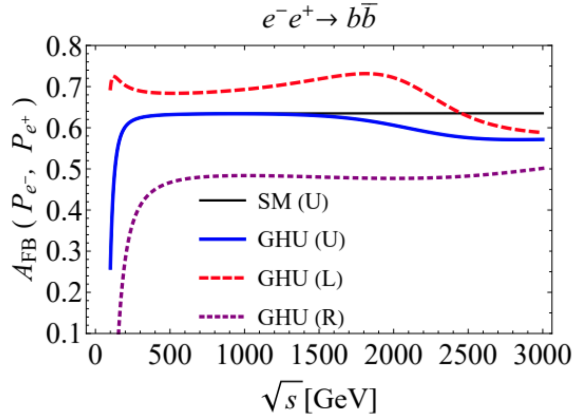


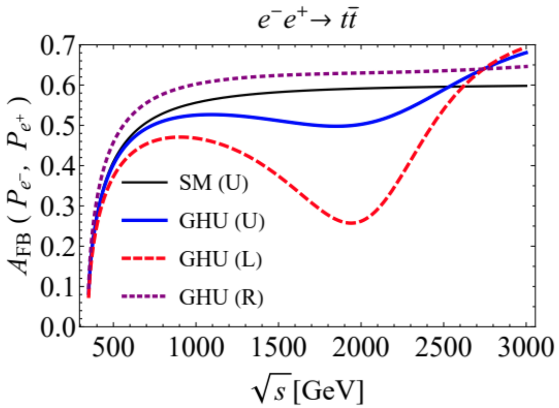


Increased sensitivity to operators representing four-fermion interactions

GUT Inspired GHU Model (Hosotani et al.)







- Effects amplified at
- higher energies

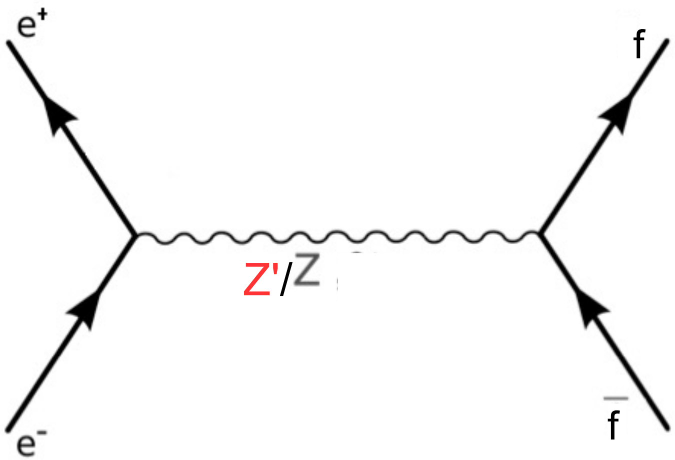
- Different patterns for
- different beam polarisations
- (L, U, R)

- Different patterns
- for different fermions
-

70

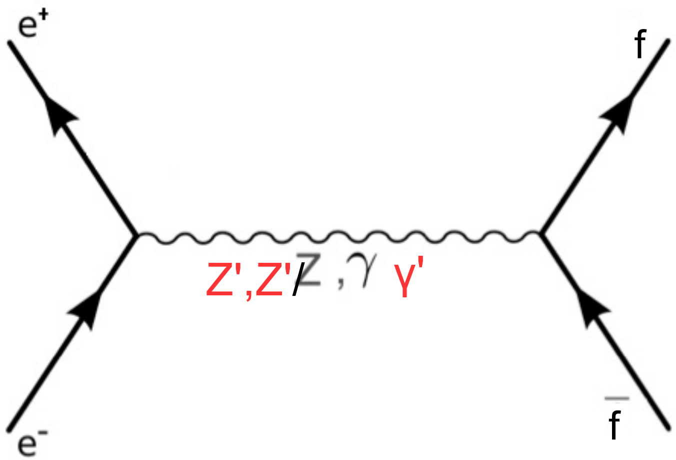
How can the Z-pole help?

On the Z-pole



- ILC/GigaZ with ~10^9 Z
- Sensitivity to Z/Z' mixing
- Sensitivity to vector (and tensor)
- couplings of the Z
  - the photon does not “disturb”

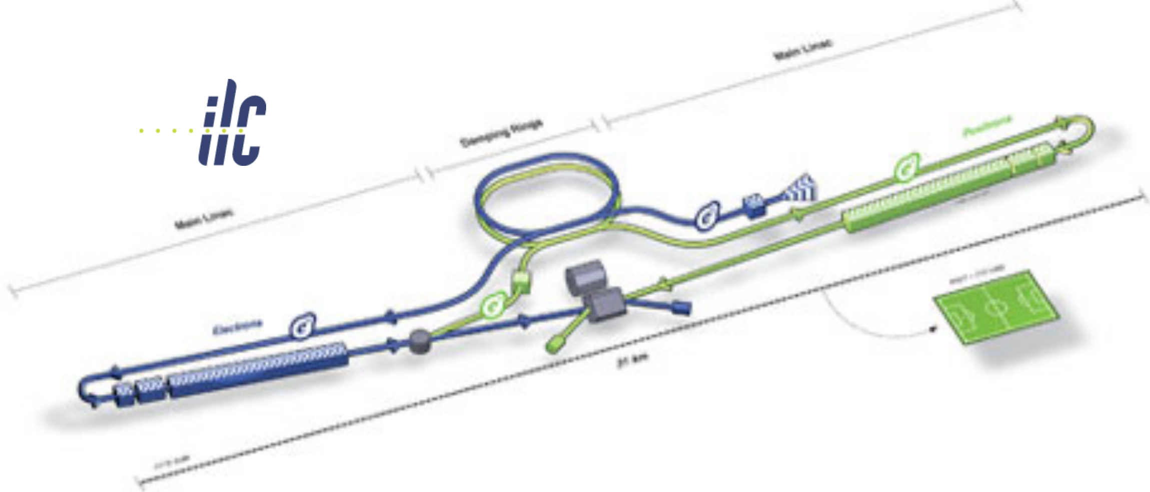
Above the Z-pole



- Sensitivity to interference effects of Z and photon!!
- Measured couplings of photon and Z can be influenced
- by new physics effects
- Interpretation of result is greatly supported by precise input
- from Z pole

Linear Electron Positron Colliders - ILC

Linear Collider Vision



Energy: 0.1 - 1 TeV
Electron (and positron) polarisation
TDR in 2013
+ DBD for detectors
Footprint 31 km

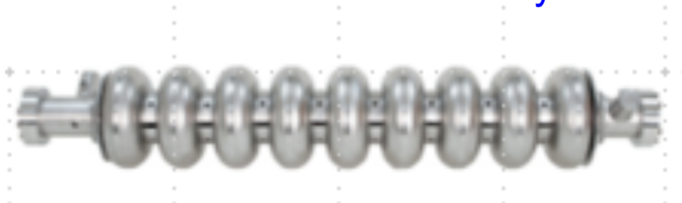
Initial Energy 250 GeV – Footprint ~20km

Under discussion in Japanese Gouvernment and inernational community
Recently: Budget request by Japanese Government of for ILC related accelerator studies (10 Oku Yen = doubling of budget)

ILC design parameters	
$\sqrt{s}$	91-500 GeV
$\mathcal{L}$	2×10^{34} cm^{-2}s^{-1}
P_{e-}	>80%
P_{e+}	upto 30%
Length	~31 km

Design Gradient: 31,5 MV/m

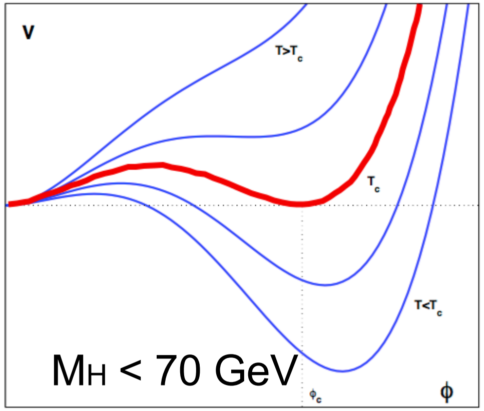
ILC Nine-Cell SRF Cavity

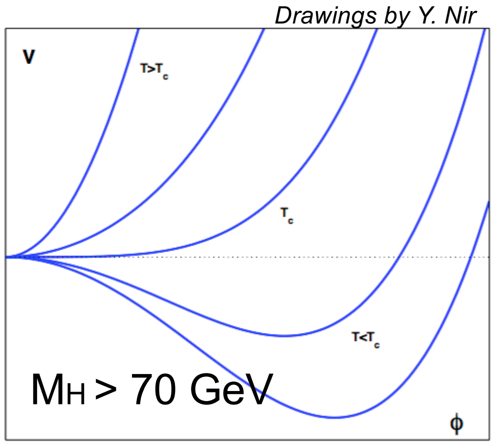


- Since 2020 ILC Development is organised within
- International Development Team
- https://linearcollider.org/team/

Phase Transition in Standard Model

Electroweak Baryogenesis requires 1st Order PT





- Coexistence Two minima at **0 and v_c at T_c**

=> 1st order phase transition
and development into “today's” shape at T=0

- No coexistence of two minima at **0 and v_c**

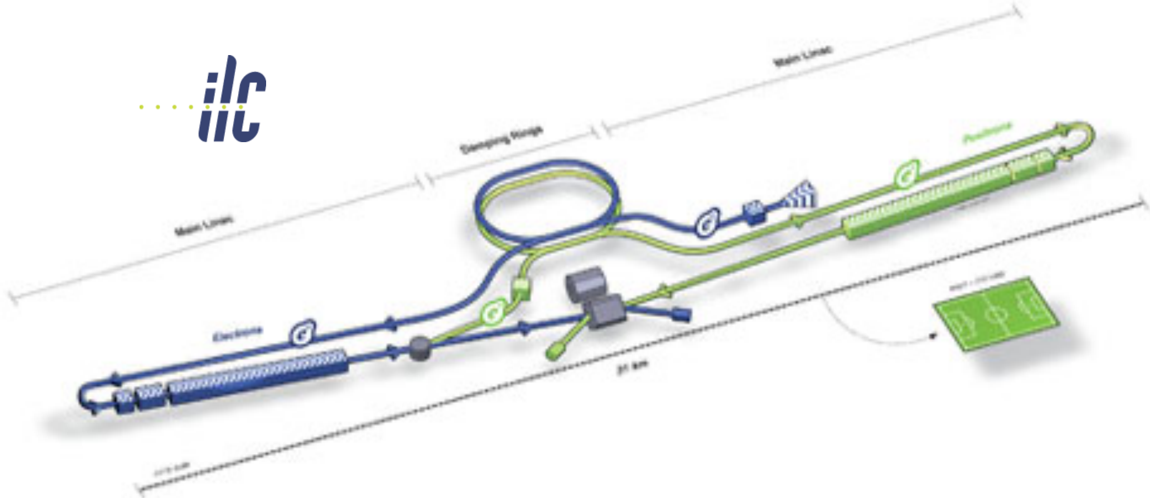
=> Cross over into “today's” shape at T=0

The discovered Higgs is too heavy to provoke a 1st order phase transition

=> New physics needed

Linear Electron-Positron Colliders

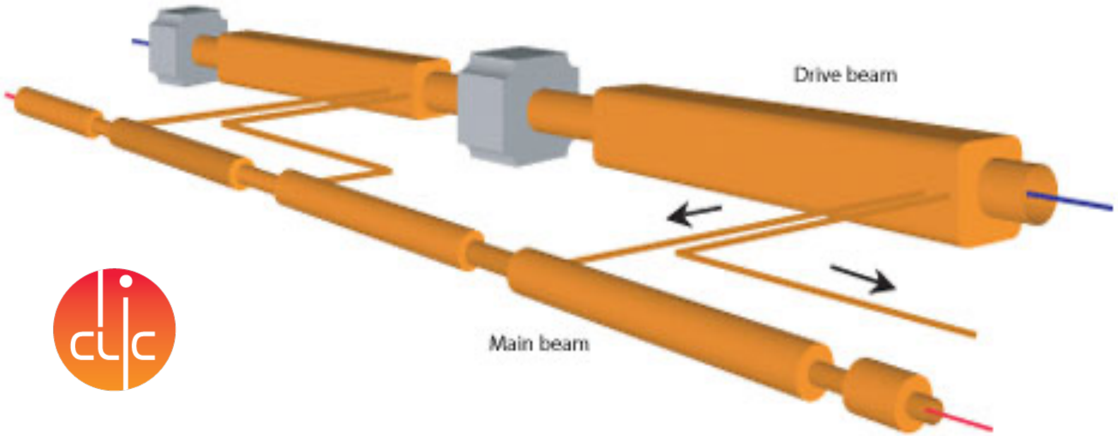
Linear Collider Vision



Japanese Gouvernment expressed its interest in project in March 2019

Energy: 0.1 - 1 TeV
Electron (and positron) polarisation
TDR in 2013
+ DBD for detectors
Footprint 31 km

Initial Energy 250 GeV – Footprint ~20km



Energy: 0.4 - 3 TeV

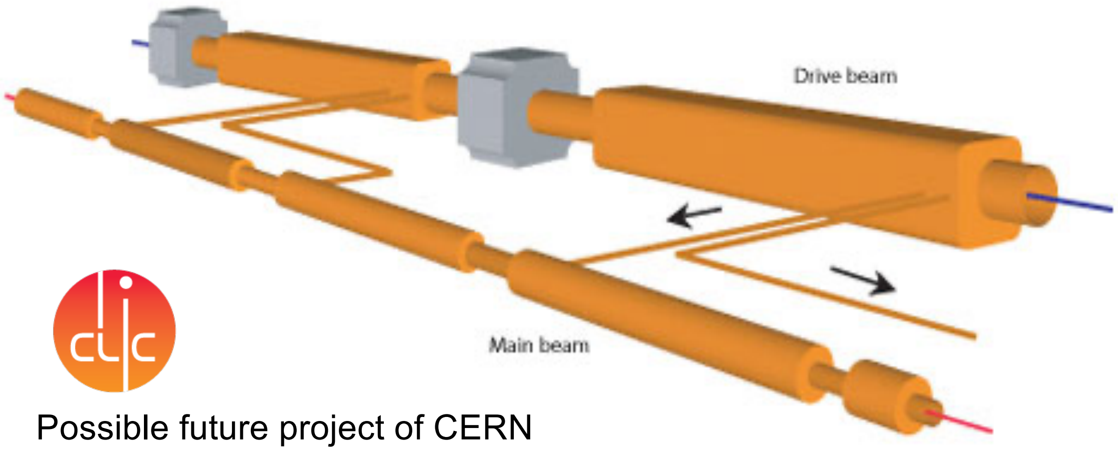
CDR in 2012

Footprint 48km

Initial Energy 380 GeV

Possible future project at CERN

Linear Electron Positron Colliders



Possible future project of CERN

Energy: 0.4 - 3 TeV

CDR in 2012
Update 2016

Footprint 48km

Initial Energy 380 GeV

Cool Copper Collider

- Based on new RF Technology
- Operation at Cryogenic temperature (LN2 ~ 80K)
- Aiming at gradients of 120 MV/m

75

New physics?

- Polarized beams play a crucial role in disentangling the two spin structures

$$\sigma = \frac{2}{3}\frac{\pi\alpha_w^2}{c_w^4}\frac{m_Z^2}{(s-m_Z^2)}\frac{2k_Z}{\sqrt{s}}(2+\frac{E_Z^2}{m_Z^2})\cdot Q_Z^2\cdot\left[1+2a+2\,\frac{3\sqrt{s}E_Z/m_Z^2}{(2+E_Z^2/m_Z^2)}\,b\right]$$

The a and b coefficients depend on beam polarization:

$e_L^- e_R^+$

$$Q_{ZL} = (\frac{1}{2} - s_w^2)\ , \qquad a_L = -c_H$$

$$b_L = c_w^2(1+\frac{s_w^2}{1/2-s_w^2}\frac{s-m_Z^2}{s})(8c_{WW})$$

$e_R^- e_L^+$

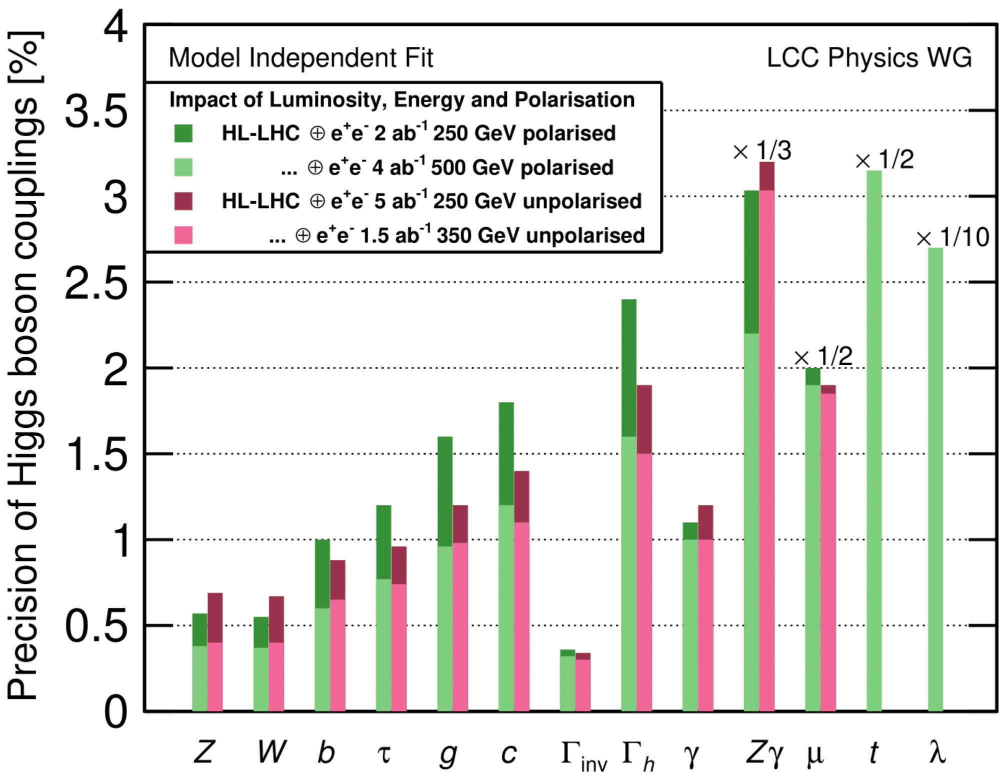
$$Q_{ZR} = (-s_w^2)\ , \qquad a_R = -c_H$$

$$b_R = c_w^2(1-\frac{s-m_Z^2}{s})(8c_{WW})$$

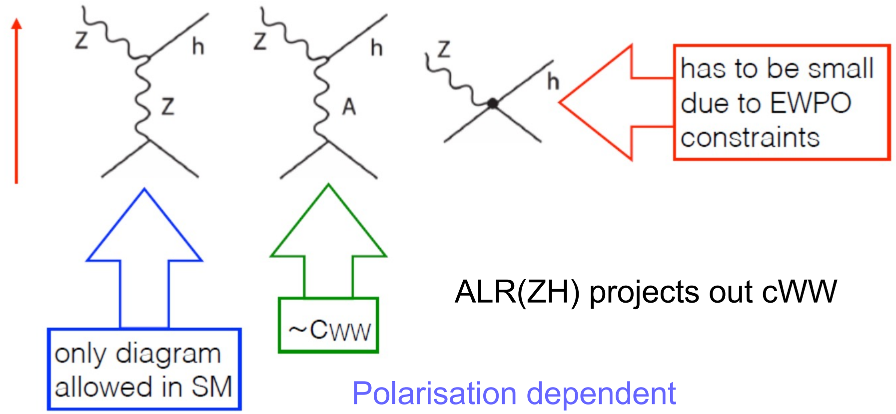
- Angular distributions in $e^+e^- \to hZ$ can also be used, but have weaker analyzing power and require more luminosity to achieve the same result

M. Perelstein: AWLC2017

EFT Framework and beam polarisation



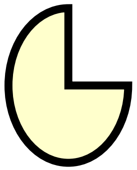
- EFT adds additional spin structure to ZH production cross section (see backup)



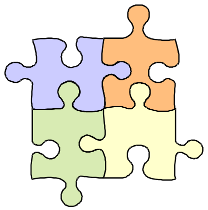
- Precision for 2ab-1 polarised = 5ab-1 unpolarised

Science drivers

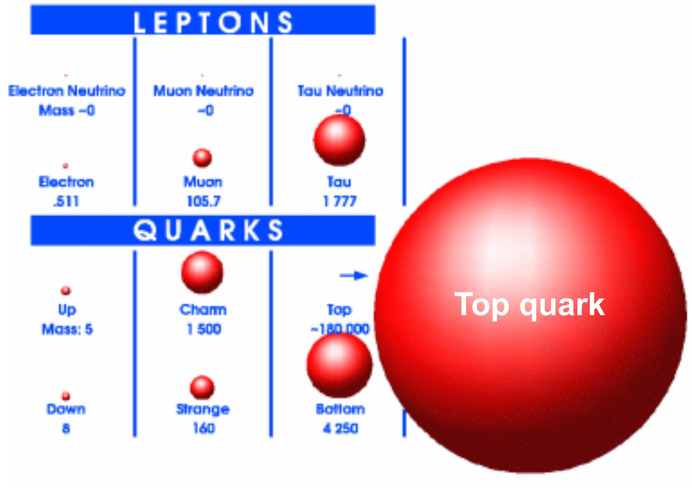
- Higgs Boson



Elementary Scalar?

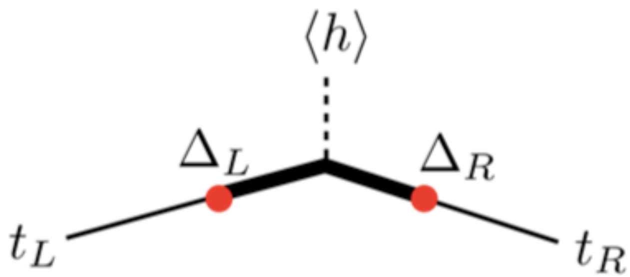


Composite object?



- Higgs and top quark are intimately coupled!
  Top Yukawa coupling O(1) !
  => Top mass important SM Parameter

- New physics by compositeness?
  Higgs <u>and</u> top composite objects?

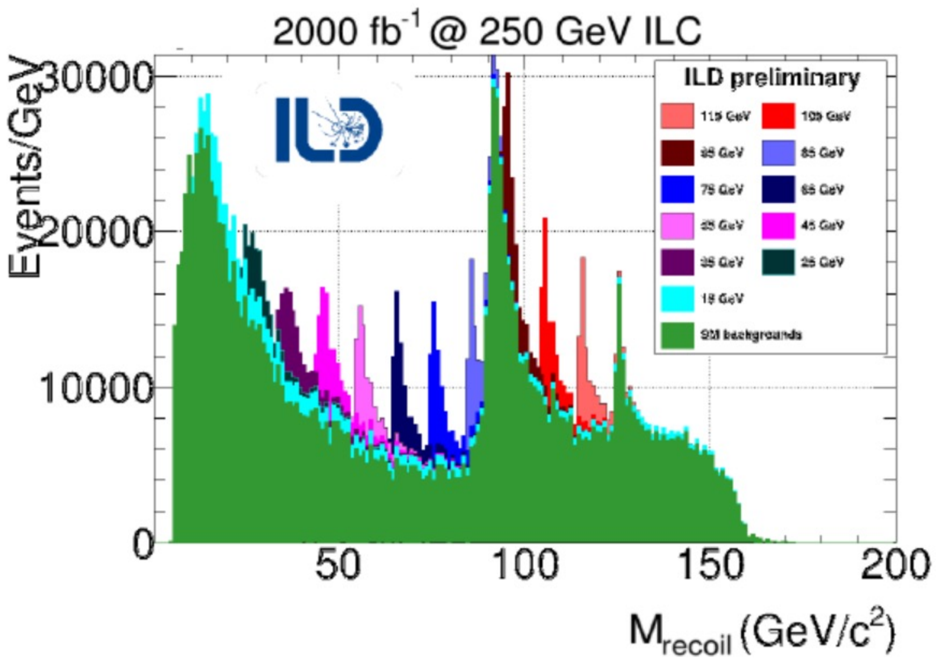


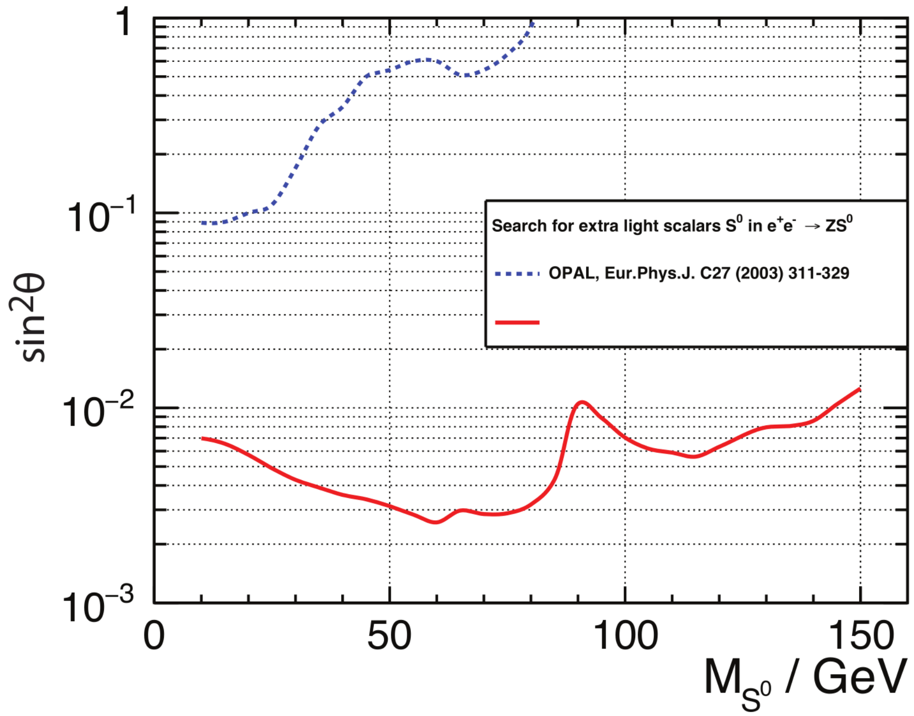
Courtesy of S. Rychkov

- e+e- collider perfectly suited to decipher both particles

Light scalar study in ILD

Light scalar may be missing piece to trigger first order 1st transition and/or the being the radion in extra dimension theories

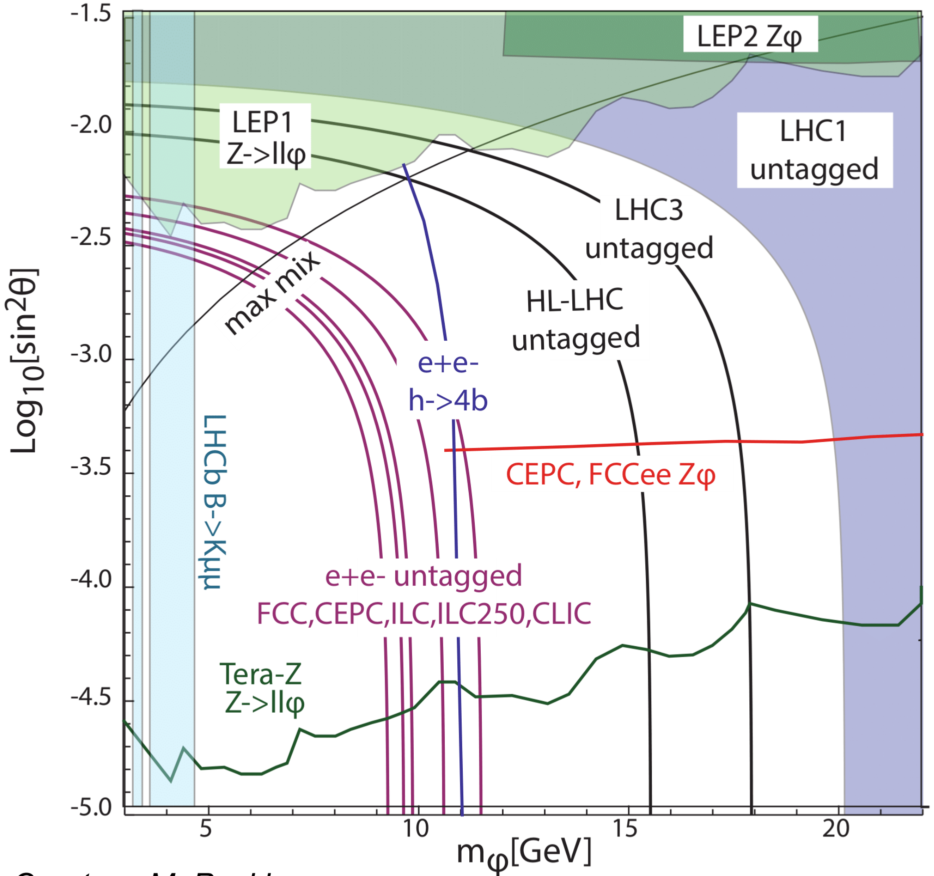




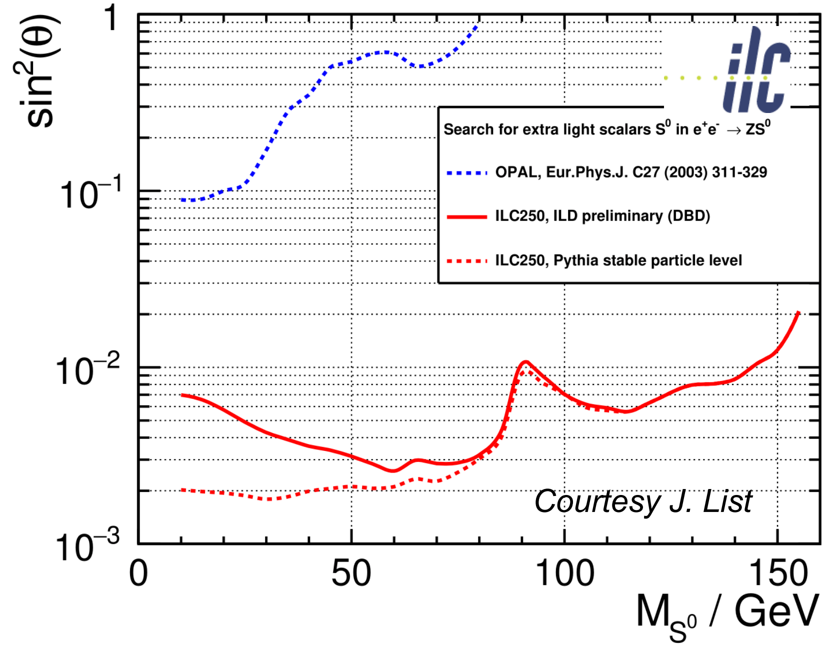
- New resonances cleanly dinstiguishable for large range of masses
- Sensitivity to mixing angle θh down to 10^{-2} (taking all relevant backgrounds into account)
- └new scalar would count as “Feebly interacting Particle” (FIPS)

Feebly interacting particles – A summary

Light scalar may be missing piece to trigger first order 1st phase transition and/or being the radion in extra dimension theories



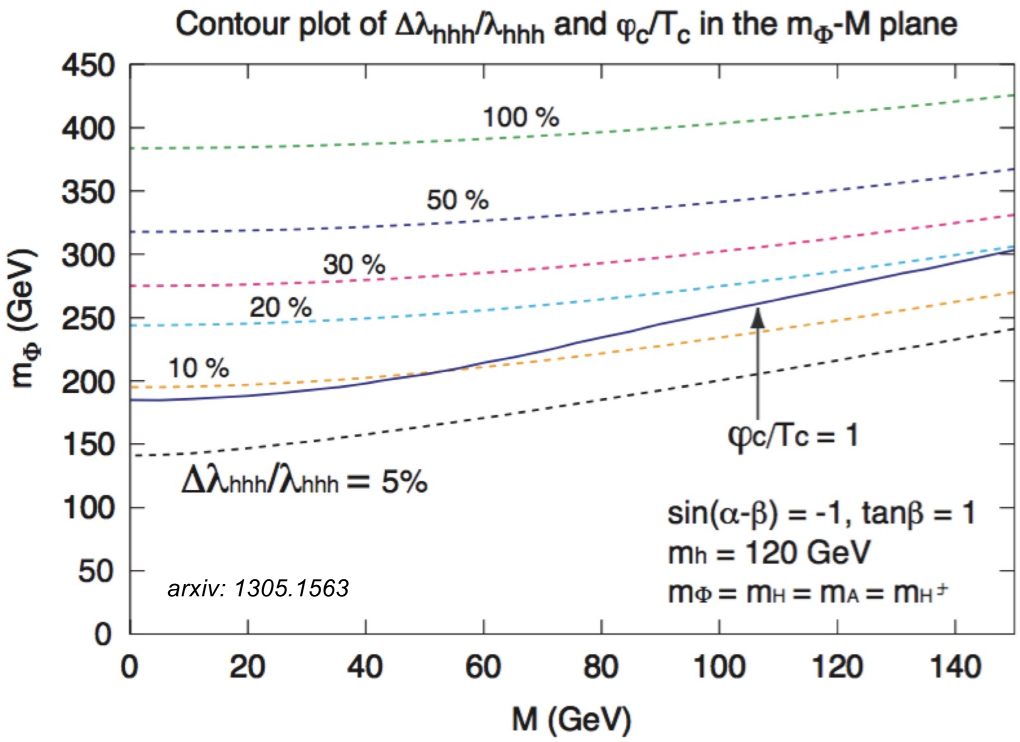
Courtesy M. Peskin



- e+e- colliders extend limits considerably w.r.t. LHC
  - Statistics helps at lowest masses
- CEPC, FCCee (>Z pole) limits order of magnitude
- better than ILC
  - Backgrounds taken correctly into account?
  - Similar at stable particle level

New particles – Extended Higgs Sector

Heavy Higgs Mass



Deviations of λ from SM Value

- New (bosonic) particle may modify λ and enable 1st order phase transition
- Impact on measurements and achievable precisions of λ ?

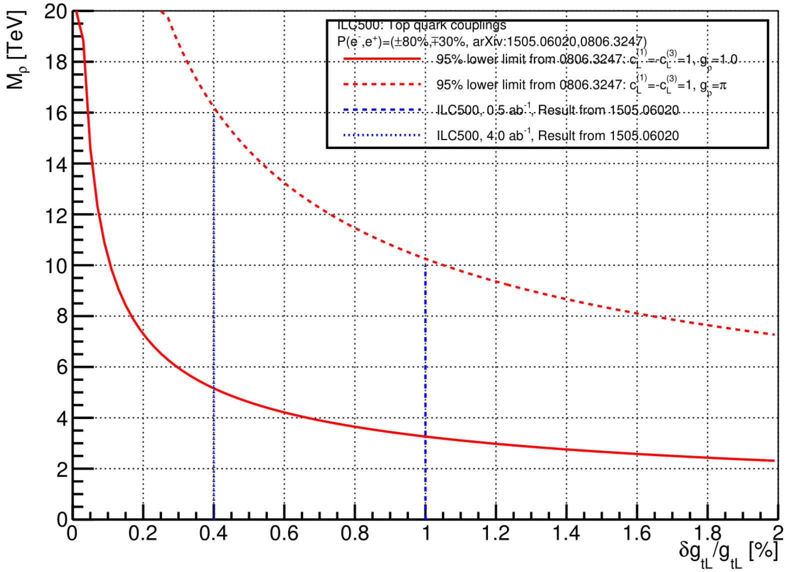
Electroweak top couplings and discovery reach

Linear Collider Vision

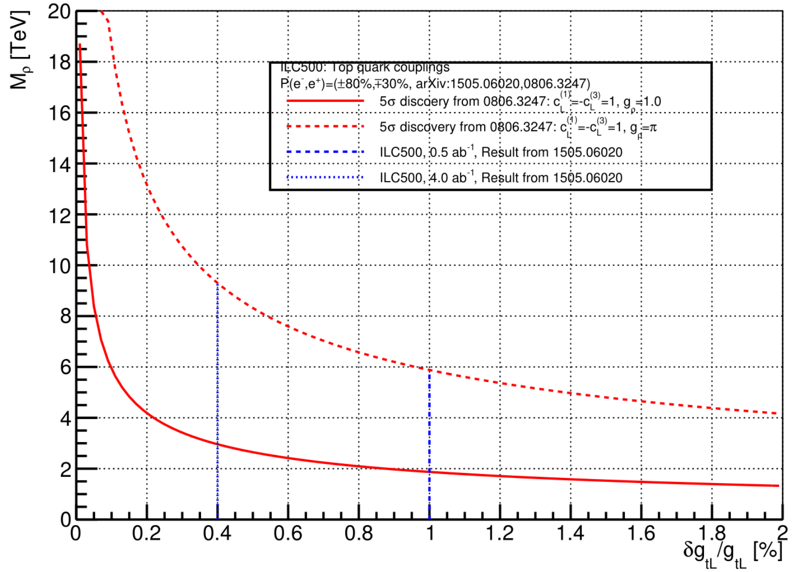
New physics reach for typical BSM scenarios with composite Higgs/Top and/or extra dimensions

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

95% Exclusion Limit



5σ discovery

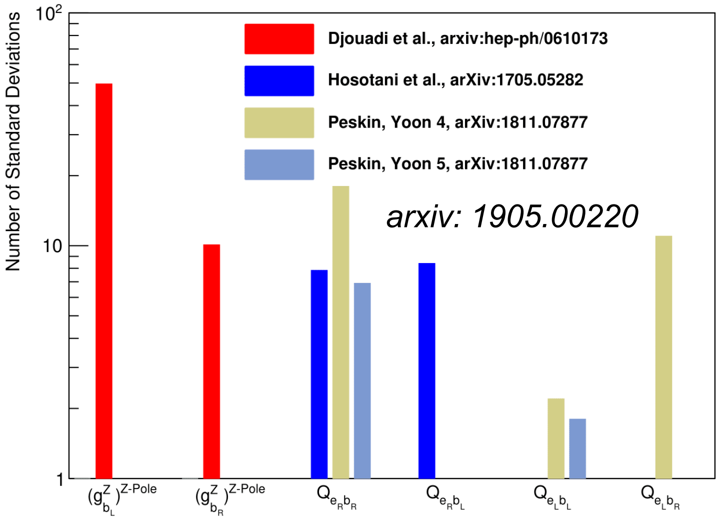


ILC@500 has discovery potential up to 10 TeV for typical BSM scenario

More cms e.g. at CLIC would of course help a great deal (also for disentangling effects)

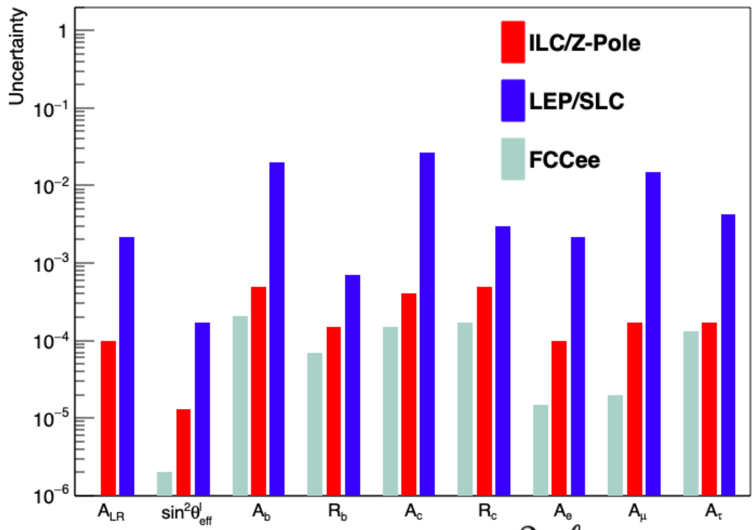
Precision on Z-pole and interplay with measurements above pole

Example: b couplings and helicity amplitudes



- Spectacular sensitivity to new physics in RS Models
  - **Complete tests only possible at LC**
  - **Discovery reach O(10 TeV)@250 GeV and O(20 TeV)@500 GeV**
- Pole measurements critical input
  - Only poorly constrained by LEP
- Pole measurements will (most likely) influence
- also top electroweak precision program
  - (t,b) doublet

Don't forget: Electroweak observables



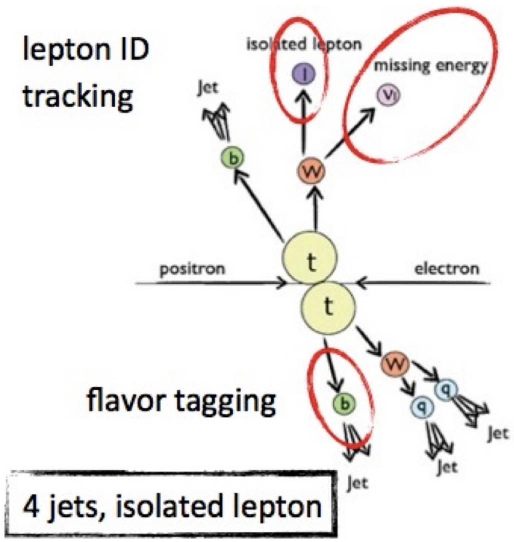
- Precise measurement of $\sin^2\theta^\ell_{\text{eff}}$.
  - Ten times better than LEP/SLD
  - Polarisation compensates for ~30 times luminosity
  - ... and ALR at LC can benefit from hadronic Z decays
  - **No assumption on lepton universality at LC**
- Complete test of lepton universality
  - Precisions of order 0.05%
- Excellent control of beam polarisation(dP/P ~ 5×10^{-4})
- and beam energy (~MeV or better) required

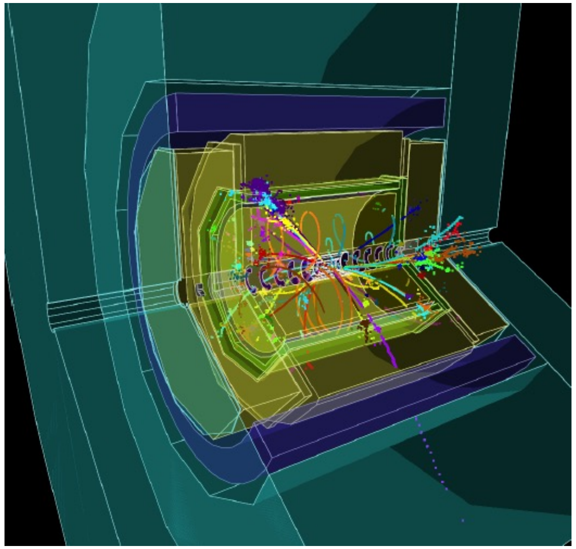
Elements of top quark reconstruction

Three different final states:

1) Fully hadronic (46.2%) → 6 jets
2) Semi leptonic (43.5%) → 4 jets + 1 charged lepton and a neutrino
3) Fully leptonic (10.3%) → 2 jets + 4 leptons

$$t\bar{t} \to (bW)(bW) \to (bqq')(b\ell\nu)$$

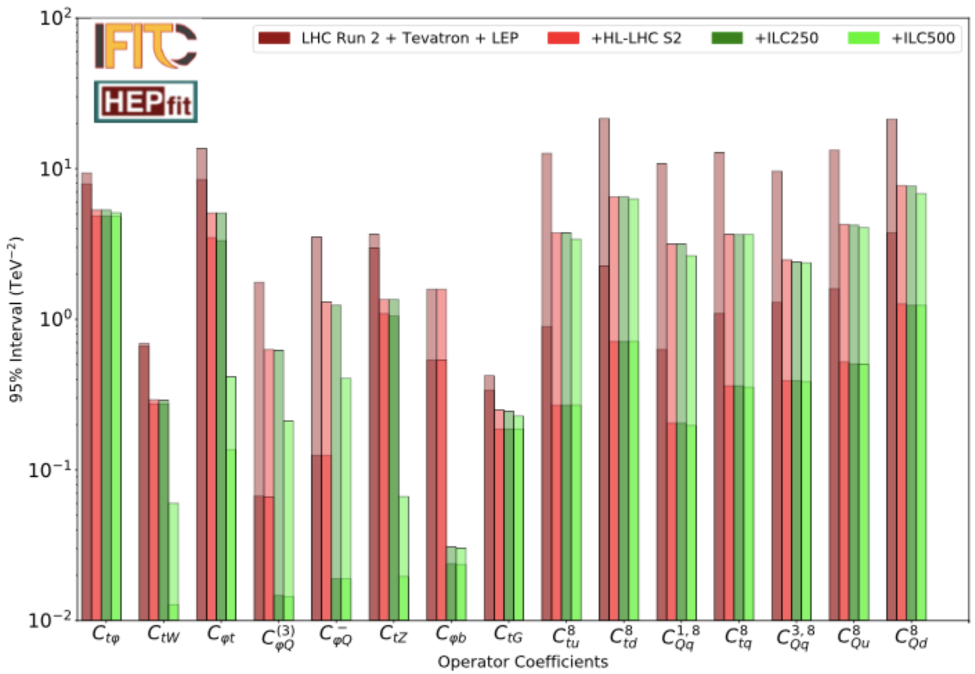




Final state reconstruction uses all detector aspects

Results shown in the following are based on full simulation of LC Detectors

Electroweak top couplings EFT-operators



arxiv:2203.07622
Updated from arxiv:1907.10619

Mapping between FF and EFT Coefficients

$$F^Z_{1V} = \frac{\frac{1}{4} - \frac{2}{3}s_W^2}{s_W c_W} - \frac{m_t^2}{\Lambda^2}\frac{1}{2 s_W c_W}\left[C^V_{\varphi q} = C^{(33)}_{\varphi u} + (C^{1(33)}_{\varphi q} - C^{3(33)}_{\varphi q})\right],$$

$$F^Z_{1A} = \frac{-\frac{1}{4}}{s_W c_W} - \frac{m_t^2}{\Lambda^2}\frac{1}{2 s_W c_W}\left[C^A_{\varphi q} = C^{(33)}_{\varphi u} - (C^{1(33)}_{\varphi q} - C^{3(33)}_{\varphi q})\right],$$

$$F^Z_{2V} = 4\frac{m_t^2}{\Lambda^2}\left[C^R_{uZ} = \mathrm{Re}\{c_W^2 C^{(33)}_{uW} - s_W^2 C^{(33)}_{uB}\}/s_W c_W\right],$$

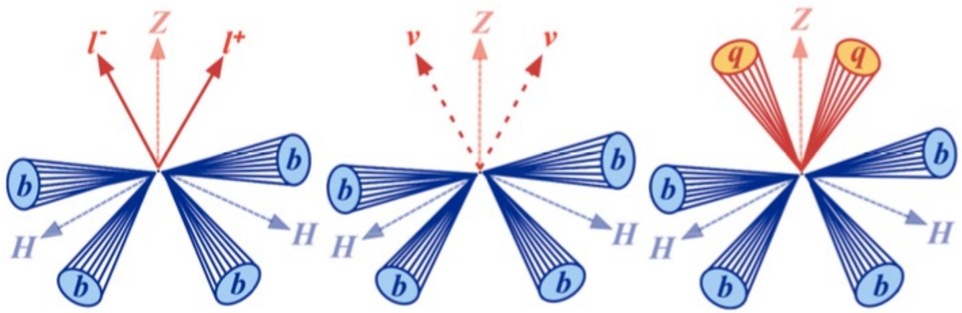
$$F^Z_{2A} = 4\frac{m_t^2}{\Lambda^2} i \left[C^I_{uZ} = \mathrm{Im}\{c_W^2 C^{(33)}_{uW} - s_W^2 C^{(33)}_{uB}\}/s_W c_W\right],$$

arxiv:1807.02121

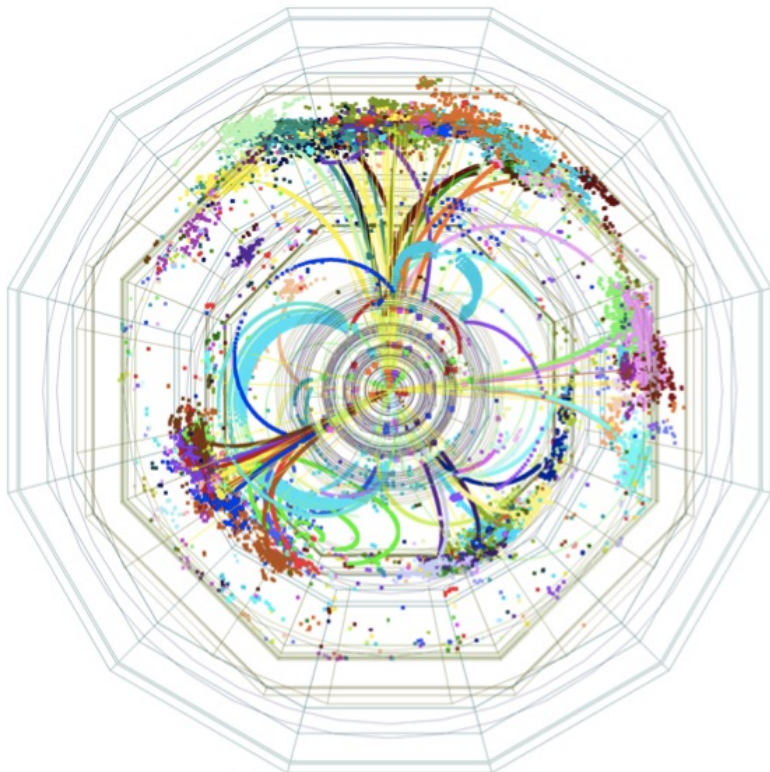
- Translation of results into EFT language confirm superiority of e+e- w.r.t. LHC
- Several operators benefit already from 250 GeV running
- Top specific operators constrained by running at 500 GeV

Higgs self-coupling – Experimental issues

Linear Collider Vision



ILD Event Display

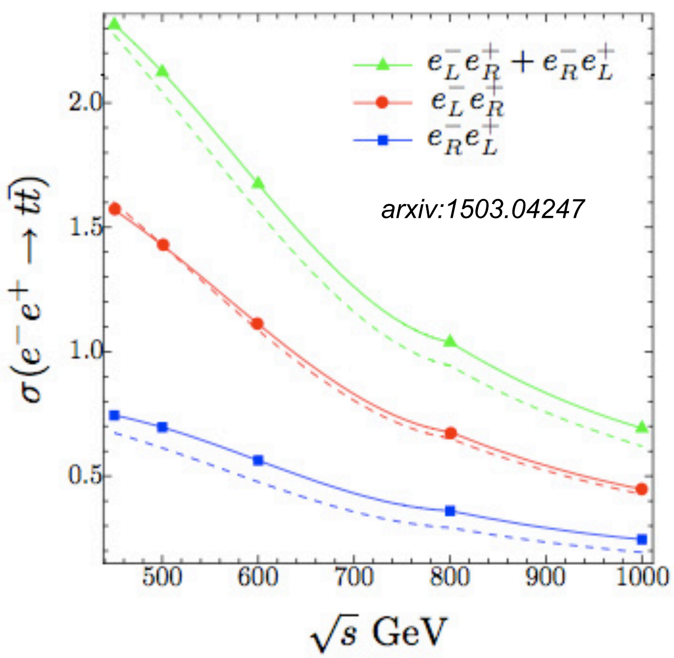


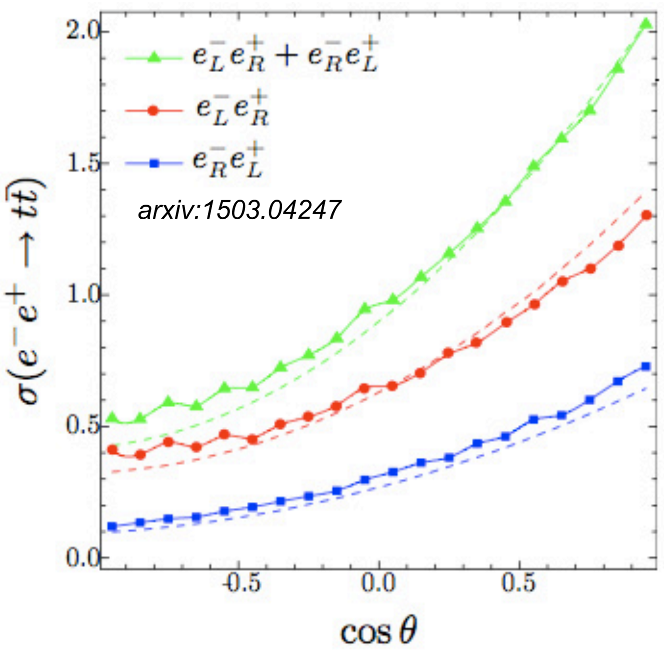
- Up to six jets in final state
  - Excellent jet and particle separation and
  - (nearly) 4pi hermeticity required

- Four b-quarks
  - Excellent flavor tagging
  - Results shown in the following profit from
  - recent improvements

Julie Munch Torndal *and* *DESY-THESIS-2016-027*

High Order Electroweak Corrections





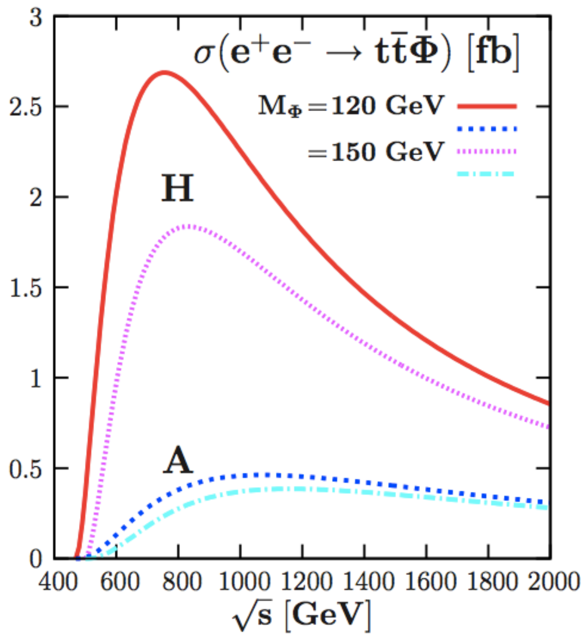
- Electroweak corrections manifest themselves differently for different beam polarisations

Beam polarisation important asset to disentangle SM and effects of new physics
Configuration $e^-_R e^+_L$ seems to lead to "simpler" corrections

Higgs Quantum Number – CP via tth

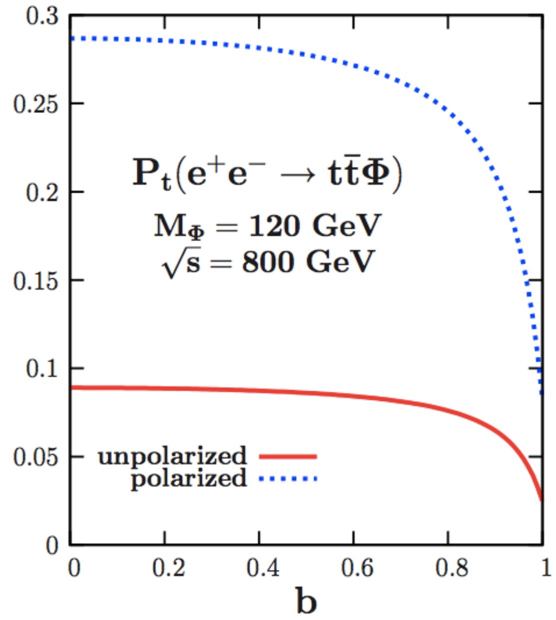
Direct coupling of top quark to CP odd and CP even scalar

Cross section



Dramatic differences for
CP odd and CP even scalar

Top quark polarisation



Sensitivity to CP odd admixture b
Merit of beam polarisation

Determination of CP nature of scalar boson in an unambiguous way

Godbole et al., LCWS07

Electroweak Precision Observables

Copied from deBlas, Higgs-Hunting 2016

- Precise measurements of W&Z properties taken at e+e- colliders
- and in part also at Tevatron/LHC

$$M_Z,\ \Gamma_Z,\ \sigma_{had}^0,\ \sin^2\theta_{\rm eff}^{\rm lept},\ P_\tau^{Pol},\ A_f,\ A_{FB}^{0,f},\ R_f^0$$

$M_W,\ \Gamma_W$ W-observables LEP2 0.02 - O(1%)

- Tevatron/LHC but in future also from e+e- colliders

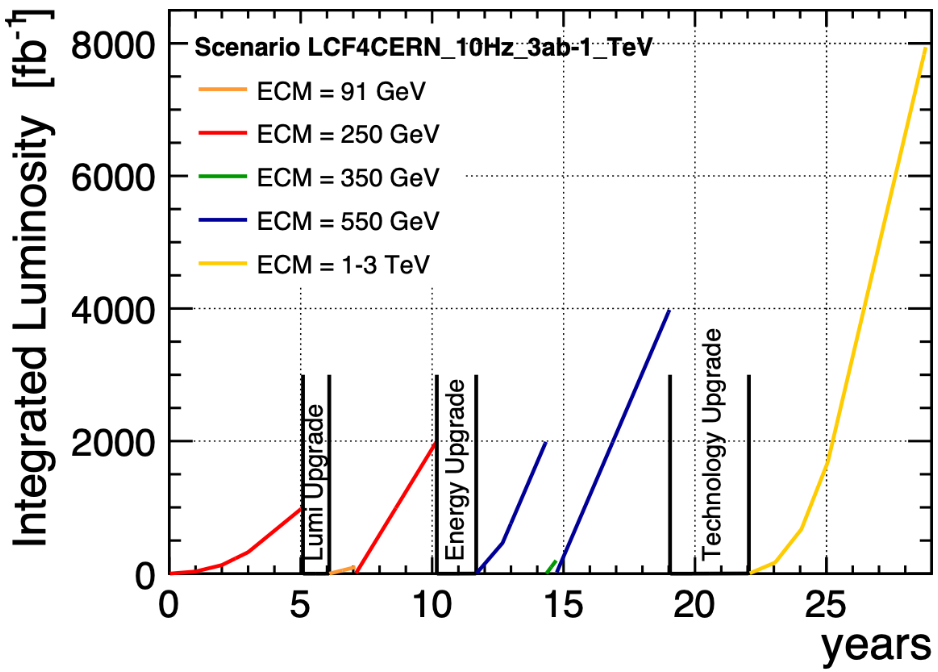
$M_W,\ \Gamma_W$	m_t	M_H
0.02-O(1%)	0.4%	0.2%

89

Running Scenarios – Shortening 550 GeV in favor of 1 TeV

Linear Collider Vision

Tech upgrade after 550 GeV



Tech upgrade after 250 GeV