Top, flavour, and electroweak at a linear collider

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INTERNATIONAL WORKSHOP ON FUTURE LINEAR COLLIDERS

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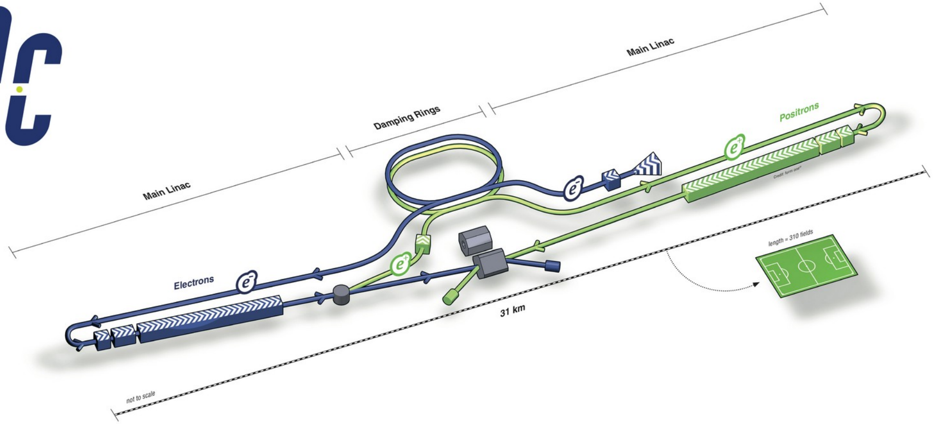
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

Thanks to **J. Fuster, V. Miralles, R. Poeschl, F. Richard, A. Robson, M. Vos, the ILD conveners group, ...** for the help preparing these slides

Apologies in advanced for the many interesting and cutting-edge studies not shown in the following slides.

Linear Colliders

- 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 Government and international community

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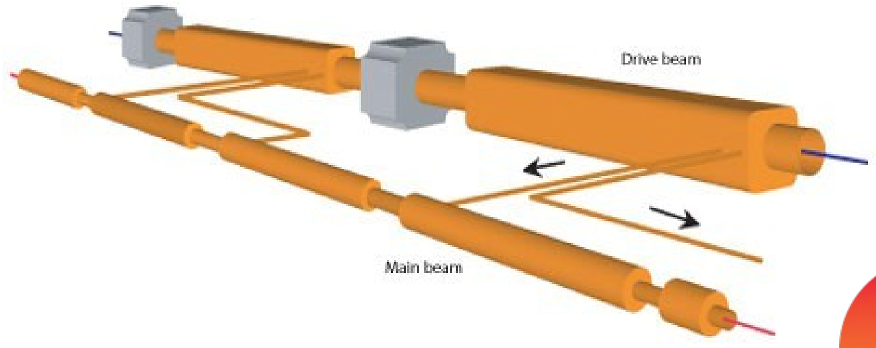


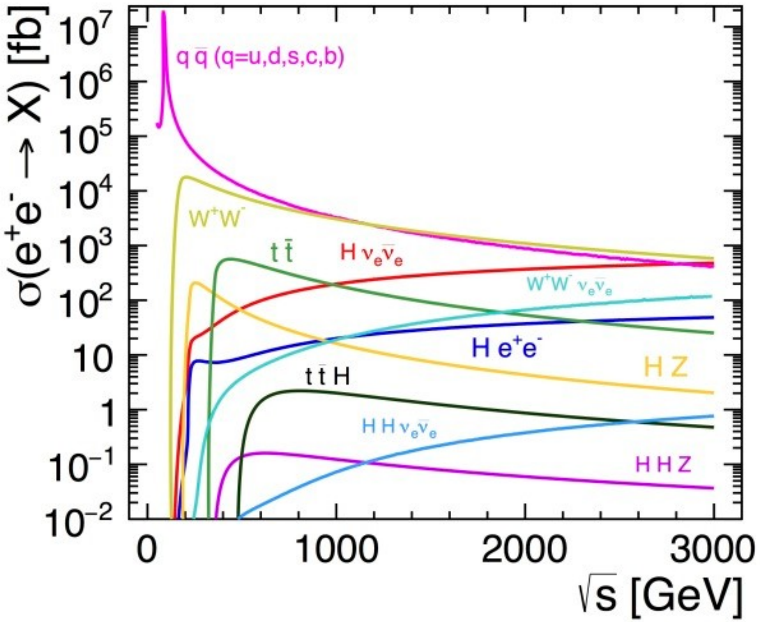
Possible future project of CERN

- Energy: 0.4 - 3 TeV
- CDR in 2012
  - Project Implementation Plan in 2018
- Electron polarisation
- Footprint 50km
- Initial Energy 380 GeV – *Footprint ~11km*

- **All Standard Model particles within reach of planned LC projects**
- High precision tests of Standard Model over wide range to detect onset of New Physics
- **Machine settings can be “tailored” for specific processes**
  - **Centre-of-Mass energy** & **Beams polarisation** (straightforward at linear colliders)

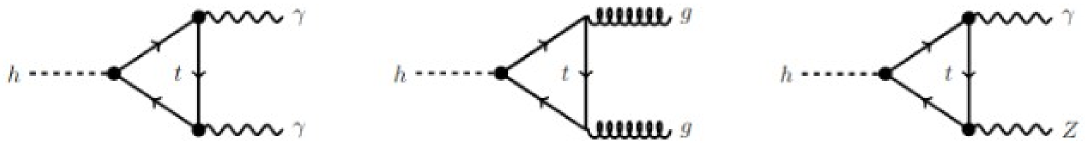
- Higgs factories but also...
  - **“light” qq factory**

    (and Z-factory at Z-pole)
  - **WW factory**
  - **Top-quark factory**
  - **ttH facotry**
  - **...**

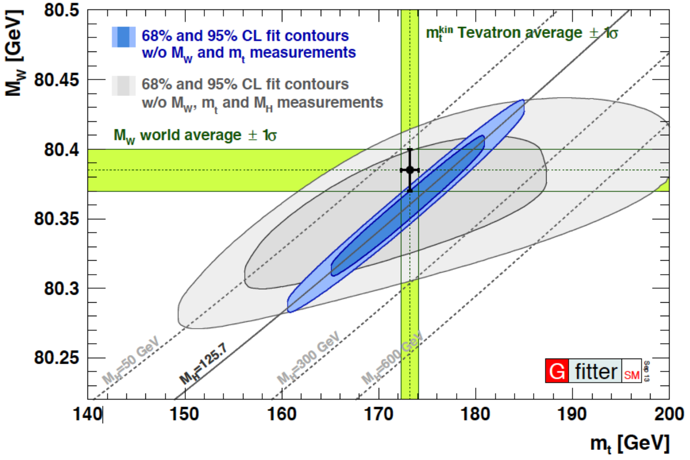


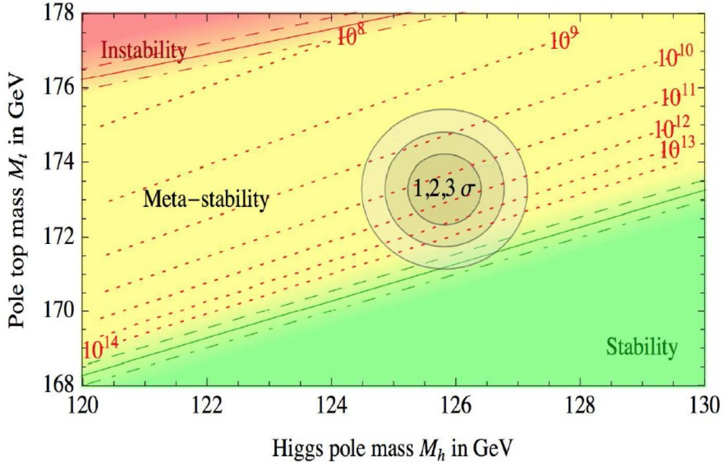
Higgs and top-quark

- "Recently" discovered particles **still under scrutiny**
  - The **heaviest** fundamental **particles** !
  - New physics by compositeness? Higgs and top composite objects?
- An enigmatic couple: the top quark has O(1) Yukawa coupling and rules the loop diagrams ($gg \rightarrow H$, $H \rightarrow gg$)



  - Top mass (&Higgs &W mass) are crucial parameters of the SM (and BSM)





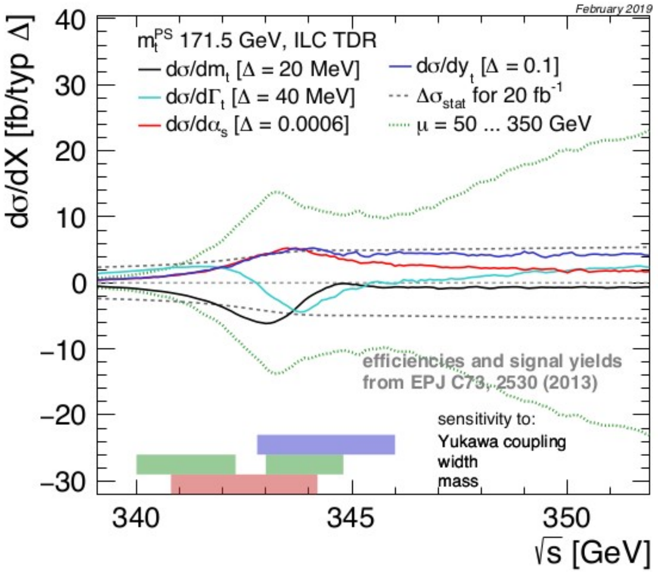
Top-quark mass: a key parameter

▶ The top threshold provides excellent sensitivity to the mass and other top quark properties

- Measurement of the top quark mass in theoretically **well-defined mass schemes**

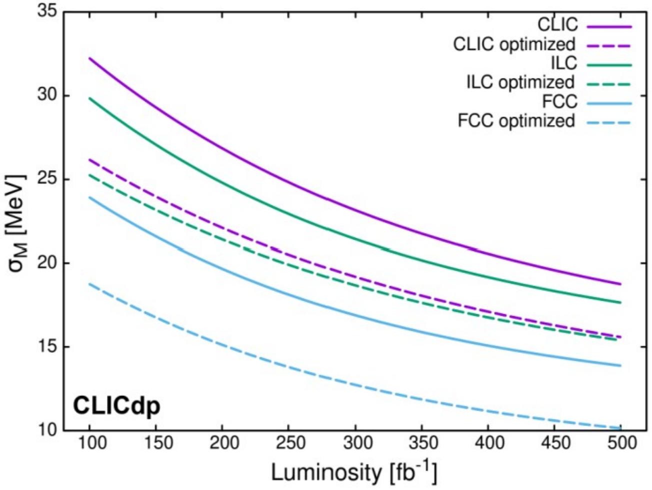
▶ **Sensitivity to :**

- **Top-quark mass, width, yukawa coupling, strong coupling constant**



▶ Optimising top-quark threshold scan at CLIC & ILC using genetic algorithm

- **K. Novak et al [PD3]**
- Top-quark **mass** can be extracted with s**tat. unc.** of the order of **25 MeV** already for 100 fb−1
- Without losing precision on width or Yukawa coupling



See also talks from:
Top-quark : A. Hoang , Harigaya. Pathak [PD1]
b-quark mass: M. Vos [PD2] S. Tairafune [PD3/PD4]
...

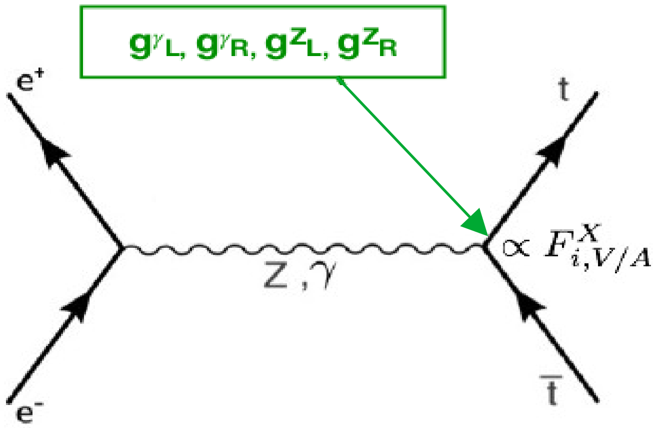
LC: power of beam polarisation

- Longitudinally polarised beams are a special feature of Linear e e Colliders:
  - SLC: P(e⁻) = ± 80%, P(e⁺) = 0%
  - ILC: P(e⁻) = ± 80%, P(e⁺) = ± 30% (upgrade 60%)
  - CLIC: P(e⁻) = ± 80%, P(e⁺) = 0%

$$P = \frac{N_R - N_L}{N_R + N_L}$$

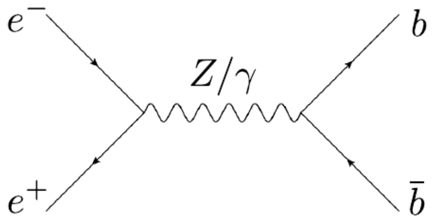
- Electroweak interactions are highly sensitive to chirality of fermions: SU(2)L x U(1)
  - Cross sections are sensitive to beam polarisation –> background suppression, signal enhancement, control of sytematics and...

- Beam polarisation allows the probe of the SM/BSM chiral structure
  - SM: Z and γ differ in couplings to left- and right-handed fermions
  - BSM: unknown chiral structure!



Two fermions

▶ Differential cross section for (relativistic) di-fermion production



$$\frac{d\sigma}{d\cos\theta}(e_L^- e_R^+ \rightarrow f\bar{f}) = \Sigma_{LL}(1+\cos\theta)^2 + \Sigma_{LR}(1-\cos\theta)^2$$

$$\frac{d\sigma}{d\cos\theta}(e_R^- e_L^+ \rightarrow f\bar{f}) = \Sigma_{RR}(1+\cos\theta)^2 + \Sigma_{RL}(1-\cos\theta)^2$$

- The helicity amplitudes Σ_{IJ}, contain the couplings g_L/g_R (or Form factors or EFT factors)
- Left/right asymmetries (characteristic for each fermion)

▶ **BSM in these topologies are mainly discussed in terms of new Z' bosons, coming from an extension of the SM gauge group**

- **Most of these models modify the top-quark couplings**

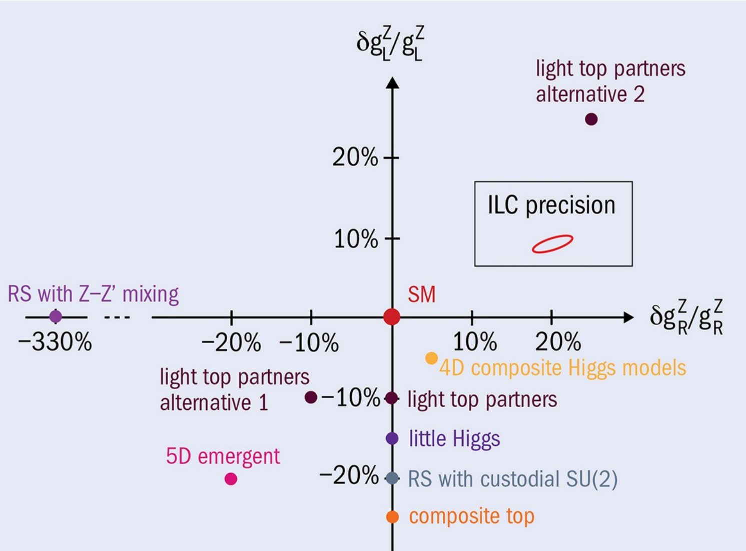
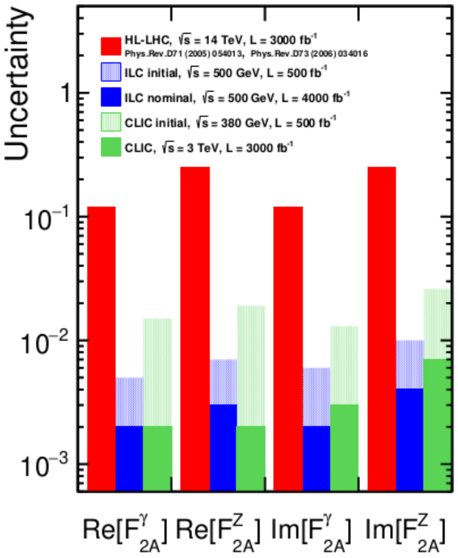


Figure from F. Richard

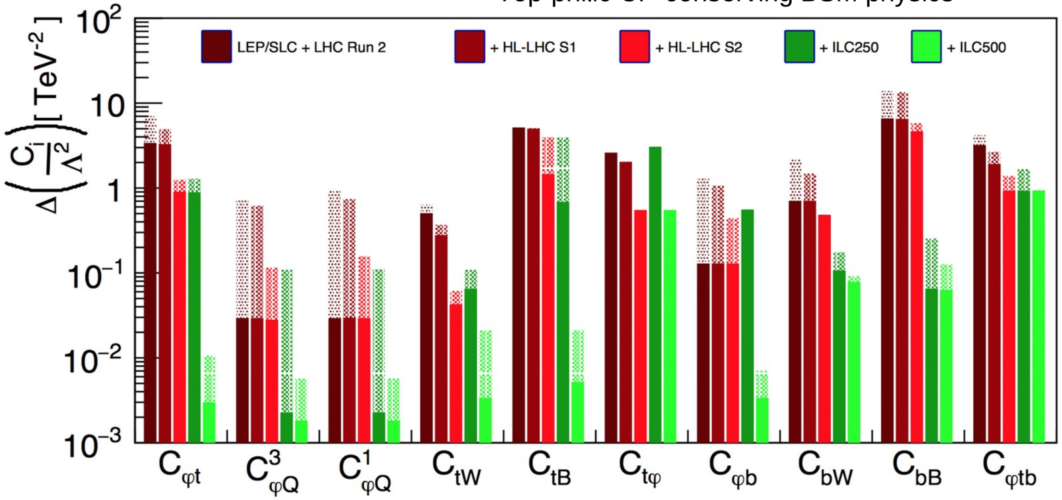
Top-Quark EW couplings

- ▶ Updated global fits with LEP/Tevatron/LHC data [for example JHEP12(2019)098]
  - Including ttZ, ttγ
- ▶ All studies show the extraordinary impact of adding the data of future LC
  - ILC 250GeV already helps for several operators (b quark observables)
  - Going above the top-quark pair production threshold is crucial for the top-operators
  - The determination of axial form factors highly benefit from higher energies



Top-philic CP-violating BSM physics,

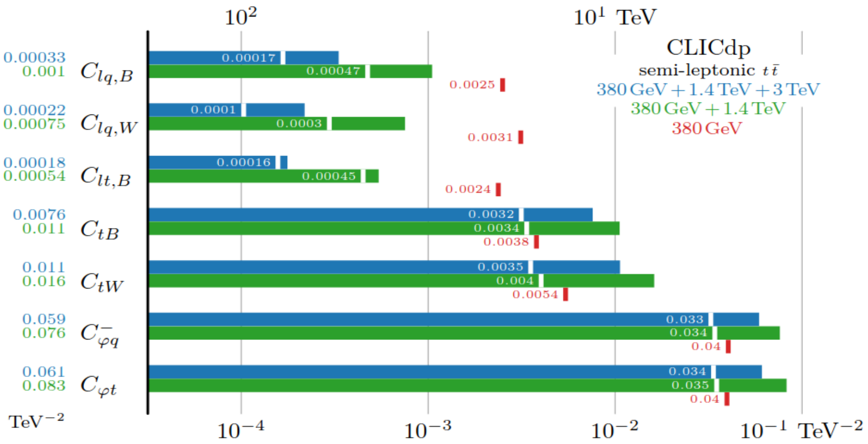
Top-philic CP-conserving BSM physics



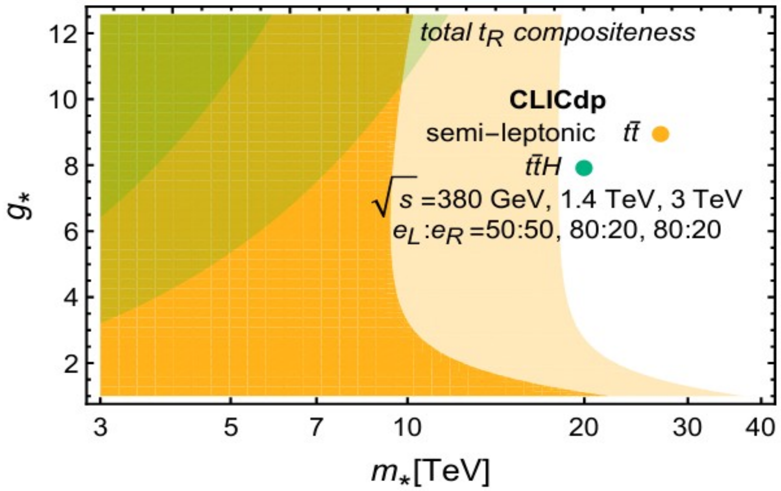
Plot: Top quark EW couplings and EFT fits [Miralles PD2]
More by [Gu, Vries, Durieux, You, Najafabadi, Goldouzian… PD2]

Top-Quark EW couplings & compositeness

- CLIC studies at higher energies (boosted tops!)
- Potential to scrutinize the EFT operators with high precision at high energies
- Prospects on top compositeness including the study of ttH production (top Yukawa coupling) & tt global fits.
- Compositeness emerging in connection to the Naturalness Problem can be conclusively probed at a LC operating at high energies



Top-philic CP-conserving BSM physics,



JHEP11(2019)003

Only the top-quark?

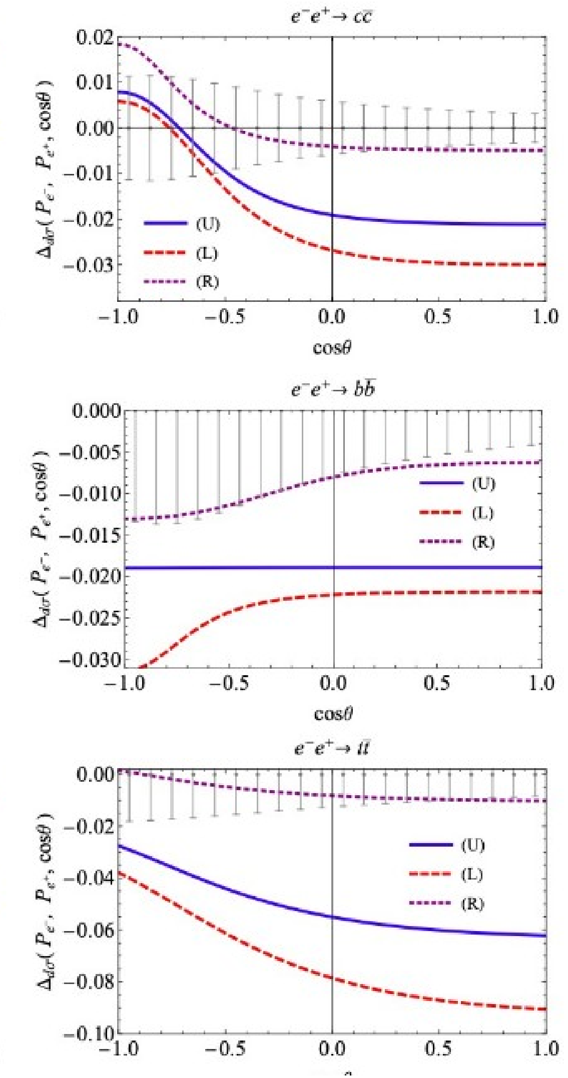
▶ **Randall-Sundrum, Grand Unification Higgs models (GUT):**

- model new strong interactions by dynamics in a bounded 5th dimension
- strong-interaction resonances become Kaluza-Klein resonances
- Higgs is the 5th component of a 5D gauge boson

▶ **Modification of the EW couplings**

- Hosotani et al arxiv:2006.0215
- These effects grow as, s/kR. (kR is the RS scale).
- Small effect at Z-pole (LEP/SLC) but visible already at 250 GeV (with polarized beams)
- **Enhanced effects at large energies (500GeV-3TeV) & with beam polarization**

▶ **Expect particularly large effects for the 3rd generation, but also for ligther fermions**



250GeV

250GeV

500GeV

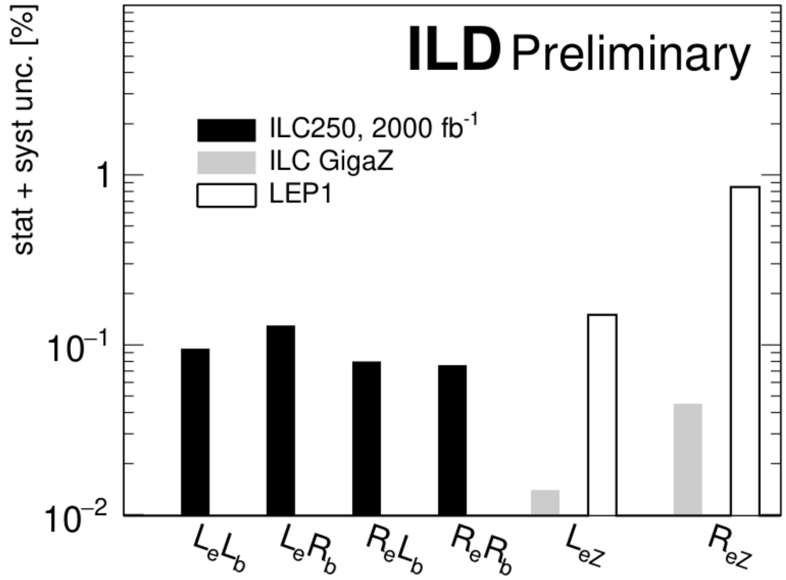
Hosotani et al arxiv:2006.0215

Access to Heavy Resonances at ILC250

- At High Energies we are sensitive to interference effects of Z and photon!!
  - Extracted EW couplings of photon and Z can be influenced by new physics effects
- At Z-Pole: we are sensitive to Z/Z' mixing
  - Sensitivity to vector (and tensor) couplings of the Z (and not “disturbance” from photons)

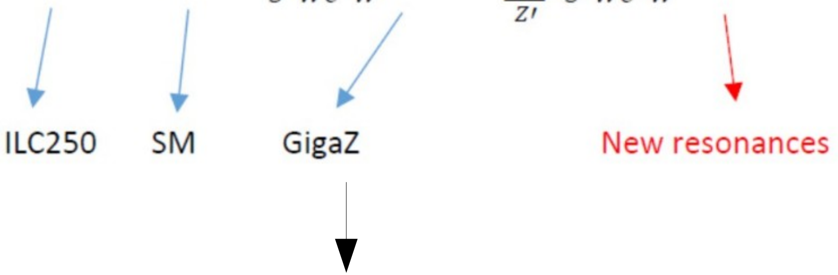
High importance of running at the Z-Pole A. Freitas [PD1], G. Durieux [PD2]

e+e- → bb Full simulation studies (cc/ss in progress) [A.I. PD3]



Couplings (notation for new resonances)

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

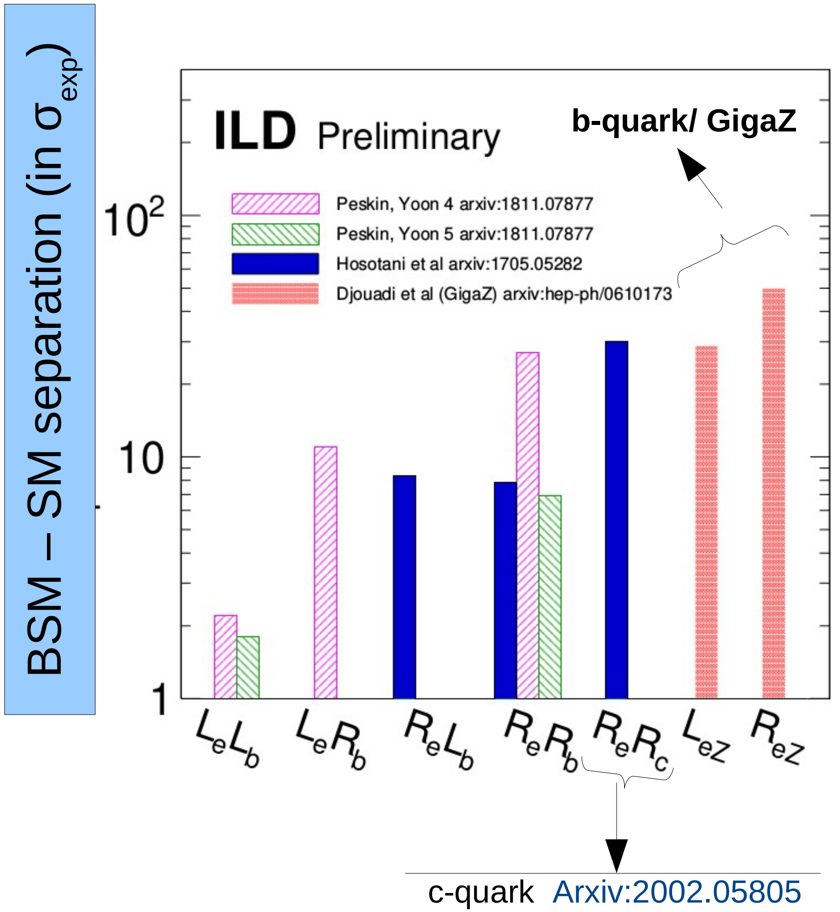


Sensitive to Z-Z’ mixing effects

(that could explain AFBb measurement of LEP?)

Arxiv:1709.04289, PoS(EPS-HEP2019)624

Access to Heavy Resonances at ILC250



▶ **BEAM POLARISATION allows to distinguish between different models**

Expected number of standard deviations for different **RS/compositeness BSM scenarios** when determining the different EW couplings to c- and b-quark at **ILC250** (with GigaZ input).

- Models that predict multi-TeV Z' resonances
- With or without mixing at Z-pole
- See backup for more details on the models

Potential for discovery of new resonances mZ' ~ O(10-20) TeV at ILC250

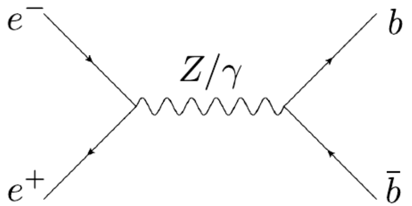
Arxiv:1709.04289, PoS(EPS-HEP2019)624

(few) Experimental challenges

- **Example of observables used to extract the electroweak couplings**
- **cross section, Rq** and forward backward asymmetry **AFB** like observables

$$R_q^0 = \Gamma_{q\bar{q}} / \Gamma_{had} (Z-pole)$$
$$\rightarrow R_q^{cont.} = \sigma_{q\bar{q}} / \sigma_{had} (s > Z-pole)$$

→ Quark identification. No need to measure an angular distribution, (but possible)



$$\frac{d\sigma}{d\cos\theta}$$

$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$

→ Angular Distribution.

Quark ID + charge measurement (quark – antiquark disentangling)

Gives access to all left/right couplings.

(few) Experimental challenges

- **C-quark pairs**

- **High efficient flavour tagging for c-quarks expected at future colliders**

- **Charge measurement**
  - **Primary method:** identification of Kaons produced D-meson decays → **K-method (requires PID)**
  - **Secondary method:** reconstruction of charged mesons → **Vtx-method**

PID is mandatory to reach competitive ac curacies

- **s-quark pairs (in progress)**
  - **Check** M. Basso's & Y. Okunawa's talk

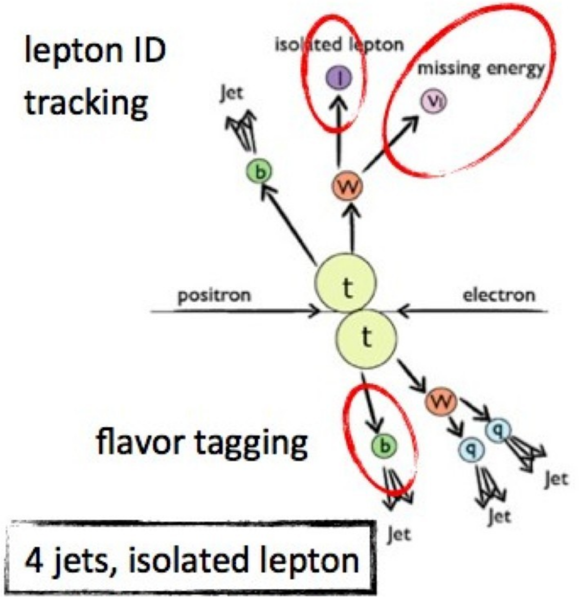
- **B-quark pairs**

- **High efficient flavour tagging for b-quarks expected at future colliders**

- **Charge Measurement**
  - **Primary method:** reconstruction of charged mesons → **Vtx-method**
  - **Secondary method:** identification of Kaons produced in b-hadron decays → **K-method (requires PID)**

PID is very useful

- **top-quark pairs… decay before hadronizing**



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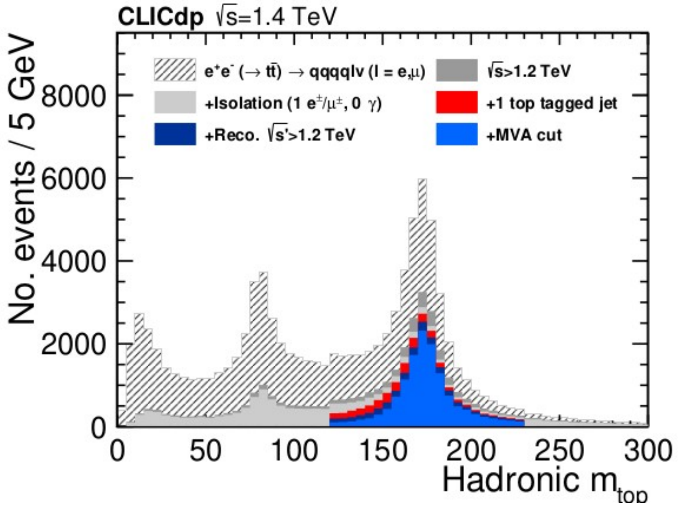
Boosted topologies

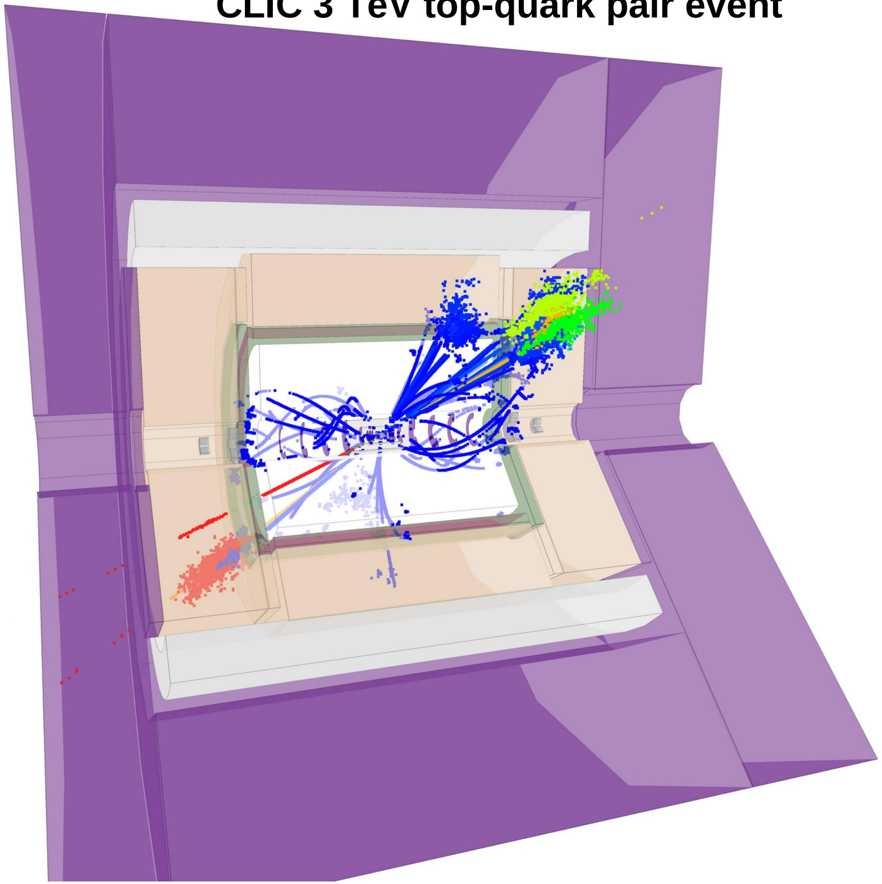
- **Even Lepton/Linear Colliders have complicated event topologies**
- Boosted jets: highly collimated jet environment above 1 TeV
- tops are reconstructed as “fat” jets with a rich substructure
  - Top tagger + MVA:

    Maximizing full potential of PFA

arxiv:2008.05526



CLIC 3 TeV top-quark pair event

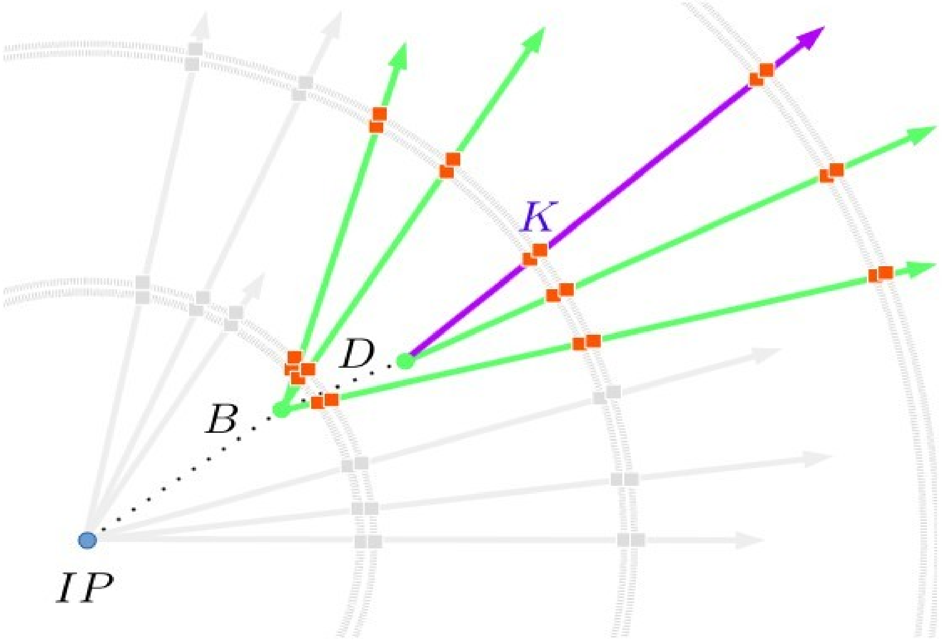


Allows O(1%) precision on cross sections and AFB measurements

Flavor tagging and PID

- **Flavor tagging**
  - Indispensable for any analysis with final state quarks
- **Quark charge measurements**
  - Important for top-quark studies but Indispensable for ee → bb/cc/ss...
- **Charge measurements:**
  - Vtx charge and **Kaon Identification**
  - High efficiency **(double tagging)**
  - High purity → control of the migrations
- **Future detectors** can base their entire measurements on double Tagging and vertex charge
  - LEP/SLC had to include single tags and semi-leptonic events

Exploit small beam spot of Linear Colliders
Vtx detector close to beampipe + low material budget
Tracking **efficiency** (>99%)

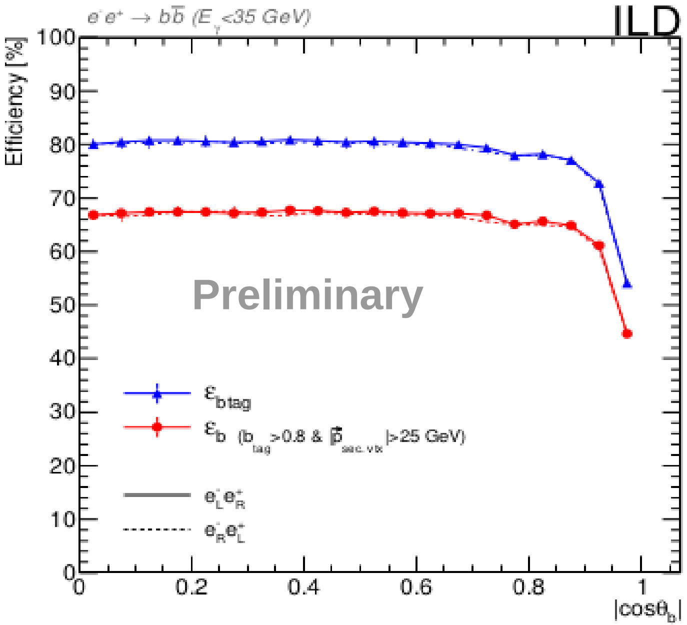


PhD thesis: S. Bilokin

Flavour tagging + PID

▶ Flavour tagging capabilities (b-quark example)

- *using LCFI+ tools from ILCsoft*



Experiment	*b*-quark Eff. [%]	*b*-quark Pur. [%]
DELPHI [19]	47%	86%
ILD (this note)	80%	98.7%

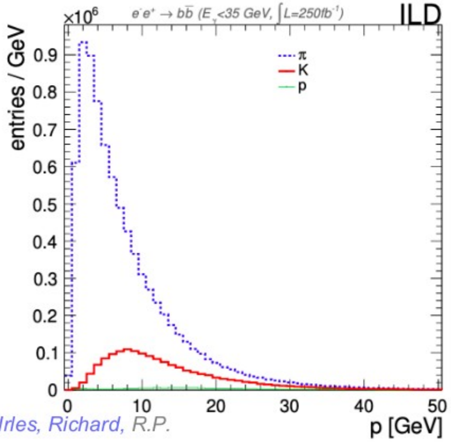
ILD note in progress → See S. Taraifune's talk

▶ **Charged Hadron PID** needed for a wide range of momentum

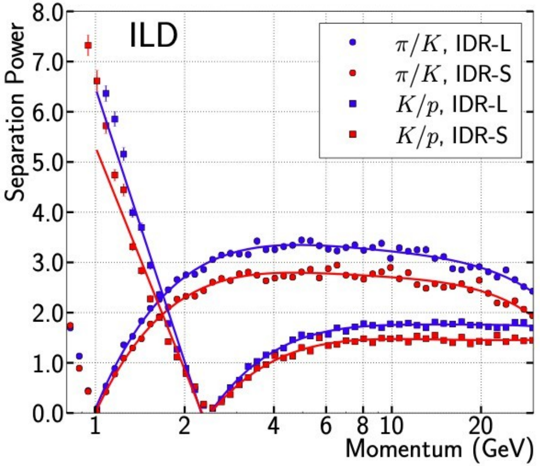
- **TPC** as the **main solution**
- TOF as complement for low momentum (and/or forward tracks)

▶ Special need of K/pion separation

Momenta and abundance of pi/K/p in ee->bb @ 250 GeV



ILD: Irles, Richard, R.P.

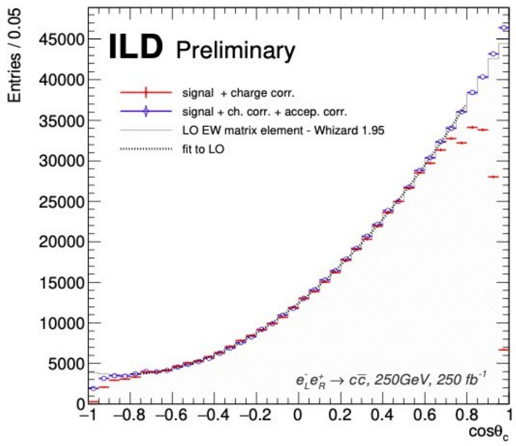


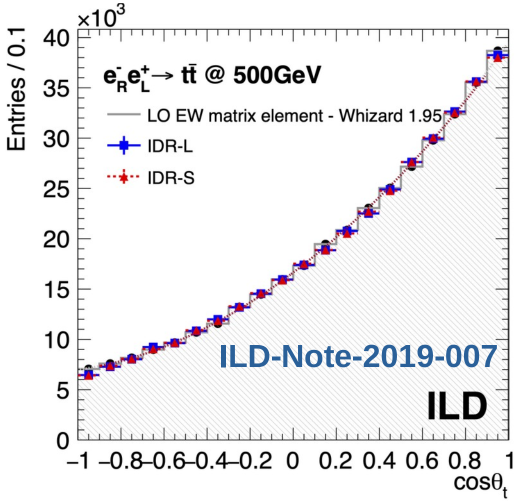
Improvable by clustering counting?
[F. Cuna, PD4/PD5]

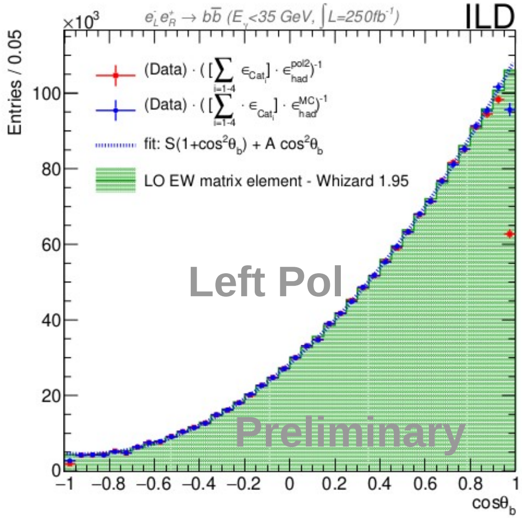
Realistic studies with full simulation

Probing the Chiral structure **of the SM and BSM** requires **:**

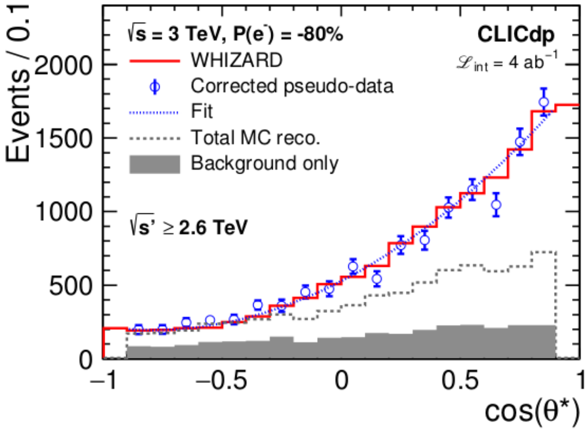
- ▶ **high precision predictions & global fits**
- ▶ **High precision measurements** (at the per mile level in some cases!!)
  - detailed studies with **full simulations with realistic detectors**
  - **Optimization of detectors and reconstruction techniques**
- ▶ EFT predictions will require input from differential distributions







arxiv:2008.05526



FULL SIMULATION STUDIES

Summary / conclusions

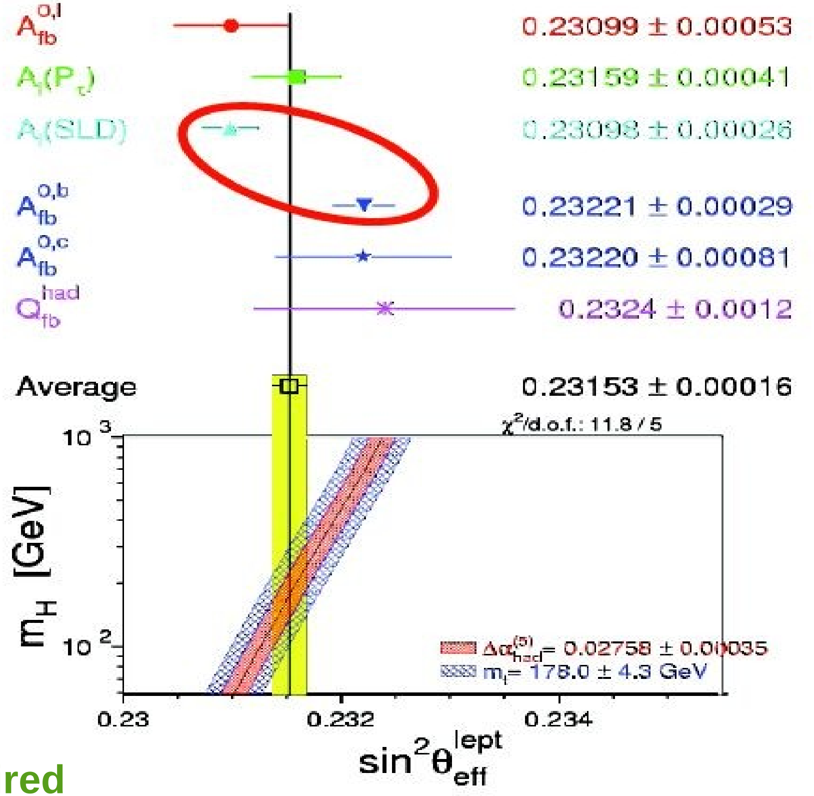
- **Linear colliders are not only Higgs Factories but EW factories.**
  - Two fermion factory, Z factory, WW, ttH, etc
  - upgradability in energy (and also at Z/WW thresholds)
  - Polarization makes possible probing the full chiral structure of the SM / BSM
- Top (but also lighter fermions!!): excellent probes for BSM
  - Already at “low energies” of the Higgs Threshold
- Heavy activity improving the predictions to address the reach of future LC
  - EFT formalism, benchmark RS models…
- And also heavy activity on optimizing / understanding the limits of the future detectors

- Not covered in this talk…
  - EW at the Zpole
  - Higgs/Top interplay in EFT
  - b/t interplay in EFT
  - Top BSM bellow the threshold (FNCN)
  - etc

Back-up slides

Not only top-quark: LEP/SLC tension

- Current LEP & SLC best $sin^2\theta^l_{eff}$ **measurements** show **tension**
  - This measurement is the one with **largest tension with the SM fit.**
  - Most precise single Individual determination of $sin^2\theta^l_{eff}$ from SLC → Left-right asymmetry of leptons
  - Most precise single Individual determination of $sin^2\theta^l_{eff}$ from LEP → forward backward assymetry (b-quark)
- Heavy quark effect, effect on all quarks/fermions, no effect at all?



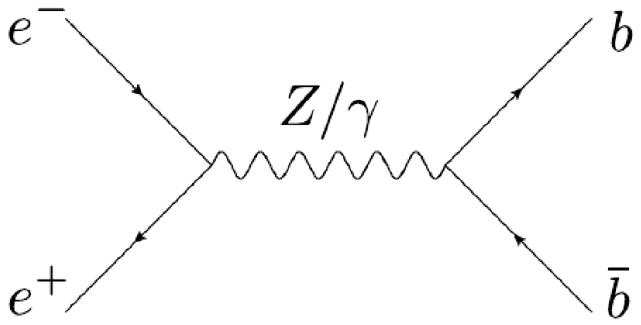
The **resolution** of this issue requires improving the the measurements precission by an order of magnitude

Per mil level of experimental precision is required

Cross sections

$$\sigma_{e^- e^+ \rightarrow q\bar{q}}$$

	Channel	σ_{unpol} [fb]	$\sigma_{-,+}$ [fb]	$\sigma_{+,-}$ [fb]
500 GeV	**q=t**	572	1564	724
	q=b	372	1212	276
	q=u+d+s+c	2208	6032	2793
250 GeV	**q=t**	--	--	--
	q=b	1756	5677	1283
	q=c	3020	8518	3565
	q=u+d+s	6750	18407	5463



▶ **Beam polarisation also enhances the cross section values**

Electroweak Physics also at the Z-pole

$$A_f = \frac{g_{Lf}^2 - g_{Rf}^2}{g_{Lf}^2 + g_{Rf}^2}$$

at an *un*polarised collider:

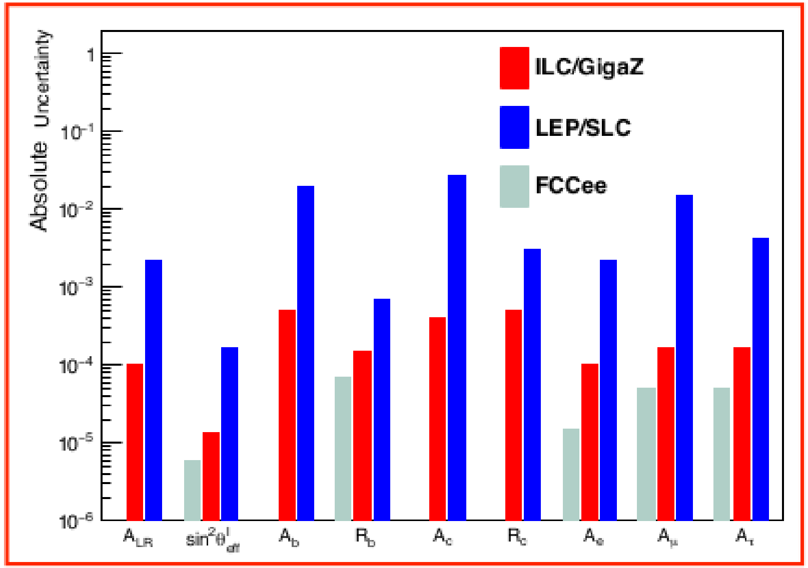
$$A_{FB}^f \equiv \frac{(\sigma_F - \sigma_B)}{(\sigma_F + \sigma_B)} = \frac{3}{4} A_e A_f$$

While at a ***polarised*** collider:

$$A_e = A_{LR} \equiv \frac{\sigma_L - \sigma_R}{(\sigma_L + \sigma_R)}$$ and $$A_{FB,LR}^f \equiv \frac{(\sigma_F - \sigma_B)_L - (\sigma_F - \sigma_B)_R}{(\sigma_F + \sigma_B)_L + (\sigma_F + \sigma_B)_R} = \frac{3}{4} A_f$$

studies by ILD:

- at least **factor 10**, often ~50 improvement **over LEP/SLC**
- **Ac nearly 100 x better** thanks to:
  - Excellent charm / anti-charm tagging:
  - excellent vertex detector
  - tiny ILC beam spot
  - Kaon-ID via dE/dx in ILD's TPC
- polarization buys:
  - a factor 100 in luminosity,



High importance of running at the Z-Pole A. Freitas [PD1], G. Durieux [PD2]

Electroweak Physics above the tt threshold

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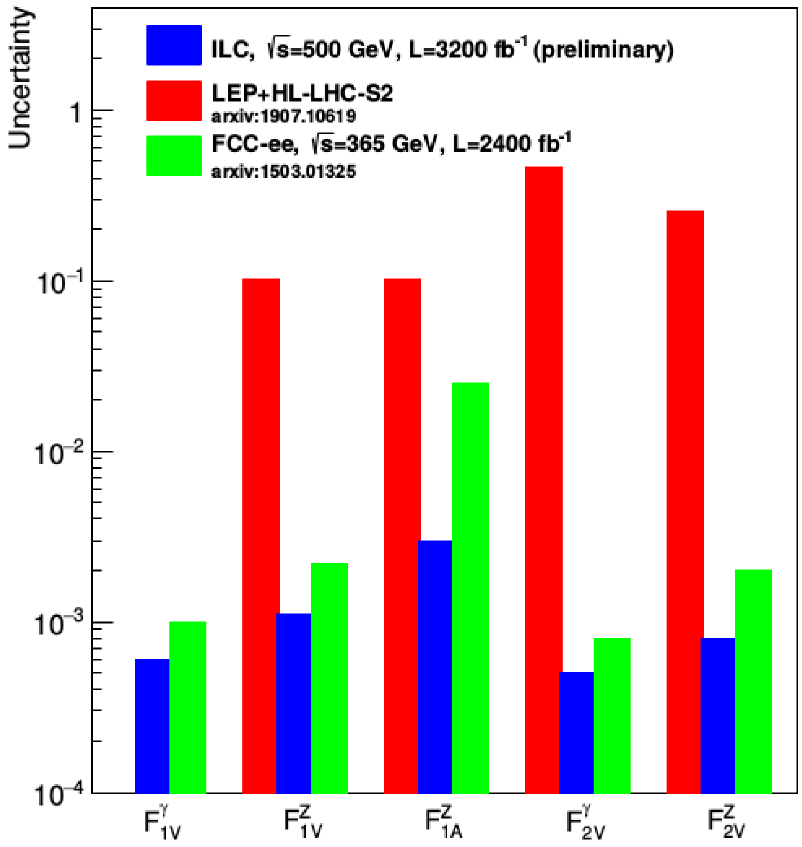


- e+e- collider way superior to LHC (√s = 14 TeV)
- Final state analysis at FCCee (polarisation)
  - Also possible at LC => Redundancy

CP conserving — CPV

$$\Gamma^{ttV}_{\mu}(k^2, q, \bar{q}) = -ie\left\{\gamma_\mu \left(F^V_{1V}(k^2) + \gamma_5 F^V_{1A}(k^2)\right) + \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu \left(iF^V_{2V}(k^2) + \gamma_5 F^V_{2A}(k^2)\right)\right\}$$

- Two remarks:
  - 500 GeV is nicely away from QCD Matching regime

    Less systematic uncertainties
  - The determination of axial form factors highly benefit from higher energies

Mapping between FF and EFT Coefficients

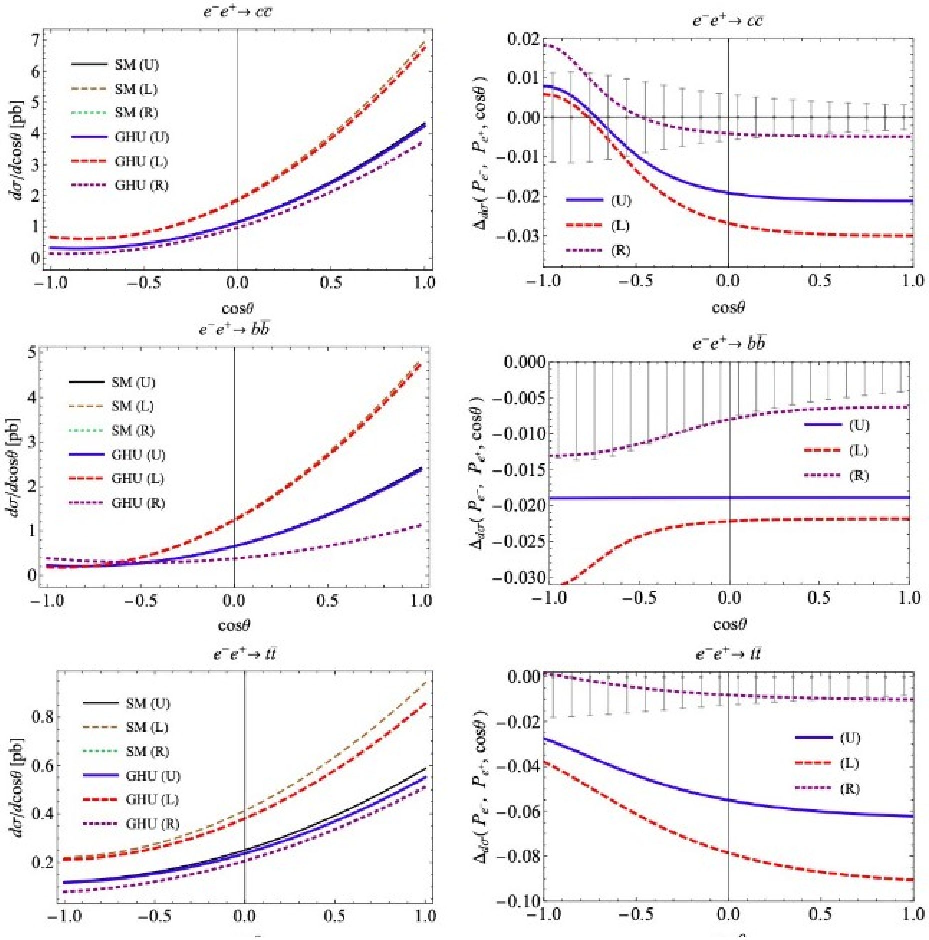
$$F^Z_{1V} = \frac{\frac{1}{4} - \frac{2}{3}s_W^2}{s_W c_W} - \frac{m_t^2}{\Lambda^2}\frac{1}{2 s_W c_W}\left[C^V_{\varphi q} = C^{(33)}_{\varphi u} + (C^{1(33)}_{\varphi q} - C^{3(33)}_{\varphi q})\right],$$

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

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

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

a BSM example: GUT Inspired Grand Higgs Unificaton Model



arxiv:2006.02157

- Model parameter is Hosotani angle θ_H yielding the Higgs-Potential as consequence of Aharanov-Bohm Phase in 5th dimension
- Model defined in Randall-Sundrum warped extra dimensions
  - KK excitations of gauge bosons and new bosons modify fermion couplings
- Predictions for ILC
  - m_{KK} = 13 TeV and θ_H = 0.1
- Deviations from SM of the order of a few %
  - Effects measurable already at 250 GeV
  - Effects amplified by beam polarisations
  - Effects for tt, bb and cc (and other light fermions)
- One concrete example for importance to measure full pattern of fermion couplings
  - Full pattern only available with beam polarisation

Slide borrowed from R. Poeschl (EF04 Snowmass process)

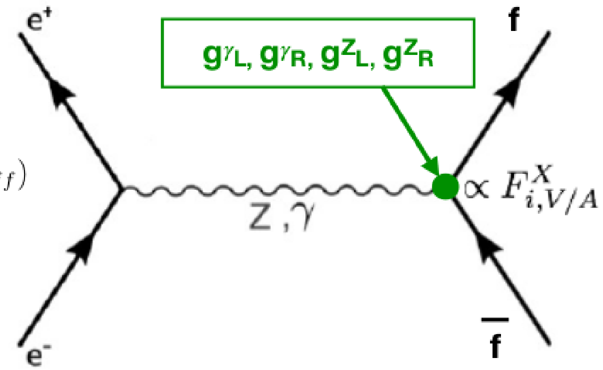
Polarisation & Electroweak Physics at high energies

- similarly, disentangle Z / γ exchange in $e^+e^- \to f\bar{f}$

g_{Lf}, g_{Rf} : helicity-dependent couplings of Z to fermions

=> $A_f = \frac{g_{Lf}^2 - g_{Rf}^2}{g_{Lf}^2 + g_{Rf}^2}$

specifically for the electron: $A_e = \frac{(\frac{1}{2} - \sin^2\theta_{eff})^2 - (\sin^2\theta_{eff})^2}{(\frac{1}{2} - \sin^2\theta_{eff})^2 + (\sin^2\theta_{eff})^2} \approx 8(\frac{1}{4} - \sin^2\theta_{eff})$



at an *un*polarised collider:

$$A_{FB}^f \equiv \frac{(\sigma_F - \sigma_B)}{(\sigma_F + \sigma_B)} = \frac{3}{4} A_e A_f$$

=> no direct access to A_e, only via tau polarisation

While at a ***polarised*** collider:

$$A_e = A_{LR} \equiv \frac{\sigma_L - \sigma_R}{(\sigma_L + \sigma_R)}$$ and $$A_{FB,LR}^f \equiv \frac{(\sigma_F - \sigma_B)_L - (\sigma_F - \sigma_B)_R}{(\sigma_F + \sigma_B)_L + (\sigma_F + \sigma_B)_R} = \frac{3}{4} A_f$$

trading theory uncertainty:

the **polarised** $A_{FB,LR}^f$ receives 7 x smaller radiative corrections than the **unpolarised** A_{FB}^f !

5

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Detector Technologies

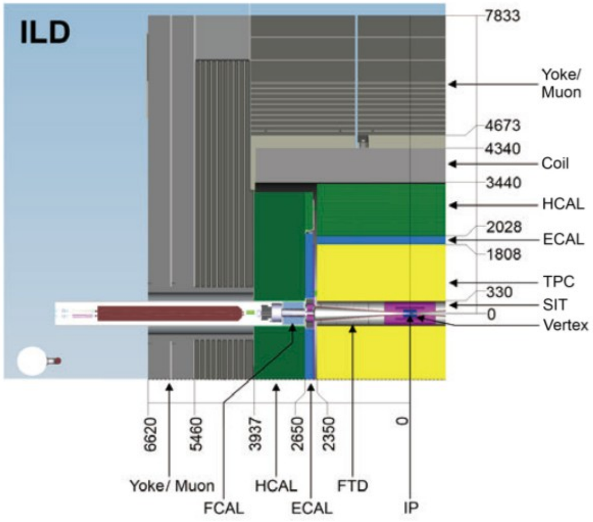
Vertex: CMOS, DEPFET, FPCCD, …

Tracker:
TPC (GEM, micromegas, pixel)
+ silicon pixels/strips

ECAL:
Silicon (5x5mm^2) or
Scintillator (5x45mm^2)
with Tungsten absorber

HCAL:
Scintillator tile (3x3 cm^2)
or Gas RPC (1x1 cm^2)
with Steel absorber

All inside solenoidal coil of 3-4 T



Detector R&D collaborations: CALICE Calorimeter for ILC, LC-TPC, FCAL Collaboration

10

ILD Design Goals

Features of ILC:
low backgrounds, low radiation, low collision rate (5-10 Hz)

These allow us to pursue aggressive detector design:

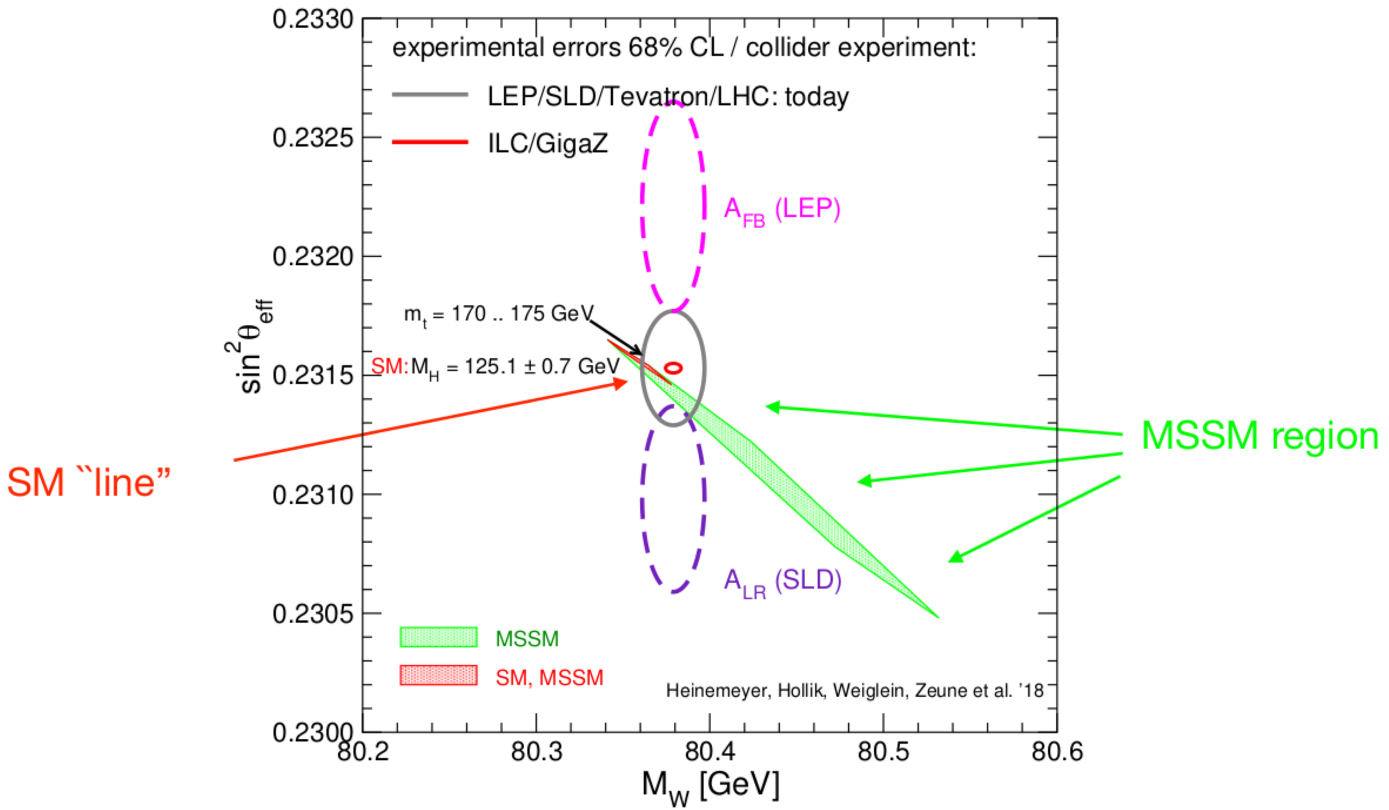
Detector Requirements ←	**Physics**
• Impact parameter resolution $\sigma(d_0) < 5 \oplus 10 / (p[\text{GeV}] \sin^{3/2}\theta)$ μm	H→bb,cc,gg,ττ
• Transverse momentum resolution $\sigma(1/p_T) = 2 \times 10^{-5}$ GeV^{-1} $\oplus$ $1 \times 10^{-3} / (p_T \sin^{1/2}\theta)$	Total e+e-→ZH cross section
• Jet energy resolution 3-4% (around E_{jet} ~100 GeV)	H→invisible
• Hermeticity θ_{min} = 5 mrad	H→invisible; BSM

R. Ete: "The ILD Software Tools and Detector Performance"

9

Electroweak precision physics: Prediction for M_W and $\sin^2\theta_{eff}$ in SM and MSSM vs. exp. accuracies

[S. Heinemeyer, W. Hollik, G. W., L. Zeune '18]



⇒ M_W and $\sin^2\theta_{eff}$ have high sensitivity for model discrimination

BSM opportunities at e⁺e⁻ colliders, Georg Weiglein, LCWS2021, 03 / 2021 27