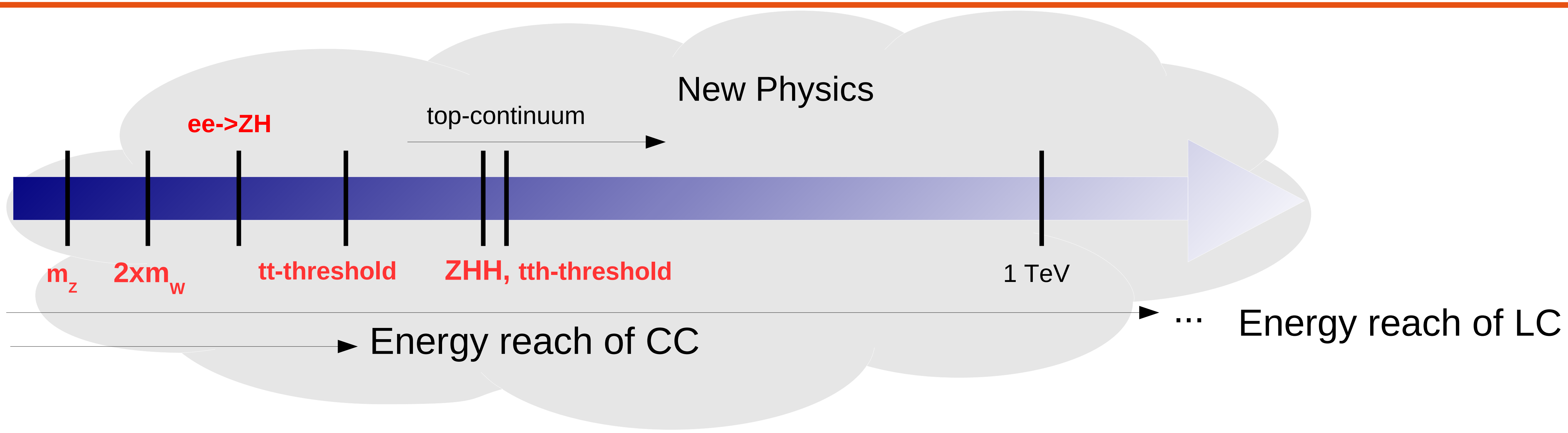
Linear Collider Facility
Physics above ttbar threshold and outlook

Roman Pöschl
On behalf of Comité Collisionneur Linéaire
Composed of IN2P3 members and Irfu members

IRN Terascale Meeting November 2024 IP2I Lyon

Physics program at future electron-positron colliders



All Standard Model particles within reach of planned e+e- colliders

High precision tests of Standard Model over wide range to detect onset of New Physics

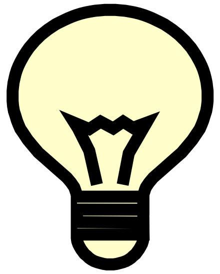
Machine settings can be “tailored” for specific processes

- Centre-of-Mass energy
- Beam polarisation (straightforward at linear colliders)

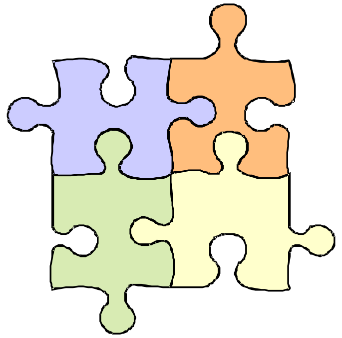
$$\sigma_{P,P'} = \frac{1}{4}[(1 - PP')(\sigma_{LR} + \sigma_{RL}) + (P - P')(\sigma_{RL} - \sigma_{LR})]$$

Background free searches for BSM through beam polarisation

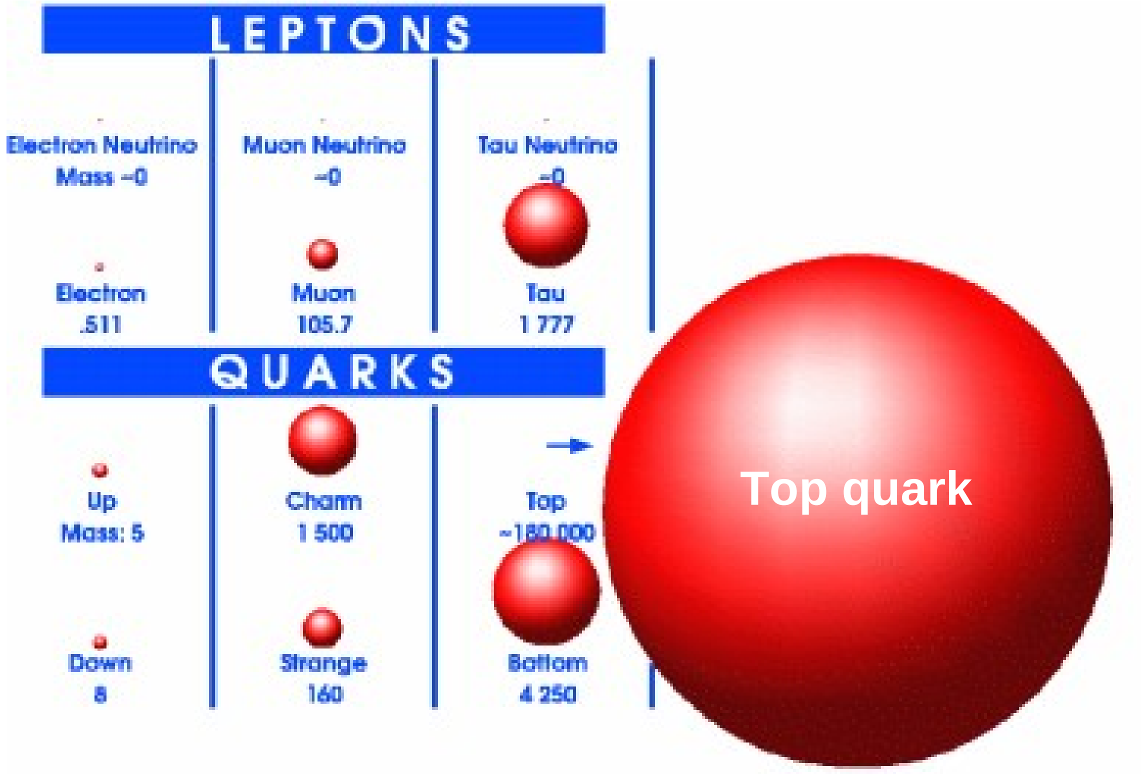
An enigmatic couple



Elementary Scalar?



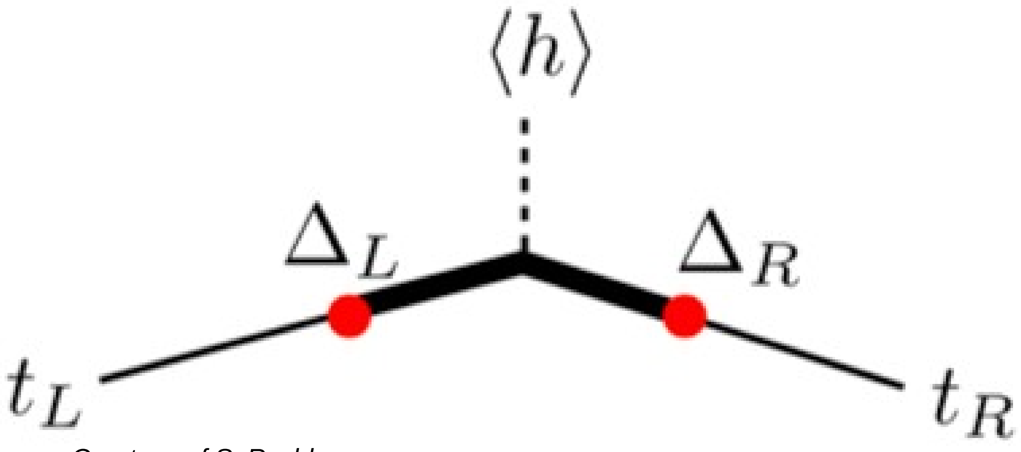
Composite object?



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

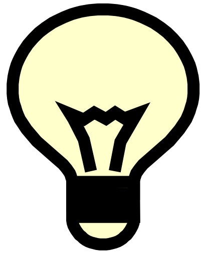
- New physics by compositeness?
  Higgs <u>and</u> top composite objects?

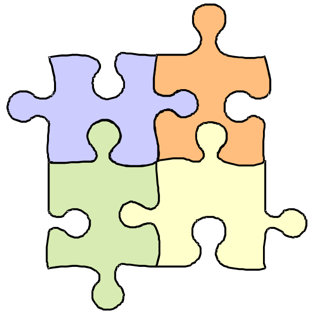
- e+e- collider perfectly suited to decipher both particles



Courtesy of S. Rychkov

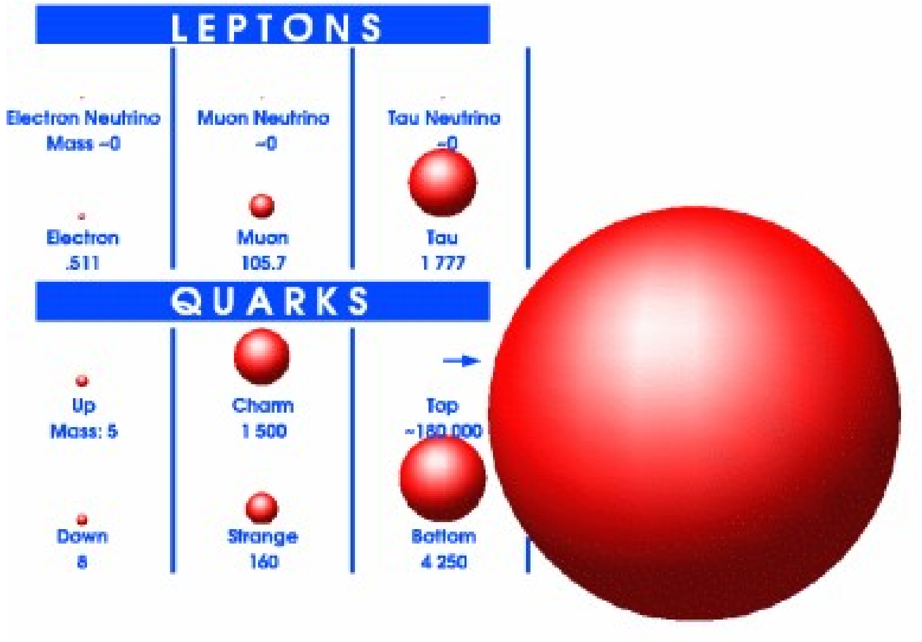
Top Yukawa Coupling

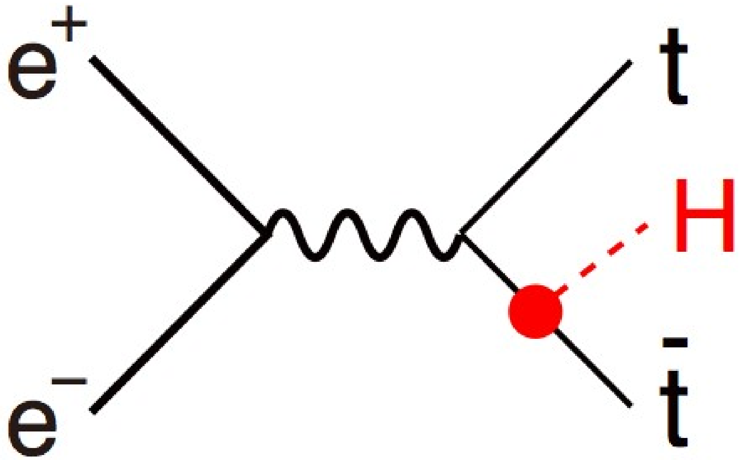




Elementary Scalar?

Composite object?





Estimation on δyt/yt in 2203.07622 for ILC

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

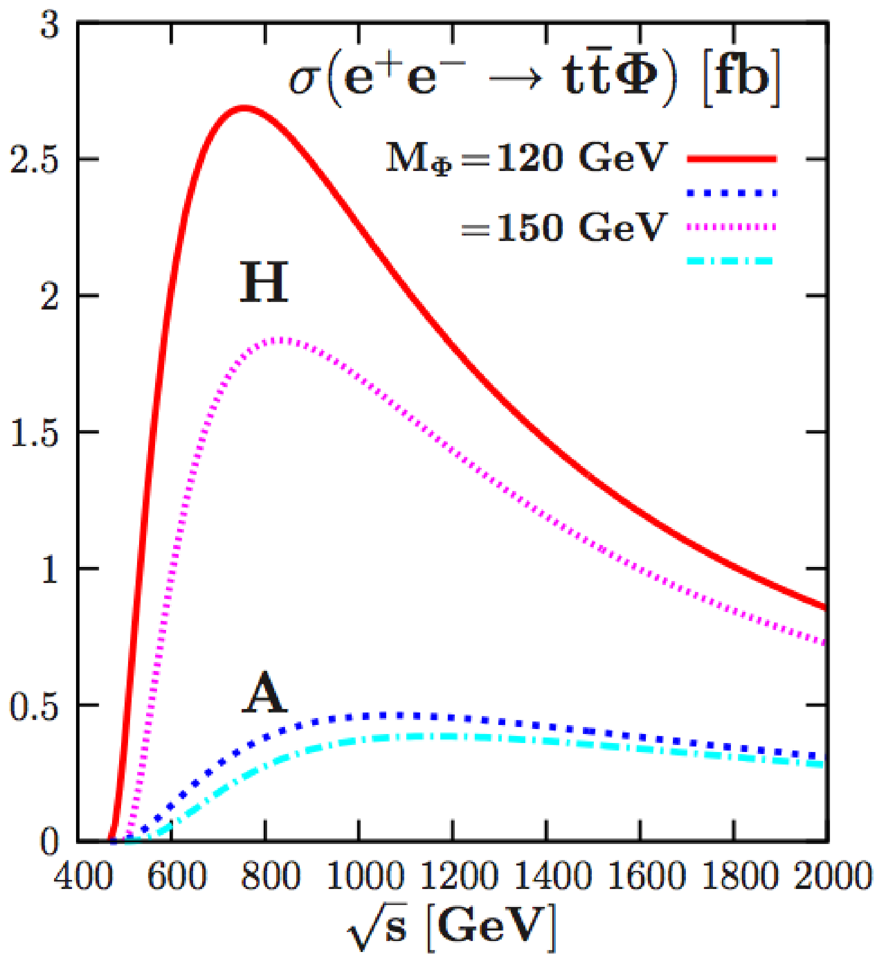
Similar prospects exist for CLIC

Higgs Quantum Numbers – CP via ttH

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

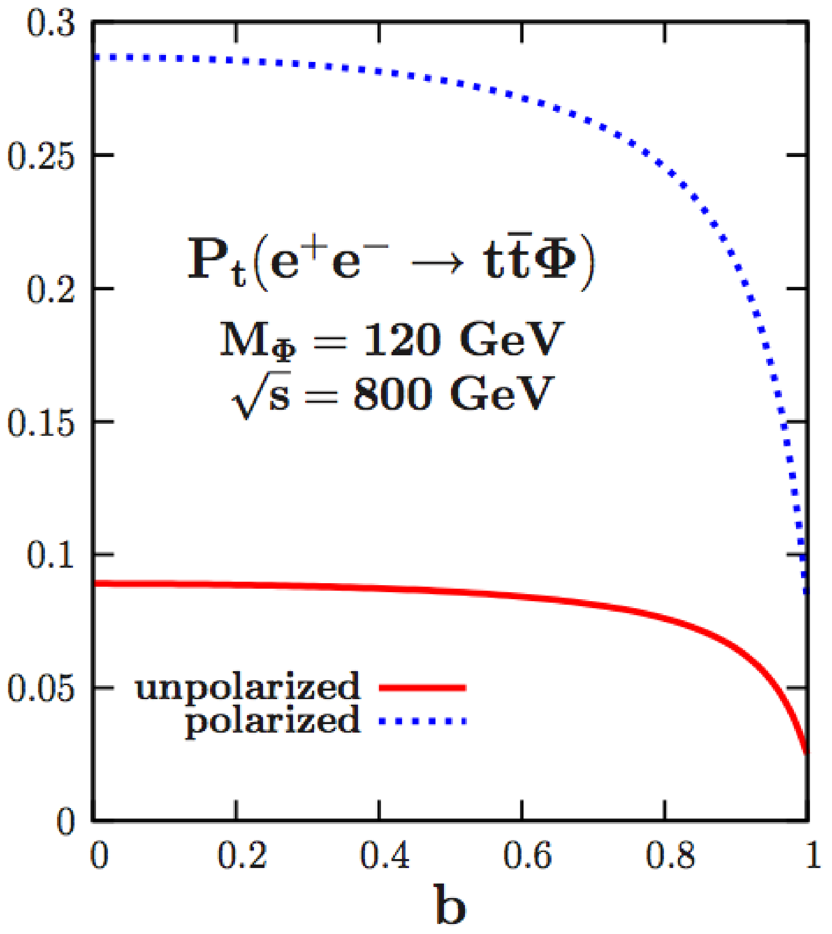
In memoriam of Rohini Godbole

Cross section



Dramatic differences for
CP odd and CP even scalar

Top quark polarisation

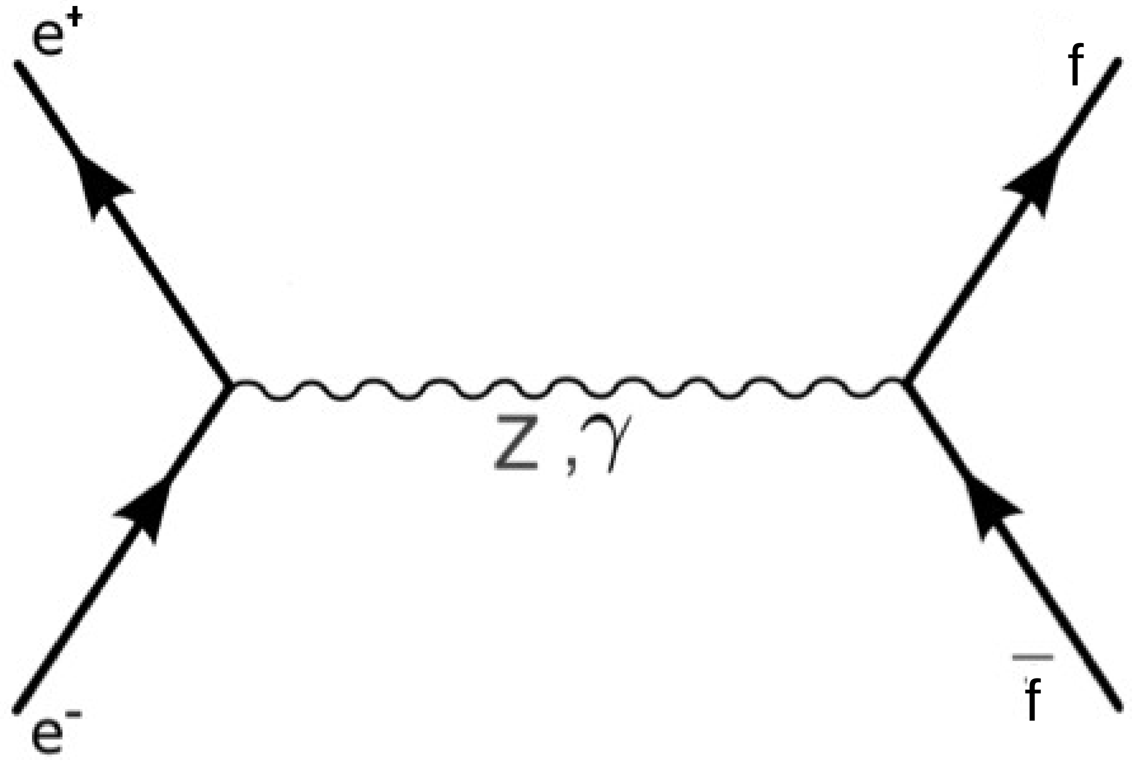


Sensitivity to CP odd admixture b
Merit of beam polarisation

Determination of CP nature of scalar boson in an unambiguous way

Godbole et al., LCWS07

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

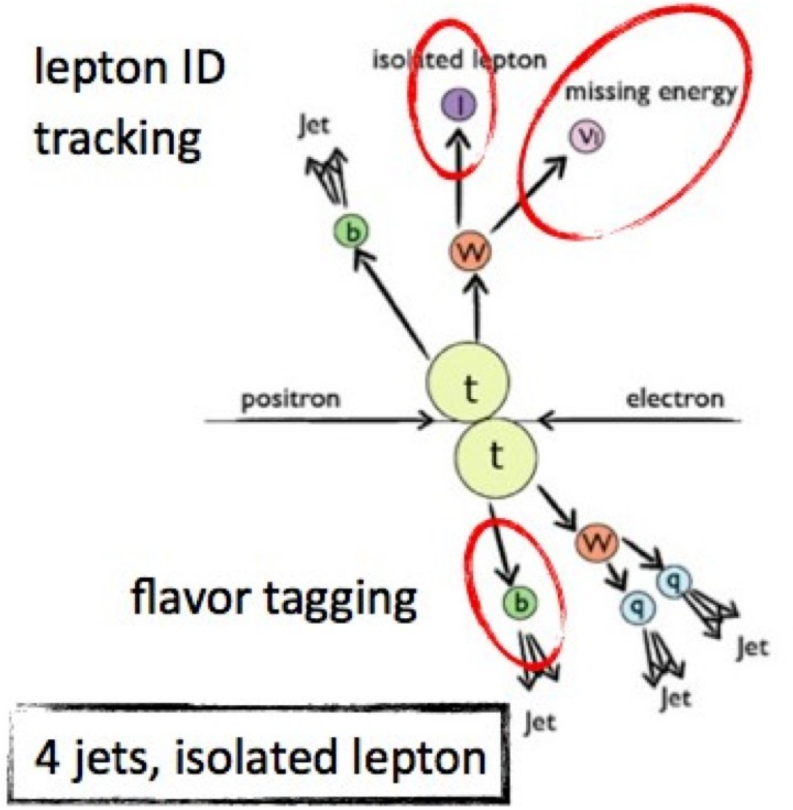
All four helicity amplitudes for all fermions **only available with polarised beams**

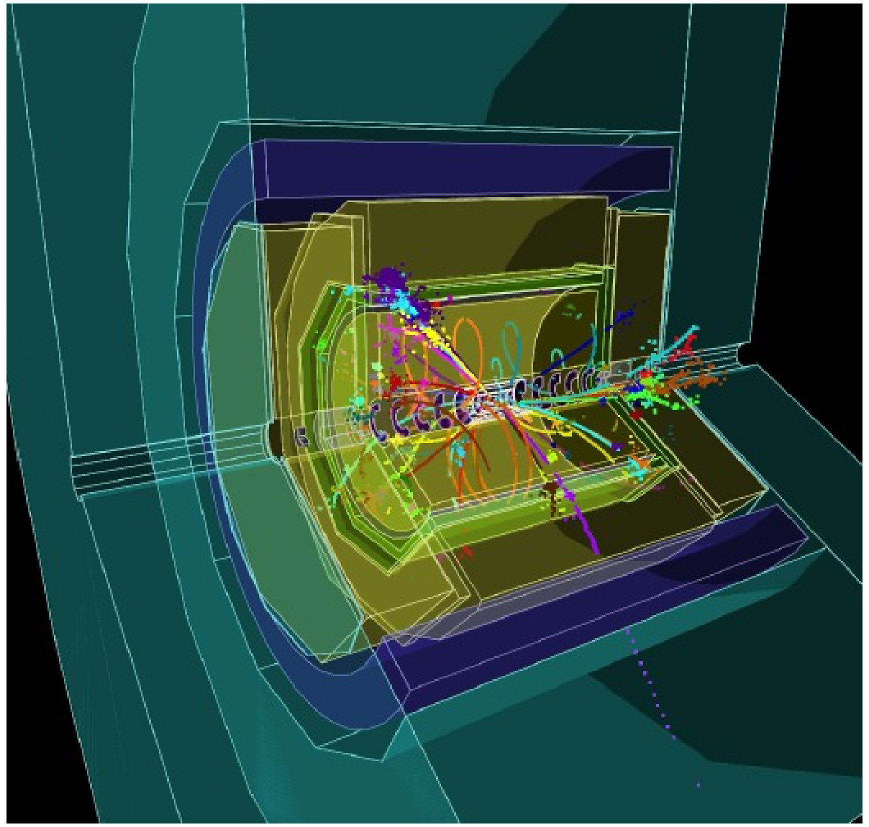
Elements of top quark reconstruction

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

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





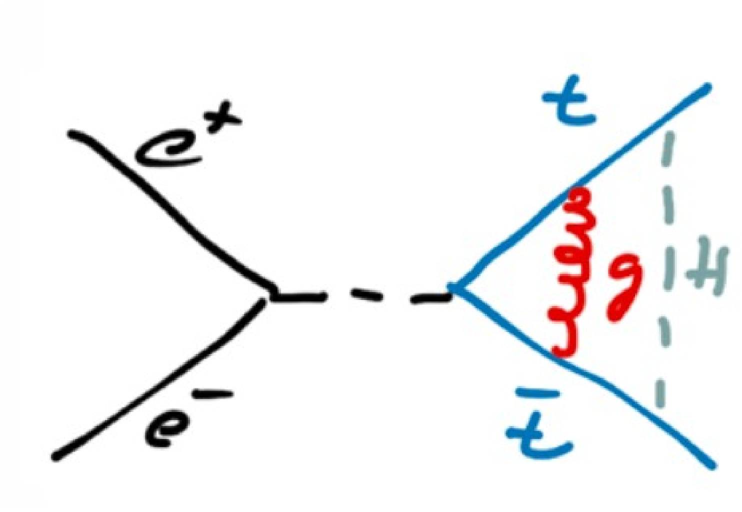
Final state reconstruction uses all detector aspects

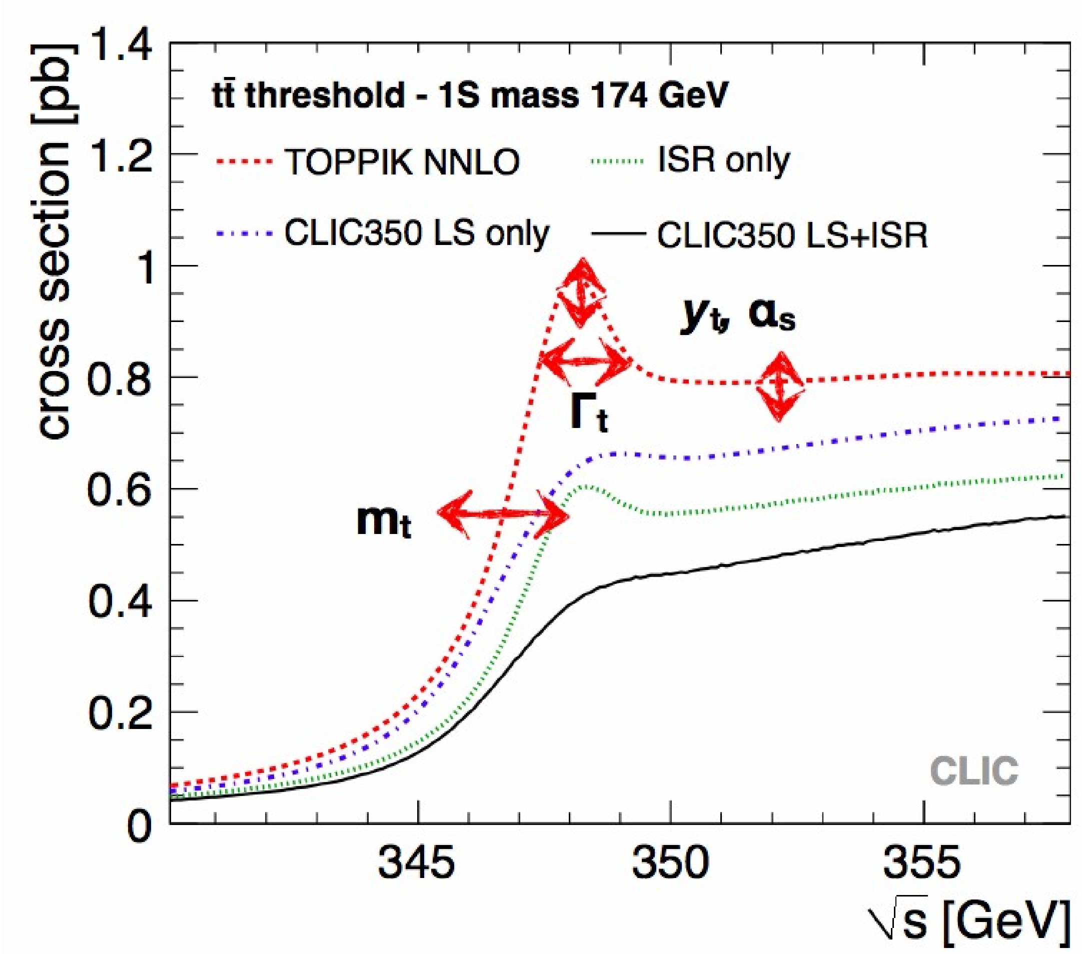
Top pair production at threshold

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

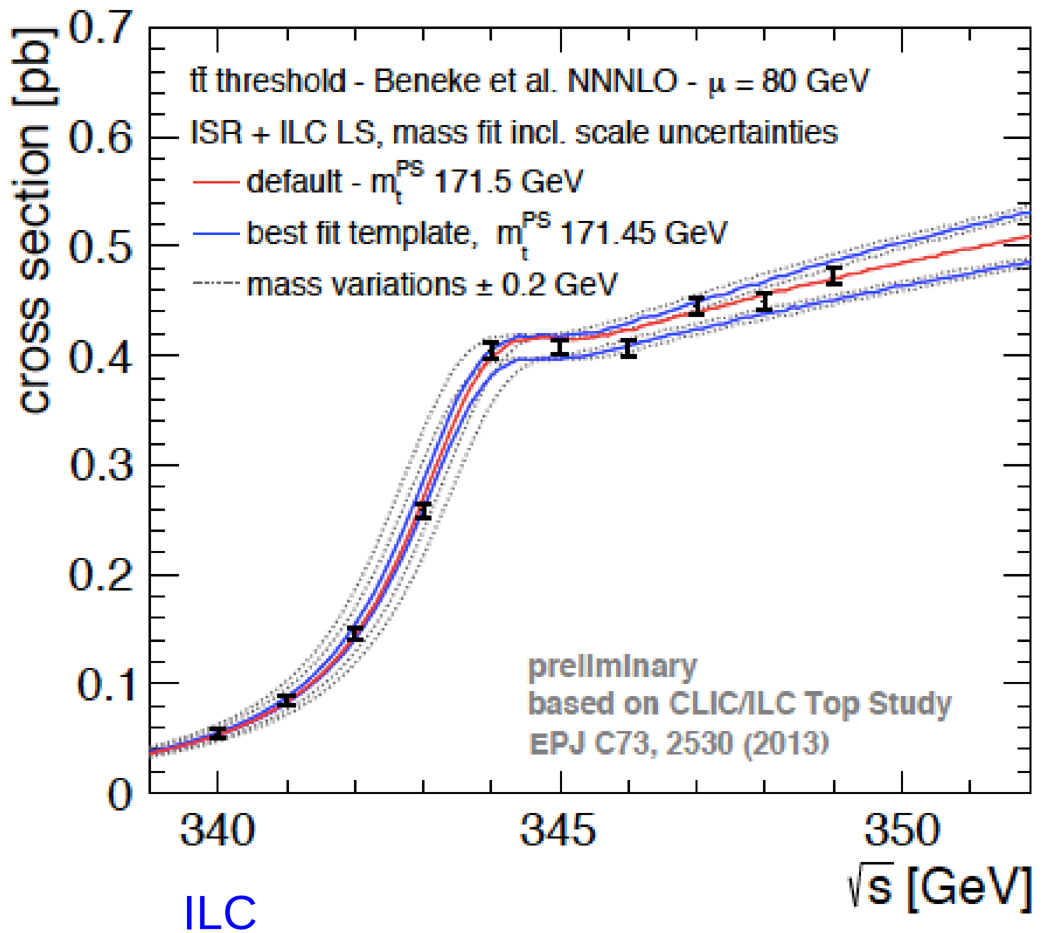
- Top mass, width Yukawa coupling
- Strong coupling constant



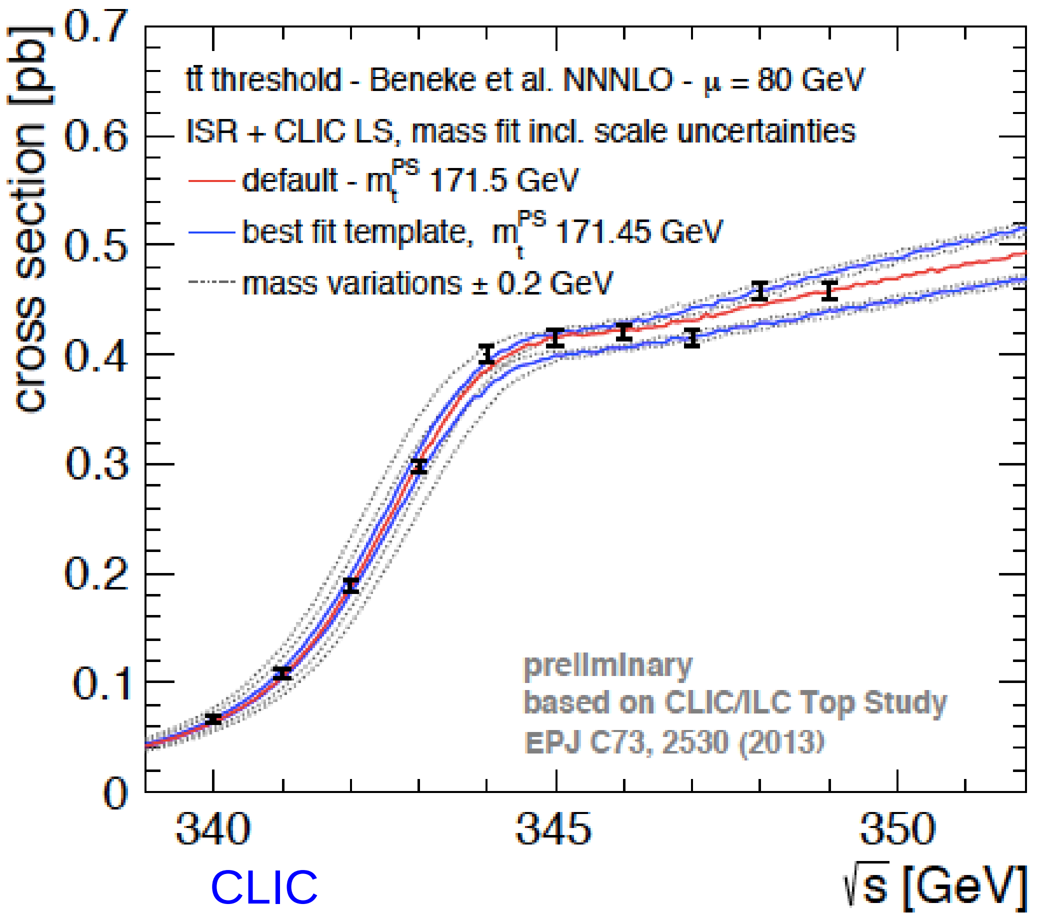


- Effects of some parameters are correlated:
- Dependence on Yukawa coupling rather weak,
- Precise external α_s helps

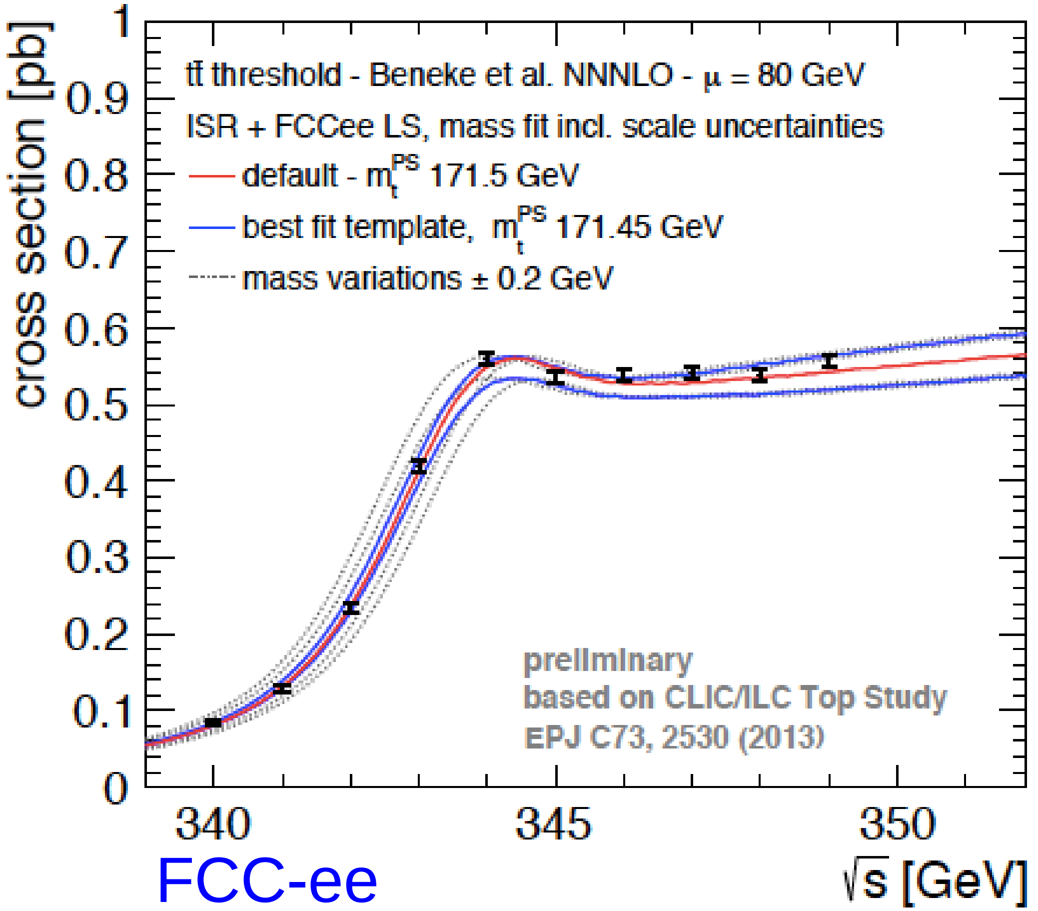
Top threshold scans at different e+e- colliders



ILC



CLIC



FCC-ee

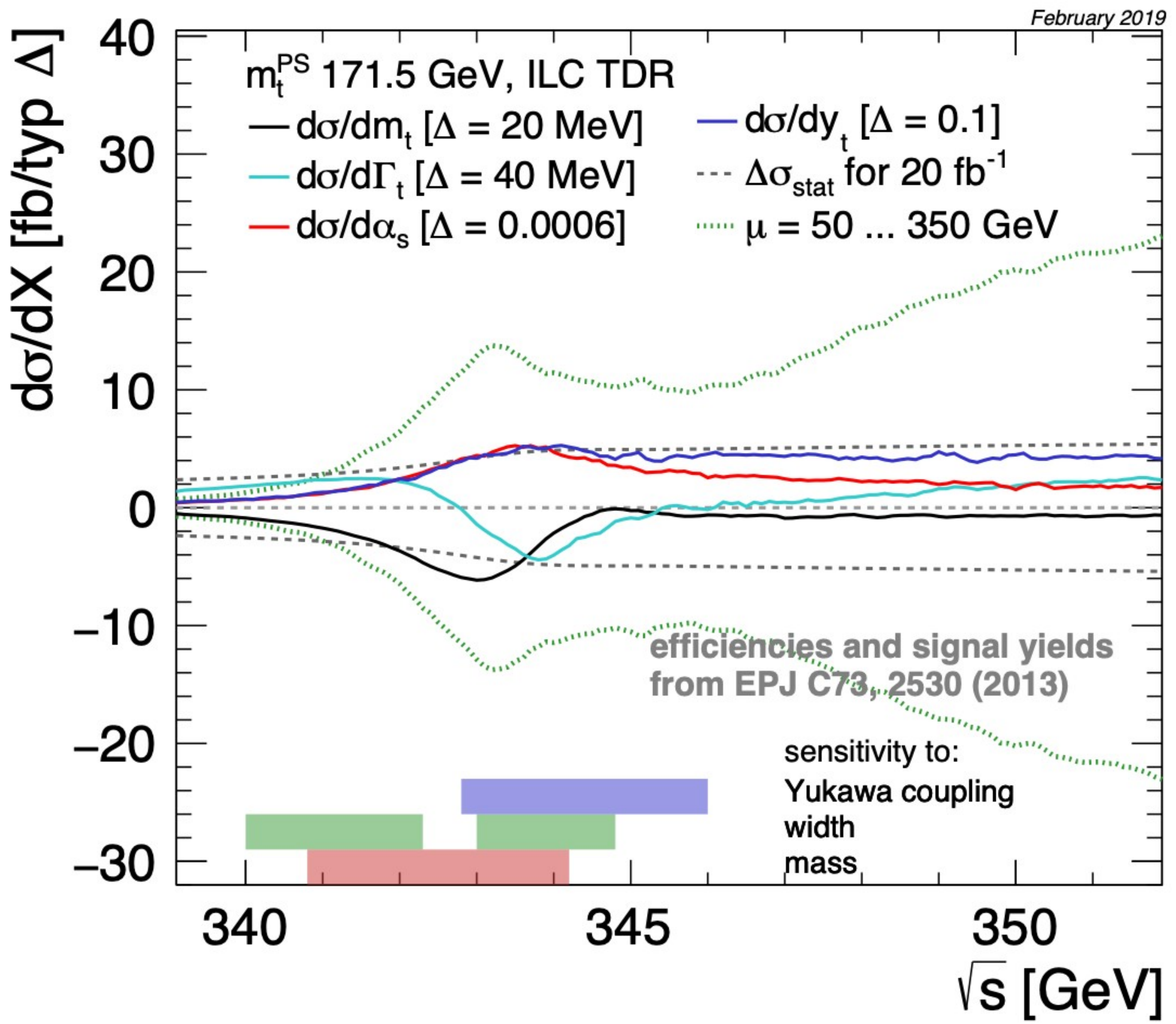
Fit uncertainty:
28.5 MeV (18 MeV stat)

Fit uncertainty:
31 MeV (21 MeV stat)

Fit uncertainty:
27 MeV (15 MeV stat)

- Results based on toy measurements of the total cross section
- Assessment with full simulation studies needed

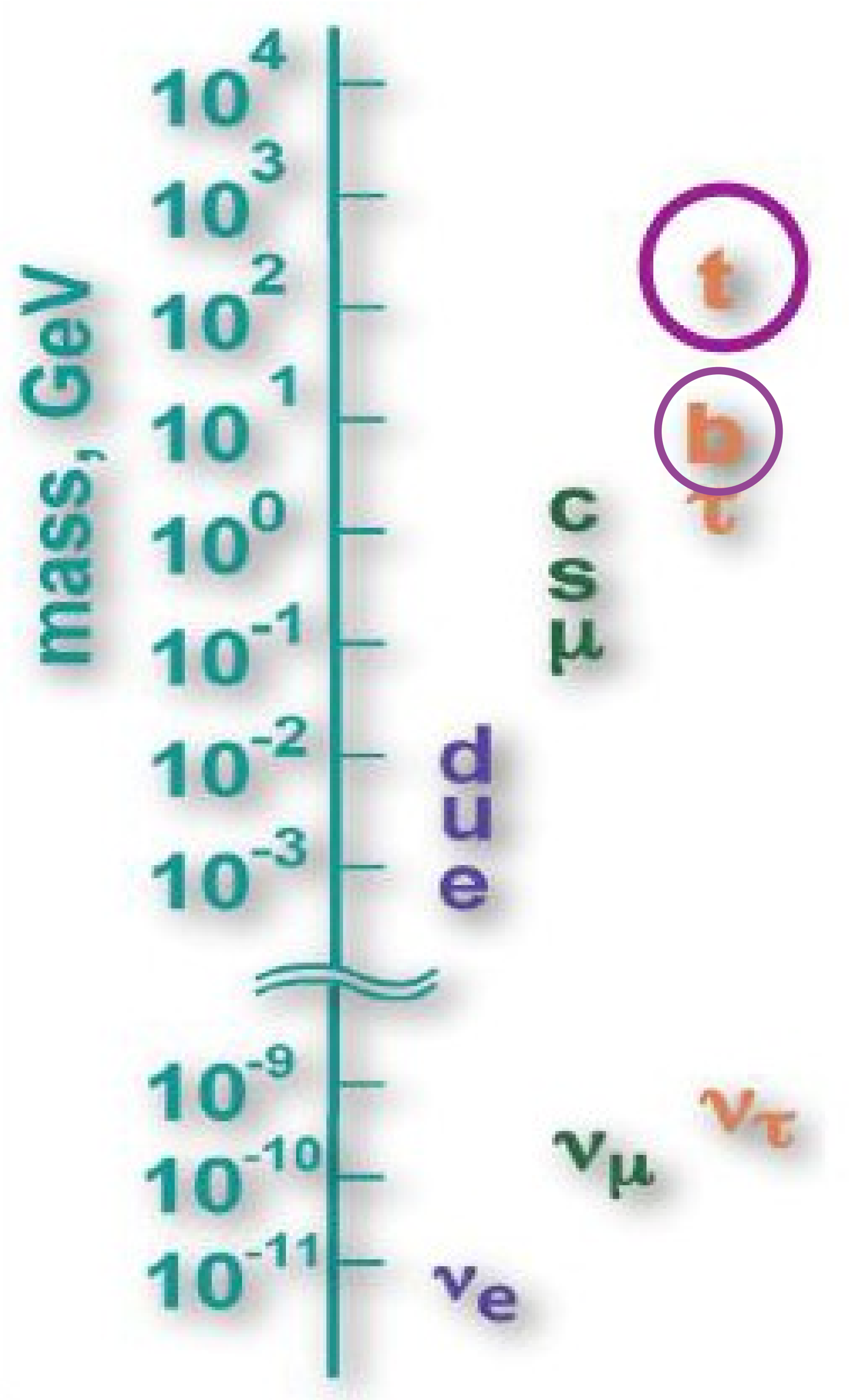
Sensitivity and error breakdown



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 (more on α_s in backup)
  - $\Delta m \sim 2.6$ MeV per 10^{-4} in α_s

Electroweak Couplings of Heavy Quarks



- 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

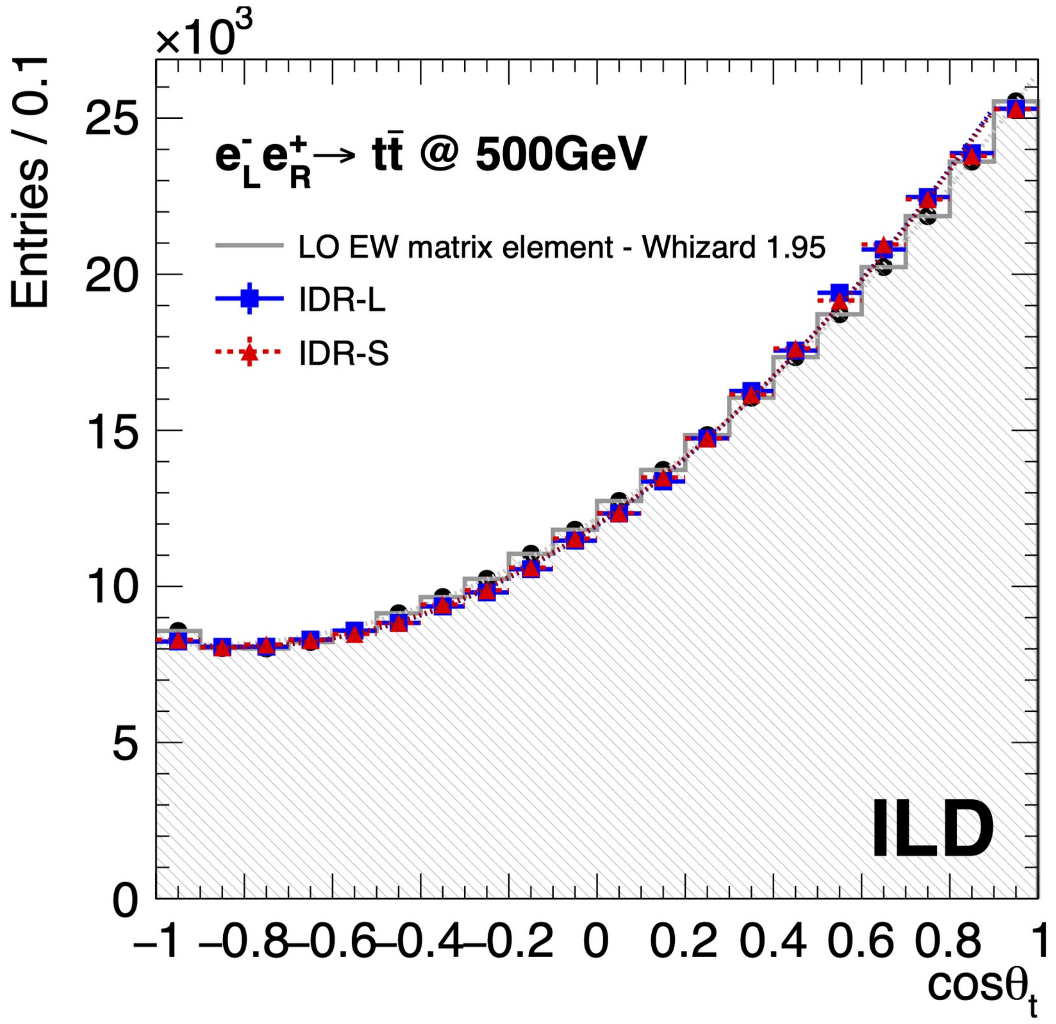
- Expect residual effects for particles with masses closest to symmetry breaking scale

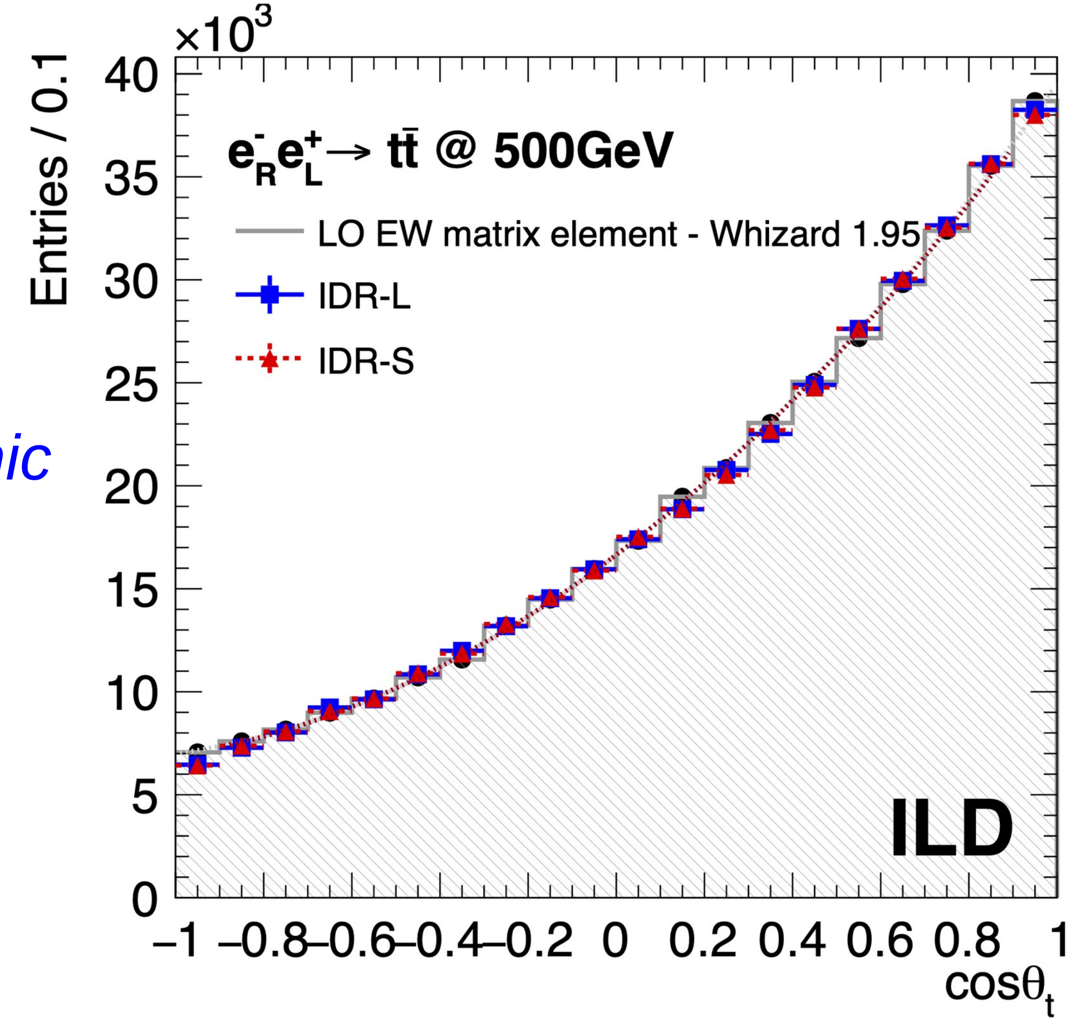
$$\begin{pmatrix} t \\ b \end{pmatrix}_L$$

- Heavy quark effect or effect on all fermions?

Strong motivation to study chiral structure of (heavy) quark vertices in high energy e+e- collisions

Top quark polar angle spectrum at 500 GeV



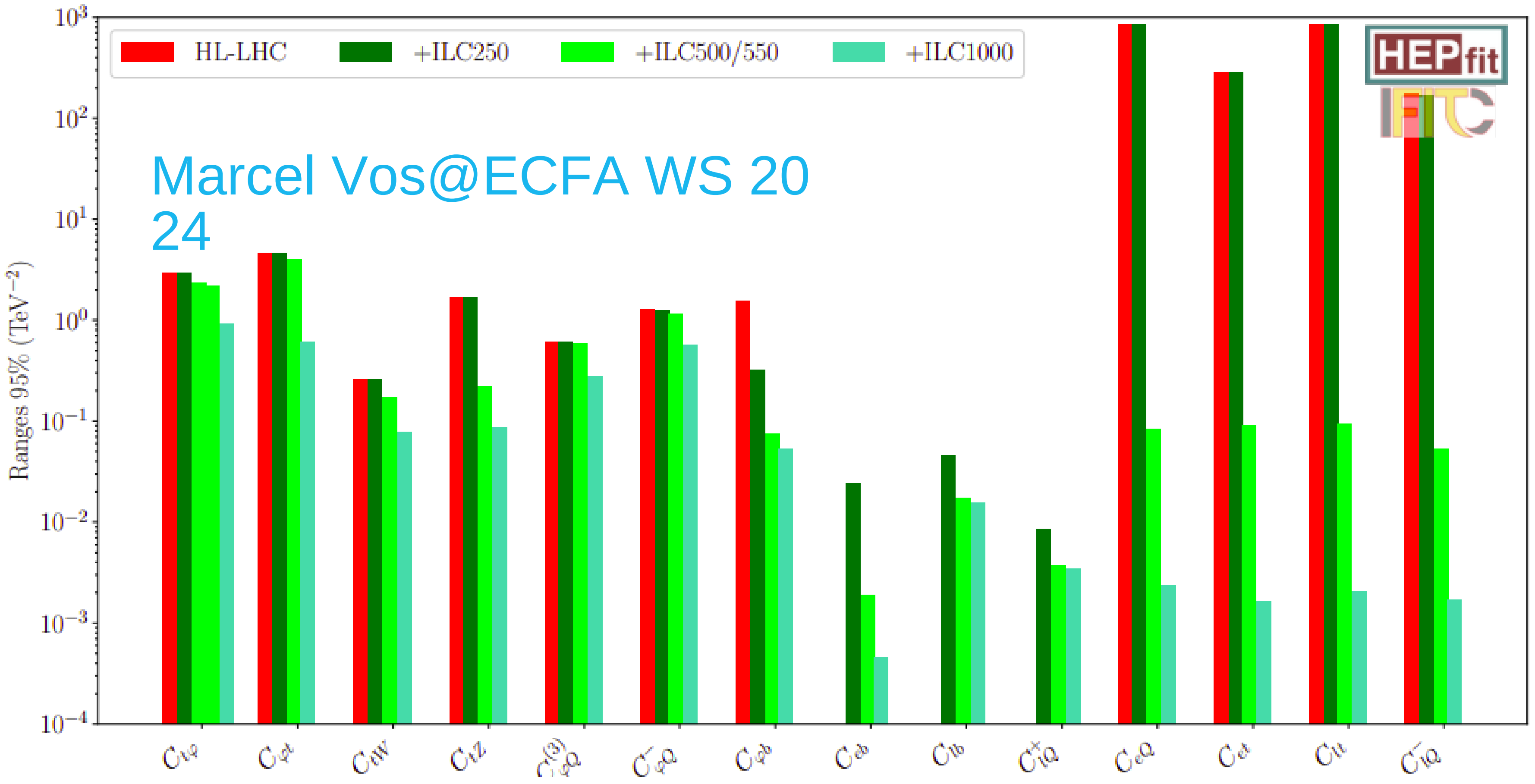


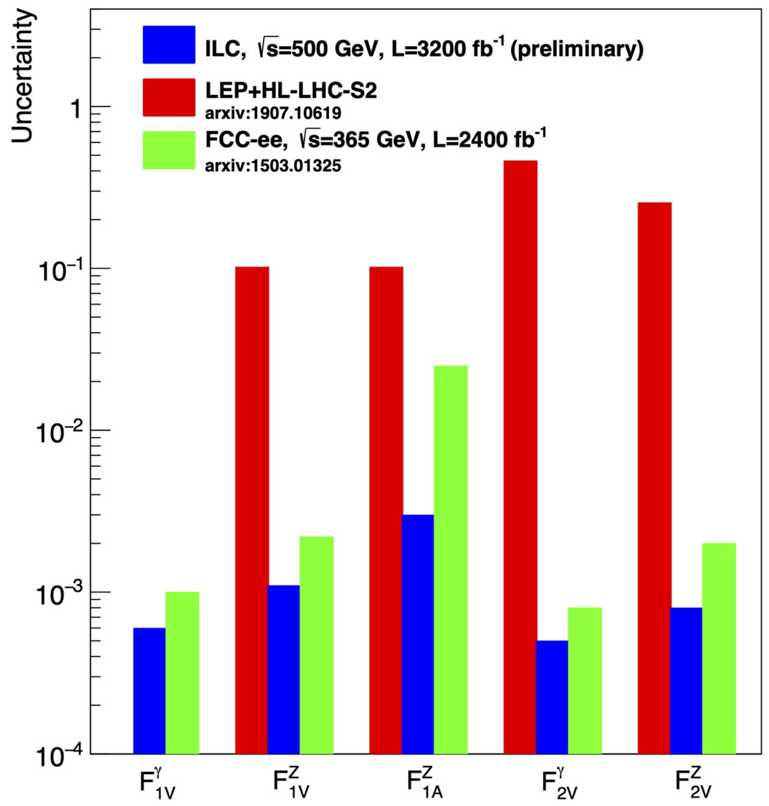
Semi-leptonic channel

ILD-Note-2019-007
Master Thesus Y. Okugawa

- 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)

Precision on electroweak form factors and couplings





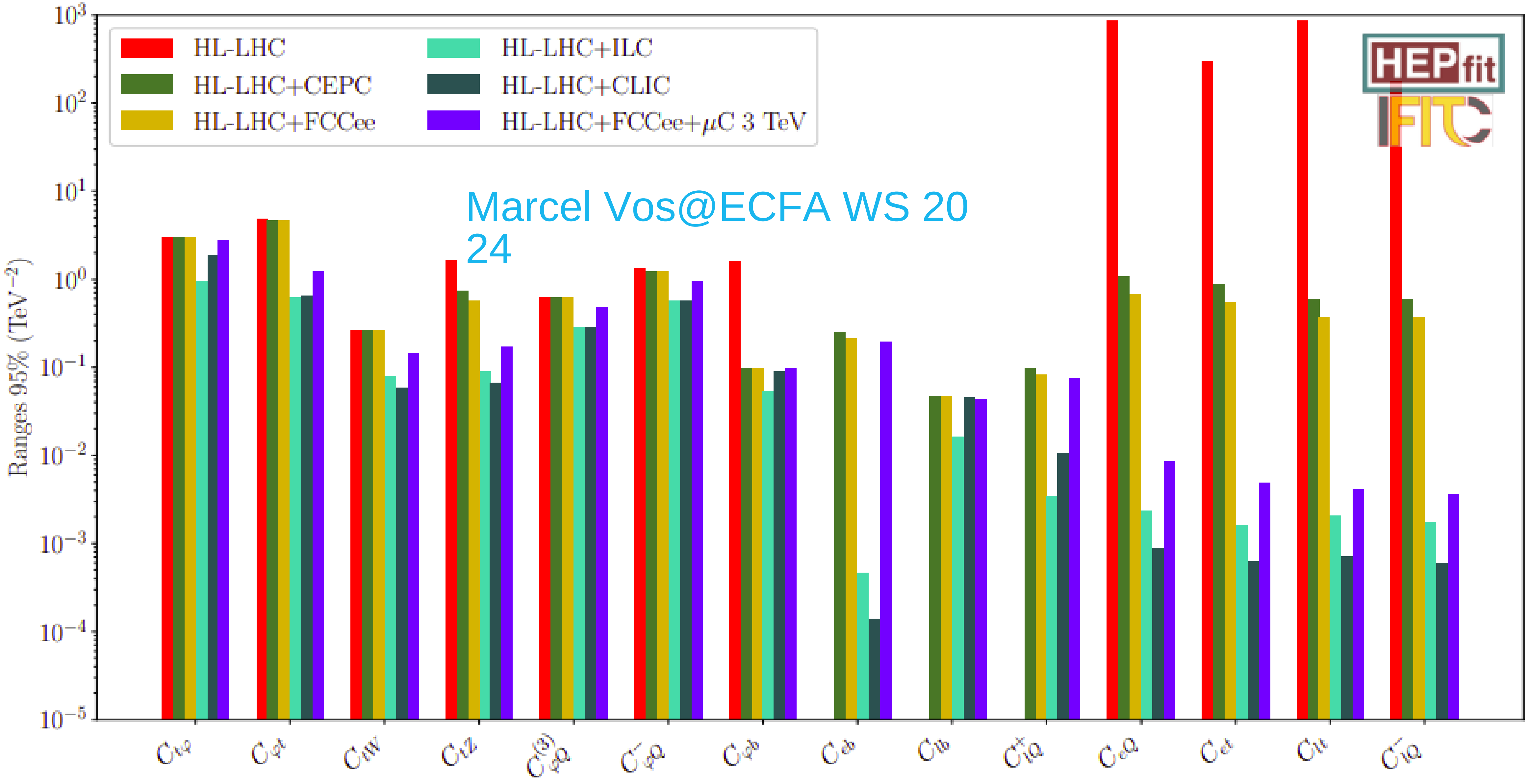
- e+e- collider way superior to LHC (√s = 14 TeV)
  - True for both, analysis in terms of Form Factors and Wilson Coefficients
- Polarised beams at ILC, final state analysis at FCCee
  - Final stat analysis also possible at LC => Redundancy should be checked again (see arxiv 1503.04247)
- :500 GeV is 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)

SMEFT Fit for different colliders

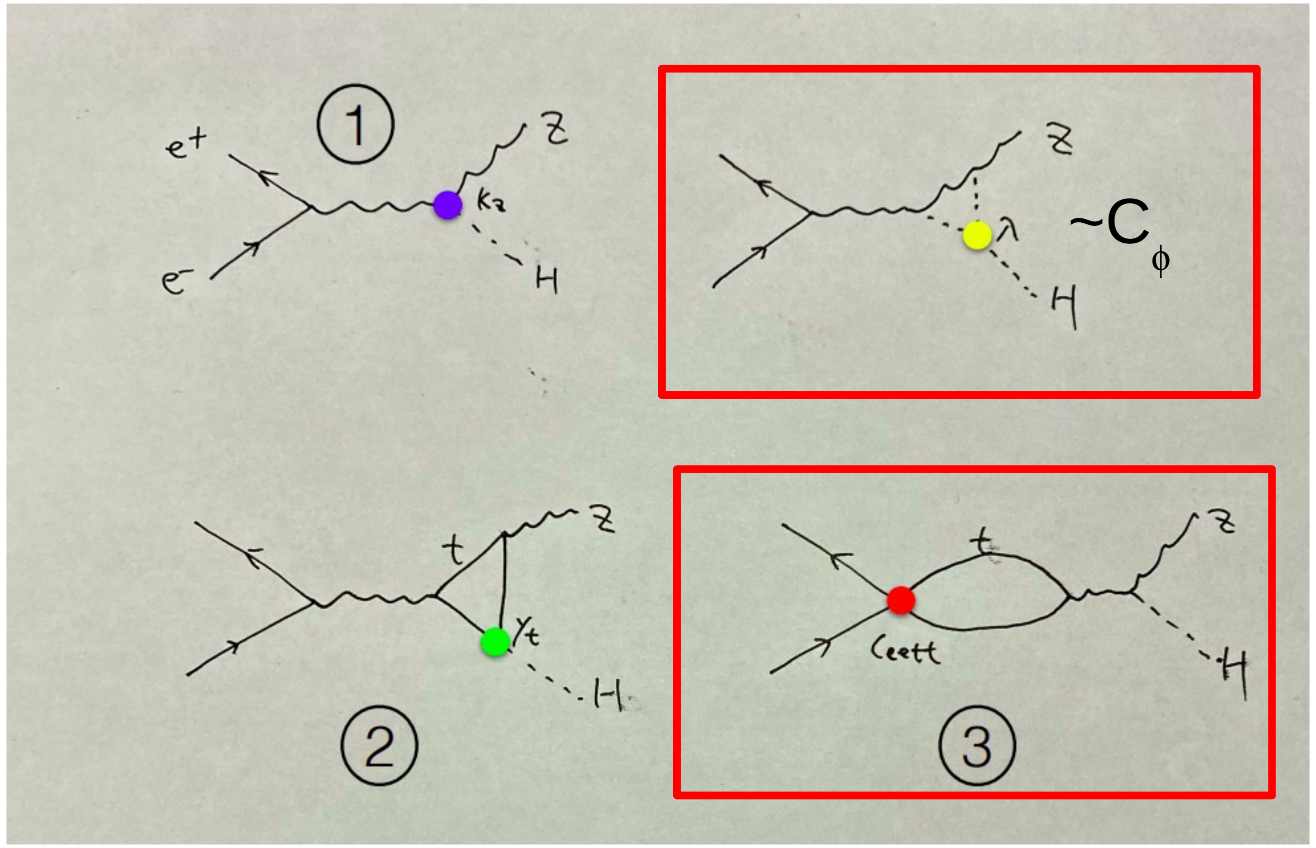


Marcel Vos@ECFA WS 2024

All e+e- colliders improve the bounds on the top sector dramatically
High-energy operation is important to provide the strongest global bounds

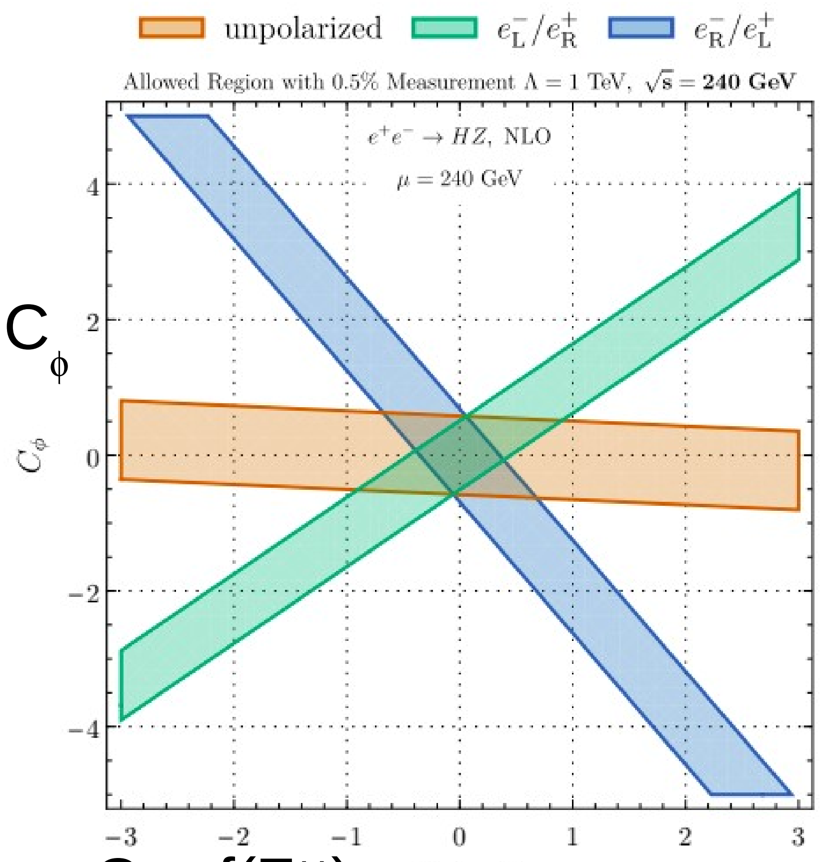
Entanglement - SMEFT NLO

NLO Contributions to ee->HZ



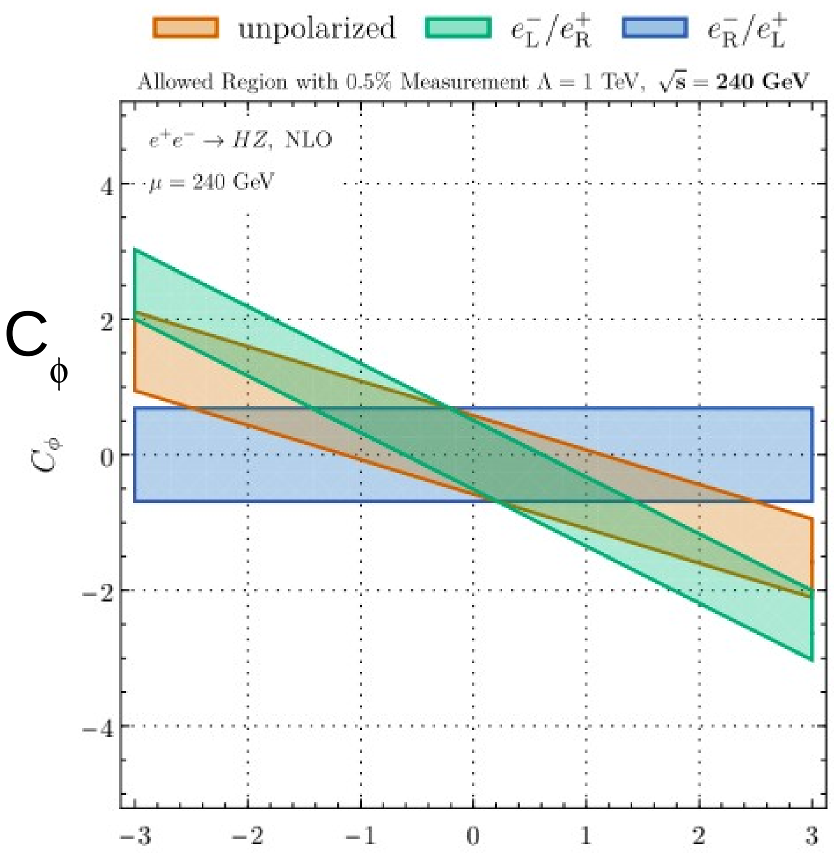
One important contribution is eett Vertex

Correlation C_ϕ to tt-Vertices arxiv:2409.11466



C_ϕ

$C_{\phi u}$=f(Ztt)



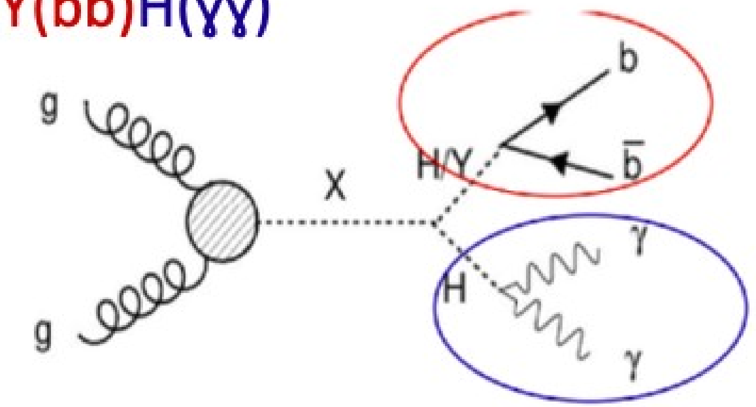
C_ϕ

C_{lq}=f(eett)

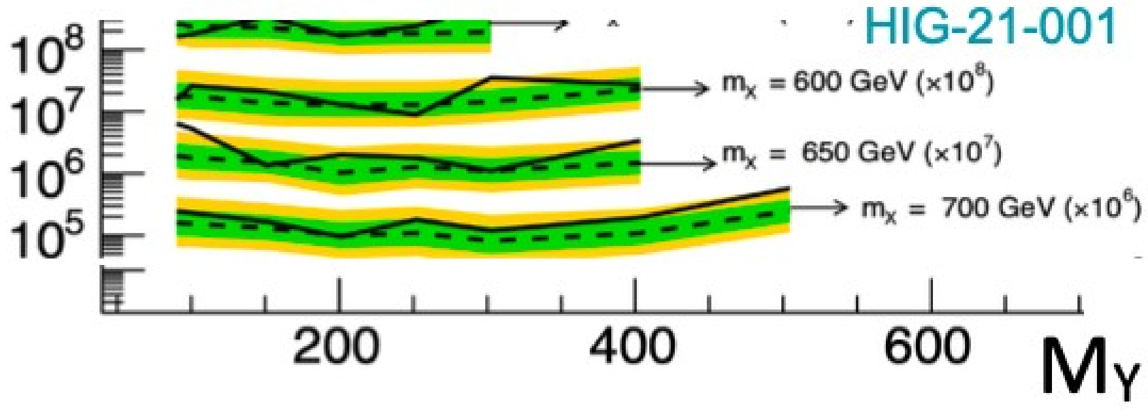
- NLO SMEFT introduces sensitivity to and constrains C_ϕ and operators involving top vertices
- Disentangling of constraints using beam polarisation
- Final word would come from higher energy measurements
- Note that C_{lq} is strongly energy dependent (-> would benefit from higher energies)

What if … the LHC makes a discovery?

Search for resonances (X) decaying to H/Y(bb)H(γγ)



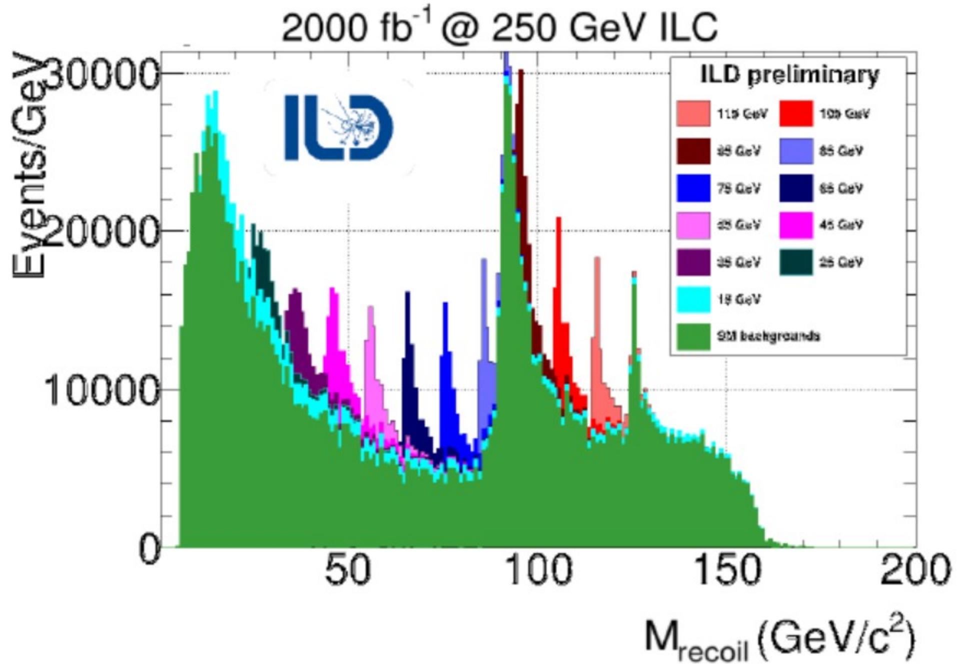
Excess at (90,100) with 650 GeV heavy resonance mass (~3.8 σ local and 2.8 σ global)



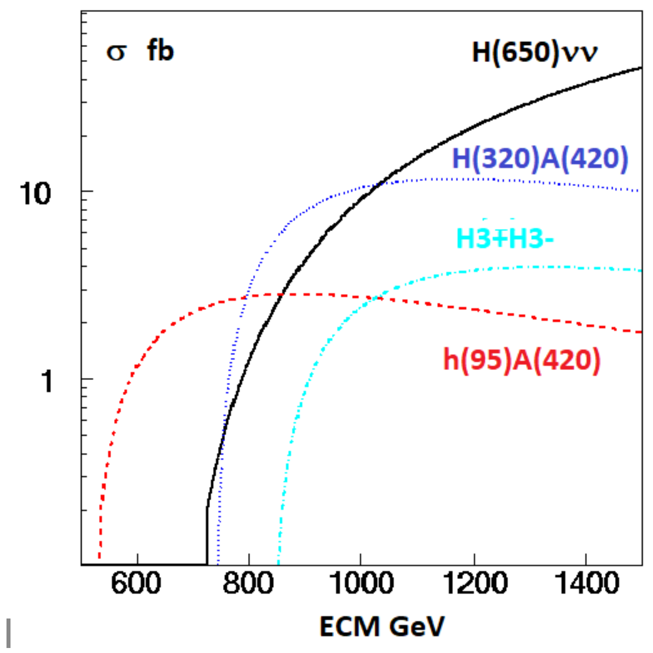
Tantalising excesses common to $\gamma\gamma$ and ττ final states!

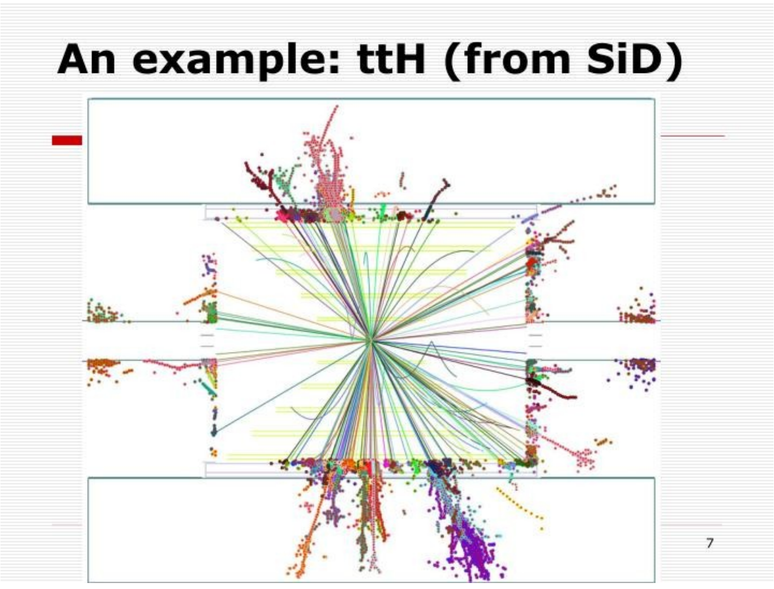
(update see last Higgs Hunting)

Light scalars are "easy" to measure

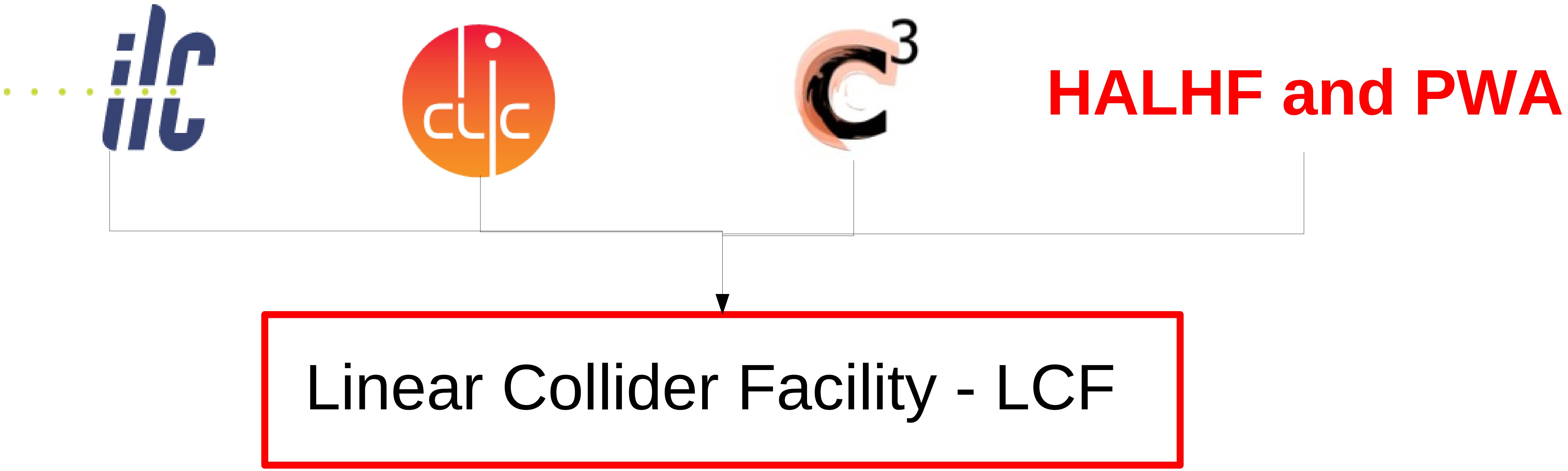


Sufficient centre-of-mass energy and hermetic detectors





LCVision



- LCVision is effort to develop a coherent plan for a LCF
  - LCF at CERN as an implementation
- Lead by S. Stapnes (CERN), J. List (DESY), M. Peskin (SLAC), Masaya Ishino (UTokyo), R.P.
- The LCF would start with an ILC-like machine
  - tunnel length of 27 km would allow to reach tt threshold using current ILC technology
  - two interaction regions
  - upgrades by innovative technologies
- CERN's current infrastructure and energy consumption as *upper limits* for LCF
- Comité Collisionneur Linéaire input to French discussion in phase with LCVision

LCVision – Communication

- Community Event at CERN 8/1/25 – 10/1/25 https://indico.cern.ch/event/1471891/

Linear Collider Vision Community Event 2025

8–10 Jan 2025
CERN
Europe/Zurich timezone

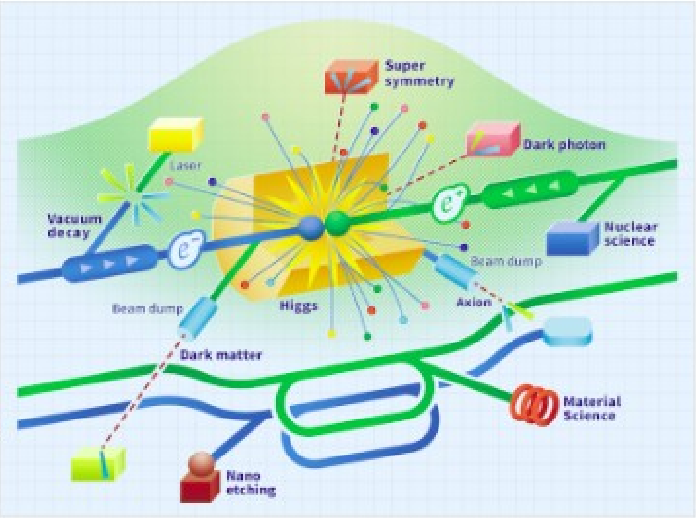
Enter your search term

- Overview
- Timetable
- Registration
- Privacy Information
- Videoconference

Administrative Support

Alexia.augier@cern.ch

Born at LCWS2024, LC Vision brings together proponents and supporters of all kinds of Linear Collider projects, in order to discuss common topics, to develop a united perspective on the long-term evolution of a Linear Collider Facility, and to propose such a facility for CERN. At this meeting, the LC Vision plans for the EPPSU will presented to the interested community.



The meeting will be run in hybrid mode, the zoom link will be communicated to registered participants only. The registration is free of charge, but please register by December 15.
For participants at CERN, a number of hostel rooms has been blocked.... A visitor card for CERN can be requested during registration.

- LC Vision e-mail list (follow link)

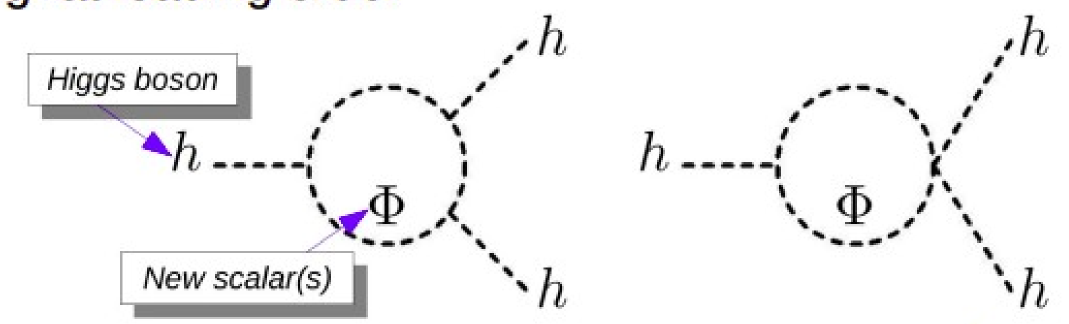
Summary and outlook

- Rich physics at and above tt threshold
- Top mass is important SM parameter
- Direct measurement of tth in clean ee environment (at least complementary to HL-LHC)
- Top physics would strongly benefit from higher energies
  - Sensitivity to electroweak couplings or EFT Coefficients improve with energy (see also backup)
  - Consistent top physics programme may shed light on fermion mass hierarchy
- (In NLO SMEFT) Top physics and Higgs physics are correlated
  - Constraints already in ee->HZ benefit strongly from beam polarisation
- Linear Collider Facility could react on discoveries/anomalies appearing at HL-LHC
  - Advocates flexibilty in energy reach
- Linear Collider Faclity would allow for a long term vision of CERN and particle physics in general
  - ... while leaving options open for now and for the future

Backup

Probing New Physics with trilinear Higgs Coupling

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

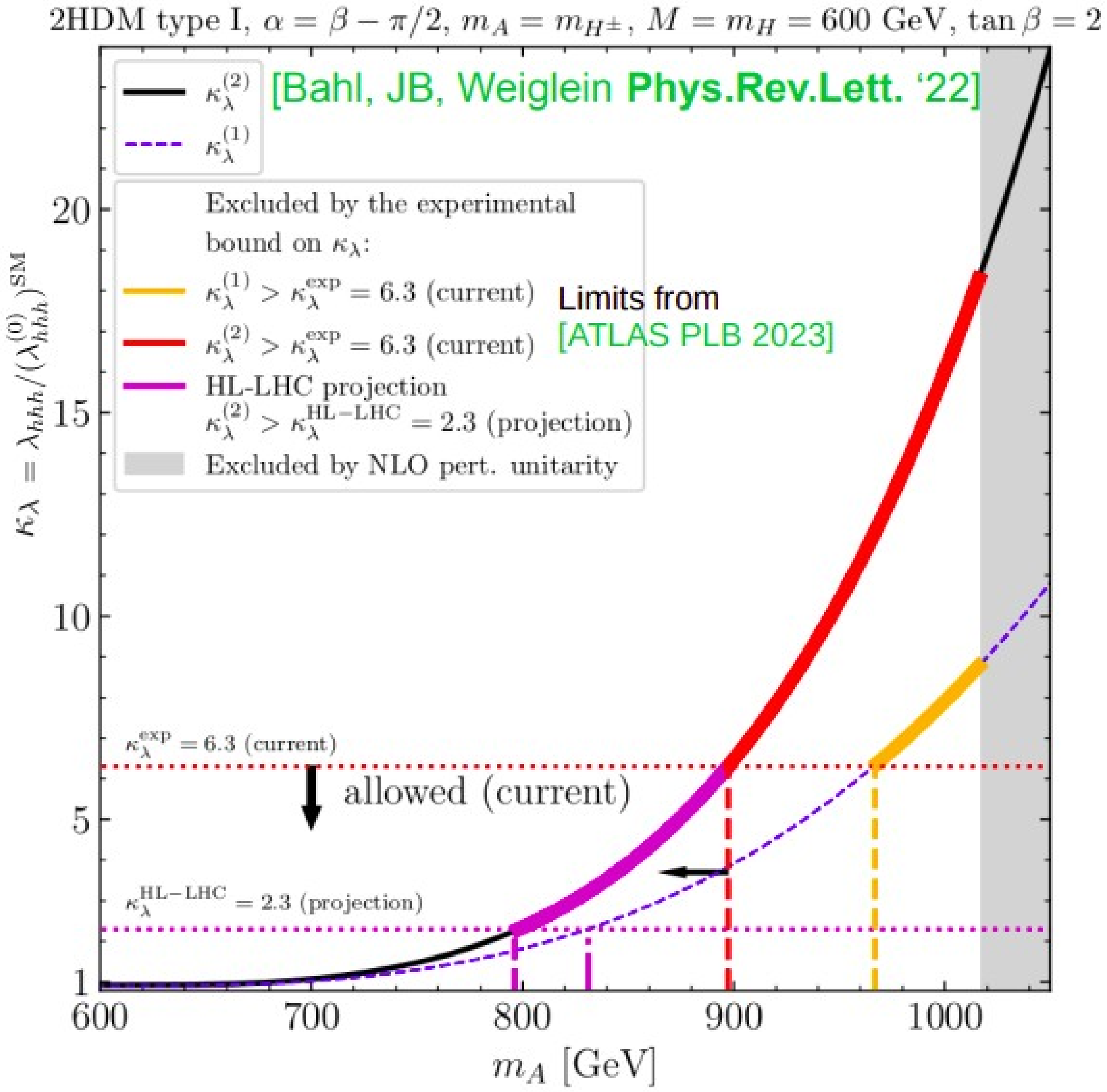


$$m_\Phi^2 = M^2 + \frac{1}{2} g_{hh\Phi\Phi} v^2 \Leftrightarrow g_{hh\Phi\Phi} = -\frac{2(M^2 - m_\Phi^2)}{v^2}$$

- Comparing latest exp. bounds

$$-1.2 < \kappa_\lambda = \frac{\lambda_{hhh}}{(\lambda_{hhh}^{(0)})^{SM}} < 7.2$$ [ATLAS 2024]

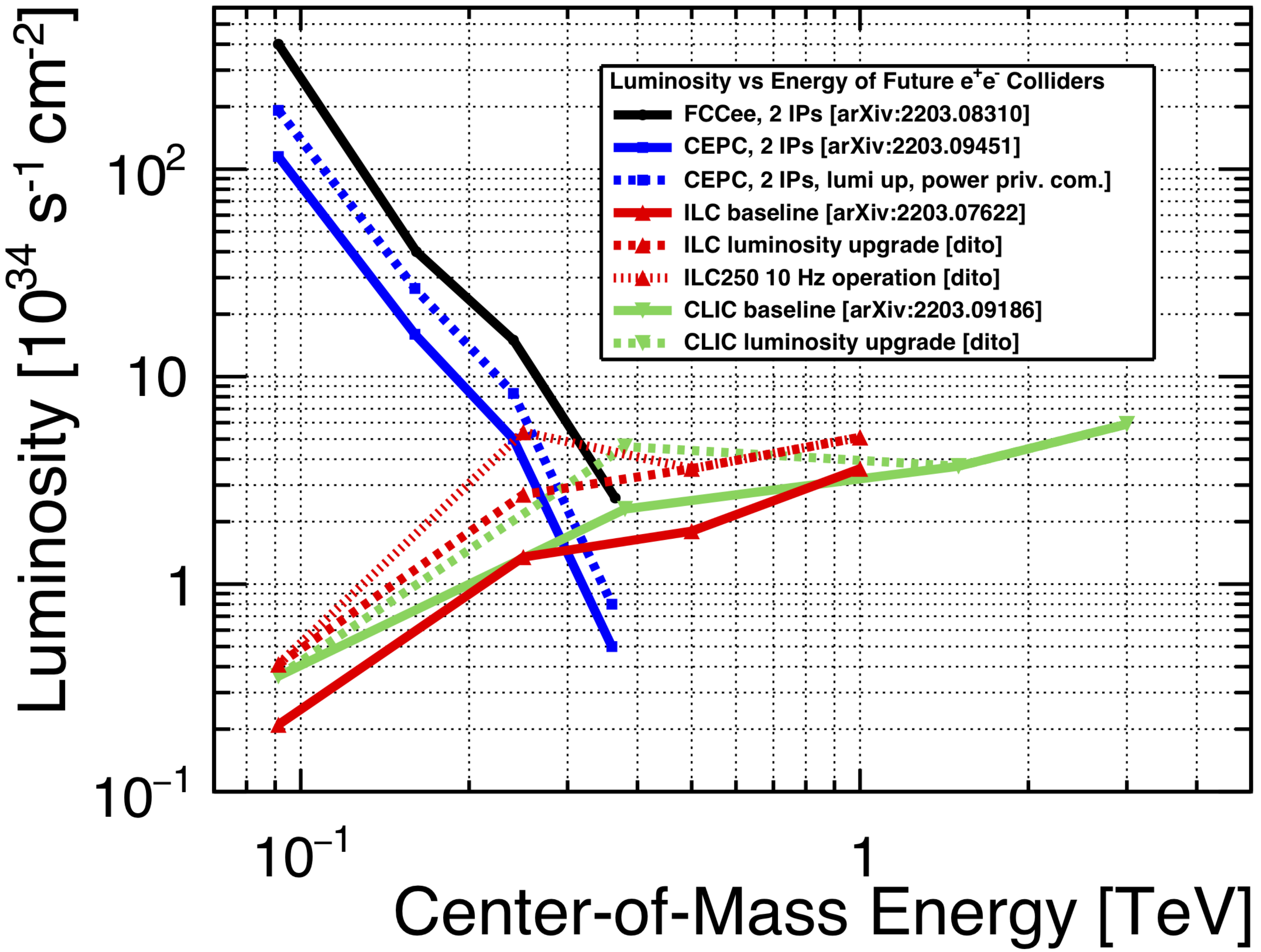
with precise theory predictions for λ_{hhh} provides a **powerful new tool to constrain BSM models**
[Bahl, JB, Weiglein **Phys.Rev.Lett.** '22]



Upshot: New particles are maybe not many TeV away but in LC reach

J. Braathen ECFA Workshop 2024

Linear vs. circular e+e- machines – Instantaneous luminosities



High energies ~above tt-threshold
Domain of linear colliders

Low energies e.g. Z-pole
Domain of circular machines
However, ...

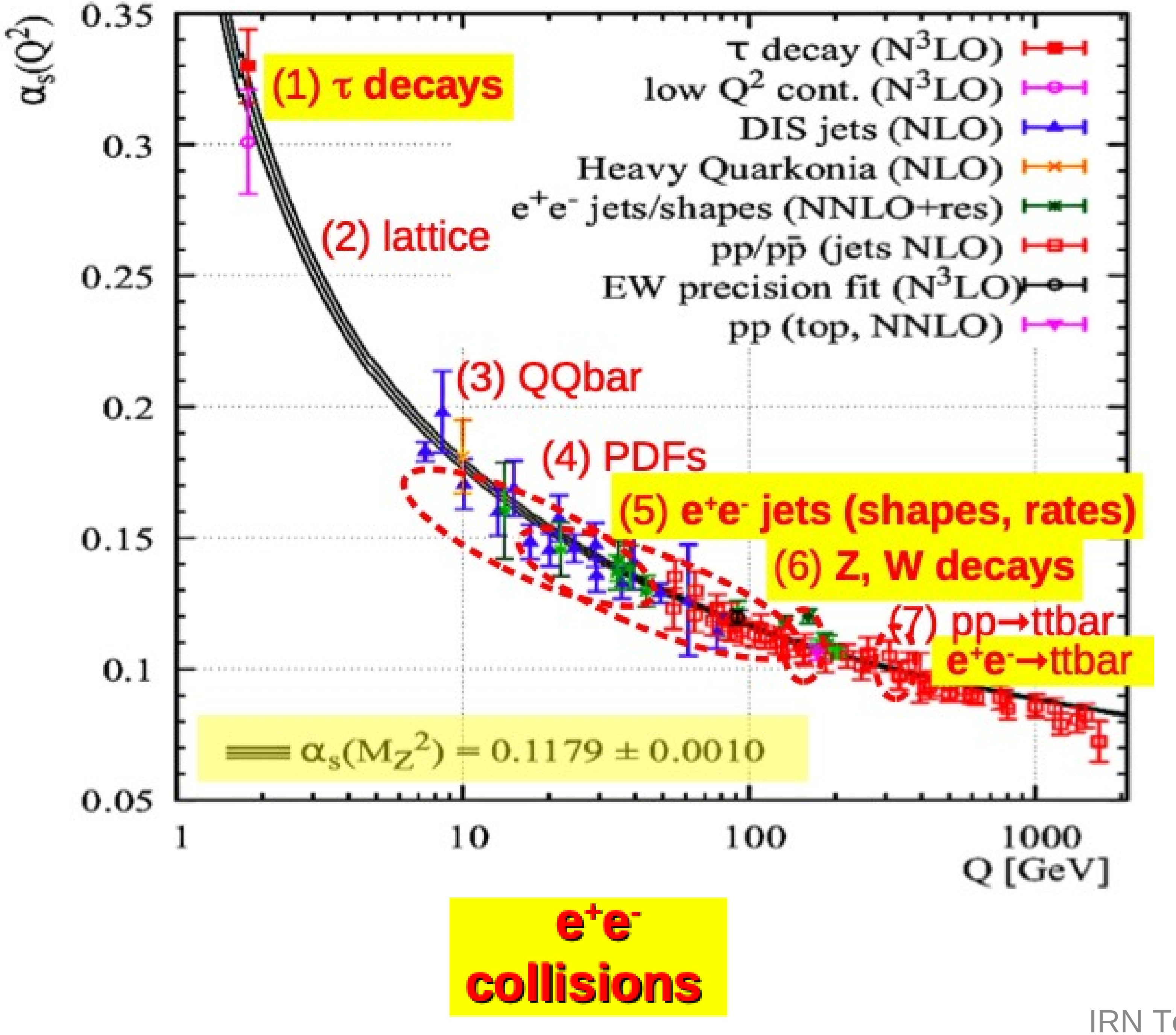
Transition region, i.e. HZ threshold
Comparable Higgs Couplings uncertainties for all proposals (see later)

Linear colliders are more versatile to test chiral theory due to polarised beams

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

Figure J. List

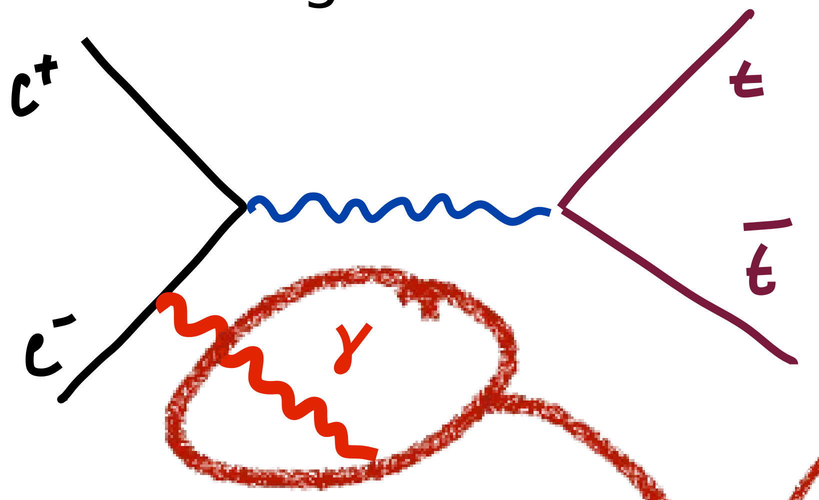
Uncertainty driver α_s



- Talk by Francesco Giuli at LCF22
  - https://indico.ectstar.eu/event/149/contributions
  - /3058/attachments/1919/2513/FCC_LFC_FGiuli_2022.pdf
- Best prospects from e+e- collisions
  - Δα/α ~0.1% for FCCee hadronic Z-decays
    - Comparable with QCD Lattice Results
  - Status for ILC Δα/α ~0.6% (arXiv:1512.05194)
    - Worth another look ?!

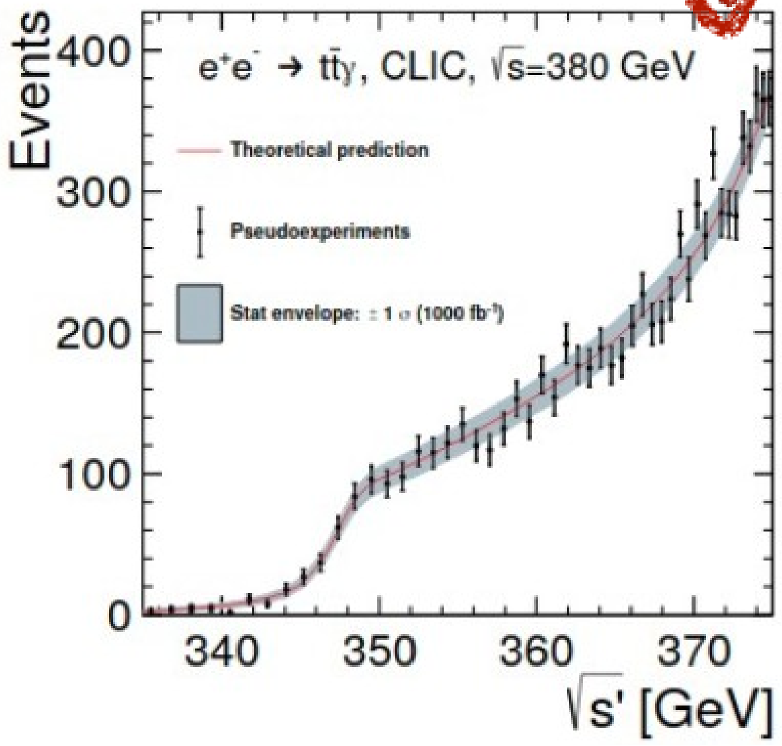
Running top mass

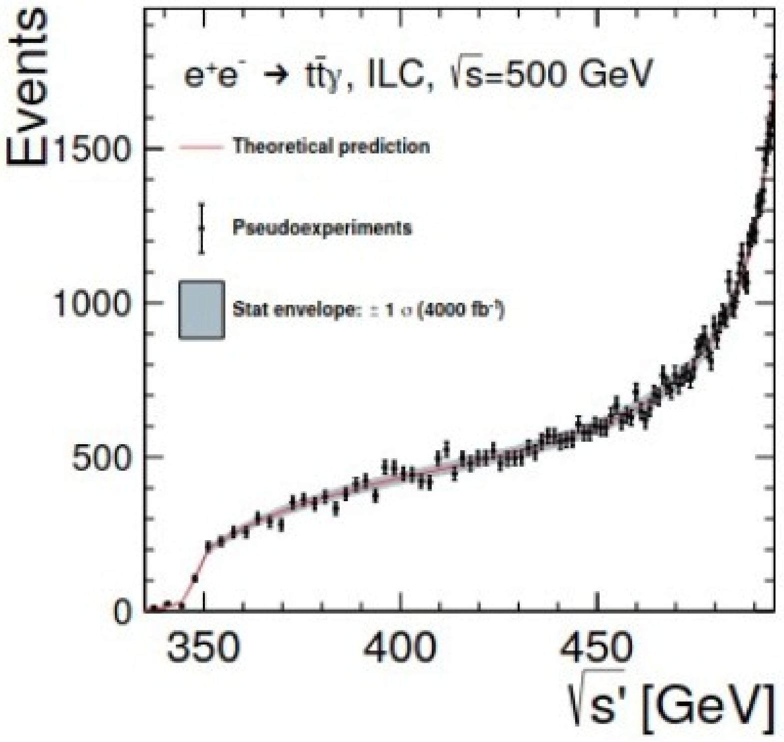
- A new(er) idea to measure the top mass in a theoretically well-defined scheme in high-energy running above the threshold



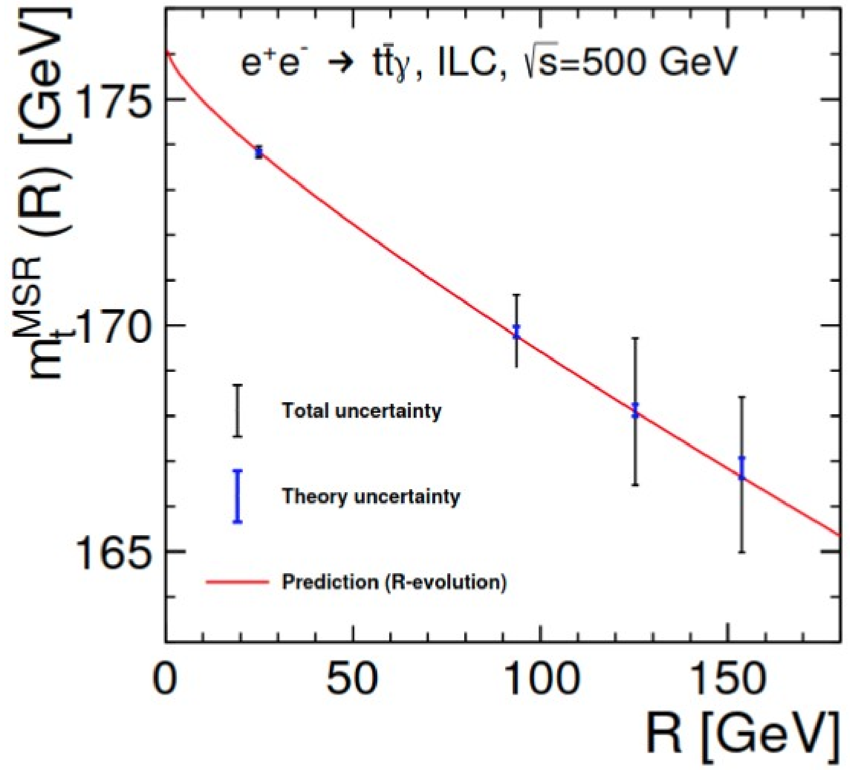
cms energy	CLIC, $\sqrt{s} = 380$ GeV		ILC, $\sqrt{s} = 500$ GeV	
luminosity [fb^{-1}]	500	1000	500	4000
statistical	140 MeV	90 MeV	350 MeV	110 MeV
theory	46 MeV		55 MeV	
lum. spectrum	20 MeV		20 MeV	
photon response	16 MeV		85 MeV	
total	150 MeV	110 MeV	360 MeV	150 MeV

matched NNLO + NNLL calculation, luminosity spectrum folded in explicitly;
Extraction of short distance MSR mass



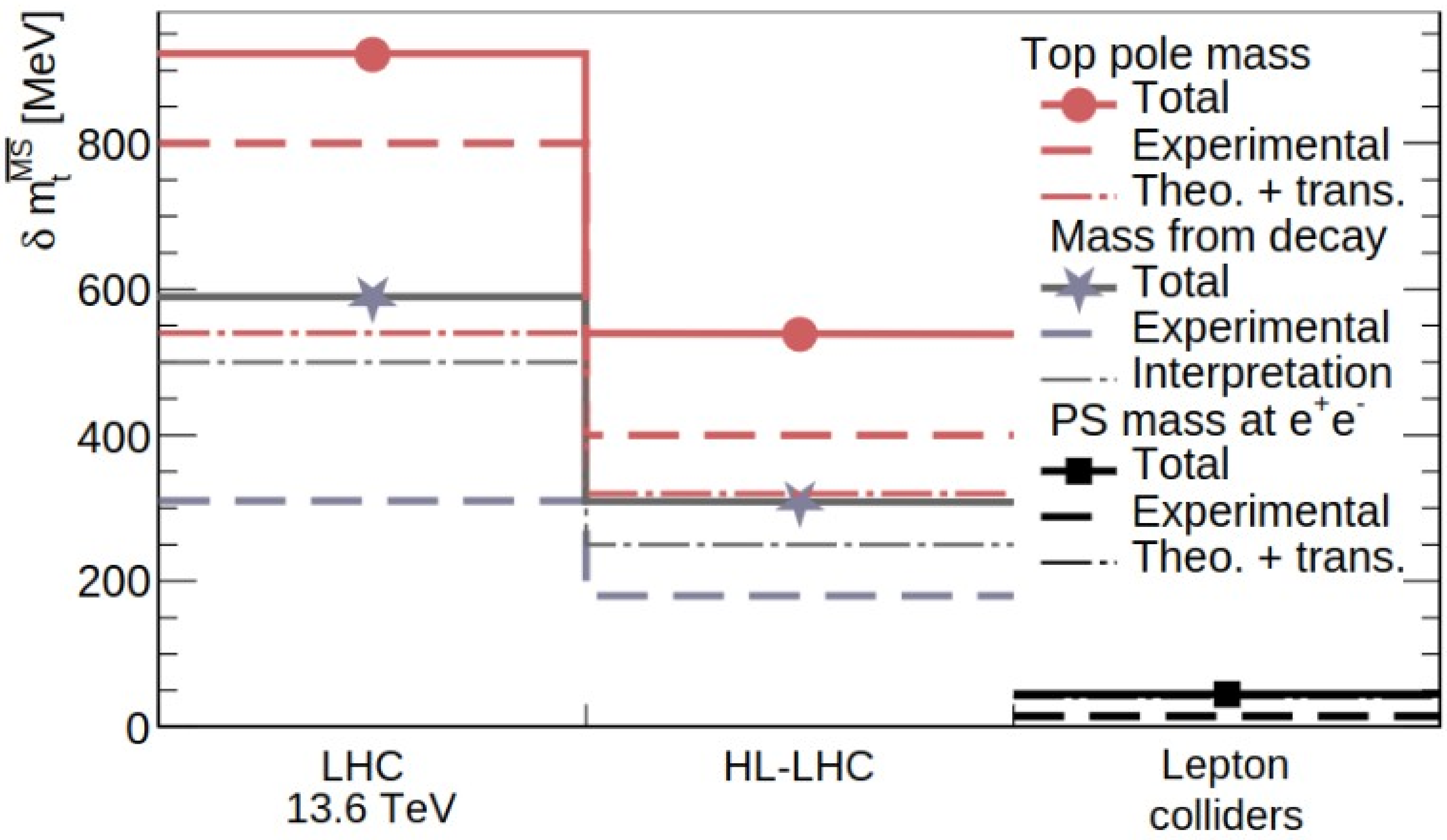


can provide 5σ evidence for scale evolution ("running") of the top quark MSR mass from ILC500 data alone



Top mass summary

Snowmass report, arXiv:2209.11267



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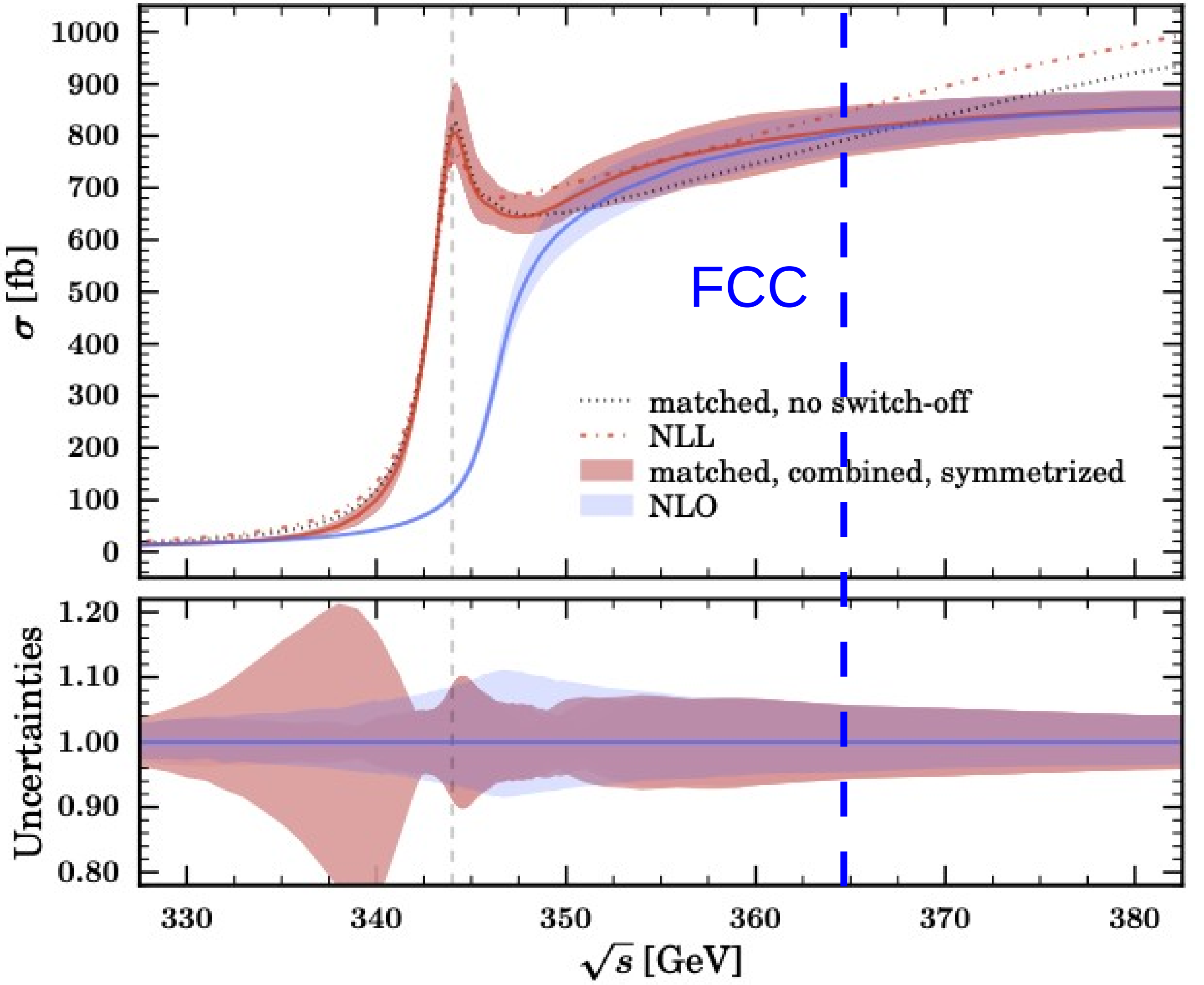
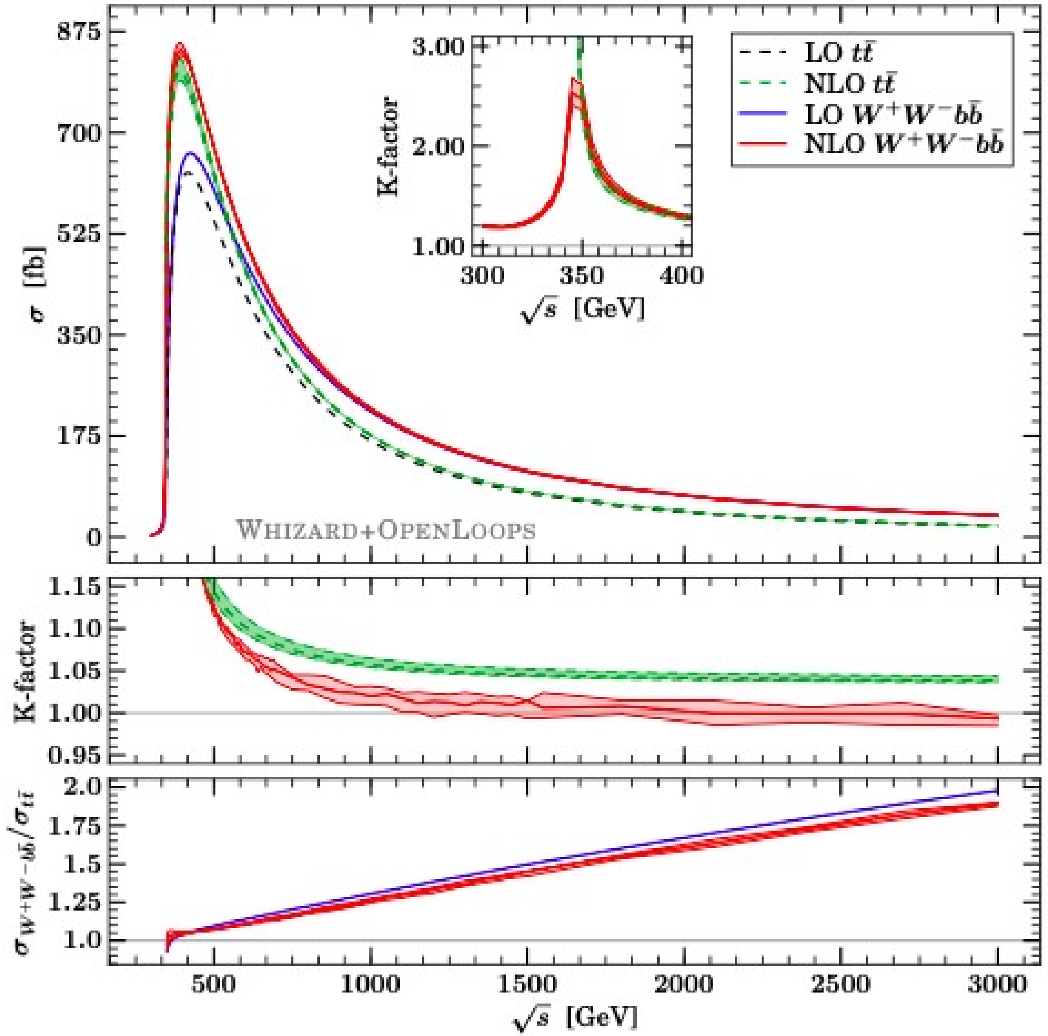
QCD uncertainties on ee->tt cross section

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

Linear Colliders

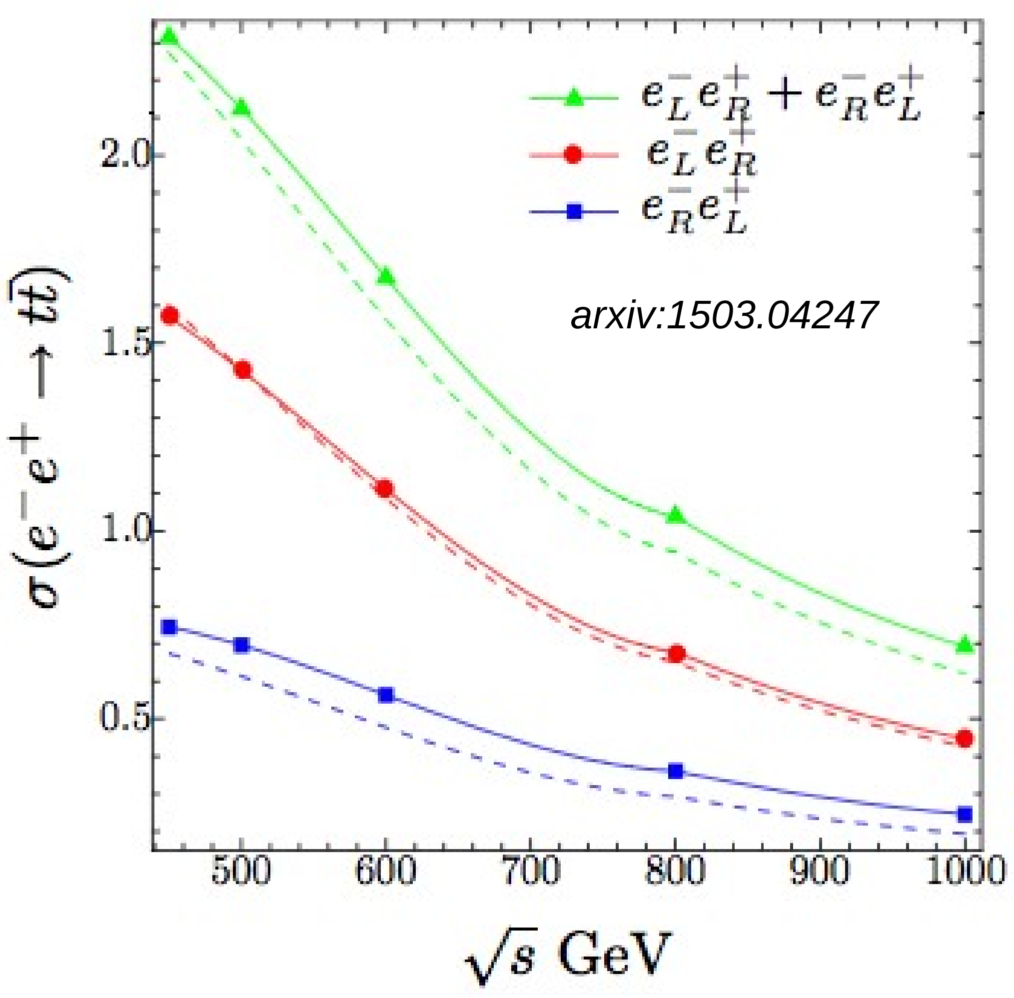


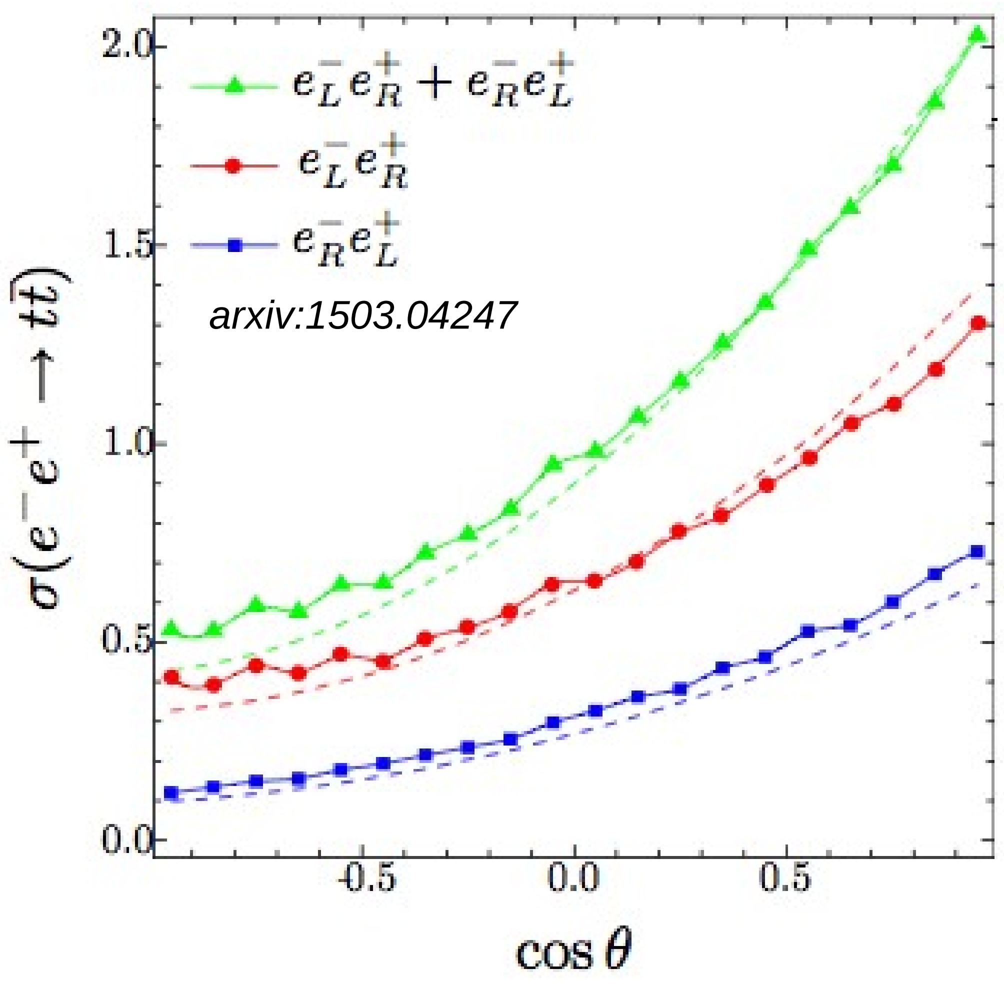


- Marching non-relativistic calculations in threshold region with tt-continuum is theoretical challenge
- QCD uncertainties shrink as energy increases
- Non resonant contributions are important (i.e. ee->tt --> ee->WbWb)

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

High Order Electroweak Corrections





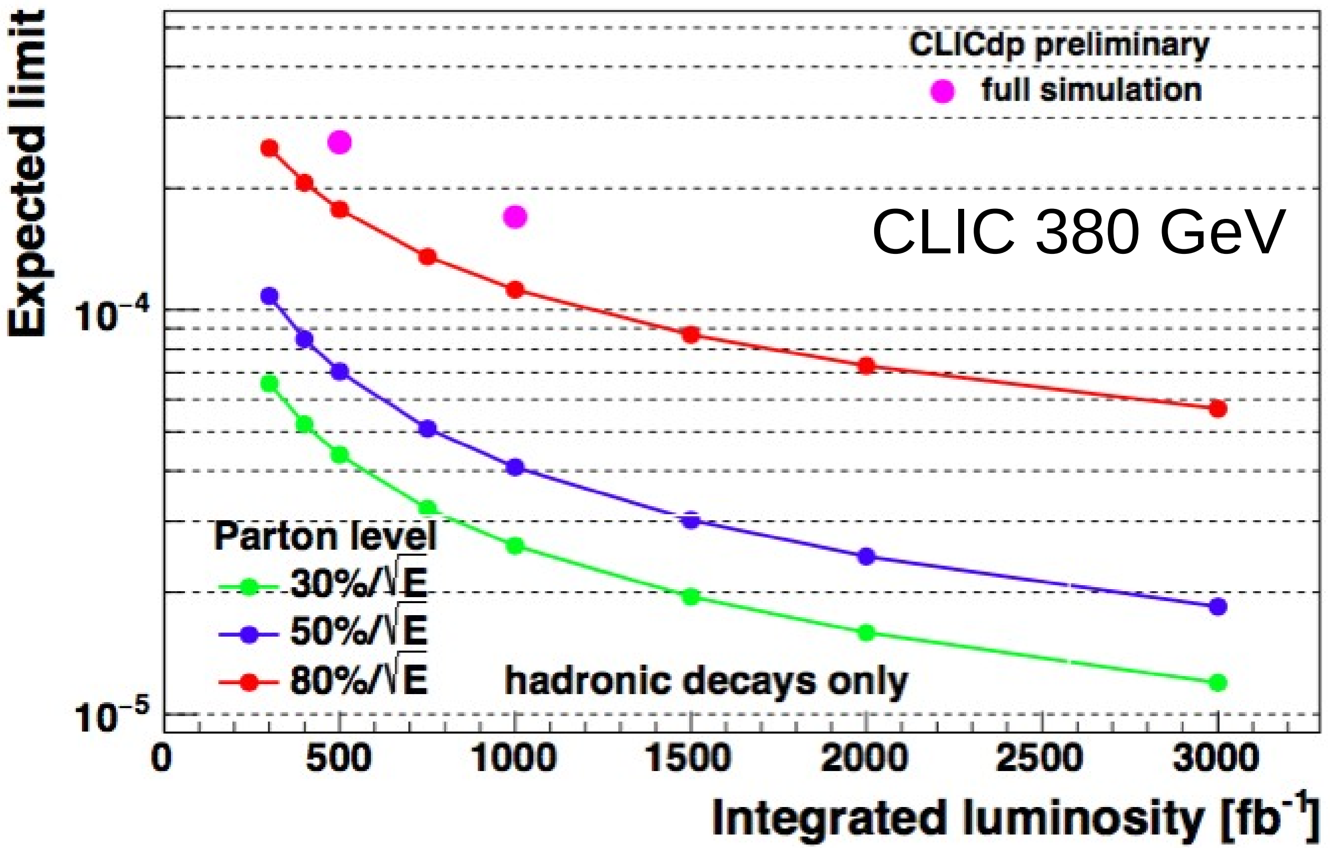
- Electroweak corrections manifest themselves differently for different beam polarisations

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

Top exotic decays 1

Expected limits on $BR(t \to ch) \times BR(h \to b\bar{b})$

Comparison with parton level results, different jet energy resolutions



Slide from 2016!!!!

- Multi-jet final state!
  - Seems that jet energy resolution on parton level cannot be propagated to detector
  - Re-assessment of reason needed
  - c and b quarks can decay semileptonically
- Higher energies may help

A.F. Zarnecki, N. v.d. Kolk

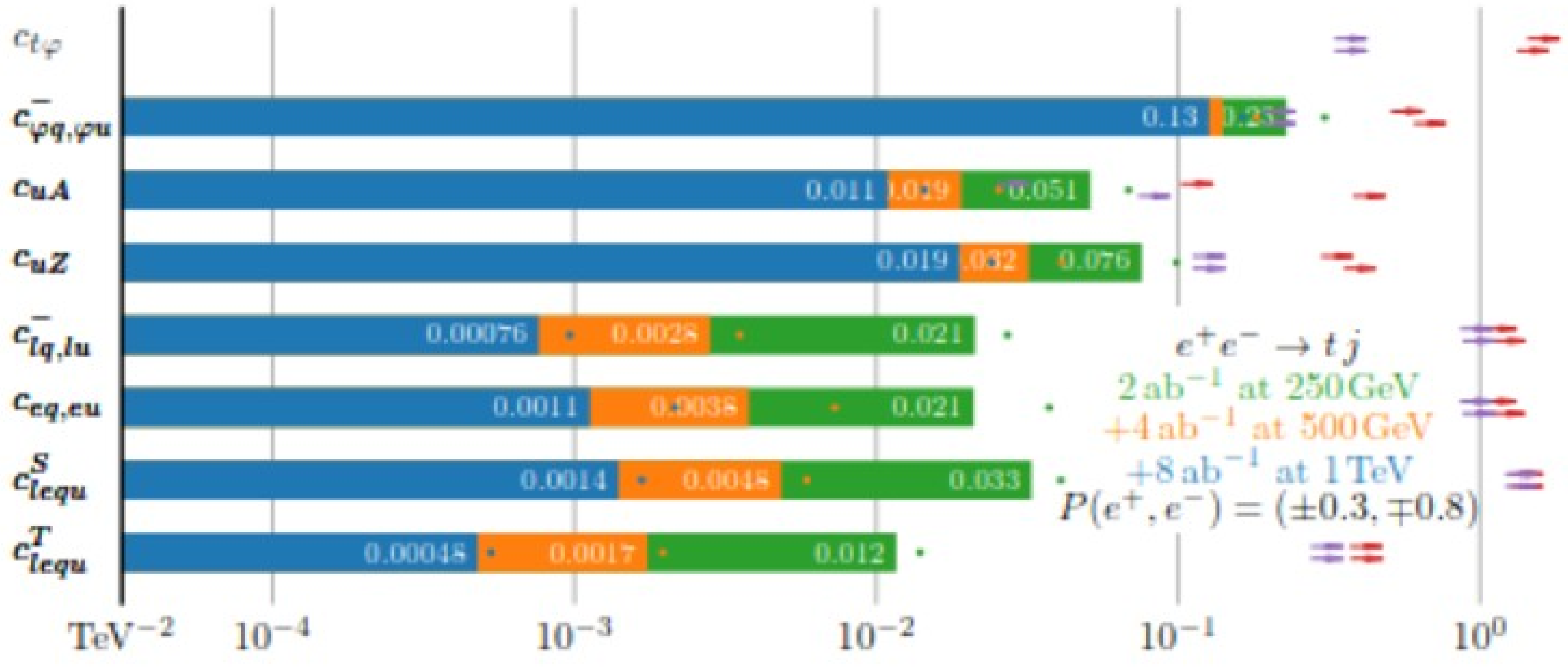
Top exotic decays 2

Lepton collider is both competitive and complementary

First top physics: e+e- → tj searches at 250 GeV

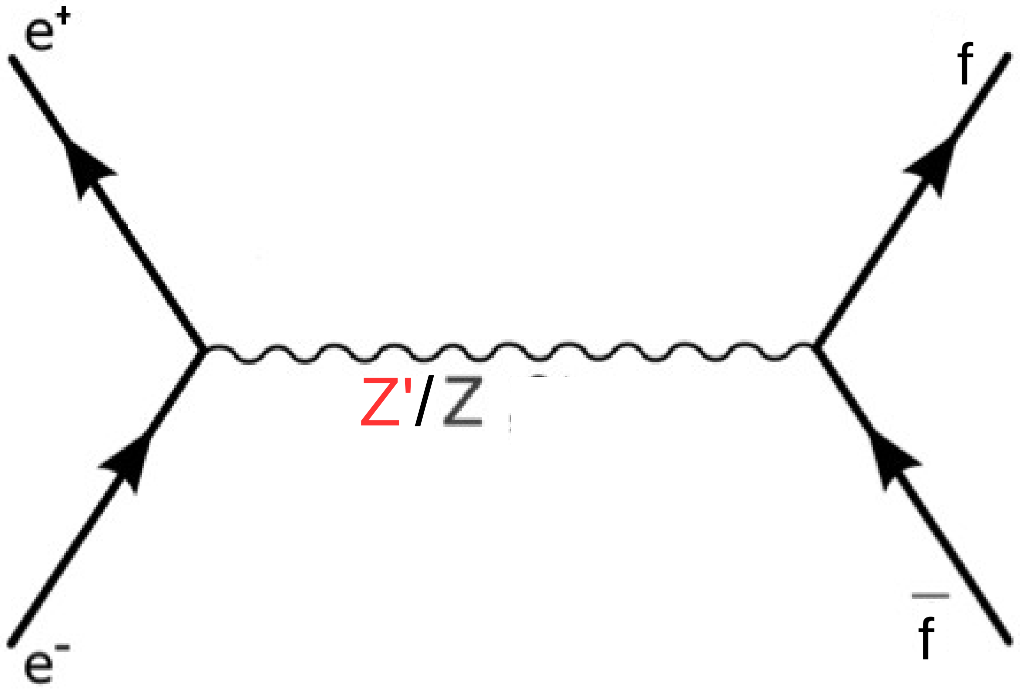
More full-simulation work needed!

H. Hesari et al., arXiv:1412.8572
G. Durieux et al., arXiv:1412.7166
Shi & Zhang, arXiv:1906.04573
ILC white paper, arXiv:2203.07622
M. Arroyo et al.,arXiv:2202.04572

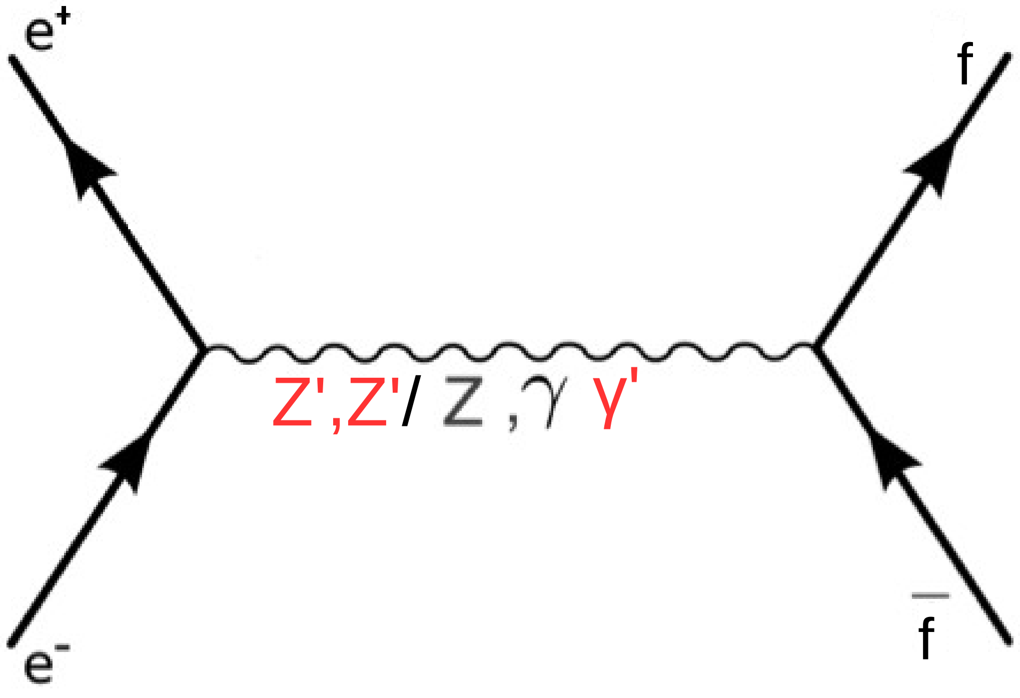


Two fermion production: Z-Pole and higher energies

On the Z-pole



Above the Z-pole

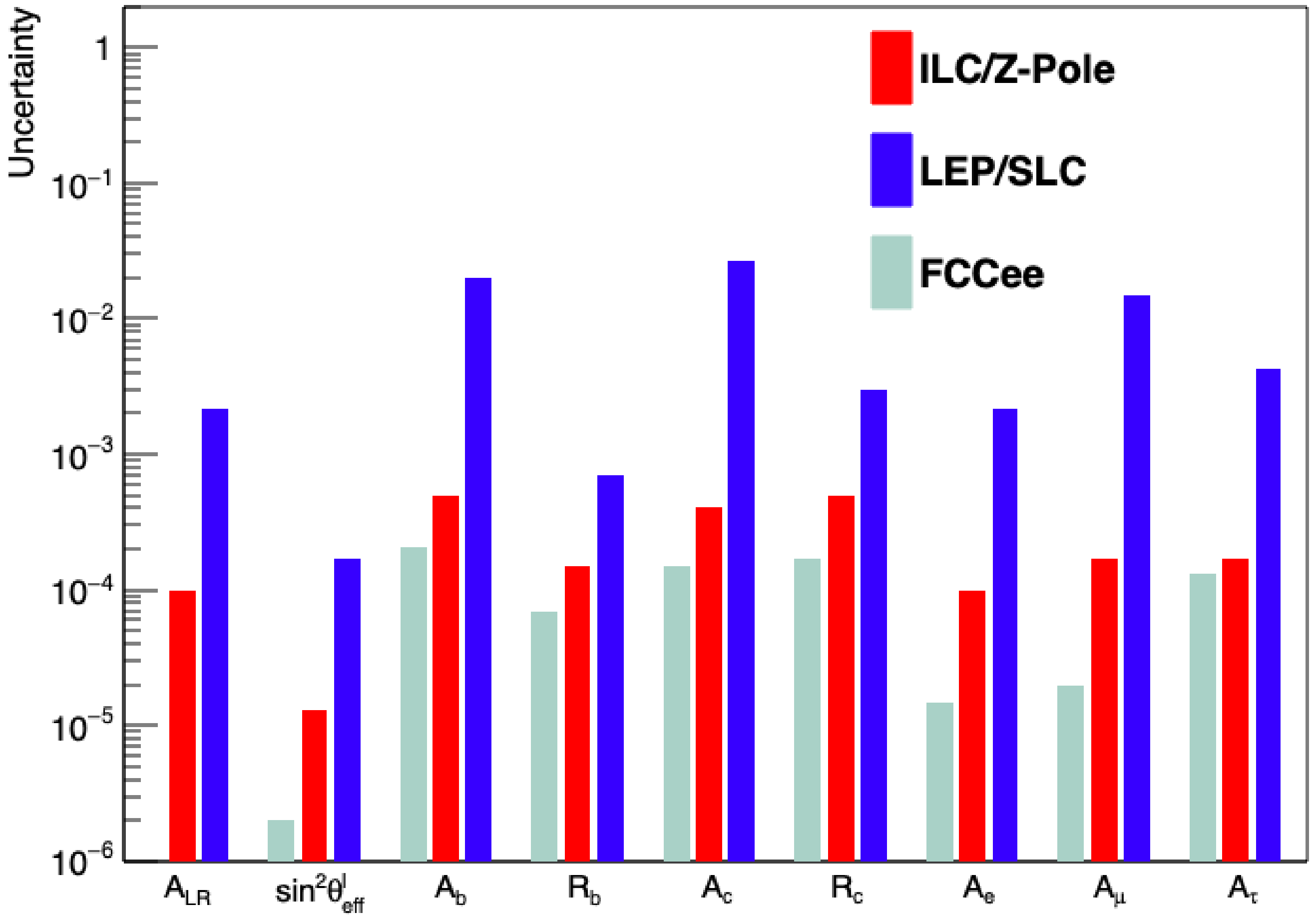


Sensitivity to Z/Z' mixing
Sensitivity to vector (and tensor) couplings of the Z

- the photon does not "disturb"

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

Z-Pole input?



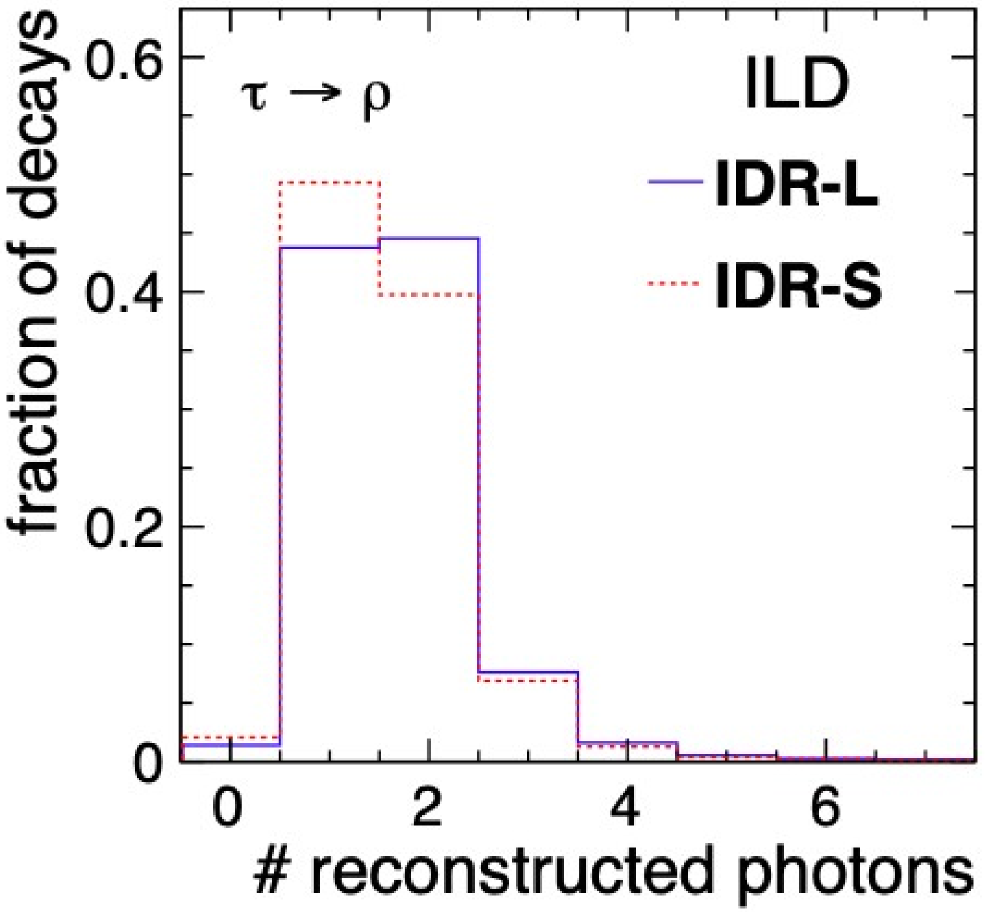
Numbers FCCee: “Mixture” of FCC CDR and
P. Janot at Precision Workshop/CERN
https://indico.cern.ch/event/1140580/timetable/

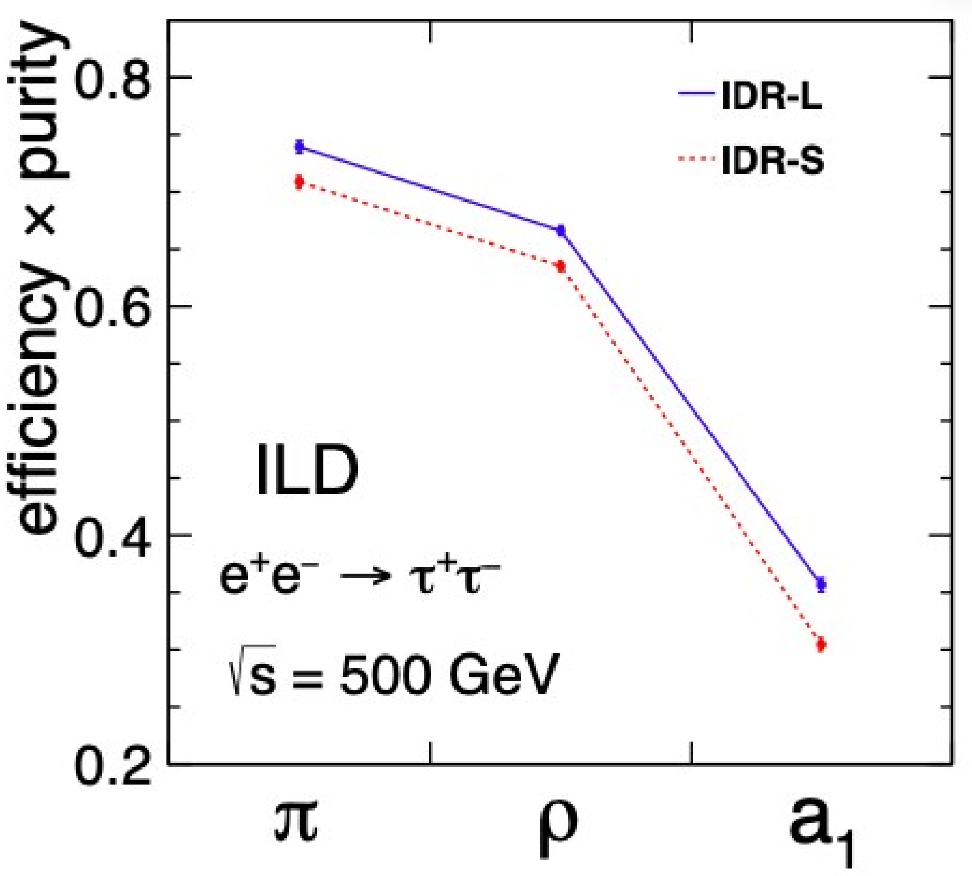
Numbers ILC: arxiv: 2203.07622 (ILC Snowmsss report)

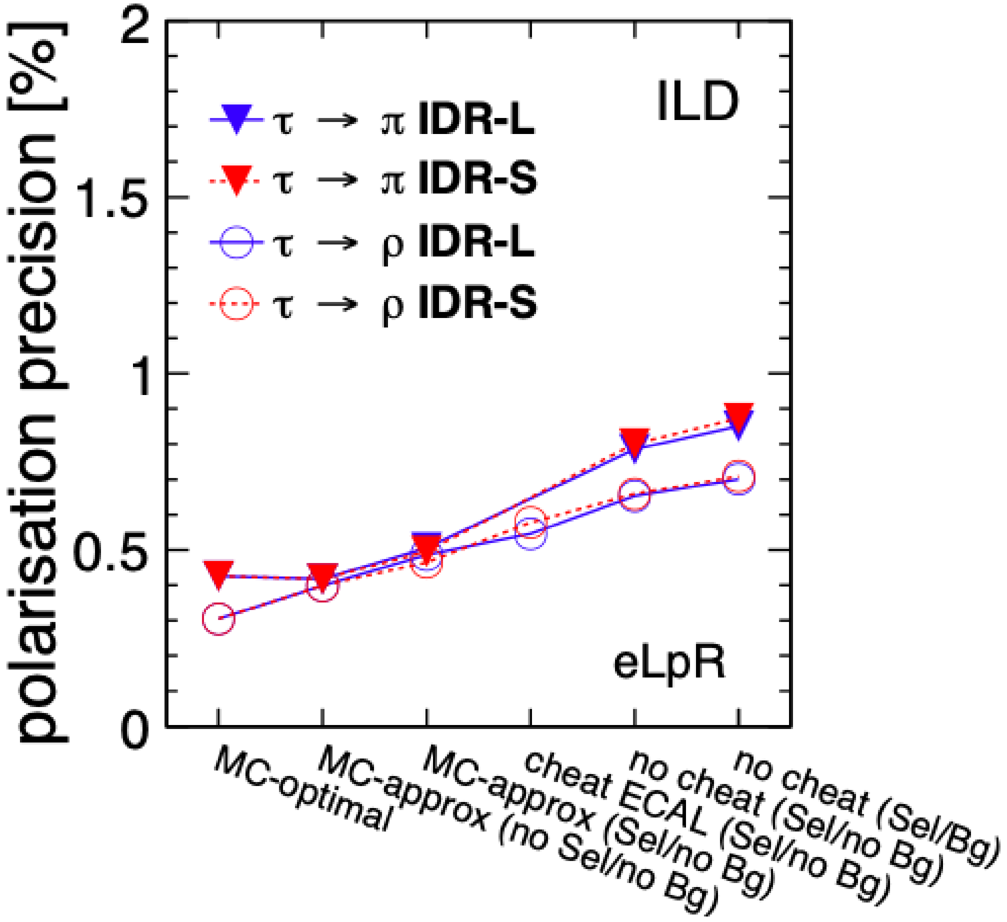
- All future colliders will improve significantly precision compared with LEP/SLC
- Comparable precisions despite differences in luminosity
  - Systematics will play a major role
- **No full simulation study exists on Z-Pole**
  - Most of the results (educated) guesses on experimental issues by extrapolations from higher energies
  - Some examples in the following

τ-lepton polarisation

$e^+e^- \rightarrow \tau^+\tau^-$ Recent study at 500 GeV for ILD IDR







Photon separation gets involved at high energies
Still often only one photon reconstructed

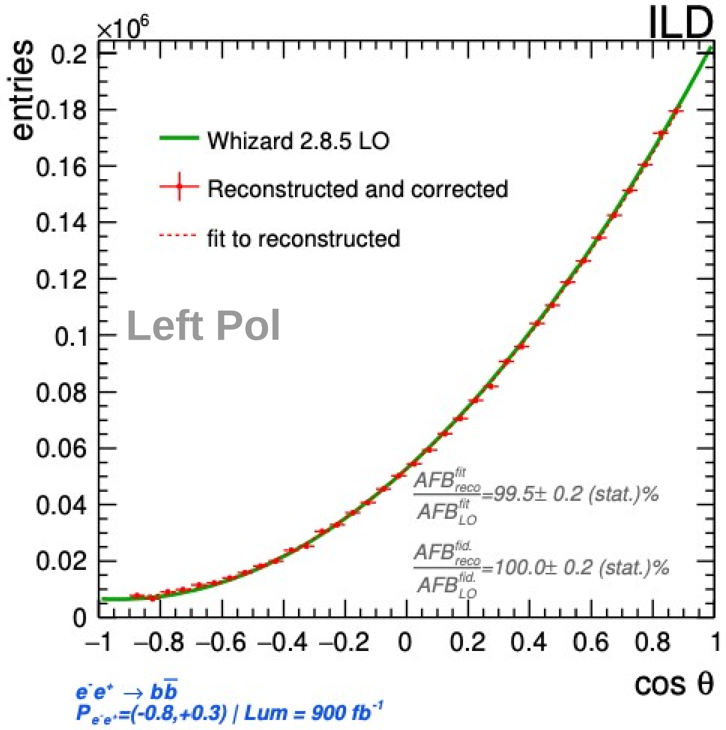
EfficiencyxPurity drops with increasing photon multiplicity

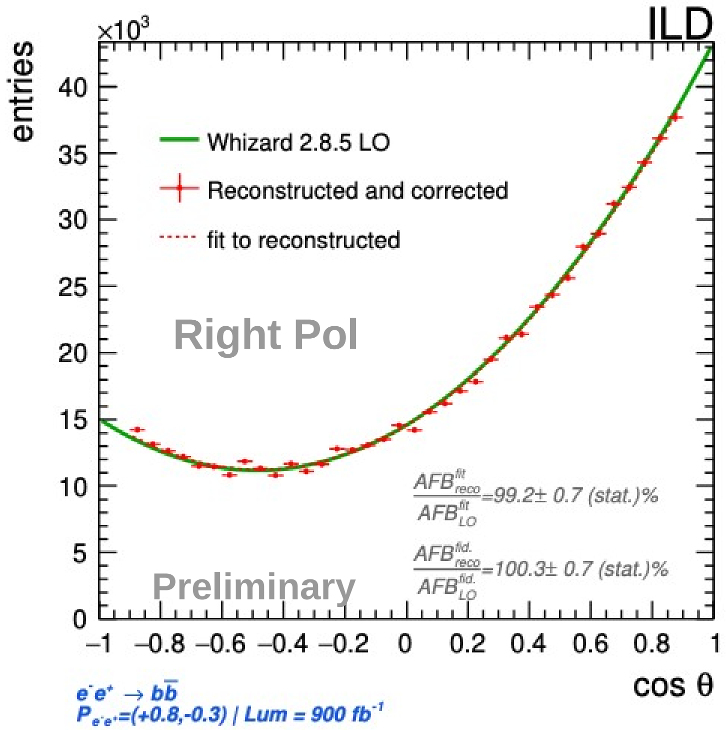
Precision of tau polarisation of order 0.3%-1%

Close-by photons are challenge for highly granular calorimeters (in particular Ecal) at high-energies
Ideal benchmark for detector optimisation
Maybe still room for improvement, better algorithms?

Decomposing ee->bb – Differential cross section

Full simulation study within ILD Concept at √s=250 GeV allows for educated guess on uncertainties on Z-Pole





Arxiv:2306.11413

Excellent agreement between predicted and reconstructed distributions

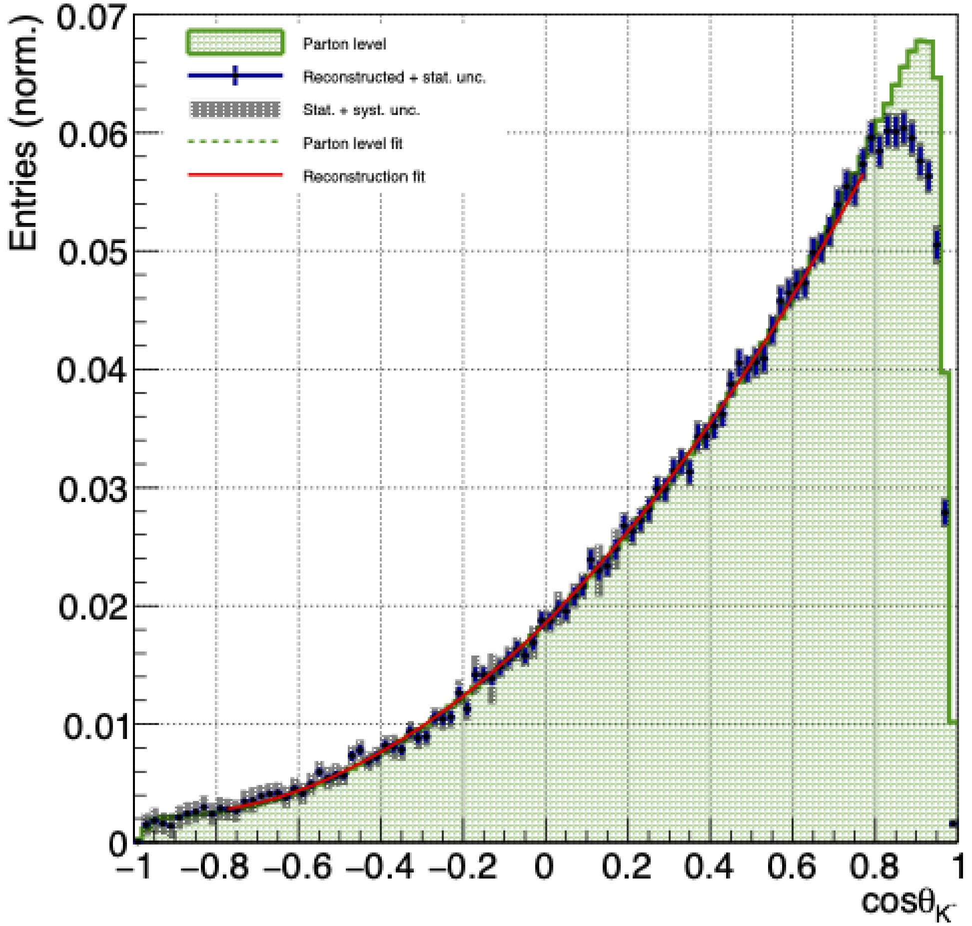
Source	$e^-e^+ \to c\bar{c}$				$e^-e^+ \to b\bar{b}$			
	$P_{e^-e^+}(-0.8,+0.3)$		$P_{e^-e^+}(+0.8,-0.3)$		$P_{e^-e^+}(-0.8,+0.3)$		$P_{e^-e^+}(+0.8,-0.3)$	
	R_c	$A_{FB}^{c\bar{c}}$	R_c	$A_{FB}^{c\bar{c}}$	R_b	$A_{FB}^{b\bar{b}}$	R_b	$A_{FB}^{b\bar{b}}$
Statistics	**0.18%**	**0.38%**	**0.27%**	**0.52%**	**0.12%**	**0.24%**	**0.23%**	**0.70%**
Preselection eff.	<0.01%	0.12%	0.02%	0.16%	<0.01%	0.08%	0.06%	0.12%
Background	0.01%	0.01%	0.02%	0.02%	0.01%	0.01%	0.06%	<0.01%
heavy quark mistag	0.11%	<0.01%	0.06%	<0.01%	0.12%	<0.01%	0.22%	<0.01%
uds mistag	0.03%	<0.01%	0.02%	<0.01%	0.08%	<0.01%	0.14%	<0.01%
Angular correlations	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%
Beam Polarisation	<0.01%	<0.01%	0.02%	0.01%	<0.01%	0.01%	0.03%	0.15%
Systematics	**0.15%**	**0.16%**	**0.12%**	**0.19%**	**0.18%**	**0.13%**	**0.29%**	**0.22%**
Total	**0.24%**	**0.41%**	**0.30%**	**0.55%**	**0.21%**	**0.27%**	**0.37%**	**0.73%**

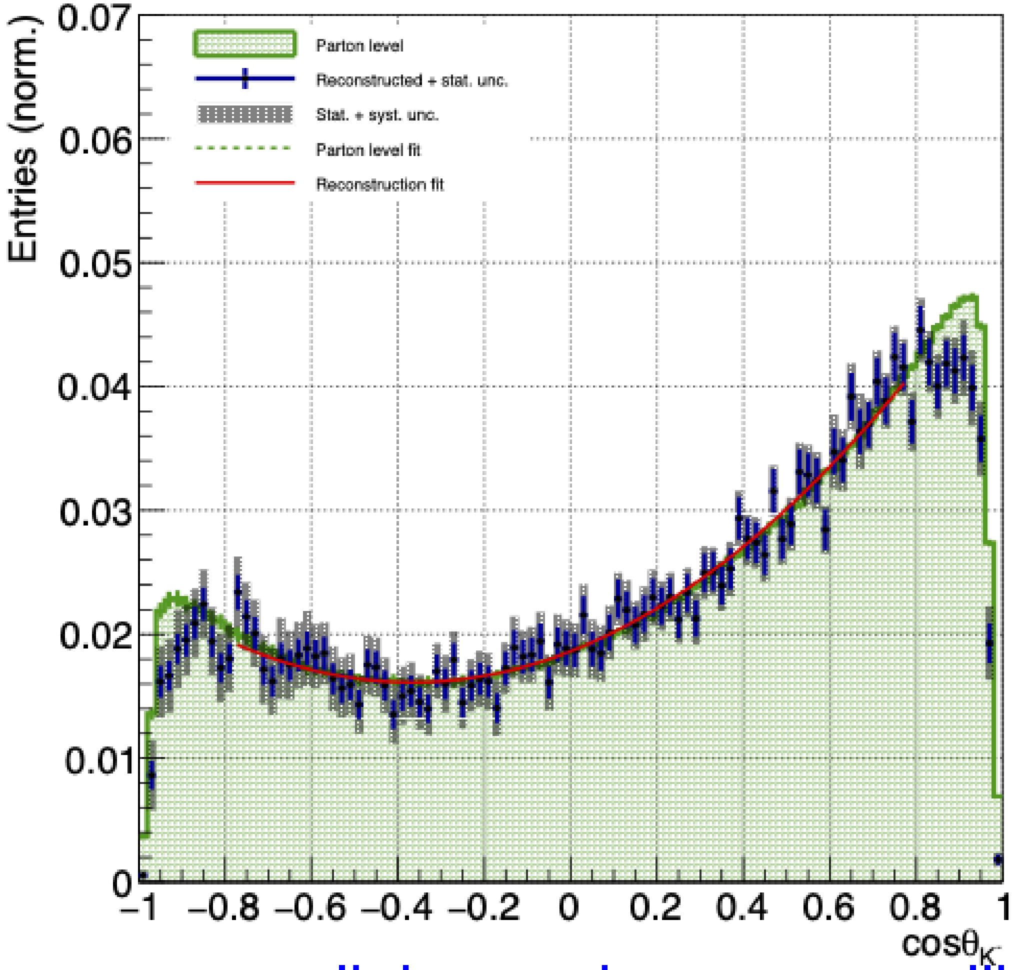
Additional complication in continuum compared with Z-Pole:
Rejection of ISR events

Light quarks at @ 250 GeV are in the making

$$e^+e^- \to s\bar{s} \text{ at } 250\,\text{GeV}$$

PhD thesis
Y. Okugawa



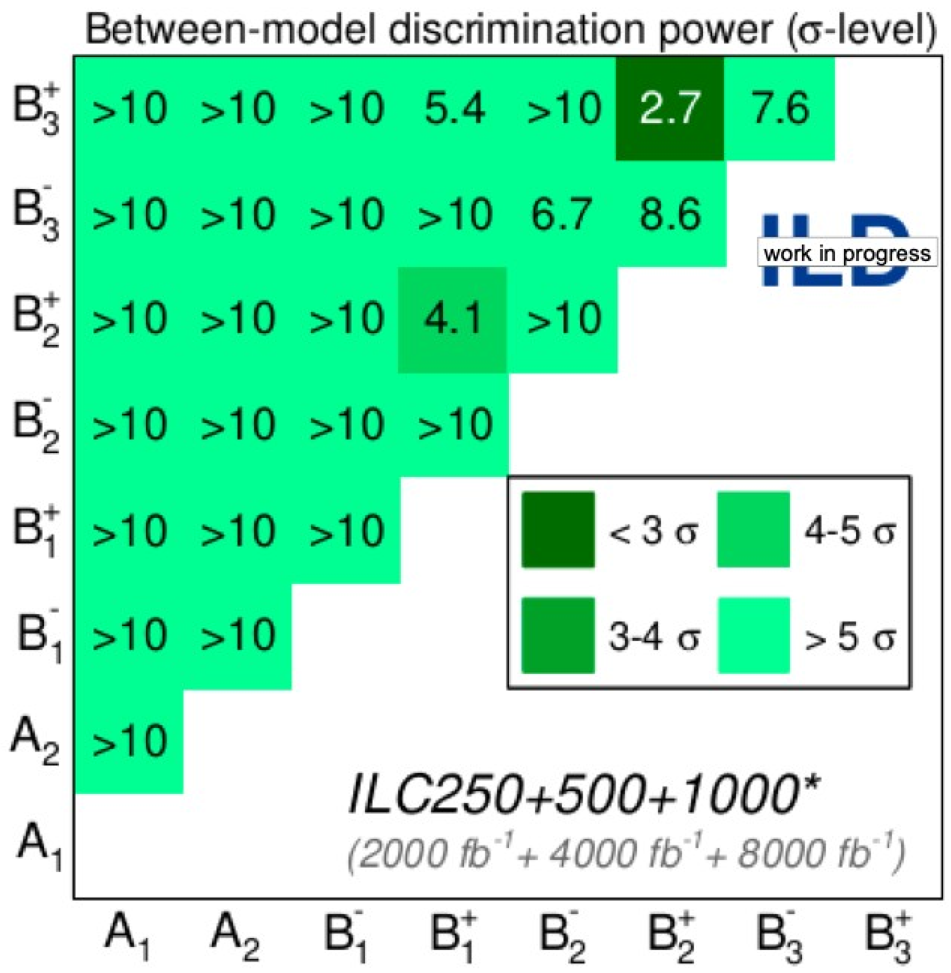


- The current analysis shows the potential to measure light quarks at e+e- colliders
- Even more than others light quarks rely on excellent particle ID
  - ... over full solid angle
- The hard cuts to get a clean sample in this analysis results in a small efficiency O(1%)
- Clear room for improvement beyond "collider flavors"

Interpretation of two fermion processes

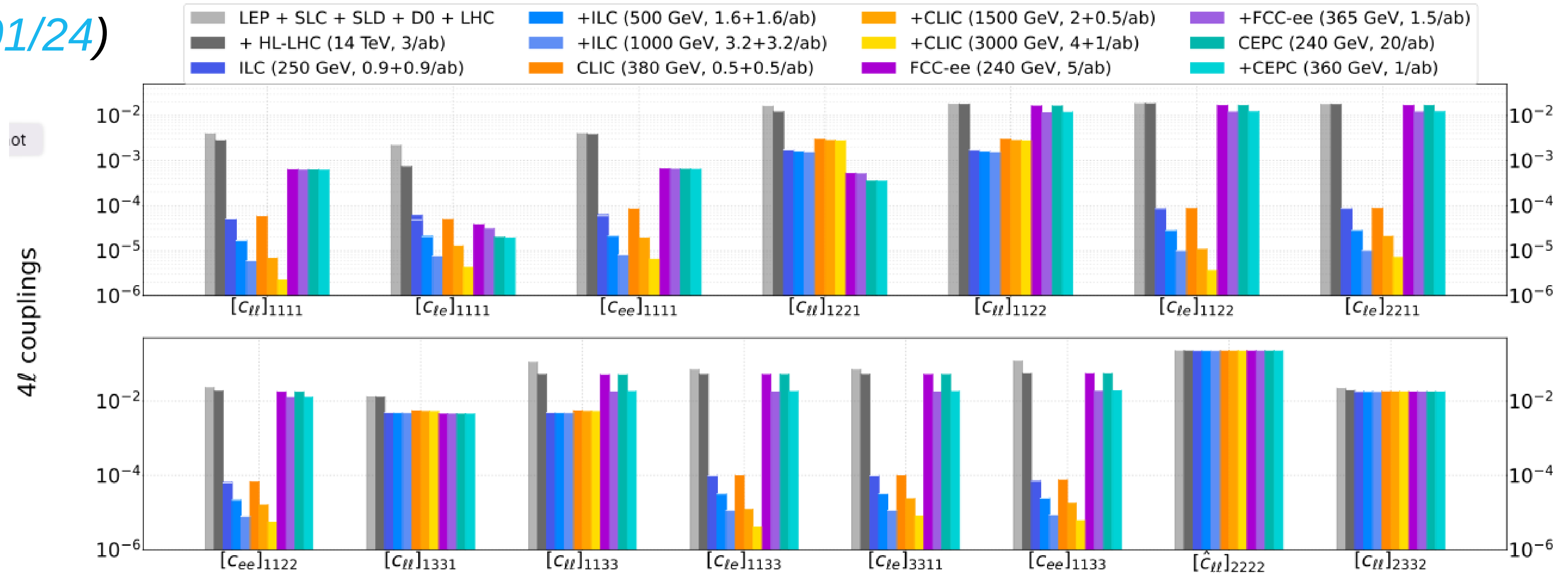
Separation power in GHU Models

J. P. Marquez et al. (ILD Meeting 17/01/24)



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 <u>and</u> higher energies
- Focused topics may be an opportunity to convey this message to the wider community
- Has to be vetted regularly against (HL-)LHC results

Existing tools / examples

– ILD $t\bar{t}$ analysis https://github.com/ILDAnaSoft/ILDbench_QQbar

Contact & Further Information

– Gitlab wiki: https://gitlab.in2p3.fr/ecfa-study/ECFA-HiggsTopEW-Factories/-/wikis/FocusTopics/TTthresh
– Sign up for egroup: ECFA-WHF-FT-TTthres@cern.ch via http://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=ecfa-whf-ft-ttthres
– and/or email the conveners of ECFA WG1 GLOBal group: mailto:ecfa-whf-wg1-glob-conveners@cern.ch

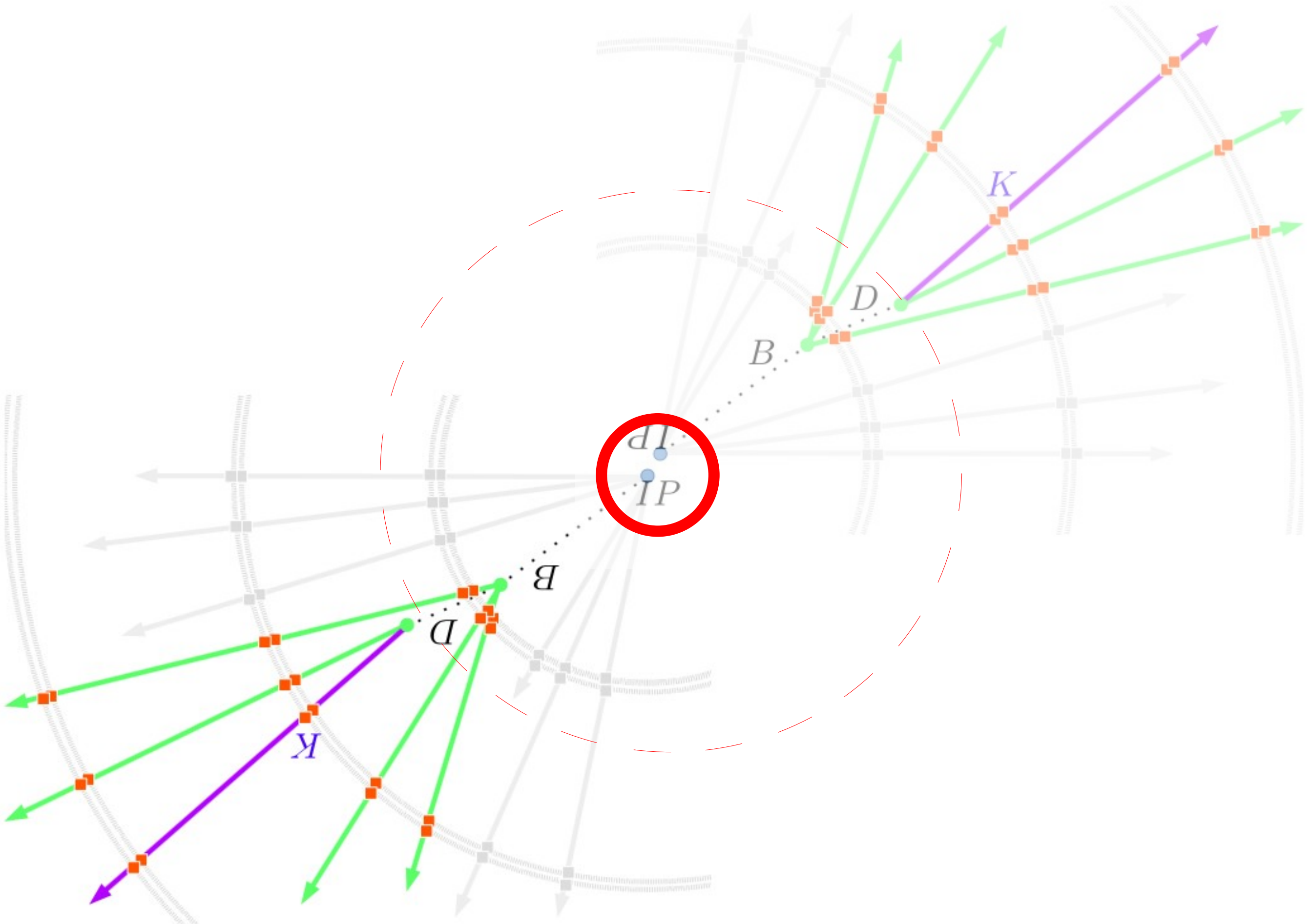
Contact & Further Information

– Gitlab wiki: https://gitlab.in2p3.fr/ecfa-study/ECFA-HiggsTopEW-Factories/-/wikis/FocusTopics/EXtt
– Sign up for egroup: ECFA-WHF-FT-EXTT@cern.ch via http://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=ecfa-whf-ft-extt
– and/or email the conveners of ECFA WG1 SeaRCHes group: mailto:ecfa-whf-wg1-srch-conveners@cern.ch

Contact & Further Information

– Gitlab wiki: https://gitlab.in2p3.fr/ecfa-study/ECFA-HiggsTopEW-Factories/-/wikis/FocusTopics/TwoF
– Sign up for egroup: ECFA-WHF-FT-TwoF@cern.ch via http://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=ecfa-whf-ft-twof
– and/or email the conveners of ECFA WG1 HTE group: mailto:ecfa-whf-wg1-hte-conveners@cern.ch

Double tagging



Important systematic error is knowledge of tagging efficiency ε_q

Can be derived from data if tagging is independent in two hemispheres, i.e. if

$$C_q = \frac{\epsilon_{double}}{\epsilon_q^2} \approx 1$$

If $C_q \neq 1$ => Hemisphere correlations => systematic error

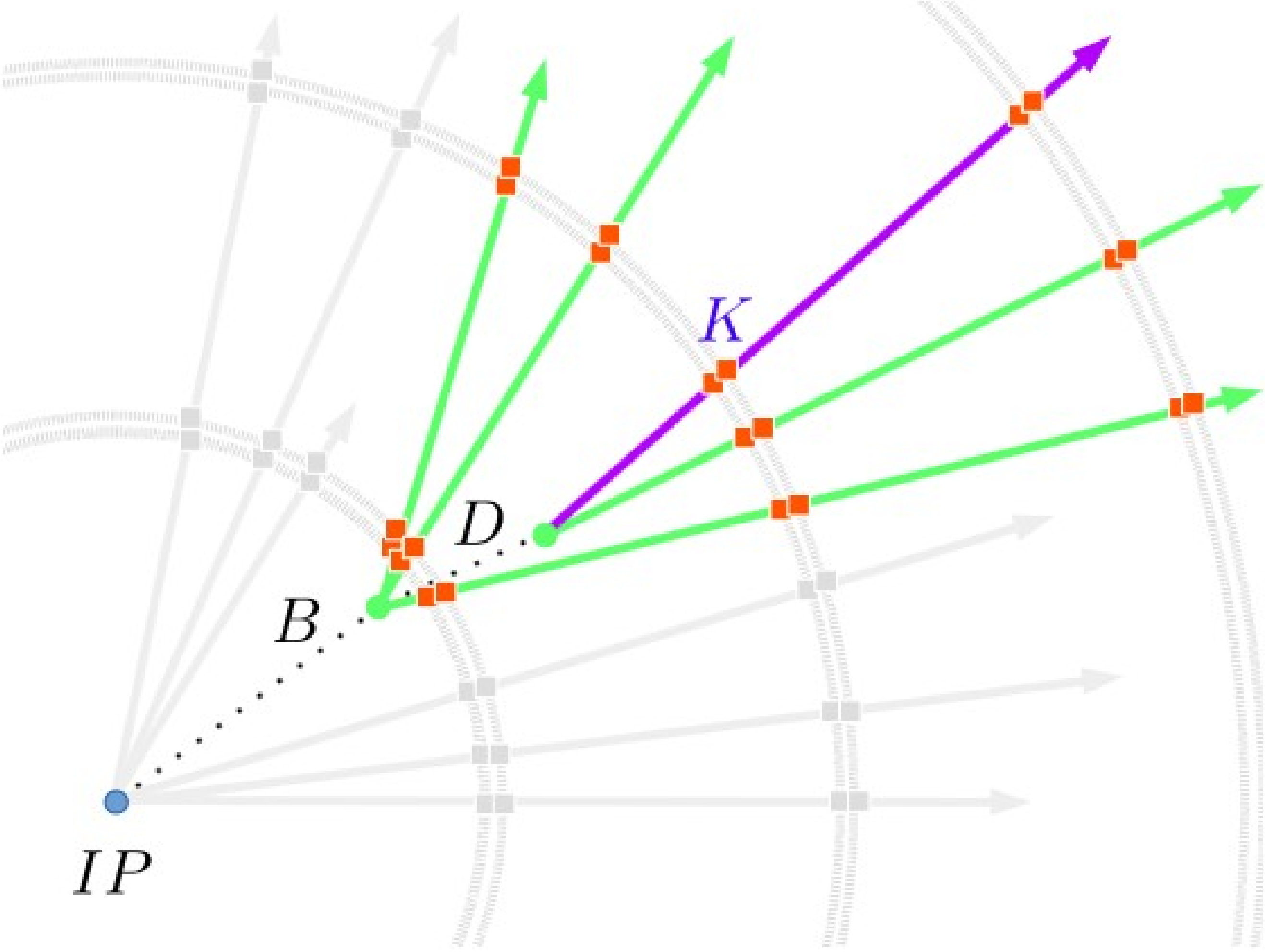
For example:

LEP (large beam spot): C_q-1 ≈ 3% => ΔR_b ≈ 0.2%

SLC (smaller beam spot): C_q -1 < 1% => ΔR_b ≈ 0.07%

Future (small/tiny beam spot): Expect C_q -1 = 0 => ΔR_b ≈ 0
to be verified however

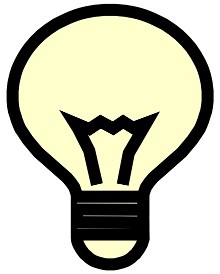
Experimental challenges - Flavor tagging and charge measurement



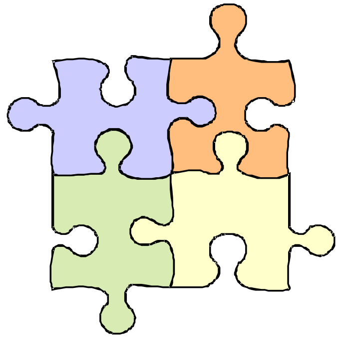
PhD thesis: S. Bilokin
A. Irles

- 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

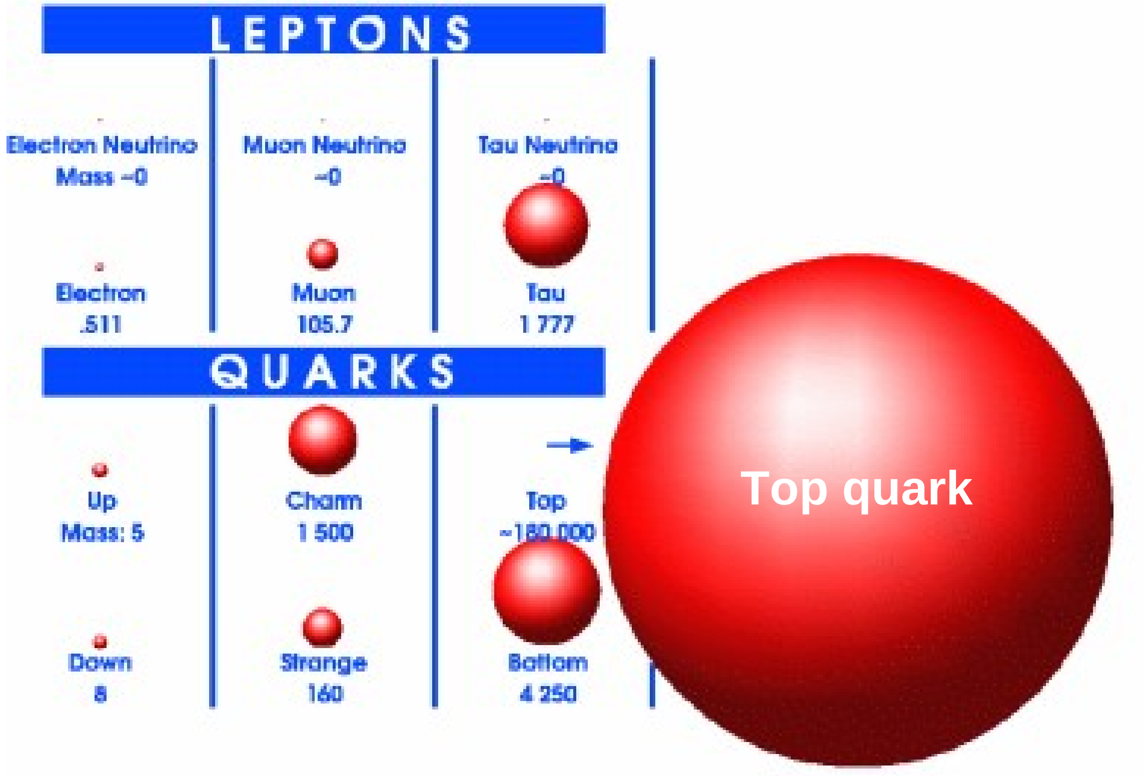
An enigmatic couple



Elementary Scalar?



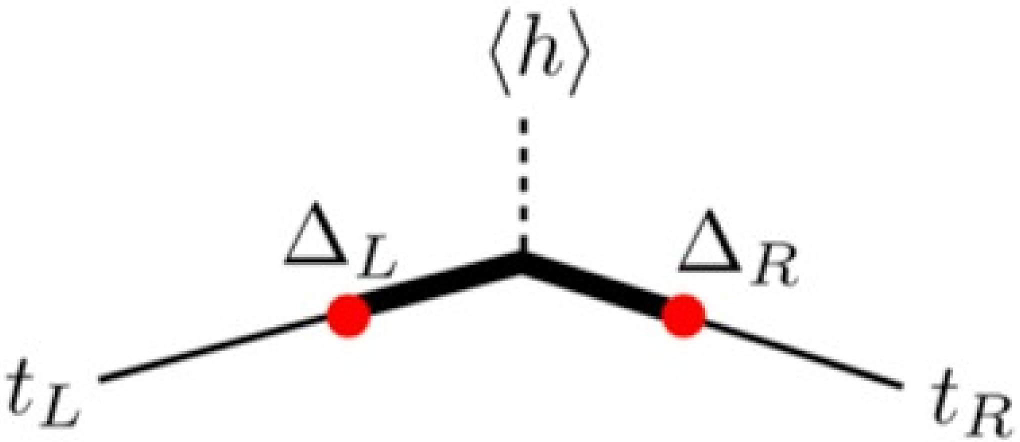
Composite object?



- 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?

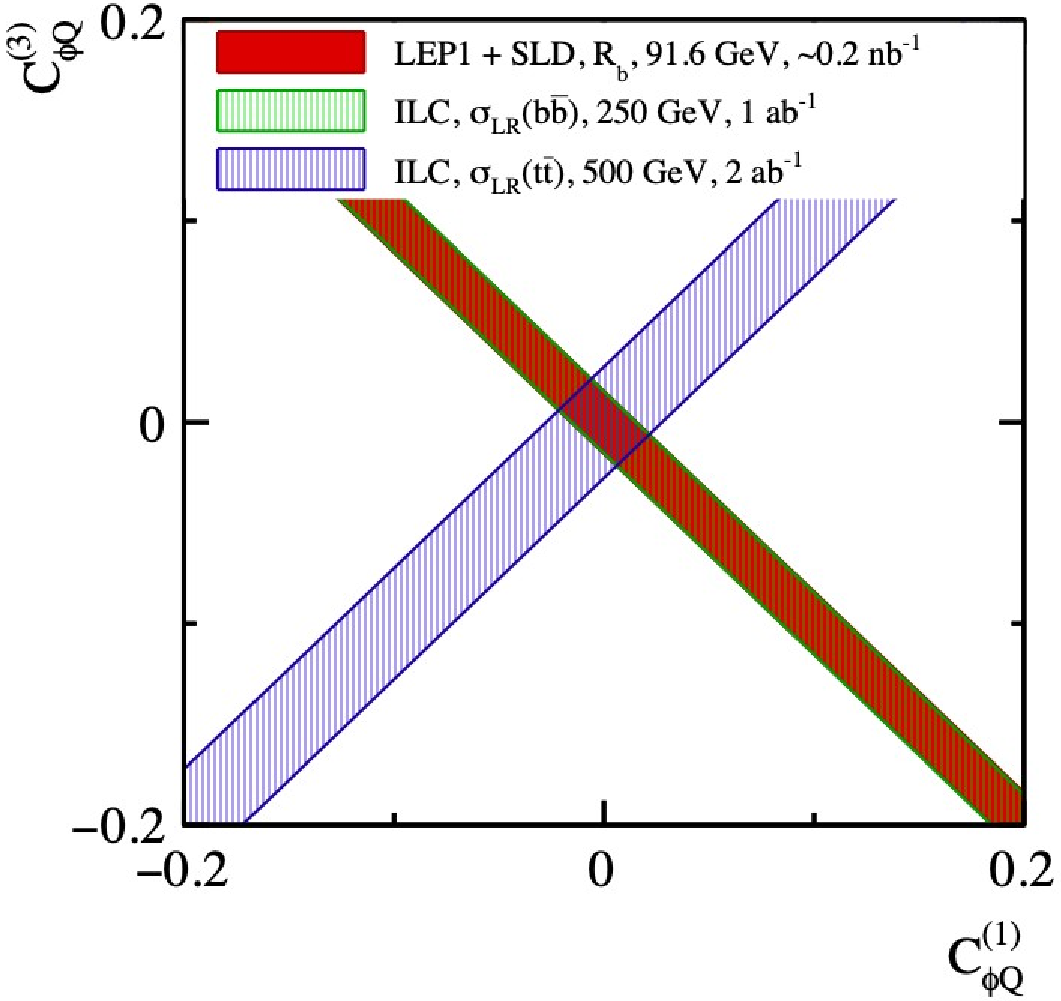
- e+e- collider perfectly suited to decipher both particles



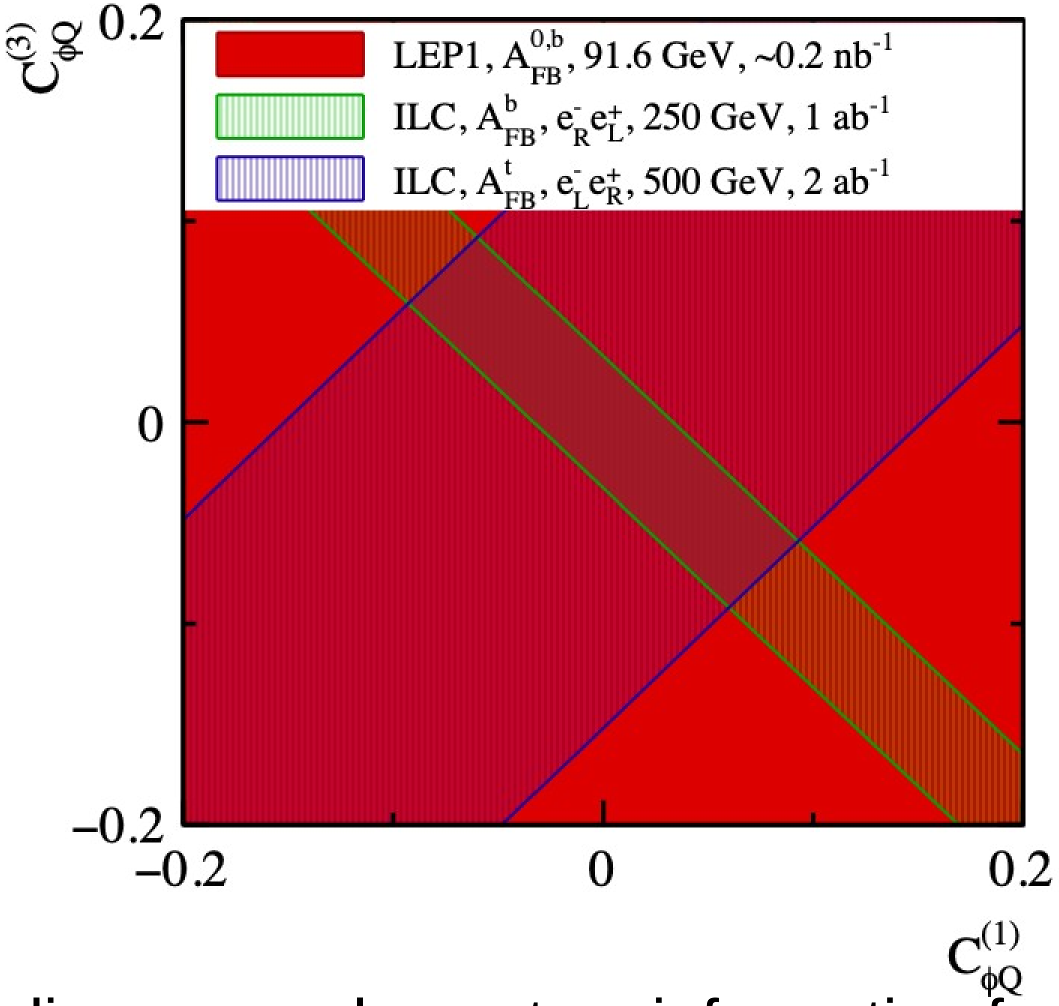
Courtesy of S. Rychkov

Interplay b/t

From cross section



From forward-backward asymmetry

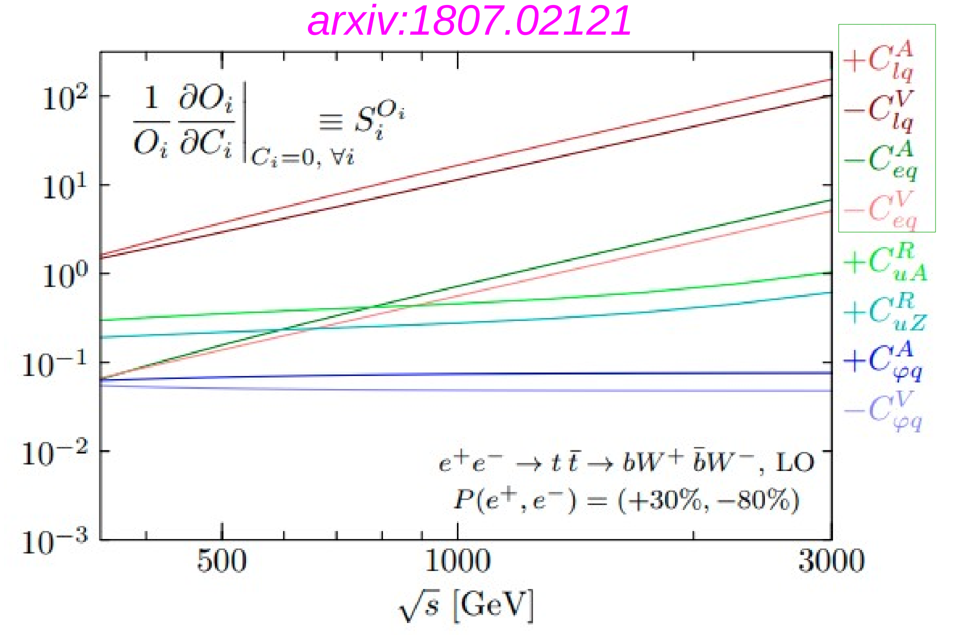


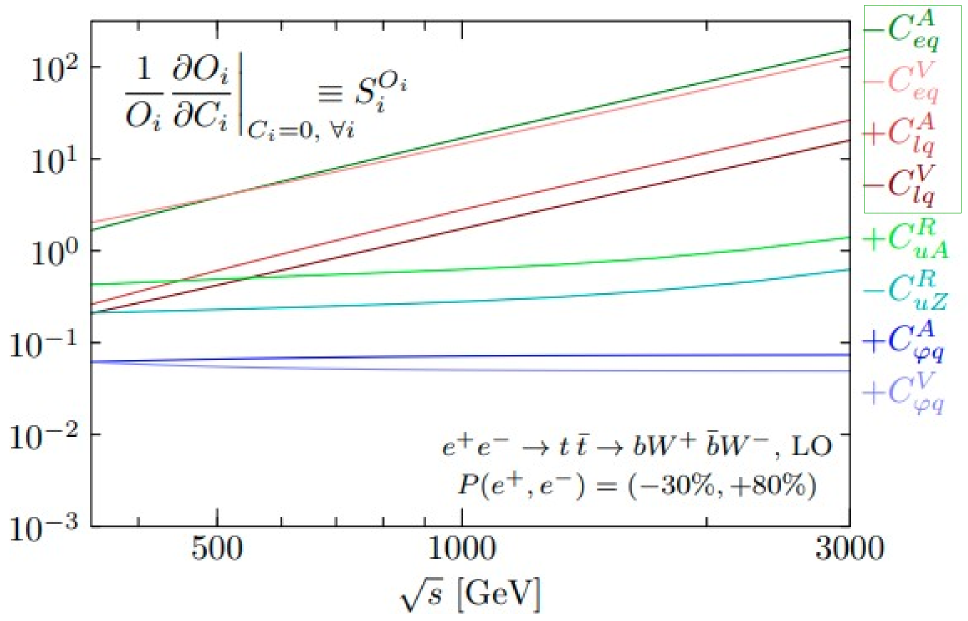
- Measurement of bottom and top observables delivers complementary information for EFT operators
- ILC@250 GeV comparable to LEP in terms of cross section => Constrain on g_{Lb}
- ILC@250 GeV drastically better than LEP in terms of AFB => Constrain on g_{Rb}
  - How would the picture look with GigaZ precisions?

Effects at higher energies

Development of EFT Operators

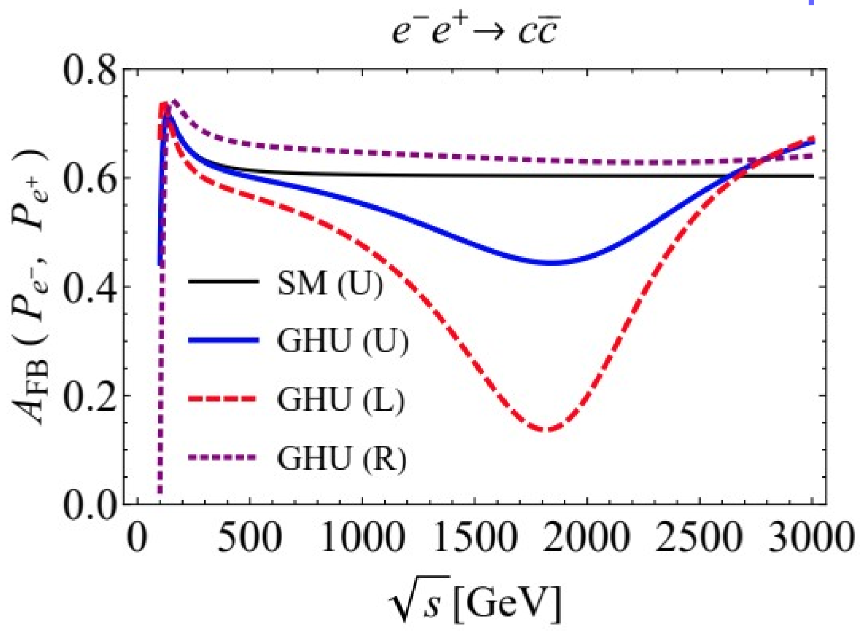
arxiv:1807.02121

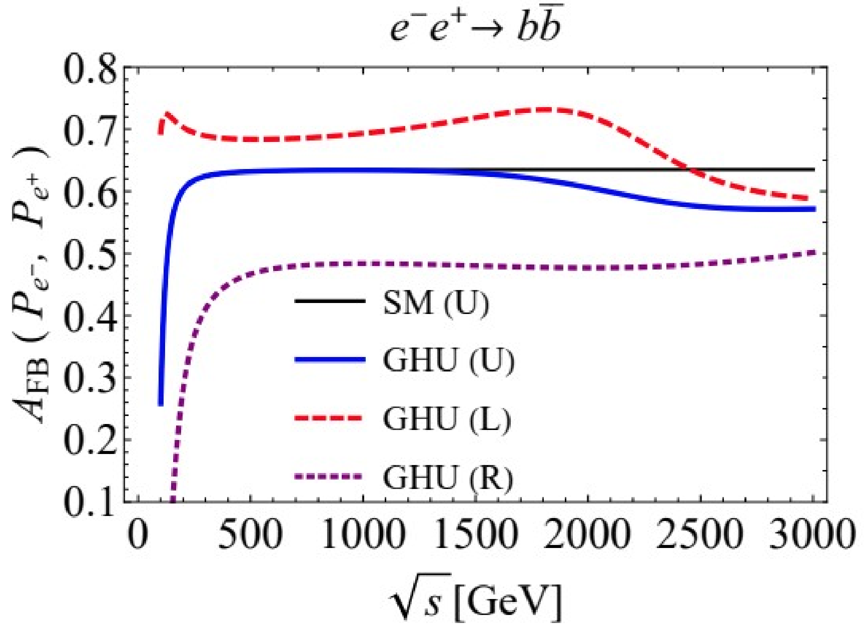


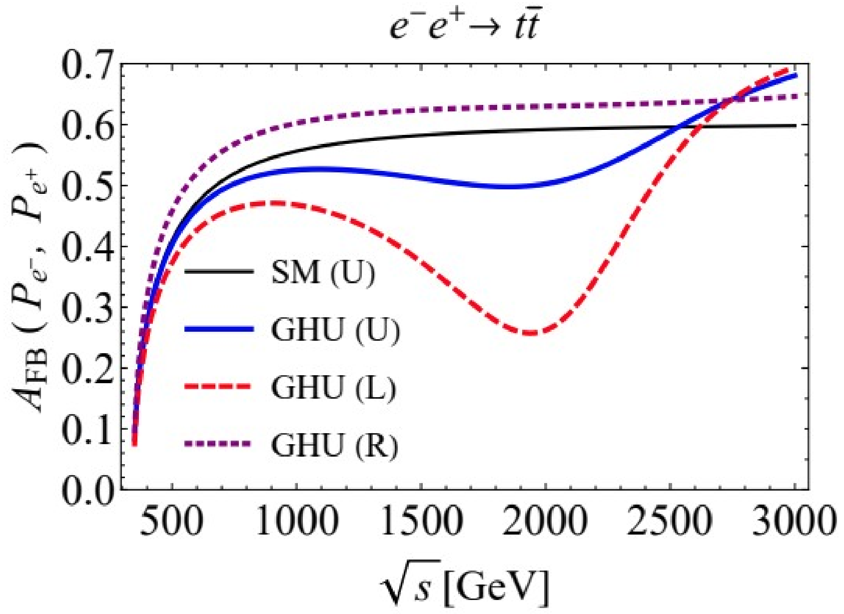


Increased sensitivity to operators representing four-fermion interactions

GUT Inspired GHU Model



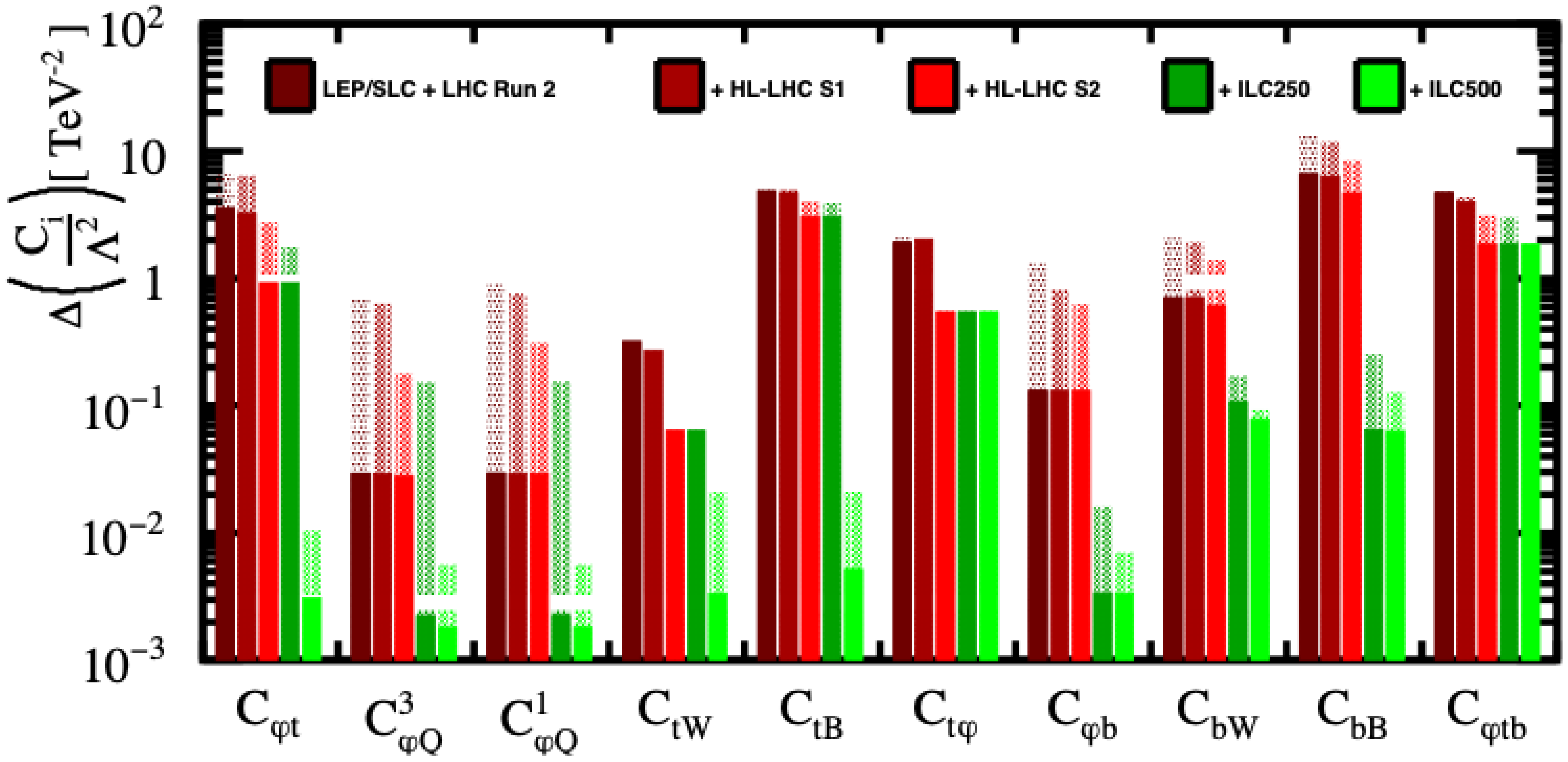




- Effects amplified at higher energies
- Different patterns for different beam polarisations (L, U, R)
- Different patterns for different fermions

Electroweak top couplings EFT-operators

arxiv:1907.10619



Mapping between FF and EFT Coefficients

$$F_{1V}^Z = \frac{\frac{1}{4} - \frac{2}{3}s_W^2}{s_W c_W} - \frac{m_t^2}{\Lambda^2}\frac{1}{2 s_W c_W}\left[C_{\varphi q}^V = C_{\varphi u}^{(33)} + (C_{\varphi q}^{1(33)} - C_{\varphi q}^{3(33)})\right],$$

$$F_{1A}^Z = \frac{-\frac{1}{4}}{s_W c_W} - \frac{m_t^2}{\Lambda^2}\frac{1}{2 s_W c_W}\left[C_{\varphi q}^A = C_{\varphi u}^{(33)} - (C_{\varphi q}^{1(33)} - C_{\varphi q}^{3(33)})\right],$$

$$F_{2V}^Z = 4\frac{m_t^2}{\Lambda^2}\left[C_{uZ}^R = \mathrm{Re}\{c_W^2 C_{uW}^{(33)} - s_W^2 C_{uB}^{(33)}\}/s_W c_W\right],$$

$$F_{2A}^Z = 4\frac{m_t^2}{\Lambda^2}i\left[C_{uZ}^I = \mathrm{Im}\{c_W^2 C_{uW}^{(33)} - s_W^2 C_{uB}^{(33)}\}/s_W c_W\right],$$

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

Z-Pole Systematics – Summary for asymmetries

Summary: Theory inputs for asymmetries

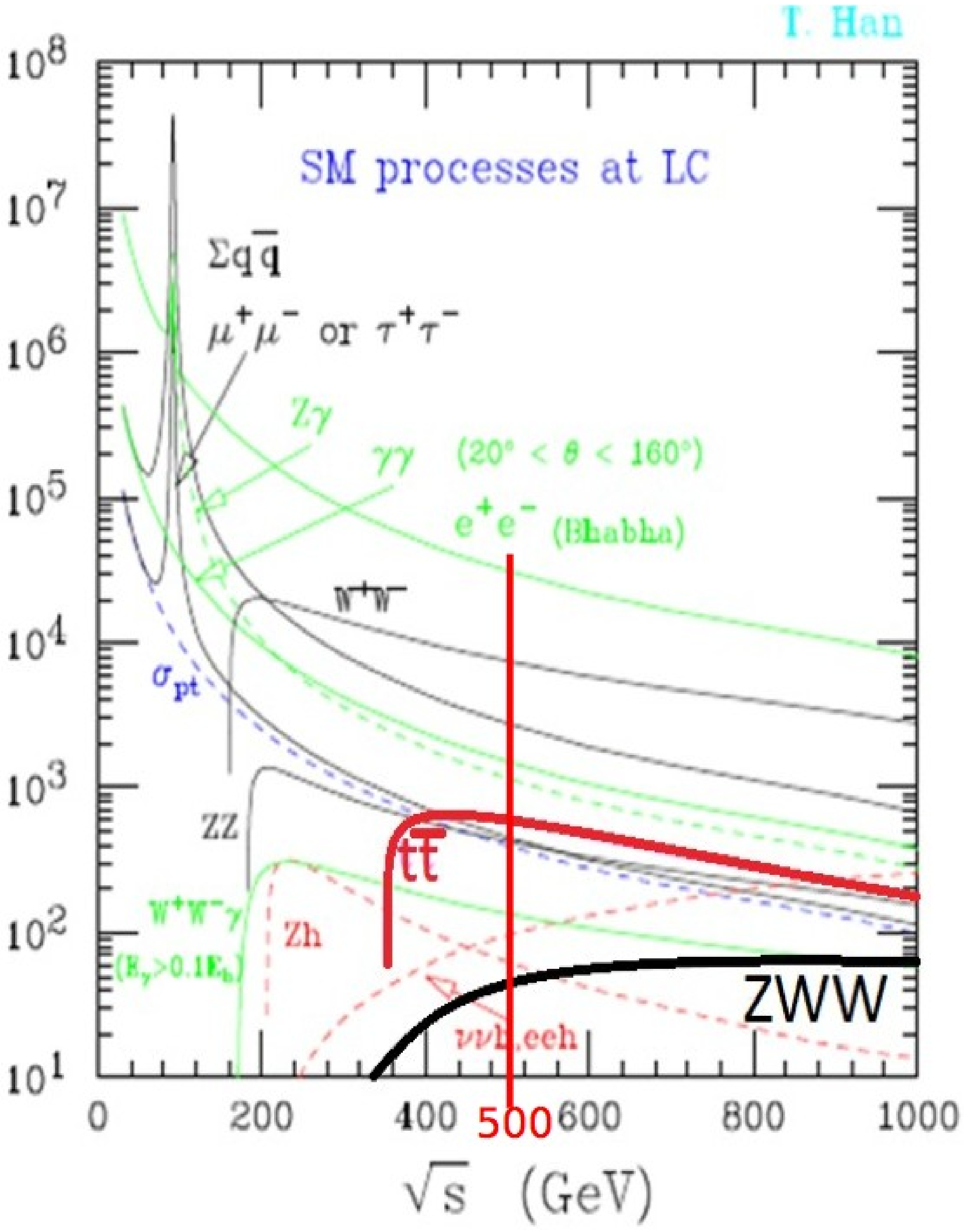
Observables	Present value (×10⁴)	TeraZ / GigaZ stat.	TeraZ / GigaZ current syst.	Theory input (not exhaustive)
A_e from P_τ (FCC-ee)	1514 ± 19	0.07	0.20	SM relation to measured quantities
A_e from A_{LR} (ILC)		0.15	0.80	
A_μ from A_{FB} (FCC-ee)	1456 ± 91	0.23	0.22	Accurate QED (ISR, IFI, FSR)
A_μ from A_{FB}^{pol} (ILC)		0.30	0.80	
A_τ from P_τ (FCC-ee)	1449 ± 40	0.05	2.00	Prediction for non-τ backgrounds
A_τ from A_{FB} (FCC-ee)		0.23	1.30	
A_τ from A_{FB}^{pol} (ILC)		0.30	0.80	
A_b from A_{FB} (FCC-ee)	8990 ± 130	0.24	2.10	QCD calculations
A_b from A_{FB}^{pol} (ILC)		0.90	5.00	
A_c from A_{FB} (FCC-ee)	65400 ± 210	2.00	1.50	
A_c from A_{FB}^{pol} (ILC)		2.00	3.70	

Projections from https://www.overleaf.com/read/xnfpvbdgfqpr

- **And also sophisticated and state of the art MC generators (signal and backgrounds)**
  - **Plus, maybe, redefined EW Precision Parameters (EWPP) and extraction procedures ?**

P. Janot, Workshop "Precision calculations for future e+e- colliders"

Cross sections



$e^+e^- \to t\bar{t}$: 500 GeV

Channel	$\sigma_{unpol.}$ [fb]	$\sigma_{-,+}$ [fb]	$\sigma_{+,-}$ [fb]
$t\bar{t}$	572	1564	724
$\mu^+\mu^-$	456	969	854
$\sum_{q=u,d,s,c} q\bar{q}$	2208	6032	2793
$b\bar{b}$	372	1212	276
γZ^0	11185	25500	19126
W^+W^-	6603	26000	150
Z^0Z^0	422	1106	582
$Z^0W^+W^-$	40	151	8.7
$Z^0Z^0Z^0$	1.1	3.2	1.22
Single t for $e^+e^- \to e^-\bar{\nu}_e t\bar{b}$ [11]	3.1	10.0	1.7

352 GeV (unpol)

450 fb

25.2 pb

11.5 pb
865 fb

$e^+e^- \to b\bar{b}$: 250 GeV

Channel	σunpol fb	σL fb	σR fb
$b\bar{b}$	1756	5629	1394
$\gamma b\bar{b}$ (Z return)	7860	18928	12512
ZZ hadronic with $b\bar{b}$	196	549	236
HZ hadronic with $b\bar{b}$	98	241	152

$e^+e^- \to c\bar{c}$: 250 GeV

$$\sigma(P_{e-} = -1, P_{e+} = +1) \approx 8518\,\text{fb}$$

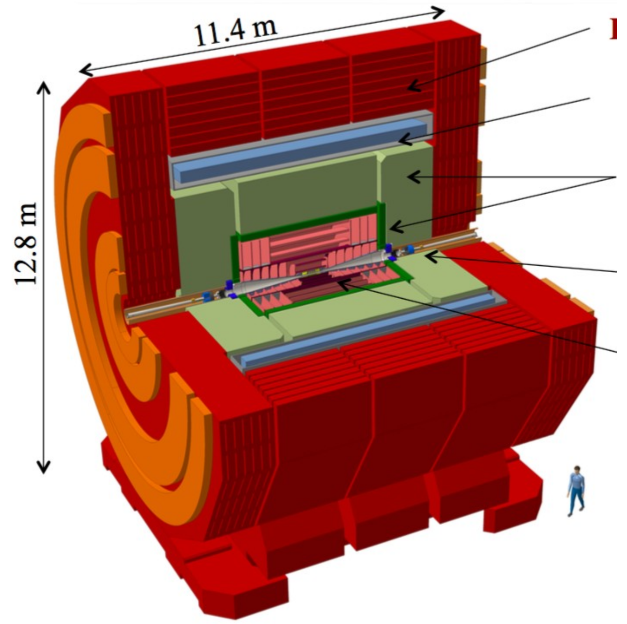
$$\sigma(P_{e-} = +1, P_{e+} = -1) \approx 3565\,\text{fb}$$

$$\sigma_{unpol.} \approx 3020\,\text{fb}$$

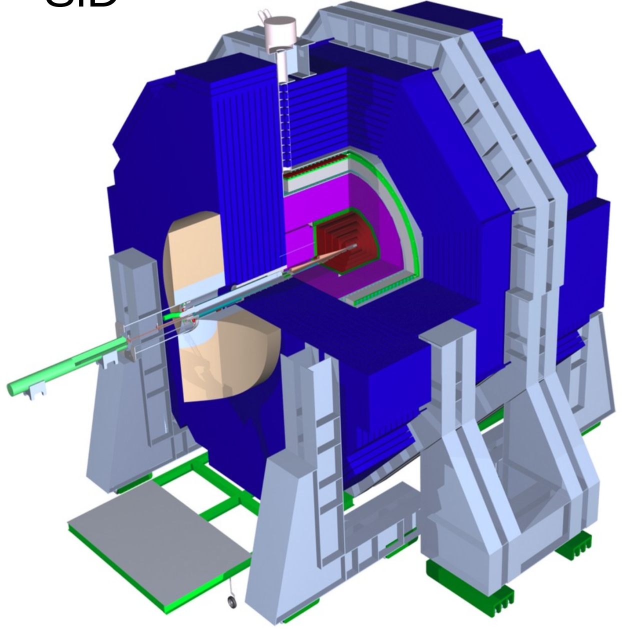
Detector requirements

e+e- detector concepts for linear colliders
Preferred solution Particle Flow Detectors

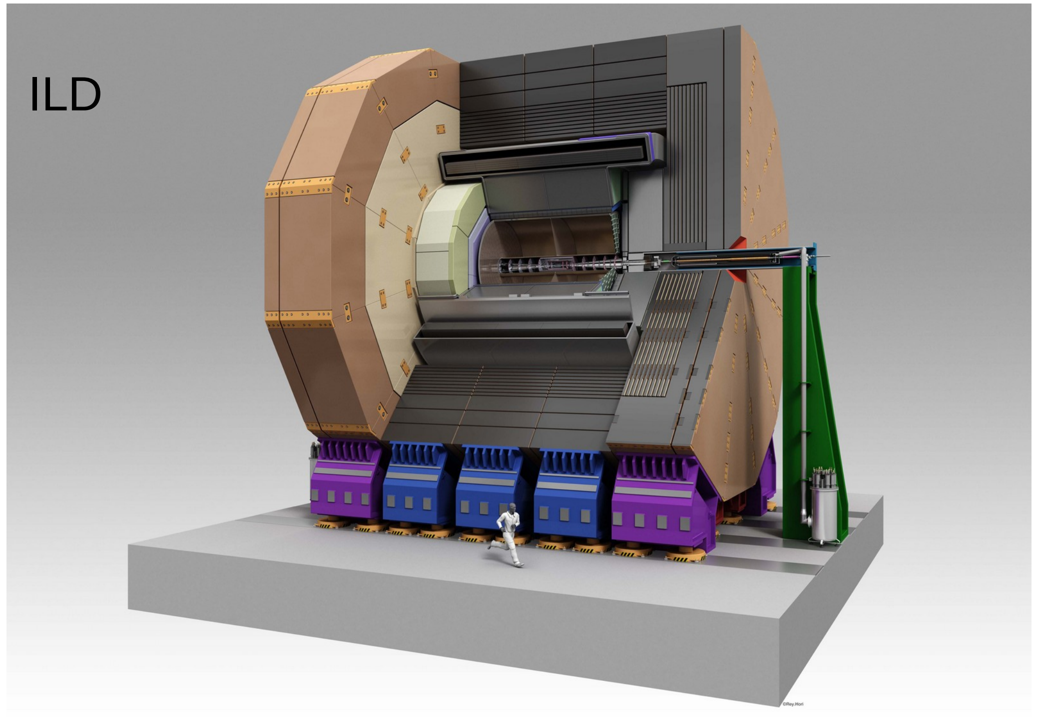
CLIC Detector



SiD



ILD



B= 4T

B= 5T

B= 3.5T

Highly granular calorimeters

Central tracking with silicon

Central tracking with TPC

Inner tracking with silicon

Detector requirements

Track momentum: $\sigma_{1/p} < 5 \times 10^{-5}$/GeV (1/10 x LEP)

(e.g. Measurement of Z boson mass in Higgs Recoil)

Impact parameter: $\sigma_{d0} < [5 \oplus 10/(p[\mathrm{GeV}]\sin^{3/2}\theta)]$ μm (1/3 x SLD)

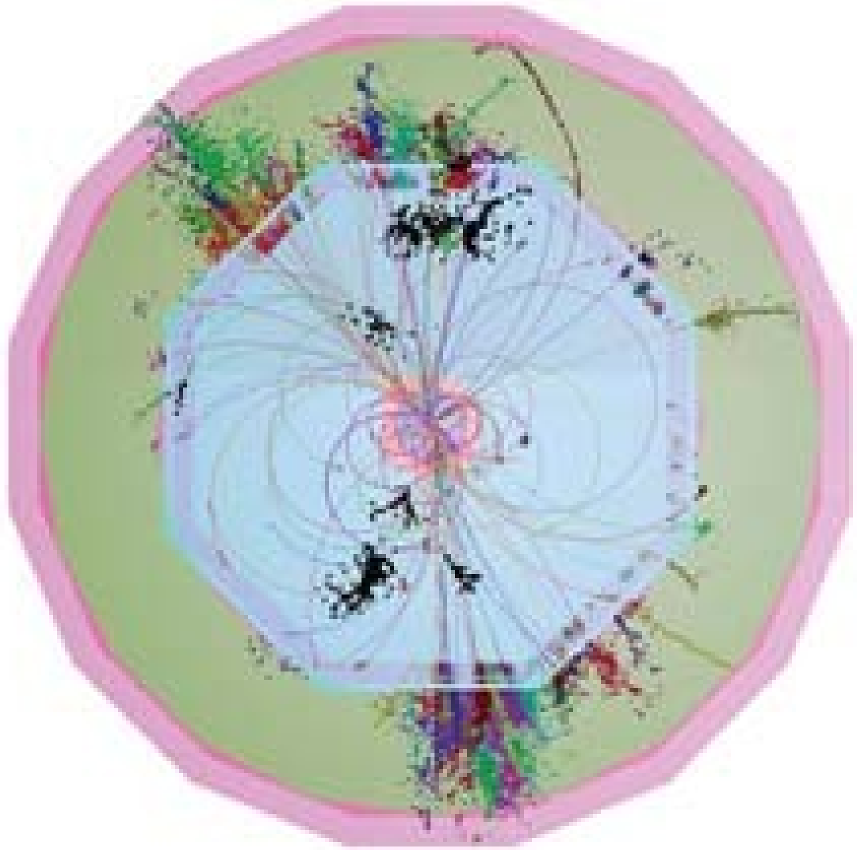
(Quark tagging c/b)

Jet energy resolution : $dE/E = 0.3/(E(\mathrm{GeV}))^{1/2}$ (1/2 x LEP)

(W/Z masses with jets)

Hermeticity : $\theta_{min} = 5$ mrad

(for events with missing energy e.g. SUSY)



Final state will comprise events with a large number of charged tracks and jets(6+)

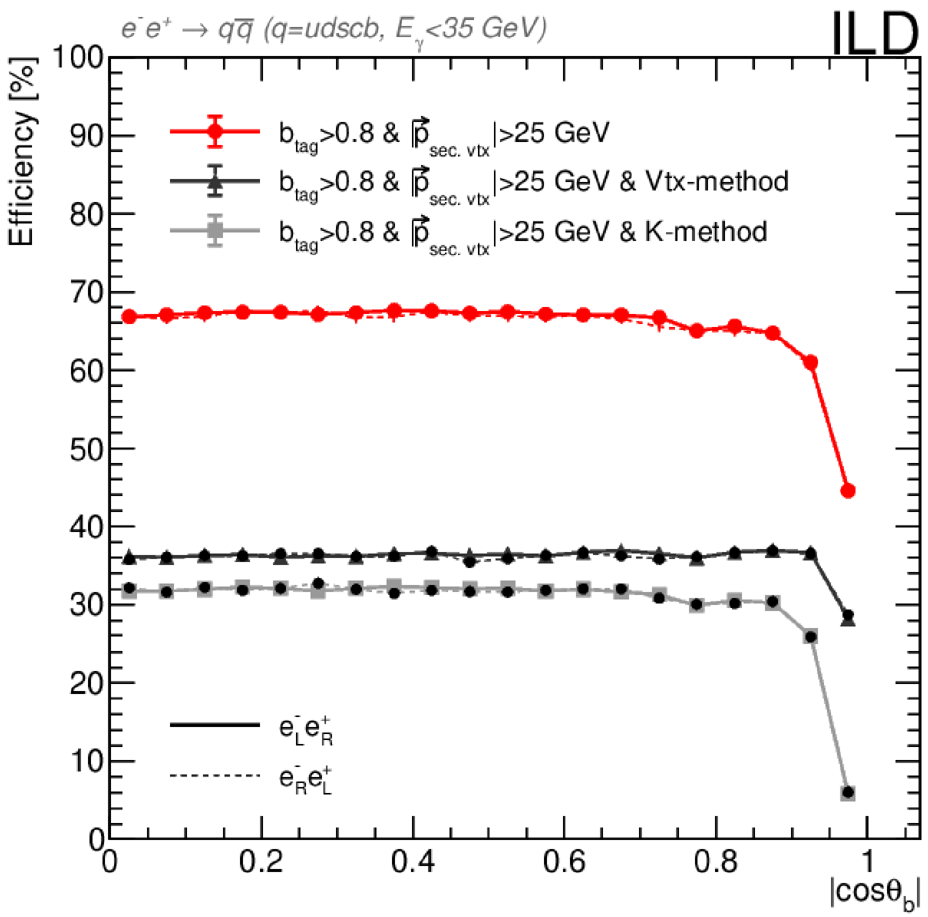
- High granularity
- Excellent momentum measurement
- High separation power for particles

Particle Flow Detectors

Detector Concepts: ILD, SiD and CLICdp

Typical efficiencies

$e^+e^- \to b\bar{b}$: 250 GeV



- Individual efficiency for correct b-tag and charge measurements using Vtx and Kaon charge
- Final efficiency ~20%
  from combination of Vtx and Kaon charge in different/same jets

$e_L^- e_R^+ \to t\bar{t}$ at 500 GeV

General selection cuts	IDR-L	IDR-S
Isolated Lepton	92.1%	92.1%
$btag_1 > 0.8$ or $btag_2 > 0.3$	81.2%	81.1%
Thrust < 0.9	81.2%	81.1%
Hadronic mass	78.2%	78.2%
Reconstructed m_W and m_t	73.4%	73.4%
t quark polar angle spectrum		
$\gamma_t^{had.} + \gamma_t^{\ell} > 2.4$	62.2%	61.8%
$\lvert p_{B,had}\rvert > 15$ GeV	34.5%	33.9%
"$t\bar{t}$ identification"	30.6%	30.2%
b quark polar angle spectrum		
No additional cuts		

Total cross section
- Typical efficiency 75%
- Independent of beam polarisation

$e_R^- e_L^+ \to t\bar{t}$ at 500 GeV

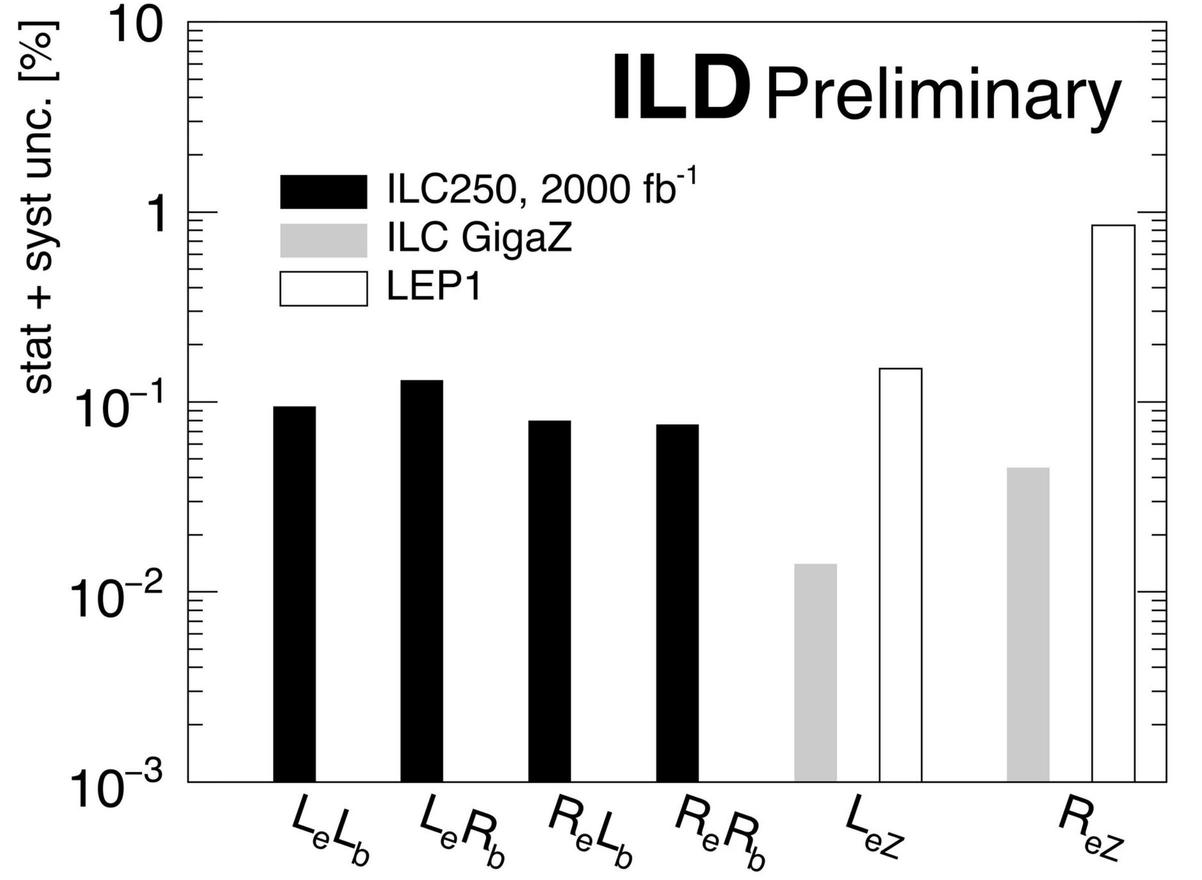
General selection cuts	IDR-L	IDR-S
Isolated Lepton	94.1%	94.0%
$btag_1 > 0.8$ or $btag_2 > 0.3$	84.9%	84.8%
Thrust < 0.9	84.9%	84.8%
Hadronic mass	82.2%	82.3%
Reconstructed m_W and m_t	77.6%	77.5%
t quark polar angle spectrum		
$\gamma_t^{had.} + \gamma_t^{\ell} > 2.4$	64.1%	64.1%
b quark polar angle spectrum		
Vtx+Vtx	10.8%	10.3%

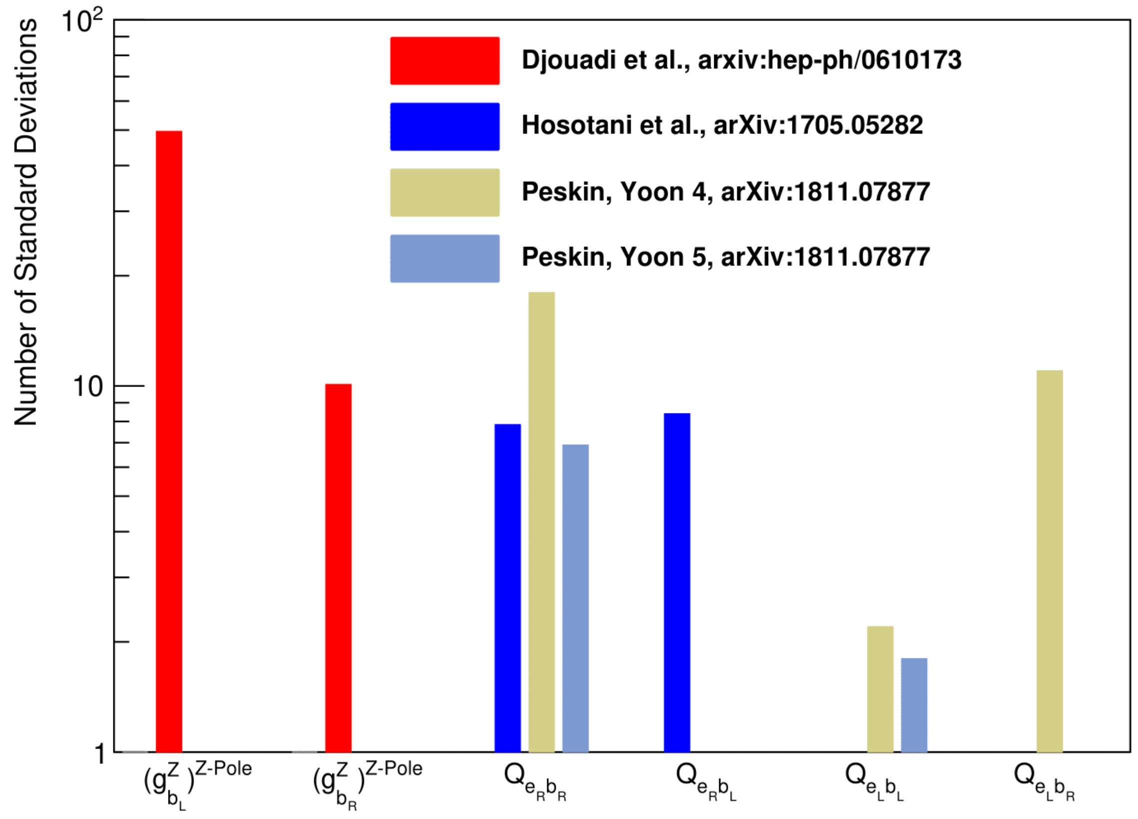
Differential cross section

- Note, difference for different beam polarisations
- Left hand polarisation more vulnerable to migrations
- Requires information from hadronic final state
- Vtx, Kaon as in bb-case

Precision on couplings and helicity amplitudes and physics reach

Example b-couplings (same observation for c-couplings, arxiv:2002.05805)





Couplings are order of magnitude better than at LEP

- In particular right handed couplings are much better constrained

New physics can also influence the Zee vertex
- in 'non top-philic' models

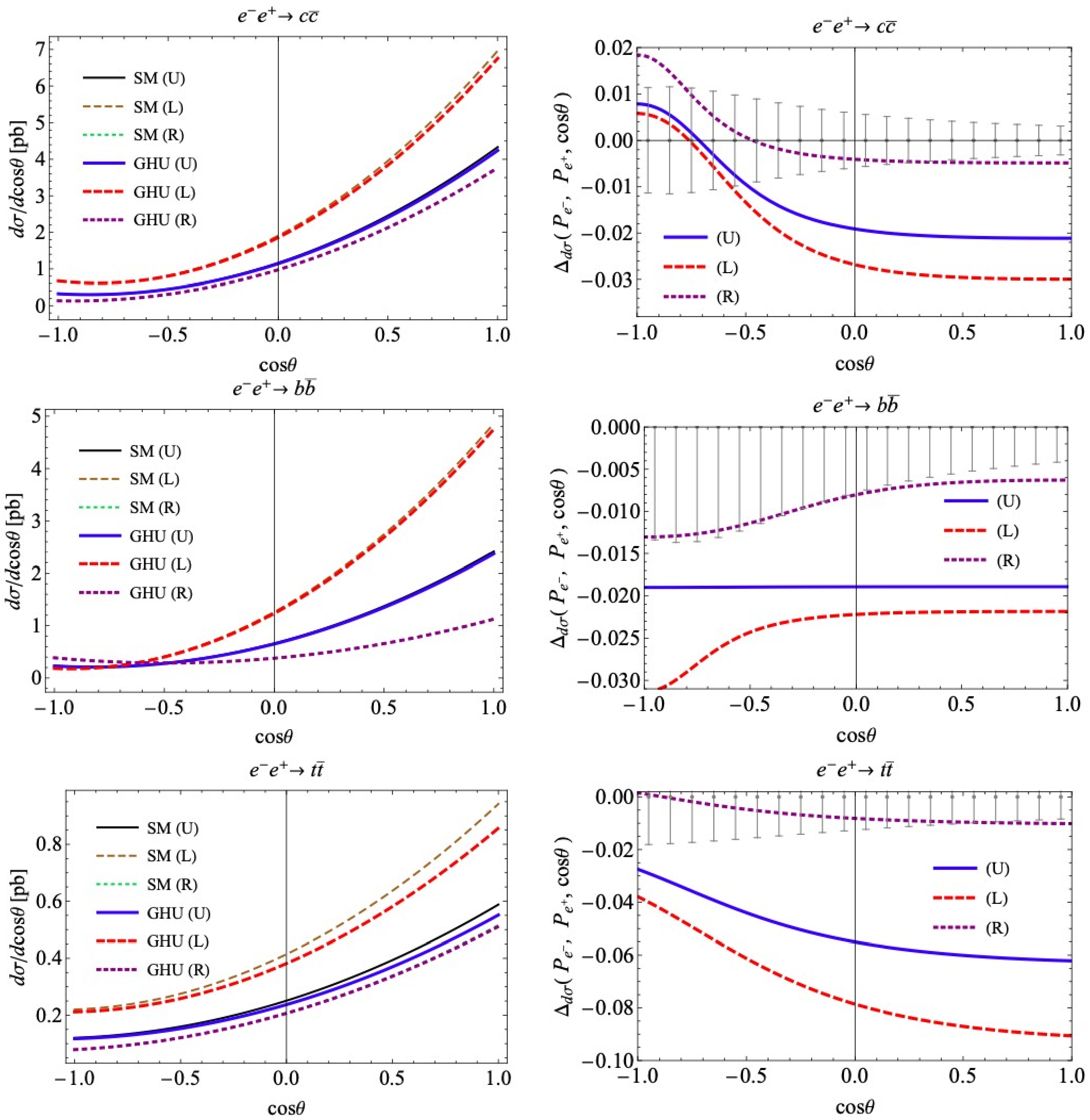
Full disentangling of helicity structure for all fermions only possible with polarised beams!!

Impressive sensitivity to new physics in Randall Sundrum Models with warped extra dimensions

- **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

Why lighter quarks? – e.g. GUT Inspired Grand Higgs Unification Model



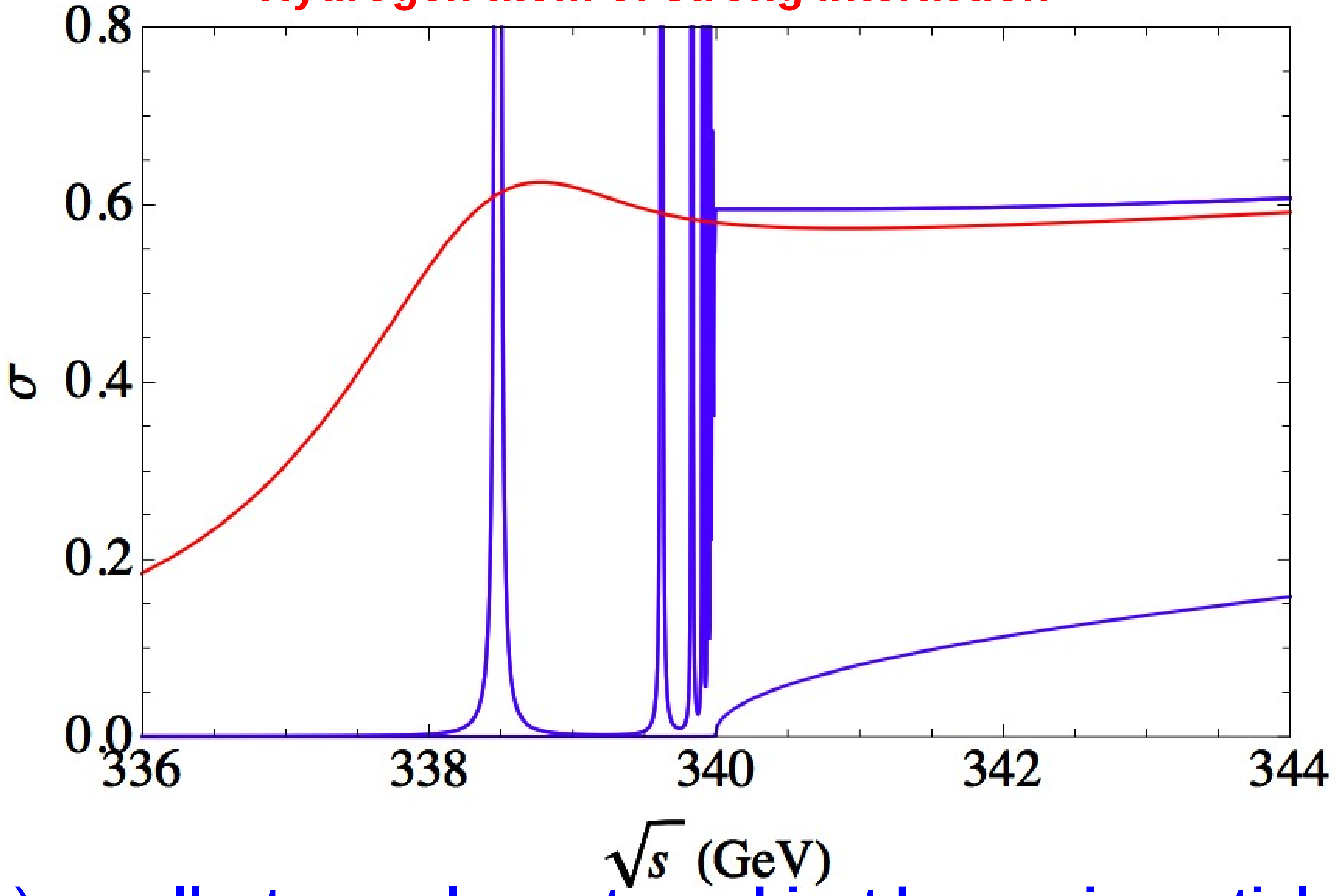
arxiv:2006.02157

- 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

Top pair production at threshold

“Bound states” at tt threshold

Hydrogen atom of strong interaction

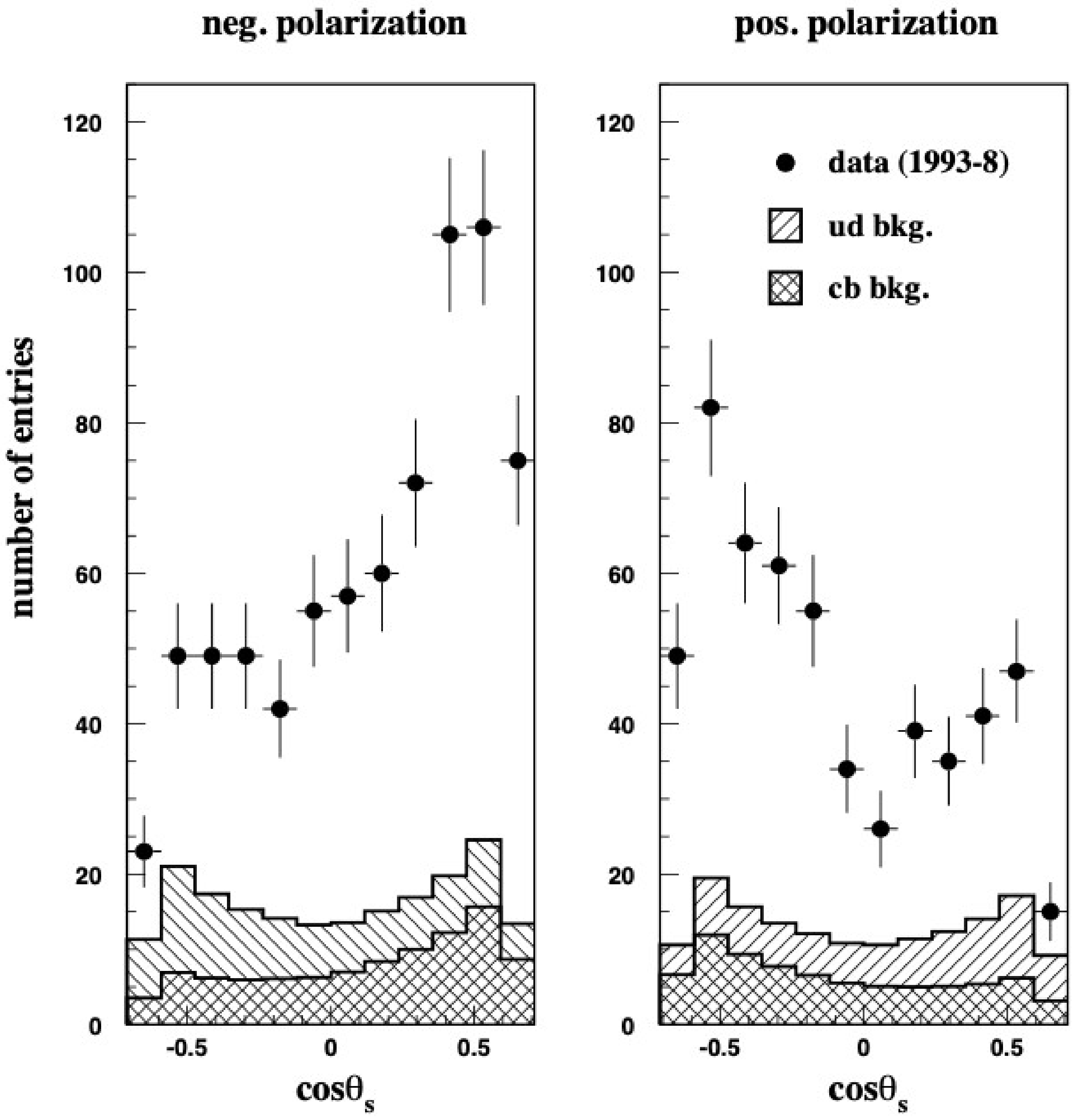


- Size O(10^{-17}m), **smallest non-elementary object known in particle physics**
  Small scale => Free of confinement effects => Ideal premise for precision calculations
  Measurement of (a hypothetical) 1^3S_1 State

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

And tomorrow ?

ee -->ss: SLD Analysis at Z Pole



- Extend the heavy quark analyses to light quarks to get full picture
- Optimise vertexing and particle ID (i.e .Kaon ID with full simulation studies

Beam polarisation and disentangling

With two beam polarisation configurations

$P(e^-) = \pm 80\%$ $\qquad$ $P(e^+) = \mp 30\%$

There exist a number of observables sensitive to chiral structure, e.g.

$$\sigma_I \qquad A^t_{FB,I} = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)} \qquad (F_R)_I = \frac{(\sigma_{t_R})_I}{\sigma_I}$$

x-section — Forward backward asymmetry — Fraction of right handed top quarks

⇩

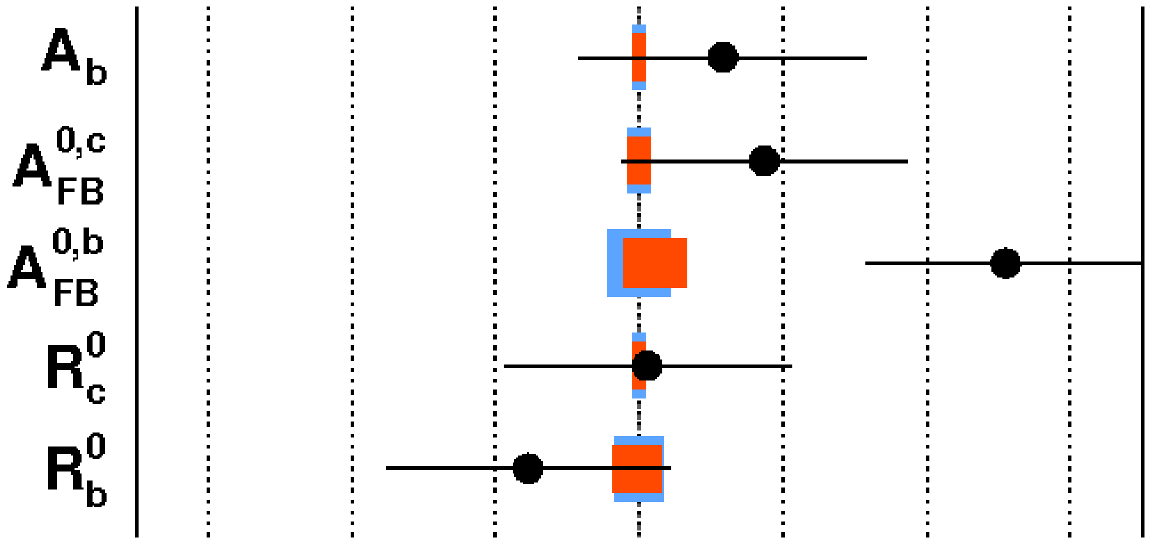
Extraction of relevant unknowns

$$F^{\gamma}_{1V},\ F^{Z}_{1V},\ F^{\gamma}_{1A} = 0,\ F^{Z}_{1A}$$
$$F^{\gamma}_{2V},\ F^{Z}_{2V}$$

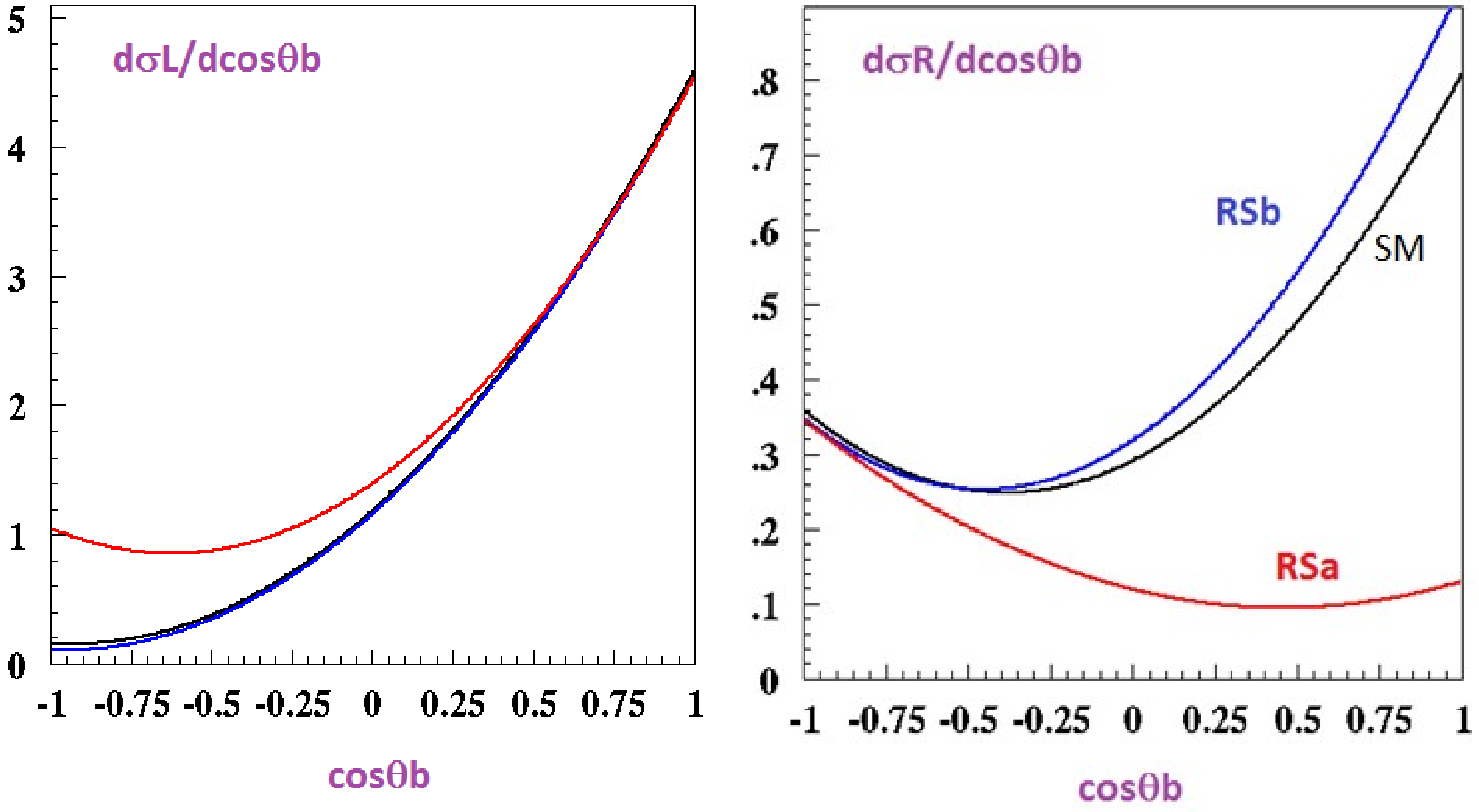
or equivalently $\quad g^{\gamma}_{L},\ g^{\gamma}_{R},\ g^{Z}_{L},\ g^{Z}_{R}$

LEP Anomaly on A_{FB}^{b}

~3σ in heavy quark observable A_{FB}^{b}



ee->bb@250 GeV

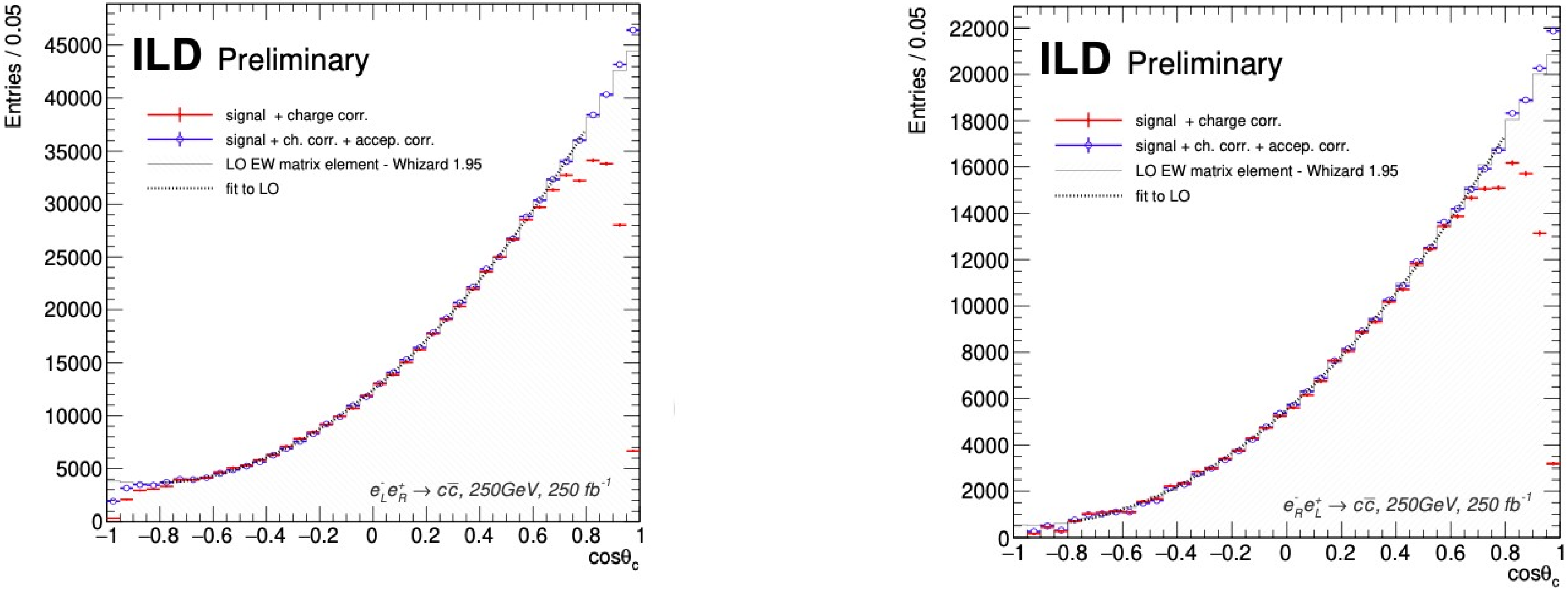


Randall Sundrum Models Djouadi/Richard '06

- 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 (Remember $Zb_l b_l$ is protected by cross section)
- Note that also B-Factories report on anomalies

What about lighter quarks – Differential cross section ee->cc

arxiv:2002.05805

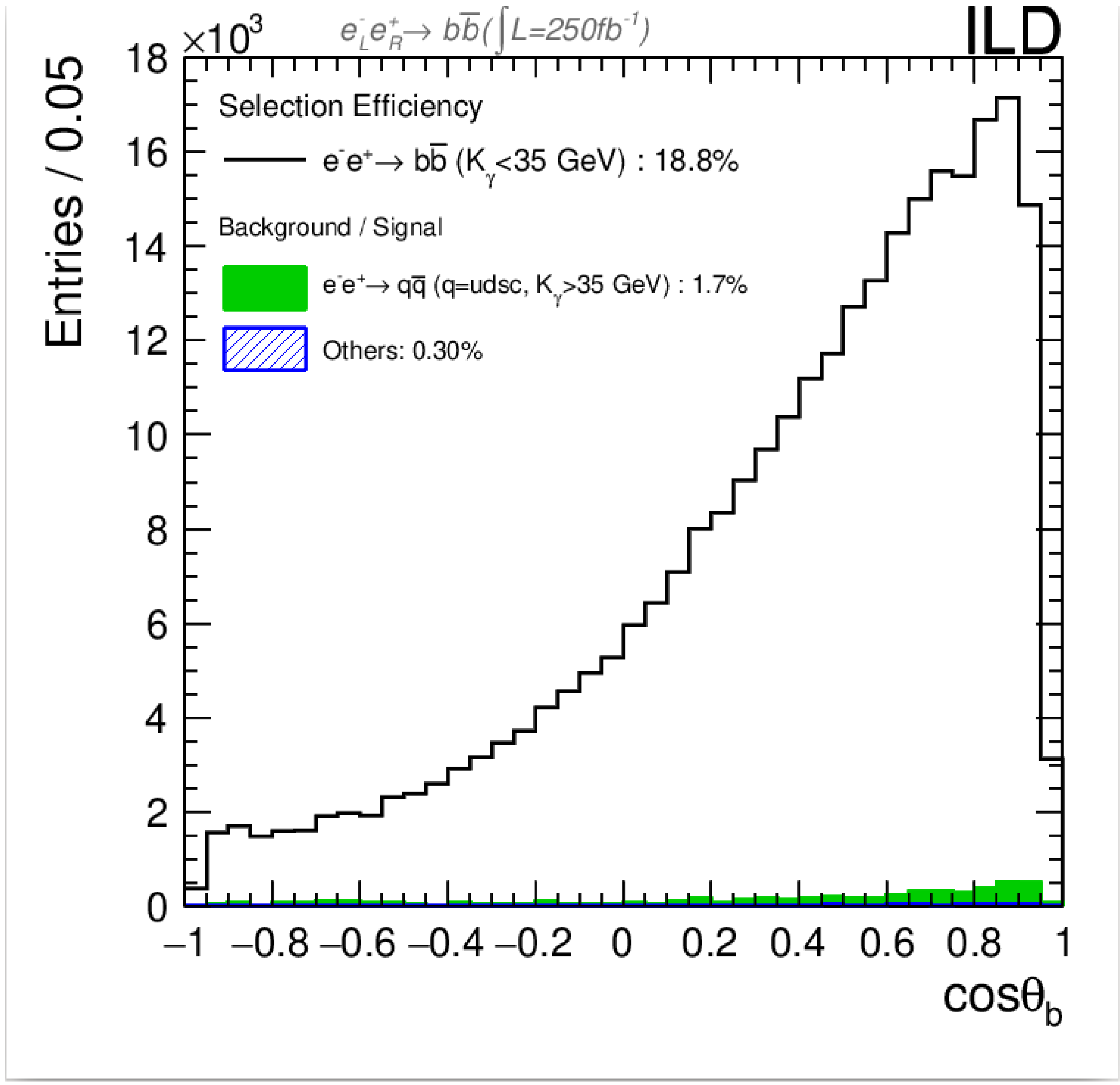


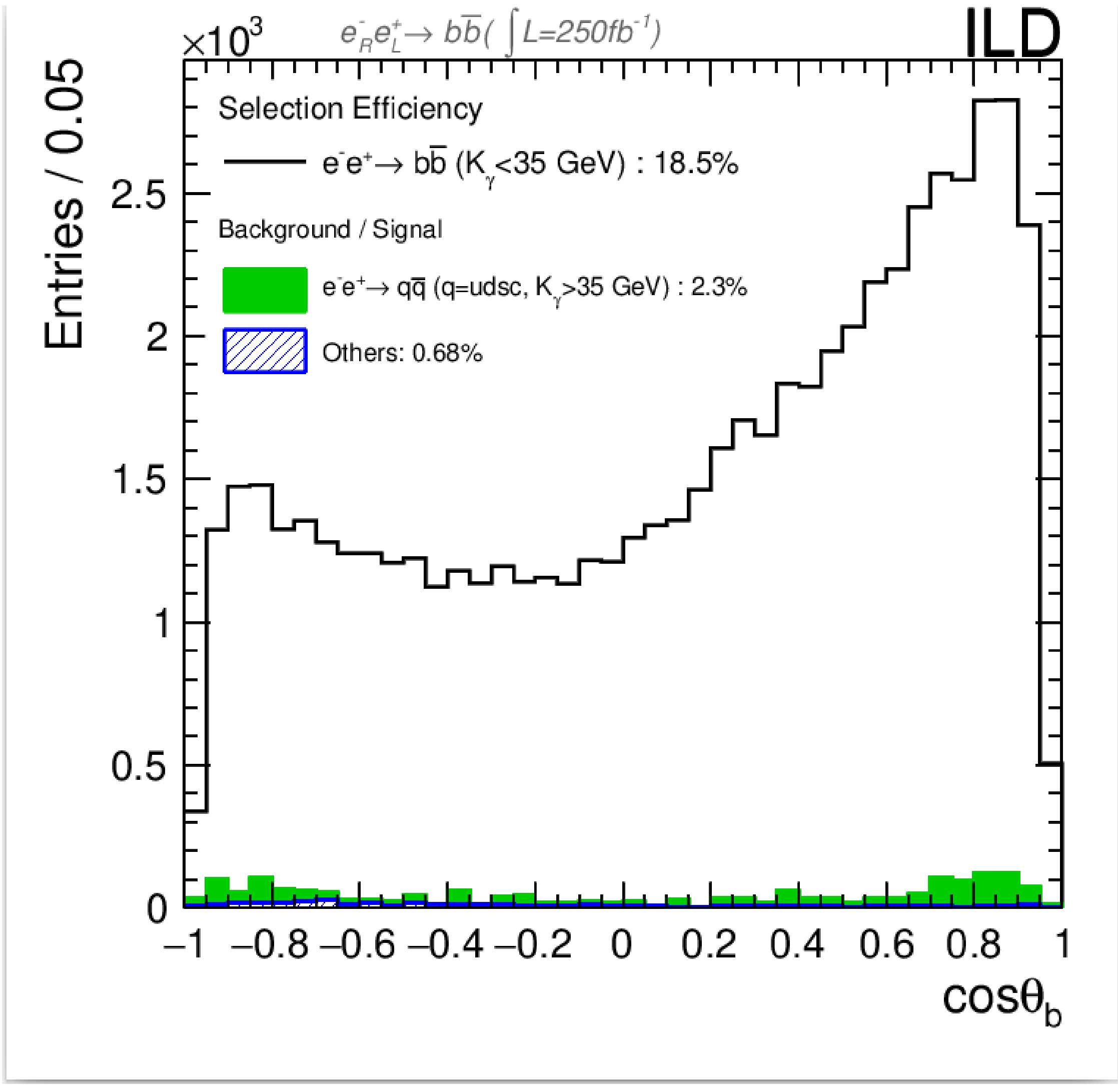
Full simulation study (with ILD concept)

Long lever arm in cos θ_c to extract from factors or couplings

ee-->bb – Signal and background

Arxiv:1709.04289, ILD Paper in progress





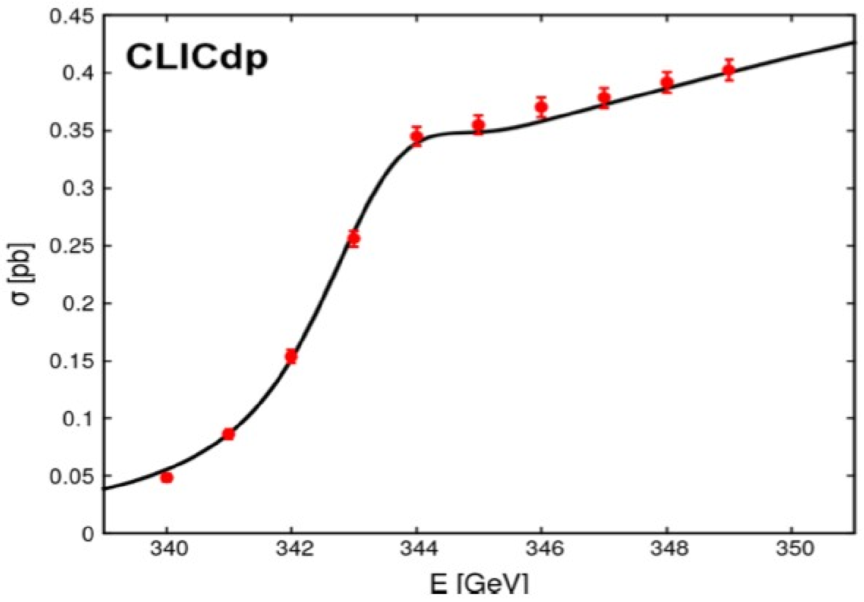
- Background levels can be kept at very small level
- However, these type of analyses seek per-mille level precision

Optimising of scanning points

Optimisation of threshold scan using "Non dominated sorting **genetic algorithm"**

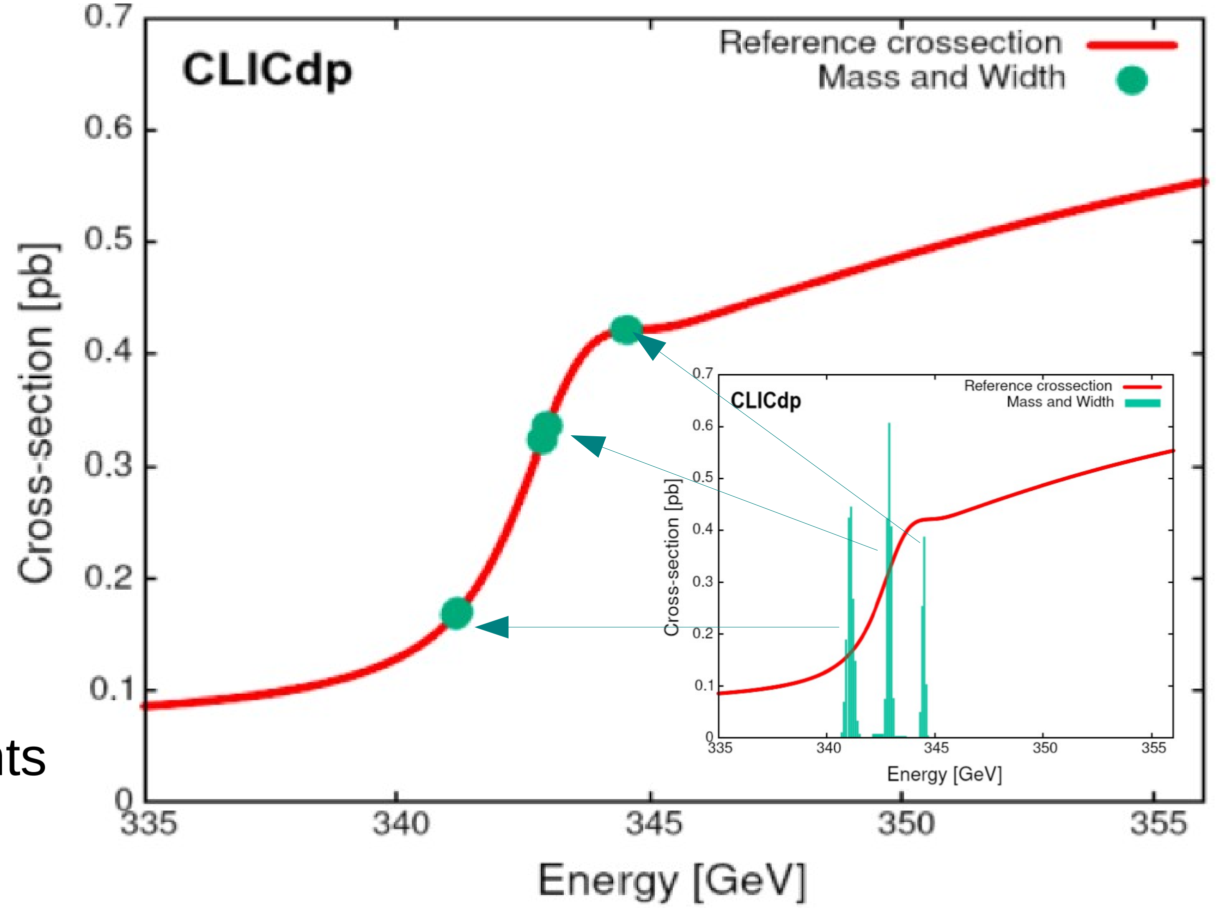
arxiv: 2103.00522

Standard scan scenario

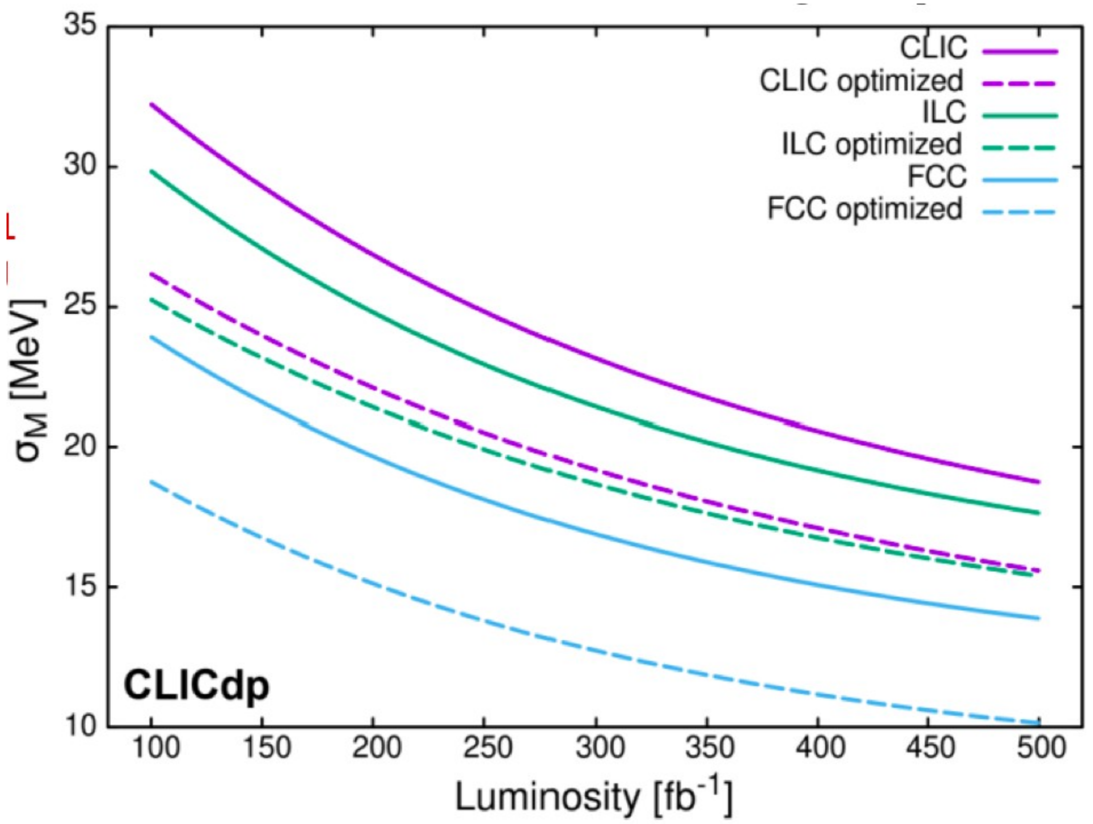


100 fb^{-1} for 10 equally distributed points

Optimised scenario for mass a width



Precision on top mass ...

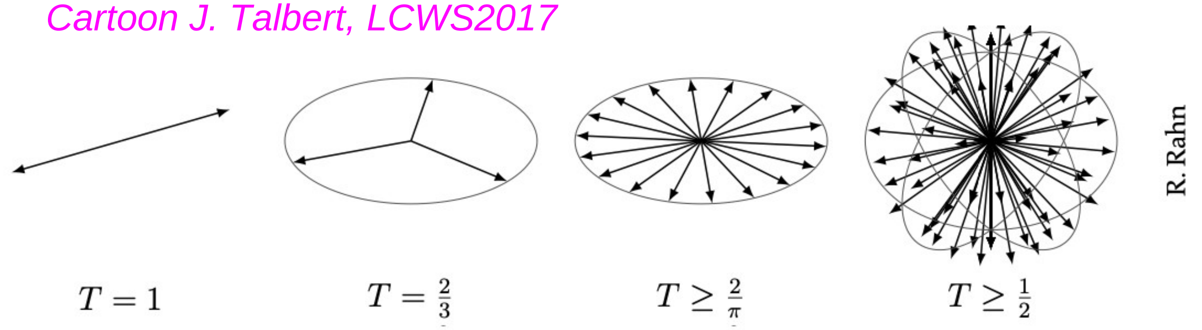


... taking luminosity spectrum into account

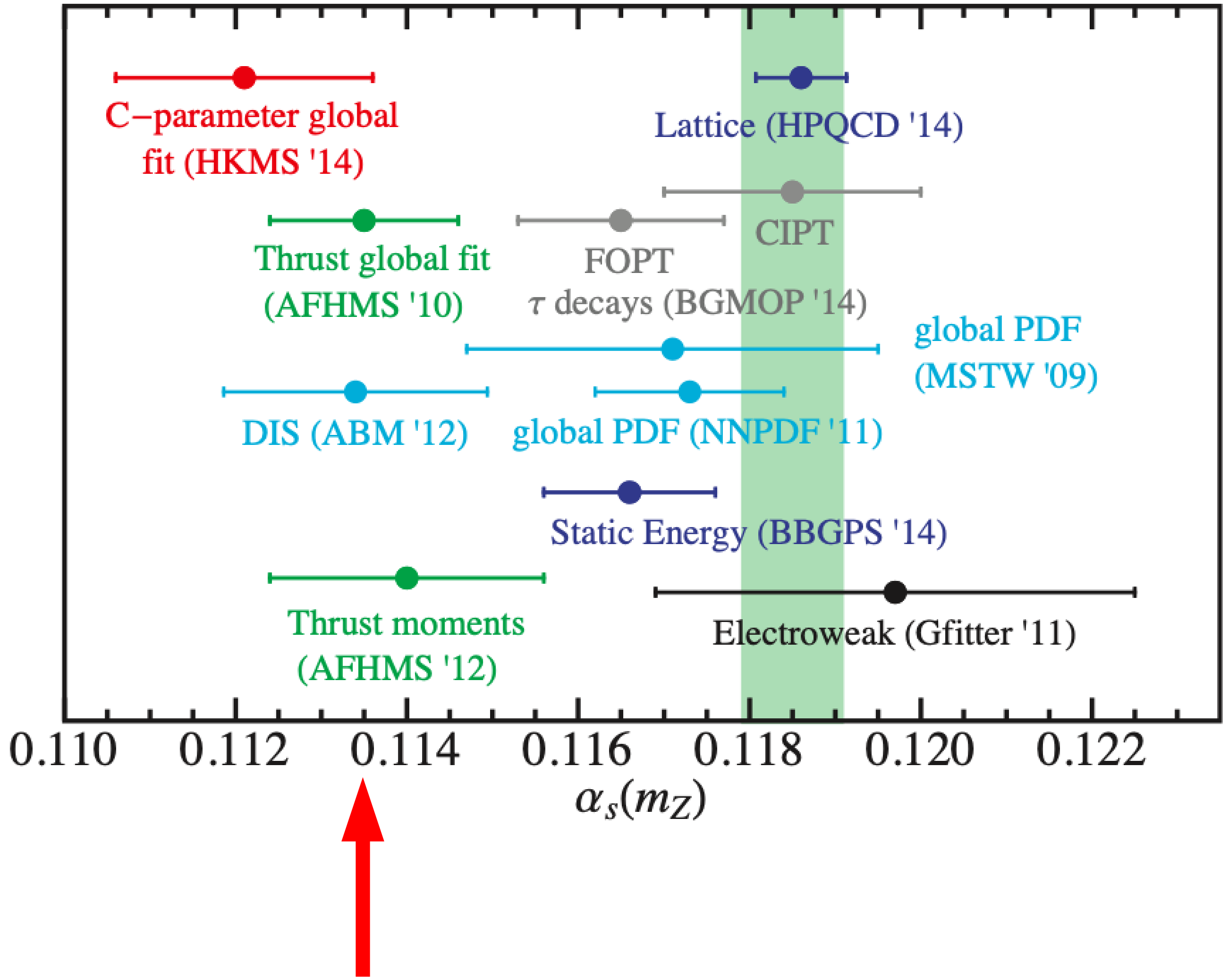
- Optimisation of threshold scan yield 25% statistical precision of top mass compared with scan using equally distributed scan points
  - Choice of measurement points with optimal sensitivity to desired quantity
- For breakdown of systematic errors see backup

Uncertainty driver α_s

Cartoon J. Talbert, LCWS2017



From arxiv:1501.04111



Event shape observables

Here brief summary see upcoming ILC Snowmass White Paper for more details

Significant discrepancy between as from lattice calculations (most precise) and QCD event shape variables

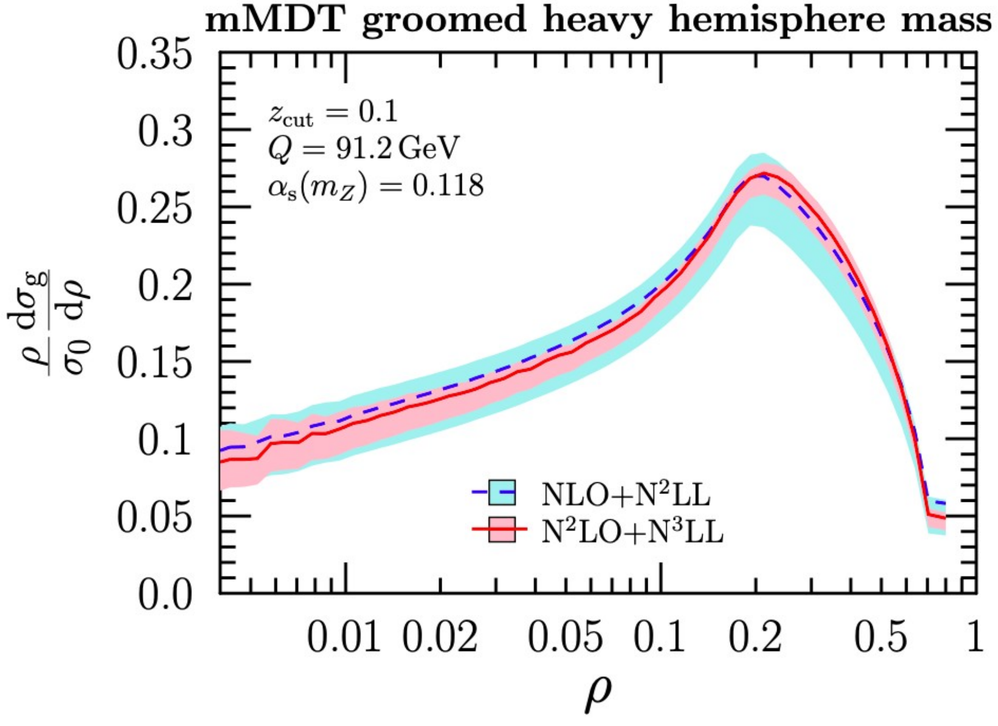
- Most “recent” e+e- input from LEP

Event shape variable are subject to non-perturbative effects

- “Power corrections” caused by soft radiation within a jet

How to take handle effects into account?

- Handling with Soft Collinear Effective Theories and/or
- “Jet Grooming”, i.e. removing soft parts from jet



Stable perturbative series after grooming
Excellent premise for extracting α_s