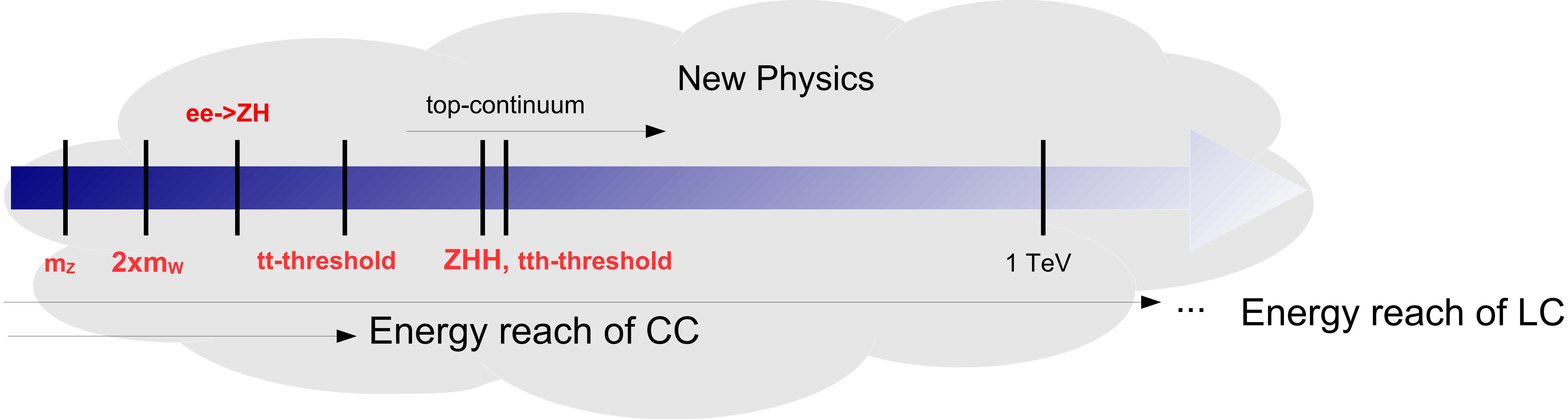
Linear Collider Facility
2-fermion processes

Roman Pöschl

TYL-FJPPN/FKPPN Meeting May 2025 Nantes

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

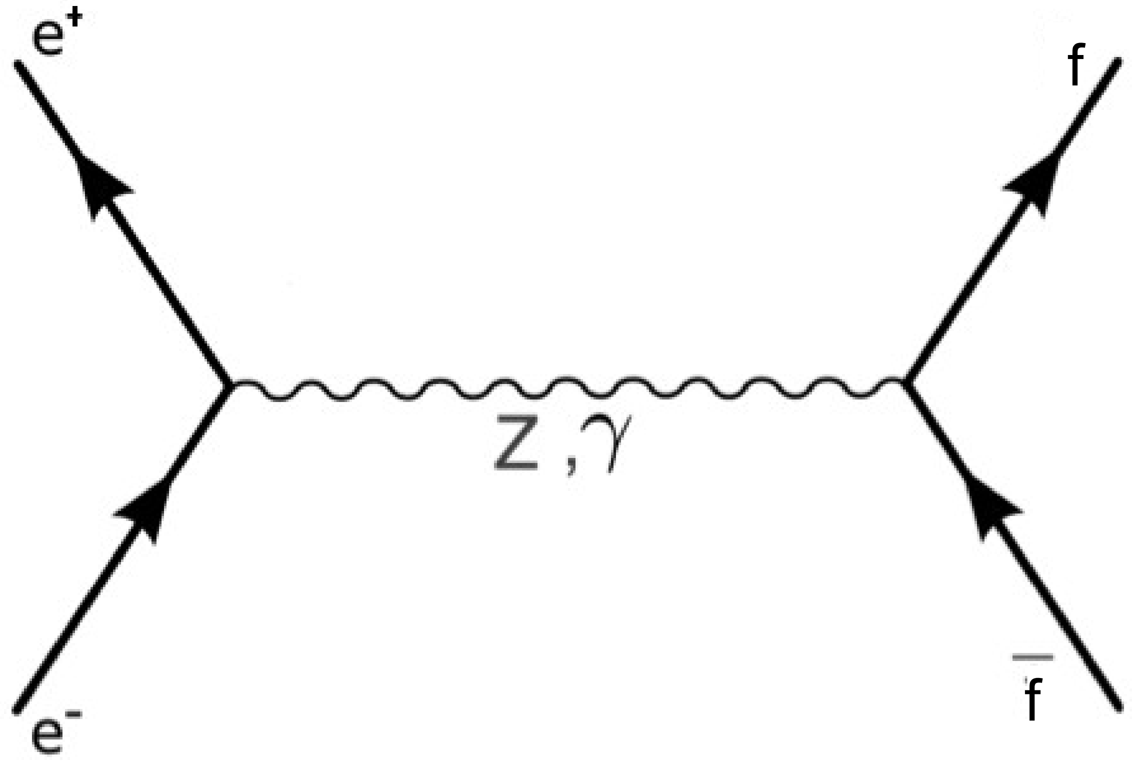
Machine settings can be “tailored” for specific processes

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

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

Background free searches for BSM through beam polarisation

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)*

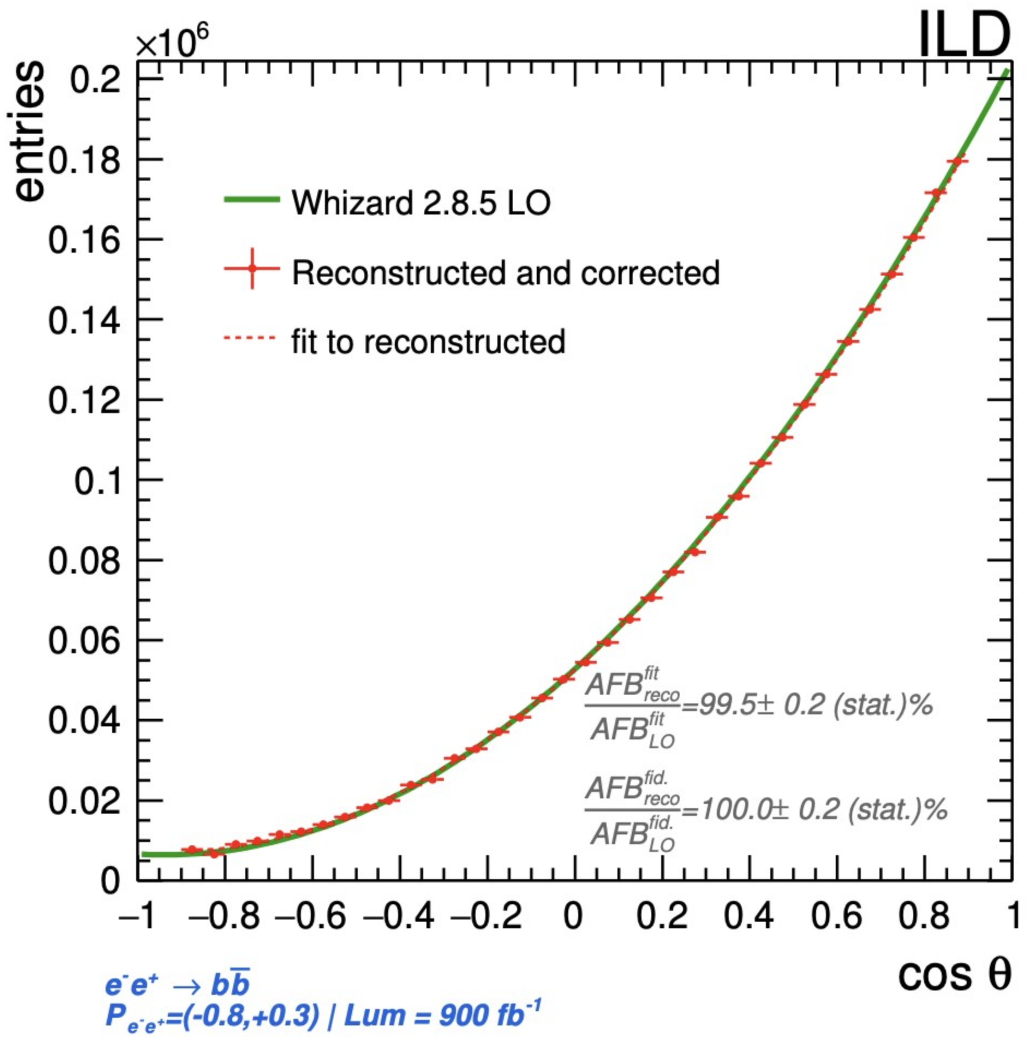
$\Sigma_{IJ} \neq \Sigma_{I'J'}$ => (characteristic) asymmetries for each fermion

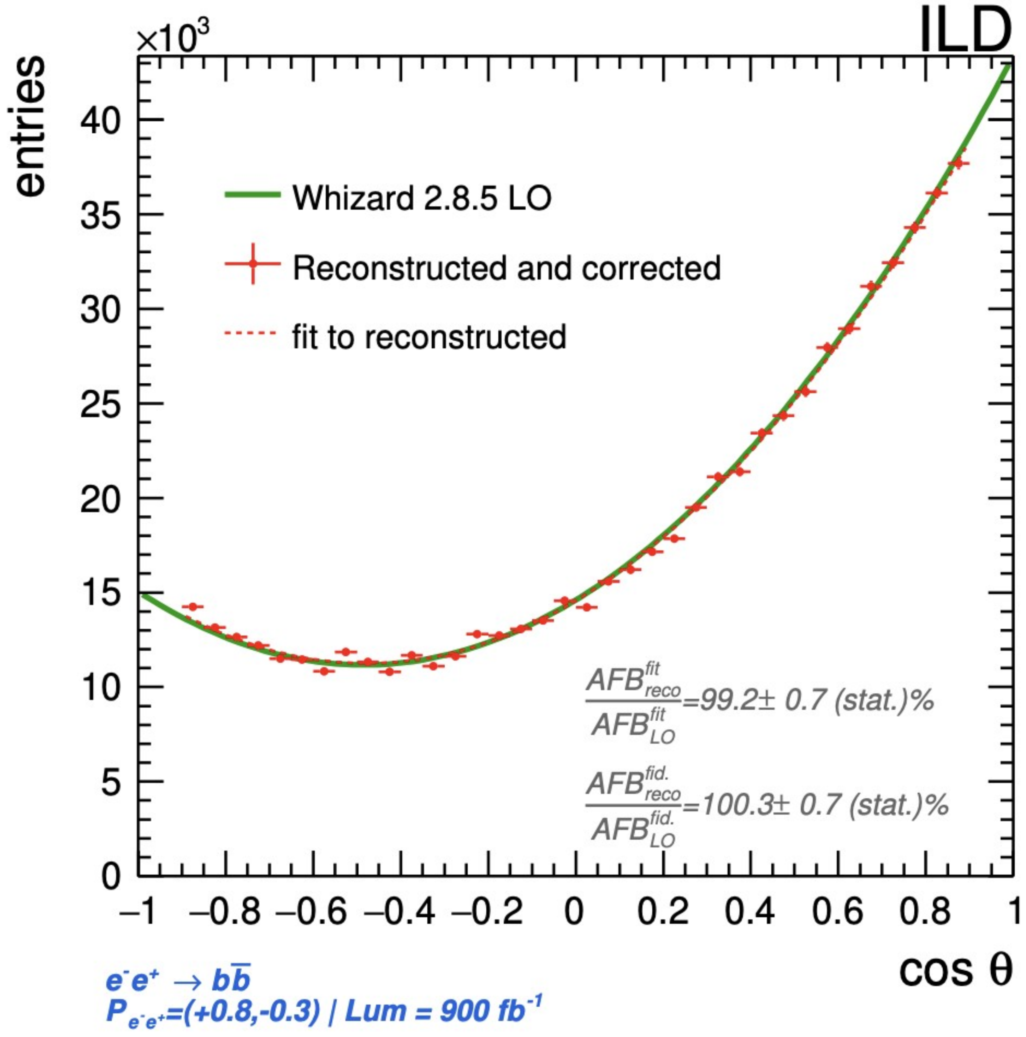
Forward-backward in angle, general left-right in cross section

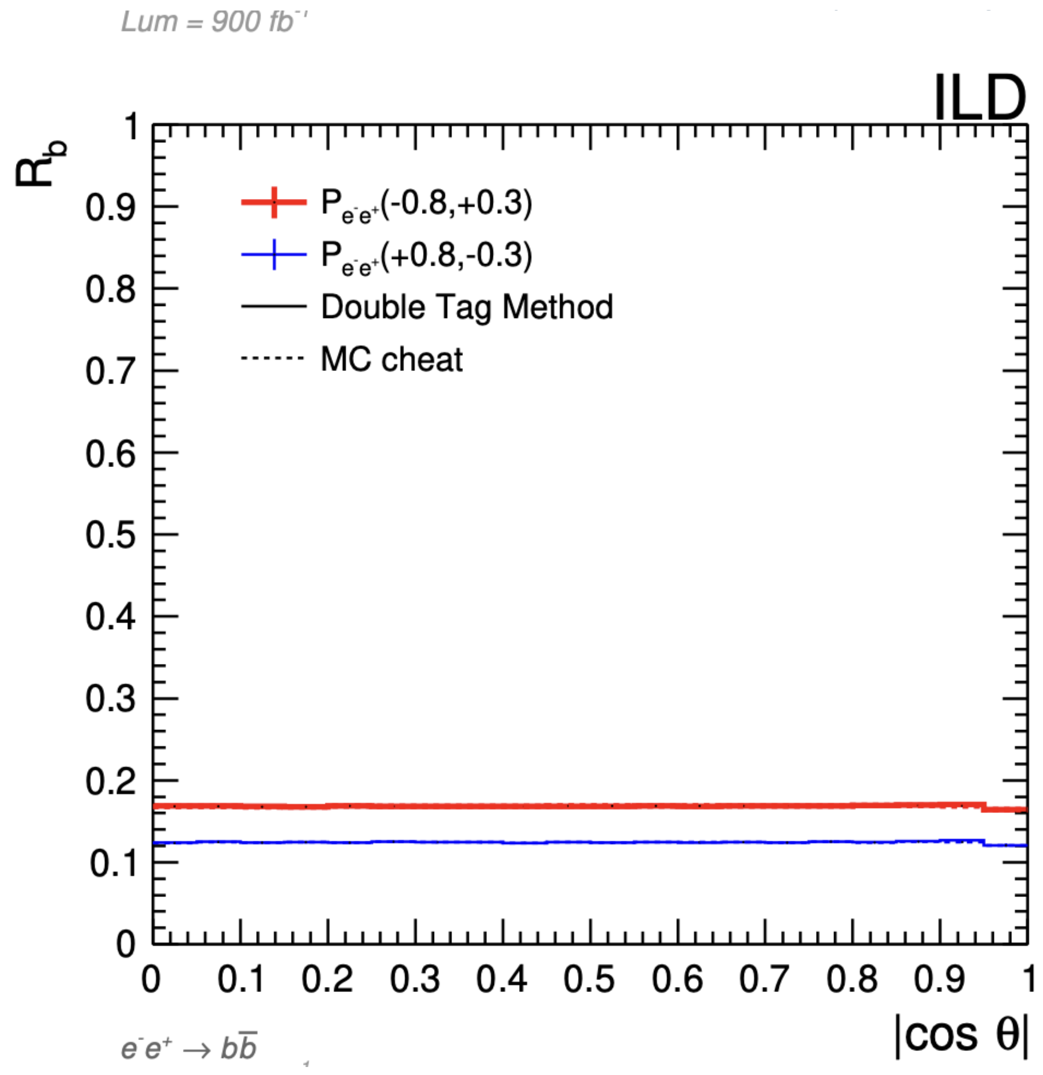
All four helicity amplitudes for all fermions **only available with polarised beams**

LC would be four colliders in one!

ee→bb at 250 GeV







- Study was carried out in earlier TYL/FJPPN project
- 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
- Full simulation study at 250 GeV is solid basis for estimations on Z pole (A_b, R_b)

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. (ILD Meeting 17/01/24)

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

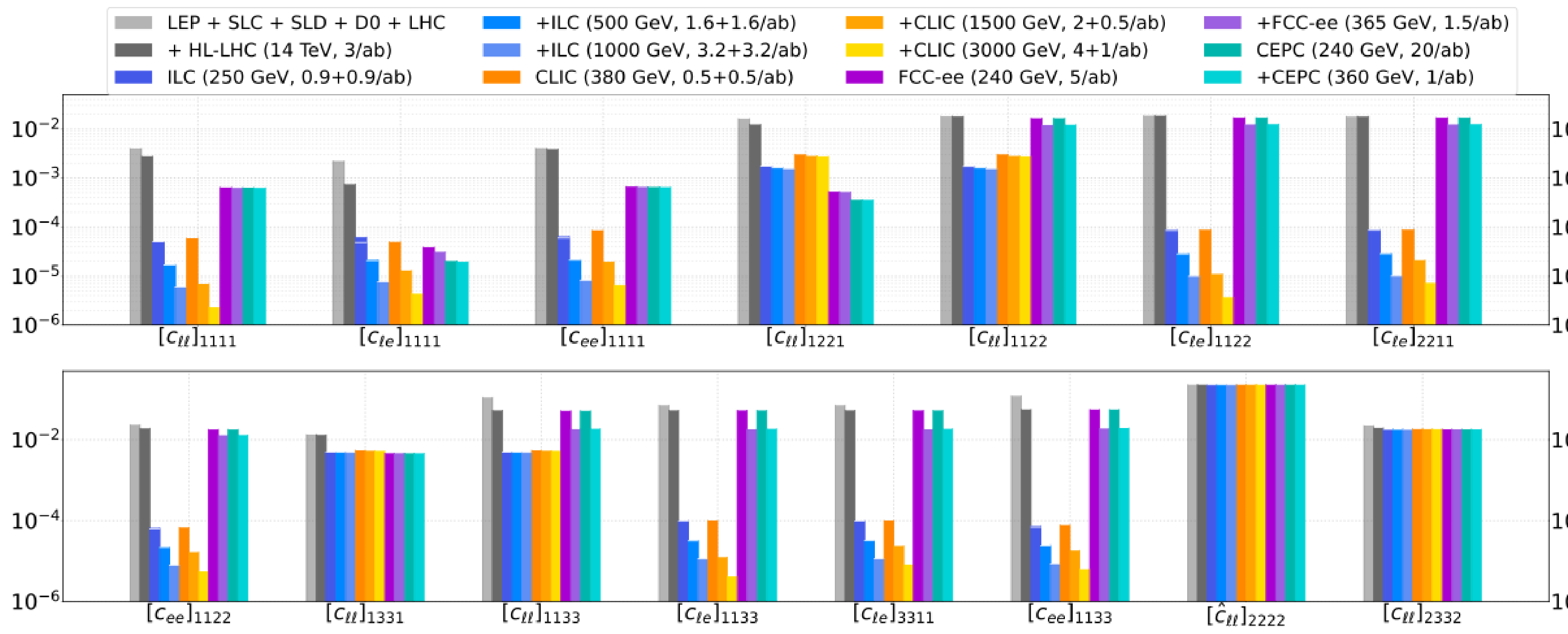
Z-fermion couplings
- C: Current precision
- R: ILC250 (Rad. Ret.)
- Z: Giga-Z

4ℓ couplings

- < 3 σ
- 3-4 σ
- 4-5 σ
- > 5 σ

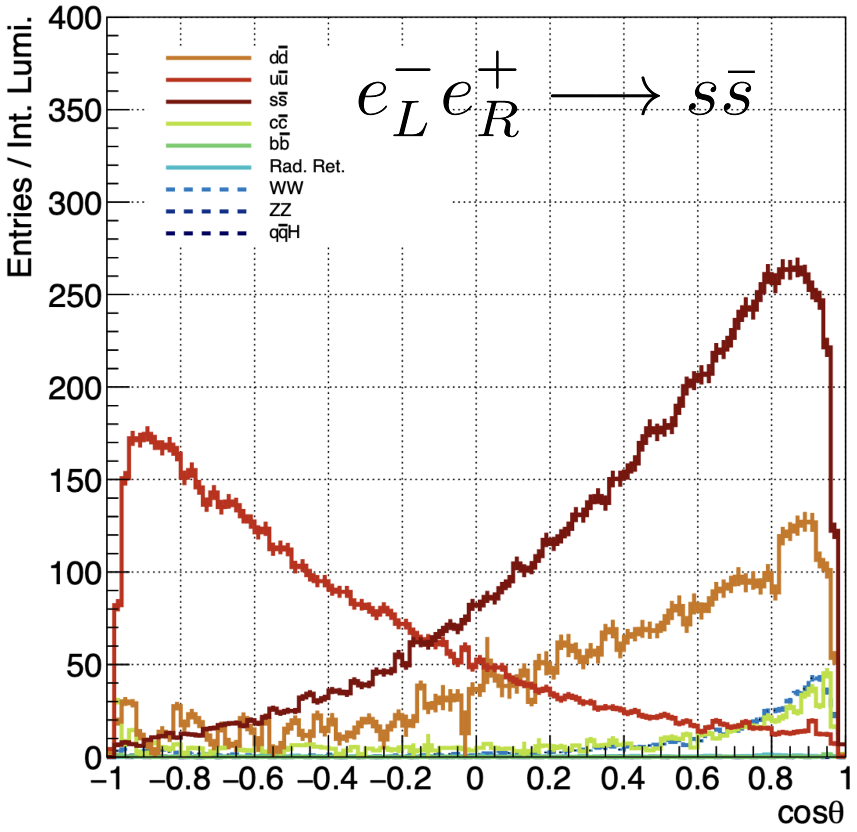
Probed mass scale: 9-25 TeV

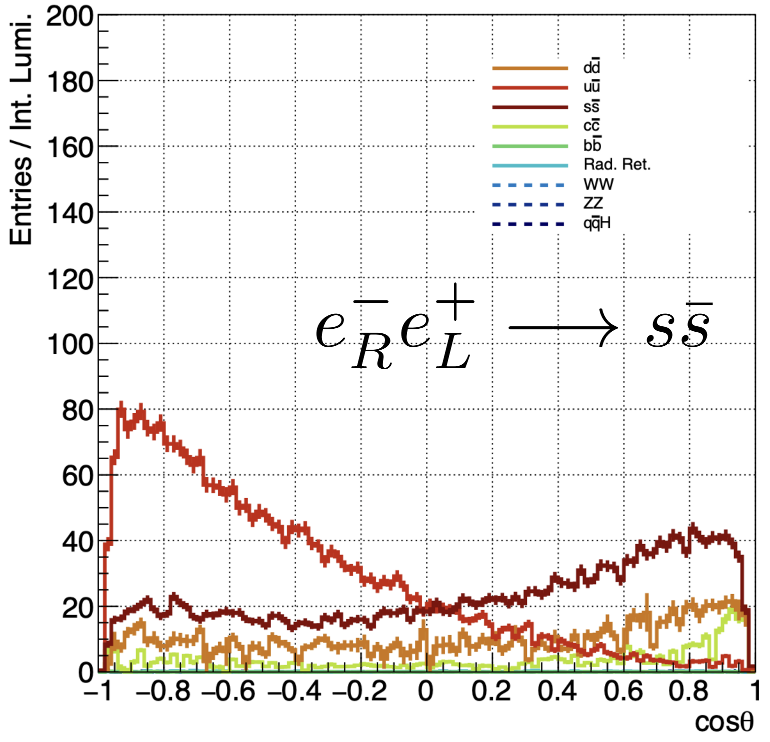
4-fermion operators in EFT (arxiv:2209.08078)



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

Lighter quarks - uds

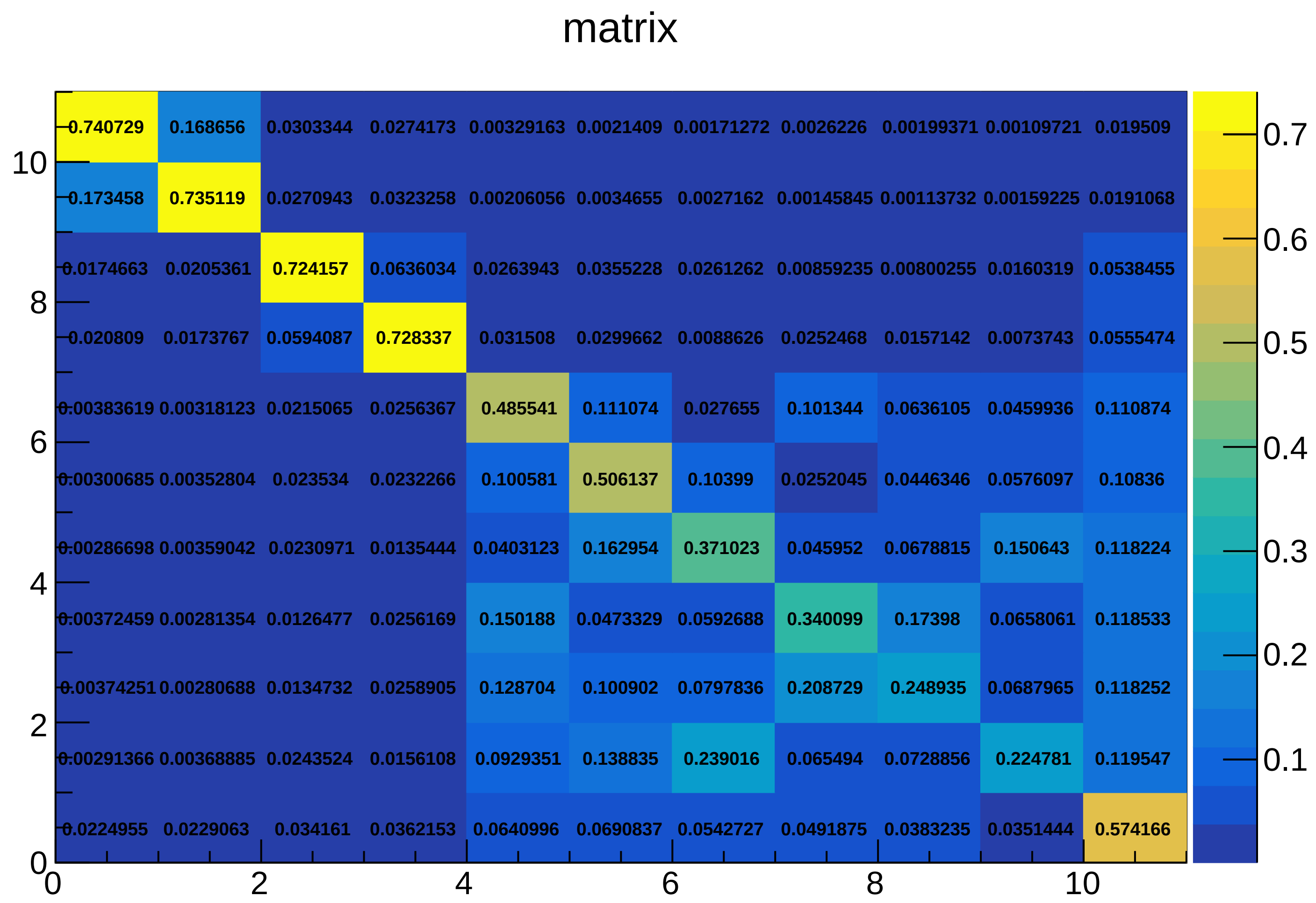


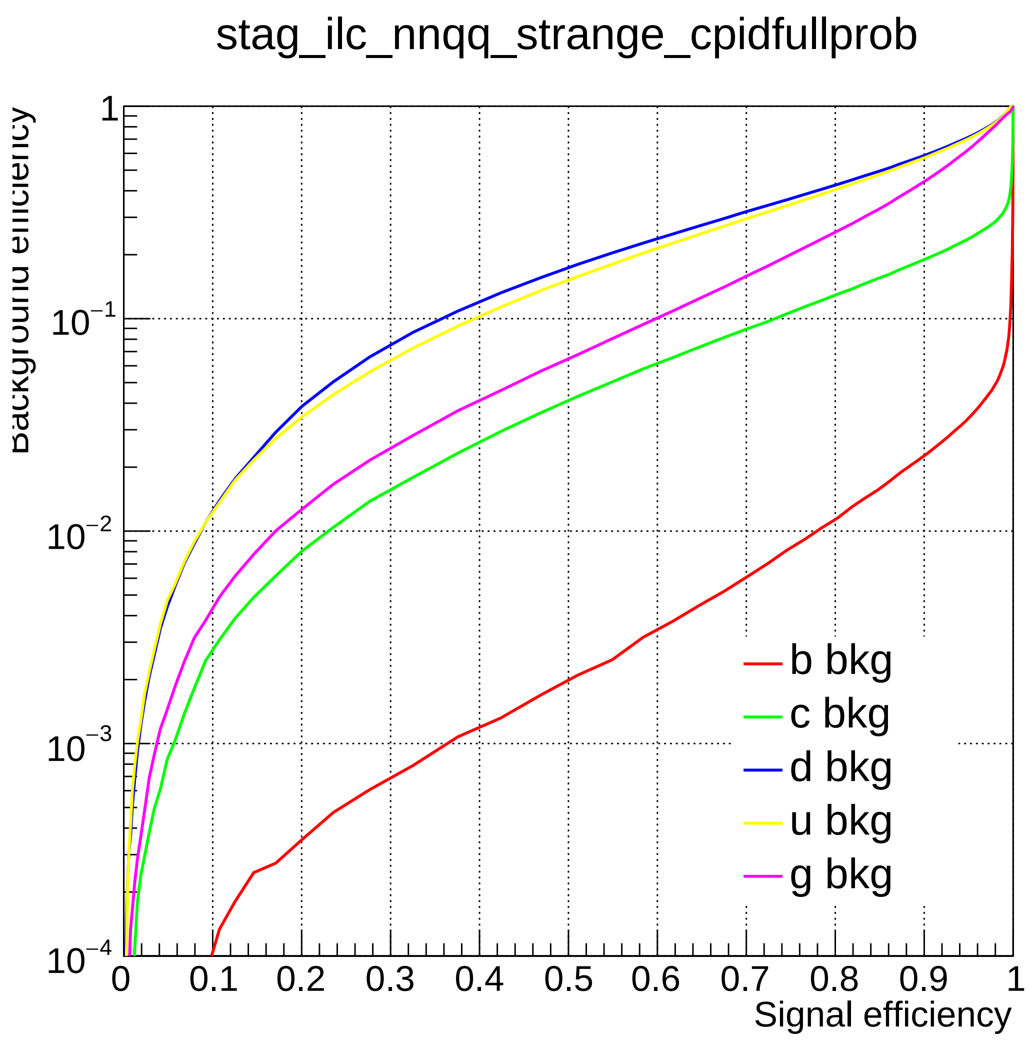


- PhD thesis of Yuichi Okugawa (IJCLab/Tohoku U, 2021-2024)
  - Polarisation (-80,+30): ΔR_s = 0.9%, $\Delta A_{fb,s}$ = 0.9%
  - Polarisation (+80,-30): ΔRs = 1.6%, $\Delta A_{fb,s}$ = 5.9%
  - Statistical error only
  - Systematic error sensitive to knowledge of background
- Analysis based on leading 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

s-tagging with Modern Flavor Tagging

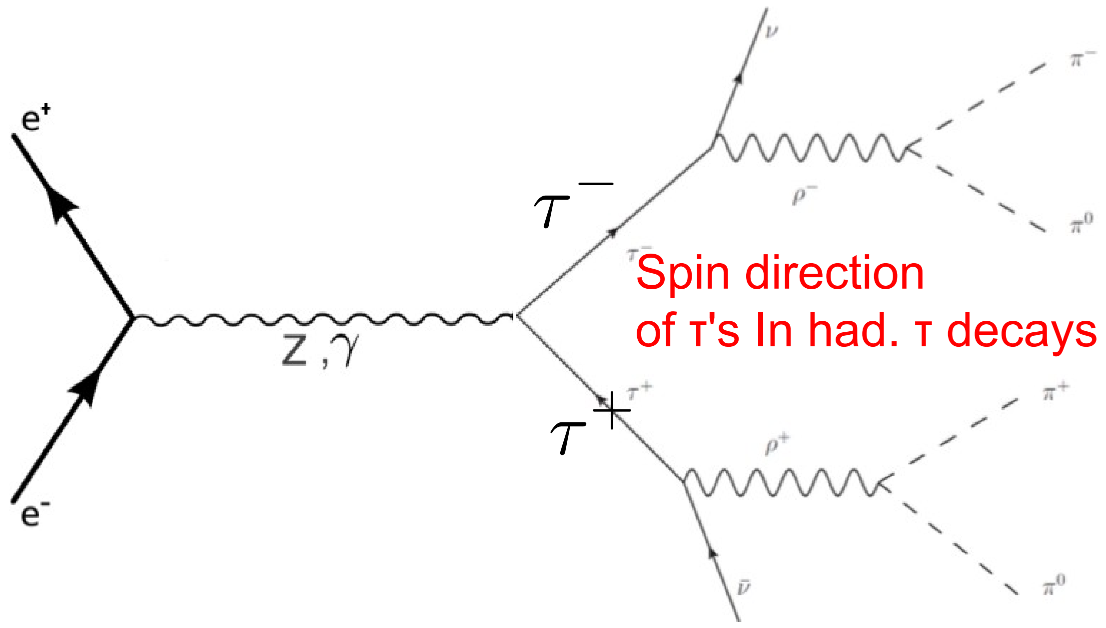


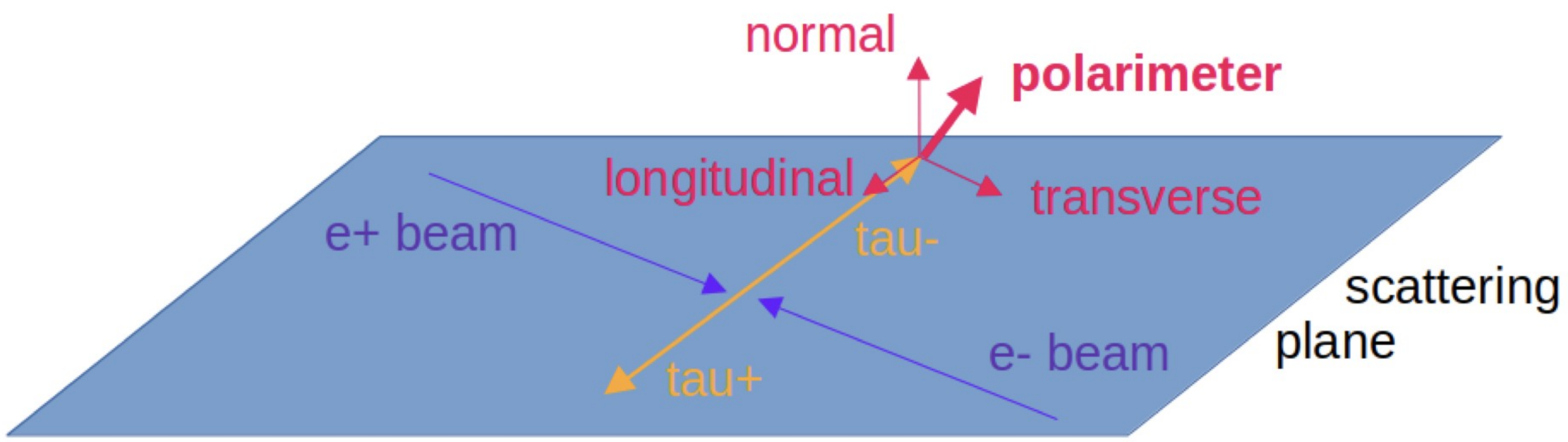


- Considerable progress in flavor tagging in recent years ...
- Mouthwatering opportunities for light quarks
- e.g. Background down to 10^{-2} at 10% efficiency
- For this working point statistical error would go down to
  - Polarisation (-80,+30): ΔR_s = 0.22%, $\Delta A_{fb,s}$ = 0.22%
  - Polarisation (+80,-30): ΔRs = 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

Reconstruction and use of τ spin polarisation

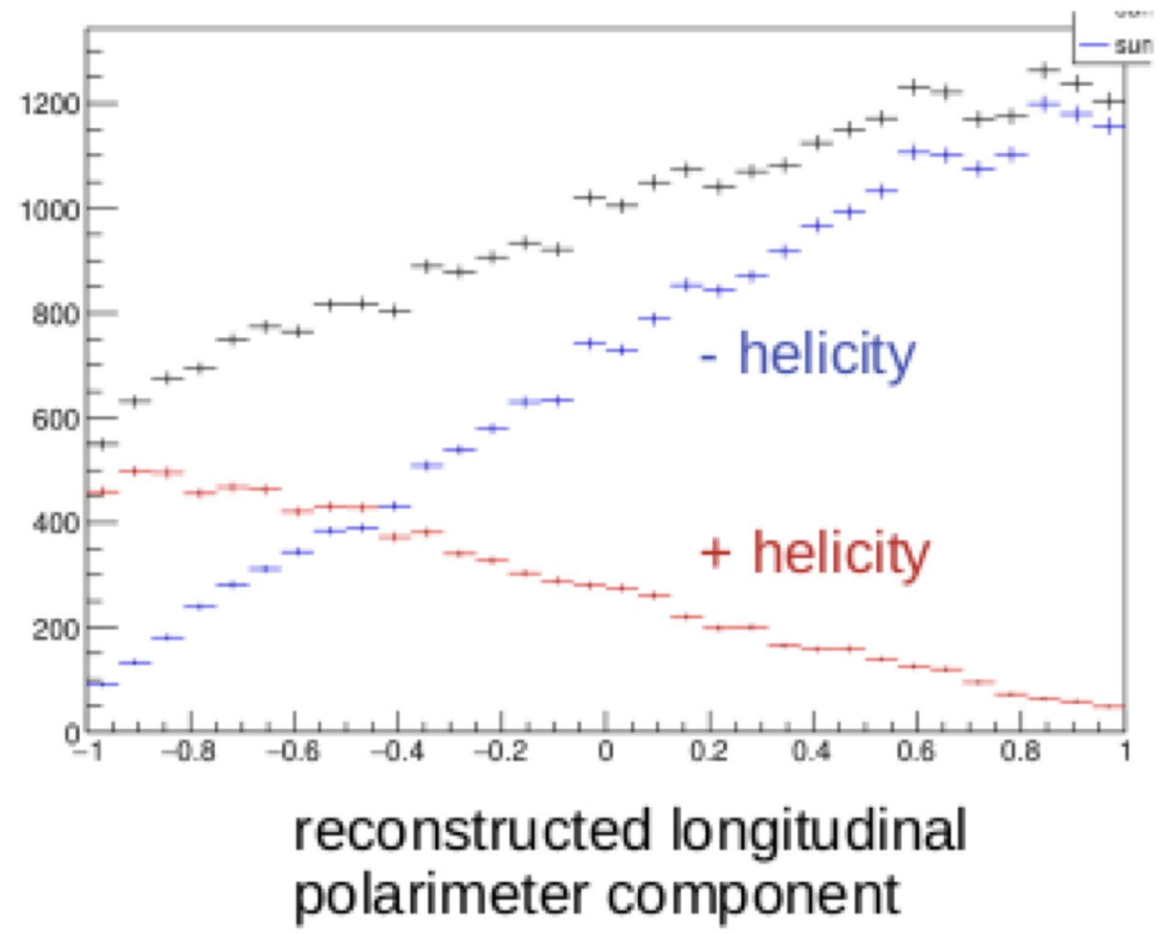




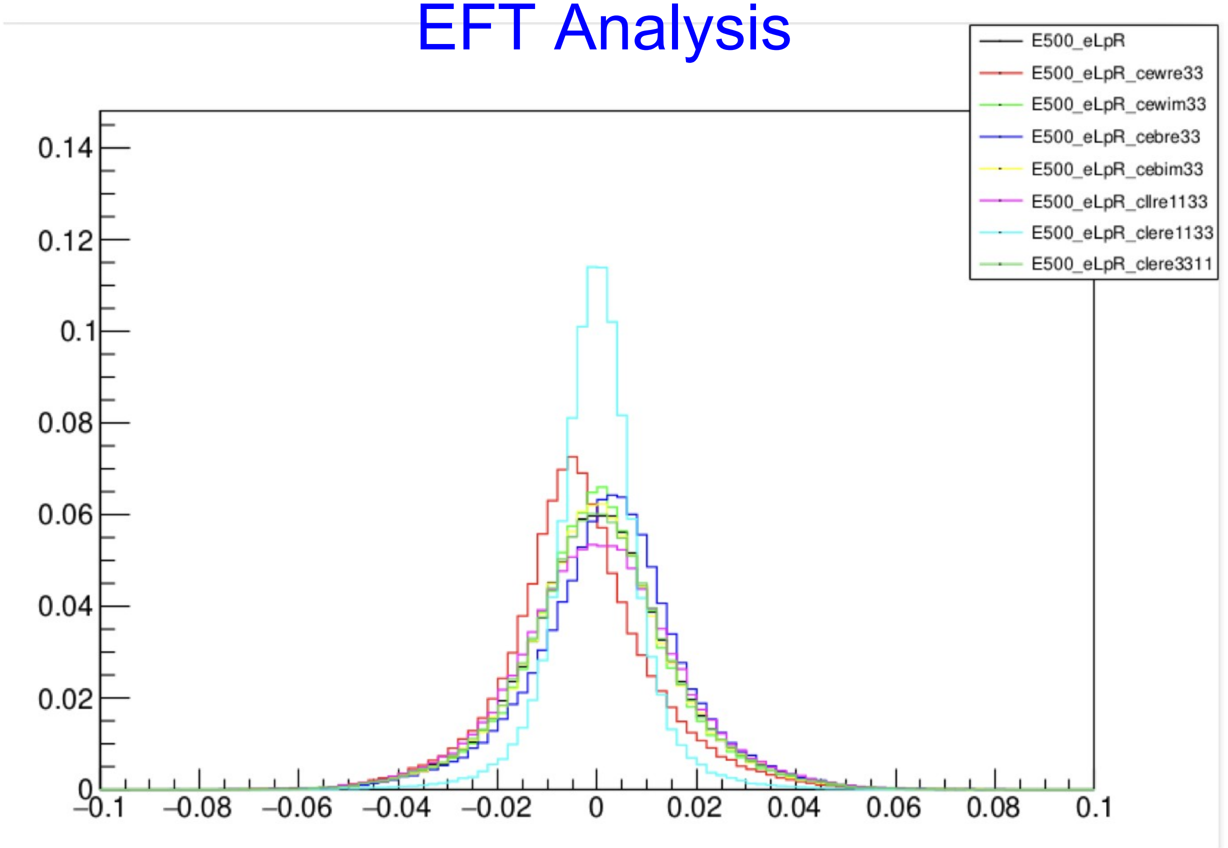
- The τ-pair final state provides unique possibilities for testing the Standard Model and discovering the effects of new physics
  - access to the spin orientation of the final state fermions by consideration of the distribution of the τ decay products
  - Probing of longitudinal polarisation (positive and negative helicity τ)
  - transverse spin components
- Spin correlations between the two final state taus

τ spin polarisation – Analysis at 500 GeV

τ-helicity



EFT Analysis

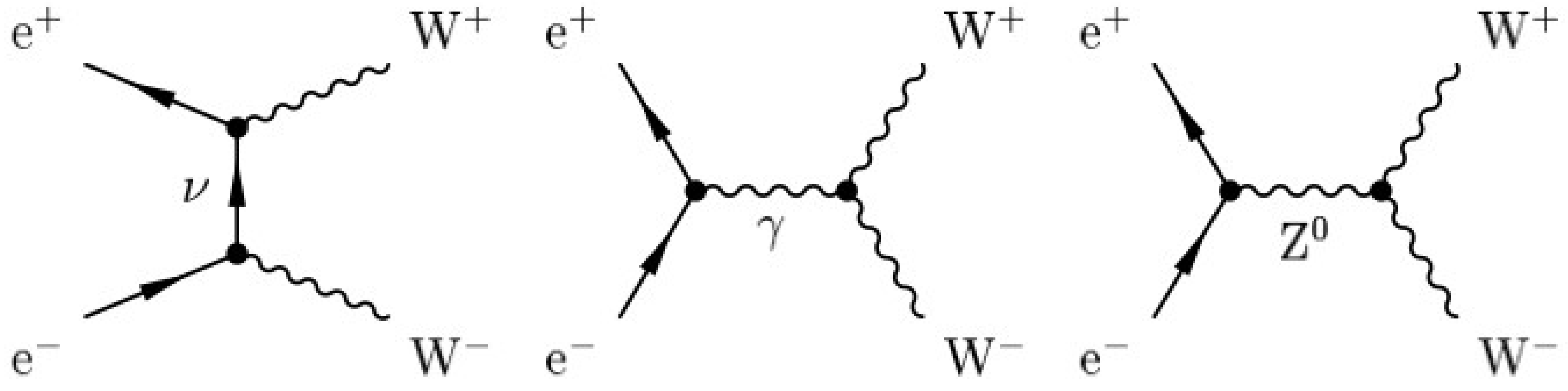


- At 500 GeV τ production "plagued" by ISR
  - ... and ISR photon often unmeasurable
- Successful helicity analysis requires kinematic constraint
- Iterative procedure to determine τ helicity

- Interface MadGraph TauDecay
- Sensitivity ot EFT operators to ttW/B operators and 4-fermion vertices

D. Jeans, ECFA Report

WW production at 250 GeV (and above)



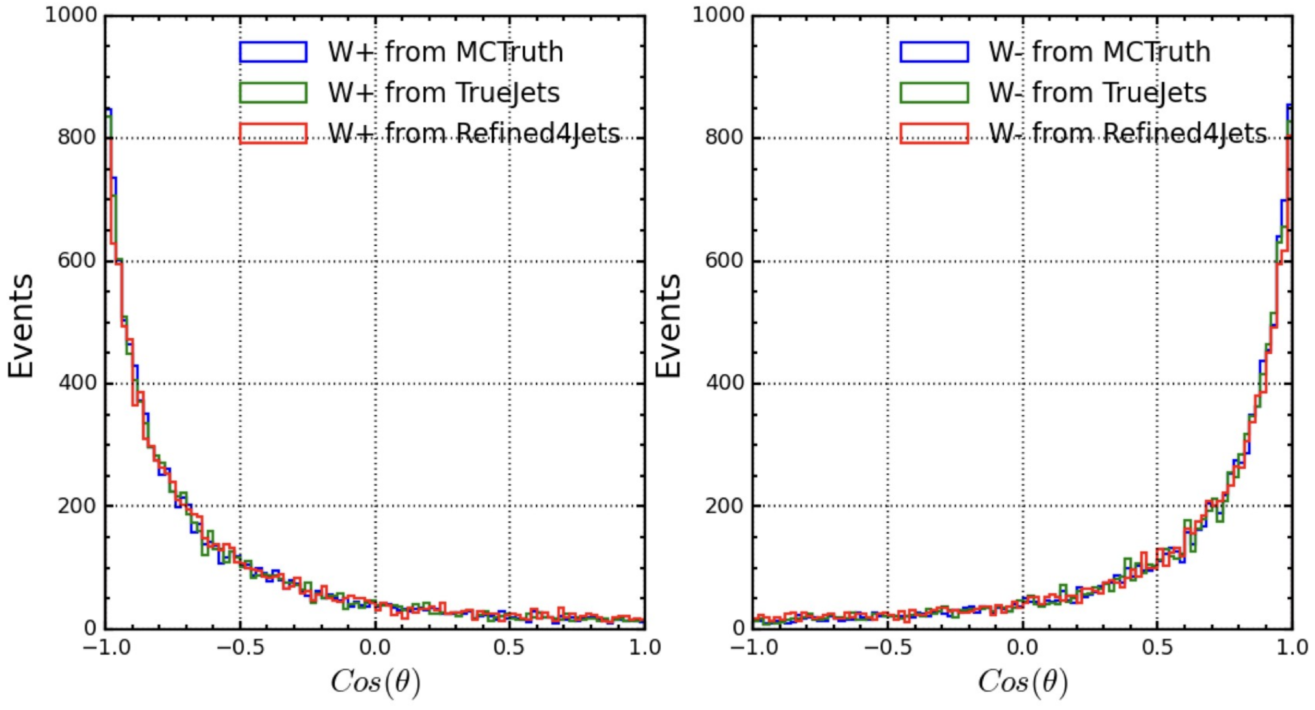
Sensitivity to triple and quartic gauge Boson couplings (TGC and QGC)

Observables depend strongly on beam polarisation

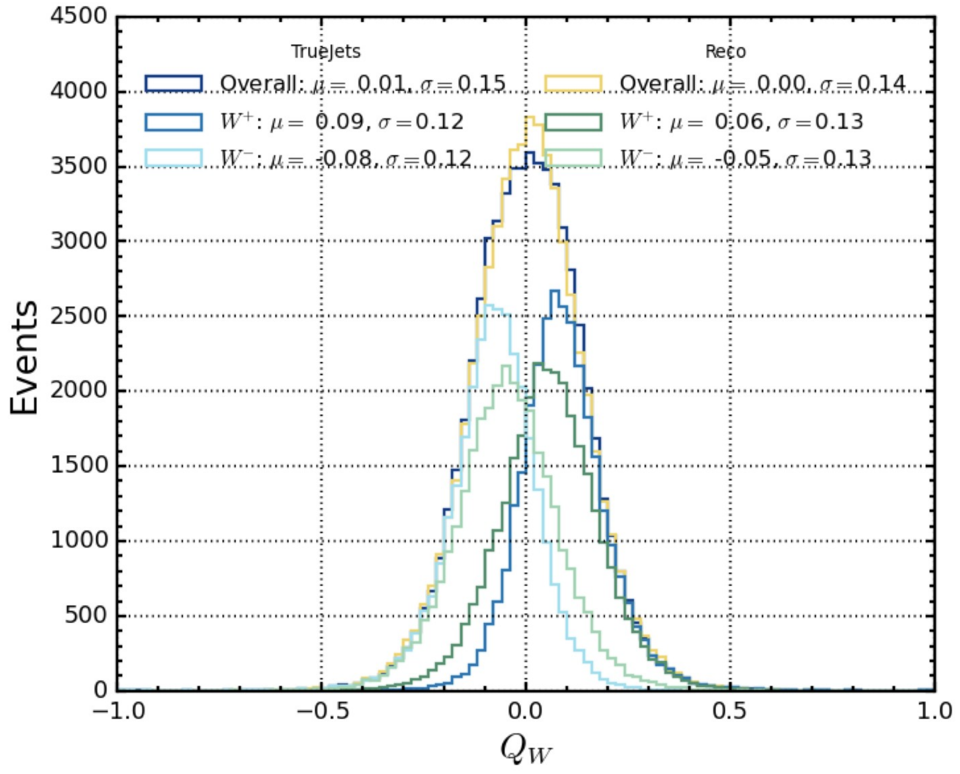
=> Enrich different helicity modes of W
=> Disentangling of couplings to Z and γ
=> in situ measurement of beam polarisation (and luminosity)

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?

LCWS 2024

- July 7th – July 11th 2024 at University of Tokyo
- Organised (among others) by Daniel and Taikan
- 341 participants
- TYL/FJPPL enabled participation of R.P.

LCVision – A unified approach

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

J. List

TYL/FJPPN – FY2025 – The team

ID[1]: HEP-16	Title: 2 fermion production at future Higgs factories					
	French Group			Japanese Group		
	name (Family name, First name)	title	lab.[2]	name (Family name, First name)	title	lab.[32]
PIs:	Pöschl, Roman e-mail: roman.poeschl@ijclab.in2p3.fr	Dr	ILCLab	Jeans, Daniel e-mail: daniel.jeans@kek.jp	Dr	KEK/IPNS
Members:	Roman Pöschl	Dr	ILCLab	Ishikawa, Akimasa	Dr	KEK/IPNS
	François Richard	Dr	ILCLab	Suehara, Taikan	Dr	U. Tokyo
	Xin Xia	PhD	IJCLab	Tian, Junping	Dr	U. Tokyo
	Jesus Hernandez	Postdoc	IJCLab	Sanuki, Tomoyuki	Dr	Tohoku U.

J. List

Summary and Conclusion

- Progress on 2-fermion studies in past fiscal year
- (Major) contributions to community documents in preparation of ESPPU 2026
  - ECFA Higgs/electroweak/top
  - LCVision documents, see https://agenda.linearcollider.org/event/10624/program
- Next fiscal year
  - Revision of ee->ss study based on modern flavor tagging
  - Continuation of ee->ττ
  - Phenomenology, e.g. global fits with 2-fermion quantities

J. List

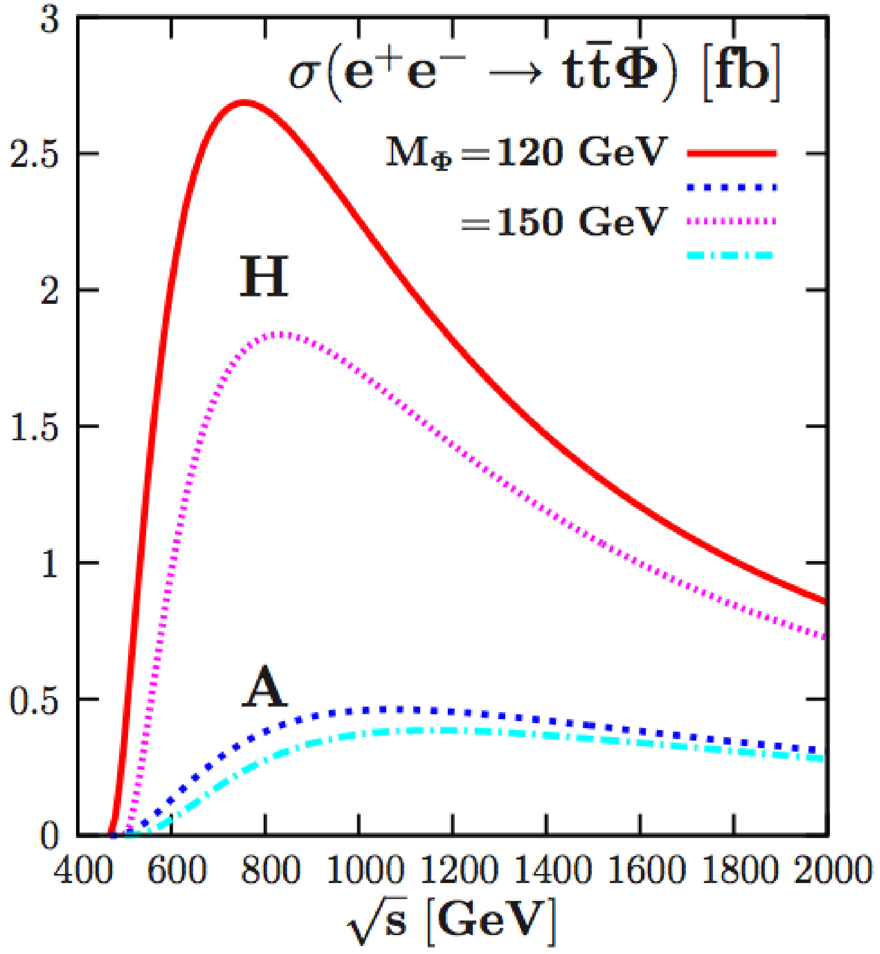
Backup

Higgs Quantum Numbers – CP via ttH

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

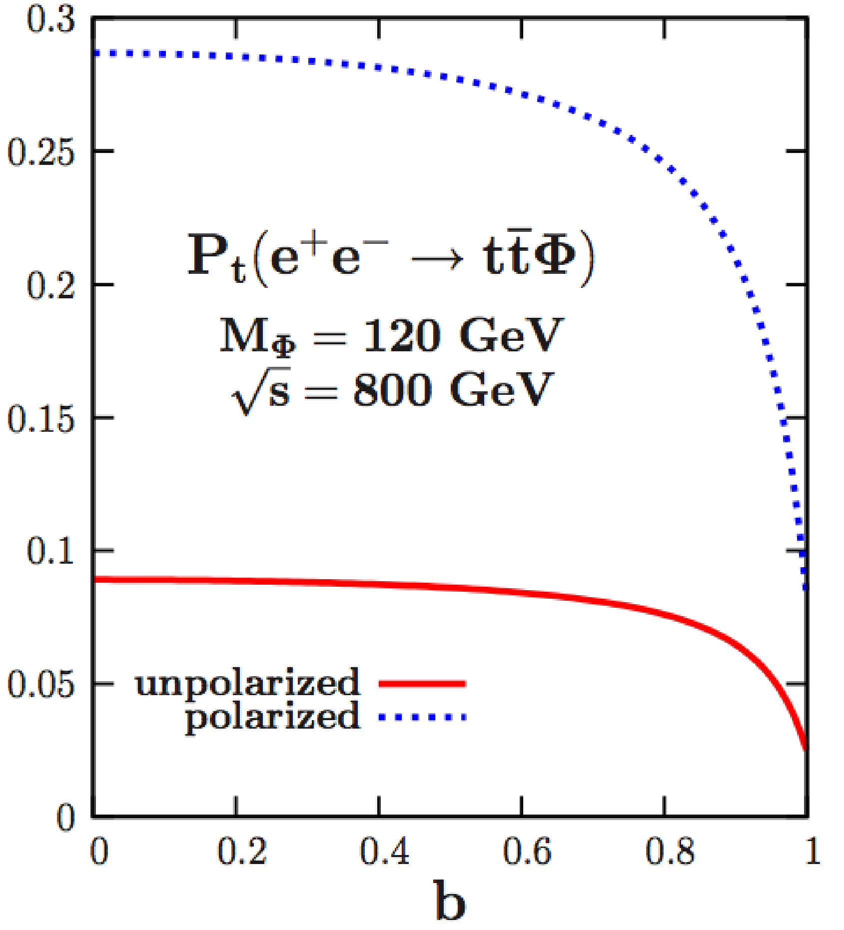
In memoriam of Rohini Godbole

Cross section



Dramatic differences for CP odd and CP even scalar

Top quark polarisation

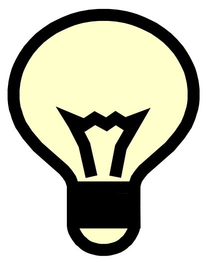


Sensitivity to CP odd admixture b
Merit of beam polarisation

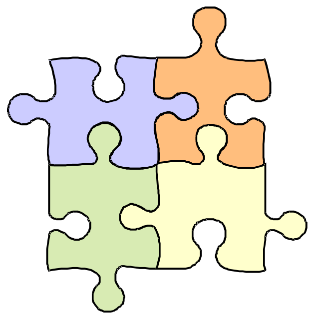
Determination of CP nature of scalar boson in an unambiguous way

Godbole et al., LCWS07

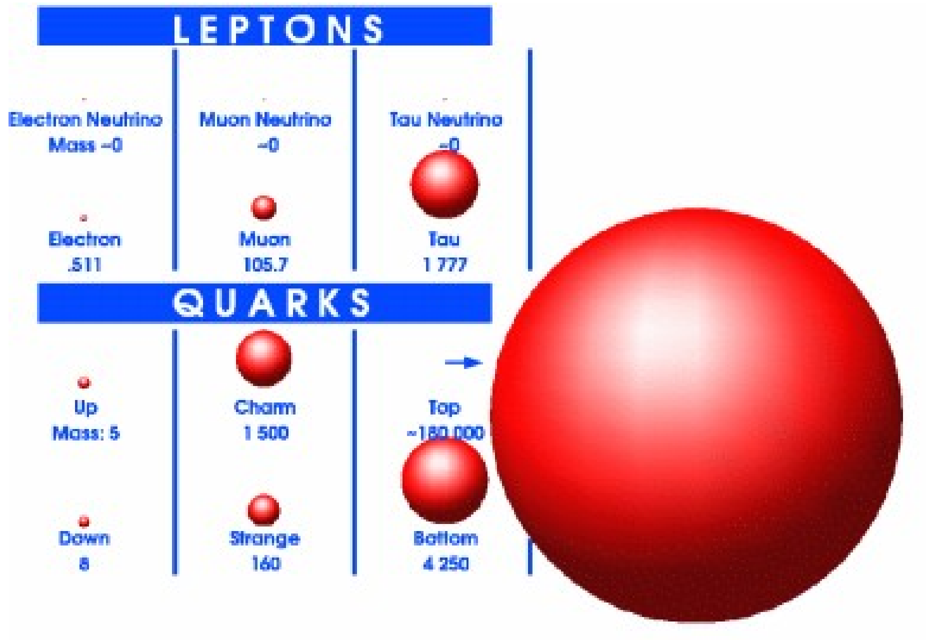
Top Yukawa Coupling

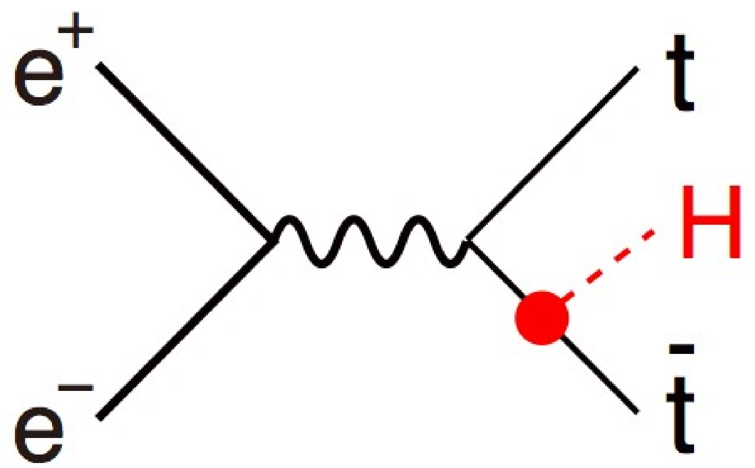


Elementary Scalar?



Composite object?





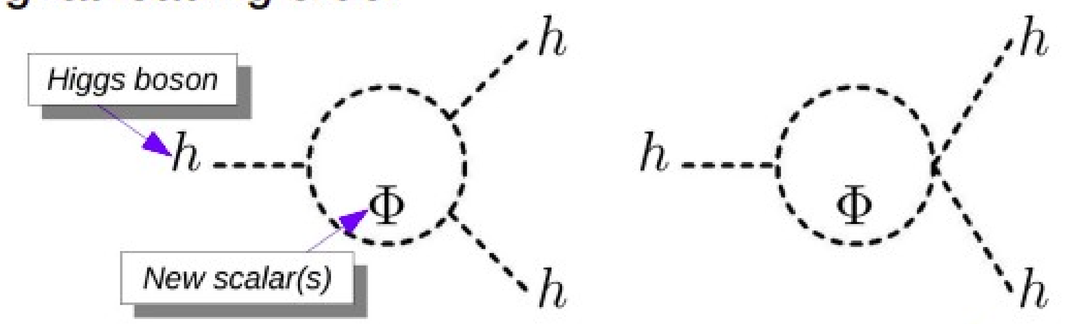
Estimation on δyt/yt in 2203.07622 for ILC

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

Similar prospects exist for CLIC

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



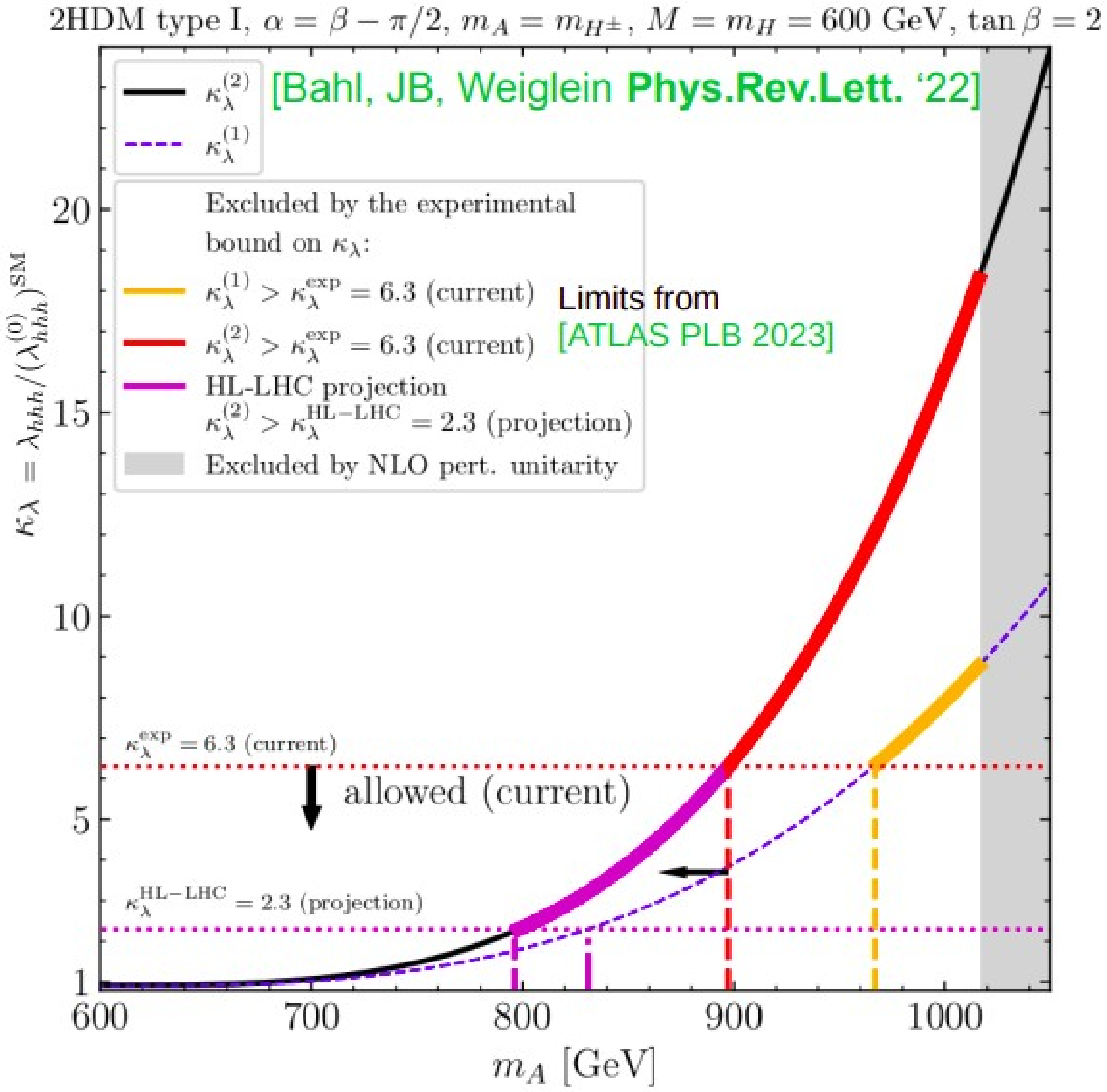
$$m_\Phi^2 = M^2 + \frac{1}{2} g_{hh\Phi\Phi} v^2 \Leftrightarrow g_{hh\Phi\Phi} = -\frac{2(M^2 - m_\Phi^2)}{v^2}$$

- Comparing latest exp. bounds

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

[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]



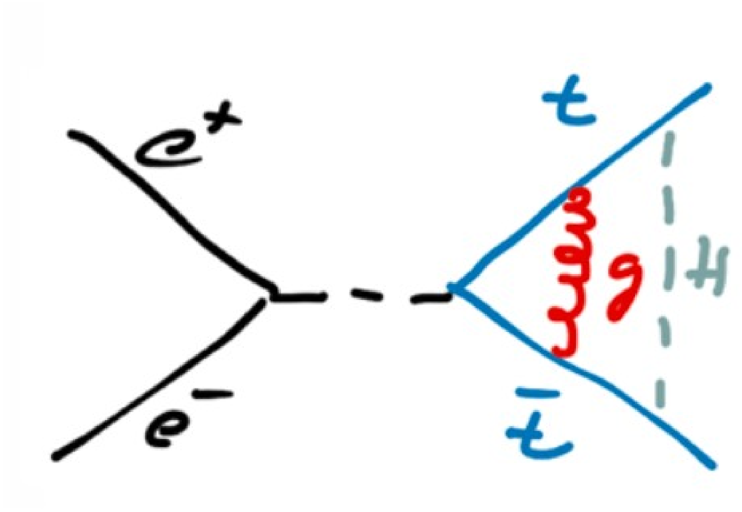
Upshot: New particles are maybe not many TeV away but in LC reach

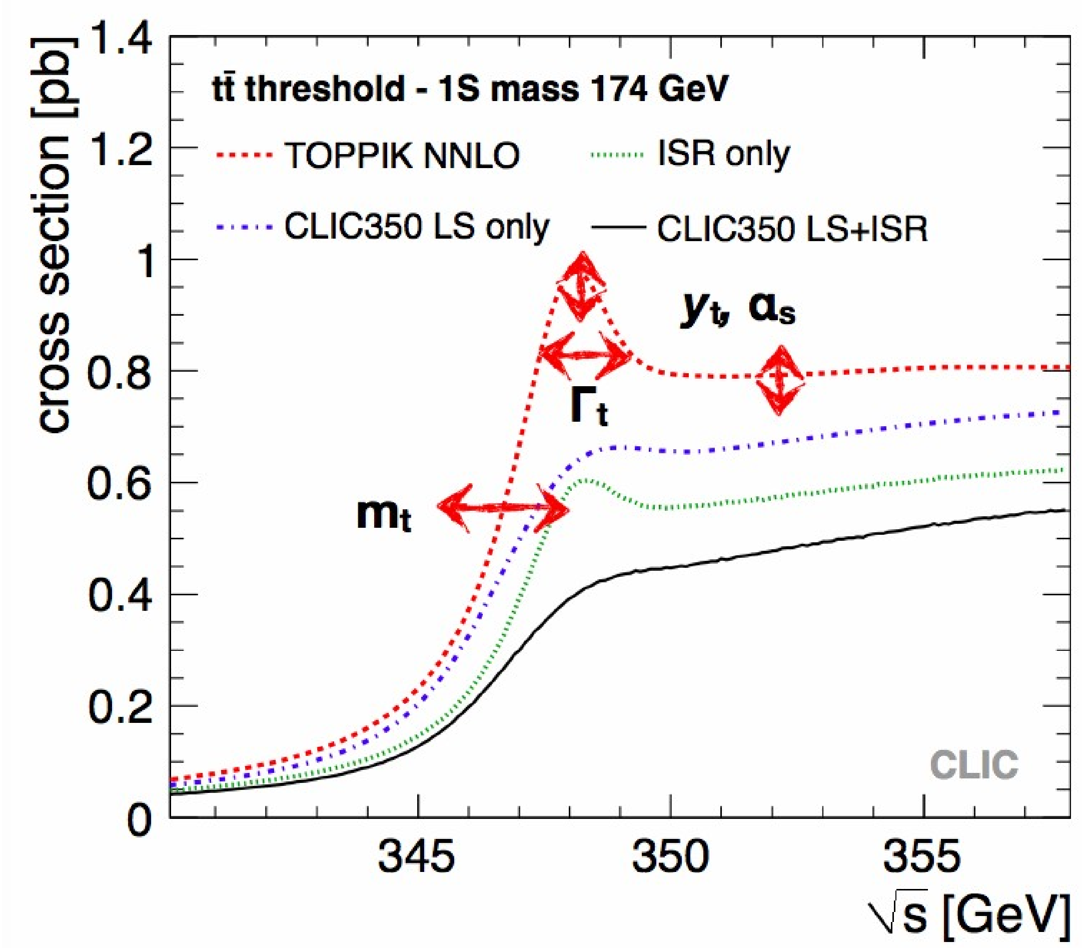
Top pair production at threshold

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

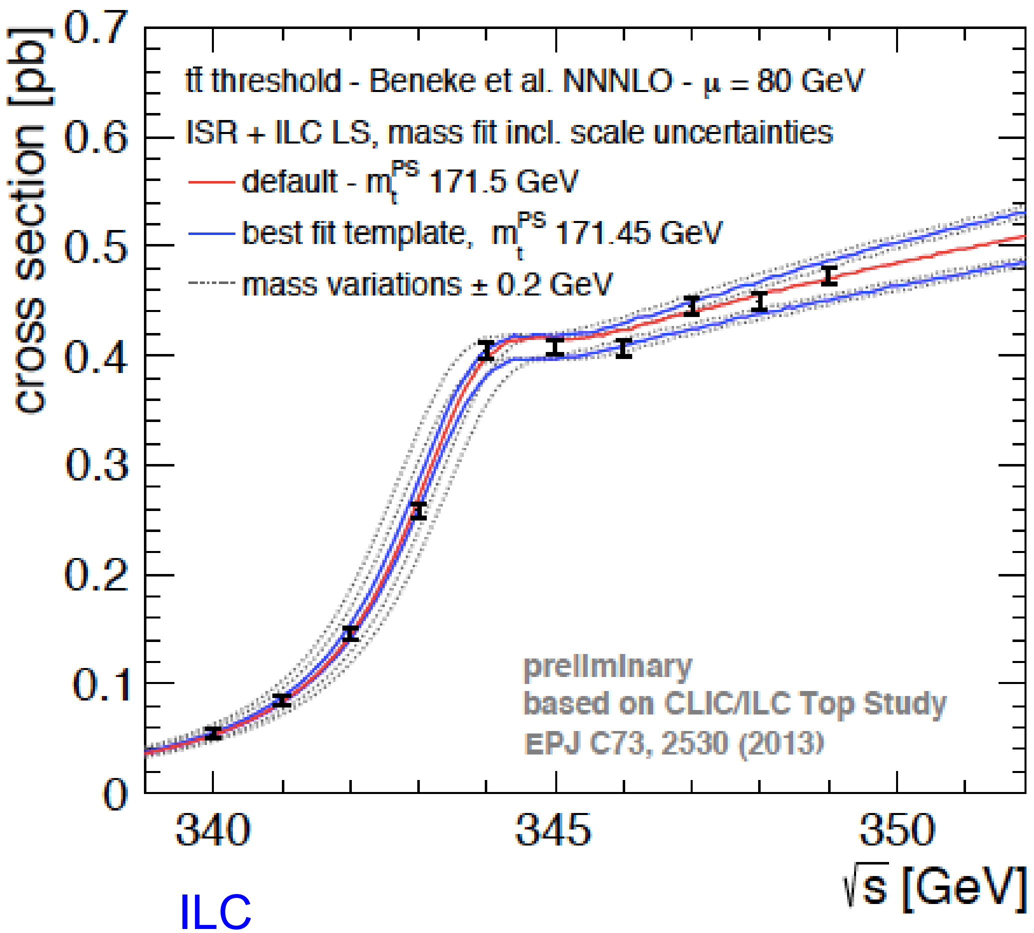
- Top mass, width Yukawa coupling
- Strong coupling constant





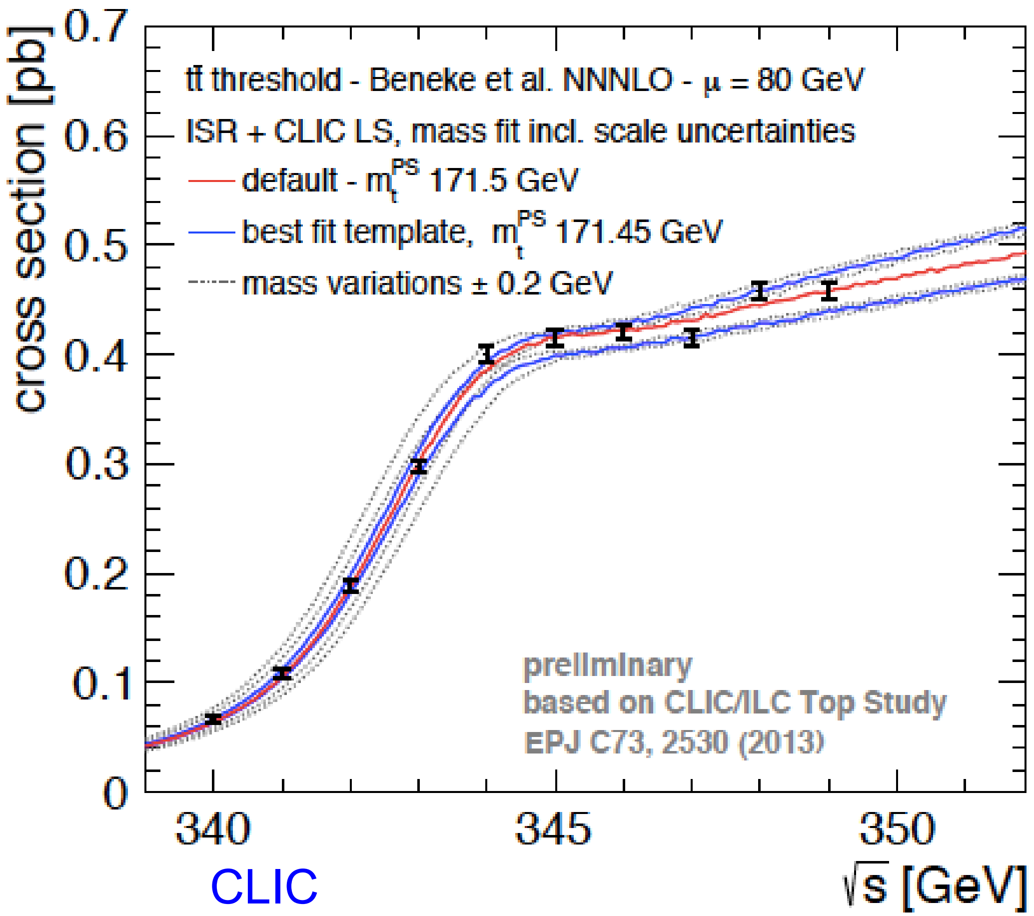
- Effects of some parameters are correlated:
- Dependence on Yukawa coupling rather weak,
- Precise external α_s helps

Top threshold scans at different e+e- colliders



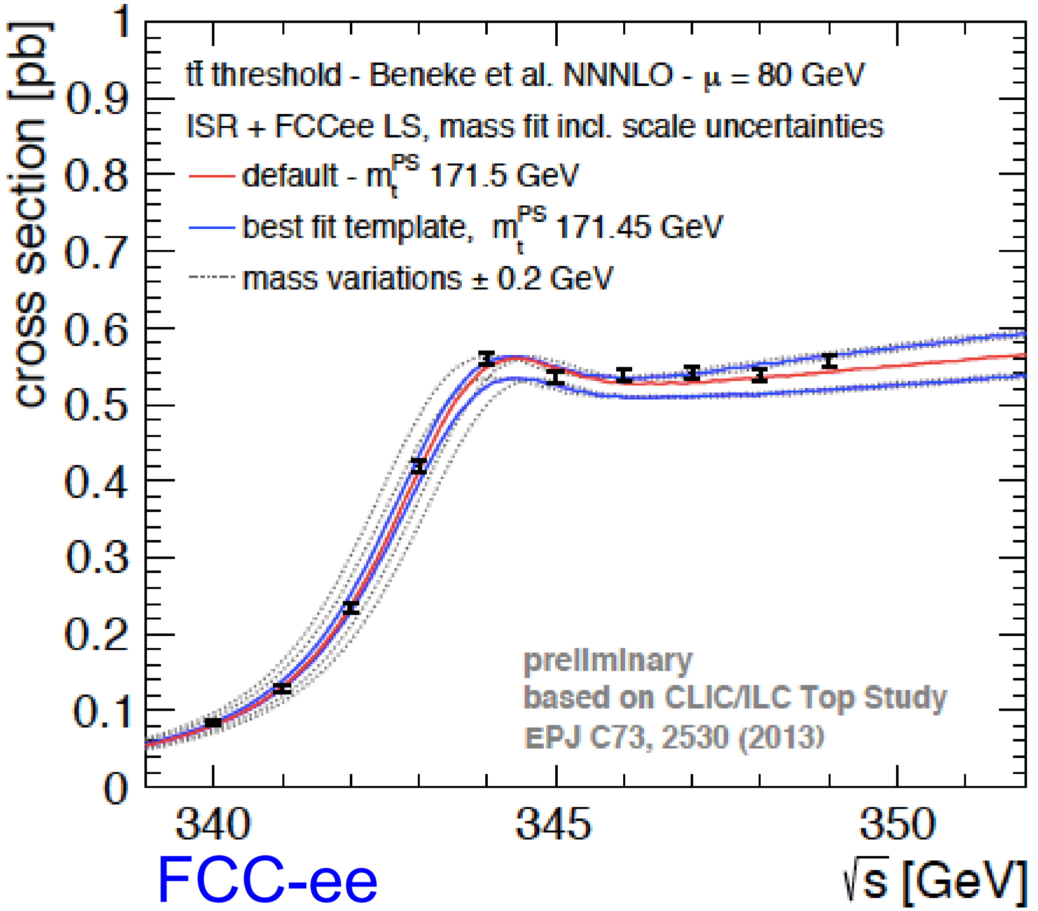
ILC

Fit uncertainty:
28.5 MeV (18 MeV stat)



CLIC

Fit uncertainty:
31 MeV (21 MeV stat)

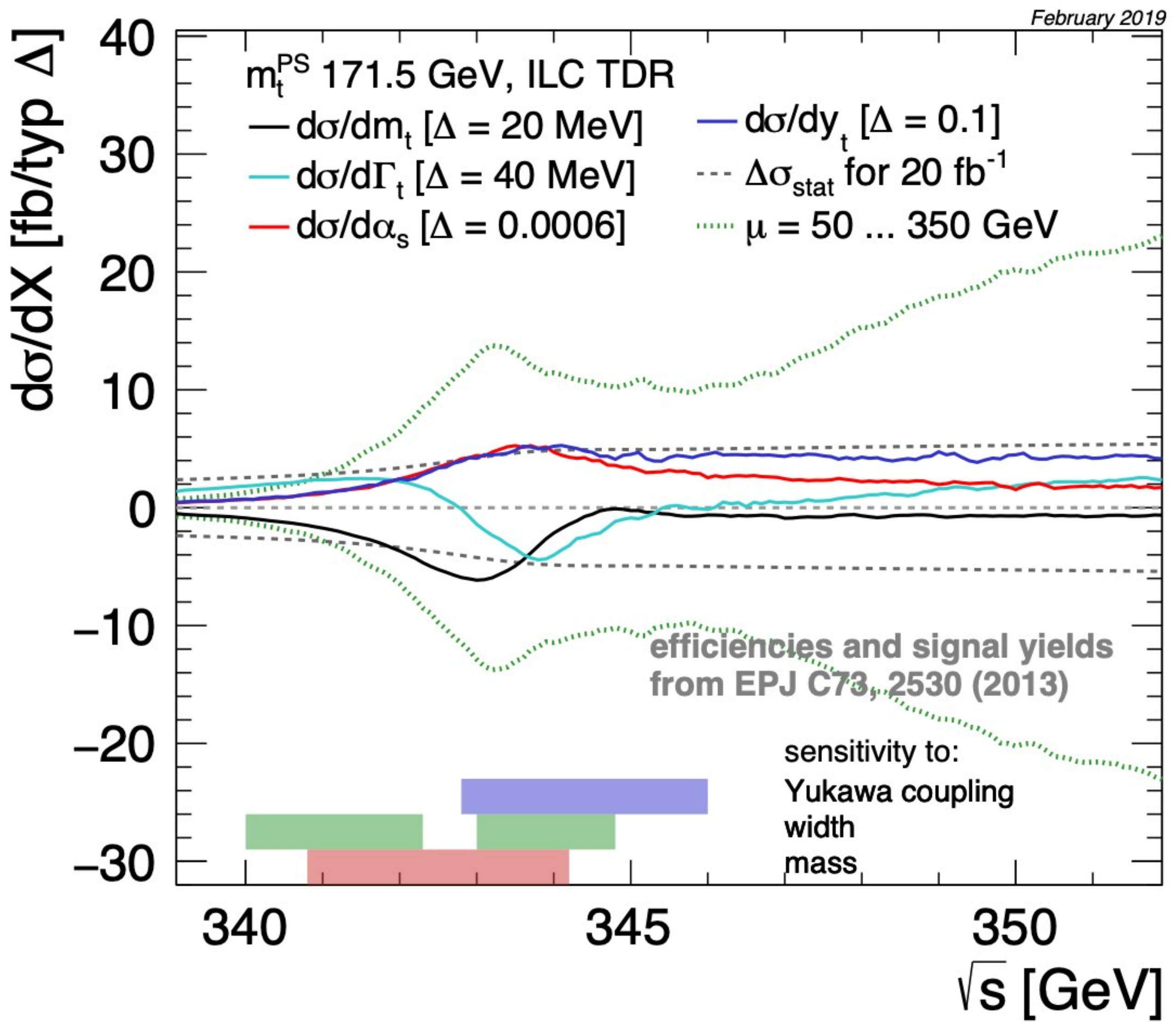


FCC-ee

Fit uncertainty:
27 MeV (15 MeV stat)

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

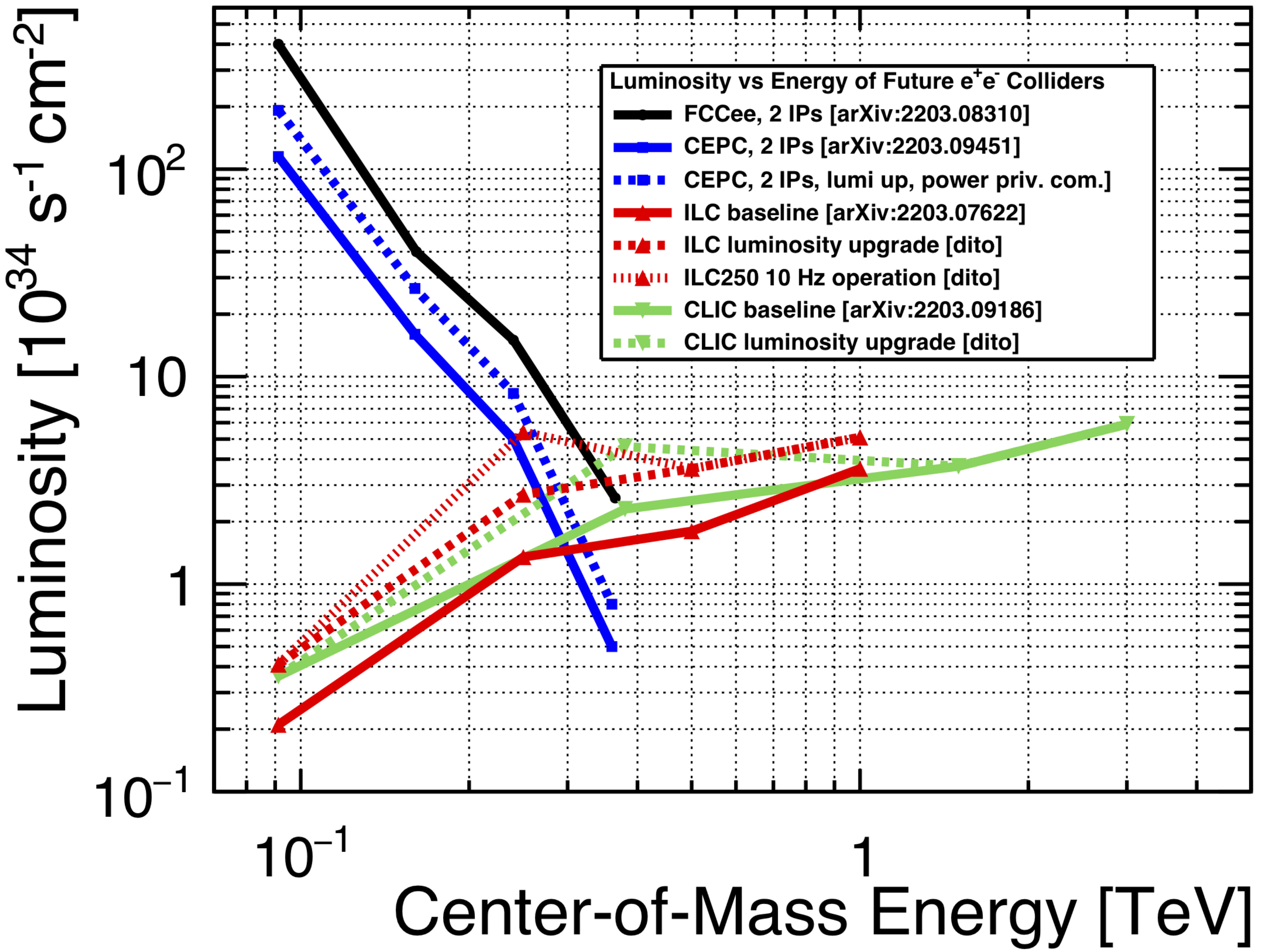
Sensitivity and error breakdown



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

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, ...

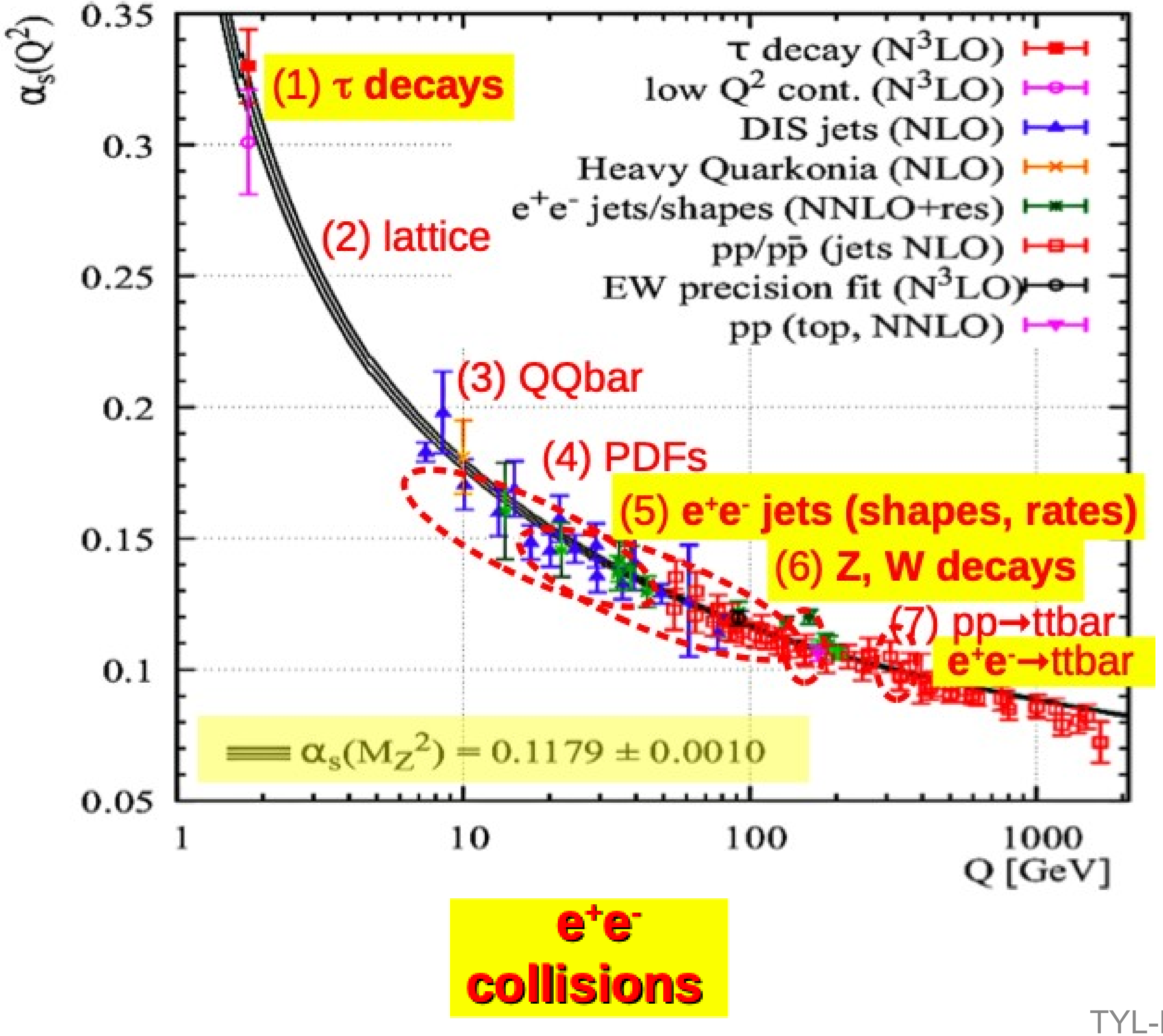
Transition region, i.e. HZ threshold
Comparable Higgs Couplings uncertainties for all proposals (see later)

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

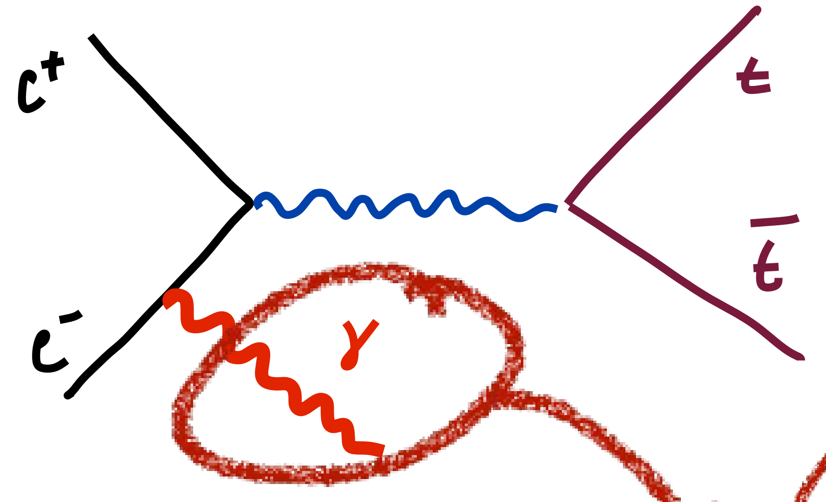
Uncertainty driver α_s



- 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 ?!

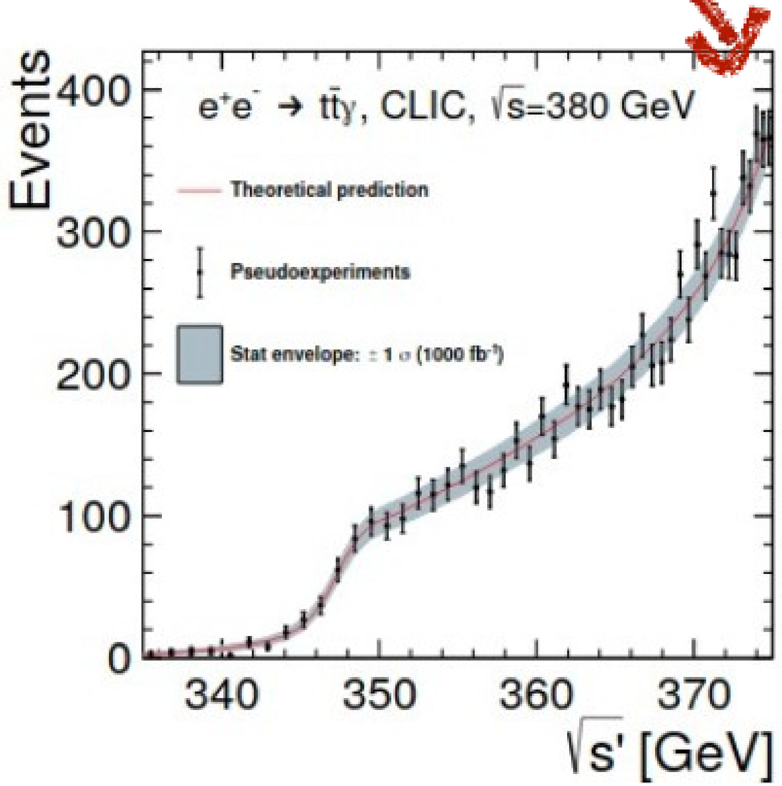
Running top mass

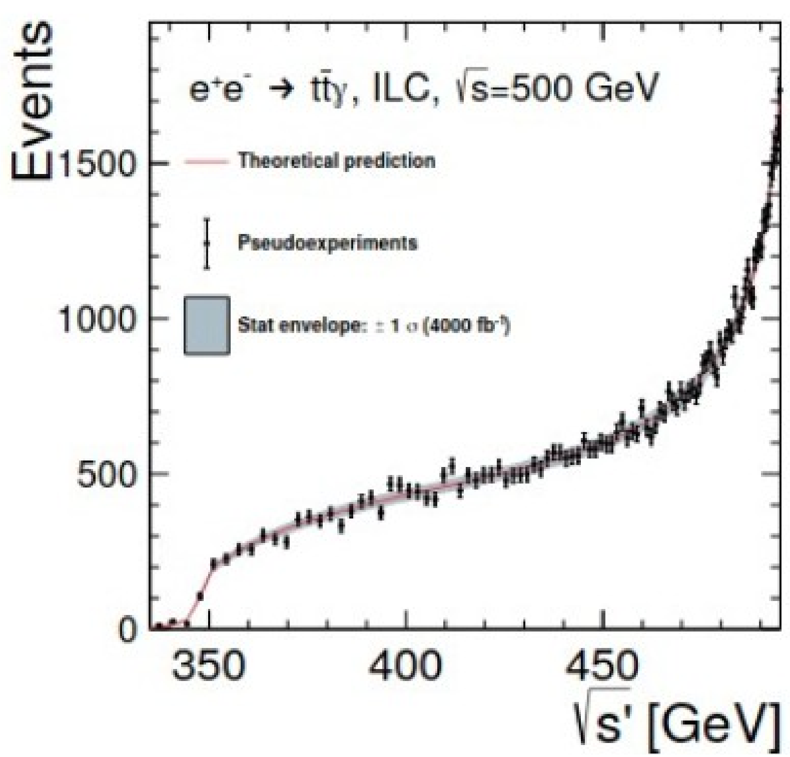
- A new(er) idea to measure the top mass in a theoretically well-defined scheme in high-energy running above the threshold



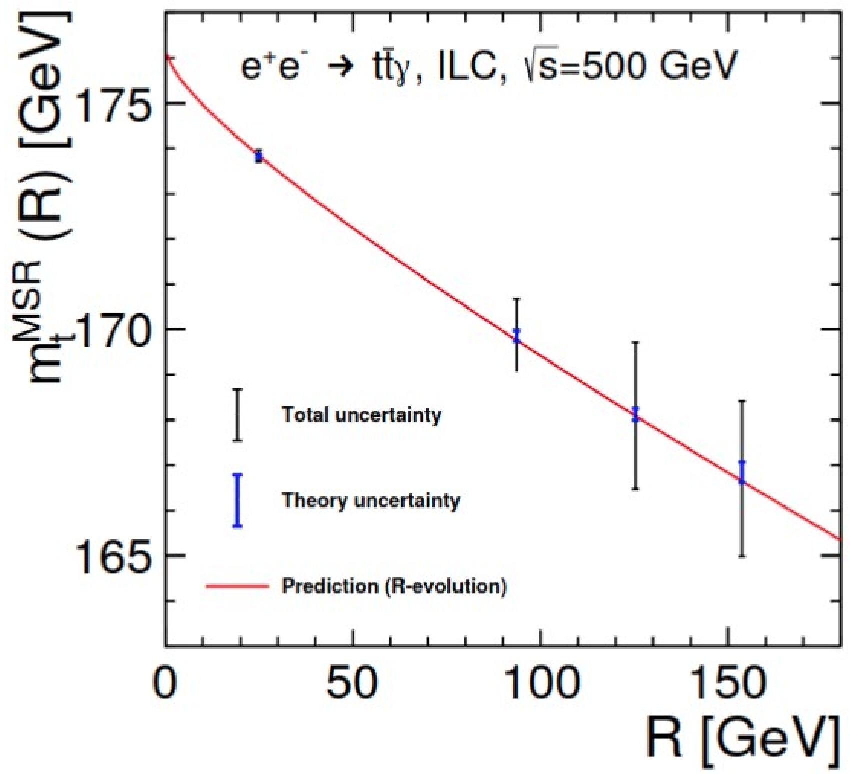
cms energy	CLIC, $\sqrt{s} = 380$ GeV		ILC, $\sqrt{s} = 500$ GeV	
luminosity [fb^{-1}]	500	1000	500	4000
statistical	140 MeV	90 MeV	350 MeV	110 MeV
theory	46 MeV		55 MeV	
lum. spectrum	20 MeV		20 MeV	
photon response	16 MeV		85 MeV	
total	150 MeV	110 MeV	360 MeV	150 MeV

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



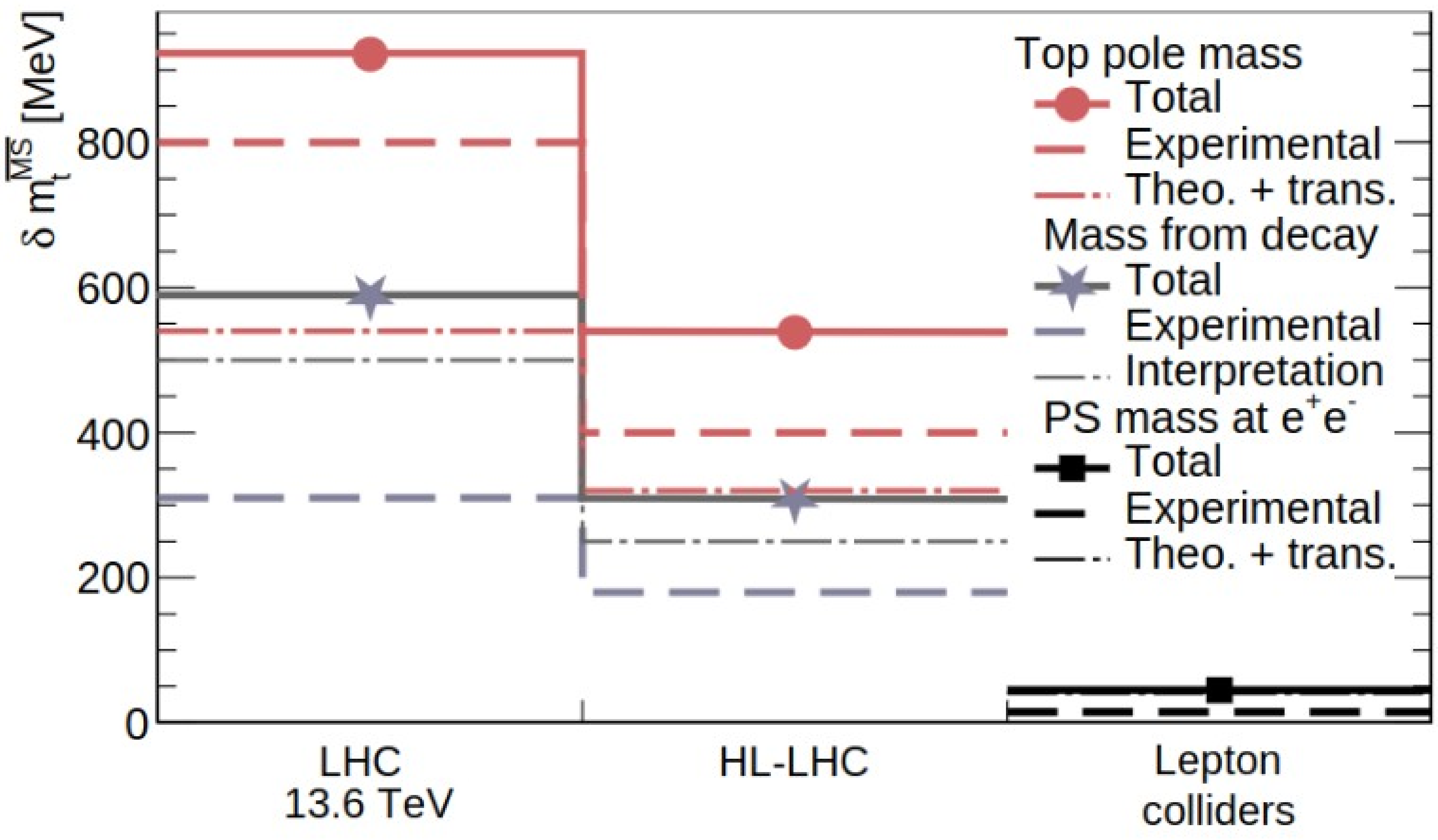


can provide 5σ evidence for scale evolution ("running") of the top quark MSR mass from ILC500 data alone



Top mass summary

Snowmass report, arXiv:2209.11267

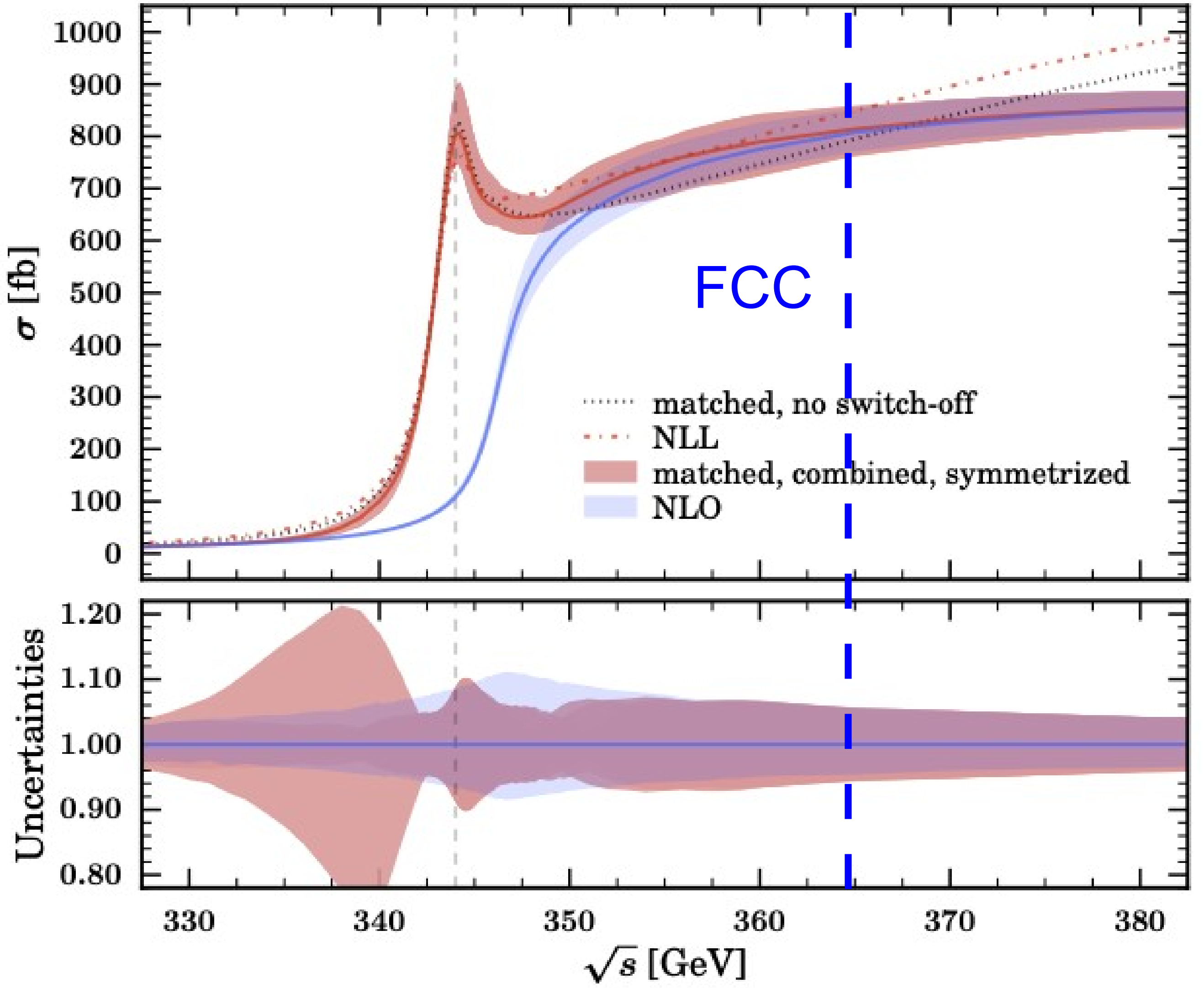


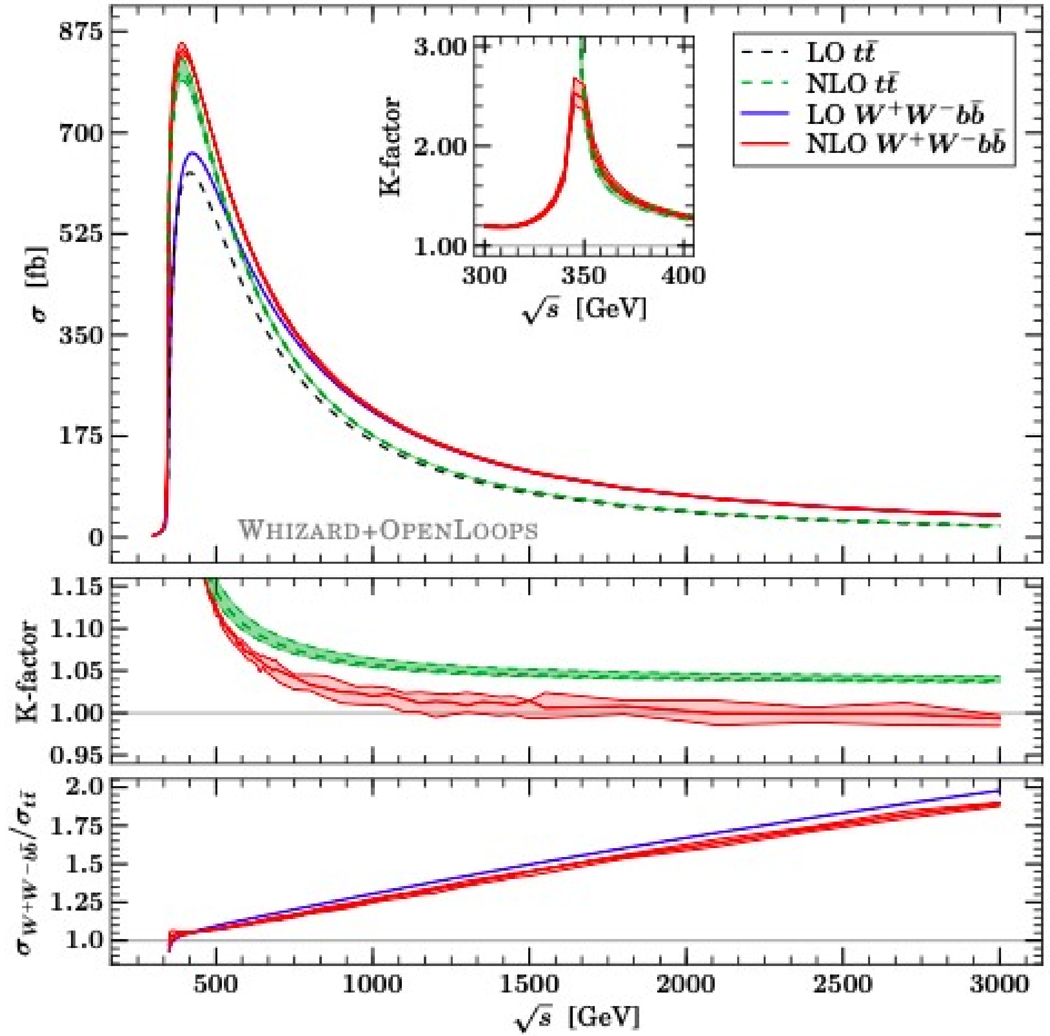
Marcel Vos@Top23

QCD uncertainties on ee->tt cross section

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

Linear Colliders

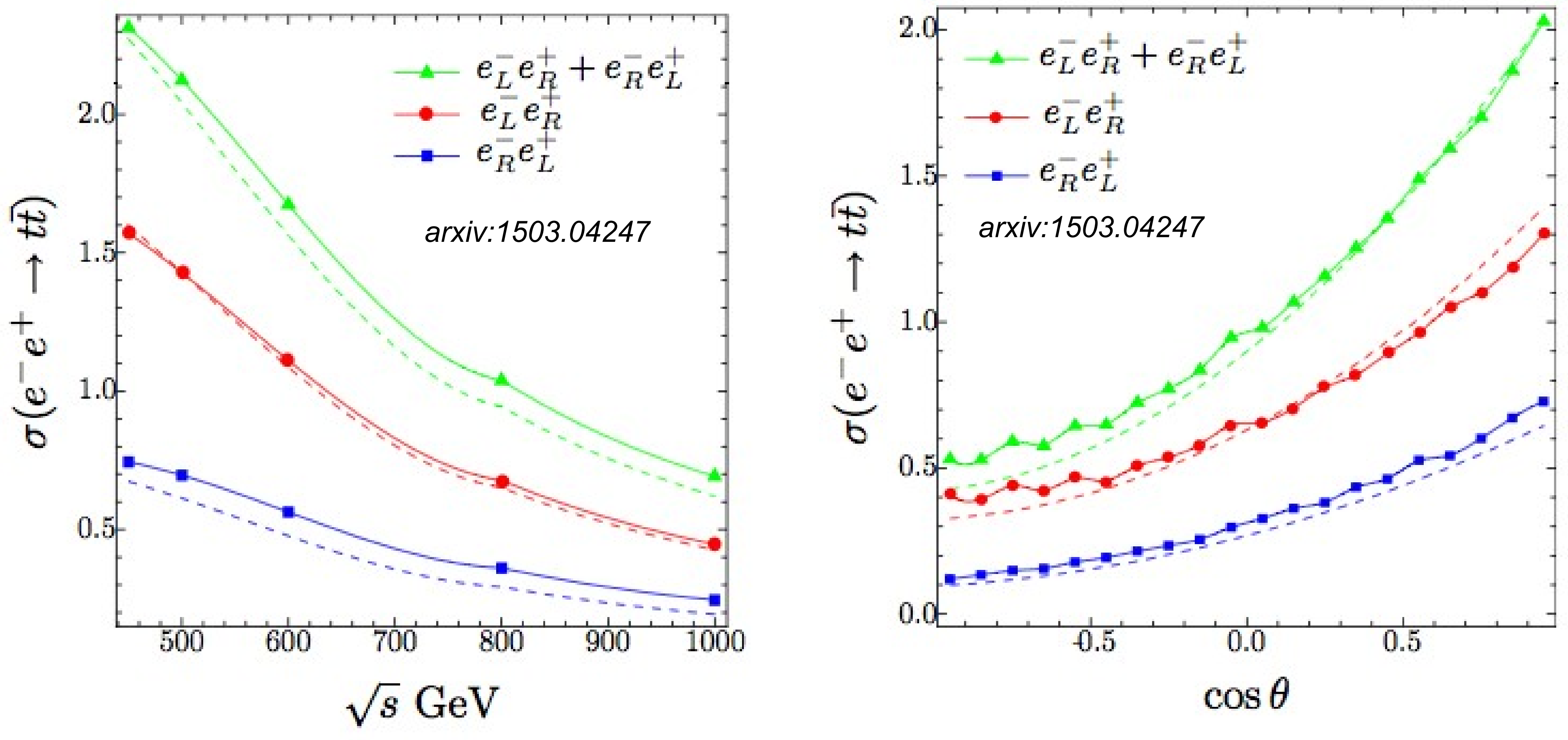




- Marching non-relativistic calculations in threshold region with tt-continuum is theoretical challenge
- QCD uncertainties shrink as energy increases
- Non resonant contributions are important (i.e. ee->tt --> ee->WbWb)

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

High Order Electroweak Corrections



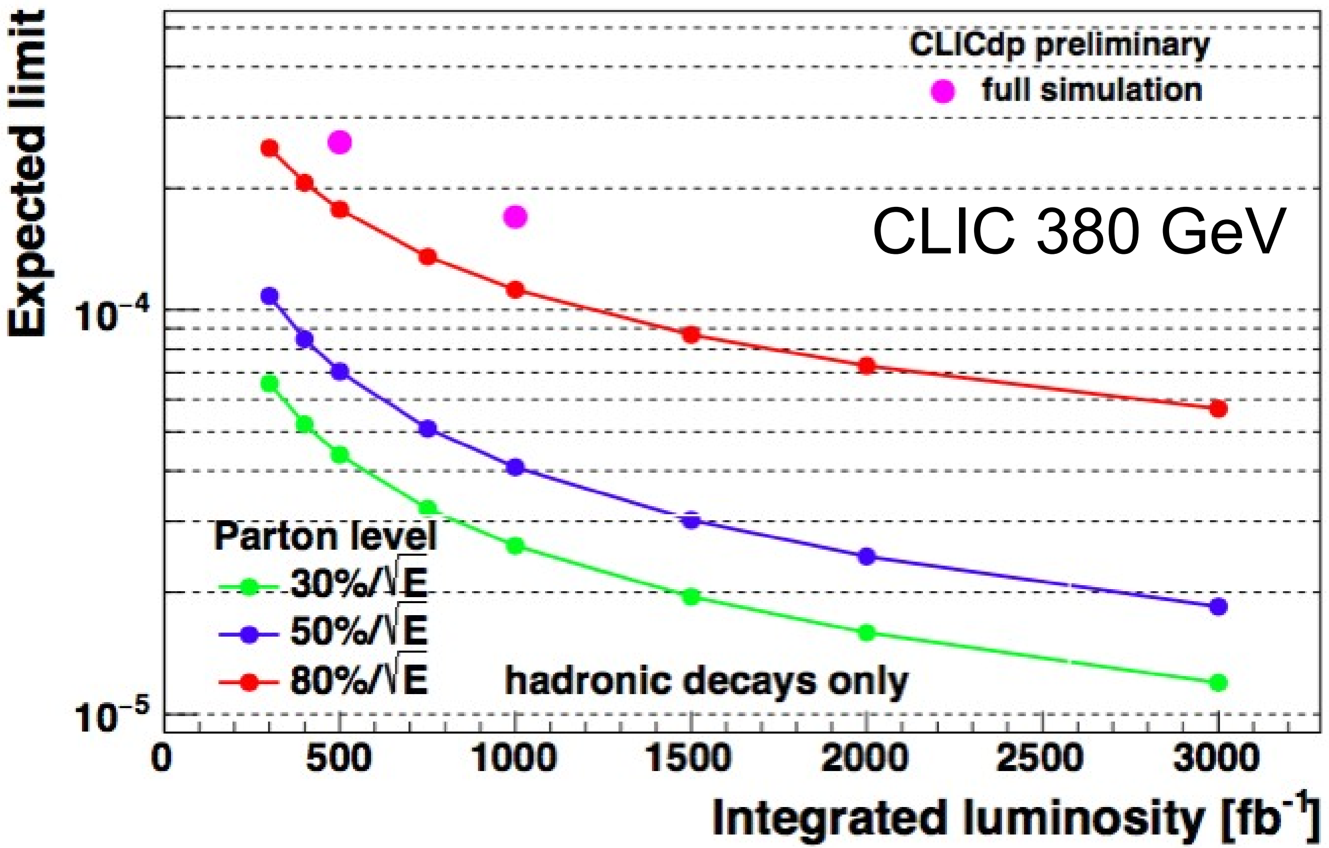
- Electroweak corrections manifest themselves differently for different beam polarisations

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

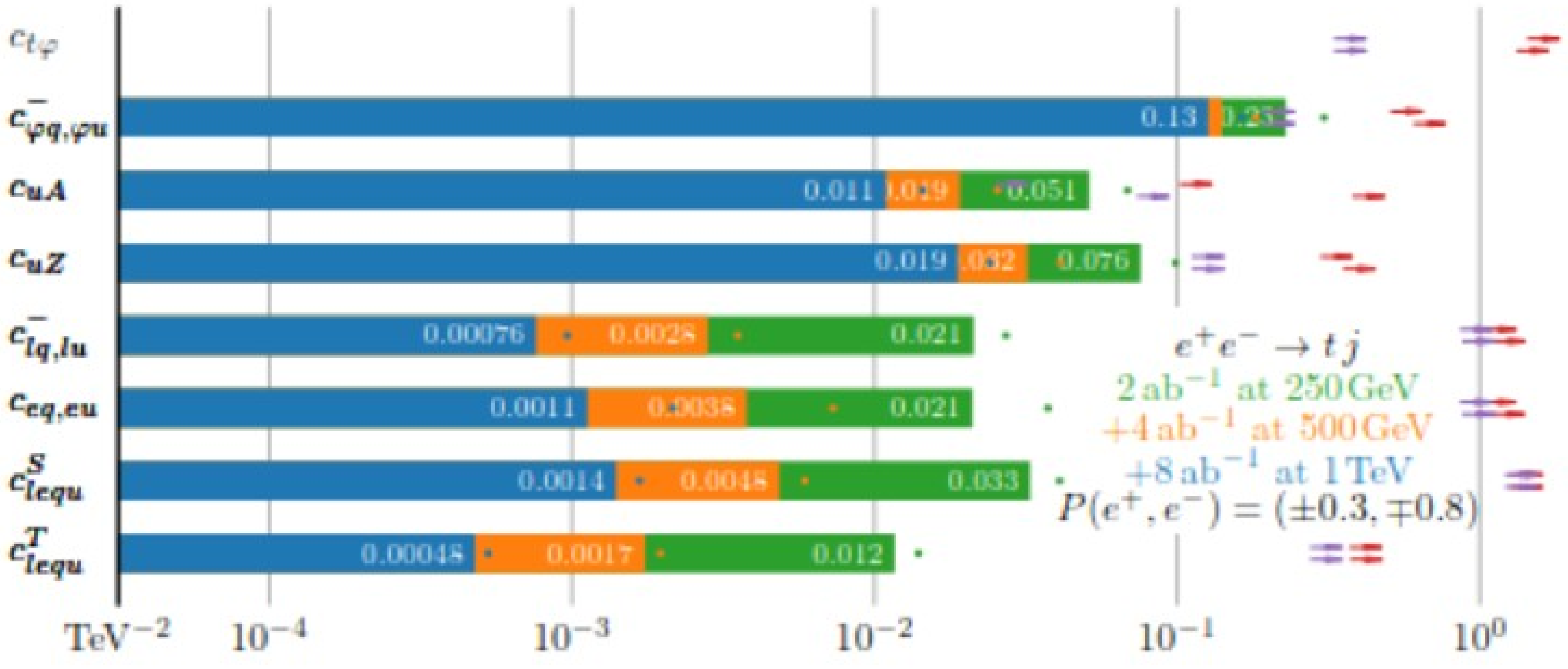
Top exotic decays 2

Lepton collider is both competitive and complementary

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

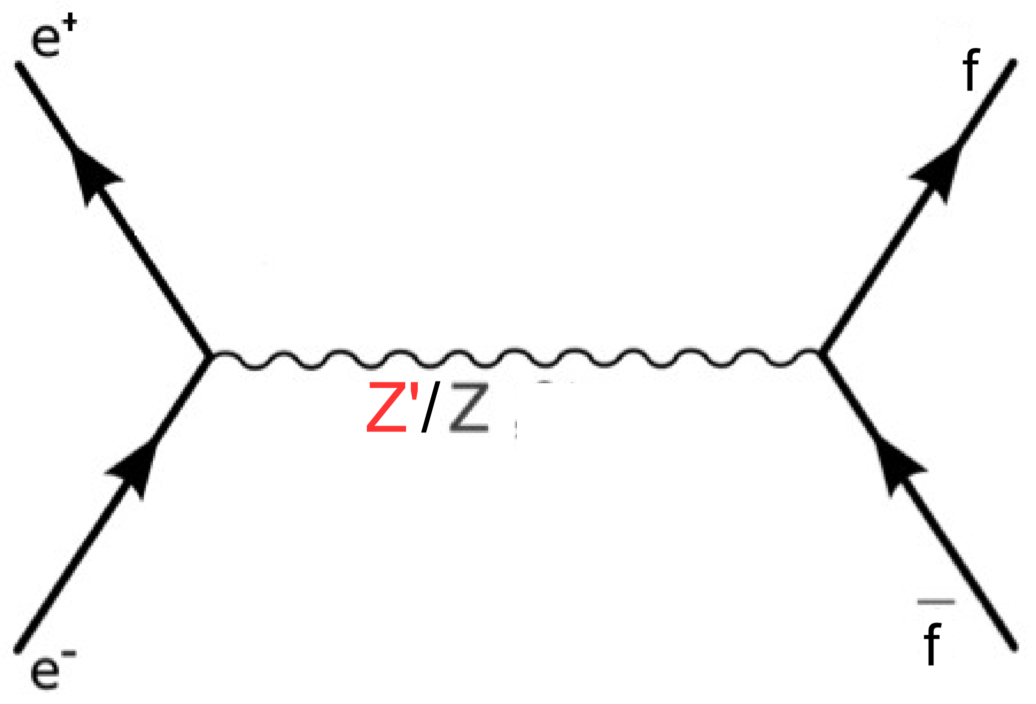
More full-simulation work needed!

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

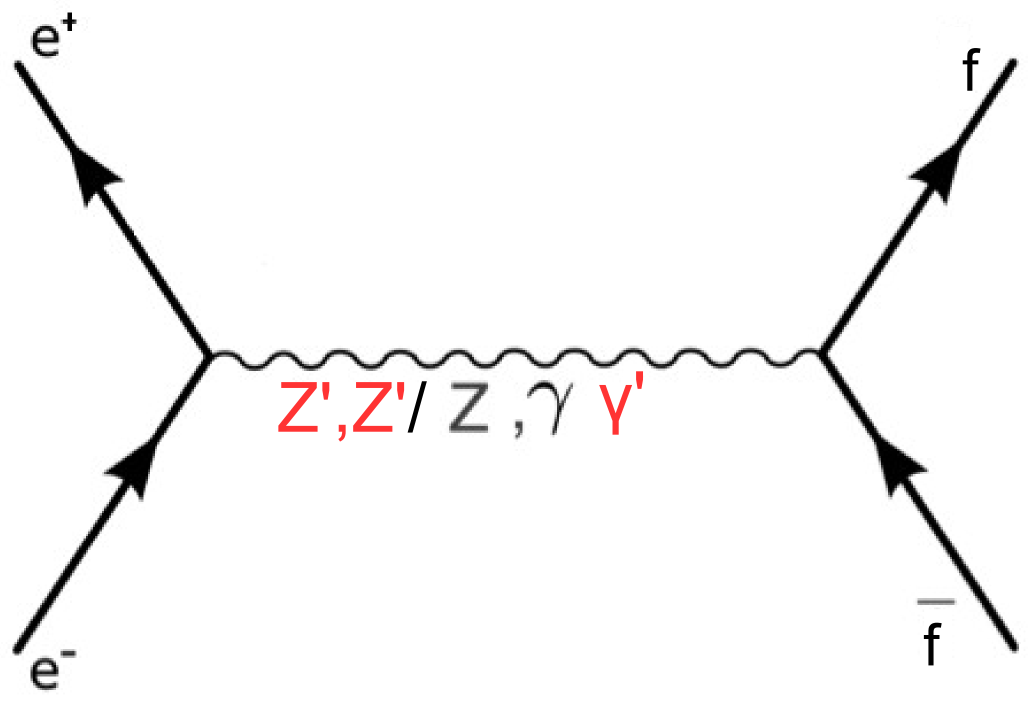


Two fermion production: Z-Pole and higher energies

On the Z-pole



Above the Z-pole

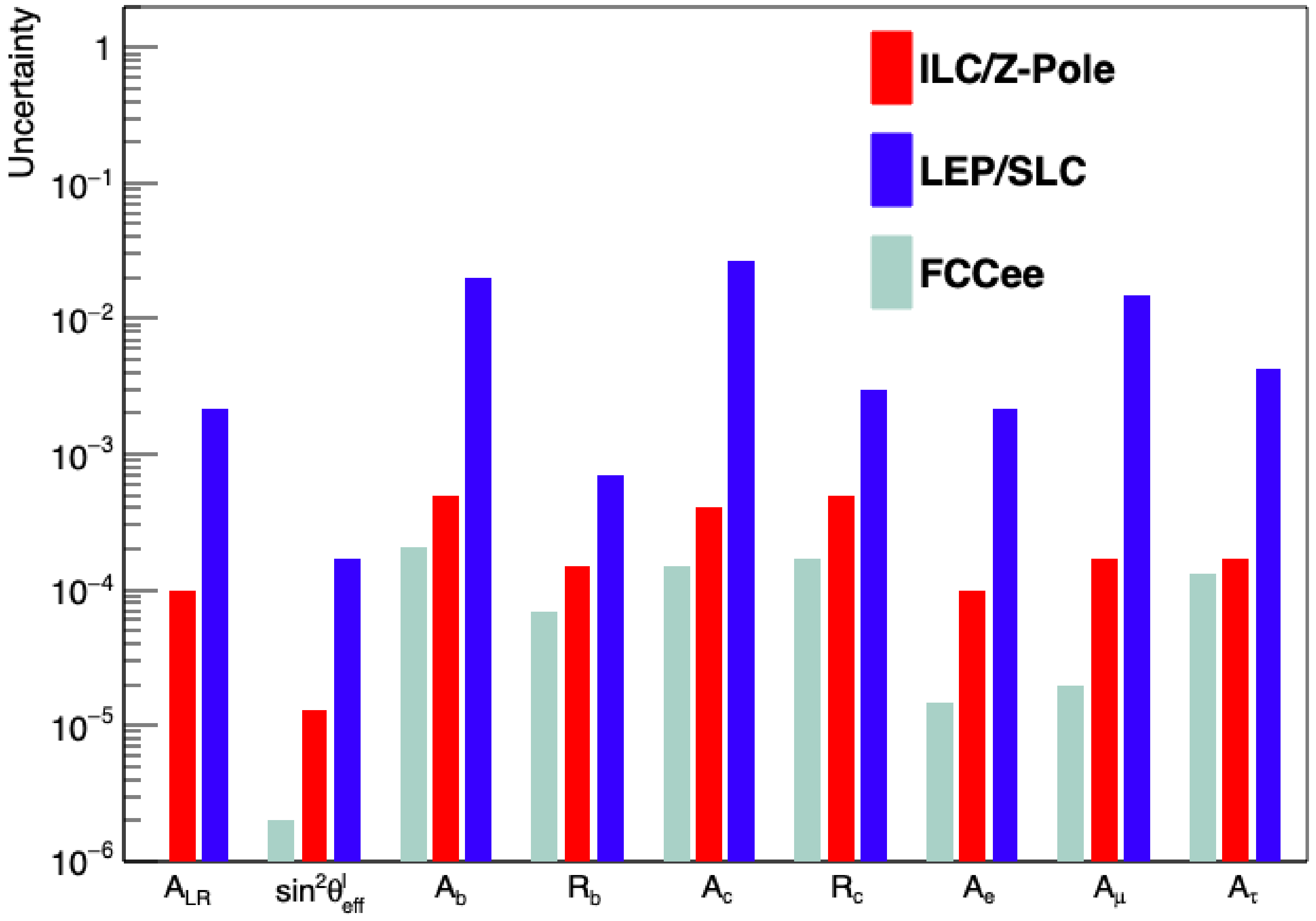


Sensitivity to Z/Z' mixing
Sensitivity to vector (and tensor) couplings of the Z

- 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?



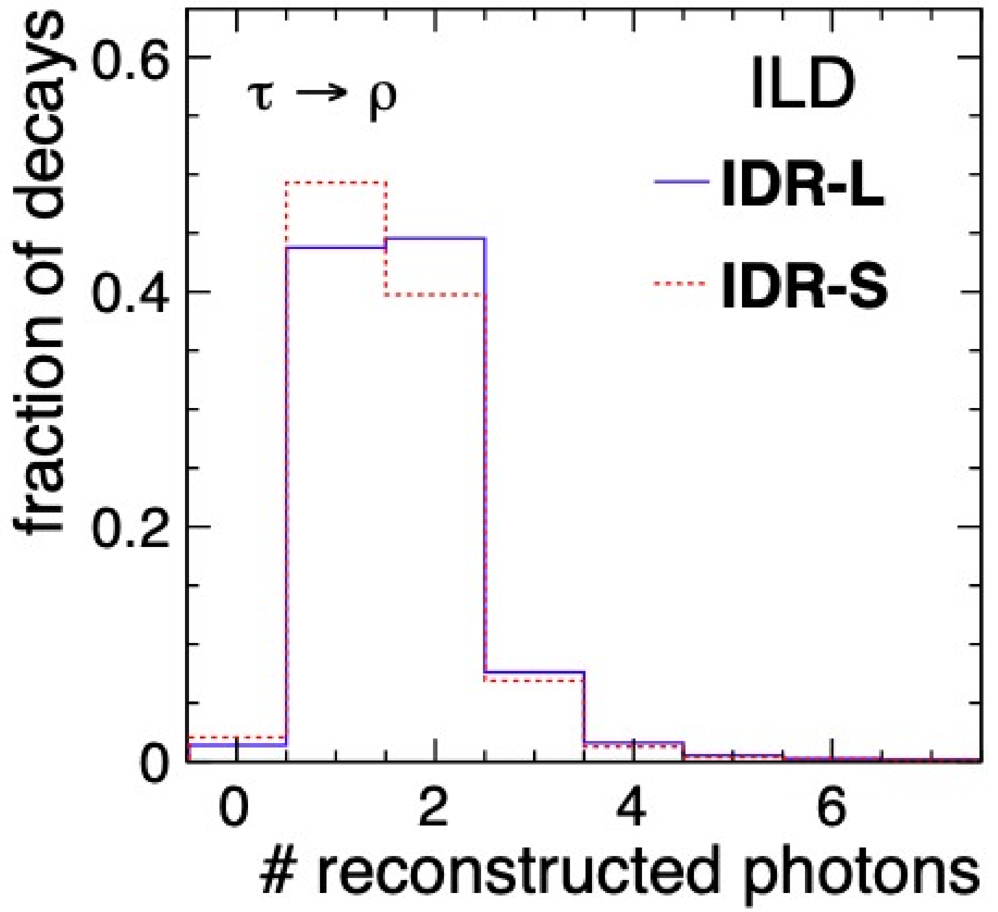
Numbers FCCee: "Mixture" of FCC CDR and
P. Janot at Precision Workshop/CERN
https://indico.cern.ch/event/1140580/timetable/

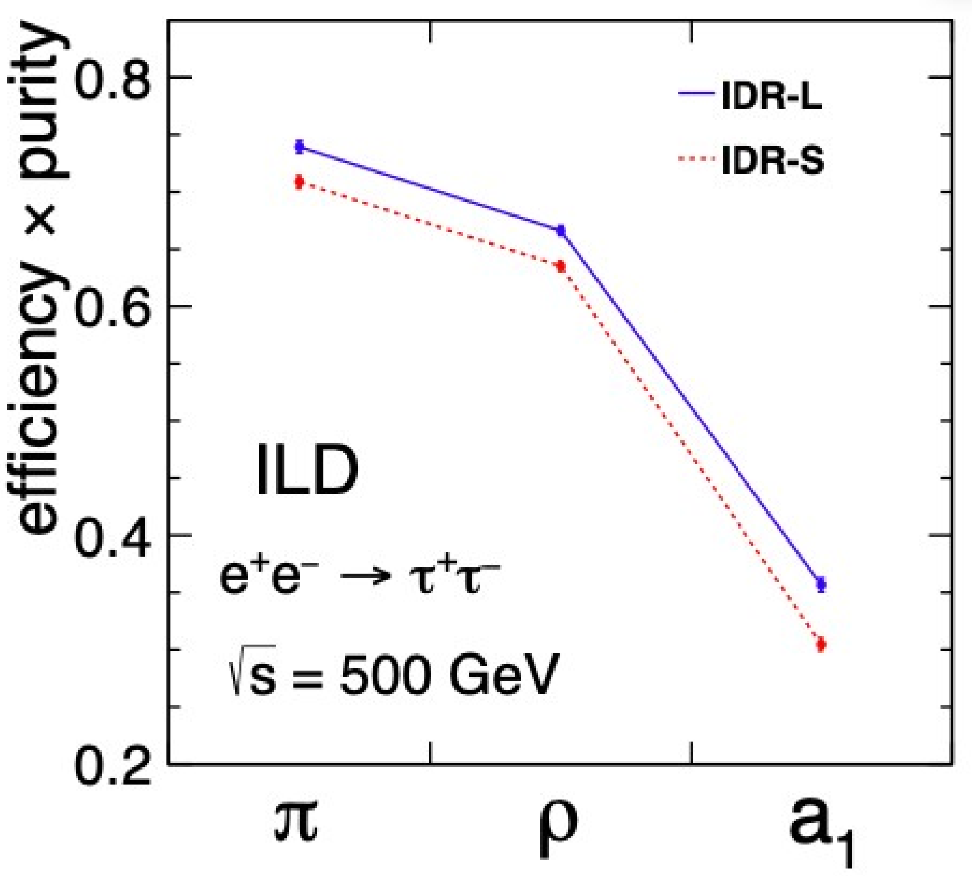
Numbers ILC: arxiv: 2203.07622 (ILC Snowmsss report)

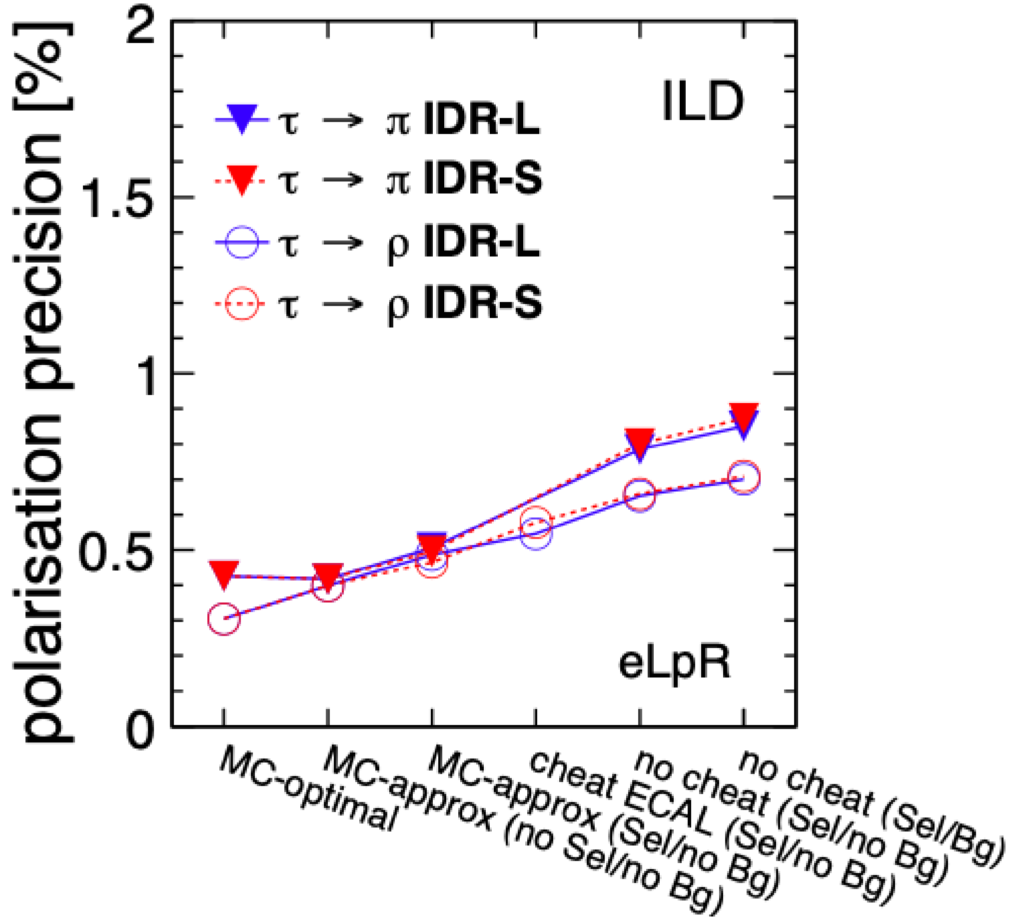
- All future colliders will improve significantly precision compared with LEP/SLC
- Comparable precisions despite differences in luminosity
  - Systematics will play a major role
- **No full simulation study exists on Z-Pole**
  - Most of the results (educated) guesses on experimental issues by extrapolations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

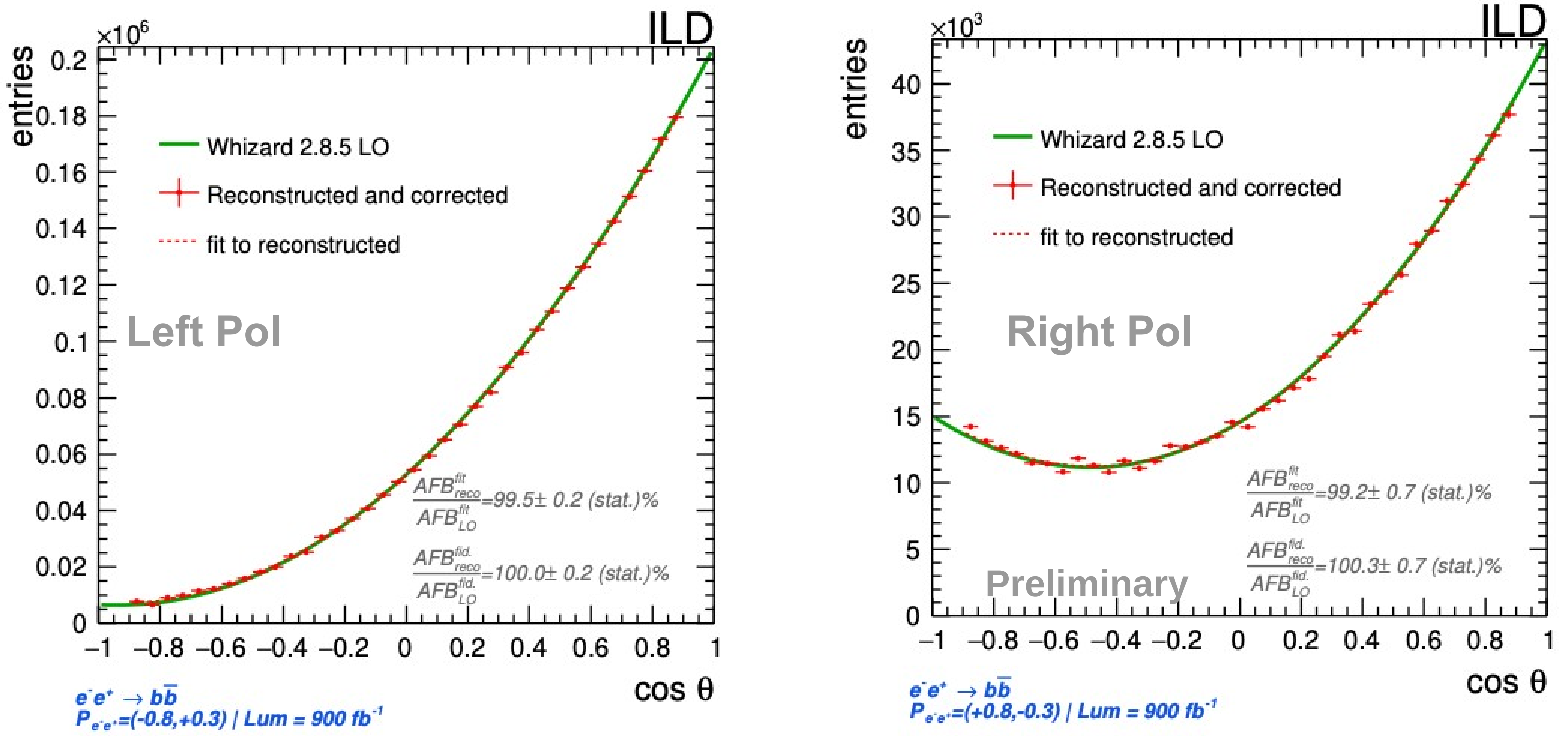
EfficiencyxPurity drops with increasing photon multiplicity

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

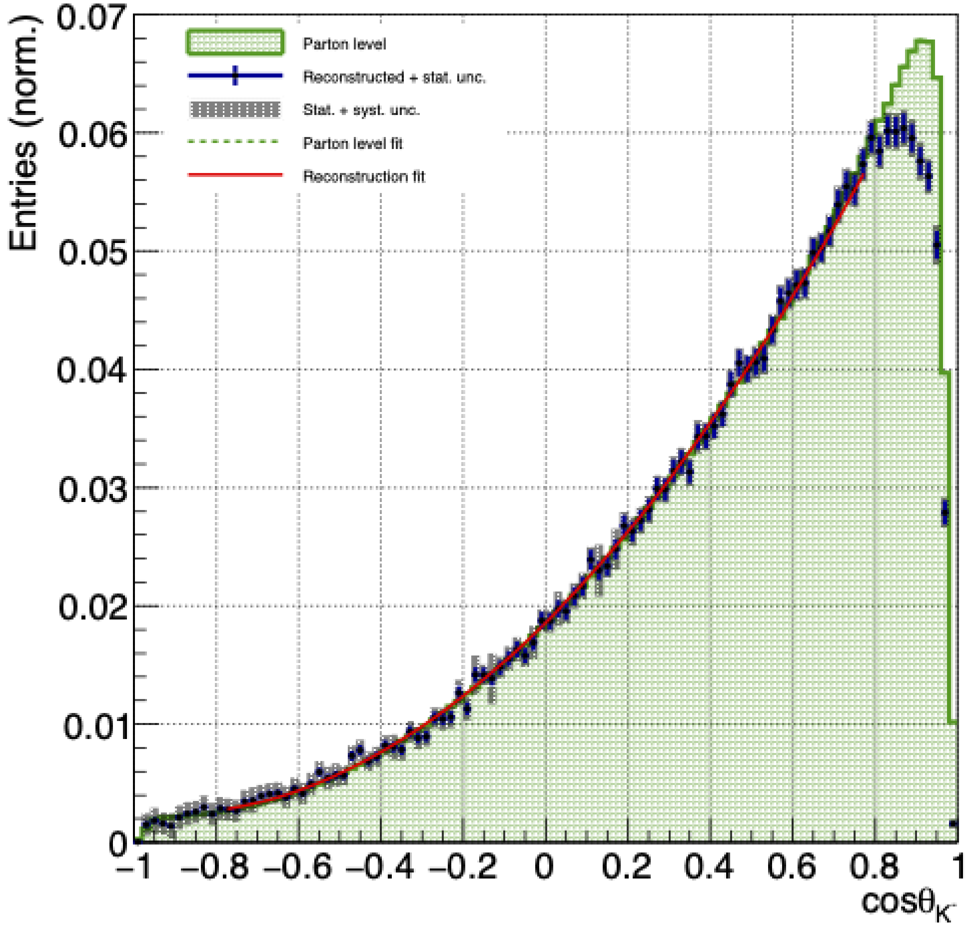
Source	$e^-e^+ \to c\bar{c}$				$e^-e^+ \to b\bar{b}$			
	$P_{e^-e^+}(-0.8,+0.3)$		$P_{e^-e^+}(+0.8,-0.3)$		$P_{e^-e^+}(-0.8,+0.3)$		$P_{e^-e^+}(+0.8,-0.3)$	
	R_c	$A^{c\bar{c}}_{FB}$	R_c	$A^{c\bar{c}}_{FB}$	R_b	$A^{b\bar{b}}_{FB}$	R_b	$A^{b\bar{b}}_{FB}$
Statistics	**0.18%**	**0.38%**	**0.27%**	**0.52%**	**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%**

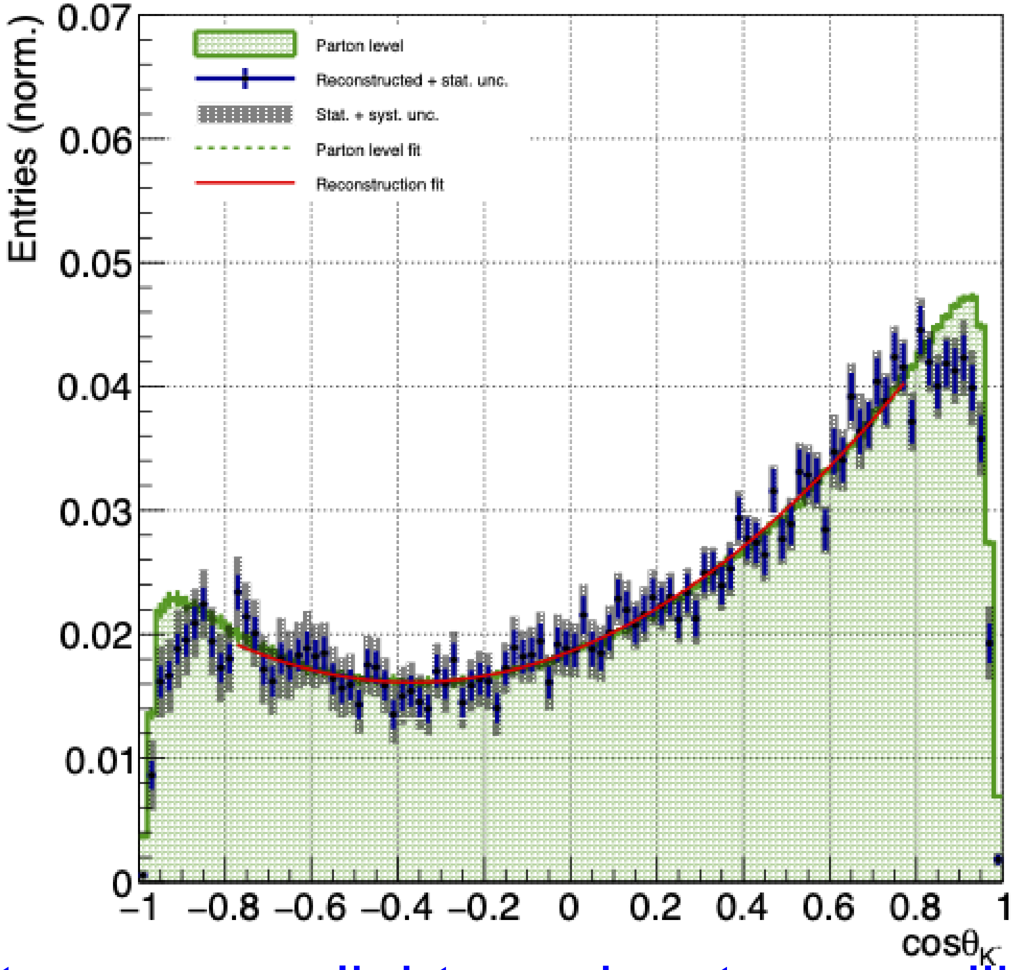
Additional complication in continuum compared with Z-Pole:
Rejection of ISR events

Light quarks at @ 250 GeV are in the making

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

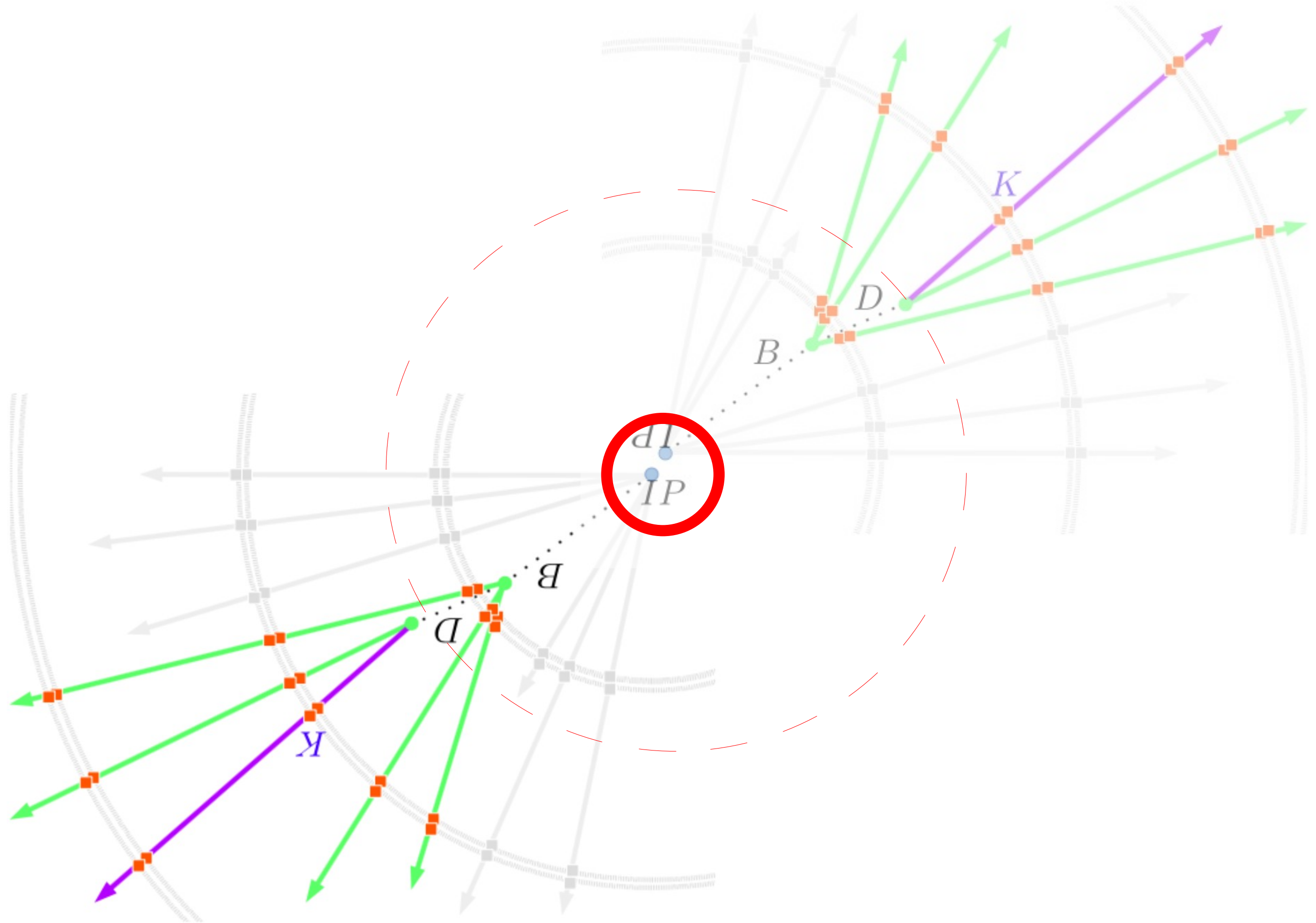
PhD thesis
Y. Okugawa





- 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”

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

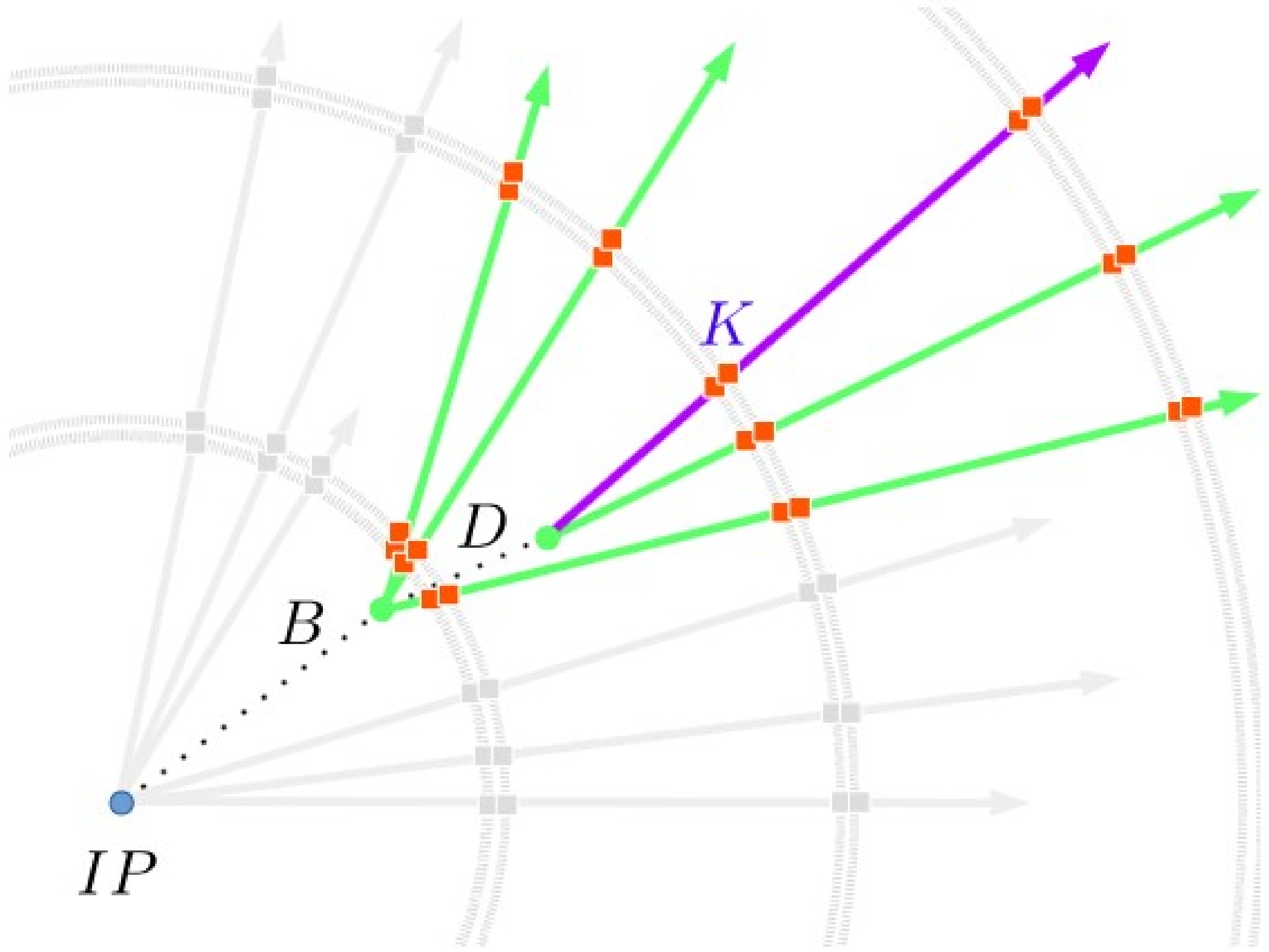
For example:

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

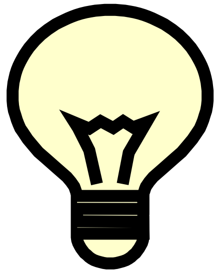
Experimental challenges - Flavor tagging and charge measurement



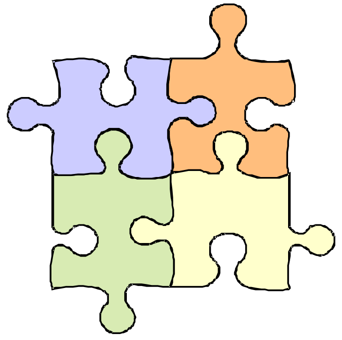
PhD thesis: S. Bilokin
A. Irles

- 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

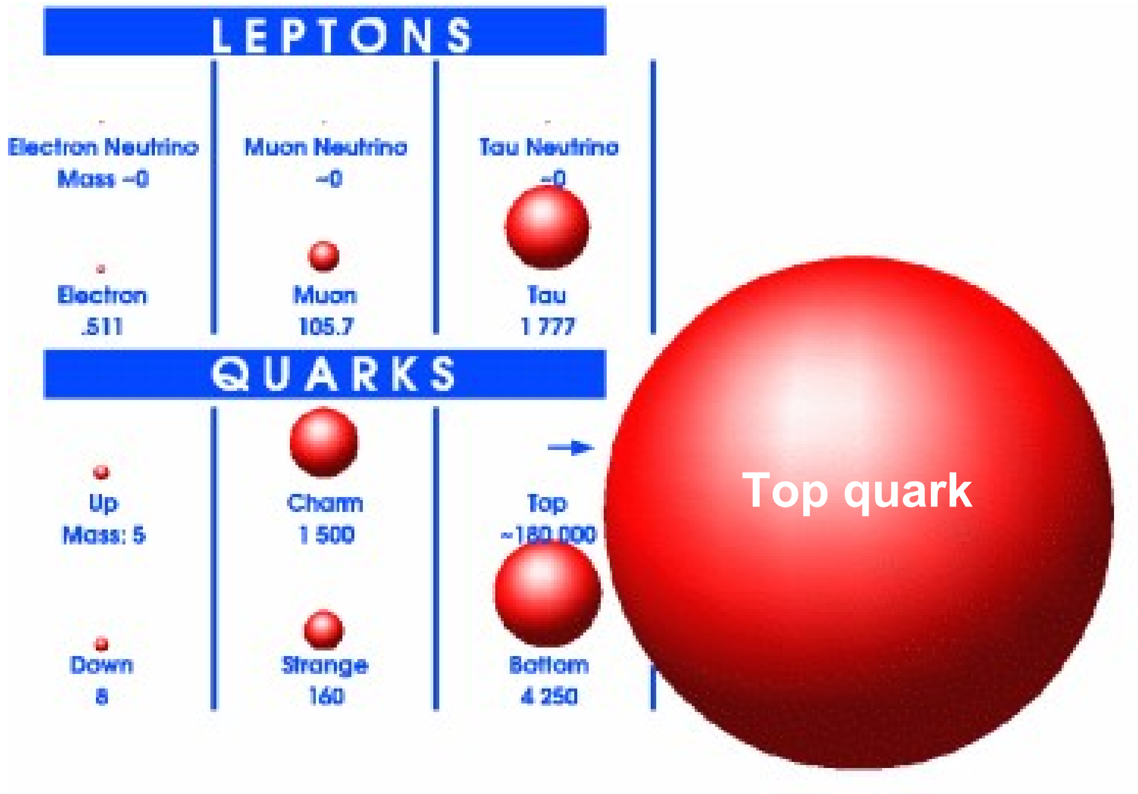
An enigmatic couple



Elementary Scalar?



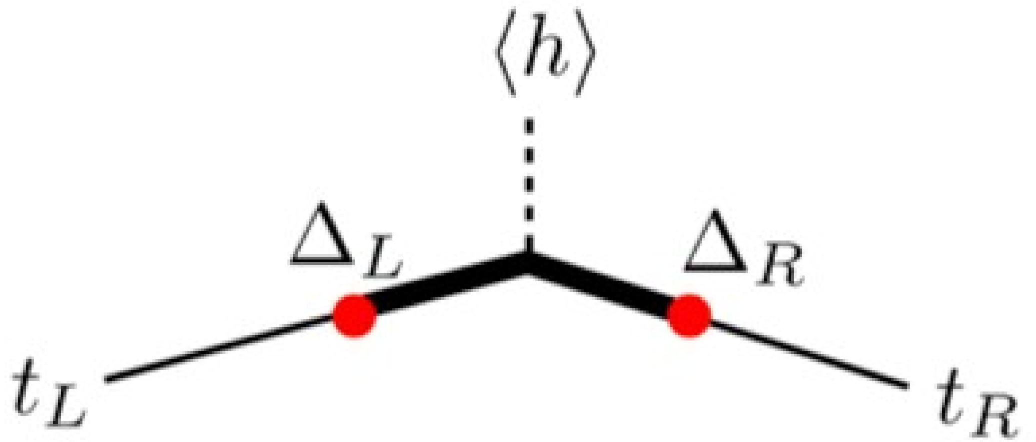
Composite object?



- 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

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

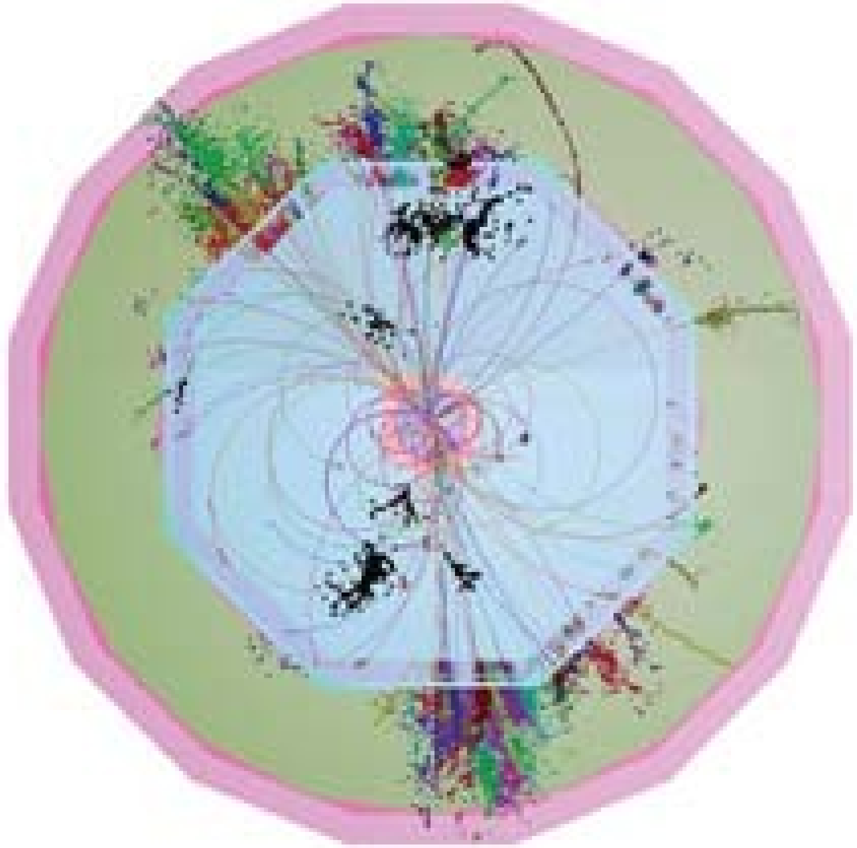
(Quark tagging c/b)

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