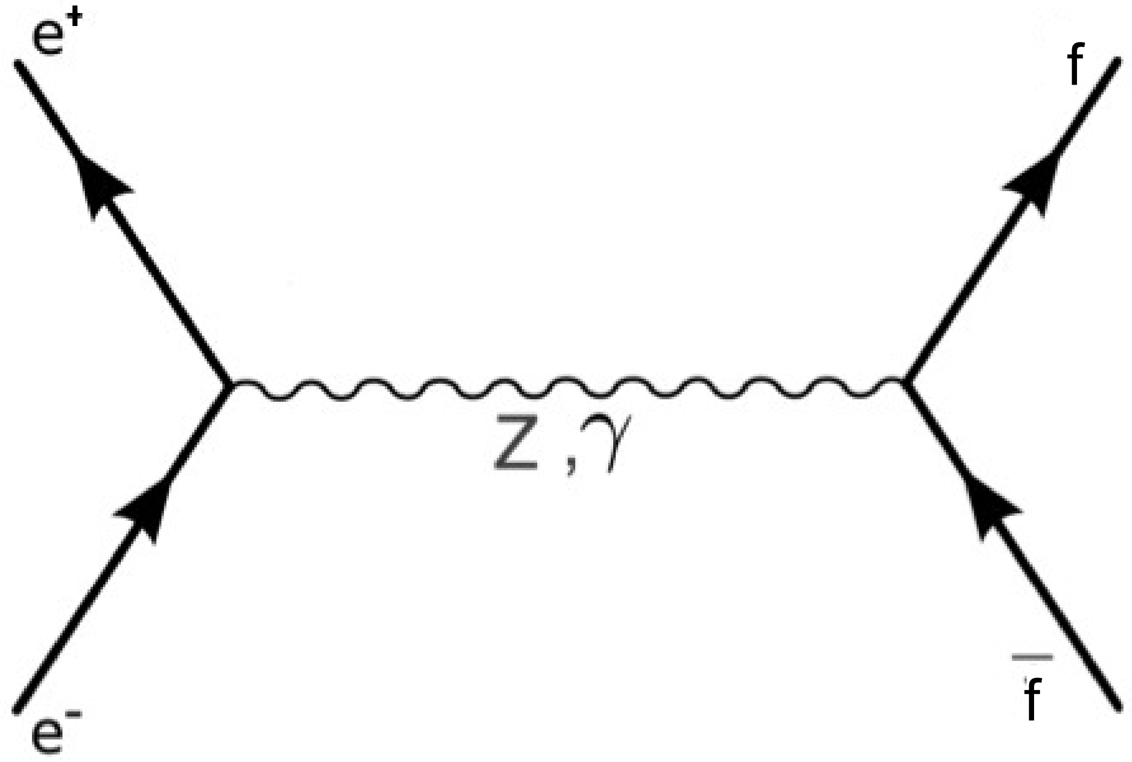
(Incomplete) assessment of focused topics identified in ECFA Study (two-fermions – top and its light siblings)

Roman Pöschl

IDT WG3 Open Physics Meeting January 2024

Got asked relatively lately to give this talk
–> I interpreted the charge very loosely
-> On several topics I am on very thin ice

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

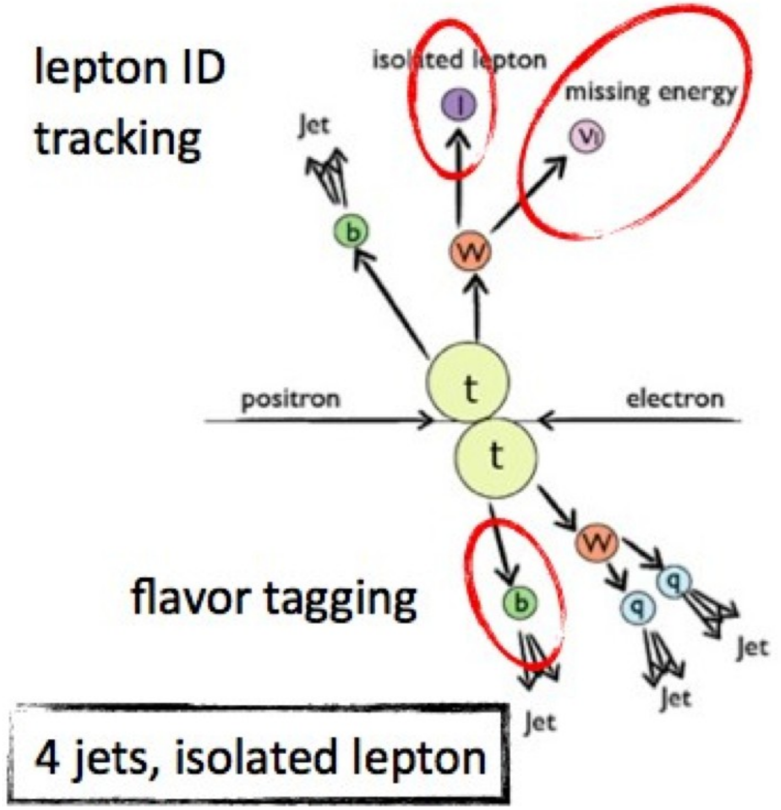
All four helicity amplitudes for all fermions **only available with polarised beams**

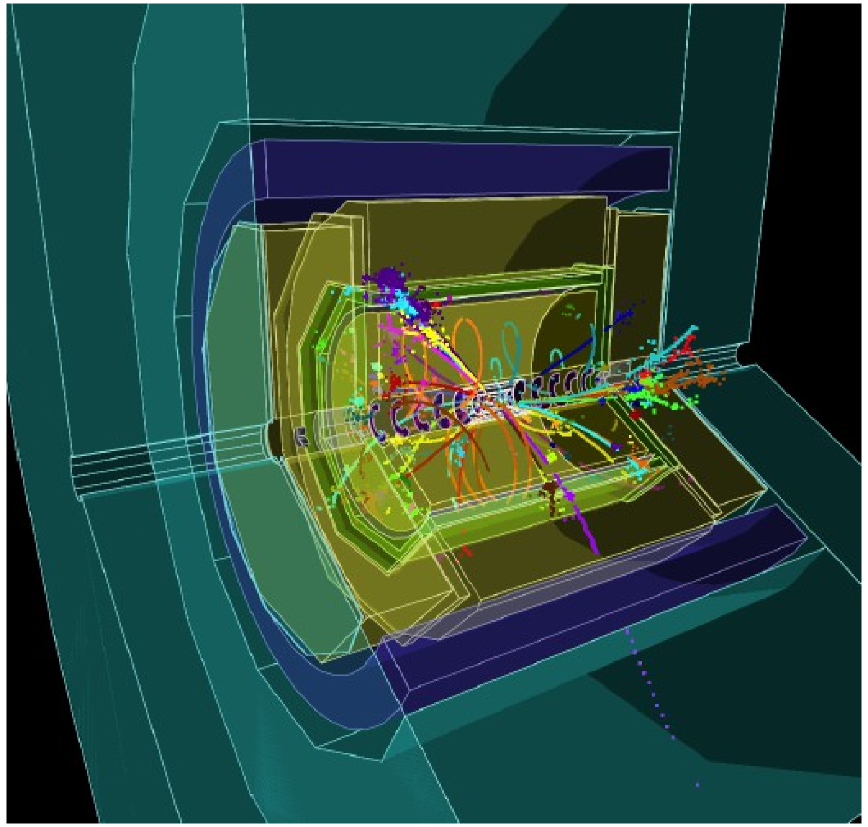
Elements of top quark reconstruction

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

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





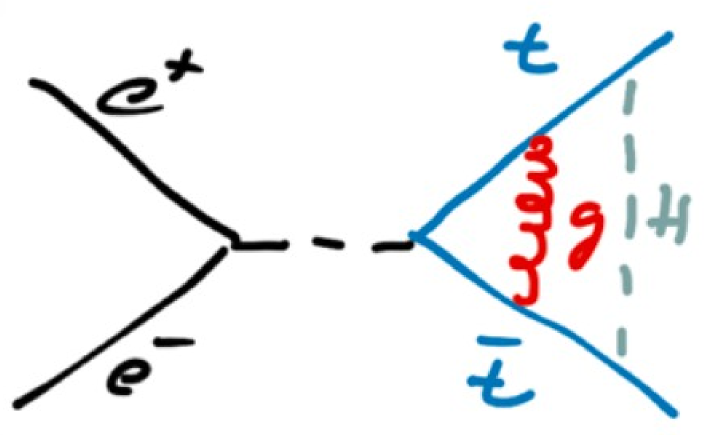
Final state reconstruction uses all detector aspects

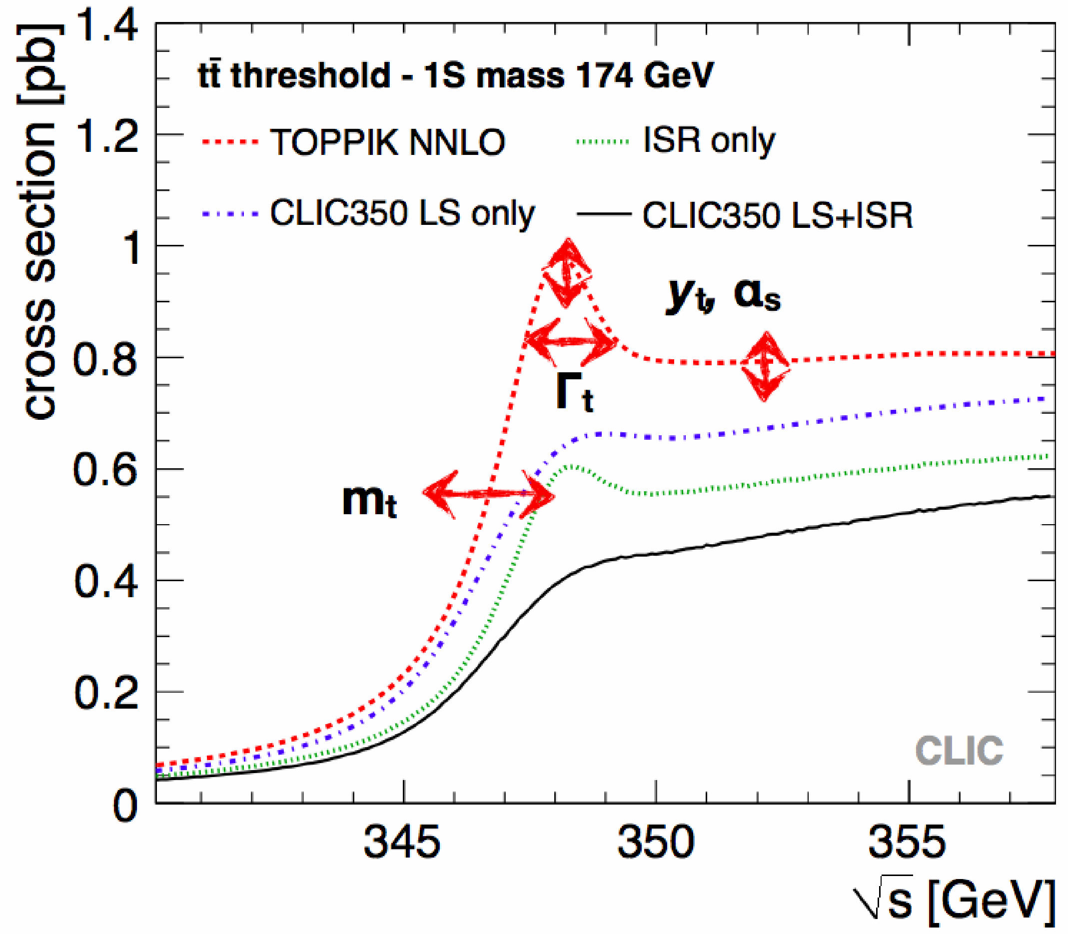
Top pair production at threshold

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

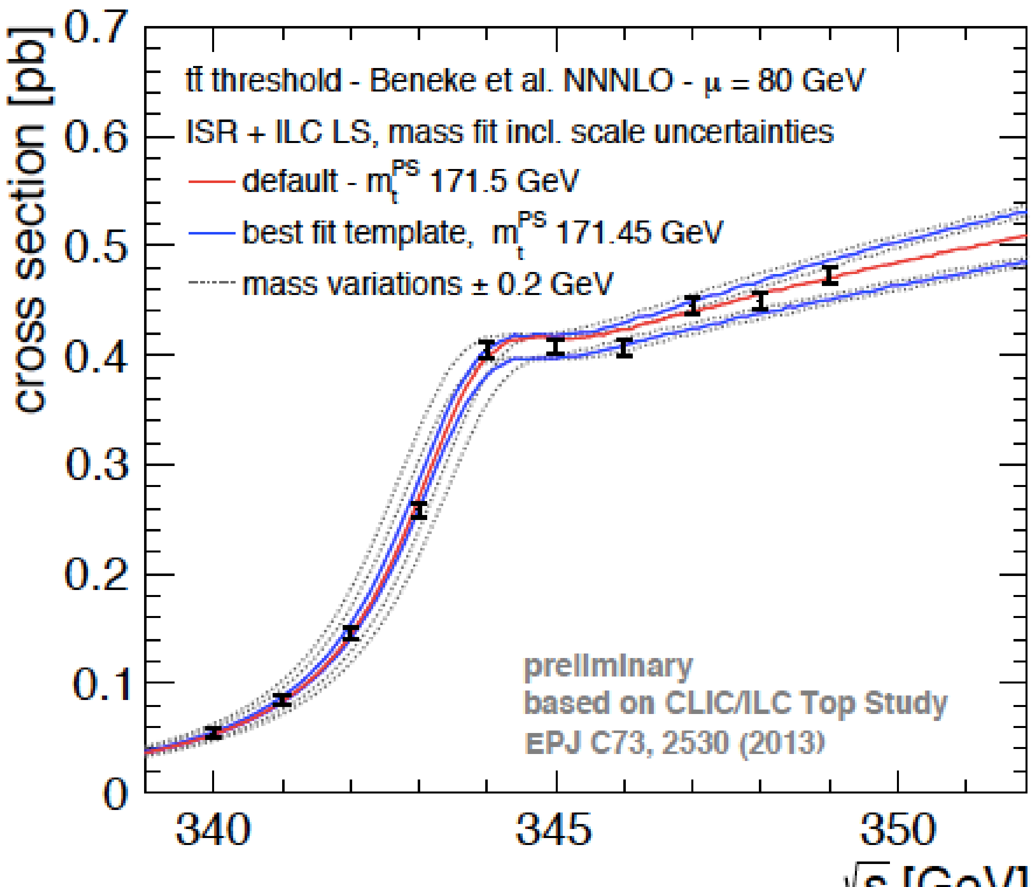
- Top mass, width Yukawa coupling
- Strong coupling constant





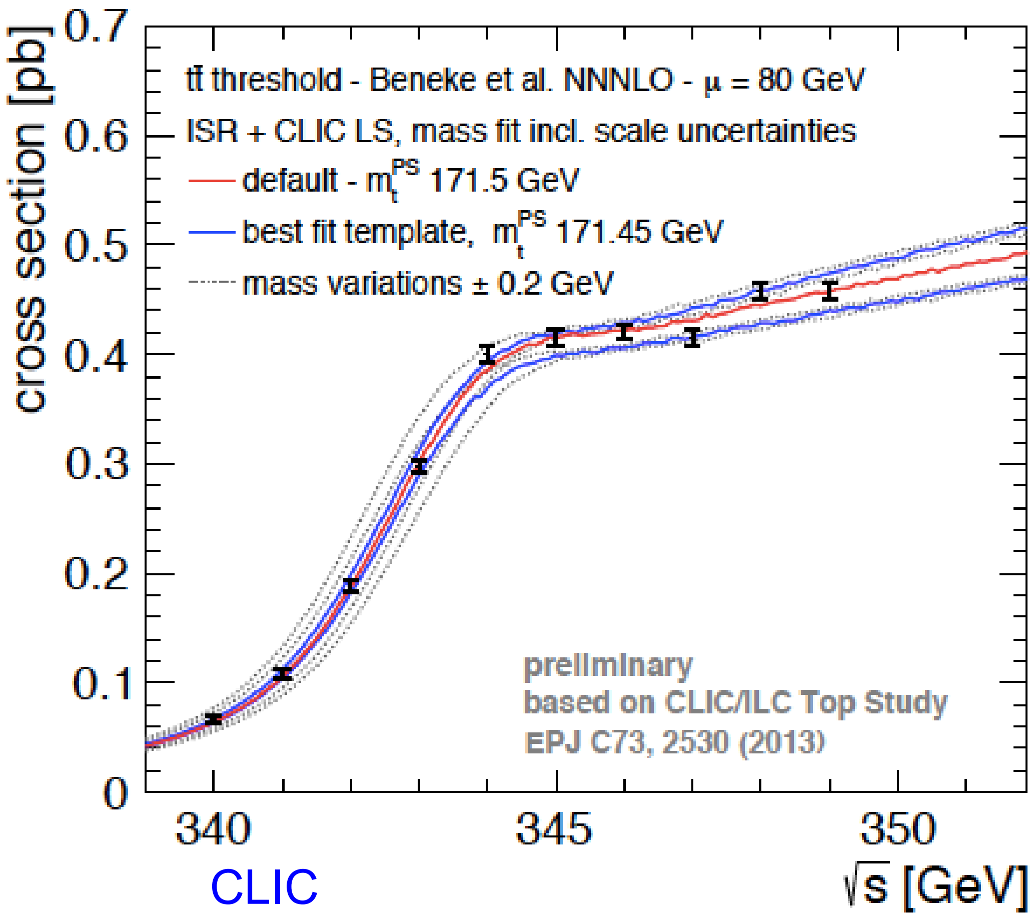
- Effects of some parameters are correlated:
- Dependence on Yukawa coupling rather weak,
- Precise external α_s helps

Top threshold scans at different e+e- colliders



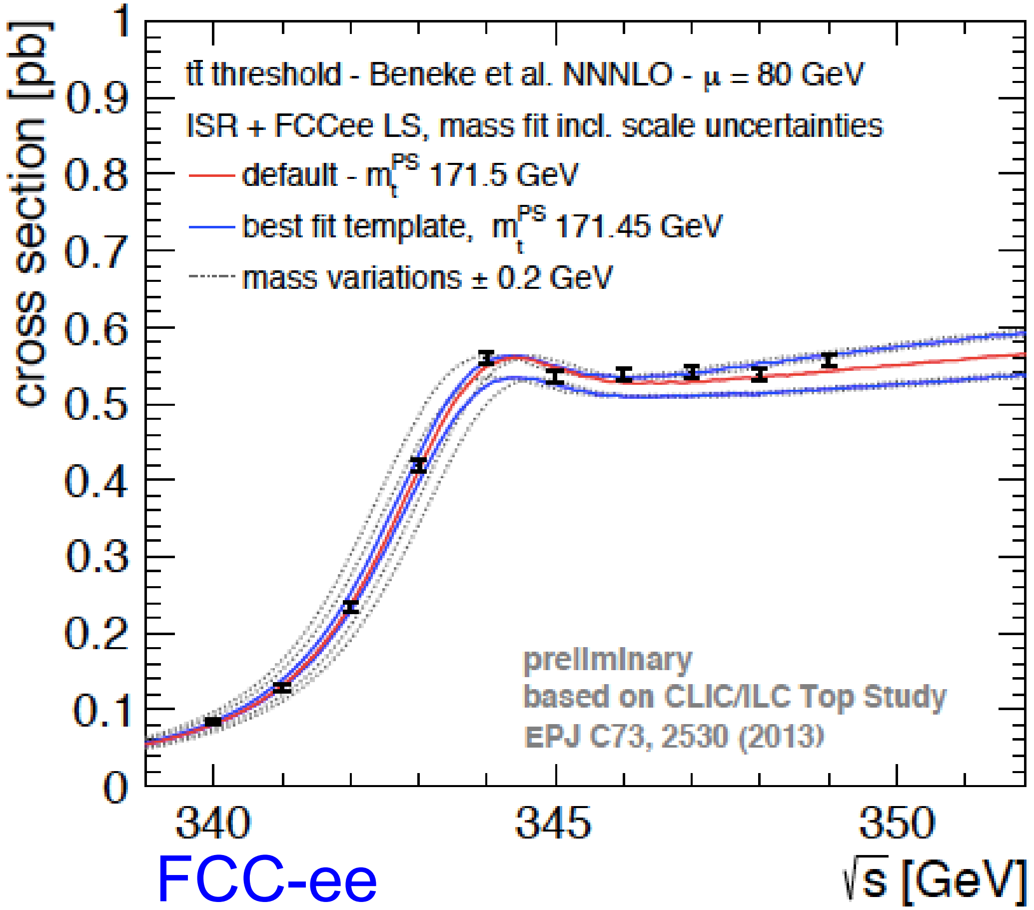
ILC

Fit uncertainty:
28.5 MeV (18 MeV stat)



CLIC

Fit uncertainty:
31 MeV (21 MeV stat)

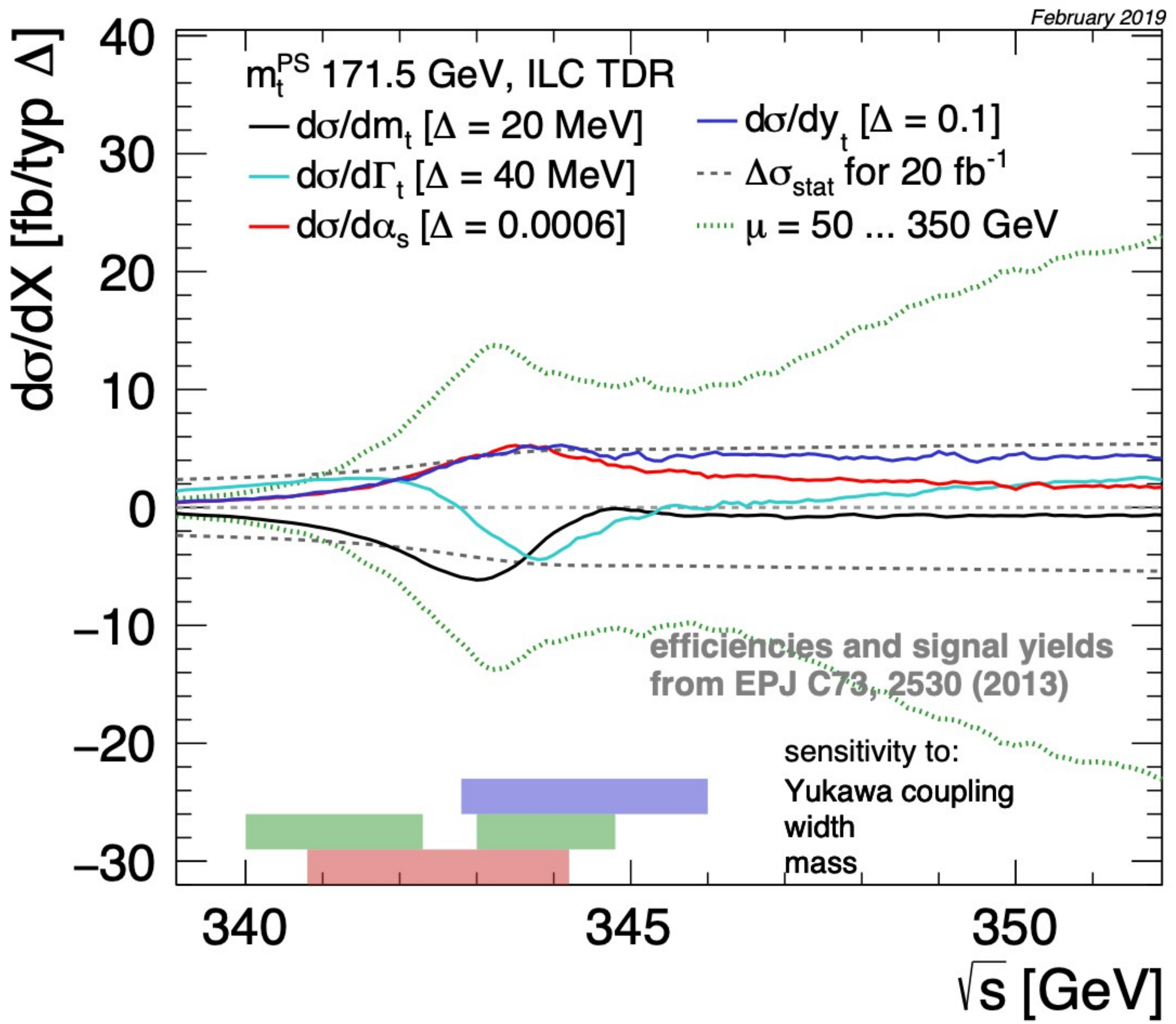


FCC-ee

Fit uncertainty:
27 MeV (15 MeV stat)

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

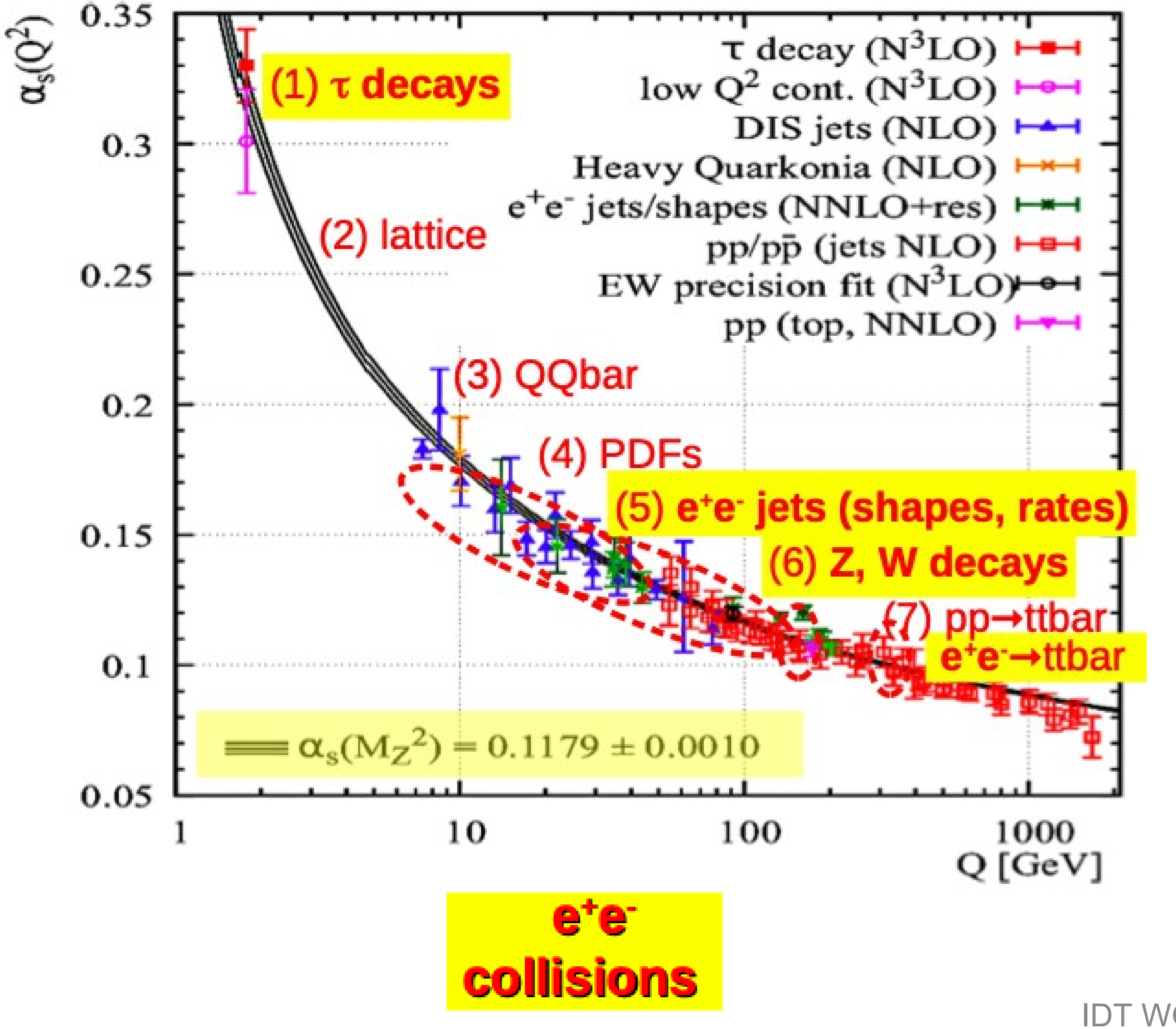
Sensitivity and error breakdown



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
  - $\Delta m \sim 2.6$ per 10^{-4} in α_s

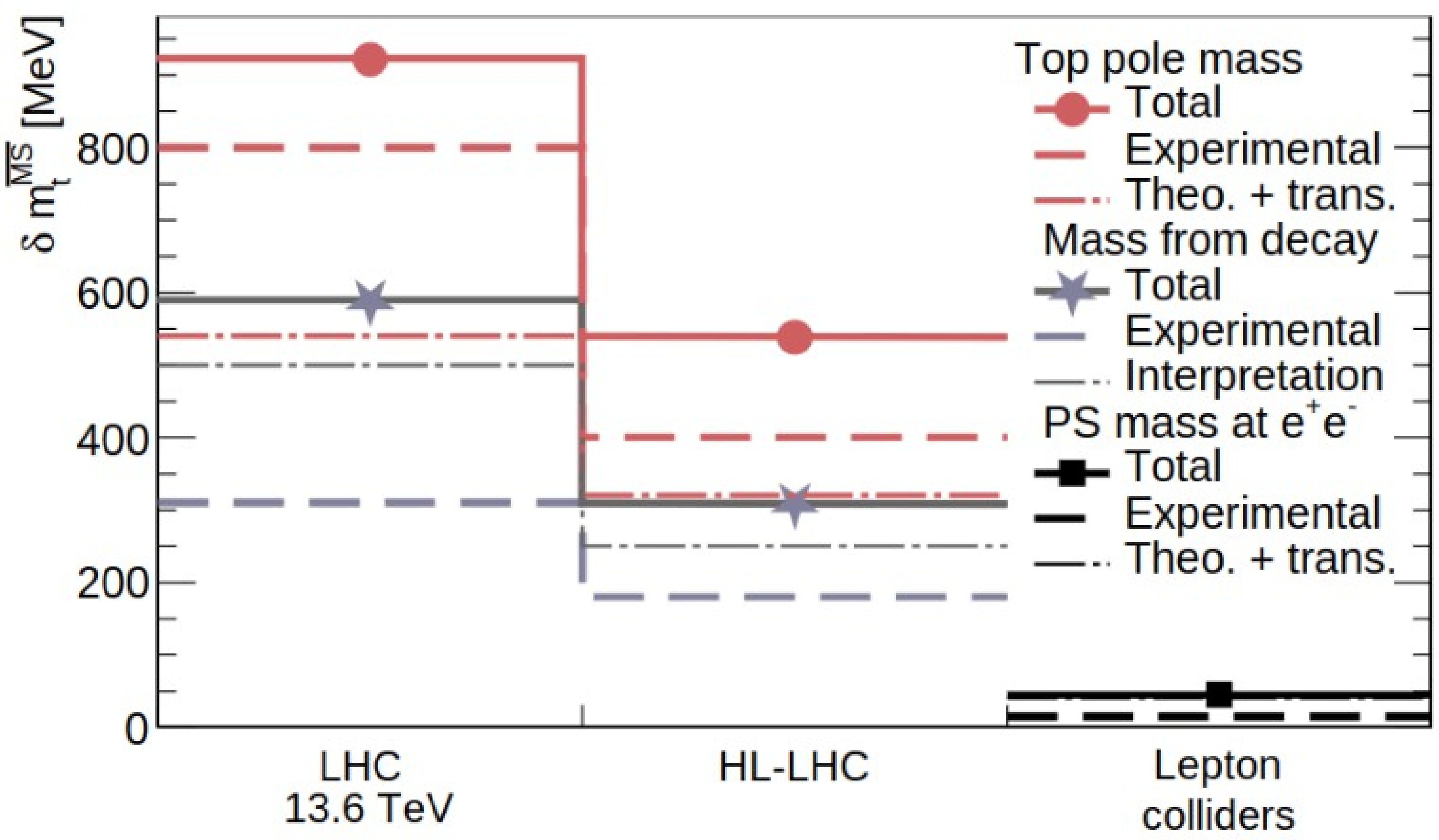
Uncertainty driver α_s



- 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 ?!

Top mass summary

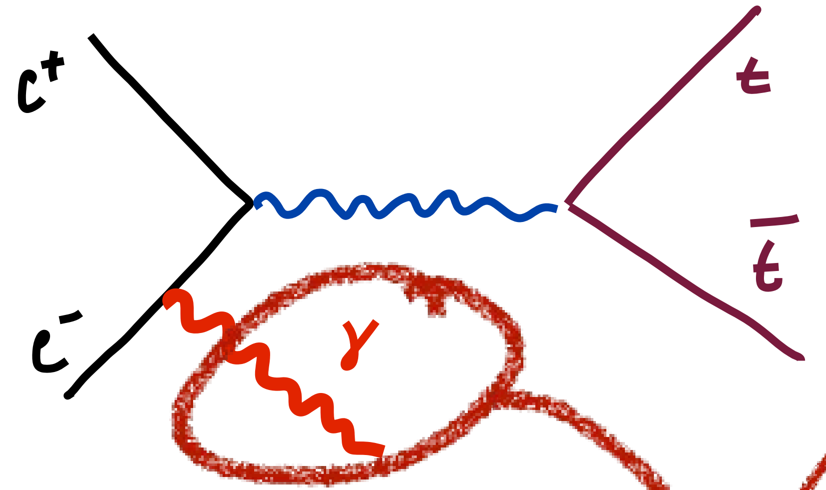
Snowmass report, arXiv:2209.11267



Marcel Vos@Top23

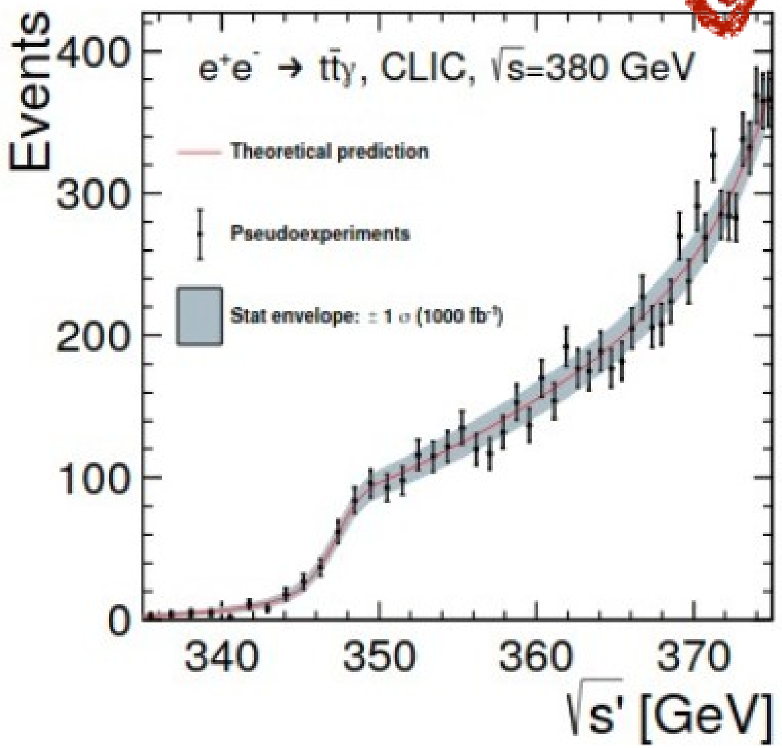
Running top mass

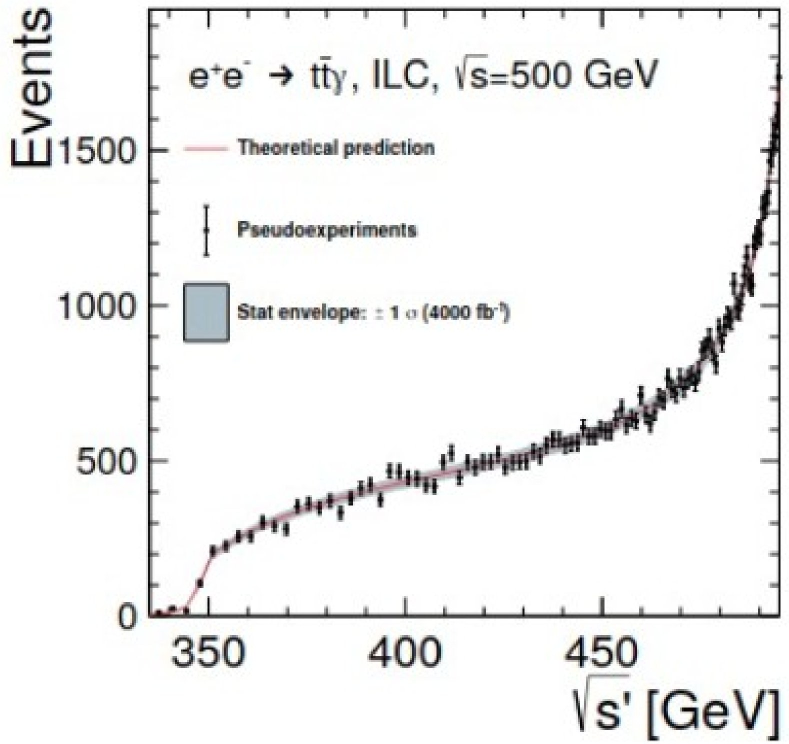
- A new(er) idea to measure the top mass in a theoretically well-defined scheme in high-energy running above the threshold



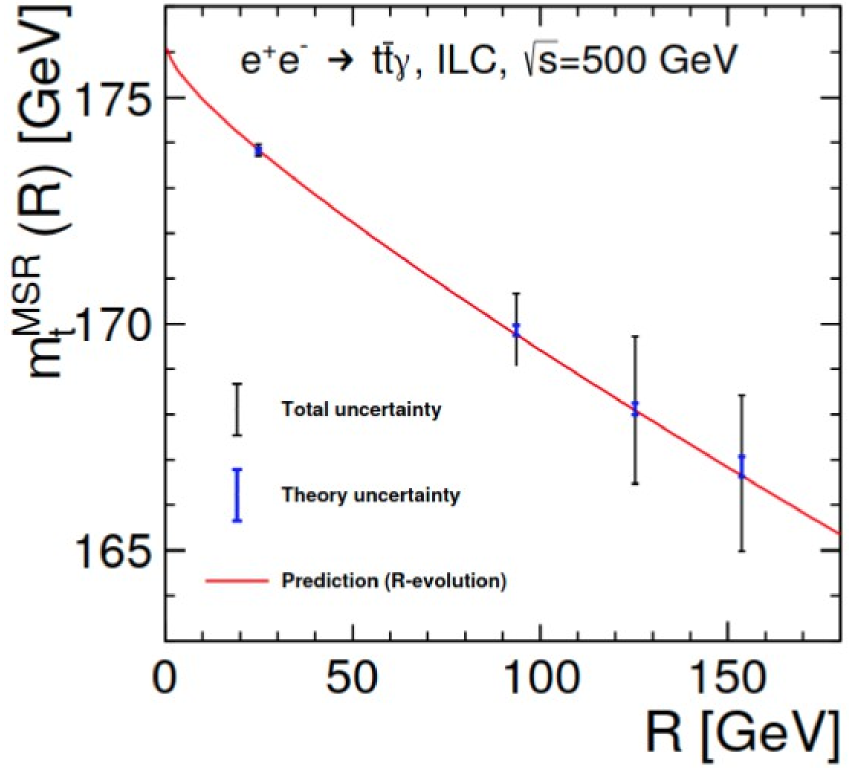
cms energy	CLIC, $\sqrt{s} = 380$ GeV		ILC, $\sqrt{s} = 500$ GeV	
luminosity [fb^{-1}]	500	1000	500	4000
statistical	140 MeV	90 MeV	350 MeV	110 MeV
theory	46 MeV		55 MeV	
lum. spectrum	20 MeV		20 MeV	
photon response	16 MeV		85 MeV	
total	150 MeV	110 MeV	360 MeV	150 MeV

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

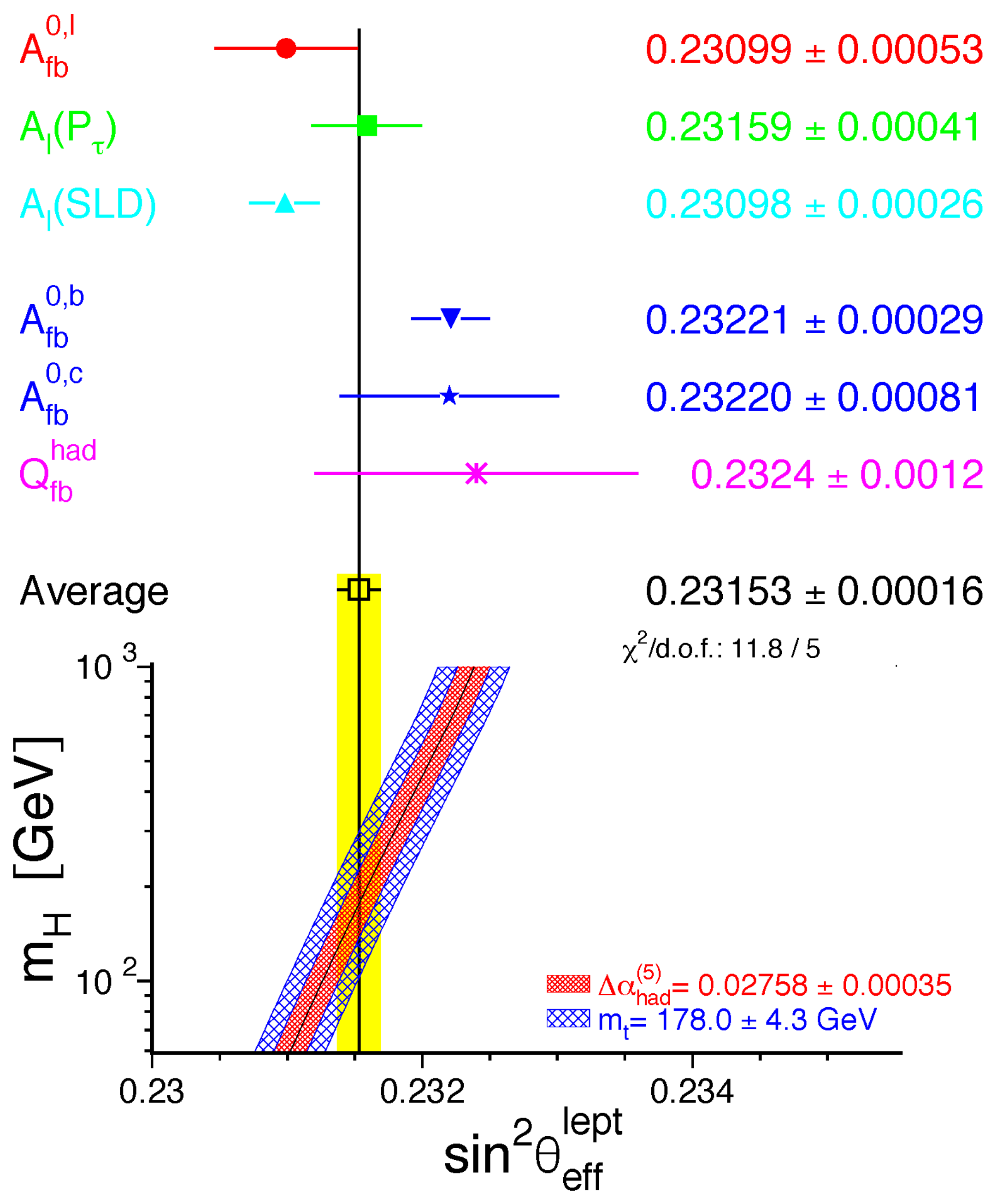




can provide 5σ evidence for scale evolution (“running”) of the top quark MSR mass from ILC500 data alone



Anomalies in LEP/SLD data



Most precise single Individual determination of $\sin^2\theta^\ell_{\rm eff.}$ from SLC

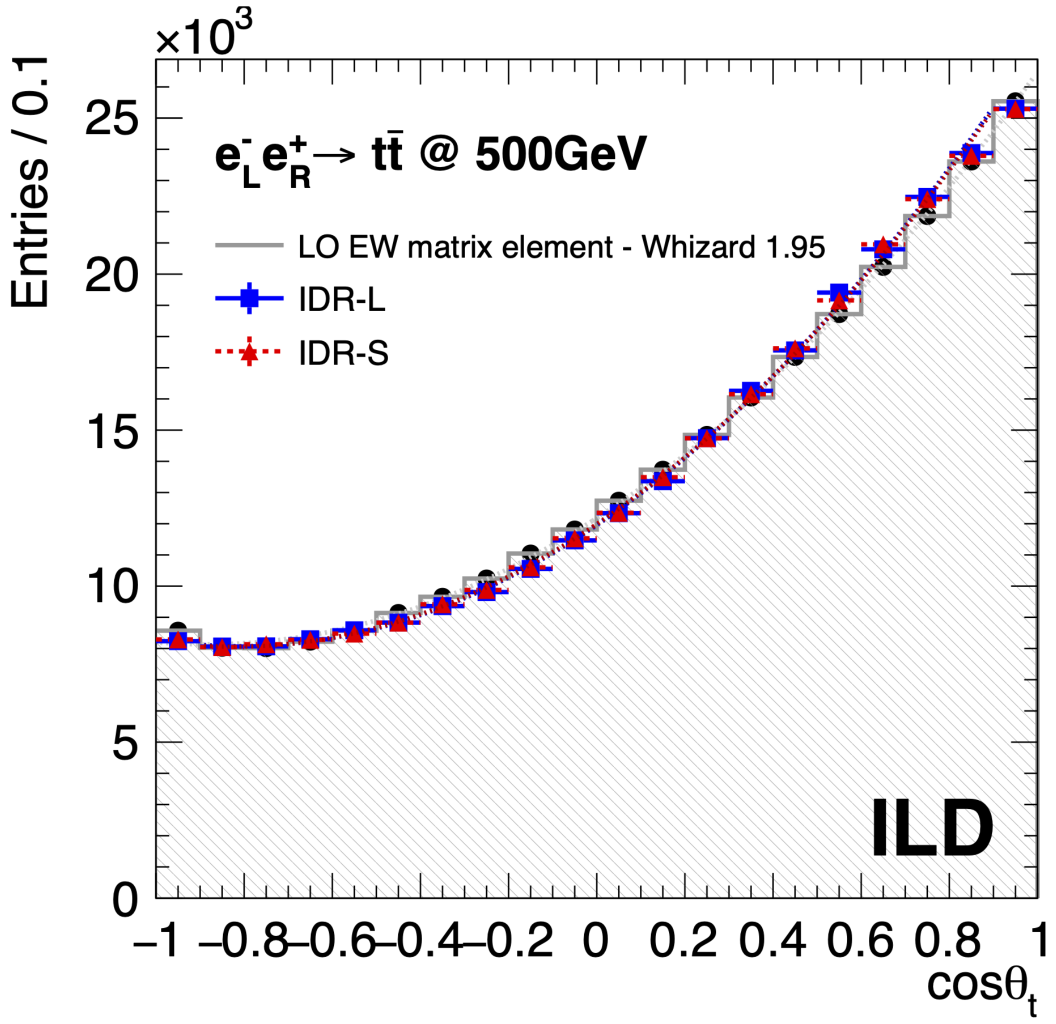
- Left-right asymmetry of leptons

- Most precise measurement of $\sin^2\theta^\ell_{\rm eff.}$ from forward backward asymmetry A^b_{FB} in ee→bb at LEP

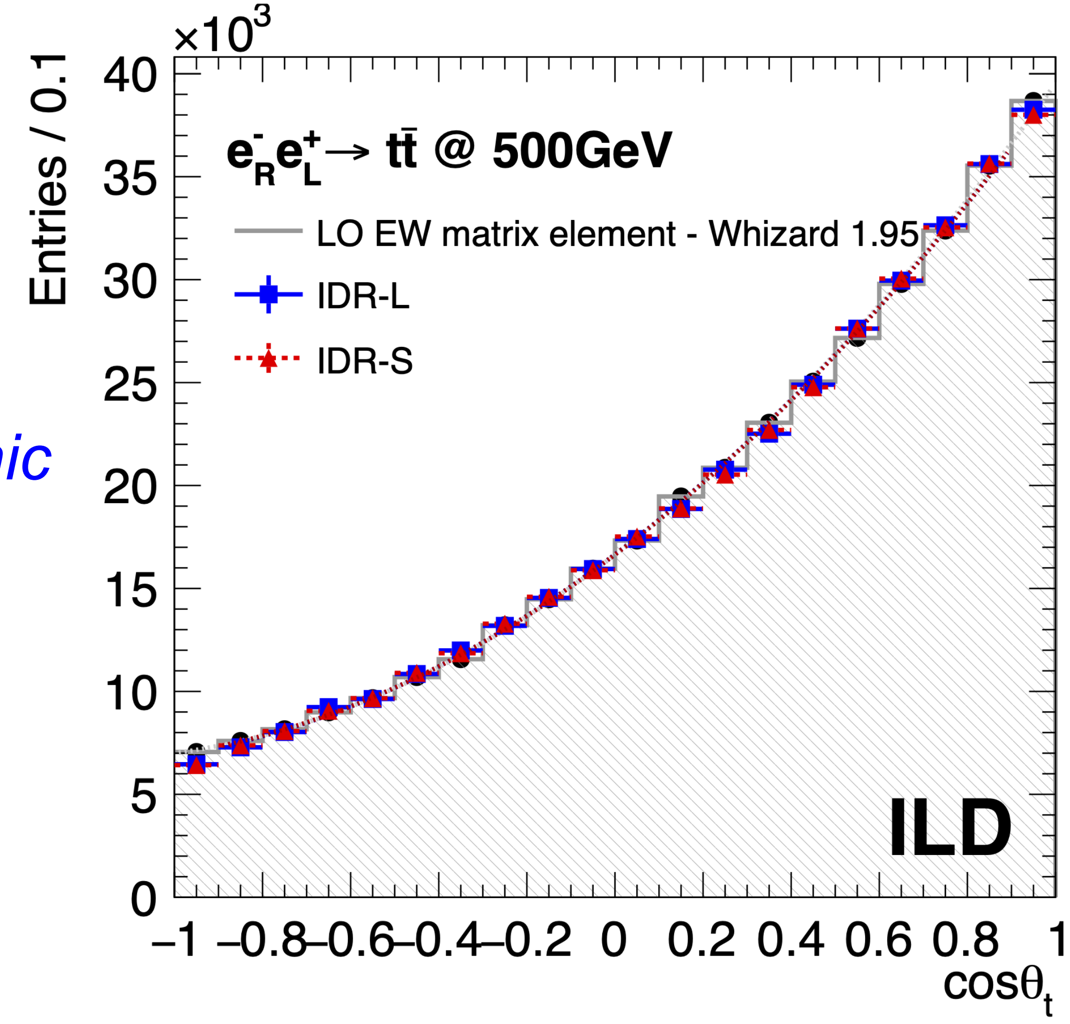
:

- Most precise determinations of $\sin^2\theta^\ell_{\rm eff.}$ differ significantly
  - Requires verification
  - **Heavy quark effect, effect on all quarks/fermions, no effect at all?**

Top quark polar angle spectrum at 500 GeV



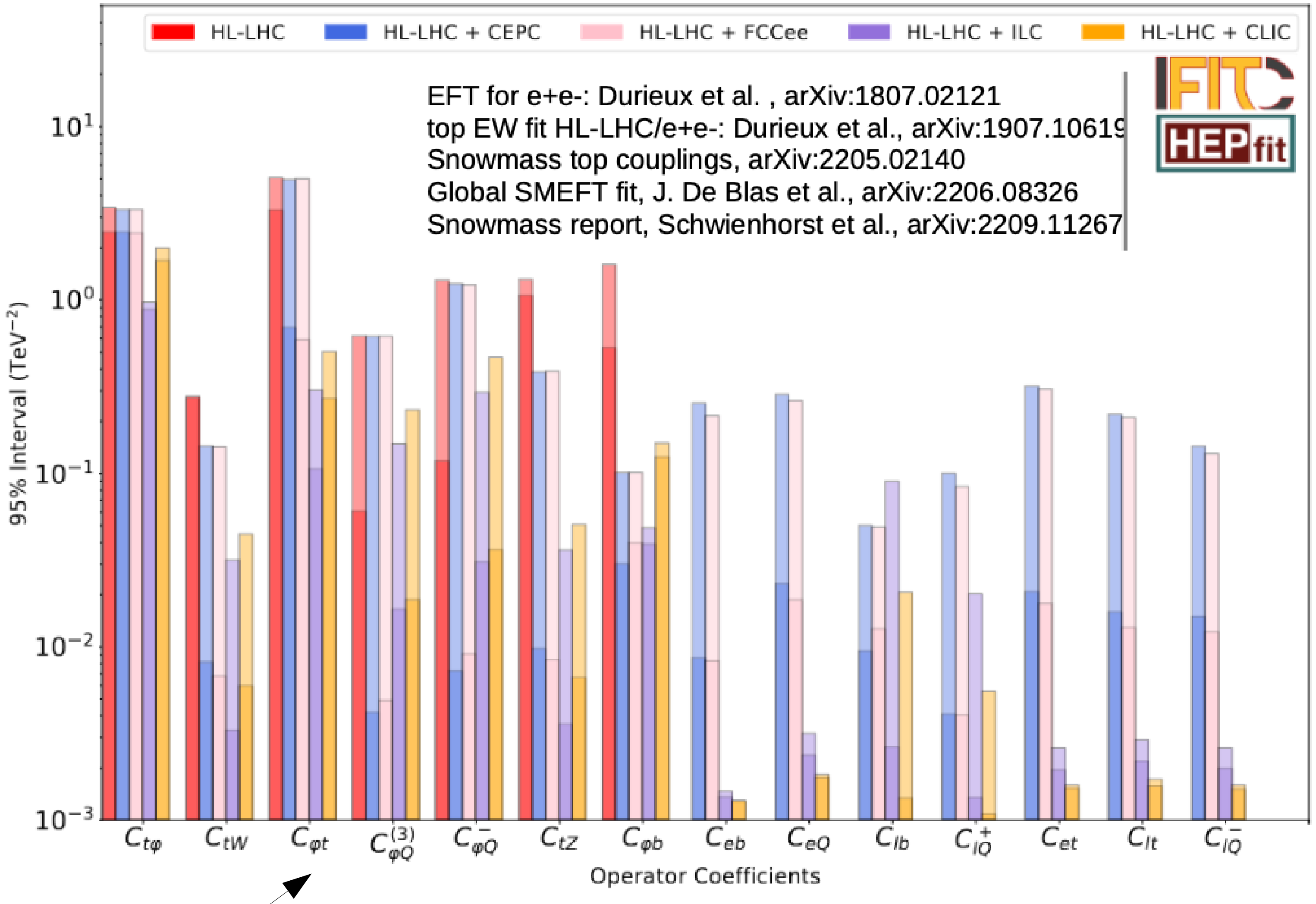
Semi-leptonic channel



ILD-Note-2019-007

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

Precision on electroweak form factors and couplings



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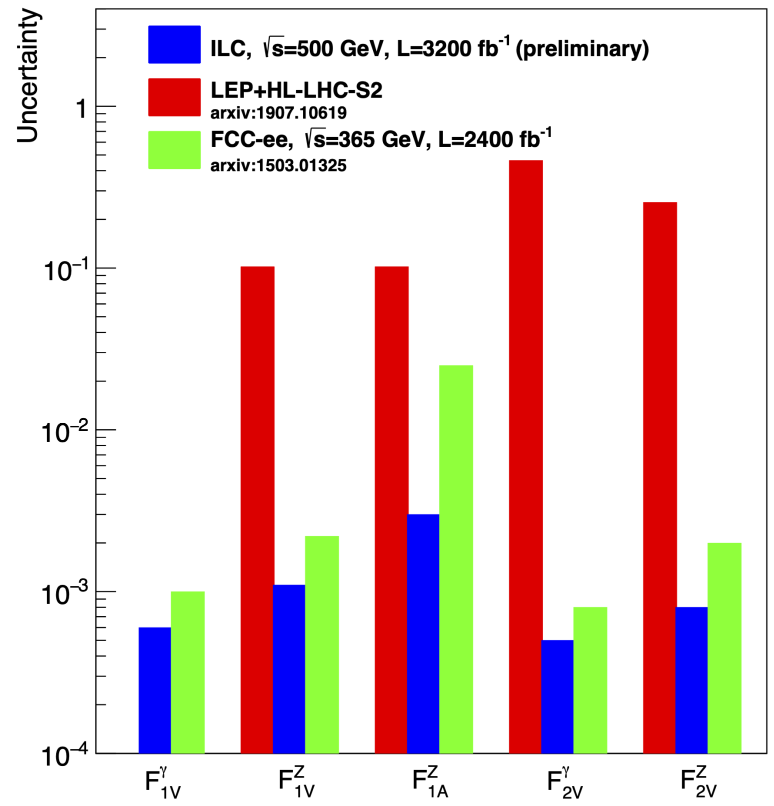
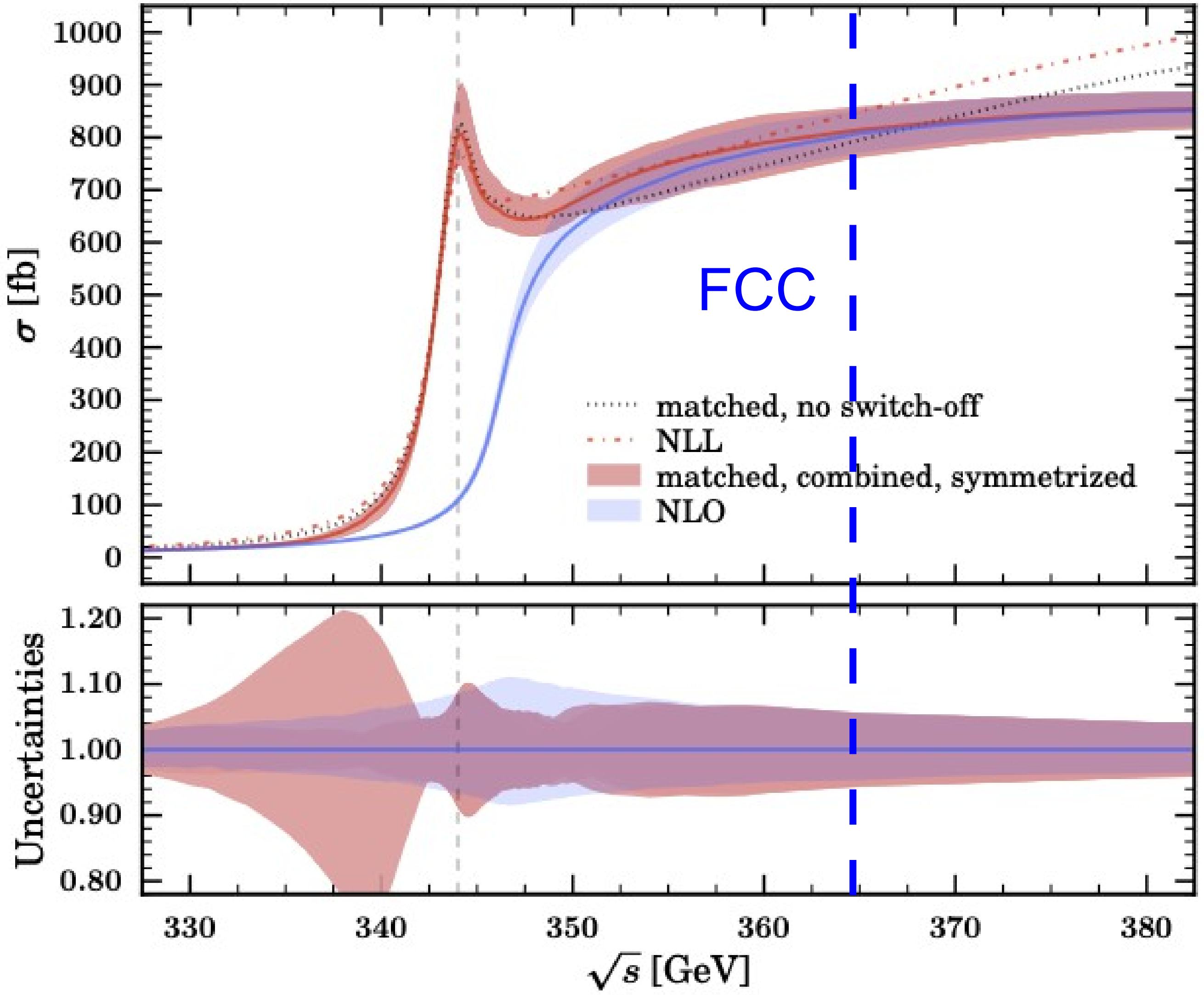


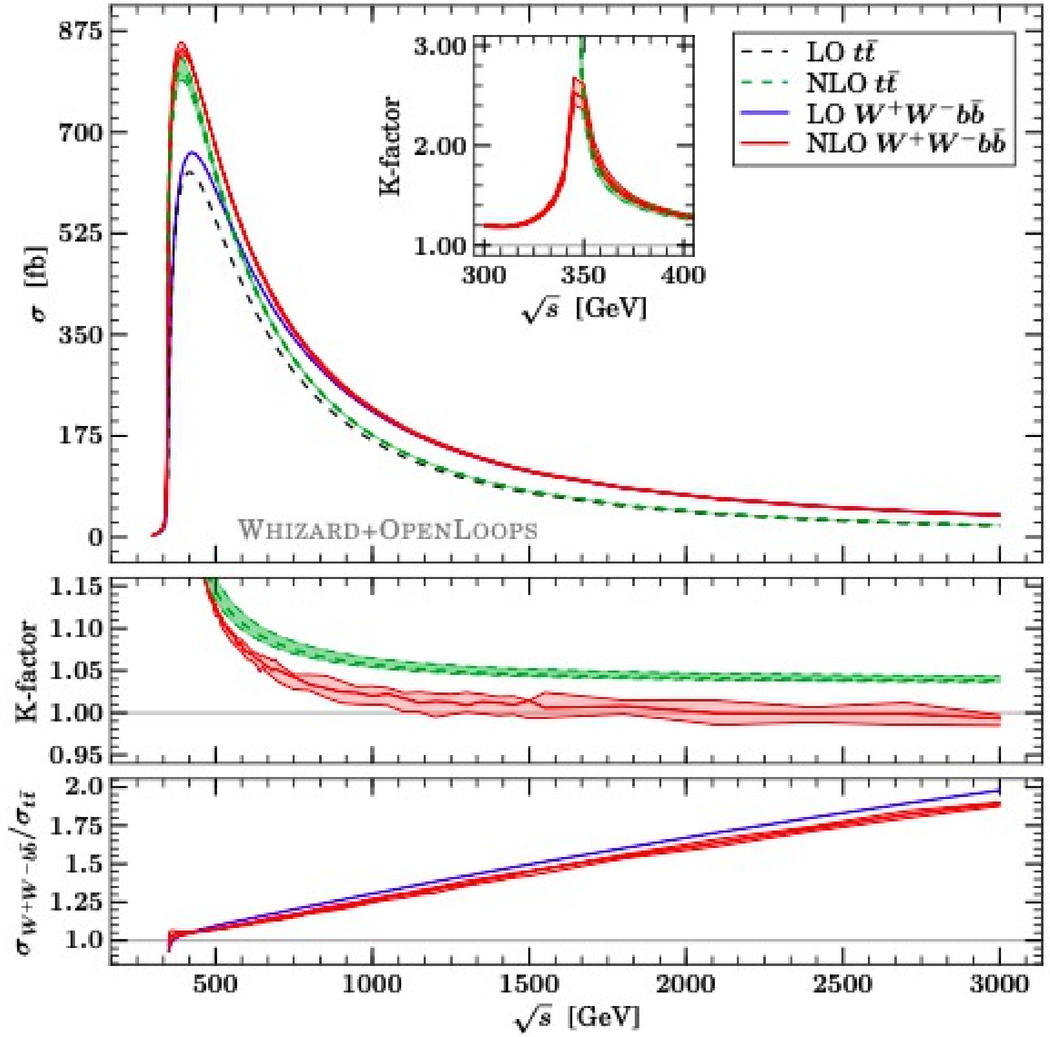
- e+e- collider way superior to LHC ($\sqrt{s}$ = 14 TeV)
  - True for both, analysis in terms of Form Factors and Wilson Coefficients
- Final state analysis at FCCee
  - Also possible at LC => Redundancy -> should be checked again (see arxiv 1503.04247)
- :500 GeV is nicely away from QCD Matching regime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

QCD uncertainties on ee->tt cross section

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

Linear Colliders

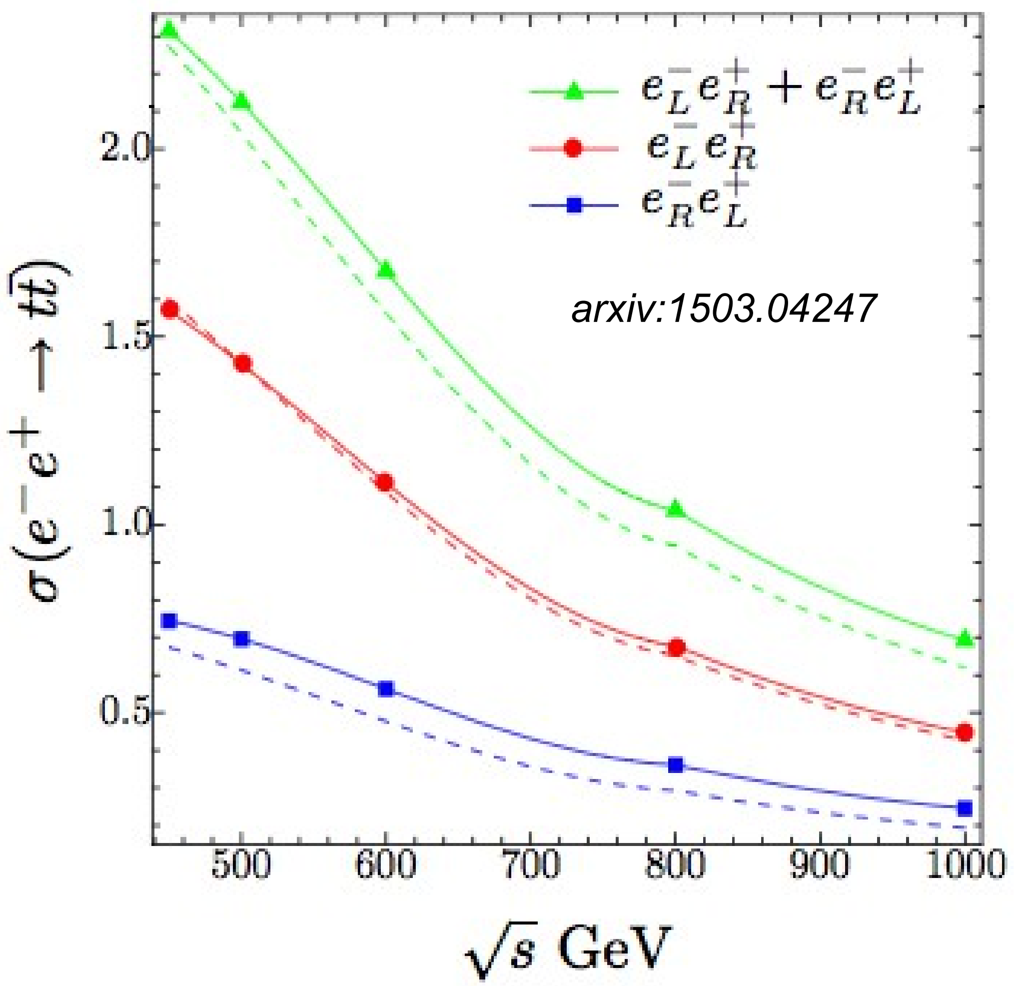


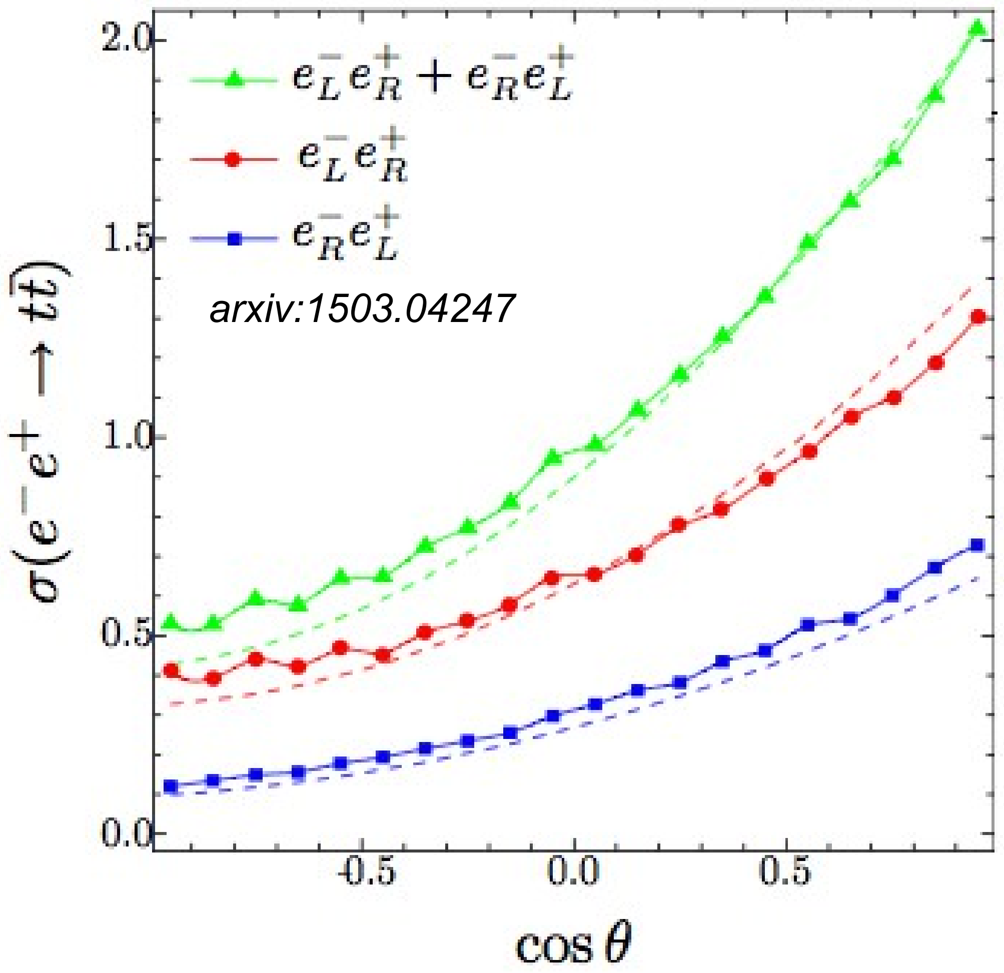


- Marching non-relativistic calculations in threshold region with tt-continuum is theoretical challenge
- QCD uncertainties shrink as energy increases
- Non resonant contributions are important (i.e. ee->tt --> ee->WbWb)

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

High Order Electroweak Corrections





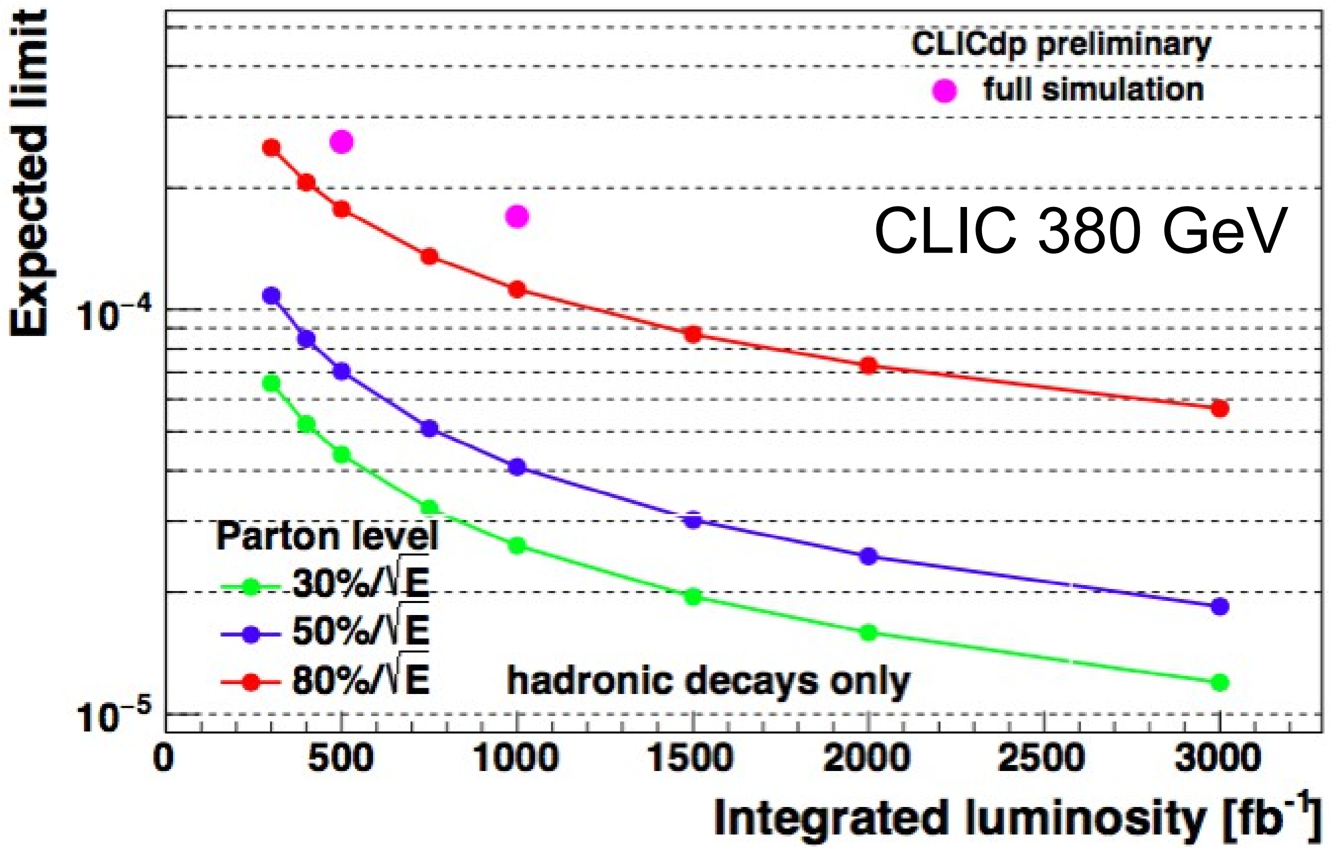
- Electroweak corrections manifest themselves differently for different beam polarisations

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

QCD uncertainties on ee->tt cross section

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

Comparison with parton level results, different jet energy resolutions



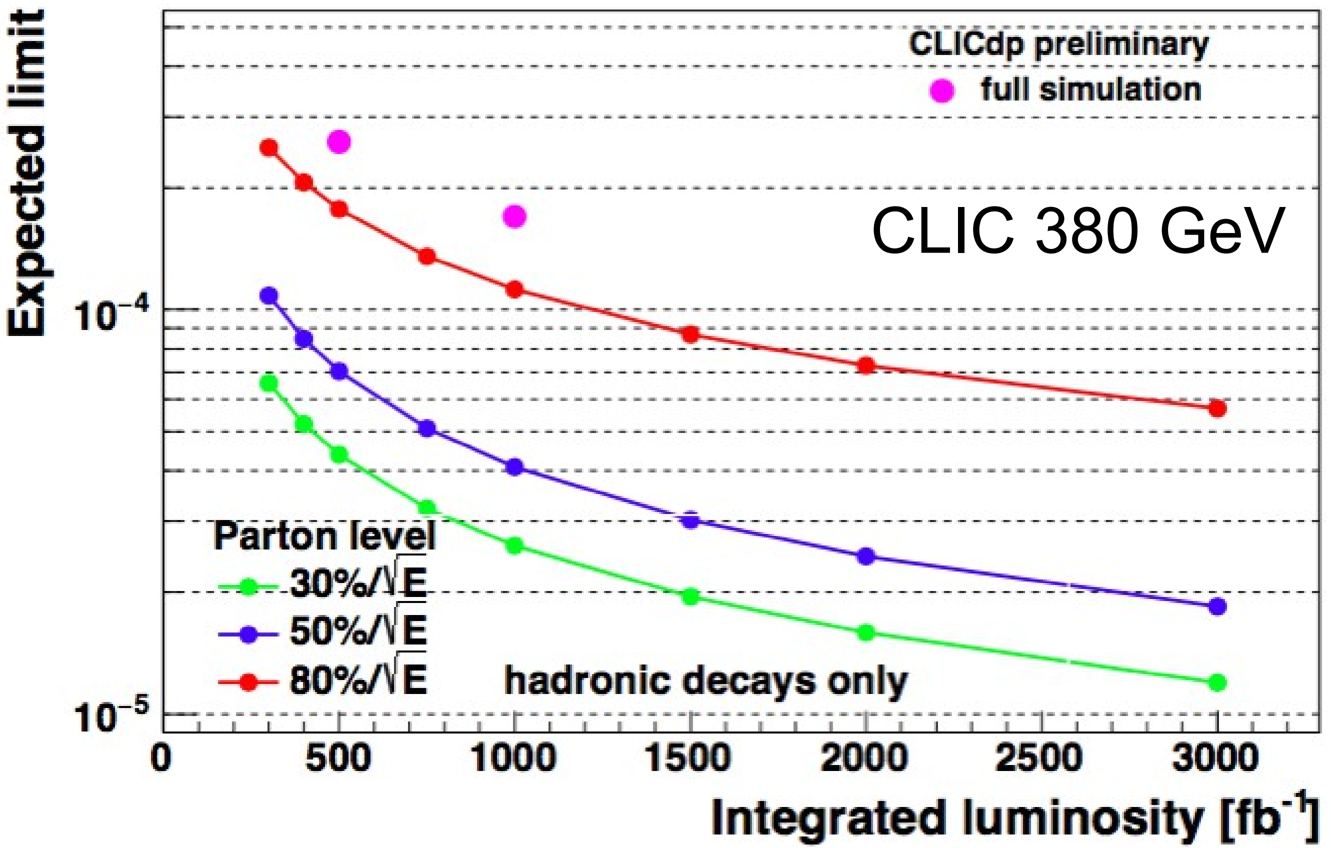
Slide from 2016!!!!

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

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



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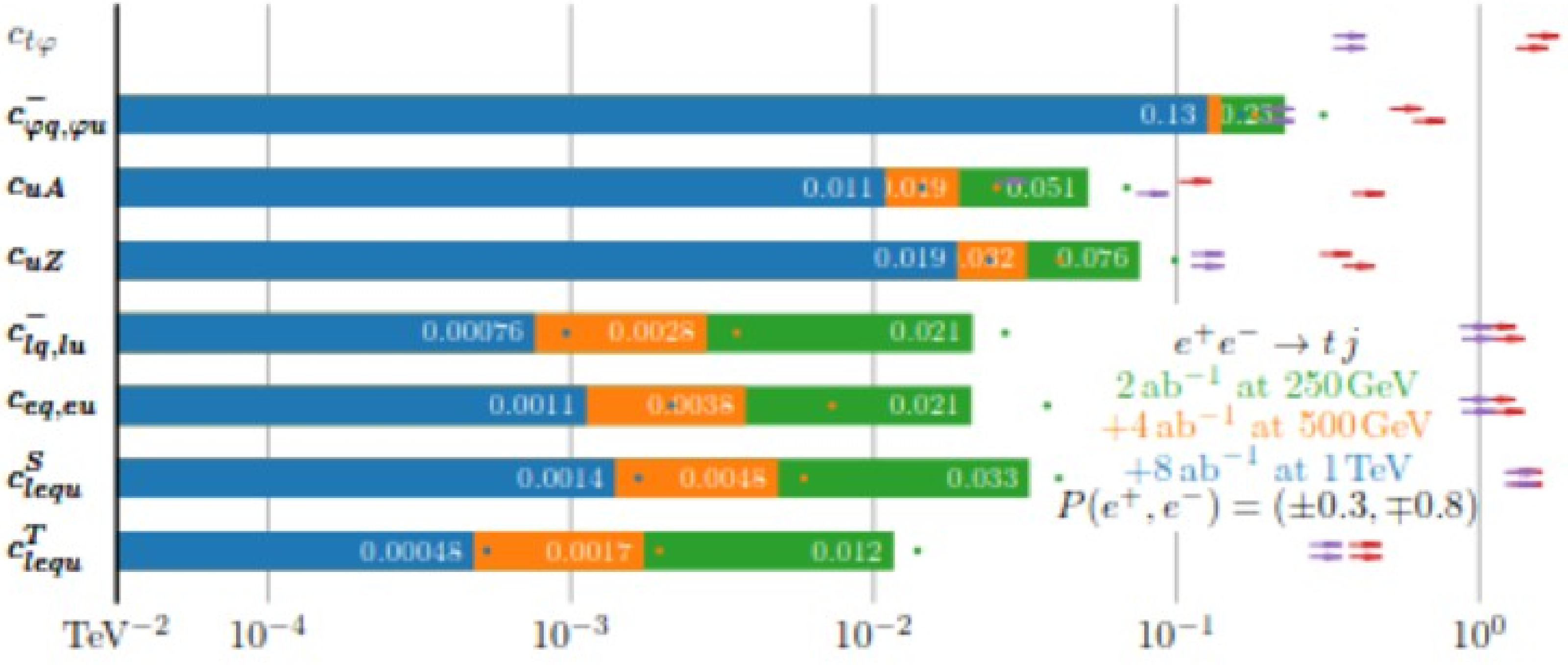
Top exotic decays 1

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



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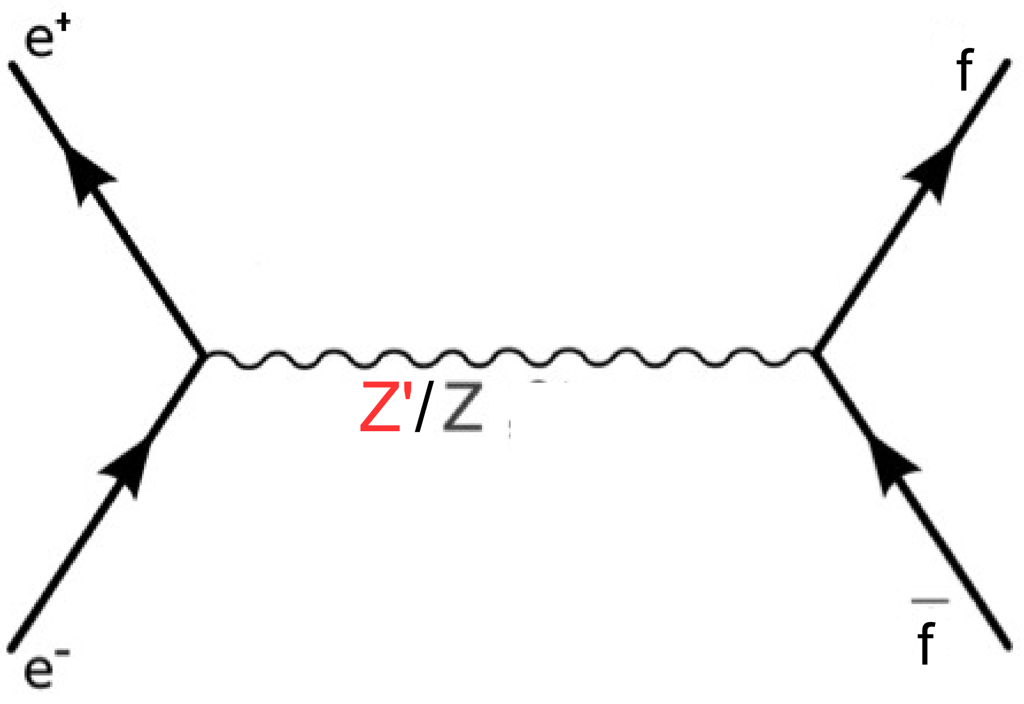
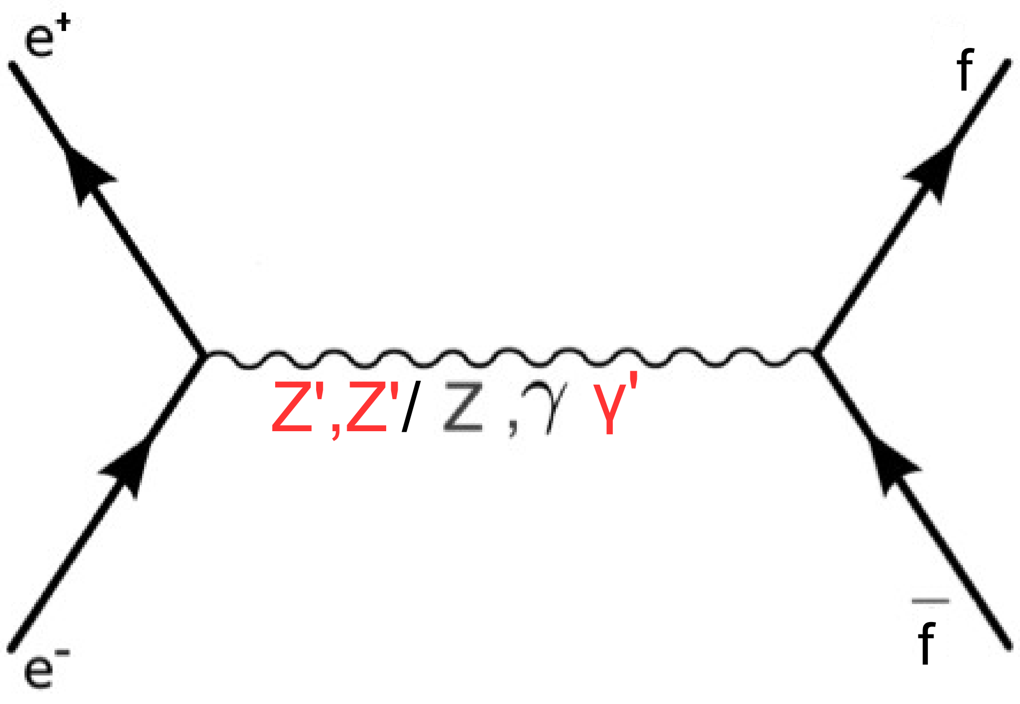
Two fermion production: Z-Pole and higher energies

On the Z-pole



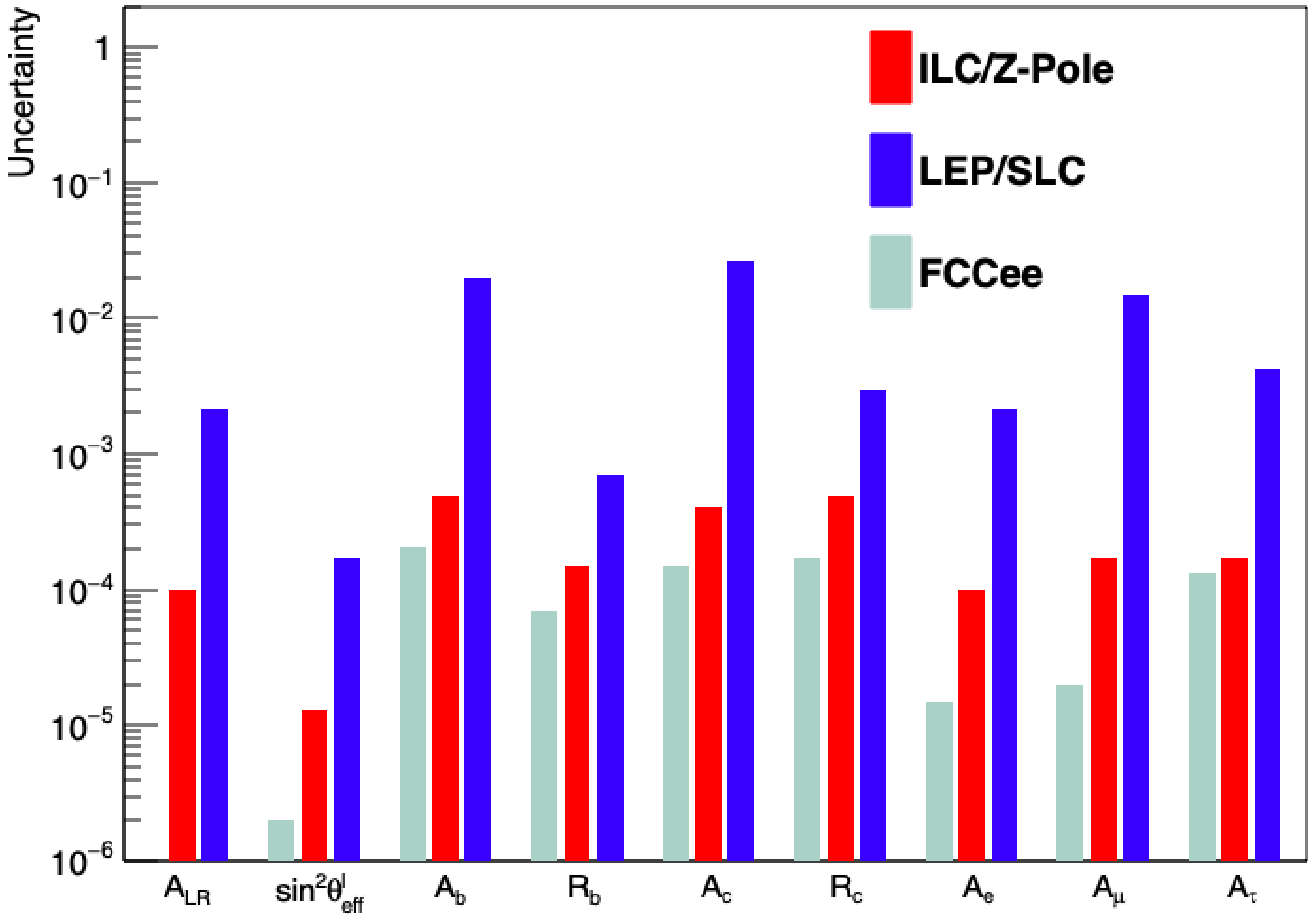
Above the Z-pole



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?



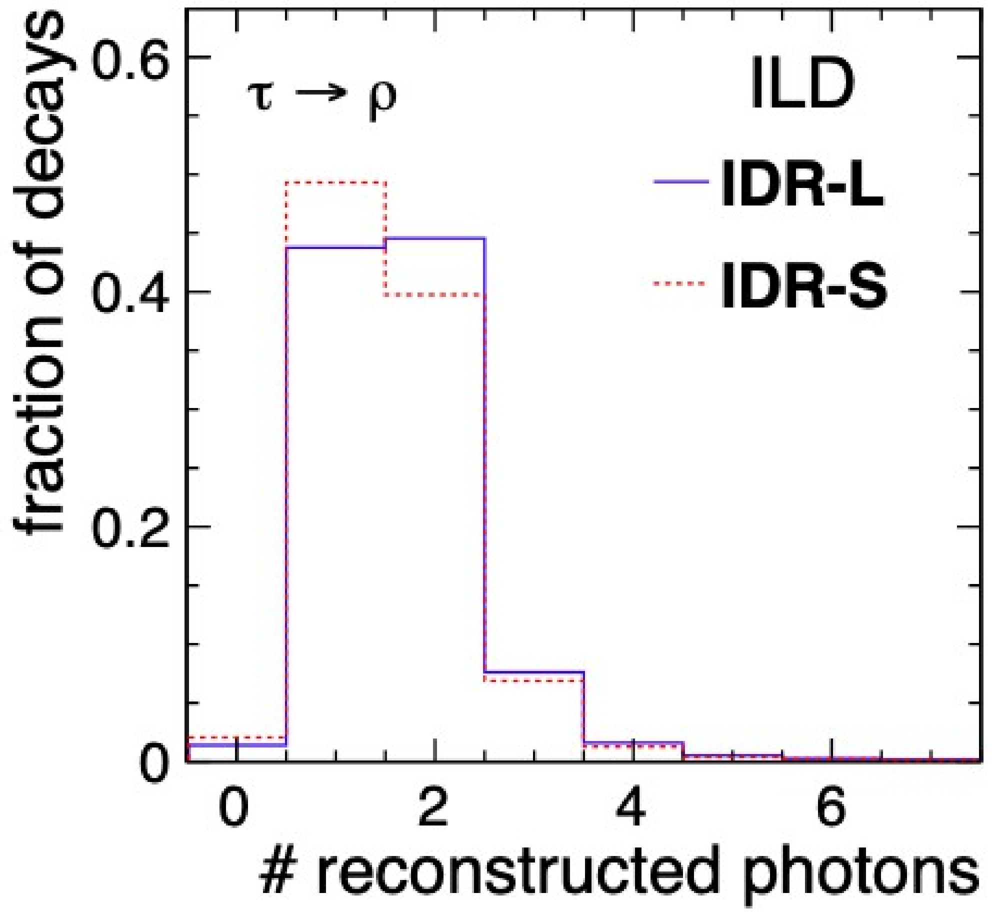
Numbers FCCee: “Mixture” of FCC CDR and
P. Janot at Precision Workshop/CERN
https://indico.cern.ch/event/1140580/timetable/

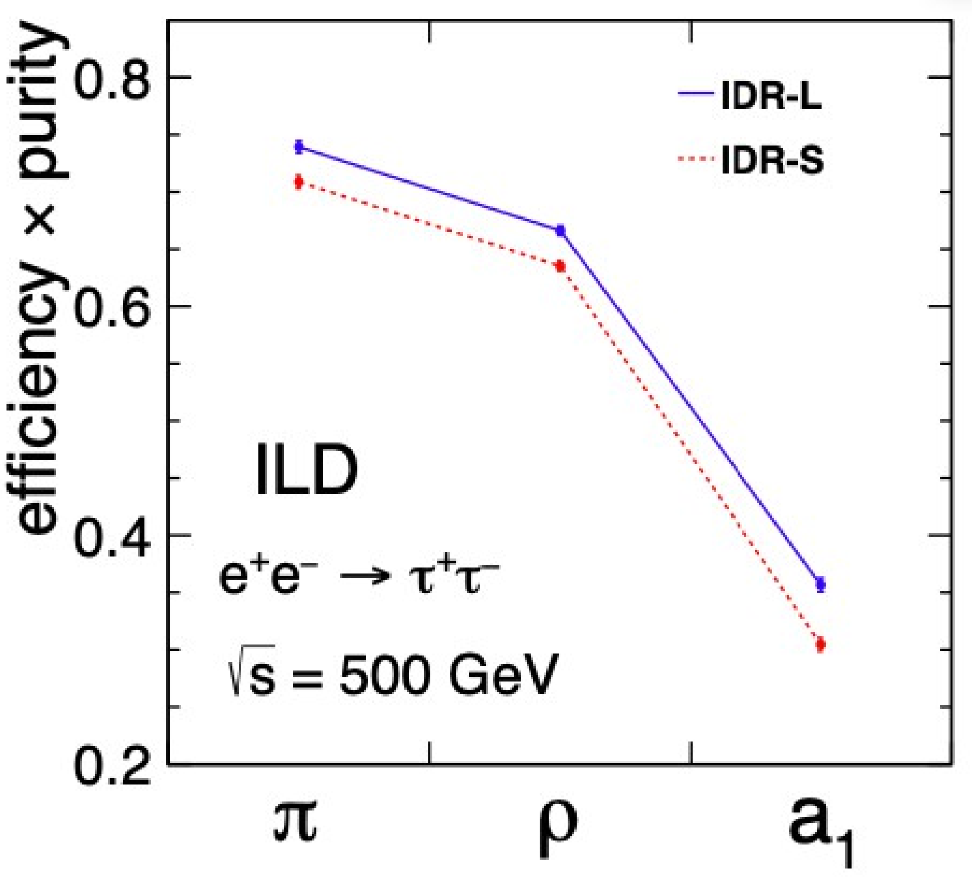
Numbers ILC: arxiv: 2203.07622 (ILC Snowmsss report)

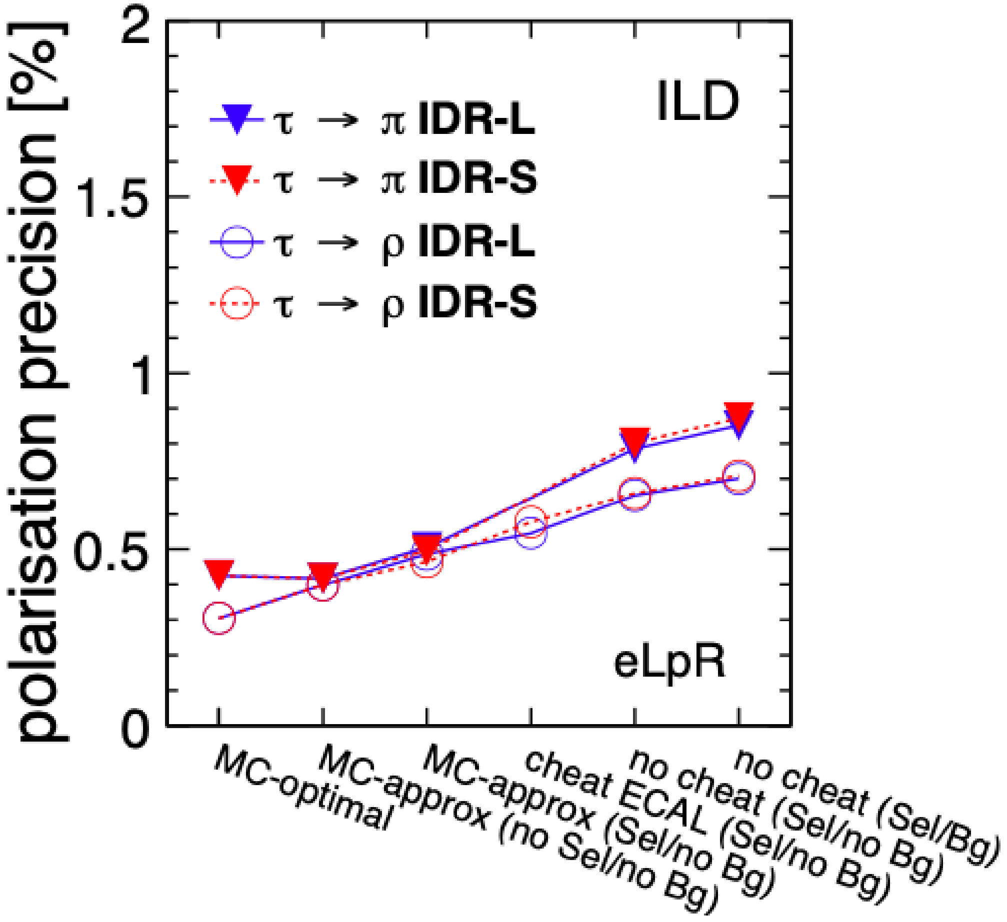
- All future colliders will improve significantly precision compared with LEP/SLC
- Comparable precisions despite differences in luminosity
  - Systematics will play a major role
- **No full simulation study exists on Z-Pole**
  - Most of the results (educated) guesses on experimental issues by extrapolations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

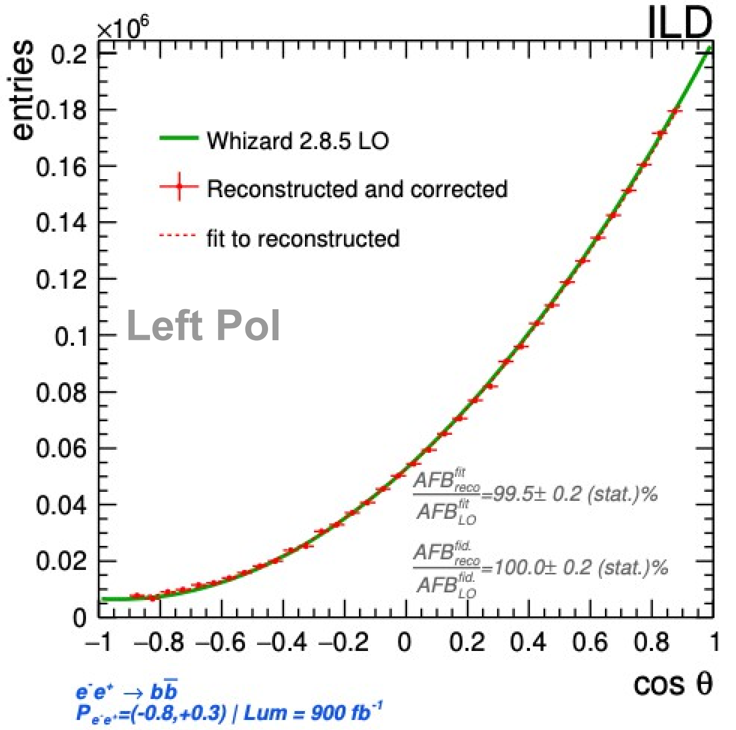
EfficiencyxPurity drops with increasing photon multiplicity

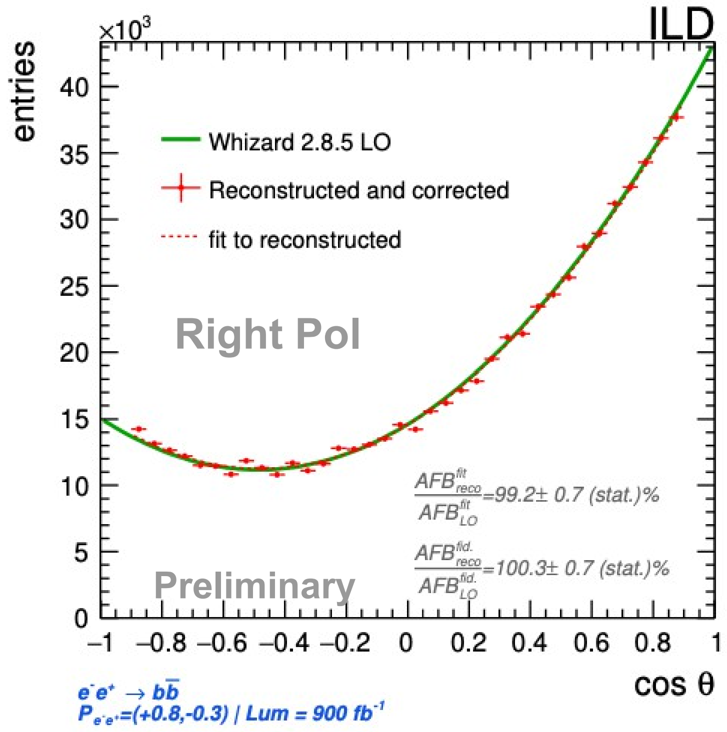
Precision of tau polarisation of order 0.3%-1%

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

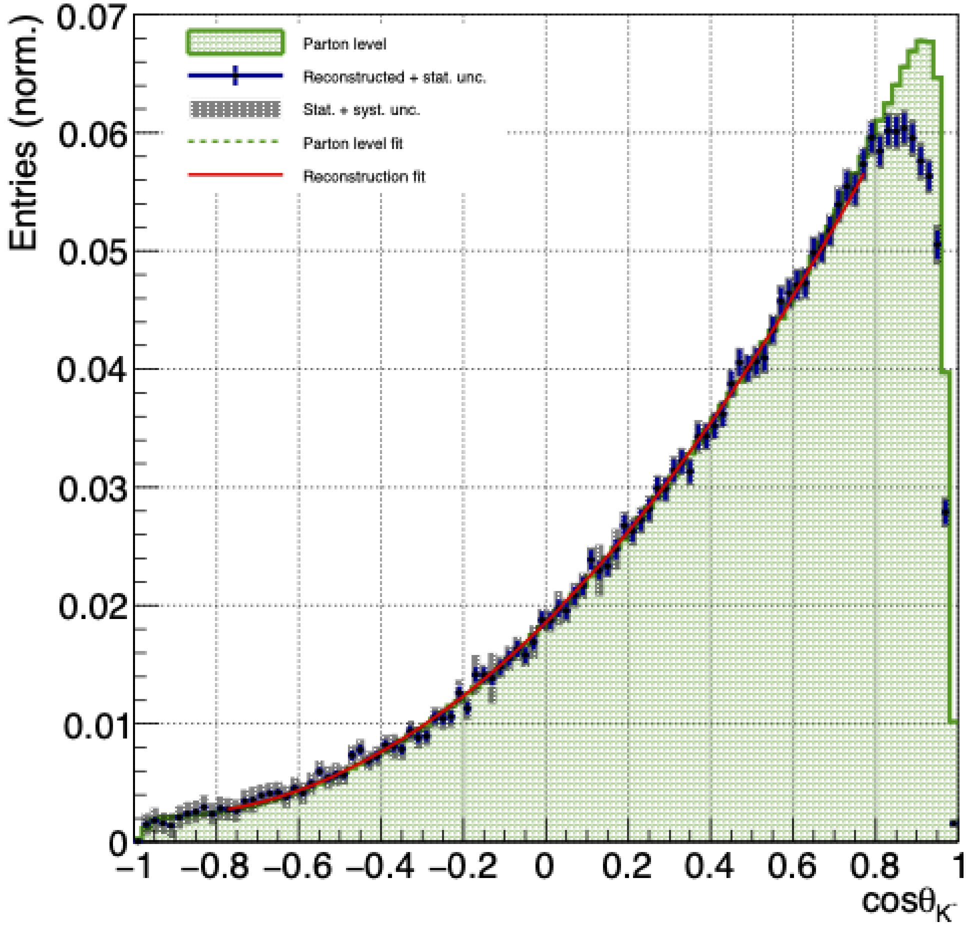
Source	$e^-e^+ \to c\bar{c}$				$e^-e^+ \to b\bar{b}$			
	$P_{e^-e^+}(-0.8,+0.3)$		$P_{e^-e^+}(+0.8,-0.3)$		$P_{e^-e^+}(-0.8,+0.3)$		$P_{e^-e^+}(+0.8,-0.3)$	
	R_c	$A_{FB}^{c\bar{c}}$	R_c	$A_{FB}^{c\bar{c}}$	R_b	$A_{FB}^{b\bar{b}}$	R_b	$A_{FB}^{b\bar{b}}$
Statistics	**0.18%**	**0.38%**	**0.27%**	**0.52%**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

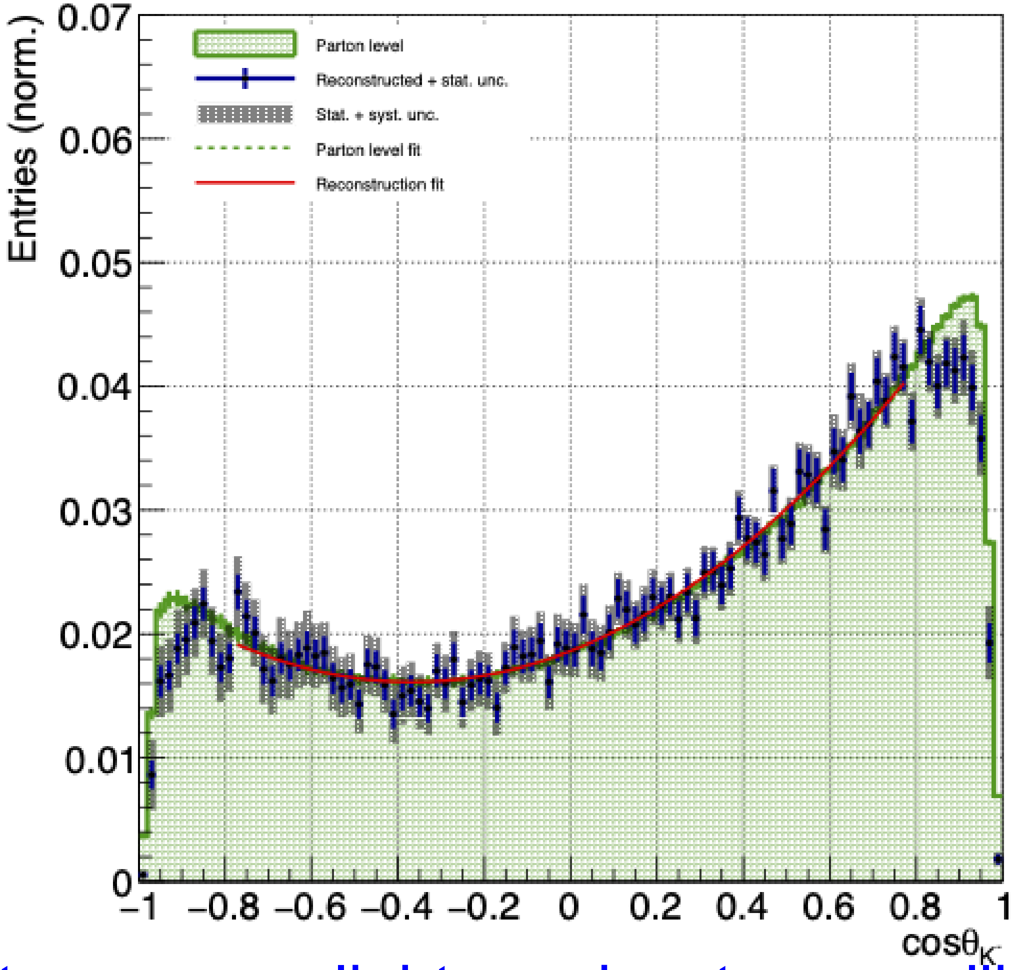
Additional complication in continuum compared with Z-Pole:
Rejection of ISR events

Light quarks at @ 250 GeV are in the making

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

PhD thesis
Y. Okugawa



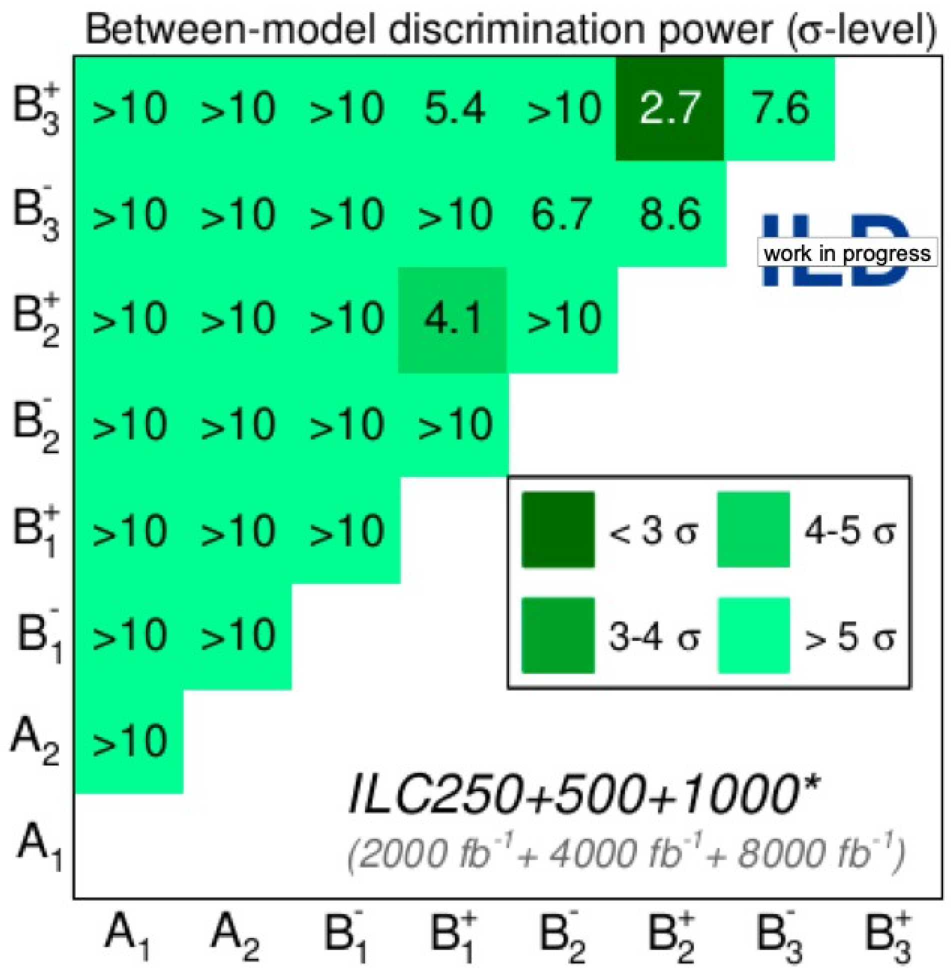


- The current analysis shows the potential to measure light quarks at e+e- colliders
- Even more than others light quarks rely on excellent particle ID
  - ... over full solid angle
- The hard cuts to get a clean sample in this analysis results in a small efficiency O(1%)
- Clear room for improvement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

Interpretation of two fermion processes

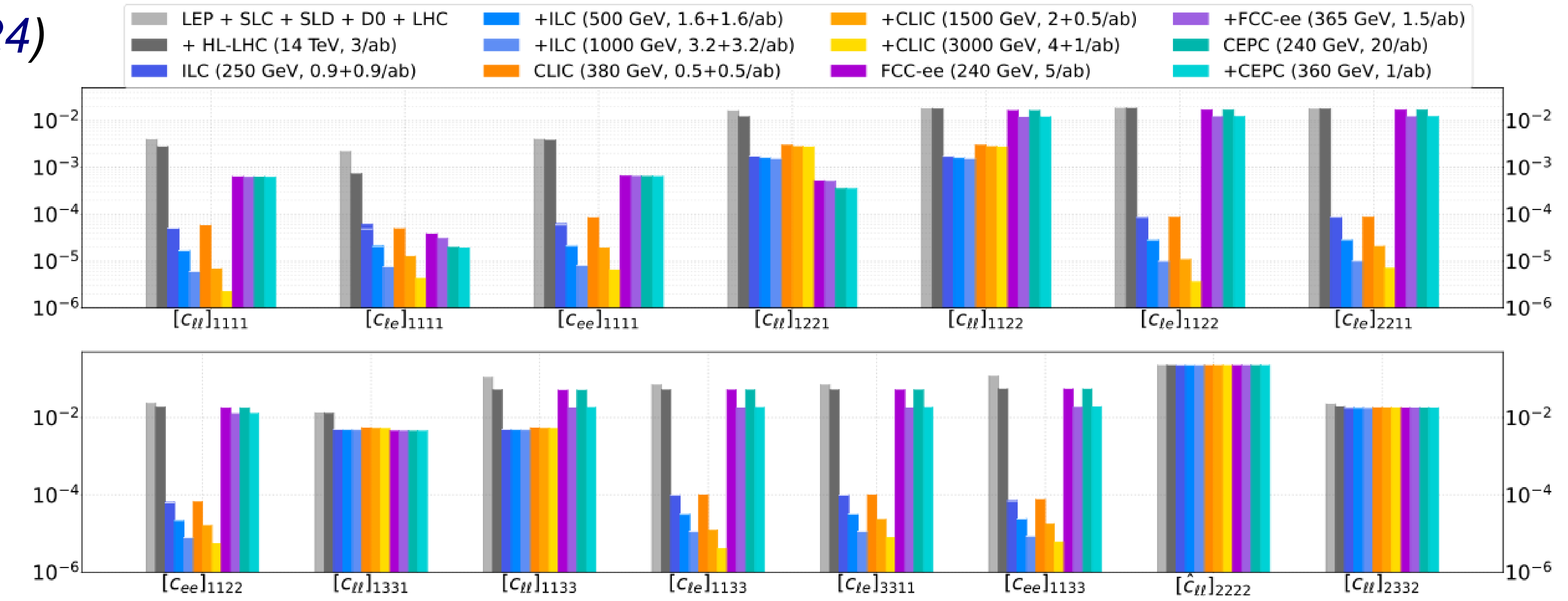
Separation power in GHU Models

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 and 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

Summary and outlook

- Lepton Focused topics are opportunity to revisit existing results in larger community
  - Many topics are (collider) "flavor blind"

- Measurement of top mass to a precision of ~50 MeV in clean environment
  - Flexibility in energy allow for complementary methods
  - Threshold scan and radiative events
  - **Full simulation needed**

- At LC Top (and tau) physics allow for complementary studies using initial and final state polarisation
  - However, for me there is no doubt that for top physics one needs higher energies
  - How dangerous in the threshold region in terms of matching uncertainties?

- Will/would probe helicity structure of electroweak fermion couplings over at least one order of magnitude in energy (Z-Pole -> ~1 TeV)
  - Full simulation on Z-Pole are still lacking

- Main challenge at all future machines will be the control of systematic errors
  - Experimentally
    - Vertex charge and particle ID
    - PFO for final state jets
  - Theoretically
    - QCD in many aspects
    - Need at least NLO electroweak predictions (and MC programs) for correct interpretation of results

Contact

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

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- and/or email the conveners of ECFA WG1 SeaRCHes group: mailto:ecfa-whf-wg1-srch-conveners@cern.ch

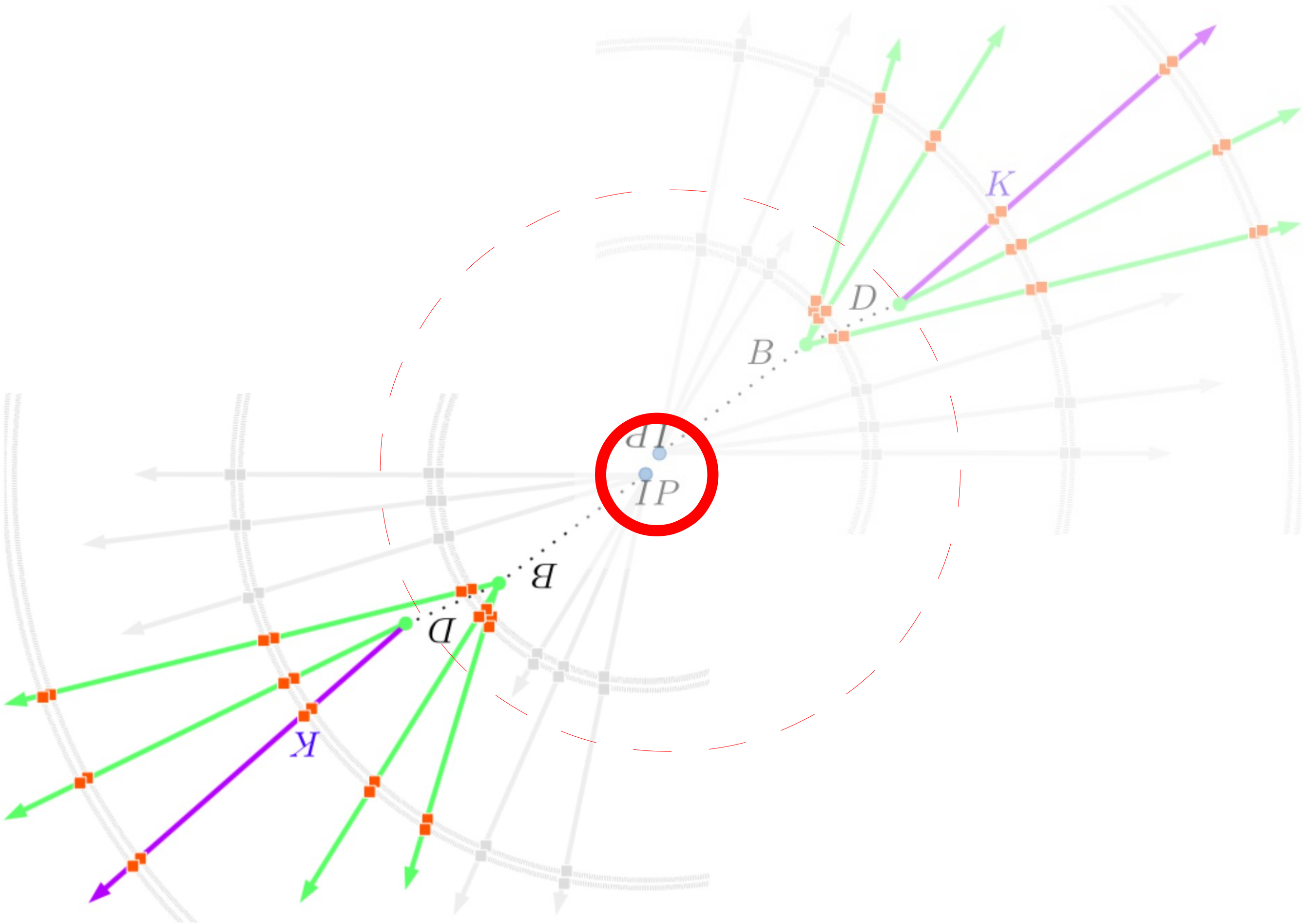
Contact & Further Information

- 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

Backup

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

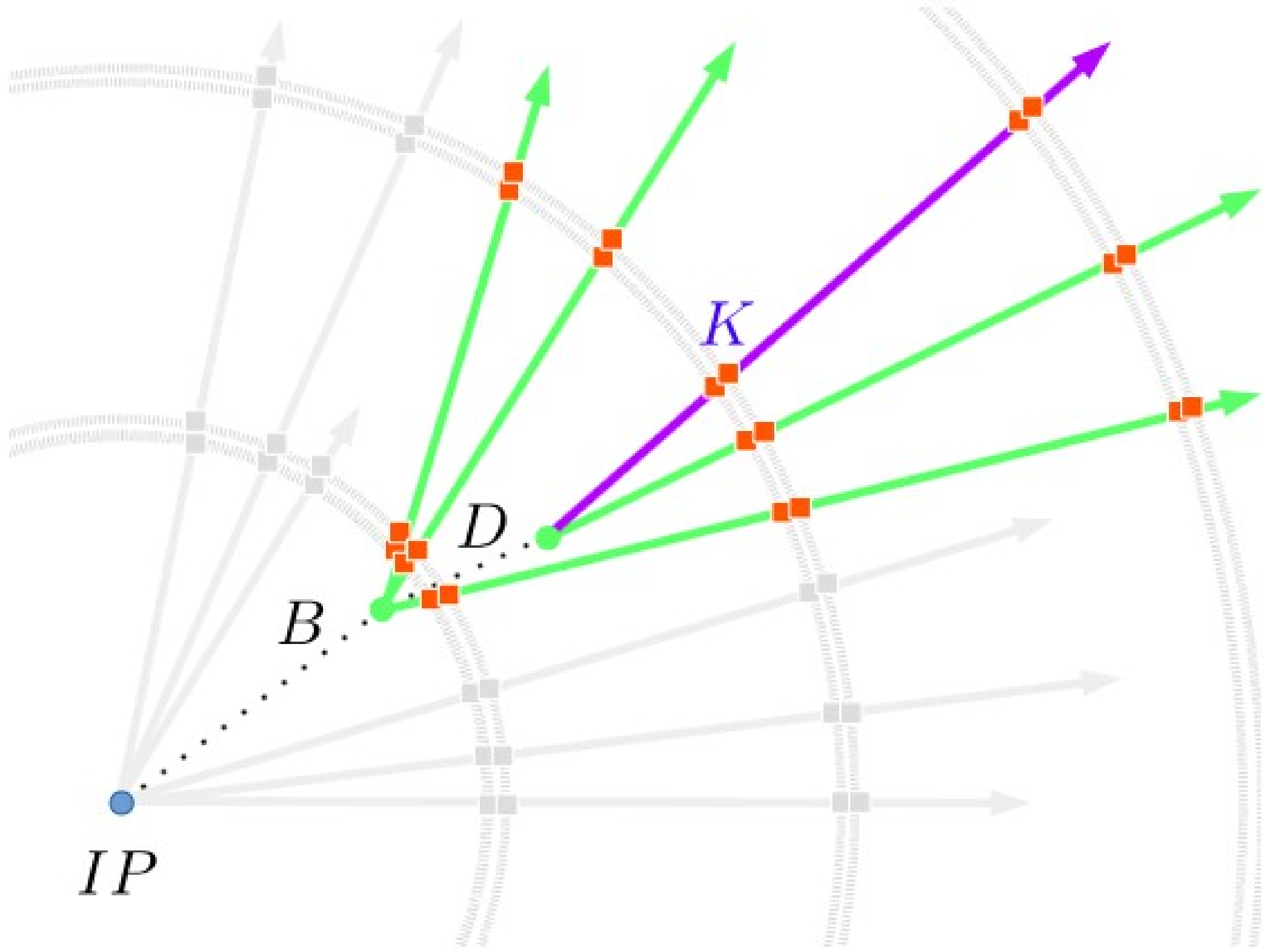
For example:

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

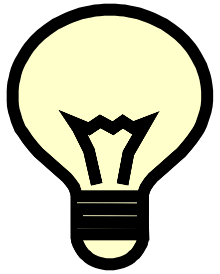
Experimental challenges - Flavor tagging and charge measurement



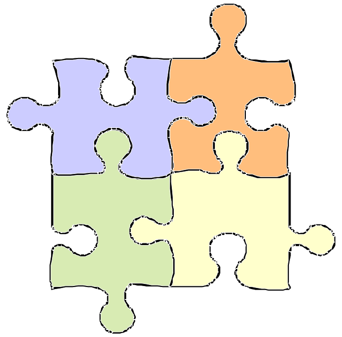
PhD thesis: S. Bilokin
A. Irles

- 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

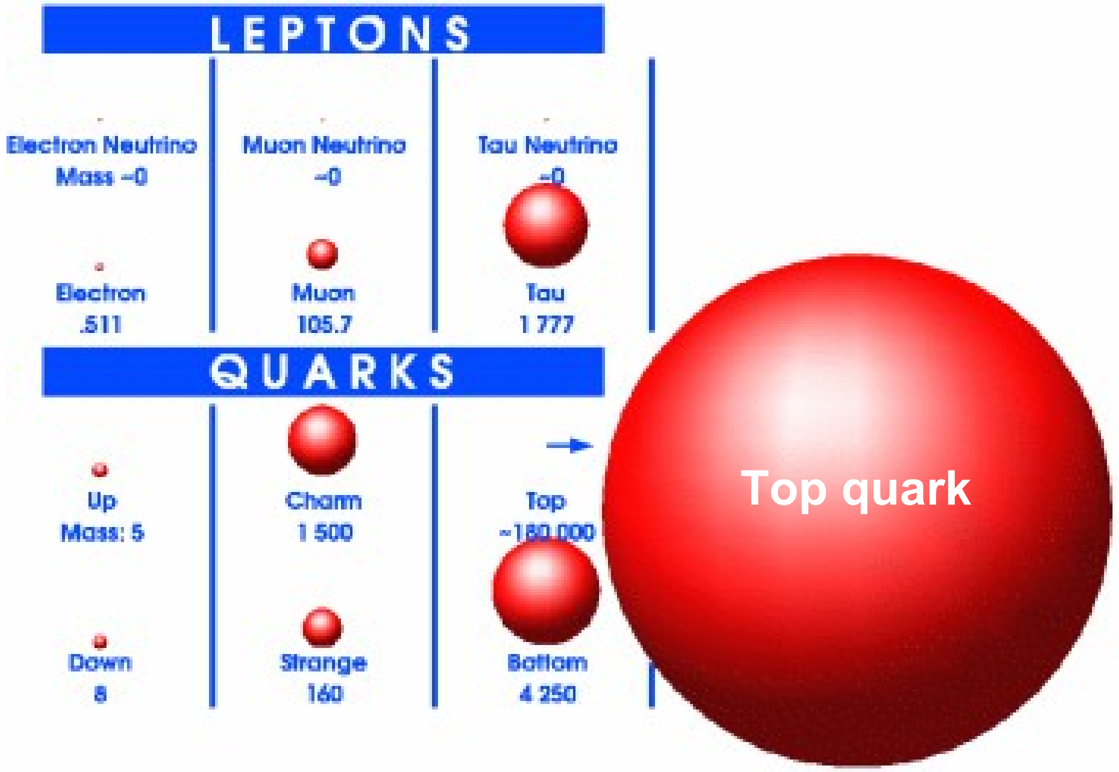
An enigmatic couple



Elementary Scalar?



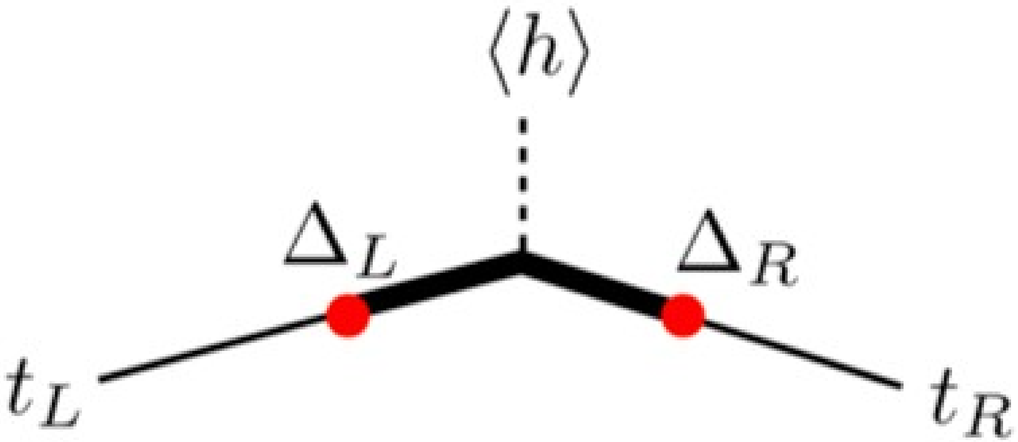
Composite object?



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

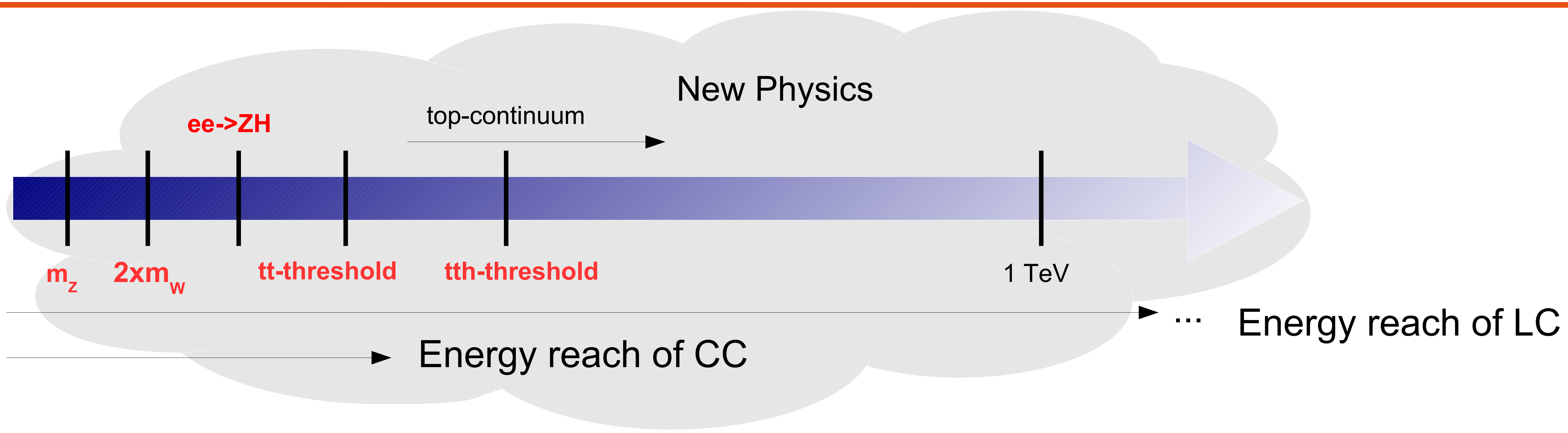
- New physics by compositeness?
  Higgs and top composite objects?

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



Courtesy of S. Rychkov

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

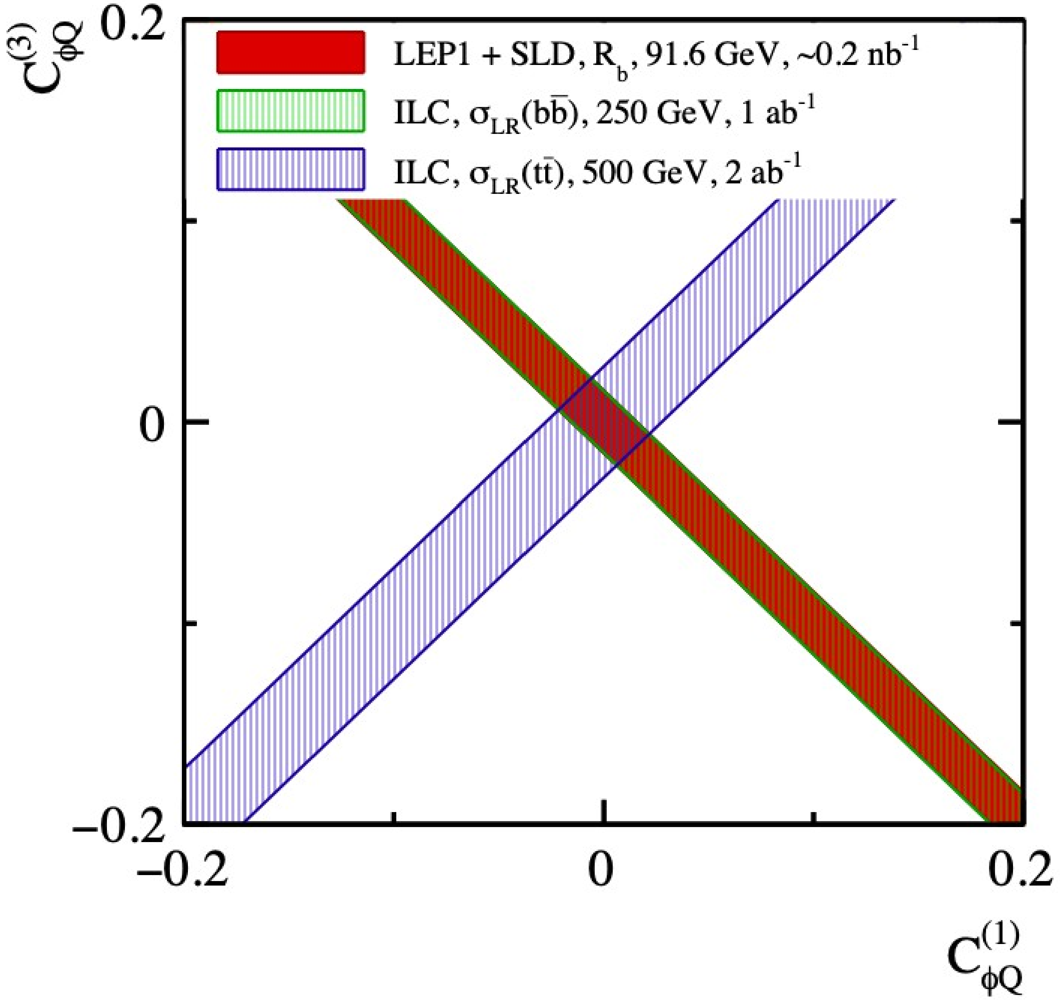
- Centre-of-Mass energy
- Beam polarisation (straightforward at linear colliders)

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

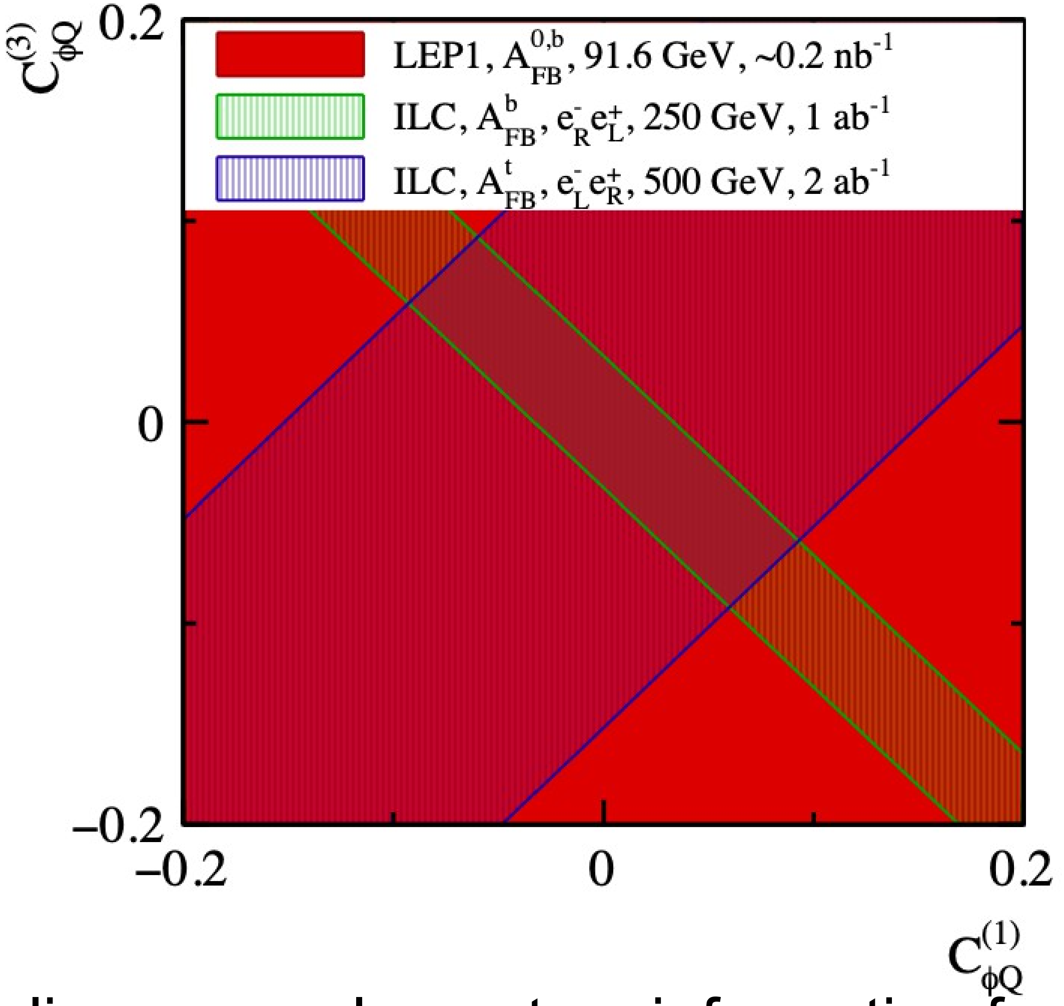
Background free searches for BSM through beam polarisation

Interplay b/t

From cross section



From forward-backward asymmetry



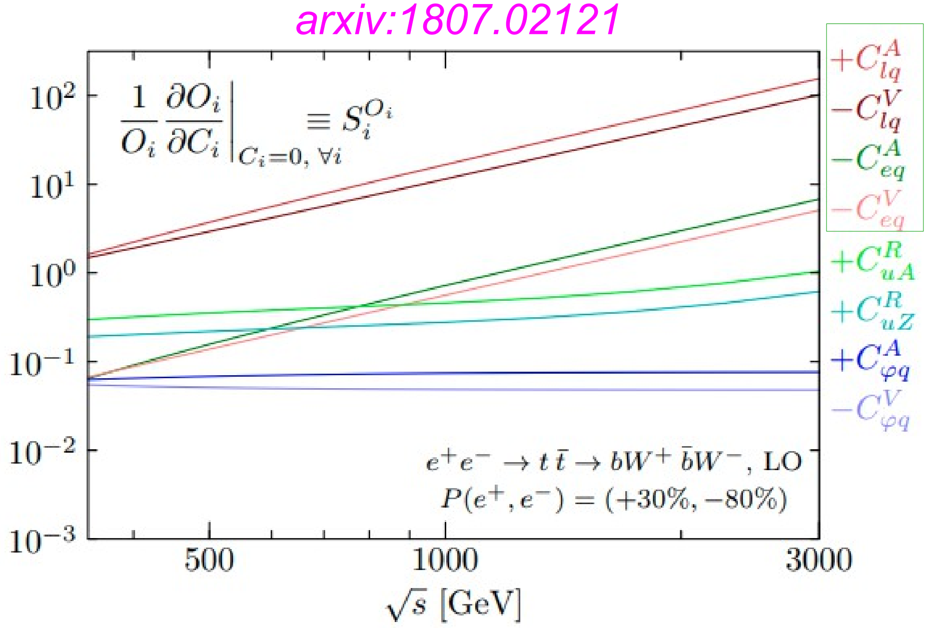
- Measurement of bottom and top observables delivers complementary information for EFT operators
- ILC@250 GeV comparable to LEP in terms of cross section => Constrain on g_{Lb}
- ILC@250 GeV drastically better than LEP in terms of AFB => Constrain on g_{Rb}
  - How would the picture look with GigaZ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

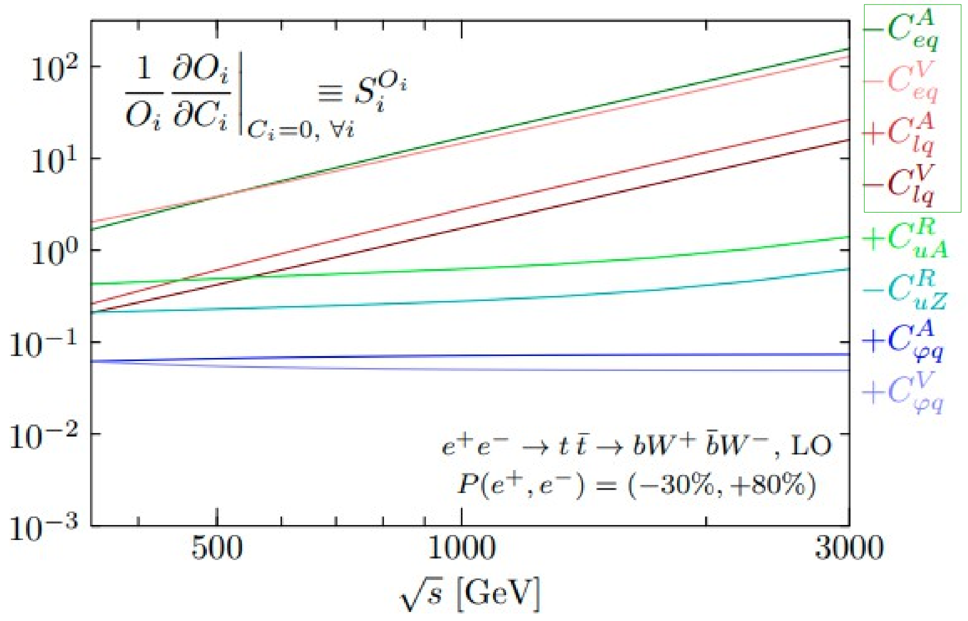
arxiv:1907.10619

Effects at higher energies

Development of EFT Operators

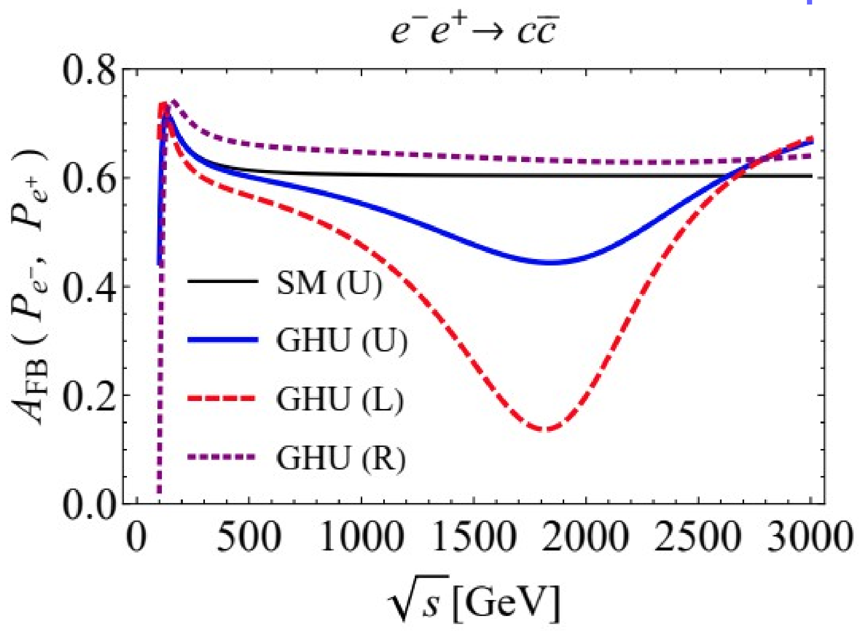
arxiv:1807.02121

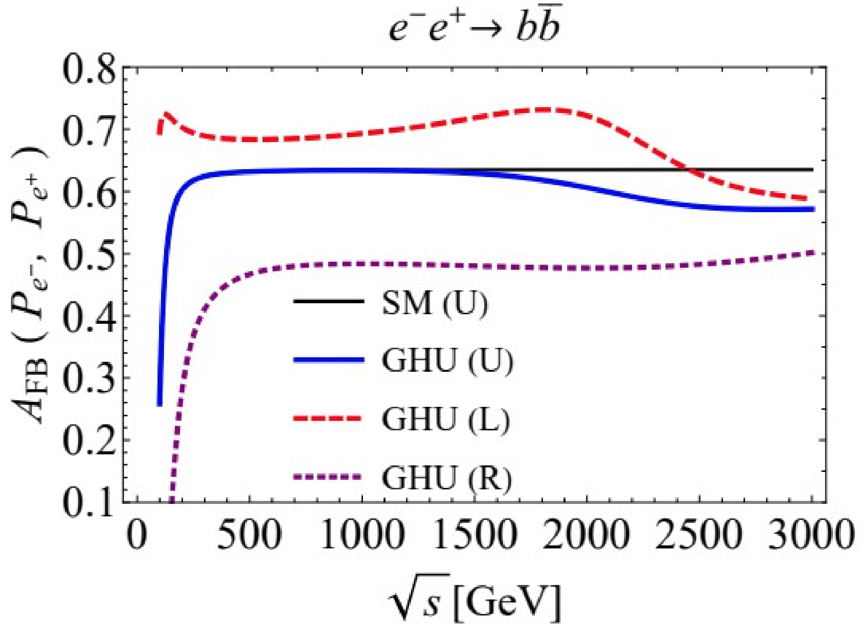


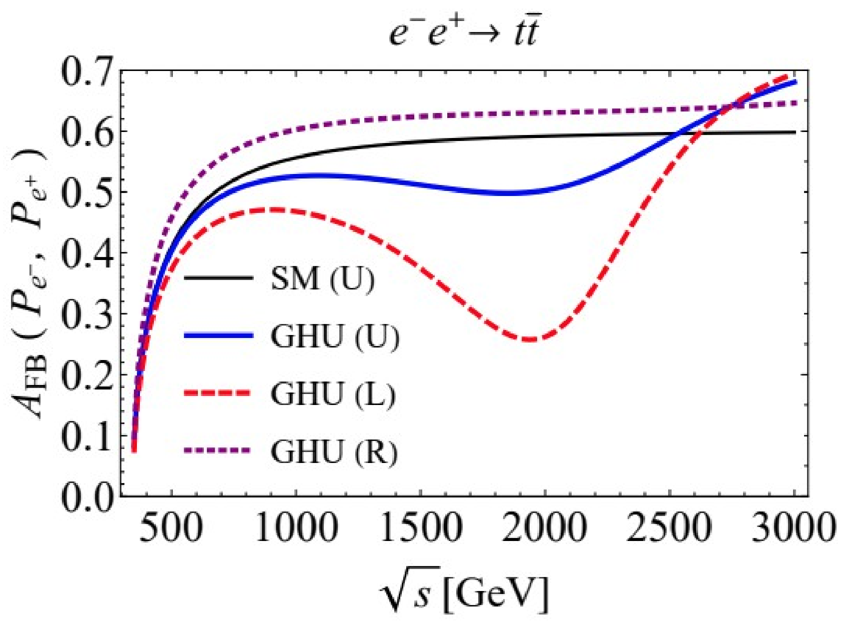


Increased sensitivity to operators representing four-fermion interactions

GUT Inspired GHU Model



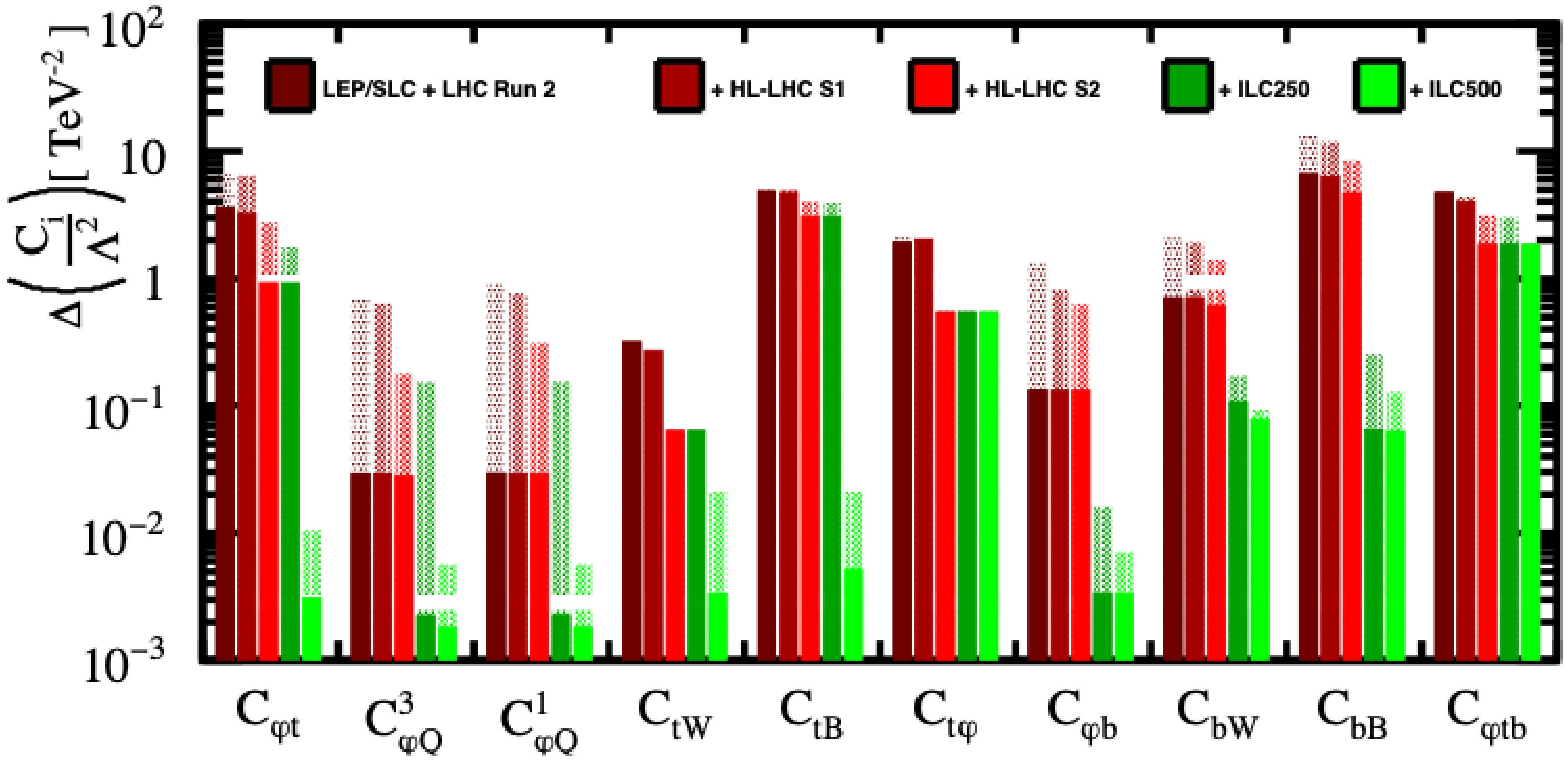




- Effects amplified at higher energies
- Different patterns for different beam polarisations (L, U, R)
- Different patterns for different fermions

Electroweak top couplings EFT-operators

arxiv:1907.10619



Mapping between FF and EFT Coefficients

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

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

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

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

arxiv:1807.02121

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

Z-Pole Systematics – Summary for asymmetries

Summary: Theory inputs for asymmetries

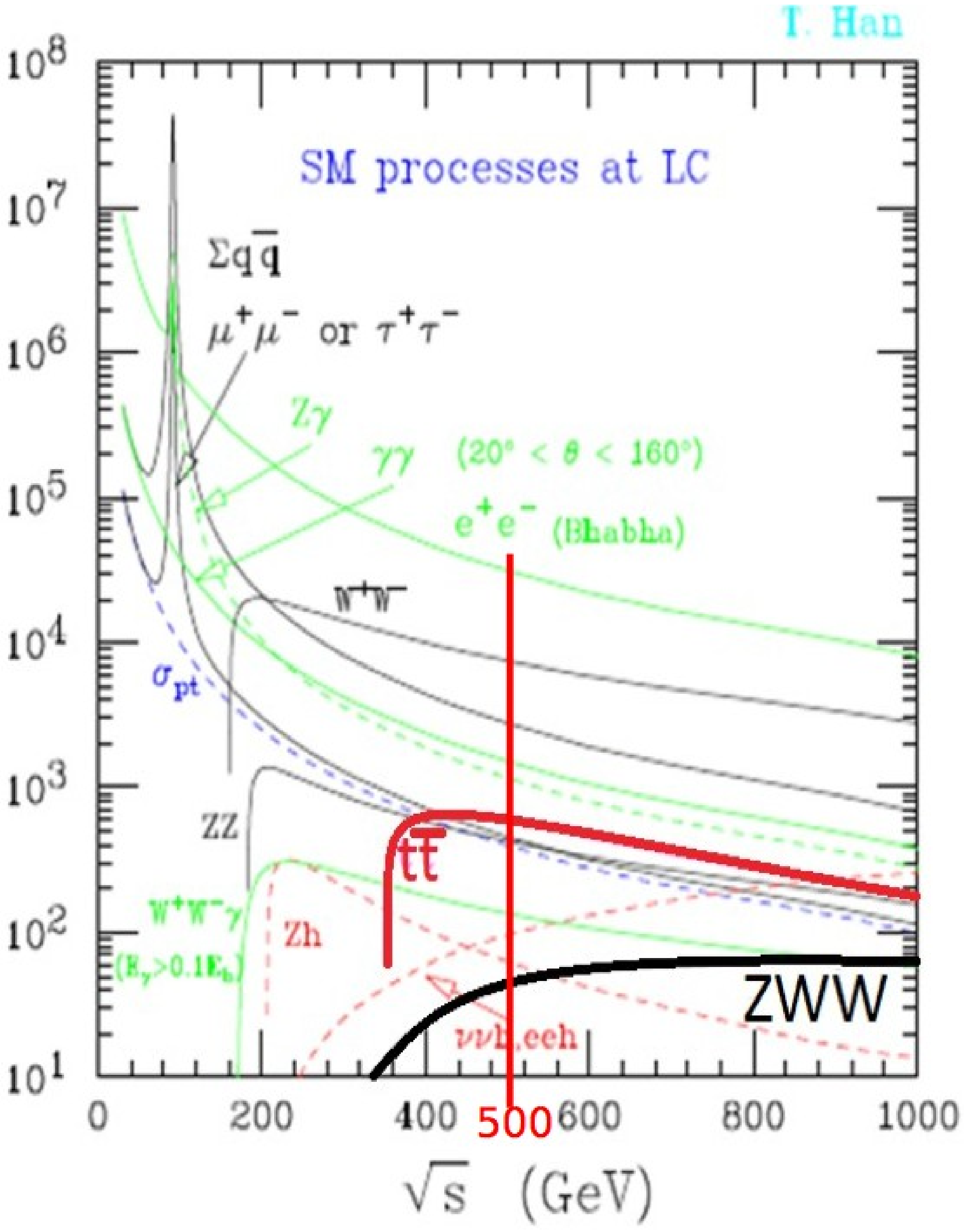
Observables	Present value ($\times 10^4$)	TeraZ / GigaZ stat.	TeraZ / GigaZ current syst.	Theory input (not exhaustive)
A_e from P_τ (FCC-ee)	1514 ± 19	0.07	0.20	SM relation to measured quantities
A_e from A_{LR} (ILC)		0.15	0.80	
A_μ from A_{FB} (FCC-ee)	1456 ± 91	0.23	0.22	Accurate QED (ISR, IFI, FSR)
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

352 GeV (unpol)

Channel	$\sigma_{unpol.}$ [fb]	$\sigma_{-,+}$ [fb]	$\sigma_{+,-}$ [fb]	352 GeV (unpol)
$t\bar{t}$	572	1564	724	450 fb
$\mu^+\mu^-$	456	969	854	
$\sum_{q=u,d,s,c} q\bar{q}$	2208	6032	2793	25.2 pb
$b\bar{b}$	372	1212	276	
γZ^0	11185	25500	19126	
W^+W^-	6603	26000	150	11.5 pb
Z^0Z^0	422	1106	582	865 fb
$Z^0W^+W^-$	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	

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

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

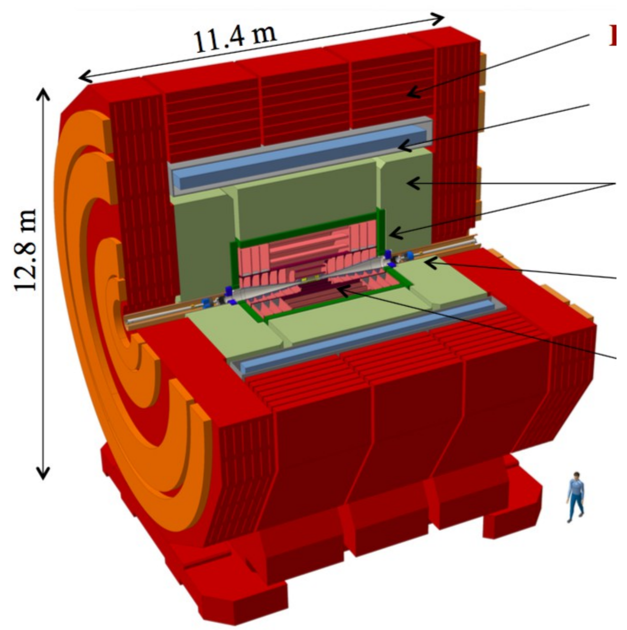
$$\sigma(P_{e^-} = +1, P_{e^+} = -1) \approx 3565\,\text{fb}$$

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

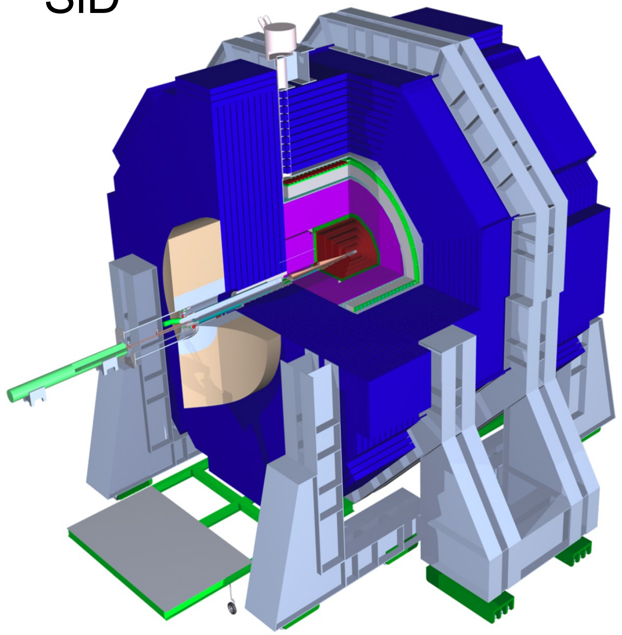
Detector requirements

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

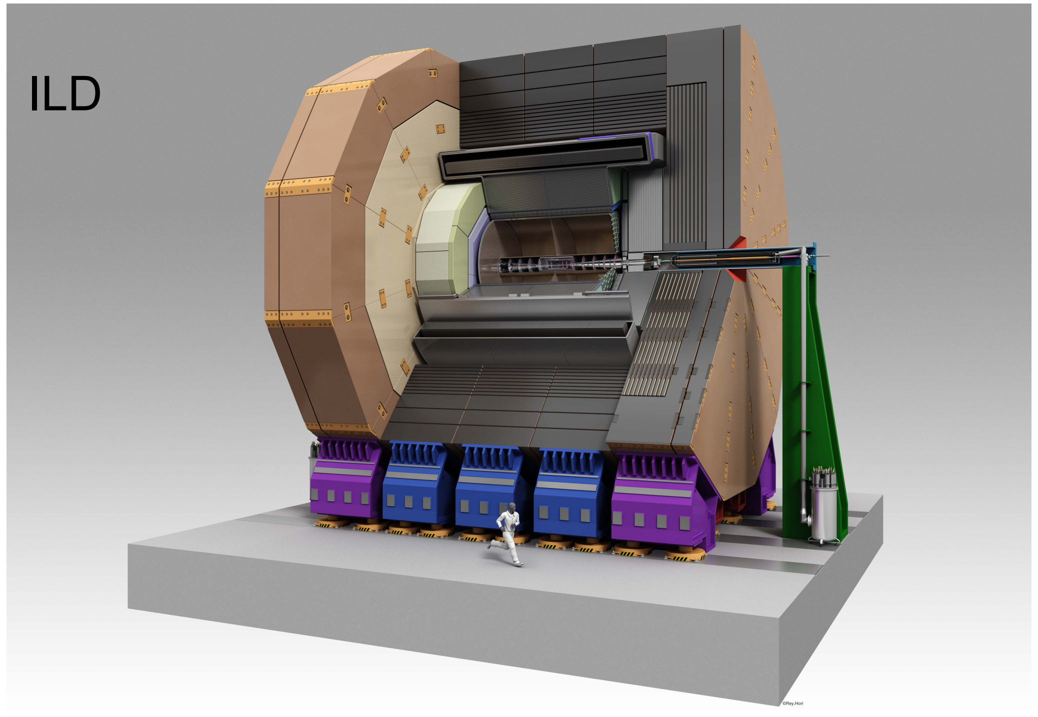
CLIC Detector



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

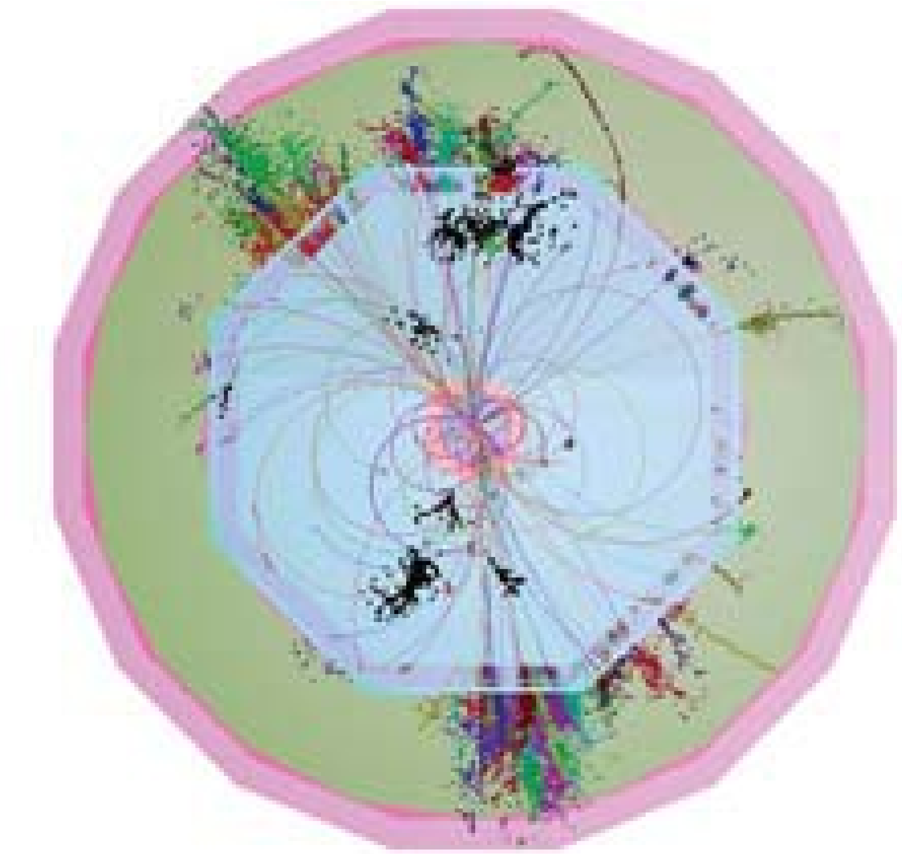
(Quark tagging c/b)

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

(W/Z masses with jets)

Hermeticity : θ_{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+)

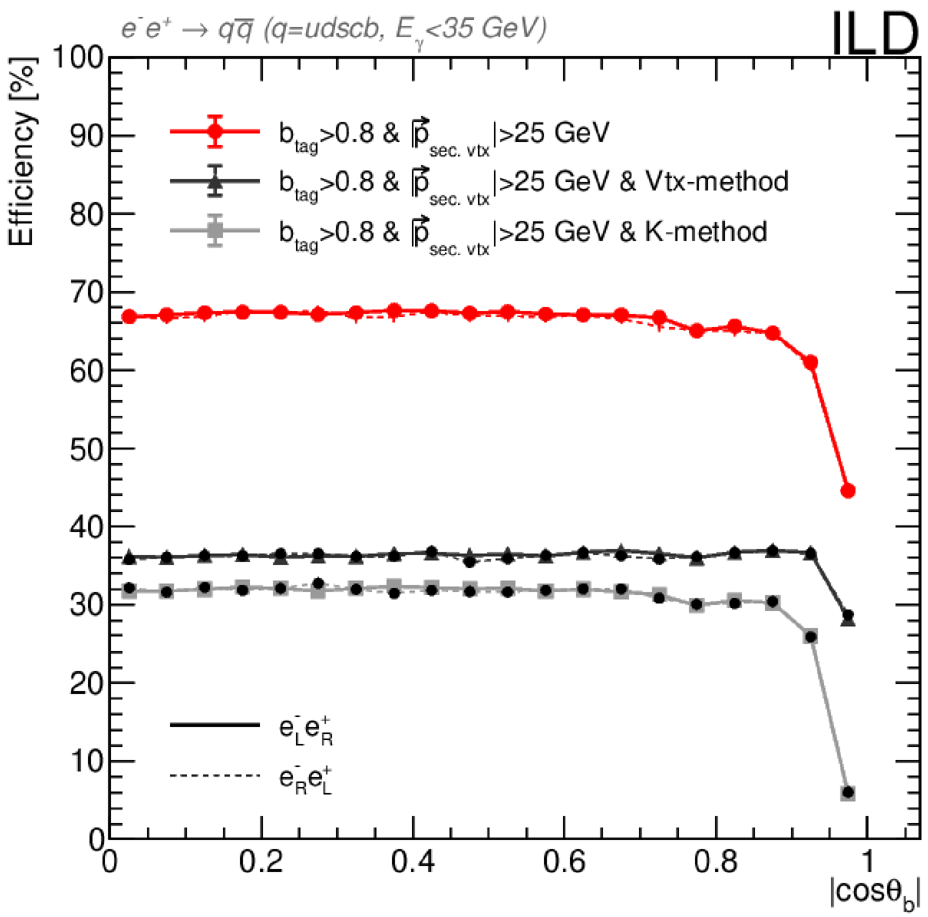
- High granularity
- Excellent momentum measurement
- High separation power for particles

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		

$e^-_R e^+_L \to t\bar{t}$ 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%

Total cross section

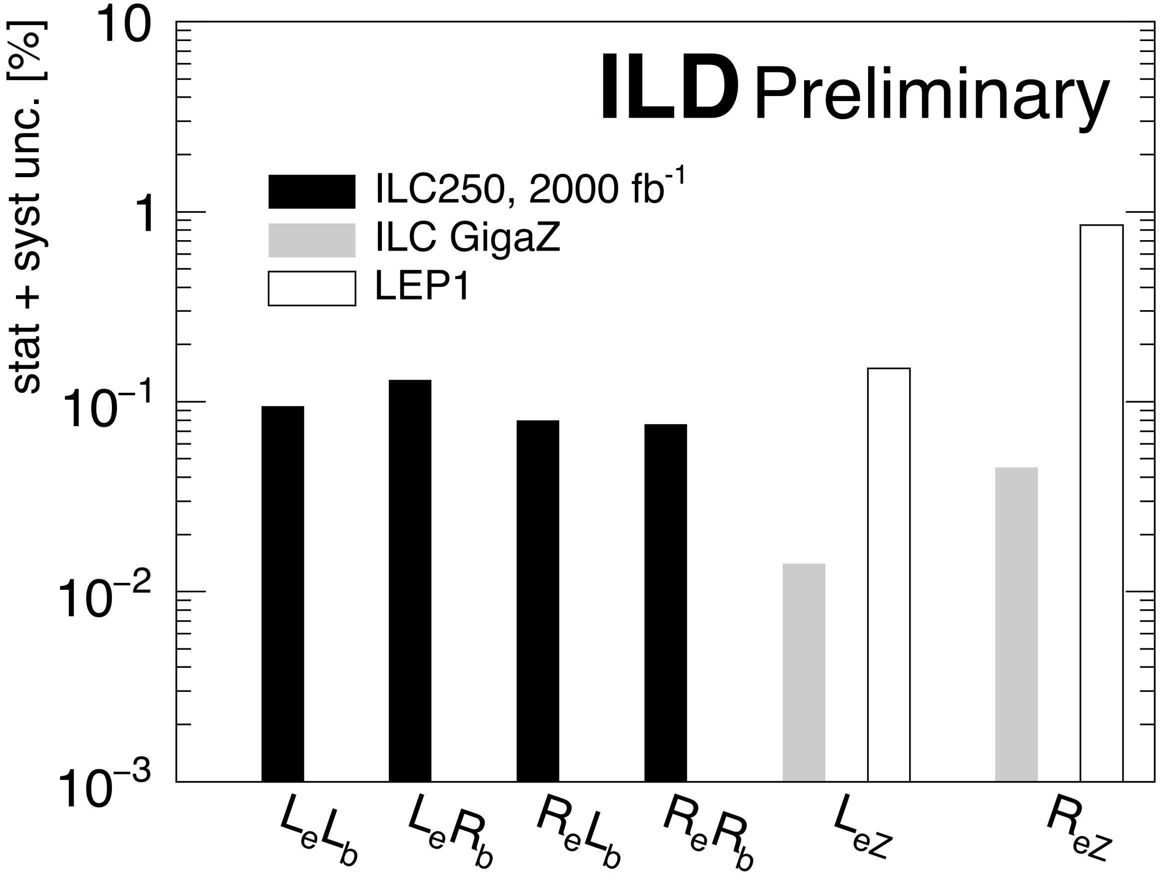
- Typical efficiency 75%
- Independent of beam polarisation

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)

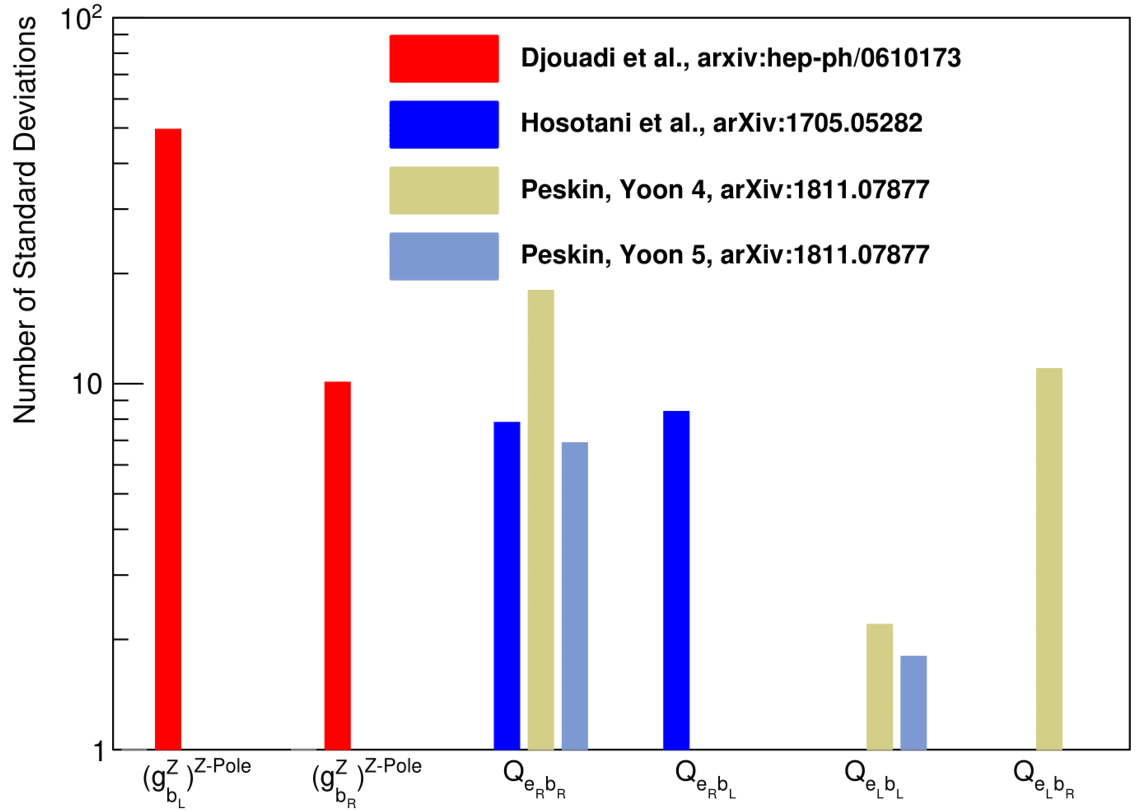


Couplings are order of magnitude better than at LEP

- 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!!

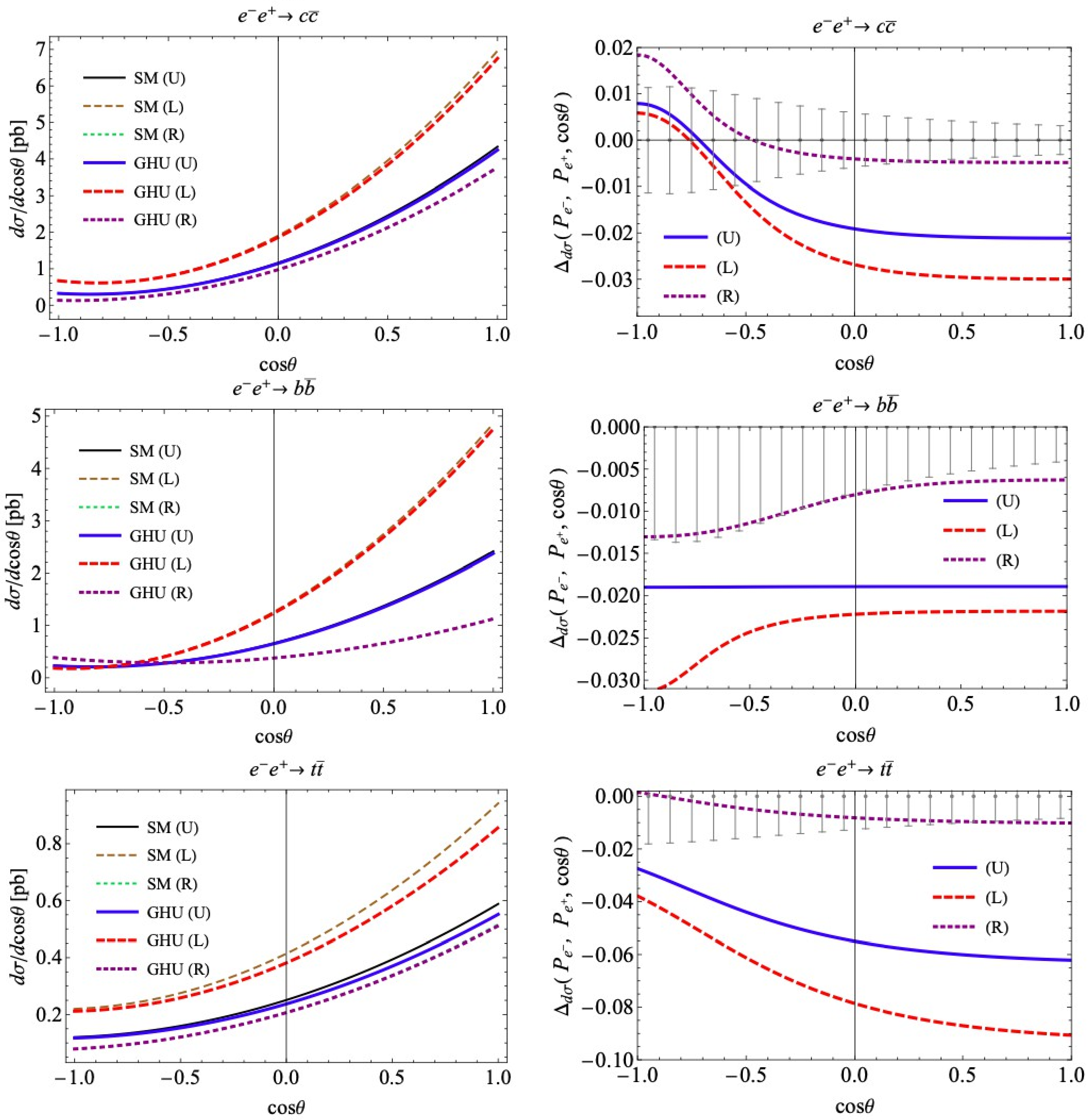


Impressive sensitivity to new physics in Randall Sundrum Models with warped extra dimensions

- **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



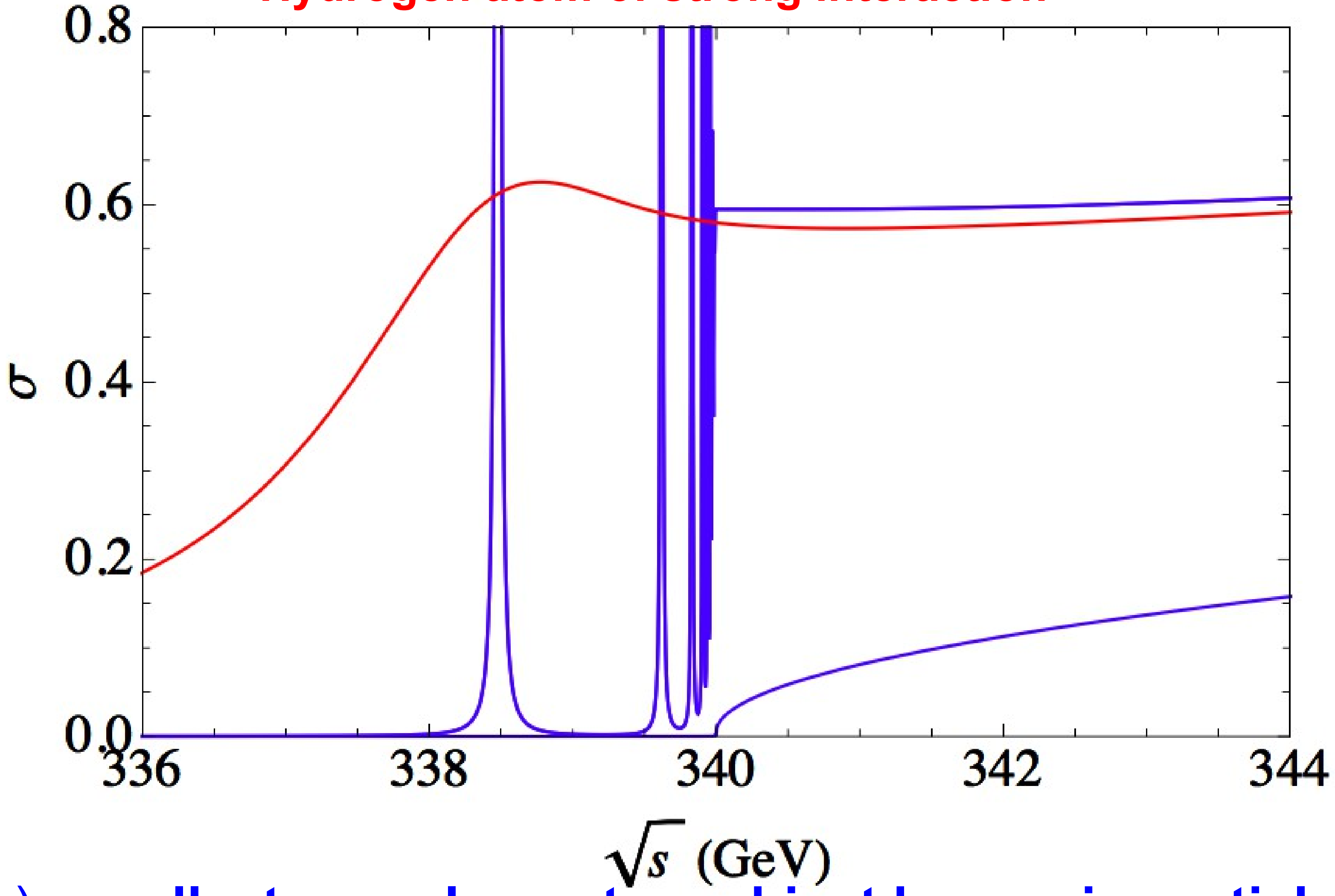
arxiv:2006.02157

- 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

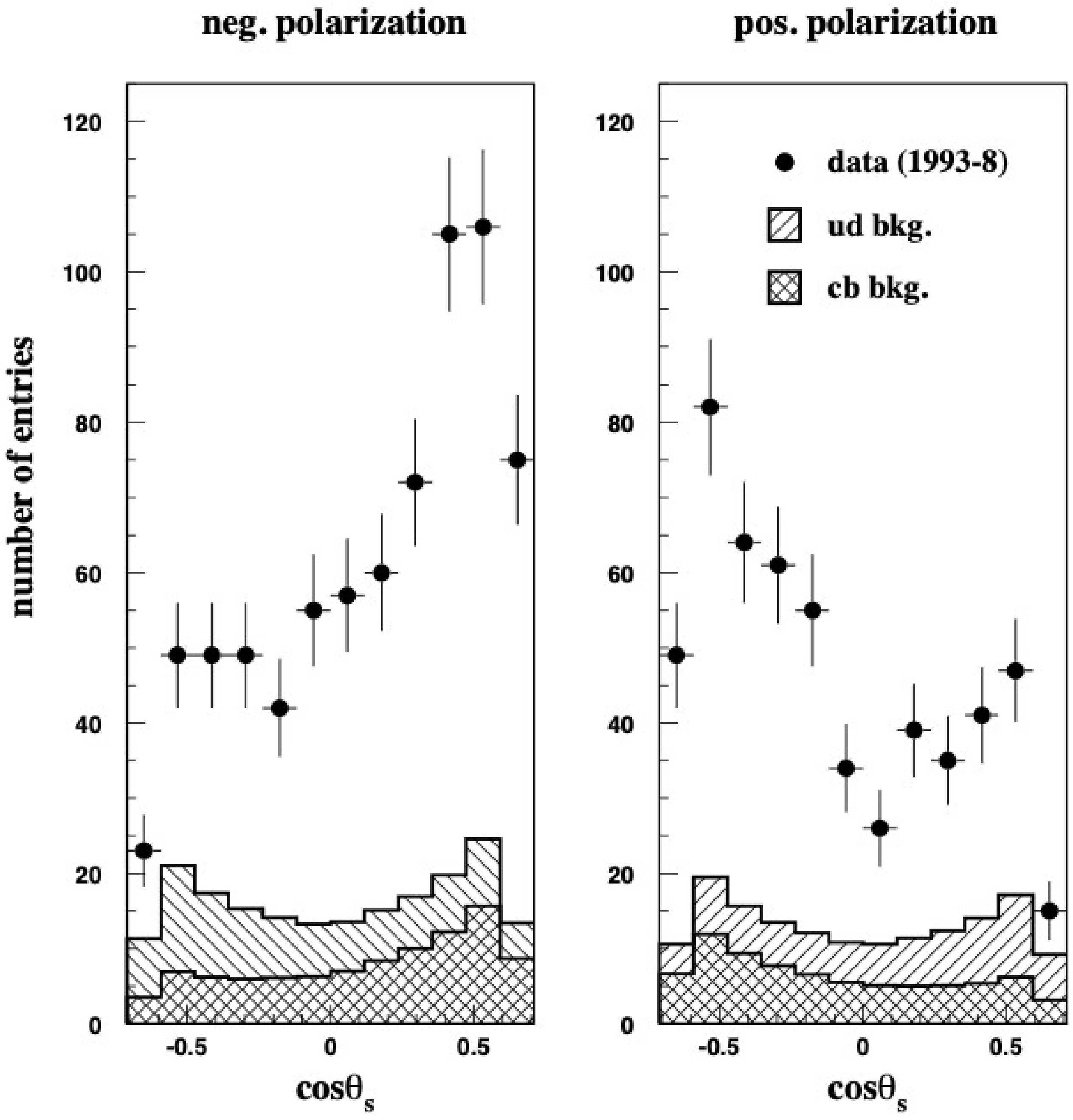


- Size O(10^{-17}m), **smallest non-elementary object known in particle physics**
  Small scale => Free of confinement effects => Ideal premise for precision calculations
  Measurement of (a hypothetical) 1^3S_1 State

- 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

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

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

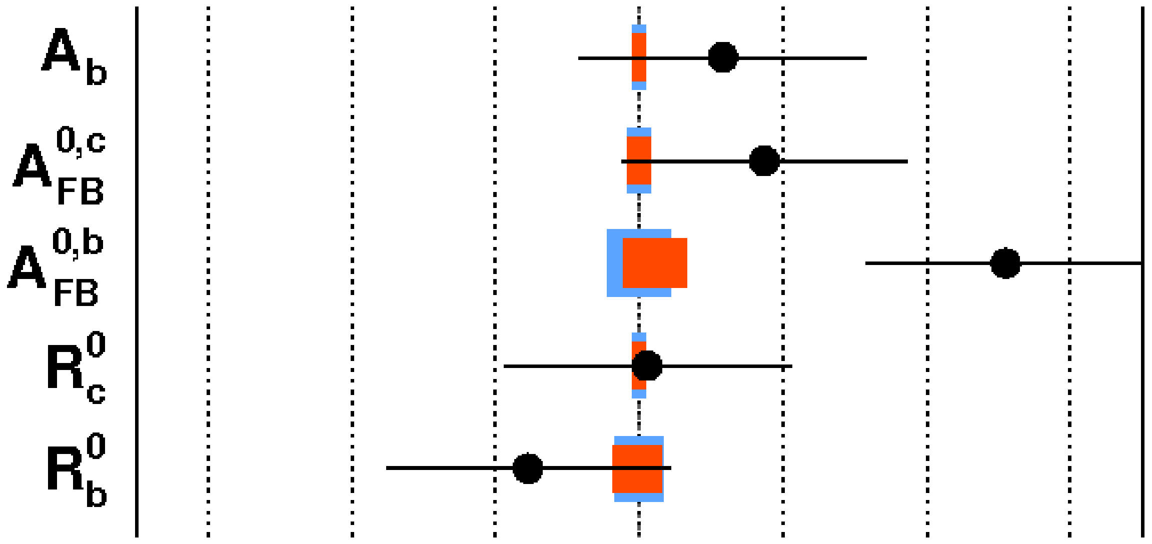
$$F^{\gamma}_{1V},\ F^{Z}_{1V},\ F^{\gamma}_{1A} = 0,\ F^{Z}_{1A}$$
$$F^{\gamma}_{2V},\ F^{Z}_{2V}$$

or equivalently

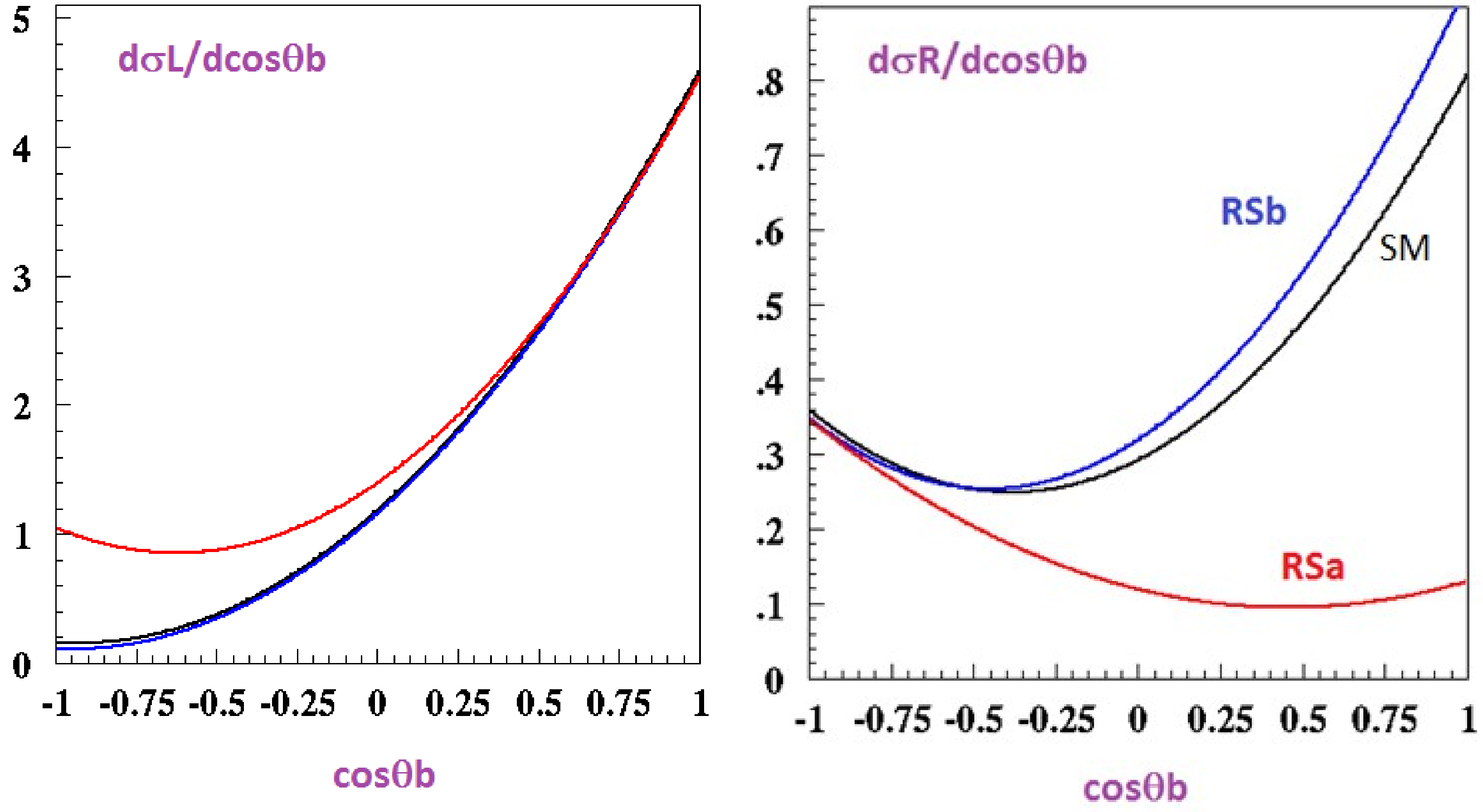
$$g^{\gamma}_{L},\ \ g^{\gamma}_{R},\ \ g^{Z}_{L},\ \ g^{Z}_{R}$$

LEP Anomaly on A_{FB}^{b}

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



ee->bb@250 GeV

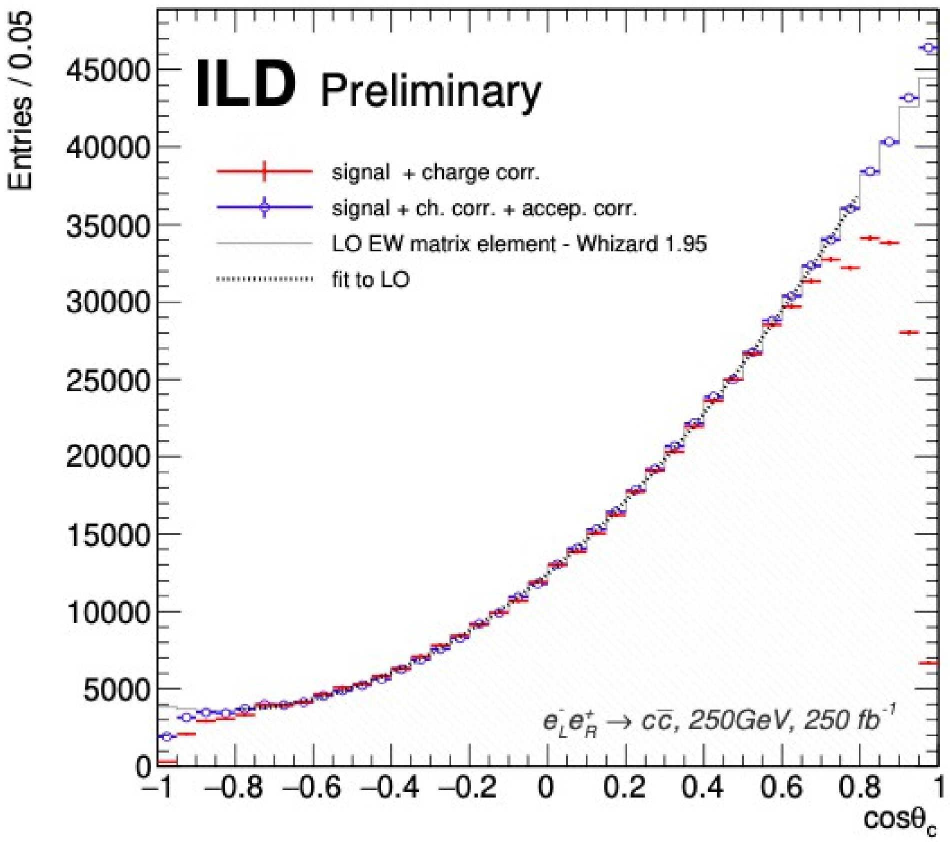


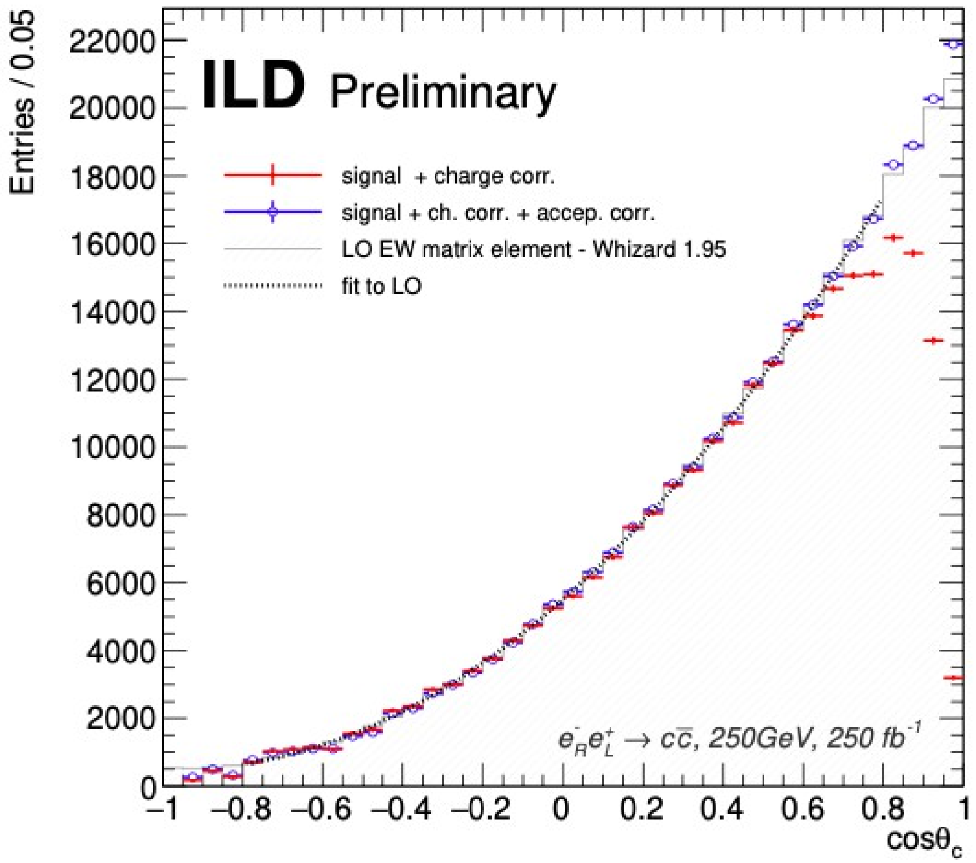
Randall Sundrum Models Djouadi/Richard '06

- 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

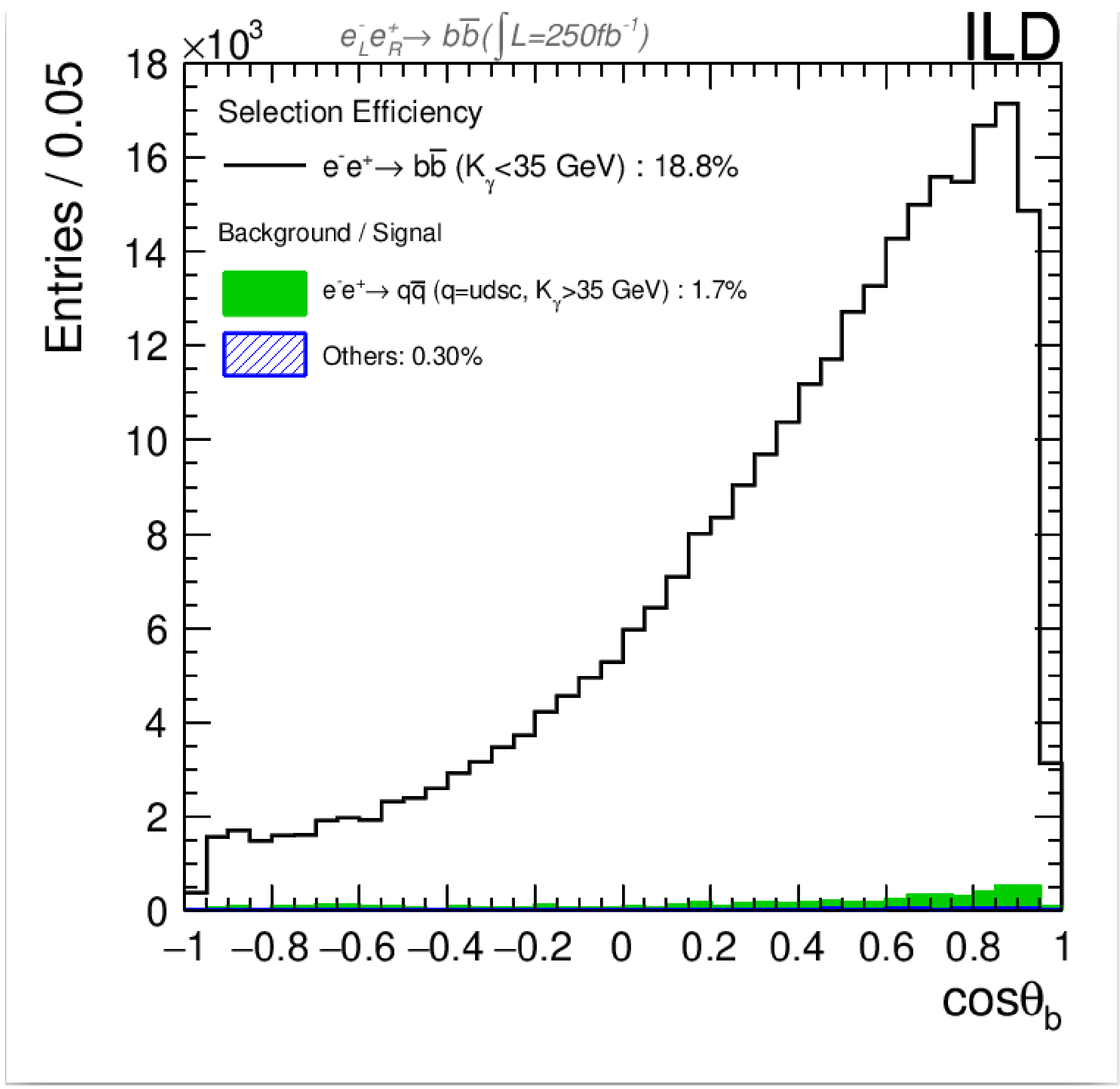


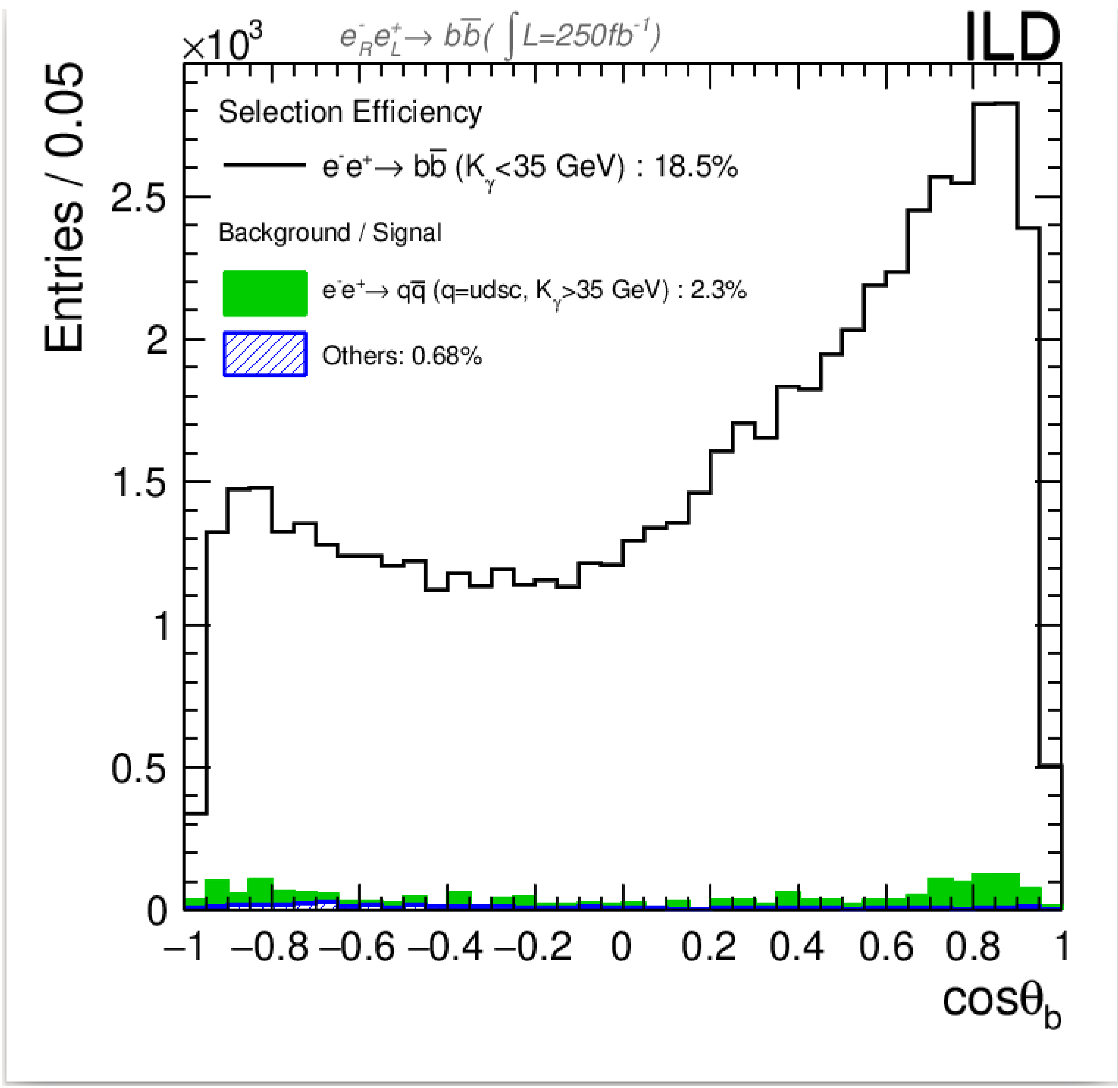


Full simulation study (with ILD concept)
Long lever arm in cos θ_c to extract from factors or couplings

ee-->bb – Signal and background

Arxiv:1709.04289, ILD Paper in progress





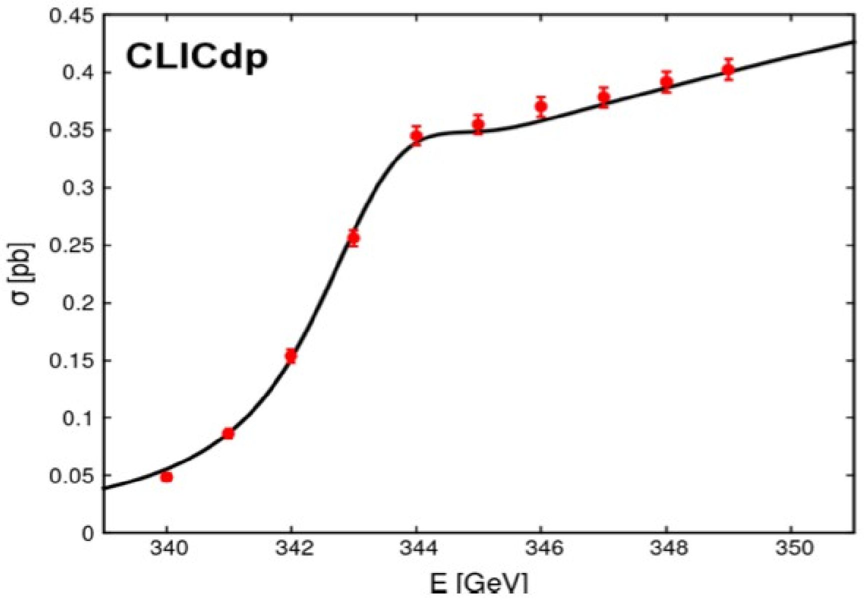
- Background levels can be kept at very small level
- However, these type of analyses seek per-mille level precision

Optimising of scanning points

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

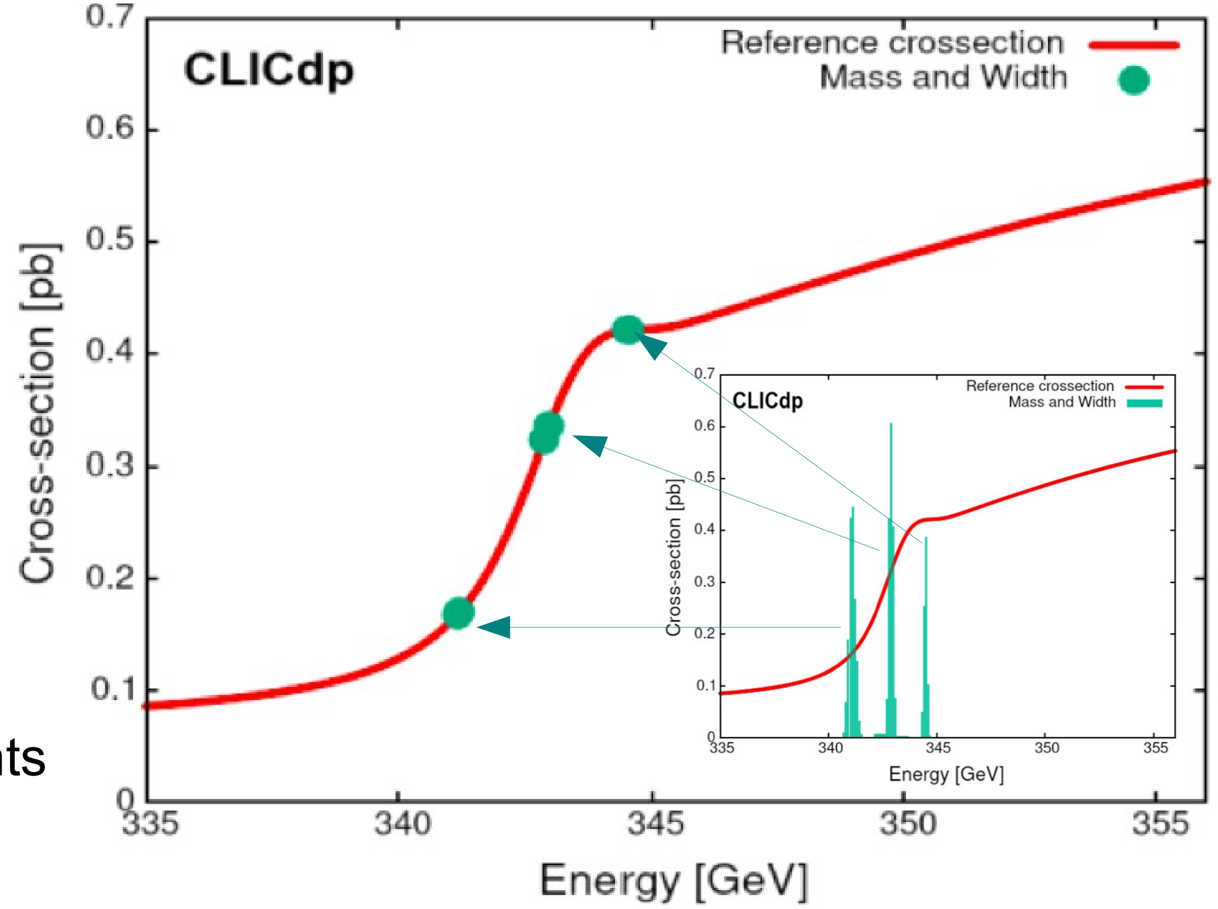
arxiv: 2103.00522

Standard scan scenario

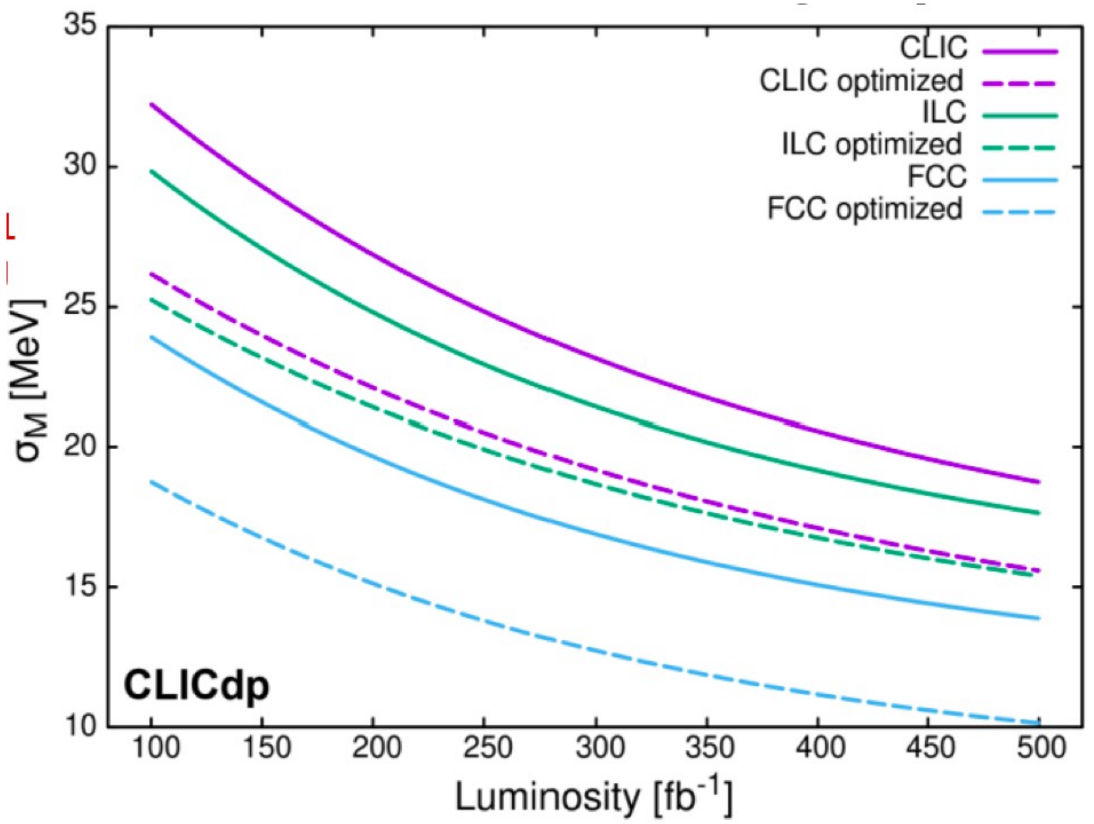


100 fb^{-1} for 10 equally distributed points

Optimised scenario for mass a width



Precision on top mass ...

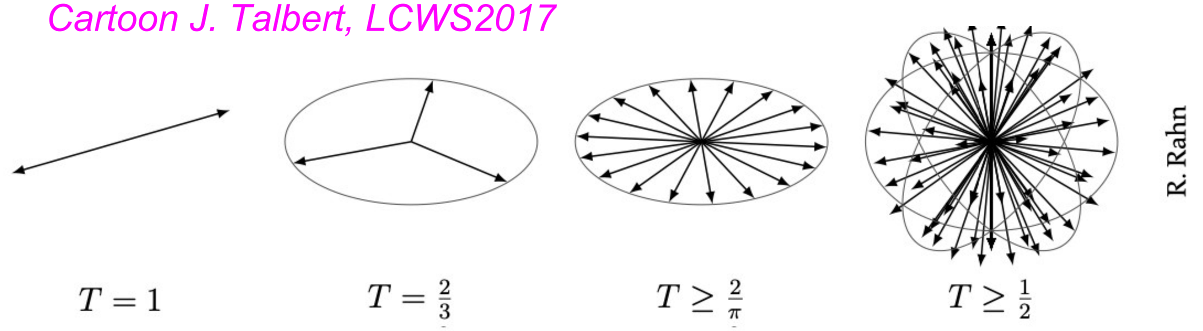


... taking luminosity spectrum into account

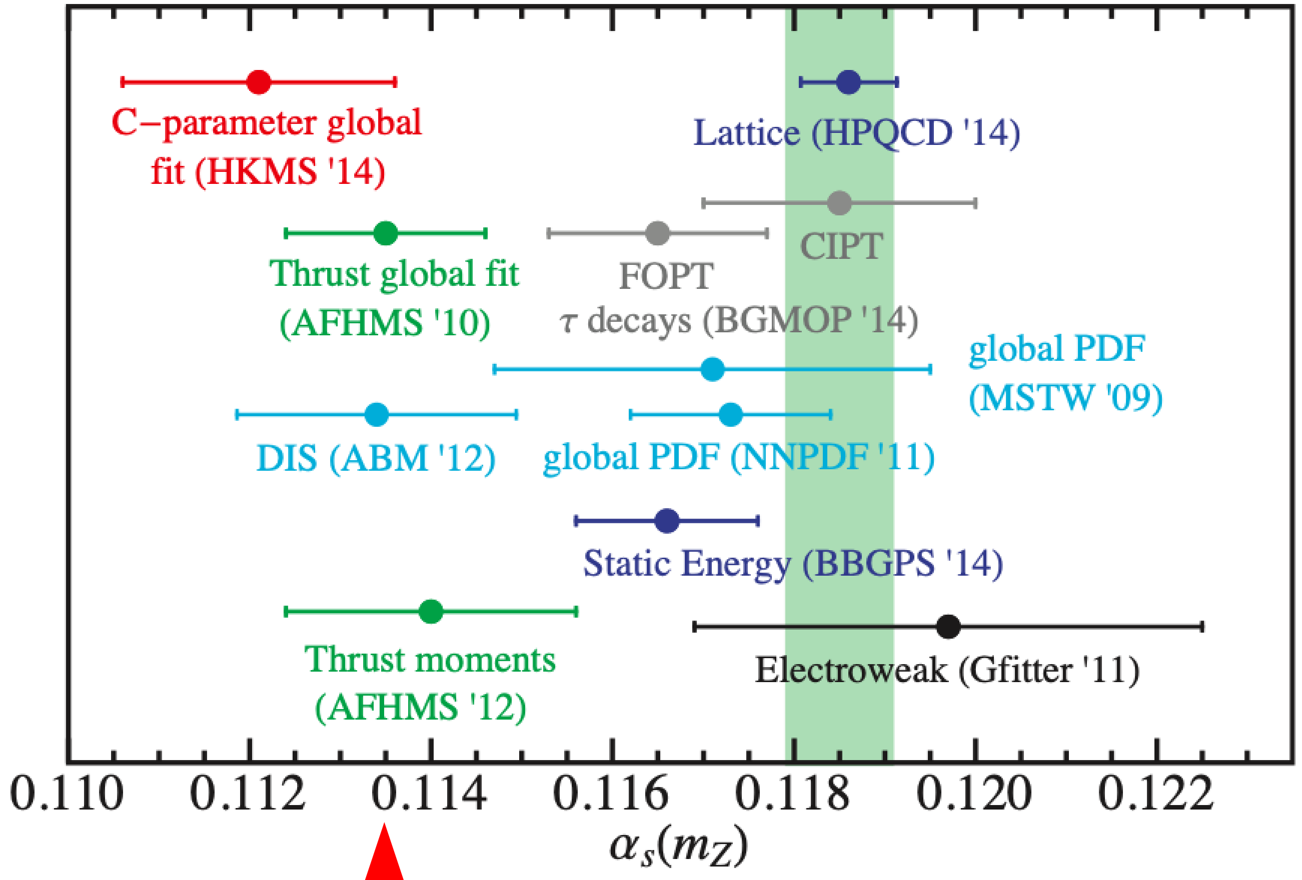
- Optimisation of threshold scan yield 25% statistical precision of top mass compared with scan using equally distributed scan points
  - Choice of measurement points with optimal sensitivity to desired quantity
- For breakdown of systematic errors see backup

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

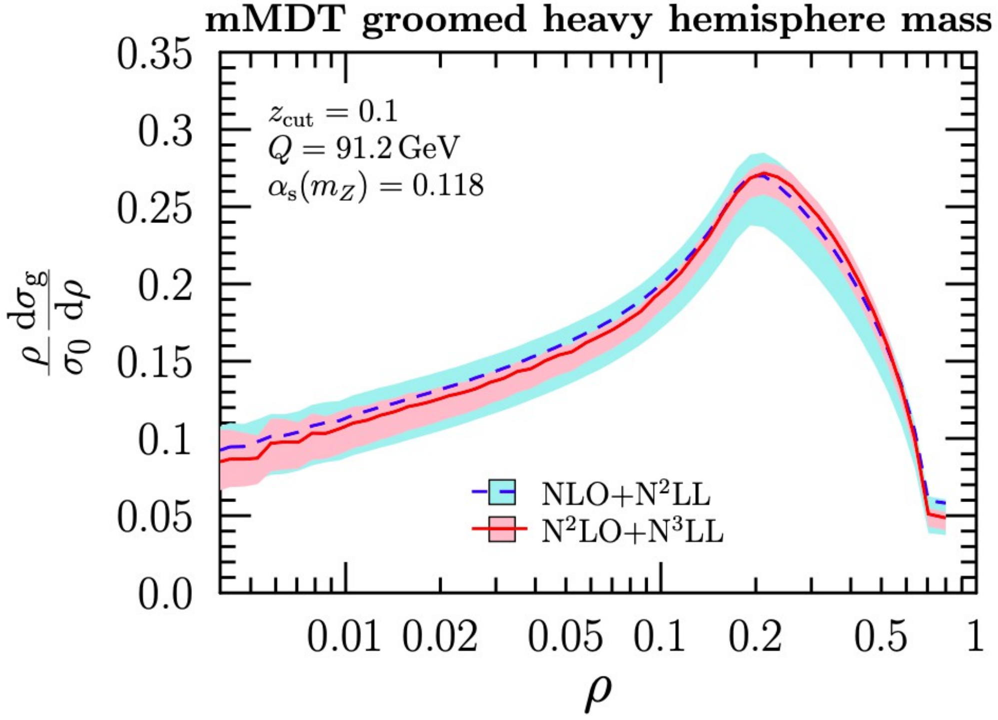
- Most "recent" e+e- input from LEP

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