Precision electroweak capabilities of ILC

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CNRS IN2P3 Les deux infinis

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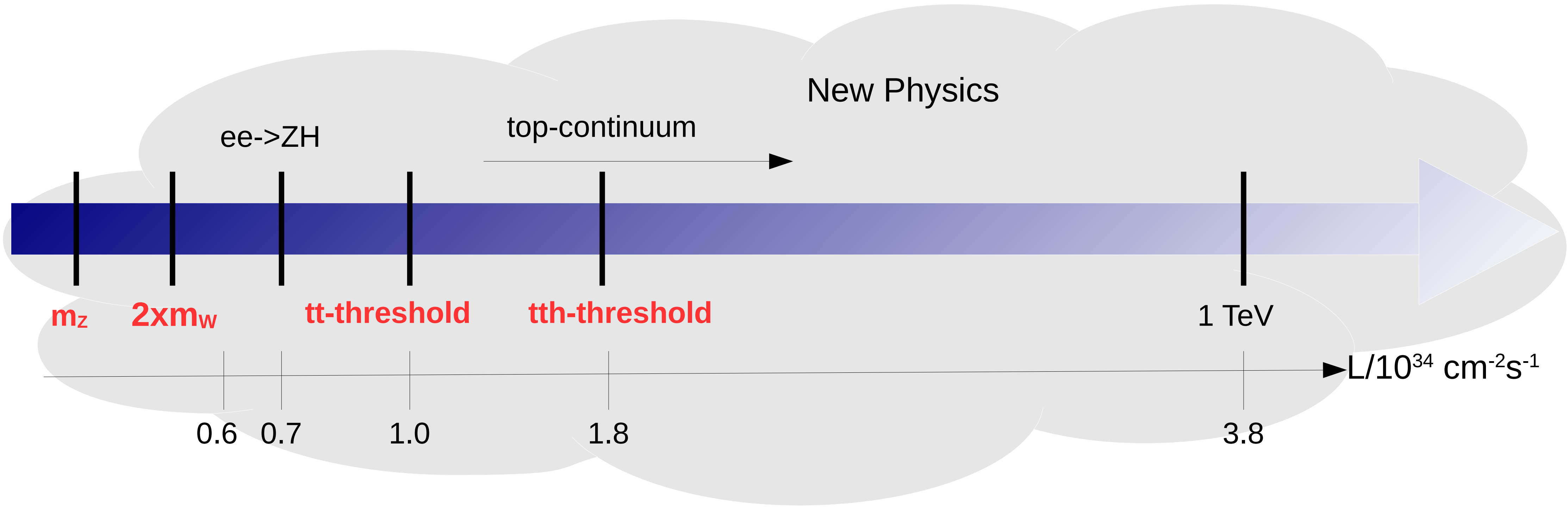
P2IO Physique des 2 Infinis et des Origines

Based on material of a number of distinguished colleagues

ECFA Higgs Study WG1 PREC Meeting – March 2022

e+e- Physics program



New Physics

top-continuum

ee->ZH

m_Z

$2xm_W$

tt-threshold

tth-threshold

1 TeV

$L/10^{34}$ cm^{-2}s^{-1}

0.6 0.7 1.0 1.8 3.8

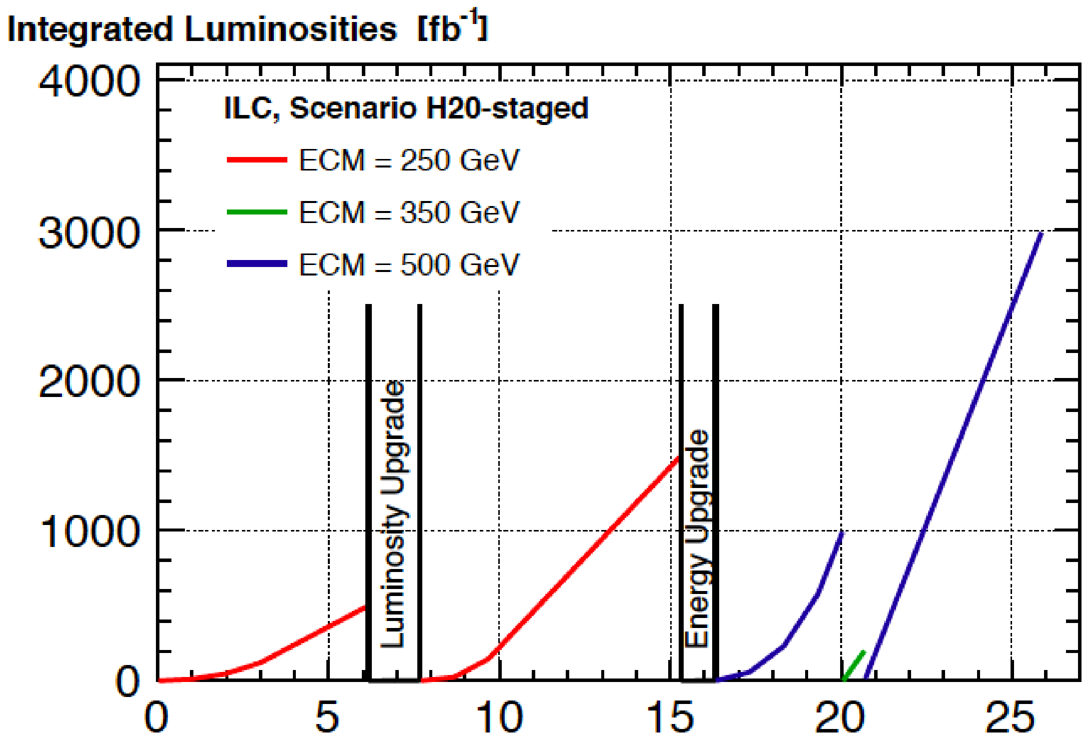
- All Standard Model particles within reach of planned e+e- colliders
- High precision tests of Standard Model over wide range to detect onset of New Physics
- Machine settings can be “tailored” for specific processes
  - Centre-of-Mass energy
  - Beam polarisation (straightforward at linear colliders)

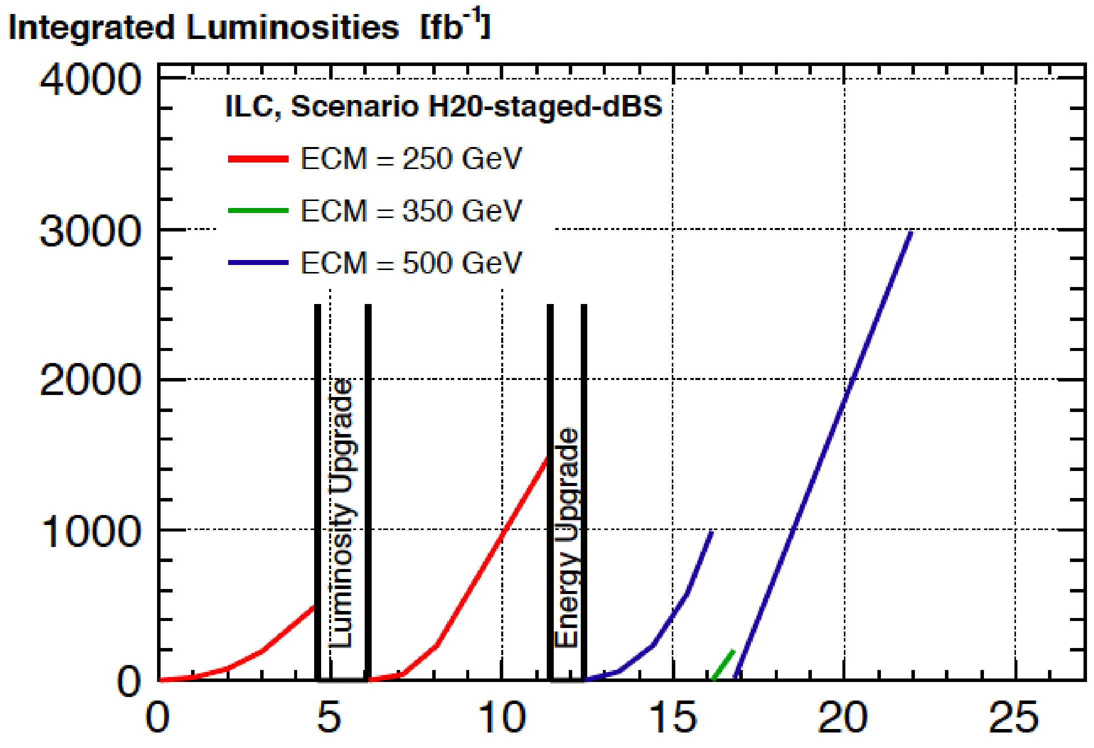
$$\sigma_{P,P'} = \frac{1}{4}\left[(1-PP')(\sigma_{LR}+\sigma_{RL})+(P-P')(\sigma_{RL}-\sigma_{LR})\right]$$

- **Background free** searches for BSM through beam polarisation

ILC Running Scenarios

arXiv:1506.07830





In 2019 – Revision of capabilities to run on the Z Pole - GigaZ

	$\mathrm{sgn}(P(e^-), P(e^+)) =$				
	(-,+)	(+,-)	(-,-)	(+,+)	sum
luminosity [fb^{-1}]	40	40	10	10	
$\sigma(P_{e^-}, P_{e^+})$ [nb]	83.5	63.7	50.0	40.6	
Z events [10^9]	2.4	1.8	0.36	0.29	4.9
hadronic Z events [10^9]	1.7	1.3	0.25	0.21	3.4

- Pole running can happen before and after the luminosity upgrade
- Further details see arxiv: 1908.08212

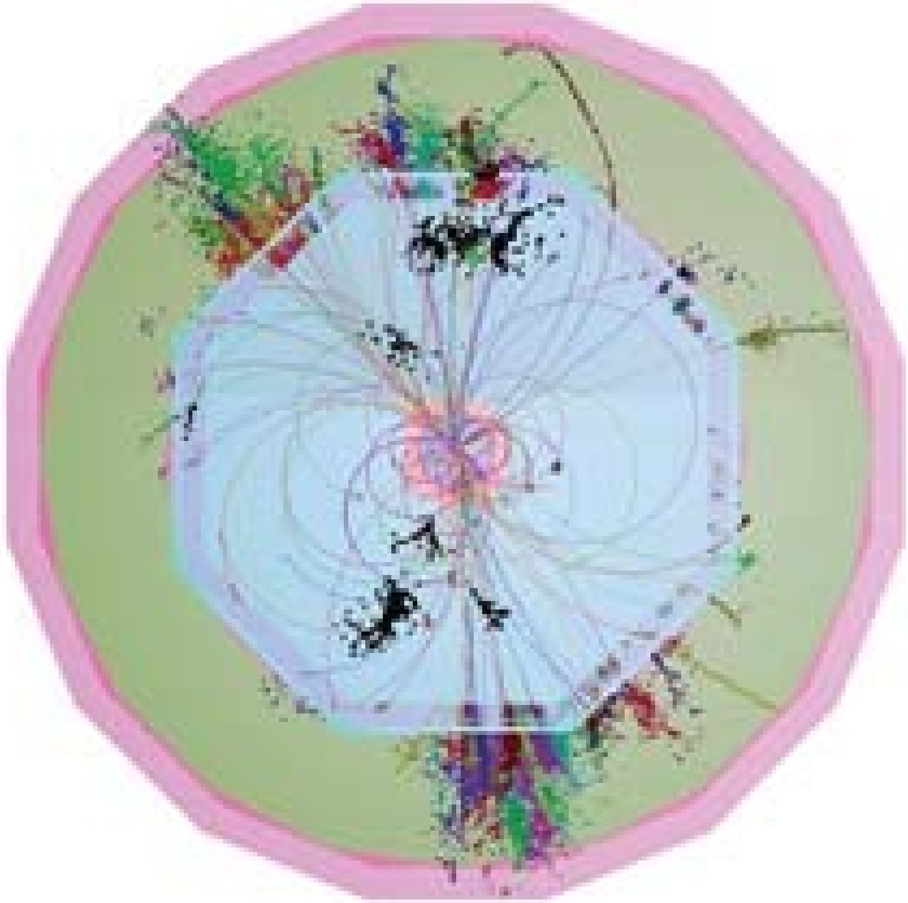
Linear vs. circular e+e- machines – Instantaneous luminosities

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, quark charge measurement)

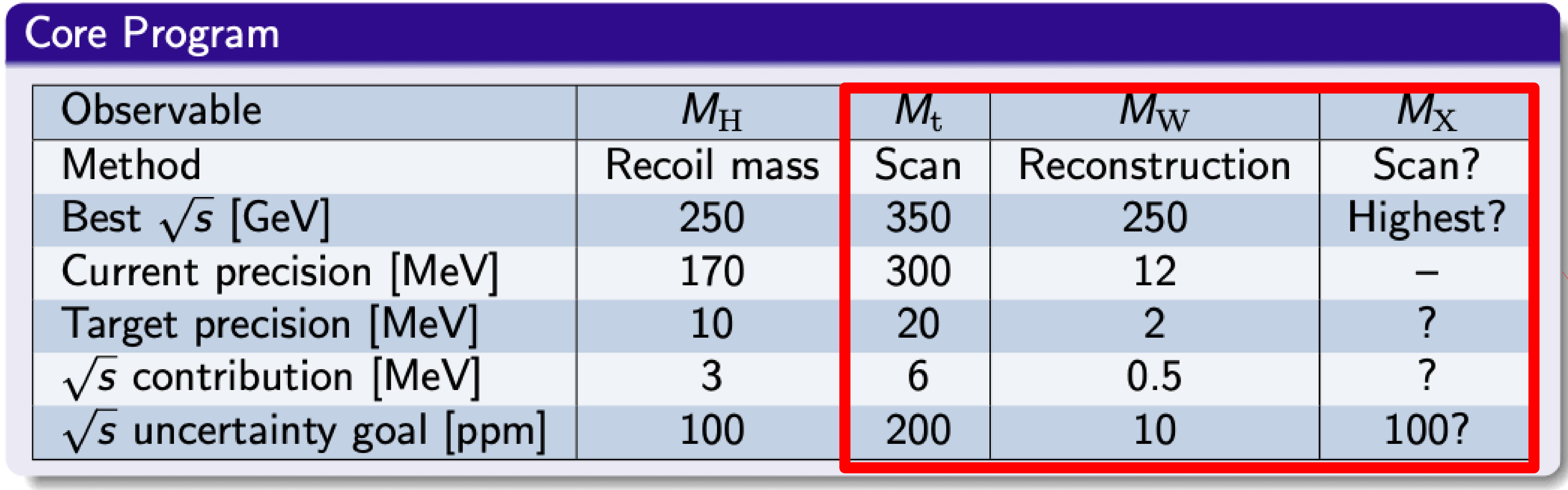


Final state will comprise events with a large number of charged tracks and jets(6+)

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

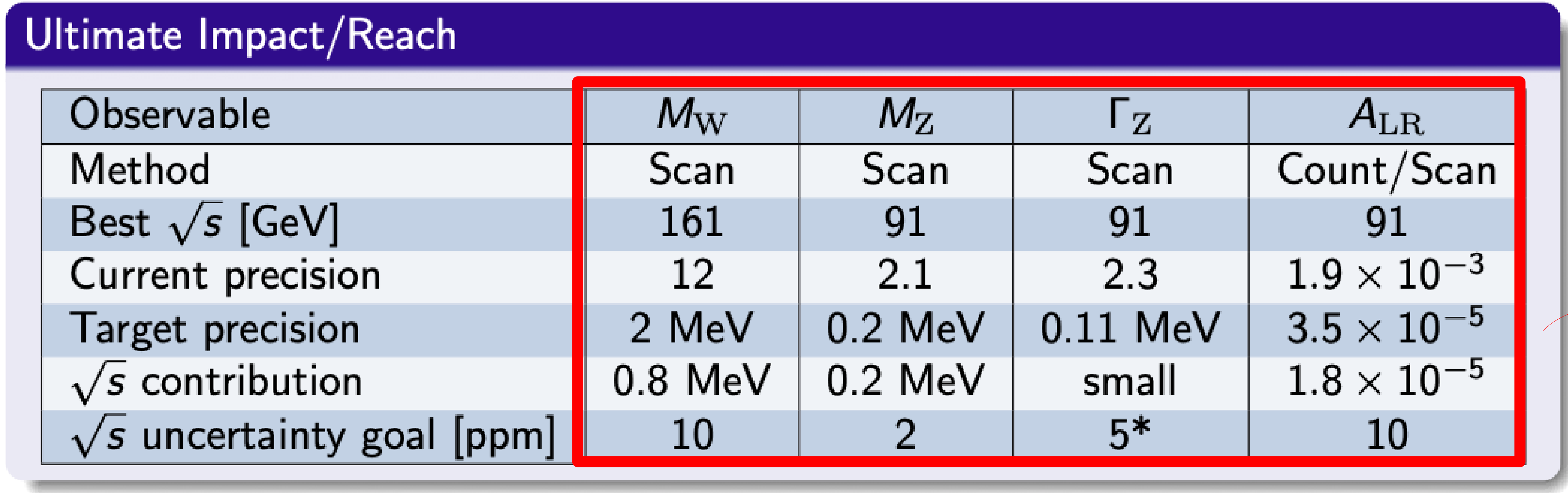
- Particle Flow Detectors

ILC Physics Targets – Energy requirements



Core Program

Observable	M_H	M_t	M_W	M_X
Method	Recoil mass	Scan	Reconstruction	Scan?
Best $\sqrt{s}$ [GeV]	250	350	250	Highest?
Current precision [MeV]	170	300	12	–
Target precision [MeV]	10	20	2	?
$\sqrt{s}$ contribution [MeV]	3	6	0.5	?
$\sqrt{s}$ uncertainty goal [ppm]	100	200	10	100?



Ultimate Impact/Reach

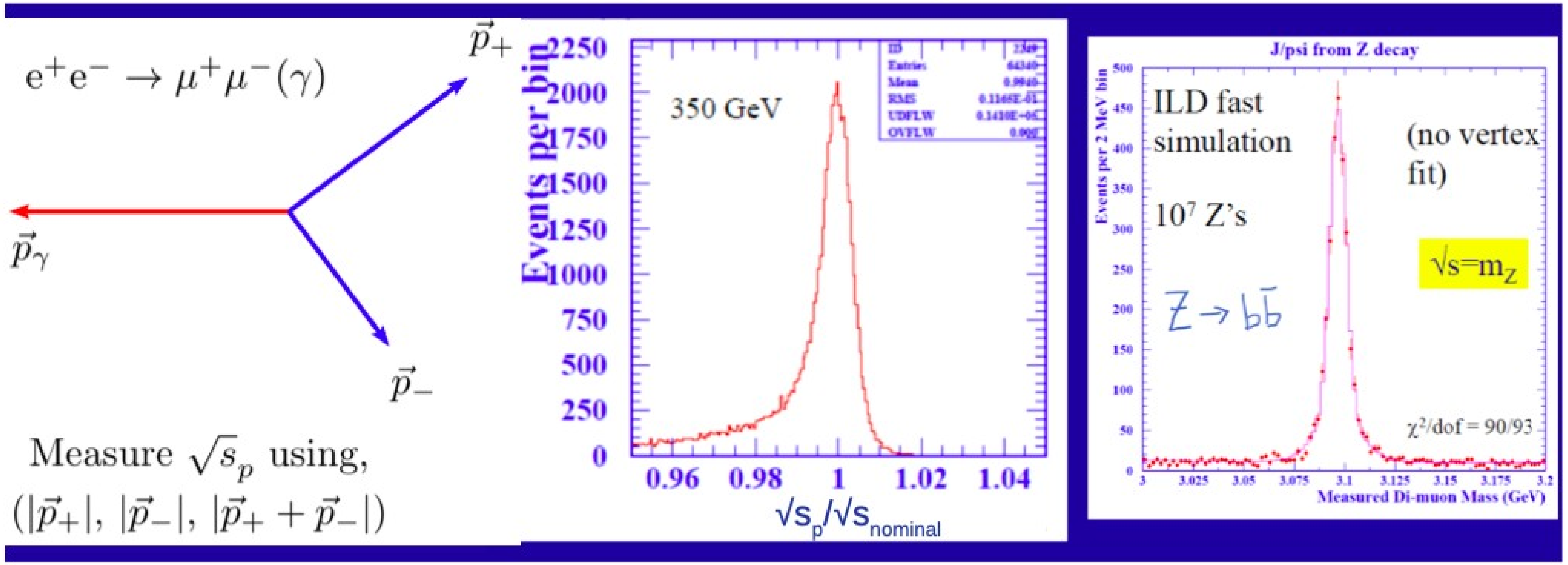
Observable	M_W	M_Z	Γ_Z	A_{LR}
Method	Scan	Scan	Scan	Count/Scan
Best $\sqrt{s}$ [GeV]	161	91	91	91
Current precision	12	2.1	2.3	1.9×10^{-3}
Target precision	2 MeV	0.2 MeV	0.11 MeV	3.5×10^{-5}
$\sqrt{s}$ contribution	0.8 MeV	0.2 MeV	small	1.8×10^{-5}
$\sqrt{s}$ uncertainty goal [ppm]	10	2	5*	10

Today

Graham Wilson, IDT WG3 MDI Meeting, https://agenda.linearcollider.org/event/9401/

Measurement of beam energy

Use dilepton **momenta**, with $\sqrt{s_p} \equiv E_+ + E_- + |\vec{p}_{+-}|$ as $\sqrt{s}$ estimator.



Measure $\sqrt{s_p}$ using, $(|\vec{p}_+|, |\vec{p}_-|, |\vec{p}_+ + \vec{p}_-|)$

Tie detector p-scale to particle masses (know J/ψ, π^+, p to 1.9, 1.3, 0.006 ppm)

Measure $< \sqrt{s} >$ and luminosity spectrum with same events. Expect statistical uncertainty of 1.0 ppm on p-scale per 1.2M $J/\psi \to \mu^+\mu^-$ (4×10^9 hadronic Z's).

- excellent tracker momentum resolution - can resolve beam energy spread.
- feasible for $\mu^+\mu^-$ and e^+e^- (and ... 4l etc).

Further remarks:

- Realistic study has to take real beam energy spread and crossing angle into account
  - Ongoing
- Momentum scale can be further constrained by with K_0 and Λ using Armenteros-Podolanski Method
  - See e.g. 2012.03620
- 10ppm at s=250 GeV and 1ppm on Z pole seem to be in reach

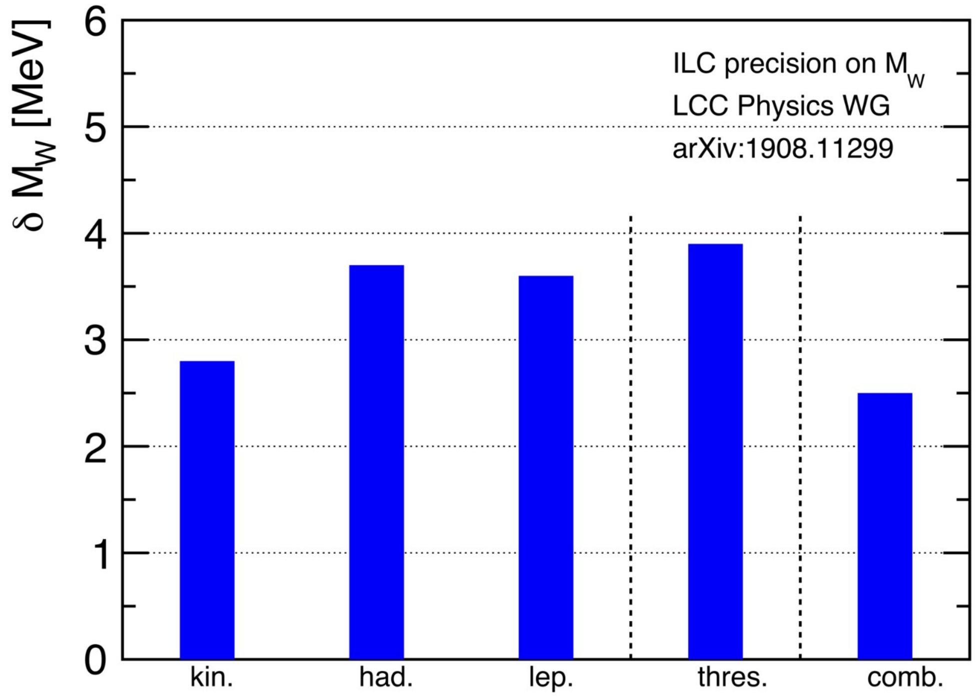
Graham Wilson, IDT WG3 MDI Meeting, https://agenda.linearcollider.org/event/9401/

W - Parameters

W Mass from ...:

- Constrained WW reconstruction
- Hadronic mass from hadronic W decays
- Lepton endpoints: $m_W^2 = E_l(E_b - E_l),\ E_l = E_b(1 \pm \beta_W)/2$
- Dilepton pseudo mass from constrained fit
- Polarised W scan

$$\Delta m_W(MeV) = 2.4(stat.) \oplus 3.2(syst.) \oplus 0.8(\sqrt{s}) \oplus \text{theory}$$

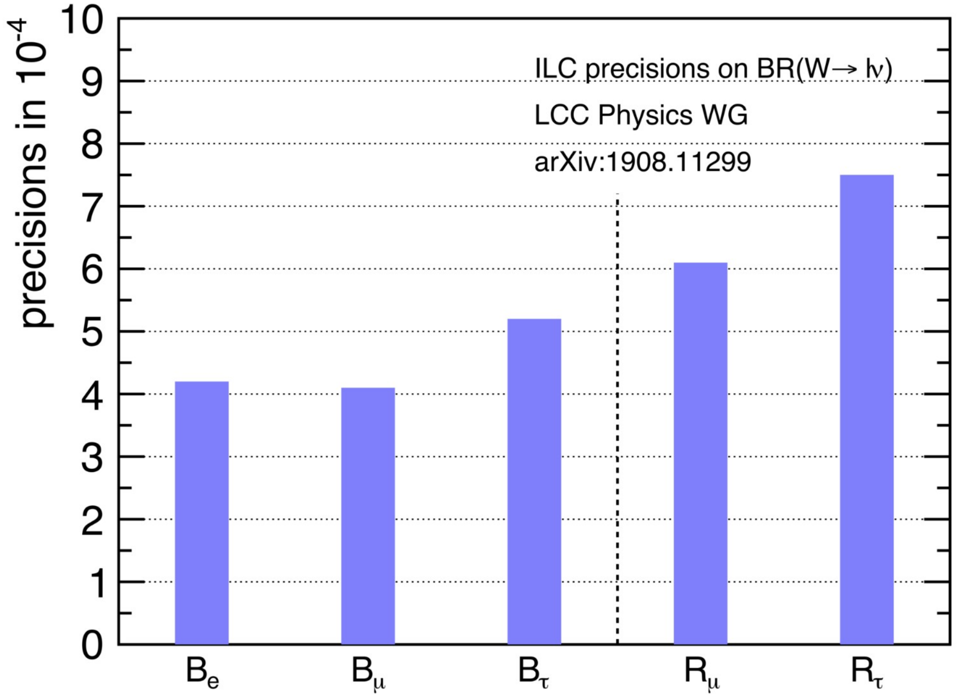


Branching ratios

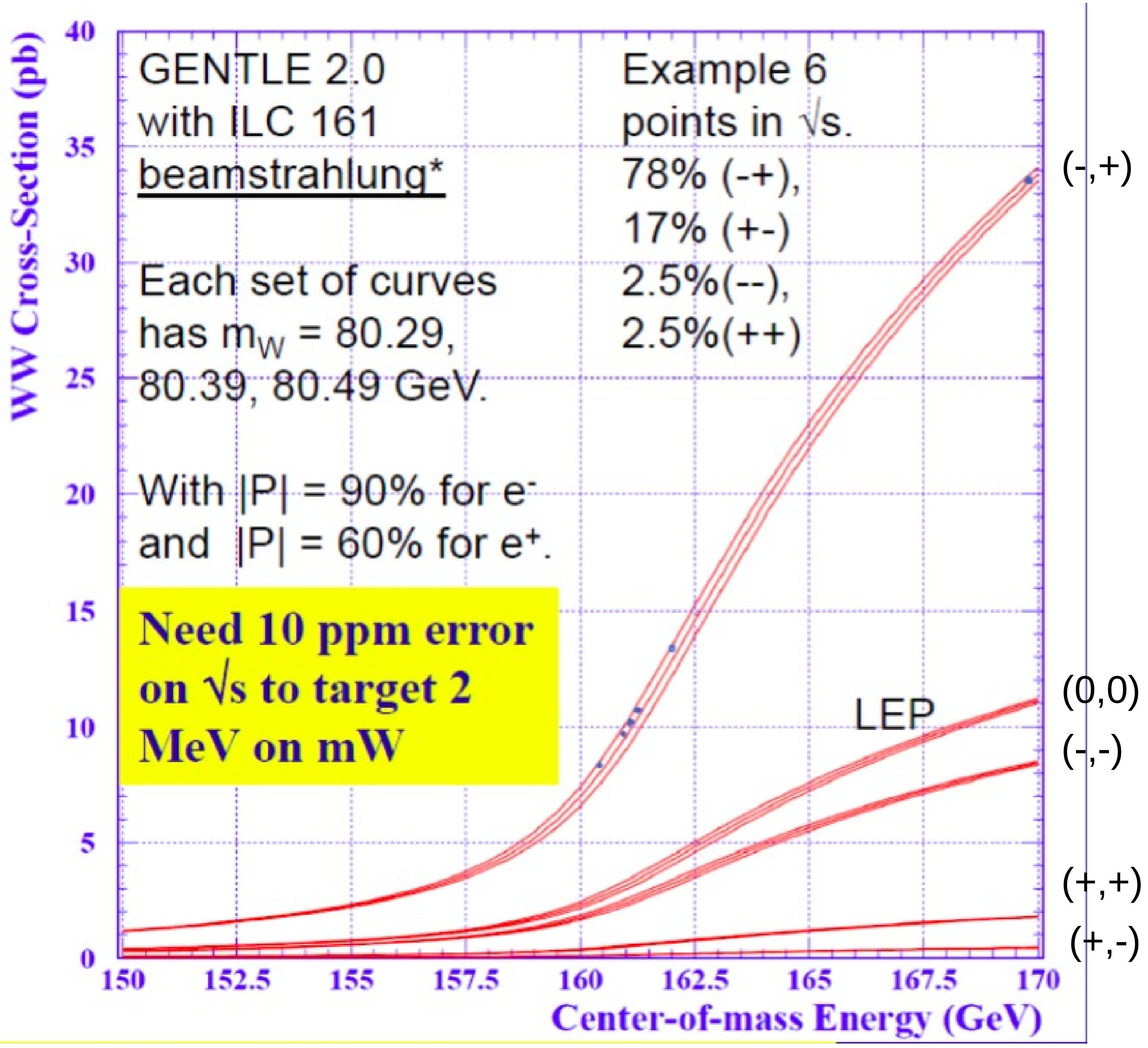
From simultaneous fit to all 10 decay combinations

=> σ_{tot} and $B_{e,\mu,\tau}$ and $B_{had} = 1 - B_e - B_\mu - B_\tau$

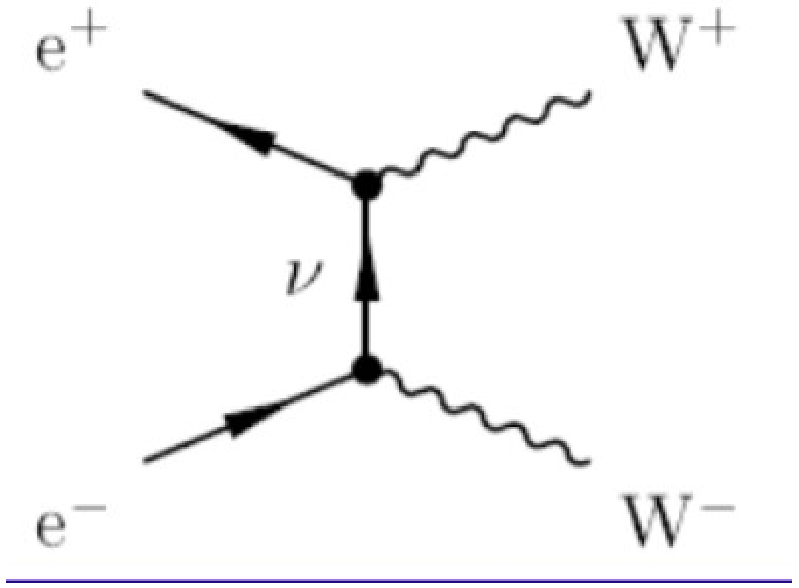
W width: $\Delta\Gamma_W = 3.2$ MeV



W - Parameters

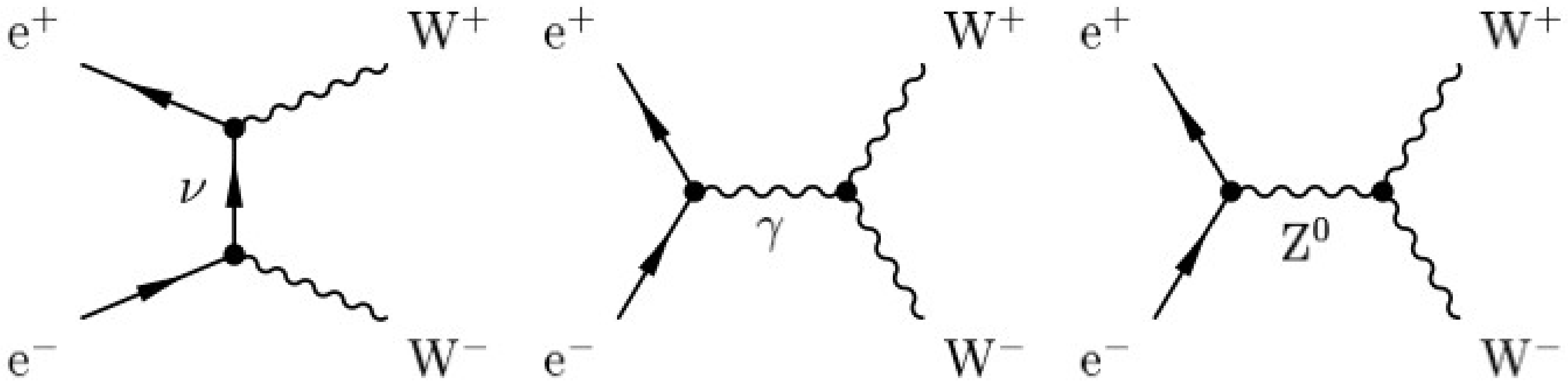


G. Wilson



- Robust method
- Beam polarisation essential to control background
- Need extreme good control of beam energy

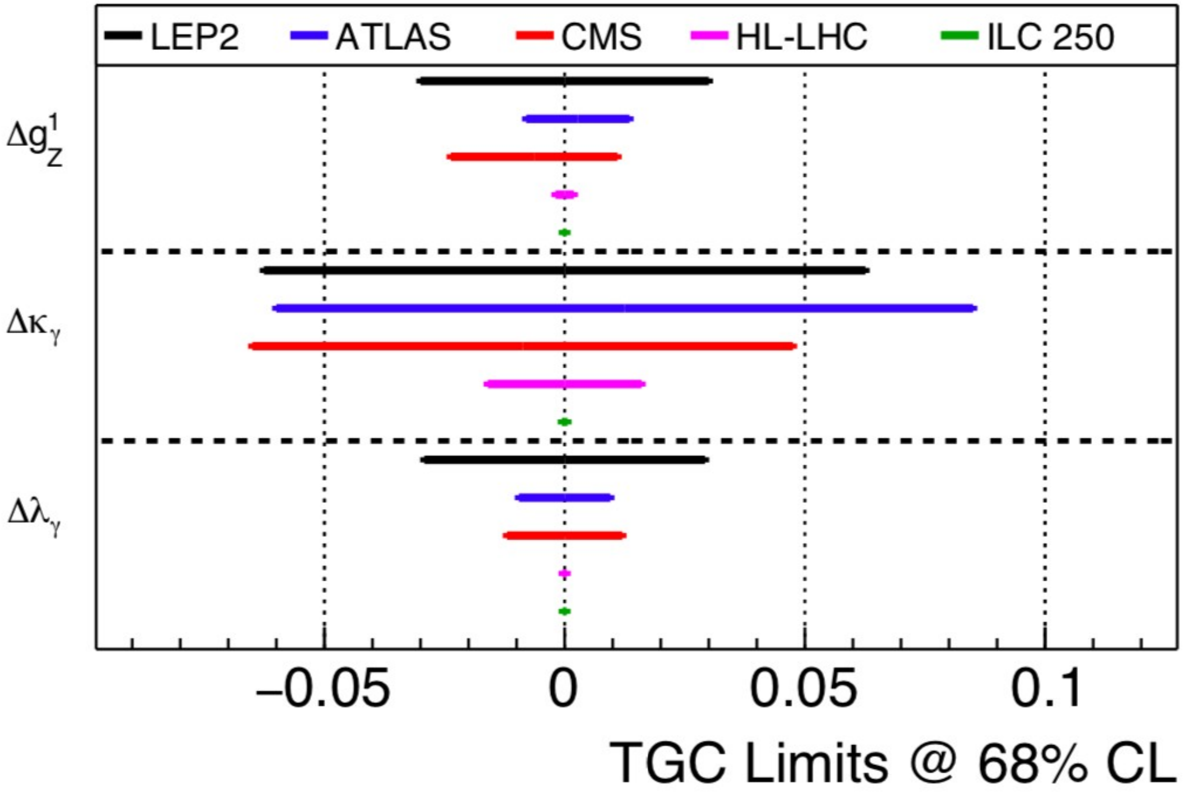
Anomalous Triple Gauge Couplings

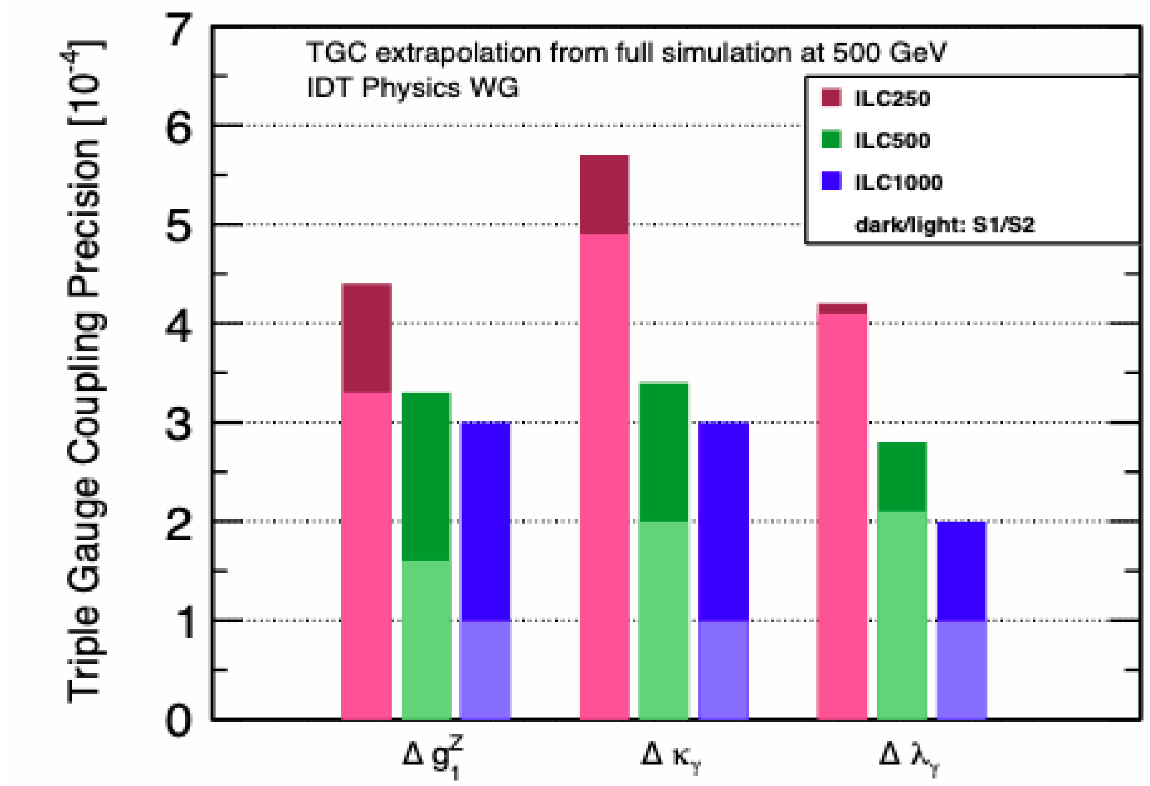


- Sensitivity to triple and quartic gauge Boson couplings (TGC and QGC)
- Observables depend strongly on beam polarisation

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

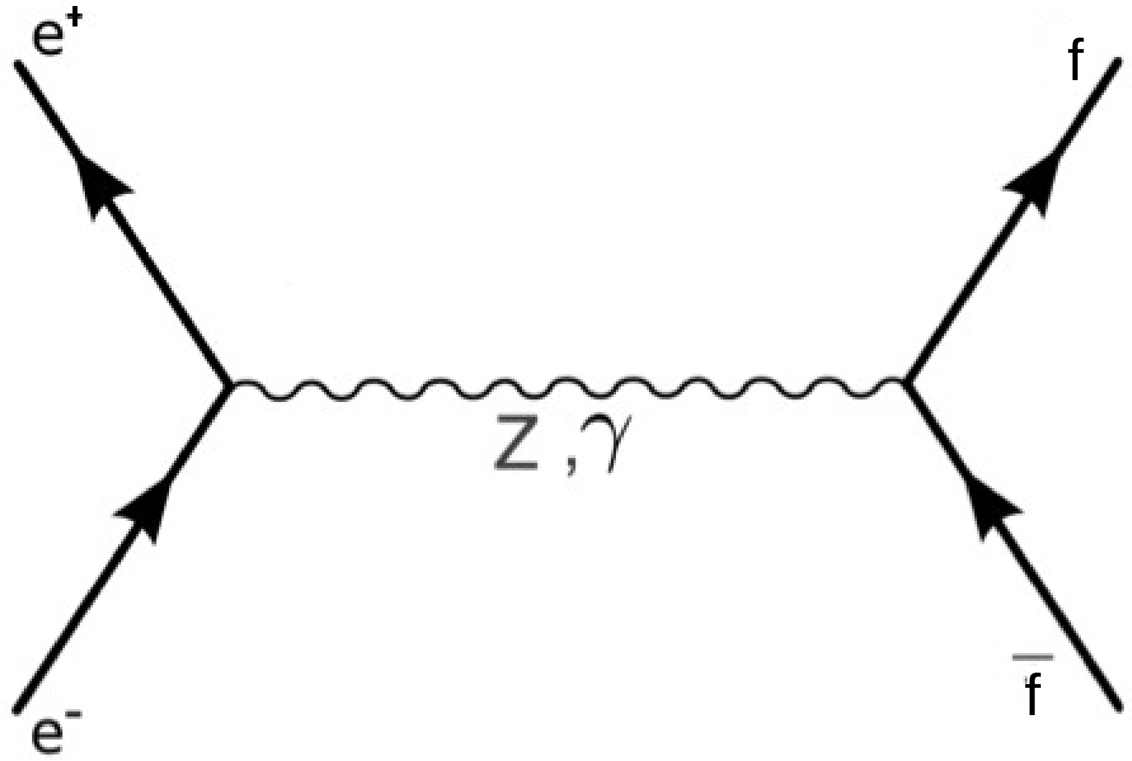
Limits on Triple Gauge Couplings@250 GeV





J. List, ILC Snowmass White Paper

Two fermion processes



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

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

*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**

Helicity amplitudes and new physics

Helicity amplitudes can be analysed in several ways (not mutually exclusive):

Oblique Parameters W, Z:

$$Q_{e_i f_j} = Q^\gamma_e Q^\gamma_f + \frac{g^Z_{e_i} g^Z_{f_j}}{\sin^2\theta_W \cos^2\theta_W} \frac{s}{s - M^2_Z + \mathrm{i}\Gamma_Z M_Z} + \frac{s}{m^2_W} f_{i,j}(W,Y)$$

Contact interactions with e.g. compositeness scale Λ:

$$Q_{e_i f_j} = Q^\gamma_e Q^\gamma_f + \frac{g^Z_{e_i} g^Z_{f_j}}{\sin^2\theta_W \cos^2\theta_W} \frac{s}{s - M^2_Z + \mathrm{i}\Gamma_Z M_Z} + \frac{g^2_{contact}}{2\Lambda^2}\eta_{e_i f_j}$$

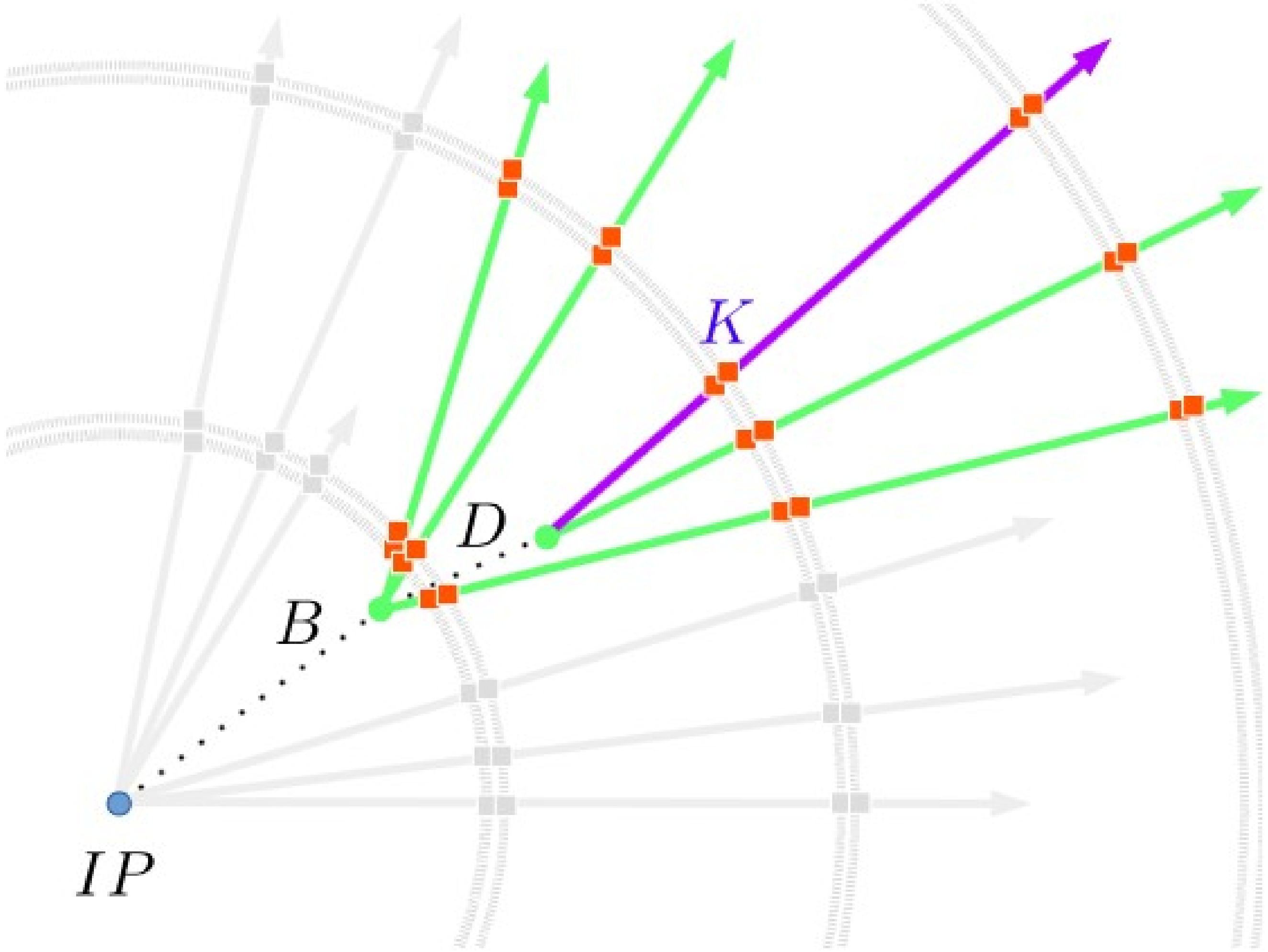
New propagators in concrete models of new physics:

$$Q_{e_i f_j} = Q^\gamma_e Q^\gamma_f + \frac{g^Z_{e_i} g^Z_{f_j}}{\sin^2\theta_W \cos^2\theta_W} \frac{s}{s - M^2_Z + \mathrm{i}\Gamma_Z M_Z} + \sum \frac{g^{Z'}_{e_i} g^{Z'}_{f_j}}{\sin^2\theta_W \cos^2\theta_W} \frac{s}{s - M^2_{Z'} + \mathrm{i}\Gamma_{Z'} M_{Z'}}$$

Always with I,j being the helicities of the initial state electron e and the final state fermion f

Remark: Have to exchange g-> Q to be conistent with conventions

Flavor tagging and charge measurement



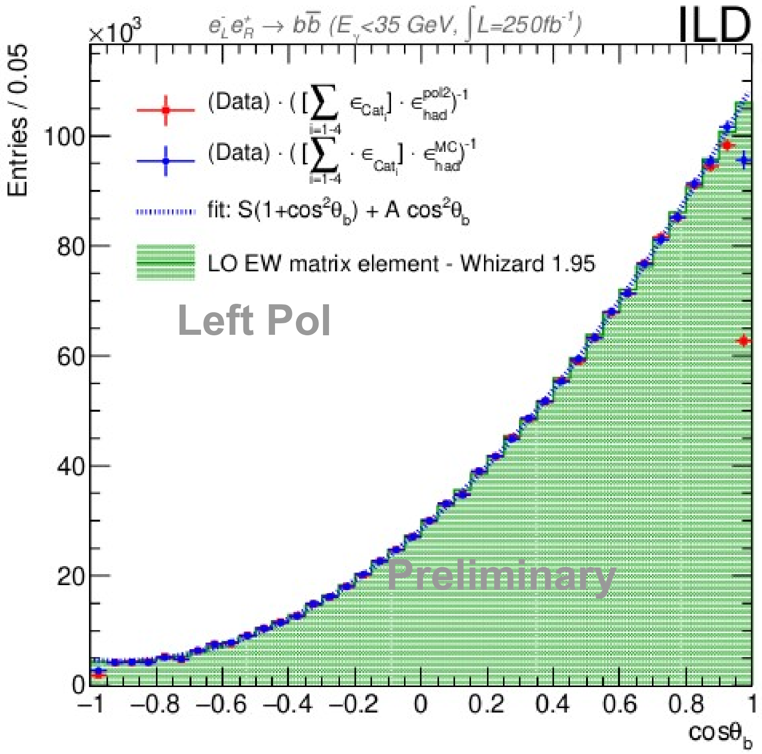
PhD thesis: S. Bilokin
A. Irles

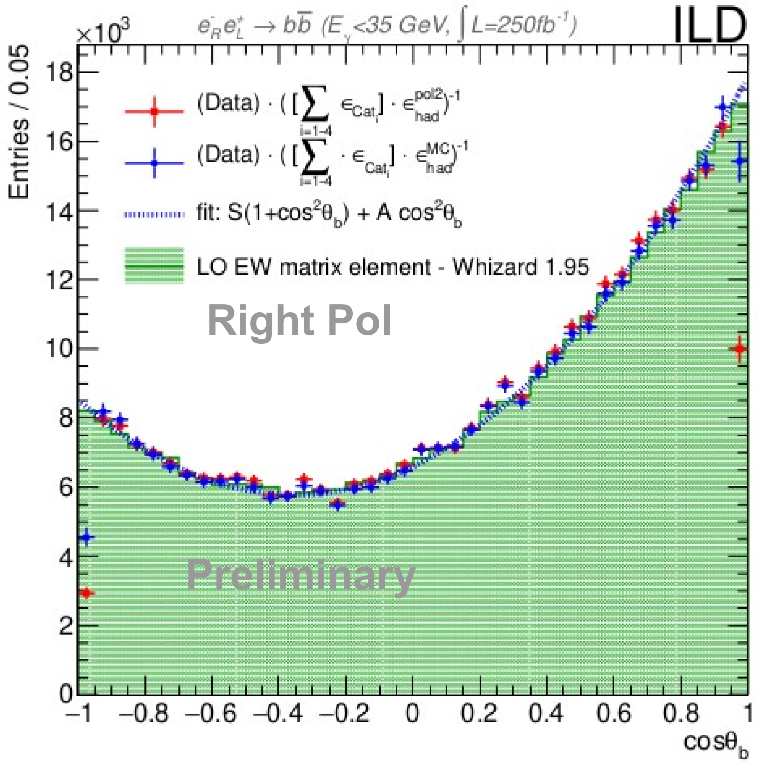
- flavor tagging
- b-quark charge measurement
  - Important for top quark studies, indispensable for ee->bb
- Control of migrations:
  - Correct measurement of vertex charge
    - Requires excellent forward acceptance
  - Kaon identification by dE/dx (and more)
- ILC/ILD can base the entire measurements on double Tagging and vertex charge
  - LEP/SLC had to include single tags and semi-leptonic events

Decomposing ee->bb – Differential cross section

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

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





Excellent agreement between predicted and reconstructed distributions

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

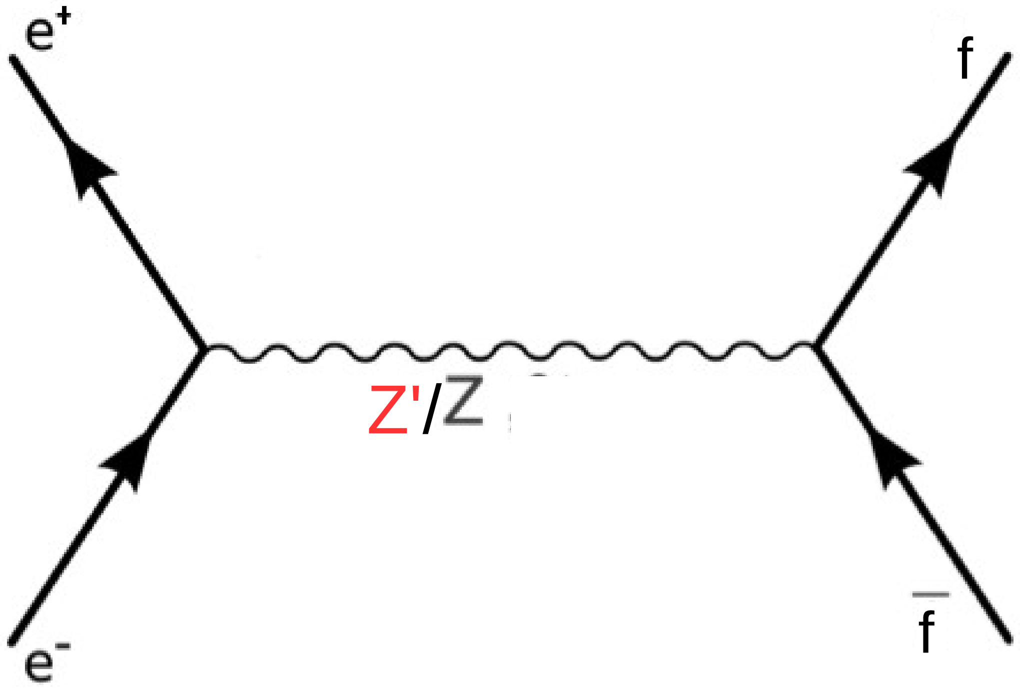
Systematic uncertainties under scrutiny:

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

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

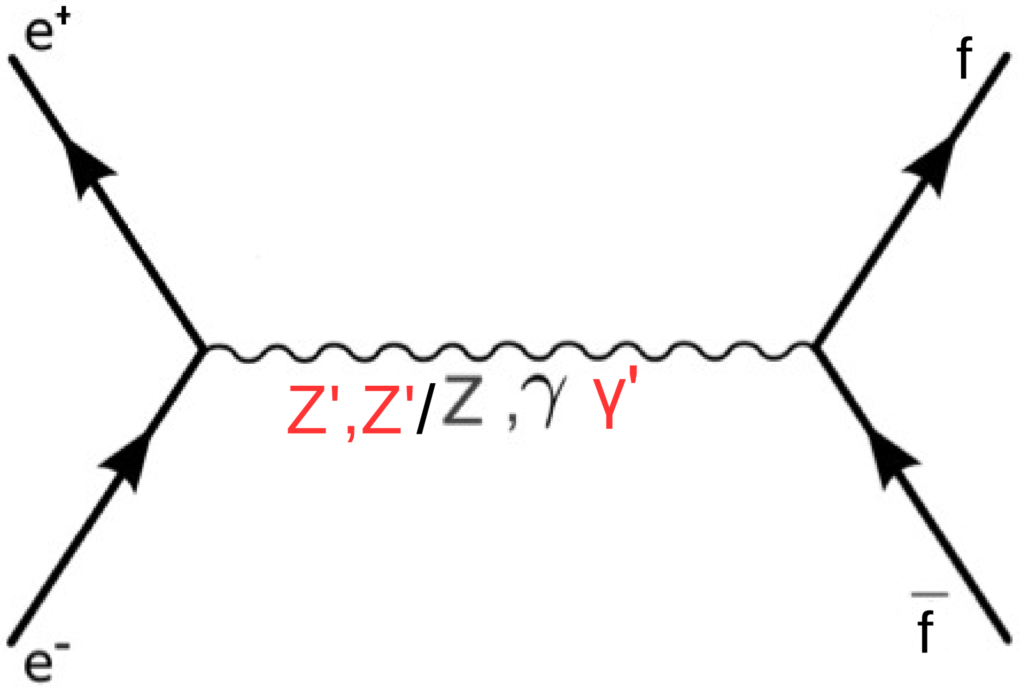
How can the Z-pole help?

On the Z-pole



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

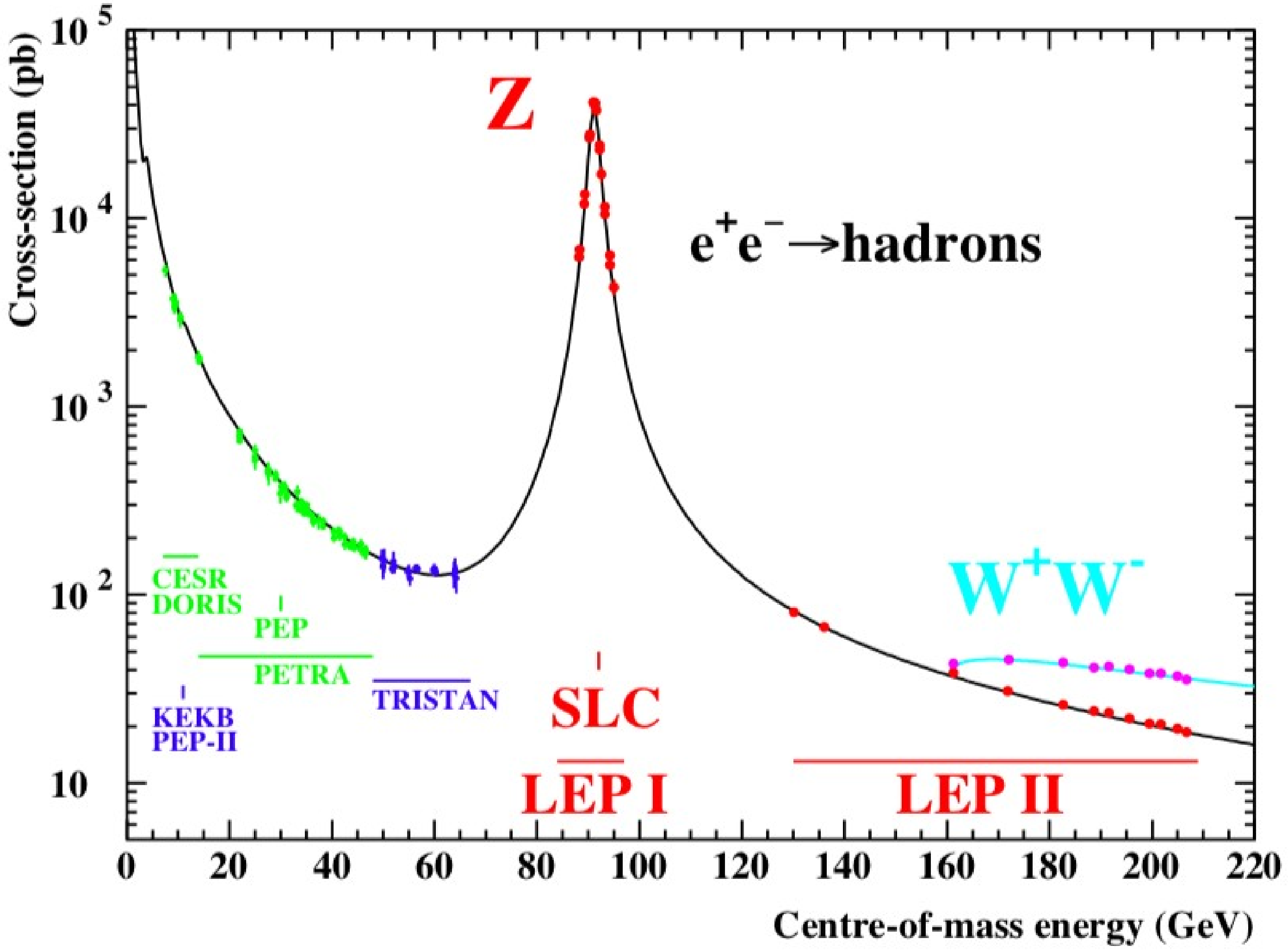
Above the Z-pole



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

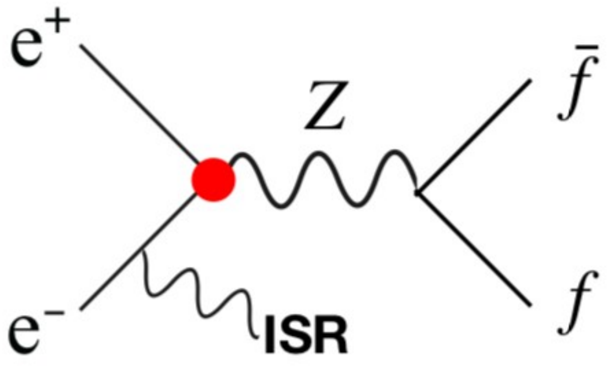
Couplings to on-shell Z Bosons

Running on Z pole “GigaZ”



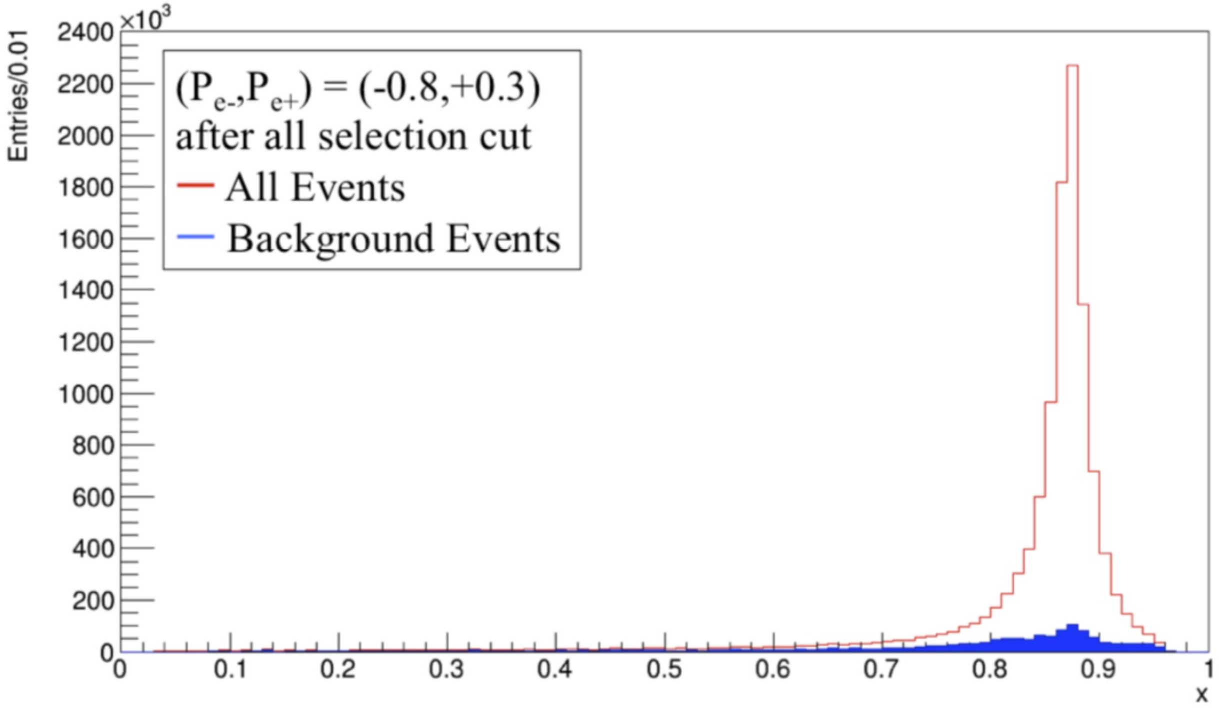
- Around 5x10^9 Z events (250xLEP)
- With beam polarisation
  ~30x250 = 7500 LEP!

Radiative return at higher energies



$$m_Z^2 = \frac{1-|\beta|}{1+|\beta|}\cdot s$$

$$\beta = \frac{|\sin(\theta_1 + \sin\theta_2)|}{\sin\theta_1 + \sin\theta_2}$$



- ~10^8 events at 250 GeV with 2ab^{-1}
- Beam polarisation

Rates and asymmetries

Partial fermion width:

$$R_f = \frac{N_f}{N_{had}} = \frac{(g_f^L)^2 + (g_f^R)^2}{\sum_{i=1}^{n_q}[(g_i^L)^2 + (g_i^R)^2]}$$

- Sensitive to sum of coupling constants
- Available at linear and circular colliders

Left-right asymmetry:

$$A_{LR} = \frac{1}{|\mathcal{P}_{eff.}|}\frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \mathcal{A}_e = \frac{(g_f^L)^2 - (g_f^R)^2}{(g_i^L)^2 + (g_i^R)^2} \sim 1 - 4\sin^2\theta^{\ell}_{eff.}$$

- Direct sensitivity to Zee vertex
- Only available at linear colliders due to beam polarisation
- Circular colliders need auxiliary measurement
  - e.g. $P_\tau \sim A_e$

Forward-backward asymmetry:

$$A_{FB}^f = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f \quad \text{for} \quad \mathcal{P}_e = 0.$$

- “Classical” observable to study P-violating effects in ee->ff
- Available at circular and linear colliders
- **Without** beam polarisation interpretation is **always model dependent**

Left-right-forward-backward asymmetry:

$$A_{FB,LR}^f = \frac{(\sigma_F - \sigma_B)_L - (\sigma_F - \sigma_B)_R}{(\sigma_F + \sigma_B)_L + (\sigma_L + \sigma_l)_R} = -\frac{3}{4}\mathcal{A}_f$$

- Combination of asymmetries above
- Only available linear colliders due to beam polarisation
- Direct and model independent measurement of A_f

Measurement of $\sin^2\theta^{\ell}_{\mathrm{eff.}}$

$$\mathcal{A}_e = \frac{(g^Z_{e_L})^2 - (g^Z_{e_R})^2}{(g^Z_{e_L})^2 + (g^Z_{e_R})^2} = \frac{2 g_{e_V}/g_{e_A}}{1 + (g_{e_V}/g_{e_A})^2} \quad \text{with} \quad g_{e_V}/g_{e_A} = 1 - 4\sin^2\theta^{\ell}_{\mathrm{eff.}}$$

How to determine *A*$_e$?

Left Right Asymmetry
Requires polarised beams

$$A_{LR} = \frac{1}{|\mathcal{P}_{eff.}|}\frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \mathcal{A}_e$$

Available at LC

Using all hadronic decays of Z!!!

Forward backward asymmetry
Has to assume lepton universality!!!

$$A^f_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f \quad \text{for} \quad \mathcal{P}_e = 0.$$

Available at LC, CC
Used e.g. In EPJC (2019) 79:474
with f = μ

Final state polarisation (r,l)
e.g. with *τ*

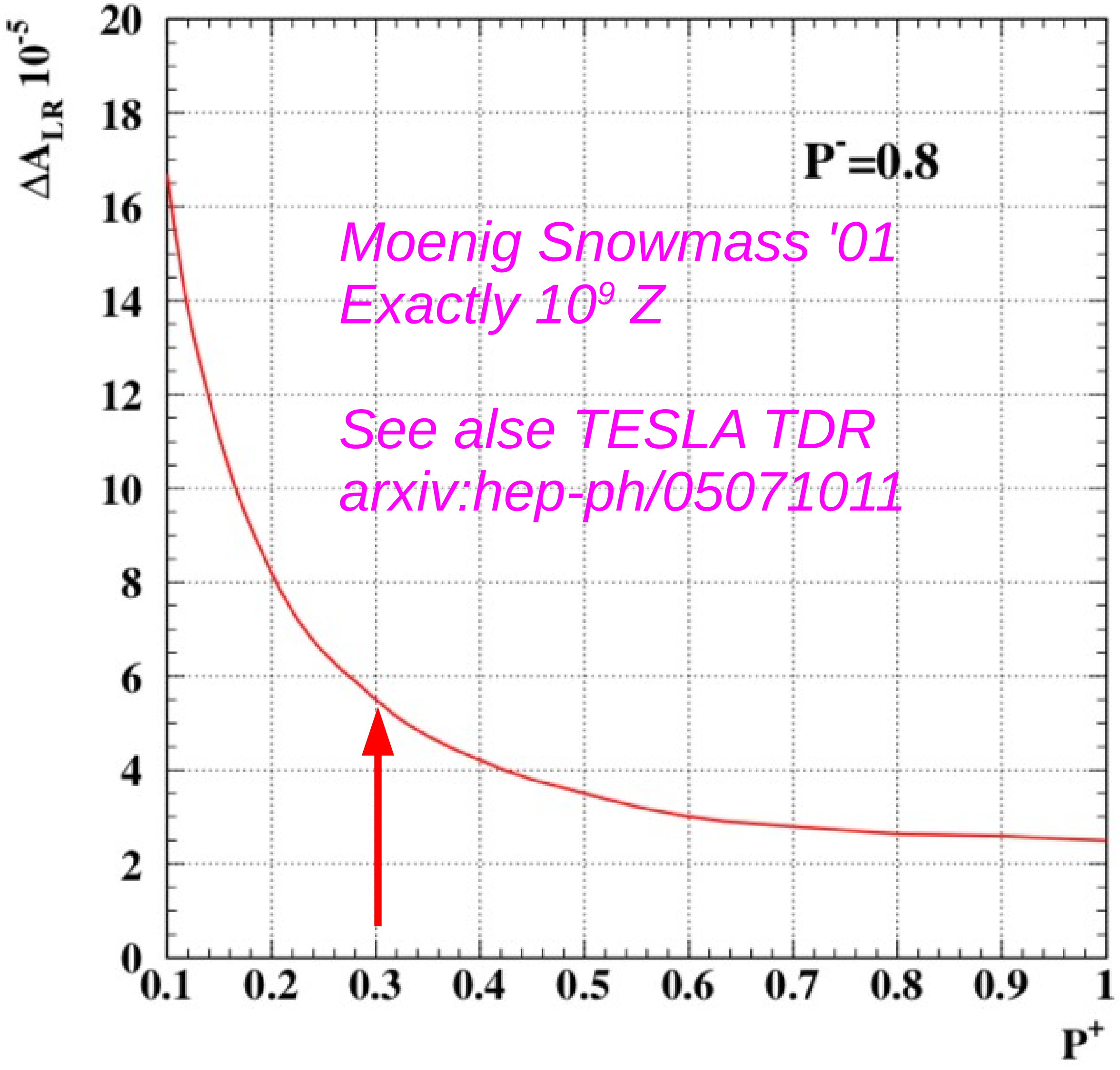
$$A^{pol}_{FB} = \frac{(\sigma_r - \sigma_l)_F - (\sigma_r - \sigma_l)_B}{(\sigma_r + \sigma_l)_F + (\sigma_r + \sigma_l)_B} = -\frac{3}{4}\mathcal{A}_e$$

Available at LC, CC

Beam polarisation is key: Remember SLC delivered most precise value of $\sin^2\theta^{\ell}_{\mathrm{eff.}}$
despite of 30 times less lumi

Measurement of $\sin^2\theta^{\ell}_{\mathrm{eff.}}$

Blondel scheme: $A_{\mathrm{LR}} = \sqrt{\frac{(\sigma_{++}+\sigma_{-+}-\sigma_{+-}-\sigma_{--})(-\sigma_{++}+\sigma_{-+}-\sigma_{+-}+\sigma_{--})}{(\sigma_{++}+\sigma_{-+}+\sigma_{+-}+\sigma_{--})(-\sigma_{++}+\sigma_{-+}+\sigma_{+-}-\sigma_{--})}}$



Moenig Snowmass '01
Exactly 10^9 Z

See alse TESLA TDR
arxiv:hep-ph/05071011

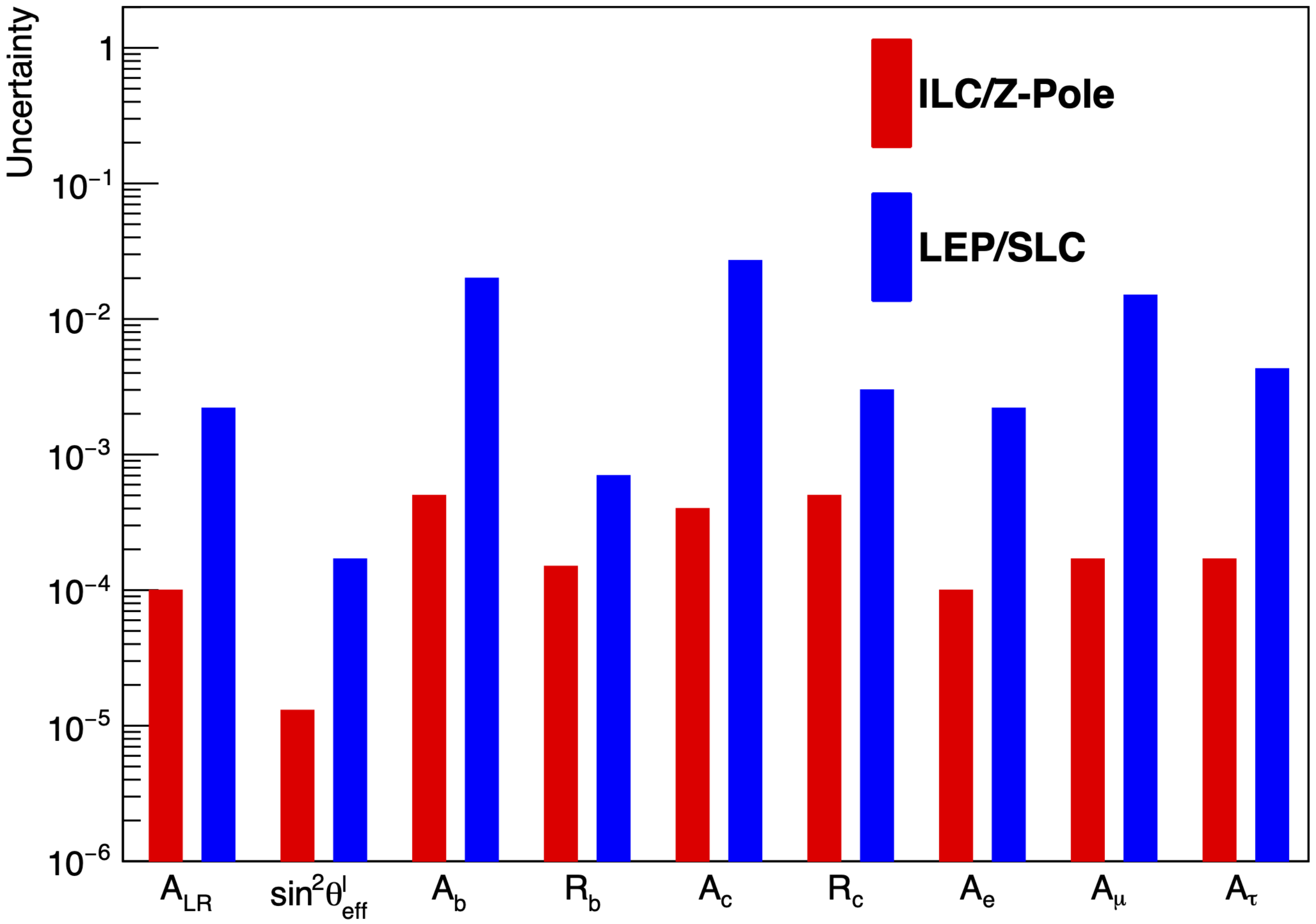
- Blondel scheme independent of polarimeter precision
  - Assumes perfect spin flip for polarised beams
  - Residuals must be monitored by polarimeter
  - Residual uncertainty of $\Delta A_{LR} = 0.5\mathrm{x}10^{-4}$ seems possible
  - The more positron polarisation the better
  - Don't forget energy dependency ($dALR/d\sqrt{s} \sim 2\mathrm{x}10^{-5}/MeV$)
    - 1 MeV precision on √s seems possible (see above)

- Precision **$\Delta A_{LR} = 1\mathrm{x}10^{-4}$** is a realistic assumption for GigaZ

=> $$\boxed{\delta\sin^2\theta^{\ell}_{\mathrm{eff.}} \sim 1.3\cdot 10^{-5}}$$

- Radiative return
  - Mainly limited by statistics **$\Delta A_{LR} = 1.4\mathrm{x}10^{-4}$**
  - Beam polarisation better than $\Delta A_{LR} = 0.5\mathrm{x}10^{-4}$ (More processes available)
  - Energy dependence much weaker than on Z-pole

Precision on Z-pole



- Z pole running of ILC will improve significantly precision w.r.t. LEP/SLD

- Precise measurement of $\sin^2\theta^\ell_{\mathrm{eff}}$.
  - Around 13 times better than LEP/SLD and a factor three better than current world average

- Considerable improvement of fermion asymmetries A_f
  - e.g.: arXiv: 1908.11299
    - *$\Delta A_b/A_b \sim 5\mathrm{x}10^{-4}$ (compare with $\Delta A_b/A_b \sim 214\mathrm{x}10^{-4}$ today)*
    - *$\Delta A_c/A_c \sim (5\oplus5)\mathrm{x}10^{-4}$ (compare with $\Delta A_c/A_c \sim 404\mathrm{x}10^{-4}$ today)*
    - For completeness note that a statistical error of 10-4 has been assumed for A_b and $3\mathrm{x}10^{-4}$ for A_c

  - Main error source
    - Knowledge of beam polarisation
    - QCD corrections that dilute forward backward asymmetry (arXiv:2010.08604) not considered but about to be looked at (once more)

Precision on couplings and helicity amplitudes in ee->bb

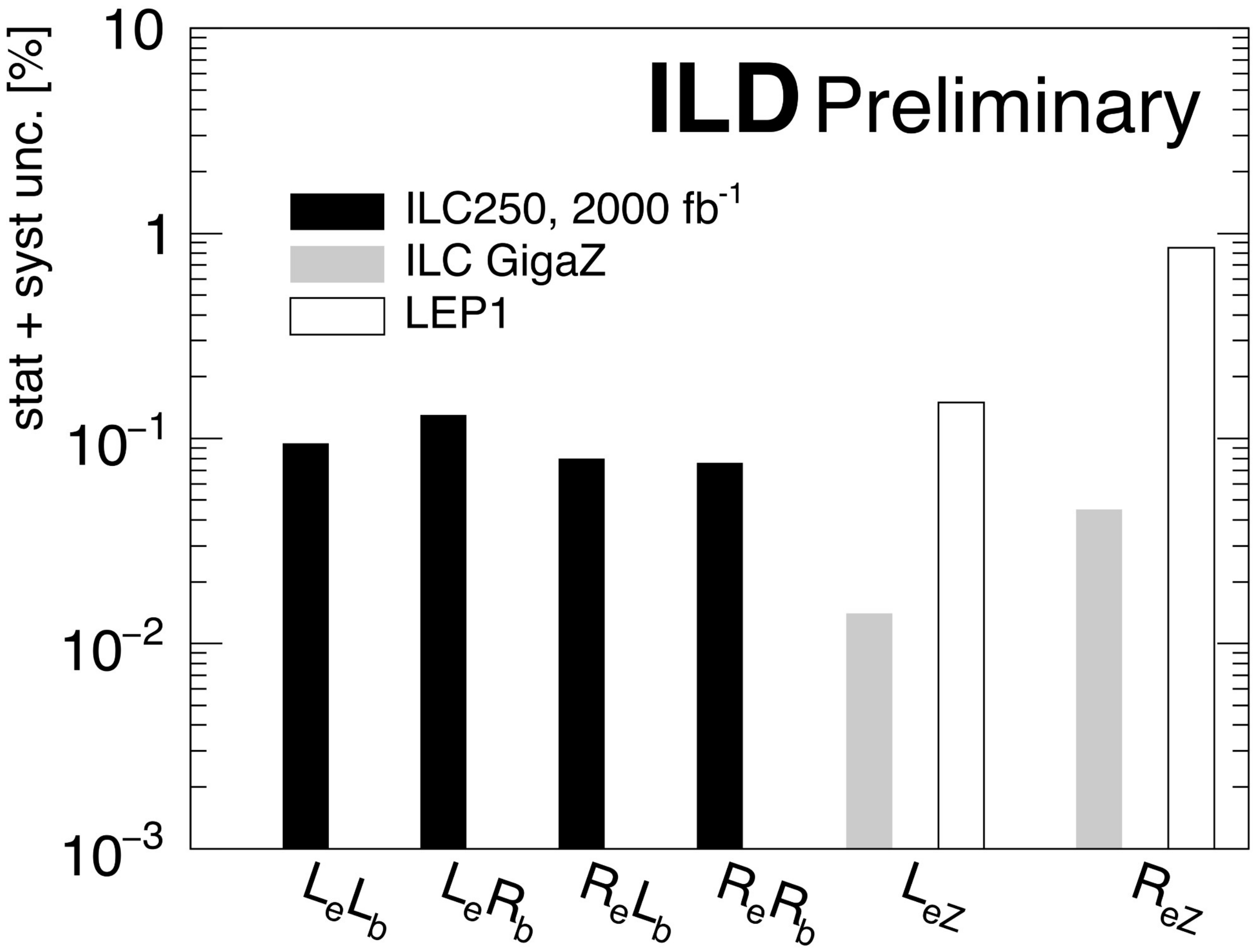
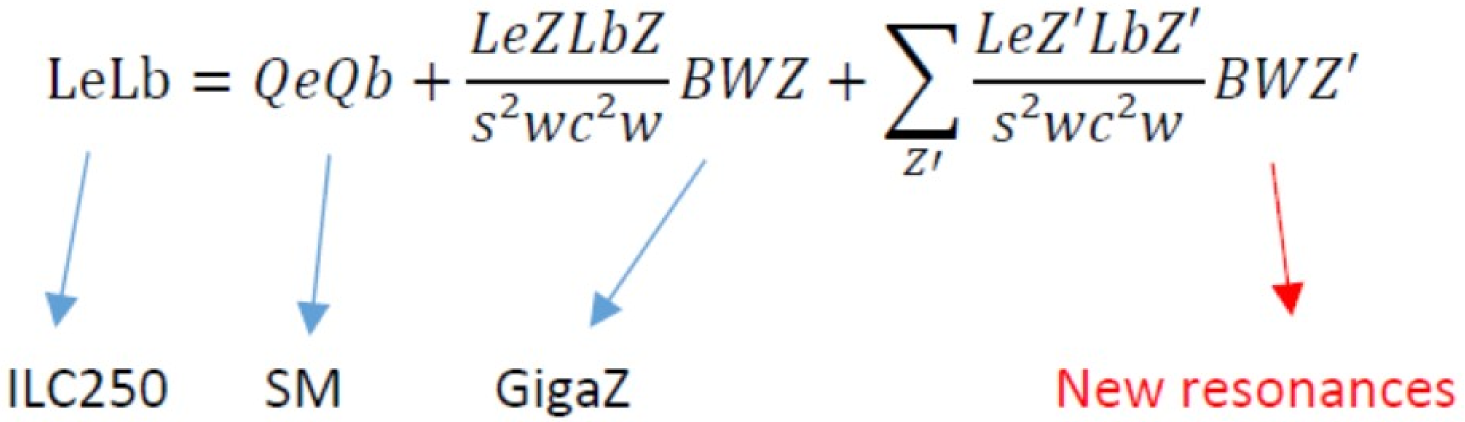


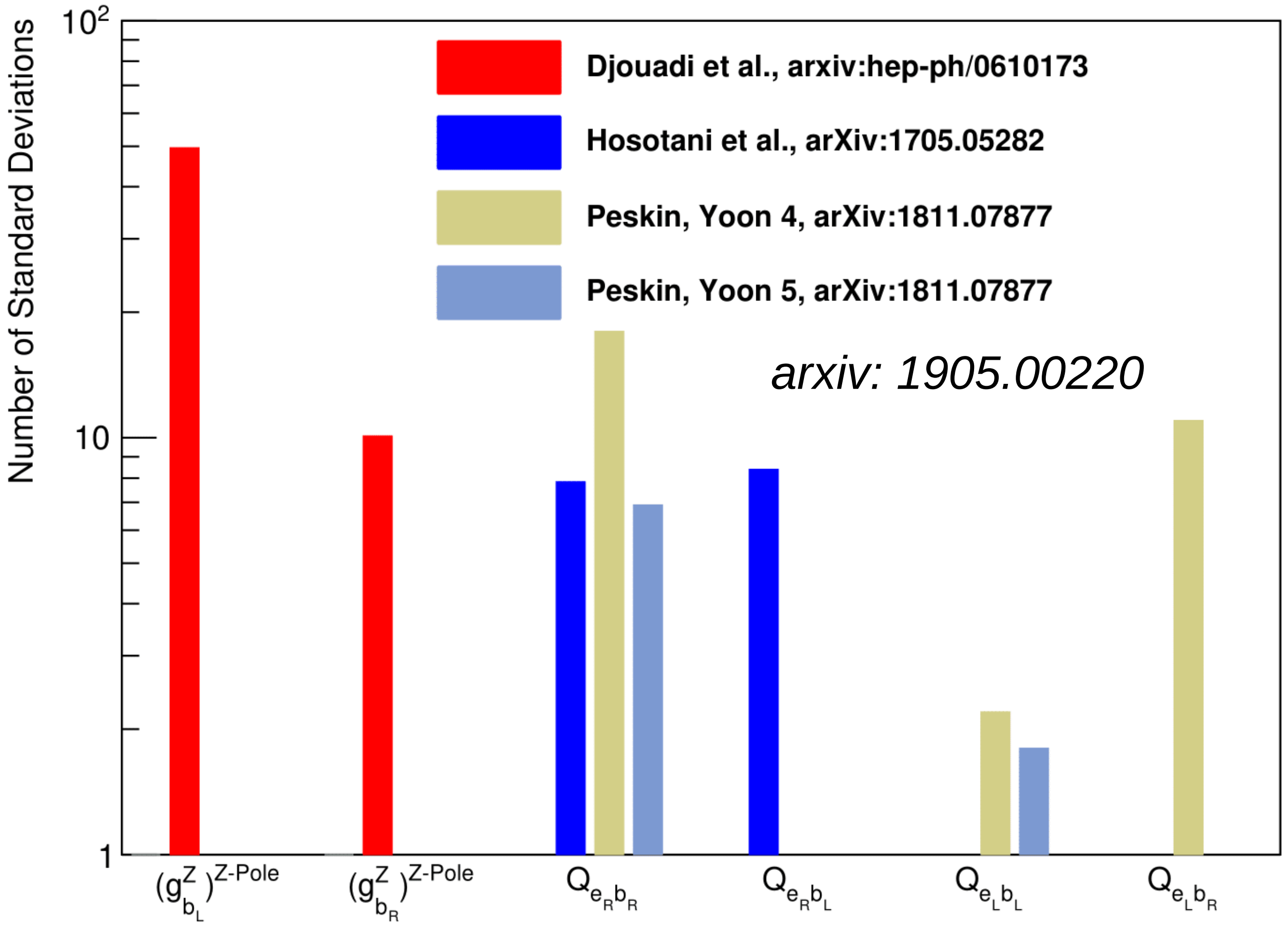
Figure: A. Irles



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

- 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!!

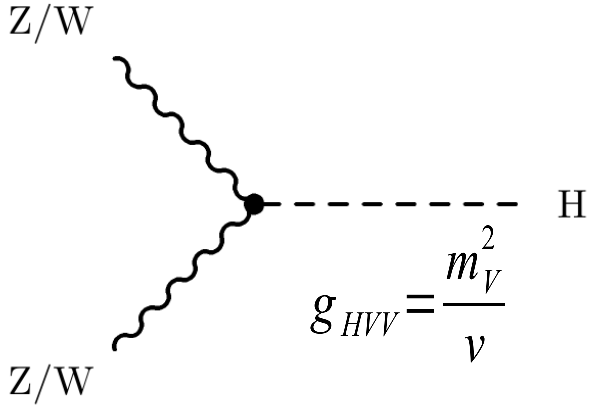
Example: b couplings and helicity amplitudes

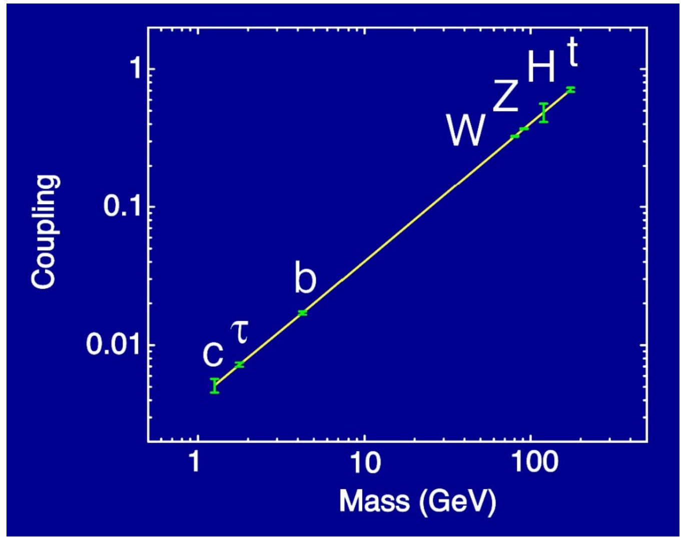


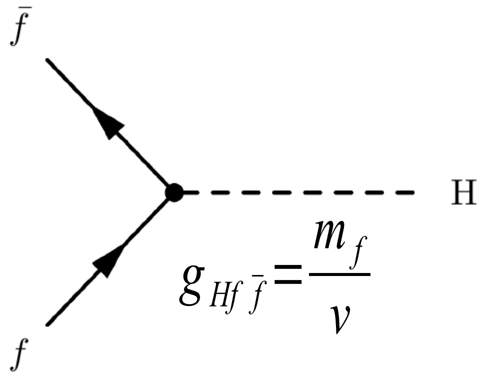
- Spectacular sensitivity to new physics in Randall Sundrum Models with warped extra dimensions
  - **Complete tests only possible at LC**
  - **Discovery reach O(10 TeV)@250 GeV and O(20 TeV)@500 GeV**
- Pole measurements critical input
  - Only poorly constrained by LEP
- Pole measurements will (most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

Fitting Higgs Couplings – Kappa and EFT

Couplings to Higgs Boson in Standard Model







Analysis using Kappa-fit:

- Simple scaling of SM-couplings
- Implies that Higgs coupling to Z in production and decay are identical
- No new operators

$$\frac{\Gamma(h \to ZZ^*)}{SM} = \kappa_Z^2 \; , \qquad \frac{\sigma(e^+e^- \to Zh)}{SM} = \kappa_Z^2$$

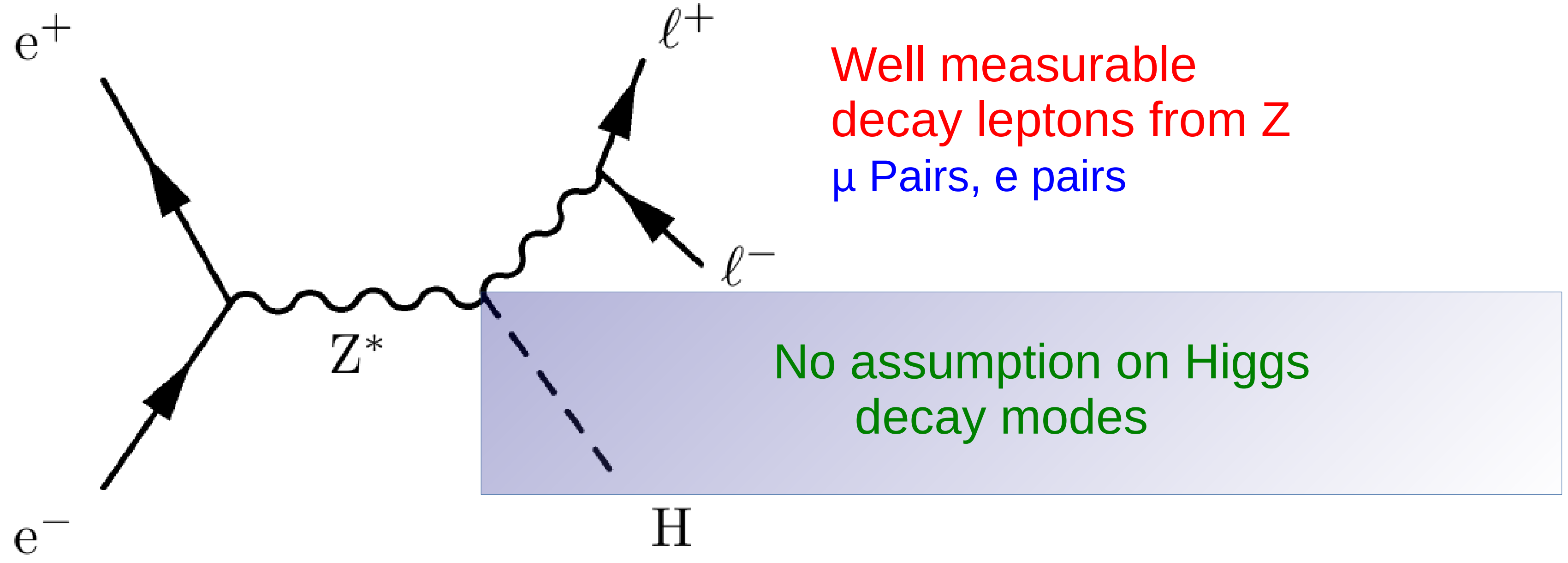
Analysis using EFT-fit:

- Introducing set of SU(2)xU(1) compatible operators
- e.g. breaks simple relation between Higgs production and decay
- Total width and Higgs to invisible as free parameters
- **Receives additional input from e.g. ee->WW and EWPO**

$$\Gamma(h \to ZZ^*)/SM = (1 + 2\eta_Z - 0.50\zeta_Z)$$
$$\sigma(e^+e^- \to Zh)/SM = (1 + 2\eta_Z + 5.7\zeta_Z)$$

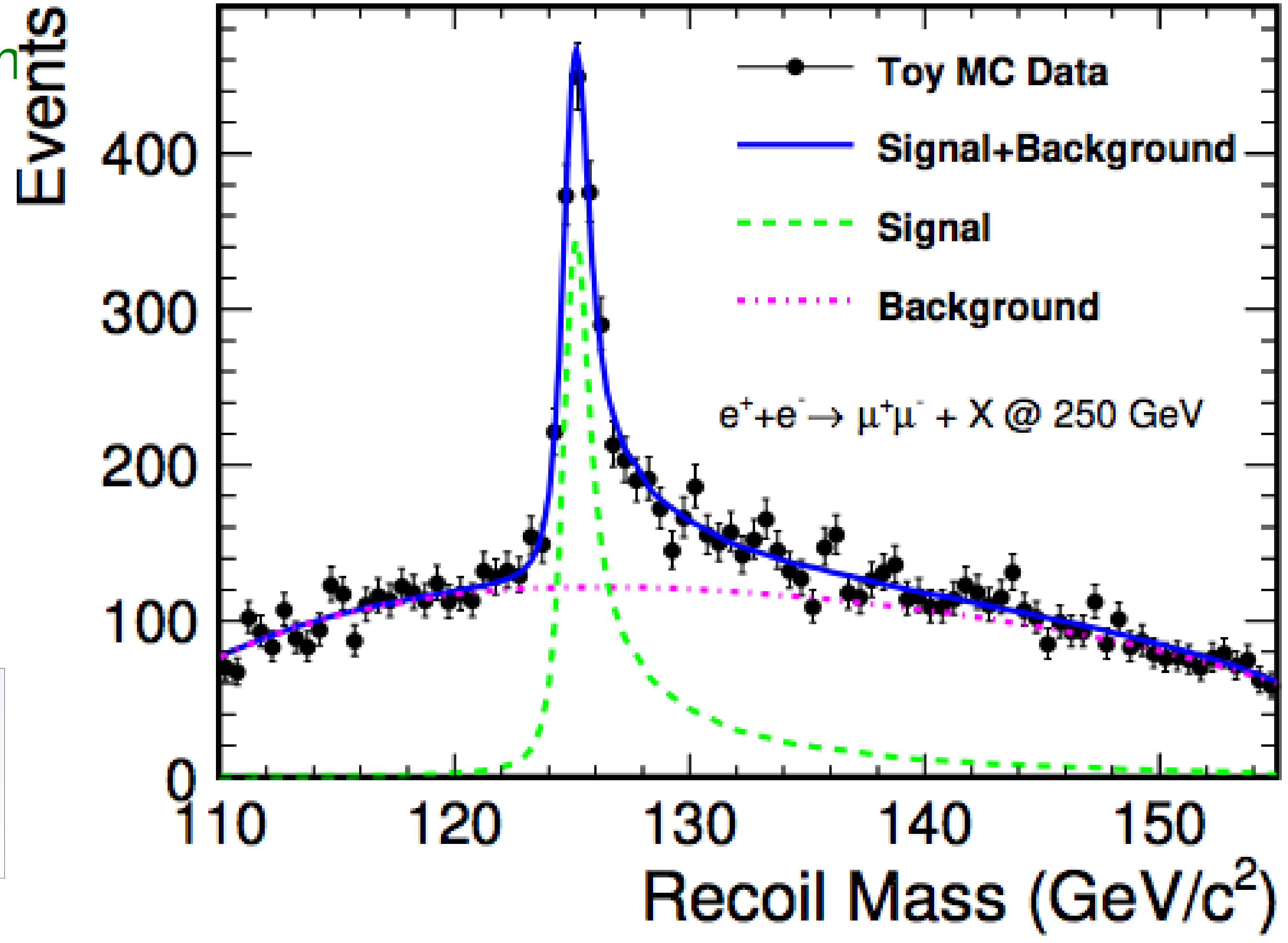
Higgs-strahlung at lepton colliders

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



Well measurable
decay leptons from Z
µ Pairs, e pairs

No assumption on Higgs
decay modes

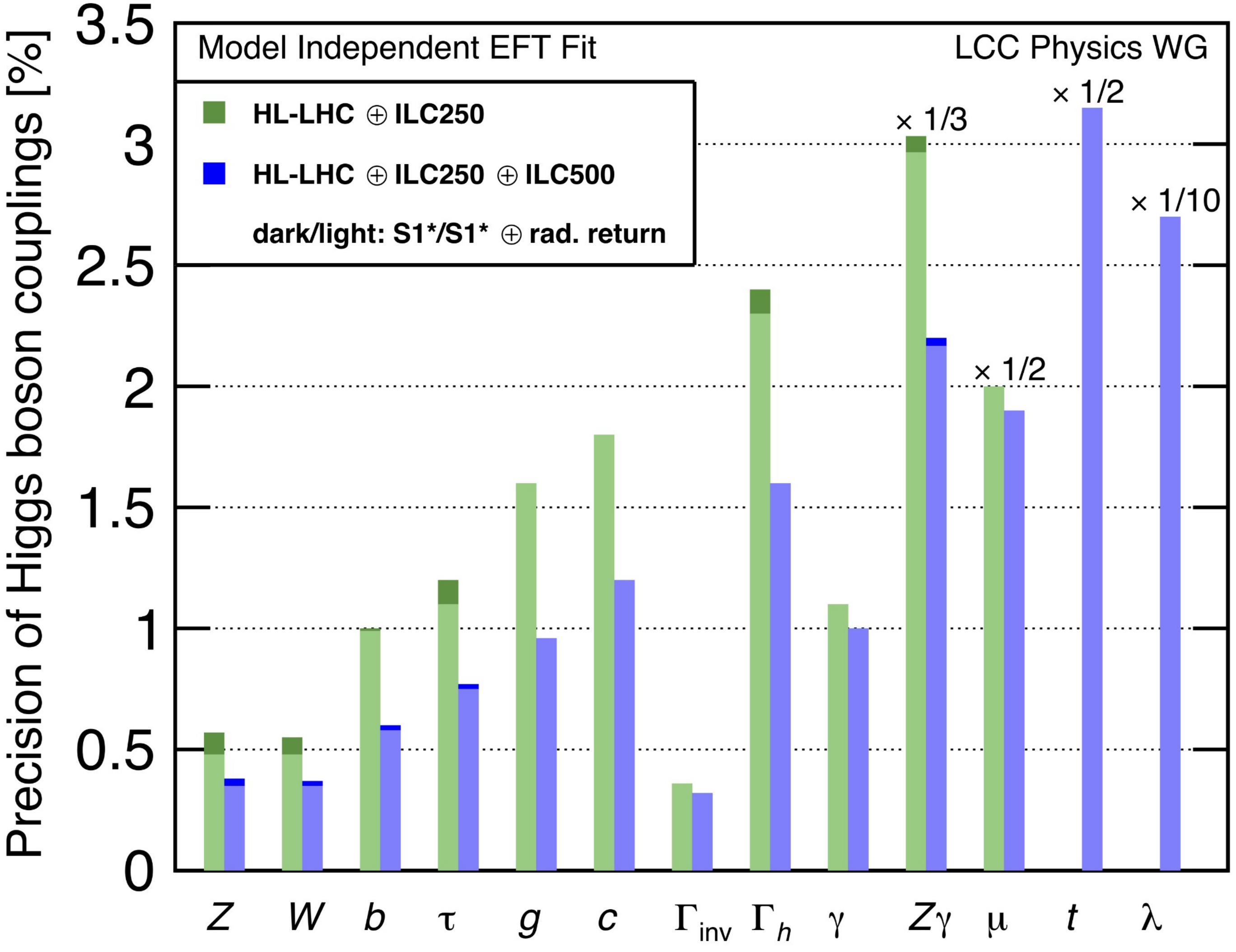


Higgs Recoil Mass: $M_h^2 = M_{recoil}^2 = s + M_Z^2 - 2E_Z\sqrt{s}$

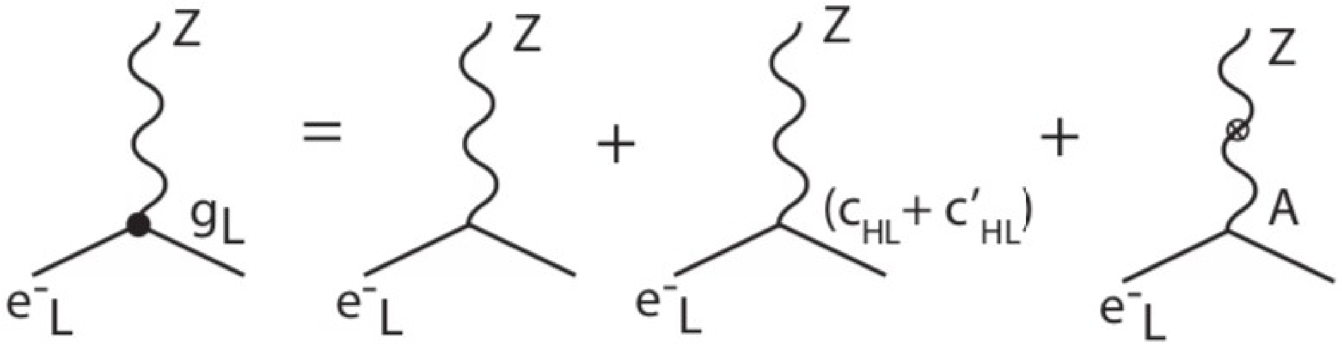
- Clean and sharp peak in Z recoil spectrum
- Illustrates precision that can be expected from e+e- colliders

EFT Framework and EWPO

Higgs couplings in EFT using A_{LR}
(Here from radiative return events

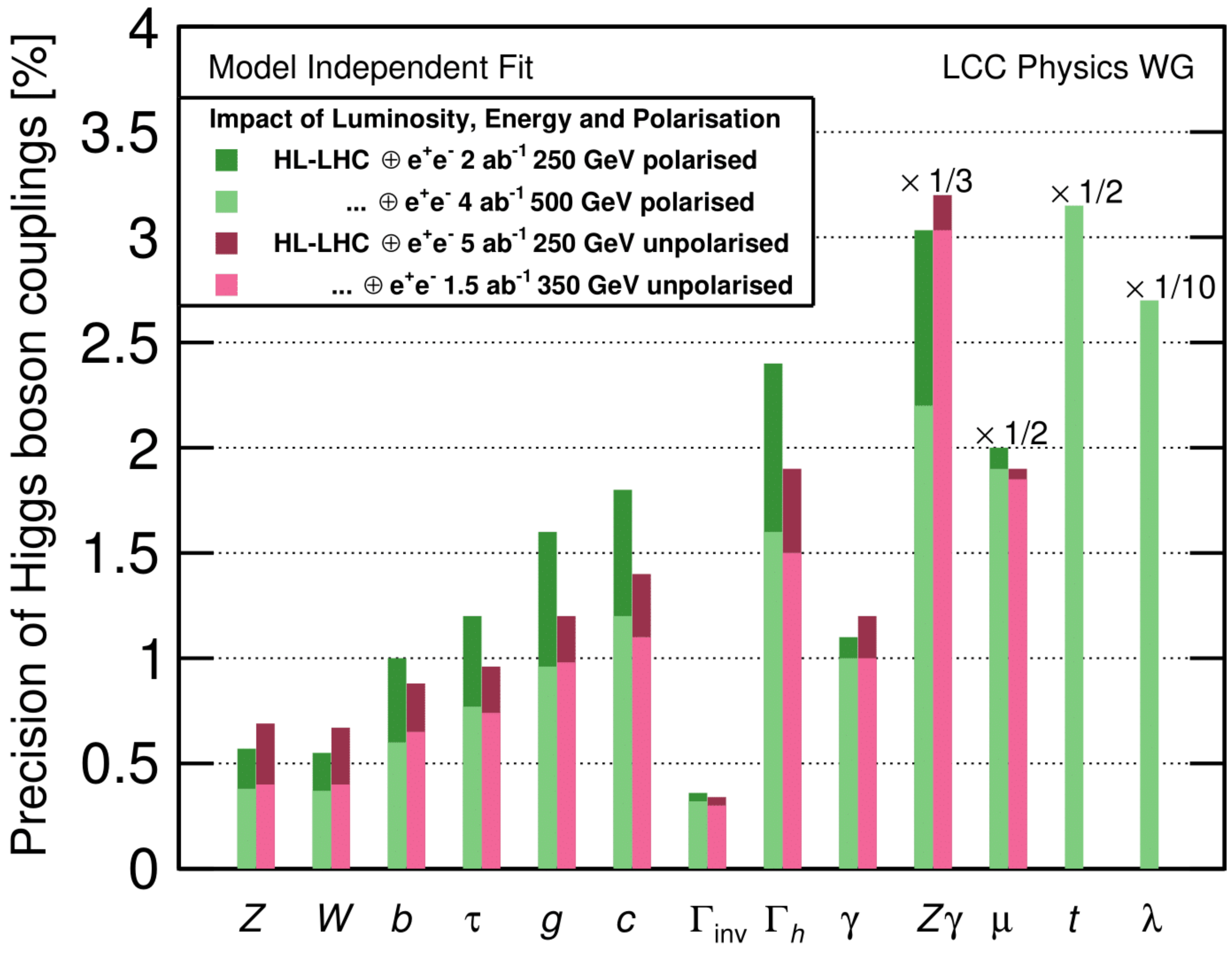


Corrections to Zee-vertex due to additional terms in EFT

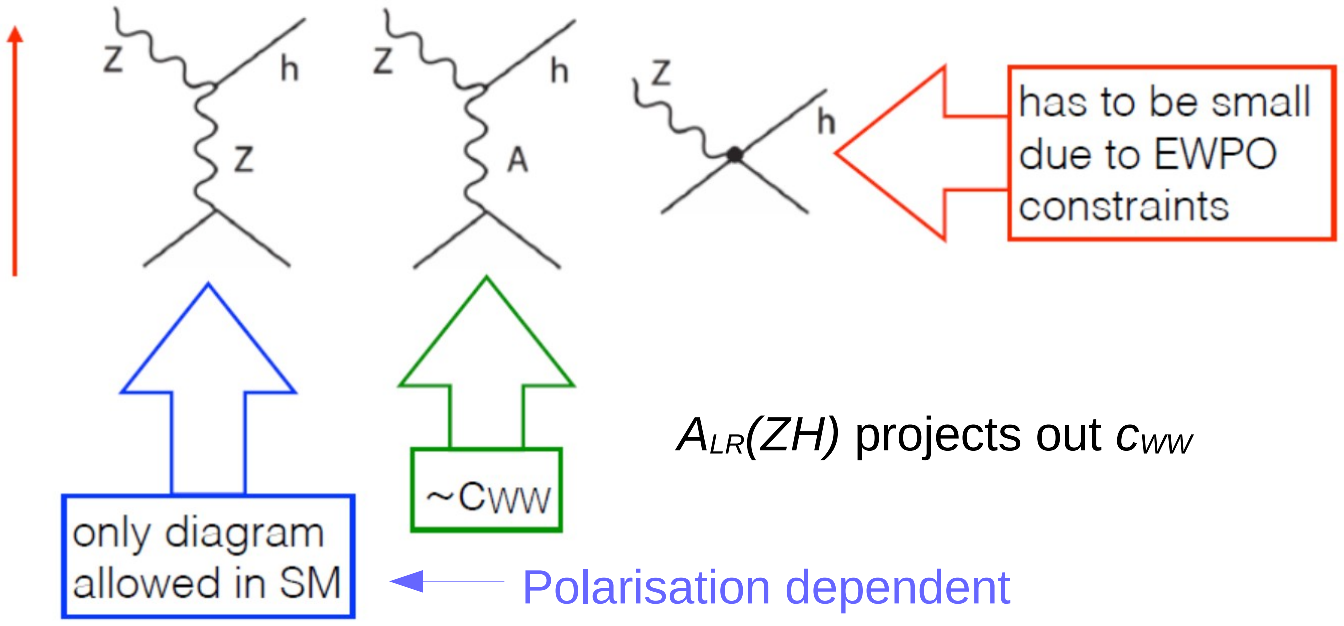


- Model independent, clean A_e from A_{LR} and Γ_e from R_e to constrain EFT fit
  - (again) No assumption of Lepton Universality
- Mild but visible improvement on some Higgs couplings at 250 GeV
  - Effect stronger in fit presented in 1905.03764 (see backup and talk by G. Durieux)

EFT Framework and beam polarisation



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



has to be small due to EWPO constraints

only diagram allowed in SM

~c_{WW}

$A_{LR}(ZH)$ projects out c_{WW}

Polarisation dependent

- Precision for 2ab^{-1} polarised = 5ab^{-1} unpolarised

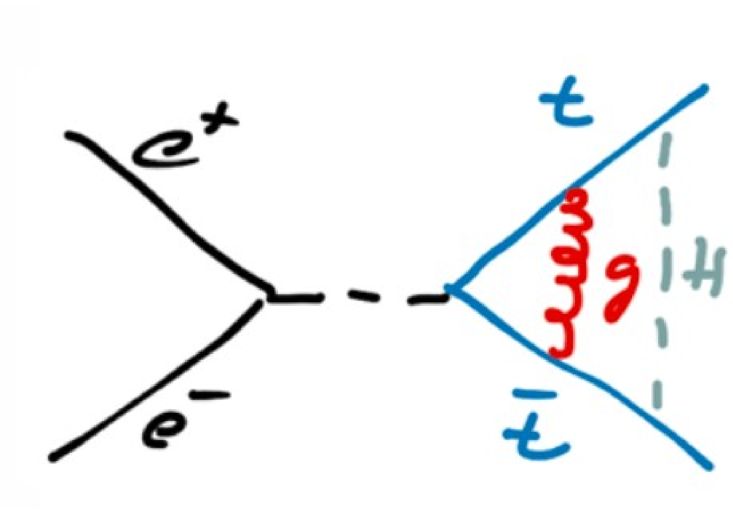
Top pair production at threshold

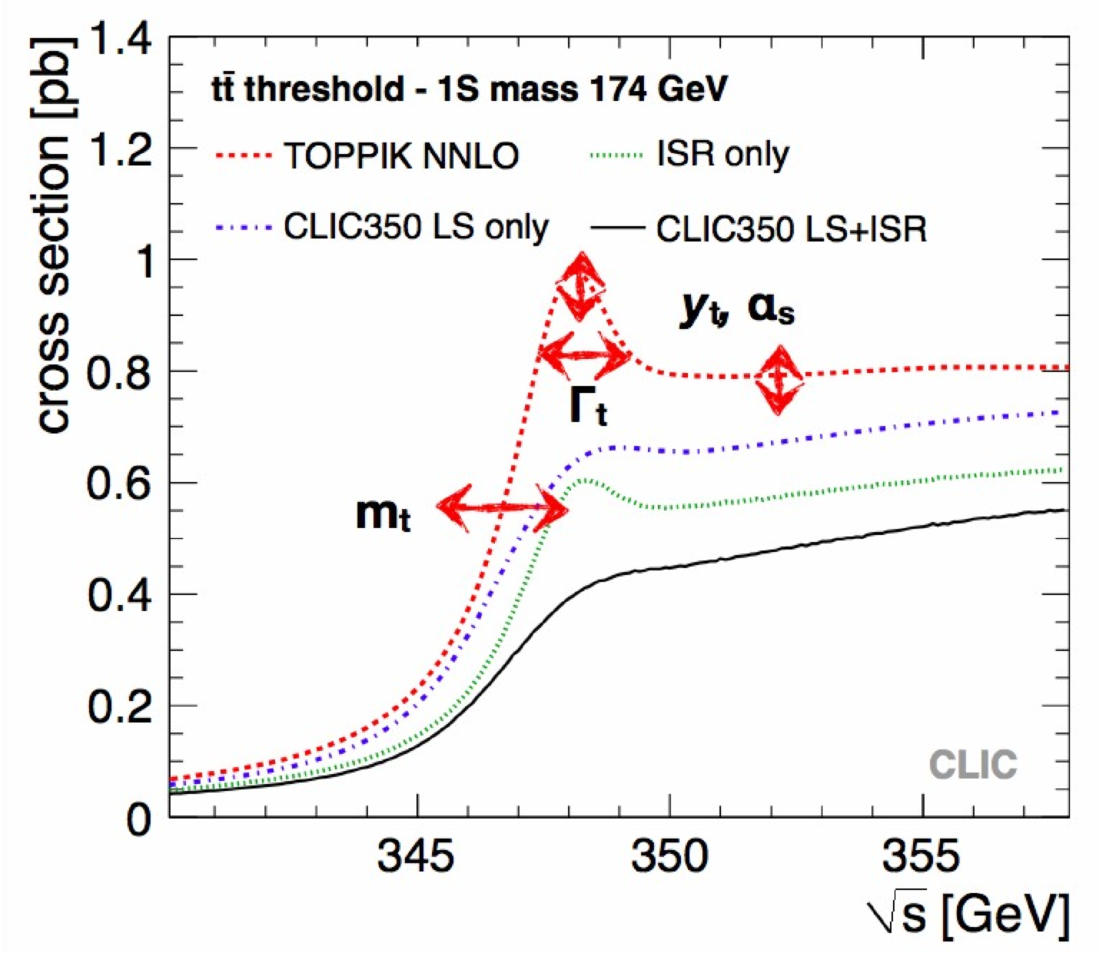
Small size of ttbar “bound state” at threshold ideal premise for precision physics

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

- Top mass, width Yukawa coupling

- Strong coupling constant

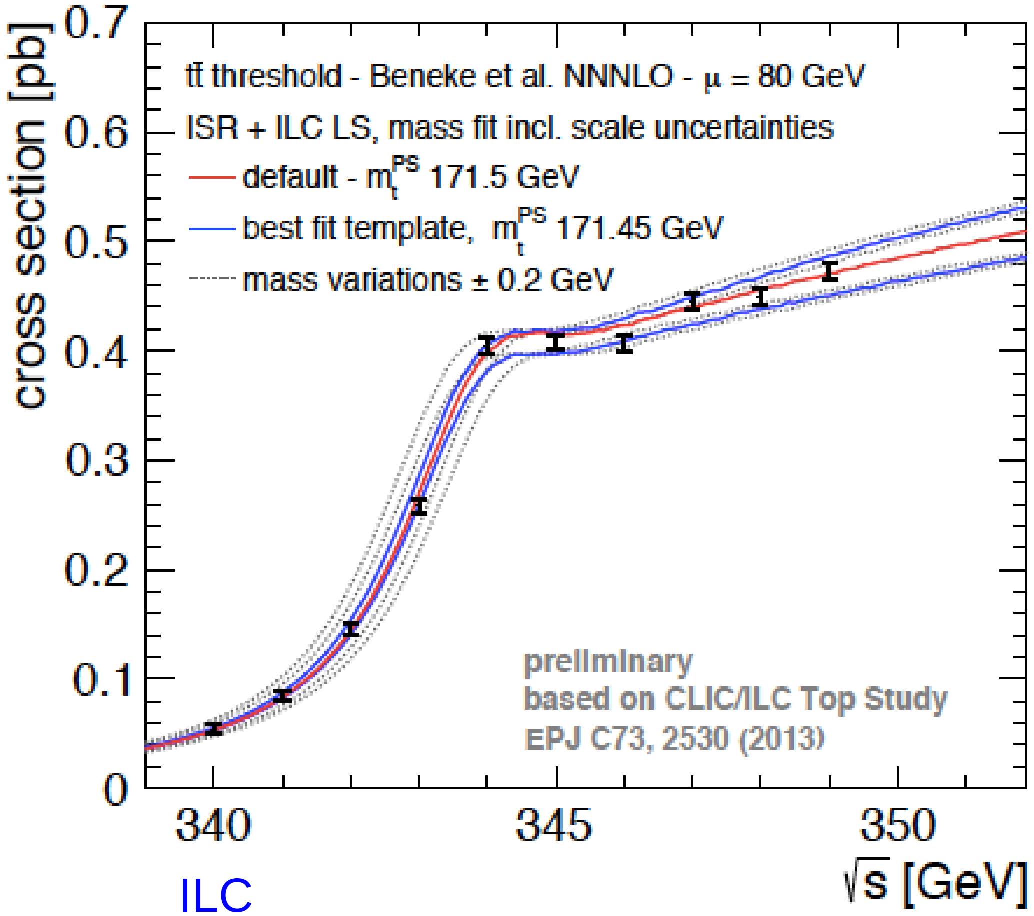




- Effects of some parameters are correlated:
- Dependence on Yukawa coupling rather weak,
- Precise external α_s helps

F. Simon, Top@LC15 Valencia

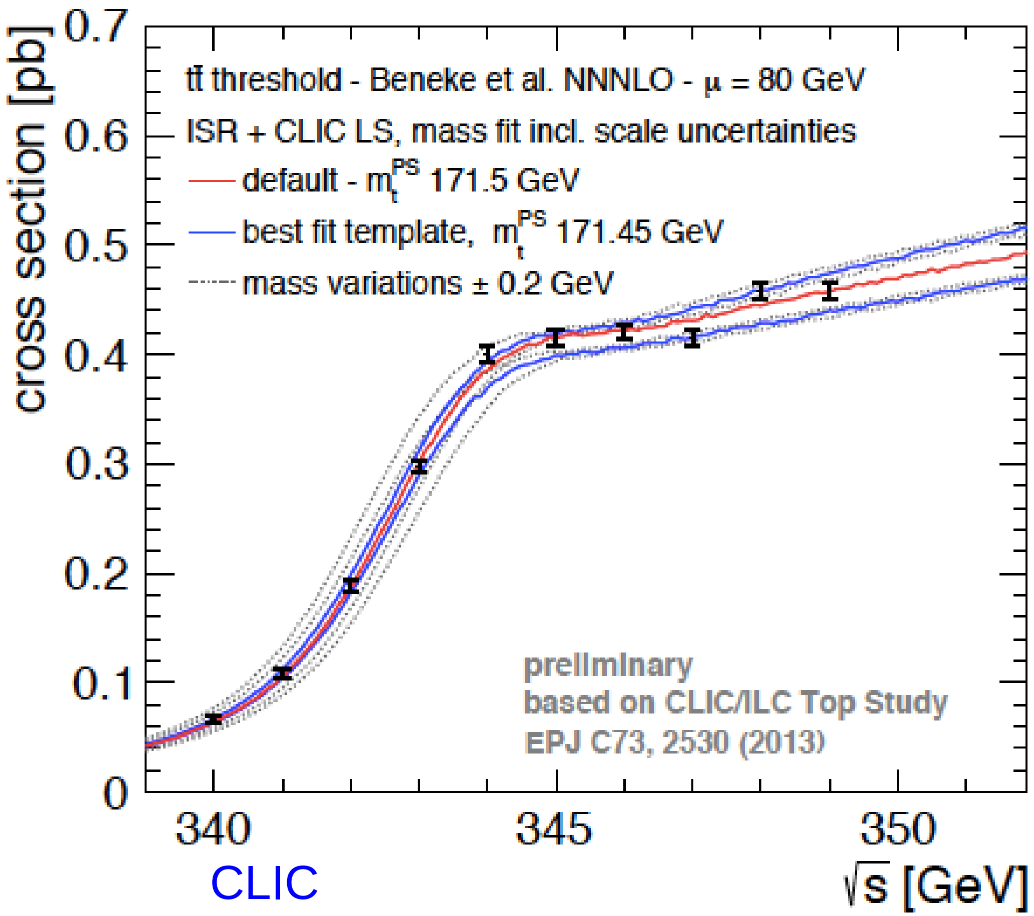
Top threshold scans at different e+e- colliders



ILC

Fit uncertainty:
28.5 MeV (18 MeV stat)

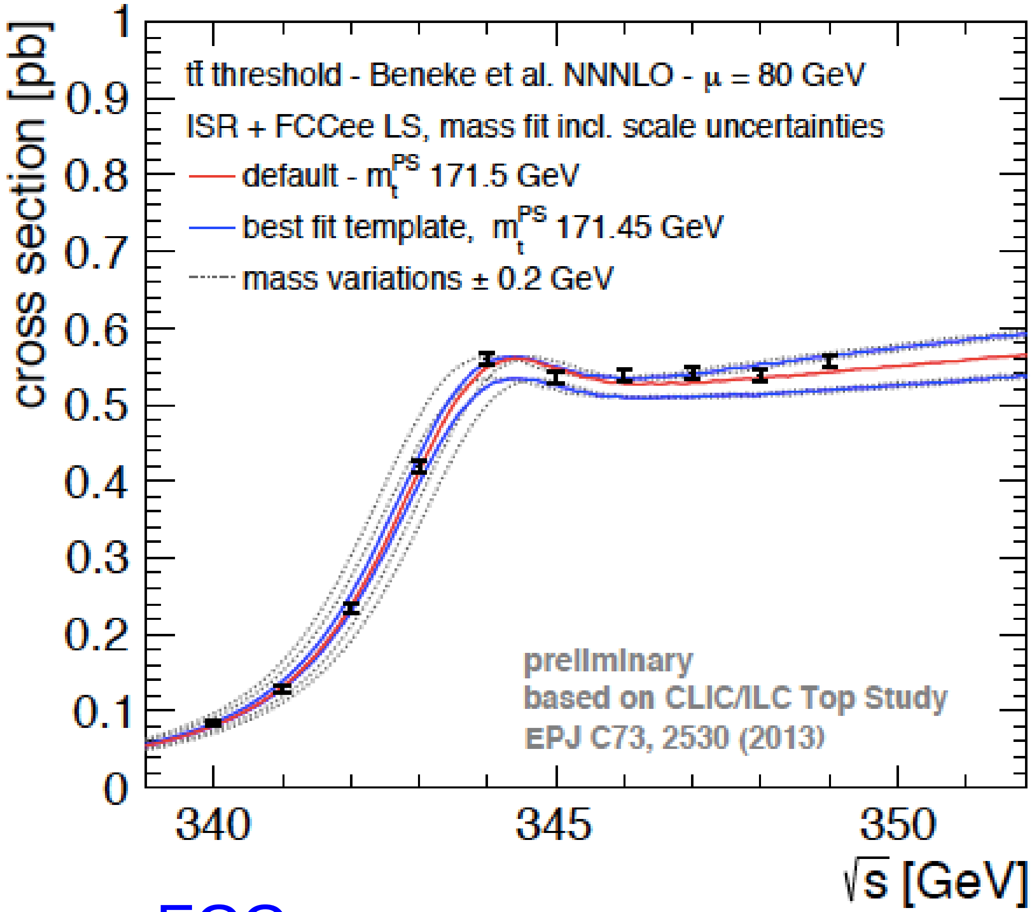
Scale uncertainty:
40 MeV



CLIC

Fit uncertainty:
31 MeV (21 MeV stat)

Scale uncertainty:
42 MeV

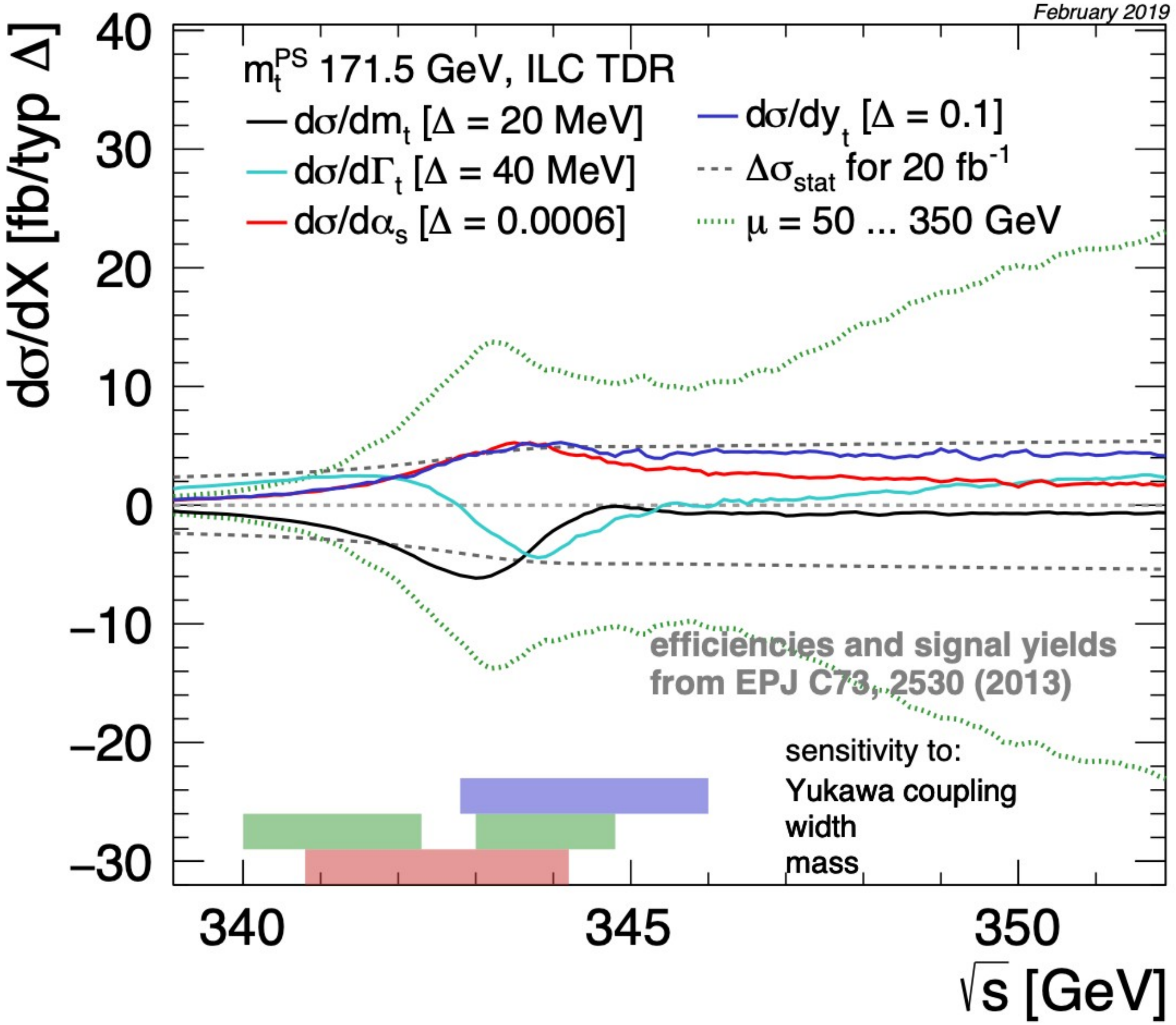


FCC-ee

Fit uncertainty:
27 MeV (15 MeV stat)

Scale uncertainty:
40 MeV

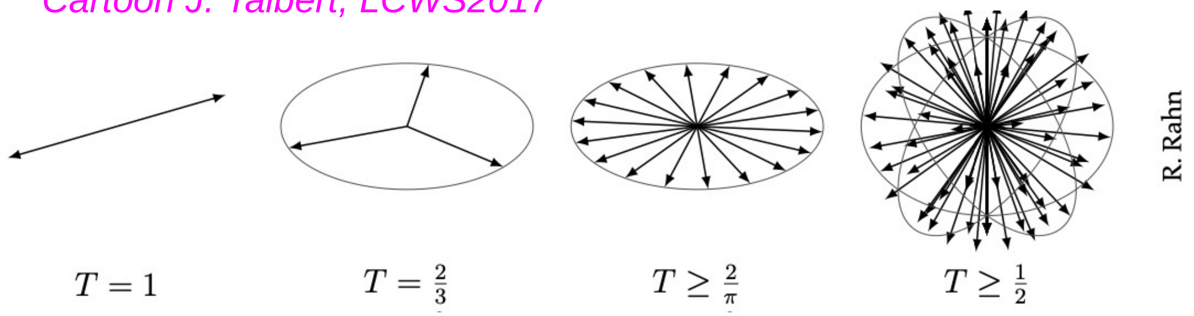
Sensitivity and error breakdown



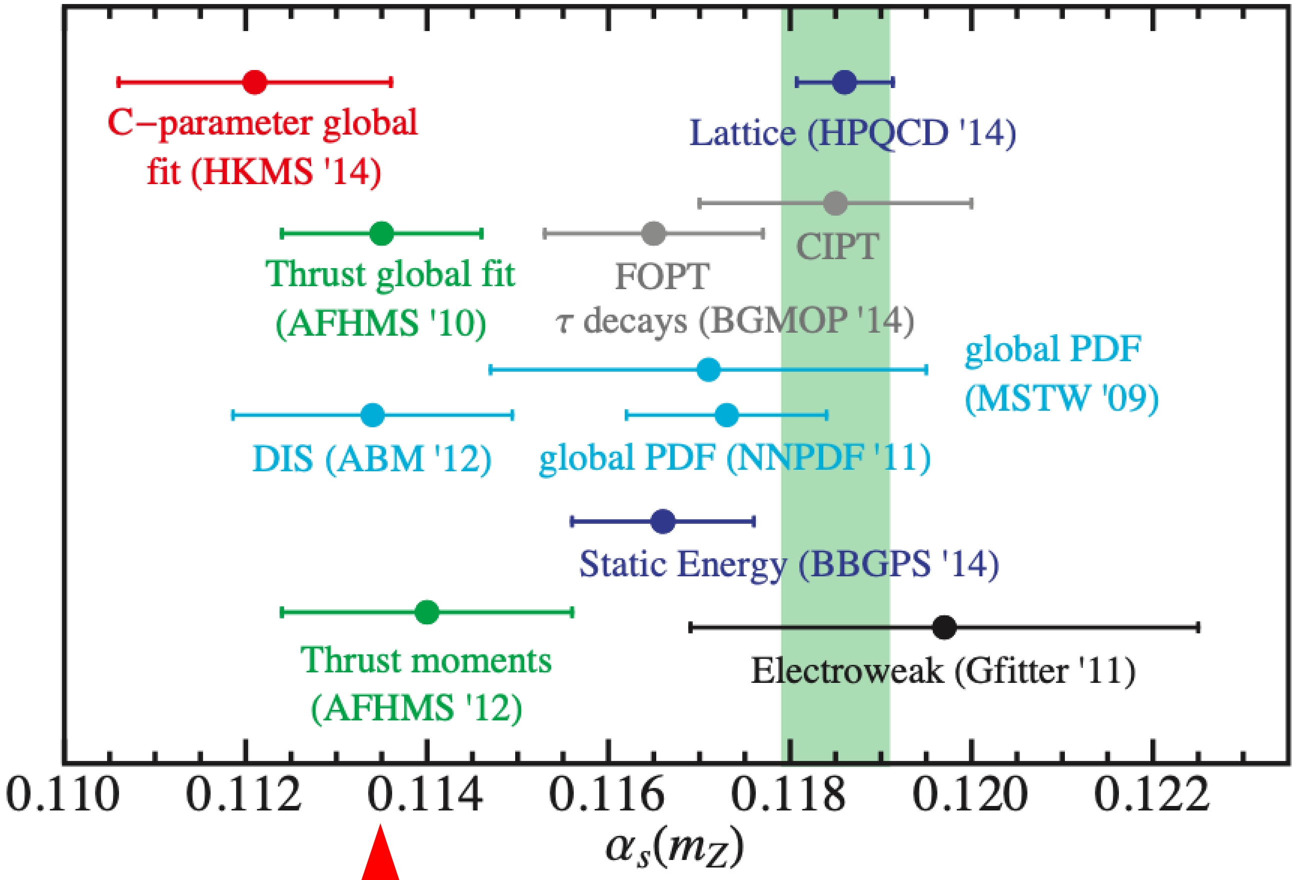
error source	Δm_t^{PS} [MeV]
stat. error (200 fb^{-1})	13
theory (NNNLO scale variations, PS scheme)	40
parametric (α_s, current WA)	35
non-resonant contributions (such as single top)	< 40
residual background / selection efficiency	10 – 20
luminosity spectrum uncertainty	< 10
beam energy uncertainty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

Uncertainty driver α_s

Cartoon J. Talbert, LCWS2017



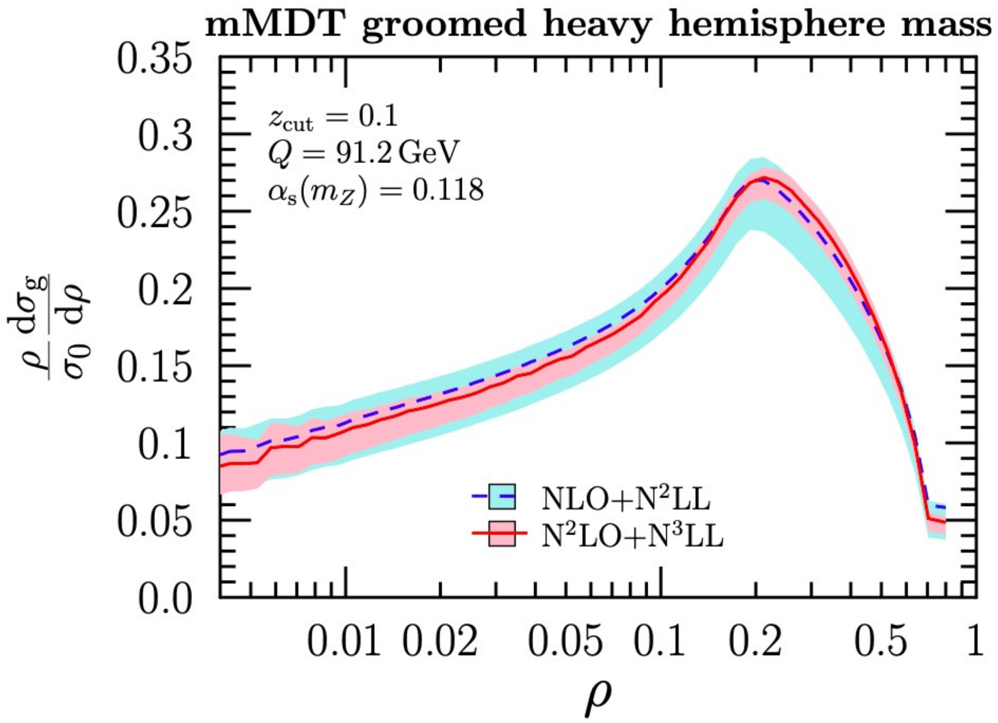
From arxiv:1501.04111



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

Summary and conclusion

- ILC is electroweak precision machine
  - Electroweak parameters are limited by systematics, not statistics
  - High precision measurements of M_Z, Γ_Z, M_W, Γ_W ,M_t and $\sin^2\theta^{\ell}_{\mathrm{eff}}$.

- ILC can (should) be run on the Z-pole
  - Electroweak precision observables deliver decisive input for interpretation at higher energies

- Full exploitation of physics potential by large energy coverage and polarised beams
  - Clean model independent measurements due to beam polarisation
    - Tests of lepton universality
  - Measurement of patterns for indirect discovery of new physics
    - Spectacular mass reach for new physics already art 250 GeV demonstrated
    - Flexibility of beam energy allows for systematic tracing of the the onset of new physics

Main challenge at future machines will be the control of systematic errors

- Experimentally (non exhaustive list)
  - Vertex charge and particle ID
  - PFO for final state jets
  - Beam energy and polarisation
- Theoretically (not discussed)
  - Need at least NLO electroweak predictions (and MC programs) for correct interpretation of results
  - α_s

Graham's shopping list

1. Can mW be measured well at center-of-mass energies above ZH production threshold? For ILC this needs a more detailed look with a full kinematic fit to qqlnu events including effects of luminosity spectrum. These events have mW information from both W's.

Acceptance?

1b. Is it really necessary to use the WW threshold for theoretical reasons?

2. Ultimate precision on center-of-mass energy using radiative return events especially in case momentum-scale systematics dominate sqrt(sp). Important for Higgs mass, top mass, and W mass.

3. Detector requirements for Z pole observables.

Forward acceptance for e+e- -> q qbar is very important.

4. Can the background be controlled well enough

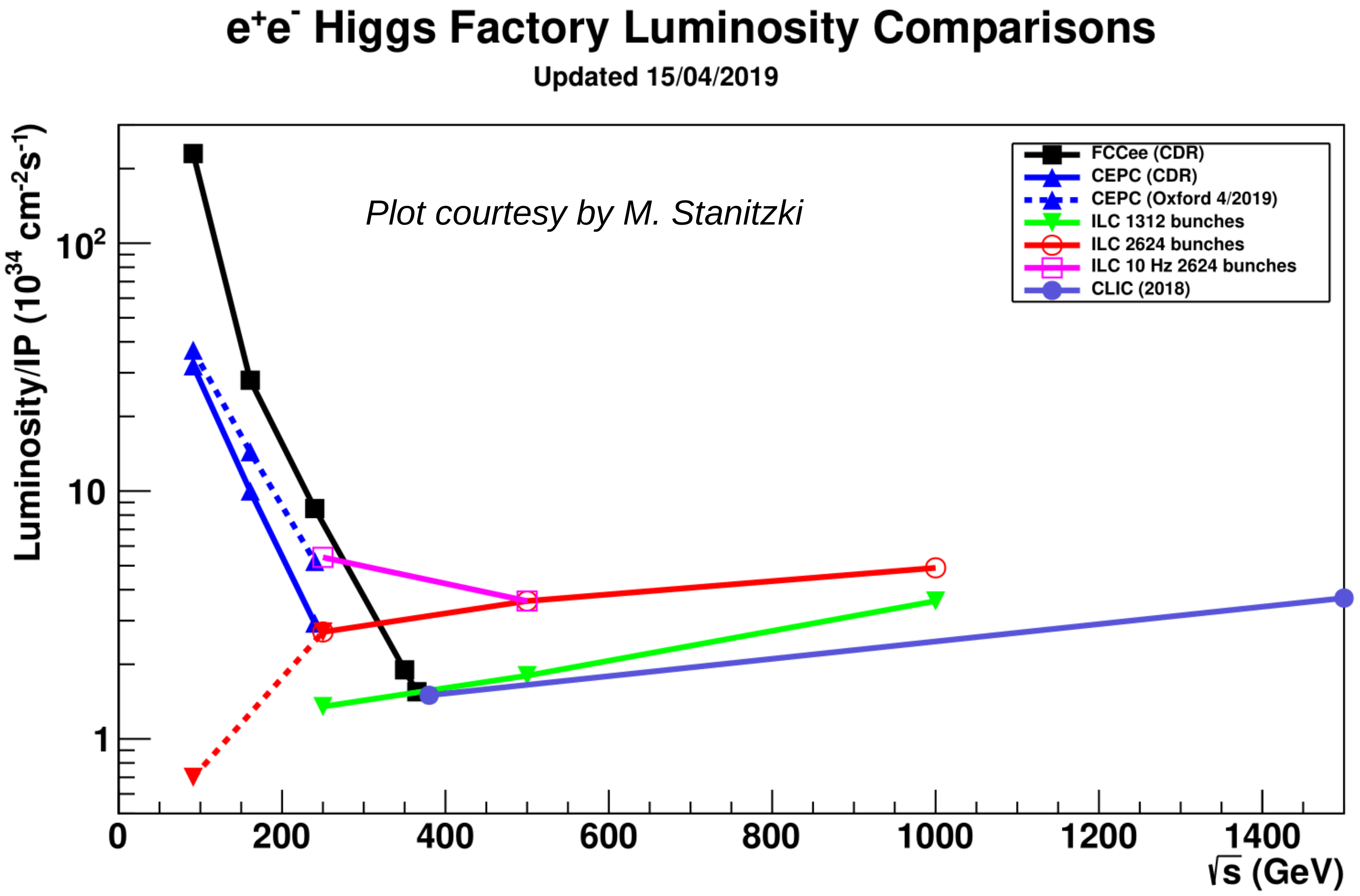
for mW from threshold measurements. Especially for 4-jet case, and

without both beams being polarized.

5. Can gamma-gamma -> hadrons background be controlled at the Z peak?

Backup

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, see later ...

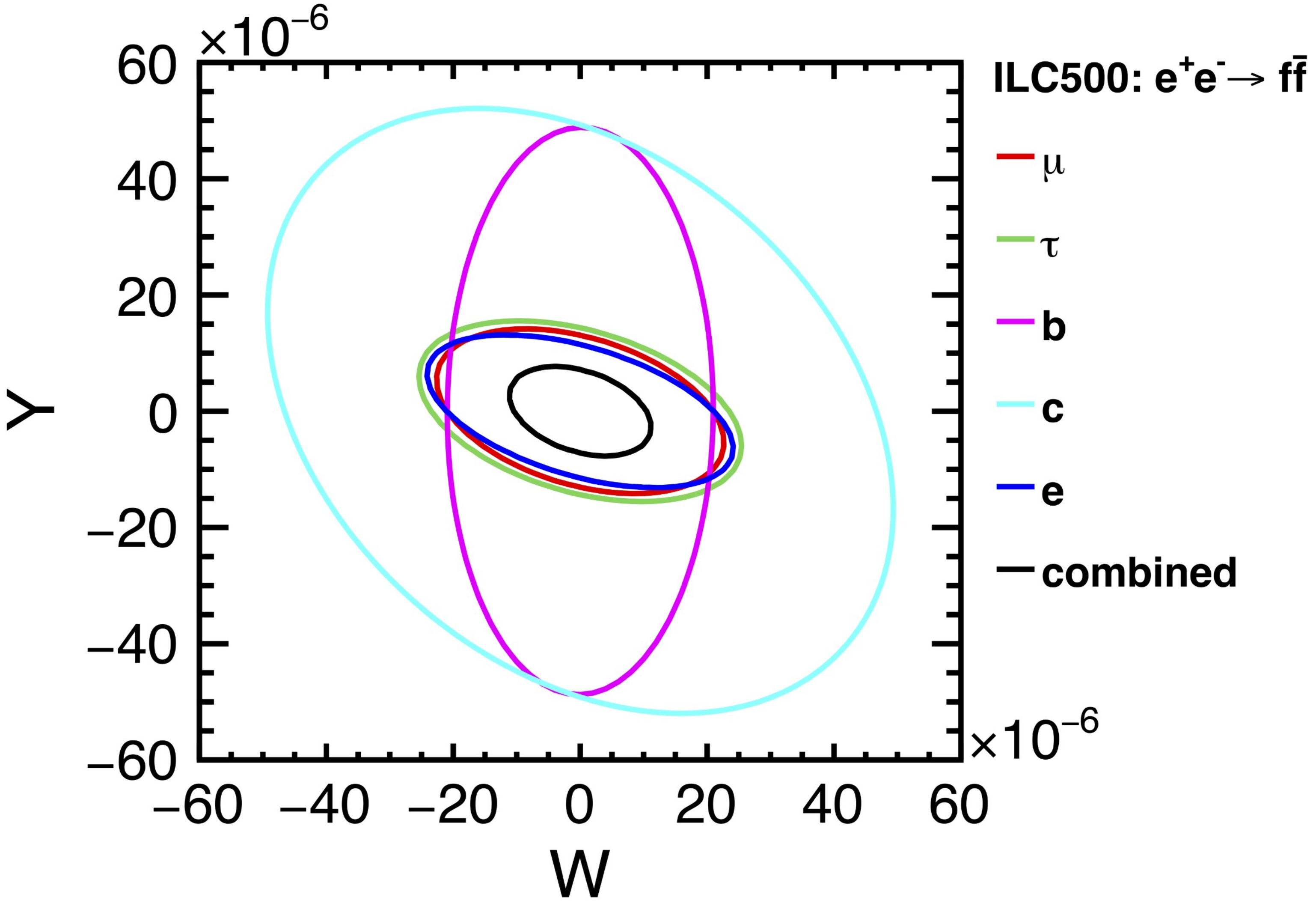
- Transition region, i.e. HZ threshold
  … not so clear
  Comparable numbers for all proposals

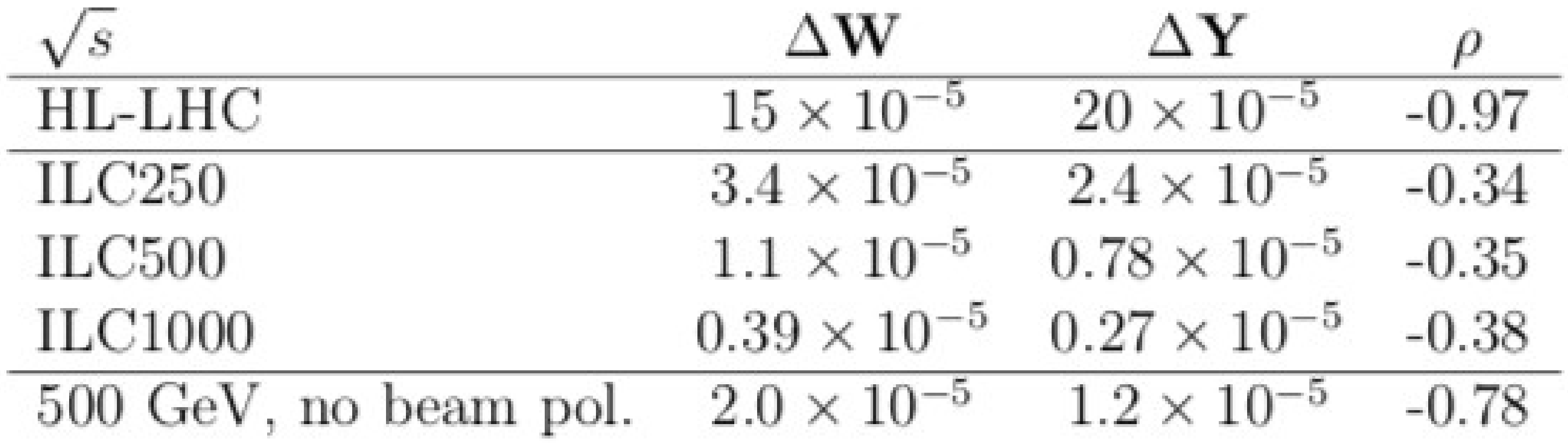
- Linear colliders are more versatile
  to test chiral theory due to polarised
  beams

- Detailed design parameters see backup

Oblique parameters

Contributions for different fermion species





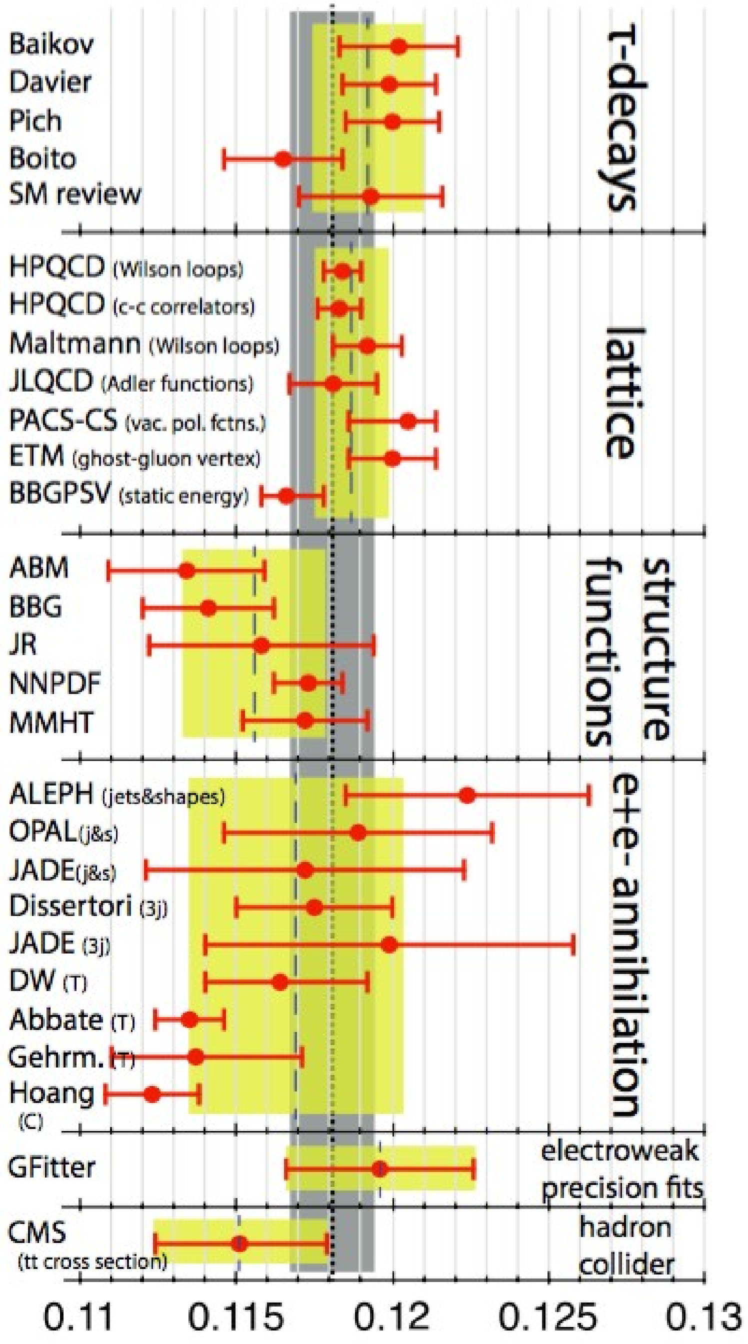
$\sqrt{s}$	ΔW	ΔY	ρ
HL-LHC	15×10^{-5}	20×10^{-5}	-0.97
ILC250	3.4×10^{-5}	2.4×10^{-5}	-0.34
ILC500	1.1×10^{-5}	0.78×10^{-5}	-0.35
ILC1000	0.39×10^{-5}	0.27×10^{-5}	-0.38
500 GeV, no beam pol.	2.0×10^{-5}	1.2×10^{-5}	-0.78

- Beam polarisation essential to disentangle effects from W and Y
- ILC250 outperforms LHC
- ILC500 and above outperforms e+e- machines w/o polarisation (at 4ab^{-1})

Uncertainty driver α_s

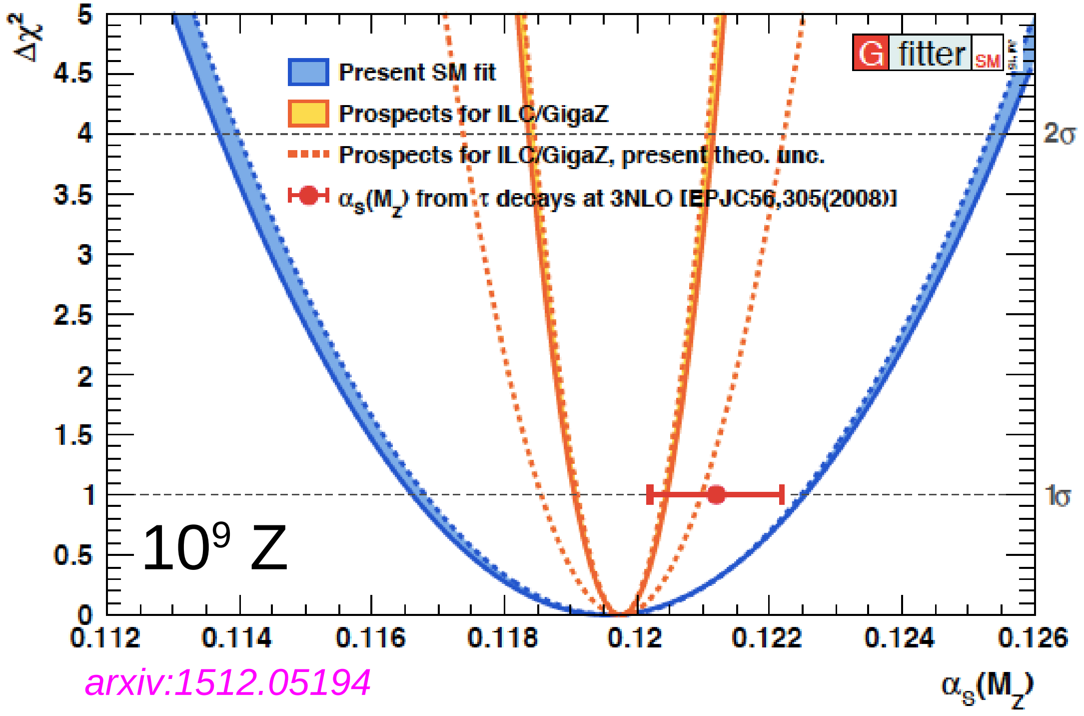
Slide made in 2016!

Current status



Dominated by lattice QCD

Prospects Z-running



arxiv:1512.05194

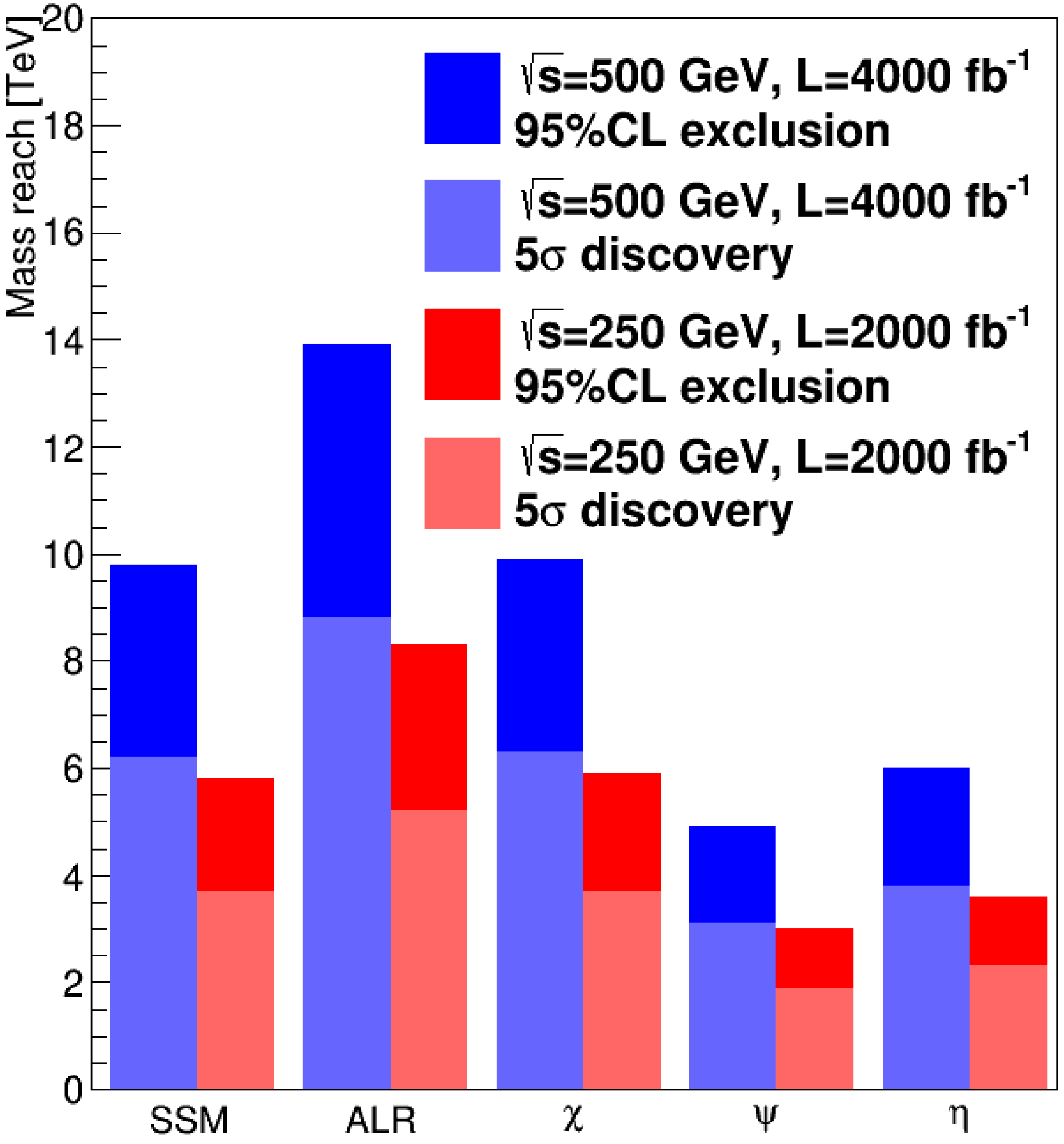
Electroweak fit with updated EWPO and theory uncertainties

$\delta\ \alpha_s(M_Z) \sim 0.0007$ for 10^9Z
$\delta\ \alpha_s(M_Z) \sim 0.0003(16)$ for 10^{12}Z

Prospects Lattice

$\delta\alpha_s(MZ) \sim 0.0003$

Mass reach for vector new bosons (Z') in 2-fermion production

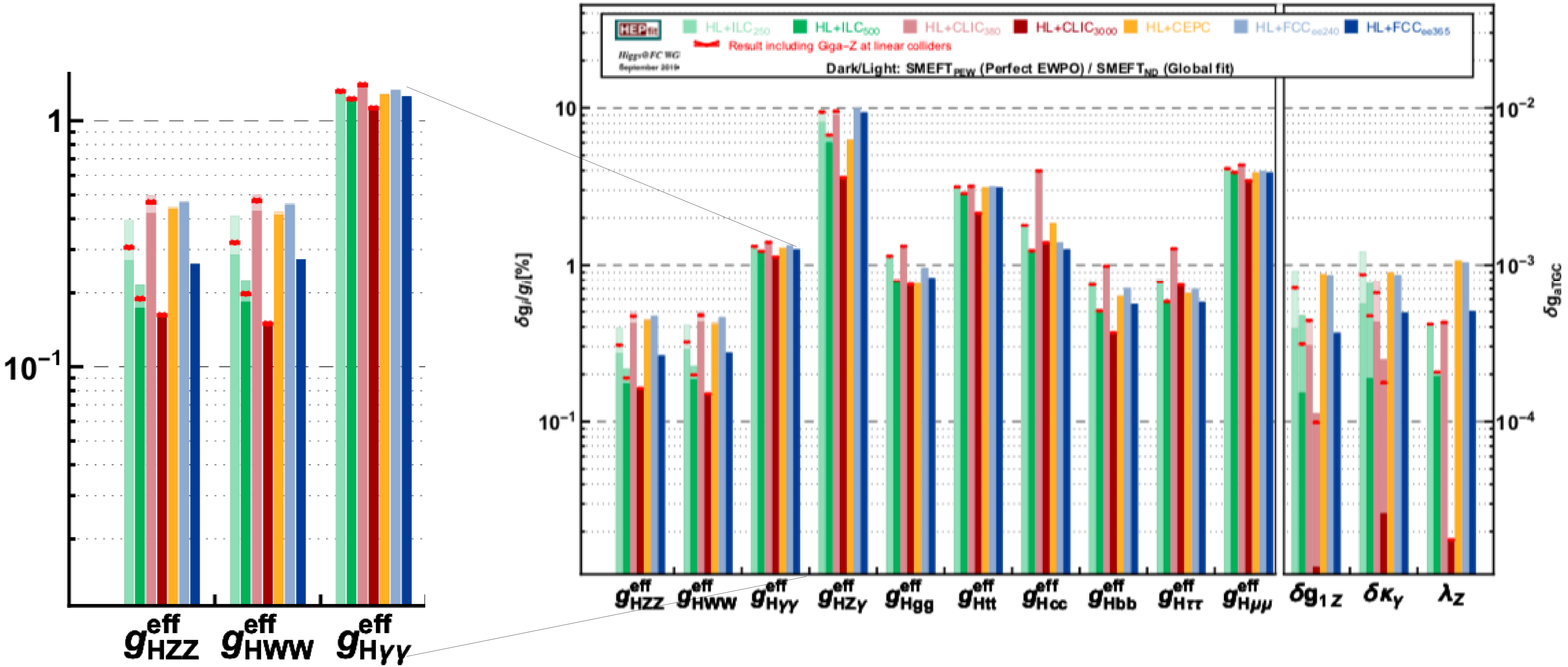


- SSM is "carbon" copy of SM Z and used as common metric in generic Z' searches
- ALR introduces an "ad hoc" $SU(2)_R$ and a Z' with orthogonal couplings to the fermions
- Χ, ψ, η are linear combinations of bosons appearing in Grand Unified Theories with couplings orthogonal to the SM Z

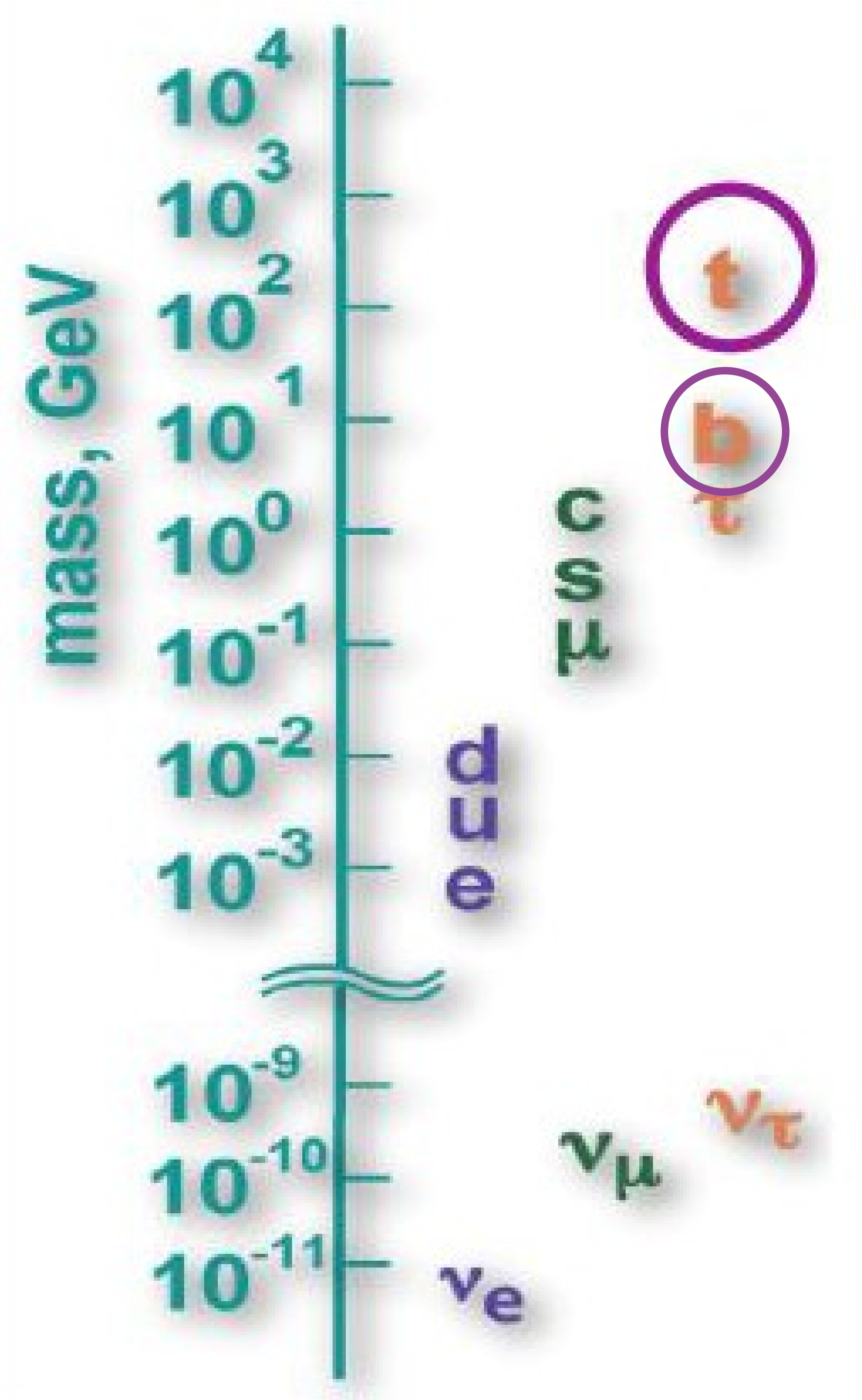
Typical mass reach 5-10 TeV

- **Reach shown for e, μ, τ**
- **Adding quarks would improve limits**

Higgs couplings and EWPO in ESU-Fit – 1905.03764



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

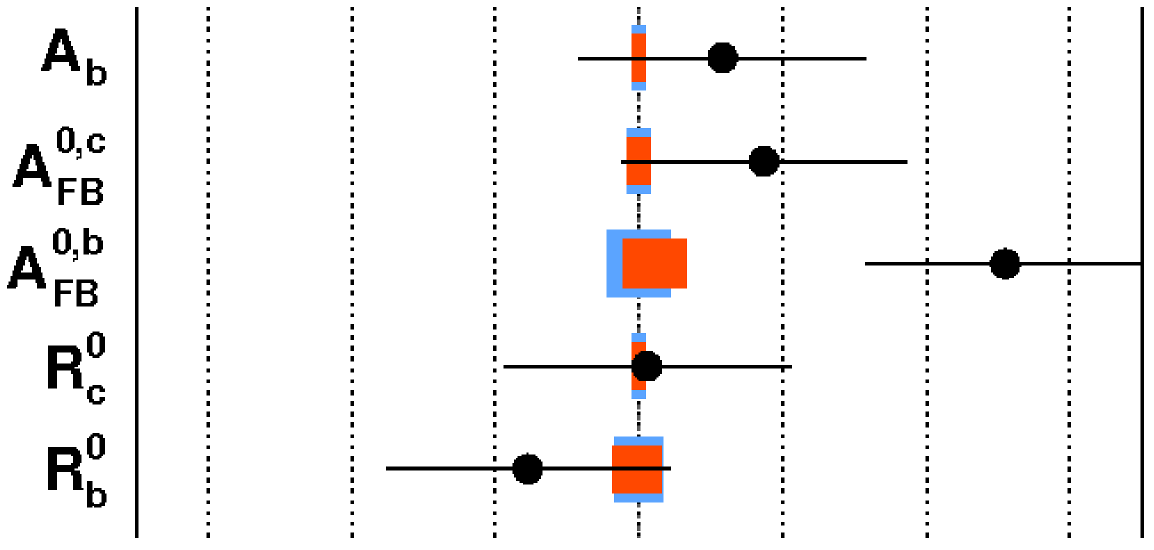
- Expect residual effects for particles with masses closest to symmetry breaking scale

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

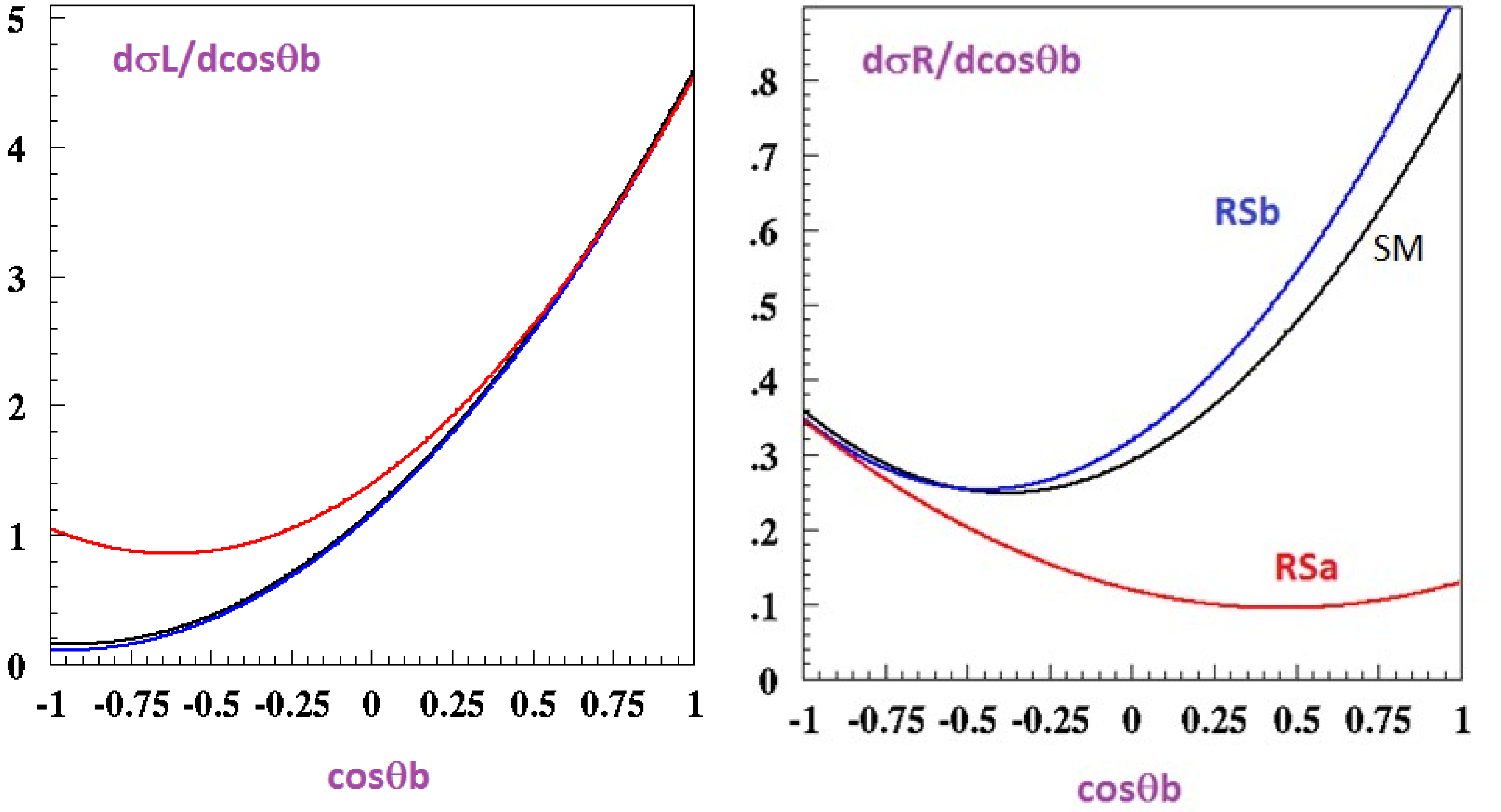
Strong motivation to study chiral structure of heavy quark vertices in high energy e+e- collisions

New physics below tt threshold? - Example b quark couplings

~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
- Randall Sundrum Models generate basically automatically a symmetry group of type $SU(2)_R$

Energy Frontier Electron-Positron Collider Projects

	√s	beam polarisation	∫Ldt for Higgs	R&D phase
ILC	0.1 - 1 TeV	e-: 80% e+: 30%	2000 fb-1 @ 250 GeV 200 fb-1 @ 350 GeV 4000 fb-1 @ 500 GeV	TDR completed in 2013
CLIC	0.35 - 3 TeV	e-: (80%) e+: 0%	1000 fb-1 @ 380 GeV 2500 fb-1 @ 1.5 TeV 5000 fb-1 @ 3 TeV	CDR completed in 2012
CEPC	90 - 240 GeV	e-: 0% e+: 0%	5600 fb-1 @ 240 GeV	CDR completed in 2018
FCC-ee	90 - 350 GeV	e-: 0% e+: 0%	5000 fb-1 @ 250 GeV 1700 fb-1 @ 350 GeV	CDR completed in Jan 2019

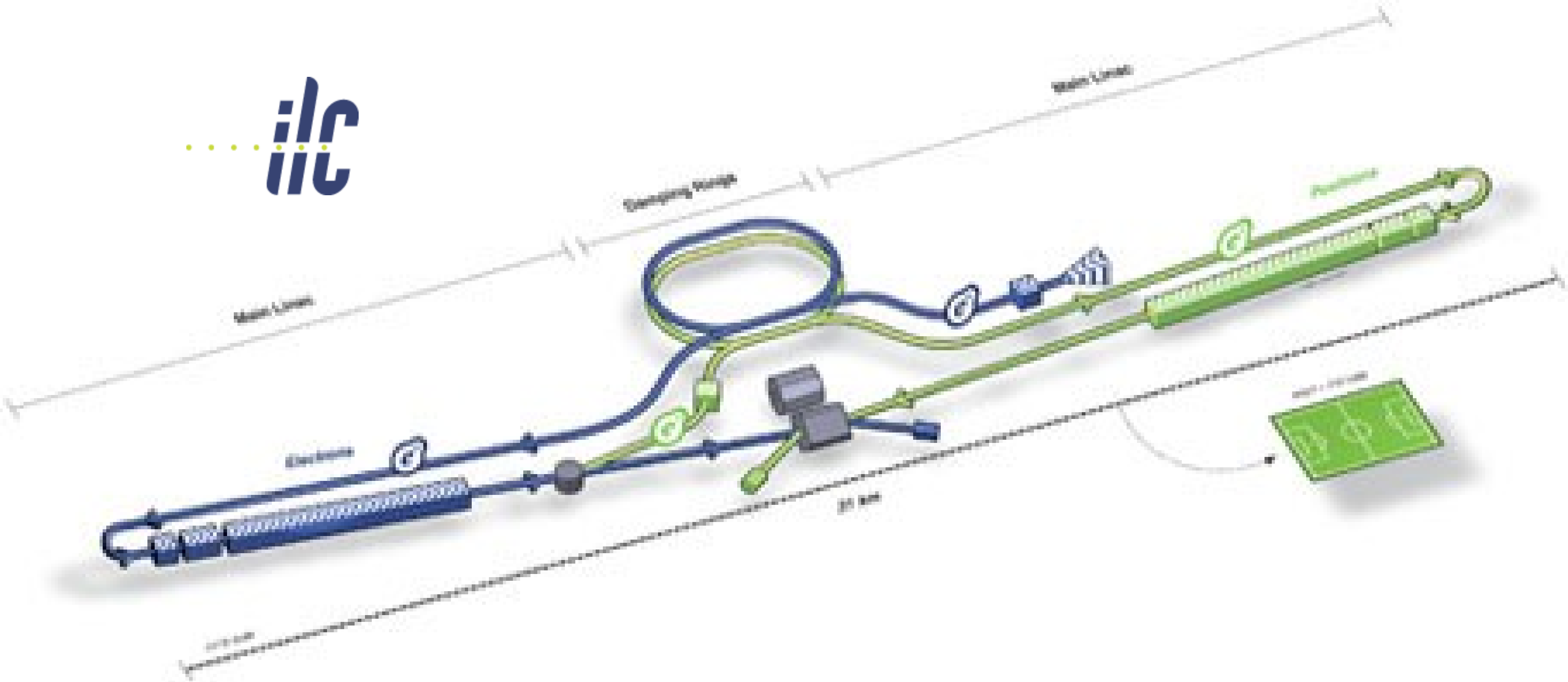
Details see talk by Y. Okada

Details see talk by M. Ruan

Table courtesy of J. Brau

Open questions

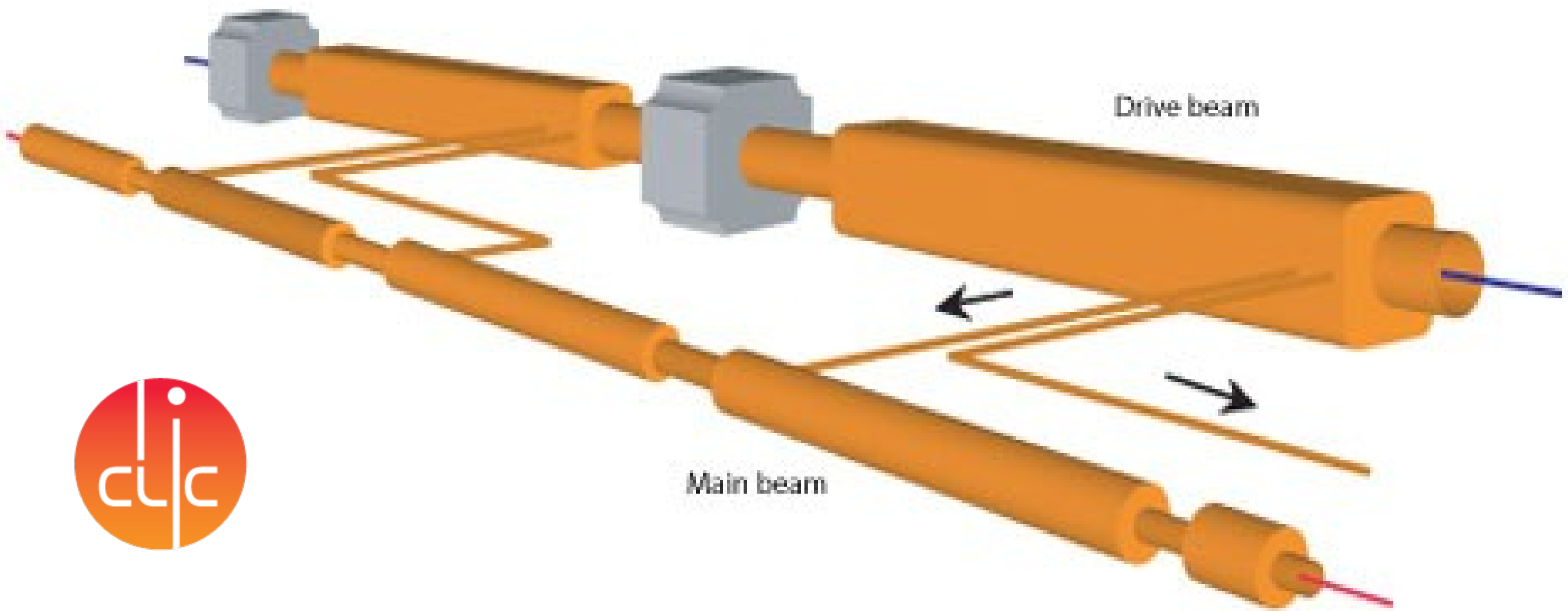
Linear Electron-Positron Colliders



Japanese Gouvernment expressed its interest in project in March 2019

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

Initial Energy 250 GeV – Footprint ~20km



Possible future project at CERN

Energy: 0.4 - 3 TeV

CDR in 2012

Footprint 48km

Initial Energy 380 GeV

New physics?

EFT: Two distinct observations

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

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

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

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

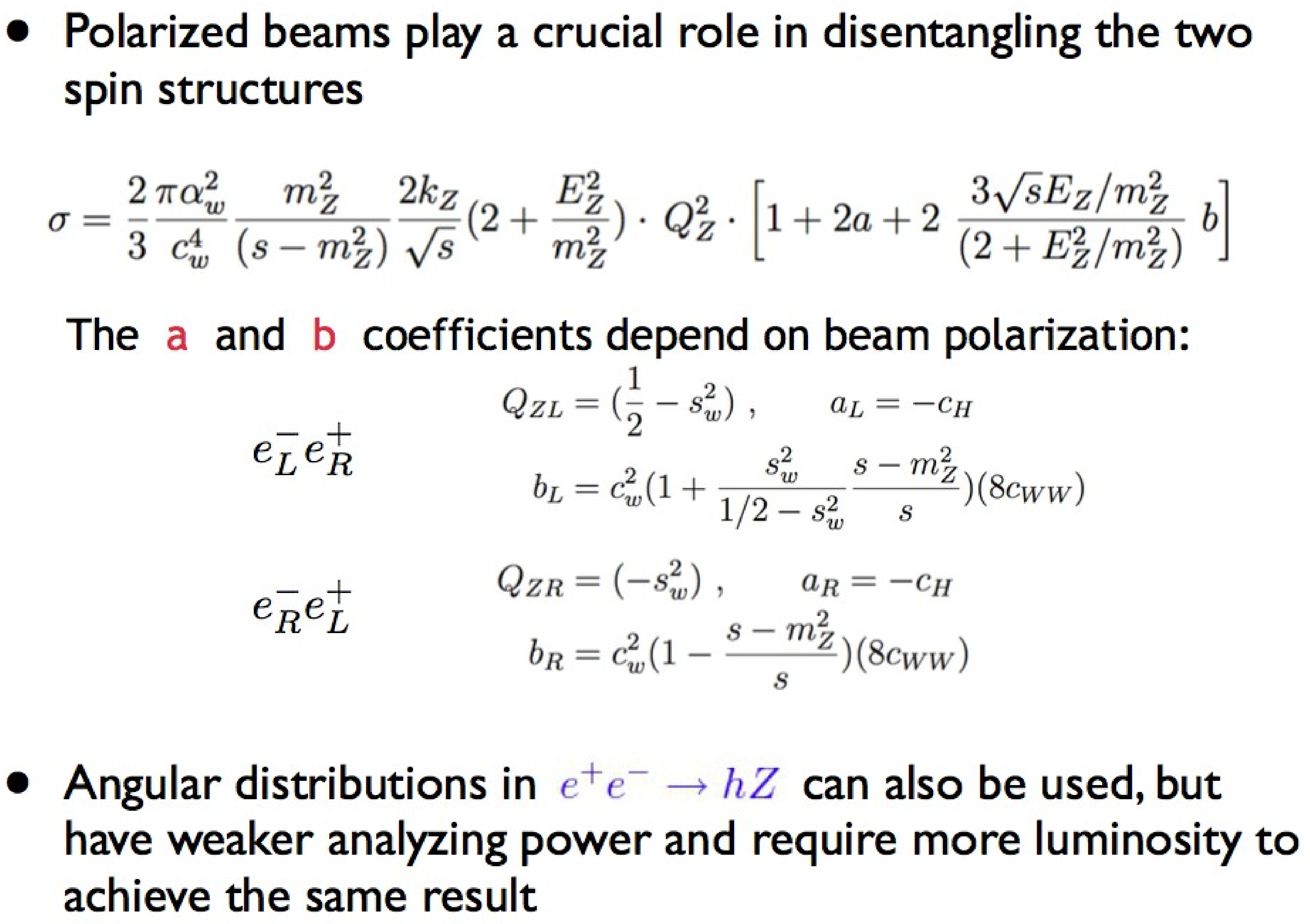
Increasing UV scales probed in EFT achieved solely by increasing the measurement precision
$c_6 \sim (g^*)^2$
Typical experimental precision 0.1-1%

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

Typical experimental precision 10%

A. Falkowski, Journée Grands Accél., LAL

New physics?



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

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

The a and b coefficients depend on beam polarization:

$e_L^-e_R^+$

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

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

$e_R^-e_L^+$

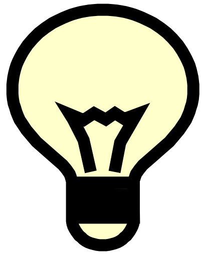
$$Q_{ZR} = (-s_w^2)\ , \qquad a_R = -c_H$$

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

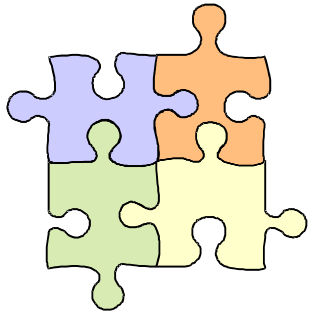
- Angular distributions in $e^+e^- \rightarrow hZ$ can also be used, but have weaker analyzing power and require more luminosity to achieve the same result

M. Perelstein: AWLC2017

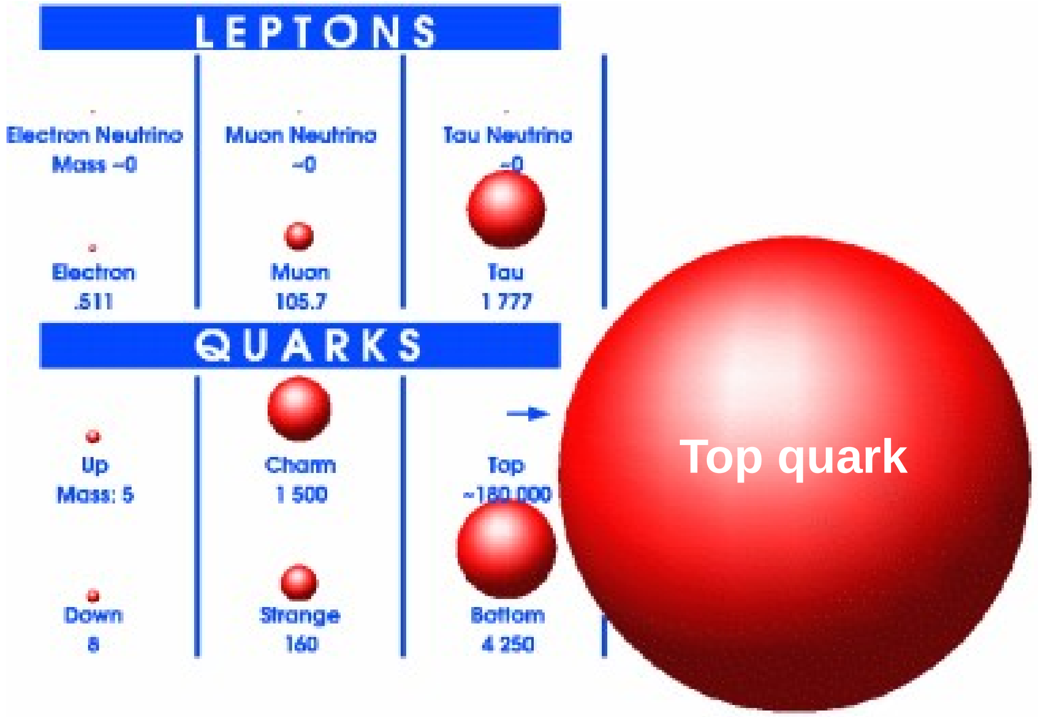
Science drivers



Elementary Scalar?



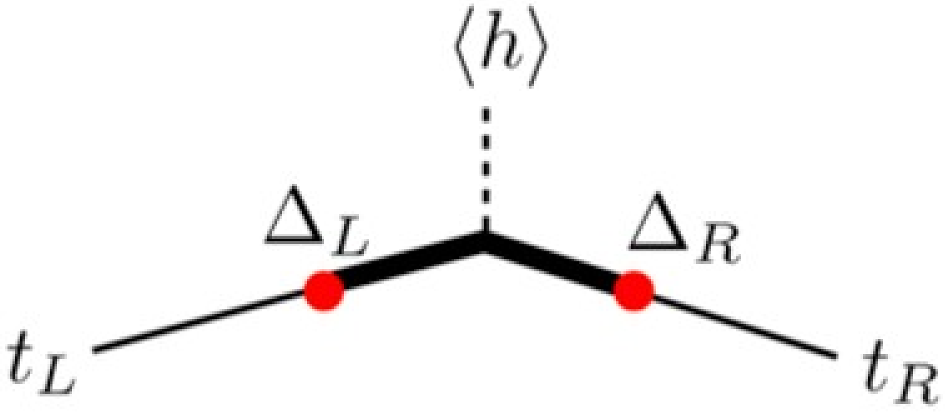
Composite object?



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

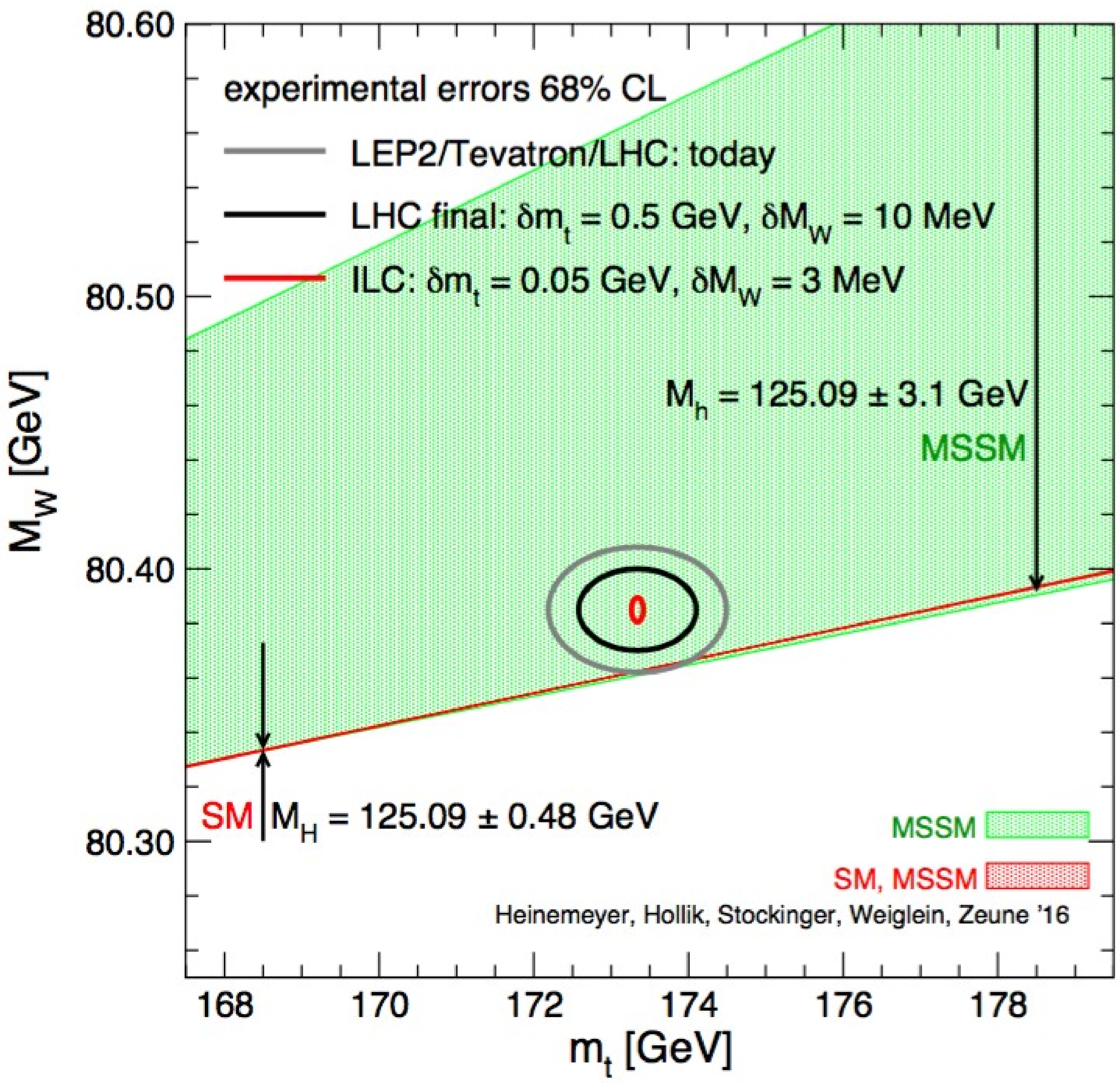
- New physics by compositeness?
  Higgs and top composite objects?

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



Courtesy of S. Rychkov

Top mass Higgs mass and BSM



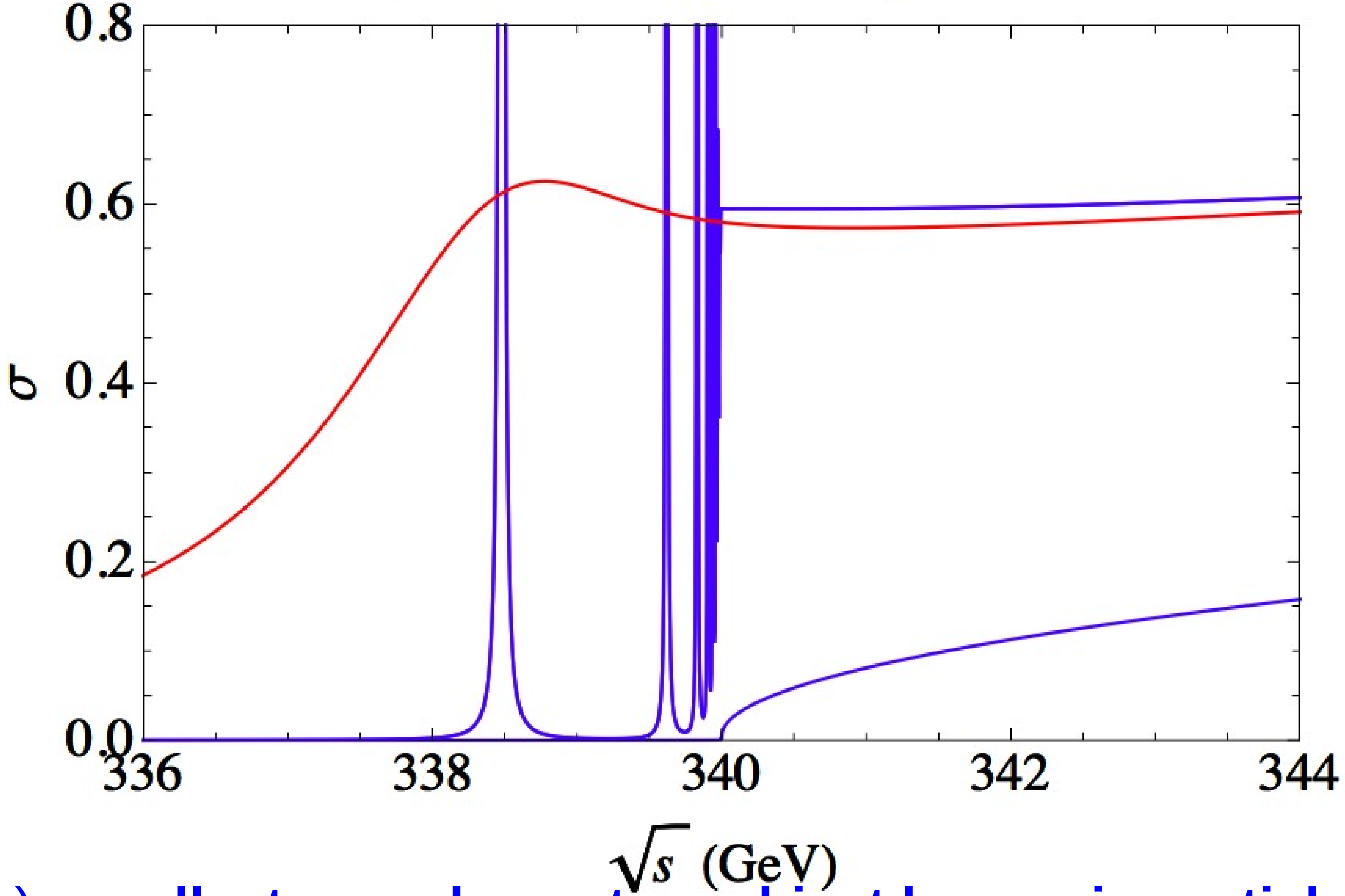
Heinemeyer, Hollik, Stockinger, Weiglein, Zeune '16

- Precise Top (and W) mass crucial to test compatibility of measured Higgs mass
- SM might not be sufficient to explain Higgs mass
- LHC may not reach sufficient discriminative power
- A lepton collider will for sure

Top pair production at threshold

“Bound states” at tt threshold

Hydrogen atom of strong interaction

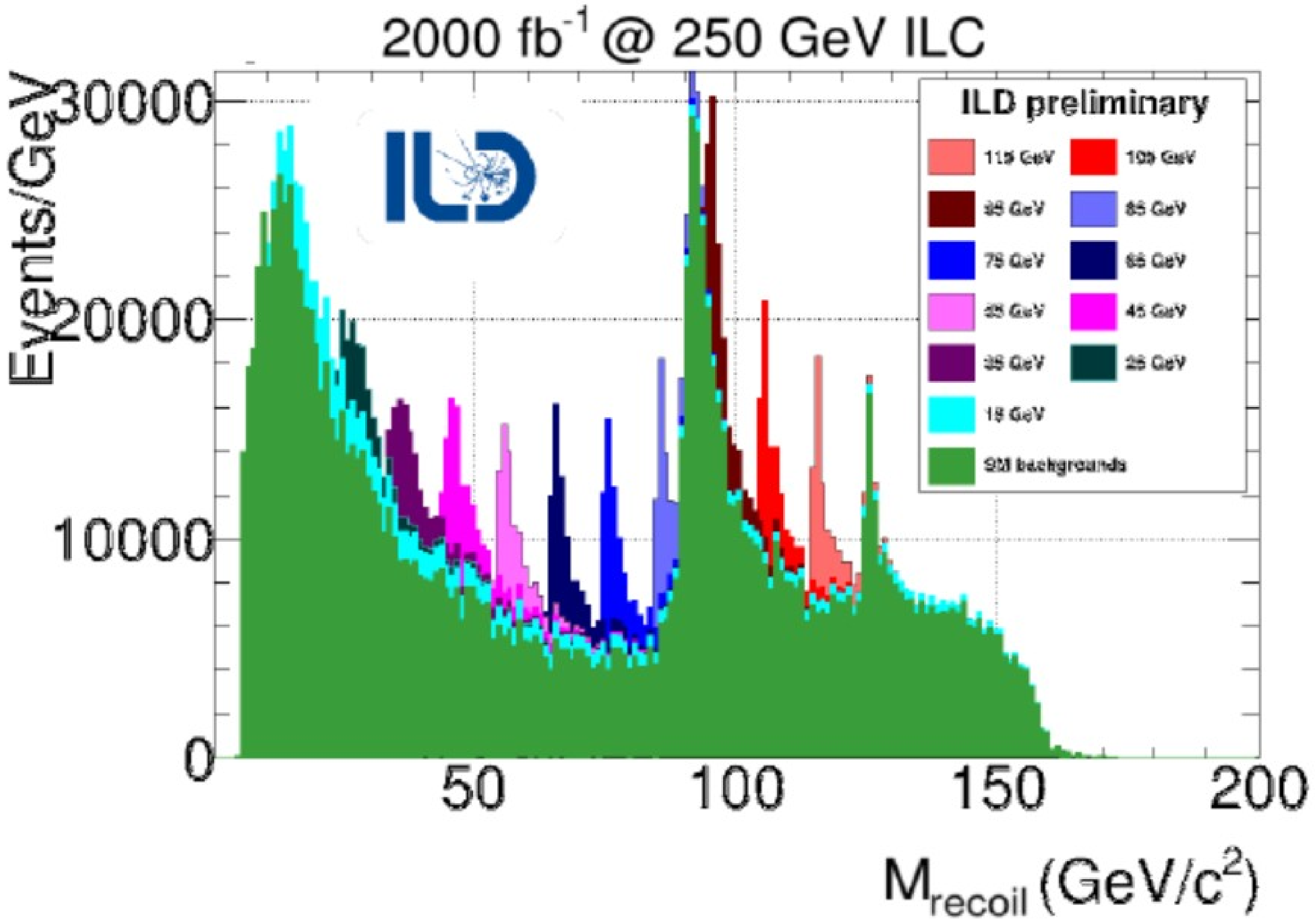


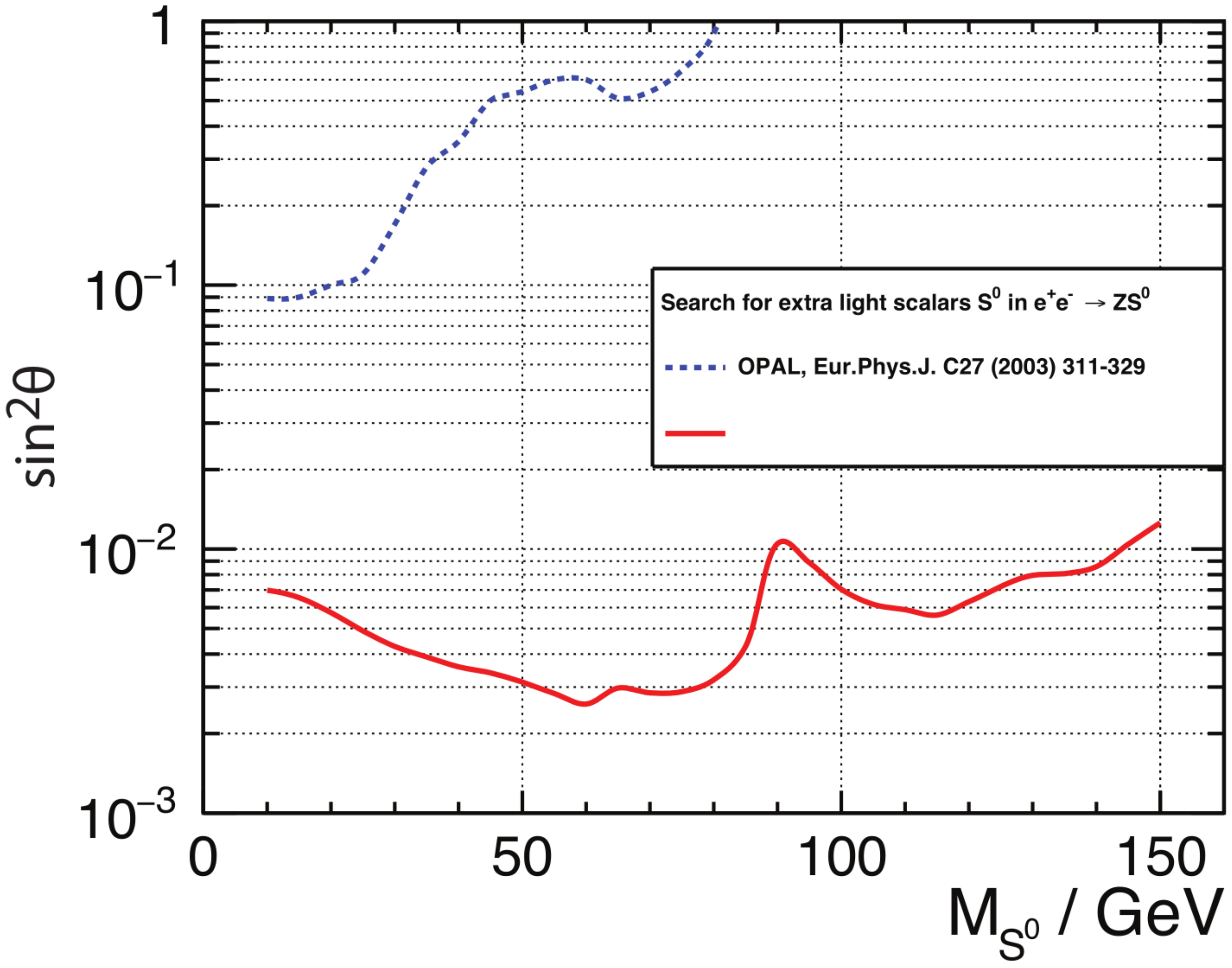
- Size O(10^{-17}m), **smallest non-elementary object known in particle physics**
  Small scale => Free of confinement effects => Ideal premise for precision calculations
  Measurement of (a hypothetical) 1^3S_1 State

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

Light scalar study in ILD

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



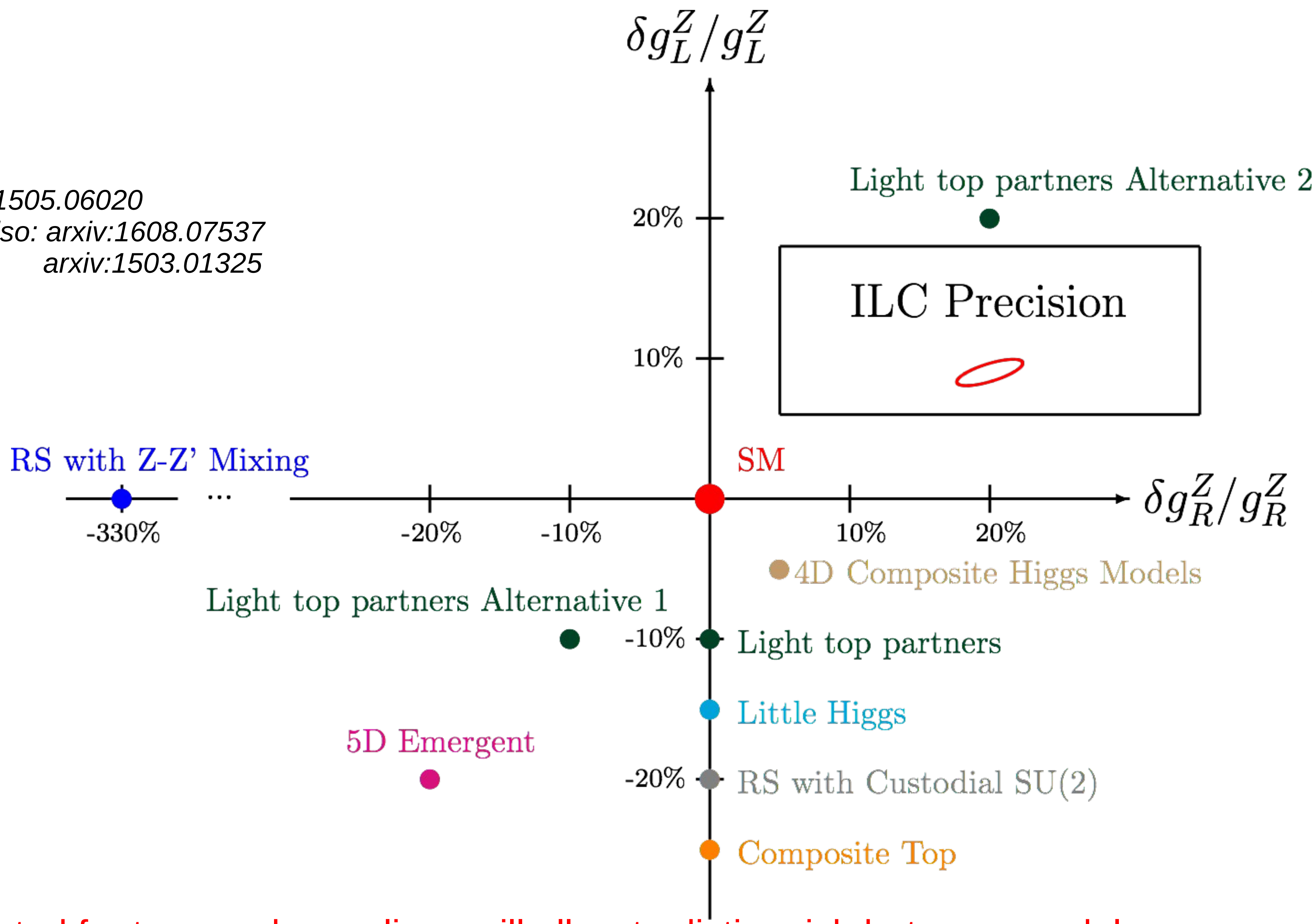


- New resonances cleanly dinstiguishable for large range of masses
- Sensitivity to mixing angle θh down to 10^{-2} (taking all relevant backgrounds into account)
- └new scalar would count as “Feebly interacting Particle” (FIPS)

Electroweak top couplings

Top is primary candidate to be a messenger new physics in many BSM models

arxiv:1505.06020
see also: arxiv:1608.07537
arxiv:1503.01325

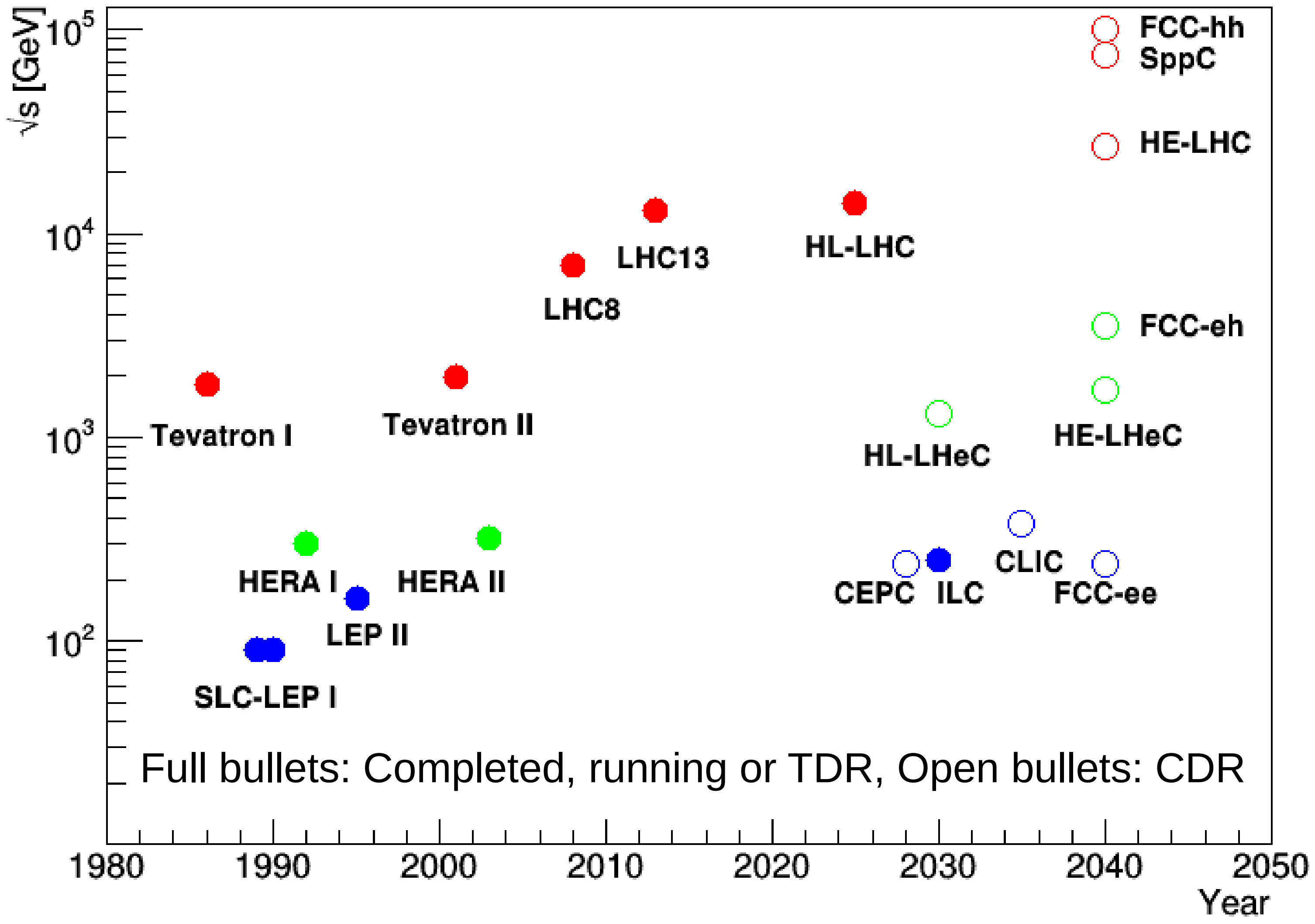


Statistical error:
√s ~ 500 GeV
L = 500 fb^{-1}

Precision expected for top quark couplings will allow to distinguish between models

Remark: All presented models are compatible with LEP elw. precision data

e+e- machines (and others) - Readiness



- ILC is the only machine that can be built now
  - European XFEL gives credbility for construction