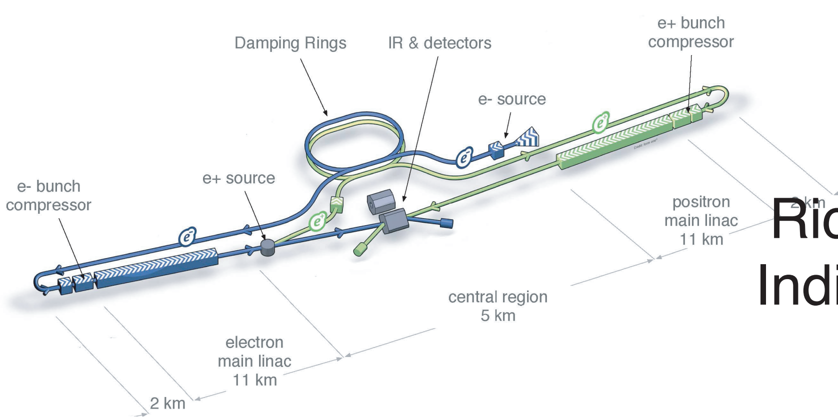
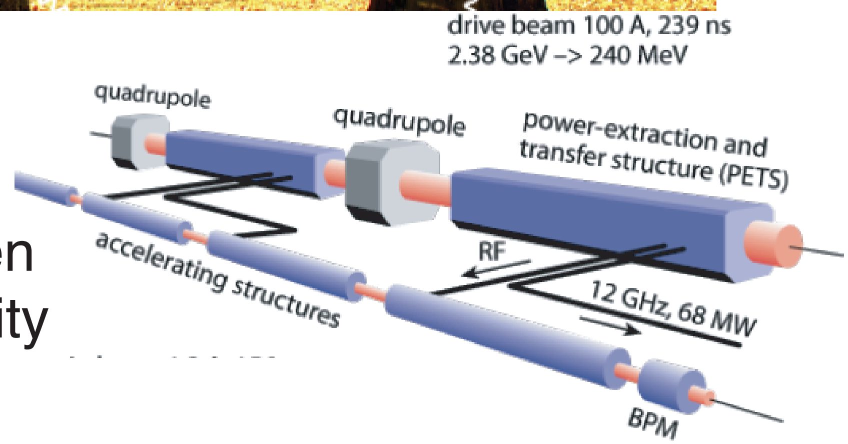
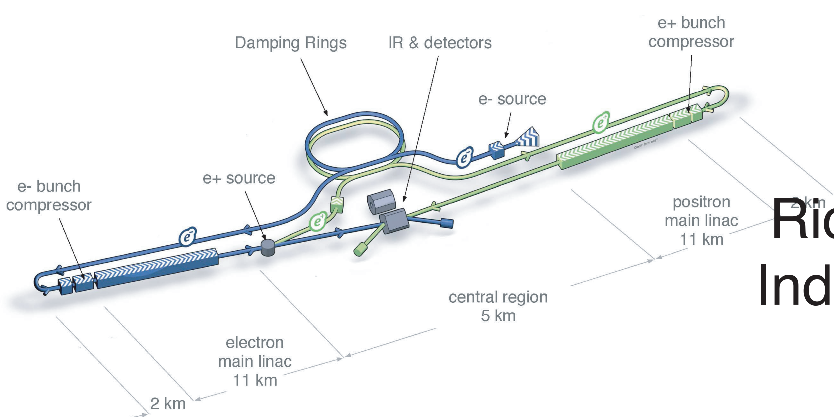
Linear Collider (not just ILC) Sensitivity Studies



Rick Van Kooten
Indiana University



e^+e^-
(not just ILC)
Sensitivity
Studies



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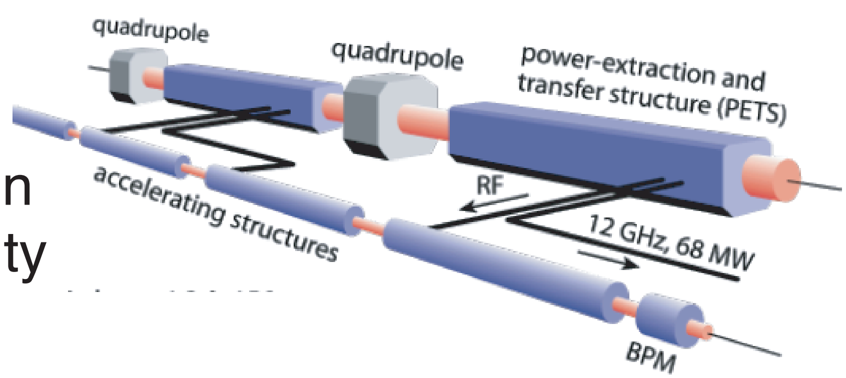


Outline

- (New) baselines for linear collider options
- Detectors
- *W*-pair production: $e^+e^- \to W^+W^-$
  Anomalous triple gauge couplings (aTGC)
- Triboson production: $e^+e^- \to VVV$
  Anomalous quartic gauge couplings (aQGC)
- Vector boson scattering: $e^+e^- \to \nu_e\bar{\nu}_e W^+W^-$
  Anomalous quartic gauge couplings (aQGC)
- Constraints from global Higgs fits
- Summary

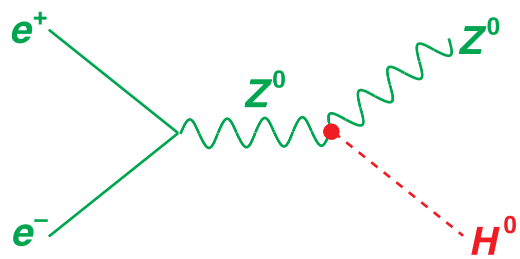
Acknowledgements

Reporting on the work of many others

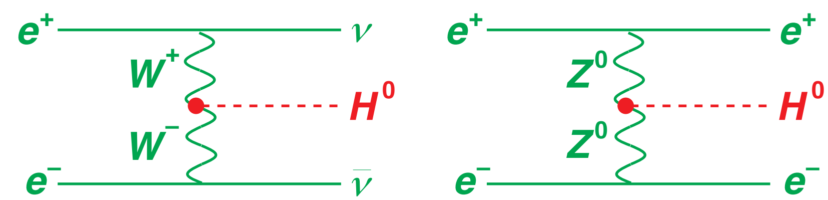
- Snowmass EW Report, arXiv:1310.6708v1 [hep-ph]
- ILC Technical Design Report | Vol. 2: Physics, arXiv:1306.6352 [hep-ph]
- Exploring Quantum Physics at an ILC, arXiv:1307.3962 [hep-ph]
- CLIC Snowmass Report, arXiv:1307.5288v3 [hep-ex]
- CLIC Physics & Detectors: CDR, arXiv:1202.5940 [physics.ins-det]
- First Look at the Physics Case of TLEP, arXiv:1308.6176 [hep-ex]
- Physics Interplay of the LHC and the ILC, hep-ph/0410364
- Determination of New Electroweak Parameters at the ILC — Sensitivity to New Physics, arXiv:hep-ph/0604048v1
- Study of Charged Current Triple Gauge Couplings at TESLA, LC-PHSM-2001-022
- Constraining anomalous Higgs interactions, arXiv:1207.1344v3 [hep-ph]

...and references therein

ILC Base Program



- "Higgs"strahlung



- Fusion

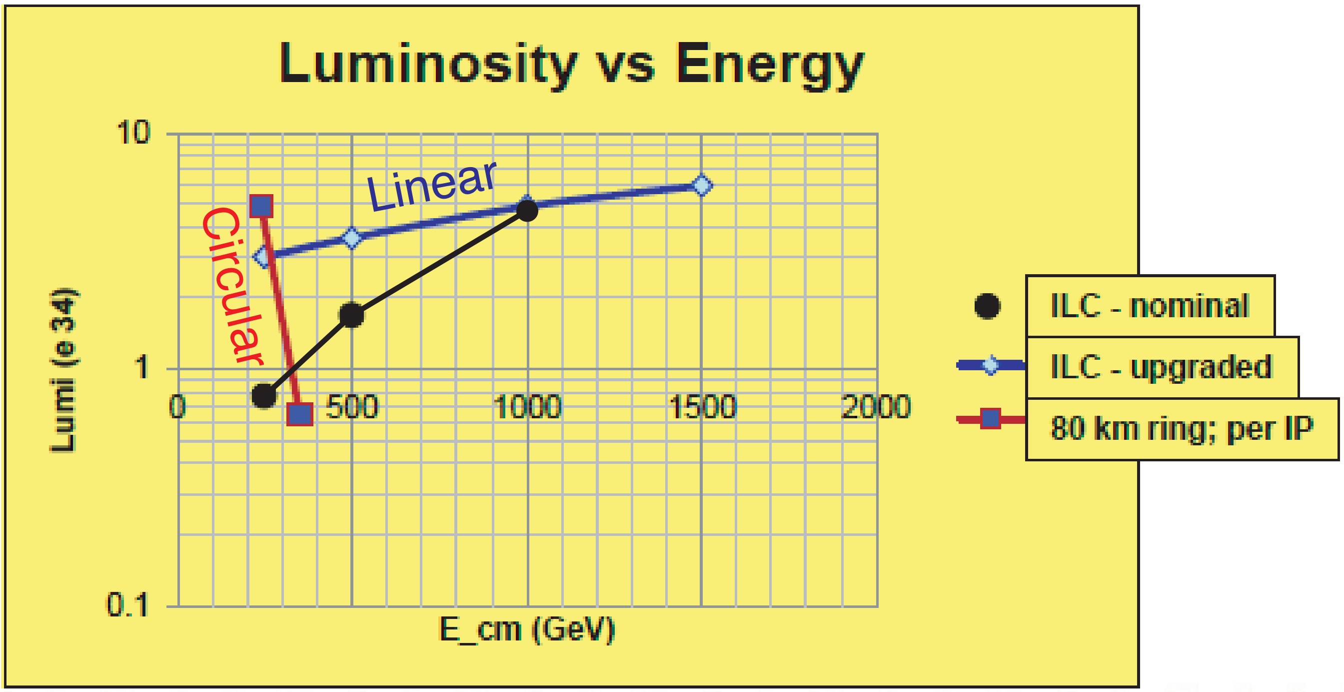
Typical ILC program, 3 – 5 years each energy:

	250 GeV	350 GeV	500 GeV	1 TeV	1.5 TeV	3 TeV
$\sigma(e^+e^- \rightarrow ZH)$	300 fb	129 fb	57 fb	13 fb	6 fb	1 fb
$\sigma(e^+e^- \rightarrow \nu\nu H)$	18 fb	30 fb	75 fb	210 fb	309 fb	484 fb
Int. Luminosity	250 fb^{-1}	350 fb^{-1}	500 fb^{-1}	1 ab^{-1}	1.5 ab^{-1}	2 ab^{-1}
# ZH events	75,000	45,500	28,500	13,000	7,500	2,000
# νvH events	4,500	10,500	37,500	210,000	460,000	970,000

Polarized

ILC Luminosity Upgrade

- ILC base program frozen long ago for global design effort (GDE) and technical design report → necessarily conservative



e.g.,TLEP, FCC_ee

- With minimal cost impacts, possible luminosity upgrade also considered for Snowmass studies:

$$\mathcal{L} = 0.75 \rightarrow 3.0 \times 10^{34} \mathrm{cm}^{-2} \mathrm{s}^{-1}$$

$$\int \mathcal{L} dt \begin{array}{l} + \text{optimistic} \\ - \text{pessimistic} \end{array}$$

Benchmark Programs

...considered for Snowmass studies

pp machines:

	LHC	HL-LHC	HE-LHC	VLHC
$\sqrt{s}$ (TeV)	14	14	33	100
$\int \mathcal{L}dt$ (fb^{-1})	300	3000	3000	3000

Linear e^+e^- machines:

Luminosity Upgrade

	ILC500	ILC1000	ILC1000-up	CLIC
$\sqrt{s}$ (TeV)	250/500	250/500/1000	250/500/1000	350/1400/3000
$\int \mathcal{L}dt$ (fb^{-1})	250+500	250+500+1000	1150+1600+2500	500+1500+2000

Considered for Higgs projections

Run scenarios:

Facility	HL-LHC	ILC	ILC(LumiUp)	CLIC
$\sqrt{s}$ (GeV)	14,000	250/500/1000	250/500/1000	350/1400/3000
$\int \mathcal{L}dt$ (fb^{-1})	3000/expt	250+500+1000	1150+1600+2500	500+1500+2000
$\int dt$ (10^7s)	6	3+3+3	(ILC 3+3+3) + 3+3+3	3.1+4+3.3

Benchmark Programs

...considered for Snowmass studies

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	LHC	HL-LHC	HE-LHC	VLHC
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Linear e^+e^- machines:

	ILC500	ILC1000	ILC1000-up (*Luminosity Upgrade*)	CLIC
$\sqrt{s}$ (TeV)	250/500	250/500/1000	250/500/1000	350/1400/3000
$\int \mathcal{L}dt$ (fb^{-1})	250+500	250+500+1000	1150+1600+2500	500+1500+2000

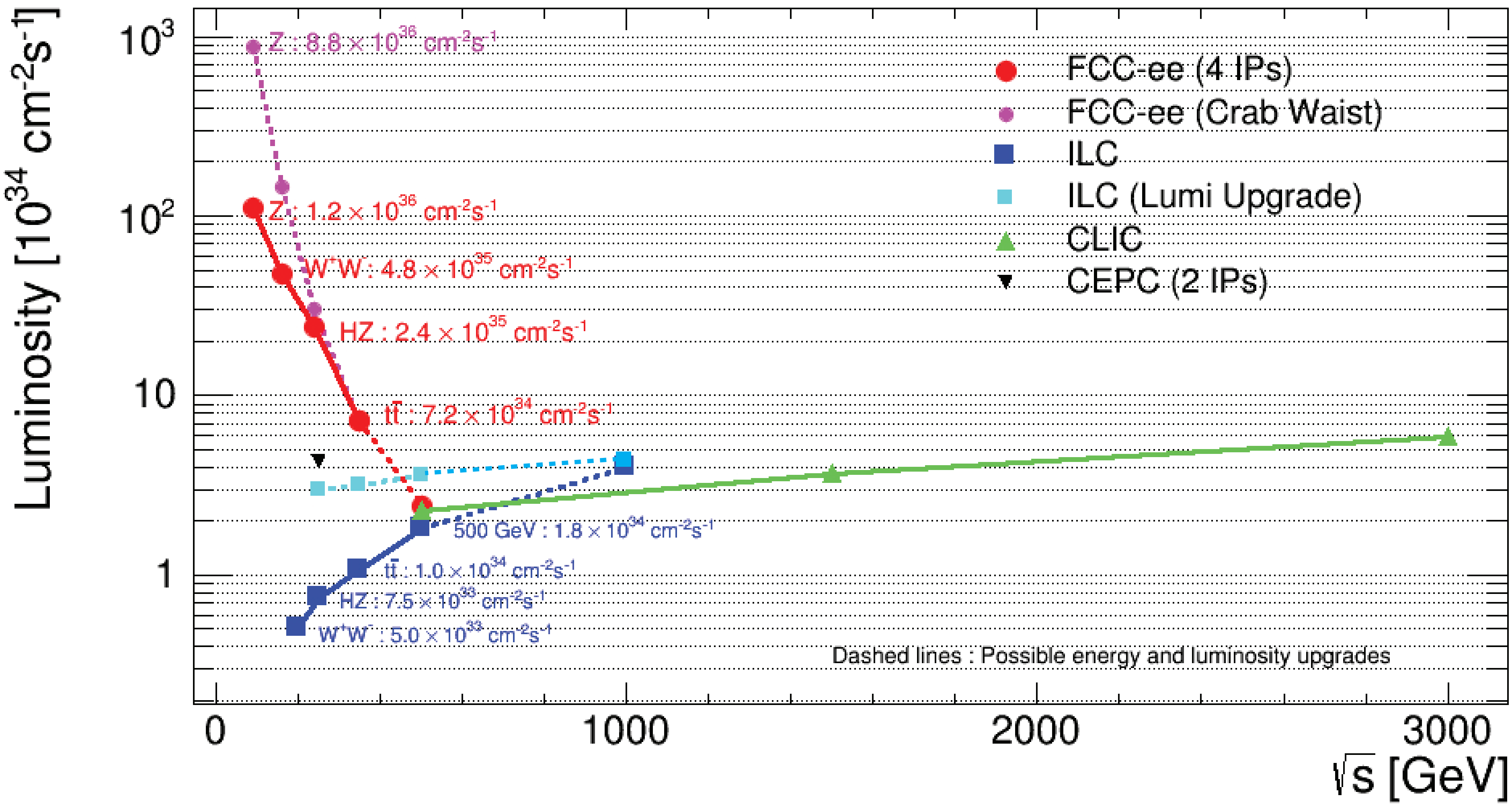
Run scenarios:

Facility	HL-LHC	ILC (*Results shown here baseline program*)	ILC(LumiUp) (*Considered for Higgs projections*)	CLIC
$\sqrt{s}$ (GeV)	14,000	250/500/1000	250/500/1000	350/1400/3000
$\int \mathcal{L}dt$ (fb^{-1})	3000/expt	250+500+1000	1150+1600+2500	500+1500+2000
$\int dt$ (10^7s)	6	3+3+3	(ILC 3+3+3) + 3+3+3	3.1+4+3.3

*...so results **may** be a bit conservative*

Benchmark Programs

...considered for Snowmass studies

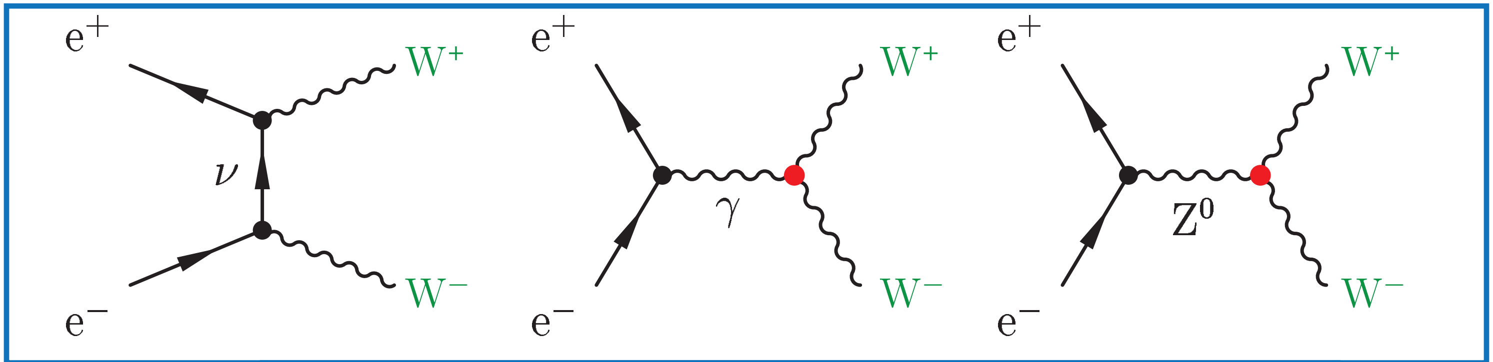


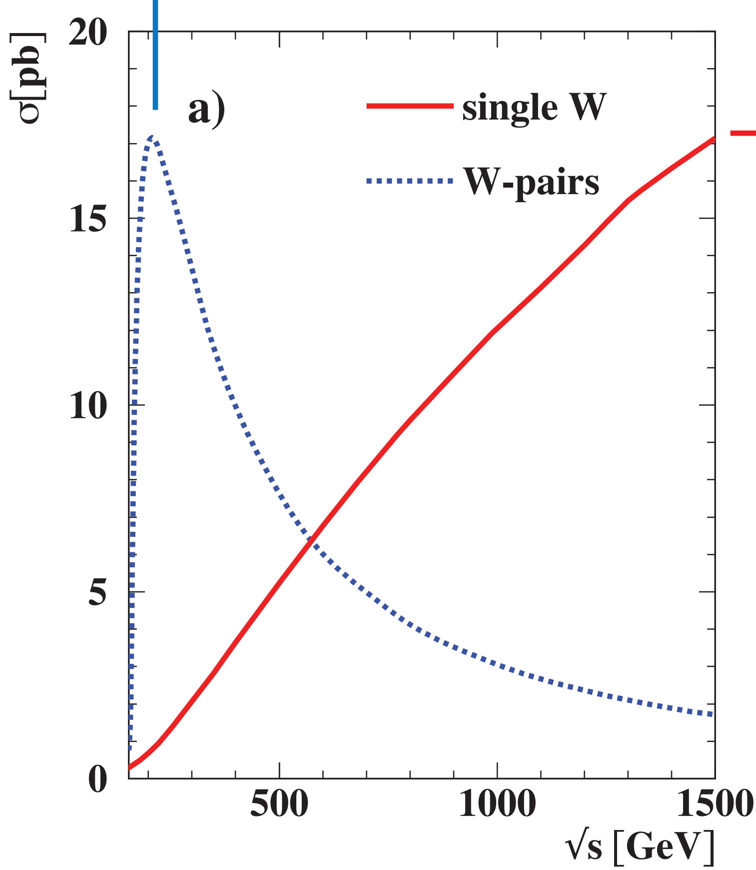
Advantages of e^+e^-

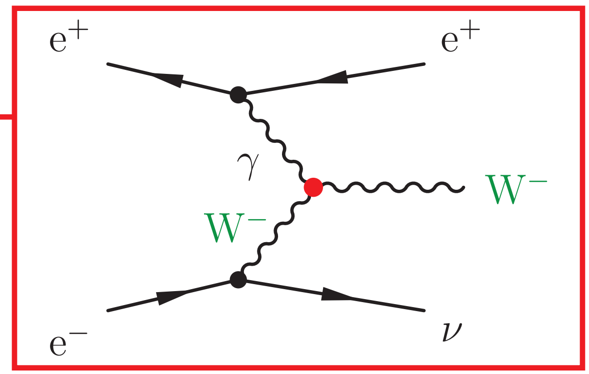
- absence of parton distribution functions
  - → known center of mass
- "democratic" in production of signal & background
  - → far smaller QCD background
  - → more electroweak, smaller theoretical uncertainties
    (modulo, e.g., earlier comments regarding NLO corrections EW VBS)
- cleanliness of final state
  - → no beam remnants
- beam structure, msec between bunch trains
  - → essentially triggerless
  - → advanced detector hardware & excellent resolutions
- • longitudinal polarization of beams, $(V-A)$ nature of W/Z
  - → $\mathcal{P}(e^-) = 80 - 90\%$, $\mathcal{P}(e^+) = 30 - 60\%$
  - → e_L and e_R different multiplets, access completely different couplings

Making W's

...dominant W production processes at a linear collider







- This is the vector boson fusion diagram – not studied much for TGC's since W-pair process so powerful

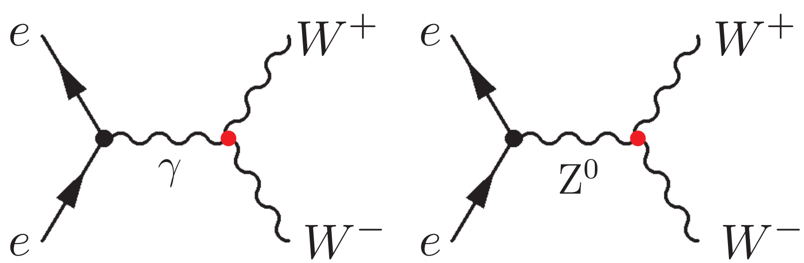
$e^+e^- \to W^+W^-$

...for triple gauge couplings

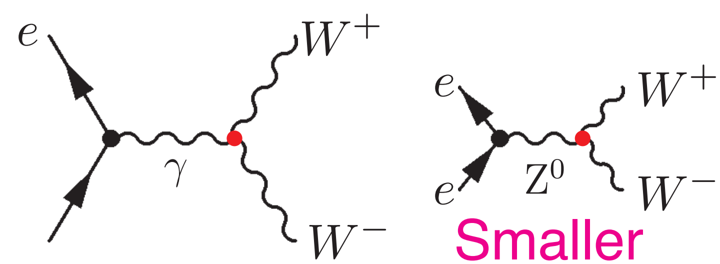
Production at linear colliders would be first time W^+W^- production measured with polarized beams

$$\sigma = \frac{1}{4}(1-\mathcal{P}^+)(1+\mathcal{P}^-)\sigma_R + \frac{1}{4}(1+\mathcal{P}^+)(1-\mathcal{P}^-)\sigma_L$$

Left-handed electrons

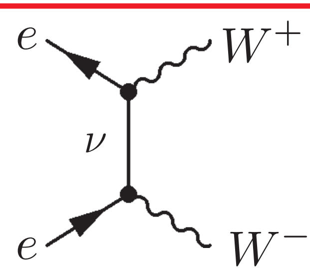


Right-handed electrons



Smaller

Disentangle the $WW\gamma$ and WWZ couplings

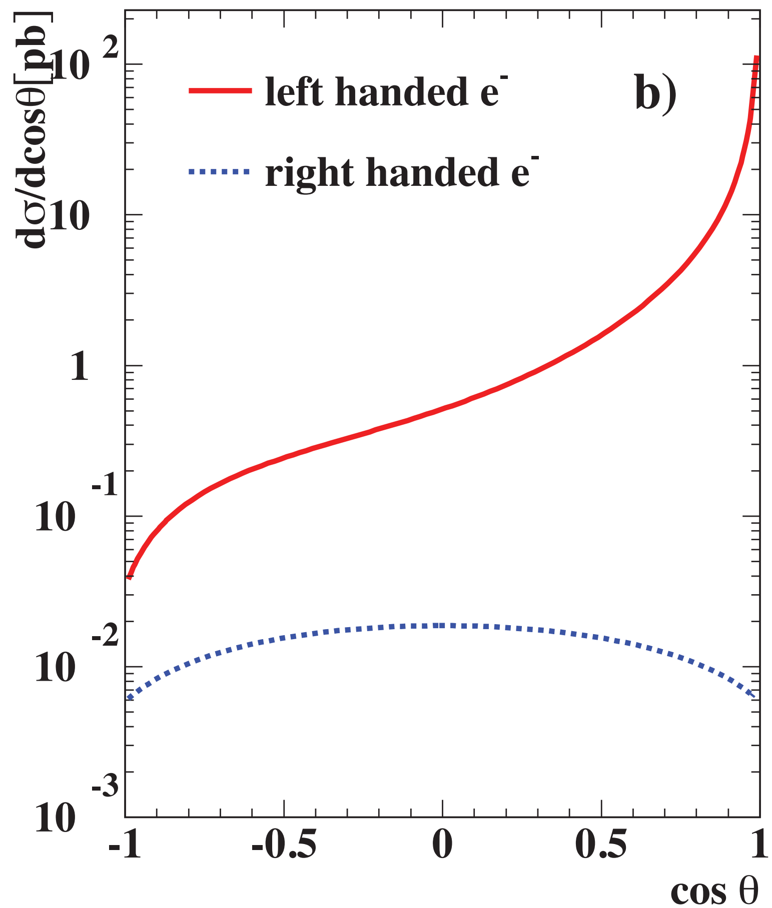


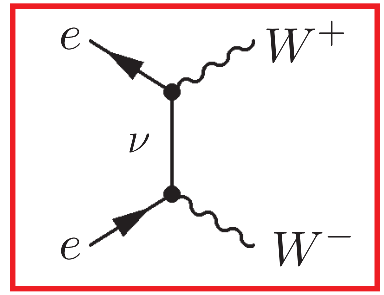
Turn off

$e^+e^- \to W^+W^-$ ...for triple gauge couplings

Production at linear colliders would be first time W^+W^- production measured with polarized beams

$$\sigma = \frac{1}{4}(1-\mathcal{P}^+)(1+\mathcal{P}^-)\sigma_R + \frac{1}{4}(1+\mathcal{P}^+)(1-\mathcal{P}^-)\sigma_L$$

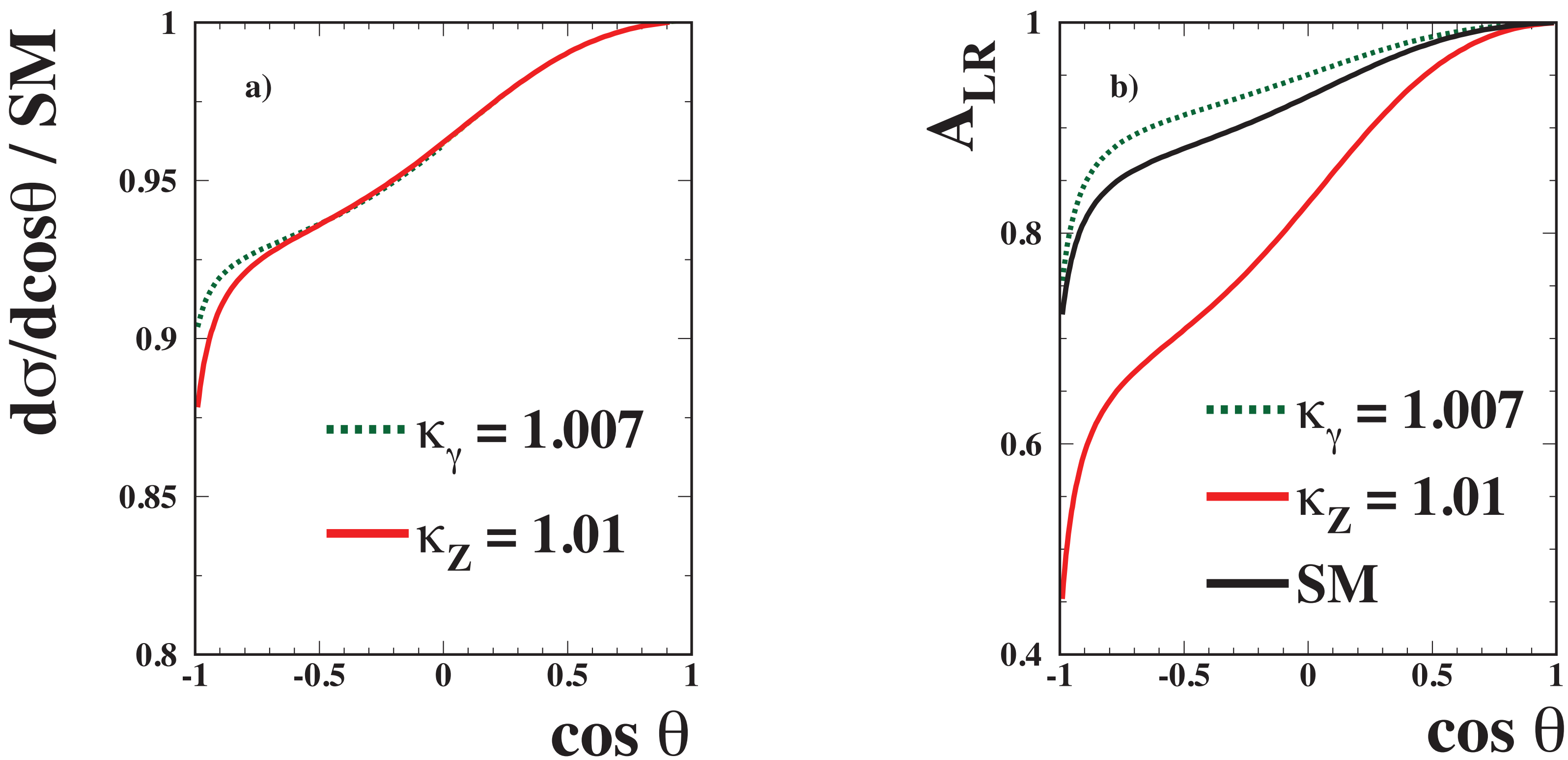




$e^+e^- \rightarrow W^+W^-$ ...for triple gauge couplings

Production at linear colliders would be first time W^+W^- production measured with polarized beams

$$\sigma = \frac{1}{4}(1-\mathcal{P}^+)(1+\mathcal{P}^-)\sigma_R + \frac{1}{4}(1+\mathcal{P}^+)(1-\mathcal{P}^-)\sigma_L$$



- Polarization increases sensitivity to aTGC's

$e^+e^- \to W^+W^-$

...for triple gauge couplings

- Usual multidimensional fits to *W*-production angles and angles of *W*-decay products, different polarizations
- *W*'s boosted, better resolution on *W*-production angle than LEP2
- Use all three decay topologies:

$$W \to qq', W \to qq'$$
$$W \to qq', W \to \ell\nu$$
$$W \to \ell\nu, W \to \ell\nu$$

Most sensitive
select with good efficiency,
rather low background

$\pm 1\sigma$ uncertainties to per mille level or better

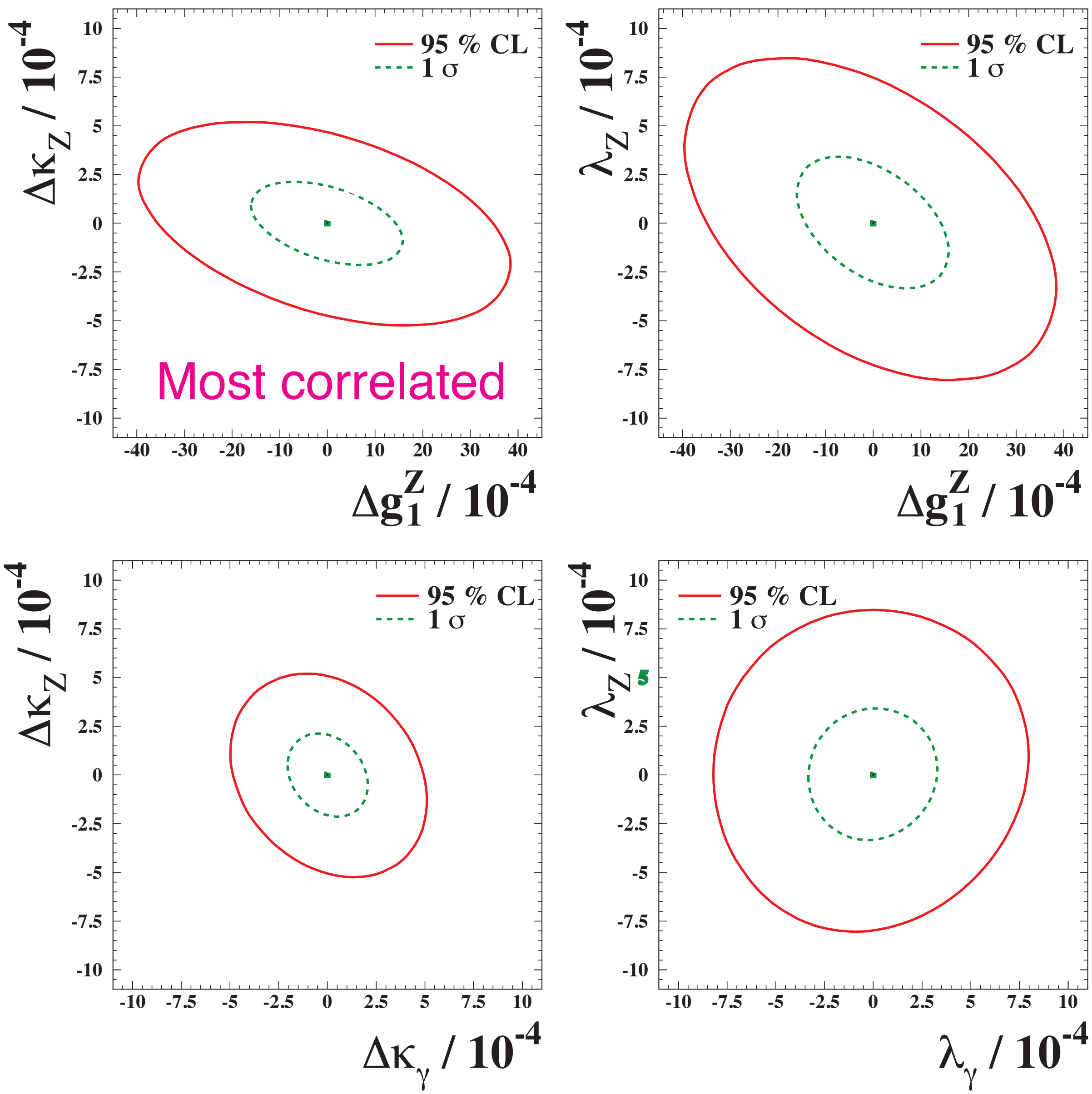
coupling	error $\times 10^{-4}$	
	$\sqrt{s} = 500$ GeV	$\sqrt{s} = 800$ GeV
C,P-conserving, $\mathrm{SU}(2) \times \mathrm{U}(1)$ relations:		
Δg_1^Z	2.8	1.8
$\Delta\kappa_\gamma$	3.1	1.9
λ_γ	4.3	2.6
C,P-conserving, no relations:		
Δg_1^Z	15.5	12.6
$\Delta\kappa_\gamma$	3.3	1.9
λ_γ	5.9	3.3
$\Delta\kappa_Z$	3.2	1.9
λ_Z	6.7	3.0
not C or P conserving:		
g_5^Z	16.5	14.4
g_4^Z	45.9	18.3
$\tilde{\kappa}_Z$	39.0	14.3
$\tilde{\lambda}_Z$	7.5	3.0

$\mathcal{L} = 500\ \mathrm{fb}^{-1}$ $\quad 1000\ \mathrm{fb}^{-1}$

$\mathcal{P}^- = 80\%, \mathcal{P}^+ = 60\%$

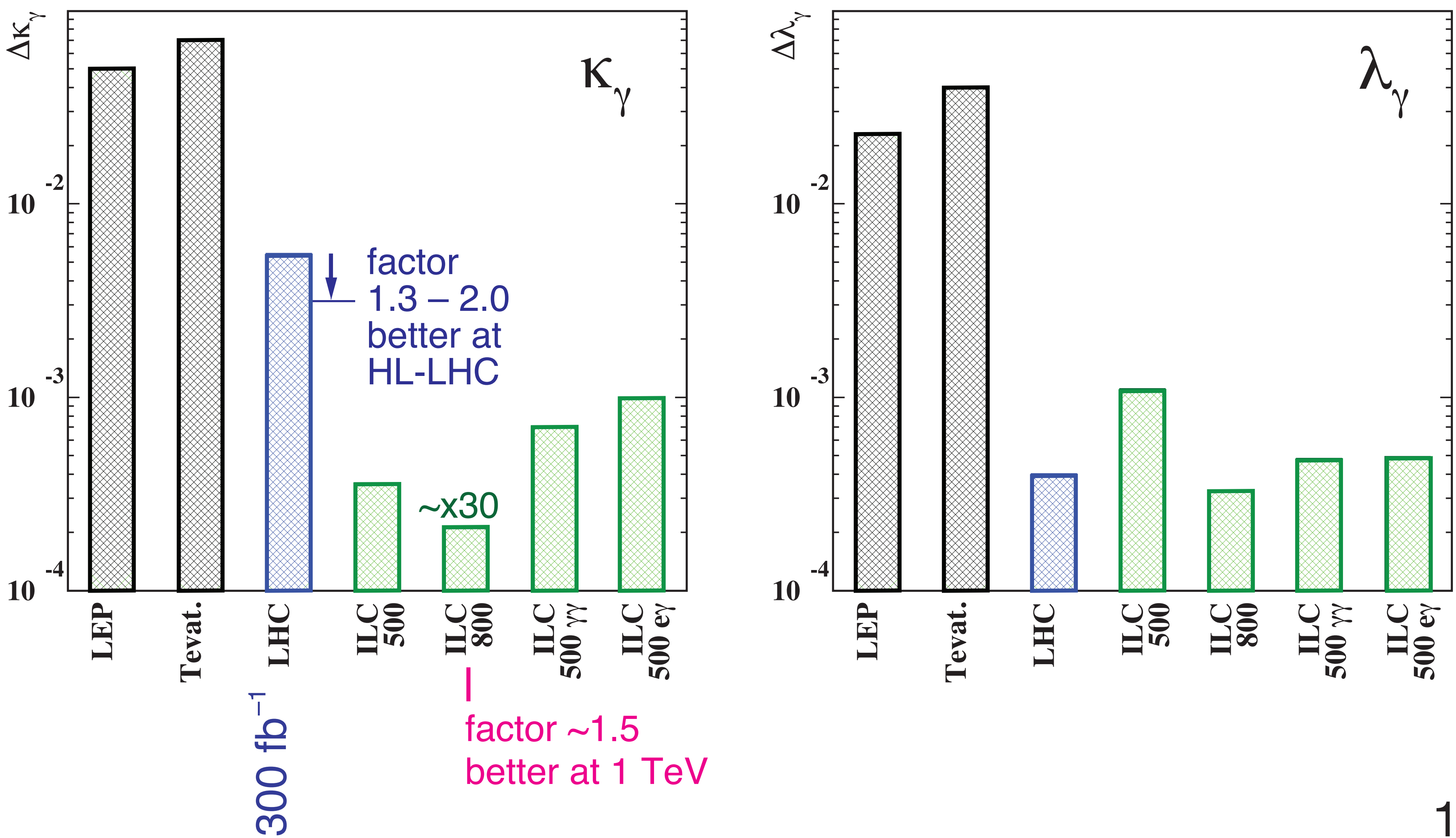
$e^+e^- \to W^+W^-$

...for triple gauge couplings



aTGC's in Context ...from $e^+e^- \to W^+W^-$

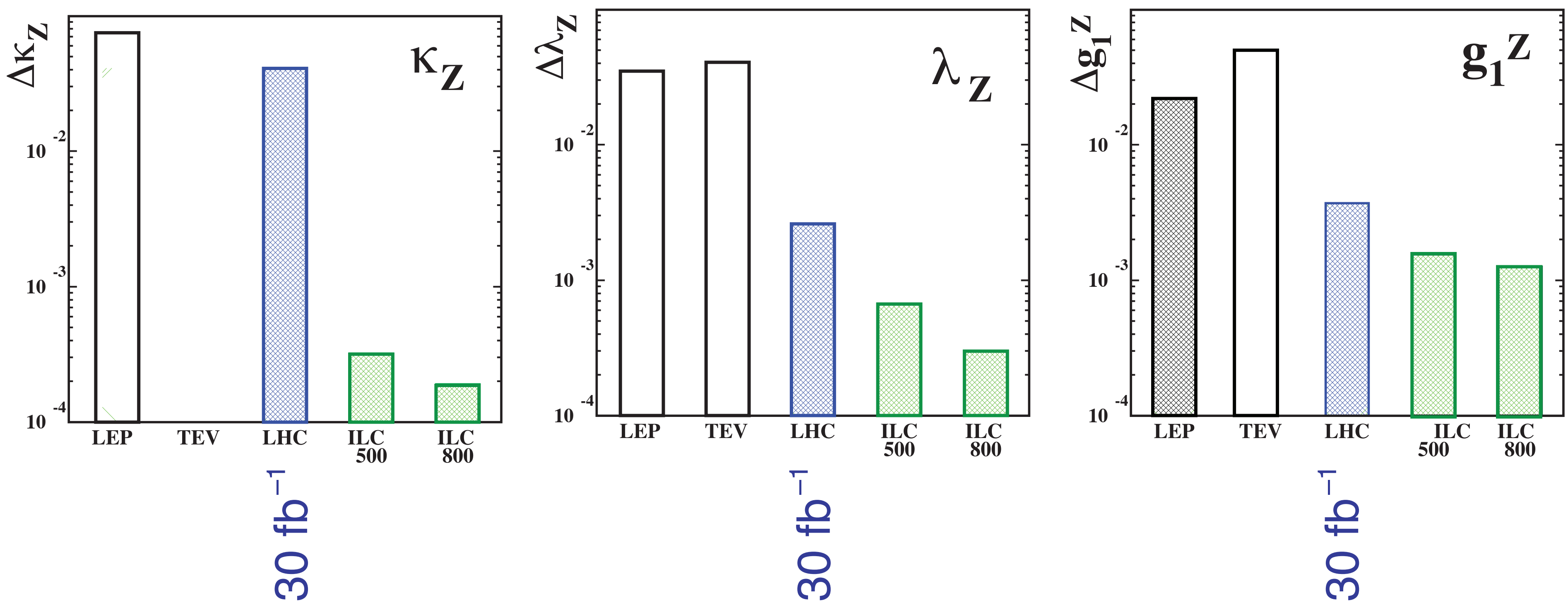
- large improvement in precision in many TGC's



aTGC's in Context

...from $e^+e^- \to W^+W^-$

- all precisions improve, many by large factors



From hep-ph/0410364, updated

TLEP?

FCC-ee: Future Circular ee Collider

- At lower energies, TLEP would have insane luminosities
- ILC at *Z* peak has "GigaZ" program

  TLEP at Z peak has "TeraZ" program
- 2×10^8 W^+W^- pairs at threshold (~1/10) and above
- "...*measurements to be performed by TLEP at this centre-of-mass energy need to be thoroughly reviewed by the starting design study*"

Triple VB Production

...for quartic gauge couplings

$$\sigma(e^+e^- \to VVV) \propto \frac{1}{s}$$

Limits usefulness to subprocess energies in the lower range where cross section of fusion process still small

$$\sigma_{\mathrm{VBS}}(e^+e^- \to \nu\bar{\nu}W^+W^-) \propto \log(s)$$

$$e^+e^- \to ZZZ$$

$$\to WWZ$$

ZH

$\hookrightarrow WW$

$\hookrightarrow ZZ$

Present in spectrum

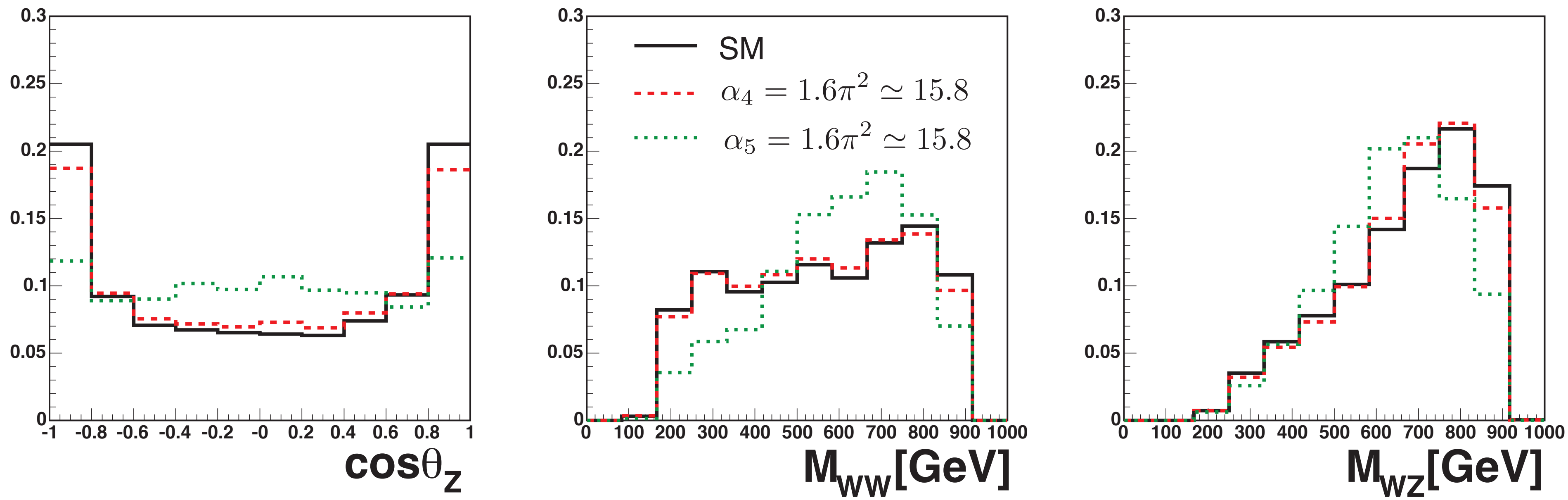
$\to WW\gamma$ Complementary (and present at lower energies)

Triple VB Production

...for quartic gauge couplings

$e^+e^- \to ZZZ$ few SM backgrounds

$\to WWZ$ dominant background is $t\bar{t}$
(reduce using e^-_R)

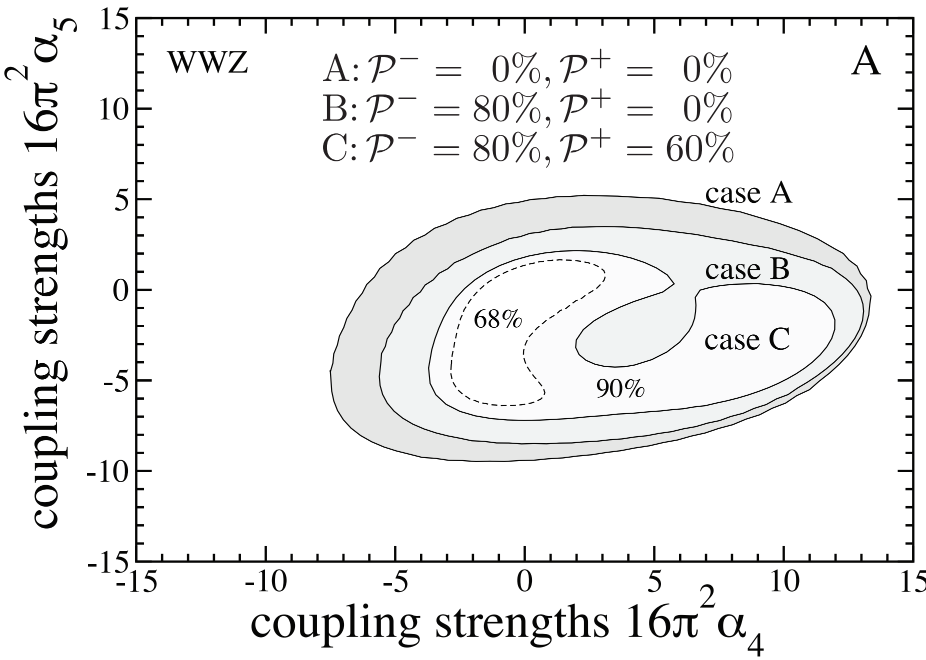


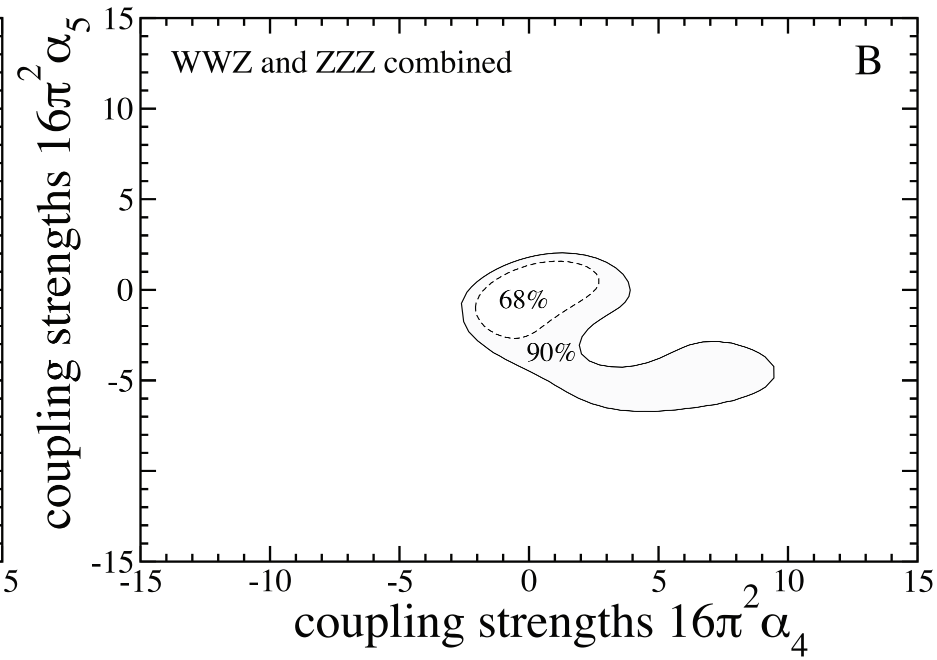
$e^+e^- \to WWZ$ 1 TeV, $\mathcal{P}^- = 80\%, \mathcal{P}^+ = 60\%, \mathcal{L} = 1000\ \mathrm{fb}^{-1}$

Triple VB Production

...for quartic gauge couplings

- constraints on aQGC's: $\alpha_4\ \alpha_5$ in EW effective chiral Lagrangian (see backup slides)
- not great, factor ~30 worse than LHC



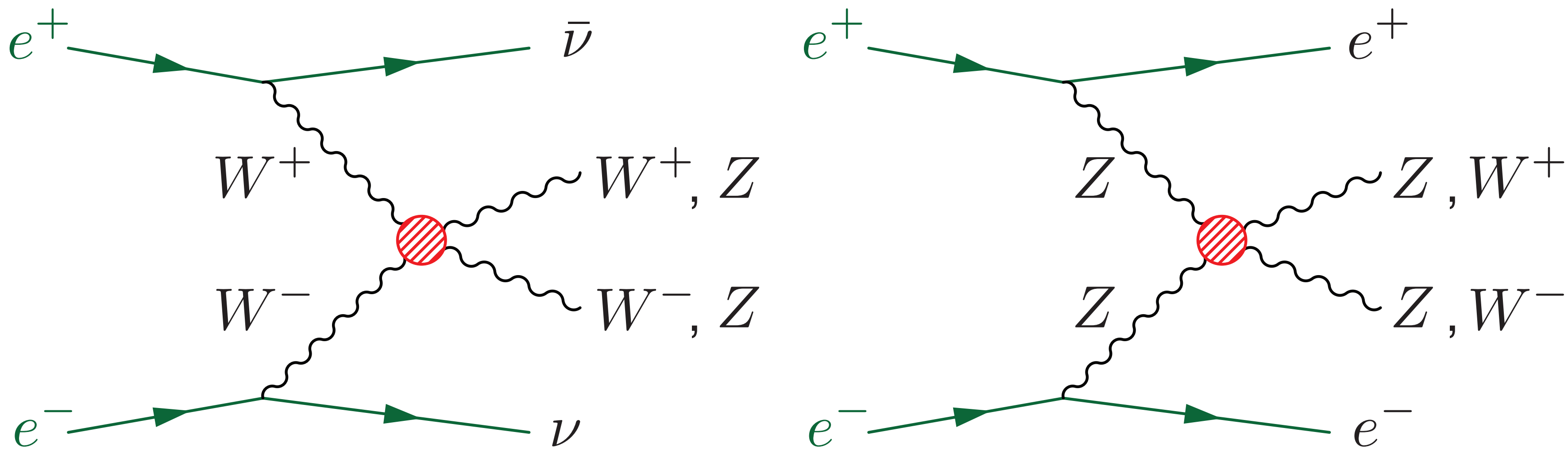


		WWZ			ZZZ	best
		no pol.	e^- pol.	both pol.	no pol.	
$16\pi^2\Delta\alpha_4$	σ^+	9.79	4.21	1.90	3.94	1.78
	σ^-	−4.40	−3.34	−1.71	−3.53	−1.48
$16\pi^2\Delta\alpha_5$	σ^+	3.05	2.69	1.17	3.94	1.14
	σ^-	−7.10	−6.40	−2.19	−3.53	−1.64

Vector Boson Scattering

...for quartic gauge couplings

- any better?



- neutrinos instead of forward jets, large missing invariant mass
- can scatter γ's instead of Z's
- in contrast to LHC, know the initial state in the scattering subprocess
- c.f. 1 TeV ILC for subprocess energy to 14 TeV LHC

$p \to q$

$q \to W/Z$

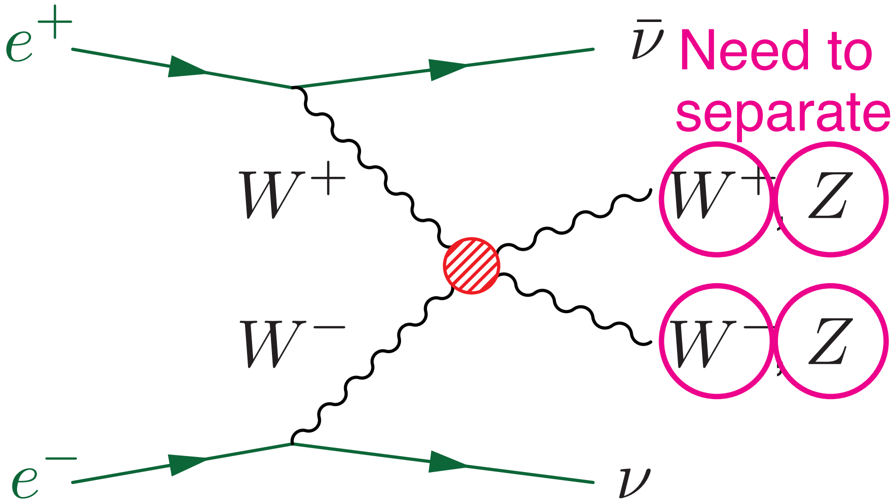
Falls ~short, higher energies better

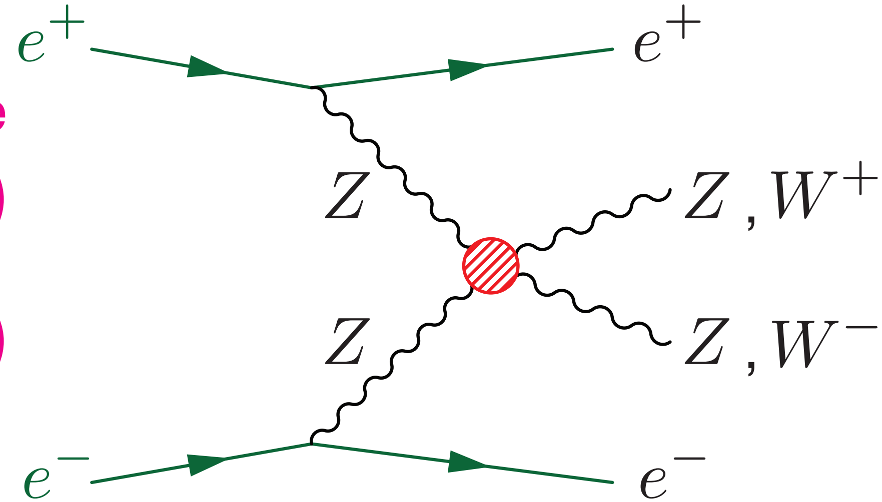
allows for an effective subprocess energy up to about 2 TeV

Vector Boson Scattering

...for quartic gauge couplings

- any better?



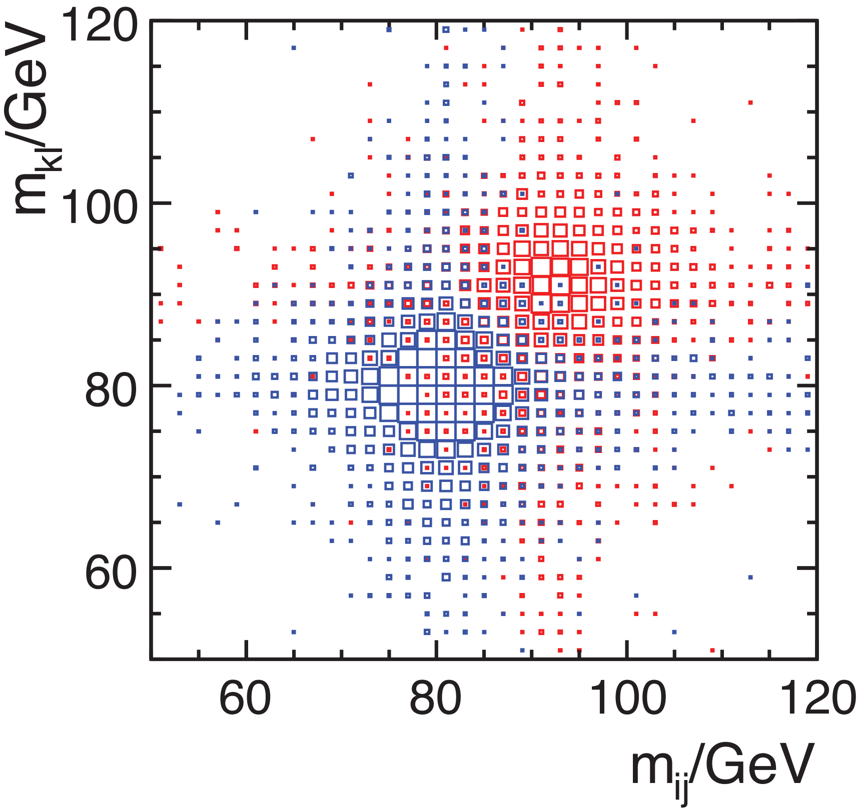


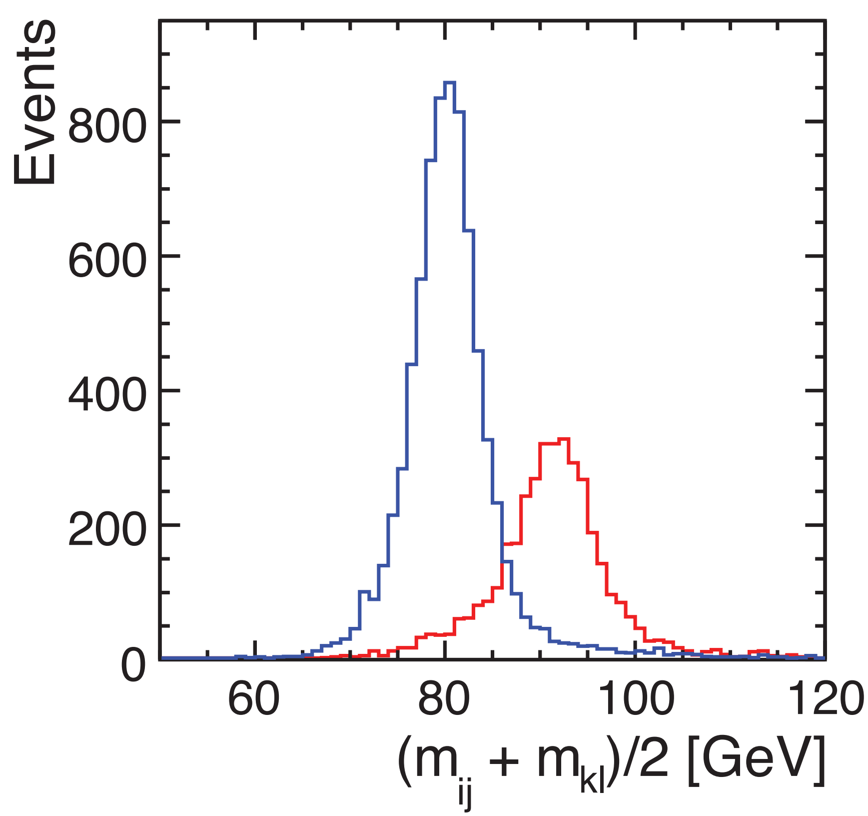
- polarization can change cross sections by up to factor 4
- can scatter $\boldsymbol{\gamma}$'s instead of Z's

Vector Boson Scattering

...for quartic gauge couplings

- final state: $e^+e^- \to \nu\bar{\nu}q\bar{q}q'\bar{q}'$, "best" jet-jet combinations





$\nu_e\bar{\nu}_e WW$
$(W^+W^- \to W^+W^-)$

$\nu_e\bar{\nu}_e ZZ$
$(W^+W^- \to ZZ)$

Hadronic *W/Z* separation is calorimeter benchmark for ILC detectors (this is the ILD detector)

Vector Boson Scattering

...for quartic gauge couplings

Process	Subprocess	σ [fb]
$e^+e^- \to \nu_e\bar{\nu}_e q\bar{q}q\bar{q}$	$W^+W^- \to W^+W^-$	23.19
$e^+e^- \to \nu_e\bar{\nu}_e q\bar{q}q\bar{q}$	$W^+W^- \to ZZ$	7.624
$e^+e^- \to \nu\bar{\nu}q\bar{q}q\bar{q}$	$V \to VVV$	9.344
$e^+e^- \to \nu e q\bar{q}q\bar{q}$	$WZ \to WZ$	132.3
$e^+e^- \to e^+e^- q\bar{q}q\bar{q}$	$ZZ \to ZZ$	2.09
$e^+e^- \to e^+e^- q\bar{q}q\bar{q}$	$ZZ \to W^+W^-$	414.
$e^+e^- \to b\bar{b}X$	$e^+e^- \to t\bar{t}$	331.768
$e^+e^- \to q\bar{q}q\bar{q}$	$e^+e^- \to W^+W^-$	3560.108
$e^+e^- \to q\bar{q}q\bar{q}$	$e^+e^- \to ZZ$	173.221
$e^+e^- \to e\nu q\bar{q}$	$e^+e^- \to e\nu W$	279.588
$e^+e^- \to e^+e^- q\bar{q}$	$e^+e^- \to e^+e^- Z$	134.935
$e^+e^- \to X$	$e^+e^- \to q\bar{q}$	1637.405

- typical cross sections for signals and backgrounds, 1 TeV

$\mathcal{P}^- = 80\%, \mathcal{P}^+ = 40\%$

Vector Boson Scattering ...for quartic gauge couplings

- sensitivities to EW effective chiral Lagrangian aQGC's

$e^+e^- \rightarrow$	$e^-e^- \rightarrow$	α_4	α_5	α_6	α_7	α_{10}
$W^+W^- \rightarrow W^+W^-$	$W^-W^- \rightarrow W^-W^-$	+	+	-	-	-
$W^+W^- \rightarrow ZZ$		+	+	+	+	-
$W^\pm Z \rightarrow W^\pm Z$	$W^-Z \rightarrow W^-Z$	+	+	+	+	-
$ZZ \rightarrow ZZ$	$ZZ \rightarrow ZZ$	+	+	+	+	+

Yes, could do
electron-electron
at LC

- e.g., ILD detector, full simulation,
  $1\ \text{TeV},\ 1000\ \text{fb}^{-1},\ \mathcal{P}^- = -80\%,\ \mathcal{P}^+ = 30\%$

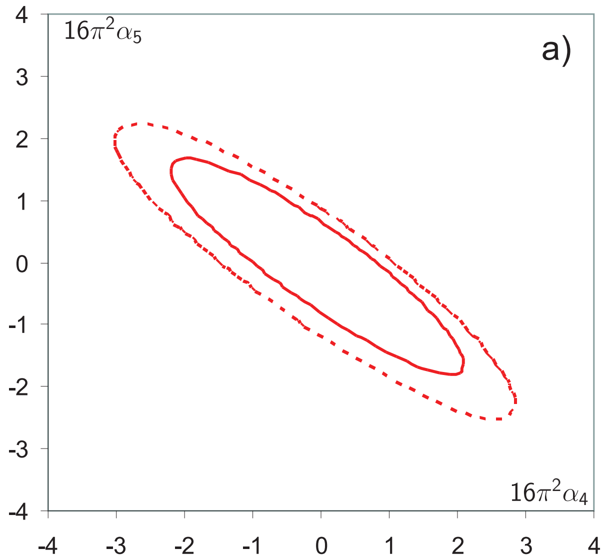
$$\boxed{\begin{array}{c} -1.38 < \alpha_4 < +1.10 \\ -0.92 < \alpha_5 < +0.77 \end{array}} \ \text{(at 90\% CL)}$$

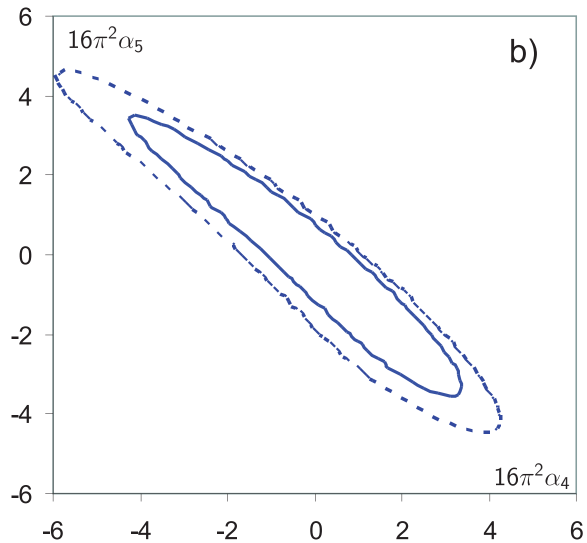
arXiv:1006.3396 [hep-ex]

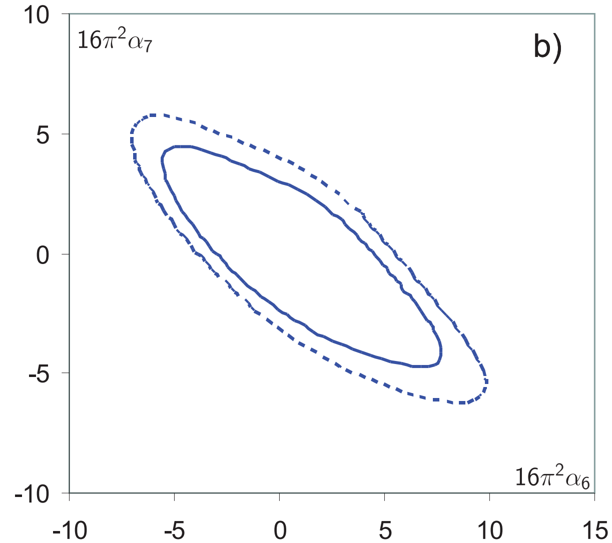
Vector Boson Scattering ...for quartic gauge couplings

- similar TESLA analysis (fast simulation)

hep-ph/0604048







coupling	$\sigma-$	$\sigma+$
α_4	-1.41	1.38
α_5	-1.16	1.09

SU(2) custodial symmetry constrained

coupling	$\sigma-$	$\sigma+$
α_4	-2.72	2.37
α_5	-2.46	2.35
α_6	-3.93	5.53
α_7	-3.22	3.31
α_{10}	-5.55	4.55

not constrained

Vector Boson Scattering ...for quartic gauge couplings

- comparison to HL-LHC?

  LC constraints significantly weaker by large factors:

parameter	300 fb^{-1}	1 ab^{-1}	3 ab^{-1}
α_4	0.066	0.025	0.016

ATLAS study, CERN preprint ATL-PHYS-PUB-2012-005, http://cds.cern.ch/record/1496527.

Vector Boson Scattering ...for quartic gauge couplings

- Compare via limits on mass M of a broad resonance in simplified models obtained from limits on α_4 (larger limit better)

Type of resonance	LHC 300 fb^{-1}		LHC 3000 fb^{-1}	
	5σ	95% CL	5σ	95% CL
scalar ϕ	1.8 TeV	2.0 TeV	2.2 TeV	3.3 TeV
vector ρ	2.3 TeV	2.6 TeV	2.9 TeV	4.4 TeV
tensor f	3.2 TeV	3.5 TeV	3.9 TeV	6.0 TeV

Best: derived from LHC $W^{\pm}W^{\pm}$ channel with less background

Type of resonance	95% CL
scalar ϕ	1.64 TeV
vector ρ	2.09 TeV
tensor f	2.76 TeV

ILC translated limits

95% CL limits

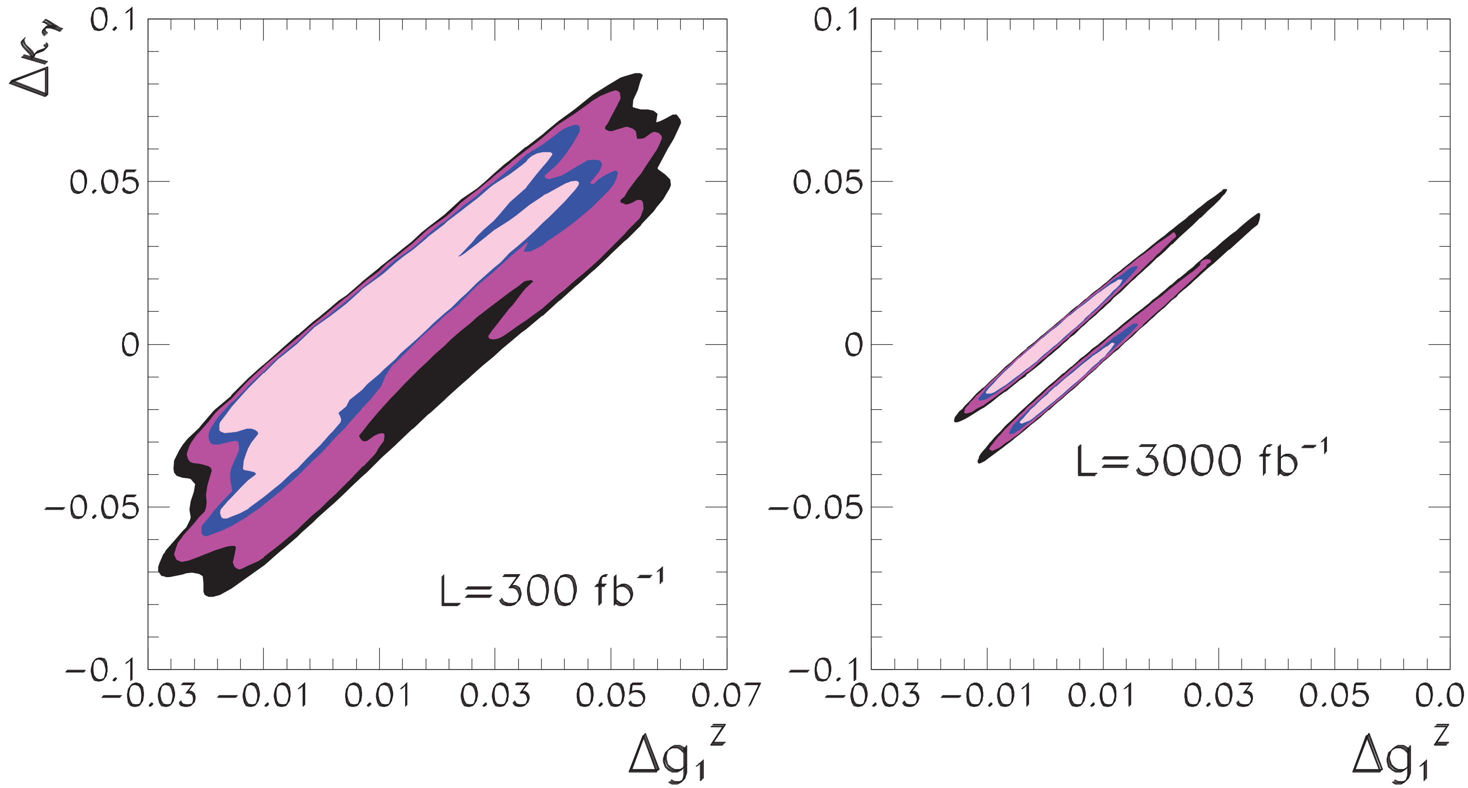
Type of resonance	LHC 300 fb^{-1}	LHC 3000 fb^{-1}
scalar ϕ	0.9 TeV	1.3 TeV
vector ρ	1.2 TeV	1.7 TeV
tensor f	1.6 TeV	2.3 TeV

Derived from LHC $W^{+}W^{-}$ channel with significant background

Snowmass EW report: arXiv:1310.6708v1 [hep-ph]

TGC's from global fit to Higgs data

- Constraints due to analysis of projected Higgs properties data from LHC and HL-LHC, could then *combine* with direct measurements



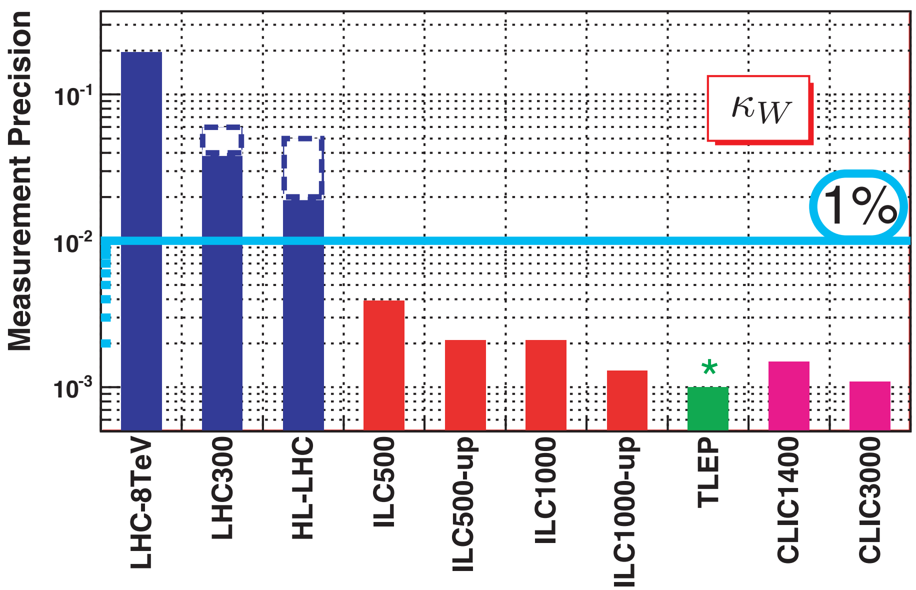
90%, 95%, 99%, 3σ allowed regions

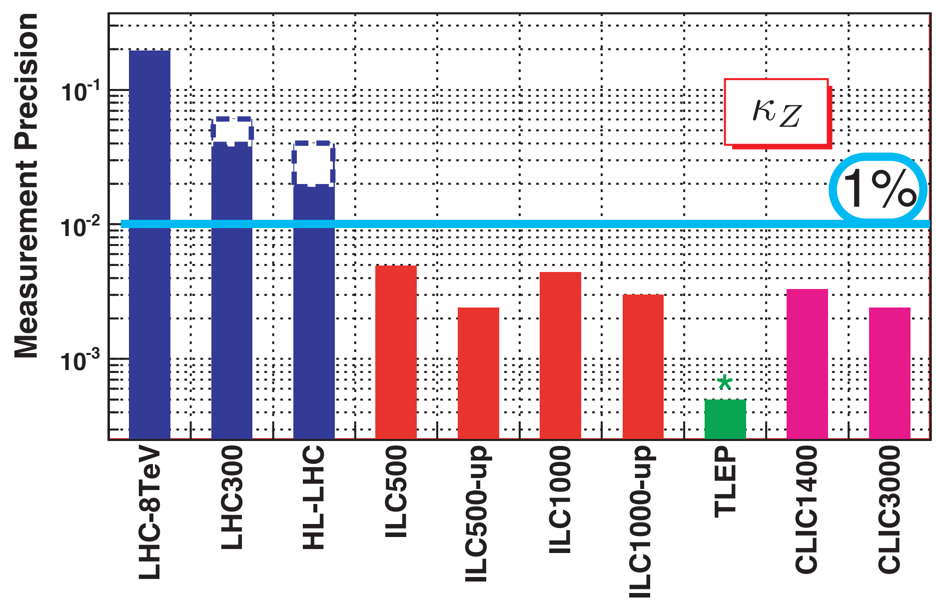
arXiv:1207.1344v3 [hep-ph] extended
in Snowmass EW report

TGC's from global fit to Higgs data

- What if analysis done using as input projected precisions on Higgs properties from linear collider options? Include aQGC's? e.g.:

Snowmass Higgs report, arXiv:1310.8361 [hep-ex]





- Precision on deviations of Higgs couplings: g_{HWW}, g_{HZZ}

Inquiries sent to authors – interested

Summary/Conclusions

- LC options can bring significant new insights to multi-boson interactions
- Anomalous triple gauge couplings, induced by dim-6 operators, are significantly better probed by high-energy linear collider options
- Anomalous quartic gauge couplings, induced by dim-8 operators, are significantly better probed (by 1-2 orders of magnitude) by the LHC, due to the stronger growth of the anomalous cross section with energy
- Global fits with Higgs properties are useful
- Complementarities abound!

Verbatim from Snowmass EW report

EW effective chiral Lagrangian

The deviations of the couplings from the SM values are expressed in terms of the α_i parameters as

$$\Delta g_1^{\gamma} = 0 \qquad \Delta\kappa^{\gamma} = g^2(\alpha_2 - \alpha_1) + g^2\alpha_3 + g^2(\alpha_9 - \alpha_8) \tag{4.5}$$

$$\Delta g_1^{Z} = \delta_Z + \frac{g^2}{c_w^2}\alpha_3 \qquad \Delta\kappa^{Z} = \delta_Z - g^2(\alpha_2 - \alpha_1) + g^2\alpha_3 + g^2(\alpha_9 - \alpha_8) \tag{4.6}$$

and

$$\lambda^{\gamma} = -\frac{g^2}{2}\left(\alpha_1^{\lambda} + \alpha_2^{\lambda}\right) \qquad \lambda^{Z} = -\frac{g^2}{2}\left(\alpha_1^{\lambda} - \frac{s_w^2}{c_w^2}\alpha_2^{\lambda}\right) \tag{4.7}$$

Deviations from these SM values in the quartic couplings are introduced through the corrections induced by the α_i to the couplings that preserve custodial $SU(2)$ symmetry,

$$\Delta g_1^{\gamma\gamma} = \Delta g_2^{\gamma\gamma} = 0 \qquad \Delta g_1^{\gamma Z} = \Delta g_2^{\gamma Z} = \frac{g^p p}{c_w^2 - s_w^2}\alpha_1 + \frac{g^2}{c_w^2}\alpha_3 \tag{4.9a}$$

$$\Delta g_1^{ZZ} = 2\Delta g_1^{\gamma Z} + \frac{g^2}{c_w^4}\alpha_4 \qquad \Delta g_2^{ZZ} = 2\Delta g_1^{\gamma Z} - \frac{g^2}{c_w^4}\alpha_5 \tag{4.9b}$$

$$\Delta g_1^{WW} = 2c_w^2\Delta g_1^{\gamma Z} + g^2\alpha_4 \qquad \Delta g_2^{WW} = 2c_w^2\Delta g_1^{\gamma Z} - g^2\left(\alpha_4 + 2\alpha_5\right) \tag{4.9c}$$

$$h^{ZZ} = g^2\left(\alpha_4 + \alpha_5\right). \tag{4.9d}$$

EW effective chiral Lagrangian

Propagator/oblique $\mathcal{L}'_0 = \frac{v^2}{4}\,\mathrm{tr}\,\{\mathbf{T}\mathbf{V}_\mu\}\,\mathrm{tr}\,\{\mathbf{T}\mathbf{V}^\mu\}$

Propagator/oblique $\mathcal{L}_1 = gg'\,\mathrm{tr}\,\{\mathbf{B}_{\mu\nu}\mathbf{W}^{\mu\nu}\}$

aTGC $\mathcal{L}_2 = \mathrm{i}g'\,\mathrm{tr}\,\{\mathbf{B}_{\mu\nu}[\mathbf{V}^\mu, \mathbf{V}^\nu]\}$

aTGC $\mathcal{L}_3 = \mathrm{i}g\,\mathrm{tr}\,\{\mathbf{W}_{\mu\nu}[\mathbf{V}^\mu, \mathbf{V}^\nu]\}$

aQGC $\mathcal{L}_4 = (\mathrm{tr}\,\{\mathbf{V}_\mu\mathbf{V}_\nu\})^2$

aQGC $\mathcal{L}_5 = (\mathrm{tr}\,\{\mathbf{V}_\mu\mathbf{V}^\mu\})^2$

aQGC $\mathcal{L}_6 = \mathrm{tr}\,\{\mathbf{V}_\mu\mathbf{V}_\nu\}\,\mathrm{tr}\,\{\mathbf{T}\mathbf{V}^\mu\}\,\mathrm{tr}\,\{\mathbf{T}\mathbf{V}^\nu\}$

aQGC $\mathcal{L}_7 = \mathrm{tr}\,\{\mathbf{V}_\mu\mathbf{V}^\mu\}\,(\mathrm{tr}\,\{\mathbf{T}\mathbf{V}_\nu\})^2$

Propagator/oblique $\mathcal{L}_8 = \frac{1}{4}g^2\,(\mathrm{tr}\,\{\mathbf{T}\mathbf{W}_{\mu\nu}\})^2$

aTGC $\mathcal{L}_9 = \frac{1}{2}\mathrm{i}g\,\mathrm{tr}\,\{\mathbf{T}\mathbf{W}_{\mu\nu}\}\,\mathrm{tr}\,\{\mathbf{T}[\mathbf{V}^\mu, \mathbf{V}^\nu]\}$

aQGC $\mathcal{L}_{10} = \frac{1}{2}\,(\mathrm{tr}\,\{\mathbf{T}\mathbf{V}_\mu\})^2\,(\mathrm{tr}\,\{\mathbf{T}\mathbf{V}_\nu\})^2$