Heavy bosons in high-energy lepton colliders

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High energy e^+e^- colliders

Project	ILC	CLIC	FCC (hh ee he)	CEPC
Accelerator	SC Linac	NC Linac	Ring	Ring
Site	Japan	CERN	CERN	China
Energy	250 GeV	380 GeV	240 GeV	240 GeV
→ Upgrade	> 1 TeV	3 TeV	365 GeV	-
Length	20 km (→ 50 km)	12 km (→ 30 km)	100 km (→hh, he)	100 km (→SppC)
Status	TDR	CDR	CDR	CDR

- "As Higgs factories, all the four contenders have a similar reach" (EPPSU Physics Briefing book)
  - Linear: control initial polarization to access more parameters
  - Circular: more luminosity
- ILC: inter-governmental discussion ongoing → decision
- CLIC/FCC/CEPC: technical design (TDR) → decision

ILC: Recent situation & Timelines

2019

- "Expression of Interest" from Japanese government (MEXT) (Mar.)
- KEK ILC Intl. WG report
  - A cost sharing model proposed as well as governance model
- Support from US, DOE/DOS

2020

- ICFA meeting, SLAC (Feb.)
  - Transition to "Intl. Development Team" (IDT) proposed
- IDT Start (Jul.-Sep.), hosted at KEK
- EPPSU → Discussion with EU/UK

Late 2021 – Early 2022

- Start of preparatory phase (4 years)
- Detailed negotiations to international agreement

2025-26

- Construction start (9 years)

Strong support from US
Waiting EPPSU for Europe

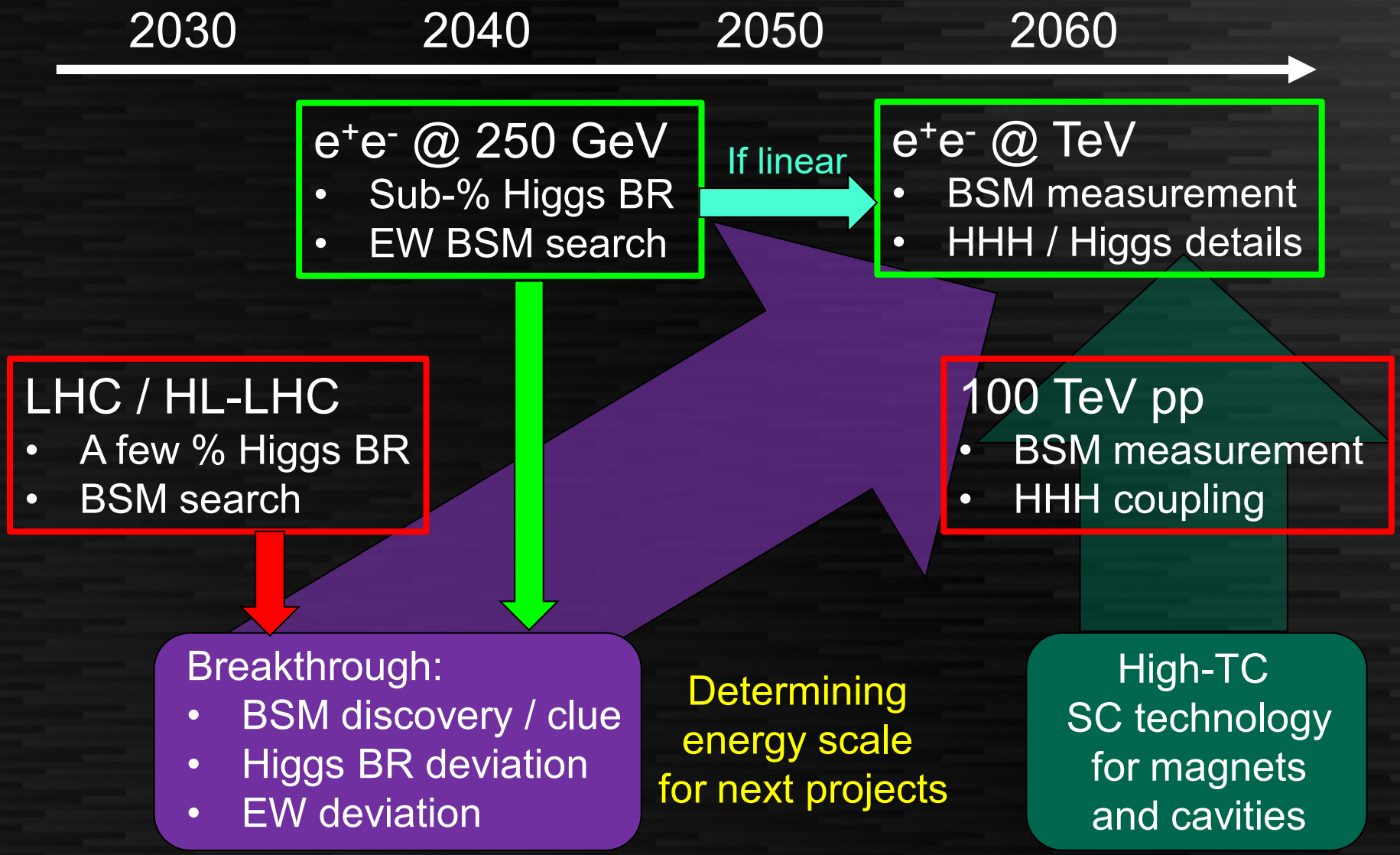
LCWS2019@Sendai

Melinda Pavek, Director of Science, Innovation and Development, US Embassy, Tokyo

…the U.S. Department of State has done our initial due diligence, and we are ready to assist our partner agencies in moving forward with the next major particle physics facility in Japan —the International Linear Collider, also known as the ILC.

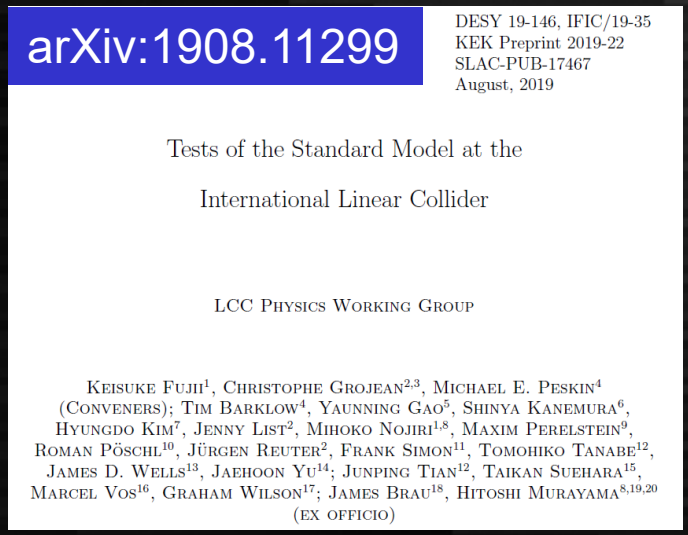
A newspaper in Japan recently reported that US Secretary of State sent a letter to Foreign Minister of Japan conveying a strong support to the ILC.

Strategy to 2060(?)



Topics on heavy bosons

- Z' with 2f final states
  (arXiv: 1908.11299, 1902.05245)
  - Quark sector, Tau polarization
    (arXiv: 1709.04289, 1912.08403)
- Scalar search by recoil method
  (arXiv: 2005.06265)
- Things to do


arXiv:1908.11299

DESY 19-146, IFIC/19-35
KEK Preprint 2019-22
SLAC-PUB-17467
August, 2019

Tests of the Standard Model at the

International Linear Collider

LCC Physics Working Group

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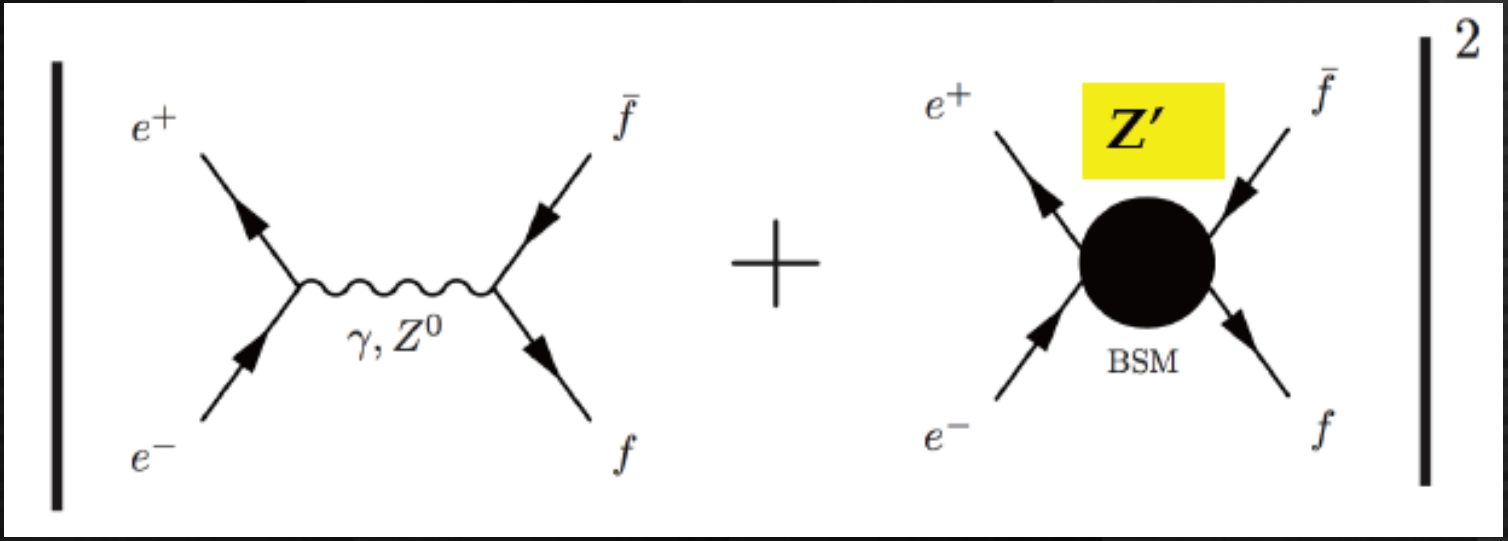
2-fermions in e^+e^- collider



Effect of virtual BSMs (Z's, WIMPs, …) as interference

Observables for detection:
- Cross section
- Production angle
- Dependence on polarization (for LC)
- Polarization (τ)

$e^+e^- \rightarrow ff$: basics

SM Cross section (80/30% polarization assumed) Whizard 1.95

Sqrt(s)	Process	$\sigma (e^-_L e^+_R)$	$\sigma (e^-_R e^+_L)$	σ (No pol.)
250 GeV	$e^+e^- \rightarrow qq$	79 pb	46 pb	50 pb
	$e^+e^- \rightarrow ll$ (μ, τ)	13 pb	10 pb	9.3 pb
500 GeV	$e^+e^- \rightarrow qq$	19 pb	4.3 pb	9.4 pb
	$e^+e^- \rightarrow ll$ (μ, τ)	10 pb	3.1 pb	5.6 pb
1 TeV	$e^+e^- \rightarrow qq$	5.6 pb	1.3 pb	2.8 pb
	$e^+e^- \rightarrow ll$ (μ, τ)	3.1 pb	0.9 pb	1.6 pb

(incl. $Z\gamma \rightarrow ff\gamma$)

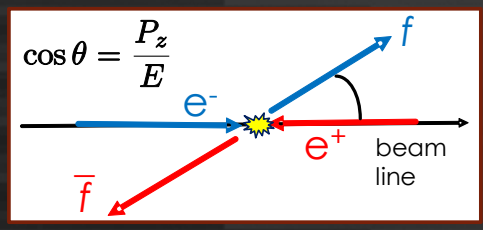
Effect of polarization

- 1.5 – 2 times more cross section at $e^-_L e^+_R$
- Independent observables with two polarization setup

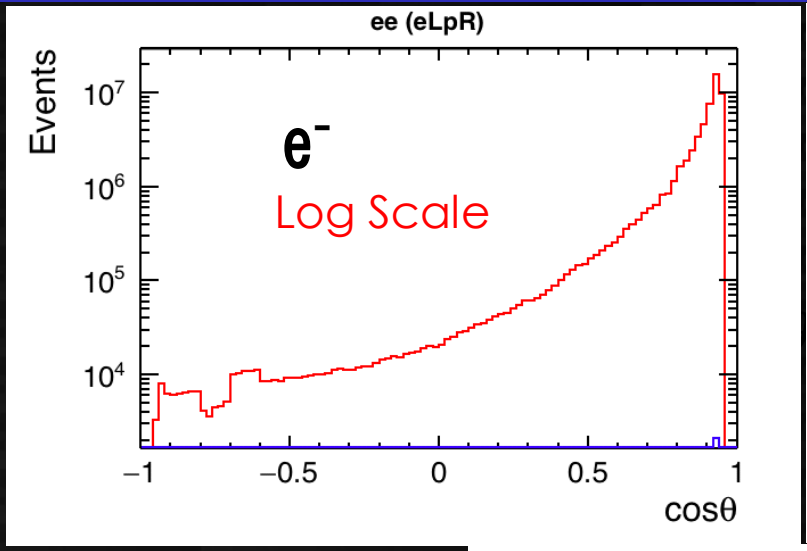
Statistical power

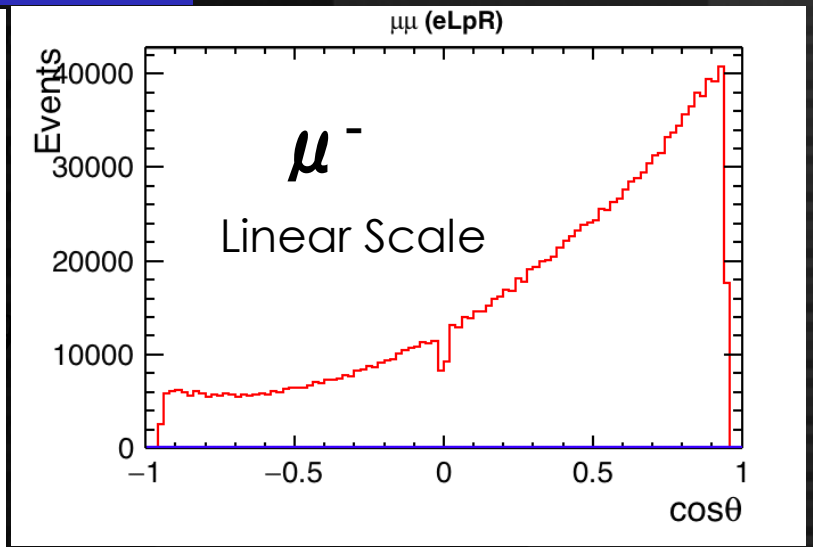
10 pb → 10^7 events / 1 ab^{-1} → 0.03% ultimate statistics

Angular distribution with Z'

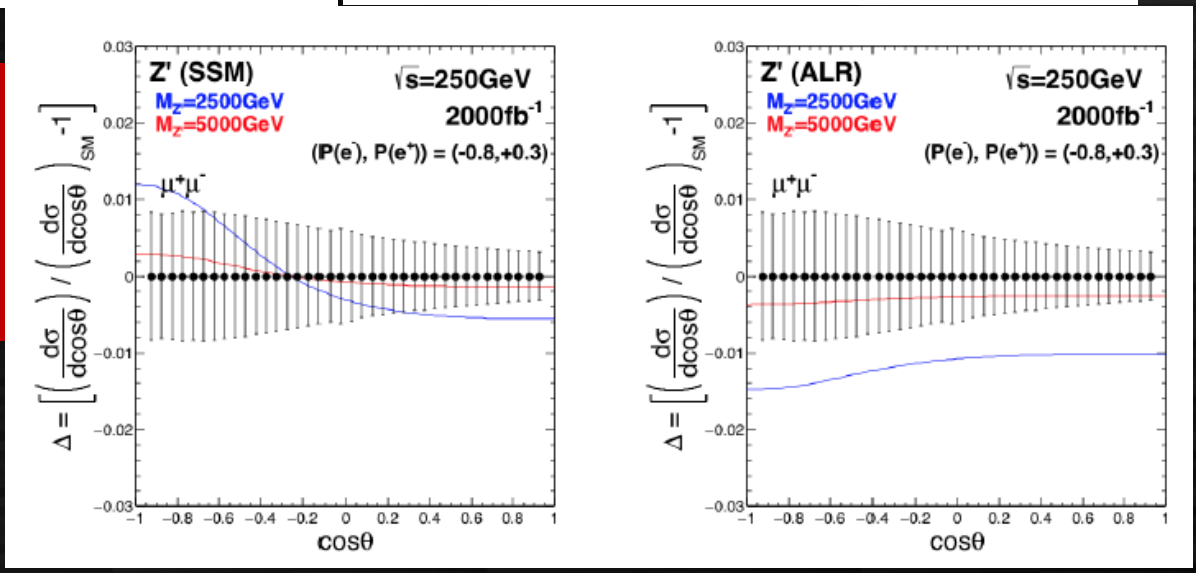


SM angular distribution (250 GeV, full sim)



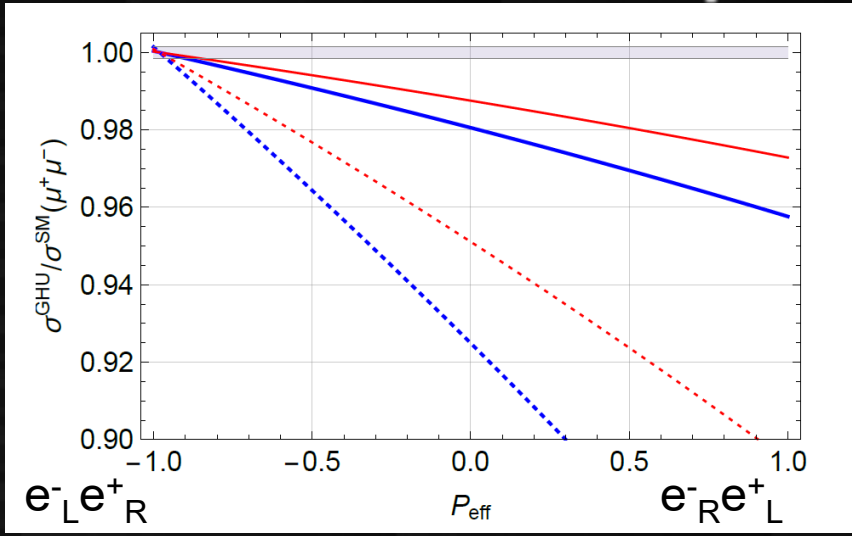


Deviation from SM by Z' models (SSM, ALR) for ee→μμ



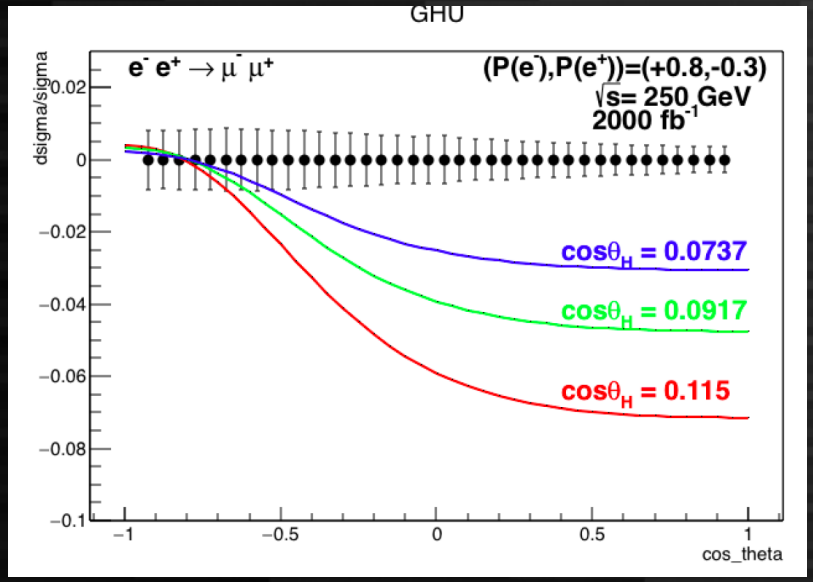
arXiv:1801.04671
arXiv:1902.05245

Polarization power: an example



Gauge-Higgs unification (GHU) predicts Z' only couples to right-handed electrons (solid: 250 GeV, dotted: 500 GeV, red: ϕ_H = 0.0917, blue: ϕ_H = 0.0737)

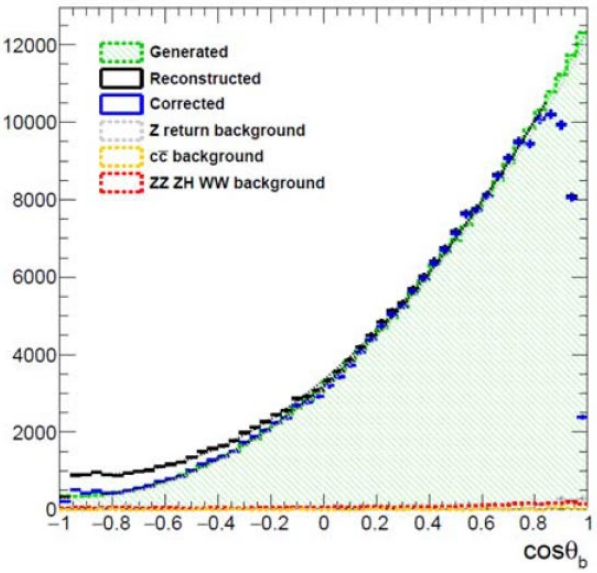
arXiv:1705.05282
arXiv:1801.04671

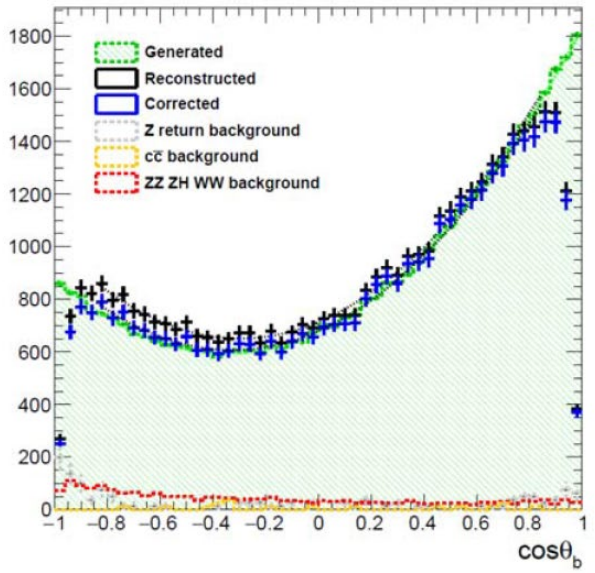


250 GeV ILC easily identifies Z' from GHU with right-handed polarization

ee → bb/cc: charge assignment

Charge assignment of b is non-trivial
Mainly using vertex charge to identify $B^+/B^-/B^0$





arXiv:1709.04289

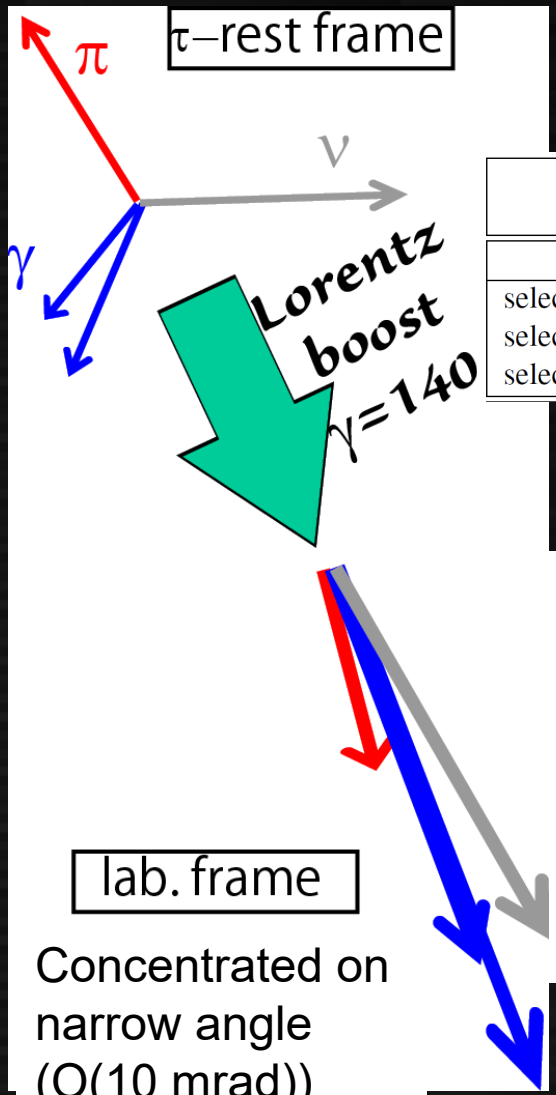
Reasonable charge assignment with 13% efficiency obtained

(can try more improvement with ML etc.)

Polarisations P P'	-80% +30%	+80% -30%
Efficiency %	13	13
Luminosity fb^{-1}	340	110
Cross section fb	3342	1012
Background %	3	5
Syst % L+Pol+back+eff	0.1+0.1+0.3+0.2	0.1+0.1+0.5+0.2
Stat+syst %	0.31+0.38	1+0.56

Uncertainty
(but with 0.5 ab^{-1})
Trying to reach 0.1-0.2%
with high statistics and
improved estimation

ee → ττ: τ polarization

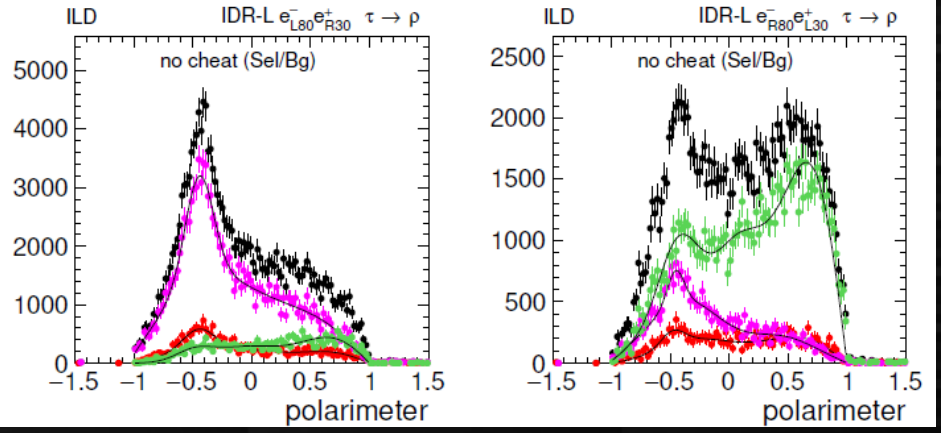


Tau polarization: have to derive decay mode of tau

arXiv:1912.08403

	true MC decay				
	$\tau^\pm \to \pi^\pm\nu$	$\tau^\pm \to \pi^\pm\pi^0\nu$	$\tau^\pm \to \pi^\pm\pi^0\pi^0\nu$	$\tau^\pm \to$ other	purity
	IDR-L				
selected as $\tau^\pm \to \pi^\pm\nu$	89.27 ± 0.38	2.06 ± 0.12	0.87 ± 0.13	9.22 ± 0.29	82.11 ± 0.45
selected as $\tau^\pm \to \pi^\pm\pi^0\nu$	6.47 ± 0.30	75.21 ± 0.36	13.32 ± 0.48	5.81 ± 0.23	86.79 ± 0.30
selected as $\tau^\pm \to \pi^\pm\pi^0\pi^0\nu$	2.20 ± 0.18	13.03 ± 0.28	64.32 ± 0.68	6.74 ± 0.25	53.86 ± 0.65

Reasonable separation of decay mode observed (can be improved)



Polarimetry example

< 1 % polarization measurement feasible at 500 GeV (easier at 250 GeV)

Exclusion / discovery for Z' models

Exclusion (95%CL) / discovery (5σ) reach at ILC

arXiv:1908.11299

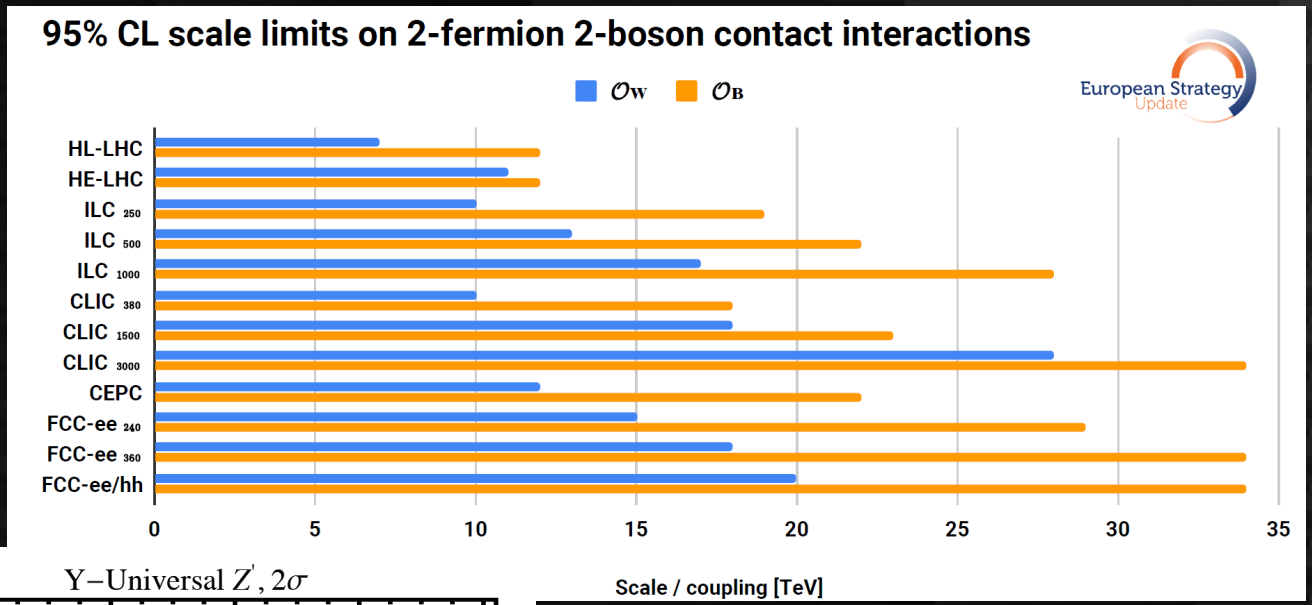
Model	250 GeV, excl.	2 ab^{-1} disc.	500 GeV, excl.	4 ab^{-1} disc.	1 TeV, excl.	8 ab^{-1} disc.
SSM	7.8	4.9	13	8.4	22	14
ALR	9.5	6.0	17	11	25	18
χ	7.0	4.5	12	7.8	21	13
ψ	3.7	2.4	6.4	4.1	11	6.8
η	4.2	2.7	7.3	4.6	12	7.9

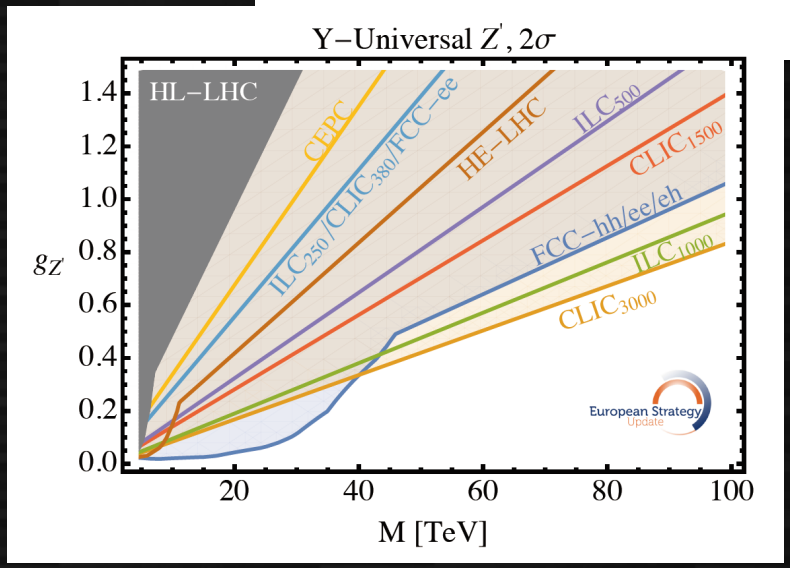
TeV

- e, μ, τ, b combined (without full consideration of systematics)
- Phenomenological model
  - SSM: Sequential Standard Model
- Theory-motivated model
  - ALR: Alternative Left-Right model
  - χ, ψ, η: E_6 group models
- 500 GeV / 1 TeV: extrapolated from 250 GeV study

ee → ff: EPPSU

"Y-universal Z'" model is considered





For universal-type Z':

- 250 GeV e^+e^- can exceed HL-LHC reach
- ~TeV e^+e^- is comparable to 100 TeV hh

ee → ff: Summary

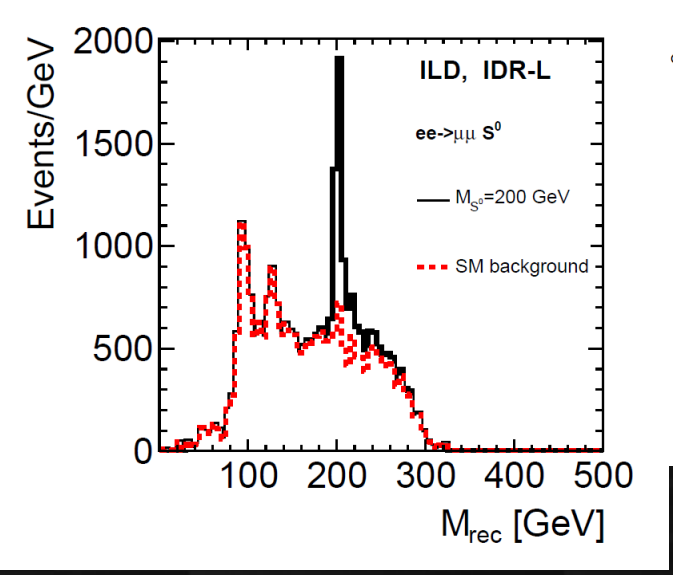
- e^+e^- can probe Z' with comprehensive way
  - Can use ee, μμ, ττ, bb, (cc), (qq)
    - Z' with weak coupling to lepton can be probed
    - Beam polarization helps a lot on some models
    - Tau polarization to 1% - can be a new probe?
- 250 GeV – 5-10 TeV Z' can be in reach
  - Depending on models
  - Can expect to exceed HL-LHC reach
- 1 TeV – should be as powerful as FCChh
- Detailed systematic studies are necessary
  - Luminosity, detection efficiency, etc.

Associate production of scalar

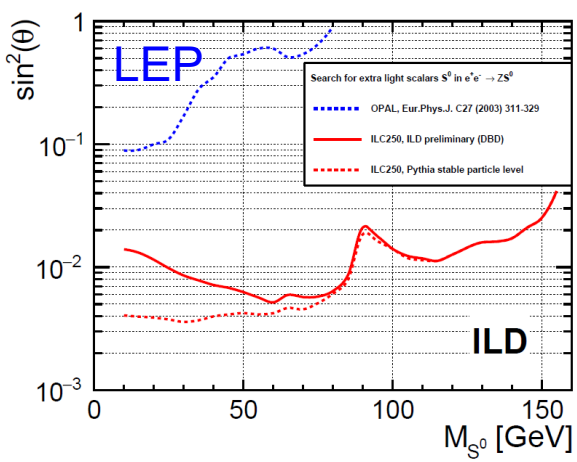
$e^+e^- \rightarrow Z^*/\gamma \rightarrow ZS^0$ (similar to ZH process)

Recoil method (model independent): arXiv:2005.06265

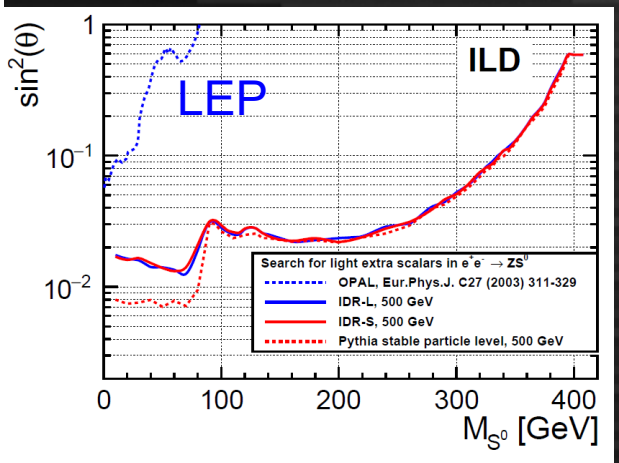
4-momentum of S^0 can be calculated from remaining Z



Recoil mass spectrum with $m(S_0) = 200$ GeV



Result with ILC250



Result with ILC500

arXiv:1801.09662

Assuming $S^0 \rightarrow bb$ (model dependent) sensitivity to ~10^{-3} can be obtained

A possible way to go

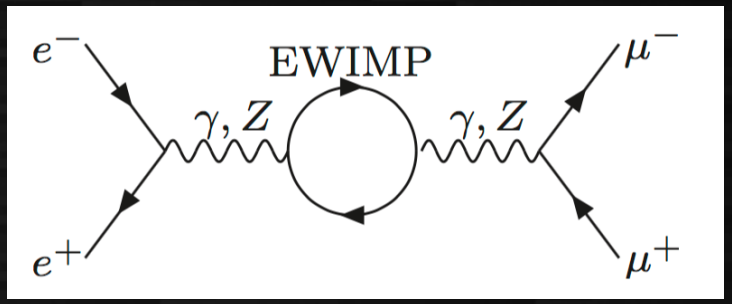
- Various Z' models has been (will be) proposed, having various couplings to various particles. Difficult to evaluate performance in a comprehensive way.
  - Experimental side: should provide performance on (total/differential) cross section etc. with multiple setup (energy/luminosity), including detailed estimation of systematic effects, with common format for combination and comparison
  - Theory side: should establish benchmarks of important Z' models to examine the importance of the measurements

Summary

- e^+e^- Higgs factory is a powerful machine not only for Higgs but for other EW studies
  - Critical to determine next energy scale
- Indirect searches of Z' at lepton colliders with $e^+e^- \rightarrow ff$ are as a powerful tool as direct searches at hadron colliders
  - Accessing various decay channel to find various (and discriminate) Z' (or other BSM) models
- Additional scalar can be found with associate production

BSM models

- Z' models
  - SSM
  - ALR (Alternative Left-Right model)
  - E_6 models (motivated from string theory)
  - Gauge Higgs Unification (Hosotani model)
- General WIMP search
  - Determined by spin of EWIMP



$e^+e^- \rightarrow ff$: basics

SM Cross section (100% polarization assumed)

Sqrt(s)	Process	$\sigma(e^-_L e^+_R)$	$\sigma(e^-_R e^+_L)$	σ (No pol.)
250 GeV	$e^+e^- \rightarrow qq$	130 pb	70 pb	50 pb
	$e^+e^- \rightarrow ll$ (μ, τ)	21 pb	16 pb	9.3 pb
500 GeV	$e^+e^- \rightarrow qq$	32 pb	5.5 pb	9.4 pb
	$e^+e^- \rightarrow ll$ (μ, τ)	18 pb	4.3 pb	5.6 pb
1 TeV	$e^+e^- \rightarrow qq$	9.4 pb	1.6 pb	2.8 pb
	$e^+e^- \rightarrow ll$ (μ, τ)	5.2 pb	1.3 pb	1.6 pb

Remaining topics

- Precise estimation of systematic effects
  - To total cross section
  - To differential cross section
  - To polarization, charge assignment, tau pol etc.
  - Combine channels with (partially correlated) systematics
- Broader models to examine
  - Different couplings to generations
  - Different couplings to lepton/quark
  - Different effects to polarization