Distinguishing contact interaction models at the ILC with polarized beams

Andrei Tsytrinov

The Abdus Salam ICTP Affiliated Centre,

Technical University of Gomel, Belarus

3rd LCFORUM Meeting,
7-9 February 2012,
DESY Hamburg, Germany

with *A.A. Pankov* (Gomel & Trieste) & *N. Paver* (Trieste)

Outline

- Variety of New Physics Scenarios (NP)
- Parameterization of NP (compositeness, *Z'*, *W'*, *LQ*, $\tilde{\nu}$, KK, G_n ,...) in

terms of four-fermion CI

- NP indirect effects at e^+e^- **ILC**

  - Processes: $e^+e^- \rightarrow \overline{f}\, f \;\; (f = e, \mu, \tau, c, b)$
- Discovery reach on NP parameters
- Identification reach of contact interactions at the ILC

  (pair-wise comparison and model independent approaches)
- Observables: polarized differential distributions

Introduction

It is generally expected that NP beyond the SM will manifest itself at future colliders such as the LHC and ILC either:

- **directly,** as in the case of new particle production, e.g., *Z'* and *W'* vector bosons, SUSY or Kaluza-Klein (KK) resonances, or

- **indirectly** through *deviations* of observables from the SM predictions.

In the case of **indirect** discovery many different NP scenarios may lead to the **same** or **very similar** experimental signatures. These NP scenarios predict *new particle exchanges* which can lead to **CI** below direct production threshold.

Various New Physics possibilities

- Composite models
- Heavy *Z'* exchanges
- Scalar and vector leptoquarks
- Sneutrino exchange
- Anomalous Gauge Couplings (AGC)
- Exchange of gauge boson KK towers
- Virtual KK graviton exchange (ADD)
- etc.

If New Physics effects are discovered, it is crucial to have good search strategies to determine its origin.

Proposed techniques:

- **Monte Carlo best fits** *(G.Pasztor & M.Perelstein*, hep-ph/0111471)
- **Integrated cross sections weighted by Legendre polynomials** *(T.Rizzo*, **JHEP** 0210 (2002))
- **ILC:**
  - — **Center-Edge Asymmetries A_{CE} and $A_{CE,FB}$**: offer a possibility of easily discriminating spin-1 from spin-2 exchanges

    (*P. Osland, N. Paver, A.A. Pankov*, **P.R.D** 68 (2003);

    A.A. Pankov, N. Paver, **P.R.D** 72 (2005))
  - — **polarized differential distributions** for $e^+e^- \to \bar{f}\ f$

    (*A.A. Pankov, N. Paver, A.T.*, **P.R.D** 73 (2006); **P.R.D** 75 (2007))
- **LHC:**
  - — A_{CE} **at LHC**

    (E.W. Dvergsnes, P. Osland, N. Paver & A.A. Pankov, **P.R.D** 69 (2004); **IJMP** A 20 (2005))

    A.T., A. Pankov, N. Paver, P. Osland **P.R.D** 78 (2008)**;** 79 (2009); 82 (2010); 84 (2011)

Here, we will consider the problem of how to **distinguish** the potential New Physics scenarios from each other at the ILC. In particular, we will **discuss such a technique** based on the polarized angular distributions which offer a way to uniquely identify spin-2 graviton exchange, parameterized by CI (operator of dim. 8) as well as “conventional” (dim 6) CI.

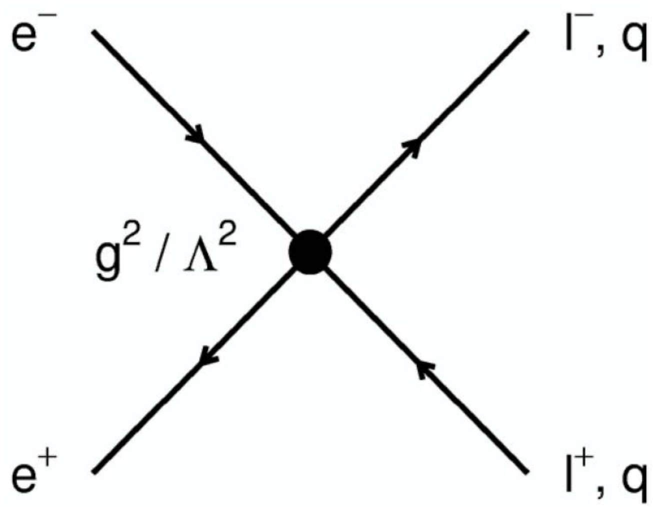
Nonstandard Scenarios

- Framework of effective Lagrangians (expansion in s/Λ^2)
- "Conventional" (dim-6) four-fermion contact interactions (**CI**) [compositeness]:
- effective Lagrangian:

$$\mathcal{L}^{\mathrm{CI}} = 4\pi \sum_{\alpha,\beta} \frac{\eta_{\alpha\beta}}{\Lambda^2_{\alpha\beta}} \left(\bar{e}_\alpha \gamma_\mu e_\alpha\right)\left(\bar{f}_\beta \gamma^\mu f_\beta\right),$$

$$\eta_{\alpha\beta} = \pm 1, 0;\ \alpha, \beta = \mathrm{L}, \mathrm{R}.$$

Operators of dim-6

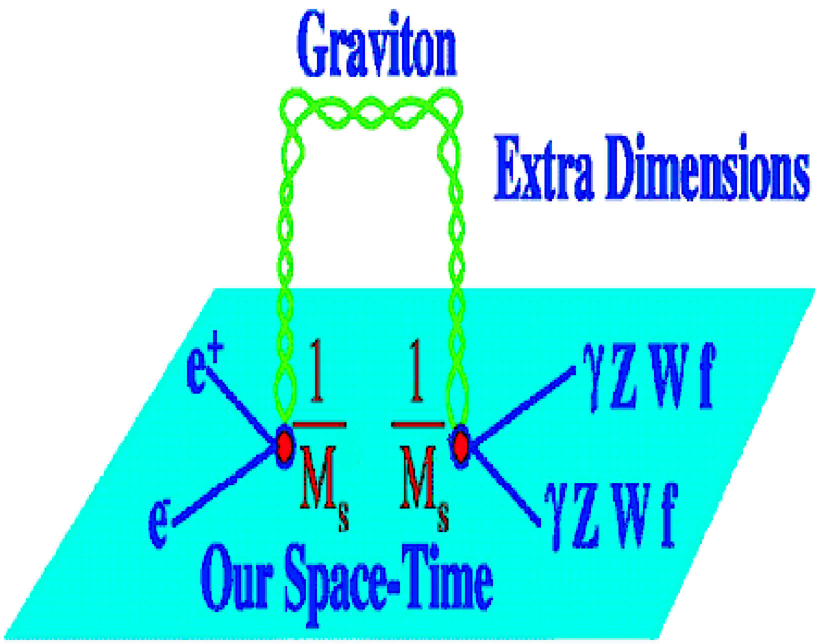


- Can describe also exchanges of heavy *Z', W',* Leptoquarks, *etc.*
- Current limits on "compositeness" scales [LHC]: **$\Lambda_{\ell\ell qq} > 10$ TeV**

[CERN-PH-EP-2011-198]

• ADD scenario: Gravity in "large" compactified extra dimensions (gauge hierarchy)

• Gravity only can propagate in the full 4+N space



• Virtual exchange of the graviton KK excitation states is governed by the effective Lagrangian (similar to dim-8 CI):

$$\mathcal{L}^{\mathrm{ADD}} = i\frac{4\lambda}{{\Lambda_H}^4} T^{\mu\nu} T_{\mu\nu},$$

where Λ_H is the cut-off scale (convention of *Hewett*), λ = ± 1.

• current lower limit [LHC]: Λ_H > 1.7 TeV

- TeV $^{-1}$ - scale extra dimensions

Also SM gauge bosons may propagate in the additional dimensions: exchange of γ and Z KK excitations. Effective (contactlike) interaction:

$$\mathcal{L}^{\mathrm{TeV}} = -\frac{\pi^2}{3M_C^2}\Big[Q_e Q_f(\bar{e}\gamma_\mu e)(\bar{f}\gamma^\mu f) + \\ +(g_{\mathrm{L}}^e \bar{e}_{\mathrm{L}}\gamma_\mu e_{\mathrm{L}} + g_{\mathrm{R}}^e \bar{e}_{\mathrm{R}}\gamma_\mu e_{\mathrm{R}}) \times (g_{\mathrm{L}}^f \bar{f}_{\mathrm{L}}\gamma^\mu f_{\mathrm{L}} + g_{\mathrm{R}}^f \bar{f}_{\mathrm{R}}\gamma^\mu f_{\mathrm{R}})\Big] \,.$$

$M_C \gg M_{W,Z}$: inverse of the compactification radius

Discovery reach

- Observables: polarized angular distributions $d\sigma/d\cos\theta$
- Processes: $e^+e^- \to \bar{f}f$, *(s,t,u*− channels)
- $d\sigma \propto |\mathrm{SM} + \mathrm{NewPhysics}|^2$
- Assumption: no deviation from the SM is observed within the experimental accuracy.
- **Deviations** of observables from the SM predictions:

$$\Delta(\mathcal{O}) = \frac{\mathcal{O}(SM+NP) - \mathcal{O}(SM)}{\mathcal{O}(SM)}, \qquad \mathcal{O} = d\sigma/d\cos\theta$$

- deviations must be compared to foreseen experimental uncertainties $\delta\mathcal{O}$ [statistical plus systematic].

Discovery reach: $$\chi^2(\mathcal{O}) = \sum_{\{P^-,\ P^+\}} \sum_{\text{bins}} \left(\frac{\Delta(\mathcal{O})^{\text{bin}}}{\delta\mathcal{O}^{\text{bin}}}\right)^2.$$

- Constraints on Λ_H, Λ's, M_C [expected discovery reaches] from:

$$\chi^2(\mathcal{O}) \leq 3.84 \quad (95\%\ \text{C.L.})$$

Experimental inputs:

Bhabha and Møller scattering $(|\cos\theta| < 0.9,\ \epsilon \simeq 100\%,$ bin width:
$\Delta\cos\theta = 0.2)$;
$\mu^+\mu^-,\ \tau^+\tau^-\ (|\cos\theta| < 0.98,\ \epsilon = 95\%)$;
$\bar{c}c\ (\epsilon = 35\%)$; $\bar{b}b\ (\epsilon = 60\%)$

radiative corrections included:

$e^+e^- \to \bar{f}\ f\ \ (ZFITTER \oplus ZEFIT)$ [D. Bardin et al., S. Riemann]

$e^+e^- \to e^+e^-$ (structure functions approach)

$\delta P^{\pm}/P^{\pm} = 0.2\%,\ \delta\mathcal{L}_{\mathrm{int}}/\mathcal{L}_{\mathrm{int}} = 0.5\%.$

95% C.L. discovery reaches (in TeV). Left and right entries refer to the polarization configurations $(|P^-|, |P^+|)$=(0,0) and (0.8,0.6), respectively. $\sqrt{s} = 0.5$ TeV, $\mathcal{L}_{\text{int}} = 100 fb^{-1}$

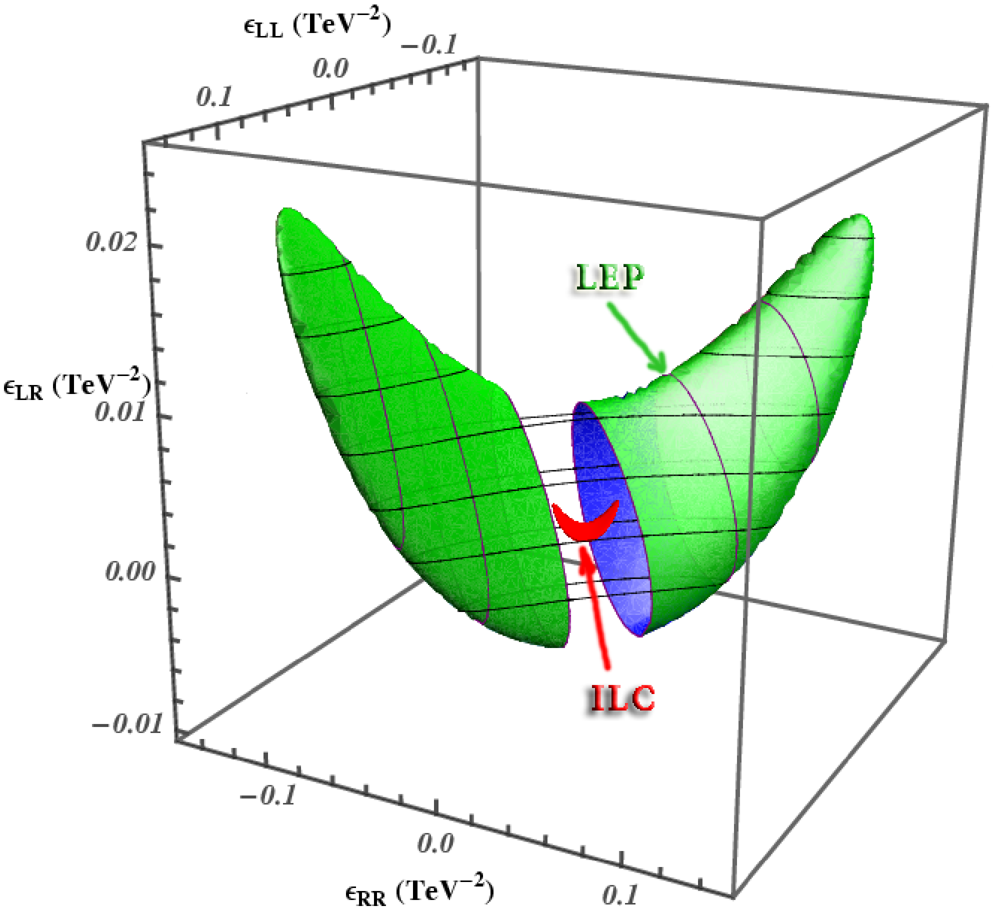
Model	Process $e^+e^- \to e^+e^-$	$e^+e^- \to l^+l^-$	$e^+e^- \to \bar{b}b$	$e^+e^- \to \bar{c}c$
Λ_H	4.1; 4.3	3.0; 3.2	3.0; 3.4	3.0; 3.2
Λ_{VV}^{ef}	76.2; 86.4	89.7; 99.4	76.1; 96.4	84.0; 94.1
Λ_{AA}^{ef}	47.4; 69.1	80.1; 88.9	76.7; 98.2	76.5; 85.9
Λ_{LL}^{ef}	37.3; 52.5	53.4; 68.3	63.6; 72.7	54.5; 66.1
Λ_{RR}^{ef}	36.0; 52.2	51.3; 68.3	42.5; 71.2	46.3; 66.8
Λ_{LR}^{ef}	59.3; 69.1	48.5; 62.8	51.3; 68.7	37.0; 57.7
Λ_{RL}^{ef}	$\Lambda_{RL}^{ee} = \Lambda_{LR}^{ee}$	48.7; 63.6	46.8; 60.1	52.2; 60.7
M_C	12.0; 13.8	20.0; 22.2	6.6; 10.7	10.4; 12.0

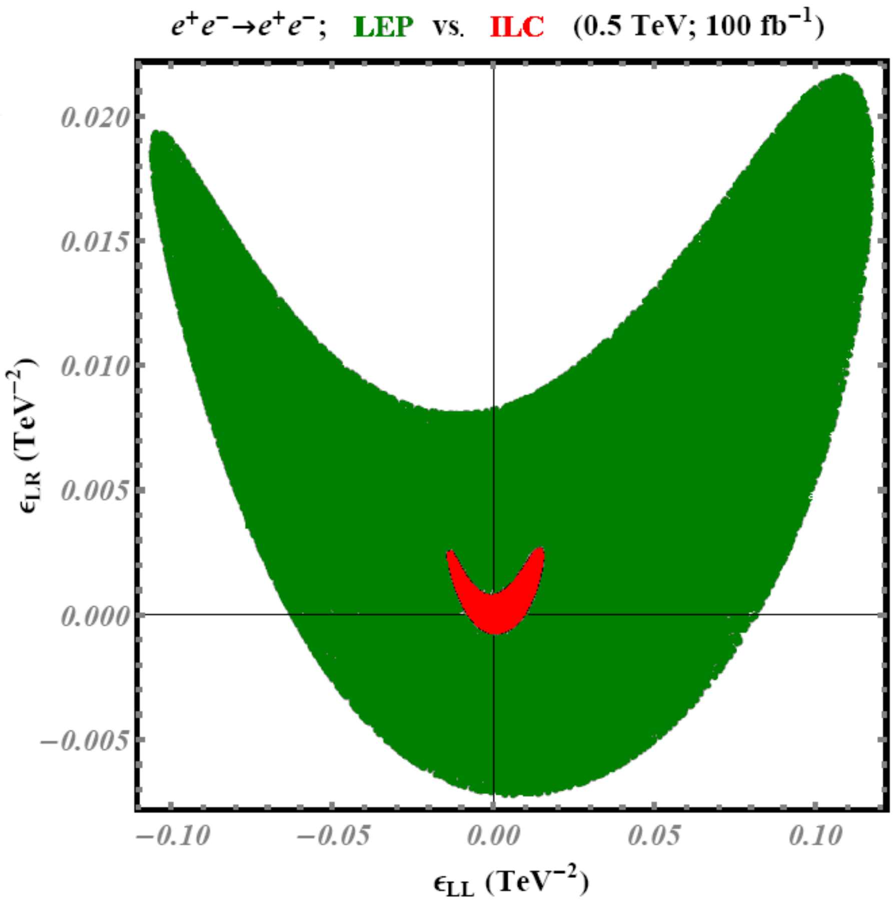
See also *S.Riemann, T.Rizzo, S.Godfrey.*

Generalized approach:
Model-independent analysis of CI – unpolarized beams

- Bhabha scattering: $\chi^2(\Lambda_{RR}, \Lambda_{LL}, \Lambda_{LR}) \leq 7.82 \quad (95\%\ \text{C.L.})$

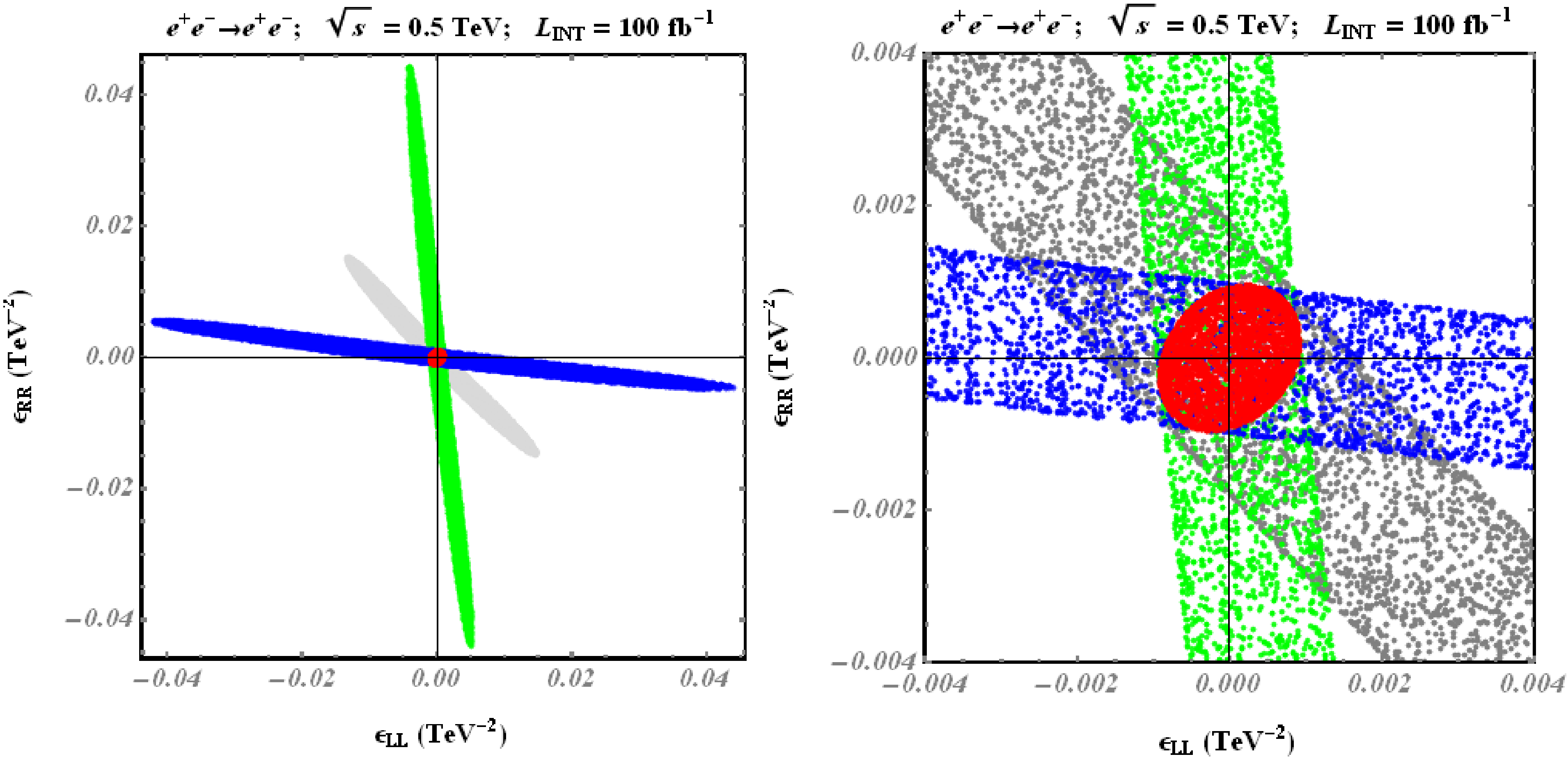
LEP vs. unpolarized **ILC** (0.5 TeV, 100 fb^{-1}):





ILC with longitudinally polarized beams

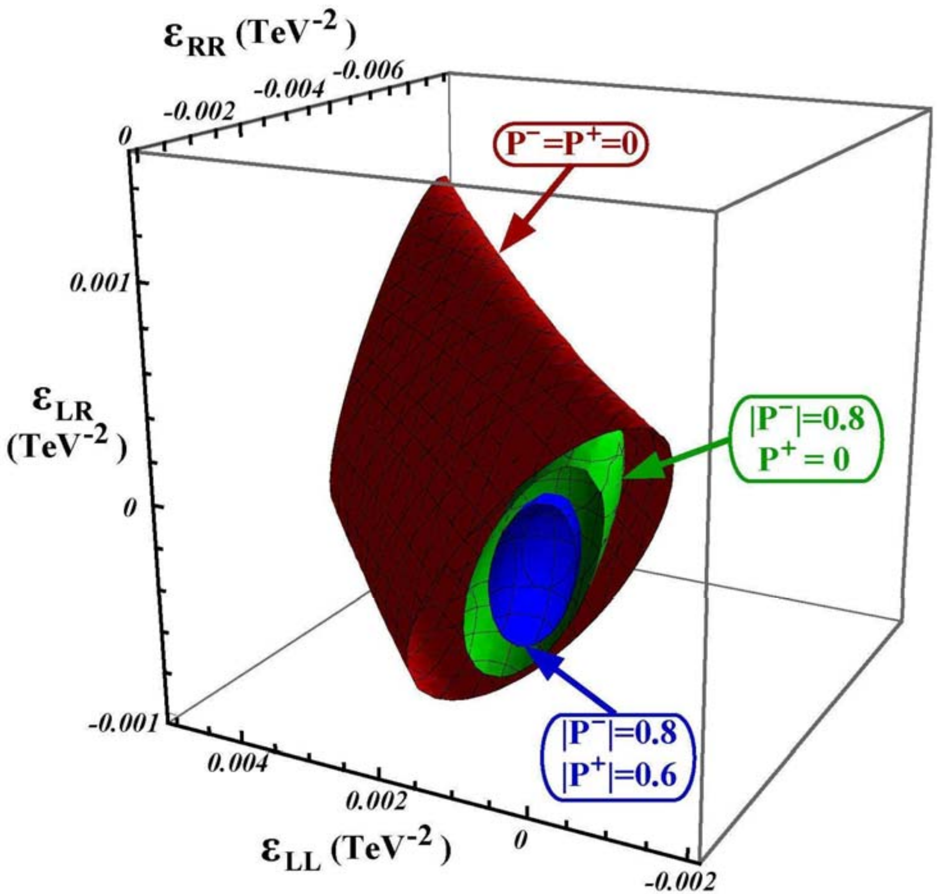
- Bhabha scattering: $\chi^2(\Lambda_{RR}, \Lambda_{LL}, \Lambda_{LR}) \leq 7.82 \quad (95\%\ \mathrm{C.L.})$

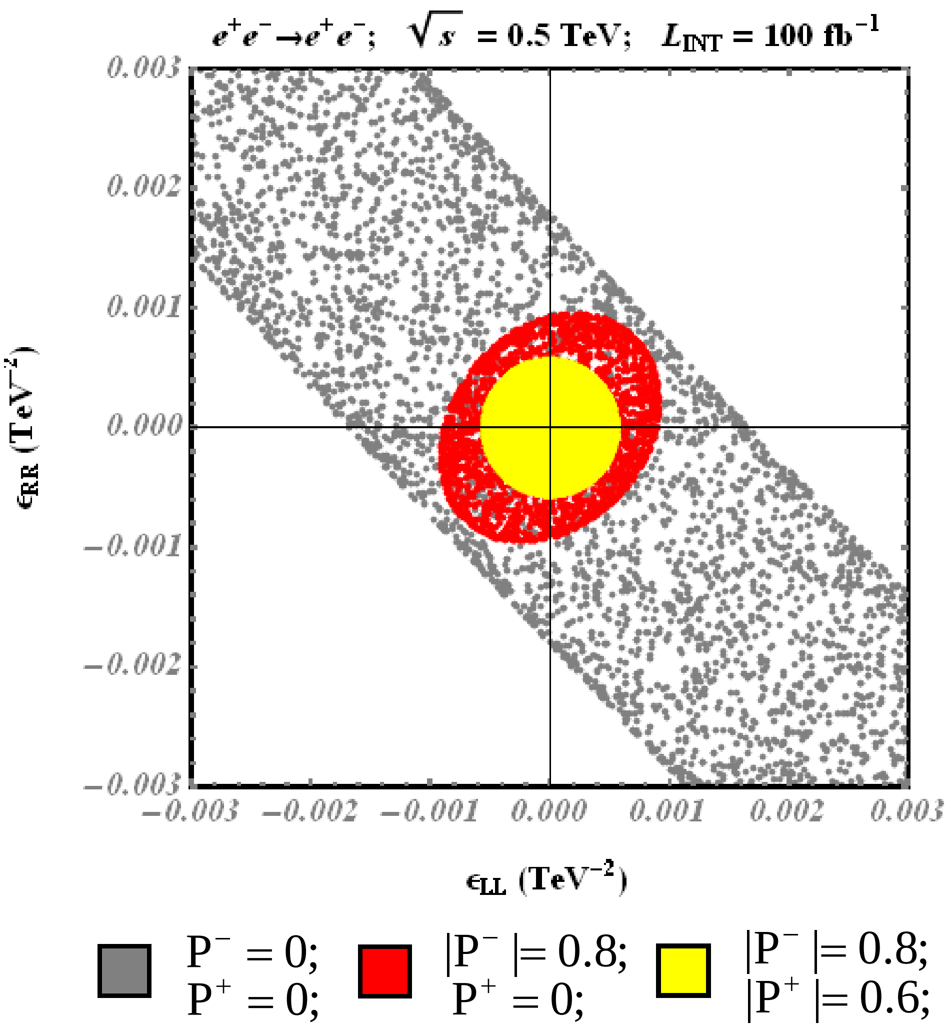


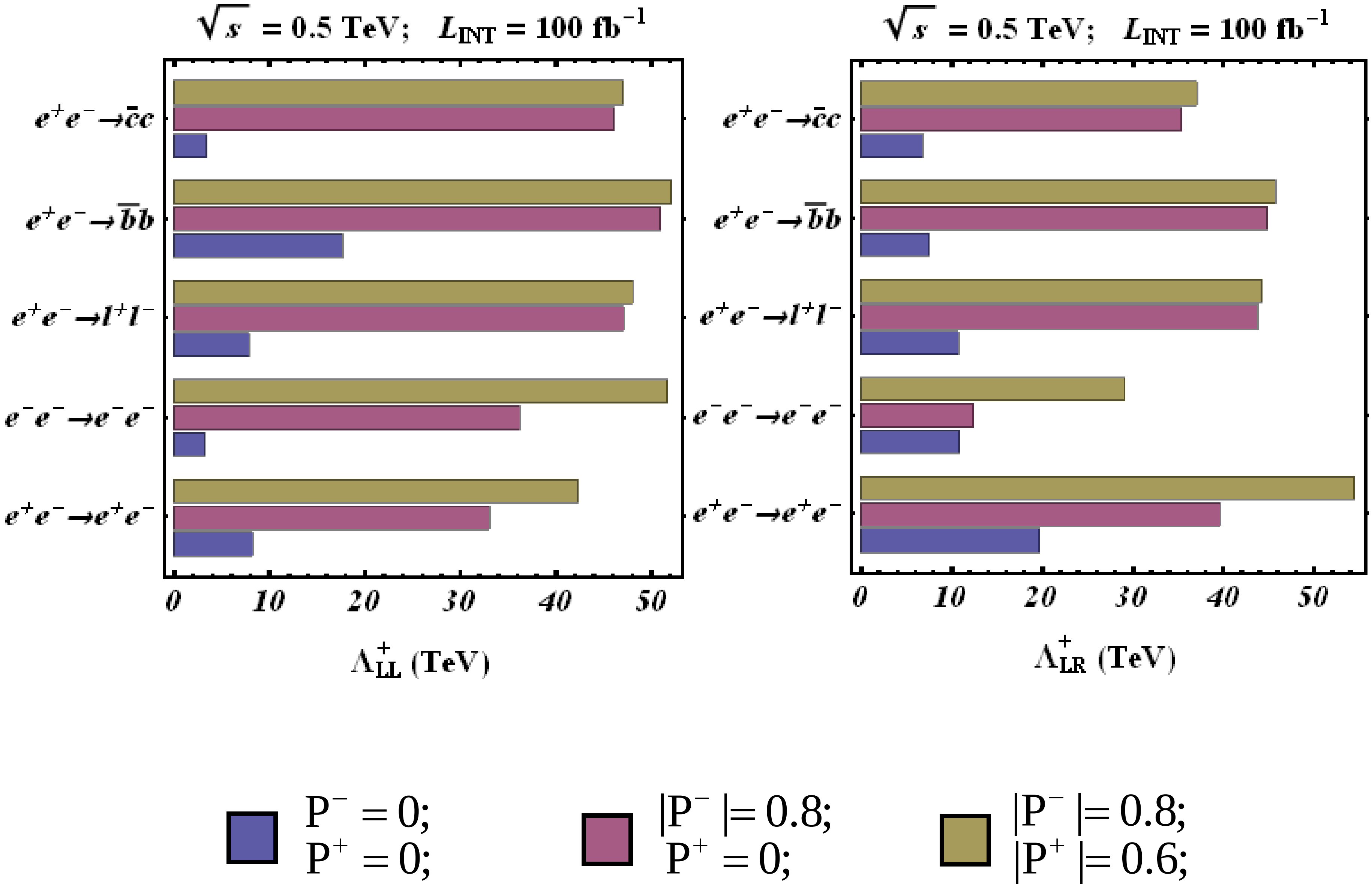
$P^- = 0;\ P^+ = 0;$ $P^- = 0.8;\ P^+ = 0;$ $P^- = -0.8;\ P^+ = 0;$ $|P^-| = 0.8;\ P^+ = 0;$

Model-independent analysis of CI: role of polarization

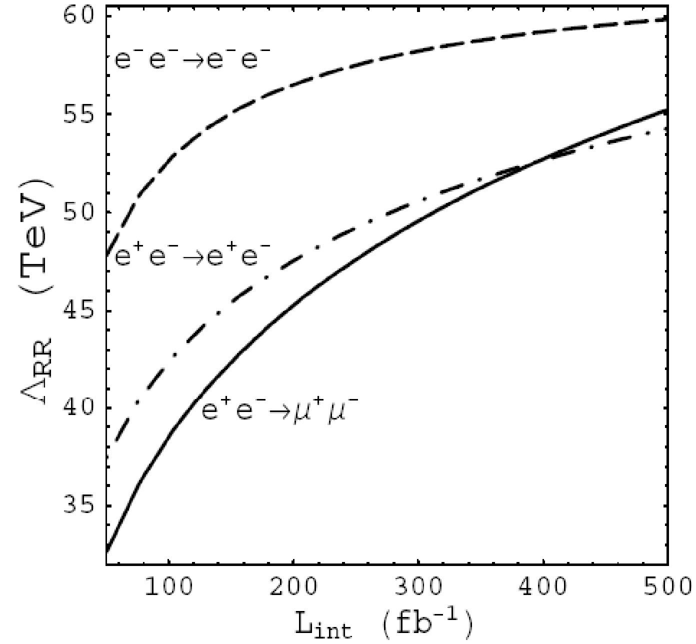
- Bhabha scattering: $\chi^2(\Lambda_{RR},\Lambda_{LL},\Lambda_{LR}) \leq 7.82 \;\; (95\%\ \mathrm{C.L.})$

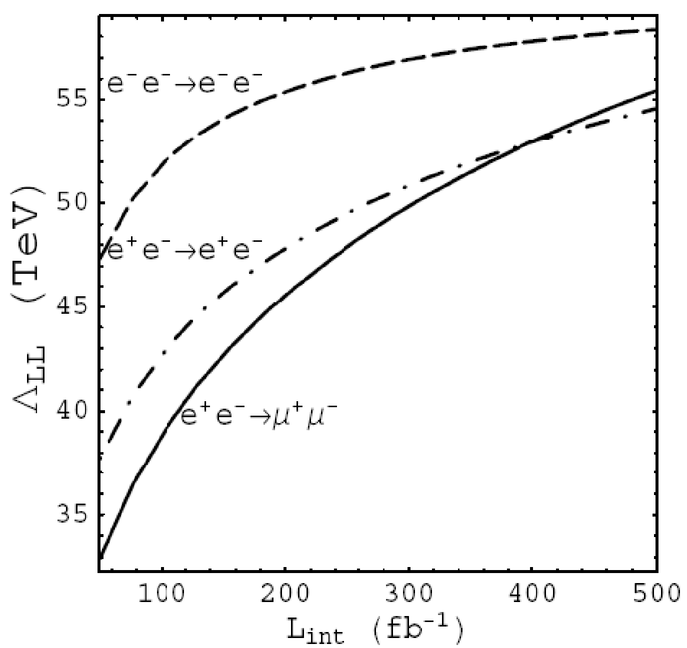


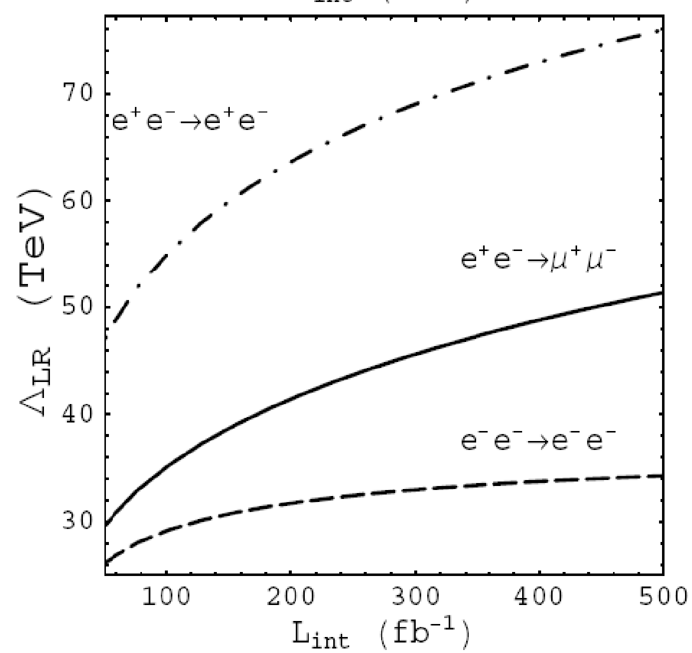



$\sqrt{s}$ = 0.5 TeV; L_{INT} = 100 fb^{-1}
$e^+e^- \to \bar{c}c$
$e^+e^- \to \bar{b}b$
$e^+e^- \to l^+l^-$
$e^-e^- \to e^-e^-$
$e^+e^- \to e^+e^-$
0 10 20 30 40 50
Λ^+_{LL} (TeV)
$\sqrt{s}$ = 0.5 TeV; L_{INT} = 100 fb^{-1}
$e^+e^- \to \bar{c}c$
$e^+e^- \to \bar{b}b$
$e^+e^- \to l^+l^-$
$e^-e^- \to e^-e^-$
$e^+e^- \to e^+e^-$
0 10 20 30 40 50
Λ^+_{LR} (TeV)
$P^- = 0;$ $P^+ = 0;$
$|P^-| = 0.8;$ $P^+ = 0;$
$|P^-| = 0.8;$ $|P^+| = 0.6;$

Model-independent bounds on CI para-meters at 95% C.L. *vs.* luminosity for ILC (0.5 TeV)







Distinction among the New Physics models

- Generic consideration - processes with s-, t-, u-channels
  identification reaches

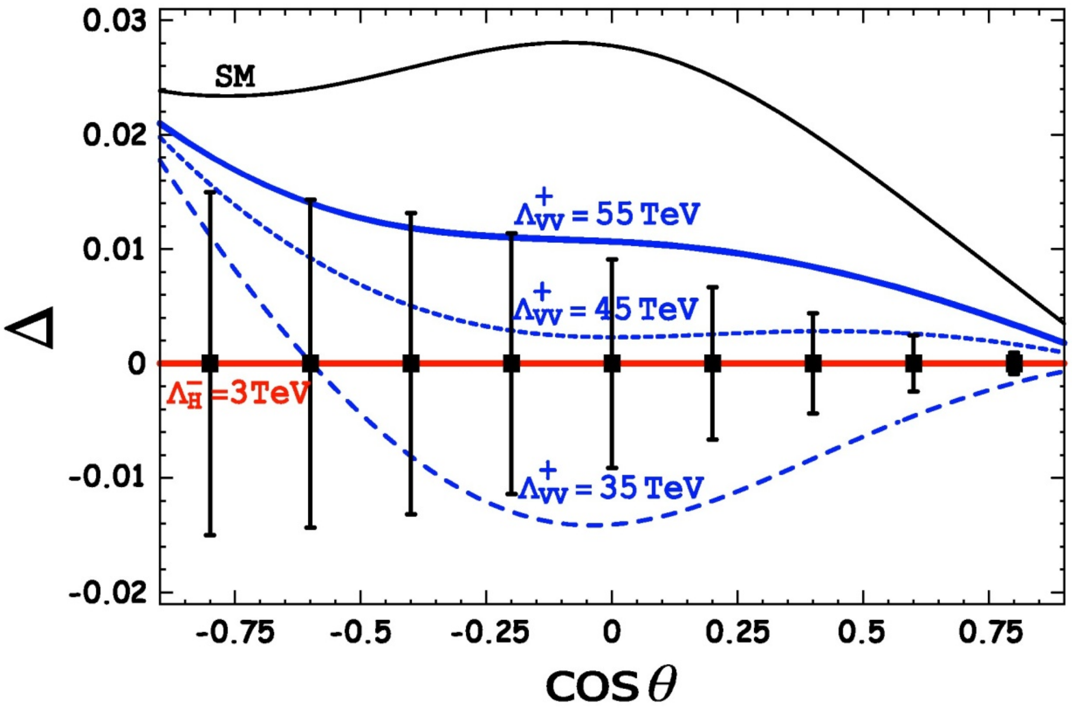
- Assumption: One of the models, say the ADD, is found consistent
  with experimental data with some value of Λ_H

- Deviations of observables from the ADD model prediction due to other models (say, the **CI** ones):

$$\tilde{\Delta}(\mathcal{O}) = \frac{\mathcal{O}(CI) - \mathcal{O}(ADD)}{\mathcal{O}(ADD)}$$

- assess the level at which ADD is distinguishable from the other models

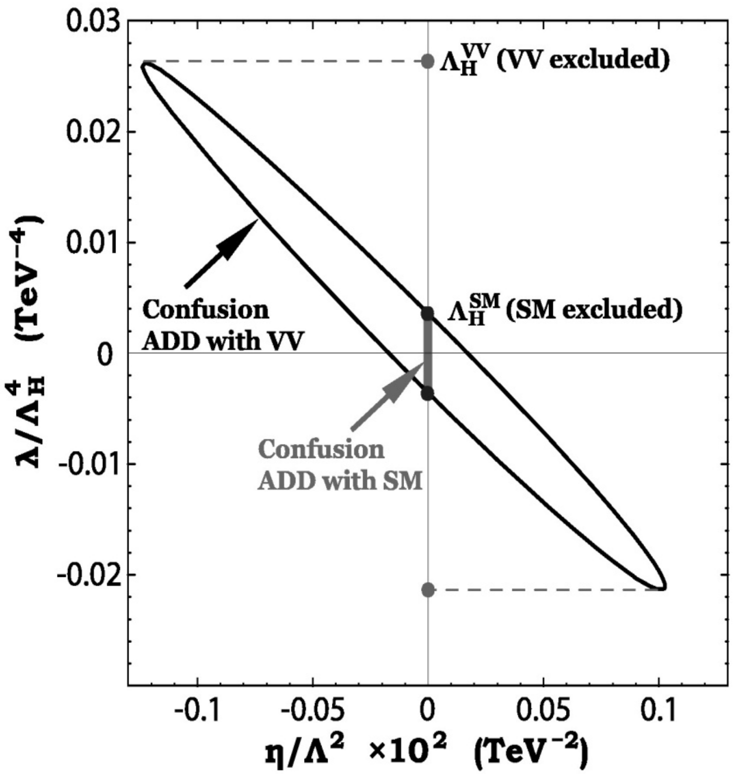
Example: CI=VV (ADD vs. VV)

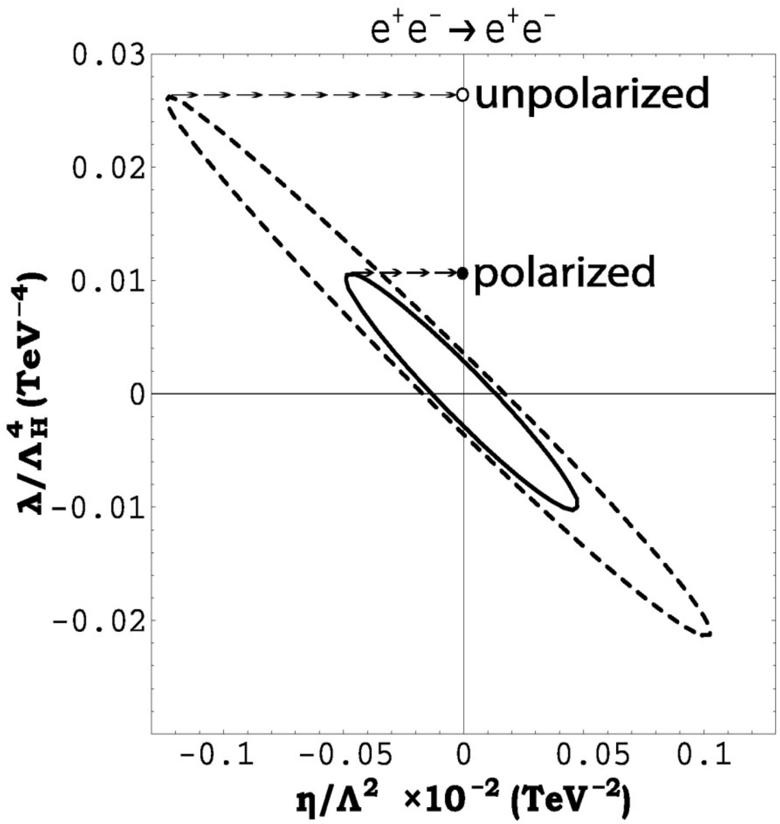


- **Region of confusion** of ADD with VV model determined by:

$$\tilde{\chi}^2(\mathcal{O}) = \sum_{\{P^-,\ P^+\}} \sum_{\text{bins}} \left(\frac{\tilde{\Delta}(\mathcal{O})^{\text{bin}}}{\tilde{\delta}\mathcal{O}^{\text{bin}}} \right)^2 \leq 3.84 \quad (95\%\ \text{C.L.})$$

$\mathcal{L}_{e^+e^-} = 100\ \text{fb}^{-1},\ \sqrt{s} = 0.5\ \text{TeV}.$

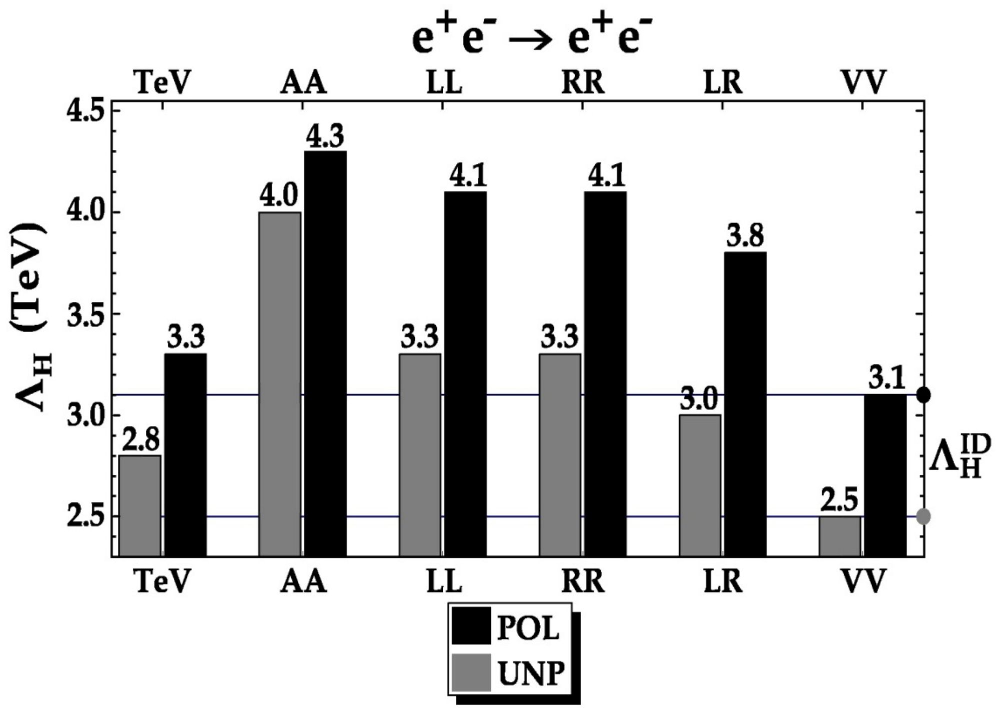


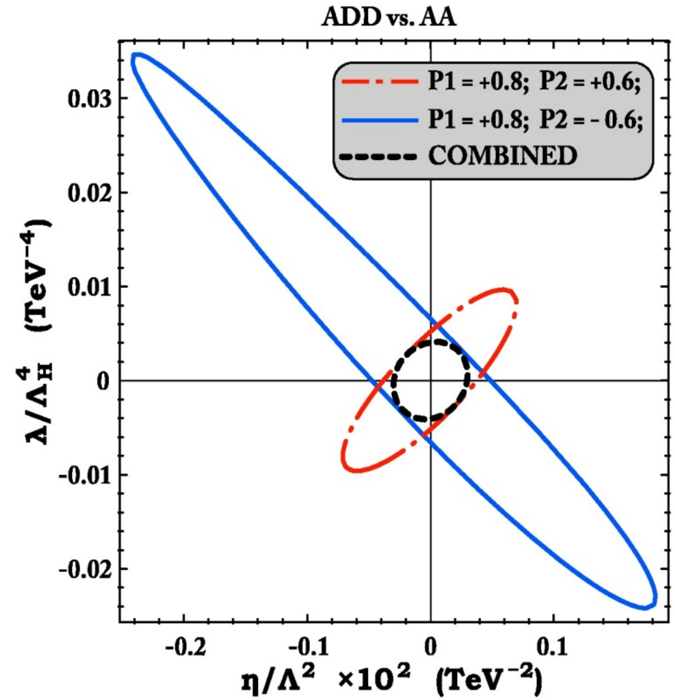


One can find a maximal absolute value of the scale parameter λ/Λ_H^4 for which the VV model hypothesis is expected to be **excluded** at the 95% C.L. for **any value of the CI parameter** η/Λ_{VV}.

We call this $\Lambda_{\rm H}^{\rm VV}$ as **exclusion reach** of the VV model.

ID reach for ADD model (pair-wise comparison)



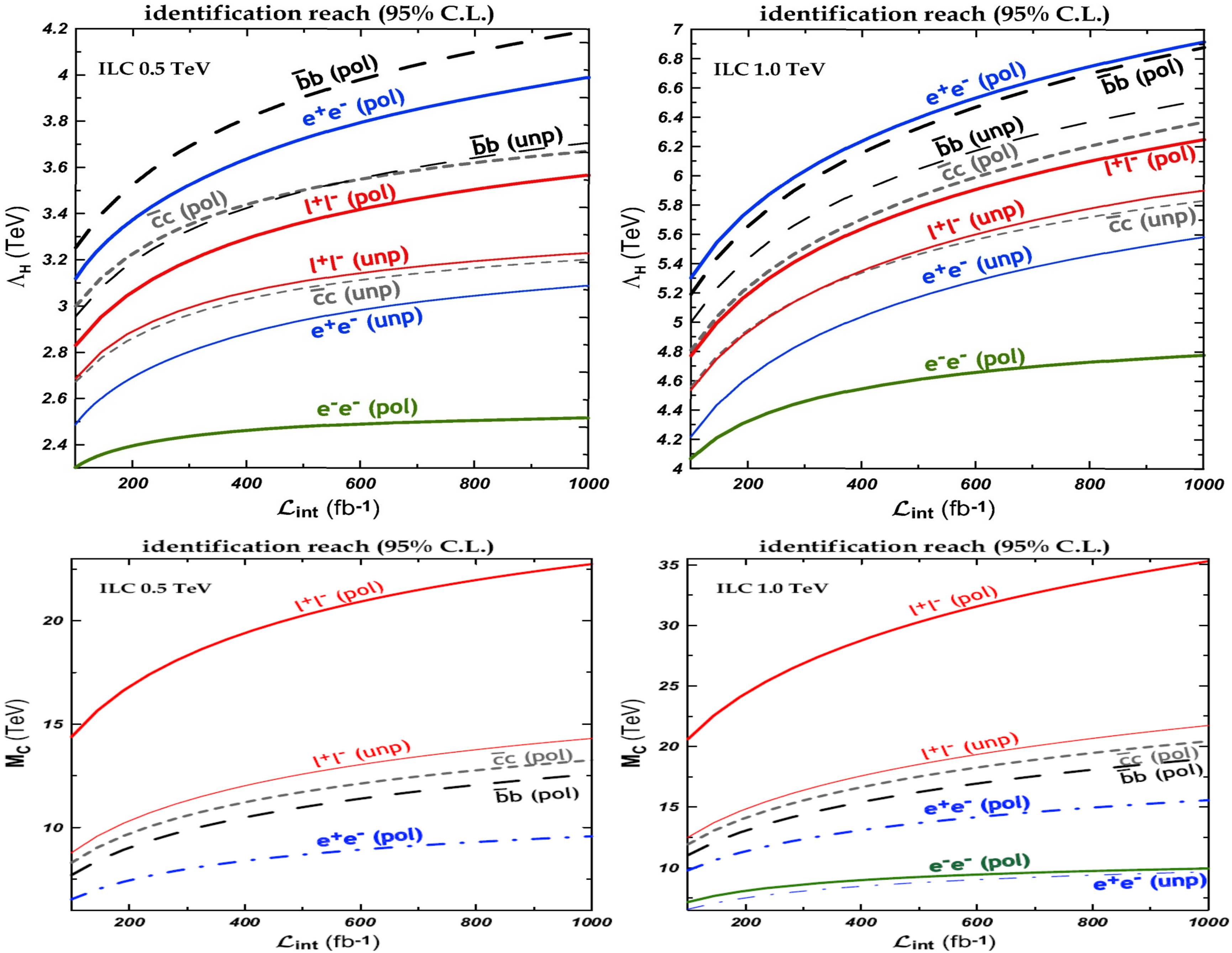


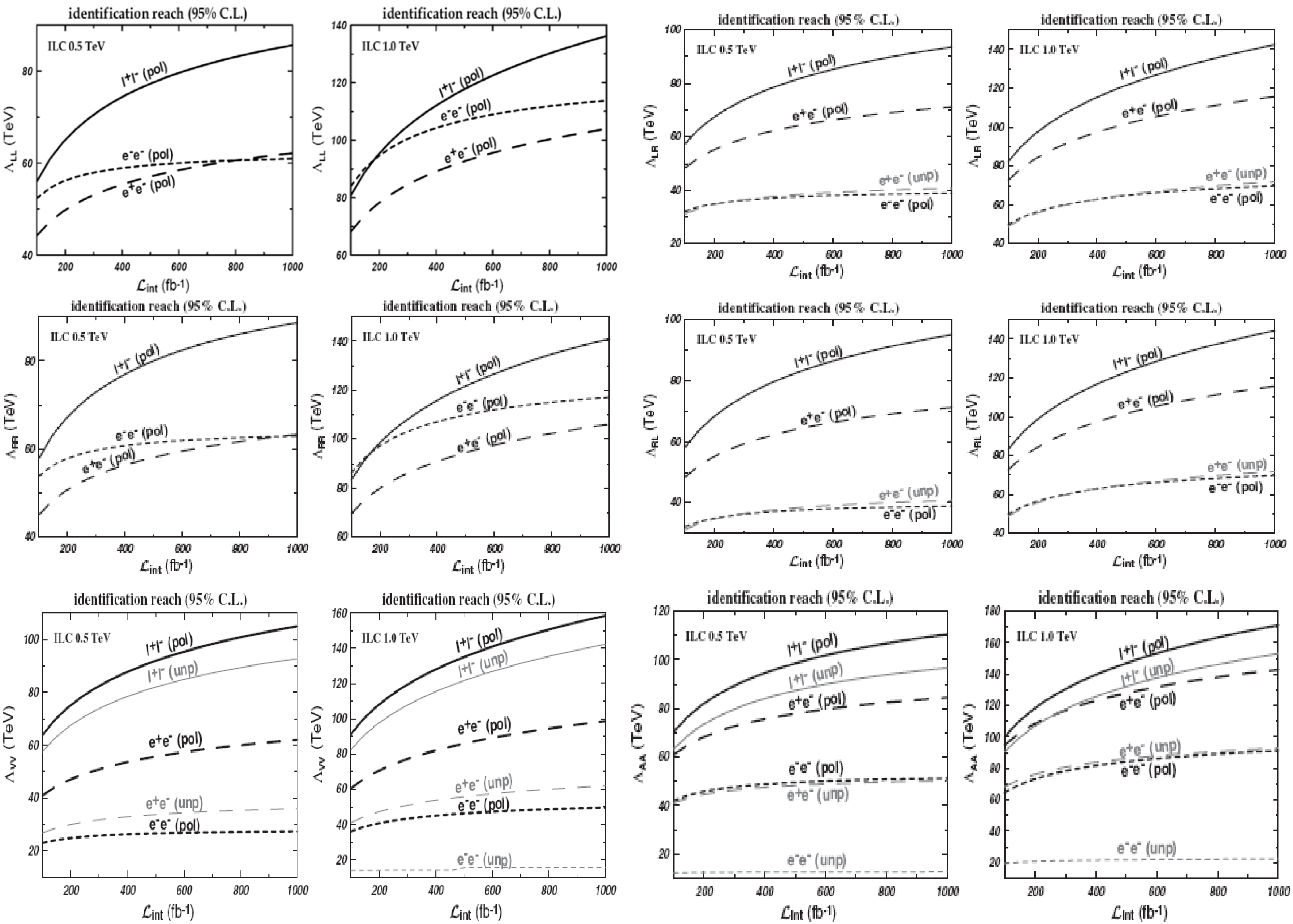
Exclusion reach: Λ_H^{VV}, ...

Identification reach:

$$\Lambda_H^{ID} = min\{\Lambda_H^{VV}, \Lambda_H^{AA}, \Lambda_H^{RR}, \Lambda_H^{LL}, \Lambda_H^{LR}, \Lambda_H^{TeV}\} \to \Lambda_H^{ID} = 2.5(3.1) \text{ TeV.}$$

ID reach for ADD, TeV and CI models




identification reach (95% C.L.)
ILC 0.5 TeV
ILC 1.0 TeV
Λ_{LL} (TeV)
Λ_{LR} (TeV)
Λ_{RR} (TeV)
Λ_{RL} (TeV)
Λ_{VV} (TeV)
Λ_{AA} (TeV)
$\mathcal{L}_{int}$ (fb-1)
l+l- (pol)
l+l- (unp)
e-e- (pol)
e-e- (unp)
e+e- (pol)
e+e- (unp)

Model-independent CI considerations

General case: for given f CI interaction could be any linear combination of individual models $[\Lambda_{\rm LL}, \Lambda_{\rm RR}, \Lambda_{\rm RL}, \Lambda_{\rm LR}]$

All $\Lambda_{\alpha\beta}$ and Λ_H simultaneously in deviation

$$\tilde{\Delta}(\mathcal{O}) = \frac{\mathcal{O}(\Lambda_{LL}, \Lambda_{RR}, \Lambda_{RL}, \Lambda_{LR}) - \mathcal{O}(\Lambda_H)}{\mathcal{O}(\Lambda_H)}; \quad \tilde{\chi}^2(\mathcal{O}) = \sum_{\{P^-,\ P^+\}} \sum_{\rm bins} \left(\frac{\tilde{\Delta}(\mathcal{O})^{\rm bin}}{\tilde{\delta}\mathcal{O}^{\rm bin}} \right)^2 .$$

Confusion region in multi-parameter space:

$$\tilde{\chi}^2 \leq \tilde{\chi}^2_{\rm CL}$$

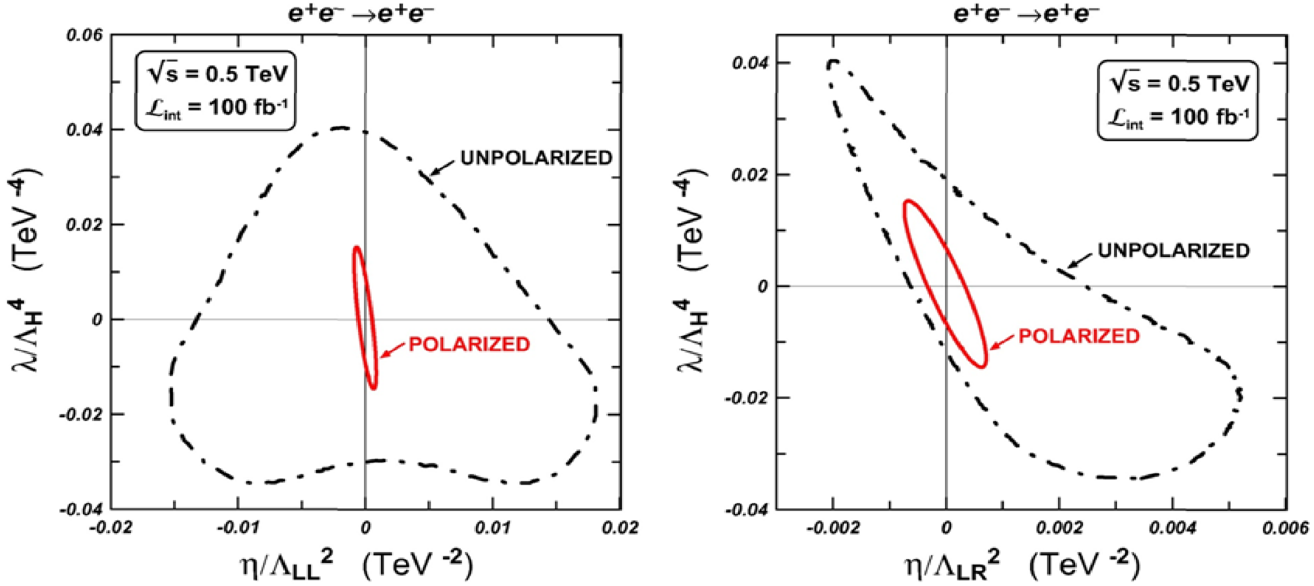
Here, for 95% C.L.:

Bhabha scattering: $\tilde{\chi}^2_{\rm CL} = 7.82$

Annihilation $\bar{f}f$ channels $(f = \mu, \tau, c, b)$: $\tilde{\chi}^2_{\rm CL} = 9.49$

Model-independent ID reach for ADD model

Two-dimensional projection of the 95% C.L. confusion region onto the planes $(\eta_{\rm LL}/\Lambda^2_{\rm LL},\ \lambda/\Lambda^4_H)$ (left panel) and $(\eta_{\rm LR}/\Lambda^2_{\rm LR}\ ,\ \lambda/\Lambda^4_H)$ (right panel) obtained from Bhabha scattering with unpolarized beams (dot-dashed curve) and with both beams polarized (solid curve).



95% CL identification reach on ADD model parameter Λ_H obtained from $e^+e^- \to \bar{f}f$ at two configurations of polarizations: $(|P^+|,|P^-|)$=(0,0) and (0.8, 0.6) respectively.

$\Lambda_H^{\rm ID}$ (TeV)	Process $e^+e^- \to e^+e^-$	$e^+e^- \to l^+l^-$	$e^+e^- \to \bar{c}c$	$e^+e^- \to \bar{b}b$
$\sqrt{s} = 0.5$ TeV, $\mathcal{L}_{\rm int} = 10^2 fb^{-1}$	2.2; 2.9	2.3; 2.3	2.3; 2.4	2.6; 2.9
$\sqrt{s} = 1.0$ TeV, $\mathcal{L}_{\rm int} = 10^3 fb^{-1}$	5.0; 6.4	4.9; 5.1	5.1; 5.3	5.8; 6.2

LHC vs. ILC

Identification reach on Λ_H (in TeV) at 95% C.L. from $p + p \to l^+ l^- + X$ at LHC and from $e^+ e^- \to f \bar{f} \;\; (f = e, \mu, \tau, c, b)$ at ILC.

Collider	Λ_H^+	Λ_H^-
LHC 100 fb^{-1}	4.8	5.0
LHC 300 fb^{-1}	5.4	5.9
ILC(0.5 TeV) 500 fb^{-1}	4.8	
ILC(1 TeV) 1000 fb^{-1}	8.8	

Identification reach on Λ_H obtained from *combination of all final fermions* at ILC.

ILC (0.5 TeV, 500 fb^{-1}) is complementary to LHC (14 TeV, 100 fb^{-1})

ILC (1 TeV, 1 ab^{-1}) allows to improve those bounds obtained at LHC.

ILC with low energy (250 GeV, 350 GeV)

Λ_H > 1.7 TeV

$\Lambda_{\ell\ell qq}$ > **10 TeV**

[CERN-PH-EP-2011-198]

ILC with 100 fb^{-1}

	Λ_H ID pol.
0.25 TeV	2.0 TeV
0.35 TeV	2.6 TeV

	Λ_{CI} ID pol.
0.25 TeV	12 – 55 TeV
0.35 TeV	20 – 70 TeV

LHC 14 TeV, 100 fb^{-1}

Λ_H ~ 5 TeV

- Identification is impossible

Λ_{CI} ~ 20 – 35 TeV

- Improvement of constraints and ID CI is possible

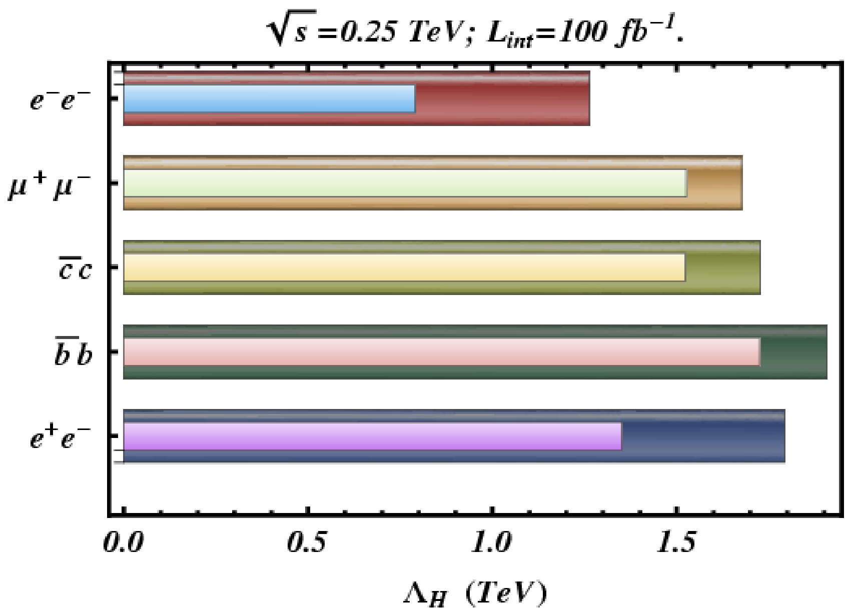
Conclusions

- If New Physics effects are discovered, it is crucial to have good search strategies to determine its origin.

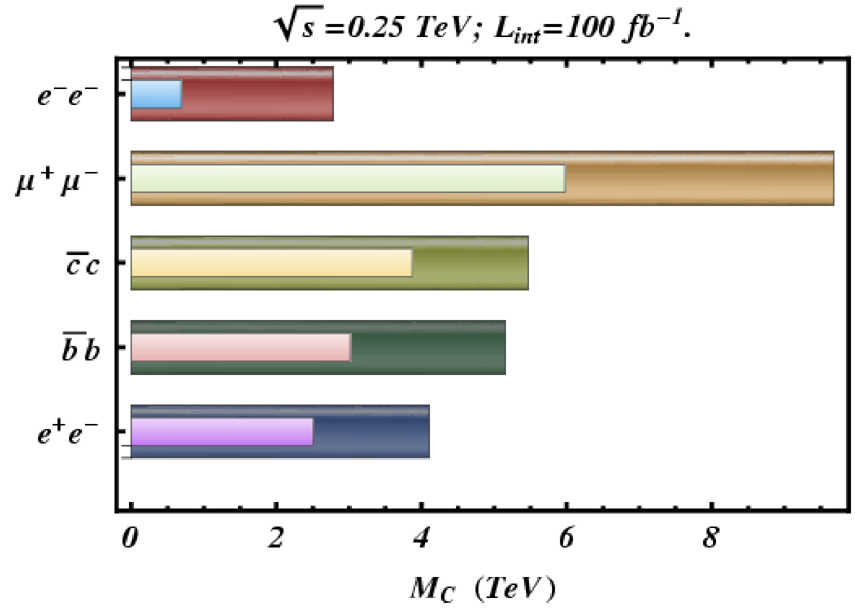
- We have considered the problem of how to distinguish the potential New Physics scenarios from each other at the ILC by using polarized differential distribution for fermion pair production processes.

- Role of e+ e- polarization is quite important.

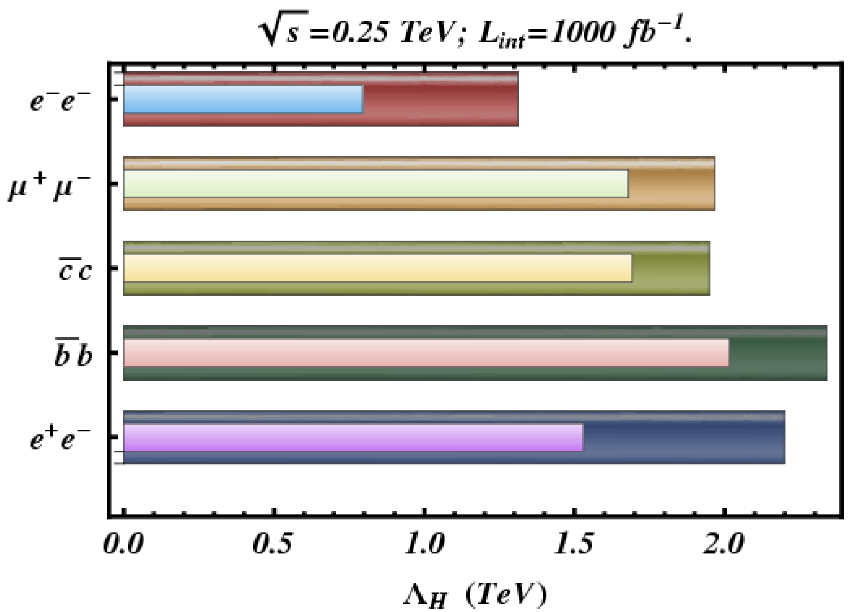
spare transparencies



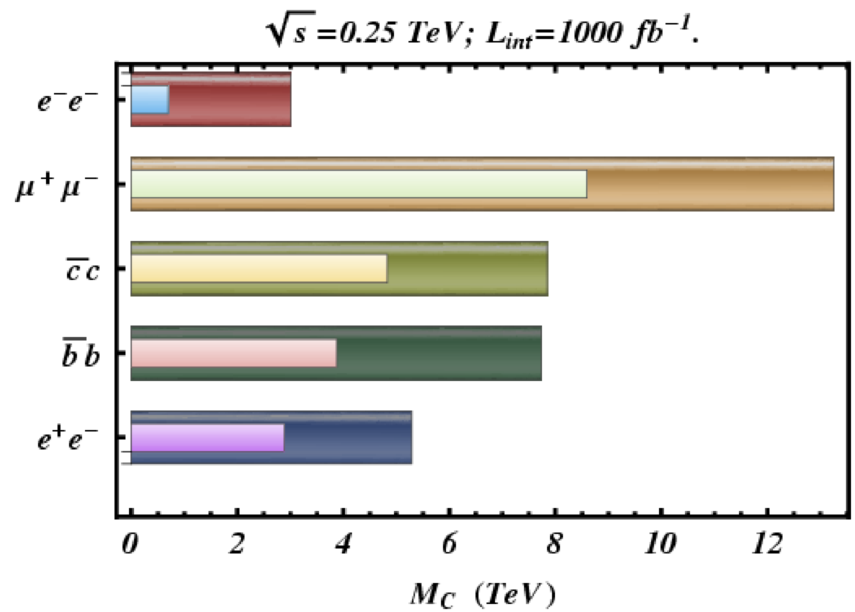
$\sqrt{s}$=0.25 TeV; L_{int}=100 fb^{-1}.
e^-e^-
$\mu^+\mu^-$
$\bar{c}c$
$\bar{b}b$
e^+e^-
0.0
0.5
1.0
1.5
Λ_H (TeV)



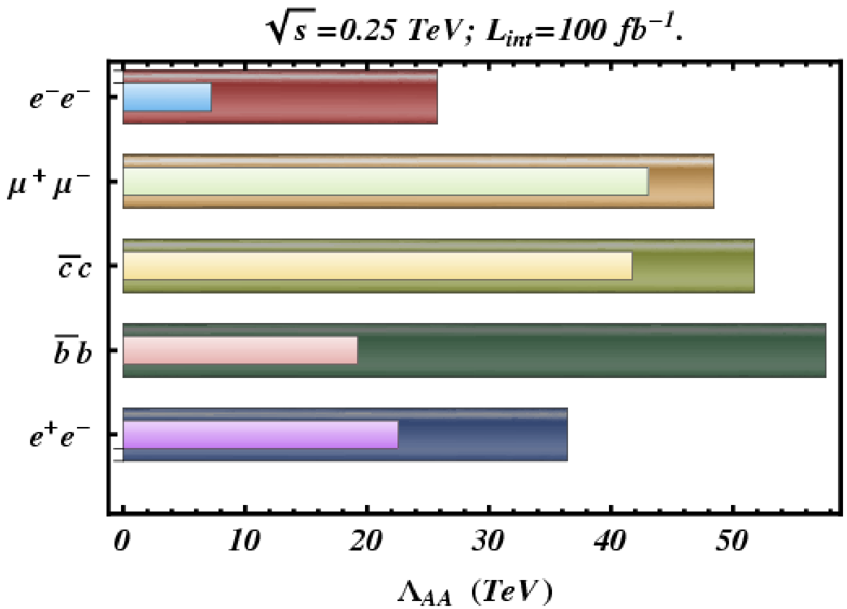
$\sqrt{s}$=0.25 TeV; L_{int}=100 fb^{-1}.
e^-e^-
$\mu^+\mu^-$
$\bar{c}c$
$\bar{b}b$
e^+e^-
0
2
4
6
8
M_C (TeV)



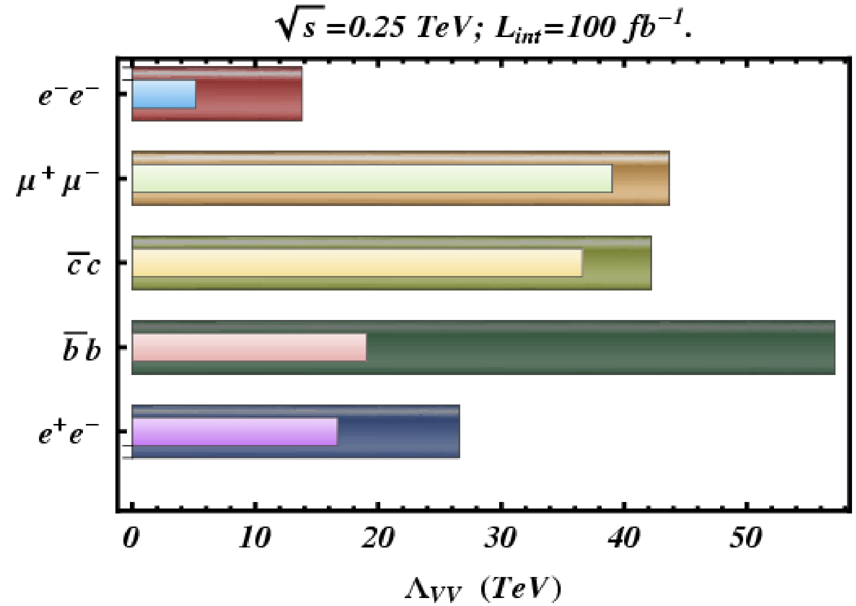
$\sqrt{s}$=0.25 TeV; L_{int}=1000 fb^{-1}.
e^-e^-
$\mu^+\mu^-$
$\bar{c}c$
$\bar{b}b$
e^+e^-
0.0
0.5
1.0
1.5
2.0
Λ_H (TeV)



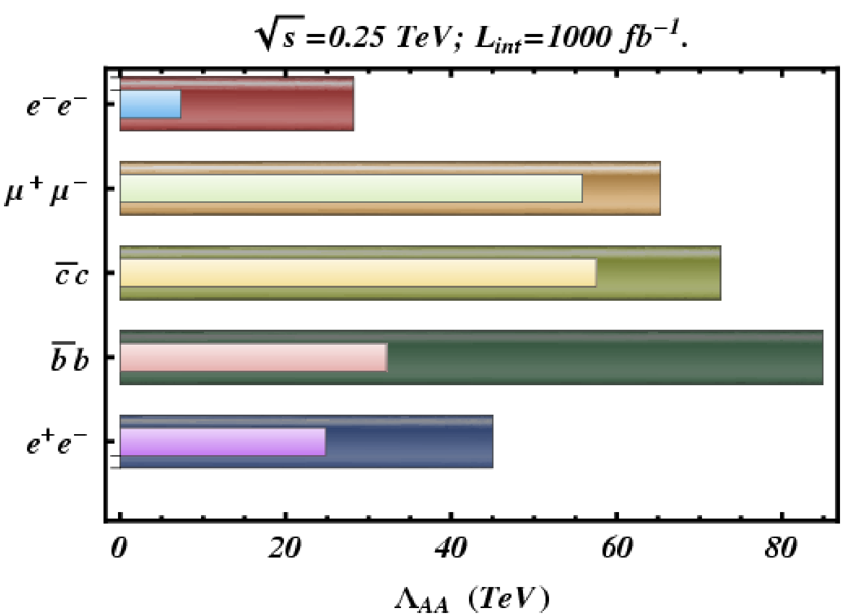
$\sqrt{s}$=0.25 TeV; L_{int}=1000 fb^{-1}.
e^-e^-
$\mu^+\mu^-$
$\bar{c}c$
$\bar{b}b$
e^+e^-
0
2
4
6
8
10
12
M_C (TeV)



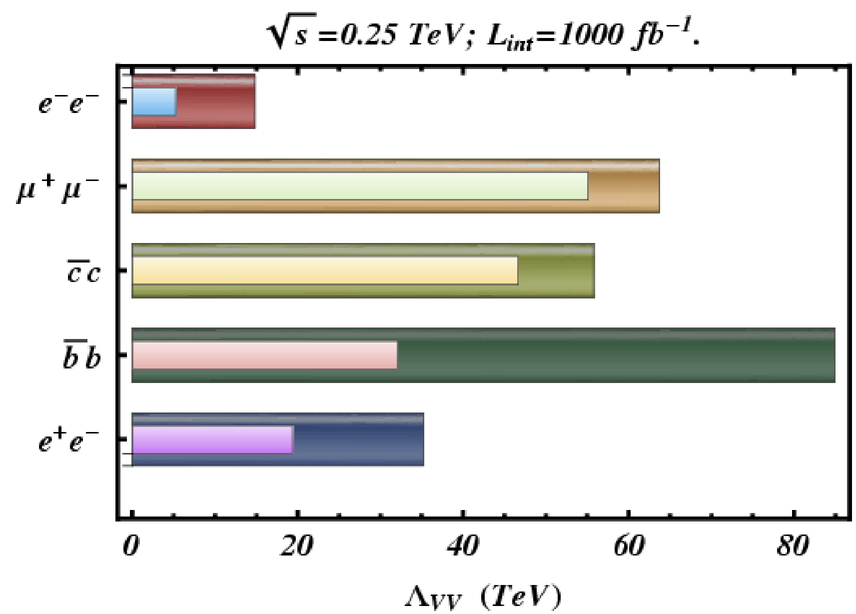
$\sqrt{s}$=0.25 TeV; L_{int}=100 fb^{-1}.
e^-e^-
$\mu^+\mu^-$
$\bar{c}c$
$\bar{b}b$
e^+e^-
0
10
20
30
40
50
Λ_{AA} (TeV)



$\sqrt{s}$=0.25 TeV; L_{int}=100 fb^{-1}.
e^-e^-
$\mu^+\mu^-$
$\bar{c}c$
$\bar{b}b$
e^+e^-
0
10
20
30
40
50
Λ_{VV} (TeV)



$\sqrt{s}$=0.25 TeV; L_{int}=1000 fb^{-1}.
e^-e^-
$\mu^+\mu^-$
$\bar{c}c$
$\bar{b}b$
e^+e^-
0
20
40
60
80
Λ_{AA} (TeV)



$\sqrt{s}$=0.25 TeV; L_{int}=1000 fb^{-1}.
e^-e^-
$\mu^+\mu^-$
$\bar{c}c$
$\bar{b}b$
e^+e^-
0
20
40
60
80
Λ_{VV} (TeV)