Identifying contactlike effective interactions at polarized ILC

N. Paver
University of Trieste & INFN-Sezione, Trieste, Italy

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with *A.A. Pankov* & *A.V. Tsytrinov* (ICTP Affiliated Centre, Gomel, Belarus)

Introduction

A Plethora of *New Physics* (NP) beyond the SM [conceptual problems]
It is generally expected that NP will manifest itself at future colliders either:

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

- **indirectly** through *deviations* of observables from SM predictions: typical case of NP interactions mediated by *heavy quanta exchanges* [$\Lambda \gg M_{W,Z}$] when collider energy is below production threshold.

In the case of **indirect** discovery, different NP scenarios may cause the same or similar experimental deviations.
Need for strategies to identify the source of corrections to SM predictions.

Proposed techniques:

- Monte Carlo-based analysis
  (*G. Pasztor, M. Perelstein*, hep-ph/0111471)

- Integrated cross sections weighted by Legendre polynomials
  (*T. Rizzo*, JHEP 0210 (2002))

- polarized Center–Edge Asymmetries [spin-1 *vs.* spin-2 exchange]
  (*P. Osland, N. Paver, A.A. Pankov*, Phys. Rev. D**68** (2003);
  A.A. Pankov, N. Paver, Phys. Rev. D **72** (2005))

- here: **combined χ^2 analysis of longitudinally polarized differential cross sections** for $e^+e^- \to \bar{f}f$
  (*A.A. Pankov, N. Paver, A.V. Tsytrinov*, Phys. Rev. D **73** (2006), hep-ph/0608285 and work in progress)

Outline

Phenomenology at the International Linear Collider (ILC) with e^- and e^+ polarized beams $\mathrm{E}_{\mathrm{C.M.}} = 0.5 - 1\,\mathrm{TeV}$,
(see G.Moortgat-Pick et al., hep-ph/0507011)

- Fermion pair production:
  $e^+e^- \to l^+l^-$ $(l = e, \mu, \tau)$;
  $e^+e^- \to \bar{q}q$ $(q = c, b)$
- observables: polarized differential cross sections ($\mathrm{d}\sigma_{\mathrm{LL}}$, $\mathrm{d}\sigma_{\mathrm{RR}}$, $\mathrm{d}\sigma_{\mathrm{RL}}$, $\mathrm{d}\sigma_{\mathrm{LR}}$)
- individual NP scenarios
- sensitivity to Λ's
- rôle of beam polarization for identification reach enhancement

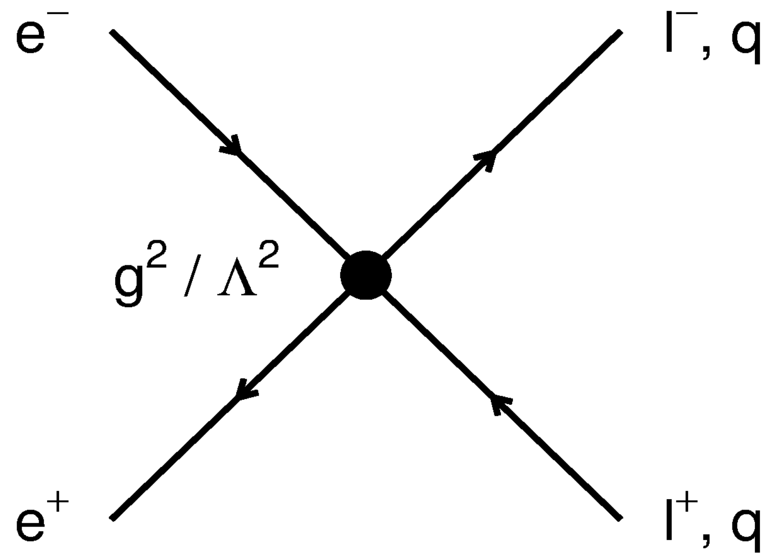
Nonstandard Scenarios

- Framework of effective Lagrangians (expansion in s/Λ^2)

- **CI**: Four-fermion contact interactions [compositeness]:

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

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

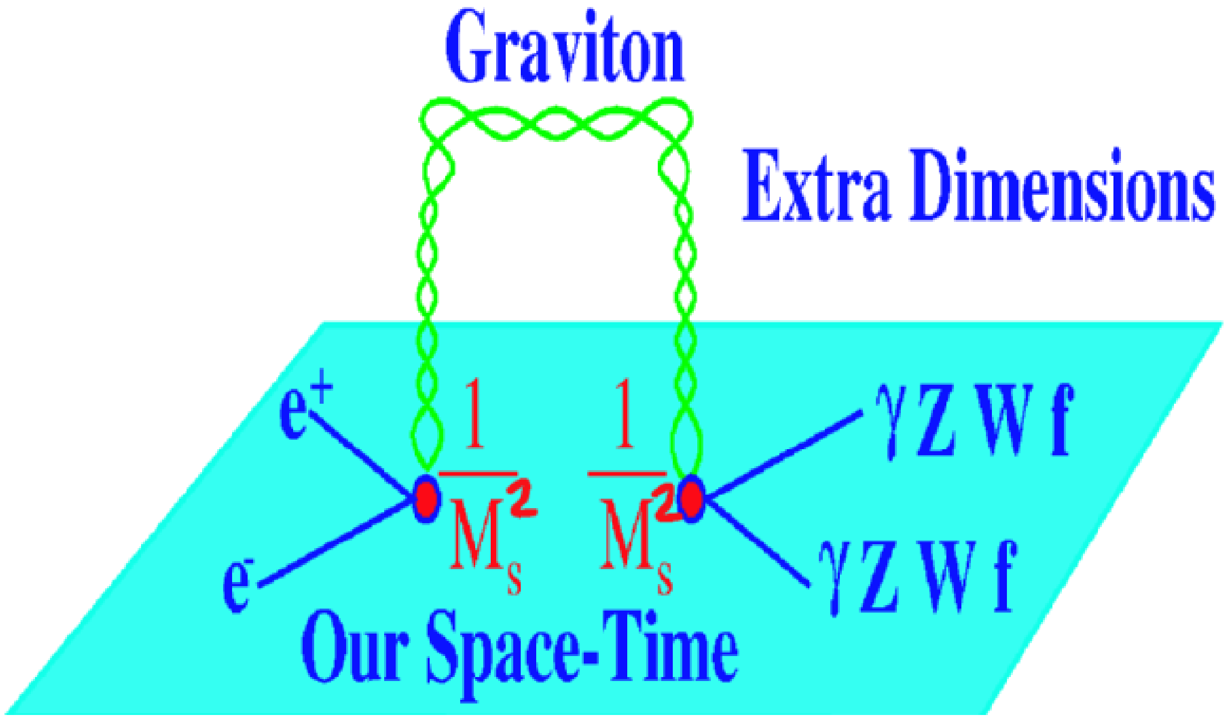


- Can describe also exchanges of heavy Z', W', Leptoquarks, *etc.*

- Current limits on "compositeness scales" [Tevatron, LEP]:
$\Lambda > 10 - 20\,{\rm TeV}$

- **ADD**: Gravity in "large" compactified extra dimensions (gauge hierarchy)

Gravity only can propagate in the full 4+N space



Effective Planck mass M_* *vs.* compactification radius R and Newton constant (M_{PL}):

$$M_{\mathrm{PL}}(10^{16}\,\mathrm{TeV}) = M_*^{(1+N/2)} R^{(N/2)}$$

For $N \geq 2$, $R \leq \mathrm{mm}$: $M_* \sim \mathrm{TeV}$ (standard model cut-off)

In the 4-dimensional space: virtual exchange of tower of spin-2 massive graviton KK excitations (spectrum spaced by $1/R$).

Effective (contactlike) Lagrangian ($Hewett$ convention):

$$\mathcal{L}^{\mathrm{ADD}} = i\frac{4\lambda}{\Lambda_H^4} T^{\mu\nu} T_{\mu\nu}, \qquad \lambda = \pm 1$$

$T_{\mu\nu}$: energy-momentum tensor of SM particles

Λ_H: cut-off scale on KK summation (expected of TeV size).

Current lower limit: $\Lambda_H > 1.3\,\mathrm{TeV}$

- 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:

$$\mathcal{L}^{\mathrm{TeV}} = -\frac{\pi^2}{3M_C^2}\left[Q_e Q_f (\bar{e}\gamma_\mu e)(\bar{f}\gamma^\mu f) + \right.$$

$$\left. +(g_{\mathrm{L}}^e \bar{e}_{\mathrm{L}}\gamma_\mu e_{\mathrm{L}} + g_{\mathrm{R}}^e \bar{e}_{\mathrm{R}}\gamma_\mu e_{\mathrm{R}}) \times (g_{\mathrm{L}}^f \bar{f}_{\mathrm{L}}\gamma^\mu f_{\mathrm{L}} + g_{\mathrm{R}}^f \bar{f}_{\mathrm{R}}\gamma^\mu f_{\mathrm{R}})\right].$$

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

  Current limit [LEP2]: $M_C > 6.8\,\mathrm{TeV}$

Discovery reaches on Models

- $d\sigma \propto |\mathrm{SM} + \mathrm{NewPhysics}|^2$

- **Deviations** of observables from the SM predictions:

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

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

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

- Assumption: no deviation from the SM is observed within the experimental accuracy.

- Constraints on Λ_H, Λ's [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;
$\delta P^\pm/P^\pm = 0.2\%$, $\delta\mathcal{L}_{\rm int}/\mathcal{L}_{\rm int} = 0.5\%$.

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.*

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. $\sqrt{s} = 1.0$ TeV, $\mathcal{L}_{\rm int} = 1000 fb^{-1}$

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	8.7; 9.4	6.7; 7.0	6.7; 7.5	6.7; 7.1
Λ_{VV}^{ef}	173.6; 205.1	218.8; 244.3	185.6; 238.2	206.2; 232.3
Λ_{AA}^{ef}	109.9; 166.1	194.7; 217.9	186.; 242.7	186.4; 210.8
Λ_{LL}^{ef}	83.7; 122.8	128.3; 165.5	154.5; 175.8	131.3; 159.6
Λ_{RR}^{ef}	80.5; 122.1	123.4; 166.1	103.5; 176.9	111.8; 164.1
Λ_{LR}^{ef}	136.6; 166.8	120.5; 156.6	124.9; 170.2	92.7; 144.6
Λ_{RL}^{ef}	$\Lambda_{RL}^{ee} = \Lambda_{LR}^{ee}$	120.8; 158.3	120.1; 151.9	129.6; 151.1
M_C	27.2; 32.5	48.3; 54.2	15.6; 26.5	26.2; 30.2

Distinction among the New Physics models

- expected identification reaches

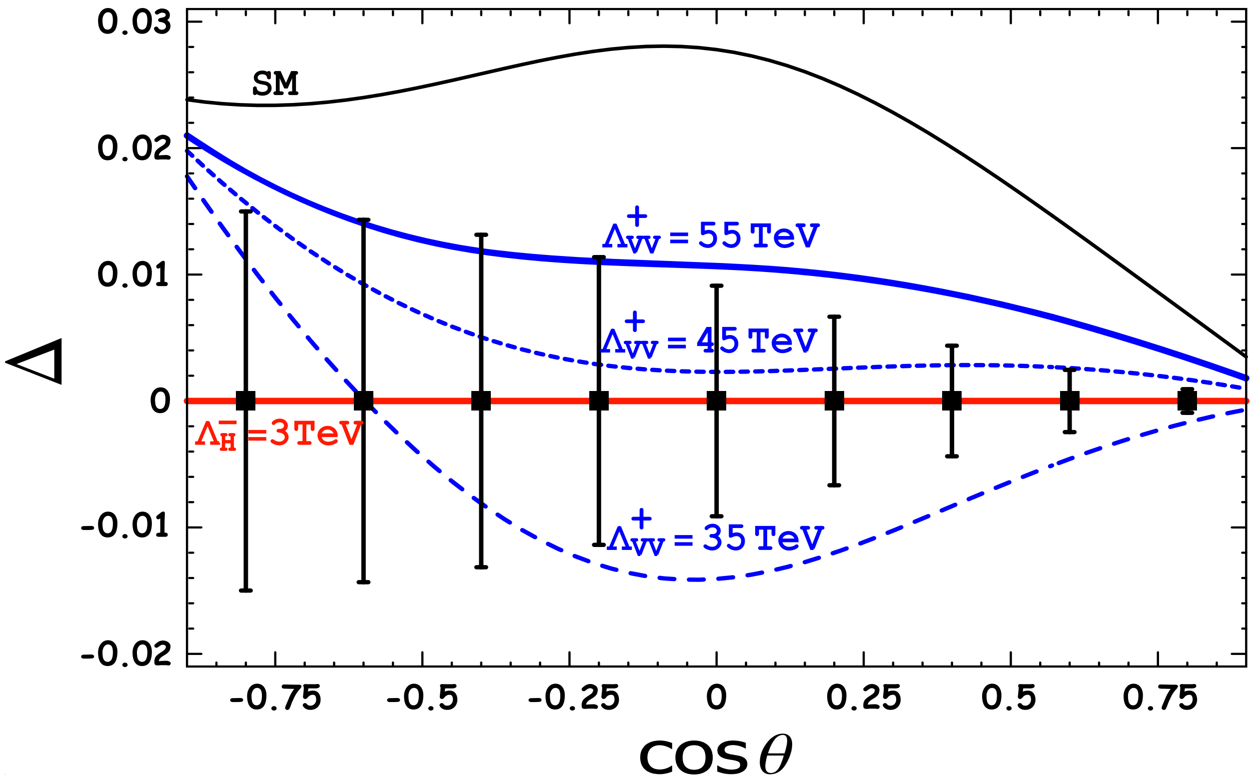
- Assumption: One of the models, say the ADD, is found consistent with experimental data with some value of Λ_H

- 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

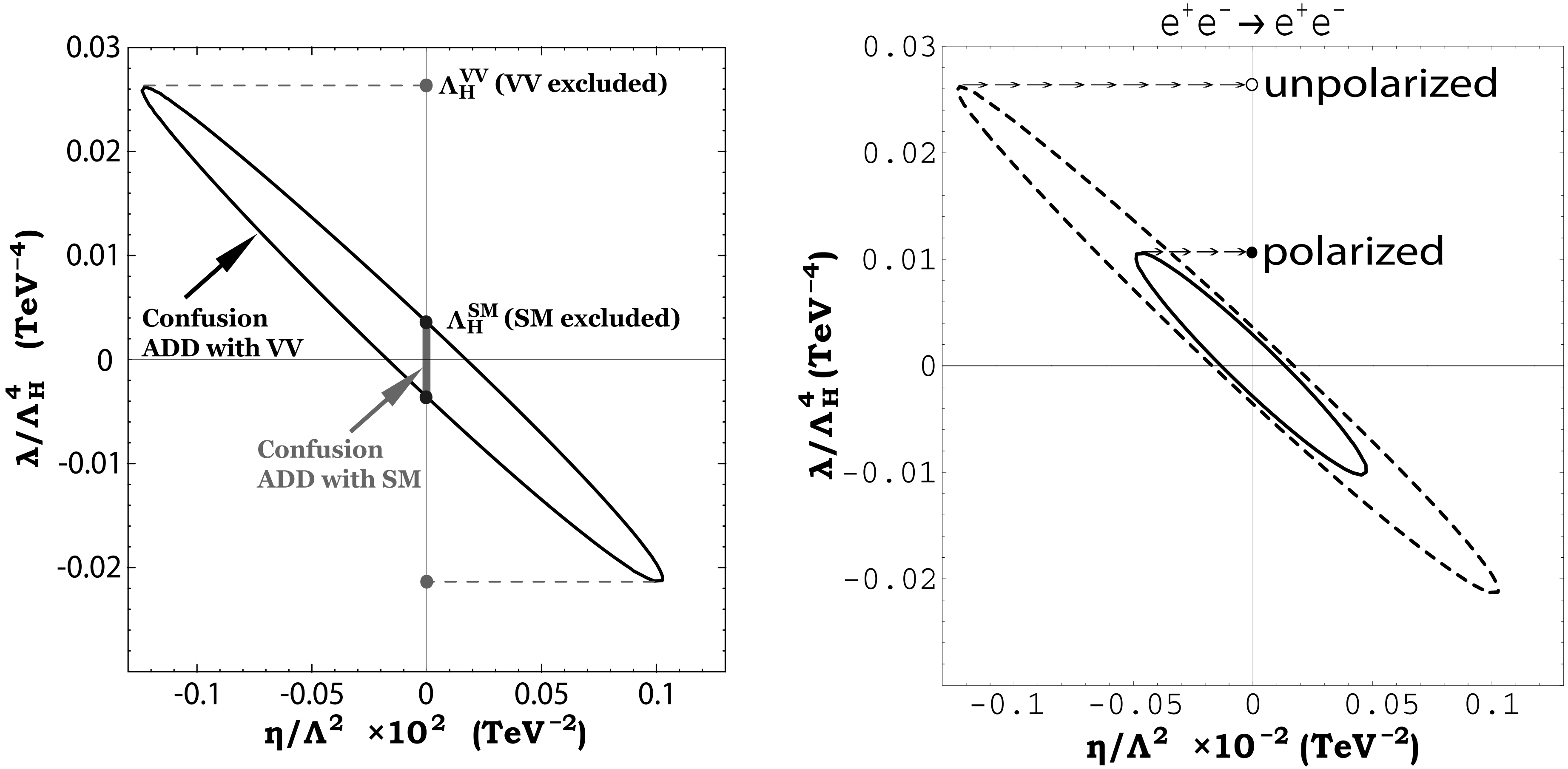
Example: CI=VV (ADD vs. VV)



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

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

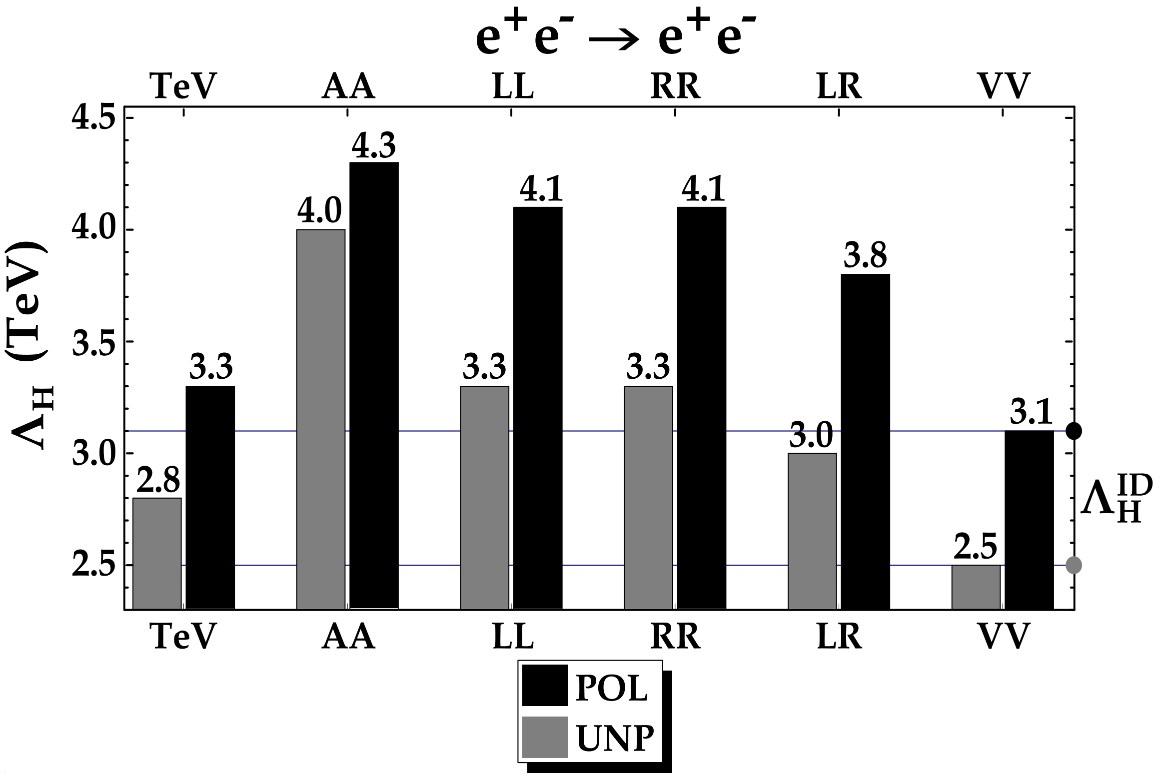
$$\mathcal{L}_{e^+e^-} = 100 \text{ fb}^{-1}, \sqrt{s} = 0.5 \text{ TeV}.$$

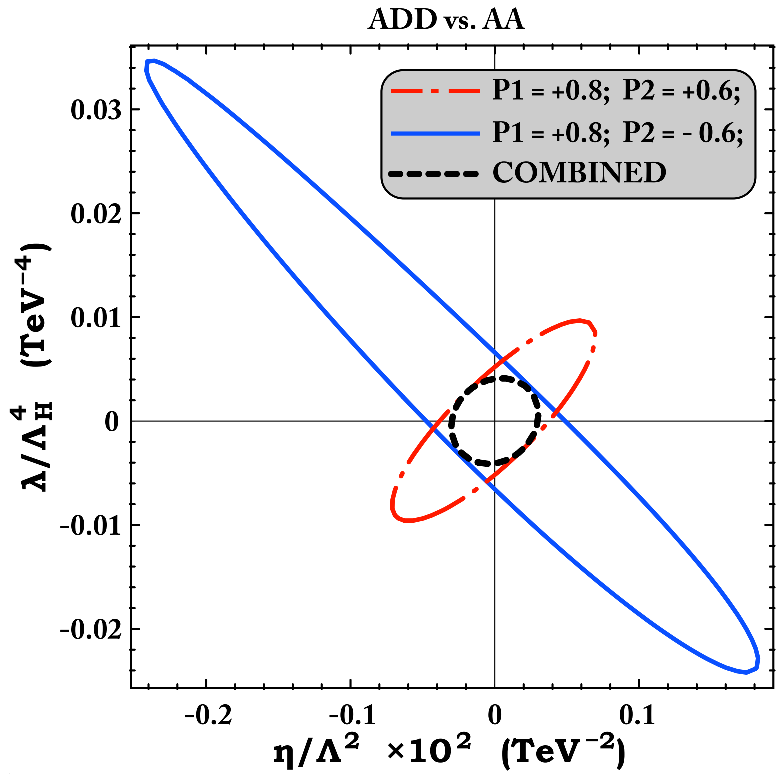


One can find a maximal absolute value of the scale parameter λ/Λ_H^4 for which the VV model hypothesis is expected to be **excluded** at the 95% C.L. for **any value of the CI parameter** η/Λ_{VV}.

We call this Λ_H^{VV} as **exclusion reach** of the VV model.

ID reach for ADD model





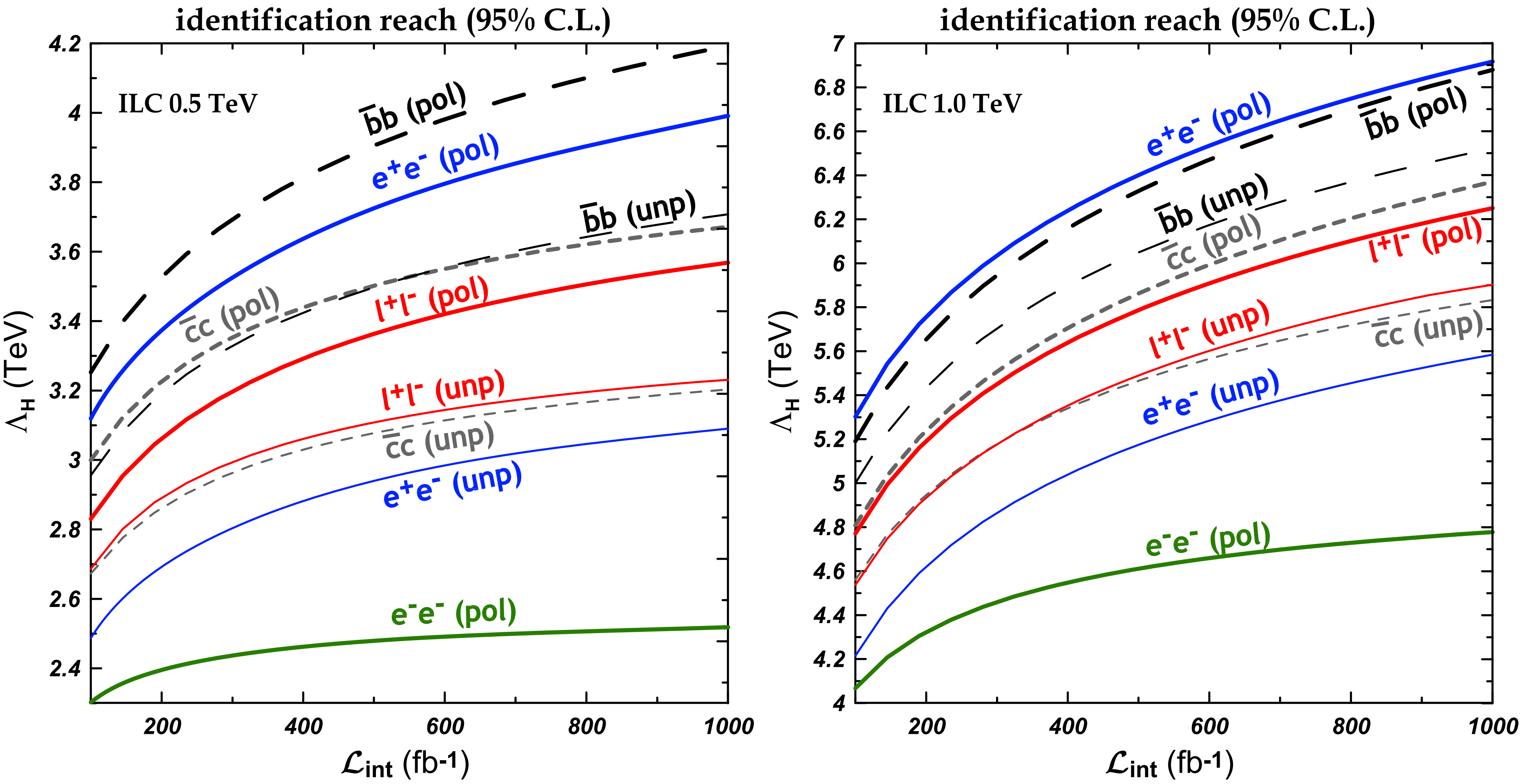
Exclusion reach: Λ_H^{VV}, ...

Identification reach:

$$\Lambda_H^{\mathrm{ID}} = min\{\Lambda_H^{\mathrm{VV}}, \Lambda_H^{\mathrm{AA}}, \Lambda_H^{\mathrm{RR}}, \Lambda_H^{\mathrm{LL}}, \Lambda_H^{\mathrm{LR}}, \Lambda_H^{\mathrm{TeV}}\}$$

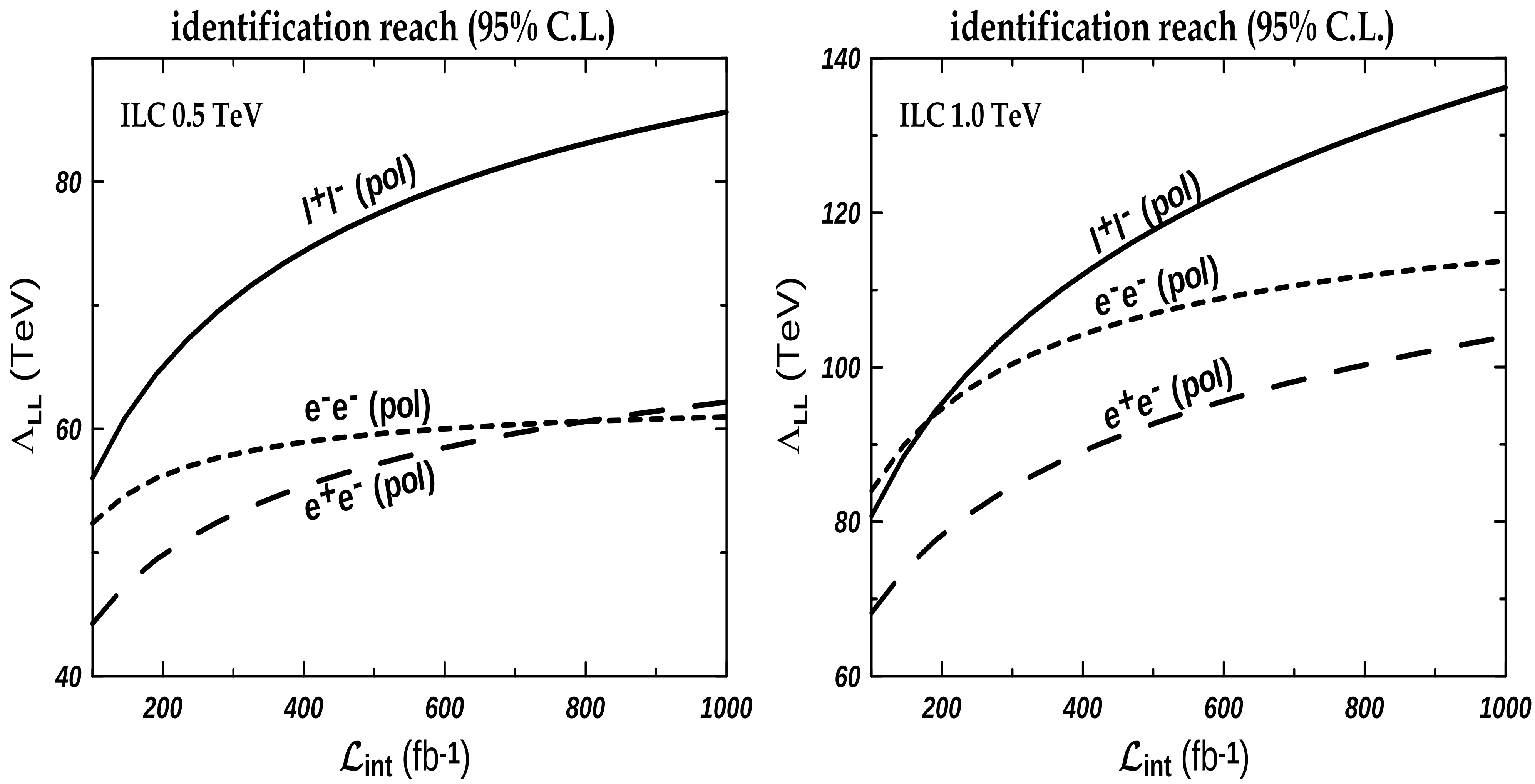
$\rightarrow \Lambda_H^{\mathrm{ID}} = 2.5(3.1)$ TeV.

ID reach for ADD model



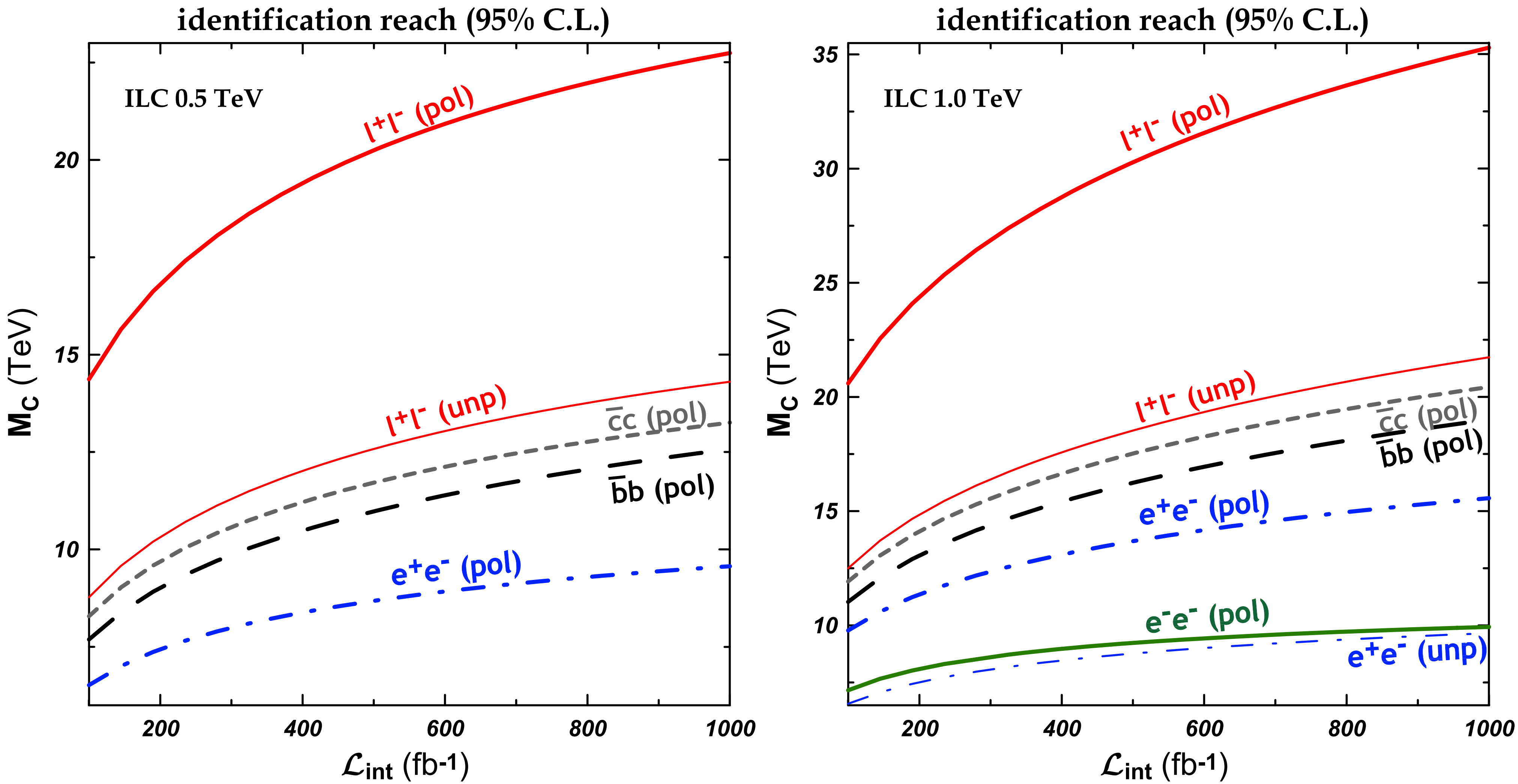
Current limit: $\Lambda_H > 1.3$ TeV

ID reach for CI models



Current limit: $\Lambda_{LL} > 15$ TeV

ID reach for TeV^{-1} model



Current limit: $\mathrm{M_C} > 6.8$ TeV

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

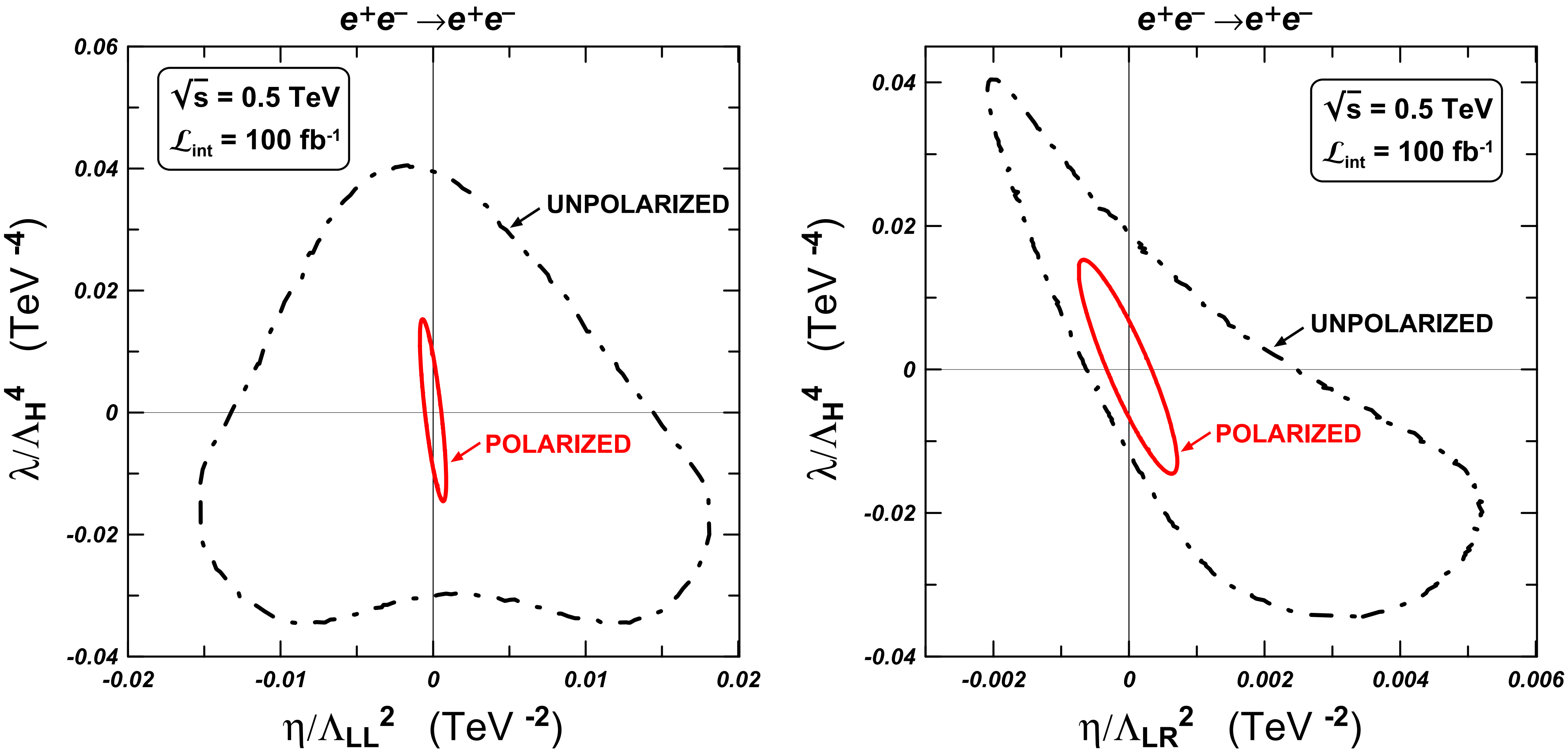
$$\tilde{\Delta}(\mathcal{O}) = \frac{\mathcal{O}(\Lambda_{LL}, \Lambda_{RR}, \Lambda_{RL}, \Lambda_{LR}) - \mathcal{O}(\Lambda_H)}{\mathcal{O}(\Lambda_H)}; \quad \tilde{\chi}^2(\mathcal{O}) = \sum_{\{P^-,\ P^+\}} \sum_{\rm bins} \left(\frac{\tilde{\Delta}(\mathcal{O})^{\rm bin}}{\tilde{\delta}\mathcal{O}^{\rm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

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

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).



Model-independent ID reach for ADD model

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.

Λ_H^{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, $\mathcal{L}_{\mathrm{int}} = 10^2 fb^{-1}$	2.2; 2.9	2.3; 2.3	2.3; 2.4	2.6; 2.9
$\sqrt{s} = 1.0$ TeV, $\mathcal{L}_{\mathrm{int}} = 10^3 fb^{-1}$	5.0; 6.4	4.9; 5.1	5.1; 5.3	5.8; 6.2

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.

- Identification reach (95% CL) depending on the ILC energy and luminosity:

  - ADD:
    $\Lambda_H = 3.1 - 6.9$ TeV (model dependent cosideration)
    $\Lambda_H = 2.9 - 6.4$ TeV (model independent cosideration)
  - TeV^{-1}: $M_C = 15 - 35$ TeV
  - VV: $\Lambda_{VV} = 62 - 160$ TeV
  - AA: $\Lambda_{AA} = 70 - 170$ TeV
  - LL: $\Lambda_{LL} = 55 - 135$ TeV
  - RR, LR and RL: $\Lambda = 57 - 142$ TeV

- Polarization is quite important, in particular in case of CI models.