

Uses of Transversely Polarized e^+e^- Colliding Beams to Uncover New Physics

(JHEP 02 (2003) 008)

- 'Transverse' polarization? Why?
 - Potential for NP study - unexplored
 - Sensitivity to special NP types -
Extra Dimensions, Anomalous Couplings...
 - Background, Analyses + reaches
→ Comparisons
 - Outlook + Conclusions
- ⇒ Spin rotators with near 100% efficiency can take longitudinally polarized beams + make them transversely polarized ... SO?

T. Rizzo
3/03

Consider

$e^+e^- \rightarrow \bar{f}f, W^+W^-$ are the dominant processes at the LC ... Symbolically, the spin (final) averaged matrix elements (squared) can be written as :

(Σ -symbols suppressed here)

$$|\overline{\mathcal{M}}|^2 = \frac{1}{4}(1 - P_L P'_L)(|T_+|^2 + |T_-|^2) + (P_L - P'_L)(|T_+|^2 - |T_-|^2) + (2P_T P'_T)[\cos 2\phi \operatorname{Re}(T_+ T_-^*) - \sin 2\phi \operatorname{Im}(T_+ T_-^*)],$$

- $P_{L,T}$ are the e^- (e^+) longitudinal + transverse polarizations
- T_{\pm} = complex helicity amplitudes $\begin{cases} T_+ = M_{+-} \\ T_- = M_{-+} \end{cases}$
- ϕ = \angle between e^- polarization + plane of final state particles

\Rightarrow \boxed{IF} $P_T^{(\prime)} = 0$ only $|T_{\pm}|^2$ can be probed by experiment:

$$\textcircled{\sigma} \sim |T_+|^2 + |T_-|^2, \quad \textcircled{A_{LR}} = \frac{|T_+|^2 - |T_-|^2}{|T_+|^2 + |T_-|^2}$$

BUT

IF P_T, P_T' both are $\neq 0$

\rightarrow $\text{Re}, \text{Im}(T_+ T_-^*)$ probed.

{ Note unlike A_{LR} , we need Both beams
polarized to form asymmetries
(for A_{LR} , $P_L' = 0$ is ok) $\left. \begin{array}{l} \text{A} \\ \text{unique} \\ \text{reason for 2} \\ \text{beam polarization} \end{array} \right\}$

IF $P_T^{(1)}$ were available, what New Physics
BSM can be probed using transverse
polarization asymmetries ??

GOAL : Discovery new physics ...

IDENTIFY IT ... (Model ?)

Explore IT in all detail ...

The more tools, the better we will do !

Over the years, very little work has been done on e^+e^- collisions
w/ transverse polarized beams both in the SM +
BSM:

R. Budny, Phys. Rev. **D14**, 2969 (1976); H.A. Olsen, P. Osland and L. Overbo, Phys. Lett. **B97**, 286 (1980); K. Hikasa, Phys. Rev. **D33**, 3203 (1986); C.P. Burgess and J.A. Robinson, Int. J. Mod. Phys. **A6**, 2709 (1991); A. Djouadi, F.M. Renard and C. Verzegnassi, Phys. Lett. **B241**, 260 (1990); F.M. Renard, Z. Phys. **C44**, 75 (1989); J.L. Hewett and T.G. Rizzo, Z. Phys. **C44**, 75 (1987) and Z. Phys. **C36**, 209 (1987); J. Fleischer, K. Kolodziej and F. Jegerlehner, Phys. Rev. **D49**, 2174 (1994); for a recent discussion of this option at the LC, see K. Desch, talk given at the International Workshop on the Linear Collider, LCWS2002, Jeju Island, Korea, Aug. 2002.

Here we will ask if P_T helps to probe for New Physics
(exchange) in $e^+e^- \rightarrow f\bar{f}, \dots$ etc

(Yes!)

- Unexplored

If we are lucky NP will be seen directly
by new particle production, e.g. SUSY

- But, perhaps, NP will be indirectly observed through deviations in σ , asymmetries... etc revealed by precision measurements: LC

e.g., Contact interactions

- Lots of NP \rightarrow CI's : \Leftrightarrow Mass Scale

$\left(\begin{array}{l} \Lambda \\ m_{\tilde{g}} \\ M_{Z'} \\ M_c \\ m_{LQ} \\ M_H \end{array} \right)$	•	Compositeness (spin-1)	
	•	\tilde{g} Exchange, SUSY \cancel{X}	(spin-0)
	•	Z'	(spin-1)
	•	gauge KK	(spin-1)
	•	LQ / BL	
	•	Gravity in Extra dims	$\left\{ \begin{array}{l} ADD^* \\ RS^\dagger \end{array} \right.$

* Arkani-Hamed, Dimopoulos + Dvali - many small resonances $> 10^6$ GeV

† Randall - Sundrum ~ ^{big} resonances with ~100's of GeV separation

Consider $e^+e^- \rightarrow f\bar{f}$ ($m_f=0$)

- We can easily obtain all the amplitudes in the SM $\{ Z', \text{ gauge KK, cont. int. } \dots \}$ and in the ADD case

→ When spin-2 is present, the amplitudes contain higher powers of $z = \cos\theta$ than in the case of the SM, Z', \dots Unique

Transverse Polarization Asymmetry :

$$\frac{1}{N} \frac{dA}{dz} = \frac{\int_+ \frac{d\sigma}{dzd\phi} - \int_- \frac{d\sigma}{dzd\phi}}{\int_{\text{all}} d\sigma} \leftarrow \text{note}$$

(\int_{\pm} = integrate regions where $\cos 2\phi$ is \pm)

isolates the $\text{Re}(T_+ T_-^*)$ part of $|\bar{M}|^2$

(These are small #'s - normalized to full σ !)
(not unique!)

charges \downarrow Z -couplings $\downarrow \downarrow$

$$\left. \begin{aligned} f_{LL} &= Q_e Q_f + g_Z (v_e - a_e)(v_f - a_f) P \\ f_{LR} &= Q_e Q_f + g_Z (v_e + a_e)(v_f + a_f) P \\ f_{RL} &= Q_e Q_f + g_Z (v_e - a_e)(v_f + a_f) P \\ f_{RR} &= Q_e Q_f + g_Z (v_e + a_e)(v_f - a_f) P \end{aligned} \right\} + \dots$$

Weak Coupling

$$g_Z = \frac{G_F M_Z^2}{2\sqrt{2}\pi\alpha}$$

Z -prop.

$$P = \frac{1}{s - M_Z^2 + iM_Z\Gamma_Z}$$

For Z , gauge KK, cont. int's
fey's augmented etc only

$e^+e^- \rightarrow f\bar{f}$
($m_f=0$)
Amplitudes

$$\left\{ \begin{aligned} T_{+-}^{++} &= f_{LL}(1+z) - f_0(z+2z^2-1) \\ T_{+-}^{+-} &= f_{LR}(1-z) - f_0(z-2z^2+1) \\ T_{+-}^{-+} &= f_{RL}(1-z) - f_0(z-2z^2+1) \\ T_{+-}^{--} &= f_{RR}(1+z) - f_0(z+2z^2-1) \end{aligned} \right.$$

spin-2

ADD

$$\longrightarrow f_0 = \frac{\lambda s^2}{4\pi\alpha M_H^2}$$

$\lambda = \pm 1$
 $M_H =$ cut-off scale in Hewitt notation

$$\left(f_0 = \frac{\lambda s^2}{4\pi\alpha M_H^2} \left[1 - i \frac{\pi M_H^2 (\sqrt{s})^{2-2\epsilon} \Gamma_{\epsilon-1}}{16 M_H^2 \epsilon^2} \right] \right)$$

$$Z = \cos\theta$$

In the SM AND in all models with new

s-channel spin(-0 or)1 exchanges ...

$$\frac{1}{N} \frac{dA}{dz} \sim (1-z^2)$$

(almost everything but gravity)

\therefore non-sin² θ behavior (for all f) signals
spin-2 exchange !!

[Fig.]

\Rightarrow How to probe deviations from $(1-z^2)$?

- Note the interference between spin-1 + 2 exchange induces a z-odd term in $N^{-1} dA/dz$...

$$(i) \quad A_{FB} = \frac{1}{N} \left\{ \int_{z>0} dz \frac{dA}{dz} - \int_{z<0} dz \frac{dA}{dz} \right\}$$

(=0 for spin-1)

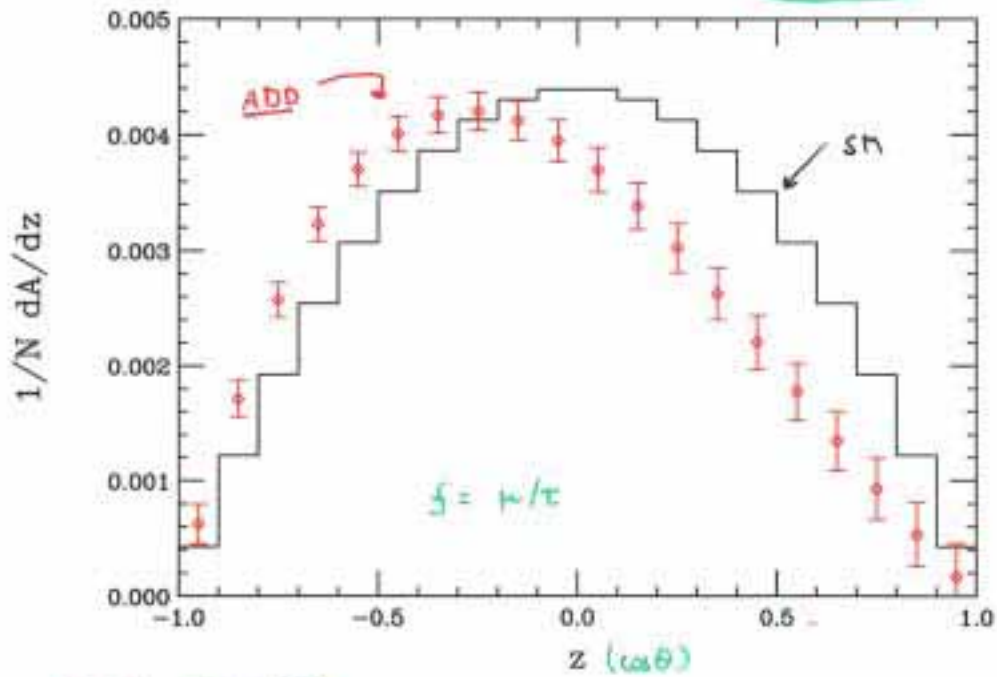
$$(ii) \quad \langle P_n \rangle = \frac{1}{N} \int dz P_n(z) \frac{dA}{dz} \quad (n=1,2,3)$$

$\langle P_{1,2} \rangle \neq 0$ for gravity

$\sqrt{s} = 500 \text{ GeV}$ $L = 500 \text{ fb}^{-1}$

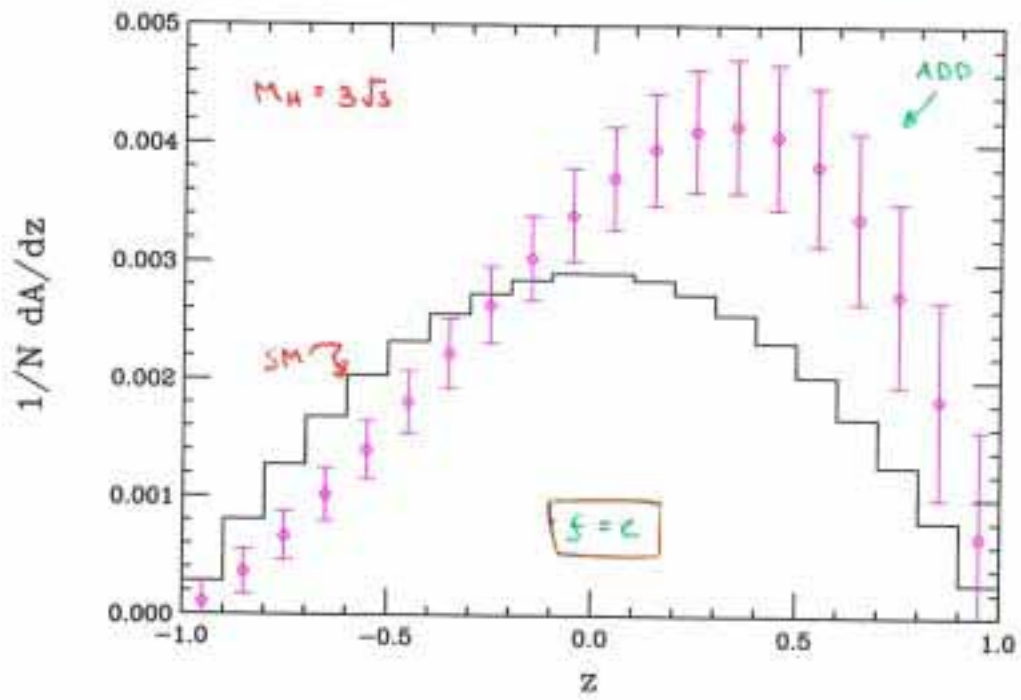
$P_T = 0.8$ $P_T' = 0.6$

$M_H = 3\sqrt{s}$

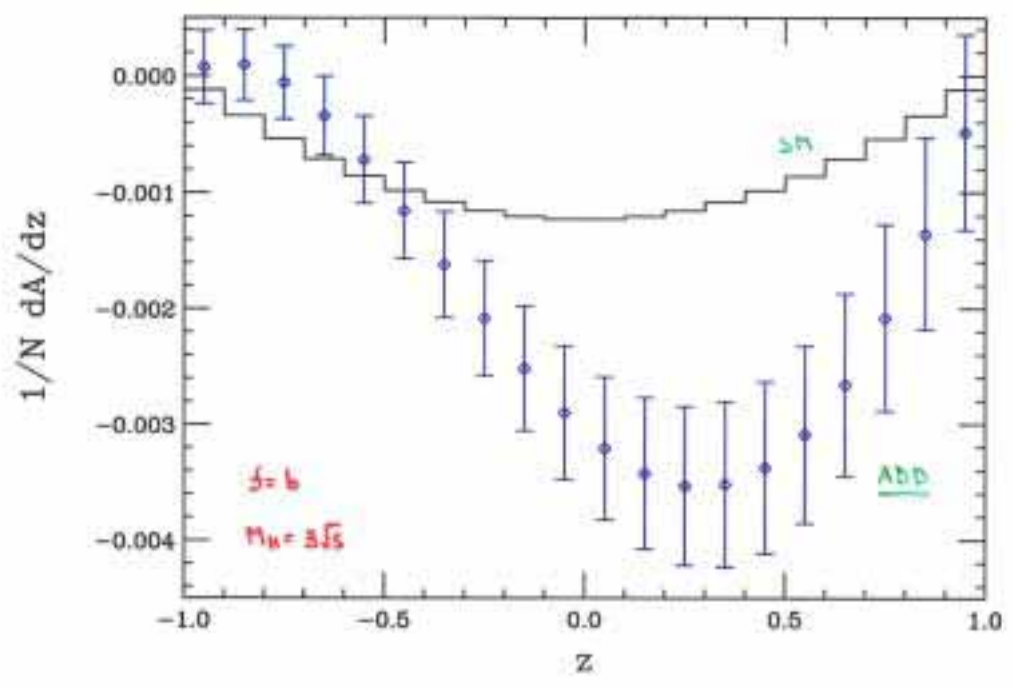


Note asymmetry
around $z=0$...

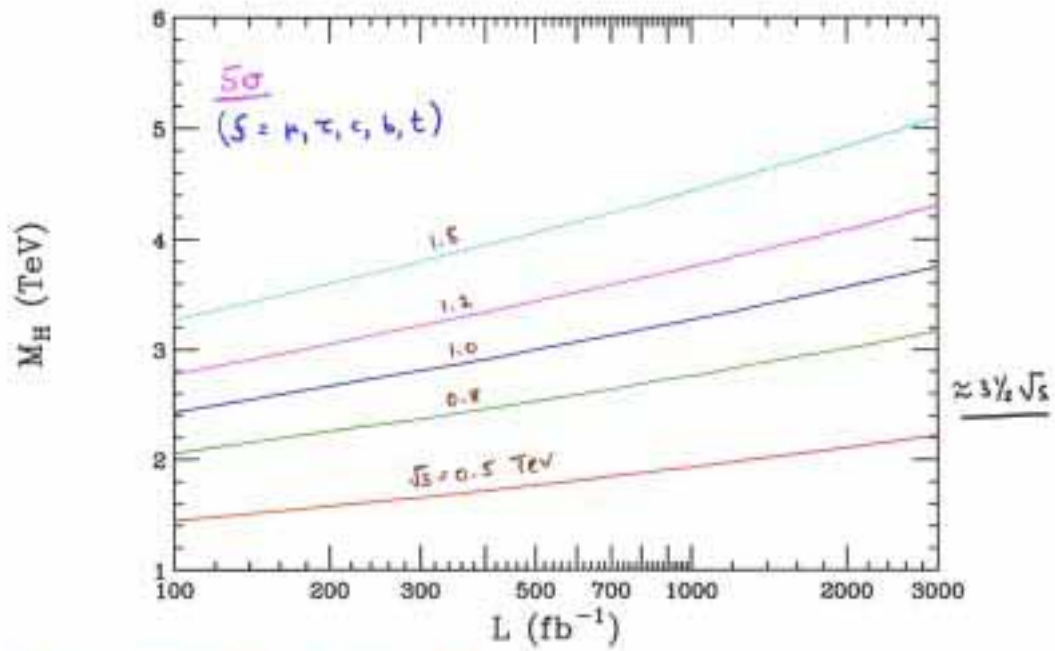
$\sqrt{s} = 500 \text{ GeV}$ $L = 500 \text{ fb}^{-1}$ $P_{\tau, \tau'} = 0.8, 0.6$



$\sqrt{s} = 500 \text{ GeV}$ $L = 500 \text{ fb}^{-1}$ $P_{T,T'} = 0.2, 0.6$

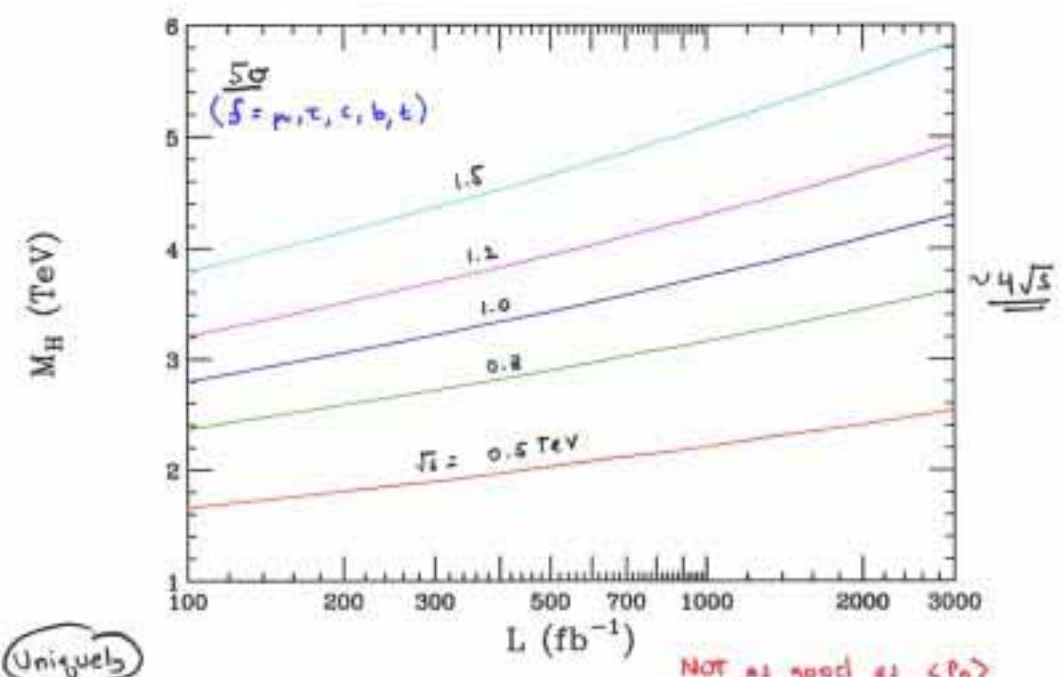


$\langle P_n \rangle$ sensitivity for $M_H \neq \infty$



Unique signal for spin-2/graviton exchange

Avg sensitivity to $M_H \neq \infty$



Uniquely

Signals graviton exchange

NOT as good as $\langle P_n \rangle$
 method using P_L 's only
 $\approx 6\sqrt{s}$

Can we do better? Yes

- Try to force a fit of the form for each final fermion f $\left\{ \begin{array}{l} \frac{1}{N} \frac{dA}{dz} = C_i (1-z^i) \\ C_i = \text{arbitrary} \end{array} \right.$

Ask: for what M_H is the CL of fits below CL for $5\sigma = 5.7 \cdot 10^{-5}$?

ID Reach

\Rightarrow low quality of fit signals deviations from simple $\sim \sin^2\theta$ behavior...

Furthermore ...

Ask: for what M_H do I agree w/ SM at 95% CL
i.e., what is the 95% CL lower bound on M_H from any deviation?

Find: for lumi's in the $\approx 1/2 - 2 \text{ ab}^{-1}$ range the bounds are systematics dominated...

E_{CM} (GeV)	reach 95%CL Reach (TeV)	ID reach Reach (TeV)
500	10.2	5.4
800	17.0	8.8
1000	21.5	11.1
1200	26.0	13.3
1500	32.7	16.7

$$\approx 21\sqrt{s} \quad \approx 11\sqrt{s} !$$

For lumi's above $\sim \frac{1}{2} \text{ab}^{-1}$ the variation in these bounds is $\leq 10\%$... \Rightarrow x2 'old' results

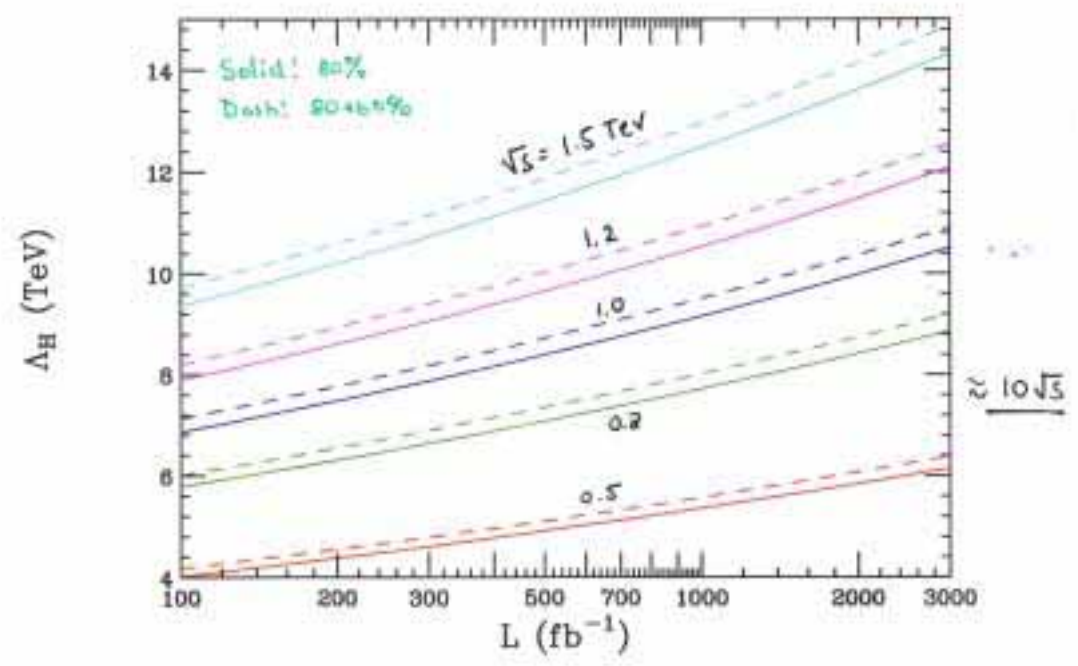
WARNING !! THEORIST at WORK !!

Since these bounds are systematics dominated they should be CAREFULLY re-examined by an experimenter...

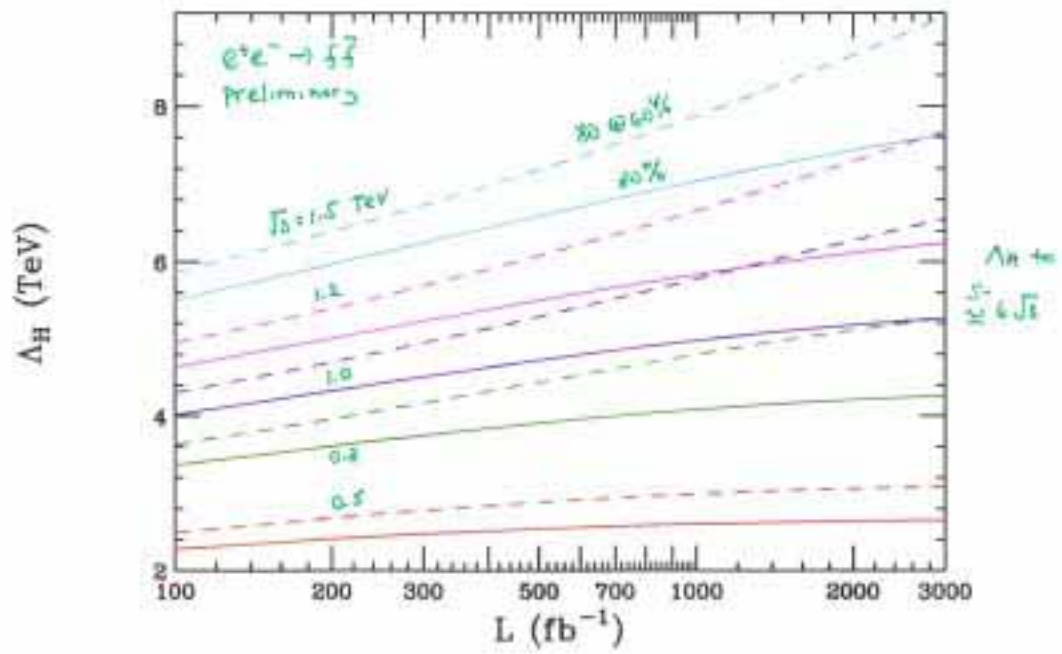
BUT

\Rightarrow Likely that P_T significantly improves 4DD sensitivity.

Standard 95% CL reach for ADD



50 ID Reach (moment: P_h)



USUAL
ADD : $f_g = \frac{\lambda s^2}{4\pi\alpha M_H^2}$

RS : $\frac{\lambda}{M_H^2} \rightarrow -\frac{1}{8\Lambda_{\text{Pl}}^2} \sum_n \frac{1}{s - m_n^2 + im_n\Gamma_n}$
 ↑
 TeV-scale gravitons

Below resonance production they look the same...
 (for \sqrt{s} fixed!)

- Data, Gabrielli + Mele :

$$f_g = \frac{\lambda s^2}{4\pi\alpha M_H^2} \left\{ 1 - i \frac{\pi M_H^4 (\sqrt{s})^{\delta-2} S_{\delta-1}}{16 M_{\text{Pl}}^{\delta+2}} \right\}$$

(usually neglected) imaginary, sub-leading term in ADD
 from graviton continuum

M_{Pl} = $4+\delta$ -dim Planck scale $\sim M_H$

$S_{\delta-1}$ = area of δ -sphere (a number)

\therefore ADD $\text{Im}(T_4 T_4^*) \neq 0$ everywhere
 RS $= 0$ away from resonances!

To probe $\text{Im}(T_+ T_-^*) \dots$

$$\frac{1}{N} \frac{dA_i}{dz} = \frac{\int_+ \frac{d\sigma}{dz d\phi} - \int_- \frac{d\sigma}{dz d\phi}}{\int_{\text{All}} d\sigma}$$

$= 0$
in SM
RS +
all spin-1
exchange
NP
model

But now \pm are regions where $\sin 2\phi$ is $\pm \dots$

$$\rightarrow N^{-1} dA_i/dz \begin{cases} = 0 & \text{in RS (away from reson.)} \\ \neq 0 & \text{in ADD} \end{cases}$$

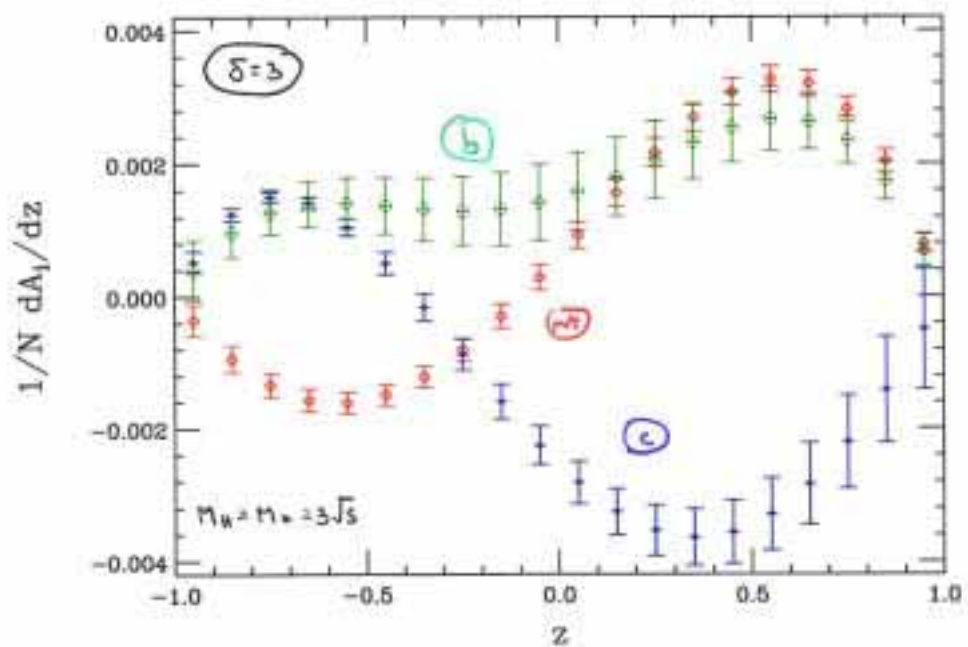
Ask: Up to what $M_H (= M_*)$ can I tell

$N^{-1} dA_i/dz \neq 0$ at 5σ for different δ ?

\Rightarrow This tells us the M_H for which ADD + RS
can be distinguished....

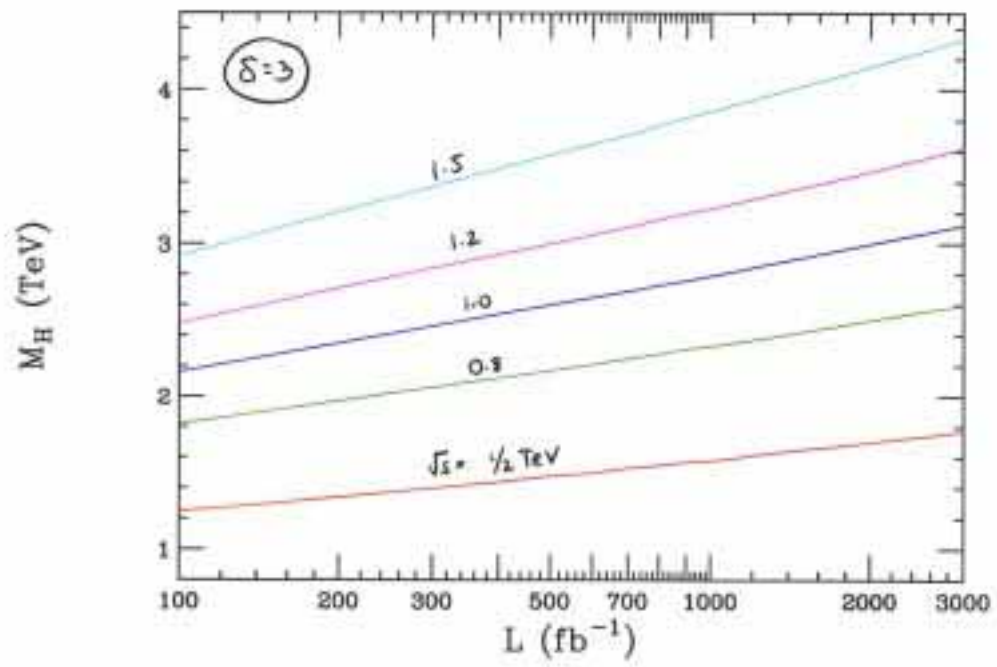
Expect: as δ grows the reach decreases
due to $(\sqrt{s}/M)^{\delta}$ dependence....

$\sqrt{s} = 500 \text{ GeV}$ $L = 500 \text{ fb}^{-1}$ $P_{T, \tau} = 0.8, 0.6$



$P_T = 0.8$
 $P_T' = 0.6$

5σ ADD vs RS differentiation



What else has been
done ?

- very little -

Transverse beam polarization in $e^+e^- \rightarrow W^+W^-^*$

Karol Kołodziej

Institute of Physics, University of Silesia,
Katowice, Poland

Fred Jegerlehner
DESY Zeuthen

Plan

- Why polarization?
- Polarized W-pair production cross sections.
- Transverse beam polarization.
- Standard Model results including $\mathcal{O}(\alpha)$ virtual corrections and bremsstrahlung.
- Conclusions and outlook.

– Extended ECFA/DESY Workshop –

– Prague, November 2002 –

* Based on work: J. Fleischer, K. Kołodziej, F. Jegerlehner, Phys. Rev. D49 (1994) 2174.

Why polarization?

Direct tests at LEP2 and indirect tests through loop effects at LEP1 of the triple gauge coupling of the $SU(2)_L \times U(1)_Y$ group \implies no expectation for large deviations from the SM at a linear collider.

Renormalizability \implies experimentally well established $Wl\nu_l$ coupling uniquely fixes the triple gauge coupling. How to disentangle the triple gauge couplings if there is fine tuning among them?

Problems

- form factors measurable only for low momentum transfer, i.e., in "classical limit", or, at resonance, where a process is dominated by a single process of one-particle exchange.
- $e^+e^- \rightarrow W^+W^-$ is measured far above the Z resonance, electroweak unification is at work \implies not possible to disentangle the photon from the Z , except for mass effects and different properties under parity.

Polarization allows to discriminate between the γ and Z s -channel contributions. The s -channel contributions suppressed at the W -pair threshold grow fast with energy.

Why polarization?

Observed is the process

$$e^+e^- \rightarrow 4f,$$

but sufficiently above the threshold

$$e^+e^- \rightarrow W^+W^- \rightarrow 4f,$$

with both W 's at resonance dominates.

The most interesting processes are

$$e^-e^+ \rightarrow W_L^-W_L^+$$

and

$$e_R^-e^+ \rightarrow W^-W^+.$$

These modes are very much suppressed with respect to the dominant transverse-transverse polarization mode with two opposite W helicities.

A high luminosity is required.

Transverse beam polarization may help to disentangle different contributions.



In e^+e^- storage rings transverse polarization is natural. How about the linear collider?

Polarized W-pair production

The differential W -pair production cross section is given by

$$\frac{d\sigma(h_e; \lambda, \bar{\lambda})}{d \cos \theta} = \frac{\beta_W}{32\pi s} \left| \sum_{i=1}^6 X_i^{(h_e)} M_{X_i}(h_e; \lambda, \bar{\lambda}) \right|^2.$$

At the tree level

$$M_0(-; \lambda, \bar{\lambda}) = S_{1(0)}^{(-)} M_{S_1}(-; \lambda, \bar{\lambda}) + T_{1(0)}^{(-)} M_{T_1}(-; \lambda, \bar{\lambda}),$$

$$M_0(+; \lambda, \bar{\lambda}) = S_{1(0)}^{(+)} M_{S_1}(+; \lambda, \bar{\lambda}),$$

where in the high energy limit, $s \rightarrow \infty$,

$$S_{1(0)}^{(+)} = -\frac{e^2}{s} \left(1 - \frac{1}{1 - \frac{M_Z^2}{s}} \right) \rightarrow 0,$$

$$S_{1(0)}^{(-)} = S_{1(0)}^{(+)} - \frac{g^2}{2s} \frac{1}{1 - \frac{M_Z^2}{s}} \rightarrow -\frac{g^2}{2s},$$

$$T_{1(0)}^{(-)} = \frac{g^2}{s} \frac{1}{\frac{1+\beta_W^2}{2} - \beta_W \cos \theta} \rightarrow \frac{g^2}{s} \frac{1}{1 - \cos \theta}.$$

Moreover,

$$\frac{M_{T_1}(h_e; \lambda, \bar{\lambda})}{M_{S_1}(h_e; \lambda, \bar{\lambda})} \rightarrow \frac{1 - \cos \theta}{2}$$

and we see that the gauge cancellations are at work.

The longitudinal beam polarization allows to study the relative weight of γ and Z couplings to W -bosons.

Transverse beam polarization

With unpolarized beams we can measure $|M_-|^2 + |M_+|^2$ through the total cross section σ

$$\begin{aligned}\frac{d\sigma}{d\cos\theta} &= \frac{1}{2} \left(\frac{d\sigma_L}{d\cos\theta} + \frac{d\sigma_R}{d\cos\theta} \right) \\ &= \frac{\beta_W}{64\pi s} (|M_-|^2 + |M_+|^2),\end{aligned}$$

with longitudinally polarized beams we can measure $|M_-|^2 - |M_+|^2$ through the left-right asymmetry A_{LR}

$$\begin{aligned}\frac{d(\sigma A_{LR})}{d\cos\theta} &= \frac{1}{2} \left(\frac{d\sigma_L}{d\cos\theta} - \frac{d\sigma_R}{d\cos\theta} \right) \\ &= \frac{\beta_W}{64\pi s} (|M_-|^2 - |M_+|^2)\end{aligned}$$

and with transverse polarized beams we can measure $\text{Re}(M_+M_-^*)$ from the azimuthal asymmetry A_T defined by

$$\begin{aligned}\frac{d(\sigma A_T)}{d\cos\theta} &= \int_0^{2\pi} \frac{d^2\sigma}{d\cos\theta d\cos\phi_W} \cos 2\phi_W d\phi_W \\ &= \frac{\beta_W}{64\pi s} 2\text{Re}(M_+M_-^*).\end{aligned}$$

(This is different from the asymmetry defined in the $e^+e^- \rightarrow f\bar{f}$ study by an overall factor)

Tri-linear gauge boson couplings are
completely fixed in the SM:



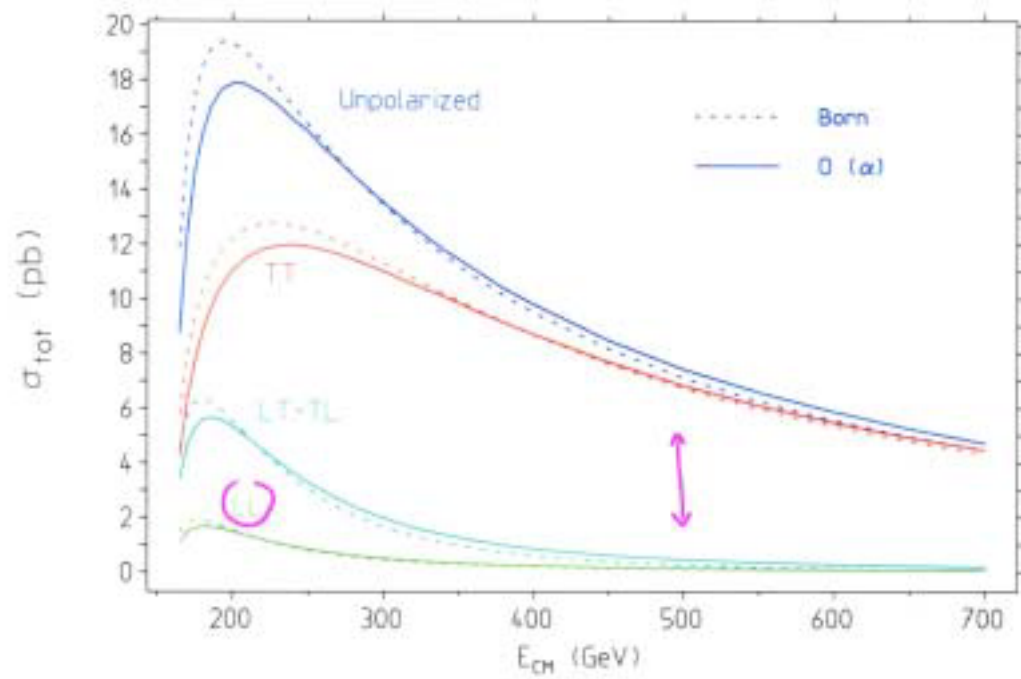
BUT: if some
'funny' NP is present
"anomalous" couplings
can arise

- LC is particularly good at probing for AC
through P_L + precision measurements

- $W_L^+ W_L^-$ can be particularly interesting in this
regard...

\Rightarrow But $e^+e^- \rightarrow W_L^+ W_L^-$ is only a small part of
the cross section - hard to isolate...

at $\sqrt{s} = 500$ GeV the W 's are mostly transverse



(FKJ 1994)

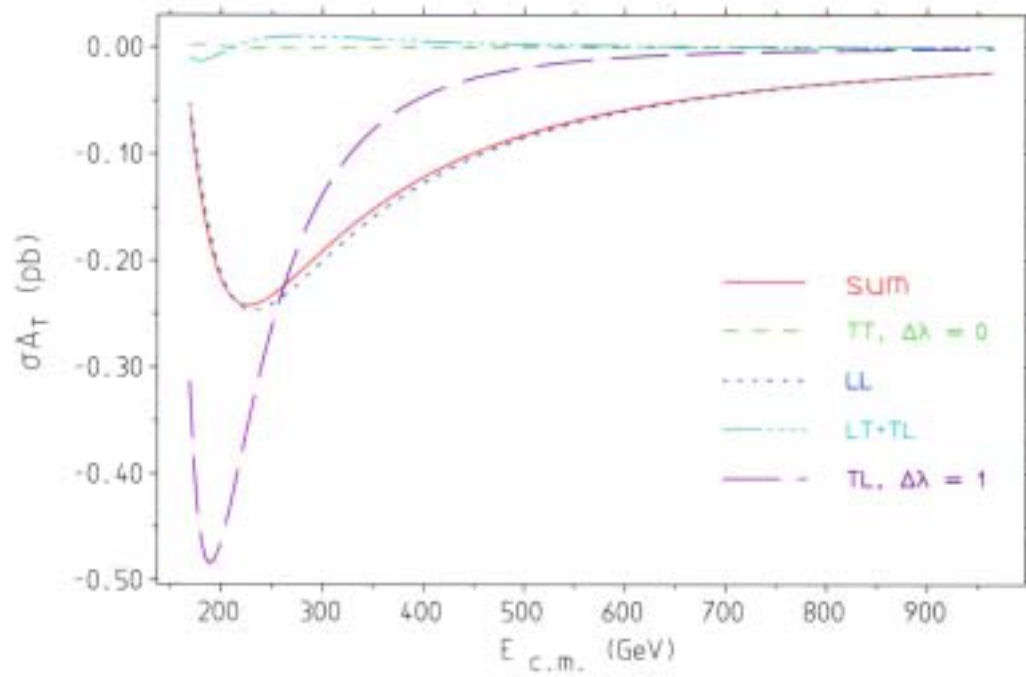
Main features of σA_T

- no TT $|\Delta\lambda| = 2$ final state contribution
as $M(+; \pm\mp) = 0$
- !!! sum over final state spins: almost pure LL
(see Fig σA_T)
- TL and LT large but cancel in sum
- rather small at 1% level
(size similar to σ_R ; probe different physics)
- note $\sigma A_{LR} \simeq \sigma_L/2 \simeq \sigma_{tot}^{unpol.}$
dominated by TT; probe different physics

transversal polarization provides an important tool for investigation of $W_L W_L$ physics, probing electroweak symmetry breaking; clean, no background !

without transversal polarization: $W_L W_L$ is small contribution which can only be dug out by angular cutting (background problem).

- A_T here comes almost completely from the LL final state ... changes in A_T probe changes in LL cross section + properties



(FKJ 1994)

HOW TO DISENTANGLE TRIPLE GAUGE COUPLINGS

The dependence of the cross section on the VWW form-factors shows up directly in the helicity amplitudes:

$$M(-; \lambda, \bar{\lambda}) = \sqrt{2}\beta_W \gamma^{2-|\lambda|-|\bar{\lambda}|} d_{\Delta\sigma, \Delta\lambda}^{J_0}(\theta) \left\{ e^2 \left(H_i^\gamma - \frac{H_i^Z}{1 - M_Z^2/s} \right) + \frac{g^2}{2} \frac{H_i^Z}{1 - M_Z^2/s} - \frac{\tilde{M}_{T_i}(-; \lambda, \bar{\lambda})}{\beta_W} \frac{g^2}{\frac{1+\beta_W^2}{2} - \beta_W \cos \theta} \right\}$$

$$M(+; \lambda, \bar{\lambda}) = \sqrt{2}\beta_W \gamma^{2-|\lambda|-|\bar{\lambda}|} d_{\Delta\sigma, \Delta\lambda}^{J_0}(\theta) \left\{ e^2 \left(H_i^\gamma - \frac{H_i^Z}{1 - M_Z^2/s} \right) \right\}$$

with the correspondence

amplitude	state
H_i^V	LL
H_0^V	TT ; $\Delta\lambda = 0$
H_{-1}^V	TL, LT ; $\Delta\lambda = -1$
H_{+1}^V	TL, LT ; $\Delta\lambda = +1$

Radiative corrections :

$$H_l^V = (2 + \gamma^{-2})A_1^V + 2A_2^V - \beta_W^2 A_3^V$$

$$H_0^V = A_1^V$$

$$H_{-1}^V = 2A_1^V + A_2^V + \beta_W A_4^V$$

$$H_{+1}^V = 2A_1^V + A_2^V - \beta_W A_4^V .$$

With A_i^V vertex corrections ($V = \gamma, Z$).

Anomalous couplings :

$$H_l^V = 2\left\{(1 + \frac{2M_W^2}{s})\delta_V + \delta\kappa_V + (1 - \frac{M_W^2}{s})\lambda_V\right\}$$

$$H_0^V = \delta g_V + \frac{s}{2\Lambda^2}\lambda_V$$

$$H_{\mp}^V = 2\delta_V + \delta\kappa_V + \lambda_V \mp \beta_W \frac{s}{\Lambda^2}\xi_V .$$

Conclusions and outlook

- Transverse beam polarization at a high-luminosity linear collider allows one to study longitudinal W physics without analyzing final state polarizations.
- A_T provides information on the Higgs mechanism.
- The program for transverse polarization effects in $e^+e^- \rightarrow W^+W^-$ still exists.
- The transverse beam polarization can be implemented into MC programs for $e^+e^- \rightarrow 4f$.

Nice

But a quantitative study is lacking!

What about graviton exchange in $e^+e^- \rightarrow W^+W^-$?

Unfortunately, it is not as beneficial as
in $e^+e^- \rightarrow \bar{f}f \dots$

[Fig]

For $\sqrt{s} = 500 \text{ GeV} \rightarrow 95\% \text{ CL search reach is}$

L	M_H	
0.1	2.77	
0.5	3.39	$\approx 7\sqrt{s}$
1.0	3.69	
(ab^{-1})	TeV	

not bad for only one observable ...

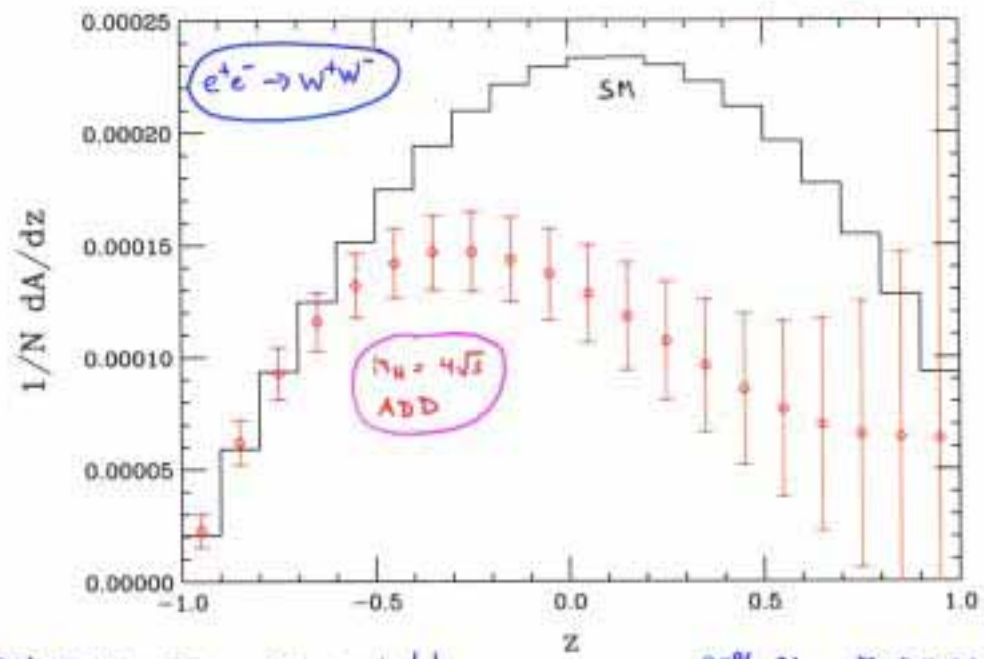
For other processes, e.g., $e^+e^- \rightarrow 2\gamma$, P_T is
even less sensitive to graviton exchange ...

(\rightarrow for $L = \frac{1}{2} ab^{-1}$ $M_H > 3.09 \text{ TeV}$) [Fig]

Ditto for $e^+e^- \rightarrow 2Z \dots$ [Fig]

$\sqrt{s} = 500 \text{ GeV}$, $\frac{1}{2} \text{ ab}^{-1}$

Transverse Polarization
Asymmetry



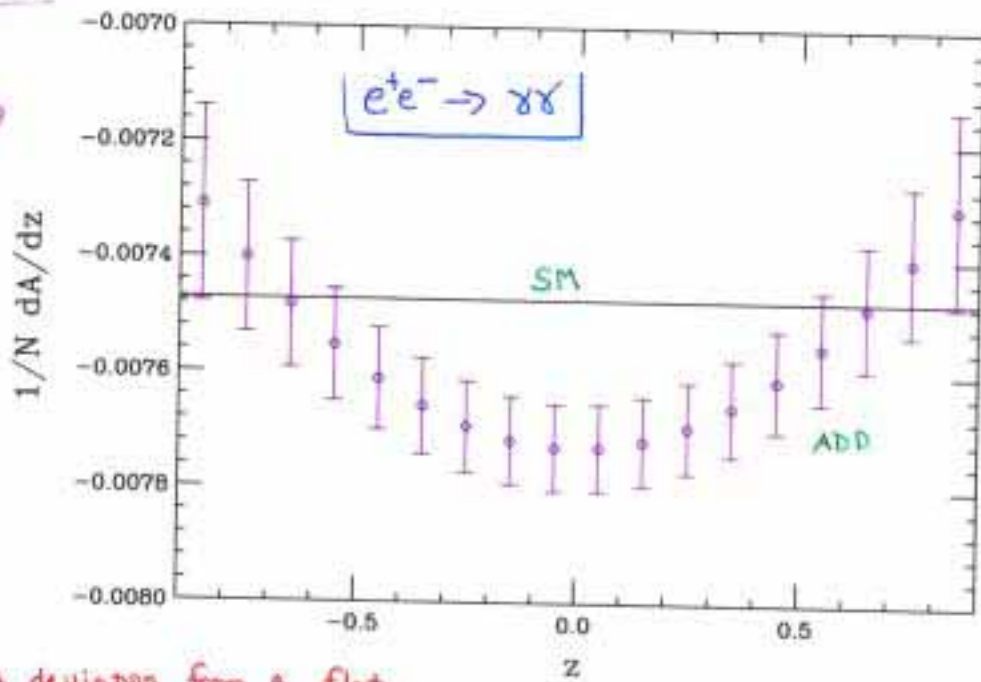
Note: no symmetry in SM result !!

95% CL $M_H \geq 3.31 \text{ TeV}$

note
scale

$$\sqrt{s} = 500 \text{ GeV}, L = \frac{1}{2} \text{ ab}^{-1}$$

$$M_H = 4\sqrt{s}$$

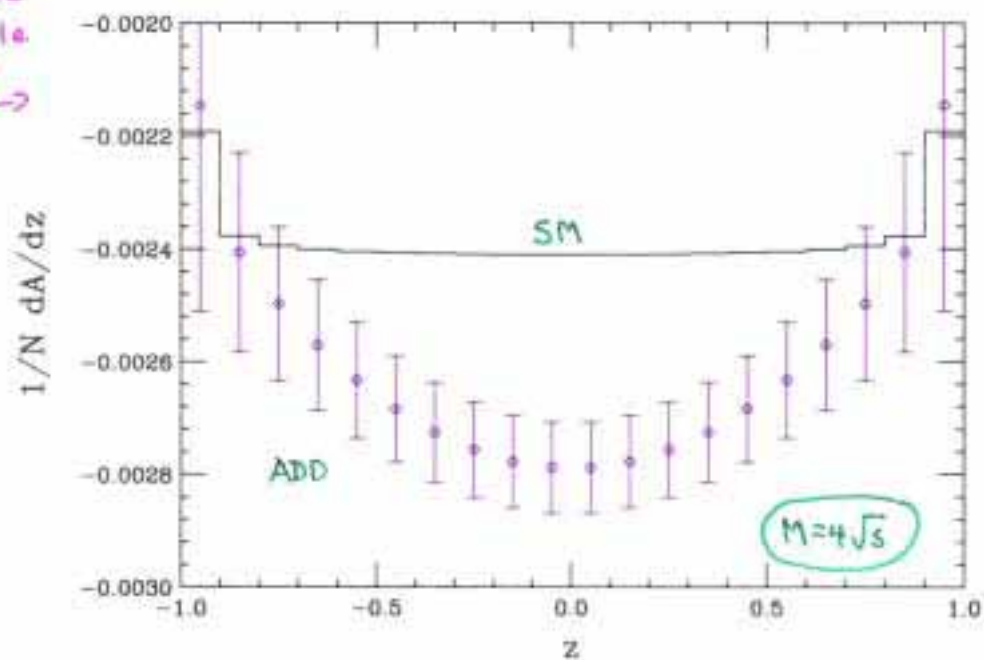


A deviation from a flat
line signals new physics

$e^+e^- \rightarrow 2Z$

$L = \frac{1}{2} \text{ab}^{-1}$
 $\sqrt{s} = 500 \text{ GeV}$

note
scale
↳



very similar to $e^+e^- \rightarrow 2\gamma$

Outlook + Conclusions

- Transverse polarization's potential for LC physics has gotten too little attention ...

THIS NEEDS TO CHANGE !!

- Is it only useful for some ^{few} cases of interest (gravity, TGV's ...) or are there wider uses ? Requires investigation ...

This study: P_T can be used to both probe for graviton exchange + to differentiate it from other NP possibilities - about twice as good as 'classic' methods
(Beware systematic errors !)

- To some extent, P_T can even differentiate extra dim models: ADD vs RS
- More work is needed in other channels