Transverse Polarization Signatures of TeV-scale gravity at LCs

- 'Transverse' polarization? Why?
- Sensitivity to gravity (= spin-2 exchange)
- Analysis + reaches (preliminary)
- Outlook + Conclusions

→ Spin rotators with near 100% efficiency can take longitudinally polarized beams + make them transversely polarized....

So??
Why??

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Consider the spin-averaged matrix element for $e^+e^- \to X\{\tilde{\mu}, W^+W^-\}$

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

- $P_{L,T}$ (e^-) ; $P'_{L,T}$ (e^+) and $T_\pm$ = complex helicity amplitudes
- ϕ = ∢ between pol of e^- + plane of final state particles
- With only P_L we probe $|T_\pm|^2$ but with P_T we probe $Re, Im\ (T_+T_-^*)$
- But we need BOTH beams polarized to form asymmetries... Unlike A_{LR} where $P_L' = 0$ is OK
- What physics can be probed by P_T ??

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 I. 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 graviton (spin-2) exchange in $e^+e^- \to f\bar{f}$ ...

(Yes!)

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

- We can easily obtain all the amplitudes in the SM { Z', gauge KK, cont. int's ... } 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' ..... Unique

Transverse Polarization Asymmetry:

$$\frac{1}{N}\frac{dA}{dz} = \frac{\int_+ \frac{d\sigma}{dz\,d\phi} - \int_- \frac{d\sigma}{dz\,d\phi}}{\int_{ALL} d\sigma}$$

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

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

(These are small #'s - normalized to full σ!)

Charges ↓ Z-couplings ↓ ↓

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

Weak coupling

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

For Z′, gauge KK, cont. int's f_{LL}'s augmented etc only

Z- prop.

$$P = \frac{s}{s - M_Z^2 + i M_Z \Gamma_Z}.$$

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

$$
\begin{aligned}
T^{+-}_{+-} &= f_{LL}(1+z) - f_s(z + 2z^2 - 1) \\
T^{-+}_{+-} &= f_{LR}(1-z) - f_s(z - 2z^2 + 1) \\
T^{+-}_{-+} &= f_{RL}(1-z) - f_s(z - 2z^2 + 1) \\
T^{-+}_{-+} &= f_{RR}(1+z) - f_s(z + 2z^2 - 1).
\end{aligned}
$$

← spin-2

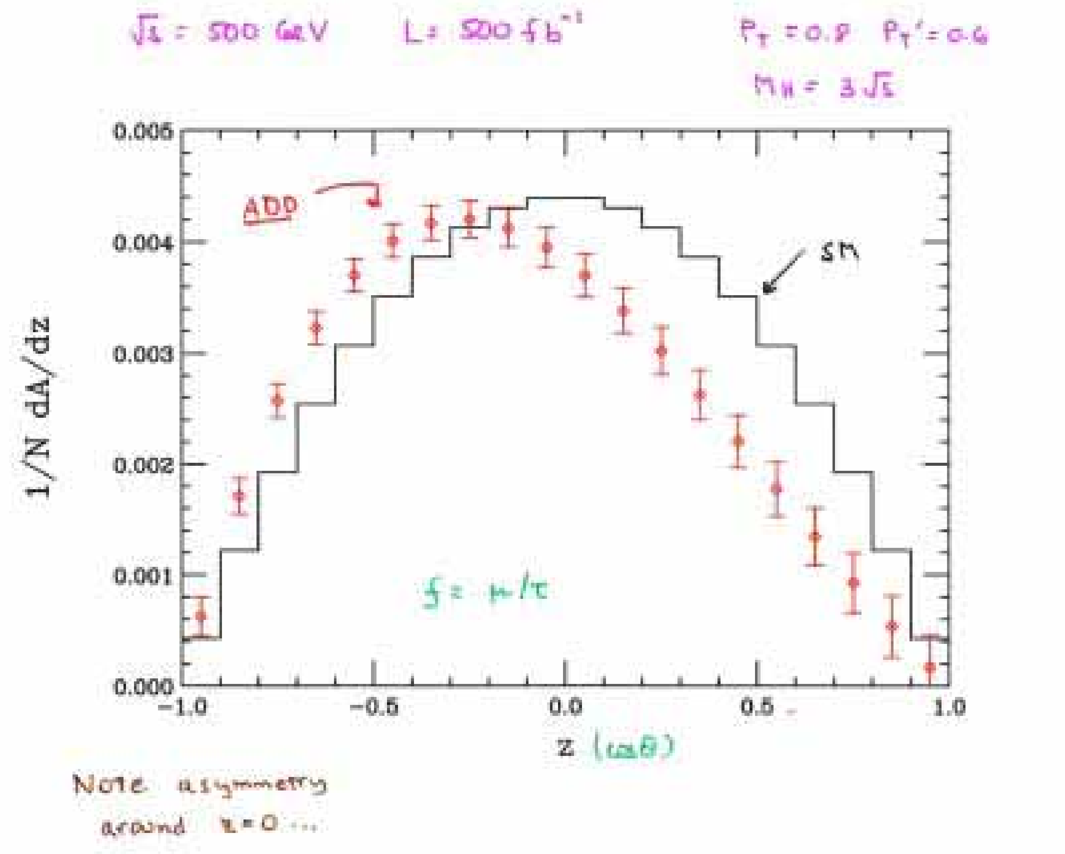
ADD ⟶ $$f_s = \frac{\lambda s^2}{4\pi\alpha M_H^4}.$$

$\lambda = \pm 1$

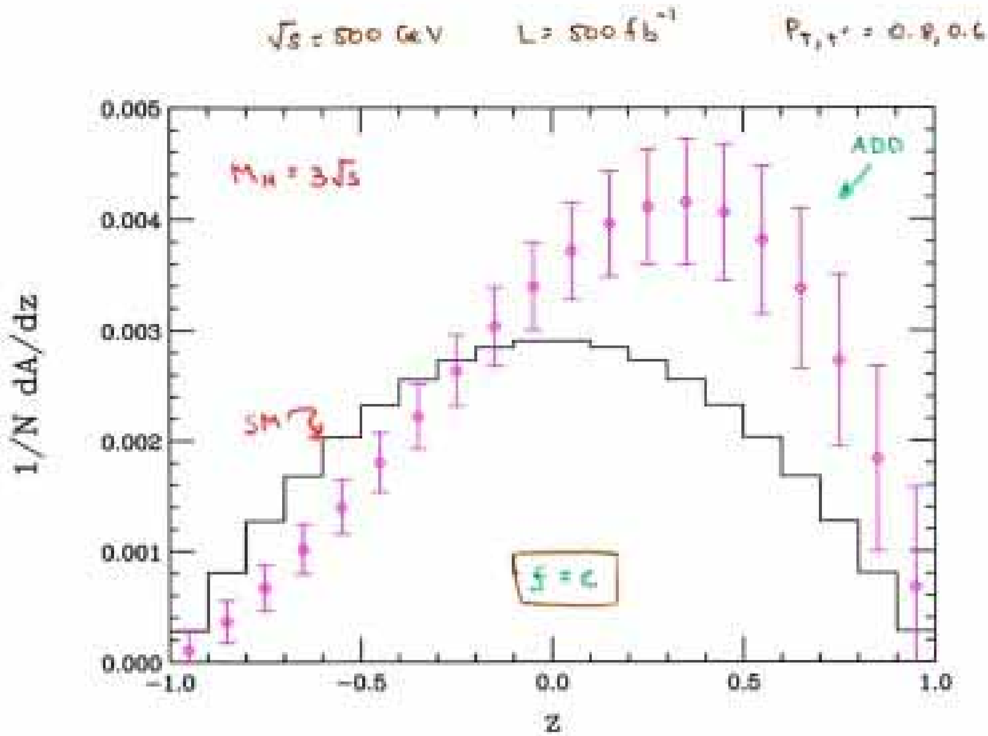
M_H = cut-off scale in Hewett notation

$$f_s = \frac{\lambda s^2}{4\pi\alpha M_H^4}\left[1 - i\frac{\pi M_H^4 (\sqrt{s})^{\delta-2} S_{\delta-1}}{16 M_D^{\delta+2}}\right].$$

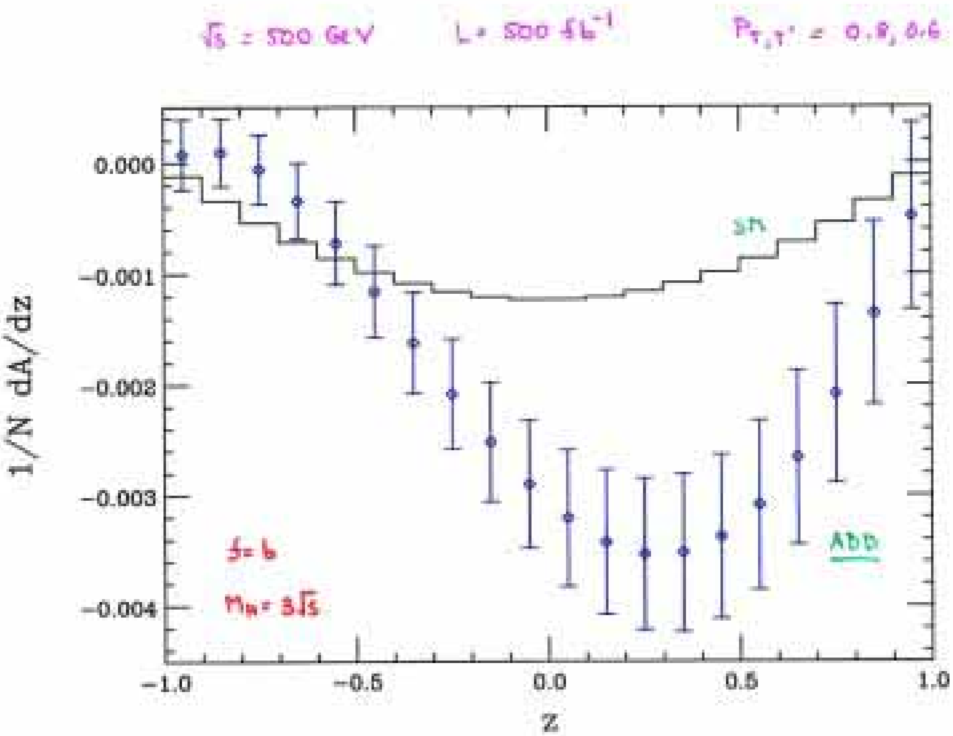
$z = \cos\theta$



√s = 500 GeV
L = 500 fb⁻¹
Pτ = 0.8 Pτ' = 0.6
MH = 3√s
ADD
SM
f = μ/τ
1/N dA/dz
z (cosθ)
0.000
0.001
0.002
0.003
0.004
0.005
−1.0
−0.5
0.0
0.5
1.0
Note asymmetry
around z=0 ...



√s = 500 GeV
L = 500 fb^-1
P_{T,+'} = 0.8, 0.6
M_H = 3√s
ADD
SM
ξ = c
1/N dA/dz
z



√s = 500 GeV
L = 500 fb⁻¹
SM
ADD
1/N dA/dz
z

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)

∴ non-$\sin^2\theta$ behavior (for all f) signals spin-2 exchange !!

[Fig.]

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

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

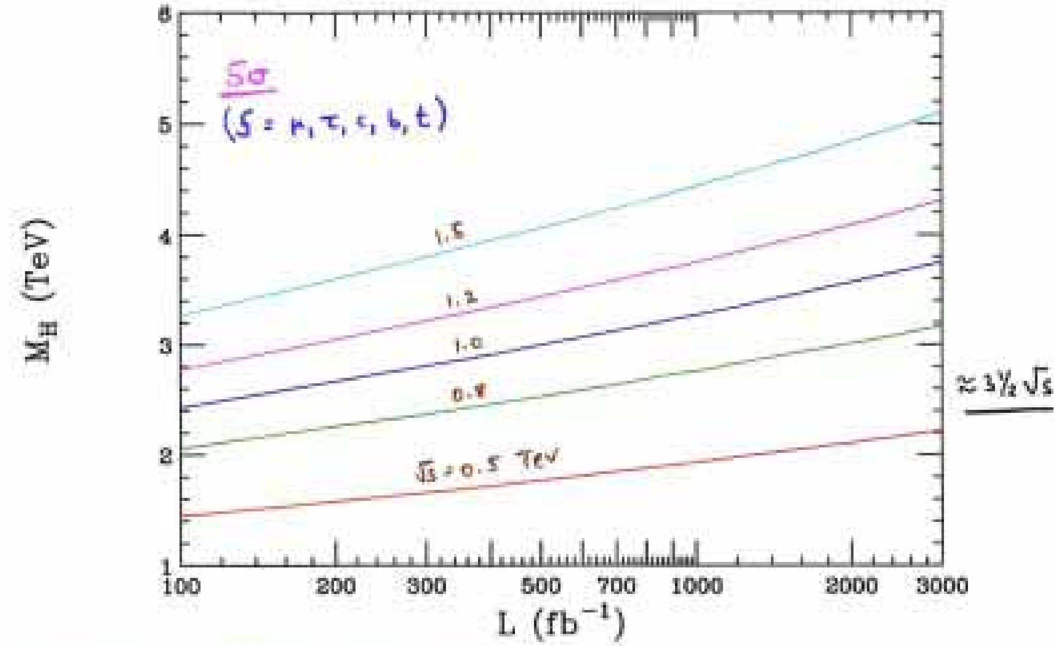
(i) $$A_{FB} = \frac{1}{N}\left\{ \int_{z>0} dz\, \frac{dA}{dz} - \int_{z<0} dz\, \frac{dA}{dz} \right\}$$

(= 0 for spin-0, -1)

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

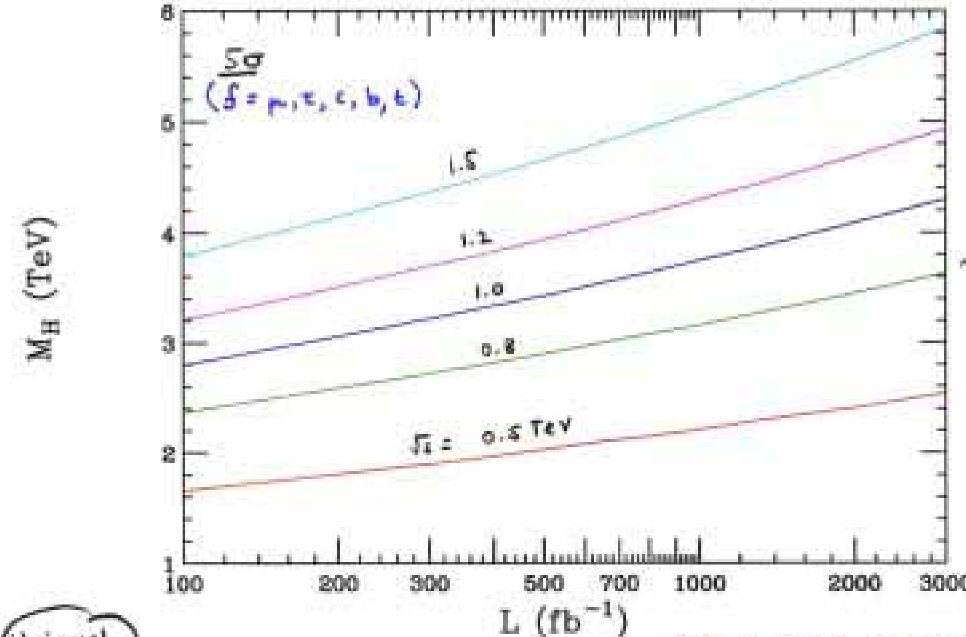
$\langle P_{1,3} \rangle \neq 0$ for graviton

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



Unique signal for spin-2/graviton exchange

A_{FB} sensitivity to $M_H \neq \infty$



$\sim 4\sqrt{s}$

Uniquely signals graviton exchange

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

Can we do better? Yes

- Try to force a fit of the form for each final fermion f

$$\left\{ \begin{array}{l} \frac{1}{N}\frac{dA}{dz} = C_i(1-z^2) \\ C_i = \text{arbitrary} \end{array} \right.$$

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

ID Reach

⇒ 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 ie, what is the 95% CL lower bound on M_H from any deviation?

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

	reach 95%CL	ID reach
E_{CM} (GeV)	Reach (TeV)	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
	$\approx 21\sqrt{s}$	$\approx 11\sqrt{s}$!

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

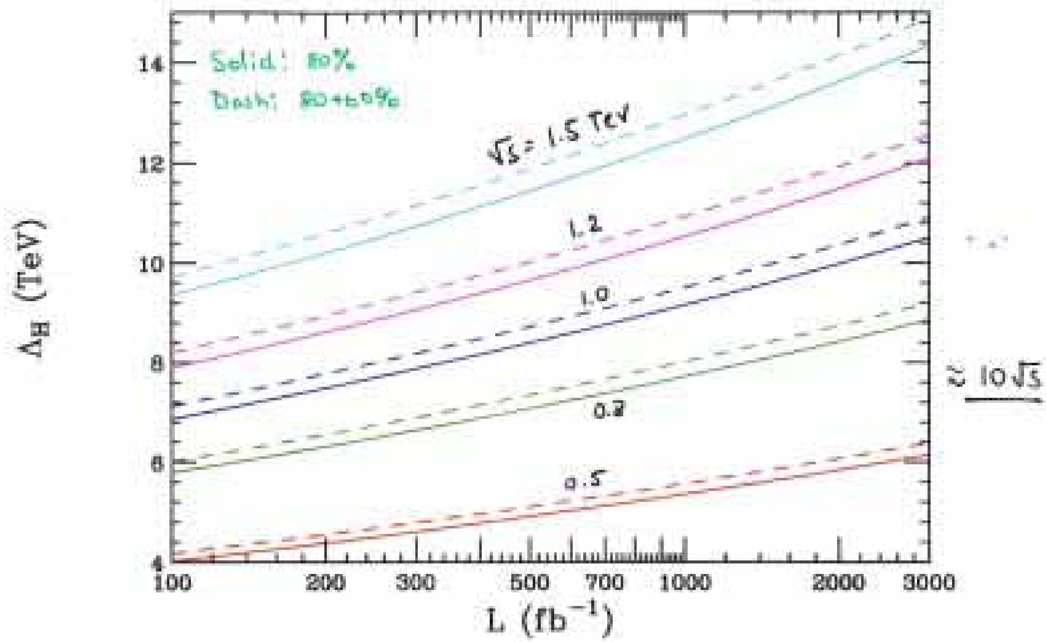
WARNING !! THEORIST at WORK !!

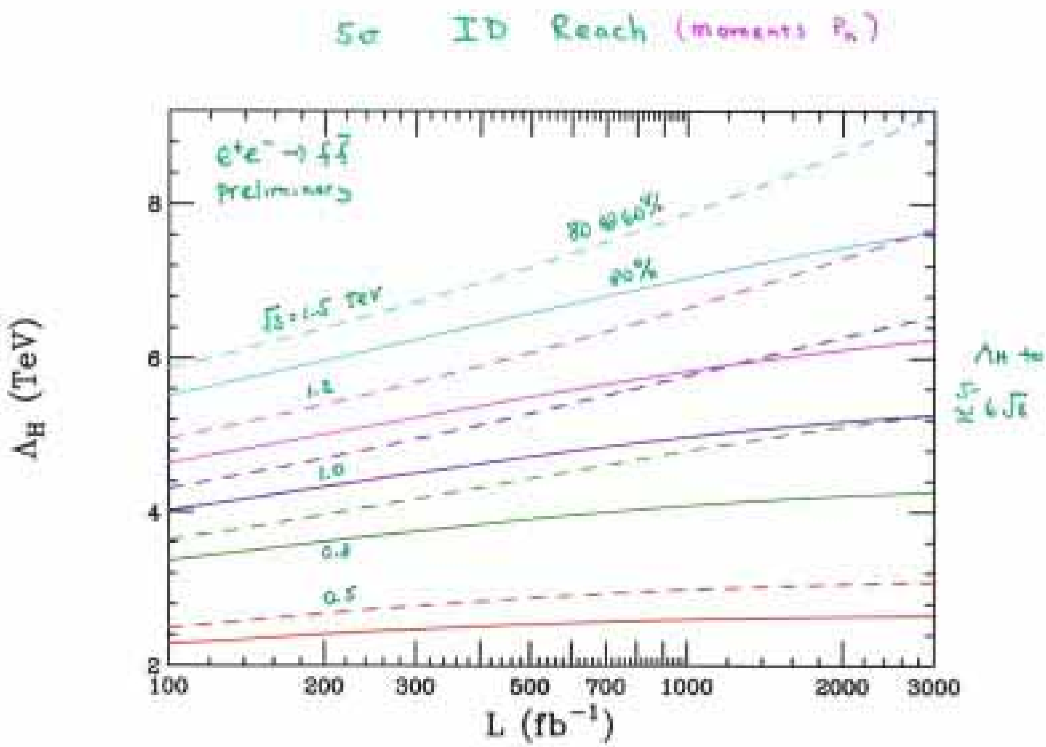
Since these bounds are systematics dominated they should be CAREFULLY re-examined by an experimenter...

BUT

$\Rightarrow$ Likely that P_T significantly improves ADD sensitivity.

'Standard' 95% CL reach for ADD





5σ ID Reach (moments P_n)
$e^+e^- \to f\bar{f}$
preliminary
80 & 60%
80%
$\sqrt{s}$ = 1.5 TeV
1.2
1.0
0.8
0.5
Λ_H (TeV)
L (fb^{-1})
2
4
6
8
100
200
300
500
700
1000
2000
3000

USUAL :
ADD :

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

RS : $\frac{\lambda}{M_H^4} \to -\frac{1}{8\Lambda_\pi^2} \sum_n \frac{1}{s - m_n^2 + i m_n \Gamma_n}$

↑ TeV-scale gravitons

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

- Datta, Gabrielli + Mele :

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

↗ imaginary, sub-leading term in ADD from graviton continuum

(usually neglected)

M_* = 4+δ-dim Planck scale ~ M_H

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

∴ ADD $\mathrm{Im}(T_+ T_-^*) \neq 0$ everywhere

RS $= 0$ away from resonances!

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

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

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

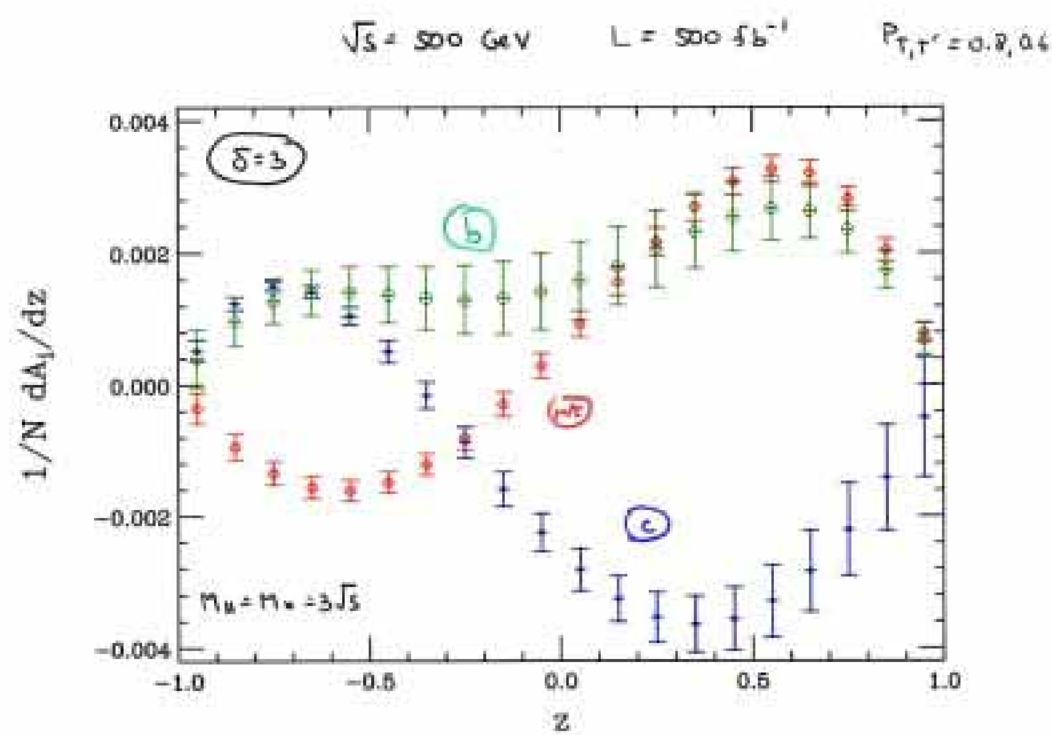
But now $\pm$ are regions where $\underline{\sin 2\phi}$ is $\pm$ ...

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

<u>Ask</u>: 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....

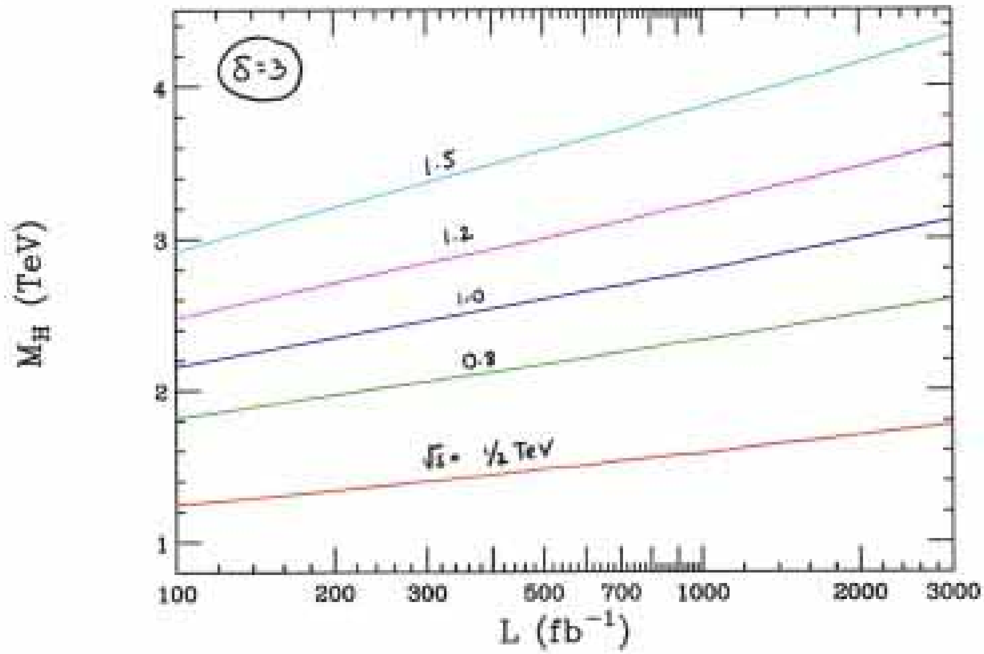
Expect: as δ grows the reach decreases due to $(\sqrt{s}/M)^\delta$ dependence....

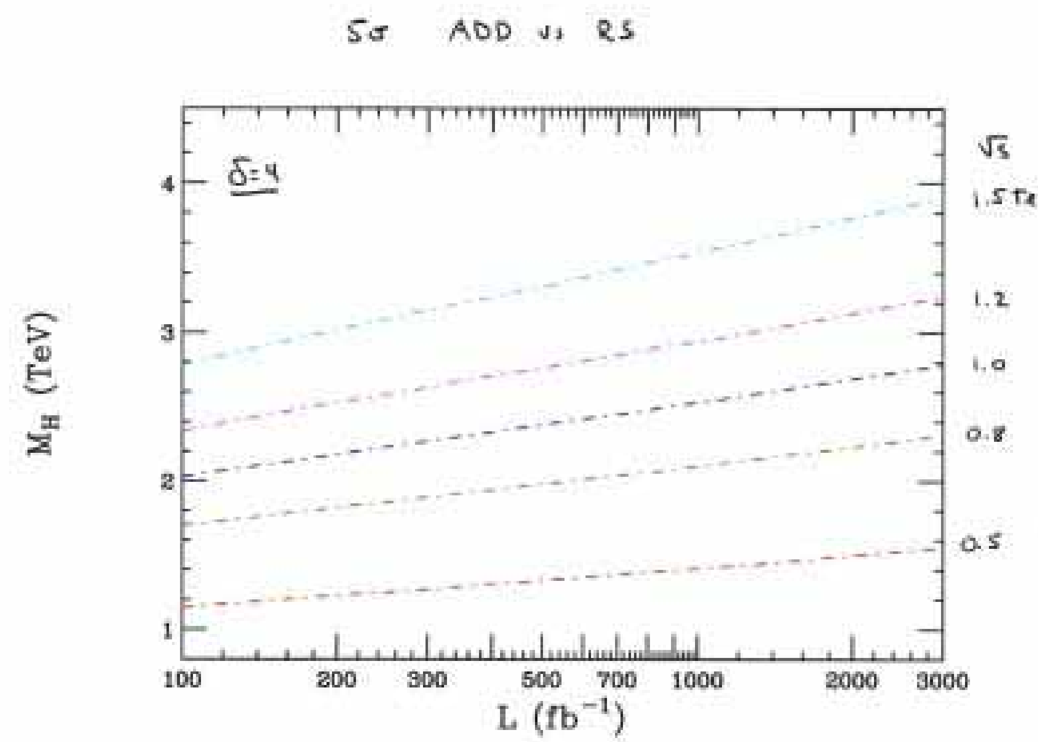


√s = 500 GeV
L = 500 fb⁻¹
0.004
0.002
0.000
−0.002
−0.004
1/N dA$_1$/dz
−1.0
−0.5
0.0
0.5
1.0
z

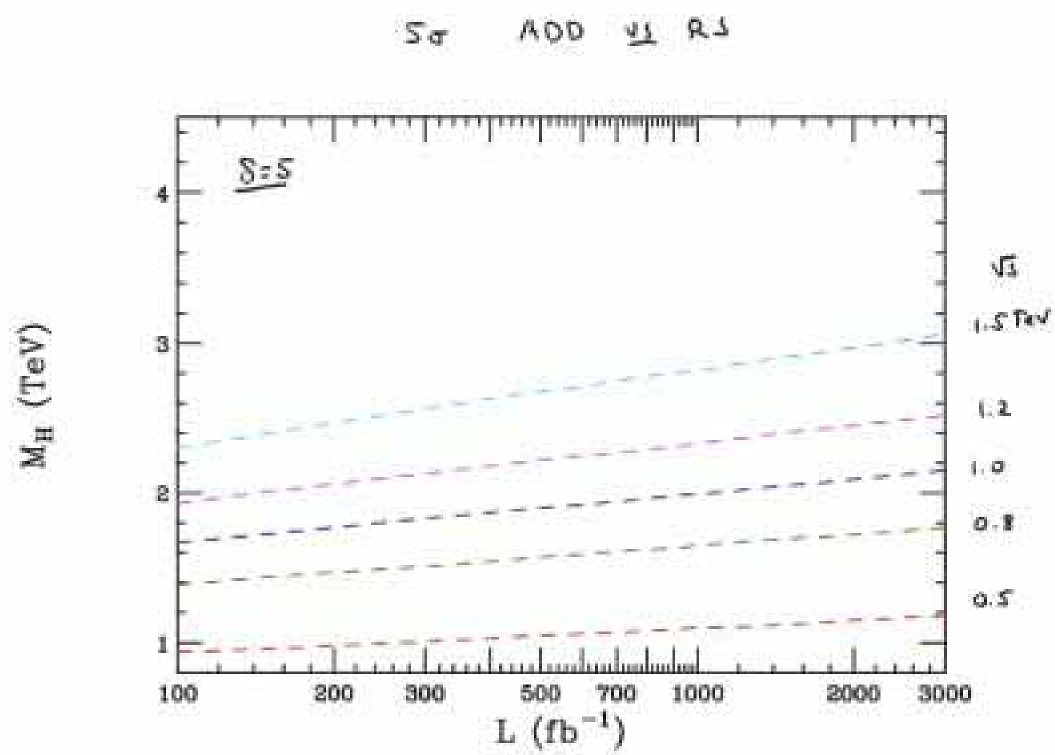
$p_T = 0.8$
$p_T' = 0.6$

5σ ADD vs RS differentiation



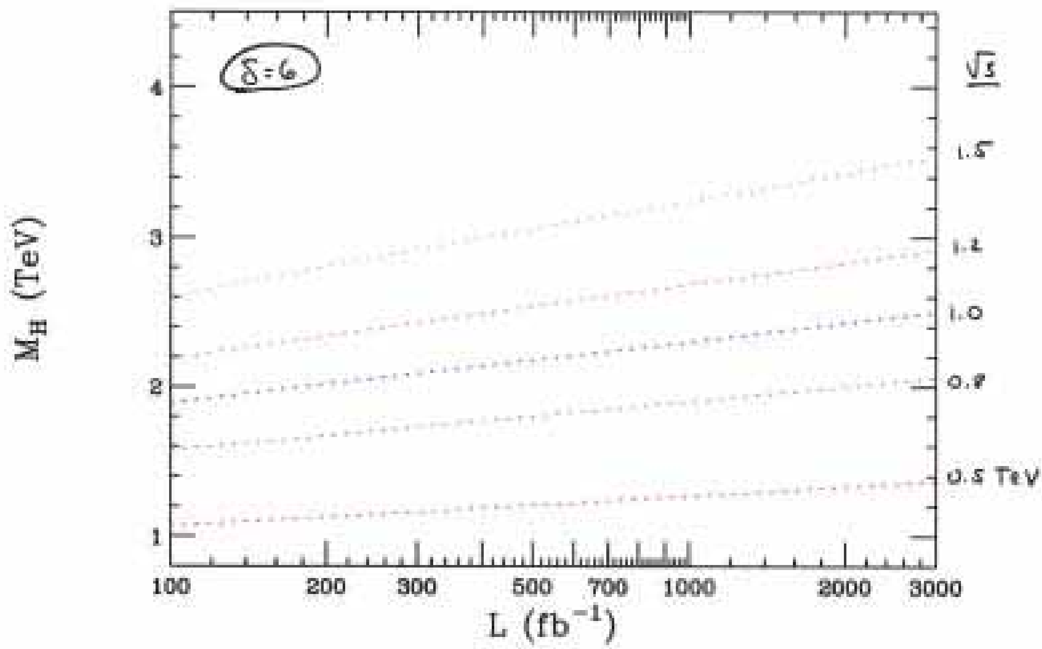


5σ ADD vs RS
δ=4
√s
1.5 TeV
1.2
1.0
0.8
0.5
M_H (TeV)
L (fb^{-1})



5σ ADD vs RS
δ=5
√s
1.5 TeV
1.2
1.0
0.8
0.5
M_H (TeV)
L (fb^{-1})

5σ ADD vs RS differentiation



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