# Unique Graviton Exchange

## Signatures at Linear Colliders

Many new physics scenarios lead to
Contact int-like deviations from the SM
in $e^+e^-$ .....

- $Z'$, compositeness, $\tilde{\nu}$, LQ, BL, extradim's,
  string excitations ......

- IF deviations ARE seen, how do we know which
  [if any of the above!] it is?

- Try fit to various hypotheses... $\boxed{\text{OR}}$

- Look for something unique for graviton exchange
  .. at a single $\sqrt{s}$

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# Unique Graviton Exchange Signatures:

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

$$\frac{1}{\sigma}\frac{d\sigma}{dz} = \frac{3}{8}(1+z^2) + A_{FB}(s)\, z \qquad z = \cos\theta$$

in the SM {or in any LQ/BL, Z′… model}

$$= \frac{1}{2}P_0 + \frac{1}{4}P_2 + A_{FB}(s)\, P_1$$

$P_n = P_n(\cos\theta)$ Legendre Poly's

$$\int_{-1}^{1} dz\; P_n P_m = \frac{2}{n+1}\,\delta_{nm}$$

define: $\langle P_n \rangle \equiv \int_{-1}^{1} dz\, \frac{1}{\sigma}\frac{d\sigma}{dz}\, P_n(z)$

→ $\langle P_0 \rangle = 1$ <u>by definition</u>

→ $\langle P_1 \rangle = \frac{2}{3} A_{FB}$ $\qquad \langle P_2 \rangle = \frac{1}{10}$

→ $\langle P_{n>2} \rangle = 0$

- $Z'/LQ/BL\ldots$ $\qquad \langle P_1 \rangle \neq \langle P_1 \rangle_{SM}$
- $\tilde{\nu}/\cancel{R}$ spin-0 exchange $\qquad \langle P_{1,2} \rangle \neq$ SM values

<u>But</u> $\langle P_{n>2} \rangle$ still $= 0$ !!

$$\frac{d\sigma}{dz} = N_c \frac{\pi\alpha^2}{s} \Big\{ \tilde{P}_{ij} \left[ A^e_{ij} A^f_{ij} (2P_0 + P_2)/3 + B^e_{ij} B^f_{ij} \cdot P_1 \right]$$

$$- \frac{\lambda s}{2\pi\alpha\Lambda_H^4} \tilde{P}_i \left[ (2\underline{P_3} + 3P_1)/5 \, v^e_i v^f_i + a^e_i a^f_i P_2 \right]$$

$$+ \frac{s^4}{16\pi^2\alpha^2\Lambda_H^8} \left[ 16\underline{P_4} + 5P_2 + 14P_0 \right]/35 \Big\}$$

- $\langle P_3 \rangle$ at order $s/\pi\alpha\Lambda_H^4$
- $\langle P_4 \rangle$ at order $( \; " \; )^2$

$\rightarrow$ $\langle P_3 \rangle \neq 0$ will be <u>dominant</u>

$$A_{LR}(z) \equiv \frac{\tilde{P}_{ij} \left[ B^e_{ij} A^f_{ij} (P_2 + 2P_0)/3 + A^e_{ij} B^f_{ij} \cdot P_1 \right] - \frac{\lambda s}{2\pi\alpha\Lambda_H^4} \tilde{P}_i \left[ (2\underline{P_3} + 3P_1)/5 \, a^e_i v^f_i + P_2 v^e_i a^f_i \right]}{\{ \text{above} \}}$$

$\langle P_{3,4} \rangle \neq 0 \implies$ <u>Graviton</u> <u>Exchange</u> !!

(Uniquely !!)

## <u>But</u> not so simple in the <u>real</u> <u>world</u>

(i) finite bin width, $N_{bins}$ + statistics

(ii) Cuts near beam pipe removes full $\theta$ coverage .. [orthonormality !!]

<u>Study</u> 'backgrounds' induced by finite $N_{bins}$ + $\theta_{cut}$.....

$$\langle P_n \rangle = \int_{-1}^{1} \frac{1}{\sigma}\frac{d\sigma}{dz} P_n(z)\, dz \Rightarrow$$

bin center

$$\sum_{bins_i} \left(\frac{N_i}{N}\right) P_n(z_i)$$

{ 'geometric backgrounds' are sensitive to $\theta_{cut}$ + $N_{bins}$

$\Rightarrow$ Real world effects induce spurious geometric 'background' contributions which need to be subtracted using MC of <u>real detector</u> for SM

$N_{bin}$ dependence ... $\Theta_{cut} = 0$

| $N_{bins}$ | $< P_2 > (10^{-2})$ | $< P_4 > (10^{-3})$ | $< P_1 >$ | $< P_3 > (10^{-3})$ |
|---|---|---|---|---|
| 10 | 9.0040 | -26.7585 | 0.66000 | -23.1000 |
| 20 | 9.7503 | -6.8285 | 0.66500 | -5.8188 |
| 50 | 9.9600 | -1.0988 | 0.66640 | -0.9330 |
| 200 | 9.9975 | -0.0687 | 0.66665 | -0.0583 |
| 1000 | 9.9999 | -0.0027 | 0.66667 | -0.0023 |
| $\infty$ | 10.0 | 0.0 | 2/3 | 0.0 |

$\leftarrow$ ("SM")

Table 1: Dependence on $N_{bins}$ for the first four moments of the normalized cross section appearing on the right hand side of Eq.(1). Both $< P_{1,3} >$ are in units of $A_{FB}$.

$N_{bins} = 20$, $\Theta_{cut}$ dependence

$\Theta_{cut}$

| Cut(mr) | $< P_2 > (10^{-2})$ | $< P_4 > (10^{-3})$ | $< P_1 >$ | $< P_3 > (10^{-3})$ |
|---|---|---|---|---|
| 0 | 9.7503 | -6.8285 | 0.66500 | -5.8188 |
| 10 | 9.7428 | -6.8981 | 0.66490 | -5.9156 |
| 50 | 9.5652 | -8.5590 | 0.66251 | -8.2301 |
| 100 | 9.0159 | -13.616 | 0.65508 | -15.341 |
| 200 | 6.9030 | -31.895 | 0.62600 | -41.974 |

Table 2: Dependence on the cut at small scattering angles in milliradions assuming $N_{bins} = 20$ for the first four moments of the normalized cross section appearing on the right hand side of Eq.(1). Both $< P_{1,3} >$ are in units of $A_{FB}$.

e.g,

SM $\sqrt{s} = 500$ GeV

| $f$ | $< P_2 > (10^{-2})$ | $< P_4 > (10^{-3})$ | $< P_1 >$ | $< P_3 > (10^{-3})$ |
|---|---|---|---|---|
| $\mu, \tau$ | 9.58 | -8.58 | 0.319 | -3.97 |
| $b$ | 9.58 | -8.58 | 0.419 | -5.21 |
| $c$ | 9.58 | -8.58 | 0.407 | -5.06 |
| $t$ | 4.41 | -6.87 | 0.269 | -3.34 |

$\langle P_3 \rangle / \langle P_1 \rangle$ Same in all cases "leakage"

note large $m_t$ effects

Table 3: SM values for the various moments of the normalized unpolarized cross section for various flavors as $\sqrt{s} = 500$ GeV. Only the top quark is assumed massive. We take $N_{bins} = 20$ and $\theta_{cut} = 50$mr.

$\Lambda_H = 2$ TeV

| $f$ | $< P_2 > (10^{-2})$ | $< P_4 > (10^{-3})$ | $< P_1 >$ | $< P_3 > (10^{-3})$ |
|---|---|---|---|---|
| $\mu, \tau$ | 8.41 | -8.03 | 0.286 | -12.69 |
| $b$ | 5.41 | -6.65 | 0.376 | -16.04 |
| $c$ | 11.76 | -9.00 | 0.448 | 5.93 |
| $t$ | 5.45 | -7.14 | 0.283 | 3.92 |

note $\langle P_{1,2,4} \rangle$ shifts

Shift in $\langle P_3 \rangle$ large ~ few 100%

$\langle P_3 \rangle / \langle P_1 \rangle$ $f$ dependent

Table 4: Same as the previous table but now assuming $\Lambda_H = 2$ TeV.

toy spin-0 exchange

| $f$ | $< P_2 > (10^{-2})$ | $< P_4 > (10^{-3})$ | $< P_1 >$ | $< P_3 > (10^{-3})$ |
|---|---|---|---|---|
| $\mu, \tau$ | 7.03 | -7.55 | 0.236 | -2.93 |
| $b$ | 4.23 | -6.41 | 0.188 | -2.34 |
| $c$ | 5.78 | -7.04 | 0.248 | -3.08 |
| $t$ | 2.35 | -5.87 | 0.148 | -1.83 |

$\langle P_3 \rangle / \langle P_1 \rangle$ same as SM

Bigger shifts in $\langle P_4 \rangle$

Table 5: Same as the previous table but now assuming the $s-$channel exchange of a 1.1 TeV scalar with universal couplings to all fermions as described in the text.

(Yukawa = e)

Note:

While $\langle P_{1,2} \rangle$ shifts occur for gravity (+ toy spin-0 model) - they are <u>Not</u> Graviton Signatures !!!

THEY <u>ARE</u> new Physics signatures...
just NOT UNIQUE to gravity.

We only care about

$$\underline{\langle P_{3,4} \rangle} \quad !$$

Look at $\frac{1}{\sigma}\frac{d\sigma}{dz} \sim \frac{d\sigma^+ + d\sigma^-}{dz}$

and $\sim P \frac{d\sigma^+ - d\sigma^-}{dz}$

$\{$stat, lumi, pol, ...

$$\chi^2 = \sum_{dist}\sum_{f}\sum_{n=3,4} \left(\langle P_n\rangle - \langle P_n\rangle_{sm}\right)^2 / err_{nf}^2$$

$\geq 25$ $\qquad$ ($\chi^2_{sm} = 0$ by definition)

$\delta L/L = 0.25\%$ , $\delta P/P = 0.3\%$ etc

$\rightarrow$ $e^+e^- \rightarrow f\bar{f}$ ID reach for gravity [Plot]

$\rightarrow$

- This method will work for processes w/o u- or t-channel poles ...

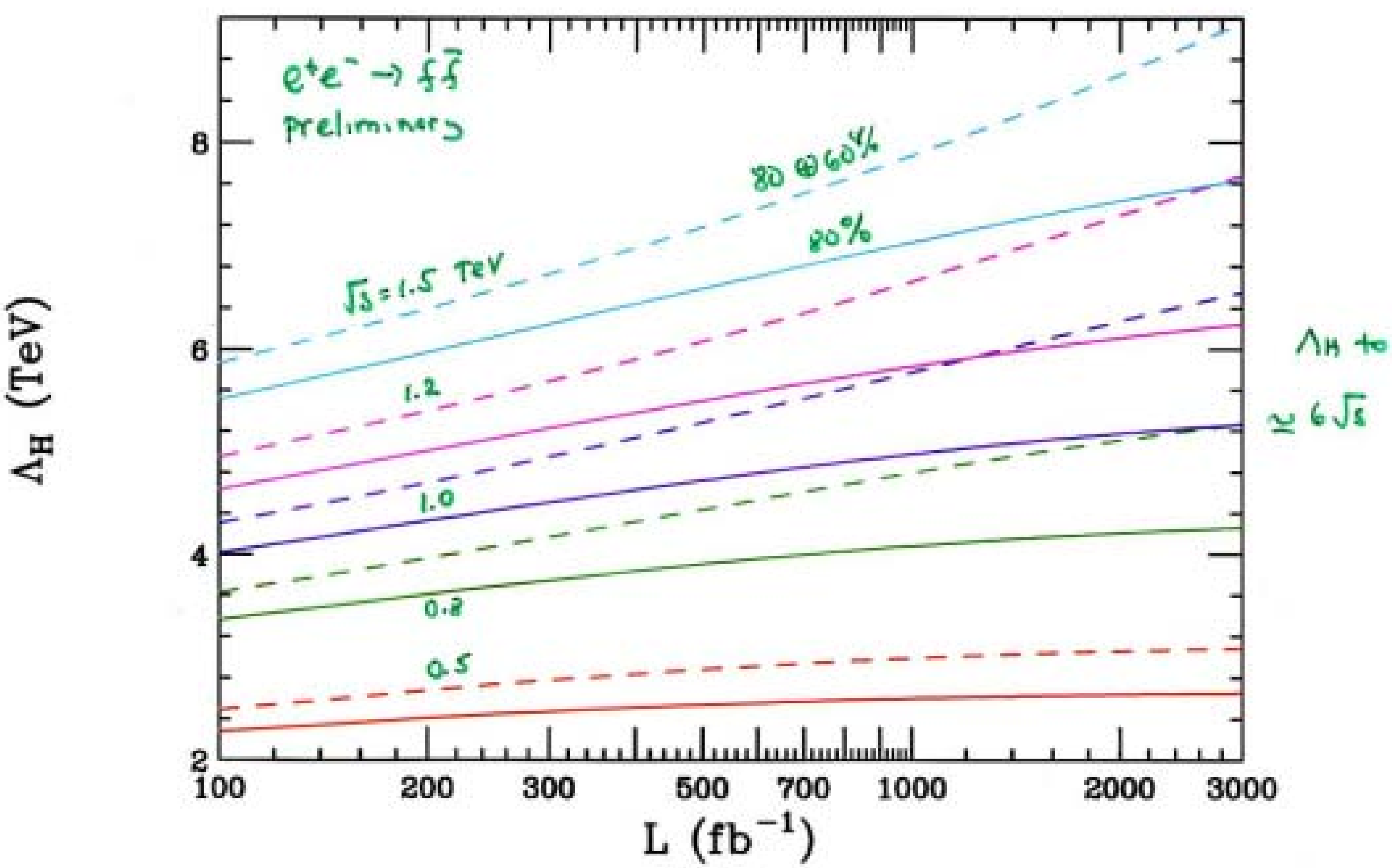
( $\rightarrow$ they contain all $P_n$ , e.g., )

$\times$ $e^+e^- \rightarrow e^+e^-$, $\gamma\gamma$, $ZZ$ $\qquad$ $e^-_L e^+_{(R)} \rightarrow W^+W^-$ $\times$

However $\qquad$ $e^-_R e^+_{(L)} \rightarrow W^+W^-$ is pure s-channel :

$+$ $\frac{1}{\sigma}\frac{d\sigma}{dz} = a_0 P_0 + a_2 P_2$ in SM $\{$or Z' ...$\}$

5σ ID Reach



$e^+e^- \to f\bar{f}$
preliminary
80 ⊕ 60%
80%
$\sqrt{s}$ = 1.5 TeV
1.2
1.0
0.8
0.5
$\Lambda_H$ to
$\simeq 6\sqrt{s}$
$\Lambda_H$ (TeV)
L ($fb^{-1}$)
2
4
6
8
100
200
300
500
700
1000
2000
3000

note

again, Gravity induces $\left\{ \begin{array}{l} \langle P_1 \rangle \\ \langle P_3 \rangle, \langle P_4 \rangle \neq 0 \end{array} \right.$

For ALL final state $W^+W^-$ polarizations

$\rightarrow$ <u>not</u> $Z'$ <u>or</u> contact int $\left[ \sim \bar{e} e\, W_{\mu\nu} W^{\mu\nu} \right]$

($\langle P_2 \rangle$ deviation only)

But anomalous couplings <u>do</u> induce $\left\{ \begin{array}{l} \langle P_1 \rangle, \\ \langle P_{3,4} \rangle \neq 0 \ldots \end{array} \right.$

$$\frac{d\sigma}{dz} = \frac{\pi \alpha^2}{2s} \beta \left( \Sigma_{TT} + \Sigma_{TL+LT} + \Sigma_{LL} \right) \qquad (e^-_R e^+_L)$$

$$\Sigma_{TT} = 2\beta^2 F_1^2 (1-z^2)$$

$$\Sigma_{LL} = (1-z^2) \frac{\beta^2 s^2}{4 M_W^4} \left\{ F_3 - (1 - 2M_W^2/s) F_1 + \frac{\beta^2 s}{2 M_W^2} F_2 \right\}^2$$

$$\Sigma_{LT+TL} = \frac{s\beta^2}{2M_W^2} \Big\{ (F_3 + \beta \underline{z} F_5)^2 (1+z^2) + F_5^2 (1-\underline{z}^2)^2 + 2(F_3 + \beta \underline{z} F_5)\, \underline{z} (1-\underline{z}^2) F_5 \Big\}$$


$$F_5 \sim g_5^V \epsilon^{\mu\alpha\beta\rho} (q - \bar{q})_\rho \quad (\not{C}, \not{P})$$

(appears at 1-loop in SM)$_{VVA}$

<u>BUT</u> $\langle P_1 \rangle, \langle P_{3,4} \rangle \neq 0$ <u>only</u> for TL+LT final state

$\Rightarrow$ $\langle P_{1,3,4} \rangle \neq 0$ in $e^-_R e^+ \to W^+W^-$

Excludes $Z'$ / contact int'$s$ AND

$\langle P_{1,3,4} \rangle \neq 0$ in TT/LL excludes

$g_5^V$ anomalous coupling as source

IF a pure RH $e^-$ beam WERE available + pure TT + LL W polarizations THEN

$\chi^2$ w/ $\langle P_{1,3,4} \rangle \to$ ID reach [fig]

However

We don't have 100% RH $e^-$ ....

What can we do ?

$\to$ What happens w/ 60% $e^+$ + 80% $e^-$ (or even 90% + 90%) ?

- Since $d\sigma_R \ll d\sigma_L$ the 'background' from the $e^-_L e^+ \to W^+W^-$ piece is still very large ...

$\therefore$ SO LARGE that $\langle P_{1,3,4} \rangle$ are large and shifts can be due to, e.g., $Z'$ not just gravity

$\to$ NP not gravity signal !! [Fig]

$e^+e^- \to W^+W^-$

$\sqrt{s} = 500$ GeV

| | $<P_2>(10^{-1})$ | $<P_4>(10^{-3})$ | $<P_1>(10^{-2})$ | $<P_3>(10^{-2})$ | |
|---|---|---|---|---|---|
| SM | -2.14 | -6.94 | 0.0 | 0.0 | only RH |
| $\Lambda_H = 2$ TeV | -2.16 | -8.88 | -4.88 | 2.46 | |
| ① SM' | 1.05 | -113.30 | 44.24 | -13.07 | mixed |
| ② SM" | -1.11 | -41.33 | 14.30 | -4.22 | |

Table 6: Moments of the normalized $W$ pair production cross section assuming purely right-handed electrons and isolating the $TT + LL$ final states at $\sqrt{s}$=500 GeV. An angular cut $|\cos\theta| \leq 0.9$ has been applied. The SM prediction is compared with that for KK graviton tower exchange. Also shown is the SM prediction, labelled by SM'(SM") for the case of 80% right-handed $e^-$ and 60% left-handed $e^+$ polarization(both beams with 90% polarization.)

① $P_{e^-} = -80\%$ $\quad P_{e^+} = 60\%$

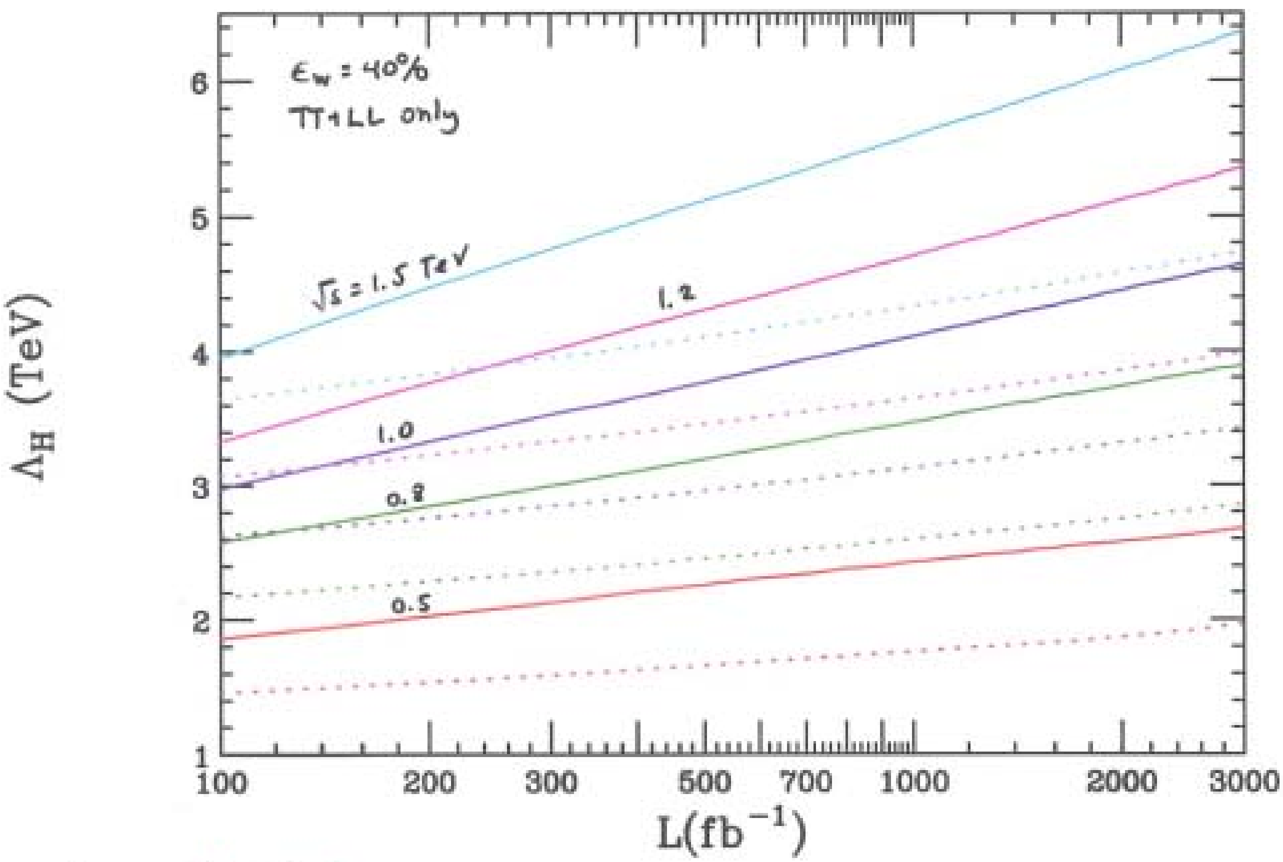
② $P_{e^-} = -90\%$ $\quad P_{e^+} = 90\%$

Show large LH contamination not allowing unique gravity signature

Solid = pure RH $e^-$

dots = $\begin{cases} 80\% \text{ RH } e^- \\ 60\% \text{ LH } e^+ \end{cases}$

5σ ID reach




w/ 80% RH $e^-$ 60% LH $e^+$ → <u>NOT</u> ID reach !

∴ We need to <u>ISOLATE</u> $d\sigma_R$ w/ only $\tau\tau + LL$ final states

• Measure $d\sigma$ w/ various polarizations

⇒ + combine to get $d\sigma_R$

e.g.

$P_{e^-} = -80\%$ $P_{e^+} = +60\%$ ⊕ $P_{e^-} = 80\%$, $P_{e^+} = -60\%$

$d\sigma_1 = (1.8)(1.6)\, d\sigma_R + (0.2)(0.4)\, d\sigma_L$ w/ $\tau\tau \oplus LL$ only

$d\sigma_2 = (0.2)(0.4)\, d\sigma_R + (1.8)(1.6)\, d\sigma_L$

→ "solve" for $\boxed{d\sigma_R}$

But don't forget $\delta P/P \neq 0$ ! [Fig]

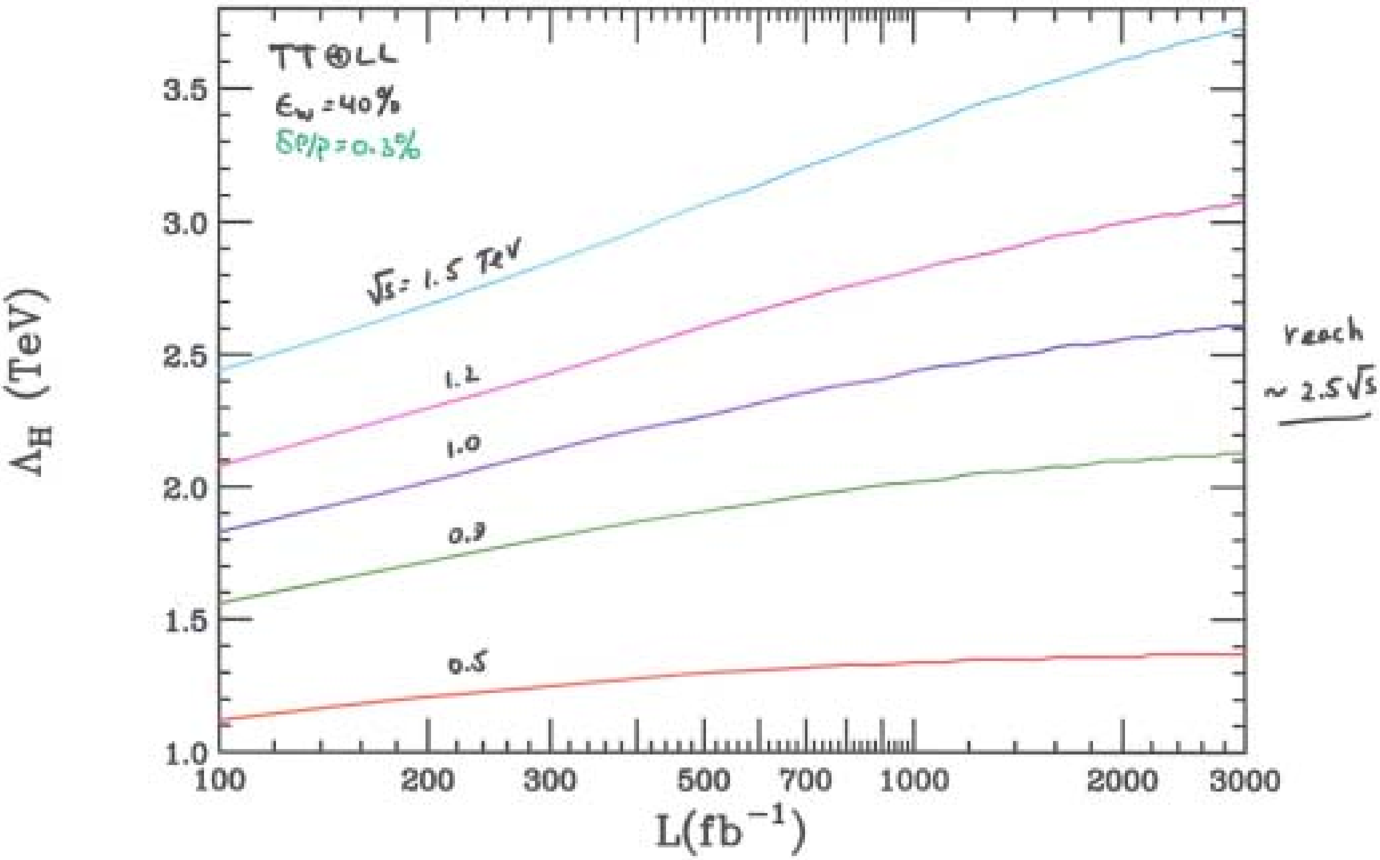
Coefficients must be precisely known

$\delta P$ → error on coeff's !!

ID reach is only $\sim 2.5\sqrt{s}$ ! <u>vs</u>

$\underline{\sim 6\sqrt{s}}$ for $f\bar{f}$

fit to $e^-_R e^+ \to W^+W^-$ extracted



# Conclusions

- Graviton exchange signatures can be $\boxed{\text{uniquely}}$ ID'd in $e^+e^- \to f\bar{f}$ and, possibly, $e^-_R e \to W^+W^-$
- More work needs to be done to really understand how well this can be done