❼ Alternative Theories

- Contact interactions
- Models with Z's
- Extra dimensions
- Conclusions

Contact Interactions

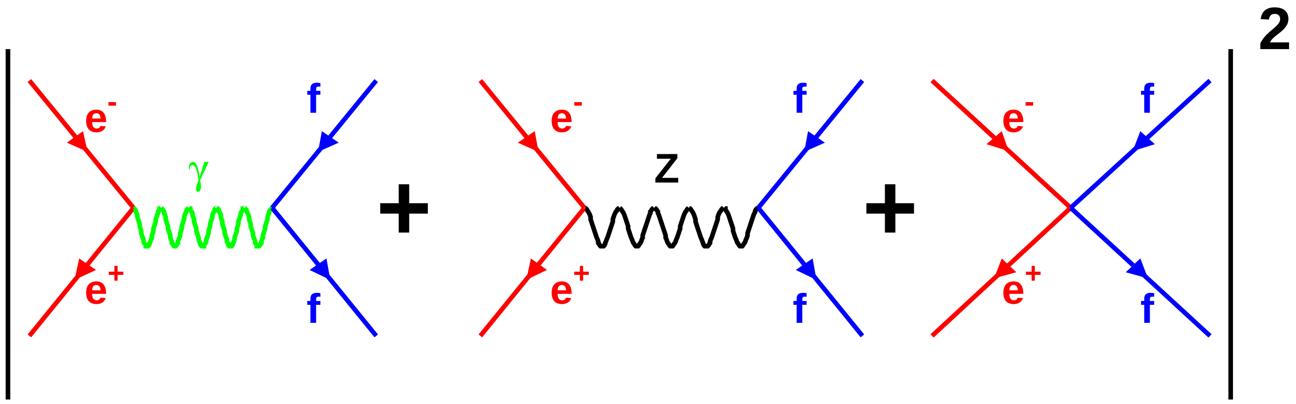
Very heavy exchange-particle: Propagator $\propto \frac{1}{M^2}$
Effective Lagrangian:

$$\mathcal{L}_{eff} = \sum_{i,k=L,R} \lambda^2_{ik}/M^2 \alpha^{ik} (\bar{e}_i \gamma^\mu e_i)(\bar{f}_k \gamma^\mu f_k)$$

with $\alpha^{ik} = \pm 1$

Scale-parameter $\Lambda^2 = \frac{4\pi M^2}{\lambda^2}$

(e.g. μ decay $\Lambda = \left(\sqrt{2} G_\mu\right)^{-1/2} \sim 250\,\mathrm{GeV}$)



$$\frac{d\sigma}{d\cos\theta} = SM(s,t) + C_2(s,t)\frac{1}{\Lambda^2} + C_4(s,t)\frac{1}{\Lambda^4}$$

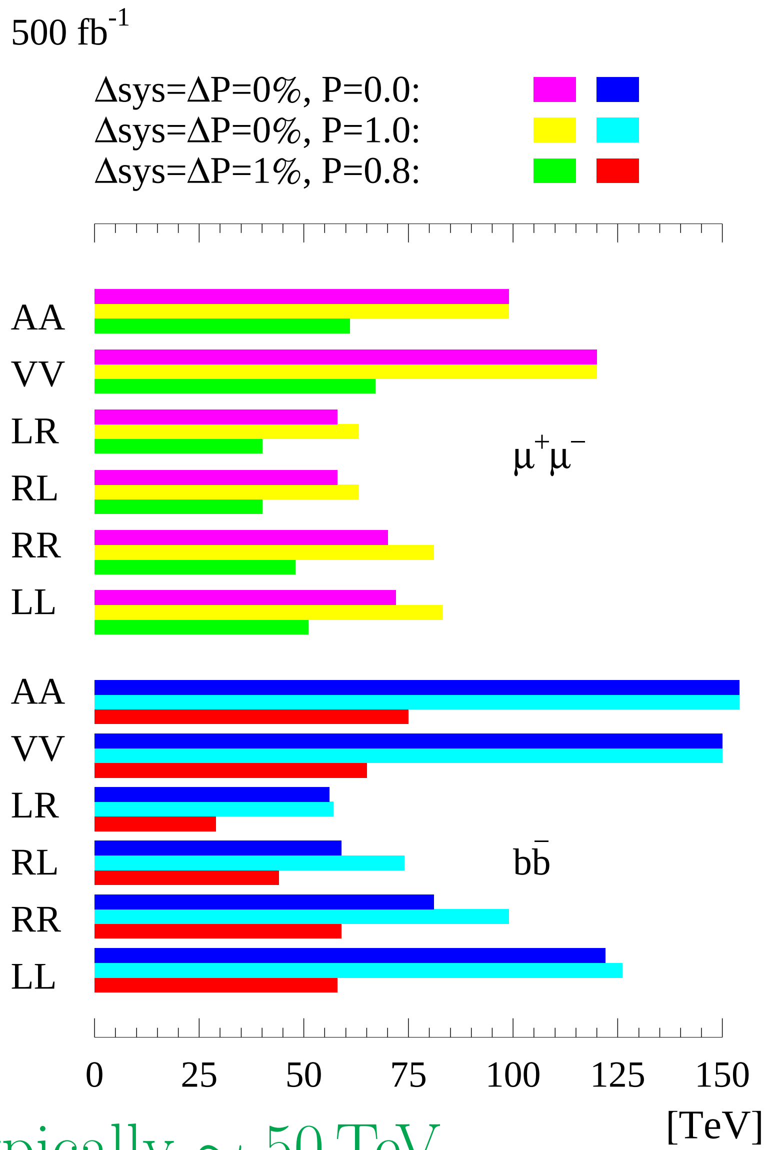
(Equivalent to t-channel exchange of a heavy scalar with mass M and coupling λ)

Main sensitivity is in interference term, so large dependence on helicity structure

Assumptions

- $\sqrt{s} = 500\,\text{GeV},\ \mathcal{L} = 500\,\text{fb}^{-1}$
- b-tagging efficiency $\varepsilon_\text{b} = 60\%$
- systematic error 0, 1% (pessimistic)

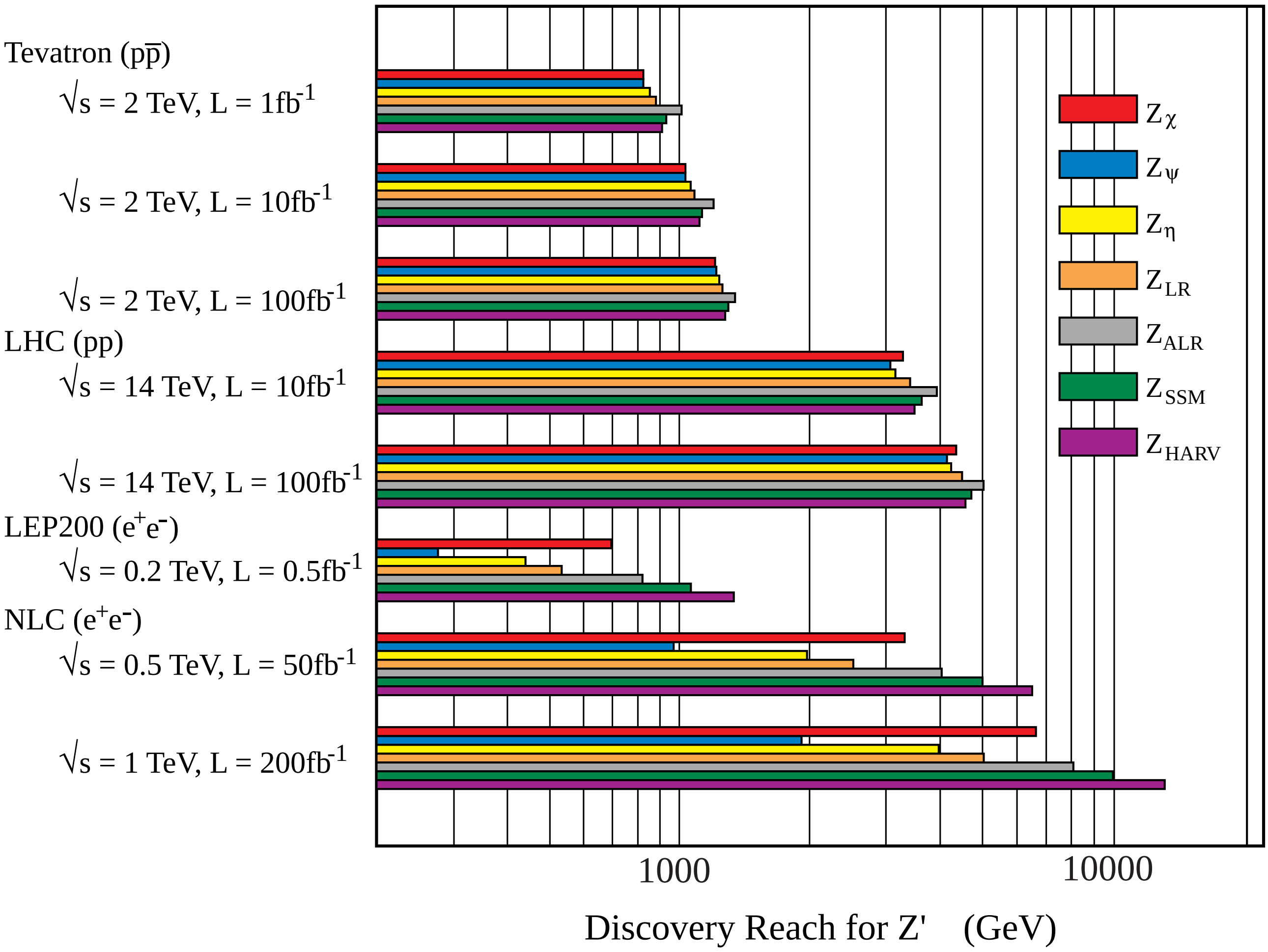
Results



- limits typically ~ 50 TeV
- systematics will dominate, otherwise $\Lambda_\text{lim} \propto \mathcal{L}^{1/4}$
- polarization helps little
- LHC reach similar but in different channels

Models with Z's

- models with extended gauge groups (left-right-symmetric, E_6) normally require additional Z-bosons
- in principle Z and Z' mix, however $Z - Z'$ mixing angle tightly constrained by Z-precision data
- for direct production LHC reaches much higher Z'-limits than LC ($\sim 3\,\text{TeV}$)
- however for $\text{f}\bar{\text{f}}$-production Z'-exchange interferes with Z and γ exchange so that Z'-effects remain visible for $m_{Z'} \gg \sqrt{s}$
  (in the same way PEP and PETRA could measure properties of the Z)
- measurement of cross sections and asymmetries gives access to vector- and axial-vector-couplings separately
- model dependent analyzes:
  - assume a given model
  - ➡ all couplings are defined
  - can use leptonic and hadronic events
  - deviations from SM prediction translate directly into Z'-mass



- (very moderate Luminosity assumptions for LC, however statistical scaling only with $\mathcal{L}^{1/4}$ and large contributions from Luminosity systematics)
- on average limits comparable to LHC
- however much larger difference between models, since sensitivity is in interference term
- on the contrary LC is not sensitive to the total width of the Z'

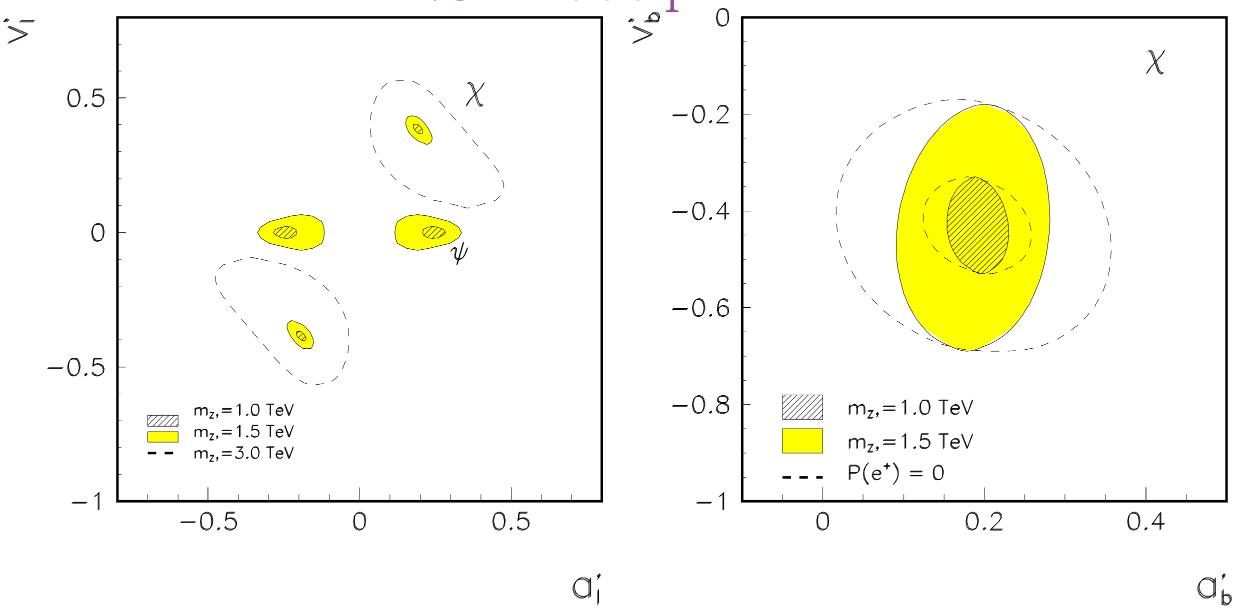
- model independent analyzes:
  - LC sensitive to normalized couplings

$$a_f^N = a'_f \sqrt{\frac{s}{m^2_{Z'} - s}}$$
$$v_f^N = v'_f \sqrt{\frac{s}{m^2_{Z'} - s}}$$

  - for leptons can obtain model independent limits/measurements on normalized couplings
  - all hadronic observables depend on product of leptonic couplings (Z'-production) and hadronic couplings (Z'-decay)
  - ➡ can measure hadronic couplings only if leptonic couplings deviate significantly from zero
- experimental assumptions:
  - beam polarizations 90/60% with $\Delta\mathcal{P}/\mathcal{P} = 1\%$
  - luminosity known to 0.5%
  - leptons can be tagged with $\varepsilon = 95 \pm 0.5\%$
  - b quarks can be tagged with $\varepsilon = 60 \pm 0.6\%$
  - measure cross sections, A_{LR} and A_{FB}^{ℓ}

Ideal case: LHC discovers a Z', so mass is known and LC can measure the couplings

95% c.l. contours for $\sqrt{s} = 500\,\mathrm{GeV}$ and $\mathcal{L} = 500\,\mathrm{pb}^{-1}$



- measure leptonic couplings to few % and b-couplings to $\sim 10\%$ for $m_{Z'} = 1.5\,\mathrm{TeV}$
- limits should roughly stay constant for $m_{Z'}/\sqrt{s} = \mathrm{const}$
- the LC can distinguish the models over basically the full LHC discovery range

Large extra dimensions

Hierarchy-problem:

Why is $m_{\mathrm{H}} \sim 100\,\mathrm{GeV} \ll \mathrm{M}_{\mathrm{pl}} \sim 10^{19}\,\mathrm{GeV}$?

Possible answers:

- SUSY (already seen)
- in reality is $\mathrm{M}_{\mathrm{pl}} \sim 100\,\mathrm{GeV}$ but it appears so large because gravity lives in $4+n$ dimensions

$$\mathrm{M}_{\mathrm{pl}}^2 = \mathrm{M}_{\mathrm{D}}^{2+\mathrm{n}}\mathrm{R}^{\mathrm{n}}$$

R : compactification radius of extra dimensions

$$\Rightarrow R = \mathrm{M}_{\mathrm{pl}}^{\frac{2}{\mathrm{n}}}\mathrm{M}_{\mathrm{D}}^{-(\frac{2}{\mathrm{n}}+1)}$$

$$\sim 10^{\frac{30}{n}-17}\left(\frac{1\,\mathrm{TeV}}{\mathrm{M}_{\mathrm{D}}}\right)^{1+\frac{2}{n}}\,[\mathrm{cm}]$$

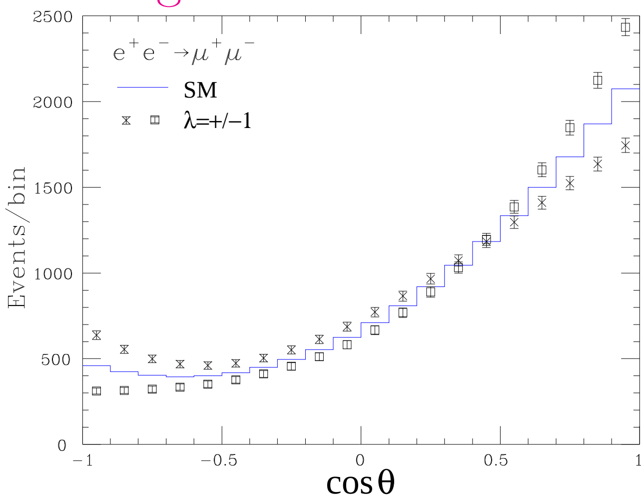
$n=1$	$R=\mathcal{O}(10^{13}\mathrm{cm})$	excluded
$n=2$	$R=\mathcal{O}(1\mathrm{mm})$	~excluded
$n=7$	$R=\mathcal{O}(1\mathrm{fm})$	

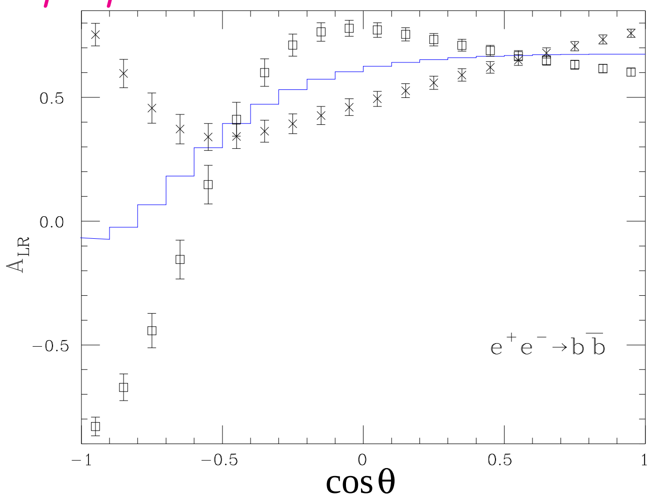
Experimental signatures:

- In the bulk of the extra dimensions there live a huge number of graviton states (Kaluza-Klein towers G^*)

➠ Expect effects in single γ production
($e^+e^- \to \gamma G^*$, G^* invisible)
and fermion pair production
($e^+e^- \to G^* \to f\bar{f}$)

e.g. G^*-effects in $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to b\bar{b}$





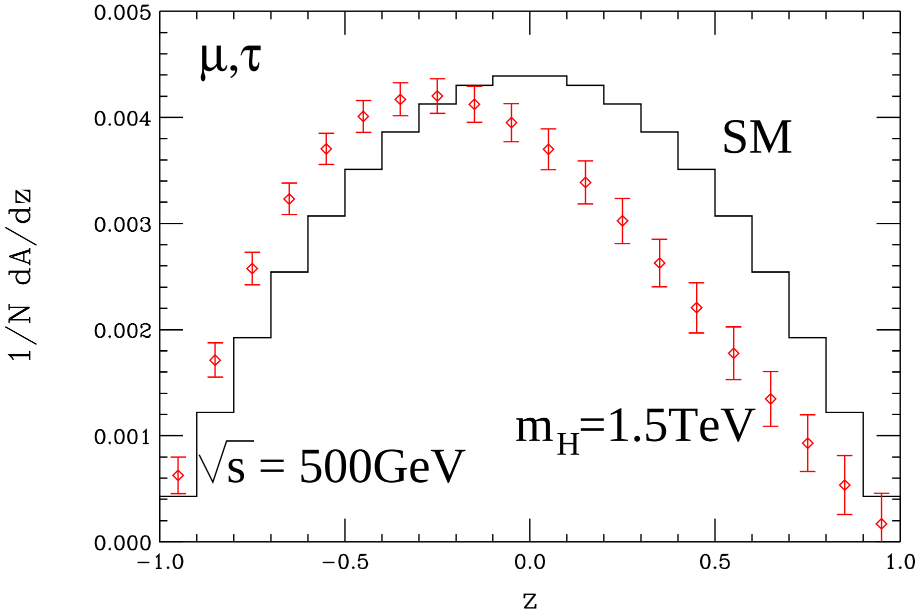
- LC limit $M_D < 4(7)$ TeV for $\sqrt{s} = 0.5(1)$ TeV
- LHC comparable
- $\cos\theta (= z)$ dependence very different from Z'

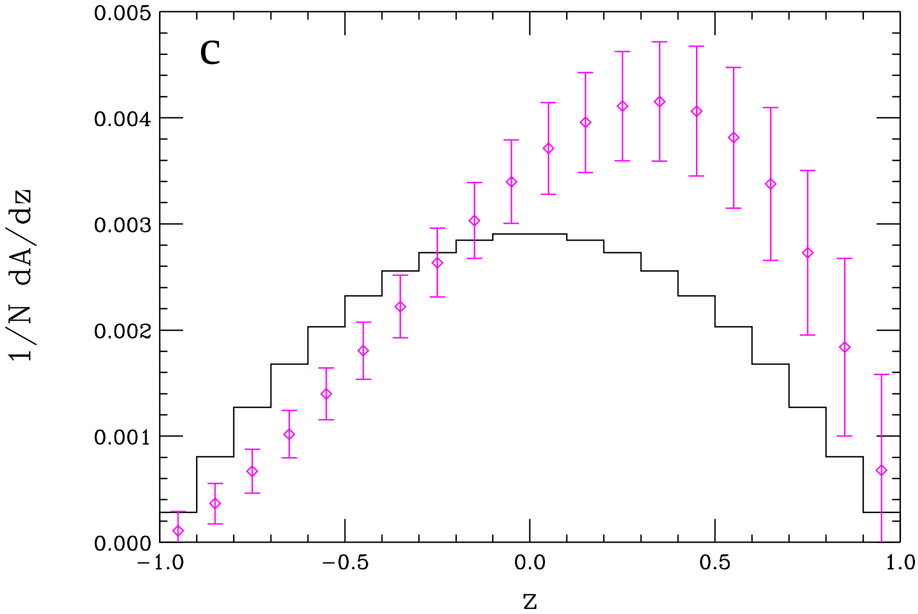
Additional possibility: transverse polarization

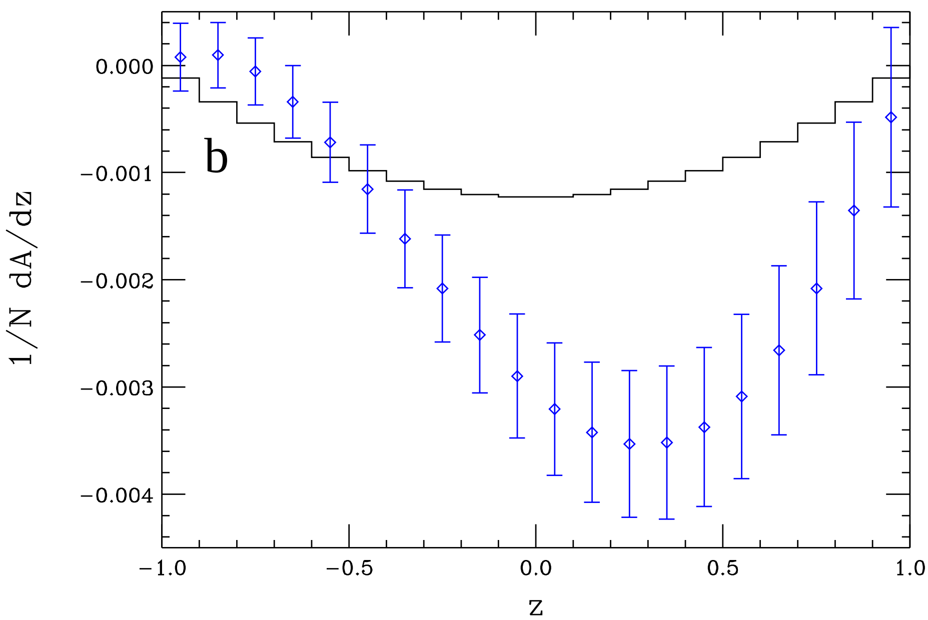
- with transverse beam polarization there exists an azimuthal asymmetry depending on $\cos\theta \longrightarrow$ plot
- this asymmetry is symmetric in $\cos\theta$ for vector or scalar particle exchange
- for tensor exchange (gravitons) it receives an asymmetric component

➠ Graviton and Z' exchange can be distinguished up to $M < 10\sqrt{s}$

- extra dimensions can be excluded up to $M_D <$ 10(22) TeV for $\sqrt{s} = 0.5(1)$ TeV
  (highest reach at next generation colliders)


μ,τ
SM
m_H=1.5TeV
$\sqrt{s}$ = 500GeV
1/N dA/dz
z
0.005
0.004
0.003
0.002
0.001
0.000
−1.0
−0.5
0.0
0.5
1.0


c
1/N dA/dz
z
0.005
0.004
0.003
0.002
0.001
0.000
−1.0
−0.5
0.0
0.5
1.0


b
1/N dA/dz
z
0.000
−0.001
−0.002
−0.003
−0.004
−1.0
−0.5
0.0
0.5
1.0

Conclusions on alternatives

- The LC is sensitive to a "General new physics scale" of order 50 TeV
- In concrete models (Z', extra dimensions) this translates into mass scales of few TeV
- LC and LHC have similar reach but are highly complementary
  - The LC is mainly sensitive to $e^+e^-\ell^+\ell^-$ and $e^+e^-b\bar{b}$ couplings while LHC is sensitive to $\ell^+\ell^-q\bar{q}$ (q=u,d)
  - LHC mainly sees the pure new physics while LC sees its interference with the SM
  - The LHC can discover that there is "something new" by seeing a resonance, then the LC can distinguish models by measuring the couplings