Z', Z_{KK}, Z^* and all that:

current bounds and theoretical prejudices
on a heavy neutral vector boson

Roberto Contino - CERN

The case of a “standard” Z′

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} Z'_{\mu\nu} Z'^{\,\mu\nu} + g_{Z'}^{[\Psi]} \sum_a Z'_\mu \, \bar{\Psi}_a z_a \gamma^\mu \Psi_a$$

$$+ g_{Z'}^{[H]} \, H^\dagger z_H Z'_\mu \, i D^\mu H + h.c. + \ldots$$

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Z' - Z mixing after EWSB

- common assumptions:

1. same strength for the coupling to the SM fermions and the Higgs: $$g_{Z'}^{[\Psi]} = g_{Z'}^{[H]} = g_{Z'}$$
2. couplings are flavor universal (so as to avoid large FCNC)

- most popular models: heavy Z, Left-Right, E_6, (B-L), etc ....

example:

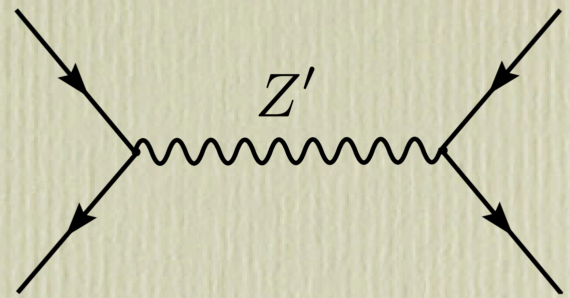
$E_6 \to SO(10) \times U(1)_\psi$

	Heavy Z (SSM)	Z_ψ from E_6
$g_{Z'}$	$g_2/\cos\theta_W$	$g_2 \tan\theta_W$
charges	$\left(T_{3_L} - Q\sin\theta_W^2\right)$	$\sqrt{\frac{72}{5}}\,Q_\psi$
$\begin{pmatrix}\nu_L \\ e_L\end{pmatrix}$	$+\frac{1}{2}$ $-\frac{1}{2} + s_W^2$	$+1$
ν_R	0	-1
e_R	s_W^2	-1
$\begin{pmatrix}u_L \\ d_L\end{pmatrix}$	$+\frac{1}{2} - \frac{2}{3}s_W^2$ $-\frac{1}{2} + \frac{1}{3}s_W^2$	$+1$
u_R	$-\frac{2}{3}s_W^2$	-1
d_R	$\frac{1}{3}s_W^2$	-1
H	$-\frac{1}{2}$	-2

Bounds from LEP precision tests

- A heavy Z' affects:

  1. LEP**2** (off-pole) observables



four-fermion operators

$$\propto \frac{g_{Z'}^{[\Psi]\,2}}{M_{Z'}^2}$$

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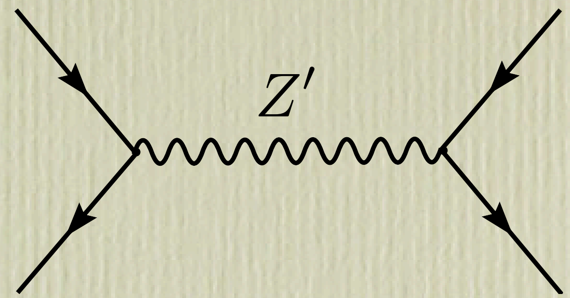

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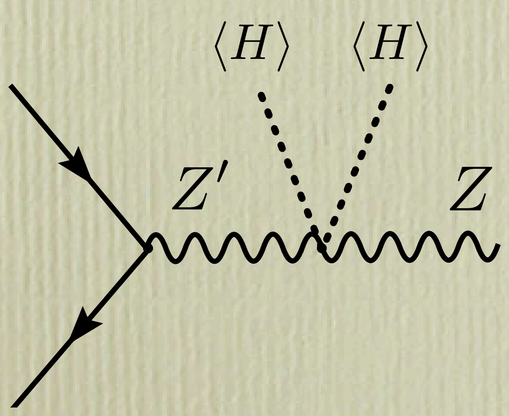
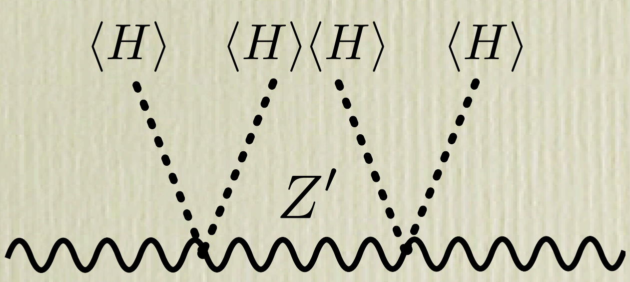
four-fermion operators

1. LEP**1** Z-pole observables only via the Z'-Z mixing (i.e. $g_{Z'}^{[H]}$)



$\propto \frac{g_{Z'}^{[H]} g_{Z'}^{[\Psi]}}{M_{Z'}^2}$



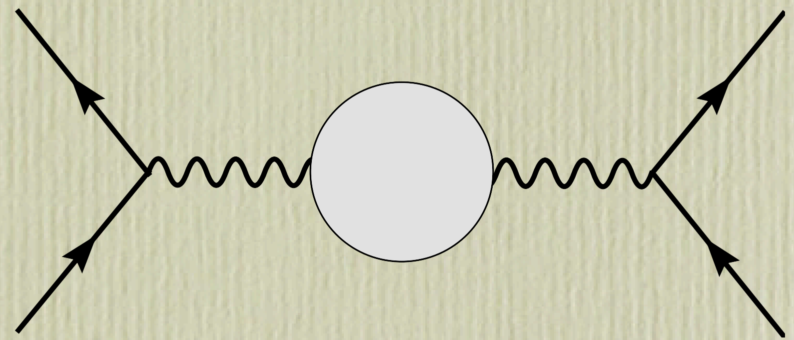
$\propto \frac{g_{Z'}^{[H]\,2}}{M_{Z'}^2}$

vertex corrections (incl. $\hat{S}$)

$\Delta\rho$ (aka $\hat{T}$)

- A universal (oblique) Z' :

one whose corrections can be recast purely as modifications of the SM gauge boson self-energies



$\longrightarrow \quad \hat{S},\ \hat{T},\ W,\ Y$

[Barbieri et al. NPB 703 (2004) 127]

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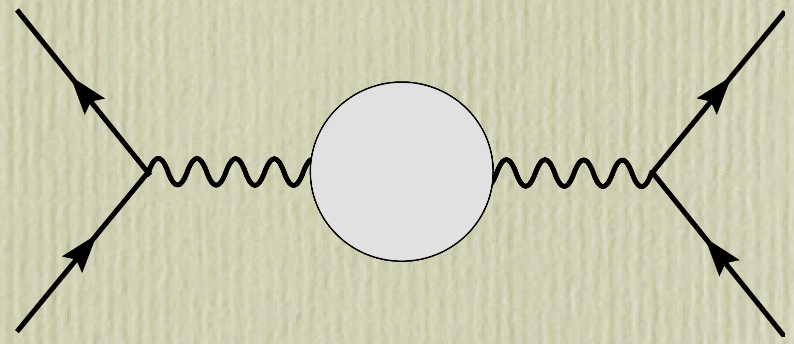

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[Barbieri et al. NPB 703 (2004) 127]

Examples:

✓ heavy hypercharge: universal

- heavy $Z, (B-L),\ Z_\psi$: not universal

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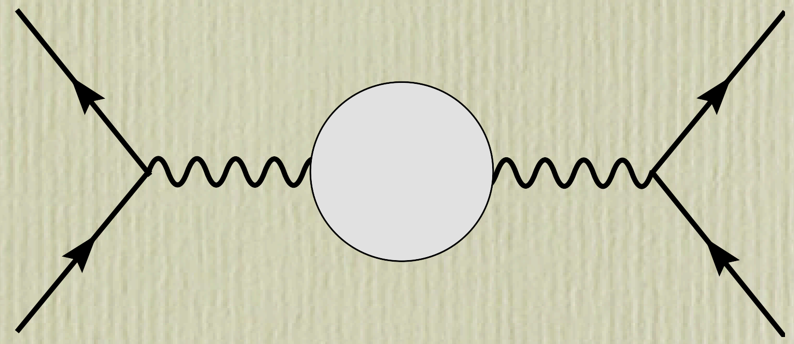

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Examples:

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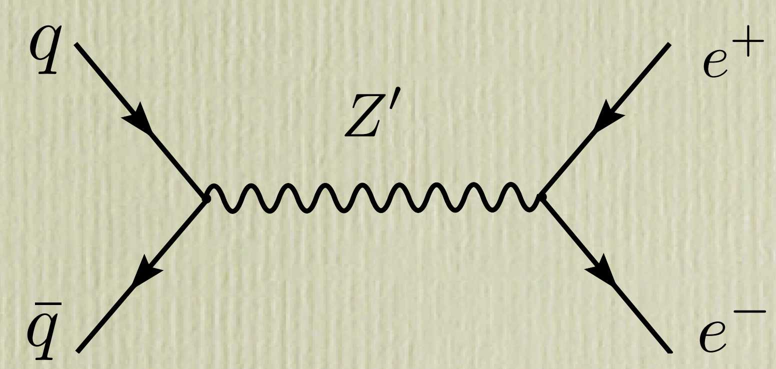
☞ Notice: the oblique basis usually does not coincide with the mass-eigenstates basis

Tevatron exclusion limits

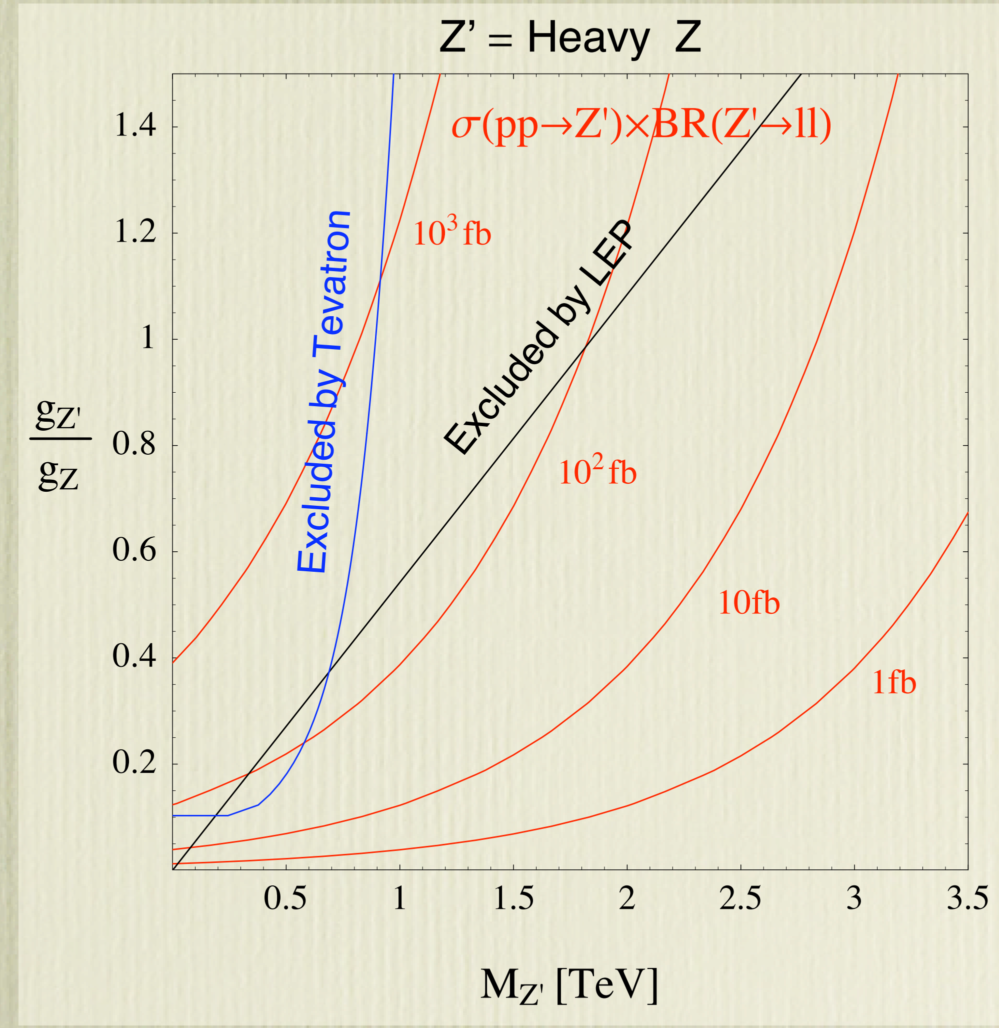
D0 and CDF search for Z'
production in Drell-Yan scattering:



☞ I will use the bounds from CDF RunII with 1.3 fb^{-1} :

[Phys Rev Lett 99 (2007) 171802 ; arXiv:0707.2524]

The case of a heavy Z (SSM)



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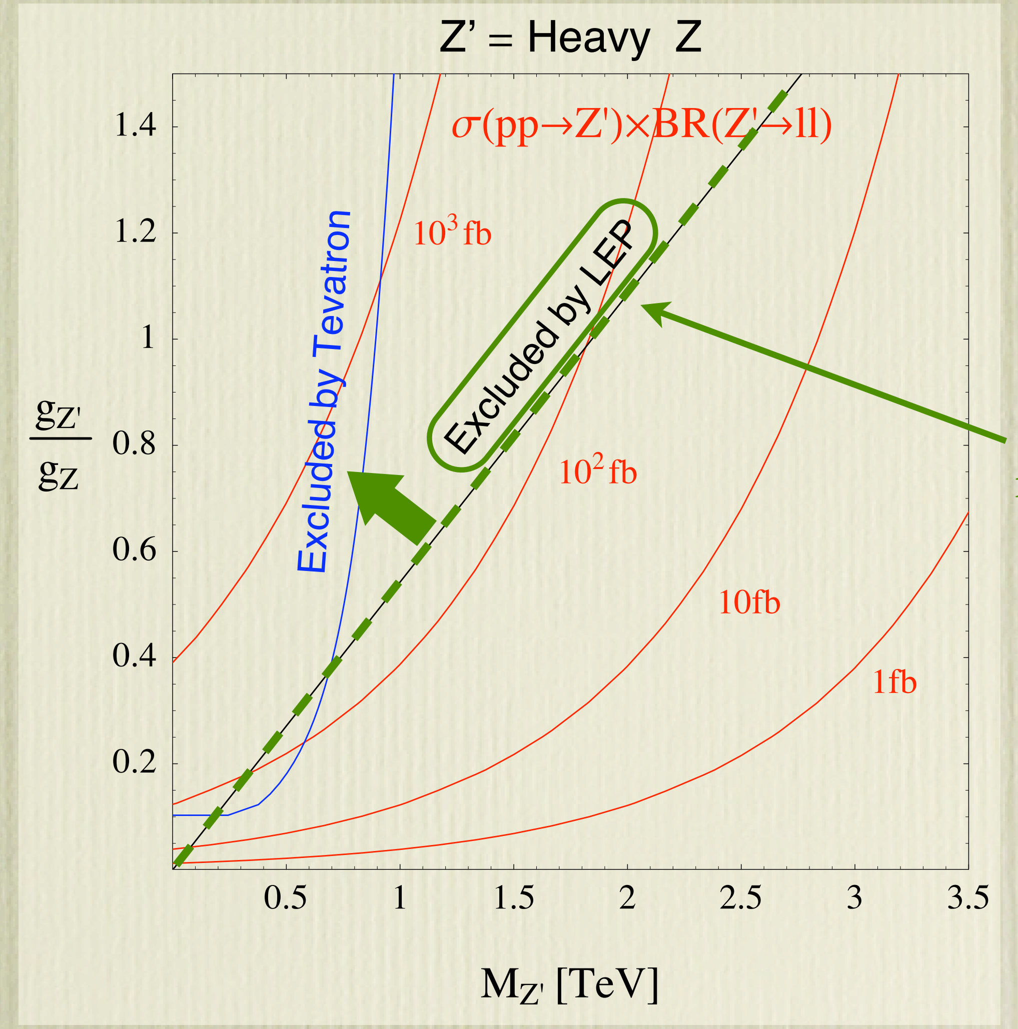

99% CL exclusion limit from LEP precision tests

fit from:

Cacciapaglia et al. hep-ph/0604111

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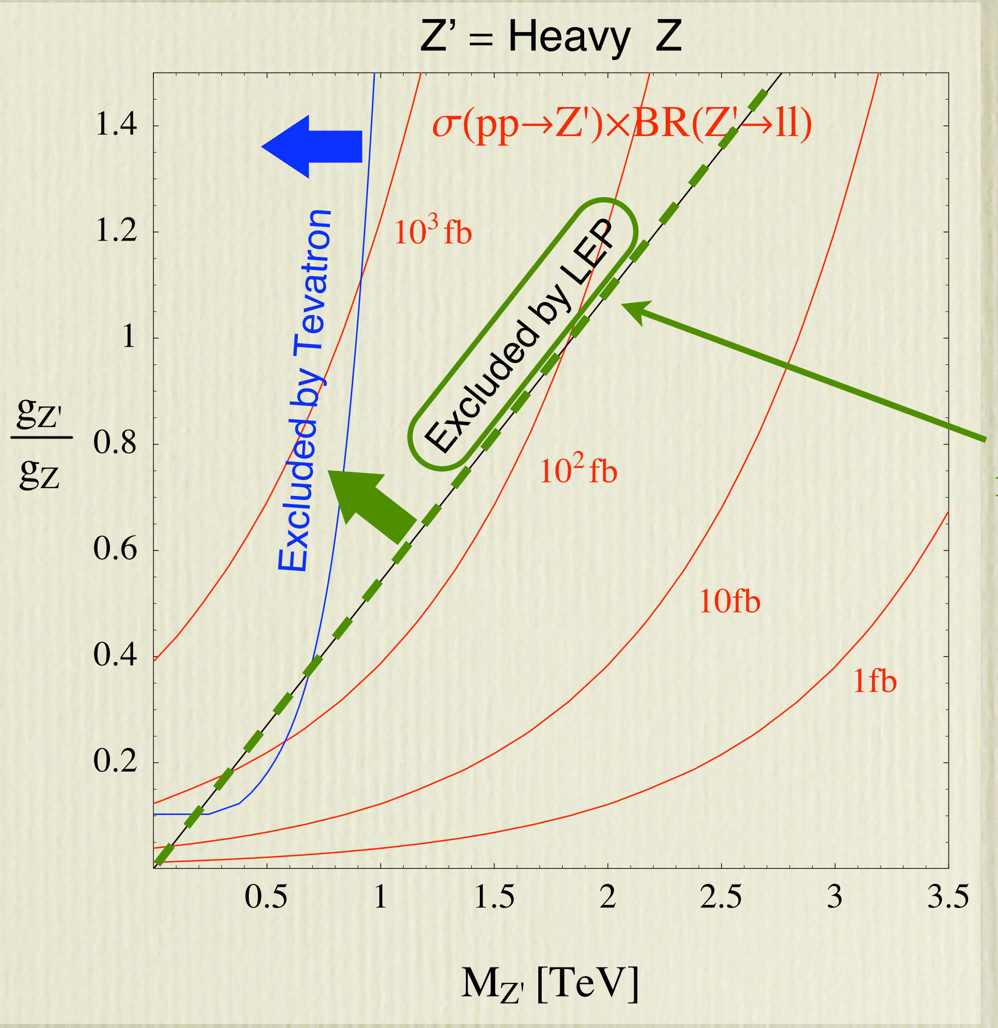

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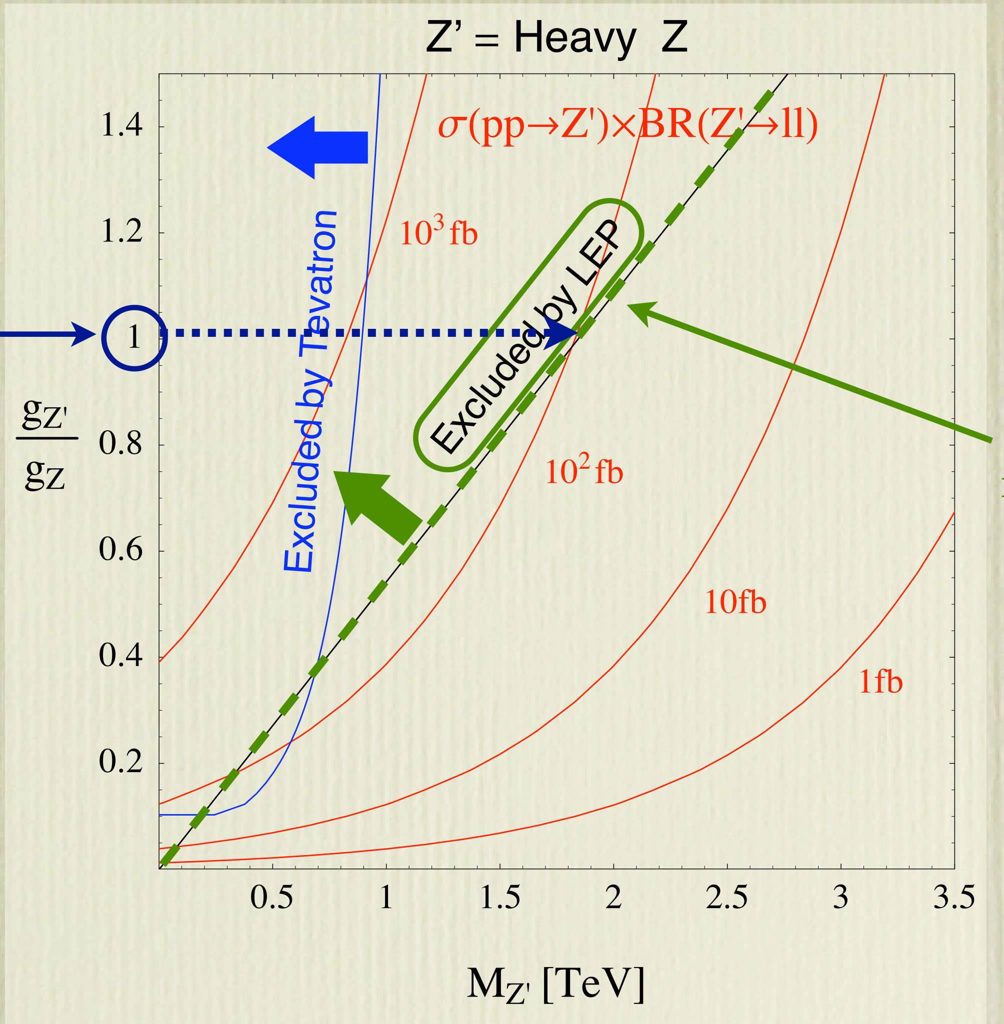
The case of a heavy Z (SSM)

SM coupling implies a bound

$M_{Z'} \lesssim 1.8\,\text{TeV}$



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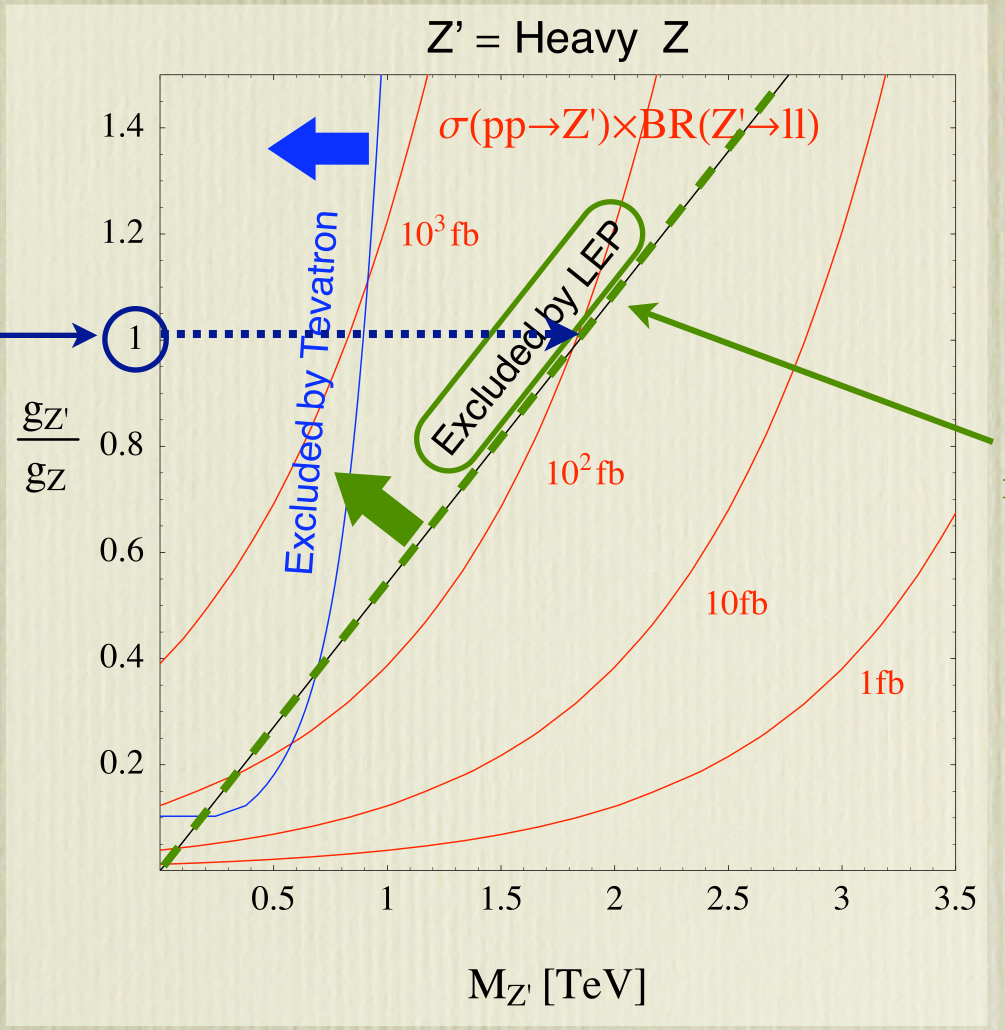

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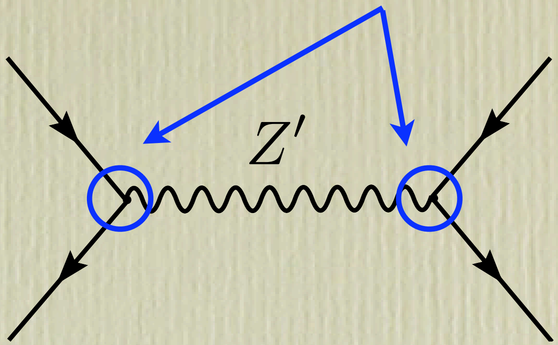
☞ **Moral**: strong couplings seem excluded... ... really true ?

$g_{Z'}^{[\Psi]}$ cannot be strong

Bounds on contact interactions from LEP**2** quite robust :



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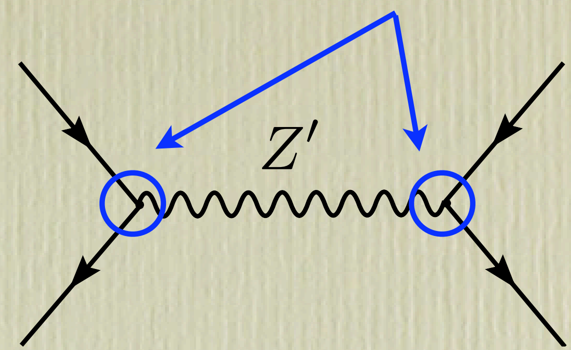

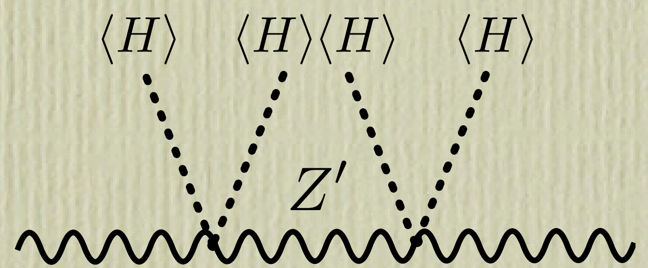

$$\propto \frac{g_{Z'}^{[H]\,2}}{M_{Z'}^2}$$

the strong bound on

$$\Delta\rho \propto [\Pi_{11}(0) - \Pi_{33}(0)]$$

can be avoided with a custodial symmetry

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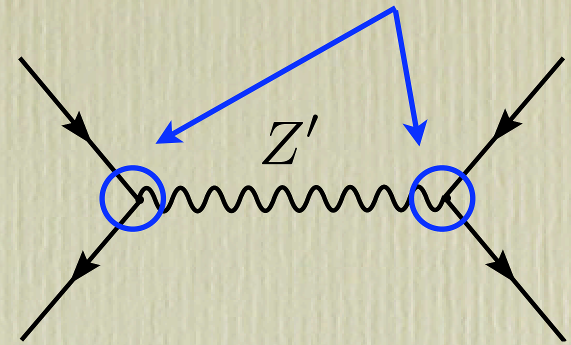

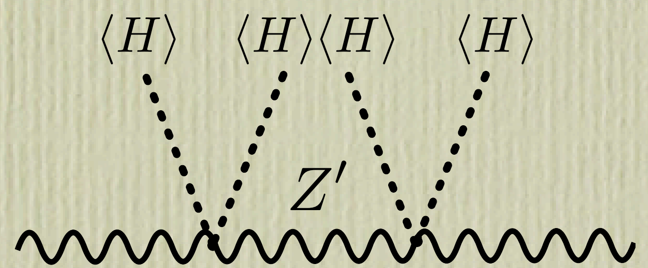

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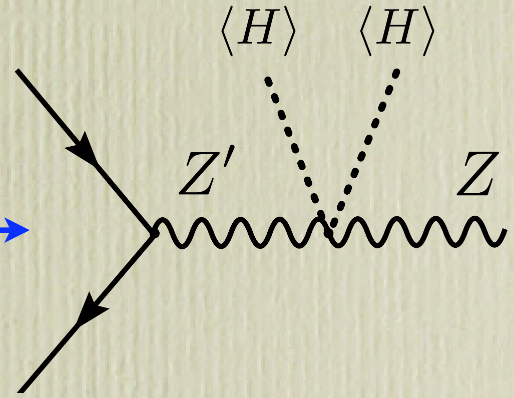
$g_{Z'}^{[H]}$ strong is compatible with LEP**1** bounds if $g_{Z'}^{[\Psi]}$ is weaker



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An alternative scheme: partial compositeness

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the SM gauge bosons could be the admixture of an elementary with a composite

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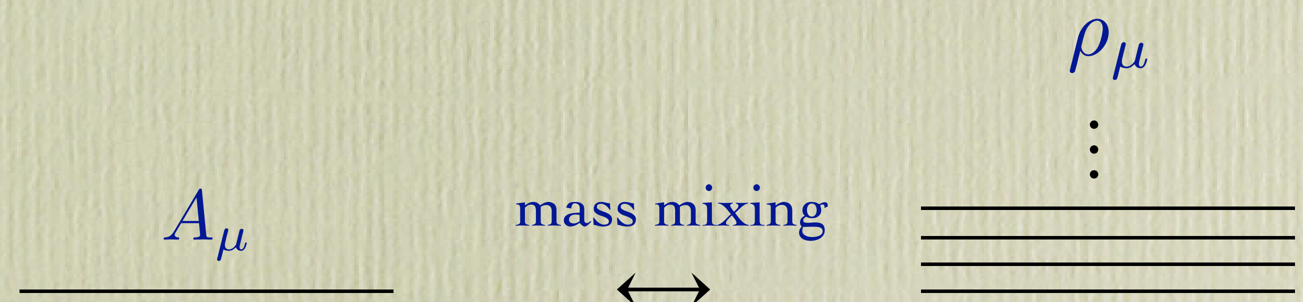

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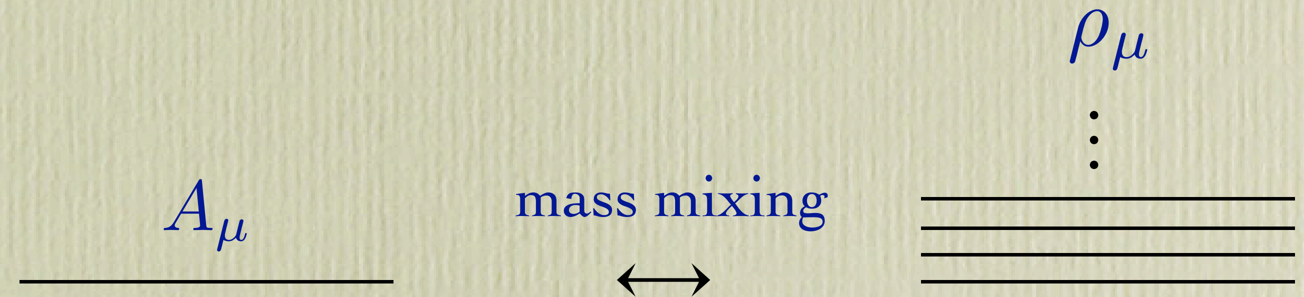

same as ρ-photon mixing in QCD ⟶

$$\mathcal{L}_{mix} = \frac{M_*^2}{2}\left(\frac{g_{el}}{g_*}A_\mu - \rho_\mu\right)^2$$

$$= \frac{M_*^2}{2}\rho_\mu^2 - M_*^2\,\frac{g_{el}}{g_*}\,A_\mu\rho_\mu + \frac{M_*^2}{2}\left(\frac{g_{el}}{g_*}\right)^2 A_\mu^2$$

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← ! Randall-Sundrum are of this type

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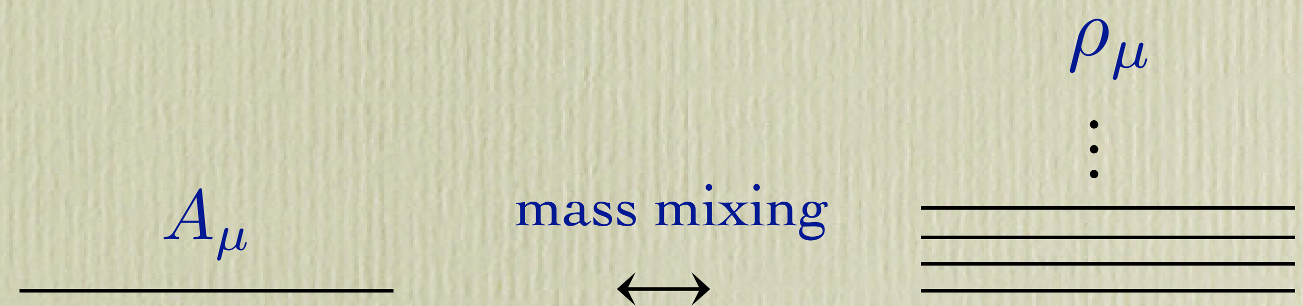

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Diagonalization:

from the composite/elementary basis
to the mass eigenstates (KK) basis

$$\begin{pmatrix} A_\mu \\ \rho_\mu \end{pmatrix} \to \begin{pmatrix} \cos\theta & \sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} A_\mu \\ \rho_\mu \end{pmatrix}$$

$$\tan\theta = \frac{g_{el}}{g_*}$$

$$g_{SM} = \frac{g_{el} g_*}{\sqrt{g_{el}^2 + g_*^2}} \simeq g_{el}$$

$$|\mathrm{SM}\rangle = \cos\theta\,|A_\mu\rangle + \sin\theta\,|\rho_\mu\rangle$$

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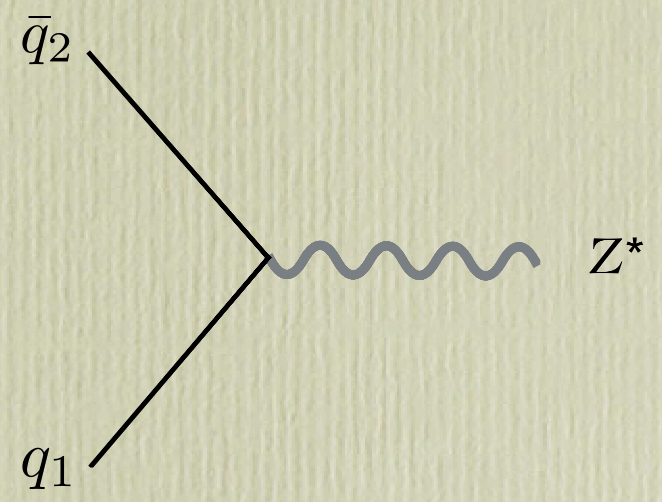
- the Higgs is a full composite (= solution to the Hierarchy Problem)
- LEP bounds imply light fermions (almost completely) elementary
- top (and bottom) can have a sizable composite component

Consequences of Partial Compositeness: Z^* production & decay

Drell-Yan production has the largest cross section:



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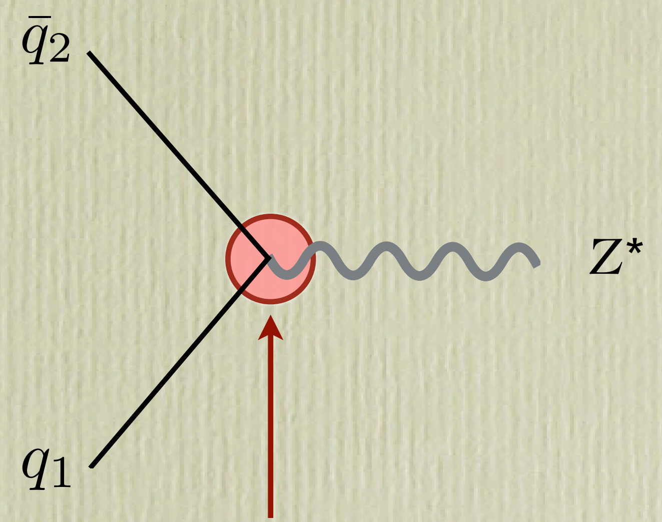

$$g_* \sin\varphi_1 \sin\varphi_2 \cos\theta_2 \; + \; g_{2\,el} \cos\varphi_1 \cos\varphi_2 \sin\theta_2 \;\simeq\; g_2 \tan\theta_2$$

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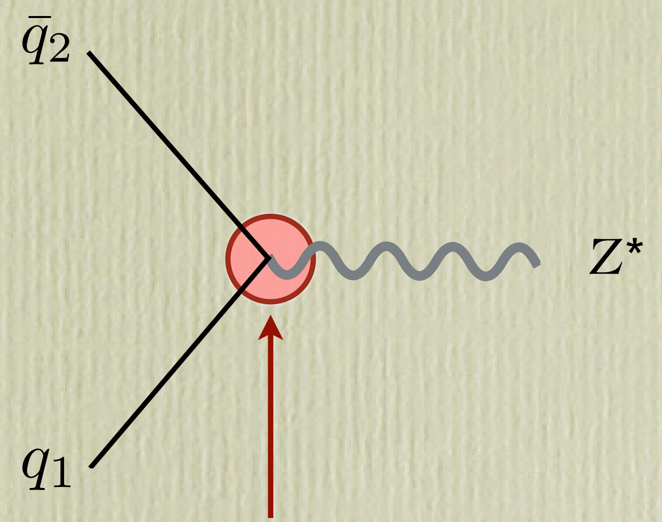

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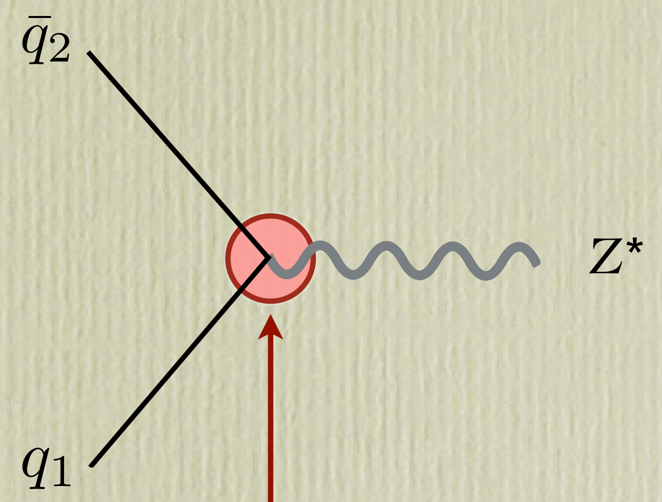

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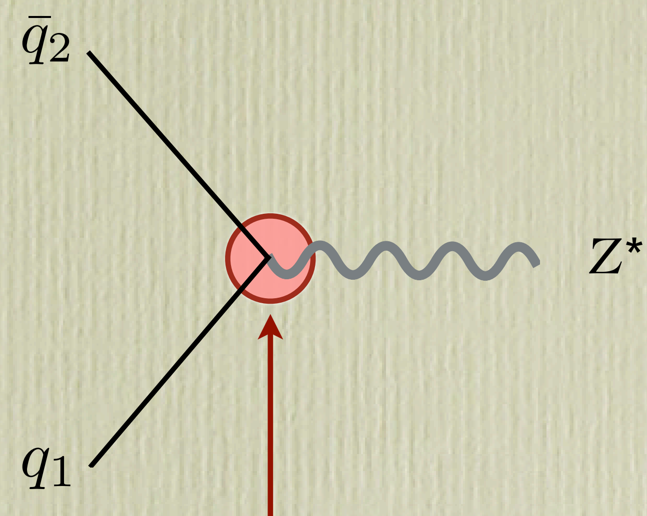

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interaction among the **composite** components — **SUPPRESSED**

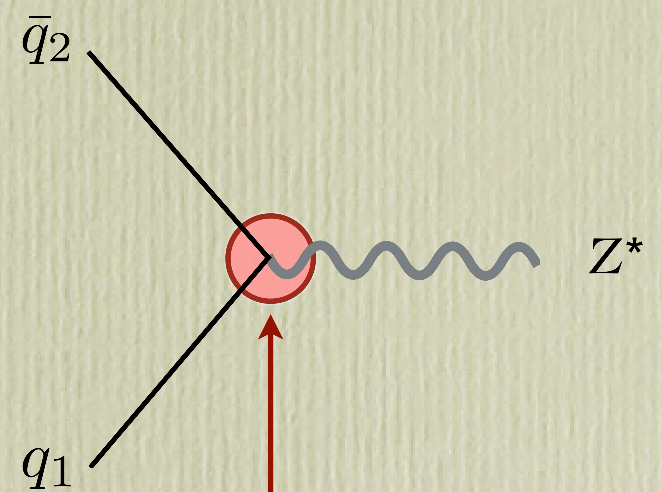
interaction among the **elementary** components

Consequences of Partial Compositeness: Z^* PRODUCTION & DECAY

$$\tan\theta_2 = \frac{g_{el2}}{g_*} \ll 1$$

suppression compared to SM strength:

Drell-Yan production has the largest cross section:



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interaction among the **composite** components

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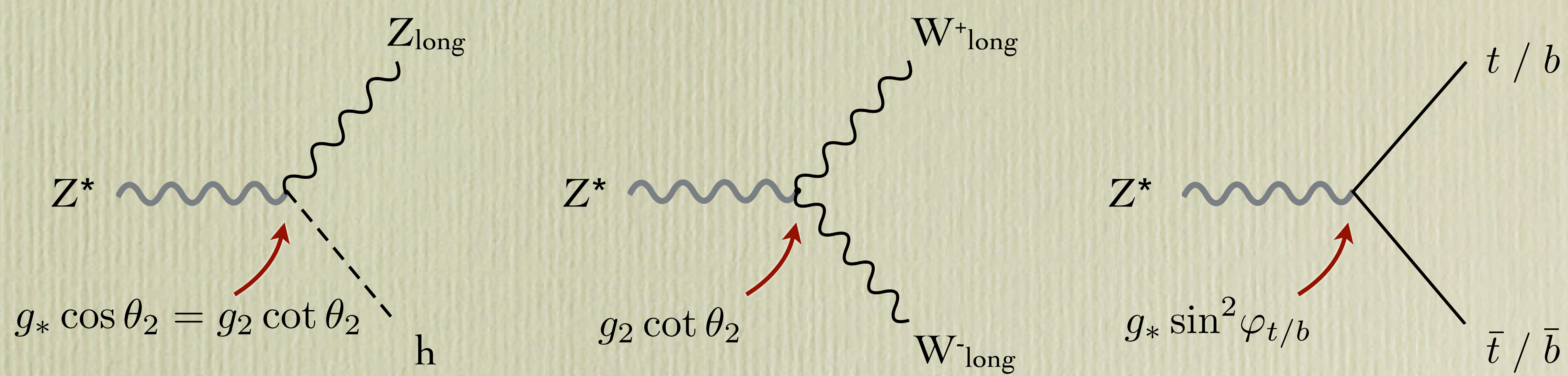
SUPPRESSED

Largest BR's to the SM particles with the largest composite component: H, W_{long}, Z_{long}, top, bottom



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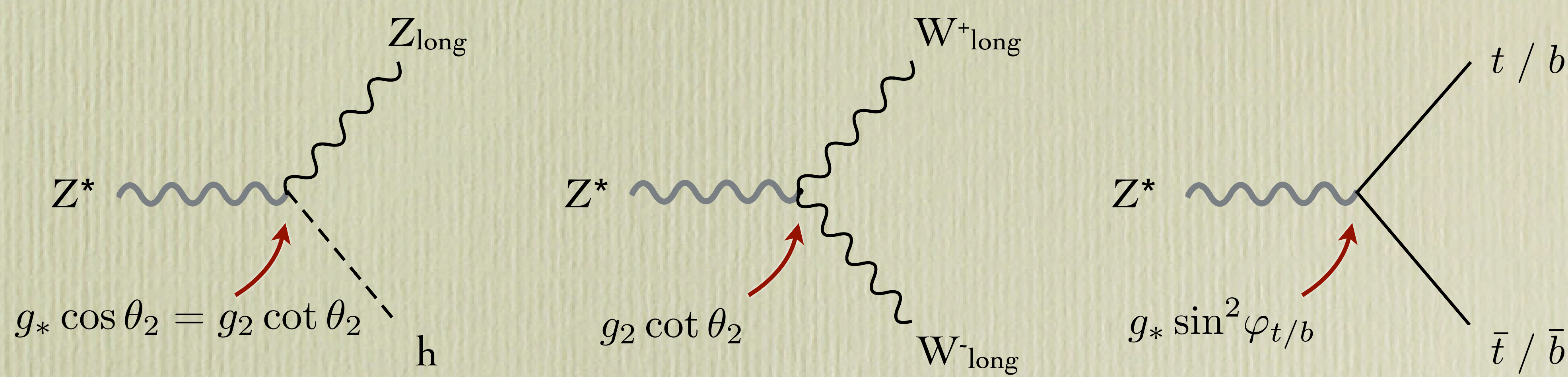
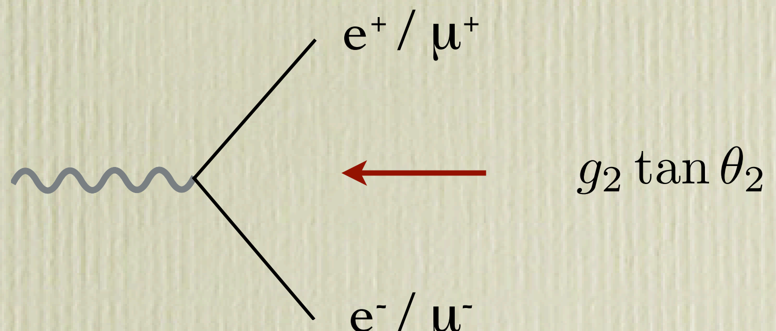


[decays to e^+e^-, $\mu^+\mu^-$

SUPPRESSED



]

<u>example</u>: the case of W^{*3}

$$\Gamma(W^{*\,3} \to q\bar{q}) = 3\,\Gamma(W^{*\,3} \to l\bar{l}) \simeq \frac{g_2^2 \tan^2\theta_2}{32\pi} M_*$$

$$\Gamma(W^{*\,3} \to t\bar{t}) = \Gamma(W^{*\,3} \to b\bar{b}) = \left(\sin^2\varphi_{t_L}\cot\theta_2 - \cos^2\varphi_{t_L}\tan\theta_2\right)^2 \frac{g_2^2}{32\pi} M_*$$

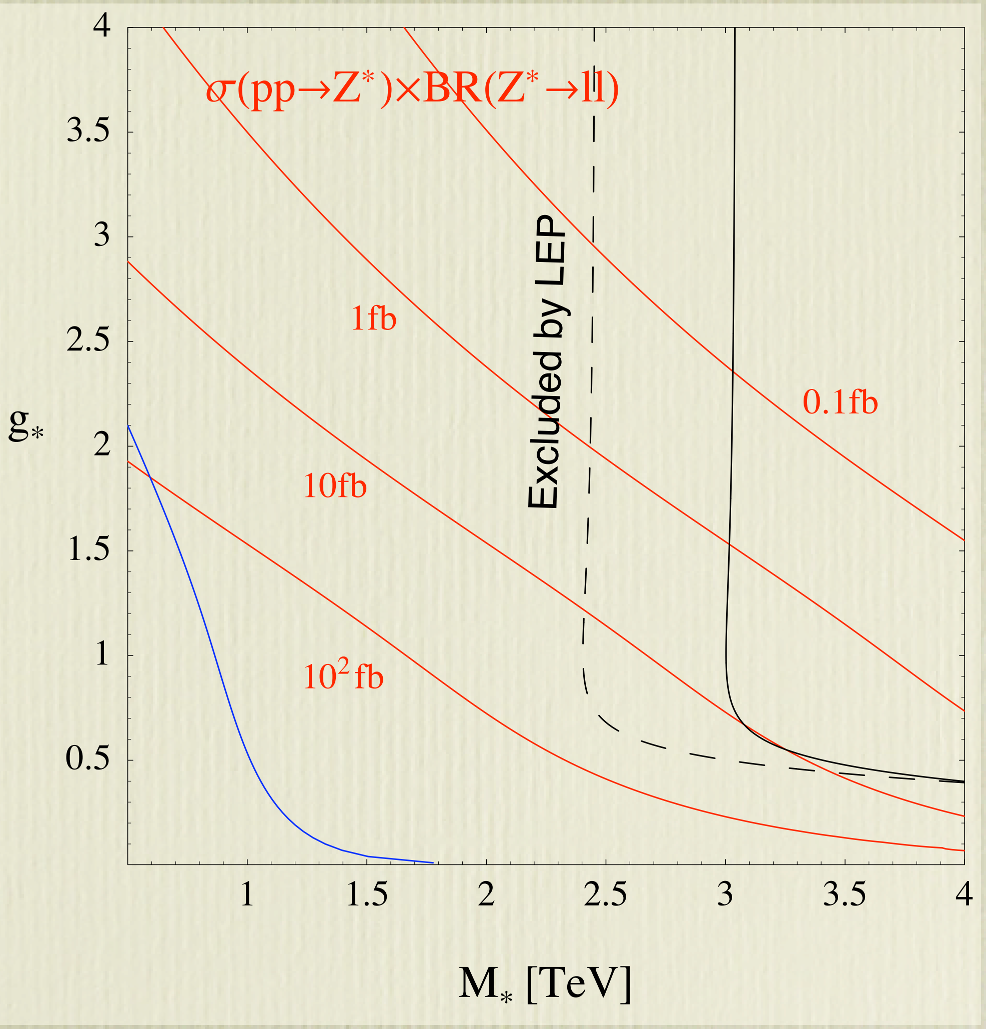
$$\Gamma(W^{*\,3} \to ZH) = \Gamma(W^{*\,3} \to W^+W^-) = \frac{g_2^2 \cot^2\theta_2}{192\pi} M_*$$

for $\begin{cases} M_* = 3 \text{ TeV} \\ \tan\theta_2 = 1/6 \\ \sin\varphi_{t_L} = 0.4 \end{cases}$

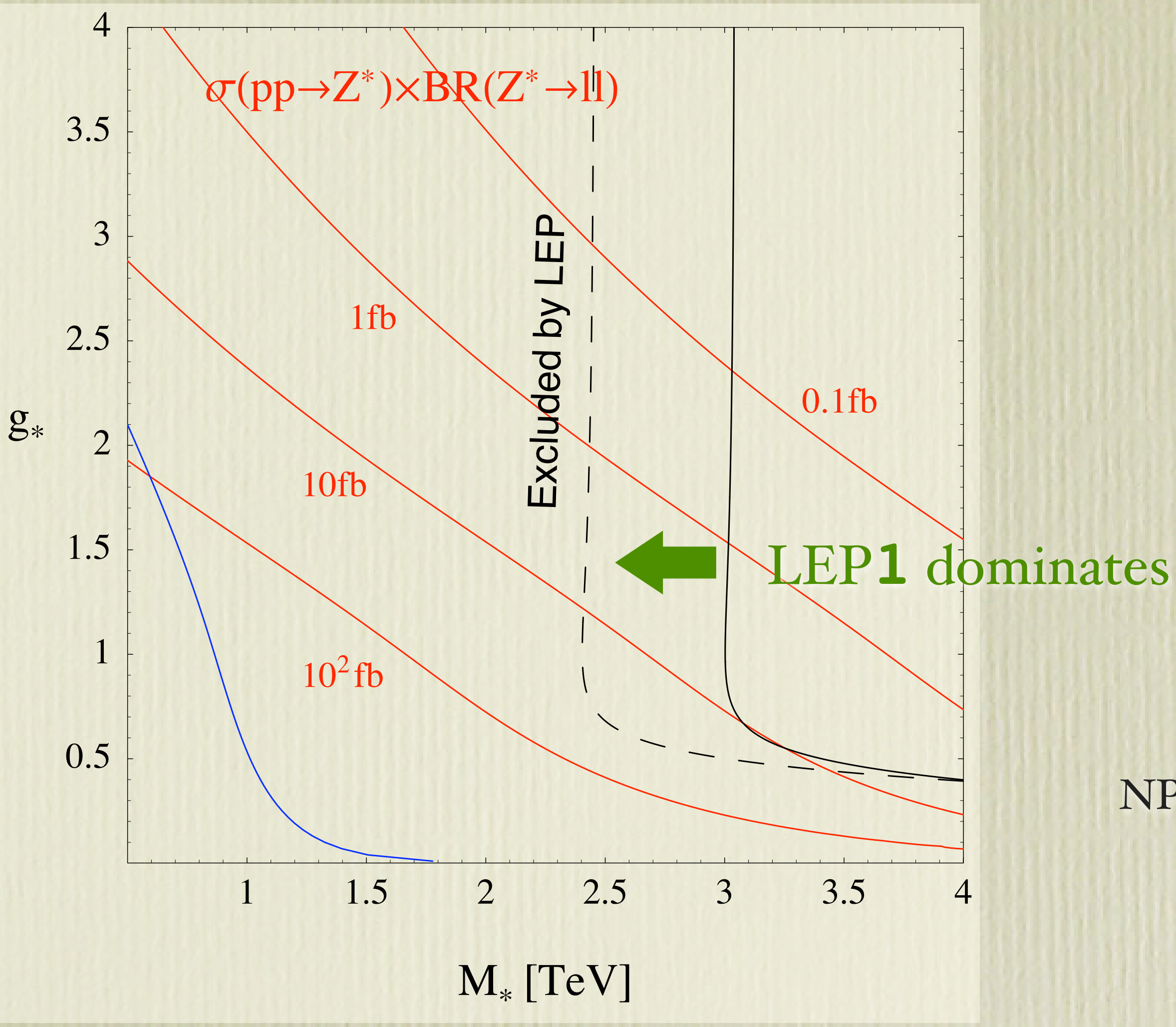
$\Gamma_{tot} = 170$ GeV

$BR(ee, \mu\mu) = 0.1\%$

$BR(tt, bb) = 5\%$

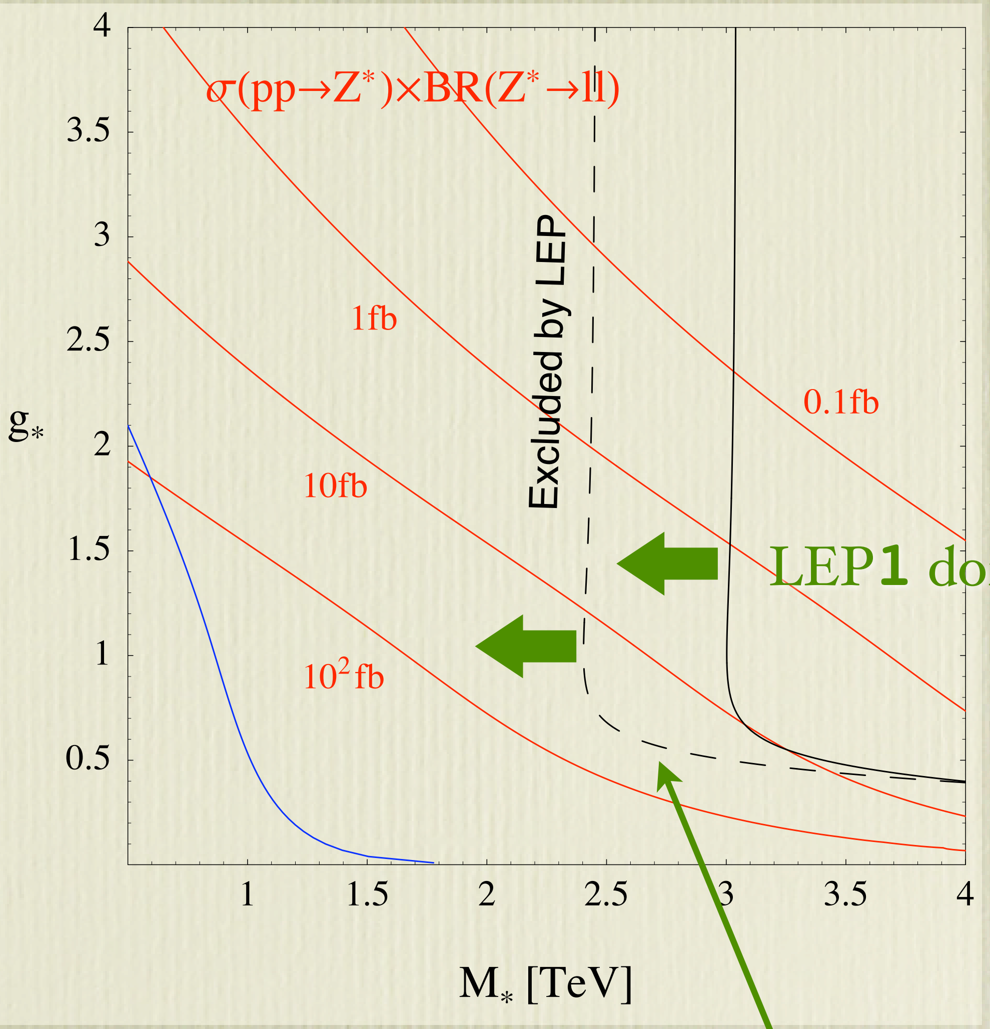


σ(pp→Z*)×BR(Z*→ll)
1fb
0.1fb
10fb
10^2 fb
Excluded by LEP
g*
M* [TeV]
4
3.5
3
2.5
2
1.5
1
0.5
1
1.5
2
2.5
3
3.5
4



fit from:

Barbieri et al.
NPB 703 (2004) 127



adding $\Delta\rho = +1 \times 10^{-3}$

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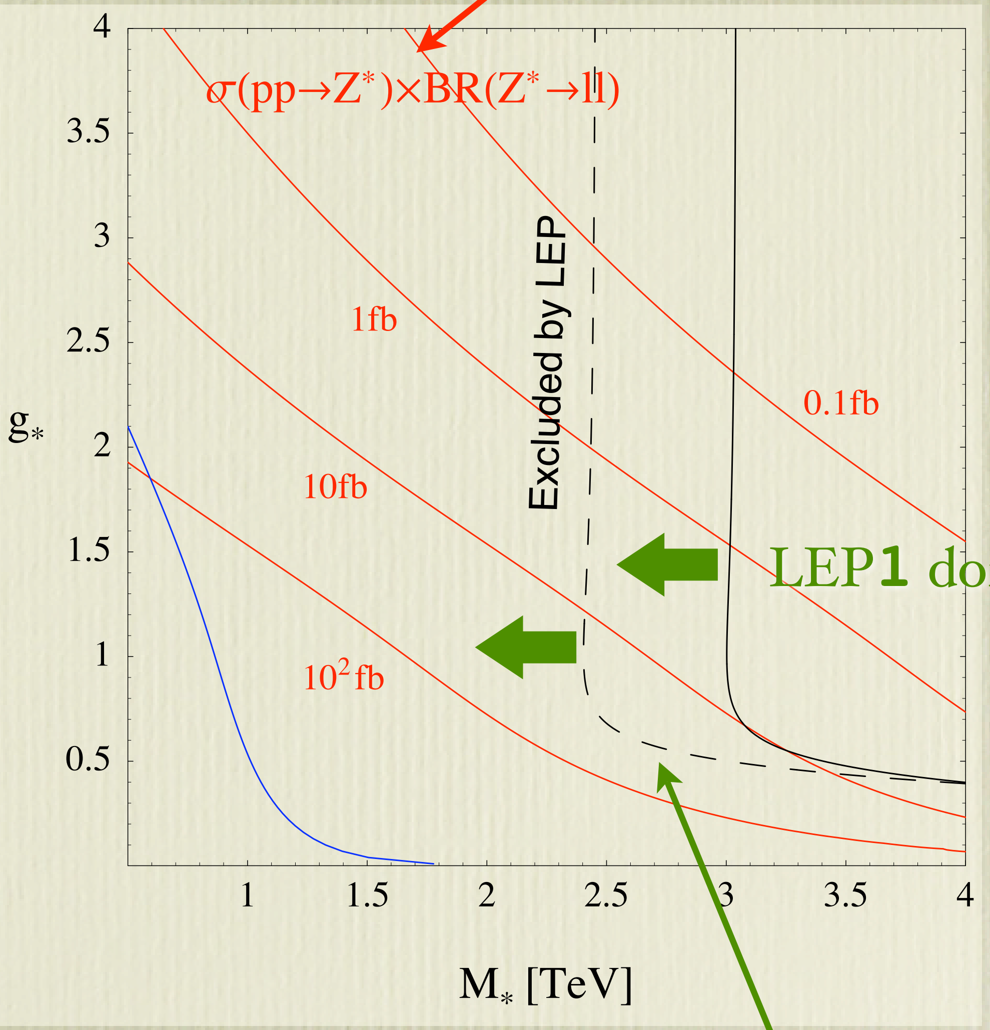
cross section refers to heavy W_{3L}



LEP**1** dominates

adding $\Delta\rho = +1 \times 10^{-3}$

fit from:

Barbieri et al.
NPB 703 (2004) 127

LHC discovery potential

Z* : $M = 2\,(3)\,\mathrm{TeV}$ with $L = 100\,(10^3)\,\mathrm{fb}^{-1}$ [Agashe et al., PRD 76 (2007) 115015]

$$Z^* \to W^+W^- \to l^+l^-\nu\nu \qquad\qquad Z^* \to Zh \to l^+l^-\,b\bar{b}$$

$$l\nu jj \qquad\qquad jj\,W^+W^- \to jj\,l\nu jj$$

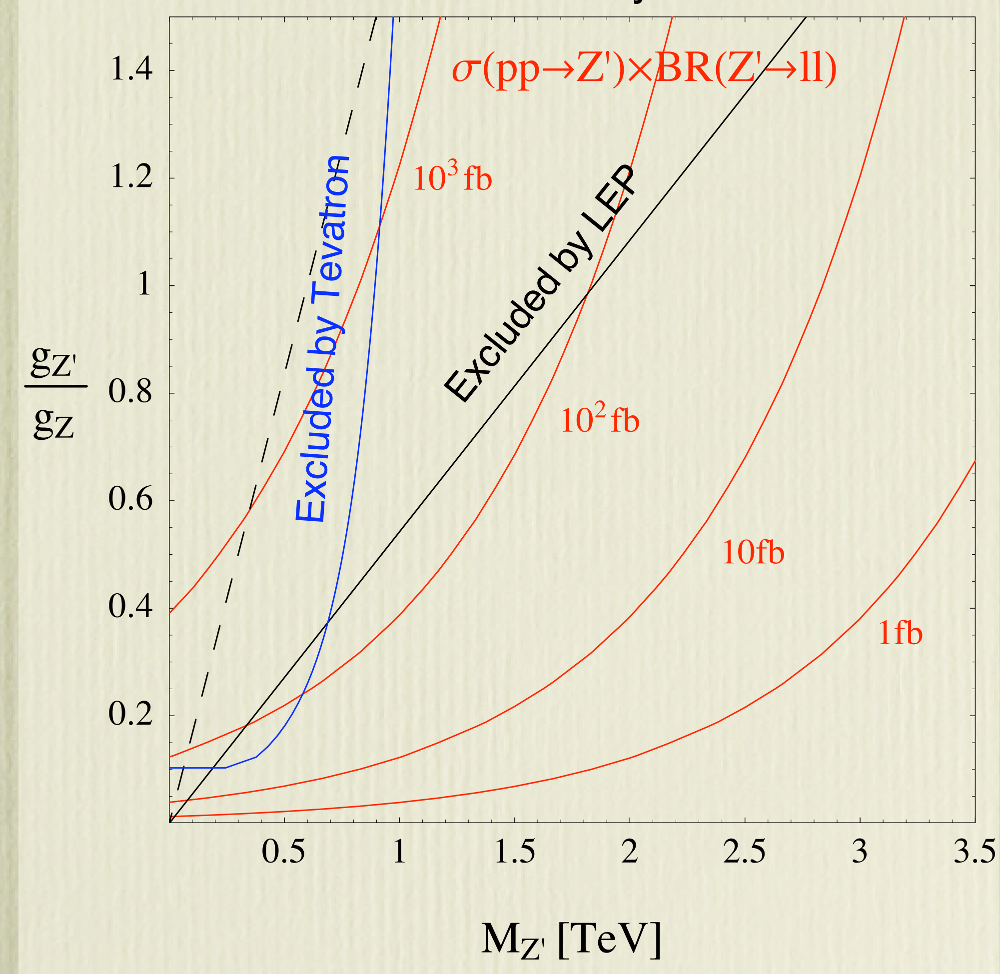
G* (heavy gluon)**:** $M = 4\,\mathrm{TeV}$ with $L = 100\,\mathrm{fb}^{-1}$ [Agashe et al., hep-ph/0612015]

$$G^* \to t\bar{t}$$

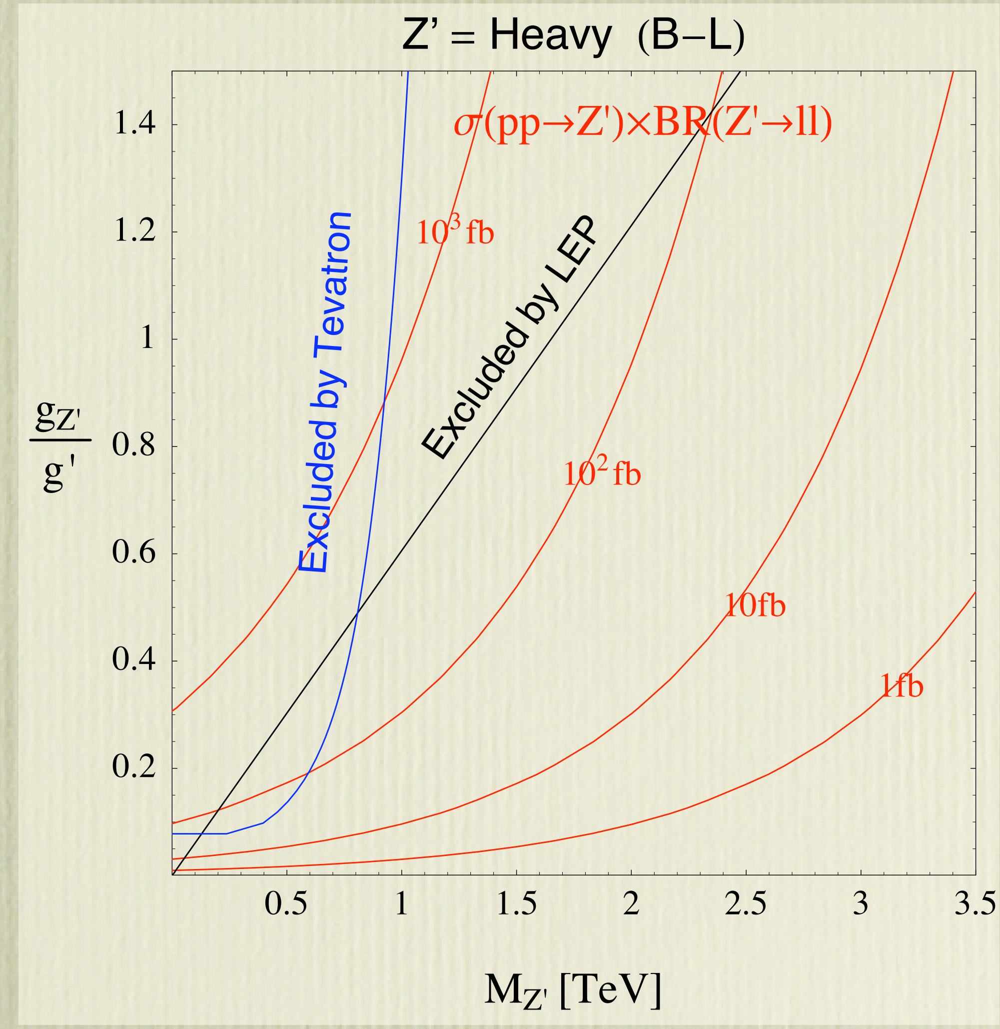
- use of a LR asymmetry
- exploit the highly-boosted tops

Backup slides

Z' = Heavy Z



$\sigma(pp\to Z')\times BR(Z'\to ll)$
10^3 fb
10^2 fb
10fb
1fb
Excluded by Tevatron
Excluded by LEP
$\frac{g_{Z'}}{g_Z}$
1.4
1.2
1
0.8
0.6
0.4
0.2
0.5
1
1.5
2
2.5
3
3.5
$M_{Z'}$ [TeV]



Z' = Heavy (B−L)
σ(pp→Z')×BR(Z'→ll)
10^3 fb
10^2 fb
10fb
1fb
Excluded by Tevatron
Excluded by LEP
gZ'/g'
MZ' [TeV]
0.2
0.4
0.6
0.8
1
1.2
1.4
0.5
1
1.5
2
2.5
3
3.5