TeV-Scale String Resonances at Hadron Colliders

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(TeV4LHC, BNL, Feb. 3, 2005)

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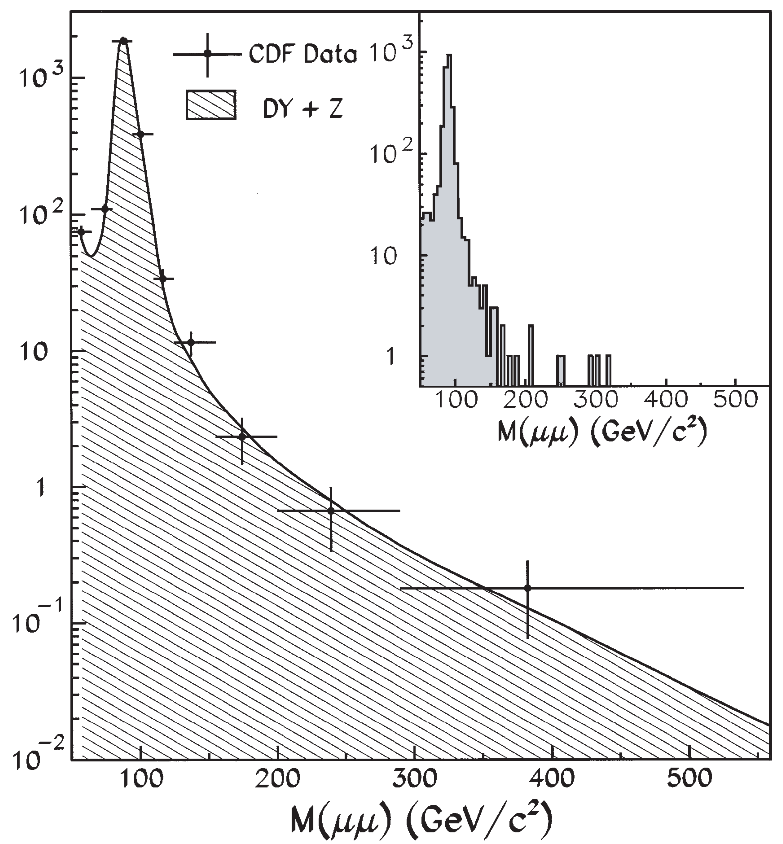
Dilepton channels for a $Z' \to \mu^+\mu^-$ [CDF, PRL 79, (1997)]:



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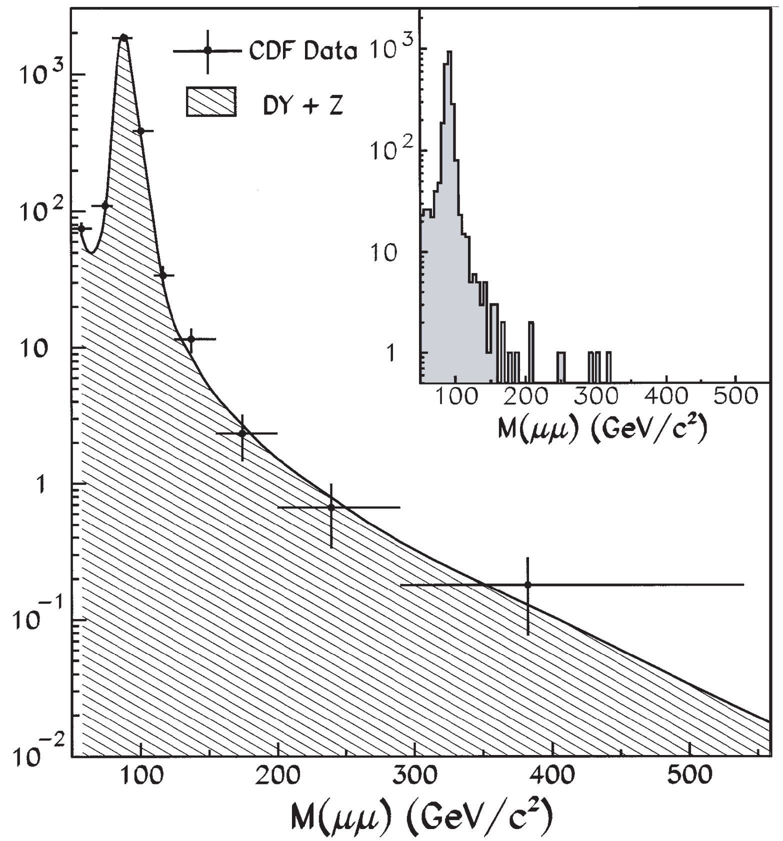

including:

$$p\bar{p} \to Z, \gamma \to \mu^+\mu^- X,$$
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$$p\bar{p} \to b\bar{b} \to \mu^+\mu^- + hadrons + X,$$
$$p\bar{p} \to t\bar{t} \to W^+b\ W^-\bar{b} \to \mu^+\nu_\mu\mu^-\bar{\nu}_\mu b\bar{b}\ X.$$

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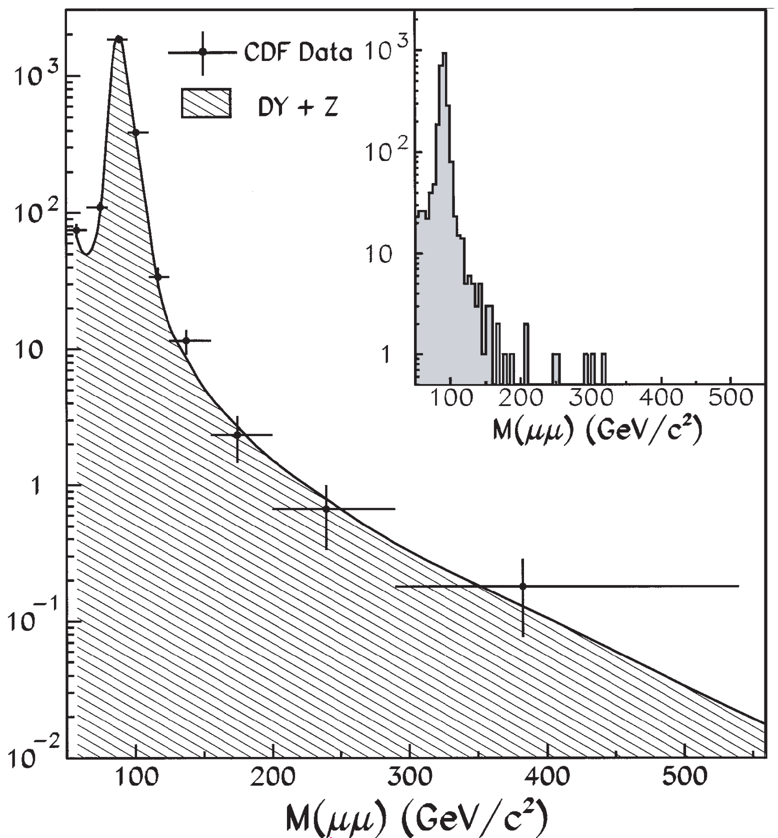

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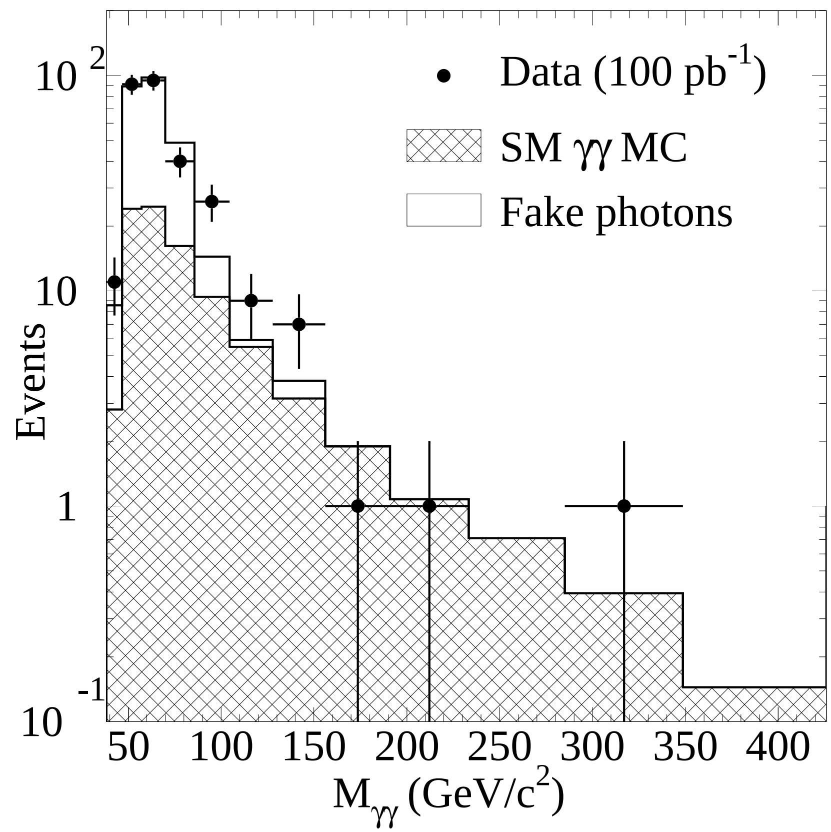
$\sigma < 40$ fb $\Rightarrow M_{Z'} > 600$ GeV.

Diphoton channel for $H \to \gamma\gamma$ [CDF, PRD (2001)]:



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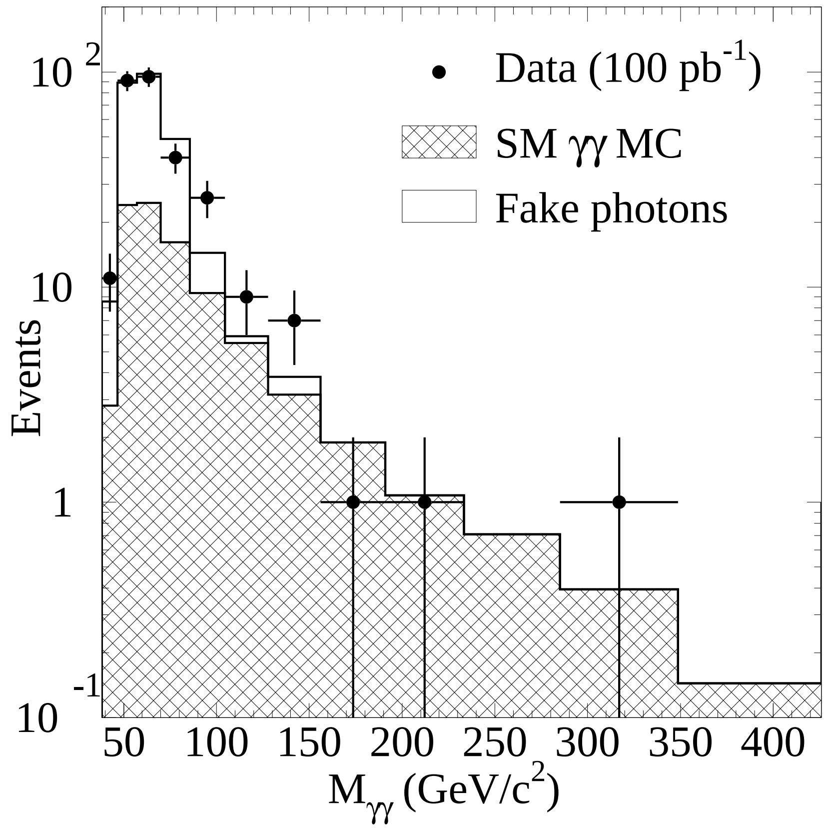

For a "leptophobic" Higgs [CDF]:

$$M_H > 82 \text{ GeV}.$$

Actually,

$$M_X > 300 \text{ GeV}.$$

Low String Scale Scenario

Physical Scales:

(i). String scale: $M_S^2 = 2\pi T = 1/\alpha'$

(ii). Quantum gravity scale:

$$\frac{1}{8\pi G_N} = \begin{cases} M_{pl}^2 & \text{for 4-dimensions} \\ M_D^{n+2} V_n & \text{for (4+n)-dim} \end{cases}$$

Relation between M_S and M_D : model-dependent

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In traditional (heterotic) string:

$$M_S = g M_{pl} = 2.4 \times 10^{18} g \text{ GeV}.$$

With large extra-dim.

$$M_S \approx g^b M_D = g^b \times \left(\frac{M_{pl}^2}{V_n} \right)^{\frac{1}{n+2}} \longrightarrow \text{TeV achievable !}$$

Observable signals

▷ At "low" energies

- "very low" : $E \ll 1/R,\ M_S$:

4−dim effective theory: as the Standard Model;
very weak effects from gravity ... ...
(e.g., the case of traditional string)

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4−dim effective theory: as the Standard Model;
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- march into the extra-dimensions: $1/R < E \ll M_S$,

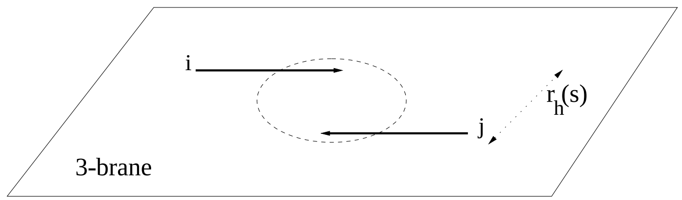
$(4+n)$−dim physics directly probed, and gravity effects observable:* mainly via light KK gravitons of mass

$$m_{KK} \sim 1/R,$$

or whatever propagate there ⇒ an effective theory (SM+KK).

*N. Arkani-Hamed, S. Dimopoulos, G. Dvali (1998);
G. Giudice, R. Rattazzi, J. Wells (1999);
T. Han, J. Lykken, R.J. Zhang. (1999);
Mirabelli, M. Peskin, M. Perelstein (1999);
J. Hewett (1999); T. Rizzo (1999); ...

▷ At “trans Planckian” energies $E > M_D, M_S$:
$(4+n)-$dim physics directly probed;
gravity dominant: black hole production*
$M_{bh} = \sqrt{s} > M_D$ for $b < r_{bh}$.



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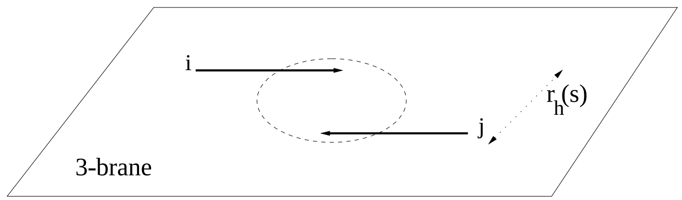

M_{BH}	$n = 4$	$n = 6$
5 TeV	1.6×10^5 fb	2.4×10^5 fb
7 TeV	6.1×10^3 fb	8.9×10^3 fb
10 TeV	6.9 fb	10 fb

copiously produced at the LHC and other TeV-scale experiments !*

*T. Banks and W. Fischler (1999); E. Emparan et al. (2000);
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*Criticism: M. Voloshin (2001).

▷ In between? $E \sim M_S$: Things are more involved.

- stringy states significant:*

$$\mathcal{M}(\text{close-string}) \sim g^2 \times \mathcal{M}(\text{open-string})$$

- s-channel poles as resonances:†

$$\mathcal{M}(s,t) \sim \frac{t}{s - M_n^2}, \quad M_n = \sqrt{n} M_S.$$

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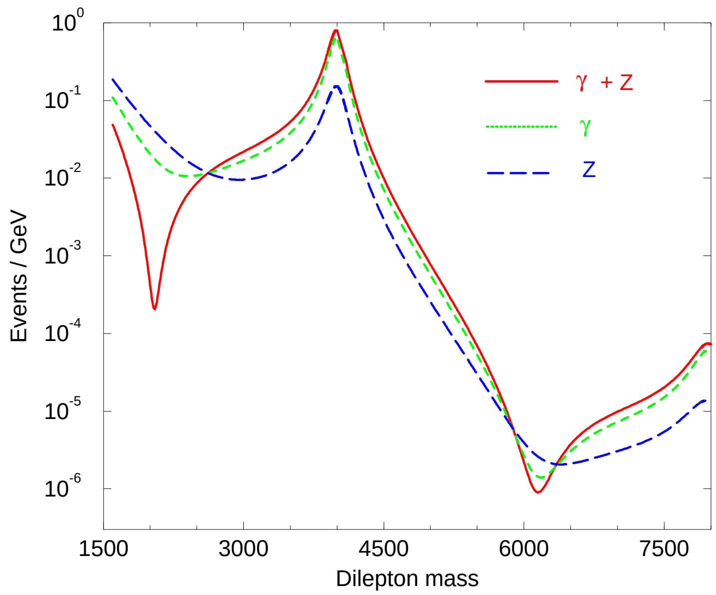

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String Scattering Amplitude

The general tree-level open-string amplitude*

$$\mathcal{M}(1,2,3,4) = g^2[A_{1234} \cdot S(s,t) \cdot T_{1234} + A_{1324} \cdot S(t,u) \cdot T_{1324} + A_{1243} \cdot S(s,u) \cdot T_{1243}\ ]$$

- The Veneziano amplitude: (basically)

$$S(s,t) = \frac{\Gamma(1-\alpha' s)\Gamma(1-\alpha' t)}{\Gamma(1-\alpha' s - \alpha' t)} \quad \xrightarrow{\alpha' s,\ \alpha' t \to 0} 1.$$

$\Rightarrow$ String resonances at the simple poles:

$$\alpha' s = n \text{ or } \sqrt{s} = \sqrt{n} M_S.$$

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model-dependent (on the SM embedding).

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It is: a 4-dim formula (in a D3-brane);
Super-string amplitudes (bosons & fermions)

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Massless Particle Scattering in Gauge Theory

Following the procedure above, one obtains general scattering amplitudes for massless SM particles as string zero-modes:

• The color-ordered kinematical factors $A's$ are the helicity amplitudes, for instance:

$g_-g_+g_+g_-$:	$A_{1234} = g^2\langle 14\rangle^2/\langle 12\rangle^2$
	$A_{1324} = g^2\langle 14\rangle^2/\langle 13\rangle^2$
	$A_{1243} = g^2\langle 14\rangle^4/(\langle 12\rangle^2\langle 13\rangle^2)$
$g_-g_+f_+f_-$:	$A_{1234} = g^2\langle 13\rangle\langle 14\rangle/\langle 12\rangle^2$
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	$A_{1243} = g^2\langle 14\rangle^3/(\langle 12\rangle^2\langle 13\rangle)$
$f_-\bar{f}_+f_+\bar{f}_-$:	$A_{1234} = g^2\langle 13\rangle^4/(\langle 12\rangle^2\langle 14\rangle^2)$
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where $\langle ij\rangle \equiv \overline{\psi_-(p_i)}\psi_+(p_j)$,* a spinor product.

*see, *e. g.*, Mangano and Parke, Phys. Rept. (1991).

- The Chan-Paton factors?

Our approach:

Instead of constructing the Chan-Paton factors explicitly, we take them as model-parameters $T's$, to be determined by matching the SM amplitudes at low energies.*

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Instead of constructing the Chan-Paton factors explicitly, we take them as model-parameters $T's$, to be determined by matching the SM amplitudes at low energies.*

We thus obtain open-string scattering amplitudes for (zero-mode) SM particles.

- By construction, it leads to correct (massless) SM amplitudes at $s \ll M_S^2$; (No statement for EWSB ...)
- It becomes "stringy" for $s \sim M_S^2$.

*Cornet, Illana and Masip (2001); Friess, Han, Hooper (2002).

Low Energy Constraint on M_S

Explicit stringy amplitudes

Consider a typical process:

$$e_L q_L \to e_L q_L$$

we have

$$\mathcal{M}_{string} = g^2 \; [\frac{s}{t} S(s,t) T_{1234} + \frac{s^2}{tu} S(t,u) T_{1324} + \frac{s}{u} S(u,s) T_{1243}]$$

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In the low-energy limit,

$$\mathcal{M}_{string} \approx g^2 \; [\frac{s}{t}(T_{1234} - T_{1324}) + \frac{s}{u}(T_{1243} - T_{1324})]$$

matching the SM amplitude:

$$\mathcal{M}_{SM} \approx g_L^2 \; \frac{s}{t} \; [2 Q_e Q_q \sin^2\theta_{\mathrm{w}} + \frac{2 g_L^e g_L^q}{\cos^2\theta_{\mathrm{w}}}] \equiv g_L^2 \; \frac{s}{t} \; F$$

$$\Longrightarrow g = g_L, \quad T_{1324} = T_{1243} \equiv T, \quad T_{1234} = F + T$$

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Then

$$\mathcal{M}_{string} = \mathcal{M}_{SM} S(s,t) + g_L^2 \frac{s}{tu} T\ [uS(s,t) + sS(t,u) + tS(u,s)].$$

where $\quad 0 \le T \le 4.$

Induced Contact Interactions

Far below the resonance $M_S^2 \gg s$,

$$
\begin{aligned}
S(s,t) &\approx 1 - \frac{\pi^2}{6}\frac{st}{M_S^4} + \ldots \\
\mathcal{M}_{string} &\approx \mathcal{M}_{SM}(1 - \frac{\pi^2}{6}\frac{st}{M_S^4}) - g_L^2(3T)\frac{\pi^2}{6}\frac{s^2}{M_S^4}
\end{aligned}
$$

and thus:

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\Delta\mathcal{M}_{SM} \sim \frac{st}{M_S^4}\mathcal{M}_{SM} + g_L^2 T\frac{s^2}{M_S^4},
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and thus:

$$\Delta\mathcal{M}_{SM} \sim \frac{st}{M_S^4}\mathcal{M}_{SM} + g_L^2 T\frac{s^2}{M_S^4},$$

Due to the $1/M_S^4$-suppression, the constraints from HERA, Tevatron etc. are not very strong

$$M_S \gtrsim 0.9 - 1.3 \text{ TeV, for } T = 1 - 4.$$

and even weaker from other low-energy data.

Collider Signatures

The string resonances

- Regge poles in Veneziano amplitudes:

$$S(s,t) \approx M_S^2 \sum_{n=1}^{\infty} \frac{(t/M_S^2)(t/M_S^2+1)\cdots(t/M_S^2+n-1)}{(n-1)!(s-nM_S^2)}$$

Near the resonances, $s \approx M_S^2$,

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Treat the resonances individually

$$\begin{aligned}
\mathcal{M}_{string} \approx \quad & g_L^2\left(2Q_eQ_q\sin^2\theta_{\mathrm{W}}\frac{s}{t} + \frac{2g_L^e g_L^q}{\cos^2\theta_{\mathrm{W}}}\frac{s}{t-M_Z^2}\right) && \text{SM term} \\
+ \quad & g_L^2(F+2T)\frac{s}{s-M_s^2} && 1^{\text{st}} \text{ resonance} \\
+ \quad & g_L^2 F\frac{s\cos\theta}{s-2M_s^2} && 2^{\text{st}} \text{ resonance} \\
+ \quad & \ldots\ldots
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$$+ \; g_L^2(F+2T)\frac{s}{s-M_s^2} \quad 1^{\rm st}\ \text{resonance}$$

$$+ \; g_L^2 F\frac{s\cos\theta}{s-2M_s^2} \quad 2^{\rm st}\ \text{resonance}$$

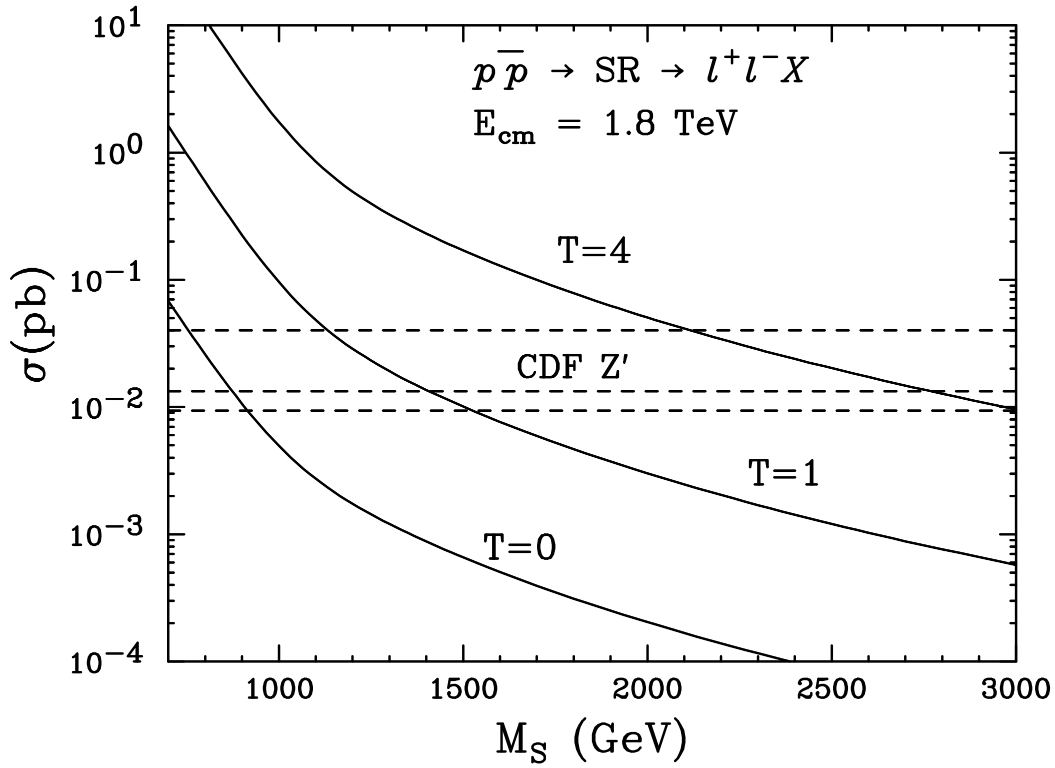
$$+ \; \ldots\ldots$$

and need to include the total width

$$\Gamma_n = \frac{g_L^2}{8\pi}\frac{|T|}{2J+1}\sqrt{n}M_S.$$

Tevatron Z' bound:†

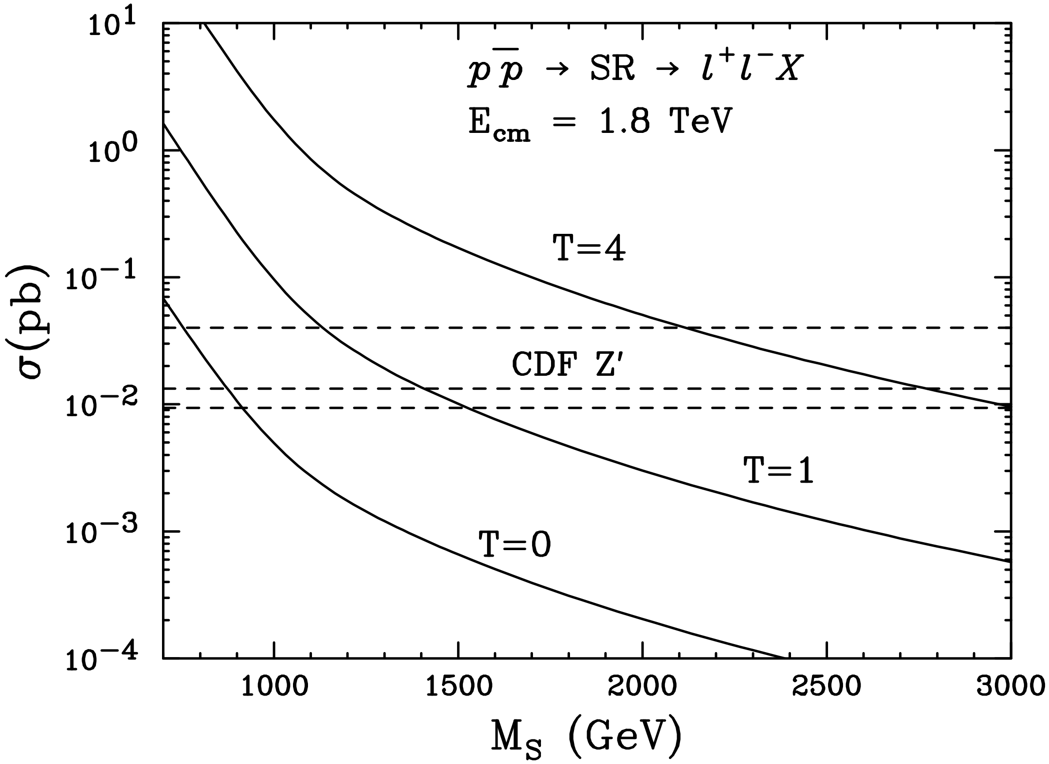
Extrapolate the CDF bound on $Z' \to \ell^+\ell^-$:
$M_{Z'} > 800$ GeV at 95% C.L. with 110 pb^{-1},
we find the current bound: $M_S > 1$ (2) TeV for $T = 1 - 4$.



†CDF, PRL (1997);
Recent study: M.Carena, A.Daleo, B.Dobrescu, T.Tait, hep-ph/0408098.

Tevatron Z' bound:[†]

Extrapolate the CDF bound on $Z' \to \ell^+\ell^-$:
$M_{Z'} > 800$ GeV at 95% C.L. with 110 pb^{-1},
we find the current bound: $M_S > 1$ (2) TeV for $T = 1 - 4$.



With 2 fb^{-1},
we expect to reach: $M_S > 1.5$ (5) TeV for $T = 1 - 4$.

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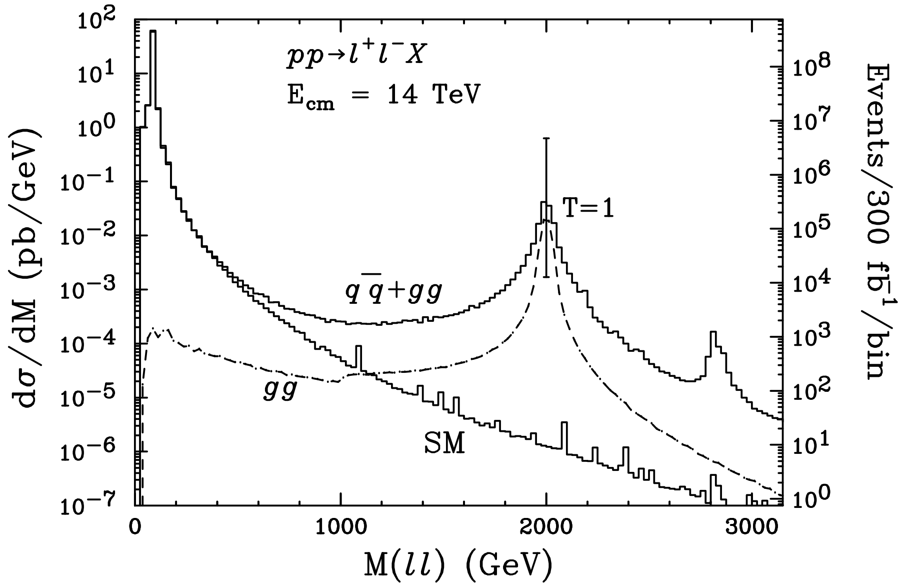
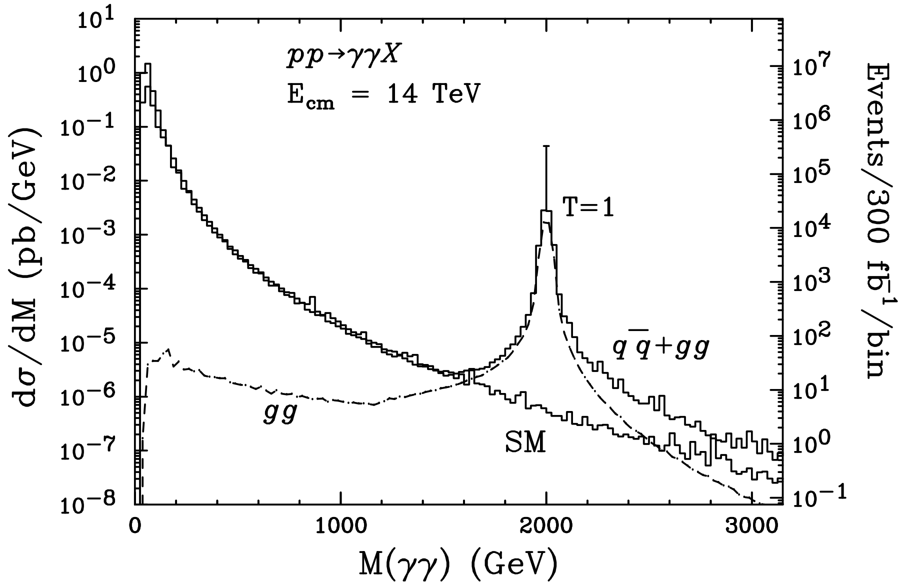
Spectacular signatures at the LHC:





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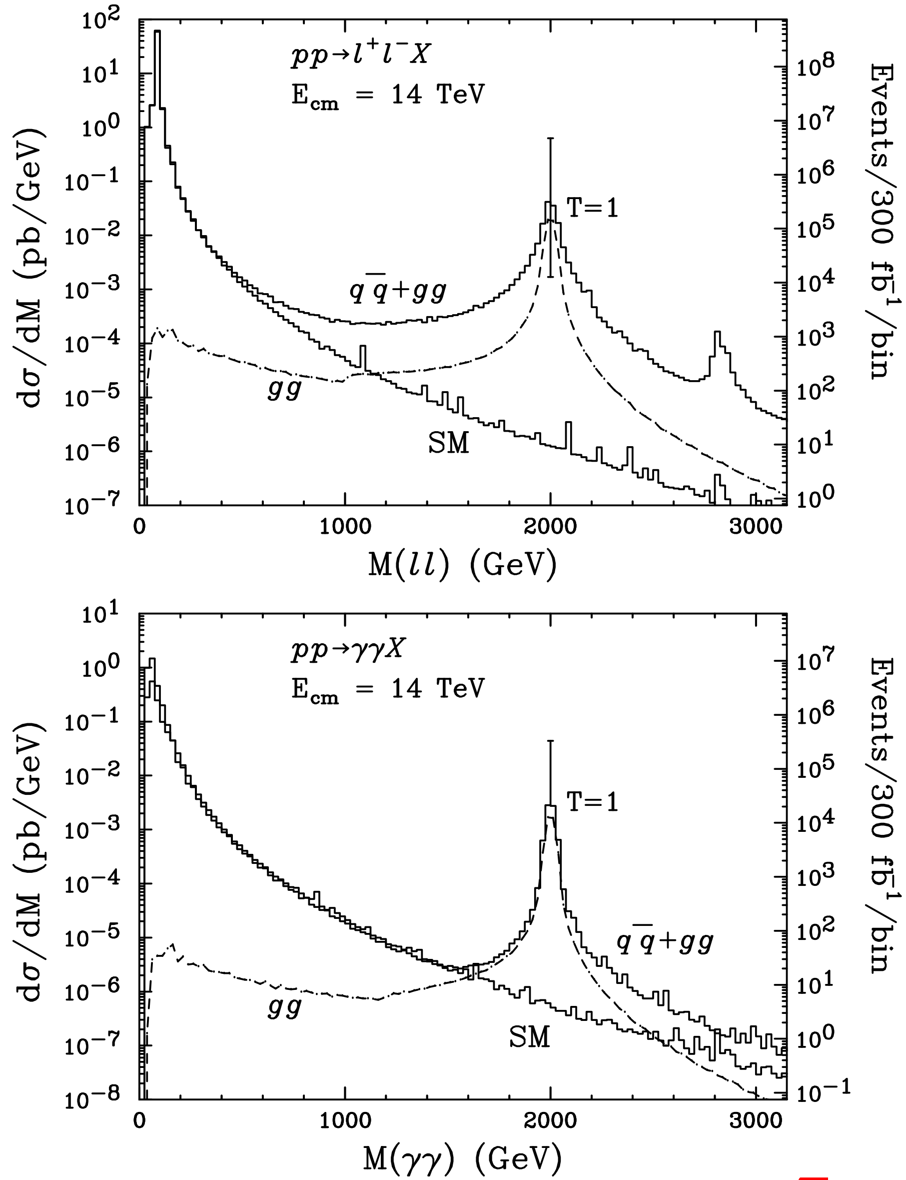


Clear signals at $M_S = 2$ TeV and $\sqrt{2}M_S$.

$gg \to \ell^+\ell^-$, $\gamma\gamma$? bosons in an extended gauge group?

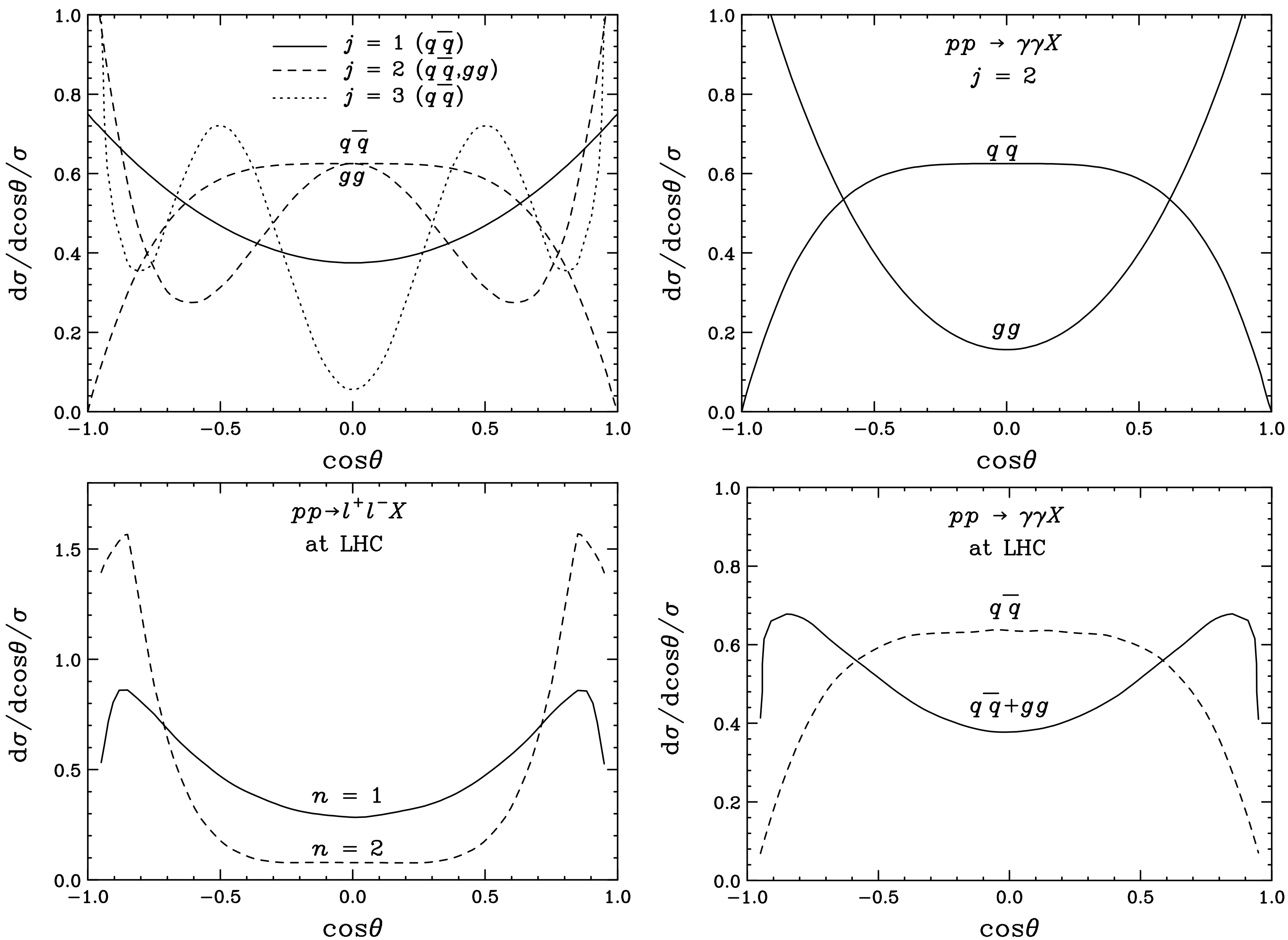
SR amplitudes & Angular momentum decomposition

DY dilepton pairs	
$A^{n=1}_{SR}(q_\alpha \bar{q}_\beta \to \ell_\alpha \bar{\ell}_\beta)$	$i g_L^2 (F_{\alpha\alpha} + 2T) \sum_{j=1}^{2} \frac{s\ \alpha_1^j\ d^j_{1,-1}}{s - M_S^2 + i\Gamma_1^j M_S}$
$A^{n=1}_{SR}(q_\alpha \bar{q}_\beta \to \ell_\beta \bar{\ell}_\alpha)$	$i g_L^2 (F_{\beta\alpha} + 2T) \sum_{j=1}^{2} \frac{s\ \alpha_1^j\ d^j_{1,1}}{s - M_S^2 + i\Gamma_1^j M_S}$
$A^{n=2}_{SR}(q_\alpha \bar{q}_\beta \to \ell_\alpha \bar{\ell}_\beta)$	$i g_L^2\ F_{\alpha\alpha} \sum_{j=1}^{3} \frac{s\ \alpha_1^j\ d^j_{1,-1}}{s - M_S^2 + i\Gamma_1^j M_S}$
$A^{n=2}_{SR}(q_\alpha \bar{q}_\beta \to \ell_\beta \bar{\ell}_\alpha)$	$i g_L^2\ F_{\beta\alpha} \sum_{j=1}^{3} \frac{s\ \alpha_1^j\ d^j_{1,1}}{s - M_S^2 + i\Gamma_1^j M_S}$
$A^{n=1}_{SR}(g_\alpha g_\beta \to \ell_\alpha \bar{\ell}_\beta,\ \ell_\beta \bar{\ell}_\alpha)$	$i g_L^2 T \frac{s\ d^2_{2,\mp1}}{s - M_S^2 + i\Gamma_1 M_S}$
Diphoton final state	
$A^{n=1}_{SR}(q_\alpha \bar{q}_\beta \to \gamma_\alpha \gamma_\beta,\ \gamma_\beta \gamma_\alpha)$	$i e^2 T \frac{s\ d^2_{2,\mp1}}{s - M_S^2 + i\Gamma_1 M_S}$
$A^{n=1}_{SR}(g_\alpha g_\beta \to \gamma_\alpha \gamma_\beta,\ \gamma_\beta \gamma_\alpha)$	$2 i e^2 T \frac{s\ d^2_{2,\mp2}}{s - M_S^2 + i\Gamma_1 M_S}$

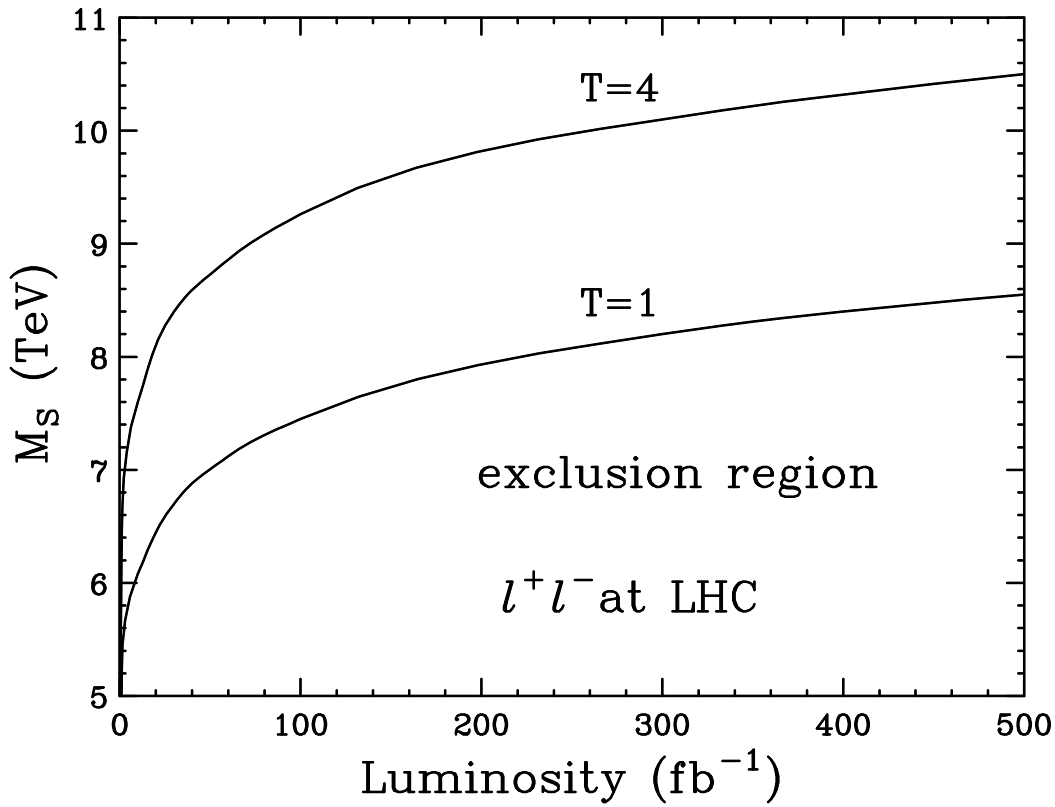
Explicit angular dependences:

process	angular dependence
$\underline{q\bar{q} \to \ell\bar{\ell}}$	
$n = 1, \quad j = 1$	$(d^1_{1,-1})^2 + (d^1_{1,1})^2 \propto \quad 1 + \cos^2\theta$
$j = 2$	$(d^2_{1,-1})^2 + (d^2_{1,1})^2 \propto \quad 1 - 3\cos^2\theta + 4\cos^4\theta$
$n = 2, \quad j = 1$	$(d^1_{1,-1})^2 + (d^1_{1,1})^2 \propto \quad 1 + \cos^2\theta$
$j = 2$	$(d^2_{1,-1})^2 + (d^2_{1,1})^2 \propto \quad 1 - 3\cos^2\theta + 4\cos^4\theta$
$j = 3$	$(d^3_{1,-1})^2 + (d^3_{1,1})^2 \propto \quad 1 + 111\cos^2\theta$
	$-305\cos^4\theta + 225\cos^6\theta$
$\underline{gg \to \ell\bar{\ell}}$	
$n = 1, \quad j = 2$	$(d^2_{2,-1})^2 + (d^2_{2,1})^2 \propto \quad 1 - \cos^4\theta$
$\underline{q\bar{q} \to \gamma\gamma}$	
$n = 1, \quad j = 2$	$(d^2_{2,-1})^2 + (d^2_{2,1})^2 \propto \quad 1 - \cos^4\theta$
$\underline{gg \to \gamma\gamma}$	
$n = 1, \quad j = 2$	$(d^2_{2,-2})^2 + (d^2_{2,2})^2 \propto \quad 1 + 6\cos^2\theta + \cos^4\theta$

Very rich structure of angular distributions:



LHC 95% C.L. sensitivity from $\ell^+\ell^-$ mode:



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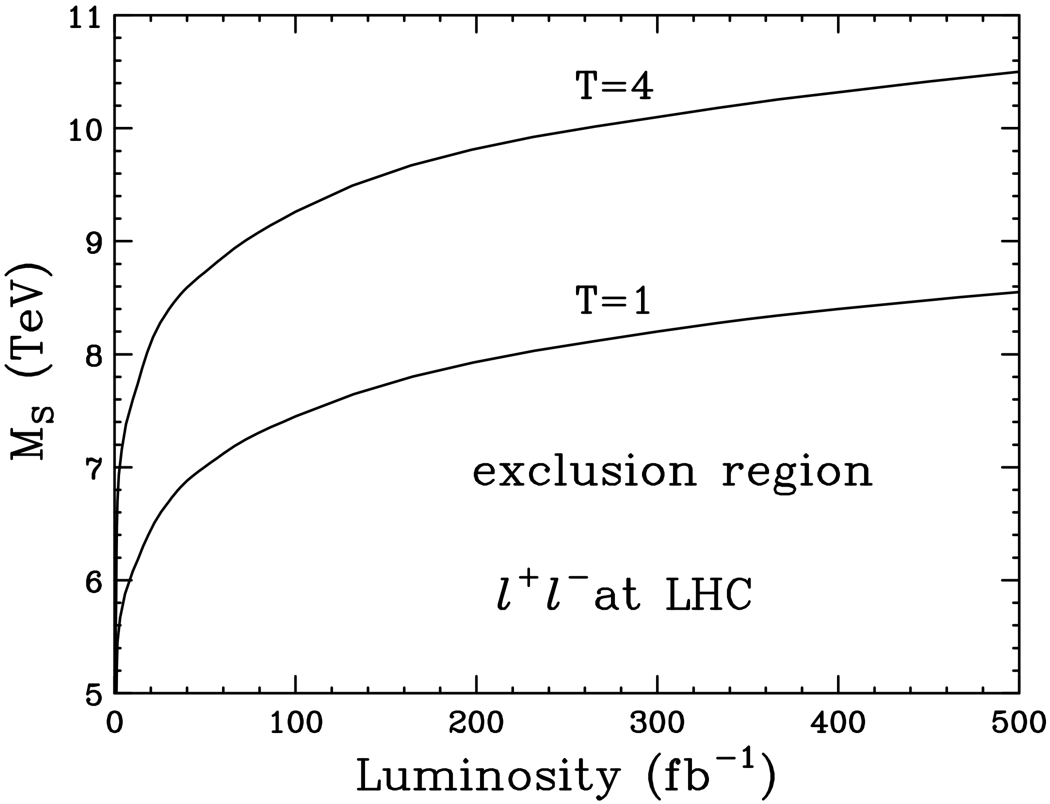

With 300 fb^{-1}, if no signal seen,

we expect to reach bounds for

$$M_S > 8\ (10)\ \text{TeV for } T = 1 - 4.$$

Summary

With $M_S \sim \mathcal{O}(1\ \text{TeV})$ and R (possibly) large,

• At low energies: $1/R < E \ll M_S$,

gravity effects observable, mainly via light KK gravitons of mass $m_{KK} \sim 1/R$.

• At "trans Planckian" energies: $E > M_D, M_S$,

gravity-effects dominant, (mainly) via black hole production.

• Near the string scale: $E \sim M_D, M_S$,

string-resonances dominant.

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▷ reproduce the SM particle amplitudes at low energies.

▷ the low-energy constraints not severe (yet).

▷ applied to hadron collider searches:

Tevatron reach, with 2 fb^{-1} : $1.5 - 3$ TeV;

LHC reach, with 300 fb^{-1} : $8 - 10$ TeV.