String Theory meets Collider Physics

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http://wwwth.mppmu.mpg.de/webdocs/eng/sst.html

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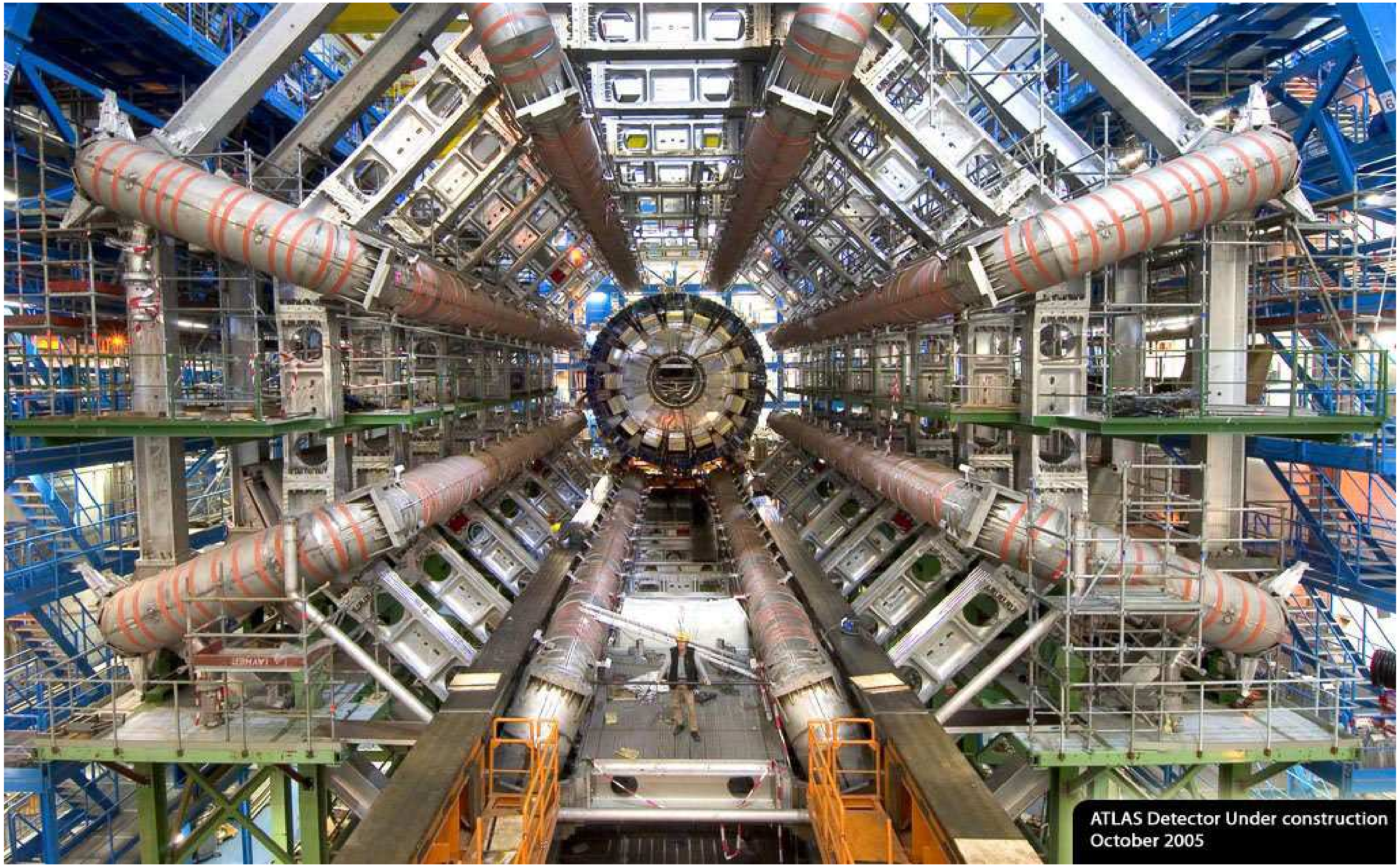
LHC

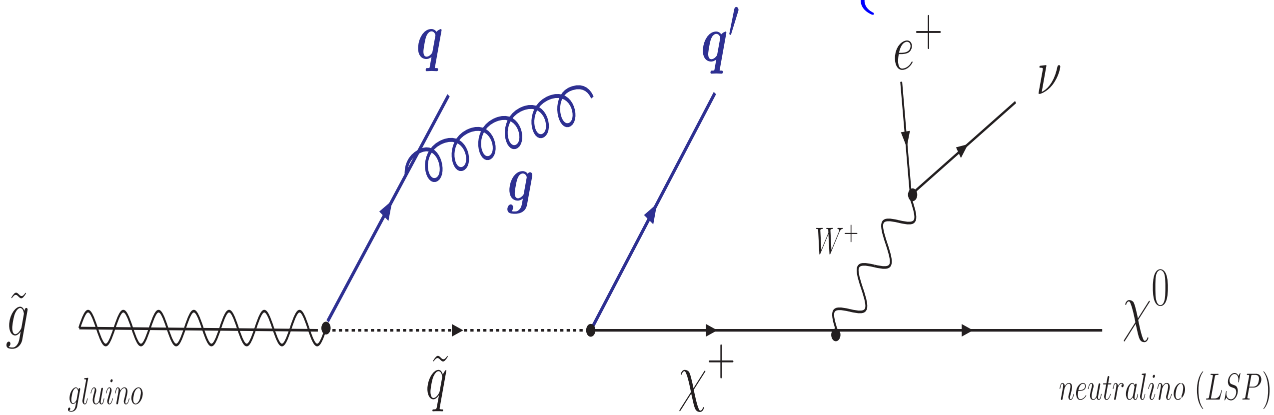


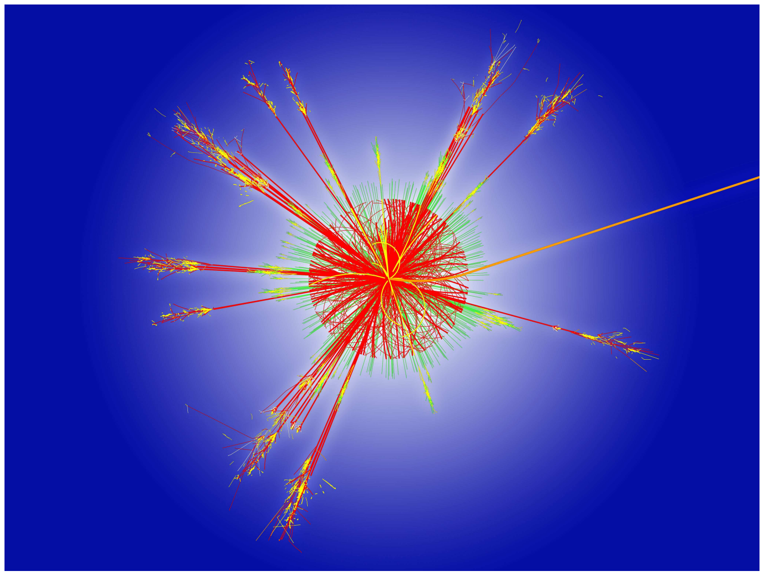
LHC operates at 14 TeV with luminosity $\sim$ 50 greater than Tevatron.
$\Longrightarrow$ huge production of (new) particles in the range of $100-1000$ GeV

QCD jets

jets of hadrons

SM background: pert. QCD
& corrections





Corrections at $\sqrt{s} \sim \mathcal{O}(\text{TeV})$

to the YM amplitudes

from new physics ?

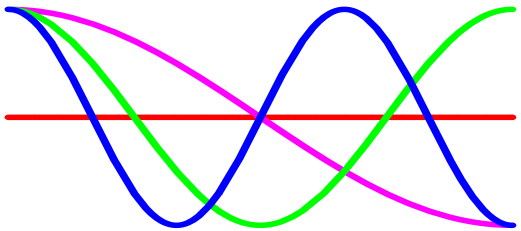
How does string theory enter ?

- The effects of new physics (*e.g.* large extra dimensions) are derived from a theory of quantum gravity (string theory)

- String theory contains and describes perturbative gluon scattering.
  String theory yields powerful methods to compute gluon amplitudes (twistor string theory)

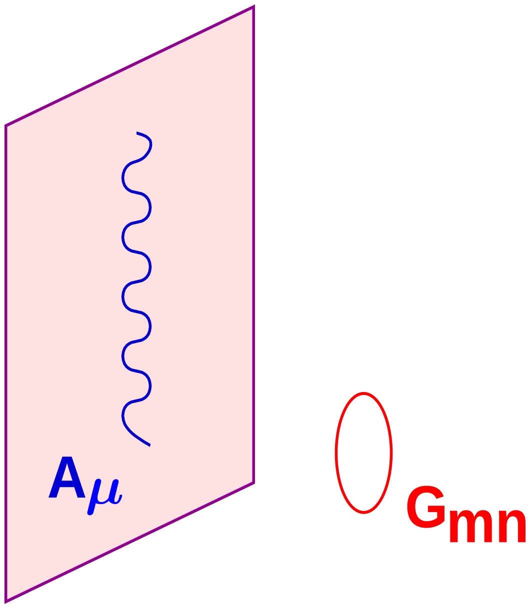
String theory: strings and membranes

Strings: spectrum



- masseless modes $m = 0$,
- (graviton g_{MN}, gauge field $A_M, \ldots$)
- massive modes $m \sim M_{\text{string}} \sim \frac{1}{\sqrt{\alpha'}}$

D-branes:



higher–dimensional objects placed into space–time

gauge fields live A_μ on membrane

$\Longrightarrow$ gauge interactions localized on membrane

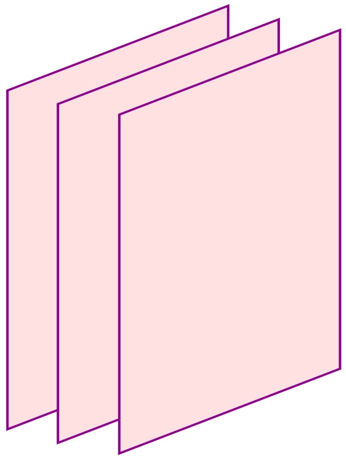
Gauge theories from/in string theory: Dp–branes

A variety of string theories contain gauge theories in their $\alpha' \to 0$ limits

E.g.: Type II with N D–branes gives $U(N)$ gauge group

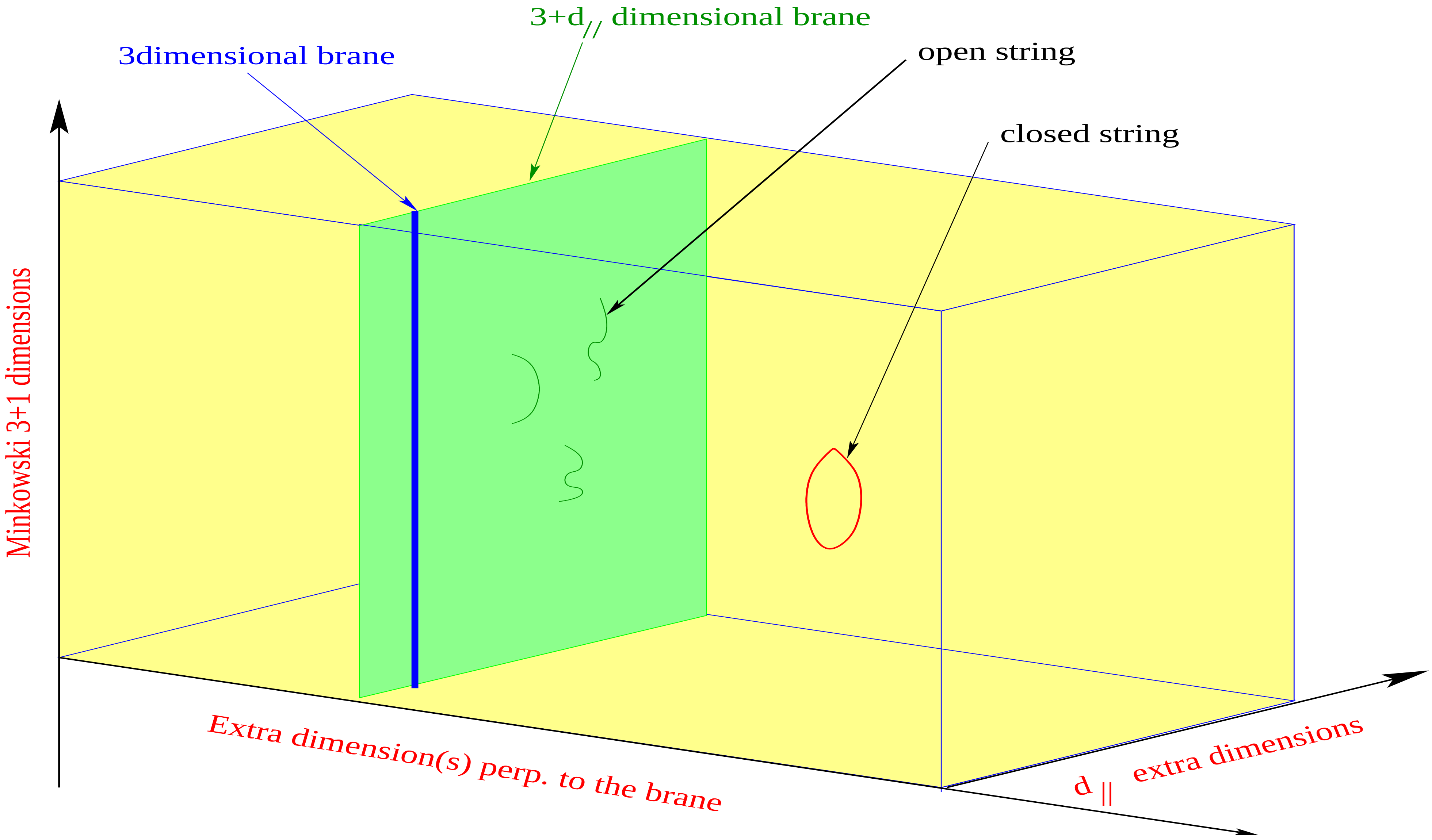
or Type I with $SO(2N)$ gauge group

E.g.: Three parallel D–branes



$\Longrightarrow$ $U(3)$ gauge group

Setup: Type IIB $\boxed{g_{YM} = g_{10}\ e^{\phi_{10}/2}}$



3+d// dimensional brane
3dimensional brane
open string
closed string
Minkowski 3+1 dimensions
Extra dimension(s) perp. to the brane
d || extra dimensions

Physics of large extra dimensions

- closed strings only (*e.g.* heterotic string):

$$\boxed{M_{\text{string}} = g_a \, M_{\text{Planck}}} \quad \Longrightarrow \quad \boxed{\boldsymbol{M_{\text{string}} \sim 10^{17} \text{ GeV}}}$$

$\Longrightarrow$ hierachy problem: $M_{\text{weak}} \ll M_{\text{Planck}}$

- open and closed strings (*e.g.* type I superstring):

$$\boxed{M_{\text{string}}^4 \, R^3 = g_a^2 \, M_{\text{Planck}}} \quad \Longrightarrow \quad \boxed{\boldsymbol{R \uparrow \Longrightarrow M_{\text{string}} \downarrow}}$$

$\Longrightarrow$ gravity and gauge interactions unified at M_{weak}

$$\boxed{R^{-1} = \left(\frac{2}{g_a^4}\right)^{1/n} M_{\text{string}} \left(\frac{M_{\text{string}}}{M_{\text{Planck}}}\right)^{2/n} \ll M_{\text{string}}} \quad \Longrightarrow R = \begin{cases} 0.1 \text{ mm} \,, & n = 2 \,, \\ \vdots & \vdots \\ 10^{-15}\text{m} \,, & n = 6 \,. \end{cases}$$

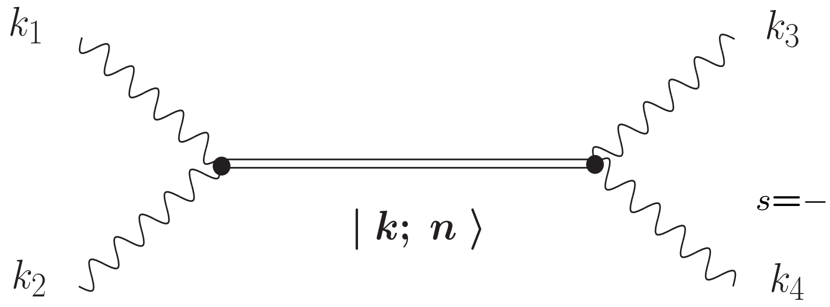
Antoniadis, Arkani–Hamed, Dimopoulos, Dvali

Weekness of gravity due to large extra dimensions:

for $M_{\text{string}} = 1\text{TeV}$ we have: $\boldsymbol{E_R \sim \; 10^{-3}\text{eV}, \ldots, 10 \text{ MeV}}$

Exchange of string Regge (SR) excitations

Exchange of SR excitations of SM particles:



s–channel
$k{=}k_1{+}k_2$

$s{=}-2k_1k_2,\ \ t{=}-2k_1k_3,\ \ u{=}-2k_1k_4$
$s{+}t{+}u{=}0$

$$A(k_1,k_2,k_3,k_4;\alpha') \sim \sum_{n=0}^{\infty} \frac{\gamma(n)}{s-M_n^2} = -\frac{\Gamma(-\alpha' s)\ \Gamma(1-\alpha' u)}{\Gamma(-\alpha' s-\alpha' u)}$$

with:

$$\boxed{M_n^2 = M_{\text{string}}^2\ n} \qquad M_{\text{string}}^2 = \alpha'^{-1} \qquad \boxed{\gamma(n) = t\ \frac{(u\ \alpha', n)}{n!}}$$

$$\gamma(n) = \frac{t}{n!} \prod_{j=1}^{n} [a(u)+j] \sim (\alpha'\ u)^n \quad ,$$

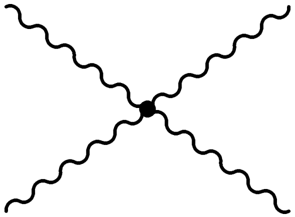
$a(u){=}u\alpha'{-}1$ = Regge trajectory
highest possible spin$=n{+}1$

New contact interaction terms

$$A(k_1,k_2,k_3,k_4;\alpha') \sim \underbrace{\frac{t}{s}}_{n=0} - \underbrace{\zeta(2)\ tu\ \alpha'^2}_{n\neq 0} + \ldots$$

Encounter infinite many contact interactions in effective theory:

α'^2



$$(\partial A)^4 \rightarrow \zeta(2)\ F^4$$

$\Longrightarrow$ α'–correction to YM theory

Generically:

$$\boxed{\sum_{n=0}^{\infty} \alpha'^{2+n}\ \zeta(2+n)\ D^{2n}\ F^4}$$

$\alpha'^2\,\zeta(2)\ F^4,\ \alpha'^3\,\zeta(3)\ D^2F^4,\ \alpha'^4\,\zeta(4)\ D^4F^4, \ldots$

Oprisa, Stieberger, 2005

Set of new interaction terms to be written

into the low–energy effective action.

Contact interactions

Stringy corrections from contact interactions, *e.g.*: $\boldsymbol{e^-_L e^+_R \to \gamma_L \gamma_R}$

$$\mathcal{A}(e^-_L e^+_R \to \gamma_L \gamma_R) = -2\ g^2_{\text{string}}\ \sqrt{\frac{u}{t}}\ \left(1 + \frac{1}{2}\ \zeta(2)\ \frac{ut}{M^4_{\text{string}}} + \ldots\ \right)$$

Cullen, Perelstein, Peskin, 2000

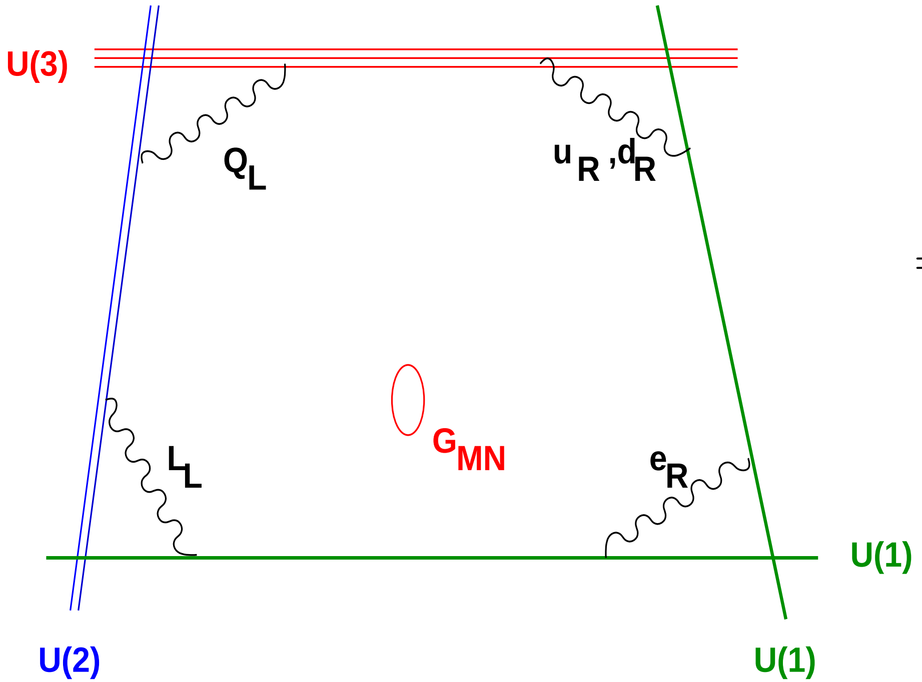
Deviations from SM cross section (Drell parametrization):

$$\frac{d\sigma}{d\cos\theta} = \frac{d\sigma}{d\cos\theta}\bigg|_{SM}\ \left(1 + \zeta(2)\ \frac{ut}{M^4_{\text{string}}}\right)$$

This yields $M_{\text{string}} > 290$ GeV.

Resonances

Intersecting D–brane models allow for the tree–process: $gg \longrightarrow g\gamma$



$\Rightarrow SU(3) \times SU(2) \times U(1) \quad (SM)$

$\Longrightarrow$ Non–SM contribution to: $pp \longrightarrow \gamma + jet$

In addition to SM–background from: $gq \rightarrow \gamma q$, $g\overline{q} \rightarrow \gamma\overline{q}$ and $q\overline{q} \rightarrow \gamma g$
(also corrected by stringy corrections)

Resonances

Multi–gluon tree–level superstring scattering (Stieberger, Taylor, 2006)

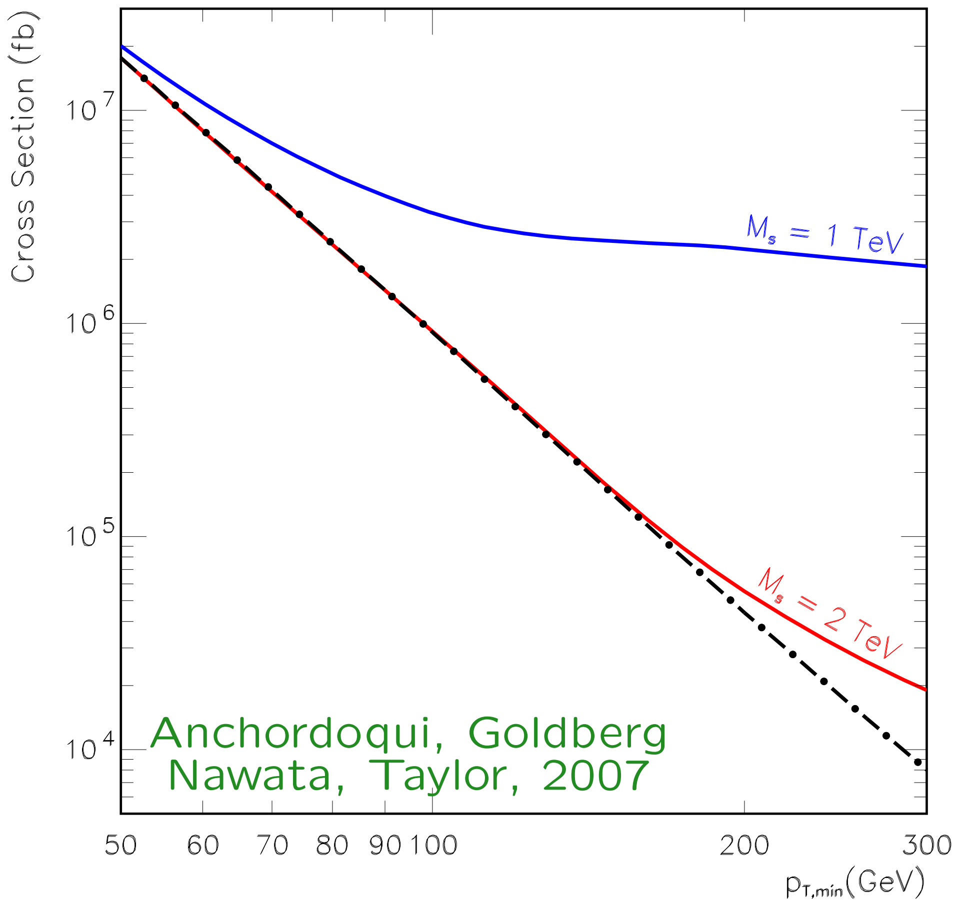
- completely model independent
- for any string compactification
- any number of supersymmetries
- even with broken supersymmetry

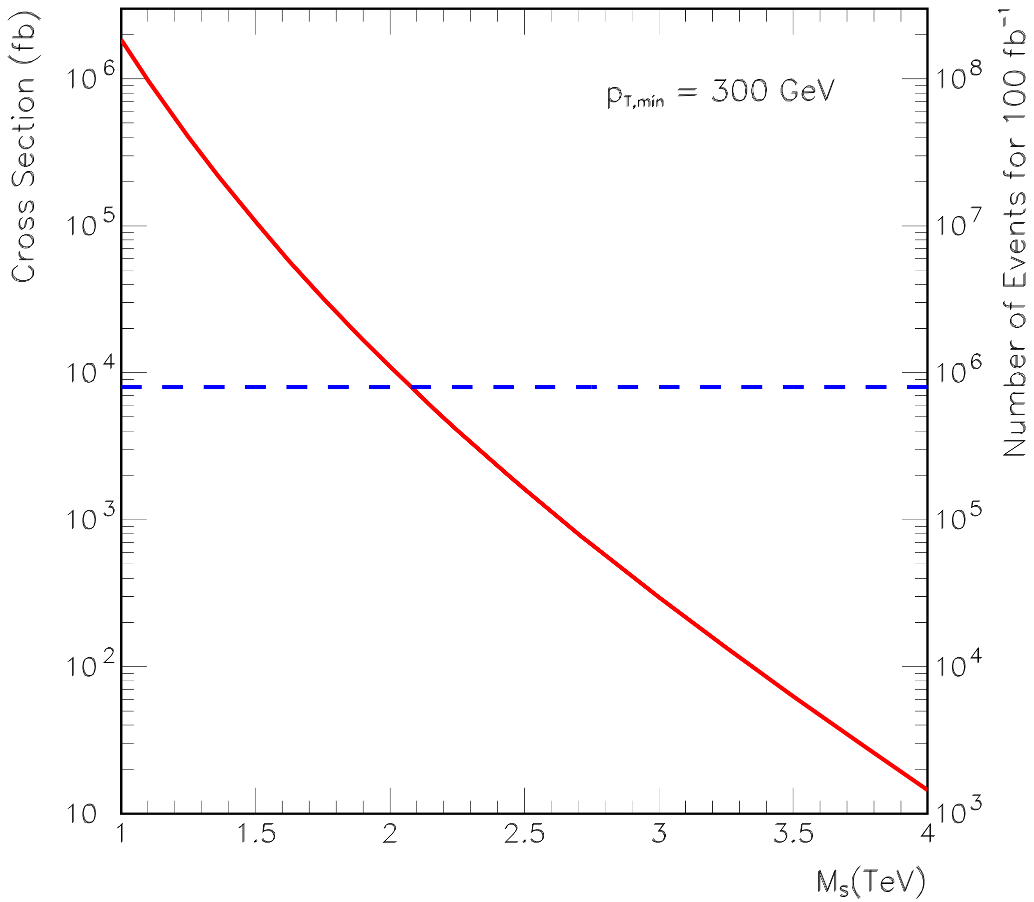
$$|\mathcal{A}(gg \to g\gamma)|^2 \sim g_{YM}^4 \, \frac{M_{\text{string}}^8 + t^4 + u^4}{M_{\text{string}}^4 \, [(s - M_{\text{string}}^2)^2 + (\Gamma M_{\text{string}})^2]} \quad , \quad s \sim M_{\text{string}}^2$$

Massive string mode propagating in the s–channel

Jet signals from low mass string theory

Compute cross section $\boldsymbol{\sigma(pp \to \gamma + jet)}$ (with parton distribution functions)





More studies and processes: Lüst, Stieberger, Taylor: *The LHC string hunter companion*

work in progress

Large extra dimensions, TeV strings and LHC

gravity & string theory:

significant effects on particle interactions at $M_{\text{string}} = 1$ TeV

- exchange of string Regge (SR) excitations of SM particles
- exchange of KK excitations of gravitons
- emission of gravitons into large extra dimensions (missing energy)

$$\boxed{\frac{\mathcal{A}_{SR}(\gamma_R\gamma_R \to \gamma_R\gamma_R)}{\mathcal{A}_{KK}(\gamma_R\gamma_R \to \gamma_R\gamma_R)} = \frac{3}{16}\,\zeta(2)\; g_{\text{string}}^{-2} + \ldots}$$

explicit computation in string theory !

Dominance of SR over KK effects is generic

in string theories with $g_{\text{string}} < 1$!

$\Longrightarrow$ LHC Laboratory for string theory effects ?!

Perspectives

$M_{\text{string}} \sim 1\text{TeV}$: [string theory **directly**]

string theory visible at LHC $\Longrightarrow$ LHC = laboratory for string theory

gluon amplitudes in string theory: model independent

$M_{\text{string}} \sim M_{\text{Planck}}$: [string theory **indirecty**]

string theory yields important explanations to the physics beyond the SM:

- **mechanisms for SUSY−breaking**
- **soft supersymmetry breaking terms**
- **dark energy** ($\Lambda = 0.003$ eV)
- **dark matter**
- **cosmology**
- ...

Soft–supersymmetry breaking terms

SUSY: $\Delta m_H^2 \sim \; m_{boson}^2 - m_{fermion}^2 = 0$

i.e. absence of *quadratic divergences* to correction of Higgs mass

SUSY–breaking: $m_{boson}^2 \; \neq \; m_{fermion}^2$

ensure the absence of *quadratic divergences* !

$\Longrightarrow$ certain soft–breaking terms are allowed
(split masses of scalars ϕ in the multiplets):

$$m_\phi^2 \; |\phi|^2, \; B \; \phi^2, \; A \; \phi^3, \; M_g \; \lambda\lambda$$

$\Longrightarrow$ compute in string theory

Soft–supersymmetry breaking terms

$$\Delta m_H^2 \sim \; m_{boson}^2 - m_{fermion}^2 \; \stackrel{!}{=} \; \mathcal{O}(\text{TeV})$$

Result: $$m_\phi \; = \; \underbrace{\xi}_{\text{3–form flux}} \; \frac{M_{\text{string}}^2}{M_{\text{Planck}}} \; = \; \mathcal{O}(\text{TeV})$$

$$M_{\text{string}} \sim 5 \times 10^{17} \text{ GeV} \; ,$$
$$1/R \sim 10^{17} \text{ GeV} \; ,$$
$$m_{3/2} \sim 10 \text{ TeV} \; ,$$
$$m_{soft} \sim 10^2 \text{ GeV}$$

Work on string phenomenology with:

D. Lüst, D. Härtl, S. Reffert, W. Schulgin