Strings at the LHC

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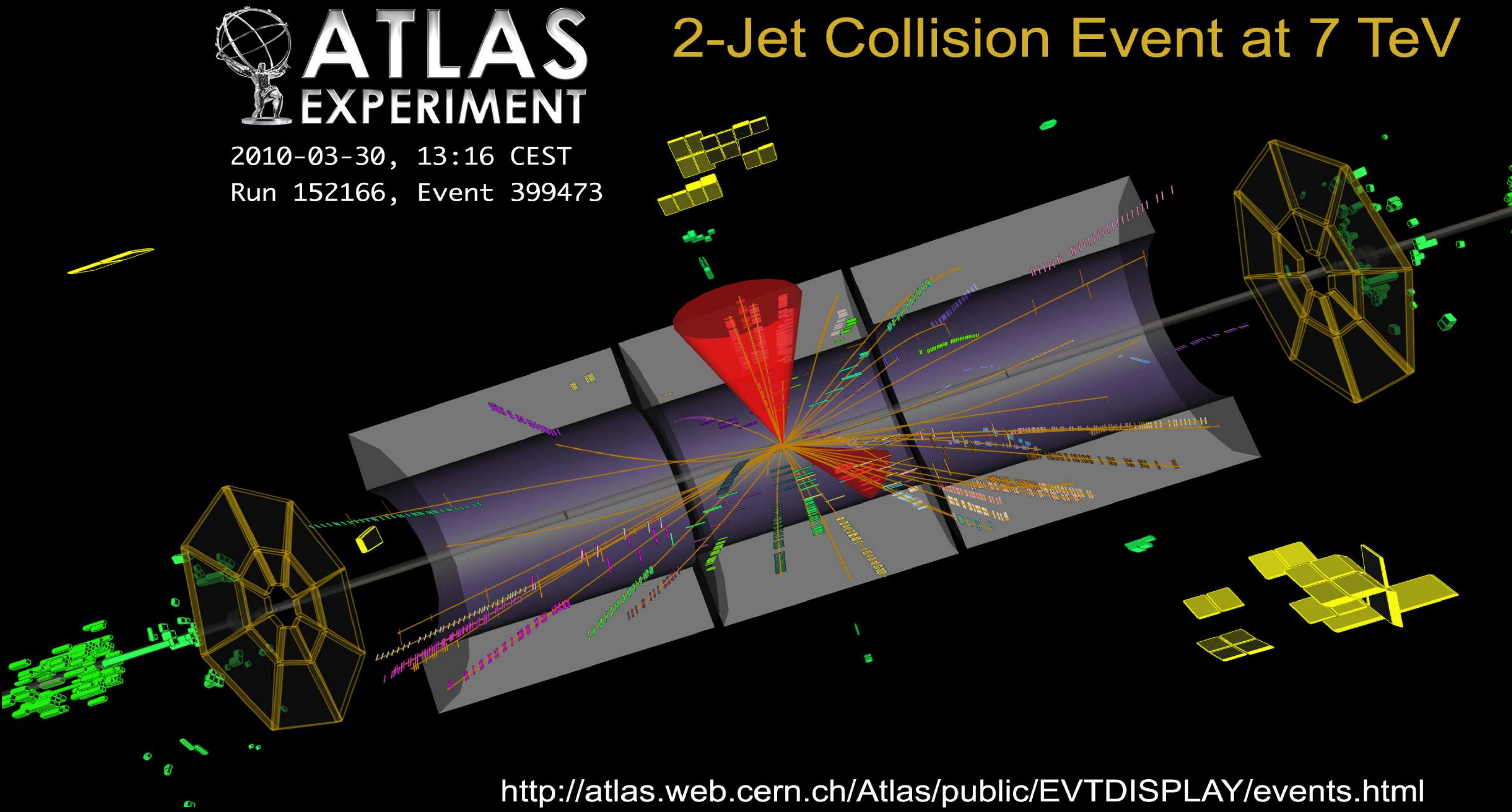


String theory can make <u>**universal predictions**</u> for QCD jets at LHC !

Outline

(1) (Brief) introduction into string theory and string phenomenology

(2) (Universal) string quantities relevant for QCD jets

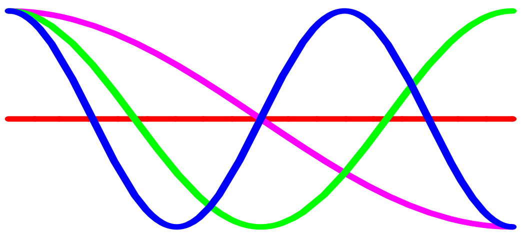
(3) Physics of large extra dimensions (= low string scale M_{string})

(4) Jet cross sections and universal string signals and predictions at LHC

String theory: strings and membranes

Strings:

spectrum

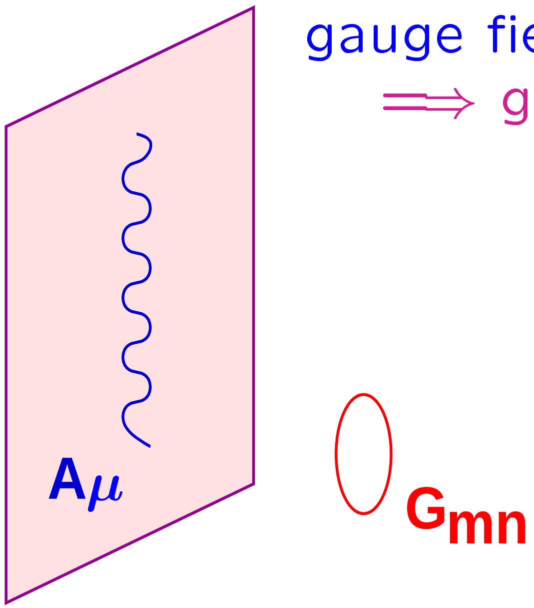


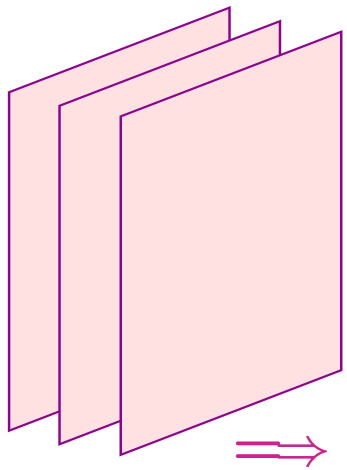
- masseless modes $m = 0$,
  (graviton G_{mn}, gauge field $A_\mu, \ldots$)
- massive modes $m \sim M_{\text{string}} \sim \frac{1}{\sqrt{\alpha'}}$

D-branes:

gauge fields live A_μ on membrane

$\Longrightarrow$ gauge interactions localized on membrane





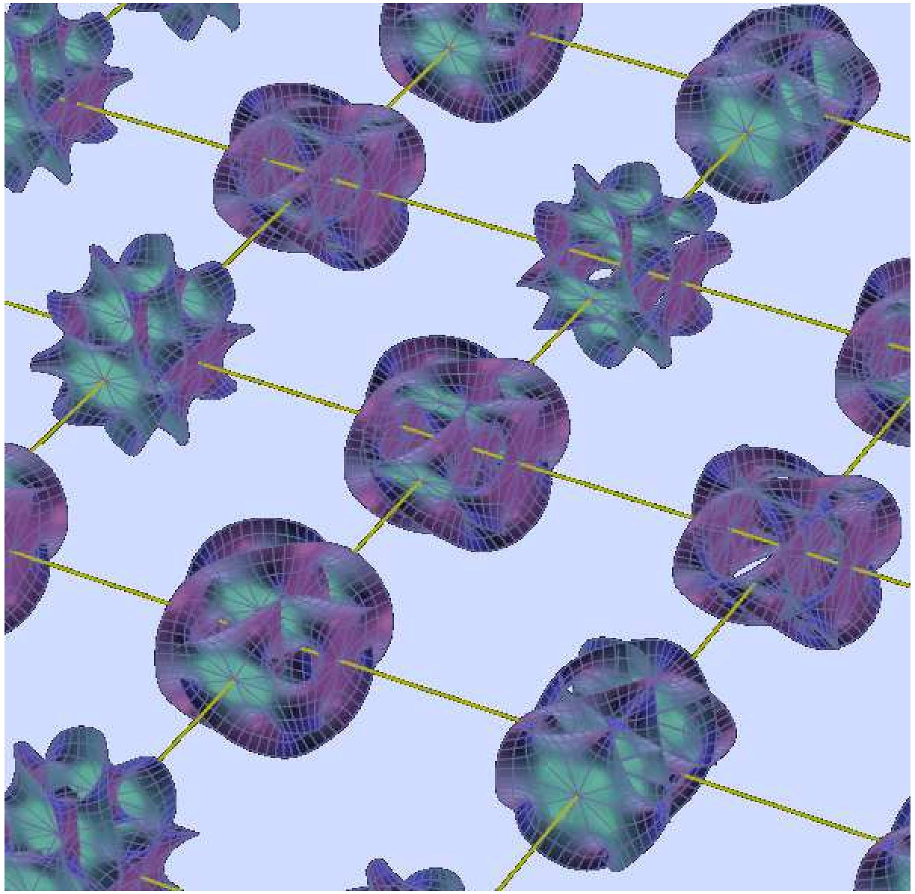
$\Longrightarrow$ $U(3)$ gauge group

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

String theory: compactification

String theory is only consistent and unique
in $D = 10$ space–time dimensions

$\Longrightarrow$ **compactification on manifold X_6**



space–time $M_4 \times X_6$

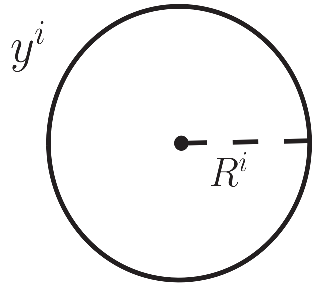
$$\binom{y^i}{x^\mu}, \quad i = 4, \ldots, 9 \quad , \quad \mu = 0, \ldots, 3$$

many possible manifolds $X_6 \Longrightarrow$ **huge number of $D = 4$ string vacua**

New string states from compactification

Each compactified coordinate y^i may be considered as cirlce of radius R^i

Kaluza–Klein states:



$$y^i \simeq y^i + 2\pi R^i$$

$$\psi(x^\mu, y^i) = e^{ik_\mu x^\mu} \; e^{ik_i y^i} \quad , \quad k_i \in \frac{n^i}{R^i} \quad , \quad n^i \in \mathbf{Z}$$

$$H = k^2 + m^2 = k_\mu k^\mu + \left(\frac{n^i}{R^i}\right)^2 + m^2$$

Moduli fields: massless scalars R^i generic to any compactification X_6

String phenomenology

In addition to the usual string excitations **new string states** appear:

- Kaluza–Klein states (KK) $m_{KK} \sim \frac{1}{R}$
- windings states $m \sim R$
- massless moduli fields (generic to any compactification) $m \sim 0$

In $D = 4$ many **new effects** and **problems:**

- computing particle masses,
- supersymmetry breaking,
- many free parameter (moduli),
- moduli stabilization, . . .

Standard approach to string phenomenology:

investigate properties of vacua, make $model - dependent$ **predictions**

Problem: predictive power of string theory is lost !

Model–independent string predictions

Question:

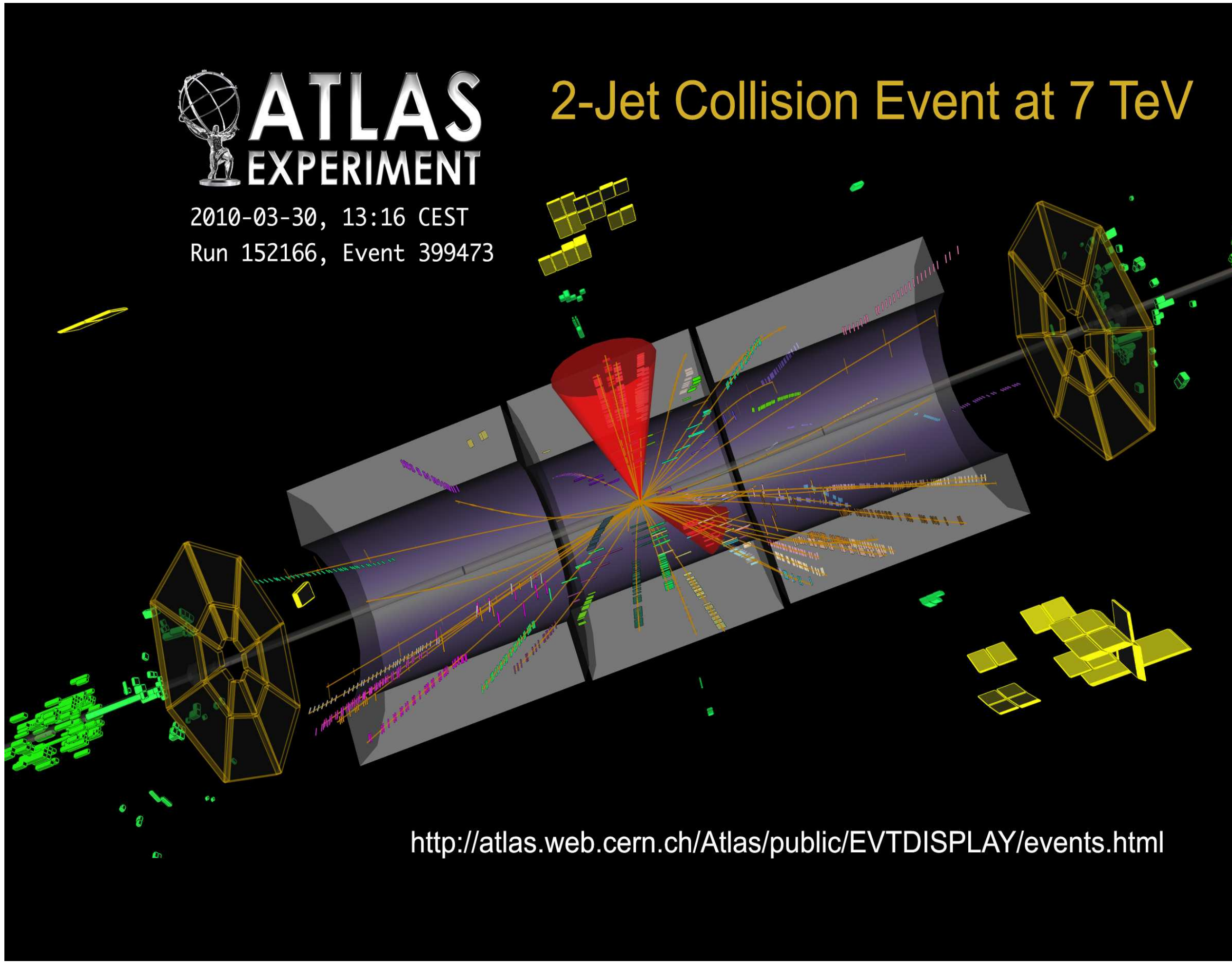
Can we make **model–independent**

low–energy **string predictions**

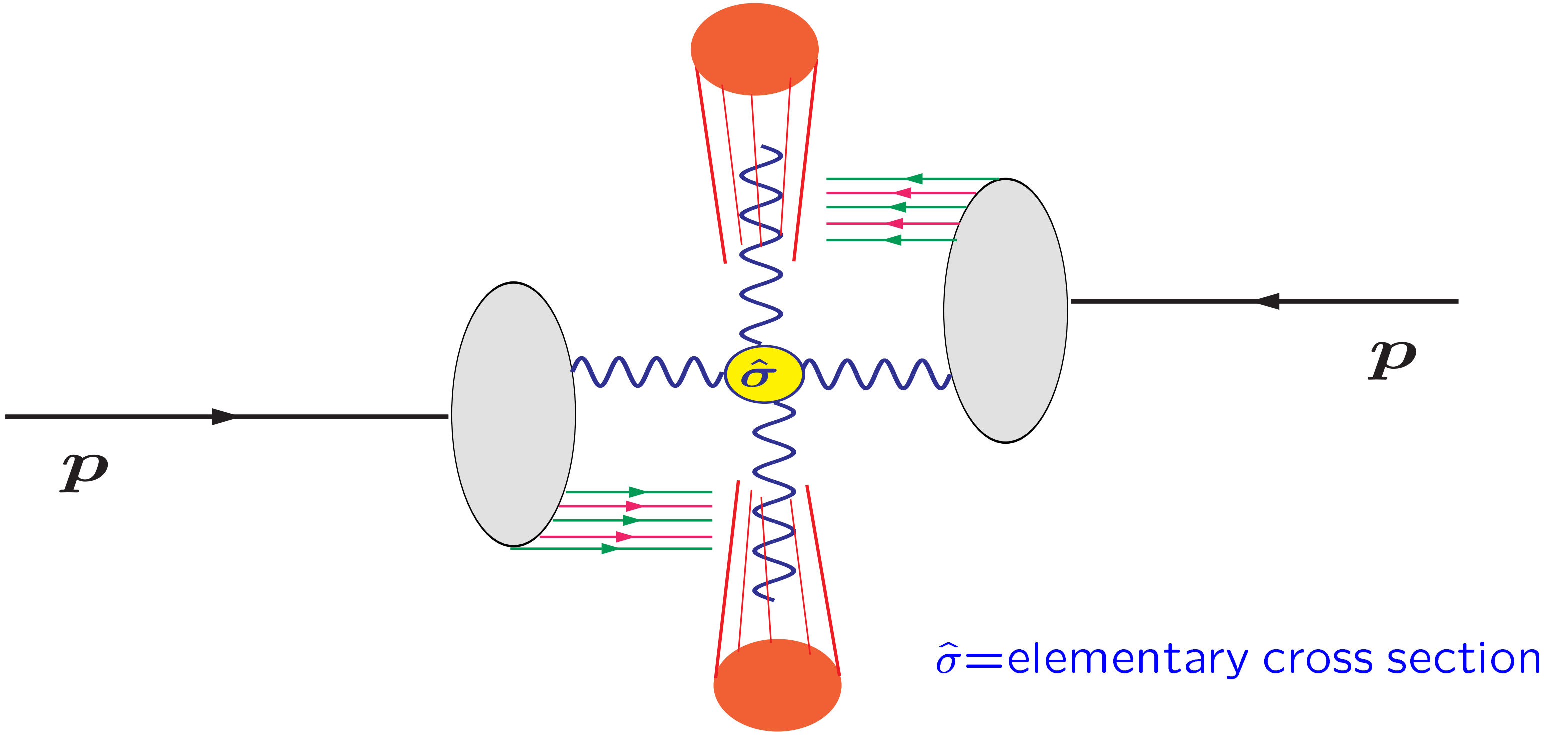
from parton amplitudes

in superstring theory ?

String signatures at LHC ?

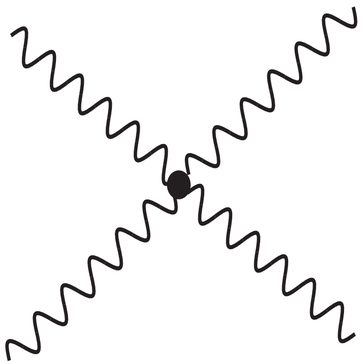


Yes: String theory can make **universal predictions** for QCD jets at LHC !

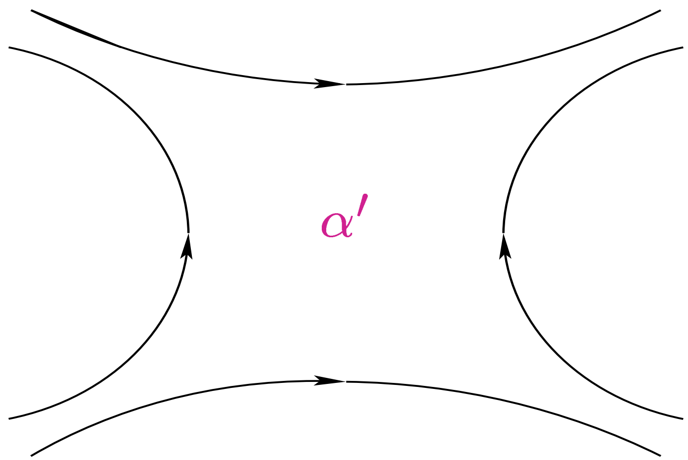


Parton amplitudes are important for (collider) phenomenology

LHC: Multijet production is dominated by tree–level QCD–scattering



Feynman 4–vertex in field–theory



string world–sheet of four interacting strings

Relevant objects: $N-$point parton amplitudes in $D = 4$

Task: compute amplitudes $\hat{\sigma}$ in string theory

$$\left.\begin{array}{c} A(g^{a_1}\dots g^{a_N}) \\ A(\chi^{a_1}\overline{\chi}^{a_2}g^{a_3}\dots g^{a_N}) \\ A(\psi^{a_1}\overline{\psi}^{a_2}g^{a_3}\dots g^{a_N}) \\ A(\phi^{a_1}\overline{\phi}^{a_2}g^{a_3}\dots g^{a_N}) \end{array}\right\}$$

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

g=gluon, χ=gaugino, ψ=fermion, ϕ=scalar

$$A_\rho(g_1^-, g_2^-, g_3^+, g_4^+) = 4\ g_{YM}^2\ V^{(4)}(\alpha')\ \frac{\langle 12\rangle^4}{\langle 12\rangle\langle 23\rangle\langle 34\rangle\langle 41\rangle}$$

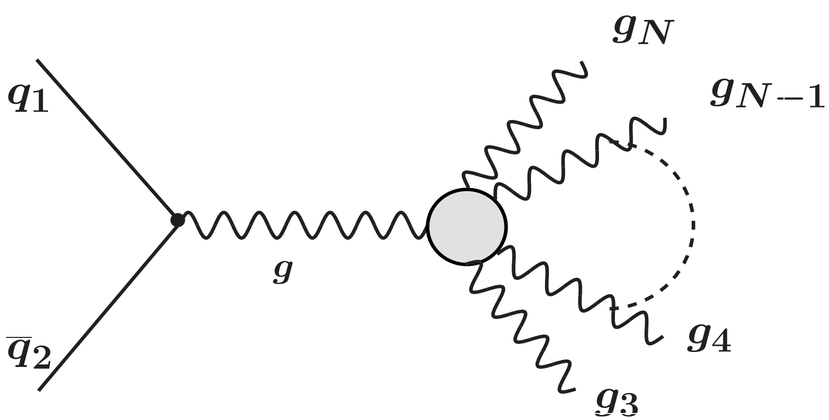
$$A_\rho(g_1^-, g_2^+, q_3^-, \bar{q}_4^+) = 2\ g_{YM}^2\ V^{(4)}(\alpha')\ \frac{\langle 13\rangle^4\langle 14\rangle}{\langle 12\rangle\langle 23\rangle\langle 34\rangle\langle 41\rangle}$$

Lüst, St.St., Taylor, arXiv:0807.3333

$$A_\rho(g_1^-, g_2^-, g_3^+, g_4^+, g_5^+) = i\, g_{YM}^3 \frac{\langle 12\rangle^4}{\langle 12\rangle\langle 23\rangle\langle 34\rangle\langle 45\rangle\langle 51\rangle} \times [\, V^{(5)}(\alpha') - 2i\, P^{(5)}(\alpha')\, \epsilon(1,2,3,4)\,]$$

$$A_\rho(g_1^-, g_2^+, g_3^+, q_4^-, \bar q_5^+) = 4\, g_{YM}^3 \frac{\langle 14\rangle^4 \langle 15\rangle}{\langle 12\rangle\langle 23\rangle\langle 34\rangle\langle 45\rangle\langle 51\rangle} \times [V^{(5)}(\alpha') - 2i\, P^{(5)}(\alpha')\, \epsilon(1,2,3,4)\,]$$

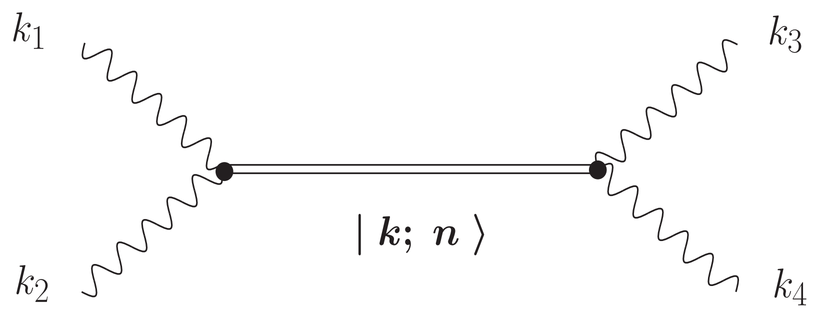
Lüst, Schlotterer, St.St., Taylor, arXiv:0908.0409



No intermediate exchange of Kaluza–Klein, winding states nor emmission of graviton !

Exchange of string Regge excitations of SM particles

Universal sum over infinite s–channel poles:



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

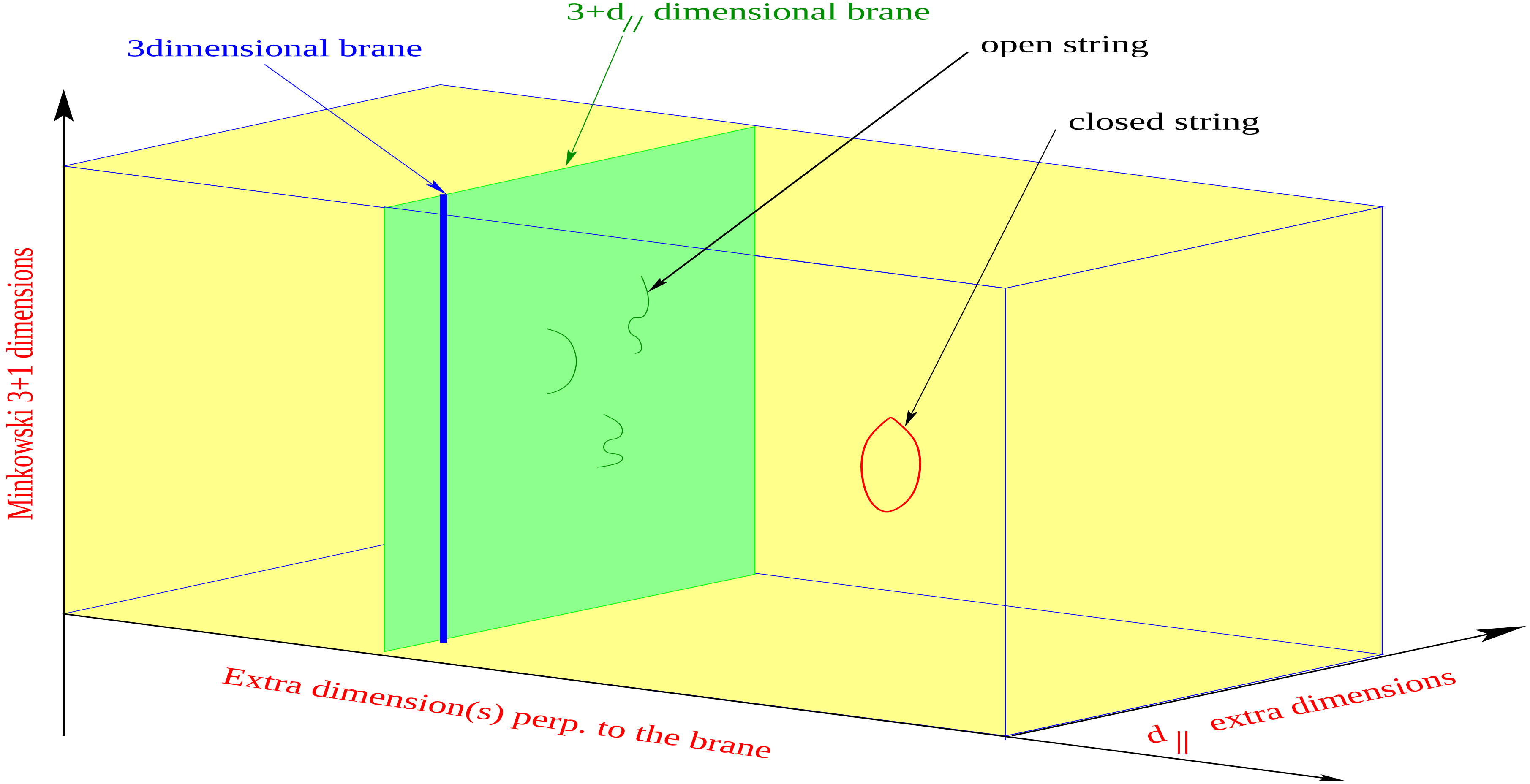
intermediate masses: $M_n^2 = M_{\text{string}}^2\ n$

residua: $\gamma(n) = t\ \frac{(u\ \alpha', n)}{n!}$

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

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

String compactification with Dp–branes



$$
\begin{aligned}
p+1 &= 4+d_{\|}\ , \\
d_{\perp} &= \text{number of transverse directions}\ , \\
d_{\|} &= \text{number of longitudinal directions}\ , \\
d_{\|}+d_{\perp} &= 6
\end{aligned}
$$

$$\mathcal{L}_{10} = M_{\text{string}}^{8} \int d^{10}X \sqrt{-g_{10}}\, R \quad + \quad M_{\text{string}}^{p-3} \int d^{p+1}X \sqrt{-g_{p+1}}\, F^2$$

$$\Downarrow \quad \textit{compactificaton}$$

$$\mathcal{L}_4 = \underbrace{M_{\text{string}}^{8} \int d^6y \sqrt{g_6}}_{V_6} \underbrace{\int d^4x \sqrt{-g_4}\, R}_{\text{Einstein}} + \underbrace{M_{\text{string}}^{p-3} \int d^{p-3}x \sqrt{g_{p+1}}}_{V_{p+1-4}} \underbrace{\int d^4x \sqrt{-g_4}\, F^2}_{\text{Yang–Mills}}$$

$$\begin{cases} V_6 = M_{\text{string}}^{8} \prod_{j=1}^{6} R_j = M_{\text{string}}^{8} \prod_{i=1}^{d_{\|}} R_i^{\|} \prod_{j=1}^{d_{\perp}} R_j^{\perp} \overset{!}{=} G_N^{-1} = M_{\text{Planck}}^2 = 8\pi\kappa_4^{-2} \\ V_{p-3} = \prod_{i=1}^{d_{\|}} (M_{\text{string}}\, R_i^{\|}) \overset{!}{=} g_{Dp}^{-2} \qquad \Longrightarrow \qquad \prod_{i=1}^{d_{\|}} R_i^{\|} \sim M_{\text{string}}^{-d_{\|}} \end{cases}$$

$$\Longrightarrow \quad \boxed{g_{Dp}^2\, M_{\text{Planck}} = 2^{5/2}\pi\, M_{\text{string}}^{7-p} \left(\prod_{j=1}^{d_{\perp}} R_j^{\perp}\right)^{1/2} \left(\prod_{i=1}^{d_{\|}} R_i^{\|}\right)^{-1/2}}$$

Physics of large extra dimensions

$$\Longrightarrow \boxed{R_j^{\perp} \uparrow \Longleftrightarrow M_{\text{string}} \downarrow}$$

Antoniadis, Arkani–Hamed
Dimopoulos, Dvali

- **gravity and gauge interactions unified at M_{weak}**
- **weakness of gravity due to large extra dimensions**

	$d_\perp = 1$	$d_\perp = 2$	$d_\perp = 3$	$d_\perp = 4$	$d_\perp = 5$	$d_\perp = 6$
$R^\perp$ $[GeV^{-1}]$	$1.6 \cdot 10^{26}$	$4 \cdot 10^{11}$	$5.4 \cdot 10^{6}$	$2 \cdot 10^{4}$	693	74
$R^\perp$ $[m]$	$1.6 \cdot 10^{11}$	$4 \cdot 10^{-4}$	$5.4 \cdot 10^{-9}$	$2 \cdot 10^{-11}$	$7 \cdot 10^{-13}$	$7 \cdot 10^{-14}$
E_R $[MeV]$	$7.7 \cdot 10^{-24}$	$3 \cdot 10^{-9}$	$2 \cdot 10^{-4}$	0.06	1	16

Size of $d_\perp$ large extra dimensions for a string scale of $M_{\text{string}} = 1\ TeV$

(for $g_{\text{string}} \simeq g^2 = \frac{1}{25}$, $\alpha = \frac{g^2}{4\pi} = 0.003$, $E_R = \frac{hc}{R^\perp}$ and $1\ GeV^{-1} \sim 10^{-15} m$)

Physics of large extra dimensions and low string scale

• **Cavendish type** experiments test **Newton's law** up to a scale of millimeters. This provides an upper bound on the large extra dimensions $\boldsymbol{R_j^{\perp}}$ to be in the **millimeter range**.

• **QCD and electroweak scattering** experiments give an upper bound on the small extra dimensions $\boldsymbol{R_i^{\parallel} \sim M_{EW}^{-1}}$.

<u>*States:*</u>

- massless string states: MSSM and graviton $M = 0$
- string Regge **(SR)** excitations: $M_{SR} \sim 1$ TeV
- **KK** modes w.r.t. $\boldsymbol{R_i^{\parallel}}$: $M_{KK^{\parallel}} \sim M_{\text{string}}$
- **winding** modes w.r.t. $\boldsymbol{R_j^{\perp}}$: $M_{W^{\perp}} \sim M_{\text{string}}$
- **KK** modes w.r.t. $\boldsymbol{R_j^{\perp}}$: $M_{KK^{\perp}} \sim 10^{-3}$eV
- **black holes**: $M_{BH} \sim M_{\text{string}}/g^2_{\text{string}}$

Physics of large extra dimensions and low string scale

$\Longrightarrow$ **Dominance of SR over KK effects is generic in string theories with $g_{\text{string}} \sim g^2_{YM} < 1$!**

What about strong gravity effects ?

Black hole production at energies $\sim \frac{M_{\text{string}}}{g^2_{\text{string}}}$

Horowitz, Polchinski 1996
Meade, Randall 2007

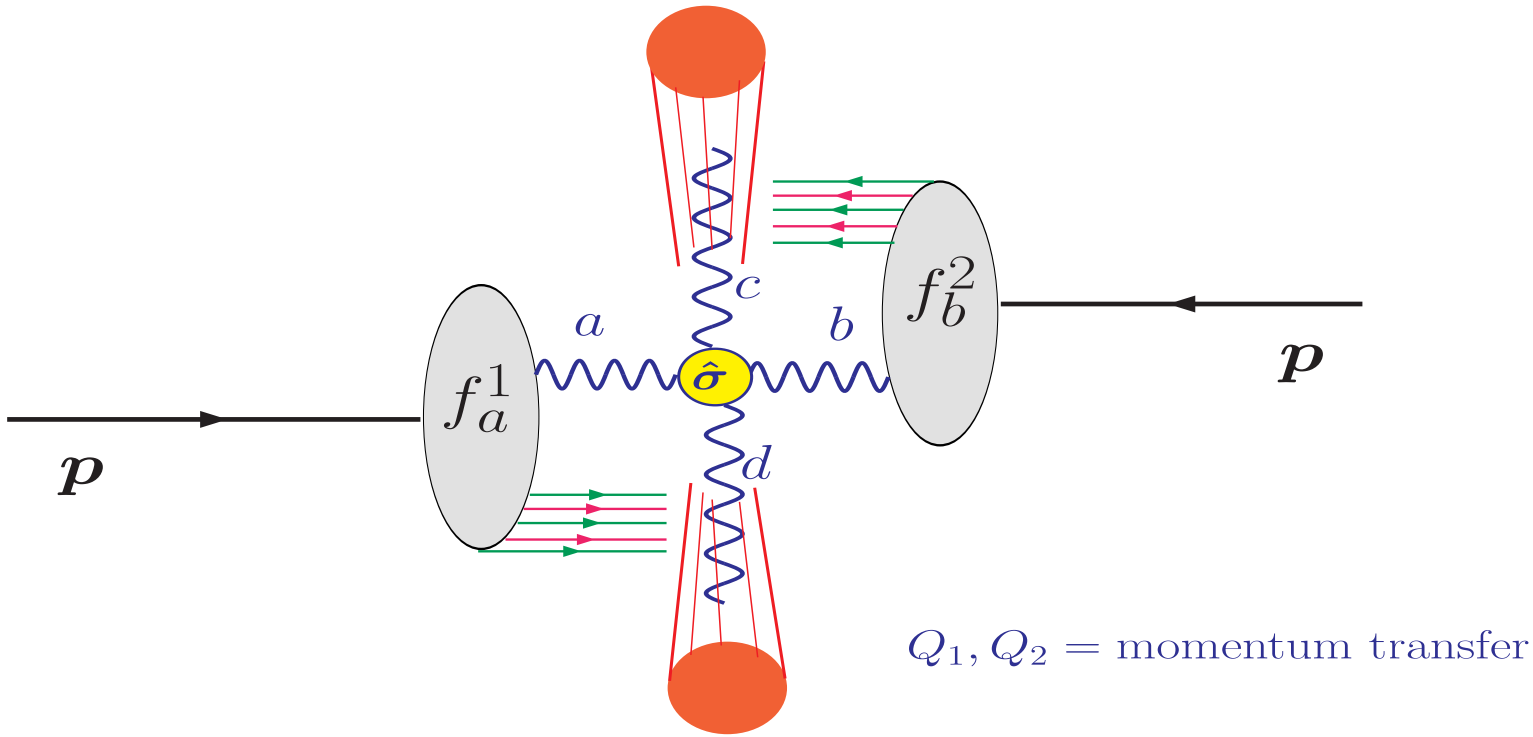
$$\boxed{n \sim g_{\text{string}}^{-4}}$$

$\Longrightarrow$ For $g_{\text{string}} < 1$ strong gravity effects occur above M_{string}

$\Longrightarrow$ We may first see SR's from 1-st, $\ldots$, n-th level

Dijet signals for low M_{string} at LHC

Two jets:



$$\sigma(pp \to 2 \text{ jets}) = \sum_{a,b,c,d} \int dx_1 \, dx_2 \, f_a^1(x_1; Q_1^2) \, f_b^2(x_2; Q_2^2) \, \hat{\sigma}_{ab\to cd}(\underbrace{s x_1 x_2}_{\hat{s}}; \underbrace{Q_1^2, Q_2^2}_{Q_1^2 = Q_2^2 = \hat{t}}, \alpha')$$

Look for **resonances of string Regge excitations** propagating in s–channel

Cross sections

Compute cross sections:

$$|\mathcal{M}(gg \to gg)|^2 \;,\; |\mathcal{M}(gg \to q\bar{q})|^2$$
$$|\mathcal{M}(q\bar{q} \to gg)|^2 \;,\; |\mathcal{M}(qg \to qg)|^2$$

} completely model–independent: for any CY orientifold !

Result:

tabulated in Lüst, Schlotterer, St. St., Taylor, arXiv:0807.3333, arXiv:0908.0409

$$|\mathcal{M}(gg \to gg)|^2 = g^4_{Dp_a} \left(\frac{1}{\hat{s}^2} + \frac{1}{\hat{t}^2} + \frac{1}{\hat{u}^2}\right) \Big\{ C(N) \left(\hat{s}^2 \, V_{\hat{s}}^2 + \hat{t}^2 \, V_{\hat{t}}^2 + \hat{u}^2 \, V_{\hat{u}}^2 \right) + D(N) \left(\hat{s} \, V_{\hat{s}} + \hat{t} \, V_{\hat{t}} + \hat{u} \, V_{\hat{u}} \right)^2 \Big\}$$

with $C(N) = \frac{2N^2}{N^2-1}$ and $D(N) = \frac{4(-N^2+3)}{N^2(N^2-1)}$

$$|\mathcal{M}(gg \to q\bar{q})|^2 = g^4_{Dp_a} \frac{N_f}{2N} \left\{ \frac{\hat{t}^2 + \hat{u}^2}{\hat{u}\hat{t}\hat{s}^2} (\hat{t} \, V_{\hat{t}} + \hat{u} \, V_{\hat{u}})^2 - \frac{2N^2}{(N^2-1)} \frac{\hat{t}^2 + \hat{u}^2}{\hat{s}^2} \, V_{\hat{t}} \, V_{\hat{u}} \right\}$$

For $N = N_f = 3$ YM–limits agree with book **"Collider Physics"** by Barger, Phillips

Cross sections

In addition we need:

$$|\mathcal{M}(q\bar{q} \to q\bar{q})|^2 \quad , \quad |\mathcal{M}(qq \to qq)|^2$$

$$|\mathcal{M}(q\bar{q} \to q'\bar{q}')|^2 \quad , \quad \begin{matrix} |\mathcal{M}(qq' \to qq')|^2 \\ |\mathcal{M}(q\bar{q}' \to q\bar{q}')|^2 \end{matrix}$$

} depend on geometry: KK and windings

tabulated in Lüst, St. St., Taylor, arXiv:0807.3333

however they are suppressed:

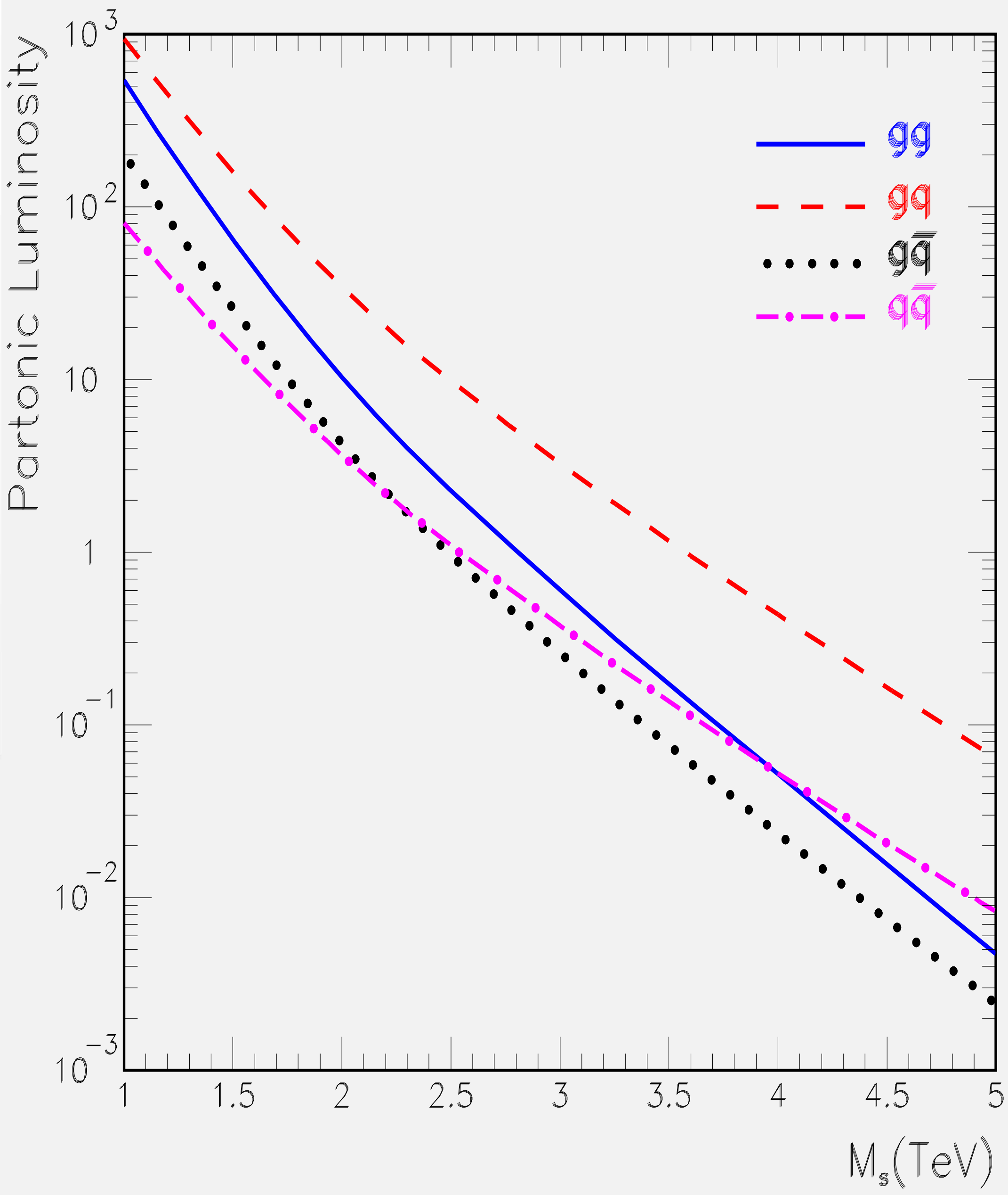
- QCD $SU(3)$ color group factors favor gluons over quarks in the initial state

- Parton luminosities in pp–collisions, at the parton center of mass energies above 1TeV, are significantly lower for $q\bar{q}$ subprocesses than for gg or gq

At any rate: they may be used to probe the internal geometry ("precision tests")

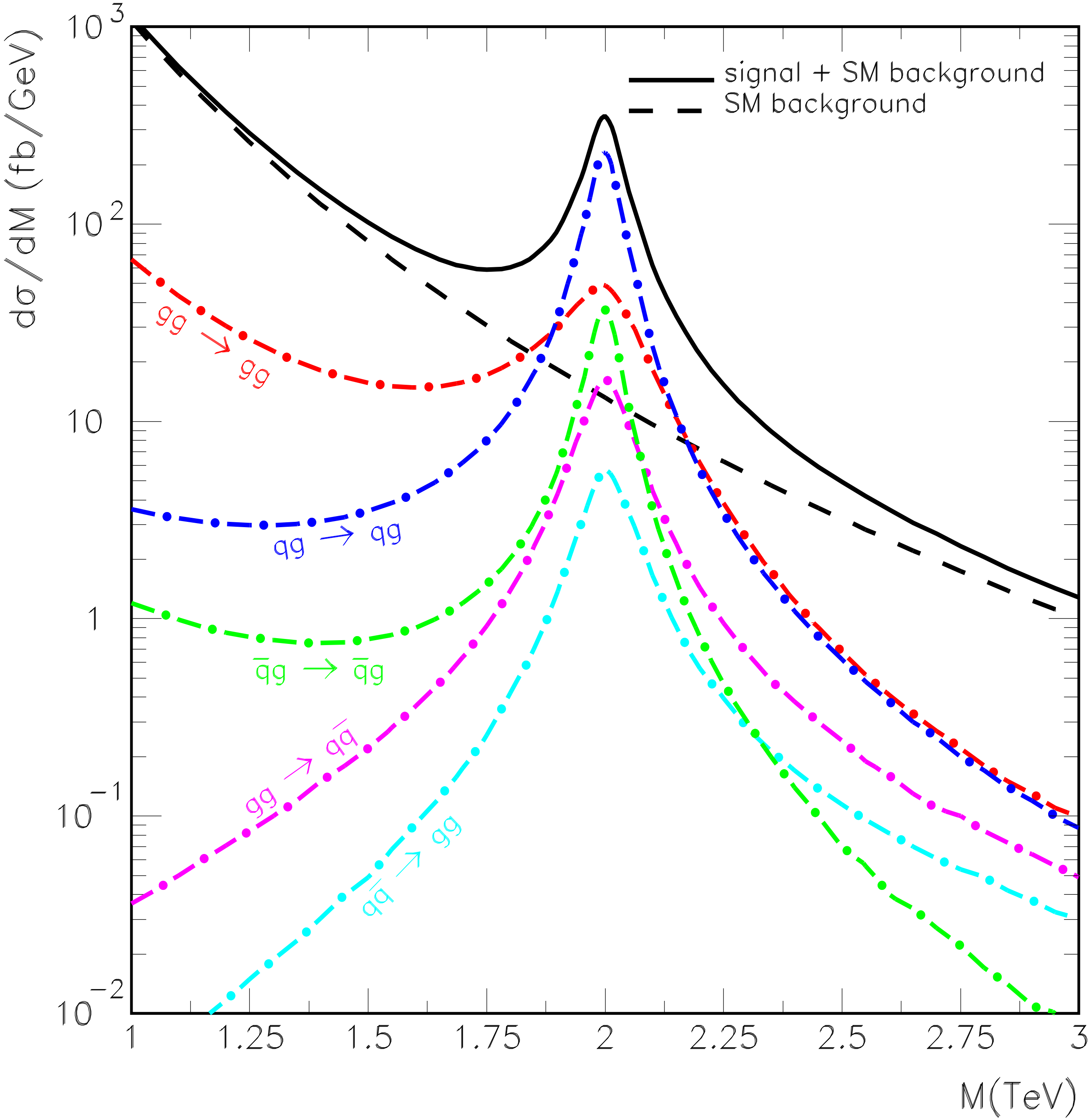
Table 9.1. *Squared matrix elements for 2 → 2 parton-parton subprocesses in QCD: q and q′ denote distinct flavors of quark, $g_s^2 = 4\pi\alpha_s$ is the coupling squared.*

Subprocess	$\|\mathcal{M}\|^2/g_s^4$	$\|\mathcal{M}(90°)\|^2/g_s^4$
$qq' \to qq'$, $q\bar{q}' \to q\bar{q}'$	$\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$	2.2
$qq \to qq$	$\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\right)-\frac{8}{27}\frac{\hat{s}^2}{\hat{u}\hat{t}}$	3.3
$q\bar{q} \to q'\bar{q}'$	$\frac{4}{9}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$	0.2
$q\bar{q} \to q\bar{q}$	$\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right)-\frac{8}{27}\frac{\hat{u}^2}{\hat{s}\hat{t}}$	2.6
$q\bar{q} \to gg$	$\frac{32}{27}\frac{\hat{u}^2+\hat{t}^2}{\hat{u}\hat{t}}-\frac{8}{3}\frac{\hat{u}^2+\hat{t}^2}{\hat{s}^2}$	1.0
$gg \to q\bar{q}$	$\frac{1}{6}\frac{\hat{u}^2+\hat{t}^2}{\hat{u}\hat{t}}-\frac{3}{8}\frac{\hat{u}^2+\hat{t}^2}{\hat{s}^2}$	0.1
$qg \to qg$	$\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}-\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{u}\hat{s}}$	6.1
$gg \to gg$	$\frac{9}{4}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}+\frac{\hat{u}^2+\hat{t}^2}{\hat{s}^2}+3\right)$	30.4



from "**Collider Physics**" by Barger, Phillips

Anchordoqui et al. arXiv:0804.2013



Any superstring theory with low $M_{\rm string}$ and $g_{\rm string} < 1$

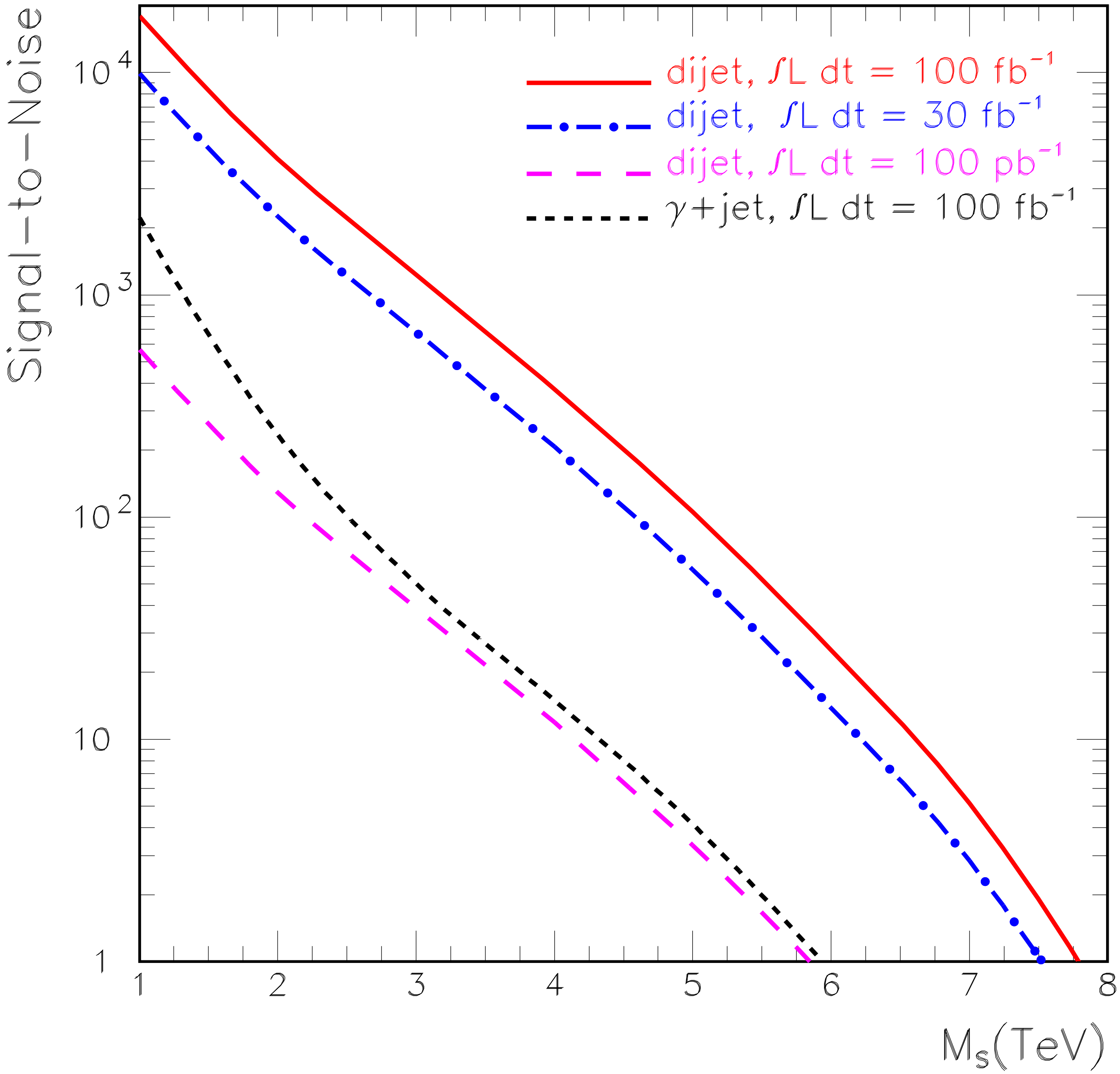
Universal deviation from SM in jet distribution

$M_{\rm string} = 2$ TeV

$\Gamma_{SR} = 15 - 150$ GeV

Anchordoqui, Goldberg, Lüst, Nawata, Taylor, St. St., arXiv:0808.0497, arXiv:0904.3547

Discovery reach: integrated luminosities



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

Future projects

While two–jet cross sections and angular distributions can provide first indications for the existence of excited states of fundamental superstrings many properties of these string resonances like their **spin and couplings to quarks and leptons** can be studied with **much higher precision** in **multi-jet processes**, in which two initial partons produce three or more particles. In these inelastic processes **string states** appear as resonances **in more than one decay channel**, therefore experimental **studies of acoplanarity and various quantities characterizing multi–jet distributions** allow more precise determination of the properties of string resonances.

- Five–parton amplitudes: *analysis for three–jet events*

  (Five–parton amplitudes computed in

  Lüst, Schlotterer, St. St., Taylor, `arXiv:0908.0409`)

- SR as external states in jets: *analysis for emission of strings*

  (Lüst, Schlotterer, St. St., Taylor, to appear)