Strings at the LHC

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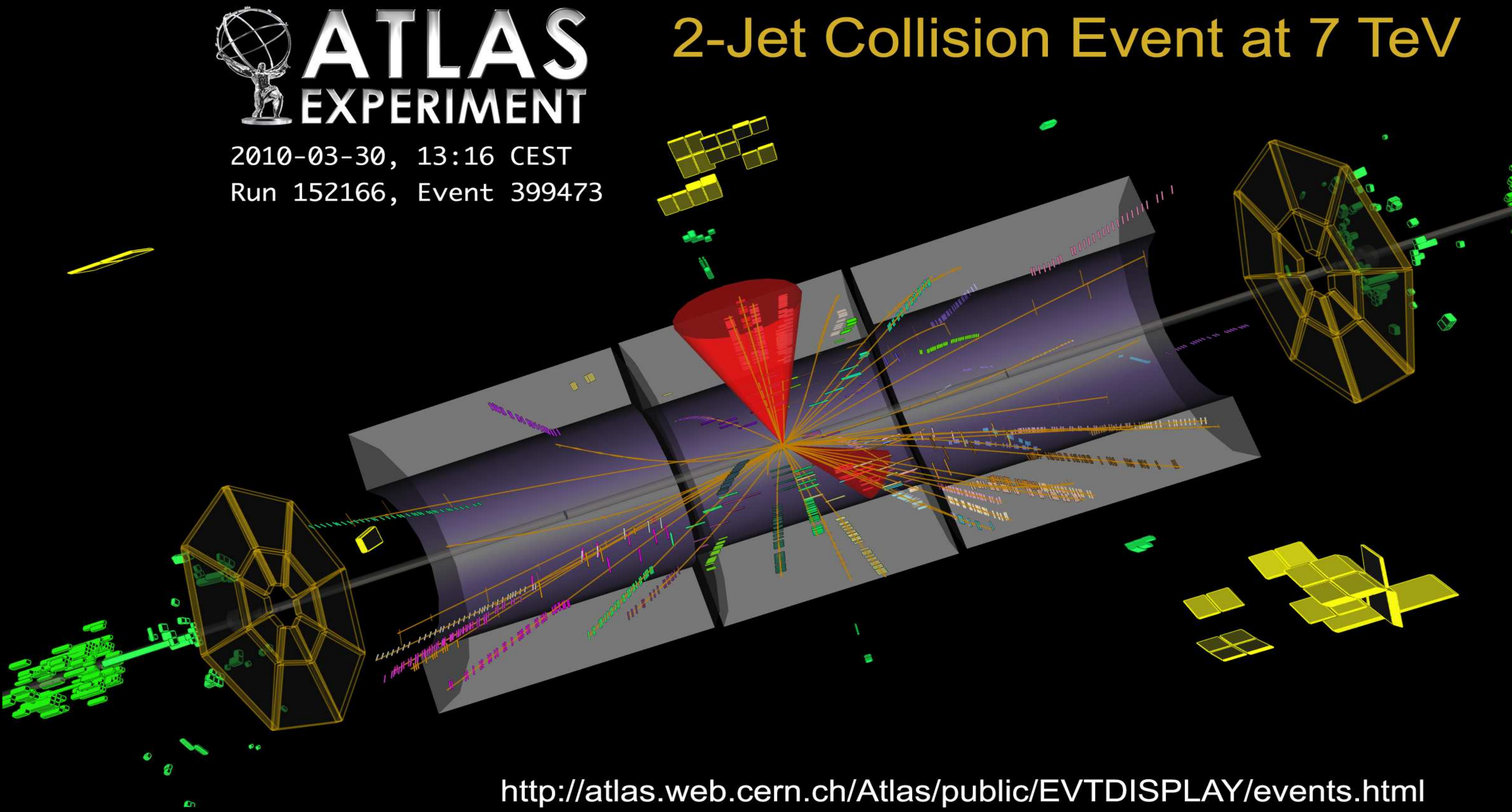


String theory can make **universal predictions** for QCD jets at LHC !

Predictions from string theory ?

Superstring theory is only consistent and unique in $D = 10$:

- compactification on manifold X_6
- many possible manifolds X_6

$\Longrightarrow$ huge number of $D = 4$ string vacua
(with MSSM like particle content)

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

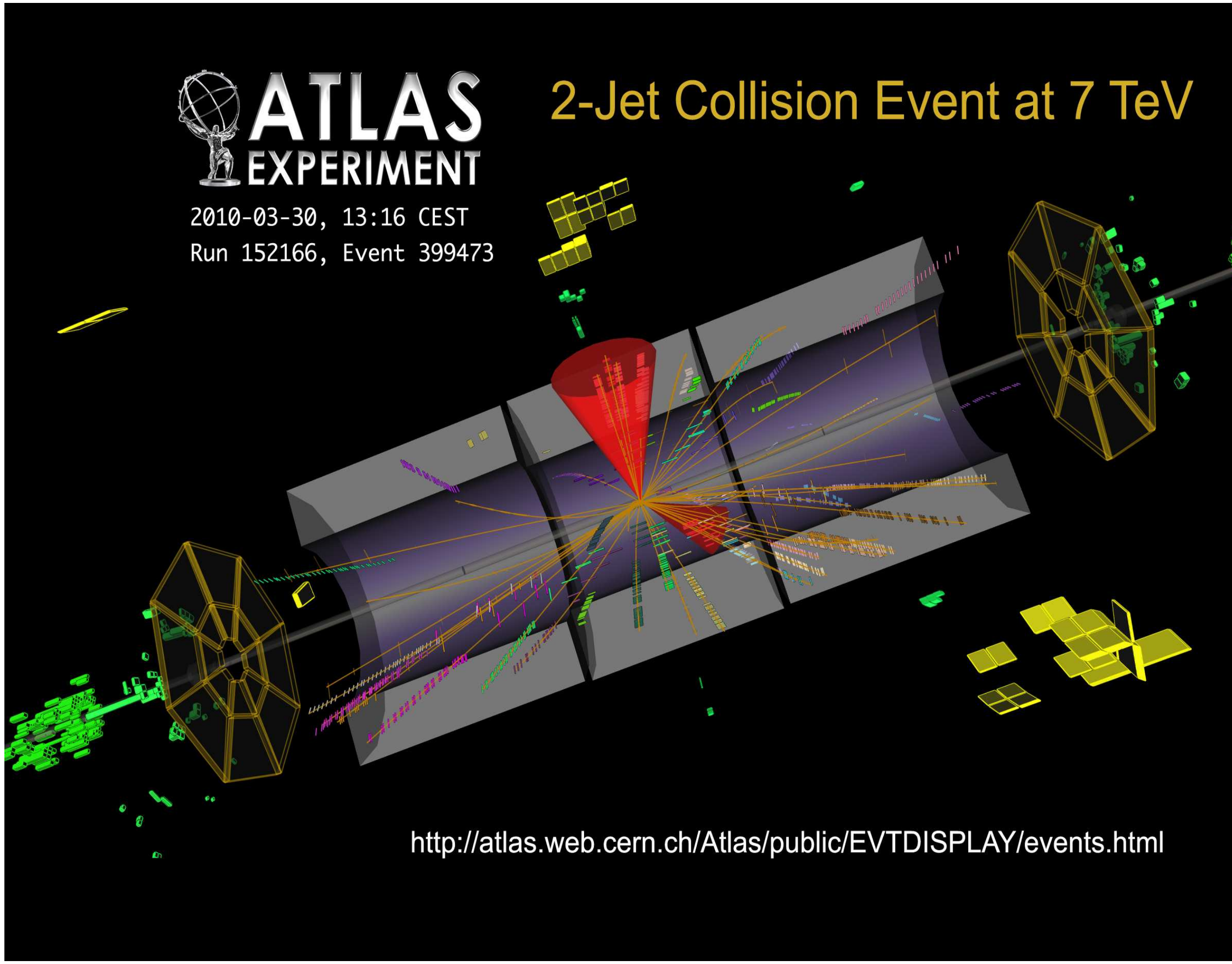
Question:

Can we make **model–independent**

low–energy **string predictions**

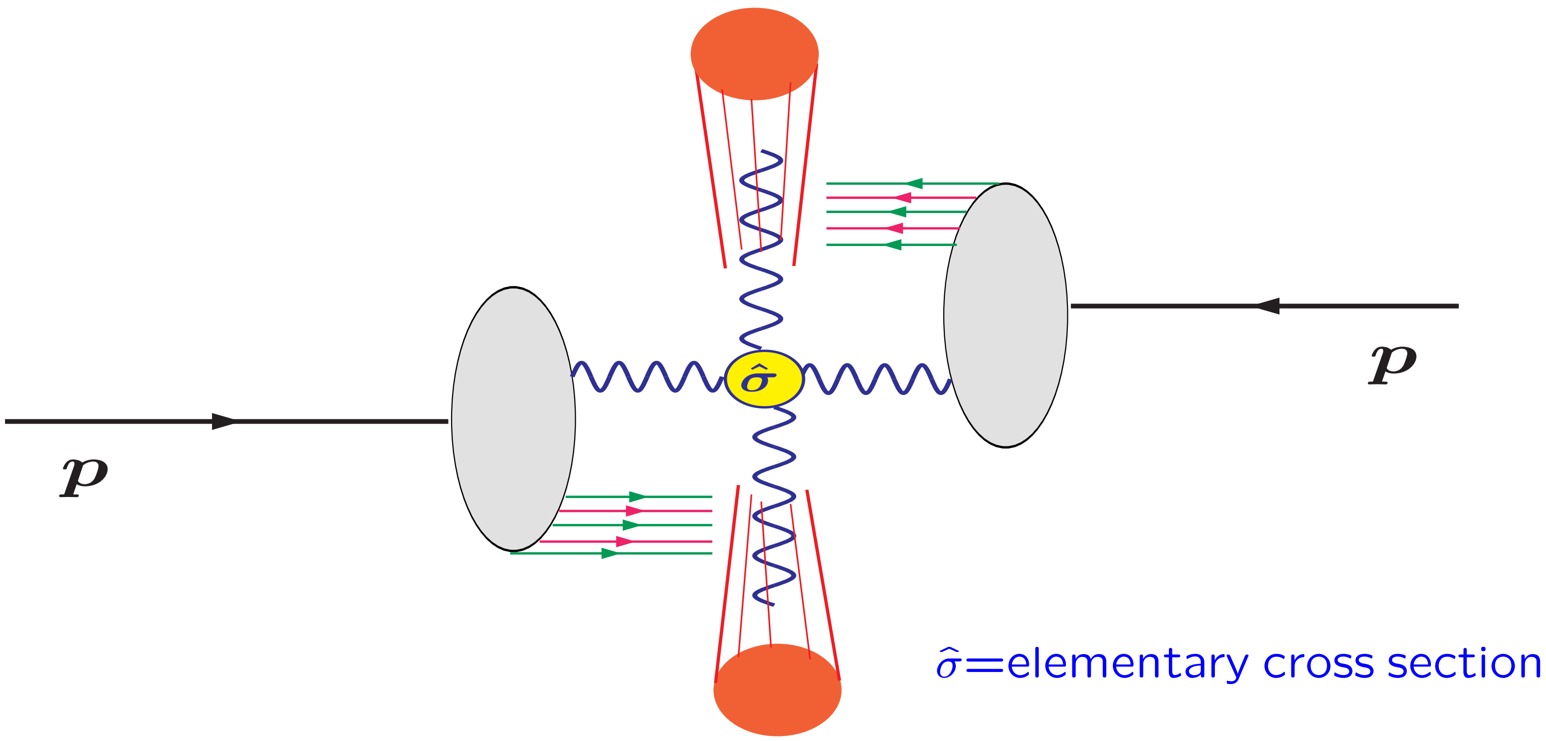
from parton amplitudes

in superstring theory ?



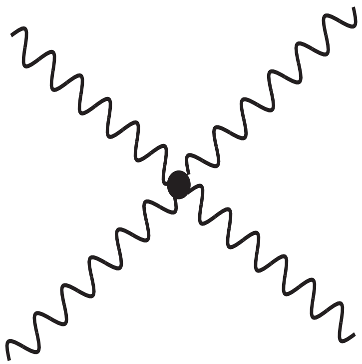
String signatures at LHC ?

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

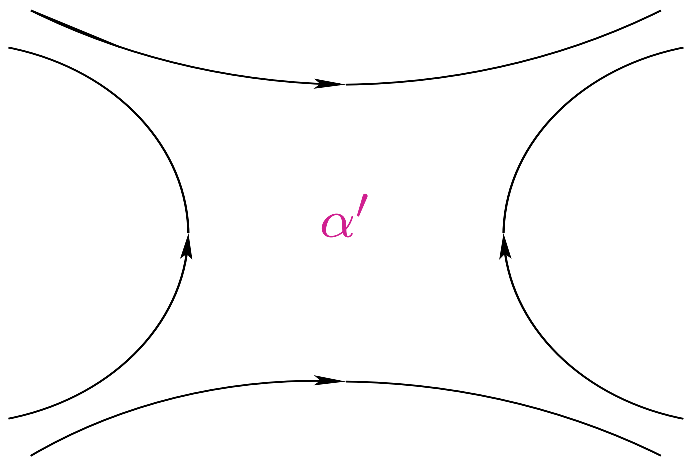


Parton amplitudes are important for (collider) phenomenology

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

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

- **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`

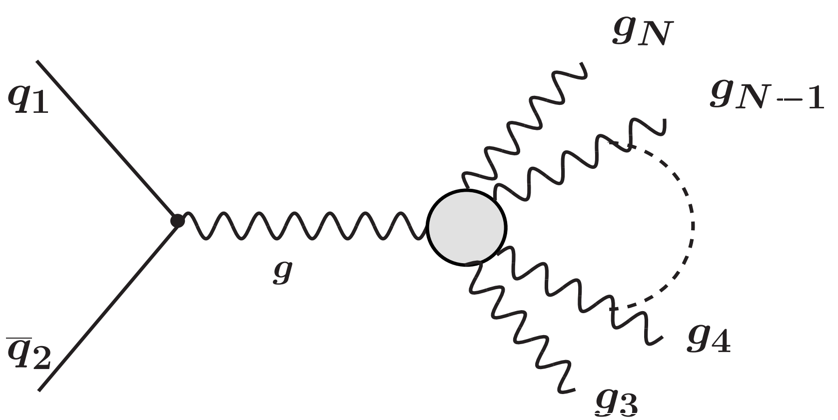
$$A_\rho(g_1^-, g_2^-, g_3^+, g_4^+, g_5^+) = i\, g_{YM}^3 \frac{\langle 12\rangle^4}{\langle 12\rangle\langle 23\rangle\langle 34\rangle\langle 45\rangle\langle 51\rangle} \times [\, V^{(5)}(\alpha') - 2i\, P^{(5)}(\alpha')\, \epsilon(1,2,3,4)\,]$$

$$A_\rho(g_1^-, g_2^+, g_3^+, q_4^-, \bar{q}_5^+) = 4\, g_{YM}^3 \frac{\langle 14\rangle^4 \langle 15\rangle}{\langle 12\rangle\langle 23\rangle\langle 34\rangle\langle 45\rangle\langle 51\rangle} \times [V^{(5)}(\alpha') - 2i\, P^{(5)}(\alpha')\, \epsilon(1,2,3,4)\,]$$

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

$$A(g^{a_1} \dots g^{a_N}) \simeq A(\psi^{a_1} \overline{\psi}^{a_2} g^{a_3} \dots g^{a_N})$$

Striking relation to all orders in α'



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

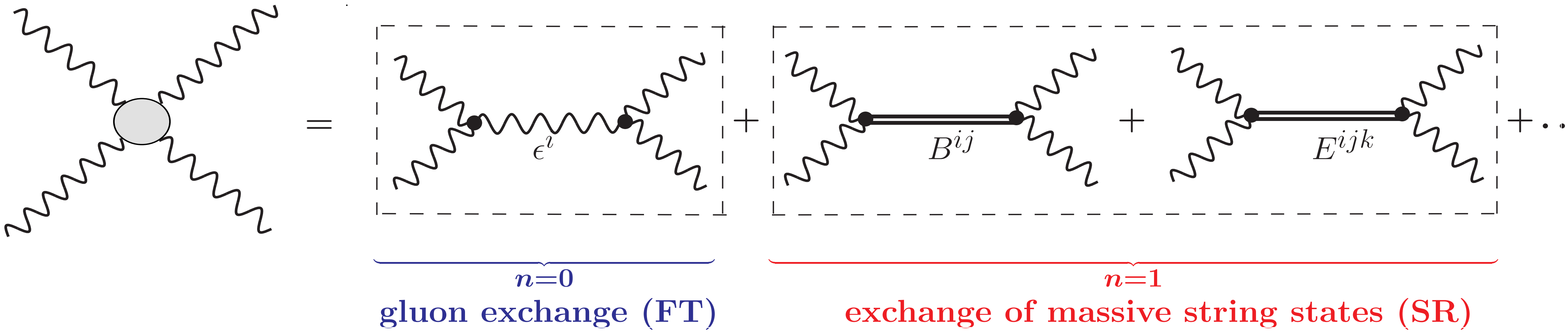
Universal sum over infinite s–channel poles

$$A_\rho(g_1,g_2,g_3,g_4) = 2\ g_{YM}^2\ \mathrm{Tr}(T^{a_1}T^{a_2}T^{a_3}T^{a_4})\ K_4(k_i,\xi_j)\ \frac{B(s,u)}{t}$$

$\hookrightarrow$ with sum over infinite s–channel poles: $\frac{B(s,u)}{t} = \sum_{n=0}^{\infty} \frac{\gamma(n)}{s+n}$

Intermediate masses: $M_n^2 = M_{\mathrm{string}}^2\ n$

$s = 2\alpha' k_1 k_2,$
$t = 2\alpha' k_1 k_3,$
$u = 2\alpha' k_1 k_4,$
$s+t+u=0$



Exchanges of string Regge excitations of SM particles

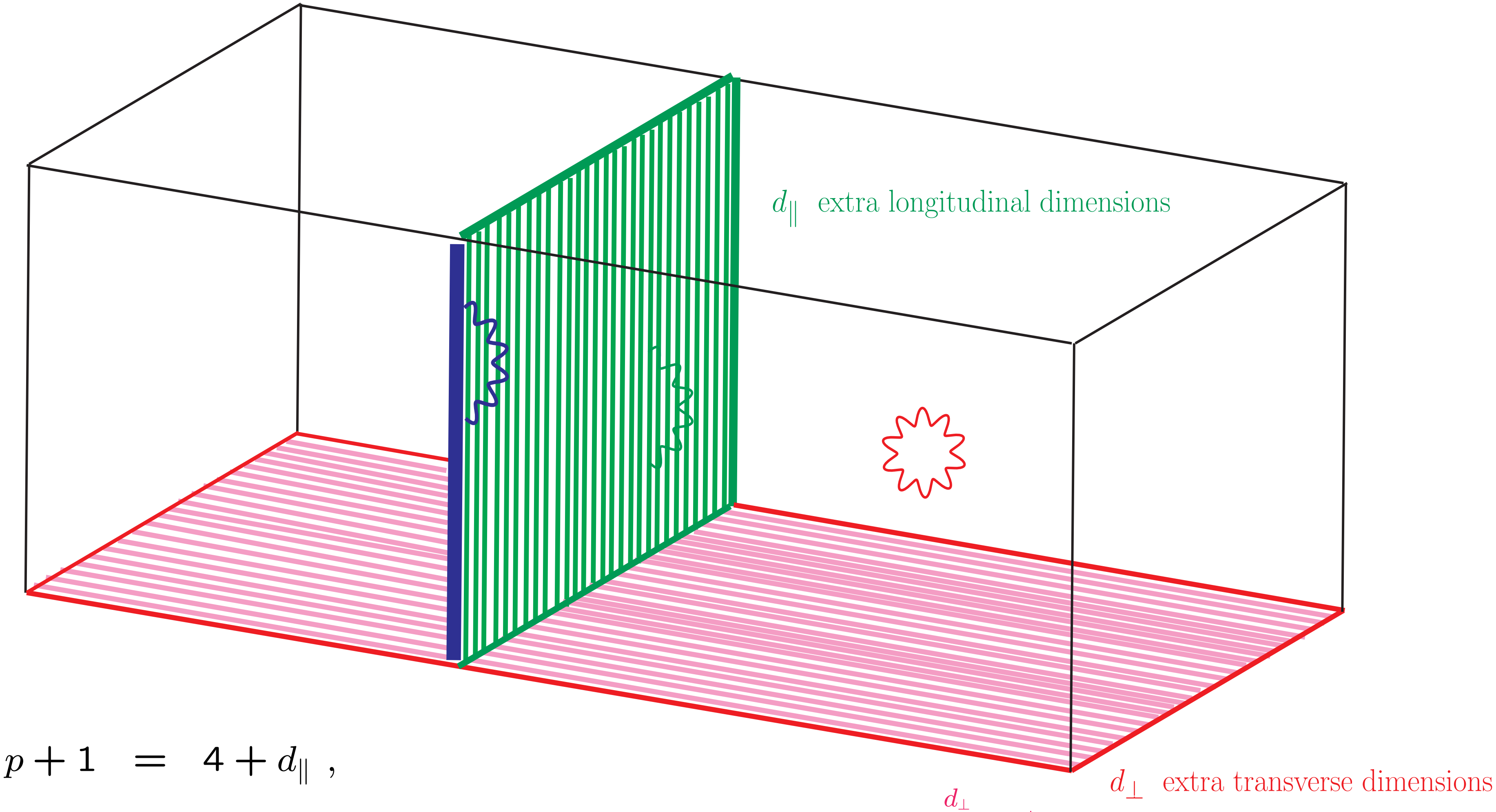
$\underline{n = 0\text{:}}$ exchange of spin $J = 1$ state ϵ^i:

$$\text{Res}_{\substack{s=0\\u=-t}} \; A_\rho(g_1, g_2, g_3, g_4) = \sum_{\epsilon(k)} K_{3,0}(\epsilon_1, k_1; \epsilon_2, k_2; \epsilon, k) \; K_{3,0}(\epsilon_3, k_3; \epsilon_4, k_4; \epsilon, -k)$$

$\underline{n = 1\text{:}}$ exchange of spin $J = 0$ state E^{ijk} and $J = 2$ state B^{ij}:

$$\text{Res}_{\substack{s=-1\\u=1-t}} \; A_\rho(g_1, g_2, g_3, g_4) = \sum_{E(k)} K_{3,1}(\epsilon_1, k_1; \epsilon_2, k_2; E, k) \; K_{3,1}(\epsilon_3, k_3; \epsilon_4, k_4; E, -k) + \sum_{B(k)} K_{3,2}(\epsilon_1, k_1; \epsilon_2, k_2; B, k) \; K_{3,2}(\epsilon_3, k_3; \epsilon_4, k_4; B, -k)$$

$$\gamma(n) = \frac{1}{n!} \frac{\Gamma(u+n)}{\Gamma(u+1)} = \frac{1}{n!} \frac{1}{u} \prod_{j=1}^{n} (a(u)+j) \sim u^{n-1} \quad , \quad \begin{array}{c} a(u)=u-1 = \text{Regge trajectory} \\ \text{highest possible spin}=n+1 \end{array}$$



$$
\begin{aligned}
p+1 &= 4+d_\parallel\ , \\
d_\perp &= \text{number of transverse directions}\ ,\ V_\perp = \prod_{j=1}^{d_\perp} R_j^\perp\ , \\
d_\parallel &= \text{number of longitudinal directions}\ ,\ V_\parallel = \prod_{i=1}^{d_\parallel} R_i^\parallel\ , \\
d_\parallel + d_\perp &= 6
\end{aligned}
$$

$$
\Longrightarrow \quad \boxed{g_{Dp}^2\, M_{\text{Planck}} \sim M_{\text{string}}^{7-p} \sqrt{\frac{V_\perp}{V_\parallel}}}
$$

Physics of large extra dimensions and low string scale

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

Antoniadis, Arkani–Hamed
Dimopoulos, Dvali

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

strength of gravitational interactions: $M^2_{\mathrm{Planck}} \sim \frac{M^2_{\mathrm{string}}}{g^2_{\mathrm{string}}} \frac{V_6}{\alpha'^3}$

strength of gauge interactions: $g^{-2}_{Dp} \sim g^{-1}_{\mathrm{string}} \frac{V_{\parallel}}{\alpha'^{d_{\parallel}/2}}$

Physics of large extra dimensions and low string scale

	$d_\perp = 1$	$d_\perp = 2$	$d_\perp = 3$	$d_\perp = 4$	$d_\perp = 5$	$d_\perp = 6$
$R^\perp$ $[GeV^{-1}]$	$1.6 \cdot 10^{26}$	$4 \cdot 10^{11}$	$5.4 \cdot 10^{6}$	$2 \cdot 10^{4}$	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 $1\ GeV^{-1} \sim 10^{-15} m$)

- **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 $\boldsymbol{R_i^{||} \sim M_{EW}^{-1}}$.

States:

- massless string states: MSSM and graviton $M = 0$
- string Regge **(SR)** excitations: $M_{SR} \sim 1$ TeV
- **KK** modes w.r.t. $\boldsymbol{R_i^{\|}}$: $M_{KK^{\|}} \sim M_{\text{string}}$
- **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**: $M_{BH} \sim M_{\text{string}}/g^2_{\text{string}}$

Couplings:

$\boldsymbol{g_{\text{string}}}$	disk	SM tree–processes ($4pt$) including **exchange of SR**
$\boldsymbol{g^{3/2}_{\text{string}}}$	sphere	$-$gravitational (bulk) couplings $-pp \rightarrow jet + g^{\mu\nu}, \ldots$
$\boldsymbol{g^2_{\text{string}}}$	cylinder	$-$exchange of graviton and KK $-$new contact interactions due to SUSY breaking: $F^3, \ldots$

$$g_{\text{string}} \sim g^2_{YM} < 1$$

Physics of large extra dimensions and low string scale

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

What about strong gravity effects ?

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

Horowitz, Polchinski 1996
Meade, Randall 2007

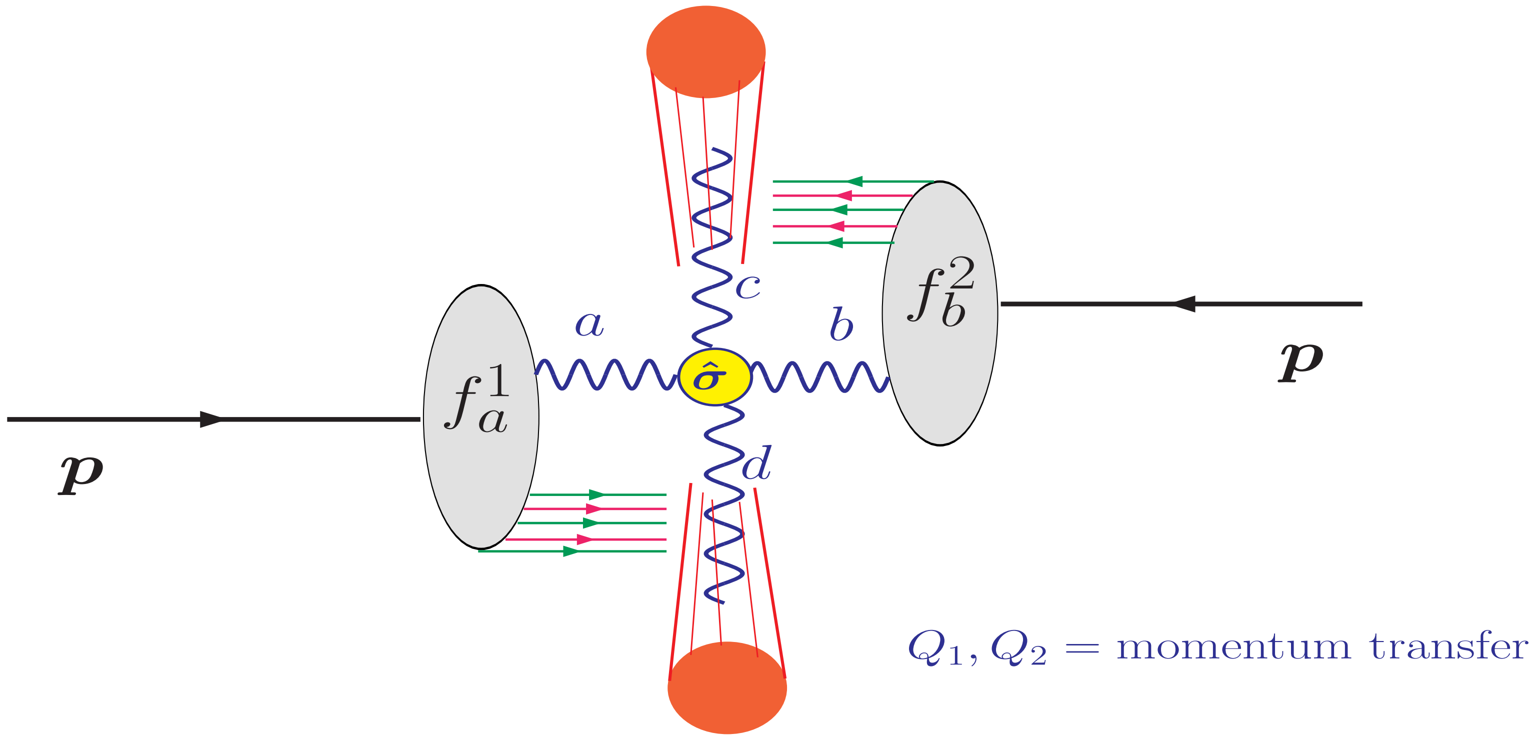
$$\boxed{n \sim g_{\text{string}}^{-4}}$$

$\Longrightarrow$ 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

Compute cross sections:

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

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

<u>In addition we need:</u>

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

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

} depend on geometry: KK and windings

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

however they are suppressed:

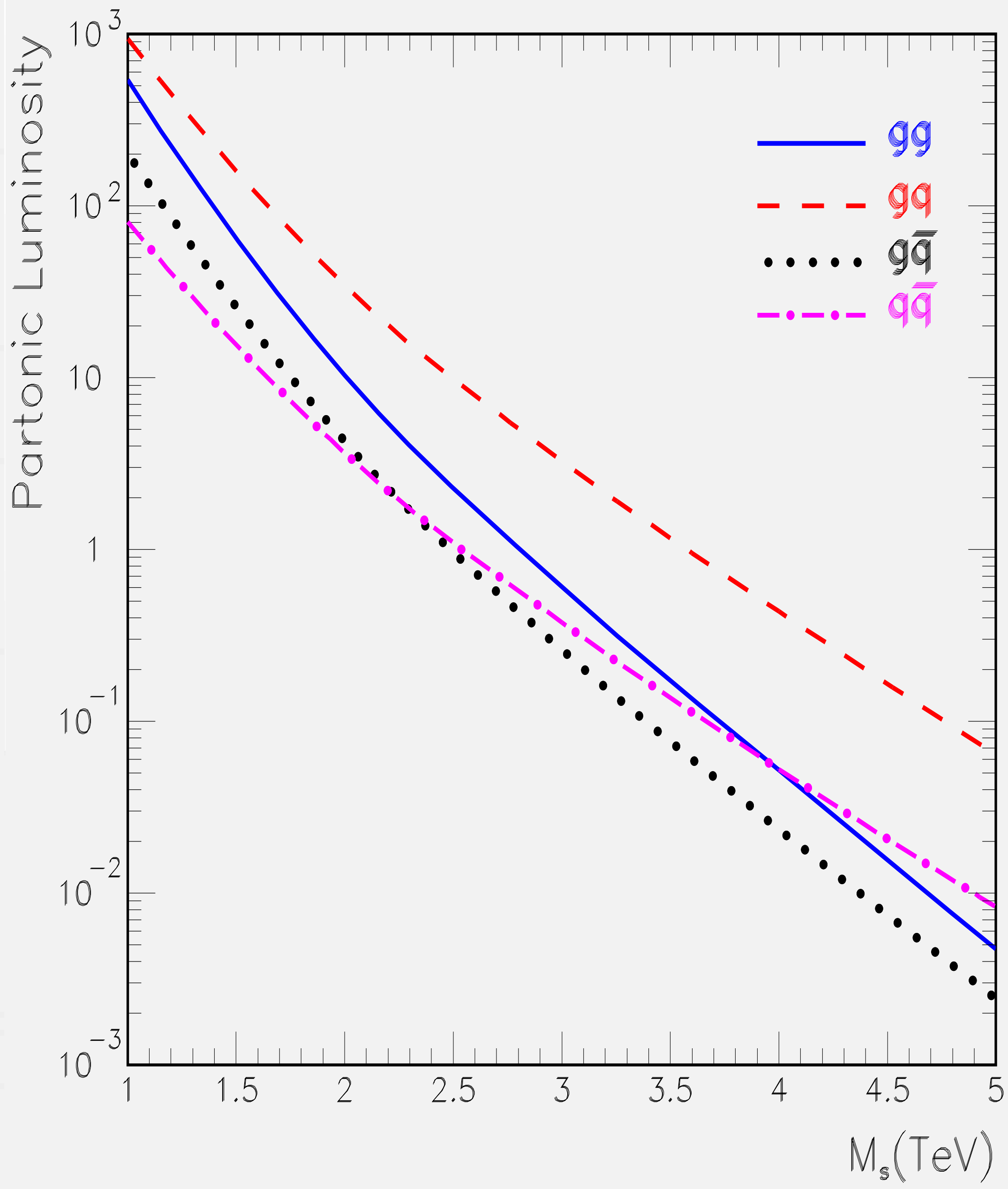
- QCD $SU(3)$ color group factors favor gluons over quarks in the initial state

- 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")

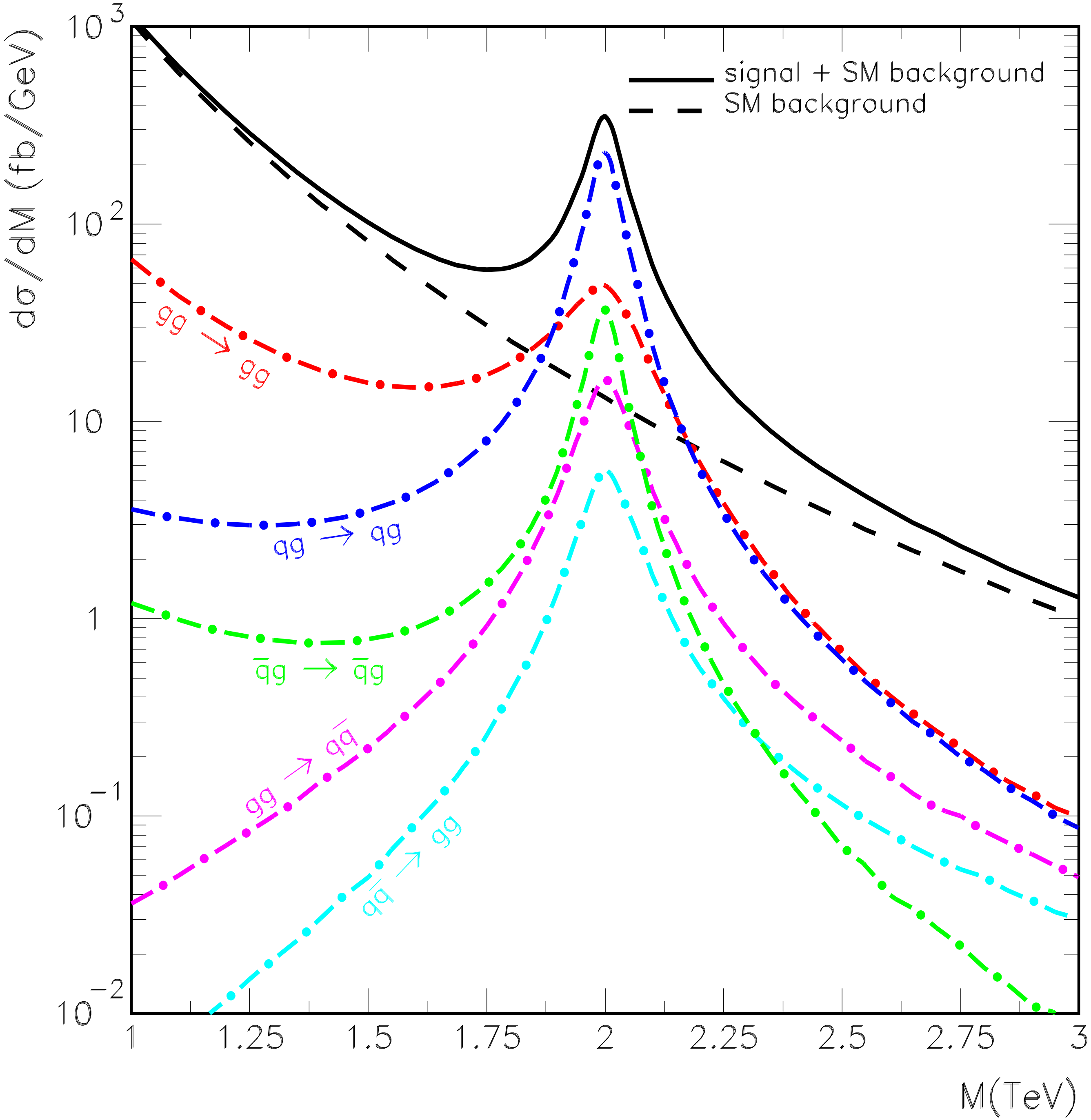
Table 9.1. *Squared matrix elements for 2 → 2 parton-parton subprocesses in QCD: q and q' denote distinct flavors of quark, $g_s^2 = 4\pi\alpha_s$ is the coupling squared.*

Subprocess	$\lvert\mathcal{M}\rvert^2/g_s^4$	$\lvert\mathcal{M}(90^\circ)\rvert^2/g_s^4$
$qq' \to qq'$ $q\bar{q}' \to q\bar{q}'$	$\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$	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_{string} and $g_{\text{string}} < 1$

Universal deviation from SM

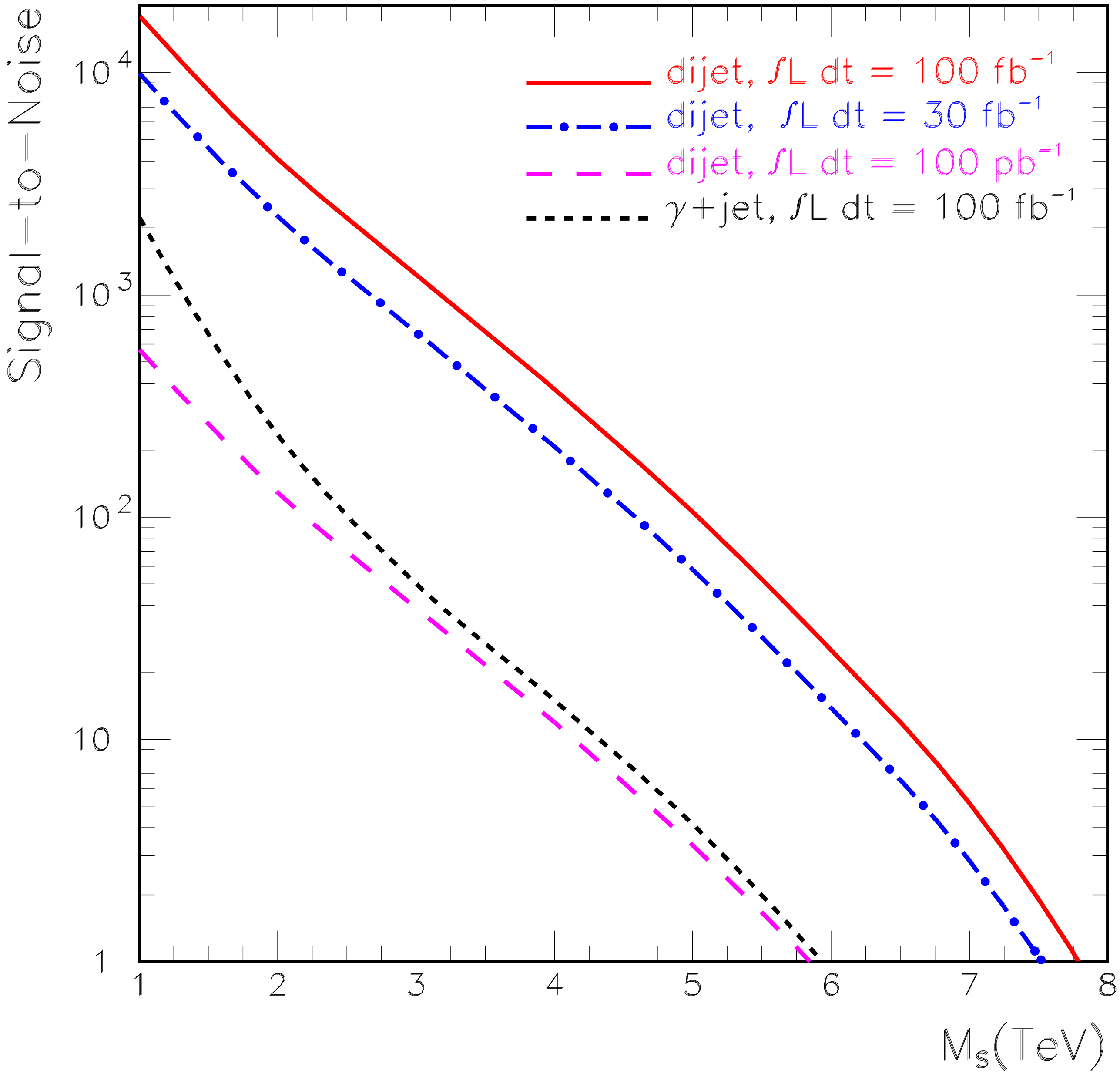
in jet distribution

$M_{\text{string}} = 2$ 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 ?!

Direct production of lightest SR states

Once the **mass threshold $M_{\textbf{string}}$ is crossed** in the center–of–mass energies of the colliding partons, one would also see **free SR states** produced **directly**, in association with jets, photons and other particles.

$\underline{n=1:}$ universal part: $B(J=2)$, $\Phi(J=0)$, $W(J=1)$, $\Omega(J=0)$

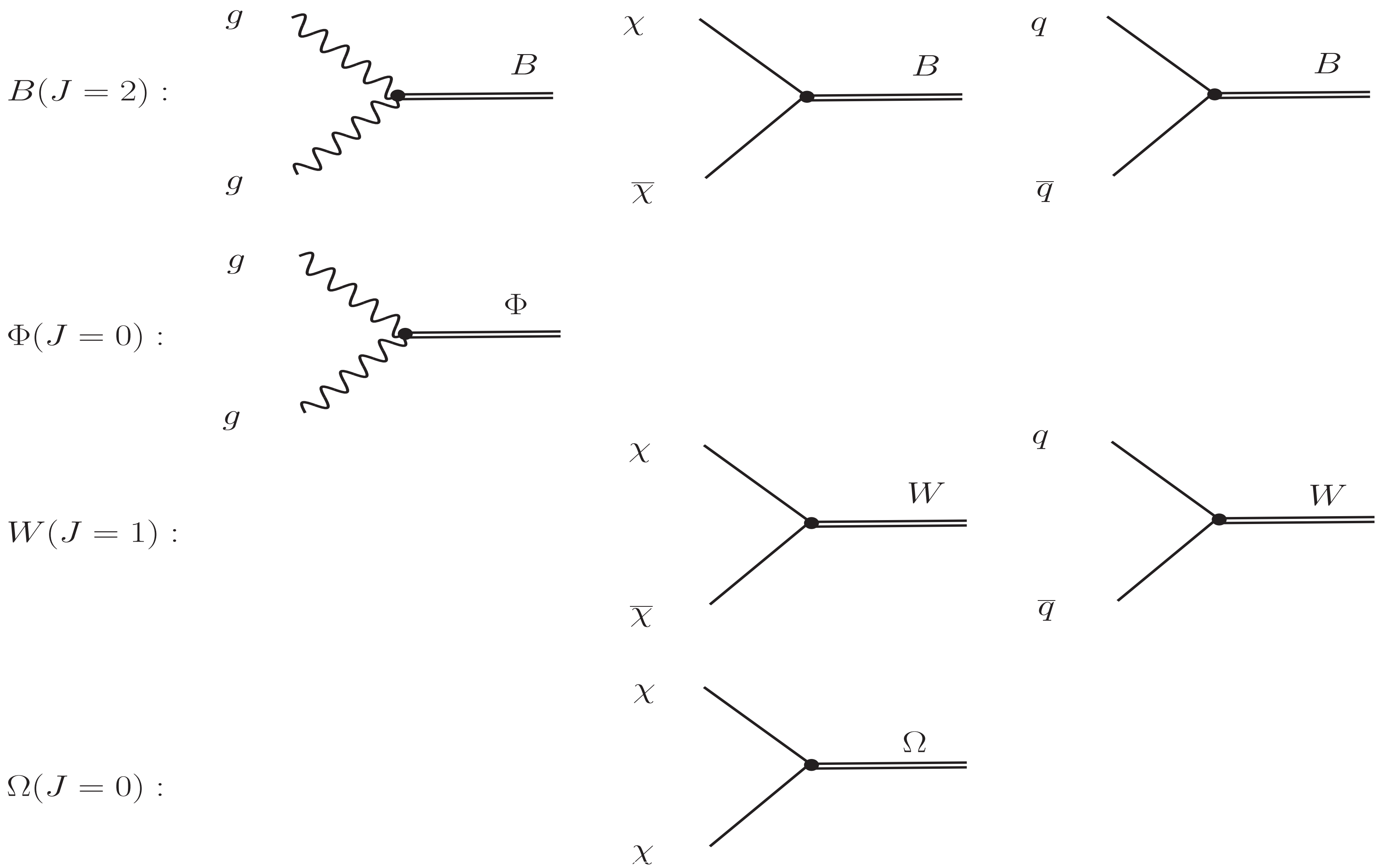
$$V_{B^a}^{(-1)}(z,\alpha,k) = \frac{g_A}{\sqrt{2\alpha'}} T^a e^{-\phi} \alpha_{\mu\nu}\, i\partial X^\mu\, \psi^\nu\, e^{ikX}\ ,$$

$$V_{\Phi^{a\pm}}^{(-1)}(z,k) = \frac{g_A}{\sqrt{2\alpha'}} T^a e^{-\phi} \Big[(g_{\mu\nu} + 2\alpha'\, k_\mu k_\nu)\, i\partial X^\mu\, \psi^\nu + 2\alpha'\, k_\mu\, \partial\psi^\mu \pm \frac{i}{6} 2\alpha'\, \epsilon_{\mu\nu\rho\lambda}\, k^\lambda\, \psi^\mu\, \psi^\nu\, \psi^\rho \Big] e^{ikX}\ ,$$

$$V_{W^a}^{(-1)}(z,\xi,k) = \frac{g_A}{\sqrt{12}} T^a\, e^{-\phi}\, \xi_\mu\, \psi^\mu\, \mathcal{J}\, e^{ikX}\ ,$$

$$V_{\Omega^a}^{(-1)}(z,k) = g_A\, T^a\, e^{-\phi}\, \mathcal{O}\, e^{ikX}\ ,$$

Feng, Lüst, Schlotterer,
St. St., Taylor, arXiv:1007.5254



<u>*E.g.:*</u>

$$|\mathcal{M}(gg \to B)|^2 = g_{YM}^2 \, \frac{(N^2-4)}{N(N^2-1)} \, M_{\text{string}}^{1/2} = \frac{5}{24} \, g_{YM}^2 \, M_{\text{string}}^{1/2}$$

Backup: Massive $D = 4$, N=1 multiplet

- $J = 3/2$ Rarita Schwinger fermion ($k^\mu \chi_\mu = 0$ and $\not{k}\, \chi_\mu = \frac{1}{\sqrt{\alpha'}}\, \bar{\zeta}_\mu$)

$$V_{J=\frac{3}{2}}(\chi, \bar{\zeta}, k) = e^{-\frac{\phi}{2}} \left(\chi^\alpha_\mu\, i\partial X^\mu + \sqrt{\alpha'}\, \bar{\zeta}^\mu_{\dot{\alpha}}\, \psi_\mu\, \psi^\nu\, \sigma_\nu^{\dot{\alpha}\alpha} \right) S_\alpha\, \Xi^{a\cap b}\, e^{ikX}$$

- $J = 1/2$ Dirac fermion ($\not{k}\, \bar{b} = \frac{1}{\sqrt{\alpha'}}\, a$)

$$V_{J=\frac{1}{2}}(\bar{b}, a, k) = e^{-\frac{\phi}{2}} \left(\bar{b}_{\dot{\beta}}\, \bar{\sigma}_\nu^{\dot{\beta}\alpha} \left[\delta^\nu_\mu + 2\alpha'\, k_\mu\, k^\nu \right] i\partial X^\mu \;\; - \frac{1}{3} a^\beta\, \psi_\mu\, \psi_\nu\, (\sigma^{\mu\nu})_\beta{}^\alpha \right) S_\alpha\, \Xi^{a\cap b}\, e^{ikX}$$

Complete N=1 multiplets:

$$\underbrace{\alpha_{\mu\nu} \quad (\chi^\alpha_\mu, \bar{\zeta}_{\mu\dot{\alpha}}) \quad (\bar{\chi}^\mu_{\dot{\alpha}}, \zeta^{\mu\alpha}) \quad \xi_\mu}_{\text{massive spin 2}} \qquad \underbrace{(\bar{b}_{\dot{\alpha}}, a^\alpha) \quad \Omega^\pm \quad \Phi^\pm \quad (b^\alpha, \bar{a}_{\dot{\alpha}})}_{\text{massive spin 1/2}}$$