

Strings at the LHC

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SUSY 2010

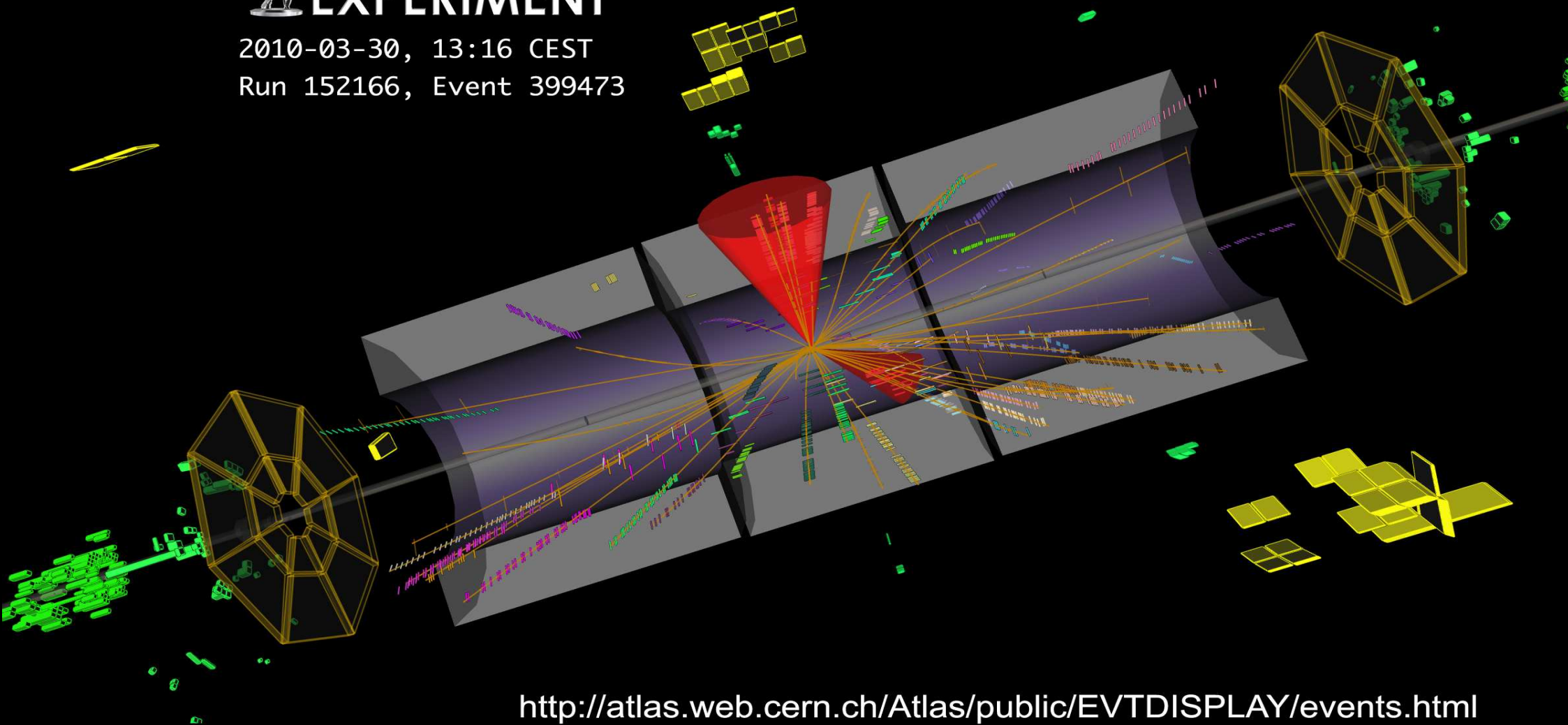
Physikalisches Institut, Bonn, Germany

August, 23–28, 2010



2010-03-30, 13:16 CEST
Run 152166, Event 399473

2-Jet Collision Event at 7 TeV



<http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html>

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

\implies 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

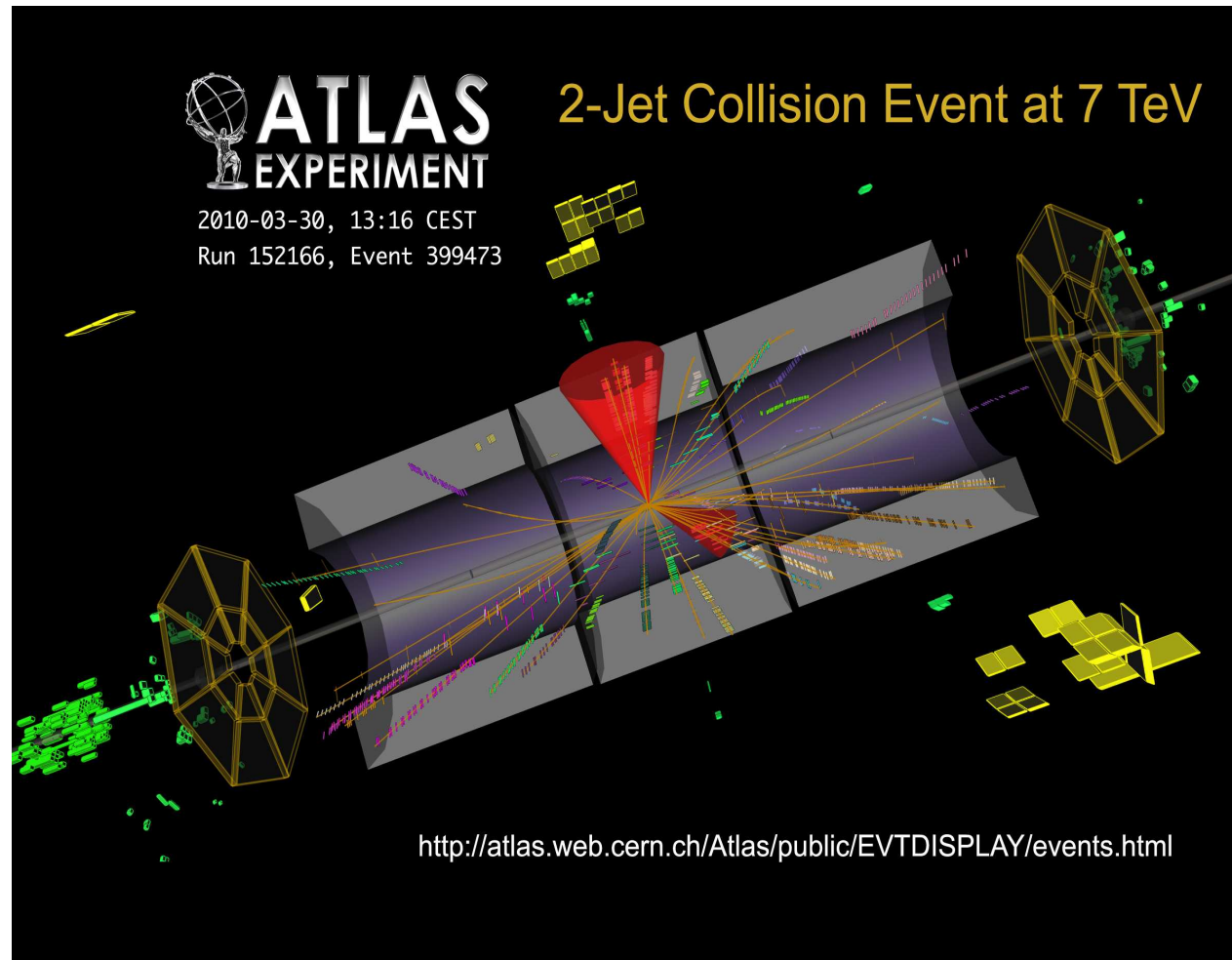
Problem: predictive power of string theory is lost !

Model-independent string predictions

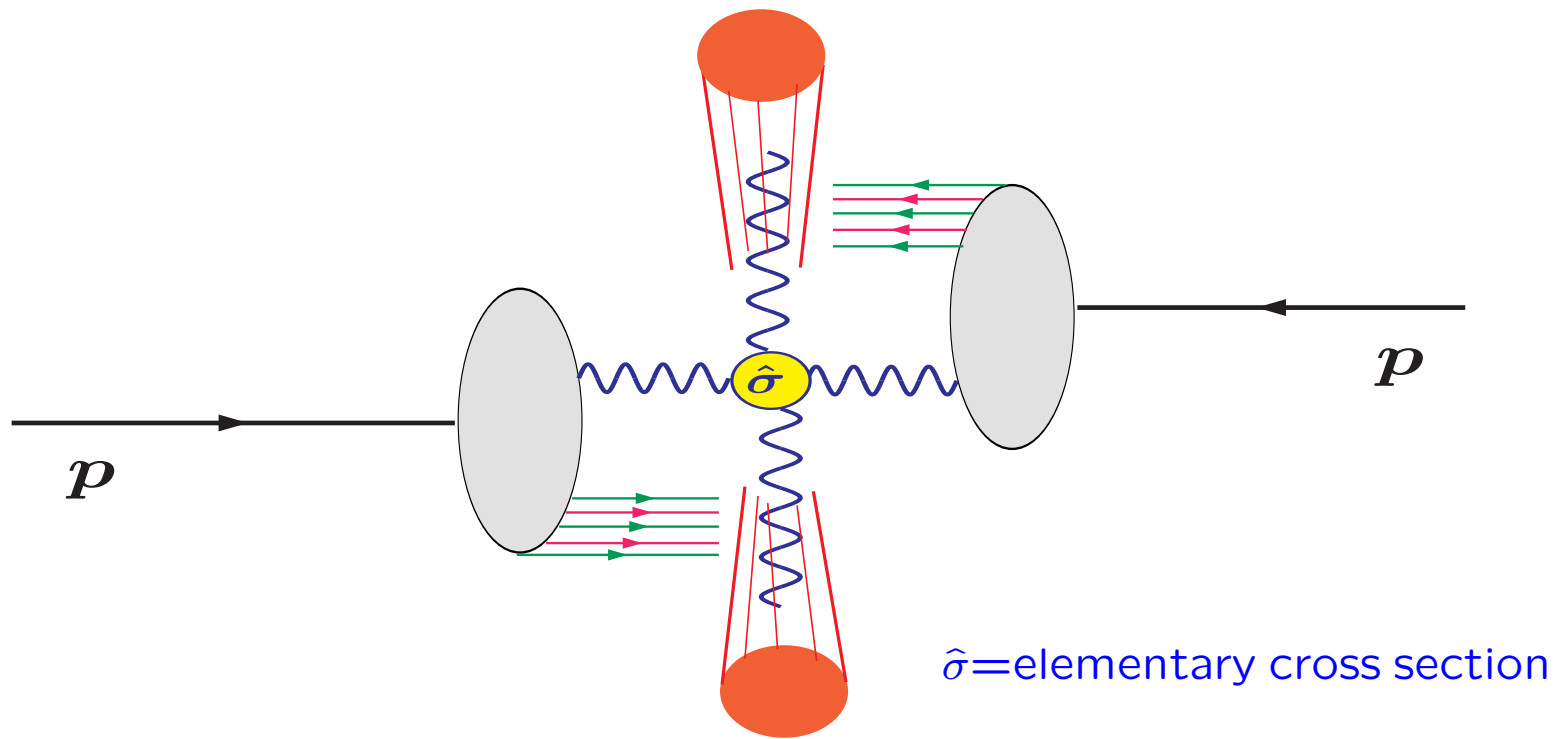
Question:

Can we make **model-independent**
low-energy **string predictions**
from parton amplitudes
in superstring theory ?

String signatures at LHC ?

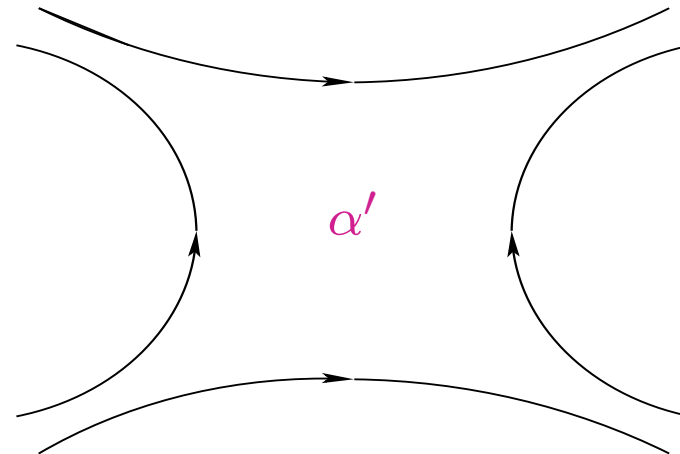
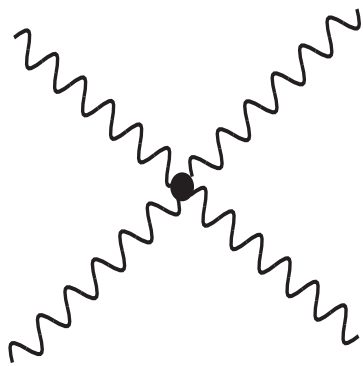


Yes: String theory can make **universal predictions** for QCD jets at LHC !



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

$$\left. \begin{aligned} &A(g^{a_1} \dots g^{a_N}) \\ &A(\chi^{a_1} \bar{\chi}^{a_2} g^{a_3} \dots g^{a_N}) \\ &A(\psi^{a_1} \bar{\psi}^{a_2} g^{a_3} \dots g^{a_N}) \\ &A(\phi^{a_1} \bar{\phi}^{a_2} g^{a_3} \dots g^{a_N}) \end{aligned} \right\}$$

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

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

$$\begin{aligned} A_\rho(g_1^-, g_2^-, g_3^+, g_4^+) &= 4 g_{YM}^2 V^{(4)}(\alpha') \frac{\langle 12 \rangle^4}{\langle 12 \rangle \langle 23 \rangle \langle 34 \rangle \langle 41 \rangle} \\ A_\rho(g_1^-, g_2^+, g_3^-, g_4^+) &= 2 g_{YM}^2 V^{(4)}(\alpha') \frac{\langle 13 \rangle^4 \langle 14 \rangle}{\langle 12 \rangle \langle 23 \rangle \langle 34 \rangle \langle 41 \rangle} \end{aligned}$$

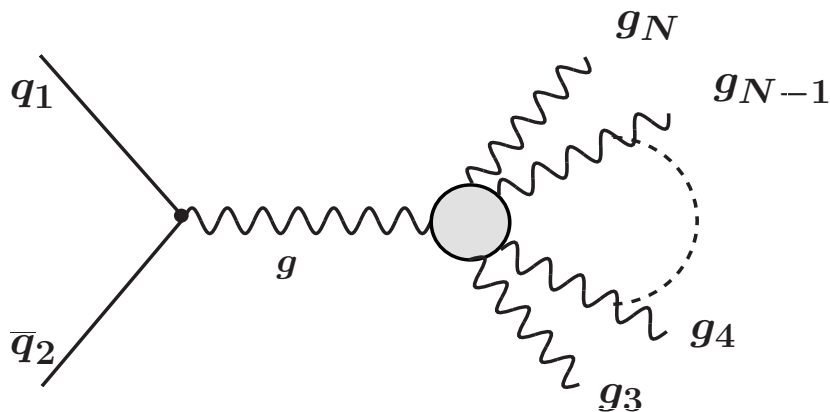
$$A_\rho(g_1^-, g_2^-, g_3^+, g_4^+, g_5^+) = i g_{YM}^3 \frac{\langle 12 \rangle^4}{\langle 12 \rangle \langle 23 \rangle \langle 34 \rangle \langle 45 \rangle \langle 51 \rangle} \\ \times [V^{(5)}(\alpha') - 2i P^{(5)}(\alpha') \epsilon(1, 2, 3, 4)]$$

$$A_\rho(g_1^-, g_2^+, g_3^+, g_4^-, g_5^+) = 4 g_{YM}^3 \frac{\langle 14 \rangle^4 \langle 15 \rangle}{\langle 12 \rangle \langle 23 \rangle \langle 34 \rangle \langle 45 \rangle \langle 51 \rangle} \\ \times [V^{(5)}(\alpha') - 2i P^{(5)}(\alpha') \epsilon(1, 2, 3, 4)]$$

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

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

**Striking relation
to all orders in α'**



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

Universal sum over infinite s-channel poles

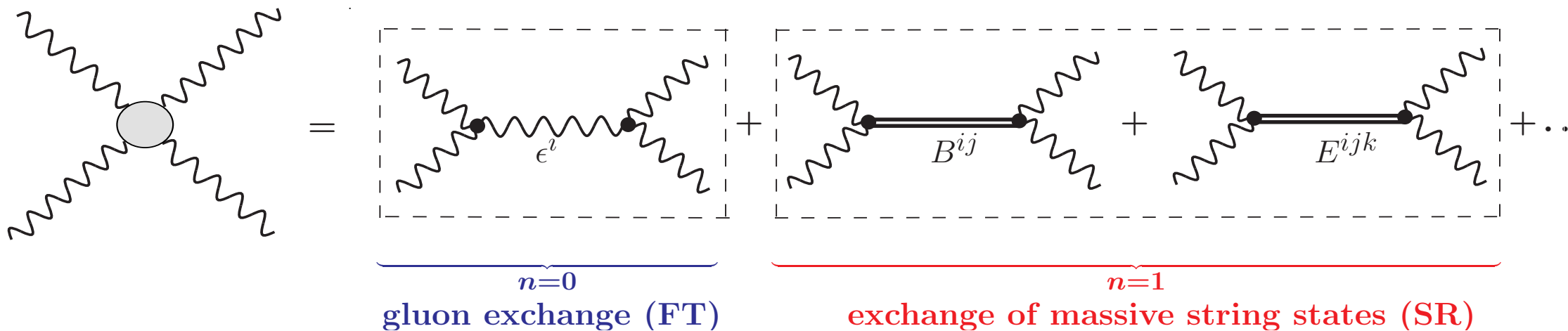
$$A_\rho(g_1, g_2, g_3, g_4) = 2 g_{YM}^2 \text{Tr}(T^{a_1} T^{a_2} T^{a_3} T^{a_4}) K_4(k_i, \xi_j) \frac{B(s, u)}{t}$$

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

Intermediate masses:

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

$$\begin{aligned} s &= 2\alpha' k_1 k_2, \\ t &= 2\alpha' k_1 k_3, \\ u &= 2\alpha' k_1 k_4, \\ s + t + u &= 0 \end{aligned}$$



Exchanges of string Regge excitations of SM particles

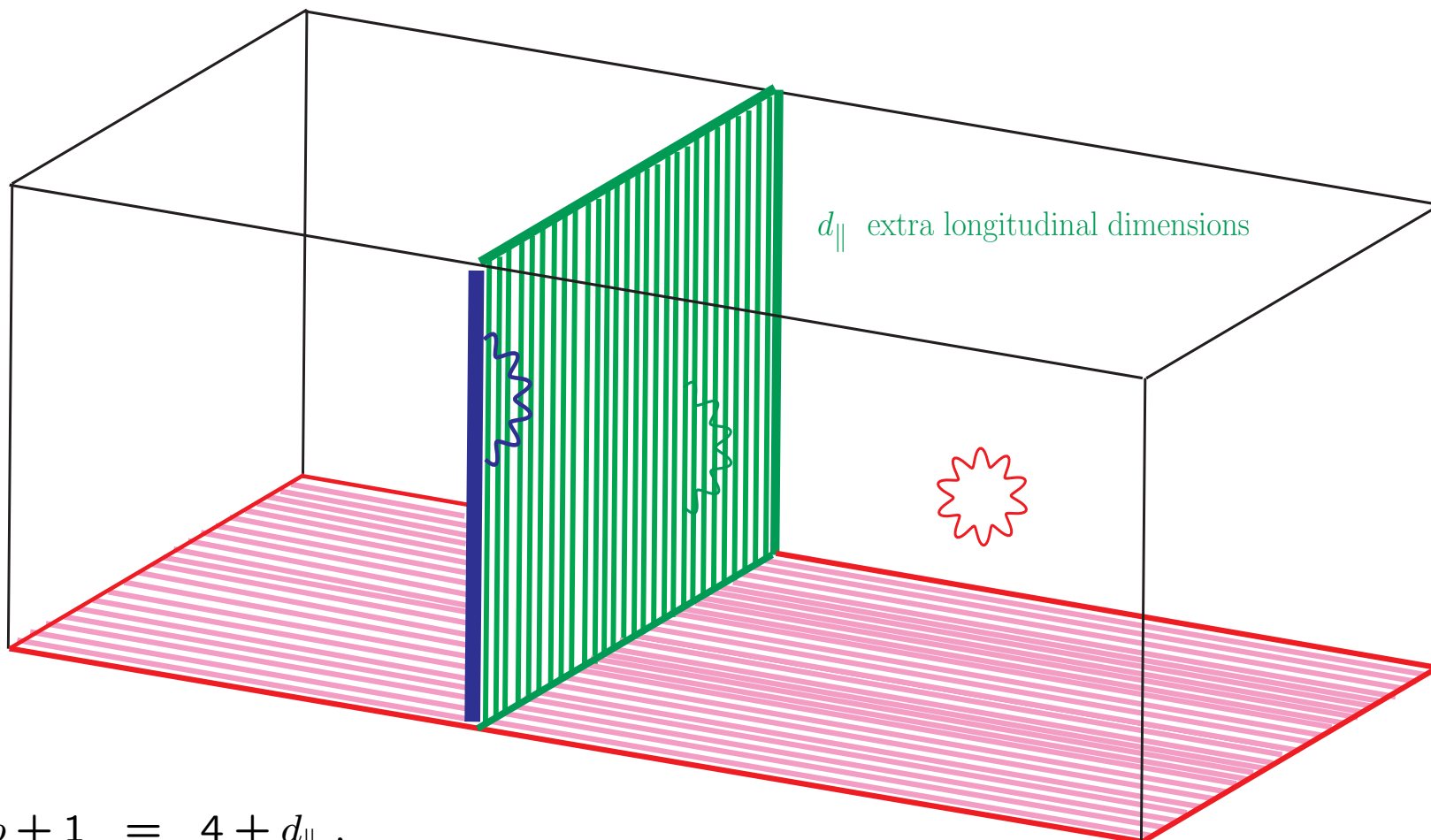
$n = 0$: exchange of spin $J = 1$ state ϵ^i :

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

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

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

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



$$p + 1 = 4 + d_{\parallel} ,$$

$$d_{\perp} = \text{number of transverse directions} , V_{\perp} = \prod_{j=1}^{d_{\perp}} R_j^{\perp} ,$$

$$d_{\parallel} = \text{number of longitudinal directions} , V_{\parallel} = \prod_{i=1}^{d_{\parallel}} R_i^{\parallel} ,$$

$$d_{\parallel} + d_{\perp} = 6$$

d_{\perp} extra transverse dimensions



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

Physics of large extra dimensions and low string scale

$$\Rightarrow \boxed{R_j^\perp \uparrow \iff M_{\text{string}} \downarrow}$$

Antoniadis, Arkani-Hamed
Dimopoulos, Dvali

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

strength of gravitational interactions: $M_{\text{Planck}}^2 \sim \frac{M_{\text{string}}^2}{g_{\text{string}}^2} \frac{V_6}{\alpha'^3}$

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

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 $M_{\text{string}} = 1 \text{ TeV}$
(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 $1 \text{ GeV}^{-1} \sim 10^{-15}m$)*

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

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

States:

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

Couplings:

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

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

Physics of large extra dimensions and low string scale



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

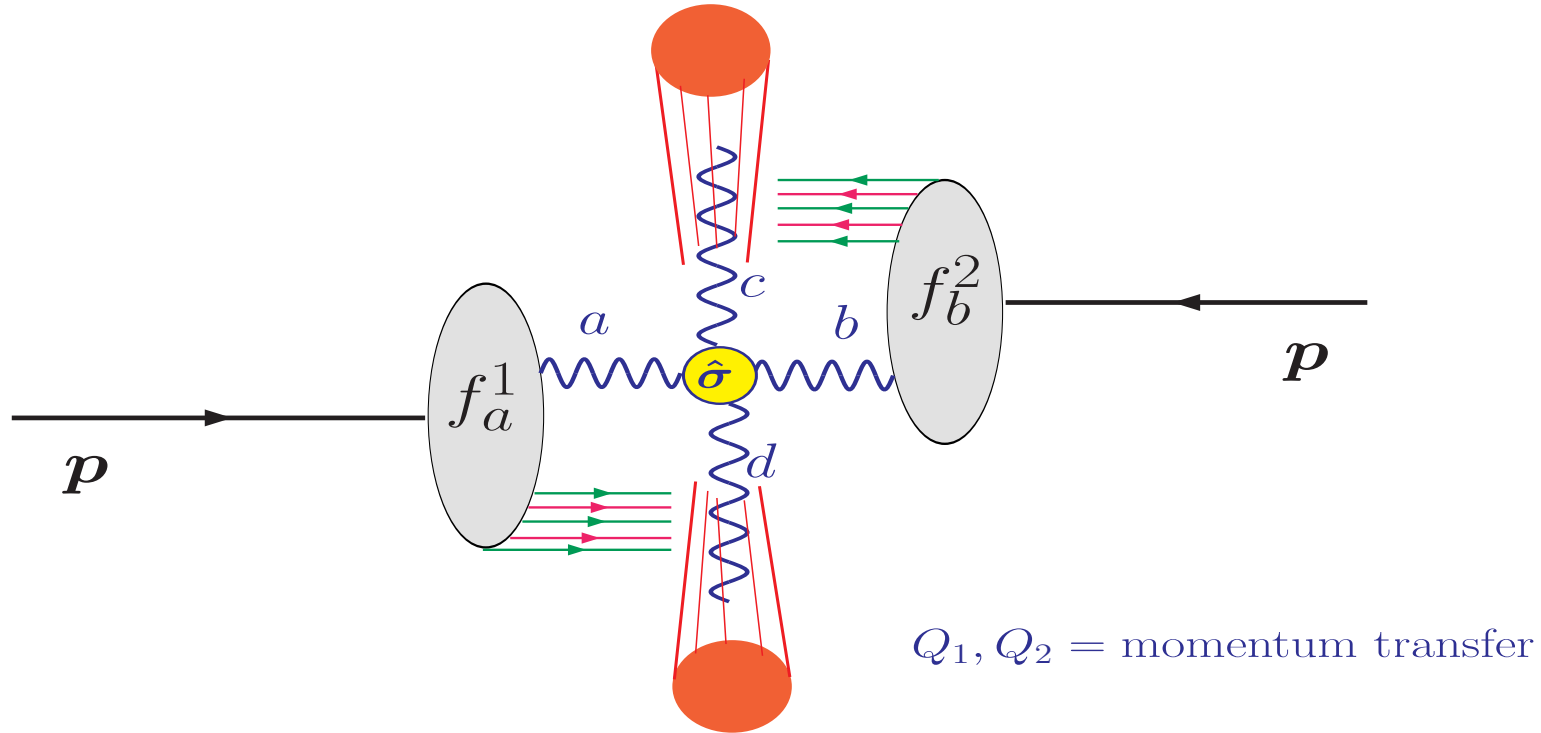
$$n \sim g_{\text{string}}^{-4}$$

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

⇒ We may first see SR's from 1-st, ..., n -th level

Dijet signals for low M_{string} at LHC

Two jets:



$$\sigma(pp \rightarrow 2 \text{ jets}) = \sum_{a,b,c,d} \int dx_1 dx_2 f_a^1(x_1; Q_1^2) f_b^2(x_2; Q_2^2) \hat{\sigma}_{ab \rightarrow cd}(\underbrace{sx_1x_2}_{\hat{s}}; \underbrace{Q_1^2, Q_2^2}_{Q_1^2=Q_2^2=\hat{t}}, \alpha')$$

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

Cross sections

Compute cross sections:

$$\left. \begin{array}{l} |\mathcal{M}(gg \rightarrow gg)|^2, \quad |\mathcal{M}(gg \rightarrow q\bar{q})|^2 \\ |\mathcal{M}(q\bar{q} \rightarrow gg)|^2, \quad |\mathcal{M}(qg \rightarrow qg)|^2 \end{array} \right\} \text{completely model-independent:} \\ \text{for any CY orientifold !}$$

Result:

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

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

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

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

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

Cross sections

In addition we need:

$$\left. \begin{array}{l} |\mathcal{M}(q\bar{q} \rightarrow q\bar{q})|^2 \quad , \quad |\mathcal{M}(qq \rightarrow qq)|^2 \\ |\mathcal{M}(q\bar{q} \rightarrow q'\bar{q}')|^2 \quad , \quad \begin{array}{l} |\mathcal{M}(qq' \rightarrow qq')|^2 \\ |\mathcal{M}(q\bar{q}' \rightarrow q\bar{q}')|^2 \end{array} \end{array} \right\} \begin{array}{l} \text{depend on geometry:} \\ \text{KK and windings} \end{array}$$

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

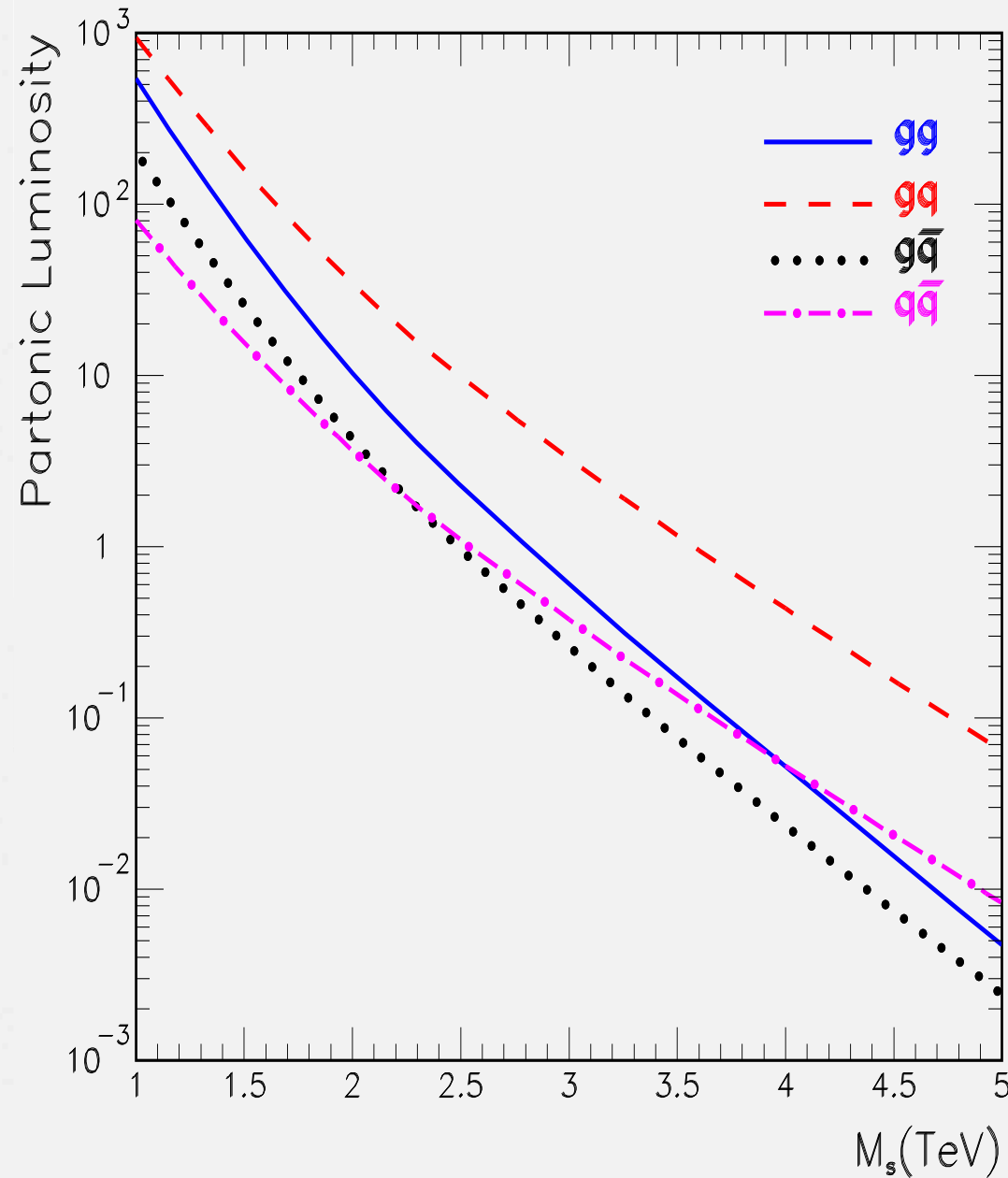
however they are suppressed:

- 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 1 TeV, 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”)

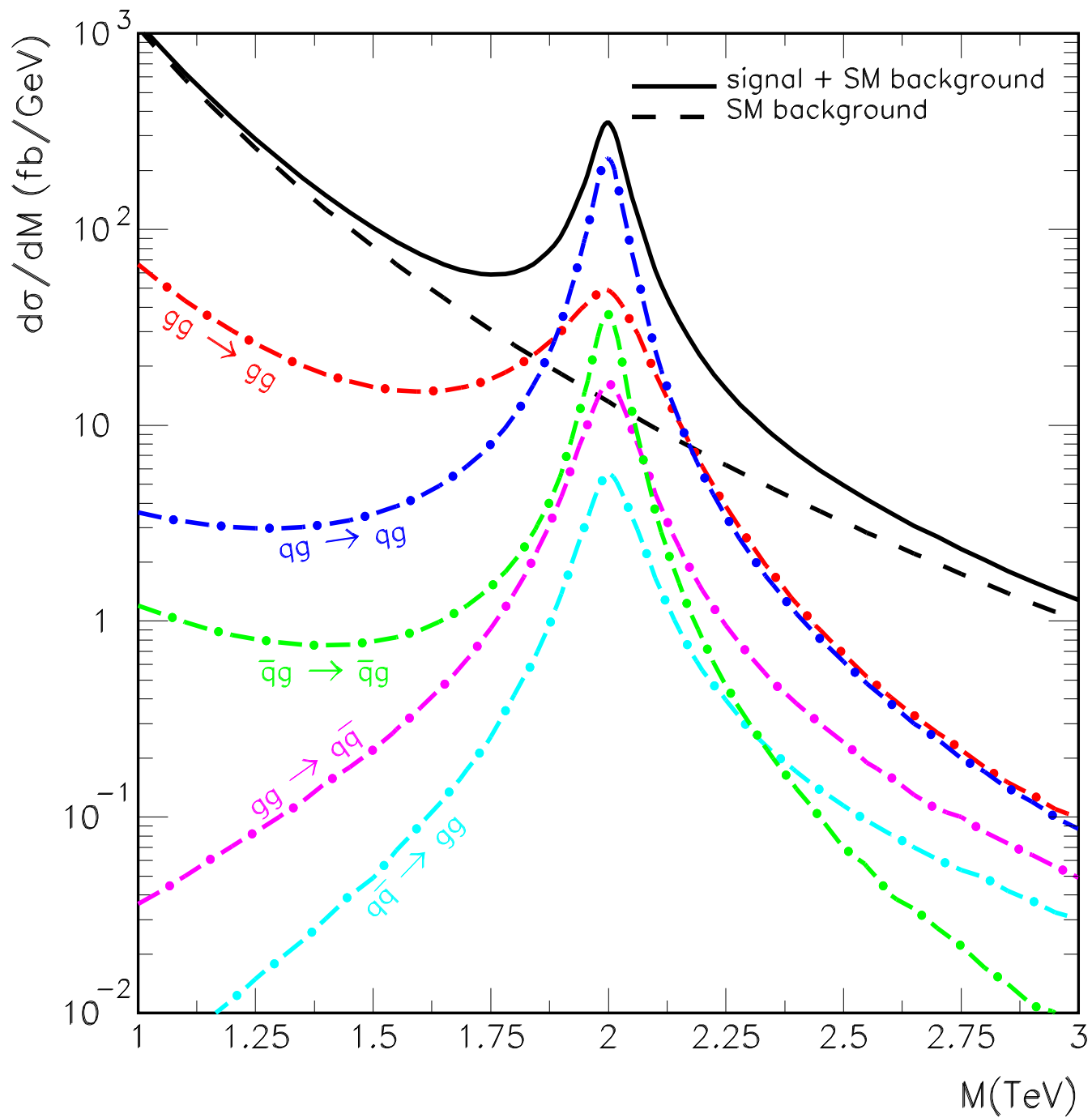
Table 9.1. Squared matrix elements for $2 \rightarrow 2$ parton-parton subprocesses in QCD: q and q' denote distinct flavors of quark, $g_s^2 = 4\pi\alpha_s$ is the coupling squared.

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



from "Collider Physics" by Barger, Phillips

Anchordoqui et al. arXiv:0804.2013



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

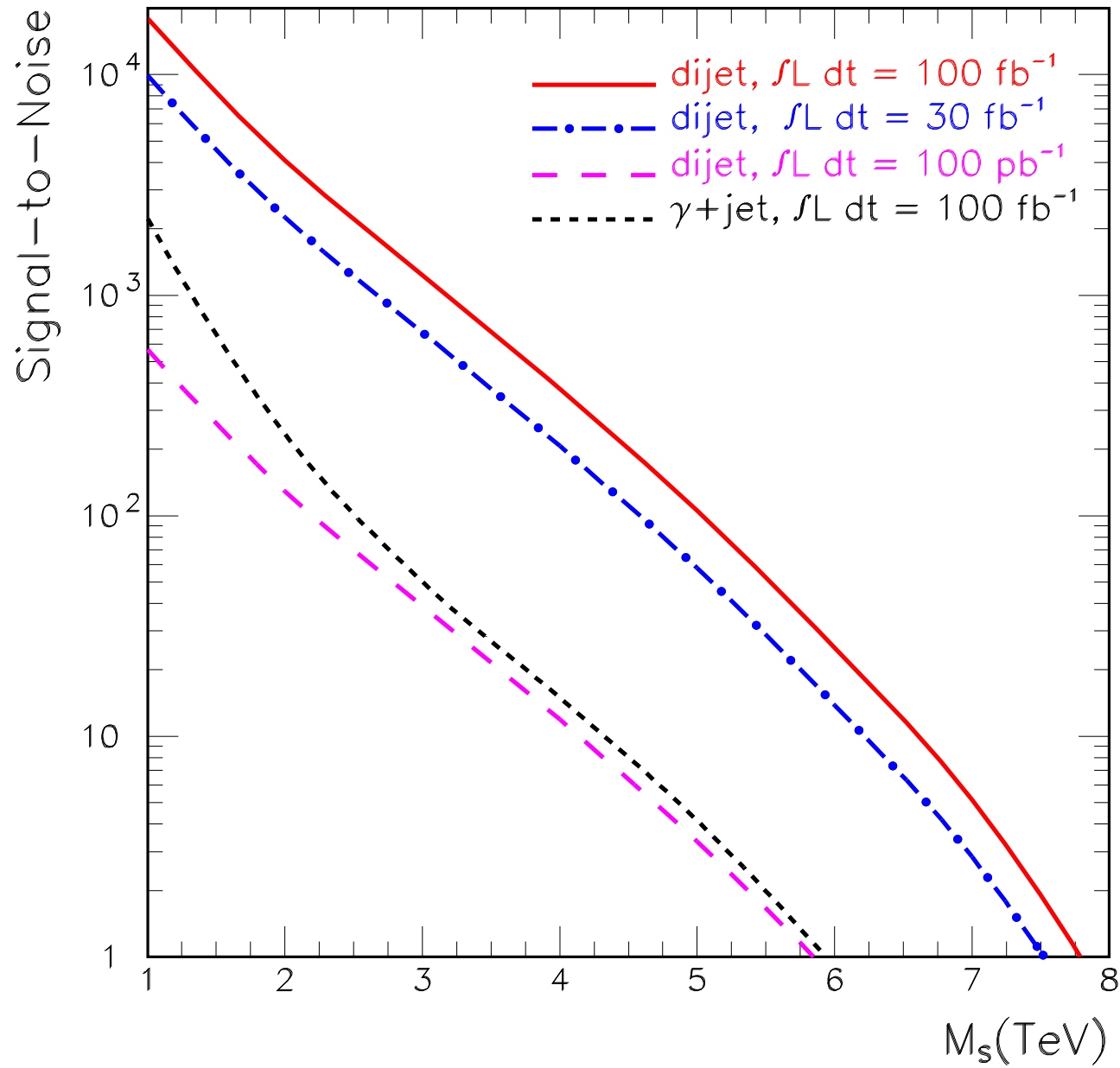
Universal deviation from SM
 in jet distribution

$$M_{\text{string}} = 2 \text{ TeV}$$

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

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

Discovery reach: integrated luminosities



⇒ LHC Laboratory for string theory effects ?!

Direct production of lightest SR states

Once the **mass threshold** M_{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.

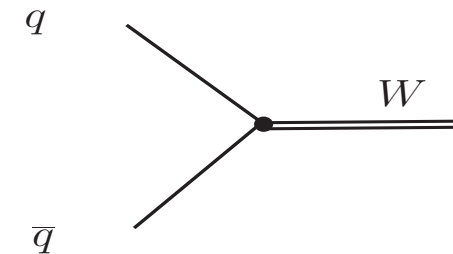
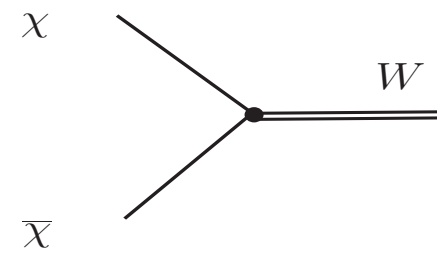
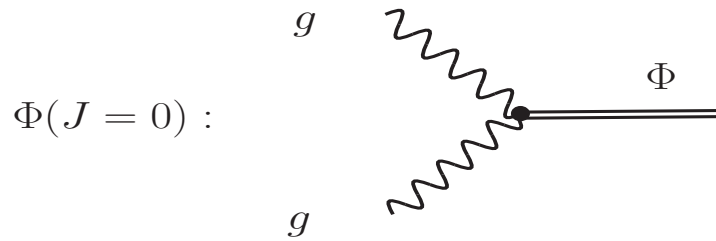
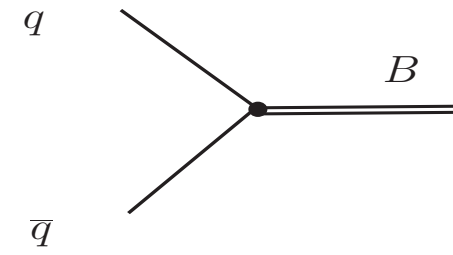
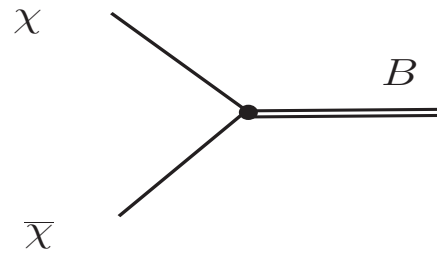
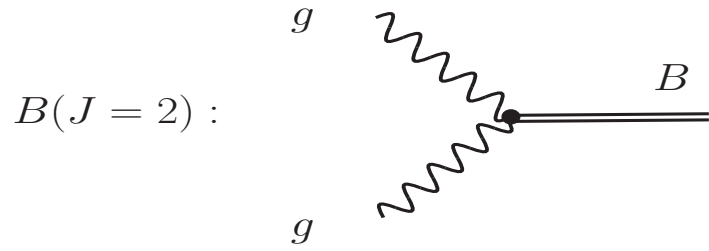
$n = 1$: universal part: $B(J = 2)$, $\Phi(J = 0)$, $W(J = 1)$, $\Omega(J = 0)$

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

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

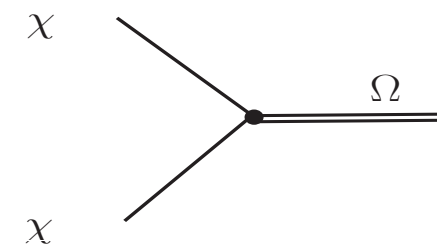
$$V_{W^a}^{(-1)}(z, \xi, k) = \frac{g_A}{\sqrt{12}} T^a e^{-\phi} \xi_\mu \psi^\mu \mathcal{J} e^{ikX} ,$$

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



$W(J = 1) :$

$\Omega(J = 0) :$



E.g.:

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

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

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

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

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

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

Complete $N=1$ multiplets:

$$\underbrace{\begin{array}{ccc} & (\chi_\mu^\alpha, \bar{\zeta}_{\mu\dot{\alpha}}) & \\ \alpha_{\mu\nu} & & \xi_\mu \\ & (\bar{\chi}_{\dot{\alpha}}^\mu, \zeta^{\mu\alpha}) & \\ & \text{massive spin 2} & \end{array}}_{\text{massive spin 2}}$$

$$\underbrace{\begin{array}{ccc} & \Omega^\pm & \\ (\bar{b}_{\dot{\alpha}}, a^\alpha) & & (b^\alpha, \bar{a}_{\dot{\alpha}}) \\ & \Phi^\pm & \\ & \text{massive spin 1/2} & \end{array}}_{\text{massive spin 1/2}}$$