RS strings, Jet substructure and thoughts on MC4BSM

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Outline

- RS strings
- Jet substructure: discovering the buried Higgs.
- Thoughts on MC4BSM.

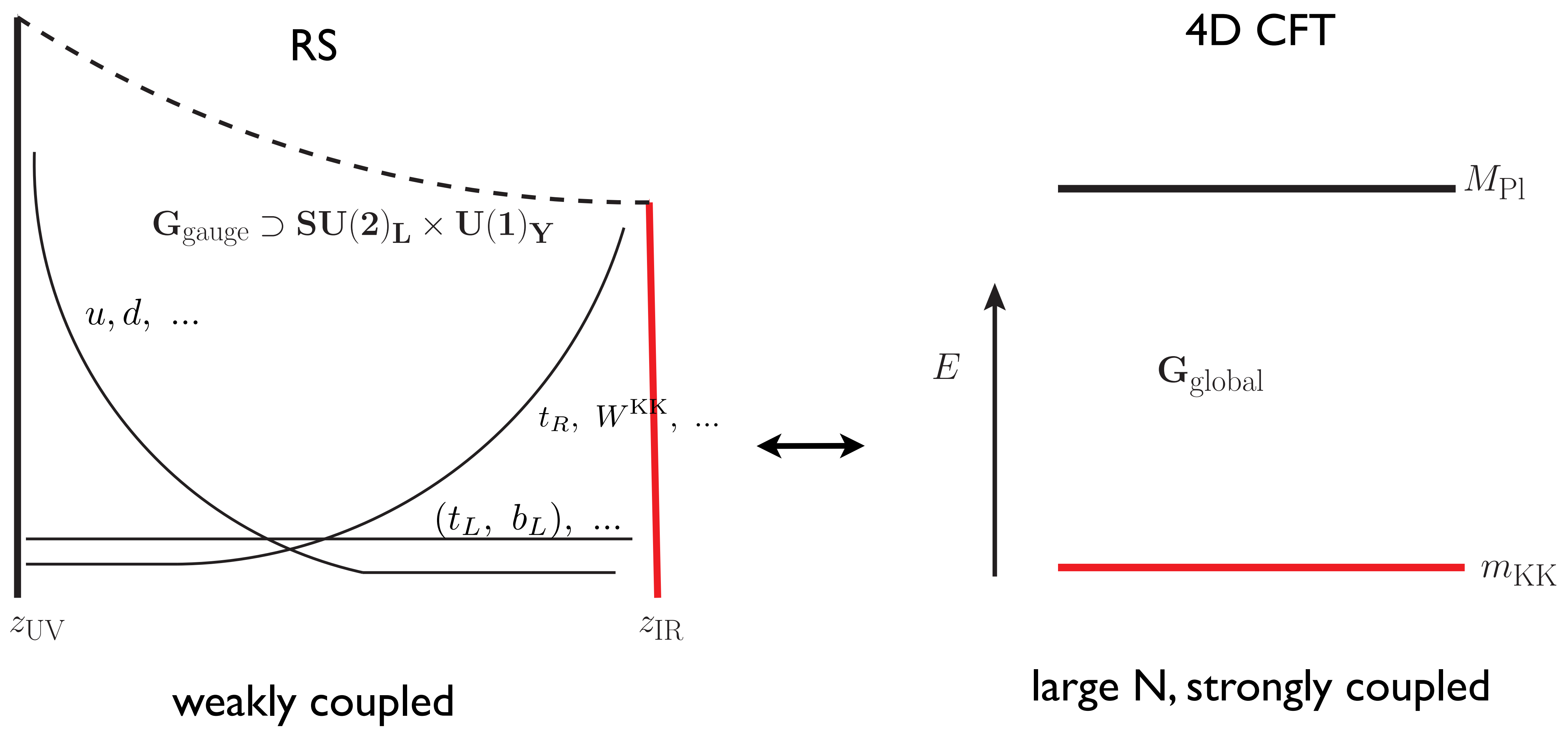
RS and strings.

M. Reece and LTW, arXiv:1003.5669

Confining Strings in RS

- I will be discussing Randall-Sundrum constructions with at least the SM electroweak gauge fields in the bulk
- This is dual to gauging global symmetries of some confining, technicolor/compositeHiggs -like theory
- KK modes are typically considered in RS models.
- Such a theory should have confining strings
- How heavy are they? Should they be part of the low-energy effective theory?

Basic setup and result.



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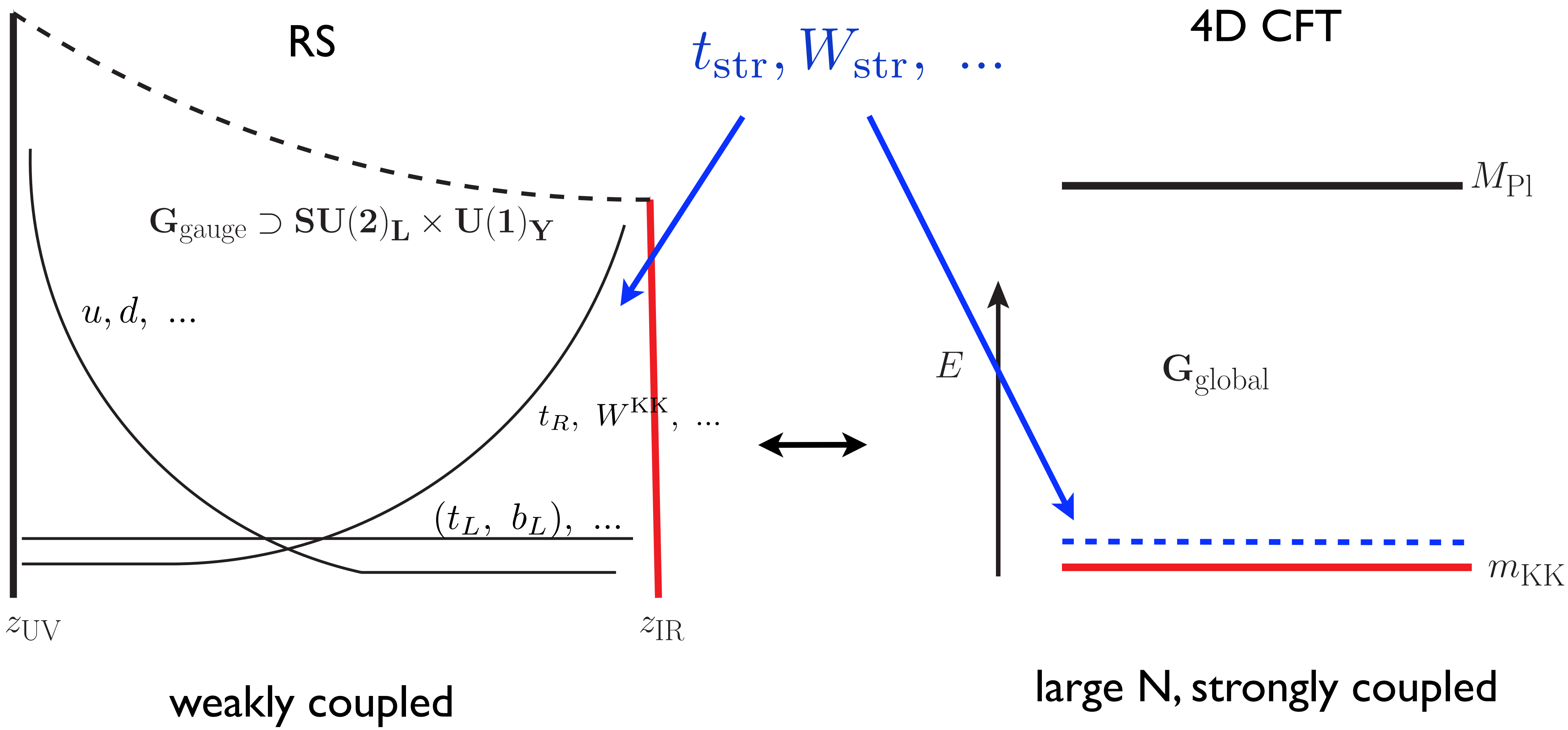


- Light string states ~ TeV
  - Higher spin, Regge-like.
  - Studied examples:

spin 2 excitations of SM gauge boson: Perelstein & Spray, arXiv:0907.3496
spin 3/2 excitations the top quark: Hassanain, March-Russell, and Rosa, arXiv:0904.4108

The Short Version of this work

- Two known arguments -- avoiding a Landau pole and completing the confining phase transition -- imply a bound of loosely $N < 10$.

- In $AdS_5 \times S^5$, the AdS curvature radius scales as $R^4 = 4\pi g_s N l_s^4$, so the bound on N bounds (Strassler; Hassanain et al; Perelstein & Spray)

$$\frac{m_{\rm str}}{m_{\rm KK}} = \frac{R_{\rm AdS}}{l_s} \leq N^{1/4} \sim 10^{1/4}$$

- Our goal: explain these arguments in detail, extend them to various examples.

Not no-go theorem. Arguments for why the light string states should generically present.

Avoiding Landau Poles

The two-point function of the global symmetry current computes its contribution to the running of $SU(2)_L$ in the SM:

$$\int d^4x\, e^{-iq\cdot x} \langle J_\mu(0) J_\nu(x)\rangle_{CFT} = -\frac{b_{CFT}}{16\pi^2}\left(q^2 g_{\mu\nu} - q_\mu q_\nu\right)\log q^2,$$

$$\frac{8\pi^2}{g^2(Q^2)} = \frac{8\pi^2}{g^2(\Lambda_X^2)} + (b_{SM} + b_{CFT})\log\frac{\Lambda_X}{Q}$$

In most examples, $b_{CFT} \sim N$ (from fields in the bifundamental of color and flavor).

Set by $b_{CFT} = 8\pi^2 R/g_5^2$ in 5D theory.

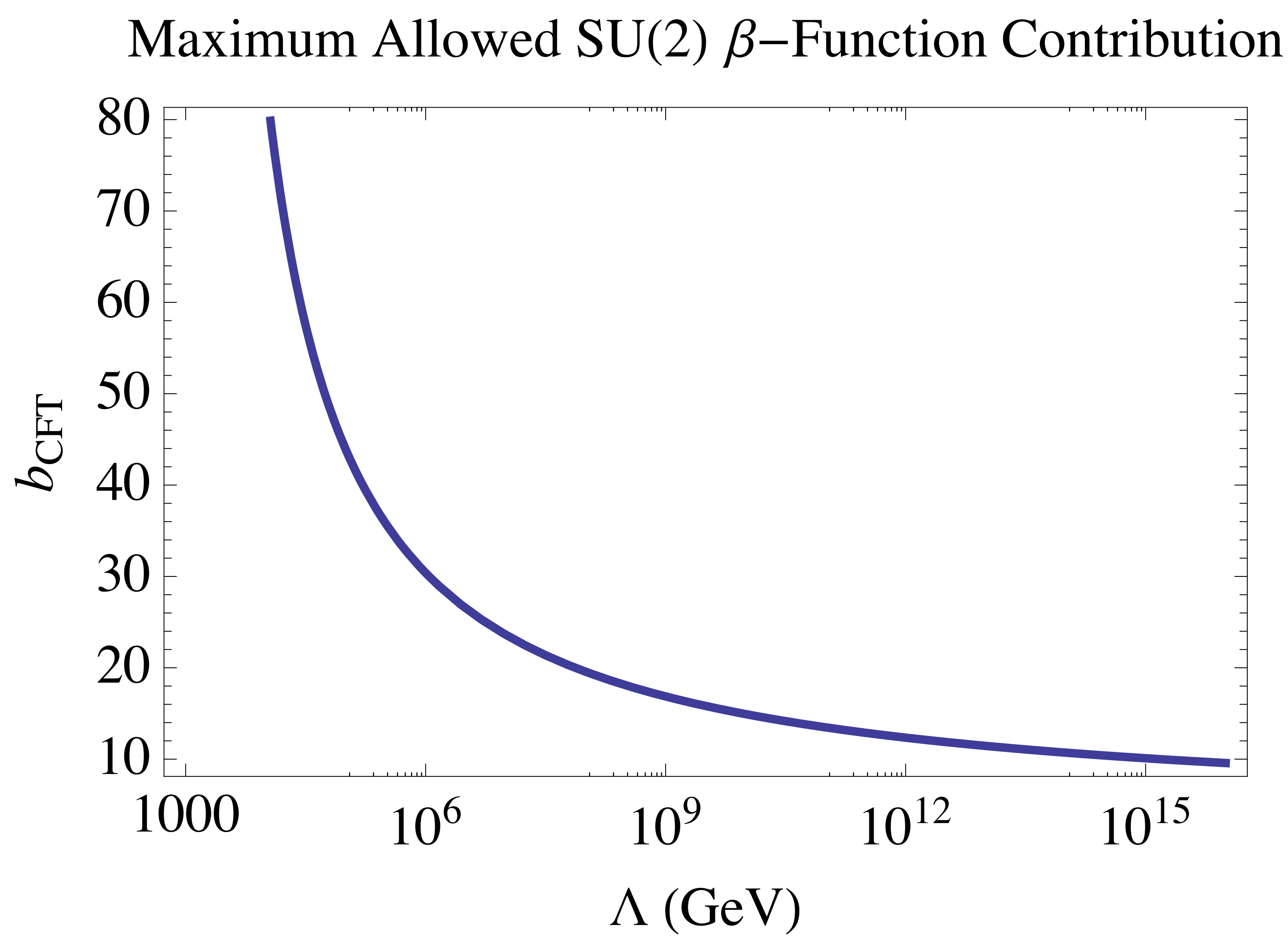


Figure 1: Bound on b_{CFT} as a function of the scale Λ below which we forbid a Landau pole.

GUT-scale hierarchy:

$$b_{CFT} \leq \frac{8\pi^2}{g^2(M_Z)} \frac{1}{\log 10^{12}} + \frac{10}{3} \approx 10. \longrightarrow \text{N < O(10)}$$

Ways out?

- If the SM gauge bosons are composite -- e.g. emerging from Seiberg duality at the bottom of some cascade -- such bounds do not apply. (Interpret Landau pole as hint of duality.) Different scenario.

- If b_{CFT} is order-one, as in some M5 brane models (Gaiotto-Maldacena), this bound does not apply.

semi-realistic model?

Cosmology

- If RS is a good description, expect the confinement/deconfinement transition to be of Hawking-Page type.

- $T > T_c$: thermal plasma, dual to AdS-Schwarzschild.

- $T < T_c$: hadronization, dual to AdS on thermal circle

- Phase transition is *first-order*.

Cosmology

- Critical temperature: $T_c \sim 2^{1/4}/(\pi z_{IR})$. (Herzog) Scale of KK modes, not string modes. $m_{\rm KK} \simeq z_{\rm IR}^{-1}$
- Entropy density $O(N^2)$ at high temperatures and O(1) at low temperatures.
  - The phase transition is slow (Creminelli et al.; Randall & Servant; Kaplan, Schuster, & Toro)
- Similarly: change in vacuum energy $O(N^2)$

$$\Delta E_{vac} = \frac{16 M_5^3 R_{\rm AdS}^3}{z_{IR}^4} = \frac{8}{\pi^2} c \frac{1}{z_{IR}^4}.$$

Cosmology

- The danger is the "empty universe problem," explained clearly in this context by Kaplan, Schuster, and Toro.

- Rate of bubble nucleation:

$$\Gamma \sim \frac{1}{z_{\mathrm{IR}}^4} e^{-\mathcal{O}(N^2)}$$

- If $\Gamma < H^4$, bubbles never meet, and the transition never completes.

The Bound

- We can't calculate the bounce action that takes us from thermal AdS to AdS-Schwarzschild. (Approximations exist for Goldberger-Wise stabilization.)

- In general, N^2 replaced with central charge c

$$a_0 z_{IR}^{-4} \exp^{-a_1 c} > c^2 z_{IR}^{-8} M_{Pl}^{-4}$$

- (Unknown order-one numbers a_0, a_1)

$$c \lesssim \frac{1}{a_1} \left(4 \log(M_{Pl} z_{IR}) + \log a_0 - 2 \log c\right)$$

$$c \sim N^2 \leq 140, \text{ if } a_1 = 1$$

Summary of Bounds

- These are two known bounds, comparably strong: $b_{CFT} \sim N < 10$ and $c \sim N^2 < 140$.
- We will see that the string scale is related to these numbers raised to small fractional powers, so is tightly bounded.
- Both of these numbers turn out to be very geometric
- Bound on c is more generic ($b_{CFT} \sim 1$ in M5 examples), but could avoid if the universe has never reheated above a temperature > TeV

4d vs 5d Masses

- We're interested in ratios of masses of 4d states (heavy string modes and light Kaluza-Klein modes)

- Our proxy for this is the ratio of length scales in the bulk theory.

$$\frac{m_{\rm str}}{m_{\rm KK}} \simeq \frac{R_{\rm AdS}}{l_s}$$

- KK masses set by z_{IR}^{-1}, location of the IR wall, "warped down" from R_{AdS}^{-1}. String masses set by warped-down string scale at IR wall.

We went through various examples and arguments of the implications of bCFT bound and cosmology bound on this ratio.

R_{AdS} vs. l_s in N=4 SYM

- Before looking at more examples, let's remind ourselves of $AdS_5 \times S^5$, where $R_{AdS}{}^4 = 4\pi g_s N l_s{}^4$.
- What's happening here can be thought of as moduli stabilization: need to fix the radius of the S^5 compactification.
- Two terms in potential: curvature ~ $1/R^2$ and flux ~ $g_s{}^2N^2/\mathrm{Vol}(S^5)^2$, in string units.
- Comparable size at minimum, sets R_{AdS}.

c Bound and Geometry

Assuming we start with 10d string theory, reduce to 5d AdS to obtain a Planck scale:

$$M_5^3 = \frac{1}{(2\pi)^7 g_s^2 l_s^8} \mathrm{Vol}_{M_5}.$$

Read off the central charge from the ⟨TT⟩ correlator as $c = 2\pi^2 M_5^3 R_{\mathrm{AdS}}^3$:

$$c = \left(\frac{R_{\mathrm{AdS}}^4}{8\pi l_s^4 g_s}\right)^2 \left(\frac{\mathrm{v}_{M_5}}{\pi^3}\right)$$

Here v_{M5} is the volume of M_5 in units of R_{AdS}.

c Bound, Numerically

- We see that c is expressed in terms of (R_{AdS}/l_s), the number we wish to bound, along with $g_s < 1$ (by S-duality) and v_{M5}.

- Smaller size of the internal manifold, i.e., small compared to the AdS space, larger $m_{str}/m_{KK} = R_{AdS}/l_s$.

$$c = \left(\frac{R_{\rm AdS}^4}{8\pi l_s^4 g_s}\right)^2 \left(\frac{{\rm v}_{M_5}}{\pi^3}\right)$$

- Normalize using $AdS_5 \times S^5$: $V_{S^5} = \pi^3$

$$\frac{m_{\rm str}}{m_{\rm KK}} \lesssim \left(140 \times 64\pi^2 \frac{\pi^3}{{\rm v}_{M_5}}\right)^{1/8} \approx 4.2 \left(\frac{\pi^3}{{\rm v}_{M_5}}\right)^{1/8} .$$

b_{CFT} Bound and Geometry

For the Landau pole bound on b_{CFT}, we need gauge fields in the bulk. There are different routes to this, but let's focus on D7 branes (Karch-Katz).

These must wrap a 3-manifold $M_3 \subset M_5$.

$$S_{\mathrm{DBI}} = -\tau_7 \int d^8\sigma \ \mathrm{tr}\sqrt{-\det(G_{\alpha\beta} + 2\pi\alpha' F_{\alpha\beta})}$$

$$\Rightarrow \quad \frac{R_{\mathrm{AdS}}}{g_5^2} = R_{\mathrm{AdS}} \times \frac{\mathrm{Vol}_{M_3}}{g_7^2} = \frac{\mathrm{v}_{M_3}}{2\pi^2} \frac{2\pi^2}{2g_s(2\pi)^5} \left(\frac{R_{\mathrm{AdS}}}{l_s}\right)^4$$

b_{CFT} Bound, Numerically

The bulk gauge coupling determines the coefficient in the ⟨J J⟩ correlator and hence b_{CFT}:

$$b_{CFT} = 8\pi^2 \frac{R_{\text{AdS}}}{g_5^2} = \frac{\text{v}_{M_3}}{2\pi^2}\left(\frac{R_{\text{AdS}}}{l_s}\right)^4 \frac{1}{4\pi g_s}.$$

Similarly to what we found for *c*, we have expressed b_{CFT} in terms (R_{AdS}/l_s), the number we wish to bound, along with $g_s < 1$ and v_{M3}.

$$\frac{m_{\text{str}}}{m_{\text{KK}}} \lesssim \left(4\pi g_s \frac{2\pi^2}{\text{v}_{M_3}}\left(\frac{8\pi^2}{g^2(m_Z^2)}\frac{1}{\log(\Lambda_{UV}/\Lambda_{TC})} + \frac{10}{3}\right)\right)^{1/4} \lesssim 3.3\left(g_s\frac{2\pi^2}{\text{v}_{M_3}}\right)^{1/4}$$

Orbifolds

- One way to reduce the volume of the internal geometry is to orbifold it.
- S^5 can be thought of as a circle fibered over CP^2; mod out by Z_k subgroup
- Doesn't change AdS_5 part of geometry: same R_{AdS}/l_s, but b_{CFT}, c lower by factor of k.
- Heavier strings at no cost?

Orbifolds

- However, run into a limit: size of the fiber shrinks from R to R/k, becomes l_s eventually
- Bound: $k < N^{1/4}$.
- Our bound on N was strict enough that this gives us only a small improvement.

The Weak Gravity Conjecture

- Interesting argument from weak gravity: add UV brane, go on branch with one D3 brane a distance R_{AdS} in the bulk, apply bound $m_W < g\, M_{Pl}$ (Arkani-Hamed, Motl, Nicolis, Vafa '06)

- Find that this means a bound on size of internal space, $\mathrm{Vol}_d > g_s\, R_{AdS}\, l_s^{d-1}$

- Examples with fluxes generically have a stronger $\mathrm{Vol}_d > g_s\, N\, R_{AdS}\, l_s^{d-1}$.

Weak-Gravity Saturation

- Suppose we knew a construction that saturates the weak-gravity bound $\mathrm{Vol}_d > g_s R_{AdS} l_s^{d-1}$ (we don't)

- It would have $c_{sat} \sim (R_{AdS}/l_s)^4$. (Contrast $(R_{AdS}/l_s)^8$ in $AdS_5 \times S^5$) Similarly for b_{CFT}

- Would be intrinsically interesting, plus the best route to decoupling strings. Does it exist?

Precision Electroweak

- One advantage of an RS description of a strongly-coupled sector is that quantities are calculable, e.g. the *S*, *T*, *U* parameters.

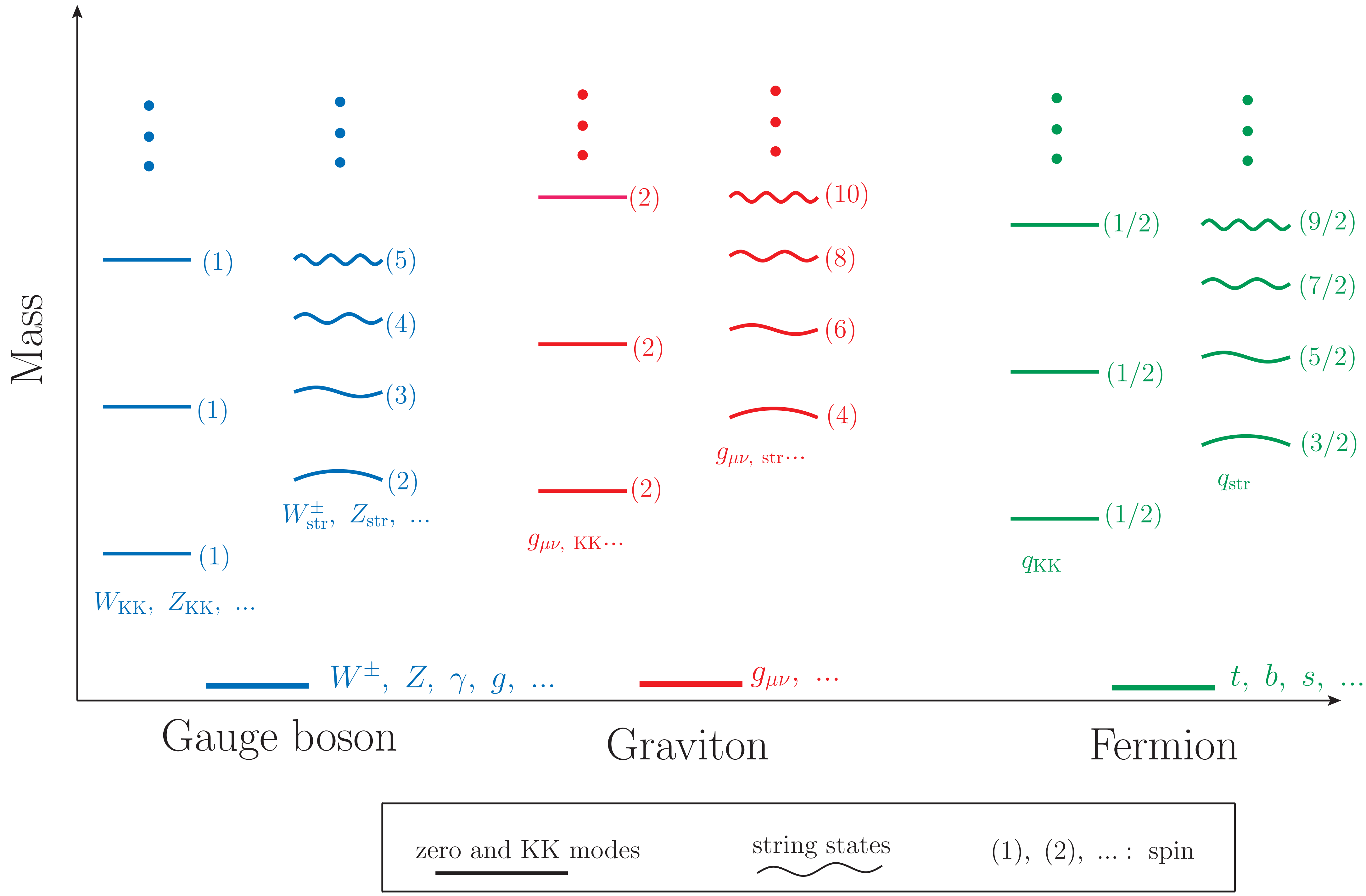
- Light strings could give $O(1)$ corrections, but probably don't change conclusions about viability.
    - E.g., custodial symmetry still protects *T*.

- It could give additional contributions to S-parameter comparable from those of the KK-mode.
    - Change preferred model parameters.

Stringy States

- What sort of states do we expect?
- Higher-spin W and Z bosons.
- Fermions model-dependent; possibly spin-3/2 top, bottom, etc.
- KK modes on internal directions.
- Higher-spin "KK gravitons" (closed strings)
- A whole zoo; challenging spectroscopy.

Spectrum

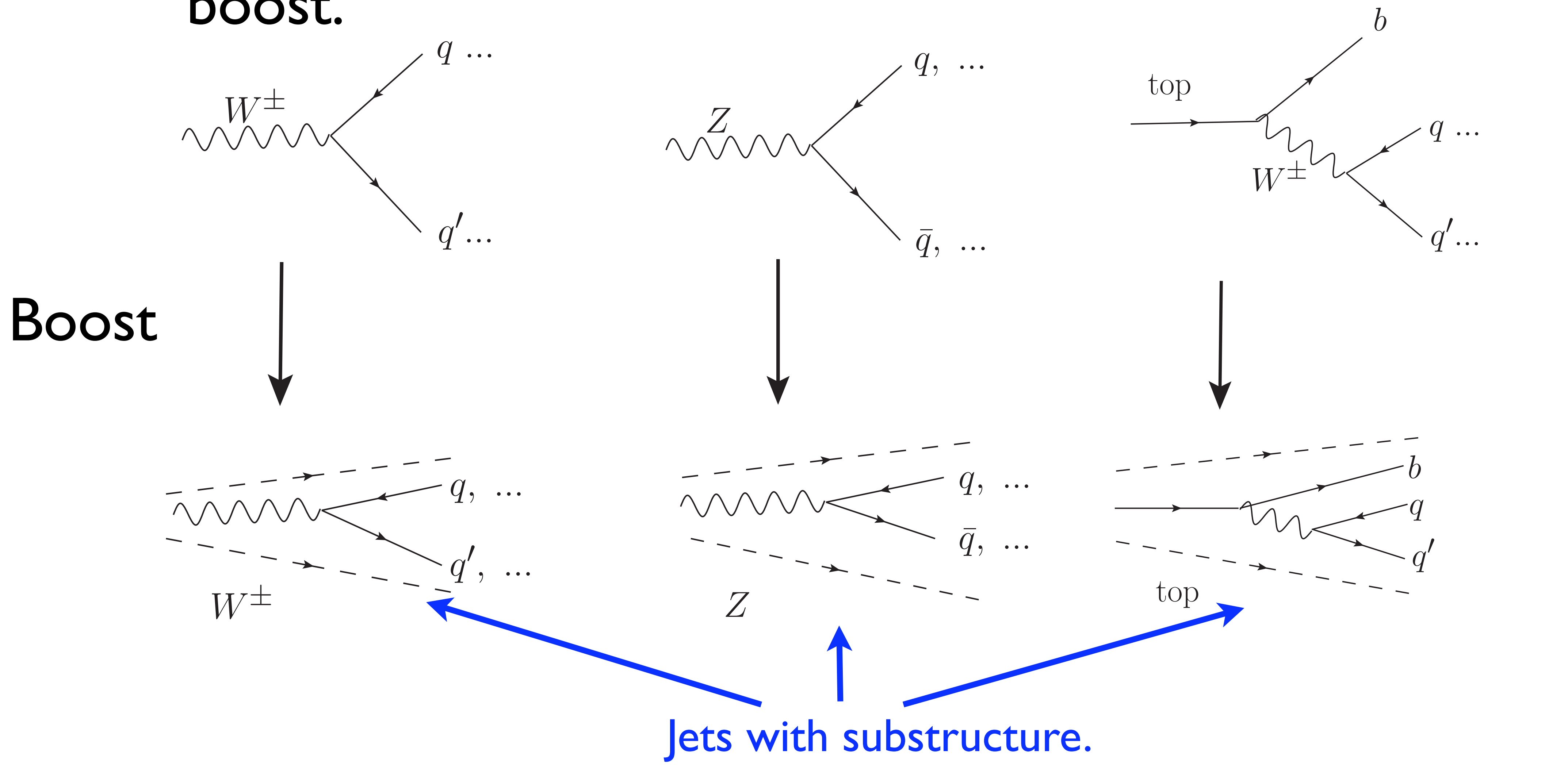


Mass
(1)
(1)
(1)
$W_{KK}, Z_{KK}, \ldots$
(5)
(4)
(3)
(2)
$W^{\pm}_{str}, Z_{str}, \ldots$
$W^{\pm}, Z, \gamma, g, \ldots$
(2)
(2)
(2)
$g_{\mu\nu}$, KK⋯
(10)
(8)
(6)
(4)
$g_{\mu\nu}$, str⋯
$g_{\mu\nu}, \cdots$
(1/2)
(1/2)
(1/2)
q_{KK}
(9/2)
(7/2)
(5/2)
(3/2)
q_{str}
$t, b, s, \ldots$
Gauge boson
Graviton
Fermion
zero and KK modes
string states
(1), (2), ... : spin

Jet substructure

Jet substructure.

- On very general grounds, we expect the TeV new physics states to have significant coupling to the W, Z, and top quark.
- When produced at TeV-scale energies, they have a large boost.



Challenge: distinguishing them from QCD jets (q and g).

Hiding Higgs.

- Alternative decay channels can dramatically change Higgs search strategy.

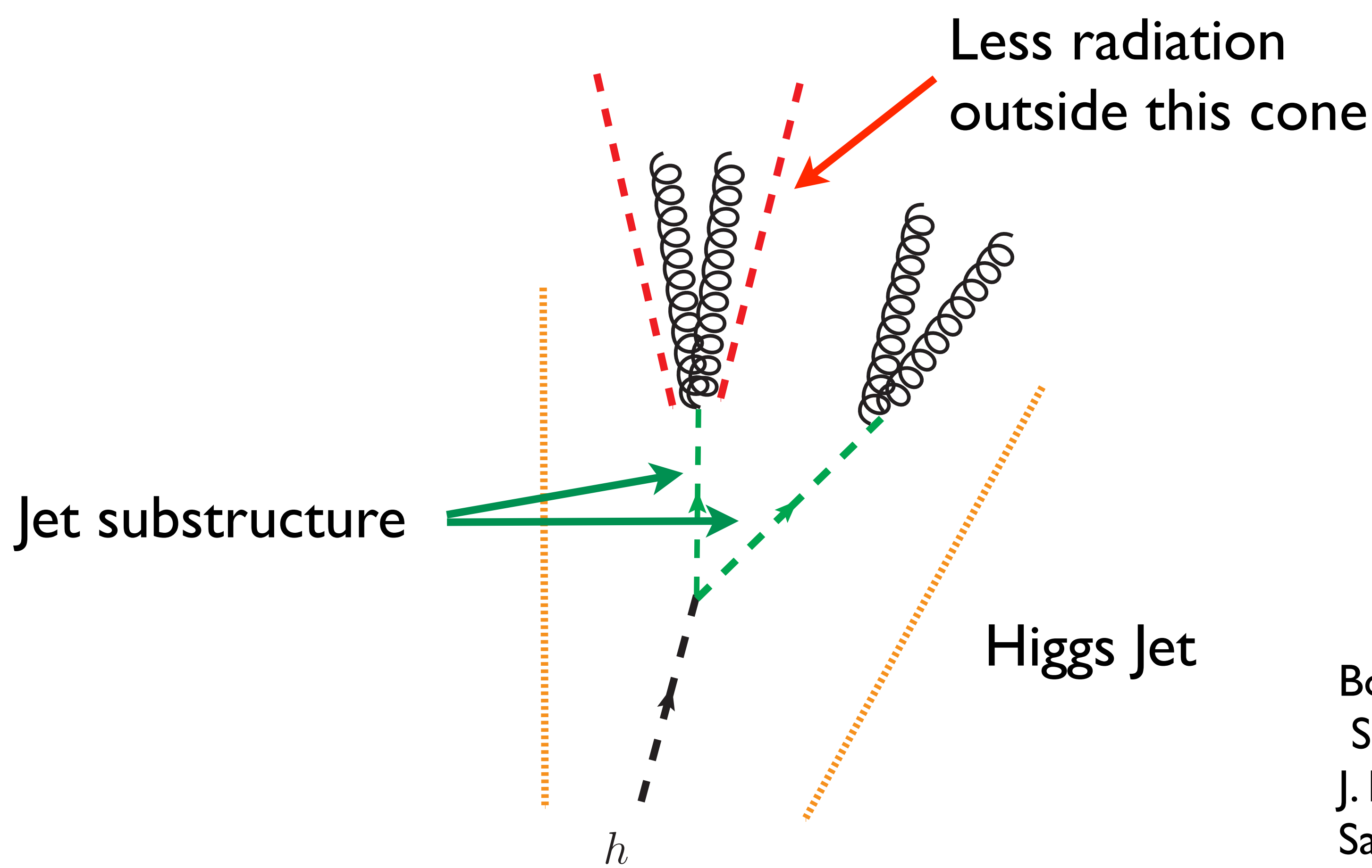
$$h \to aa \to 4\tau,\ 4b,\ \bar{b}b\bar{\tau}\tau$$

For example:
P. Graham, A. Pierce, J. Wacker, hep-ph/0605162
M. Carena, T. Han, G. Huang, C. Wagner, arXiv:0712.2466

$$h \to aa \to c\bar{c}c\bar{c},\ \text{"charming"?}$$
$$h \to aa \to gggg,\ \text{"buried"!}$$

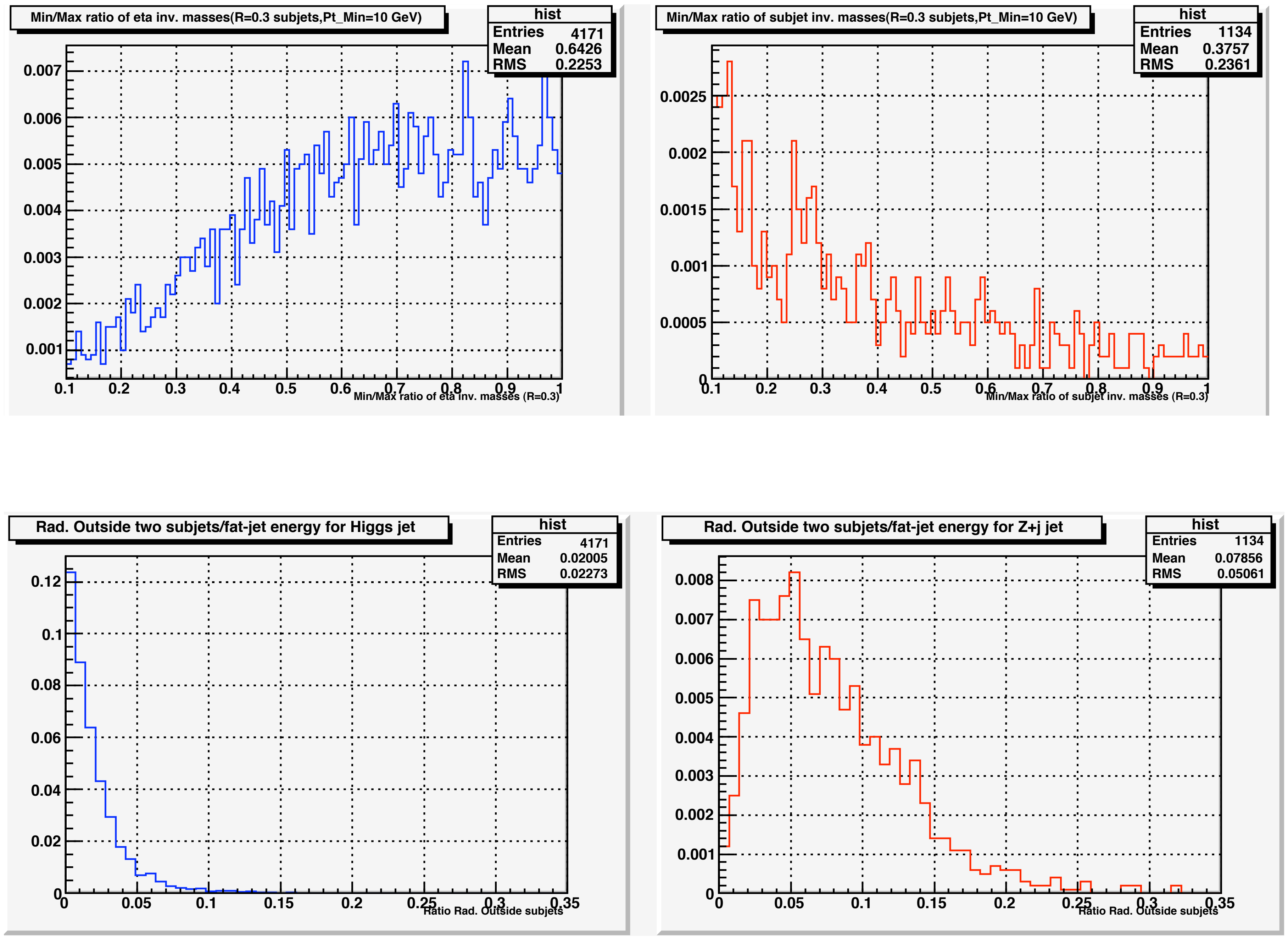
For example:
B. Bellazzini, C. Csaki, A. Falkowski, A. Weiler, arXiv:0910.3210, arXiv:0906.3026

- Why can new jet technology help?



Boosted Higgs, studied in the context of SM-like Higgs by
J. Butterworth, A. Davidson, M. Rubin, G. Salam, arXiv:0802.2470

Usefulness of the variables.



Higgs + Z signal

Z+jet background

A. Falkowski, D. Krohn, J. Shelton, A. Thalapillil, and LTW, in progress.

Encouraging results.

(rates in fb)

jet mass →

Cut	Range	S [fb]	B[fb]	S/B	$S/\sqrt{B}$ @ 100 fb^{-1}
p_T	> 200 GeV	$1.7 \cdot 10^1$	$3.3 \cdot 10^4$	$5.1 \cdot 10^{-4}$	0.9
m_j	$90 \leftrightarrow 110$ GeV	$1.0 \cdot 10^1$	$1.1 \cdot 10^3$	$9.5 \cdot 10^{-3}$	3.1
α	> 0.7	$5.1 \cdot 10^0$	$2.7 \cdot 10^2$	$1.9 \cdot 10^{-2}$	3.1
β	$< 5 \cdot 10^{-3}$	$8.2 \cdot 10^{-1}$	$3.1 \cdot 10^0$	$2.7 \cdot 10^{-1}$	4.7

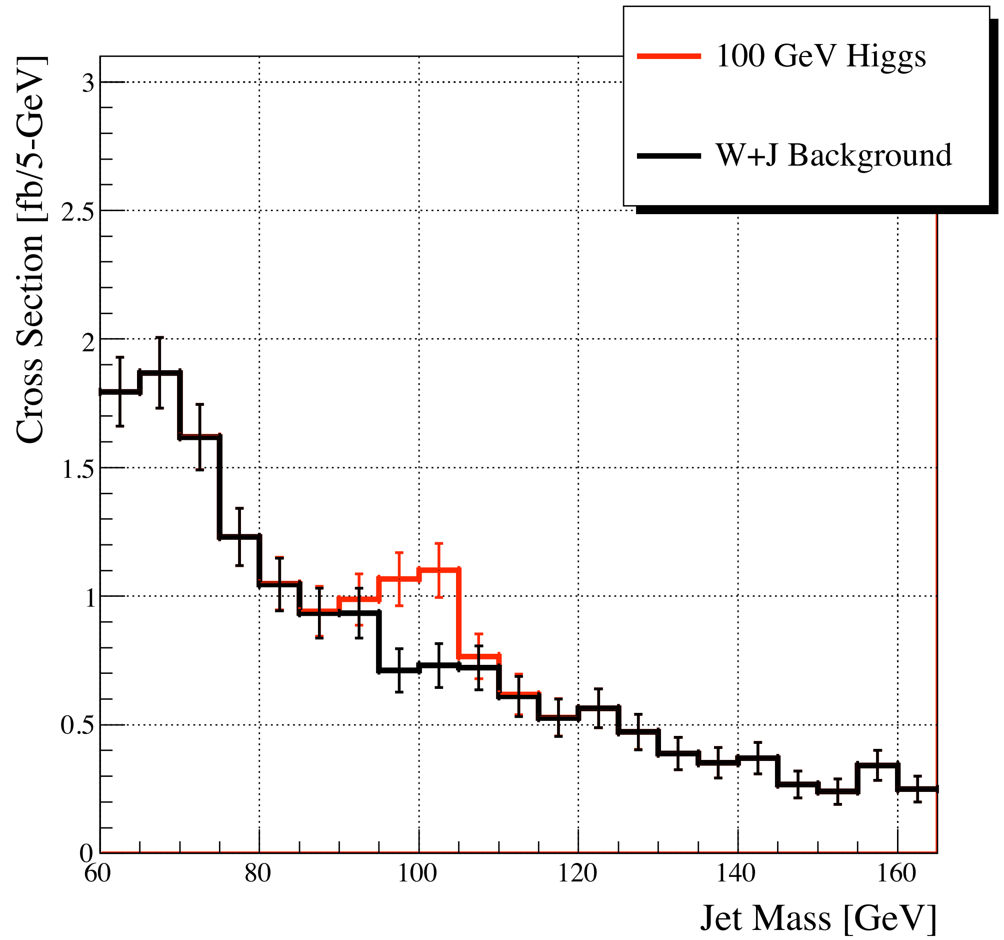
Table 2: $m_H = 100$ GeV, $R = 1.0$

2 subjets

$$\alpha = \min\left[\frac{m(j_1)}{m(j_2)}, \frac{m(j_2)}{m(j_1)}\right]$$

radiation pattern

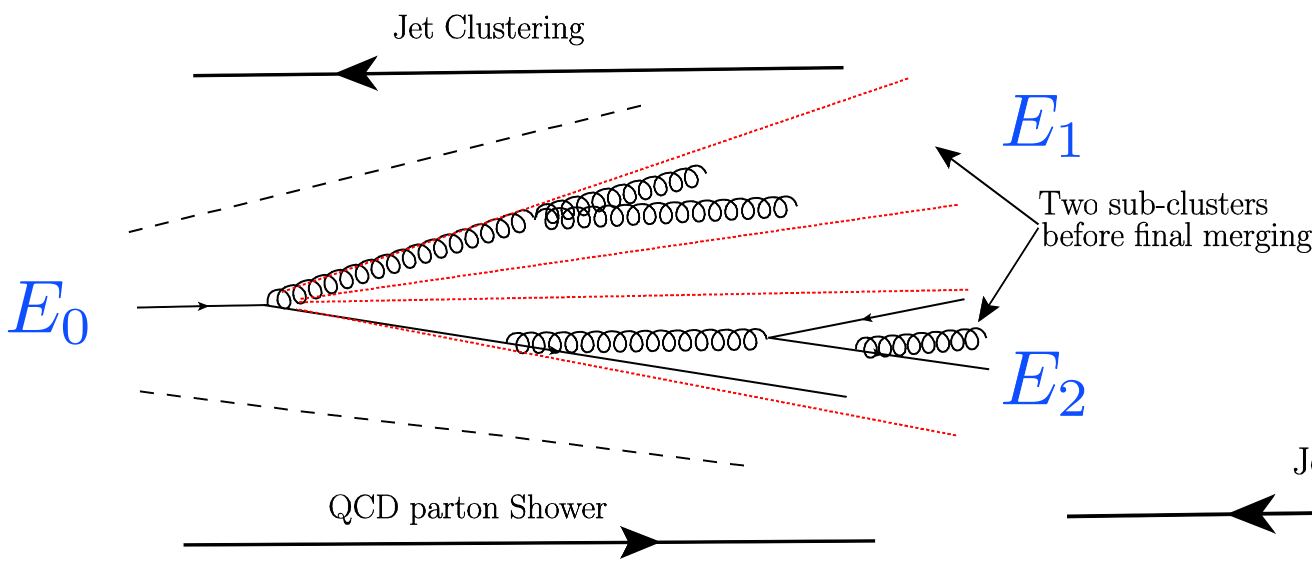
$$\beta = \frac{p_T(j_3)}{p_T(j)}.$$



Top jet substructure, z-finding

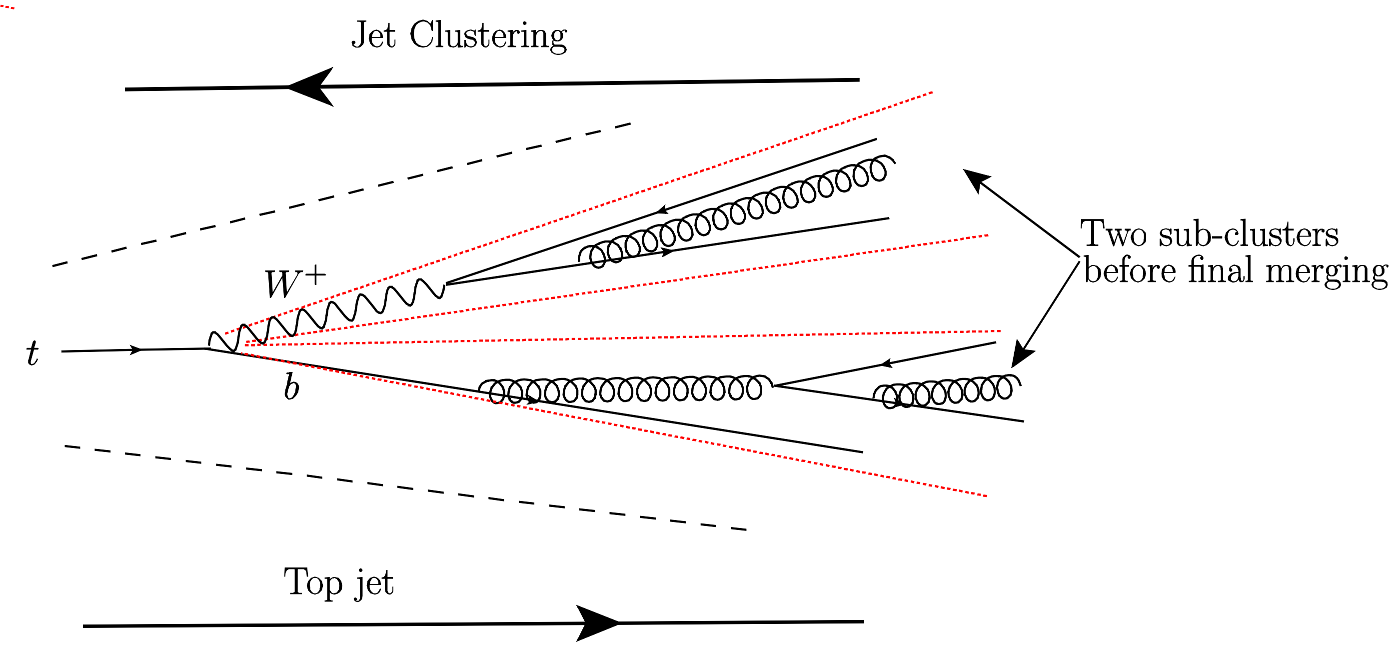
$z \to 0$ for QCD jet,

z finite for top jet.



$$z = \frac{\min(E_1, E_2)}{E_0}$$

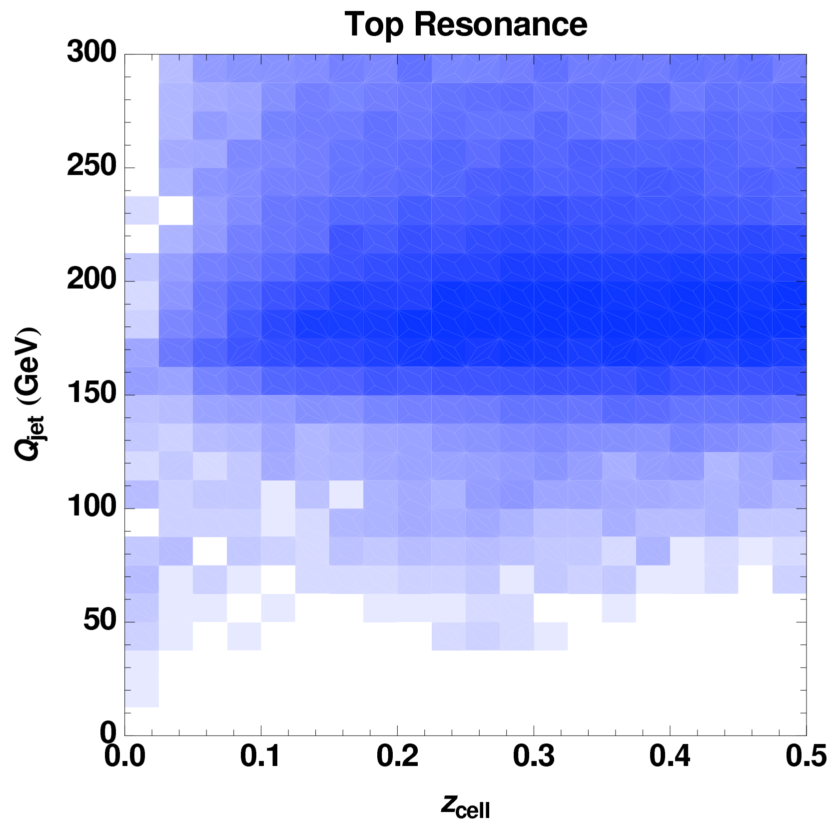
Q : jet mass

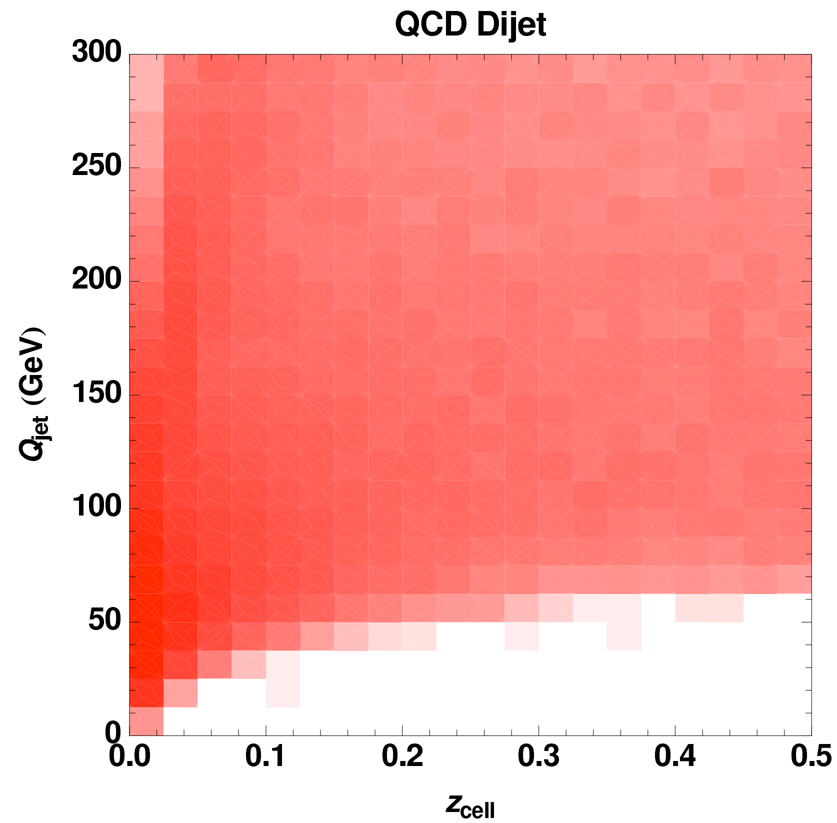


- Jet clustering history is approximately the inverse of parton shower.

Top jets vs QCD jets

J. Thaler and LTW, arXiv:0806.0023.





Related studies:

D. Kaplan, K. Reherman, M. Schwartz, B. Tweedie, arXiv: 0806.0848.

L. Almeida, S. Lee, G. Perez, G. Sterman, I. Sung, J. Virzi, arXiv:0807.0243

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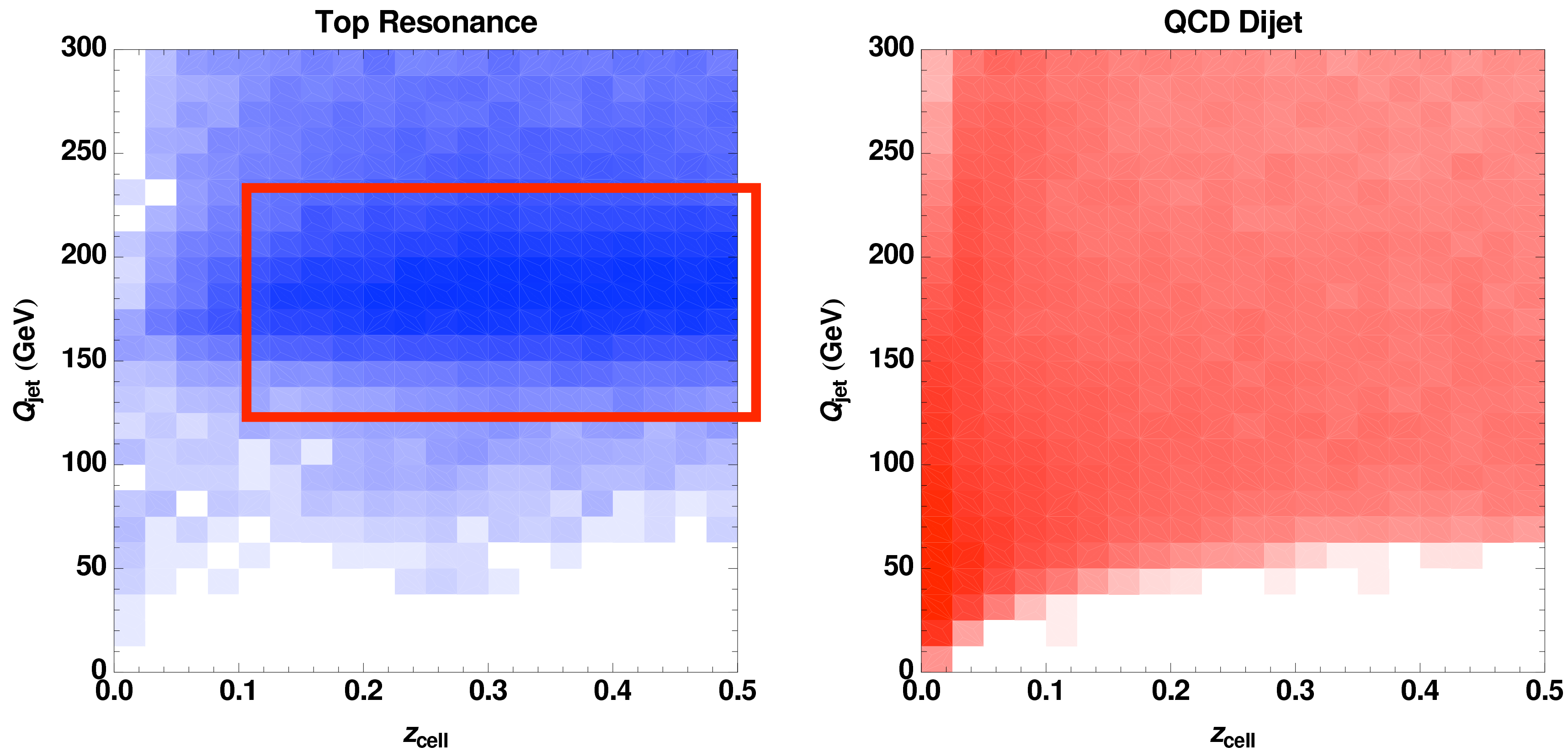

- Combined cuts on jet mass and z can enhance further the signal with respect to the background. O(100) enhancement of the signal.

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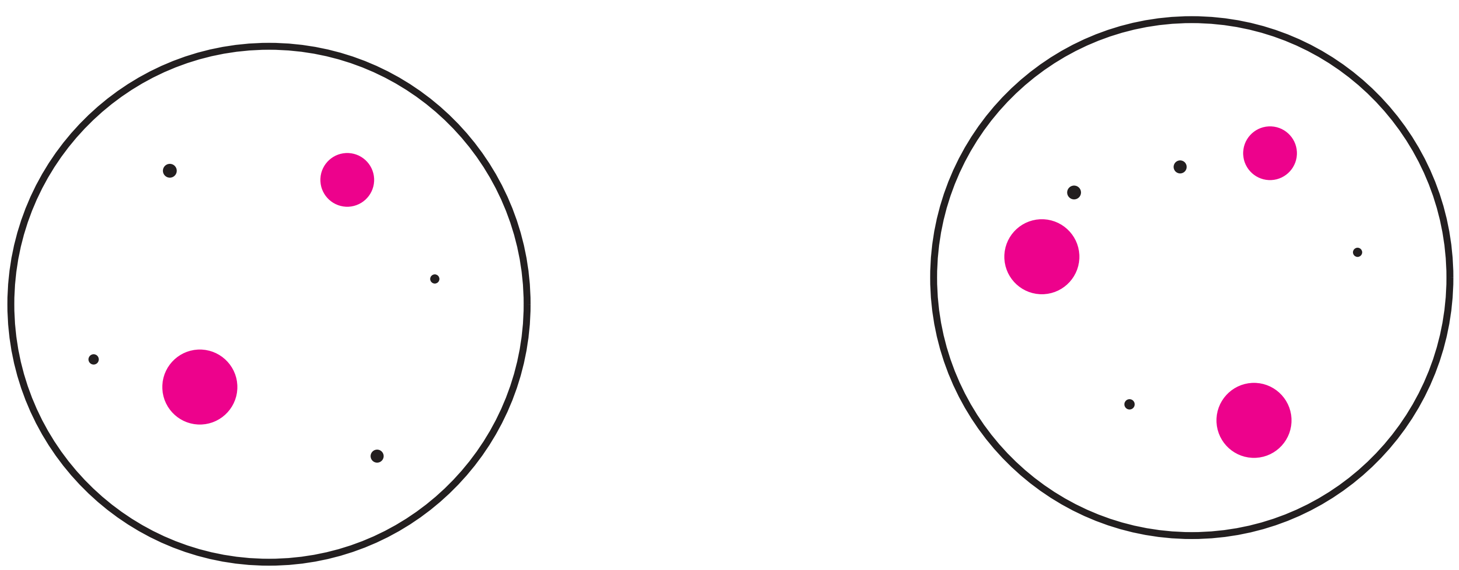
More jet shape variables.

- Top decay is more like 3-body. Span a "plane" perpendicular to the jet axis.
  - Transverse sphericity, or "planar flow"

$$S^{\perp ij} = \frac{\displaystyle\sum_{\alpha \in \text{jet}} \frac{\vec{p}_\alpha^{\perp i} \vec{p}_\alpha^{\perp j}}{|\vec{p}_\alpha^{\perp}|}}{\displaystyle\sum_{\alpha \in \text{jet}} |\vec{p}_\alpha^{\perp}|}.$$

$\vec{p}_\alpha^{\perp i}$: w.r.t. jet axis, $i = 1, 2$

J. Thaler and LTW, arXiv:0806.0023.



$\det S^{\perp} = 0$ $\qquad\qquad$ $\det S^{\perp} \neq 0$

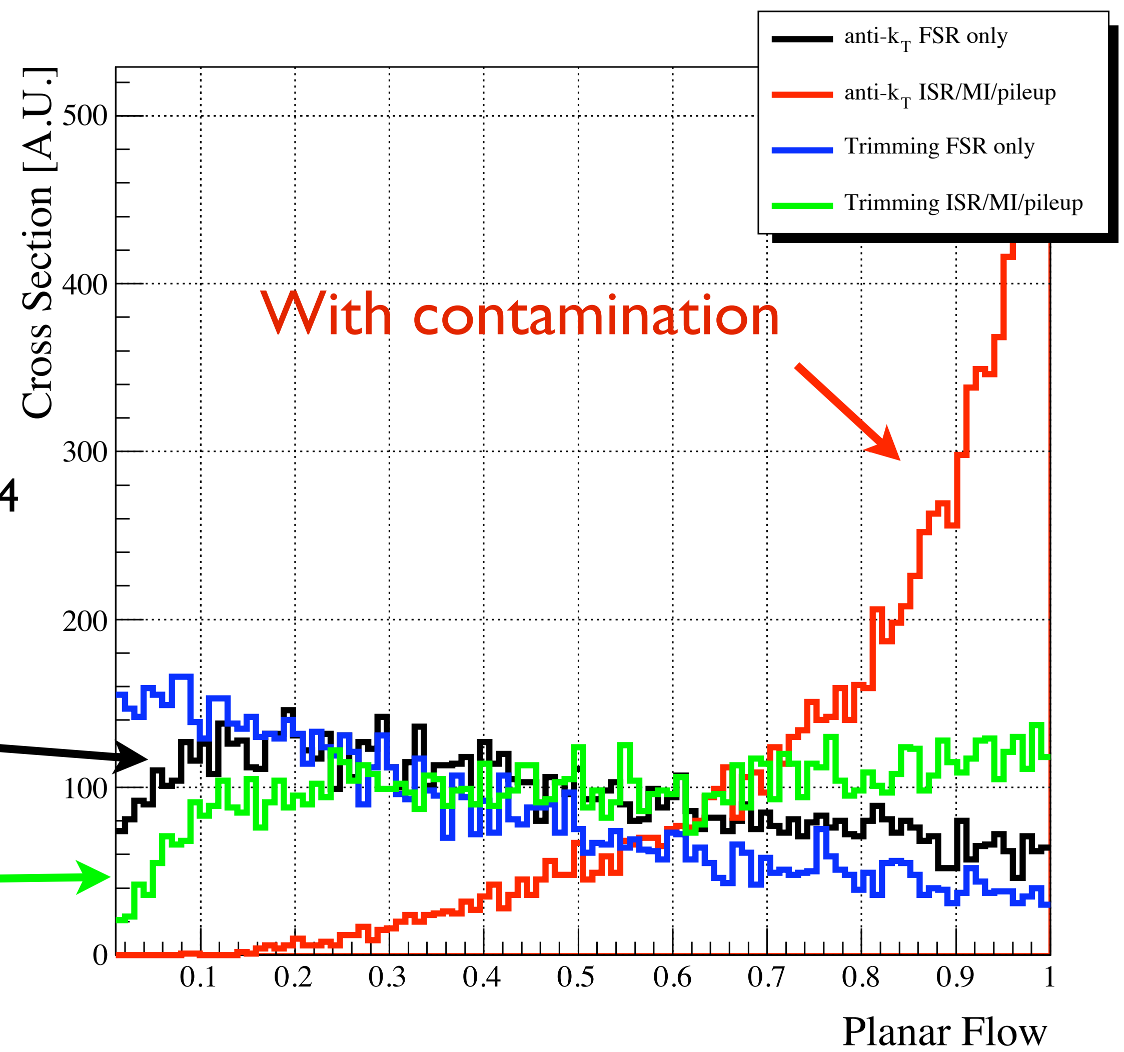
Better reconstruction of the jet shape

Planar flow

Defined in
L. Almeida, S. Lee, G. Perez,
G. Sterman, I. Sung, J Virzi, arXiv:0807.0234

With no contamination

With "trimming"



D. Krohn, J. Thaler, LTW, arXiv:0912.1342

- Can be used to further improve top tagging. An additional factor of several possible.
- Interesting to compare with improved QCD calculation, using modern technologies such as SCET.

Thoughts on MC4BSM as a user/theorist.

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- But, with the existing ones, and with the experts answering my emails, I should be able to survive (more or less) already.
- And, I am happy to become a service provider, of course for my own models, but also for other models.

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- A low energy only SUSY spectrum calculator (to LHA).
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- Color flow, long decay chain, higher dimensional operator...

MC4SM!

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- Matrix element + parton shower merging, NLO,NLL...

Peter's talk.

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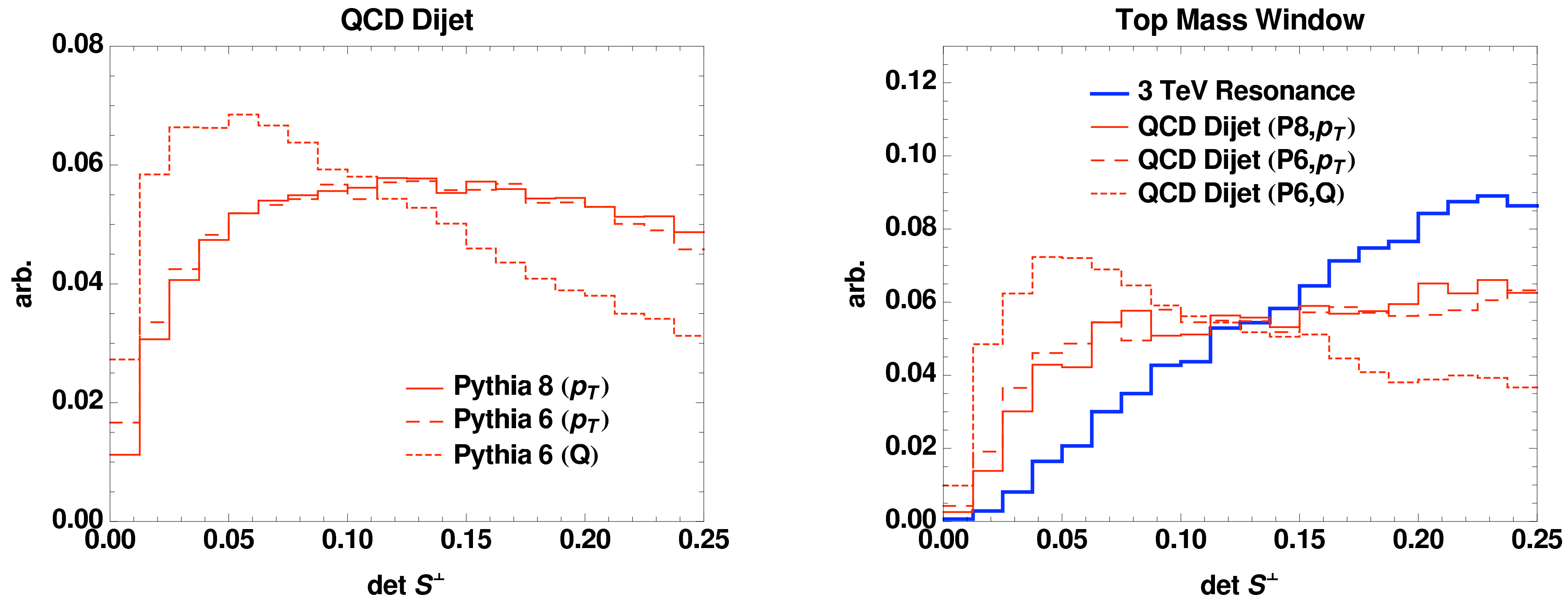
Thanks.

Using planar flow to identify top jets.



- $1 \to 3$ is not very well modeled by parton shower.
- Also affected by contamination from underlying events.

Resummation & Concavity: Stringless Argument

- Resumming one-gluon exchanges and extrapolating to large λ gives $-\sqrt{\lambda}\,/r$ Coulomb potential (Erickson, Semenoff, Zarembo)
- Bachas: static potential is concave
- Long distances: $V(r) \sim \sigma r$ (confinement)
- Assume Coulomb until $r \sim z_{IR}$
- Learn: $m_{str}\, z_{IR} \sim \sqrt{\sigma}\, z_{IR} < \lambda^{1/4}$

S-Parameter

- One example of a challenge for RS model-building is the S-parameter. Strings will change it by an unknown order-one amount.
- Approaches: either use composite Higgs, (v/M_{KK}) small (still viable)
- Or: Higgsless limit, tune fermion profiles ("delocalization") to cancel S: still viable, just different tuning.

4d vs 5d masses

- Another way to see this: for a bulk mass m_5^2 in units of R_{AdS} (for a scalar with Dirichlet b.c., for convenience), 4d masses are zeroes of $J_\nu(m_{4d} z_{IR})$ with

$$\nu = \sqrt{4 + m_5^2 R_{\mathrm{AdS}}^2}$$

- The first such zero goes as:

$$\left(\nu + 1.856\nu^{1/3} + \mathcal{O}(1)\right)$$

- Thus $m_{4d}\ z_{IR} \sim m_{5d}\ R_{AdS}$ at large m_{5d}