A Guide to Diagnosing Colored Resonances at Hadron Colliders

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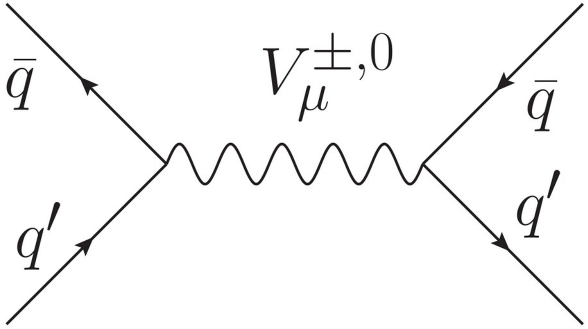
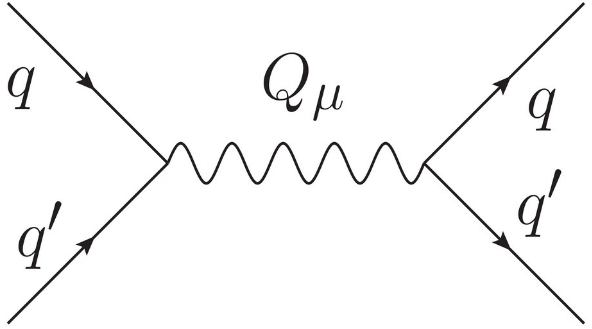
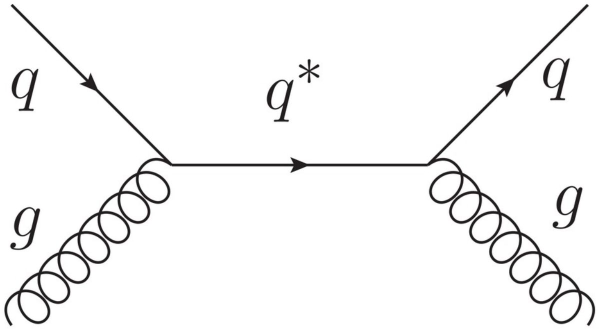
JHEP 08 (2023) 173

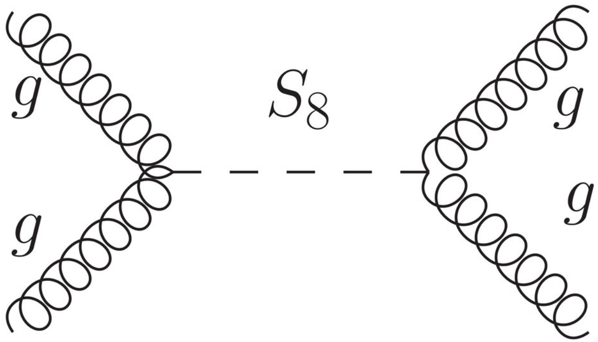
Why dijets?

- LHC is essentially a QCD machine.
- Most initial states are charged under QCD.
- Dijet resonances are among the most natural objects to search for.
  - If it's produced by a pair of partons, it can decay back into the partons.
- Finite number of possible initial states (ignoring EW only particles):
  - Quarks, gluons, and anti-quarks.
  - Can classify all quantum numbers.









Dijet Resonances

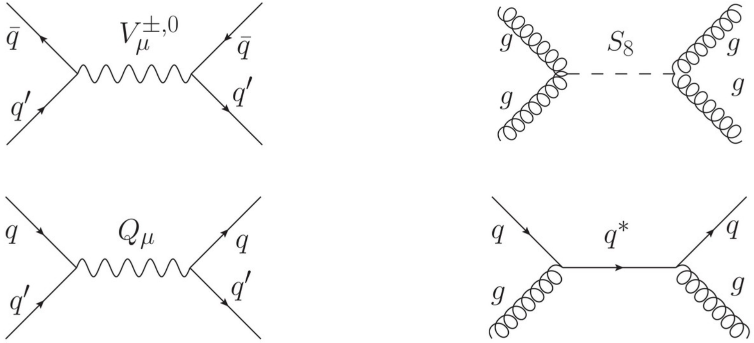
- Know the initial states:
  - Can characterize quantum numbers of possible dijet resonances.
  - Q: Left-handed doublets
  - U,D: Right-handed singlets
  - A: gluons

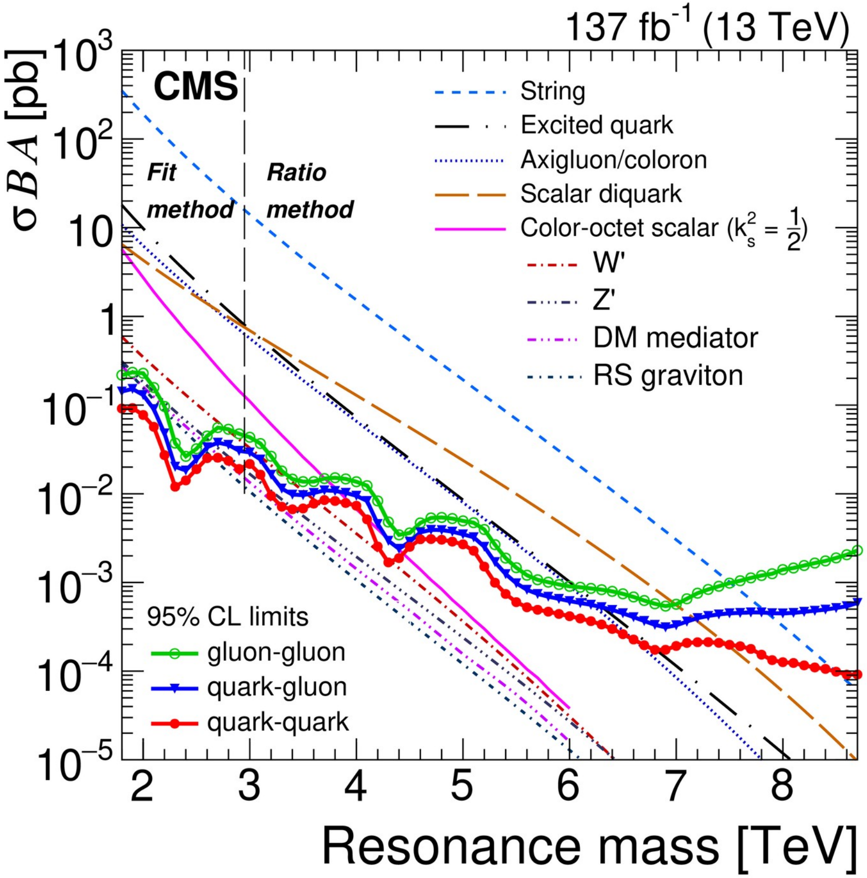
initial state	J	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$\|Q_e\|$	B
QQ	0	$\bar{\mathbf{3}} \oplus \mathbf{6}$	$\mathbf{1} \oplus \mathbf{3}$	$\frac{1}{3}$	$\frac{4}{3}, \frac{2}{3}, \frac{1}{3}$	$\frac{2}{3}$
QU	1	$\bar{\mathbf{3}} \oplus \mathbf{6}$	$\mathbf{2}$	$\frac{5}{6}$	$\frac{4}{3}, \frac{1}{3}$	$\frac{2}{3}$
QD	1	$\bar{\mathbf{3}} \oplus \mathbf{6}$	$\mathbf{2}$	$-\frac{1}{6}$	$\frac{2}{3}, \frac{1}{3}$	$\frac{2}{3}$
UU	0	$\bar{\mathbf{3}} \oplus \mathbf{6}$	$\mathbf{1}$	$\frac{4}{3}$	$\frac{4}{3}$	$\frac{2}{3}$
DD	0	$\bar{\mathbf{3}} \oplus \mathbf{6}$	$\mathbf{1}$	$-\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
UD	0	$\bar{\mathbf{3}} \oplus \mathbf{6}$	$\mathbf{1}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{2}{3}$
QA	$\frac{1}{2}, \frac{3}{2}$	$\mathbf{3} \oplus \bar{\mathbf{6}} \oplus \mathbf{15}$	$\mathbf{2}$	$\frac{1}{6}$	$\frac{2}{3}, \frac{1}{3}$	$\frac{1}{3}$
UA	$\frac{1}{2}, \frac{3}{2}$	$\mathbf{3} \oplus \bar{\mathbf{6}} \oplus \mathbf{15}$	$\mathbf{1}$	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{1}{3}$
DA	$\frac{1}{2}, \frac{3}{2}$	$\mathbf{3} \oplus \bar{\mathbf{6}} \oplus \mathbf{15}$	$\mathbf{1}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$
AA	0, 1, 2	$\mathbf{1} \oplus \mathbf{8} \oplus \mathbf{8} \oplus \mathbf{10} \oplus \overline{\mathbf{10}} \oplus \mathbf{27}$	$\mathbf{1}$	0	0	0
$Q\bar{Q}$	1	$\mathbf{1} \oplus \mathbf{8}$	$\mathbf{1} \oplus \mathbf{3}$	0	$1, 0$	0
$Q\bar{U}$	0	$\mathbf{1} \oplus \mathbf{8}$	$\mathbf{2}$	$-\frac{1}{2}$	$1, 0$	0
$Q\bar{D}$	0	$\mathbf{1} \oplus \mathbf{8}$	$\mathbf{2}$	$\frac{1}{2}$	$1, 0$	0
$U\bar{U},\ D\bar{D}$	1	$\mathbf{1} \oplus \mathbf{8}$	$\mathbf{1}$	0	0	0
$U\bar{D}$	1	$\mathbf{1} \oplus \mathbf{8}$	$\mathbf{1}$	1	1	0

Han, **IML**, Liu, JHEP12 (2010) 085

Dijet Resonances

- Many searches at the LHC for such resonances.
- No discovery yet, but what if there is one?
- Need to experimentally classify the dijet resonance.
  - Type of jets are hard to distinguish and the initial state is unknown.
  - Which partons does it couple to?
  - What is its spin?
  - What is its color representation?



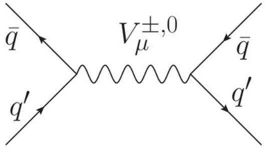


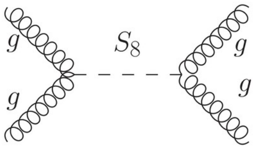
CMS JHEP 05 (2020) 033

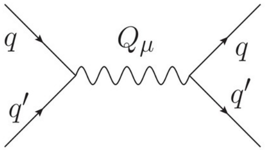
Couplings to Particles

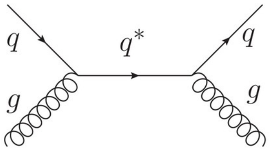
- Rapidity distribution of resonance has information about initial state parton.
  - Gluons, sea, and anti-quarks tend to carry small amounts of the proton momentum
  - Valence quarks carry tend to carry large fractions of proton momentum
  - Hence, centrality of rapidity distribution depends on initial state partons.
- Assuming decays into same states.
  - Can try to tag quark vs. gluon vs. anti-quark jets.
  - Heard some about jet charge from Zhongtian (Cosmos) Dong on Monday.

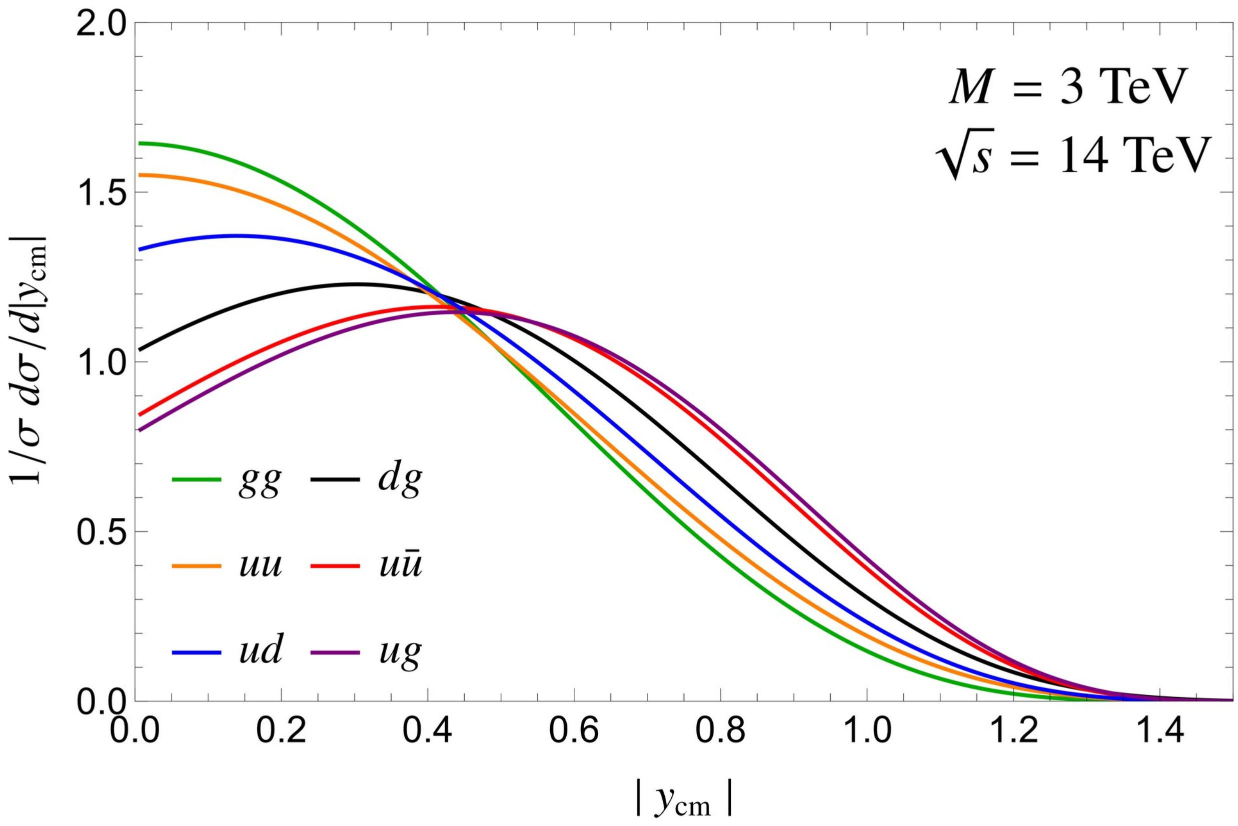
Cogan et al, JHEP02 (2015) 118; Kmosike, Metodiev, Schwartz JHEP 01 (2017) 110; Kasieczka et al SciPost 6 (2019) 069; Field, Feynman, NPB 136 (1978); etc etc











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Spin

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- Spin correlations.
  - Depending on chiral couplings, get different spin correlations.
  - Can measure with angular distributions.
- On-shell angular distributions in resonance rest frame.
  - Each higher spin gains new power of polar angle
  - Assuming jets cannot be distinguished, will symmetrize.
  - Cannot distinguish chiral couplings, but can (mostly) distinguish different spins.

Spin 1/2:
$$\frac{d\hat{\sigma}_{1/2}}{d\cos\theta} = \frac{1}{2}\hat{\sigma}_{1/2}(\hat{s}=M^2)\left(1+\frac{|\lambda_{i,L}|^2-|\lambda_{i,R}|^2}{|\lambda_{i,L}|^2+|\lambda_{i,R}|^2}\frac{|\lambda_{f,L}|^2-|\lambda_{f,R}|^2}{|\lambda_{f,L}|^2+|\lambda_{f,R}|^2}\cos\theta\right)$$

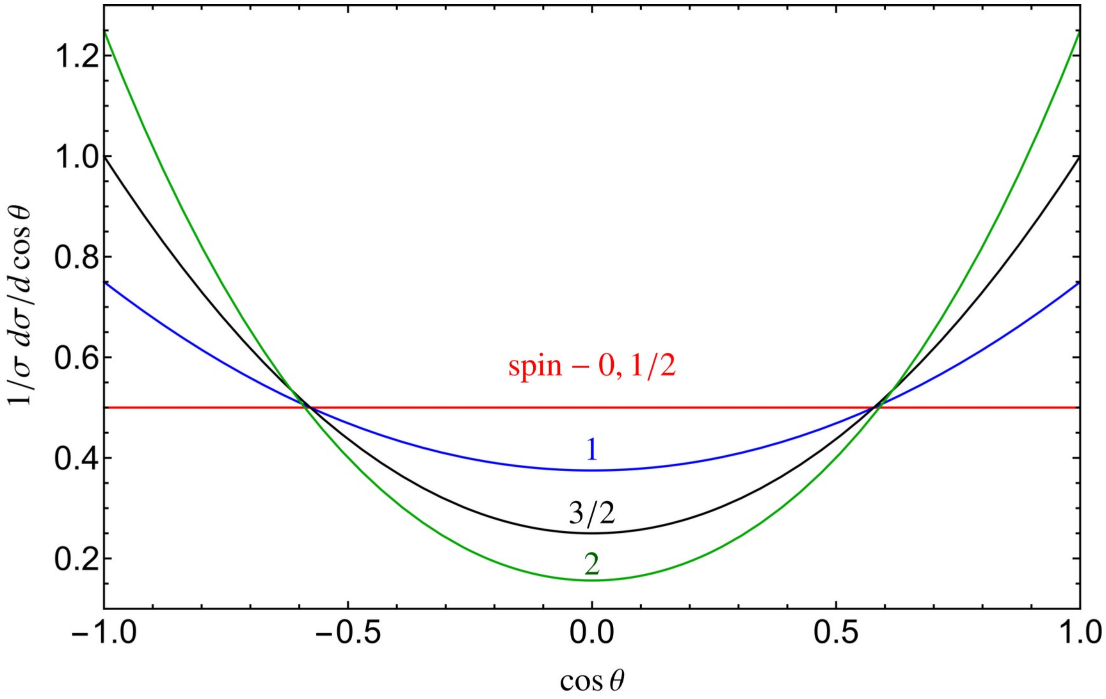
Spin 1:
$$\left.\frac{d\hat{\sigma}_{1}}{d\cos\theta}\right|_{g_L=g_R} = \frac{3}{8}\hat{\sigma}_1(\hat{s})(1+\cos^2\theta)$$

Spin 3/2:
$$\frac{d\hat{\sigma}_{3/2}}{d\cos\theta} = \frac{1}{2}\hat{\sigma}_{3/2}(\hat{s}=M^2)\left[1+3\cos^2\theta+\frac{|\lambda_{i,L}|^2-|\lambda_{i,R}|^2}{|\lambda_{i,L}|^2+|\lambda_{i,R}|^2}\frac{|\lambda_{f,L}|^2-|\lambda_{f,R}|^2}{|\lambda_{f,L}|^2+|\lambda_{f,R}|^2}\cos\theta\left(3+\cos^2\theta\right)\right]$$

Spin 2:
$$\frac{d\hat{\sigma}_{2}}{d\cos\theta} = \frac{5}{32}\sigma_2(\hat{s})\left(1+6\cos^2\theta+\cos^4\theta\right)$$

Angular Distributions

- Assuming we cannot distinguish final state jets, symmetrize distributions.
- Most resonances distinguishable.
  - Spin-0 and Spin-1/2 not distinguishable after symmetrizing.



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Color Charge

- Many resonances only differ by color representation.
  - Same spin.
  - Same coupling to partons.
  - Same charge.
- How do we tell them apart?

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UU	0	$\bar{\mathbf{3}} \oplus \mathbf{6}$	$\mathbf{1}$	$\frac{4}{3}$	$\frac{4}{3}$	$\frac{2}{3}$
DD	0	$\bar{\mathbf{3}} \oplus \mathbf{6}$	$\mathbf{1}$	$-\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
UD	0	$\bar{\mathbf{3}} \oplus \mathbf{6}$	$\mathbf{1}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{2}{3}$
QA	$\frac{1}{2}, \frac{3}{2}$	$\mathbf{3} \oplus \bar{\mathbf{6}} \oplus \mathbf{15}$	$\mathbf{2}$	$\frac{1}{6}$	$\frac{2}{3}, \frac{1}{3}$	$\frac{1}{3}$
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DA	$\frac{1}{2}, \frac{3}{2}$	$\mathbf{3} \oplus \bar{\mathbf{6}} \oplus \mathbf{15}$	$\mathbf{1}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$
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$Q\bar{U}$	0	$\mathbf{1} \oplus \mathbf{8}$	$\mathbf{2}$	$-\frac{1}{2}$	$1, 0$	0
$Q\bar{D}$	0	$\mathbf{1} \oplus \mathbf{8}$	$\mathbf{2}$	$\frac{1}{2}$	$1, 0$	0
$U\bar{U},\ D\bar{D}$	1	$\mathbf{1} \oplus \mathbf{8}$	$\mathbf{1}$	0	0	0
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Color Charge

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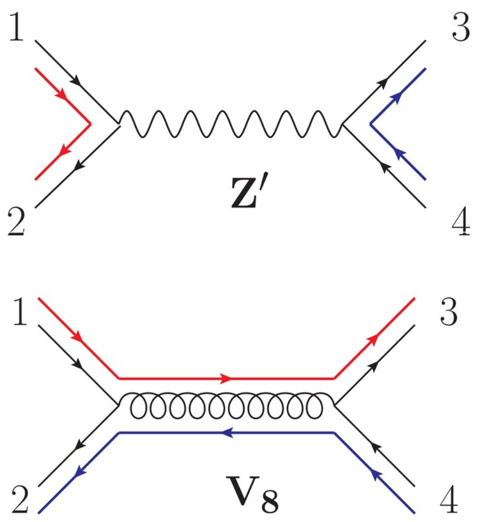
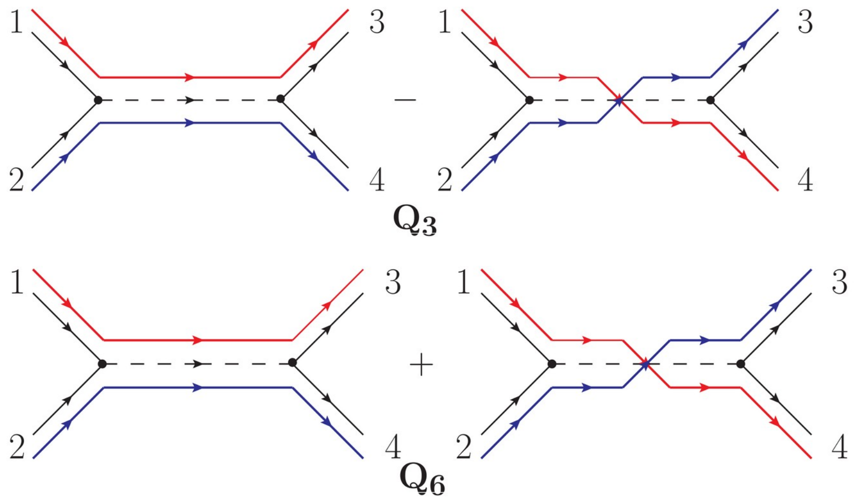
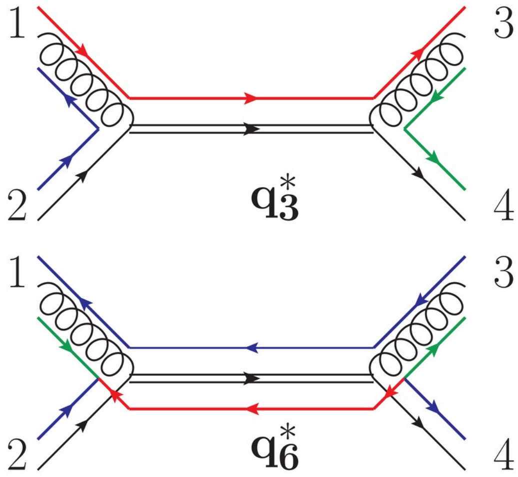
- Several resonances have same quantum numbers except color.
  - Need to distinguish
- Two-to-two not sufficient and insensitive to color.
- Look at additional radiation of a gluon.
  - Can be sensitive to interference patterns between different color connected lines.
  - Different resonance have different color connections.







Soft/Collinear Radiation

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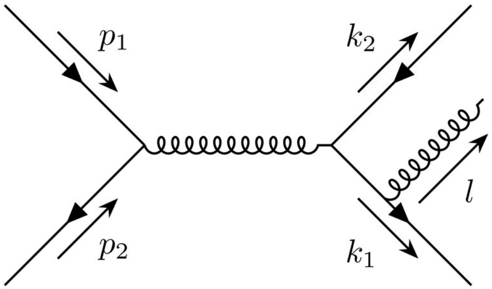


$$[k_i k_j] = \frac{k_i \cdot k_j}{l \cdot k_i \, l \cdot k_j}$$

- Take soft and collinear limit of radiated gluon.
- Different elements are sensitive to different radiation patterns.
- Studied for octet vs. singlet previously.

Ellis, Khoze, Stirling, Z.Phys. C75 (1997) 287

Quark-Antiquark:

$$\frac{|\mathcal{M}_{2\to V_1\to 3}|^2}{|\mathcal{M}_{2\to V_1\to 2}|^2} \propto g_s^2([p_1p_2]+[k_1k_2])$$

$$\frac{|\mathcal{M}_{2\to V_8\to 3}|^2}{|\mathcal{M}_{2\to V_8\to 2}|^2} \propto g_s^2\left\{\left(1-\frac{2}{N_C^2}\right)([p_1k_1]+[p_2k_2])+\frac{2}{N_C^2}([p_1k_2]+[p_2k_1]) -\frac{1}{N_C^2}([p_1p_2]+[k_1k_2])\right\}$$

Quark-Quark:

$$\frac{|\mathcal{M}_{2\to Q_3\to 3}|^2}{|\mathcal{M}_{2\to Q_3\to 2}|^2} \propto g_s^2\left\{[p_1k_1]+[p_2k_2]+[p_1k_2]+[p_2k_1]+2([p_1p_2]+[k_1k_2])\right\}$$

$$\frac{|\mathcal{M}_{2\to Q_6\to 3}|^2}{|\mathcal{M}_{2\to Q_6\to 2}|^2} \propto g_s^2\left\{[p_1k_1]+[p_2k_2]+[p_1k_2]+[p_2k_1]-\frac{2}{5}([p_1p_2]+[k_1k_2])\right\}$$

Quark-Gluon:

$$\frac{|\mathcal{M}_{2\to Q_3^*\to 3}|^2}{|\mathcal{M}_{2\to Q_3^*\to 2}|^2} \propto g_s^2\left\{[p_1k_1]+\frac{8}{9}([p_2p_1]+[k_2k_1])-\frac{1}{9}([p_2k_1]+[k_2p_1])+\frac{1}{81}[p_2k_2]\right\}$$

$$\frac{|\mathcal{M}_{2\to Q_6^*\to 3}|^2}{|\mathcal{M}_{2\to Q_6^*\to 2}|^2} \propto g_s^2\left\{[p_1k_1]+\frac{1}{3}([p_2k_1]+[k_2p_1])+\frac{4}{15}([p_2p_1]+[k_2k_1])+\frac{1}{9}[p_2k_2]\right\}$$

Gluon-Gluon:

$$\frac{|\mathcal{M}_{2\to S_8\to 3}|^2}{|\mathcal{M}_{2\to S_8\to 2}|^2} \propto g_s^2\left\{[p_1p_2]+[k_1k_2]+\frac{1}{2}([p_1k_1]+[p_2k_1]+[p_1k_2]+[p_2k_2])\right\}$$

Cross Section Scaling

- Additional radiation scaling.
  - Radiation of gluon is sensitive to color structure at vertices.
  - Ratio of 3-jet to 2-jet rates contain information about this.
  - In general, can take ratio of n+1 jets to n-jets to understand how radiation of different processes scale.

Englert, et al PRD83 (2011) 095009, JHEP02 (2012) 030; Gerwick, Plehn, Schumann PRL108 (2012) 032003; etc.

<table>
<tr><th>Initial</th><th>Color</th><th>Spin</th><th>Type</th><th>$R_{3/2}$</th></tr>
<tr><td rowspan="10">$3\otimes 3$</td><td rowspan="4">3</td><td>0</td><td>D_3</td><td>0.41</td></tr>
<tr><td rowspan="3">1</td><td>E_3^μ</td><td>0.41</td></tr>
<tr><td>D_3^μ</td><td>0.40</td></tr>
<tr><td>U_3^μ</td><td>0.39</td></tr>
<tr><td rowspan="6">6</td><td rowspan="3">0</td><td>E_6</td><td>0.29</td></tr>
<tr><td>D_6</td><td>0.29</td></tr>
<tr><td>U_6</td><td>0.28</td></tr>
<tr><td rowspan="3">1</td><td>E_6^μ</td><td>0.29</td></tr>
<tr><td>D_6^μ</td><td>0.28</td></tr>
<tr><td>U_6^μ</td><td>0.27</td></tr>
<tr><td rowspan="2">$3\otimes 8$</td><td rowspan="2">3</td><td rowspan="2">$\frac{1}{2}$</td><td>U_3^*</td><td>0.61</td></tr>
<tr><td>D_3^*</td><td>0.59</td></tr>
<tr><td rowspan="2">$8\otimes 8$</td><td rowspan="2">8_S</td><td>0</td><td>S_8</td><td>0.69</td></tr>
<tr><td>2</td><td>T_8</td><td>0.70</td></tr>
<tr><td rowspan="2">$3\otimes \bar{3}$</td><td rowspan="2">8_A</td><td rowspan="2">1</td><td>V_8</td><td>0.27</td></tr>
<tr><td>$V_8^\pm$</td><td>0.26</td></tr>
</table>

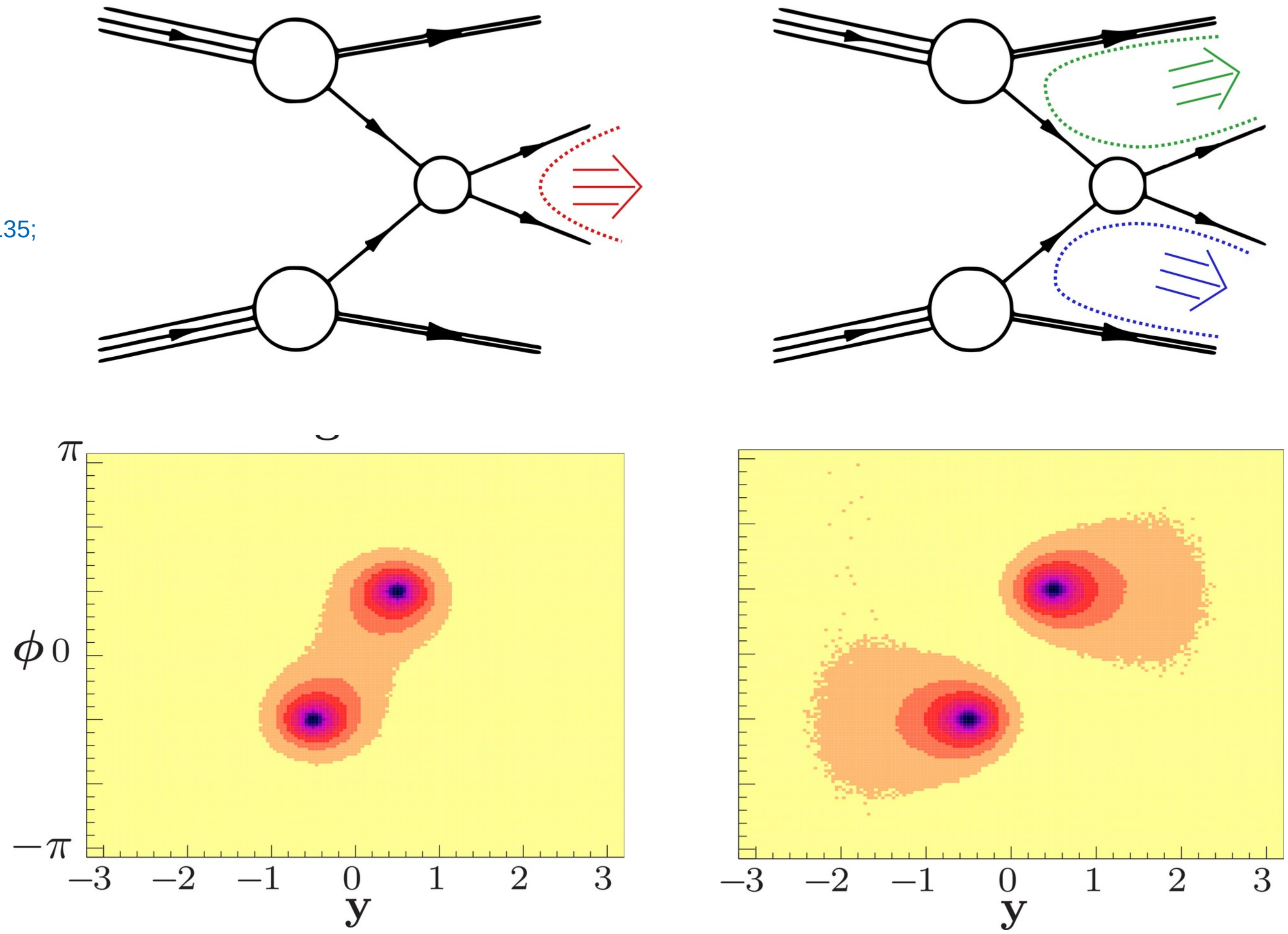
$$R_{(n+1)/n} = \frac{\sigma_{2\to n+1}}{\sigma_{2\to n}}$$

Table 2: Ratios of $2 \to 3$ resonant production cross-section over $2 \to 2$ processes at parton level with $p_T^j > 200$ GeV, $|\eta_j| < 3.0$, and $\Delta R_{jj} > 0.4$ at the 14 TeV LHC. The mass of all color resonances is set to be 3 TeV and the width is set to be 30 GeV.

Additional Color Sensitive Observables

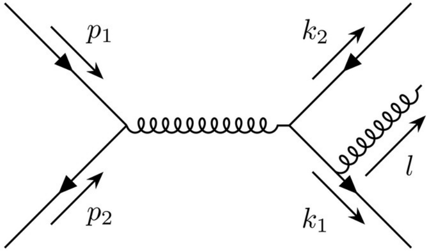
- Radiation pattern depends on color of resonance.
  - Has also been used to try to separate signal from backgrounds.
- Most work focused on singlets vs. octets.
- Past analysis often boosted the resonance.
  - Decay products closer together.
  - Radiation squeezed between the partons.
- Want to move beyond.
  - Saw radiation patterns depended on initial state and resonance color representations.
  - Look at resonance in two-to-two process without boosting.

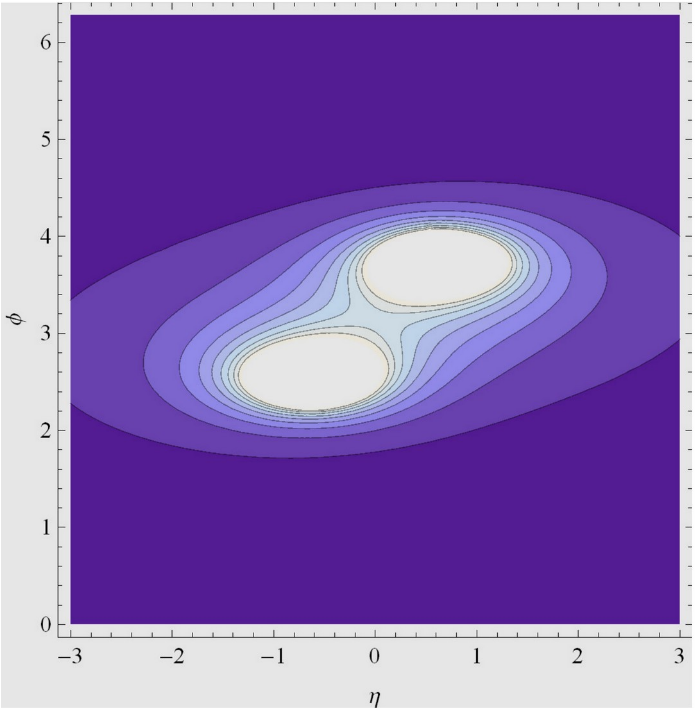
Hook, eta al JHEP04(2011) 007;
Kim, et al JHEP09 (2019) 047;
Cakroborty et al, JHEP19 (2020) 135;
Ellis et al PLB154 (1985) 435;
etc etc



Gallicchio, Schwartz, PRL105 (2010) 022001

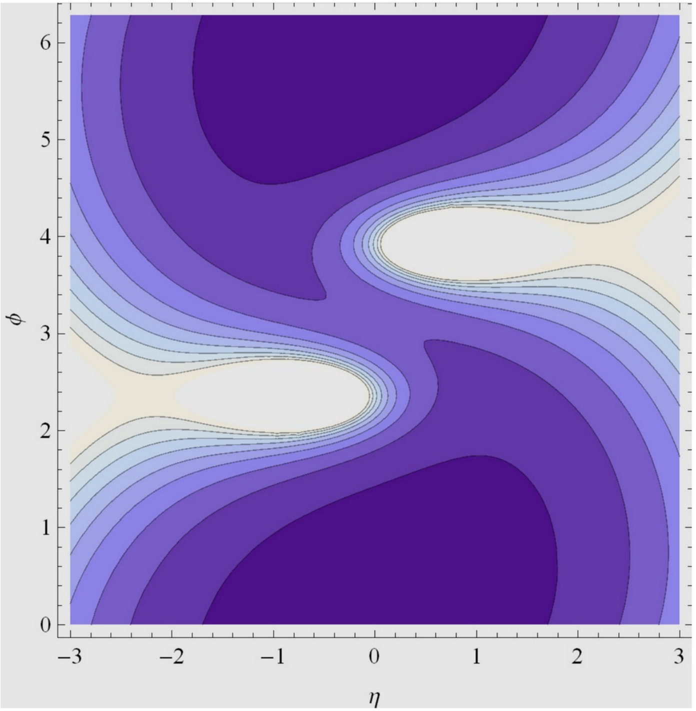
Measuring Radiation Patterns





$l_T^2[k_1\, k_2]$

Final-Final



$l_T^2[p\, k]$

Initial-Final

- Radiation between particles that are color connected.
- Create observable sensitive to regions where radiation is expected to overlap.

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Measuring Radiation Patterns

- Recall: each different resonance had a different combination of radiation patterns.
- Factor: $$[p_A p_B] = \frac{p_A \cdot p_B}{p_A \cdot l - p_B \cdot l}\left(\frac{1}{p_B \cdot l} - \frac{1}{p_A \cdot l}\right)$$

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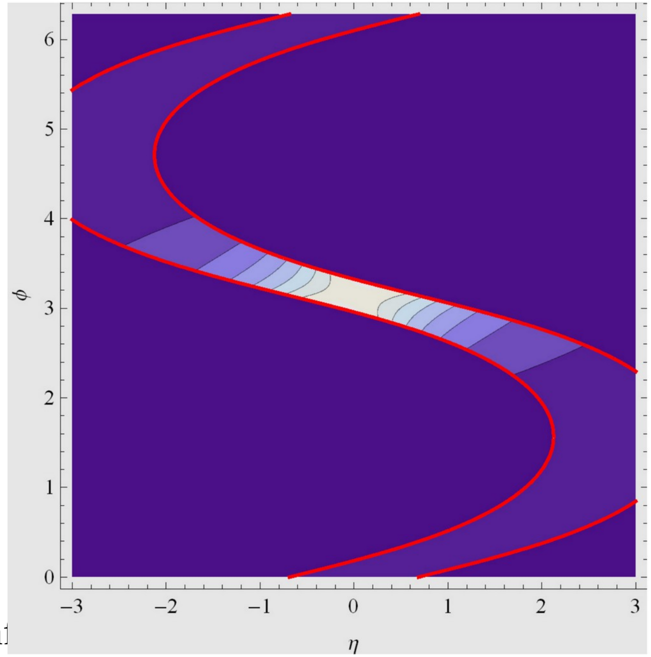
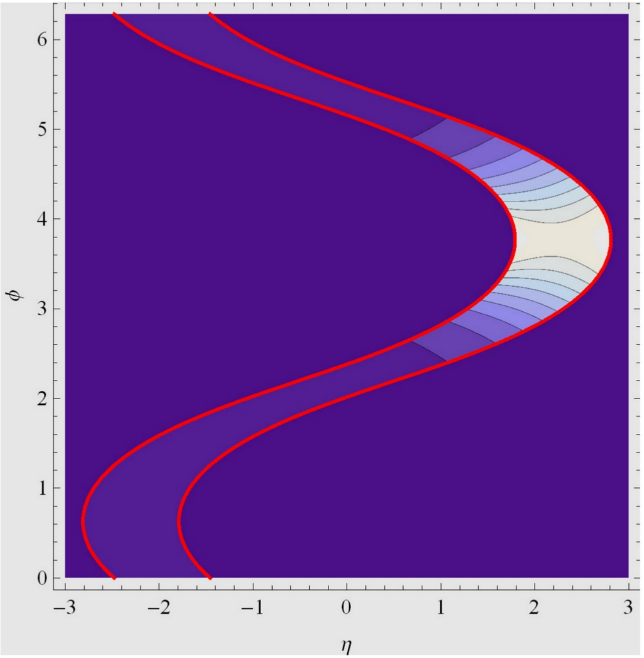
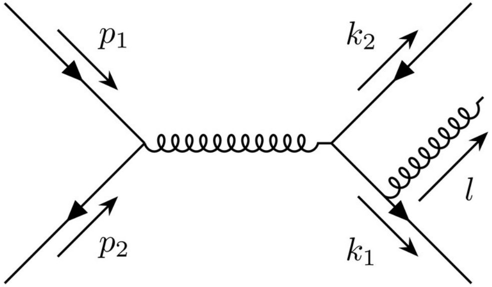
  - Parenthesis has universal soft and collinear behaviour.
- Cut on pre-factor (l_T is gluon p_T, h_T scalar sum of jet p_T): $$\frac{p_A \cdot p_B}{|p_A \cdot l - p_B \cdot l|} \geq \frac{h_T}{l_T}$$





Measuring Radiation Patterns



$$|p_A \cdot l - p_B \cdot l| \leq \frac{l_T}{h_T}\, p_A \cdot p_B$$

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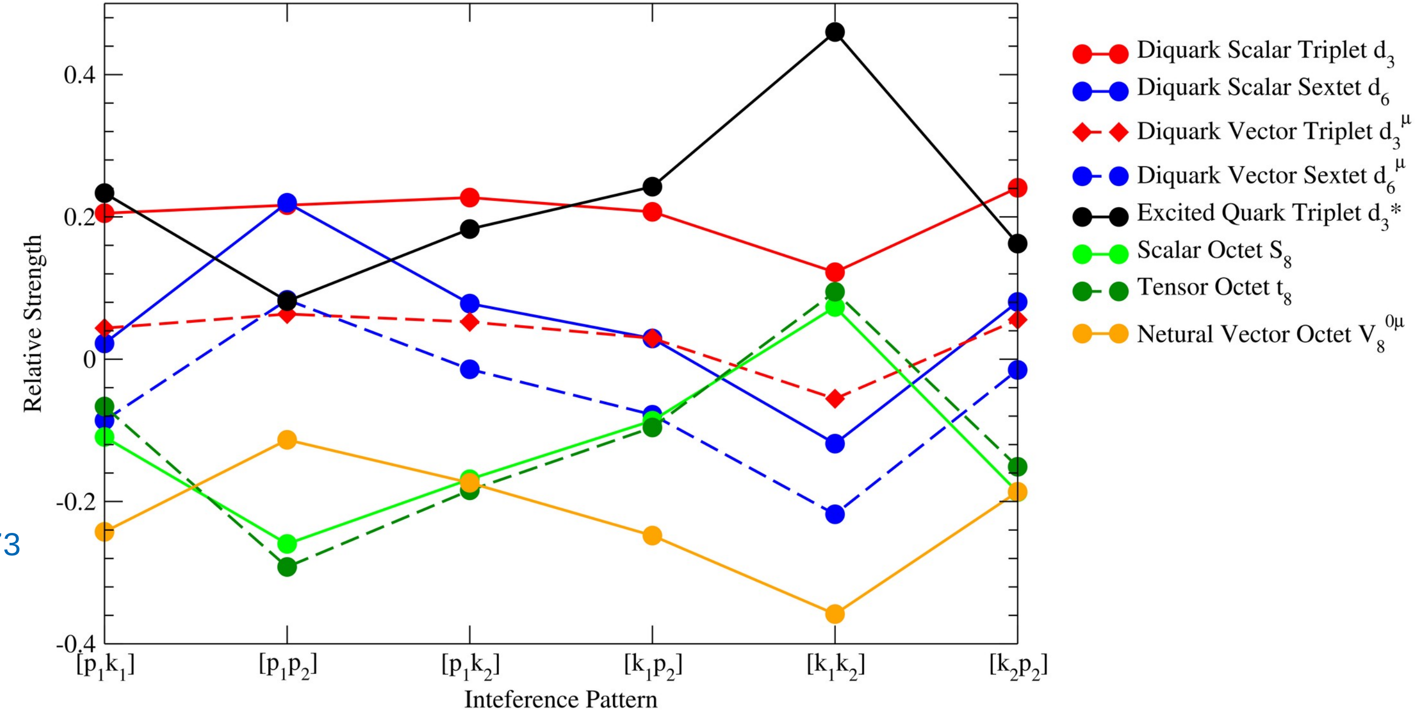
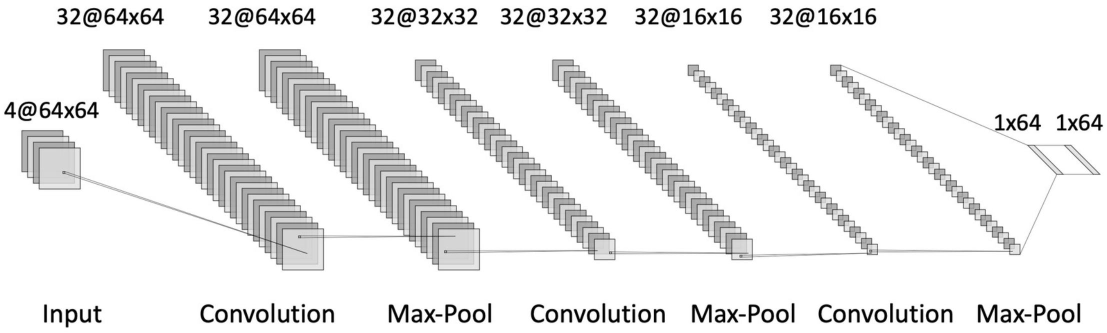
- Relative strength of different radiation patterns depend on color representation.
  - When spin and charge held constant, still have a difference.



$$p_T^{j_1} > 500\text{ GeV}, \quad p_T^{j_2, j_3} > 200\text{ GeV}, \quad \text{and}, \quad |\eta^j| < 3$$

$$p_T^{j_2} \geq 0.8\, p_T^{j_1} \quad \Delta R_{jj} > 0.4$$

Jet Images/ML



- All previous analysis parton level.
- What if we include showering and hadronization?
- Use machine learning.
  - Create three jet events.

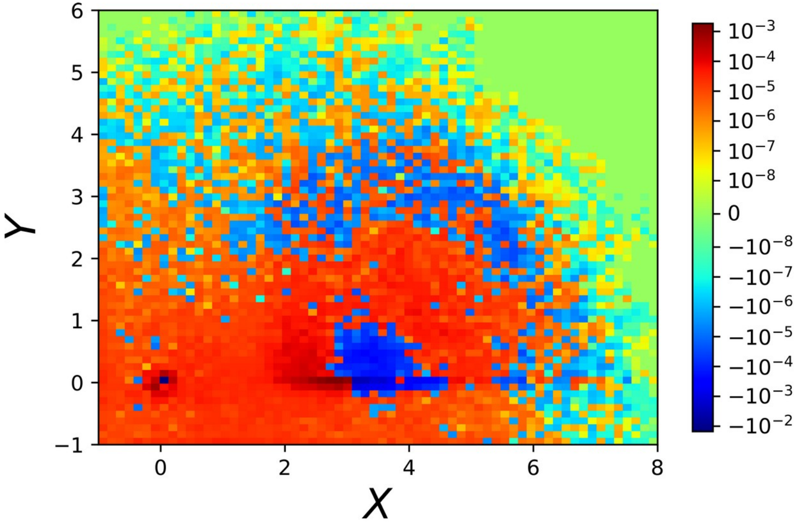
$$p\,p \to R(j) + \text{remnants} \to jjj + \text{remnants}$$

  - Generator level cuts:

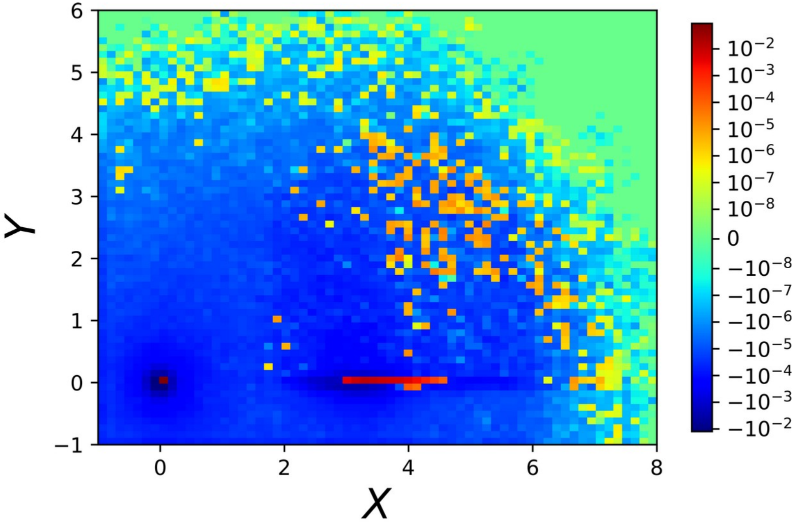
$$p_T^{j_1} > 600\ \text{GeV}, \quad p_T^{j_2} > 500\ \text{GeV}, \quad p_T^{j_3} > 100\ \text{GeV}, \quad \text{and} \quad |\,\eta_j\,| < 3,$$

- Run through Pythia8 for parton showering and hadronization.
- Cluster jets using anti-kT algorithm with R=0.4
- Include all jets with $p_T^j > 100\ \text{GeV and } |\eta_j| < 3$

Pre-Processing



(a) V_1 - V_8



(b) V_1 - S_8

- Consider three hardest jets.
  - Jet that is furthest away from other two is out of origin.
  - From the two remaining, hardest is along X-axis
  - Third jet flipped to first quadrant.

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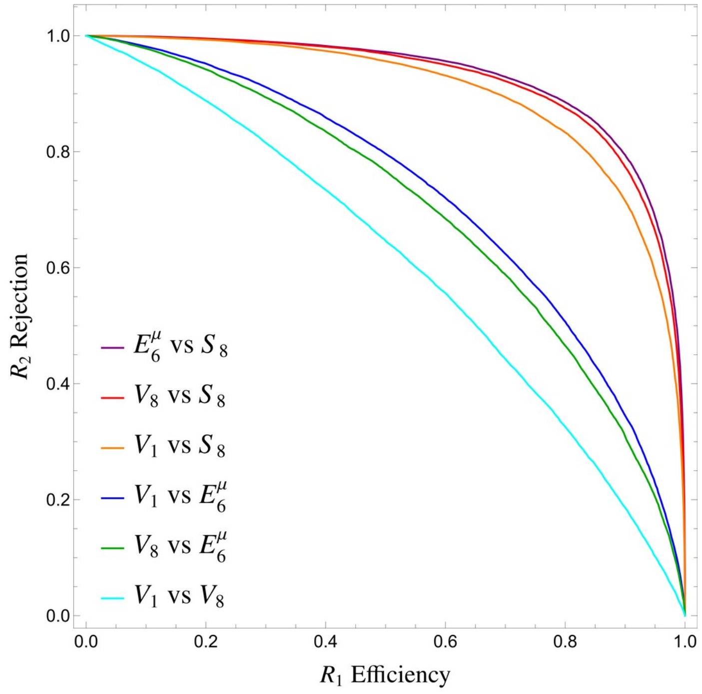
Results

- Used a Convolutional Neural Network.
  - Trained to distinguish different resonances.
- Considered four input channels:
  - Transverse momentum of positively charged particles
  - Transverse momentum of negatively charged particles
  - Transverse momentum of neutral particles
  - Charged-particle multiplicity



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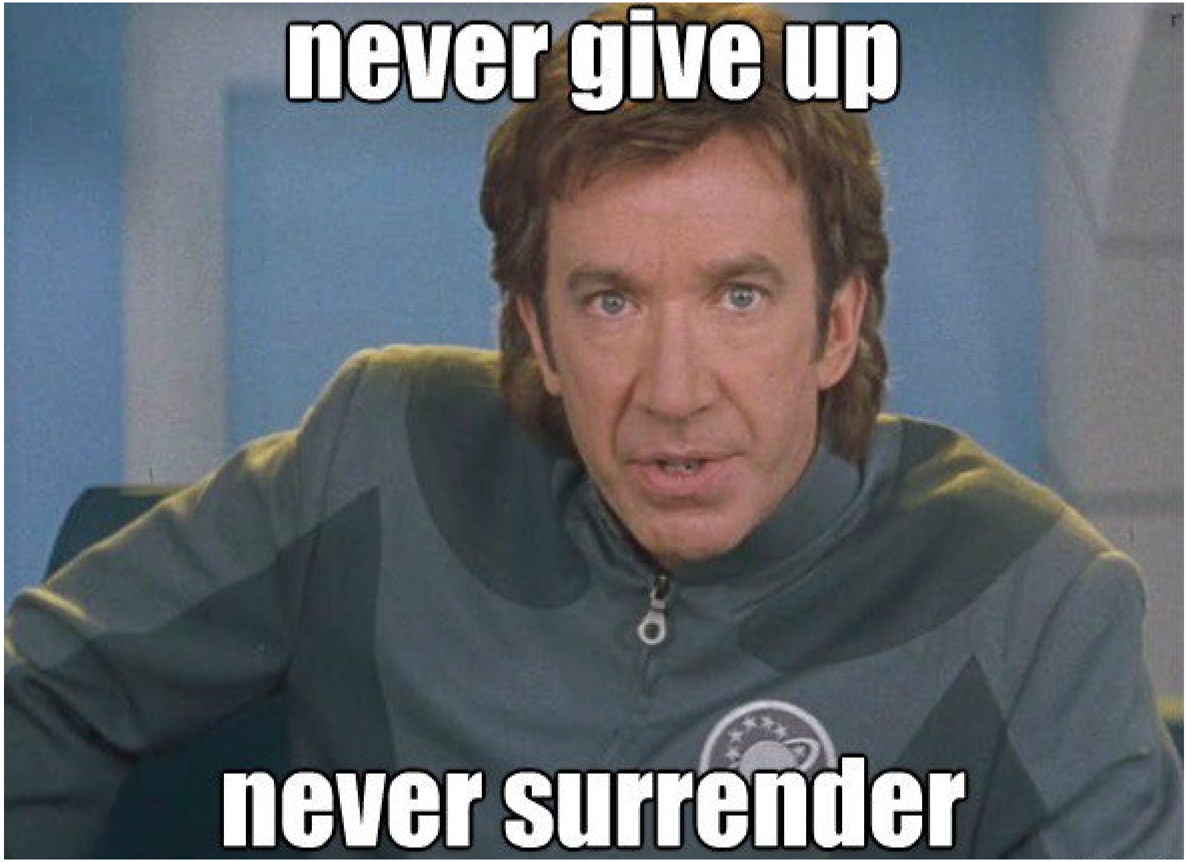
R_2 efficiency (%) at 50% R_1 acceptance	$R_2 : V_1\ (u\bar{u})$	$R_2 : V_8\ (u\bar{u})$	$R_2 : E_6^\mu\ (uu)$	$R_2 : S_8\ (gg)$
$R_1 : V_1\ (u\bar{u})$	50%	35%	20%	4.4%
$R_1 : V_8\ (u\bar{u})$	35%	50%	23%	3.1%
$R_1 : E_6^\mu\ (uu)$	20%	23%	50%	2.8%
$R_1 : S_8\ (gg)$	2.8%	1.8%	1.4%	50%

Conclusions

- Hadron colliders are QCD machines:
  - (Most) initial states are colored partons.
- Dijet resonances are the most natural things to search for.
- Categorized the possible quantum numbers of the dijet resonances.
- Gave a roadmap for measuring properties of dijets.
  - Coupling to partons: rapidity distributions/tagging light jets.
  - Spin: Angular distributions.
  - Color representation:
    - Ratio of cross section of process with additional raditiation to base resonance process.
    - Developed an observable sensitive to different radiation patterns beyond singlet vs. octet.
    - Looked at ability to distinguish via machine learning techniques

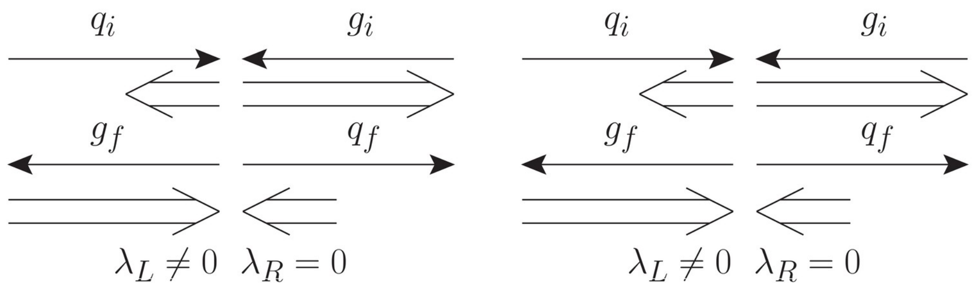
Thank You



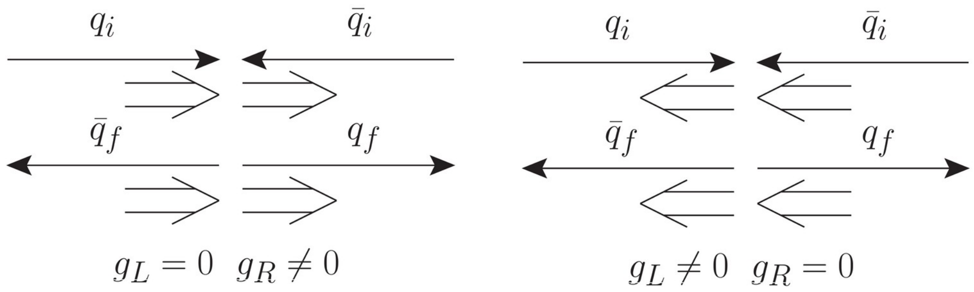
Spin

- Spin correlations.
  - Depending on chiral couplings, get different spin correlations.
  - Can measure with angular distributions.

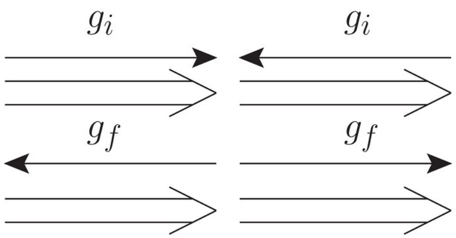
Quark-Gluon
Spin 1/2:



Quark-Antiquark
Spin 1:



Gluon-Gluon
Spin 2:



Gluon-Gluon
Spin 0: