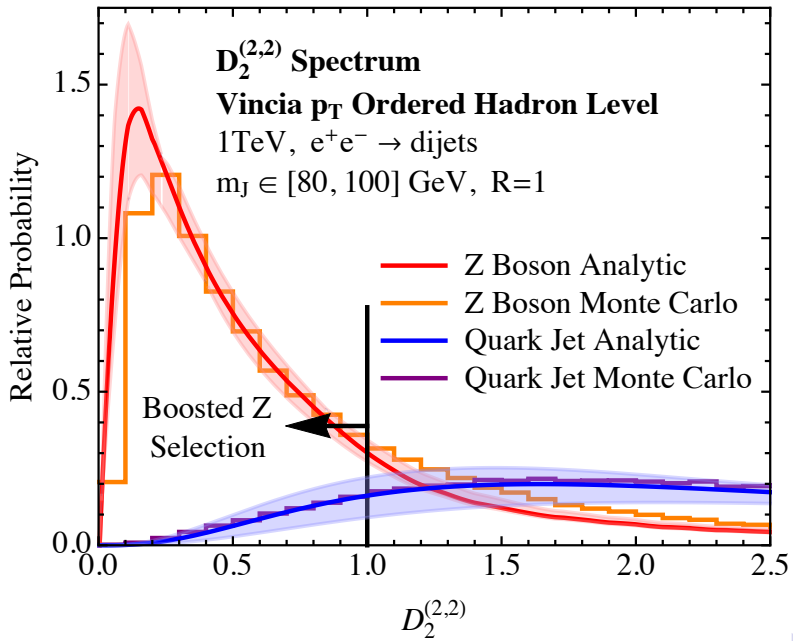
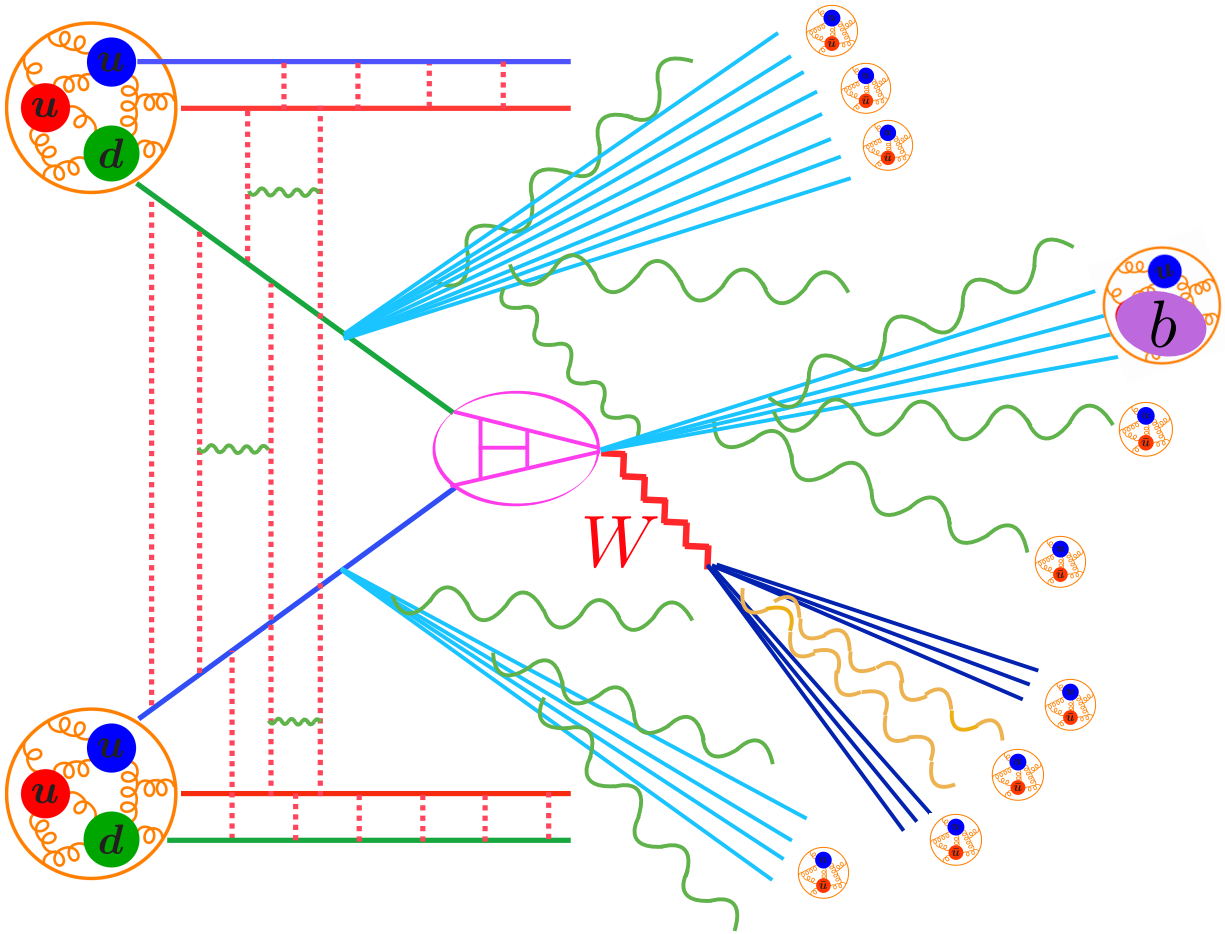
Jet Substructure: QCD as a Window into Underlying Dynamics at the LHC

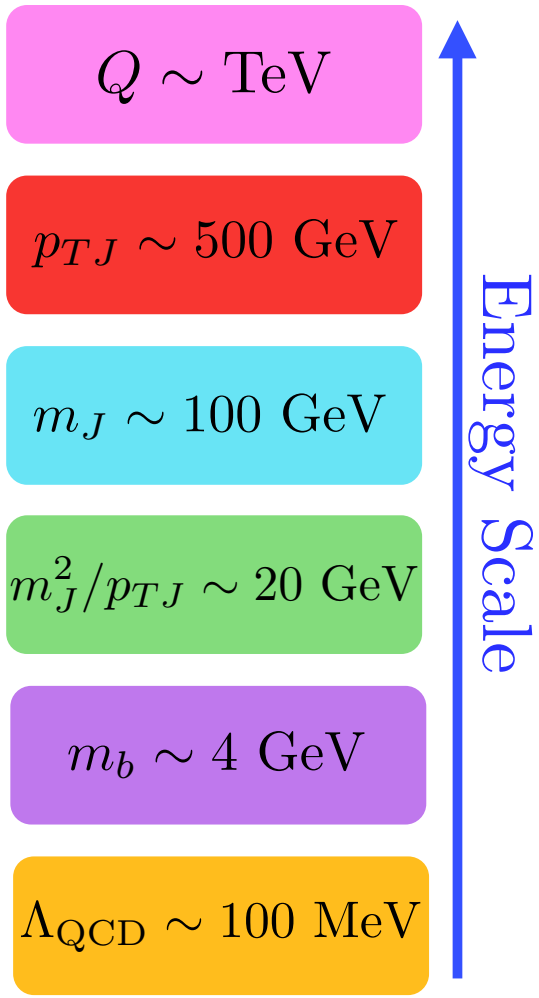
Ian Moult



QCD at the LHC

- Very complicated structure!

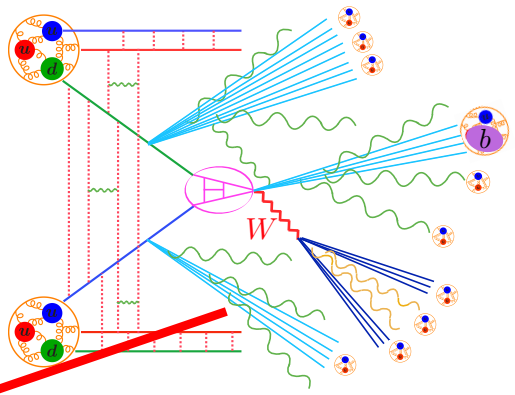




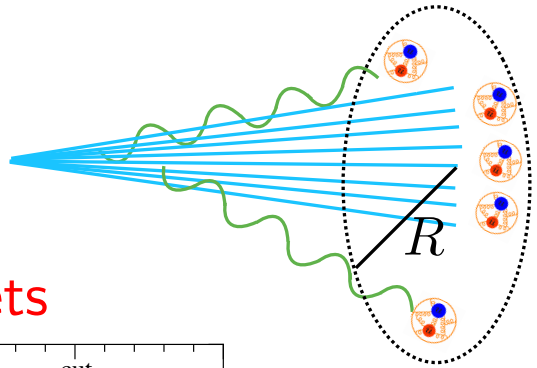
- Dominated by QCD!

Recent Progress

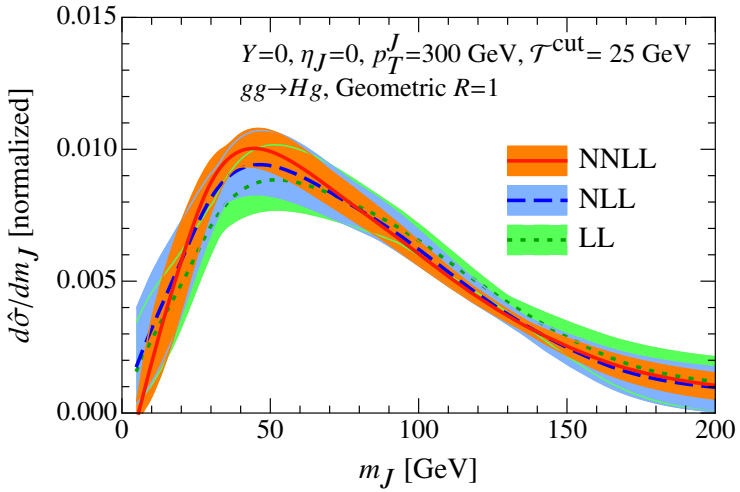
- Significant recent progress in description of more complex final states.
  - Dynamics of QCD radiation.
  - Measure properties of individual jets.



$$m_J^2 = \sum_{i,j \in J} p_i \cdot p_j$$

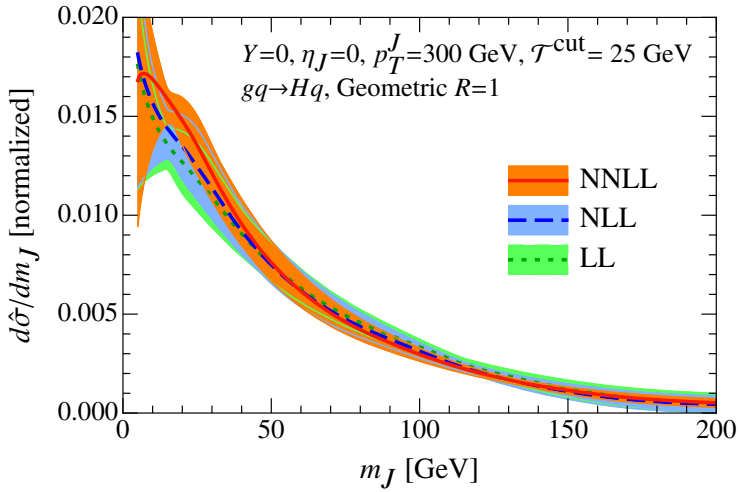


Gluon Jets



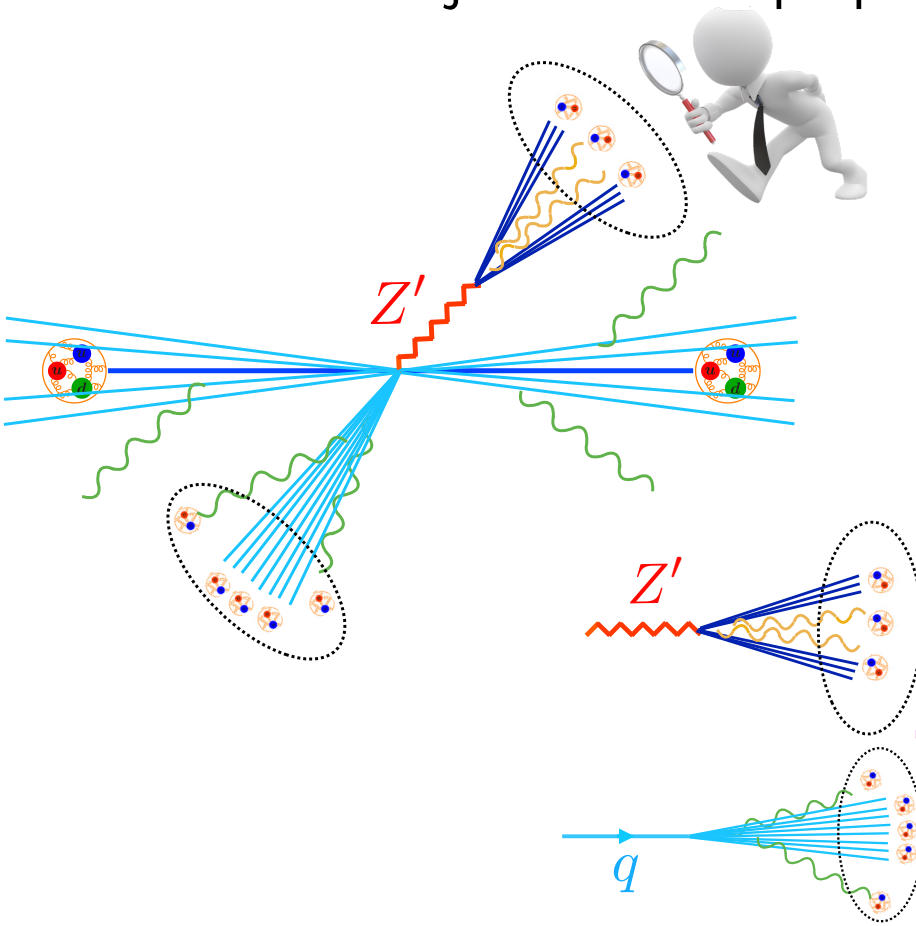
[Jouttenus, Stewart, Tackmann, Waalewijn]

Quark Jets



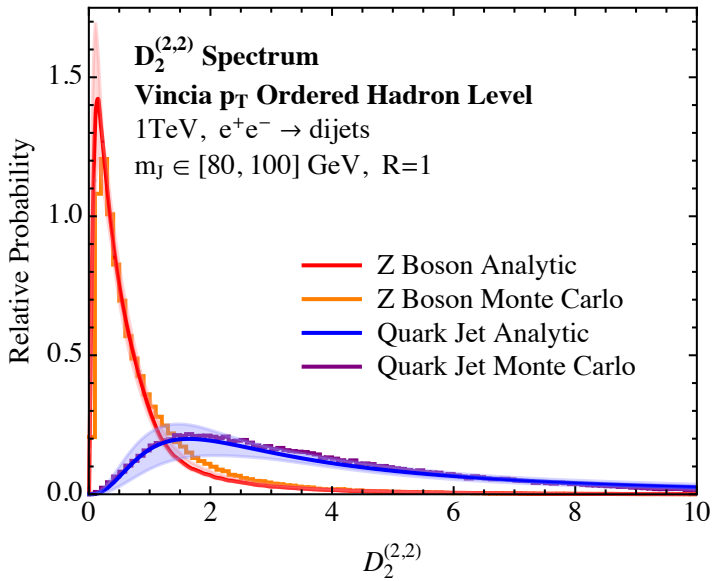
Jet Substructure

- Radiation in jets encodes properties of underlying hard scattering.



$D_2,\ N_2,\ M_2,\ \cdots$

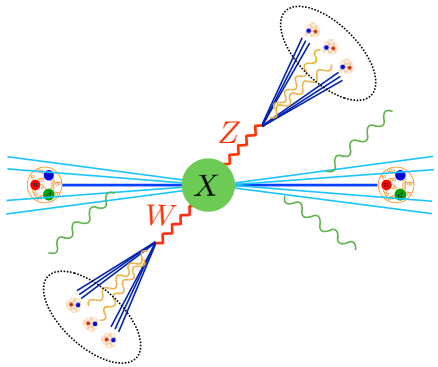
Substructure Observable

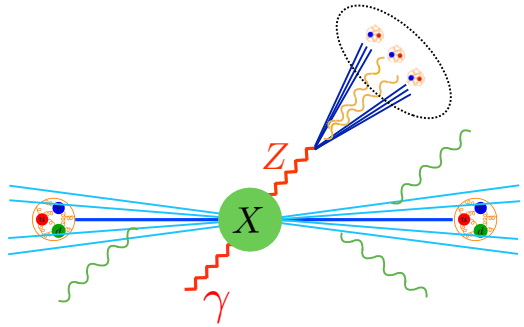


- Jet substructure: measure properties (charge, energy, etc) of radiation in a jet to extract information about its origin.

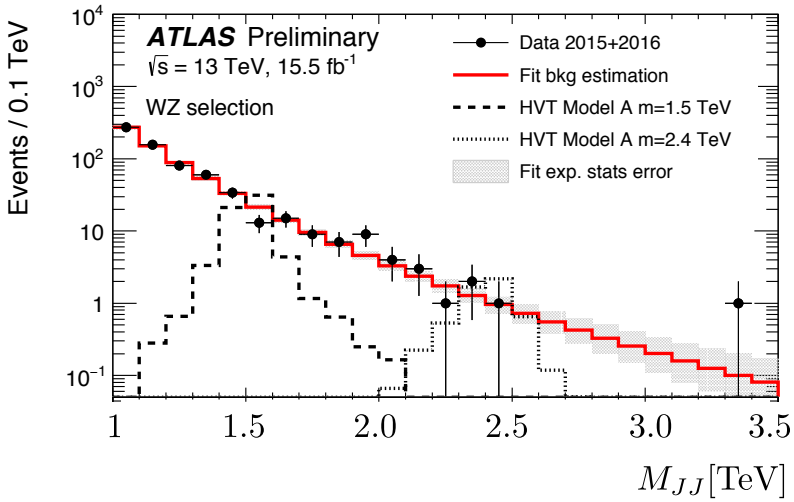
Applications: High Mass Resonances

- Particular interest in possibility of high mass resonances decaying to dibosons: WW, WZ, HZ, $\gamma\gamma$, γZ, $\cdots$

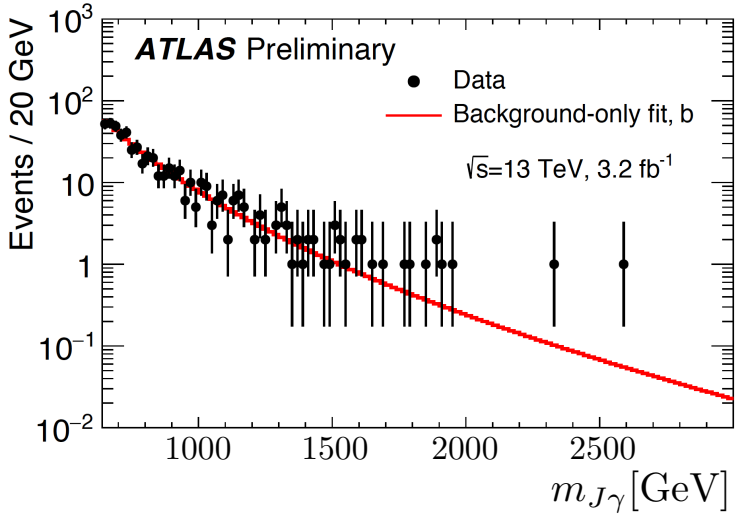




WZ Diboson Invariant Mass

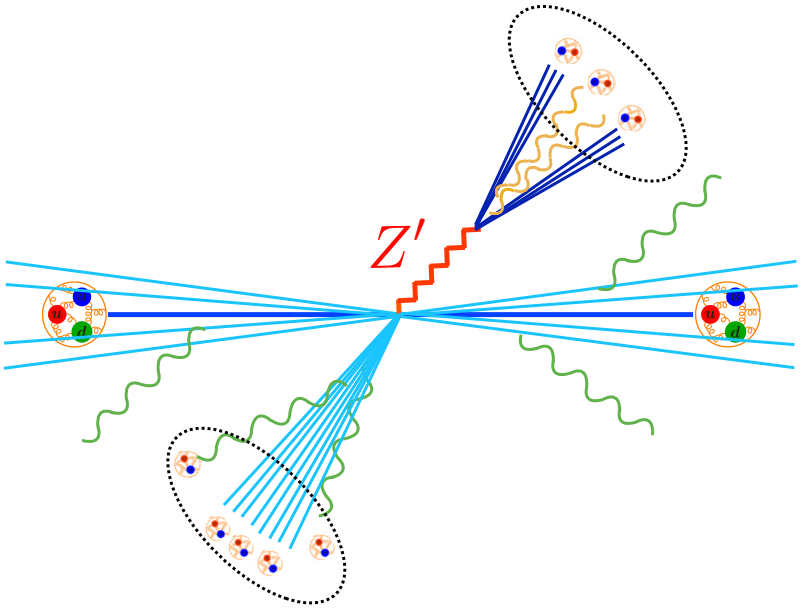


$Z\gamma$ Diboson Invariant Mass



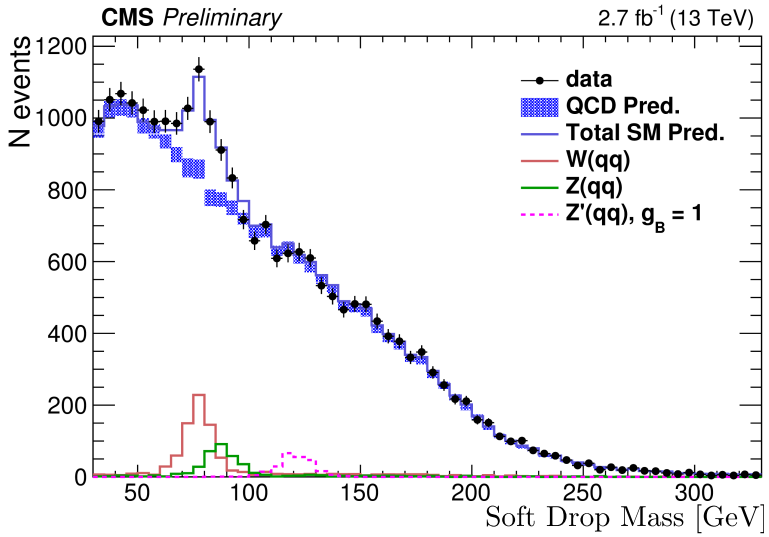
Applications: Low Mass Searches

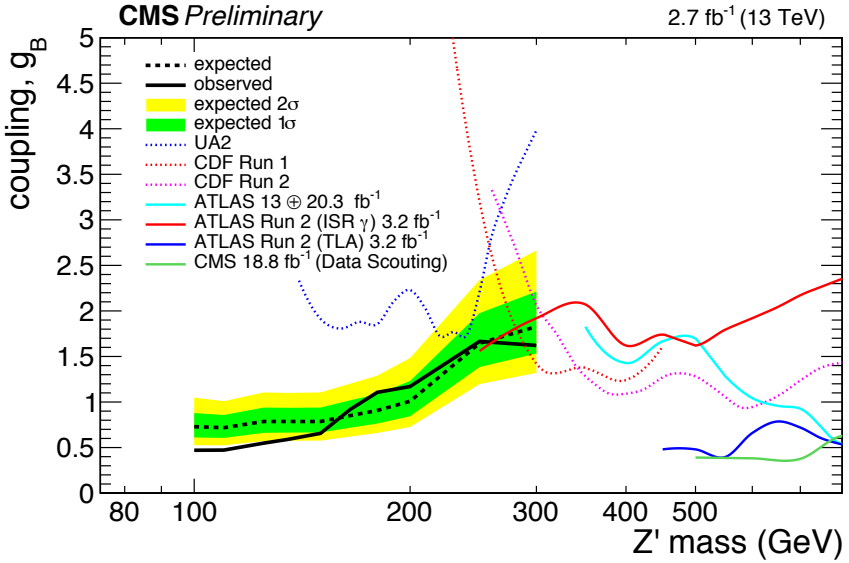
- Low mass Z' search in dijet channel.



- Find $Z' = Z/W$!

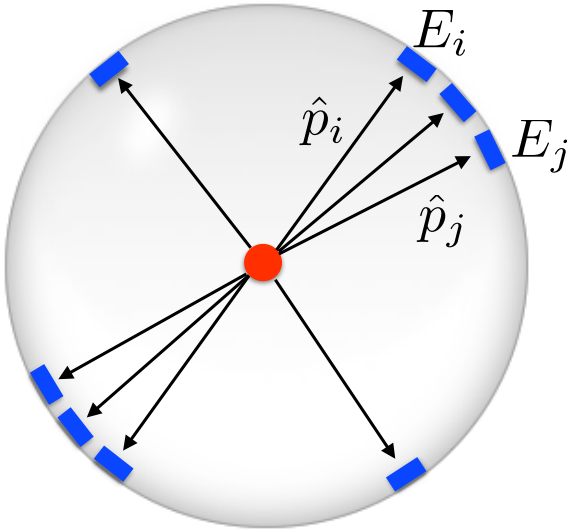
Mass Spectrum





Back to Basics: Designing an Observable

- Measure correlations of energies and angles.



$$F_N(P) = \sum E_{i_1} \cdots E_{i_N} f_N(\hat{p}_{i_1}, \cdots, \hat{p}_{i_N})$$

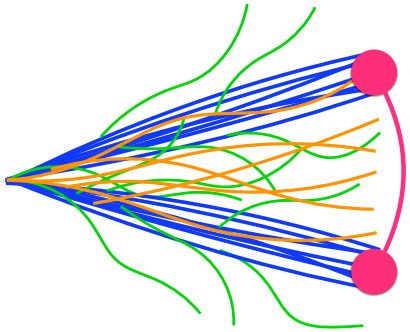
- Linear in the energies by IRC safety.
- f_N is symmetric, and $f_N \to 0$ if $\hat{p}_i || \hat{p}_j$

- Simple theoretical structure $\Longrightarrow$ Can calculate!

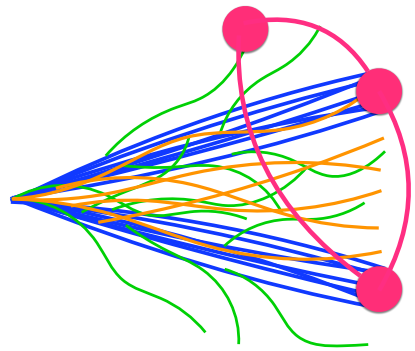
Choosing an Observable

- Measure correlations of energy and angles:
  [Larkoski, Salam, Thaler] [IM, Necib, Thaler]

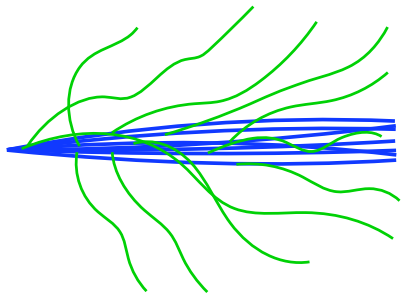
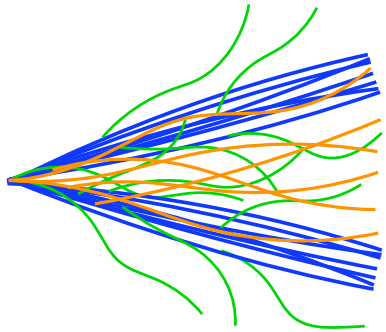
$$e_2^{(\beta)} = \frac{1}{p_{TJ}^2} \sum_{i<j\in J} p_{Ti} p_{Tj} R_{ij}^{\beta}$$



$$e_3^{(\beta)} = \frac{1}{p_{TJ}^3} \sum_{i<j<k\in J} p_{Ti} p_{Tj} p_{Tk}\, R_{ij}^{\beta}\, R_{ik}^{\beta}\, R_{jk}^{\beta}$$



$$R_{ij} = \sqrt{\Delta y_{ij}^2 + \Delta\phi_{ij}^2}$$

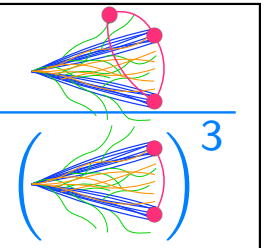
- Use to distinguish  from 

D_2

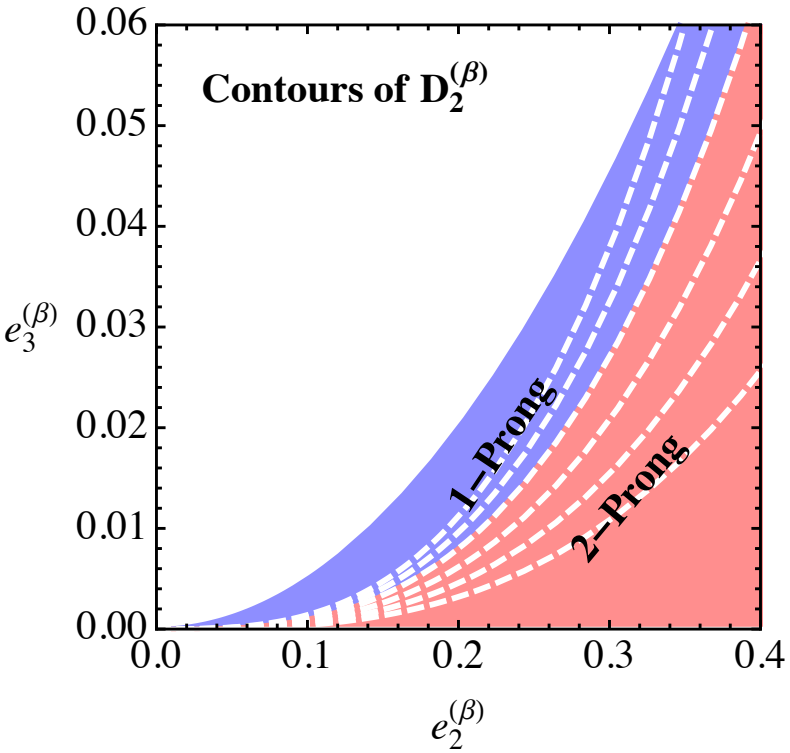
[Larkoski, IM, Neill]

- Define the discriminant

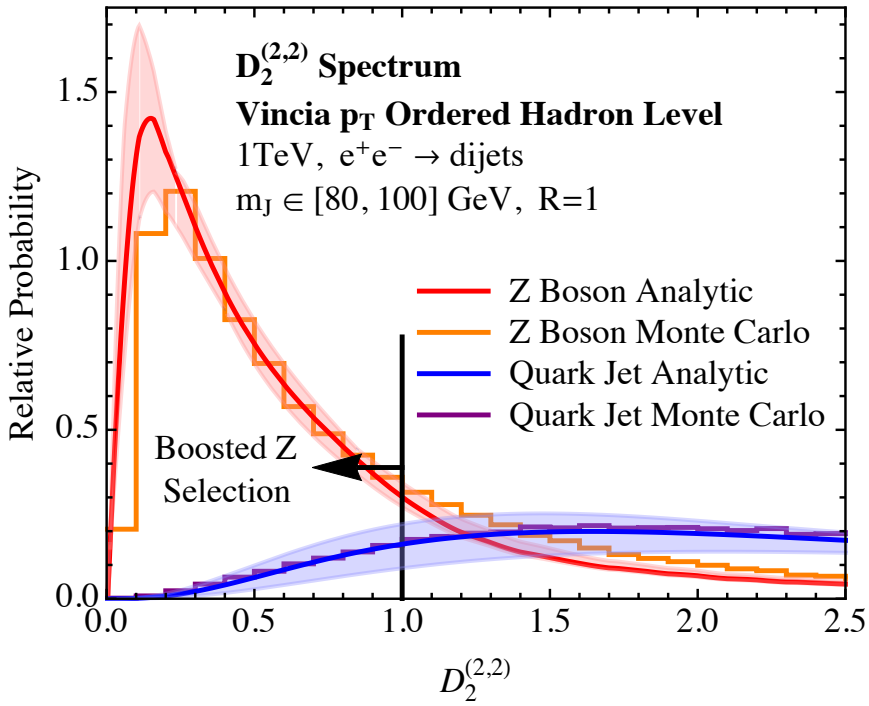
$$D_2^{(\beta)} = \frac{e_3^{(\beta)}}{\left(e_2^{(\beta)}\right)^3} =$$



$\left(e_2^{(\beta)}, e_3^{(\beta)}\right)$ Phase Space



D_2 Spectrum

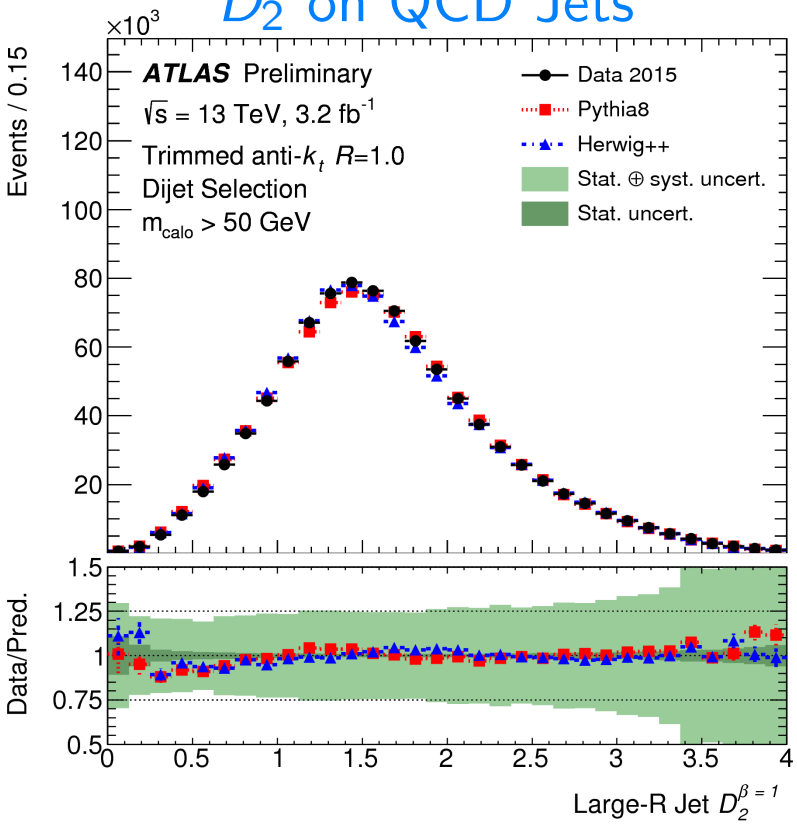


- Measures how "two-prong like" a jet is.

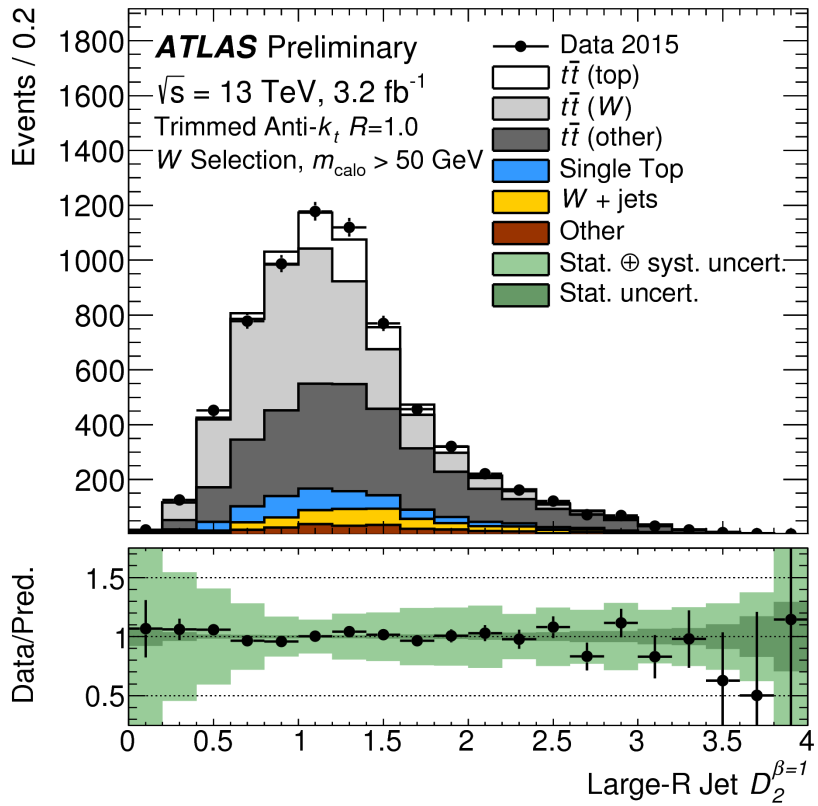
The Shape of Jets at the LHC: D_2

- D_2 measured at the 13 TeV LHC for both signal and background jets.
- Used in many recent interesting searches.

D_2 on QCD Jets



D_2 on W Jets

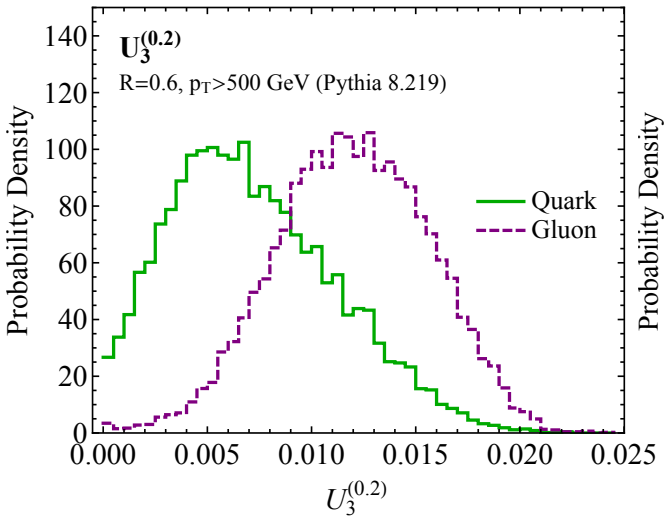


The Shape of Jets at the LHC

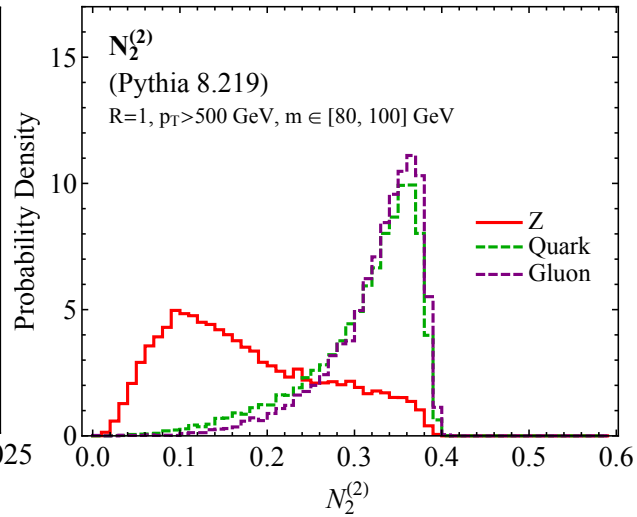
[IM, Necib, Thaler]

- Can design a variety of different observables: D_2, N_2, M_2, U_3, N_3, $\cdots$
- All take advantage of radiation pattern to probe the underlying hard interaction.

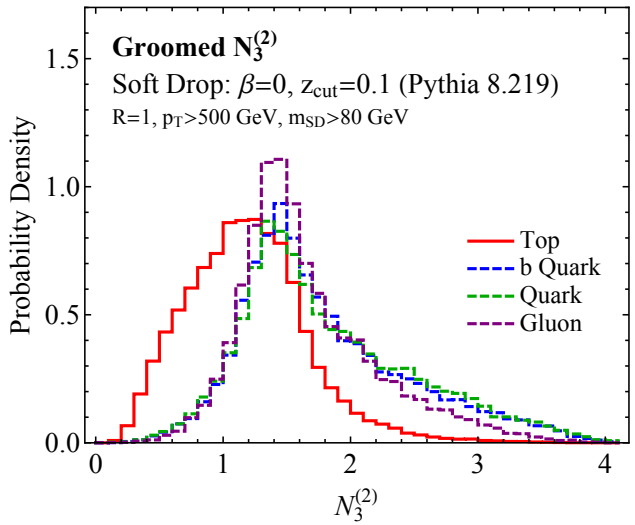
Quark vs. Gluon



$W/Z/H$ Tagging



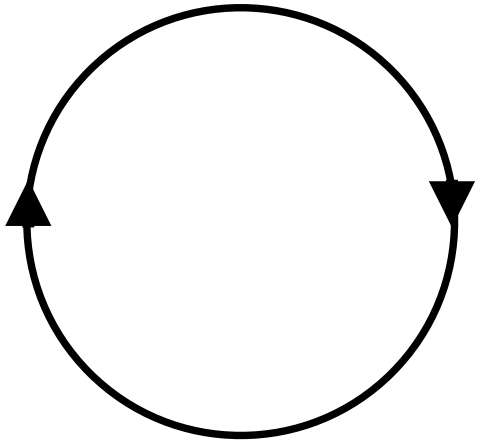
Top Tagging



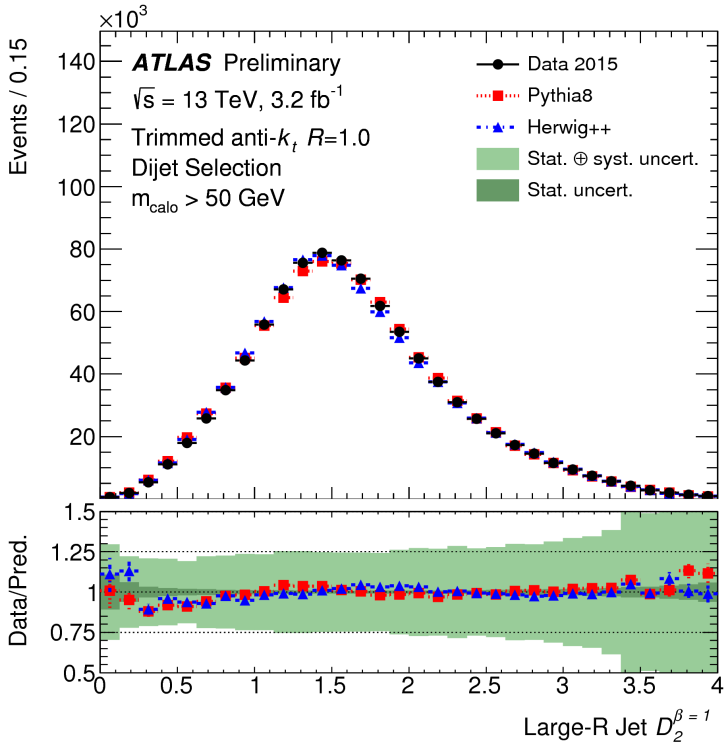
Jet Substructure for Understanding QCD

- Above results rely on a detailed understanding of QCD.
- ALL examples above are based on insights from explicit calculations.
- Driving understanding of structure of QCD in extreme limits.

More Sophisticated Calculations



More Sophisticated Techniques

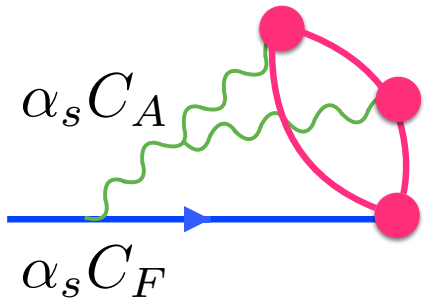


D_2: Strange Perturbative Behavior

[Larkoski, IM, Neill]

- D_2 CANNOT be computed in standard perturbation theory.
- Calculation requires understanding of all order structure of perturbation theory.
- D_2 is first non-zero with two emission, but starts at α_s:

$$\frac{d\sigma}{dD_2} \propto \frac{\alpha_s C_F}{\pi} \frac{e^{-\frac{\alpha_s}{\pi}\frac{C_A}{2}\log^2 D_2}}{D_2}$$
$$\propto \frac{\alpha_s C_F}{\pi} \frac{1}{D_2} + \cdots$$

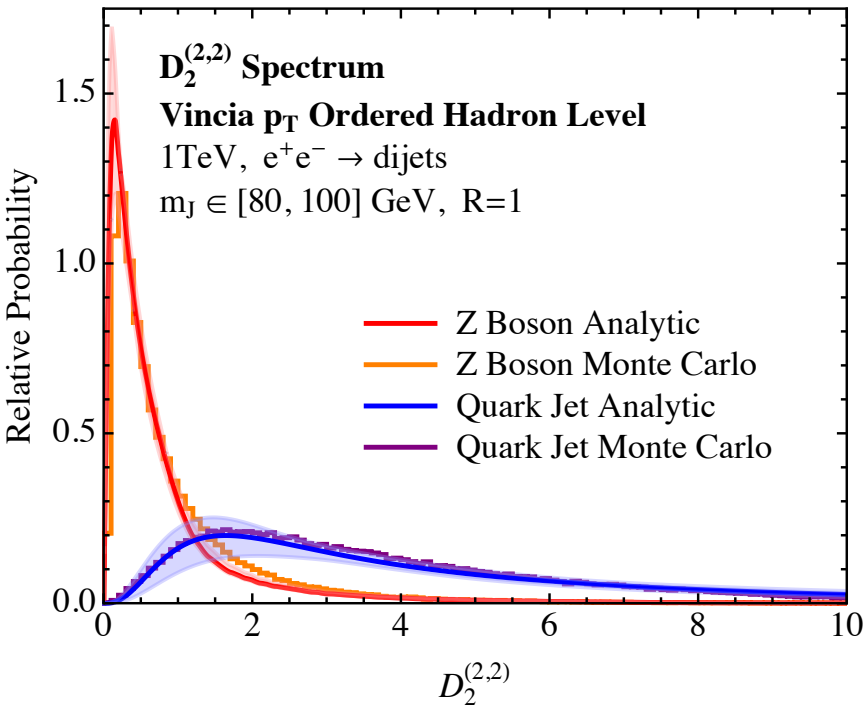


D_2: Analytic Results

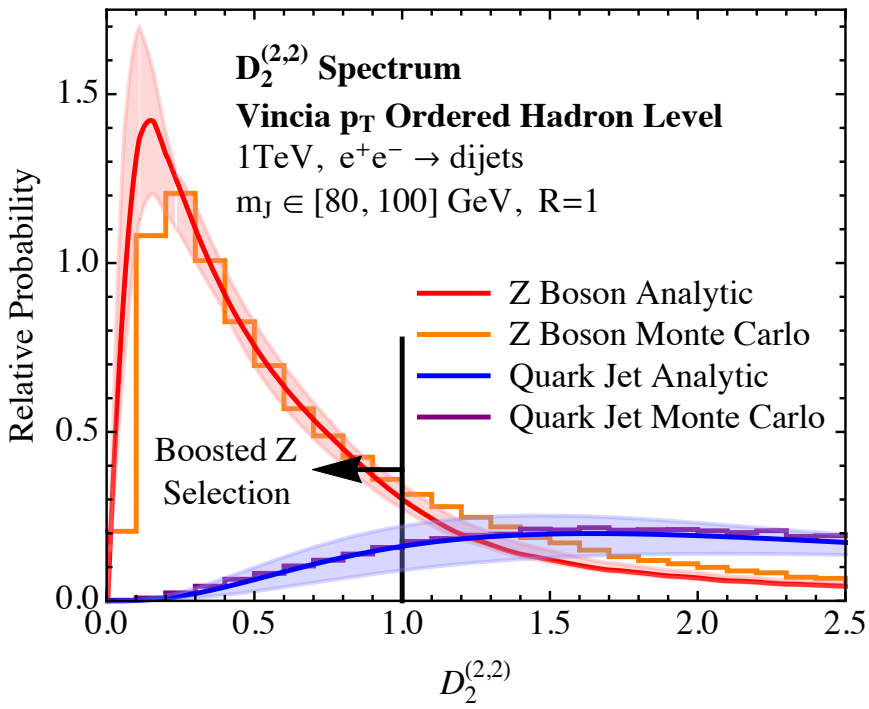
[Larkoski, IM, Neill]

- Newly developed techniques can be used to compute D_2 and understand its behavior analytically.
- Essential for optimizing reach of LHC measurements.

D_2 Spectrum

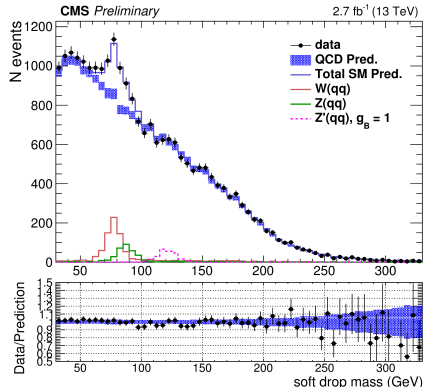


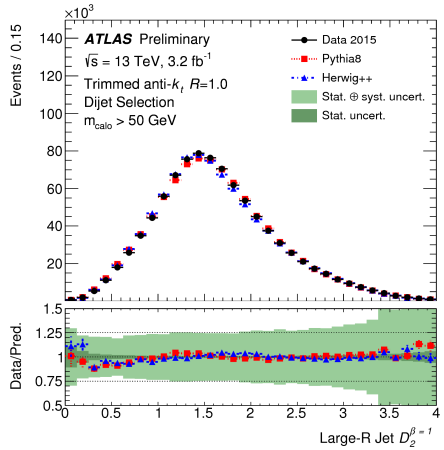
D_2 Spectrum (zoom)

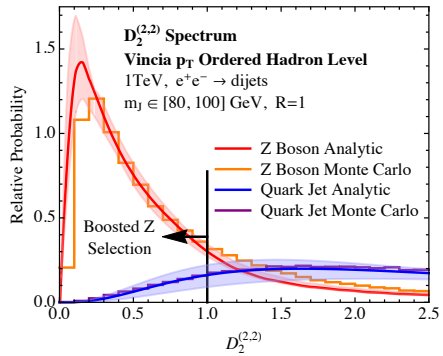


Conclusions

- Jets and jet substructure are playing a central role at the LHC.
- Can measure in a theoretically well understood way the "shape" of jets.
- New approaches are required to understand, calculate, and improve our ability to probe physics using QCD.







Thanks!