Jet Substructure at the LHC: New Observables and New Calculations

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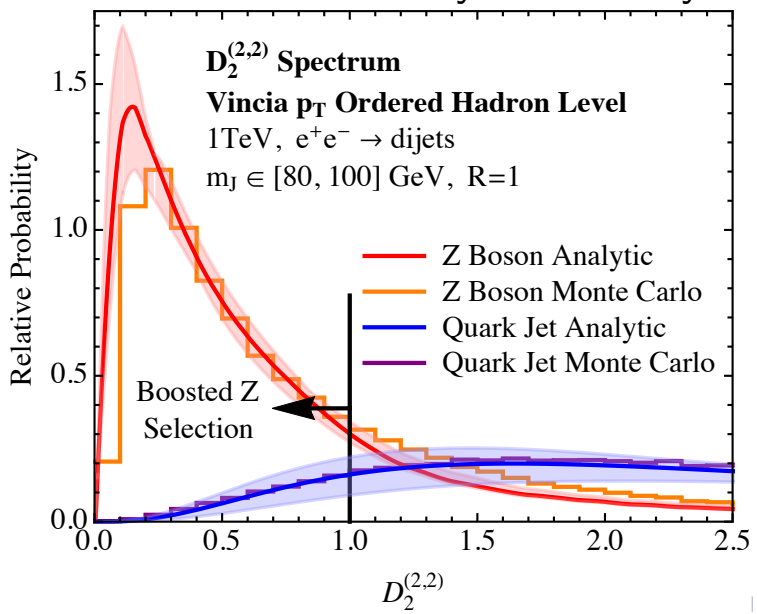
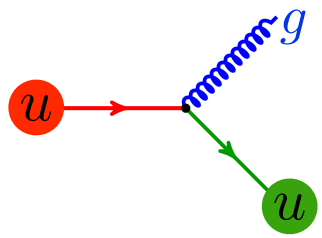


QCD

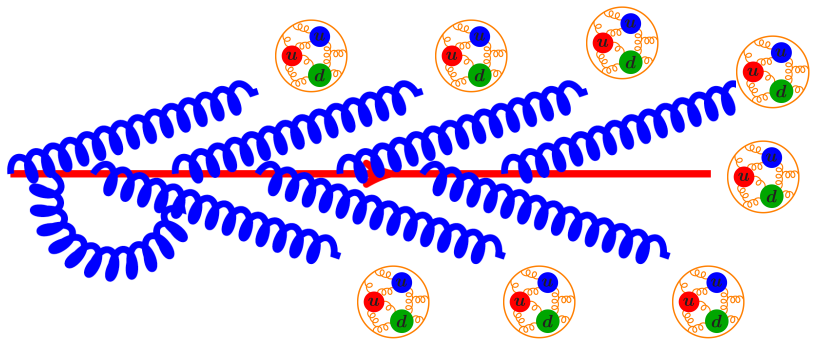
- QCD is an $SU(3)$ gauge theory:

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu a} + \sum_f \bar{q}_f (i \not{D} - m_f) q_f$$



- Microscopic degrees of freedom are quarks and gluons.

- In scattering experiments we observe collimated sprays of hadrons, called jets:

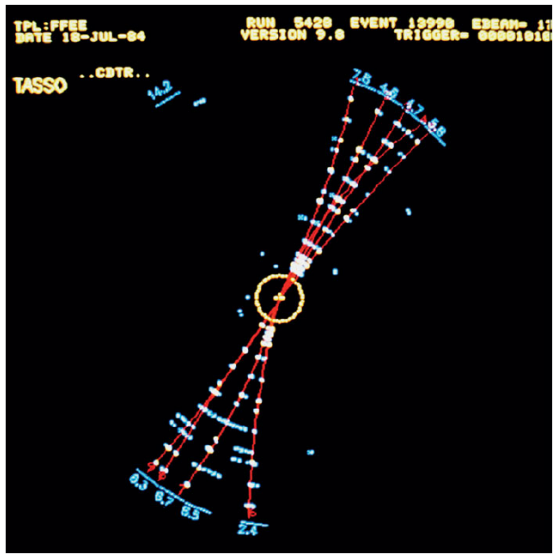


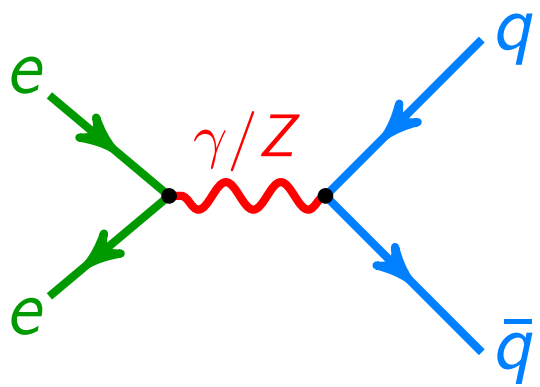
- Jets act as proxies for quarks and gluons.
- Jets are our probe of the underlying microscopic dynamics.

Jets at PETRA

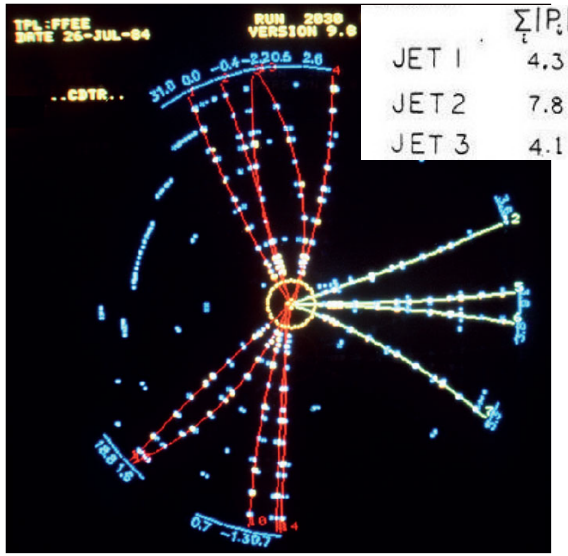
- Kinematics of jets used to infer gluon emission in hard scattering.

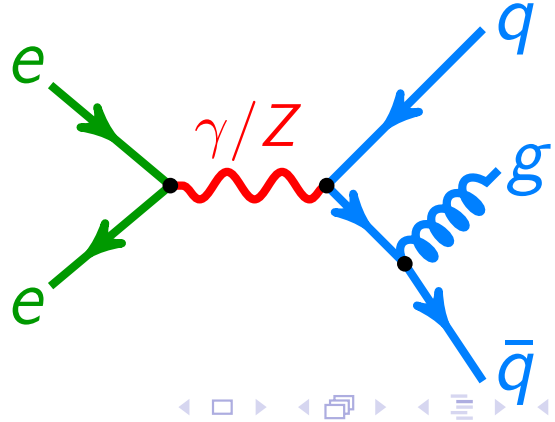
2-Jet Event





3-Jet Event

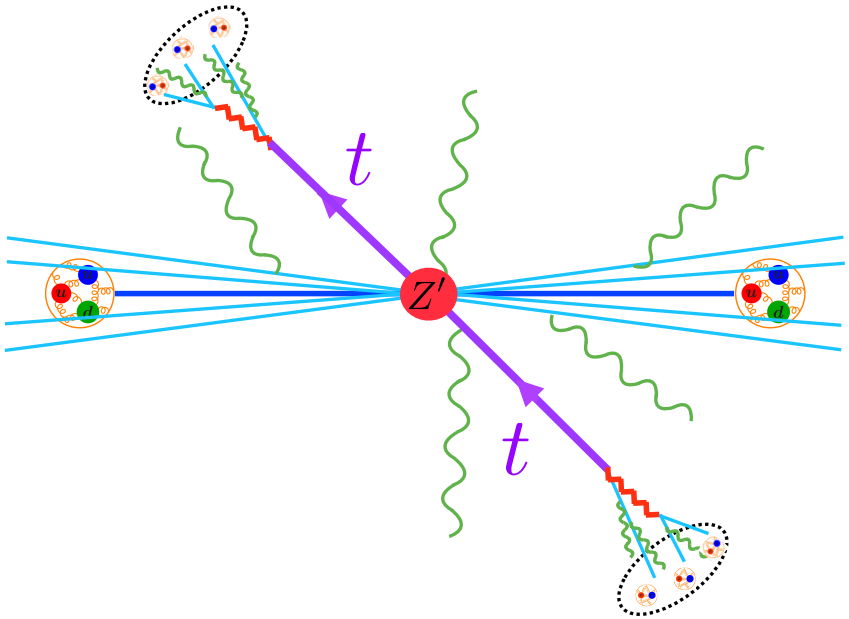




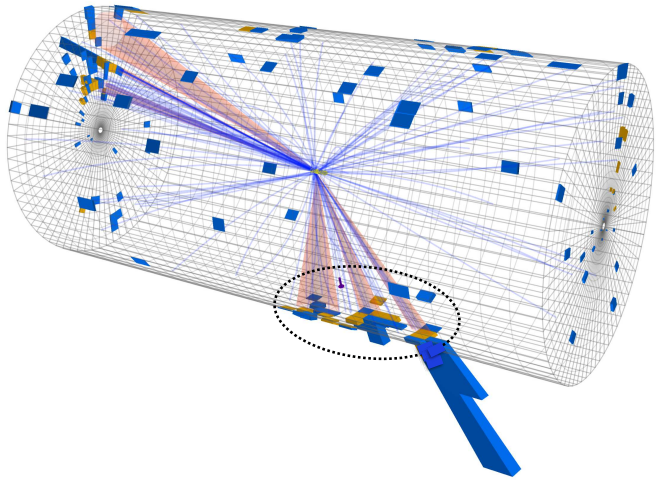
Jets at the LHC: Internal Structure

- Internal structure of jets resolved due to excellent detector resolution.
- Electroweak scale objects, $W/Z/H$ or t can have sufficiently high p_T to appear inside a jet.

Boosted Tops



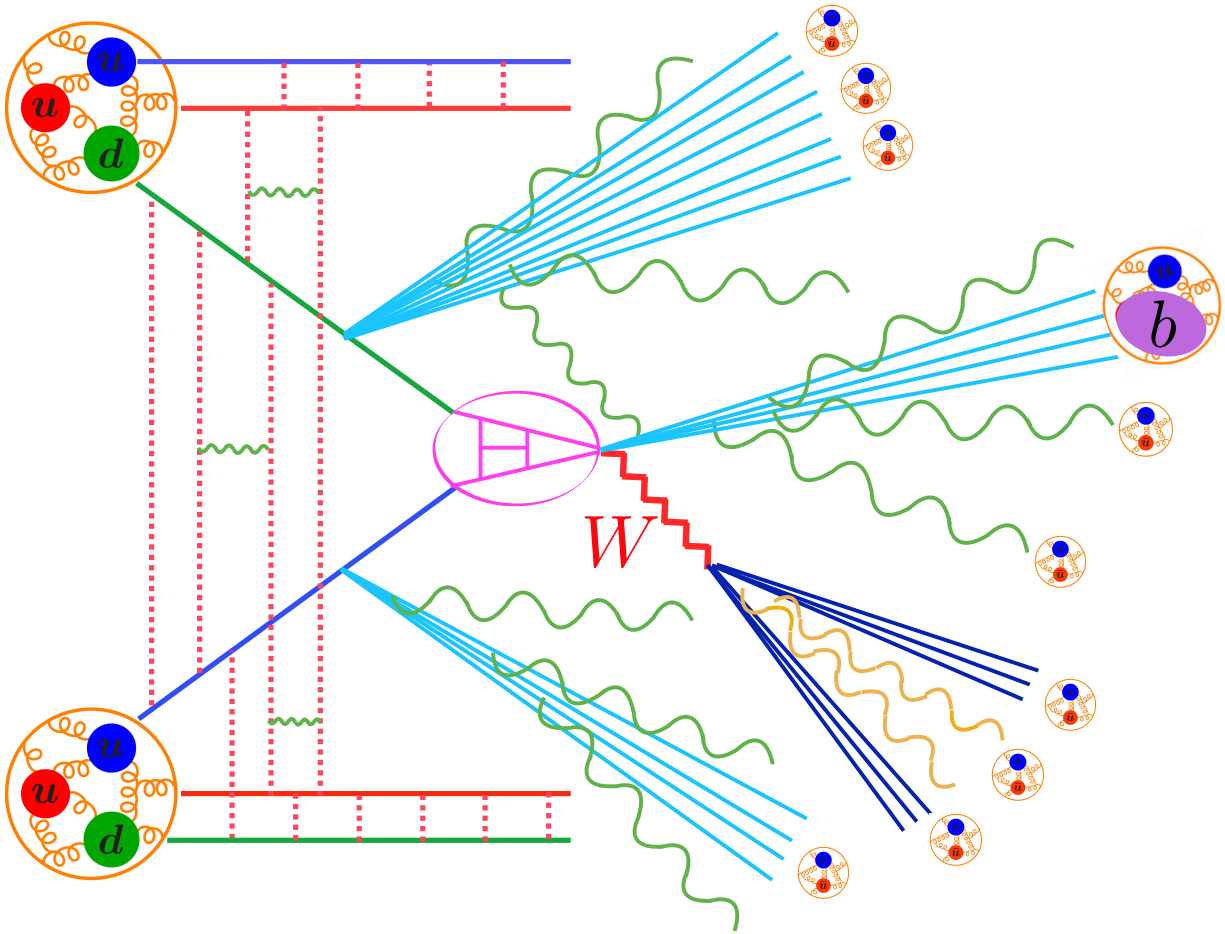
Event Display

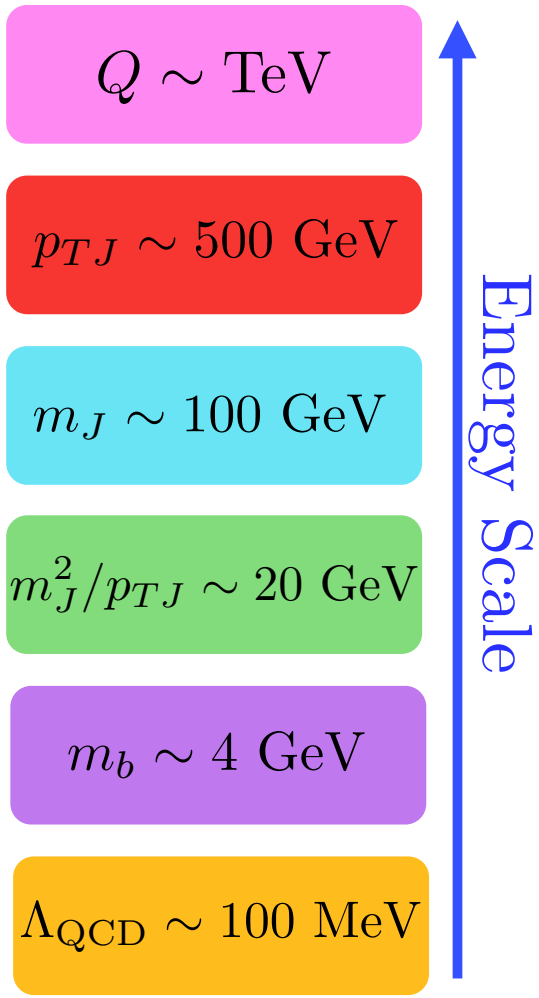


- Revolutionizes the types of questions we can/must ask about jets:
  $\Longrightarrow$ jets have substructure!

A Theorists View

- Very complicated structure!



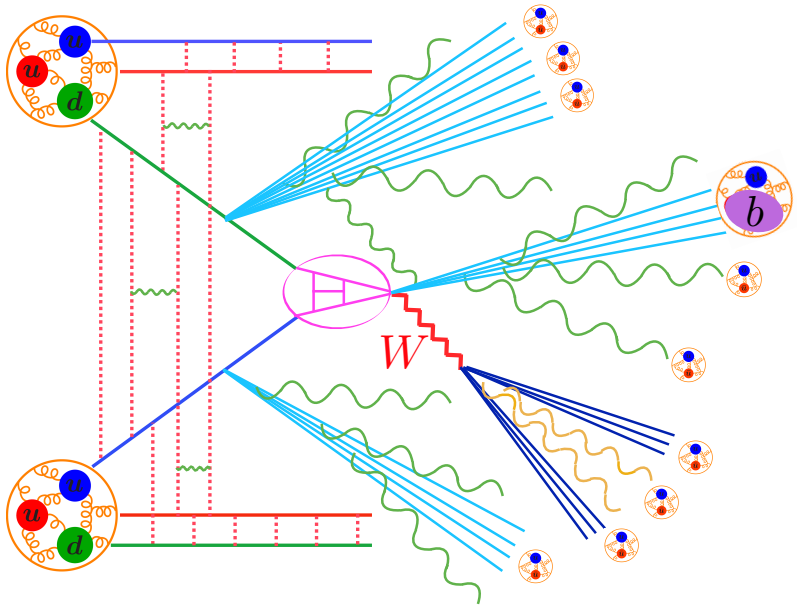


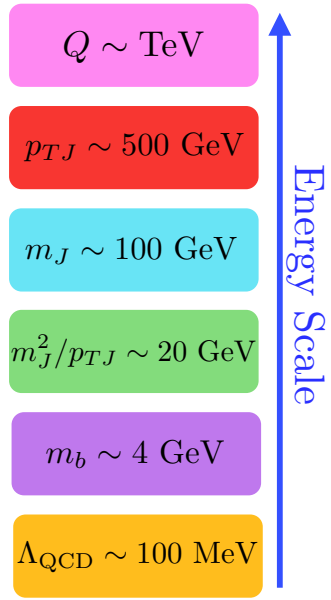
- Involves interactions at many hierarchical energy scales.

A Theorists View

- Tractable due to factorization:

$$\frac{d\sigma}{d\mathcal{M}_1\cdots} = \sum_{\{\kappa\}} \mathrm{tr} H_\kappa \mathcal{I}\mathcal{I} J_{\kappa_i} \otimes \cdots \otimes J_{\kappa_j} S_{\kappa_s} \otimes f_{p/i} f_{p/j} \otimes f_{k\to H} \otimes \cdots \otimes f_{l\to H} \otimes F + \cdots$$

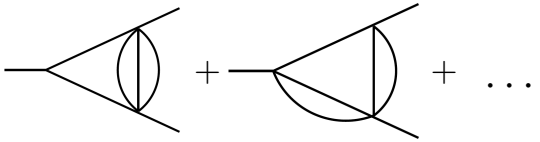


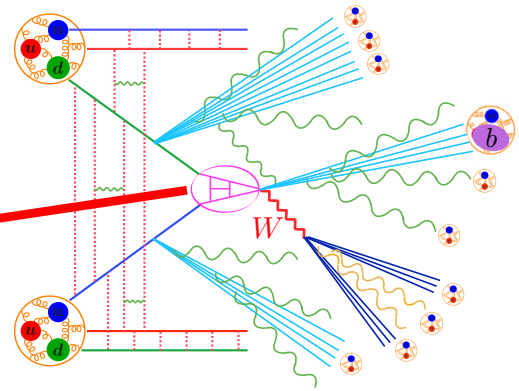


- $\frac{d\sigma}{d\mathcal{M}_1\cdots}$ written as a convolution of single scale objects.
- High energy dynamics integrated out, replaced by sources.
- Convenient formulation in effective field theory.

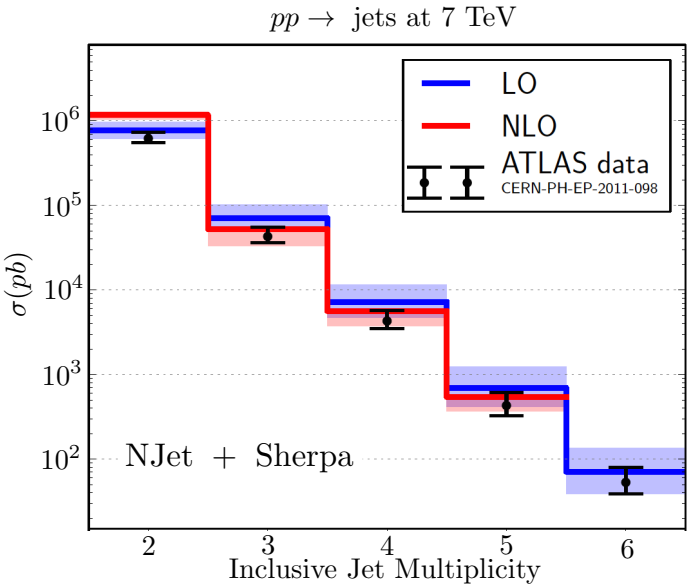
Recent Progress

- Significant recent progress in description of more complex final states.
  - Hard Scattering: H_κ



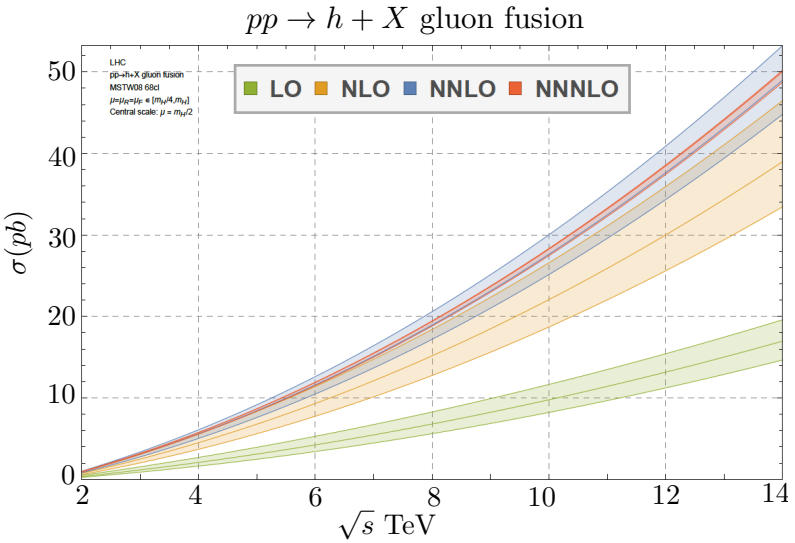


More Legs



[Badger, Biedermann, Uwer, Yundin]

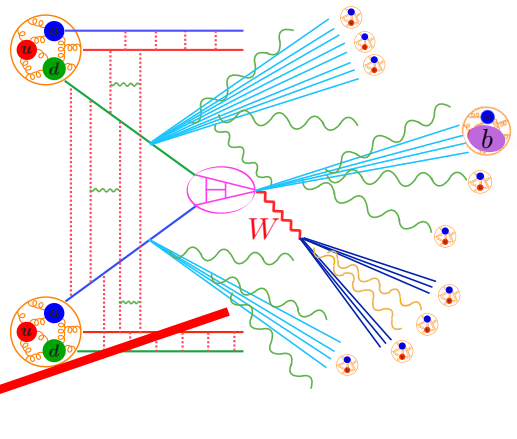
More Loops



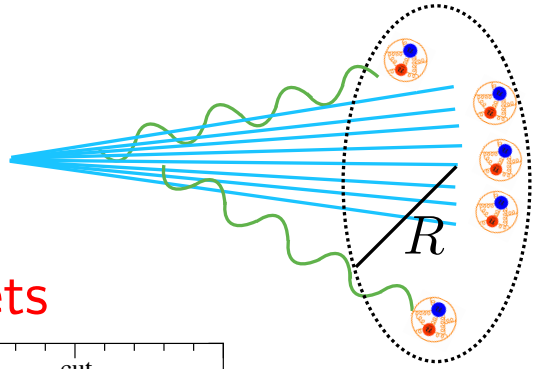
[Anastasiou, Duhr, Dulat, Herzog, Mistlberger]
[Gehrmann et al.], [Baikov et al.]

Recent Progress

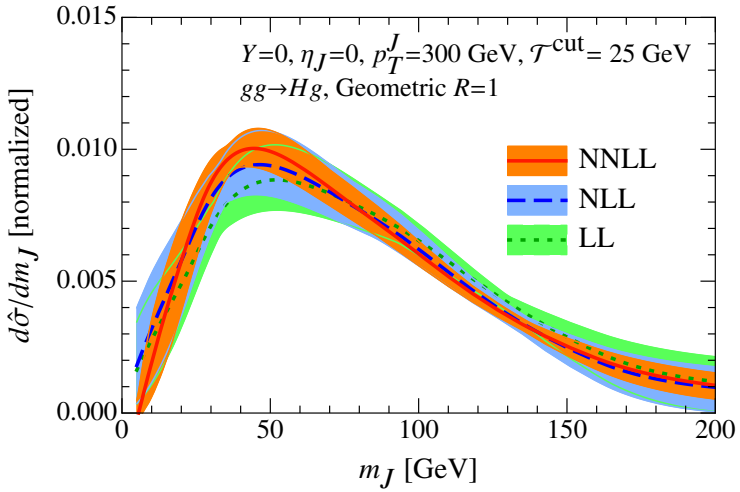
- Significant recent progress in description of more complex final states.
  - Dynamics of QCD radiation (SCET):
    $$\mathcal{I}\mathcal{I}J_{\kappa_i} \times \cdots \times J_{\kappa_j} \otimes S_{\kappa_s} \otimes F$$
  - Calculate properties of individual jets.



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

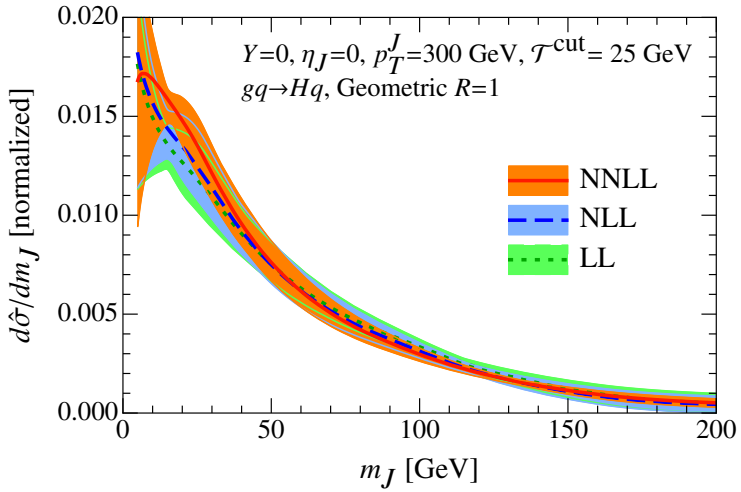


Gluon Jets



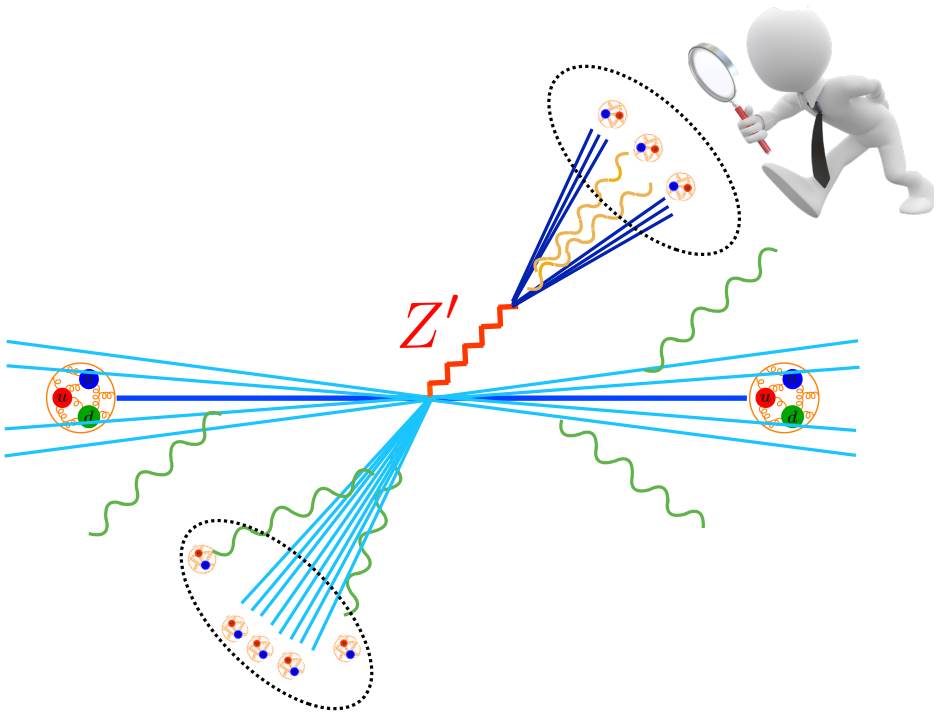
[Jouttenus, Stewart, Tackmann, Waalewijn]

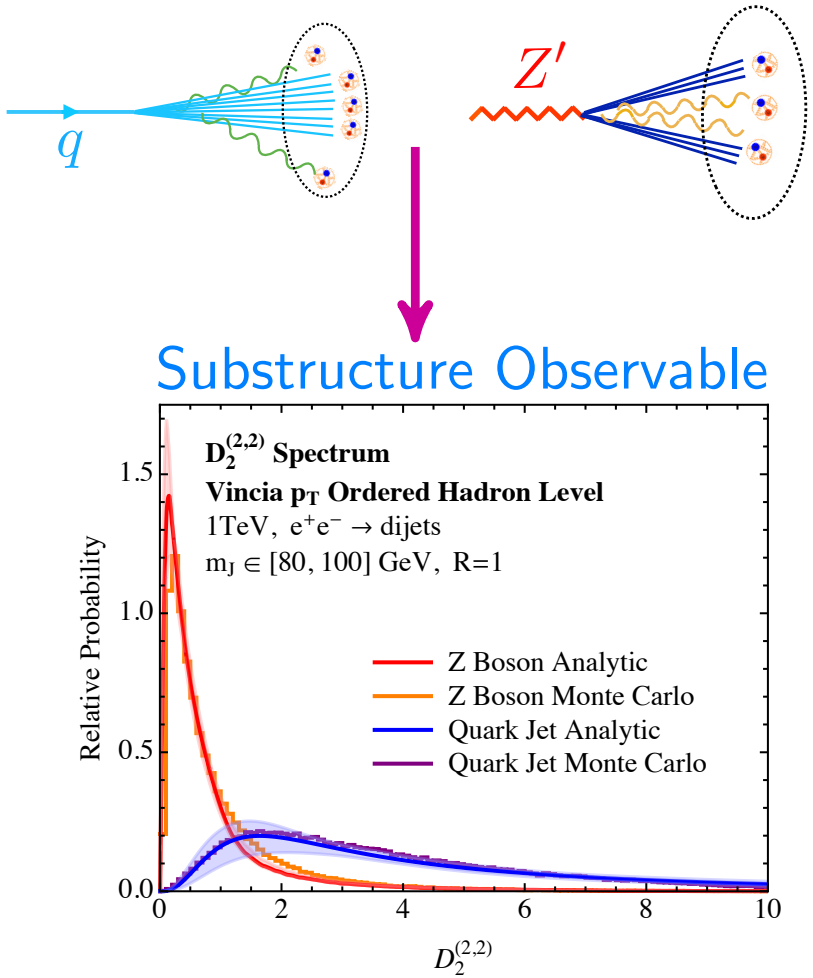
Quark Jets



Jet Substructure

- What if I want to look inside a jet?

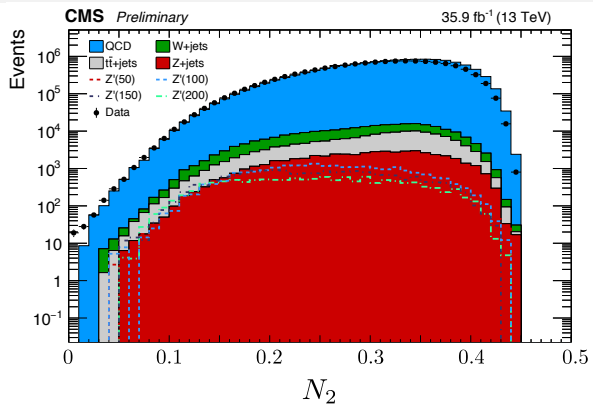


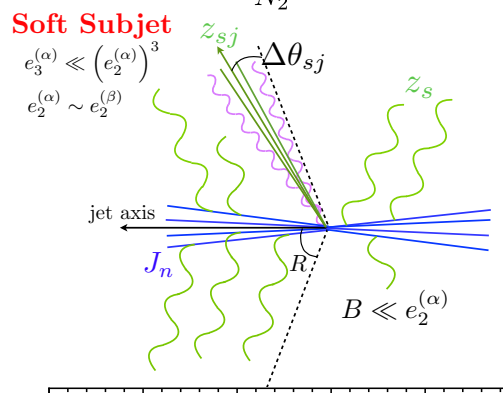


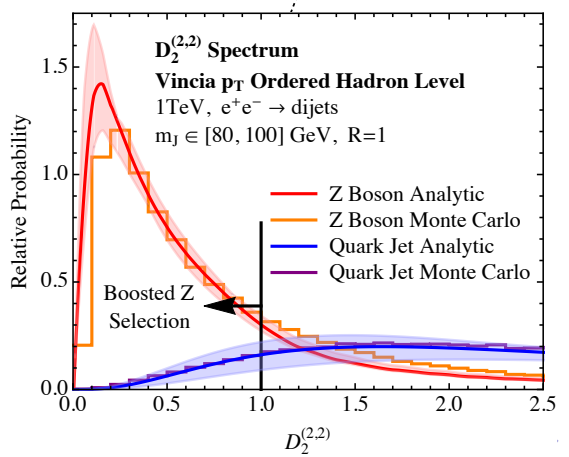
- Jet substructure: measure properties (charge, energy, etc) of radiation in a jet to extract information about its origin.

Outline

- New Observables for Jet Substructure
- Effective Field Theories for Jet Substructure
- Analytic Calculations for Jet Substructure



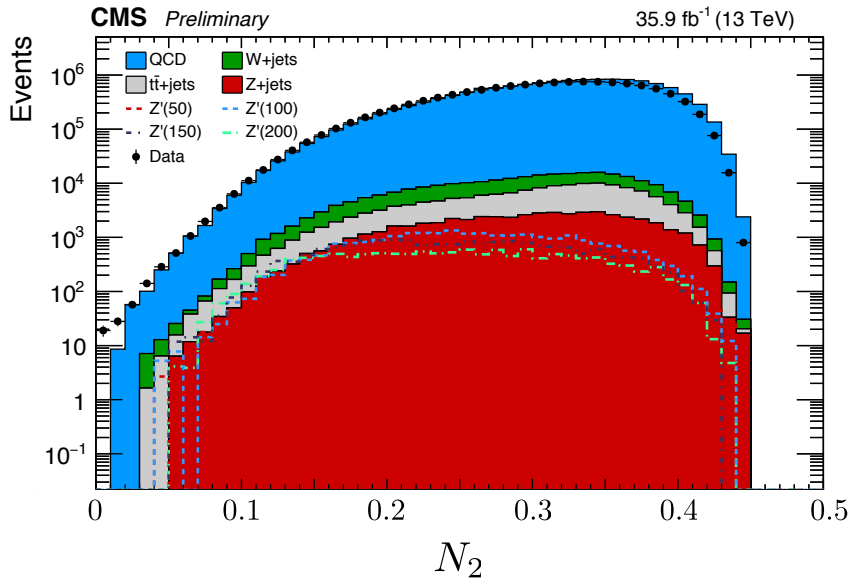




[Larkoski, IM, Neill]

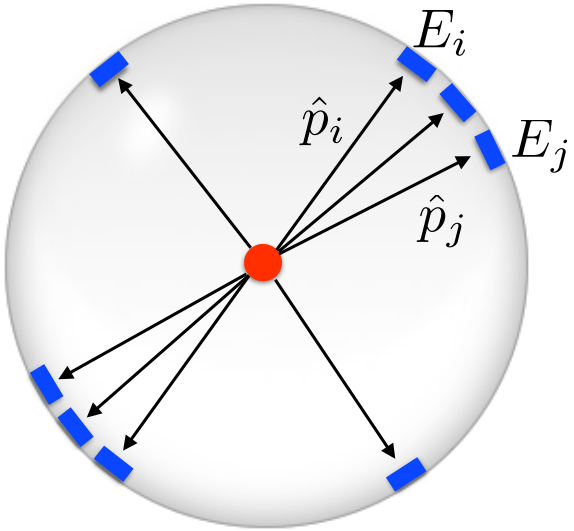
[IM, Necib, Thaler]

New Observables for Jet Substructure



Back to Basics

- What is an observable?



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

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

- Known that from this one can reconstruct any IRC safe observable.
- Is this useful for jet substructure?

$$\Longrightarrow \text{ Need to choose a basis.}$$

Generalized Energy Correlation Functions

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

General Energy Correlation Functions

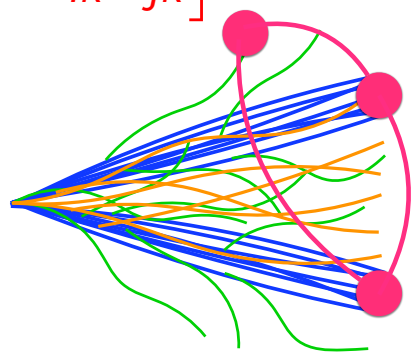
$$ {}_i e_j^{(\beta)} = \frac{1}{p_{TJ}^j} \sum_{1 \le n_1 < \cdots < n_j \le n} p_{Tn_1} p_{Tn_2} \cdots p_{Tn_j} \min \left(\prod_{s,t}^{i} R_{st}^{\beta} \right) $$

- Example: Three different ways to probe three particle correlations.

$$ {}_1 e_3^{(\beta)} = \frac{1}{p_{TJ}^3} \sum_{1 \le i < j < k \le n_J} p_{Ti} p_{Tj} p_{Tk} \min \left[R_{ij}^{\beta}, R_{ik}^{\beta}, R_{jk}^{\beta} \right] ,$$

$$ {}_2 e_3^{(\beta)} = \frac{1}{p_{TJ}^3} \sum_{1 \le i < j < k \le n_J} p_{Ti} p_{Tj} p_{Tk} \min \left[R_{ij}^{\beta} R_{ik}^{\beta}, R_{ij}^{\beta} R_{jk}^{\beta}, R_{ik}^{\beta} R_{jk}^{\beta} \right] ,$$

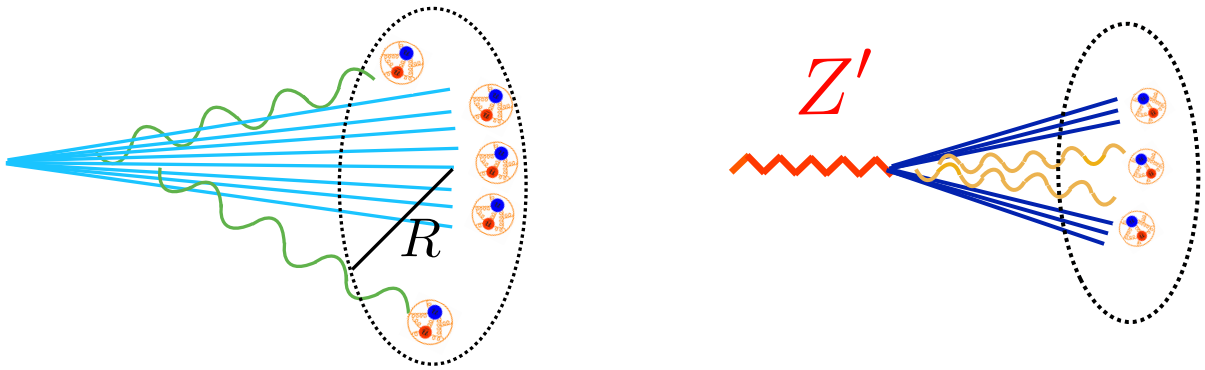
$$ {}_3 e_3^{(\beta)} = \frac{1}{p_{TJ}^3} \sum_{1 \le i < j < k \le n_J} p_{Ti} p_{Tj} p_{Tk} R_{ij}^{\beta} R_{ik}^{\beta} R_{jk}^{\beta} = e_3^{(\beta)} $$



- Flexible basis for substructure observables.

Power Counting Observables

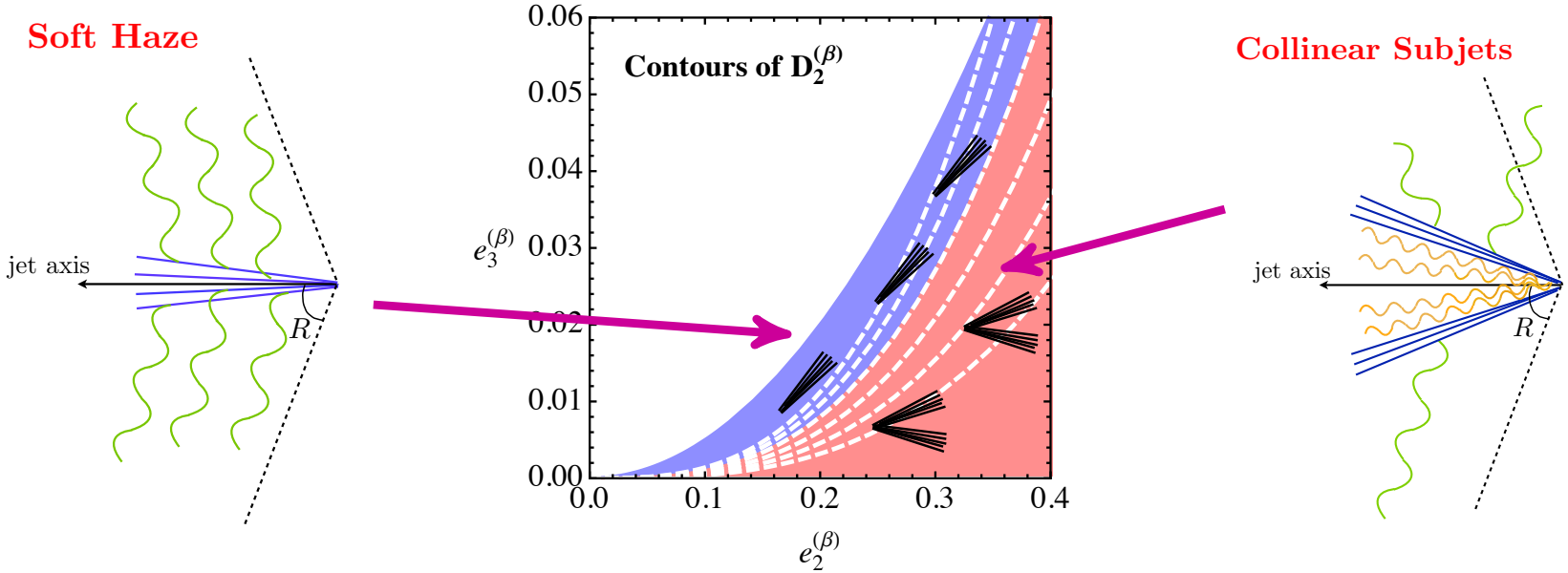
- How can we combine these observables to identify features of a jet?
- Example: Boosted $W/Z/H$ discrimination:



1. Write down Effective Field Theory (EFT) description of each configuration.
2. Identify region of validity of EFTs in terms of observables ${}_i e_j^{(\beta)}$.
3. Shared boundaries define how to separate.

Power Counting Observables: D_2

- Consider using $e_2^{(\beta)}$, $e_3^{(\beta)}$.
- Phase space separated by contours of $D_2^{(\beta)}$: $e_3^{(\beta)} = D_2^{(\beta)} \left(e_2^{(\beta)}\right)^3$



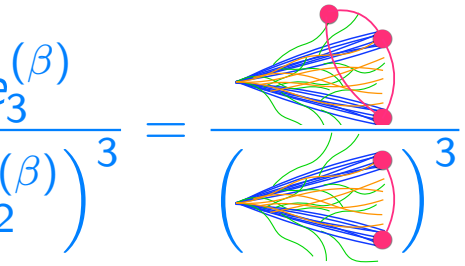
$$\left(e_2^{(\beta)}\right)^3 < e_3^{(\beta)} < \left(e_2^{(\beta)}\right)^2$$

$$e_3^{(\beta)} < \left(e_2^{(\beta)}\right)^3$$

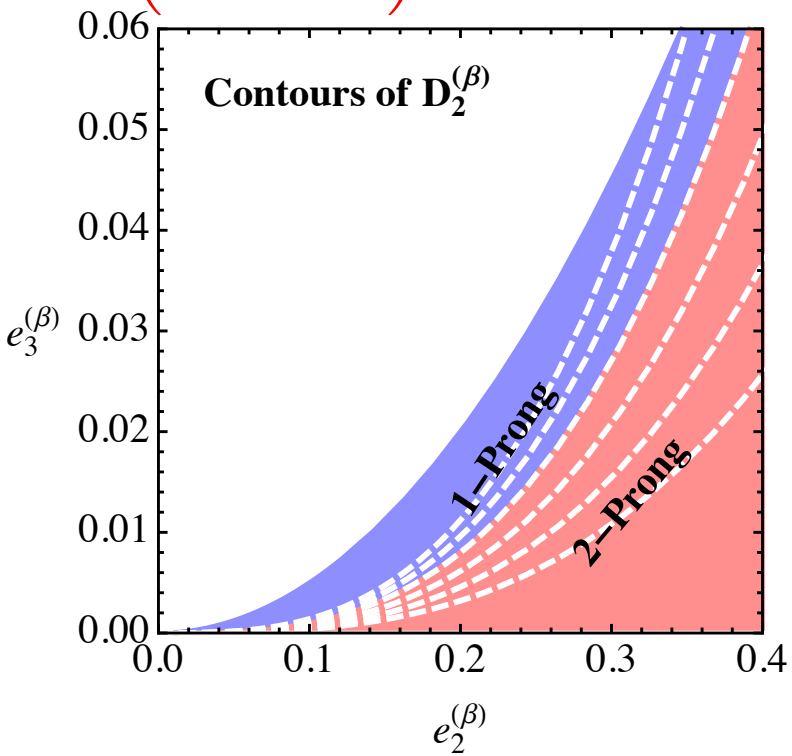
Phase Space

- Define the discriminant

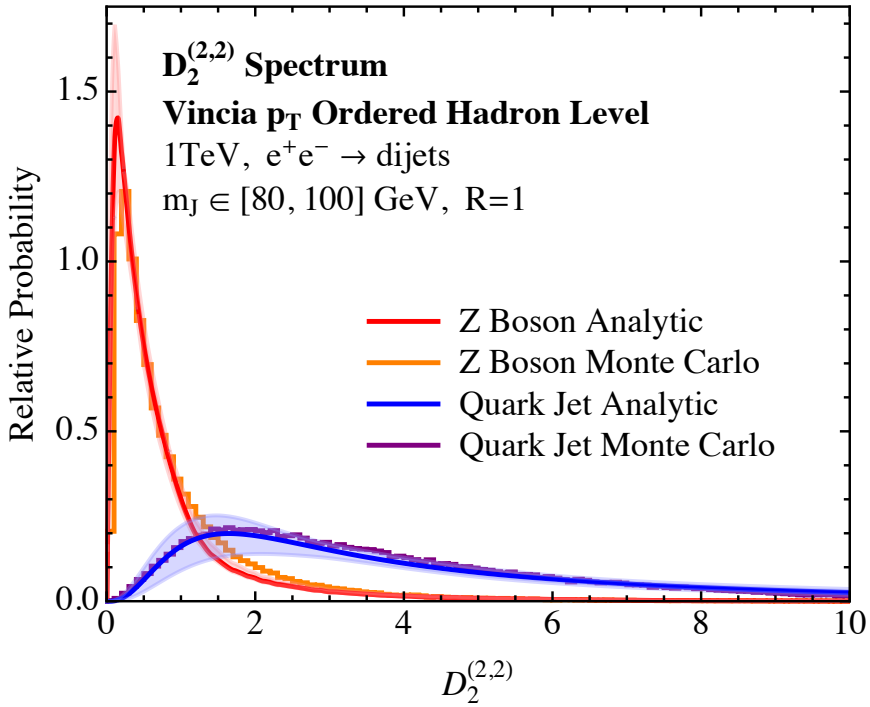
$$D_2^{(\beta)} = \frac{e_3^{(\beta)}}{\left(e_2^{(\beta)}\right)^3} =$$



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



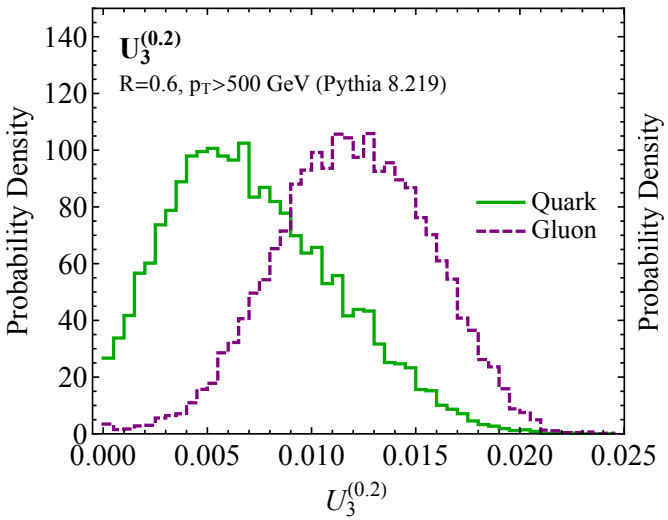
D_2 Spectrum



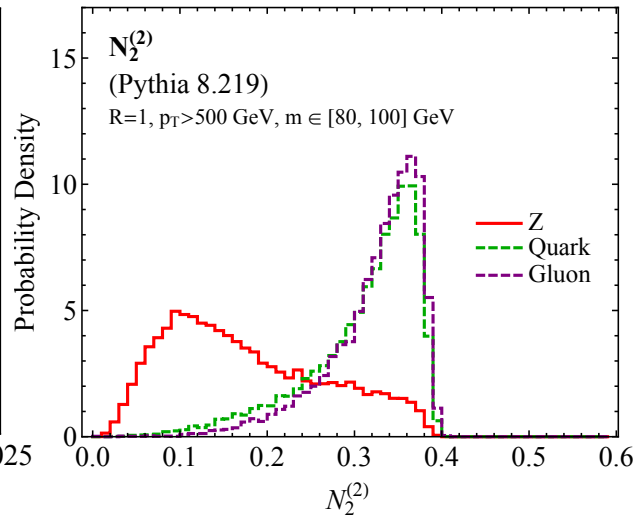
Summarizing the Observables

- Observables can be designed for a variety of purposes

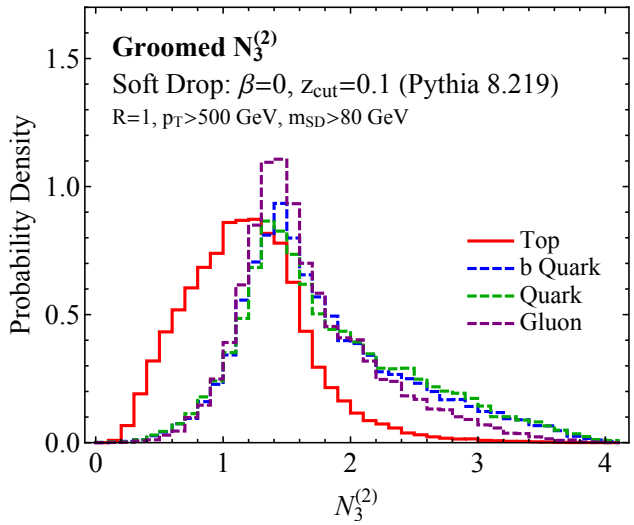
Quark vs. Gluon



$W/Z/H$ Tagging



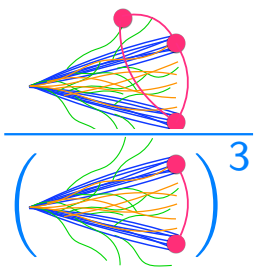
Top Tagging



- Focus on $W/Z/H$:

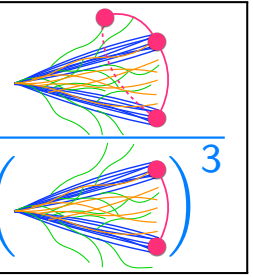
Searches at ATLAS

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



Searches at CMS

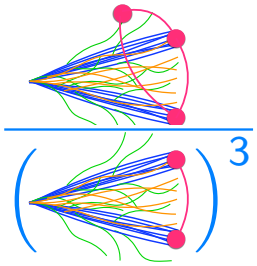
$$N_2^{(\beta)} = \frac{2e_3^{(\beta)}}{(e_2^{(\beta)})^2}$$



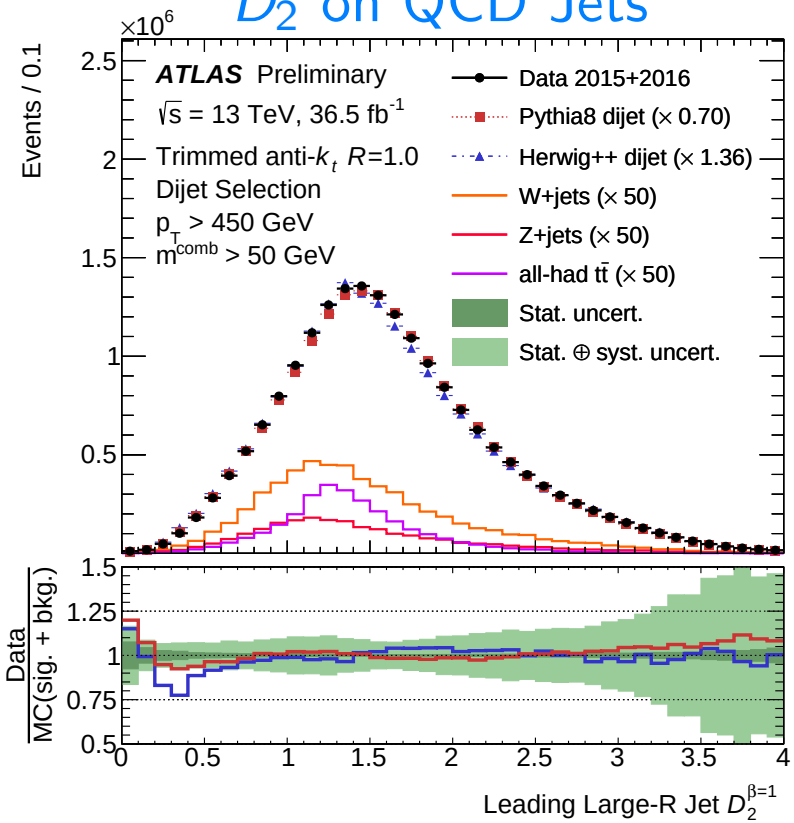
The Shape of Jets at the LHC: D_2

- D_2 is default tagger for ATLAS.

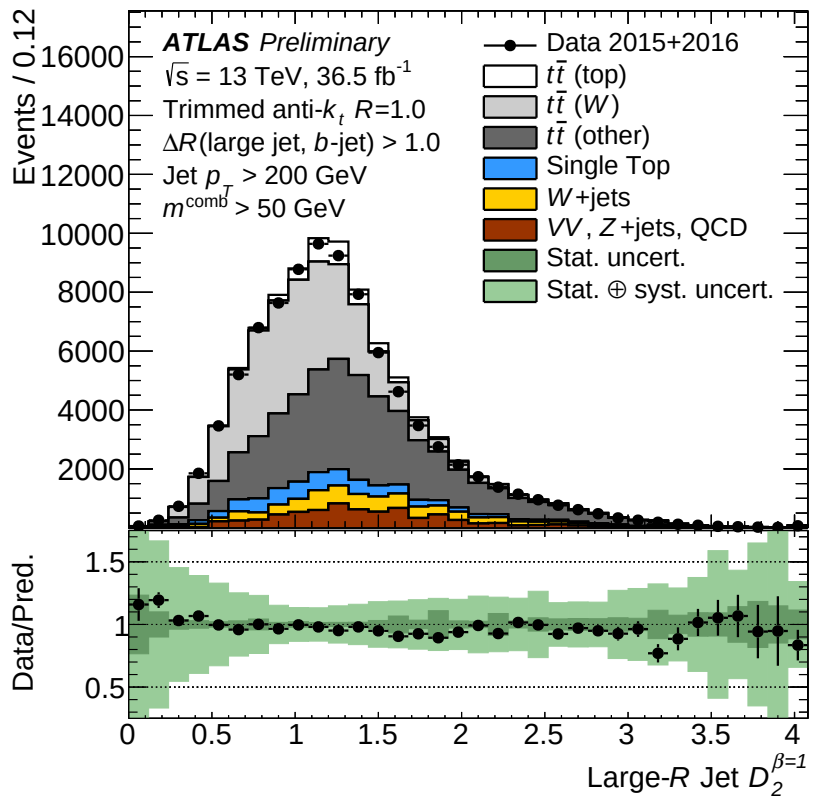
$$D_2^{(\beta)} = \frac{e_3^{(\beta)}}{\left(e_2^{(\beta)}\right)^3} =$$



D_2 on QCD Jets

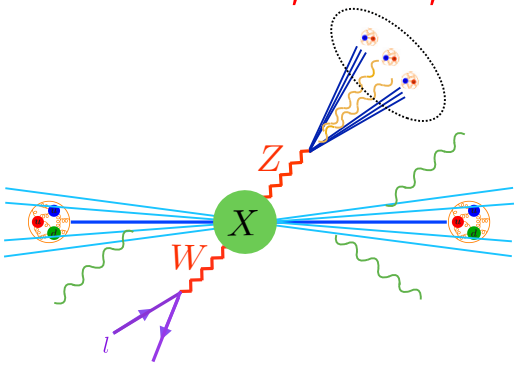


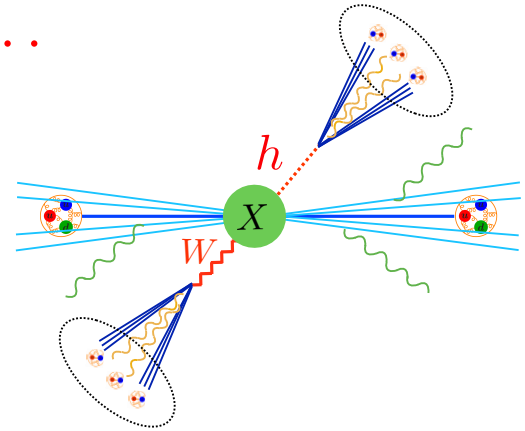
D_2 on W Jets



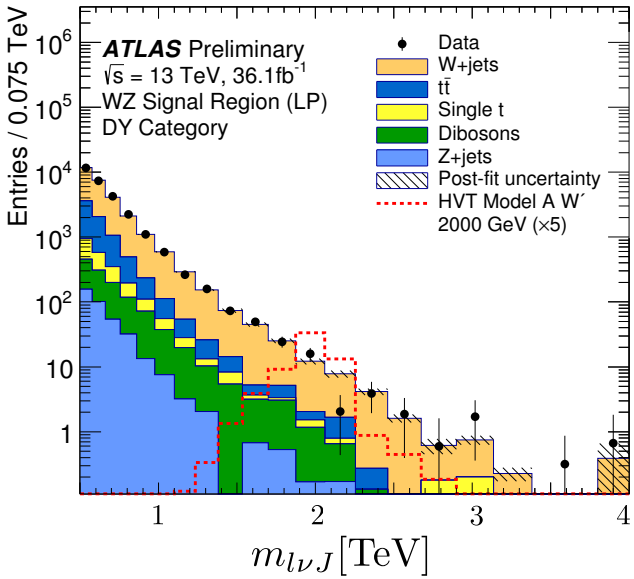
Applications: High Mass Resonances

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

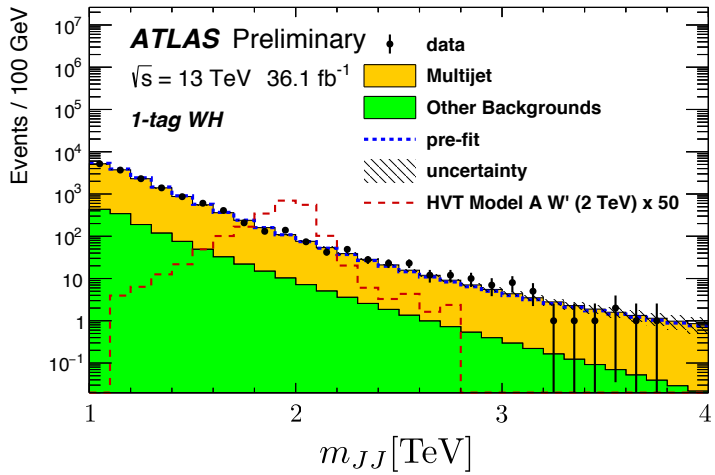




WZ Diboson Invariant Mass



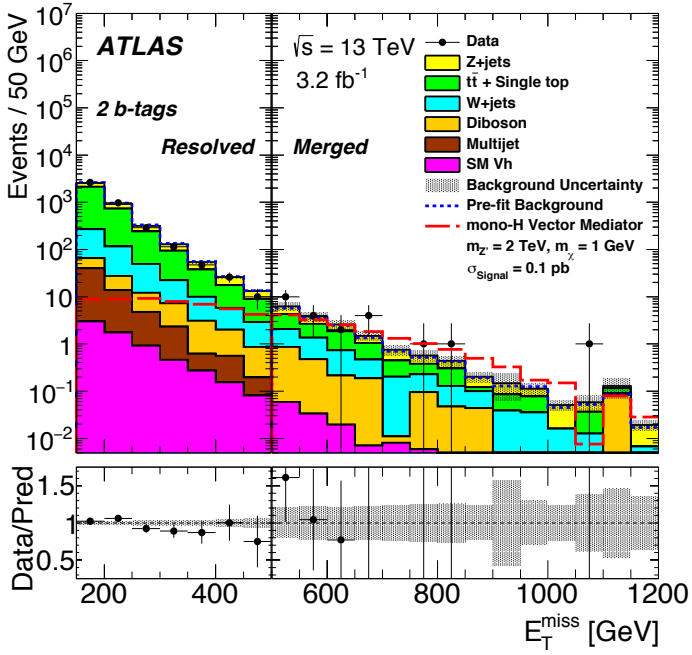
WH Diboson Invariant Mass



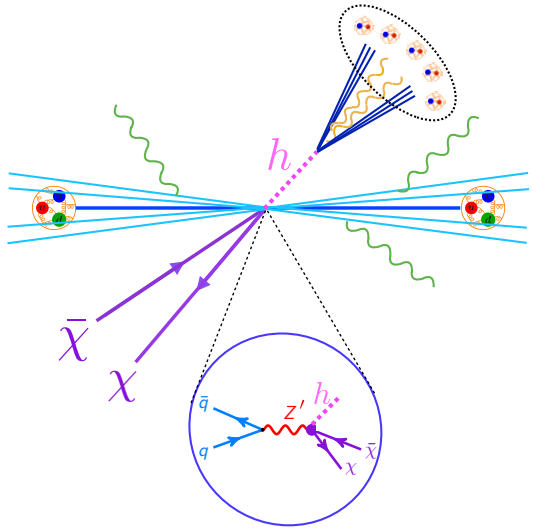
Applications: Dark Matter Searches

- Dark Matter Searches:

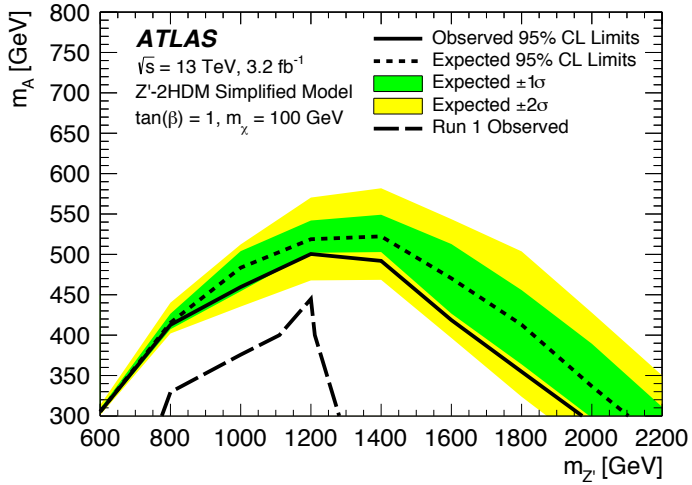
E_T^{miss}



Substructure



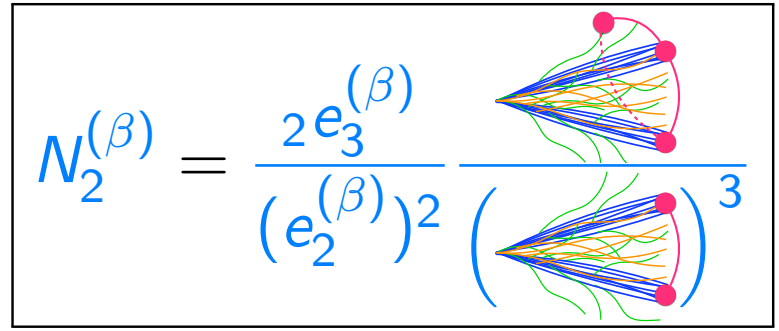
Mediator Limit



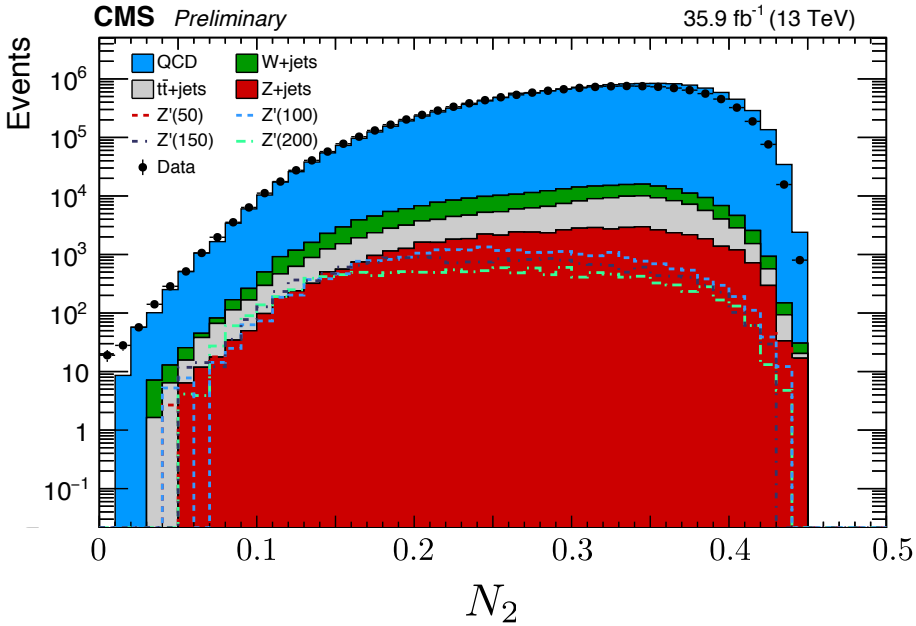
N_2 at CMS

- N_2 measured by CMS.

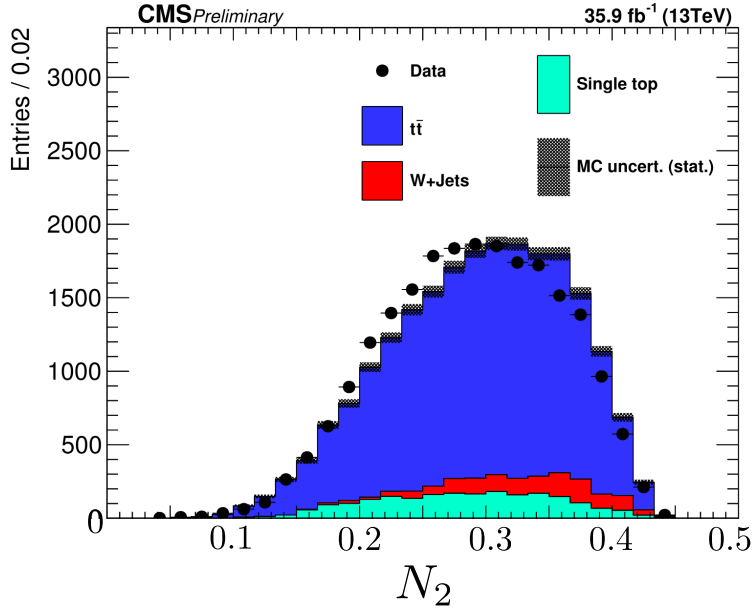
$$N_2^{(\beta)} = \frac{{}_2e_3^{(\beta)}}{(e_2^{(\beta)})^2} \frac{}{\left(\right)^3}$$



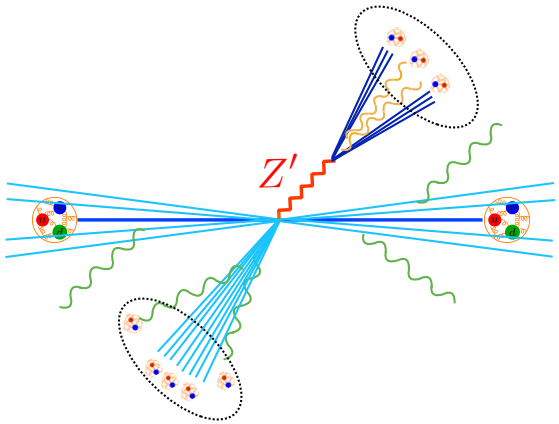
N_2 on QCD Jets



N_2 on W Jets

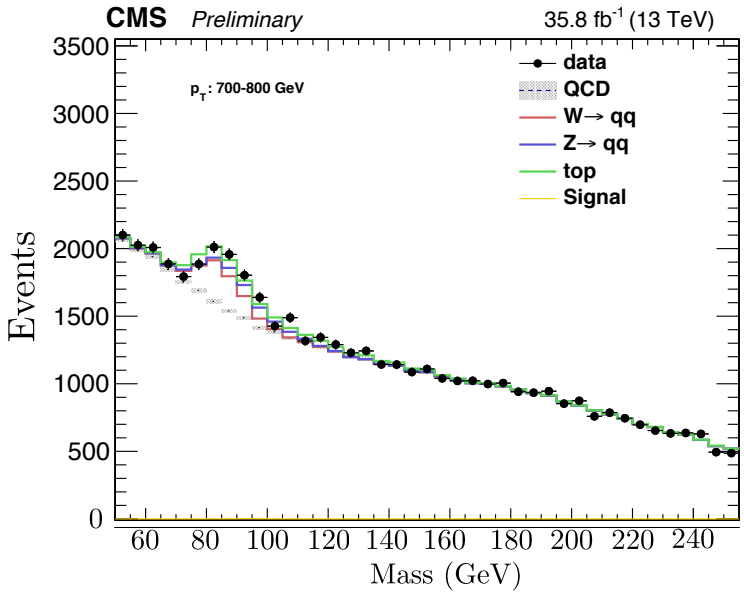


Low Mass Searches

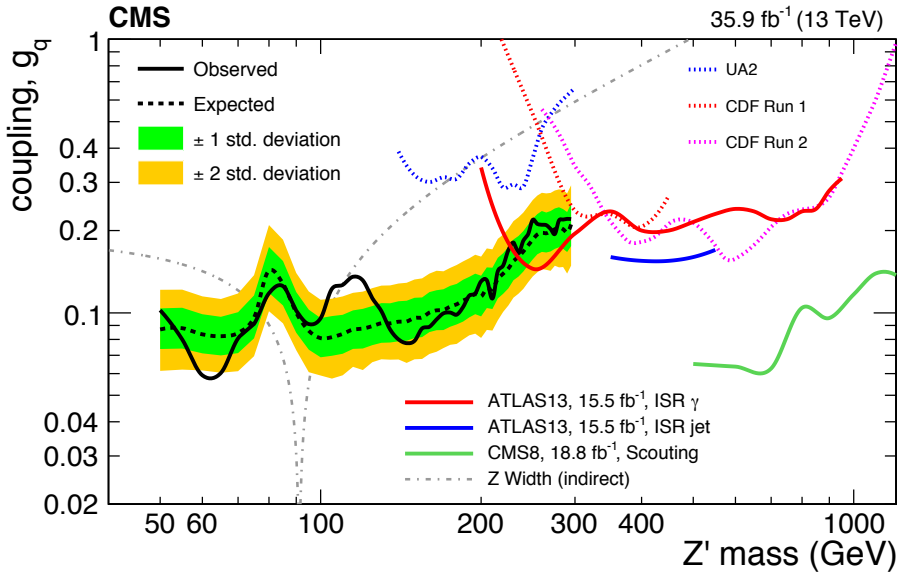


- Low mass Z' search in dijet channel.

Jet Mass Distribution



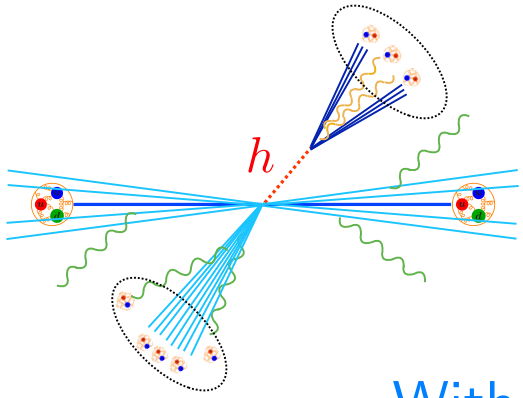
Limits from N_2



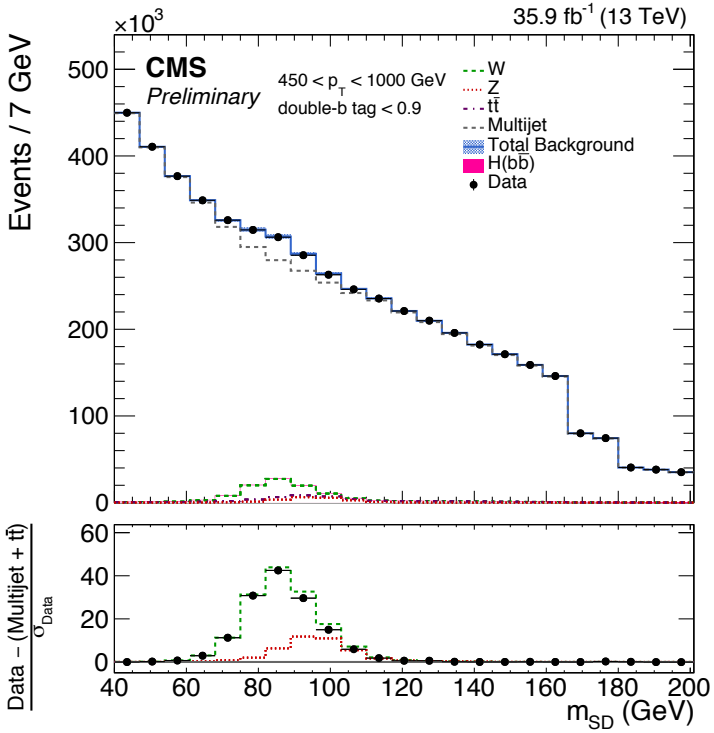
- Find $Z' = Z/W$!
- Probe new low mass, low x-sec region of parameter space!

Applications: $H \to b\bar{b}$

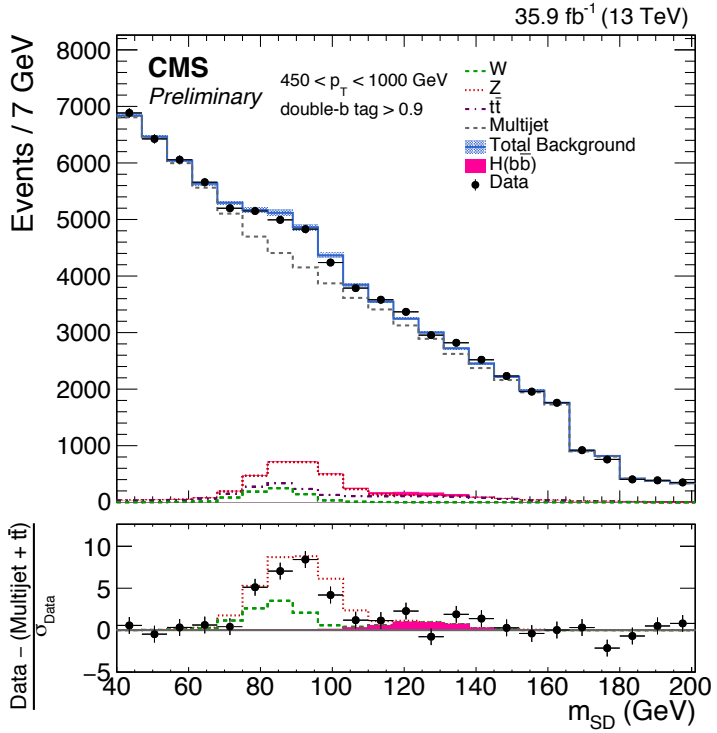
- Towards boosted $H \to b\bar{b}$.



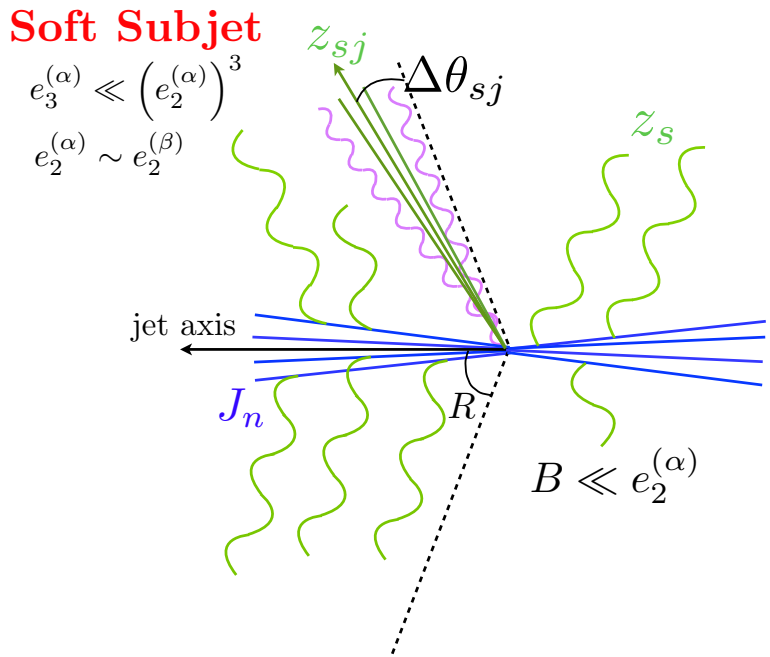
Without b-tag



With b-tag



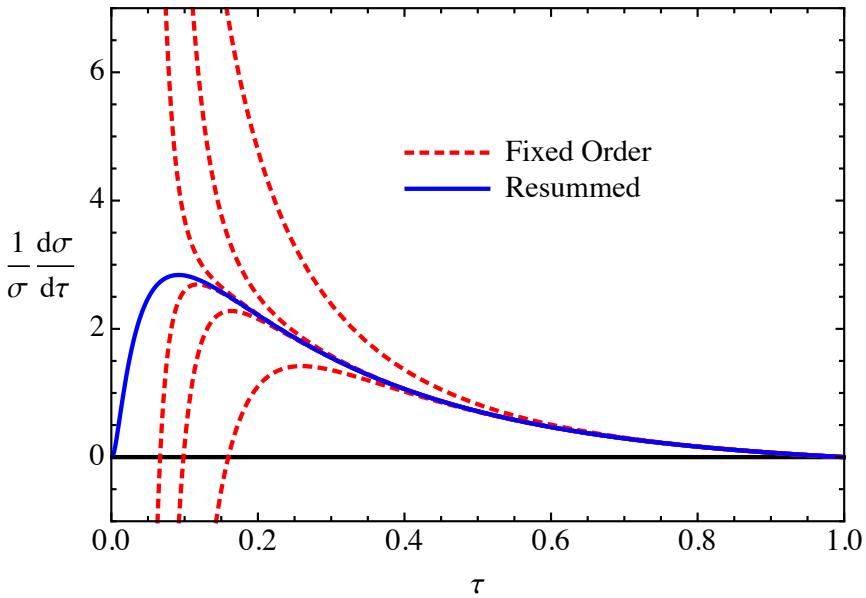
Effective Field Theory Frameworks for Jet Substructure



A Standard QCD Calculation

- QCD has soft and collinear singularities.
- If one measures an observable τ on a jet,

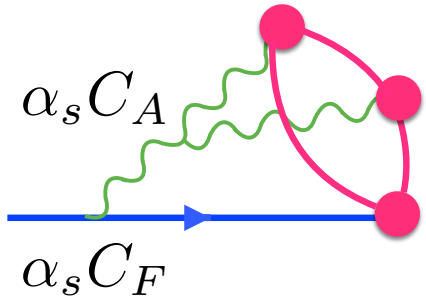
$$\frac{d\sigma}{d\tau} = -\frac{2\alpha_s C_F}{\pi}\frac{\log\tau}{\tau}\left(1 - \frac{\alpha_s C_F \log^2\tau}{\pi} + \frac{1}{2}\left(\frac{\alpha_s C_F \log^2\tau}{\pi}\right)^2 - \frac{1}{6}\left(\frac{\alpha_s C_F \log^2\tau}{\pi}\right)^3 + \cdots\right)$$
$$= -\frac{2\alpha_s C_F}{\pi}\frac{\log\tau}{\tau}\left(e^{-\frac{\alpha_s C_F}{\pi}\log^2\tau}\right)$$



- All orders resummation necessary.

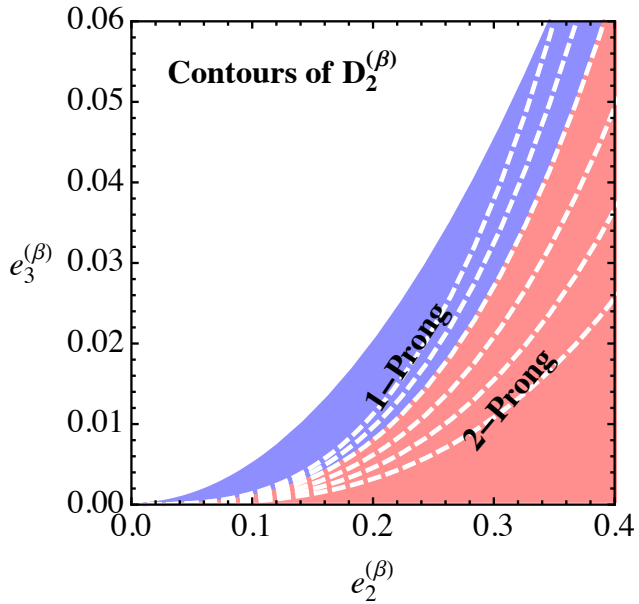
D_2

- Recall $D_2^{(\beta)} = \dfrac{e_3^{(\beta)}}{\left(e_2^{(\beta)}\right)^3}$
- First non-zero at two-emissions



- Cross section for D_2 computed by marginalization:

$$\frac{d\sigma}{dD_2} = \int de_2^{(\alpha)} de_3^{(\alpha)} \, \delta\left(D_2 - \frac{e_3^{(\alpha)}}{(e_2^{(\alpha)})^3}\right) \frac{d\sigma}{de_2^{(\alpha)} de_3^{(\alpha)}}$$



D_2

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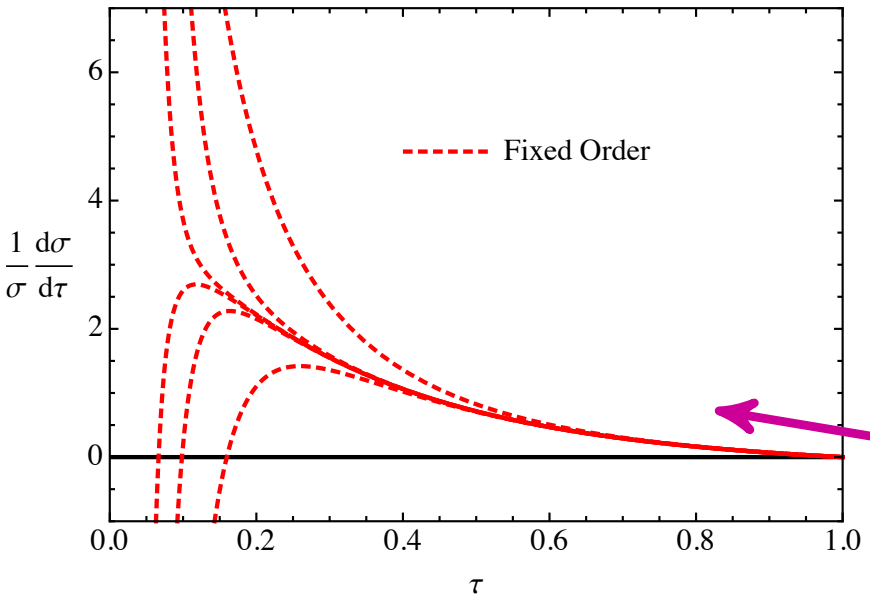
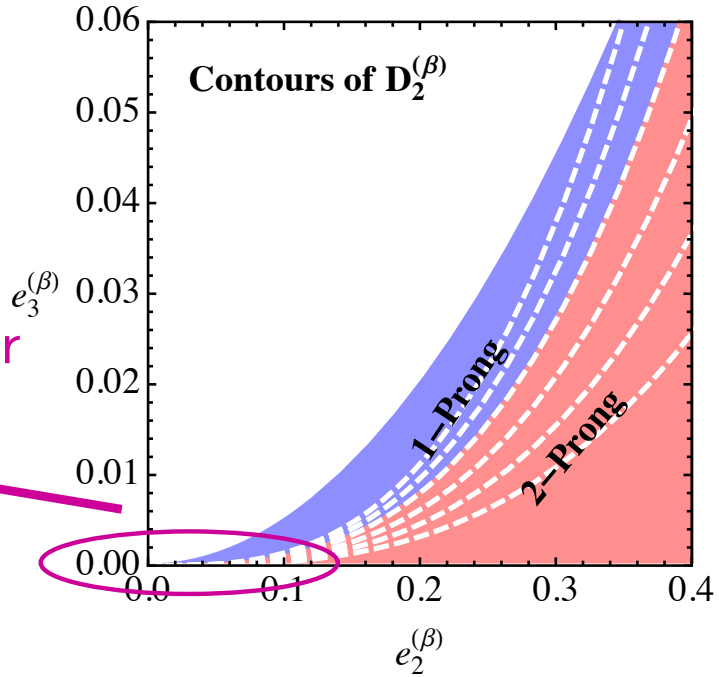
- For each value of D_2 contour of integration passes through singular region of phase space $\Longrightarrow$ not computable in fixed order perturbation theory!



Singular Region



D_2

- Cross section for D_2 computed by marginalization:

$$\frac{d\sigma}{dD_2} = \int de_2^{(\alpha)} de_3^{(\alpha)} \, \delta\left(D_2 - \frac{e_3^{(\alpha)}}{(e_2^{(\alpha)})^3}\right) \frac{d\sigma}{de_2^{(\alpha)} de_3^{(\alpha)}}$$

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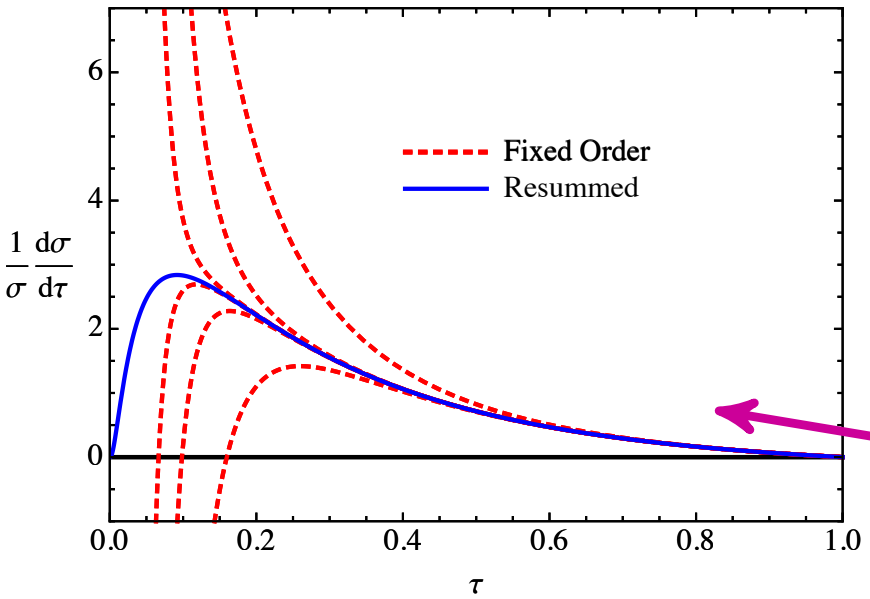
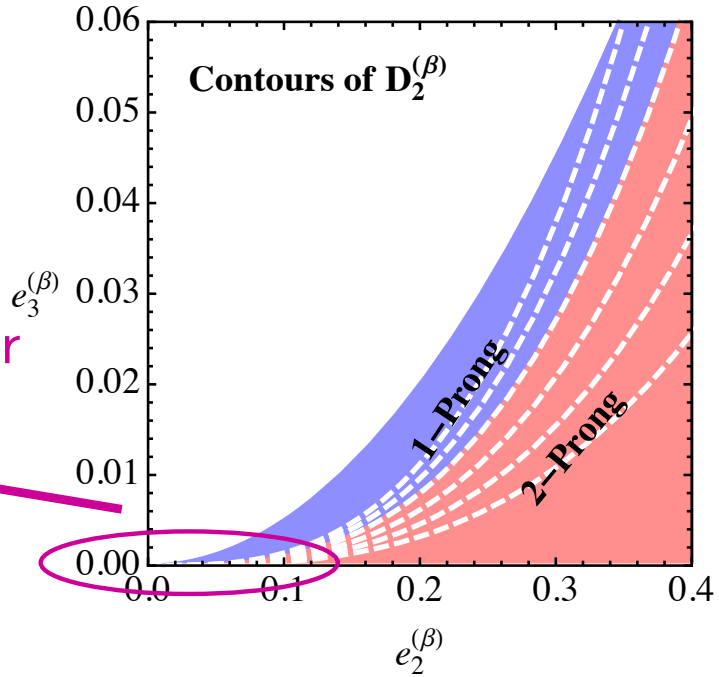


Singular Region

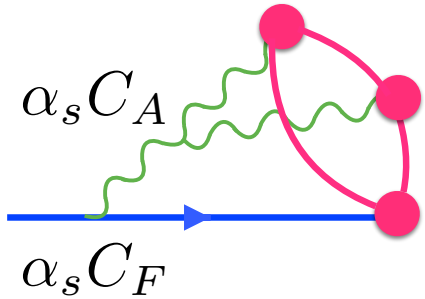


D_2

- D_2 can be computed in resummed perturbation theory.
- Resummation regulates singular region of phase space prior to integration over the contour : Sudakov Safety. [Larkoski, Thaler]
- Result starts at α_s and with a single color factor:

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

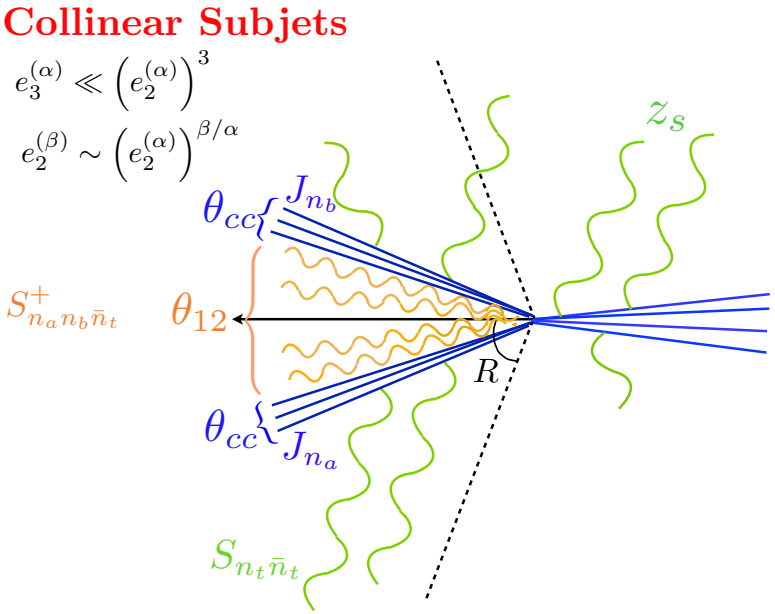
$$\propto \frac{\alpha_s C_F}{\pi} \frac{1}{D_2} + \cdots$$

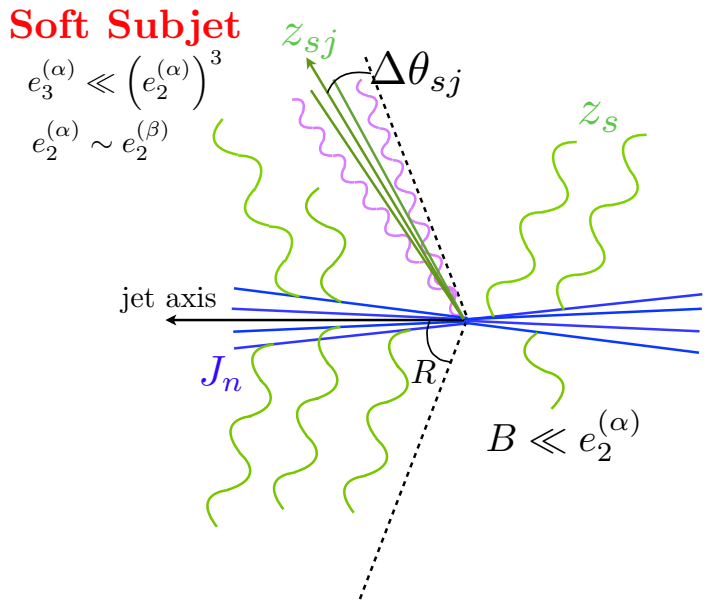


- Other examples exist with $\sqrt{\alpha_s}$ behavior.
- Requires understanding of all order structure of perturbation theory.

EFTs for Jet Substructure

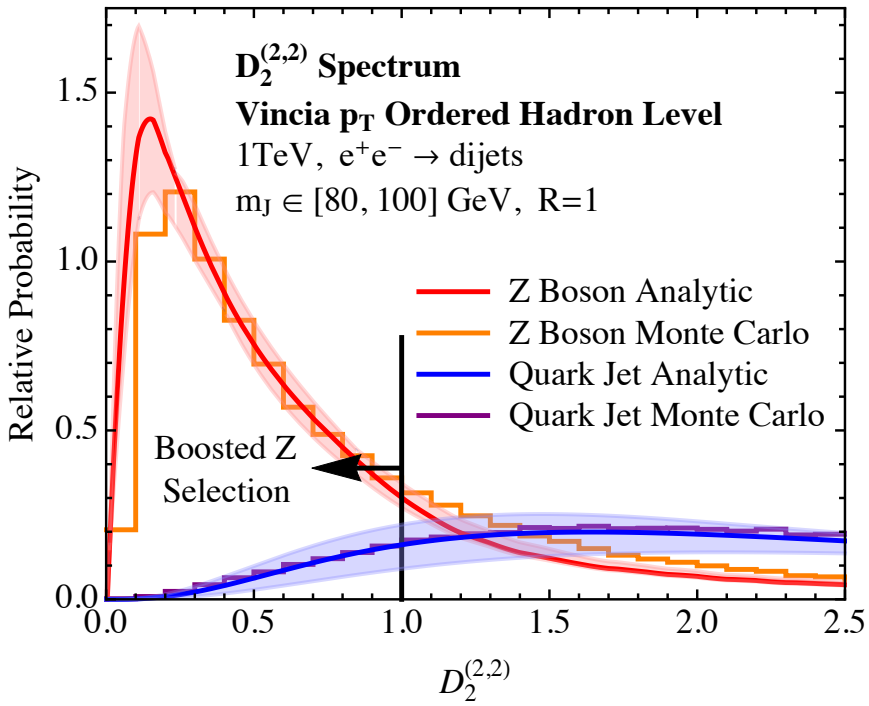
- Can understand all orders structure using Effective Field Theories.
- Dynamics of subjets iteratively integrated out and replaced by sources (Wilson lines)





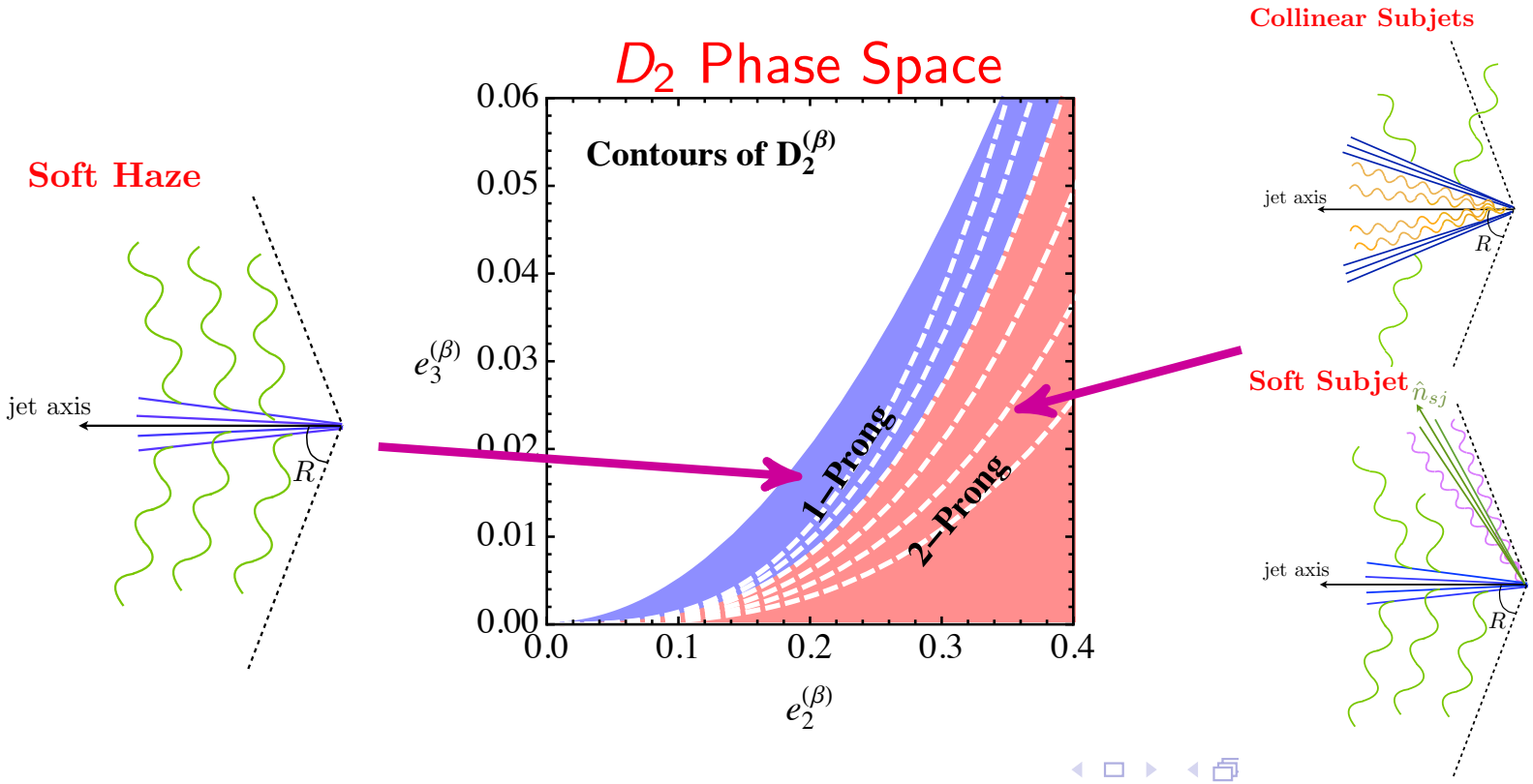
- Powerful approach to describe complicated situations.

Analytic Calculations for Jet Substructure



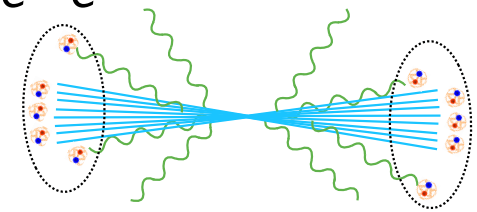
Calculation of D_2

- Set up EFT description in each region of phase space.
- Factorized description of phase space regions can be combined to make prediction for D_2.

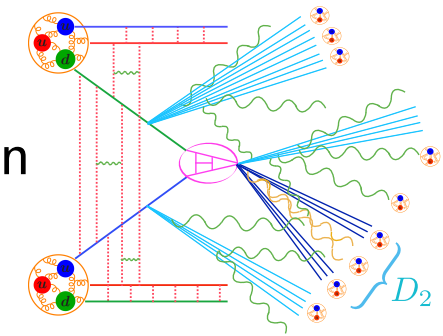


A Warm Up: e^+e^-

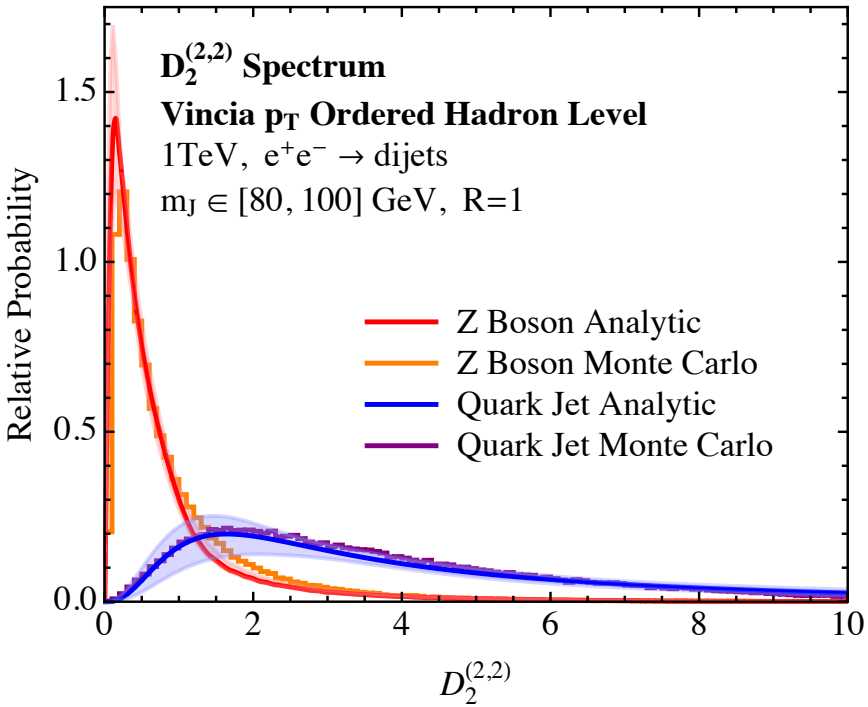
- Warm up with e^+e^-



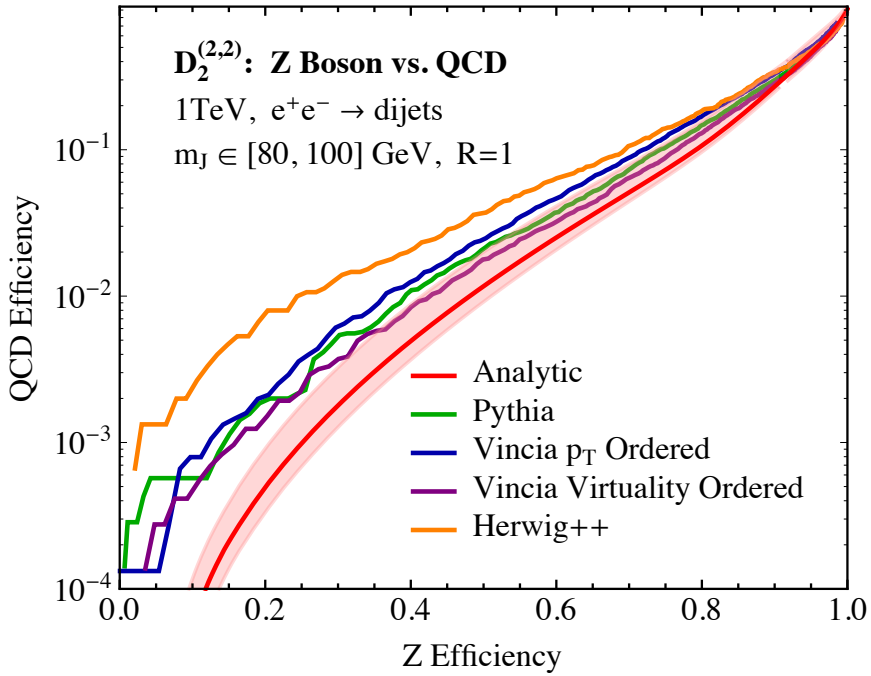
is simpler than



D_2 Spectrum

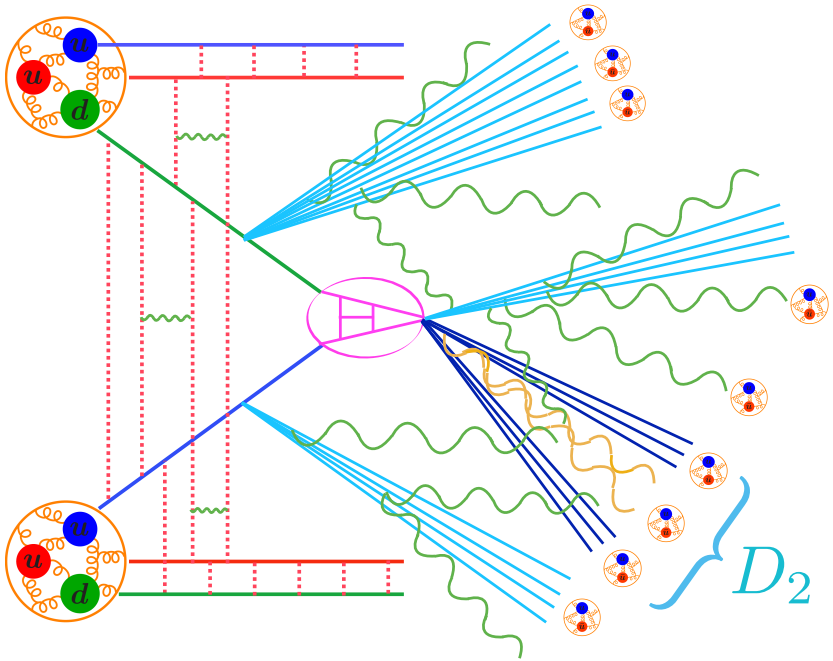


Tagging Efficiency

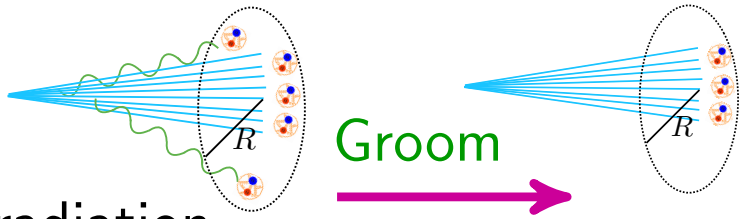


Analytic Boosted Boson Discrimination at the LHC

- Difficulties in extending to pp:



- Global color correlations
- Hadronization corrections
- Pile-Up
- Underlying event

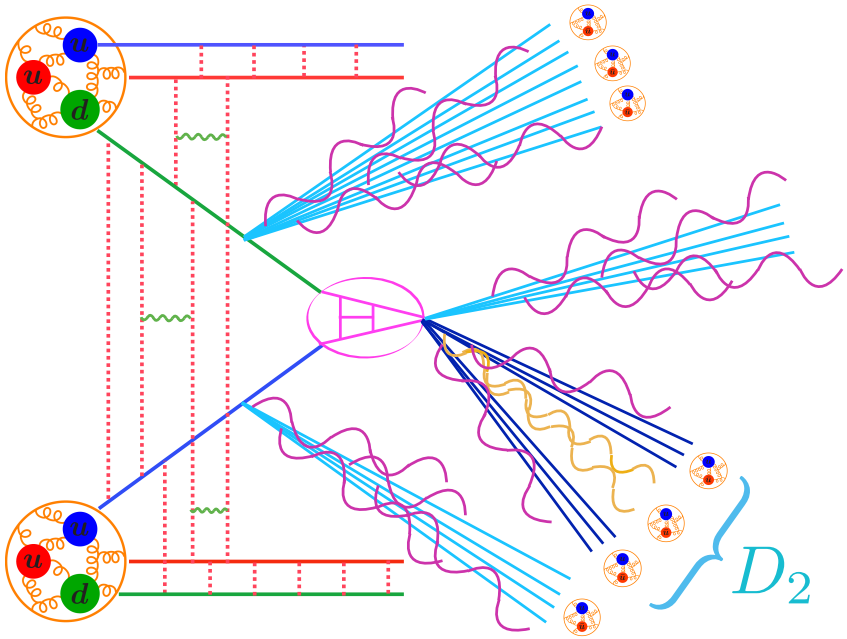


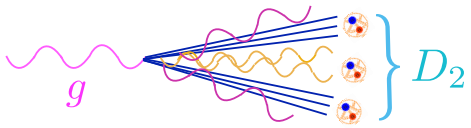
- All complications associated with soft radiation.
- Groomers remove soft radiation

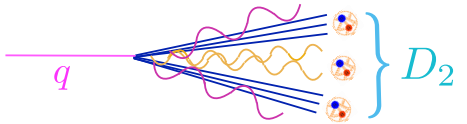
  $\Longrightarrow$ Makes calculations simpler and more universal.

Analytic Boosted Boson Discrimination at the LHC

- Grooming removes all color correlations.



$= f_g$ 

$+ f_q$ 

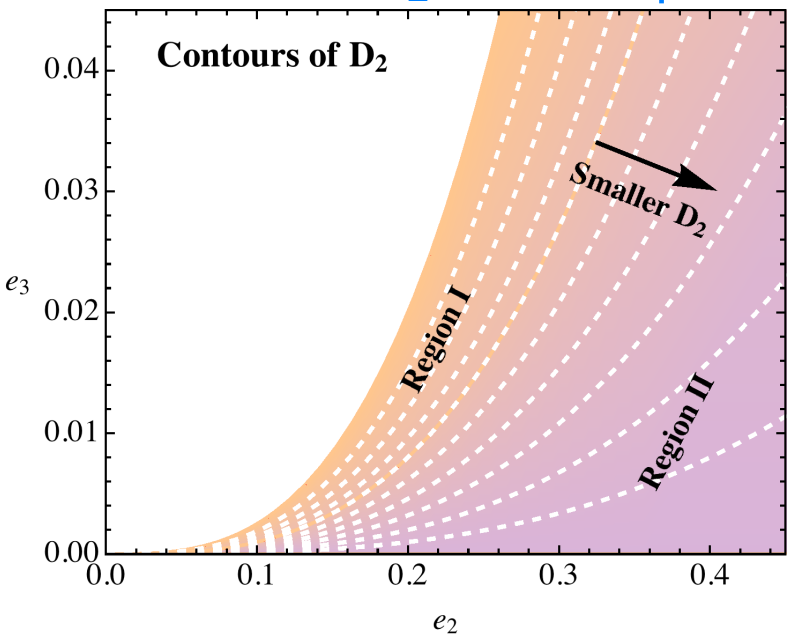
- Jet can be considered in isolation!
- Enables calculations in complicated LHC environment.

Analytic Boosted Boson Discrimination at the LHC

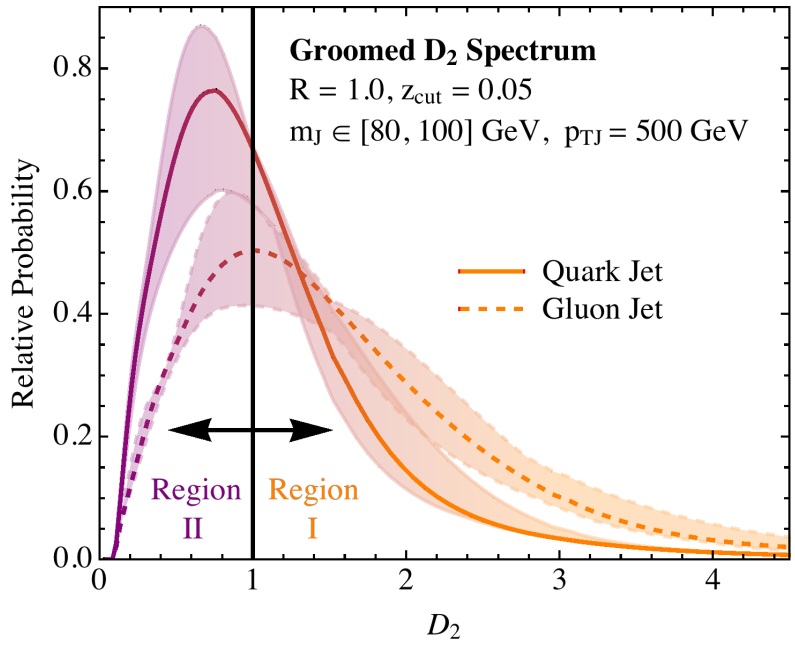
[Larkoski, IM, Neill] Forthcoming

- Calculation of groomed D_2 at the LHC.

Groomed D_2 Phase Space



Groomed D2

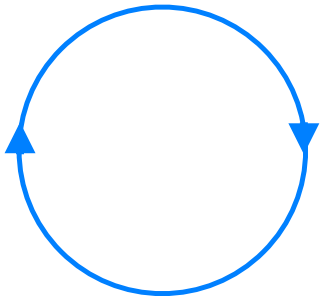


- Analytic understand of modern jet substructure tools at LHC!

Conclusions

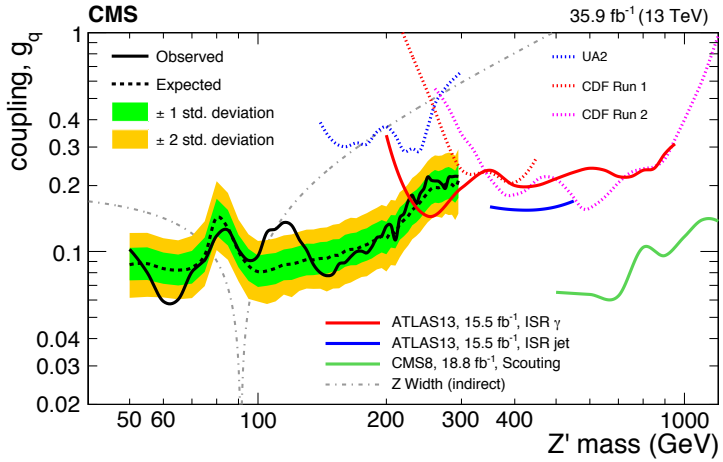
- Jet substructure provides novel ways to test the SM and to search for new physics at the LHC.

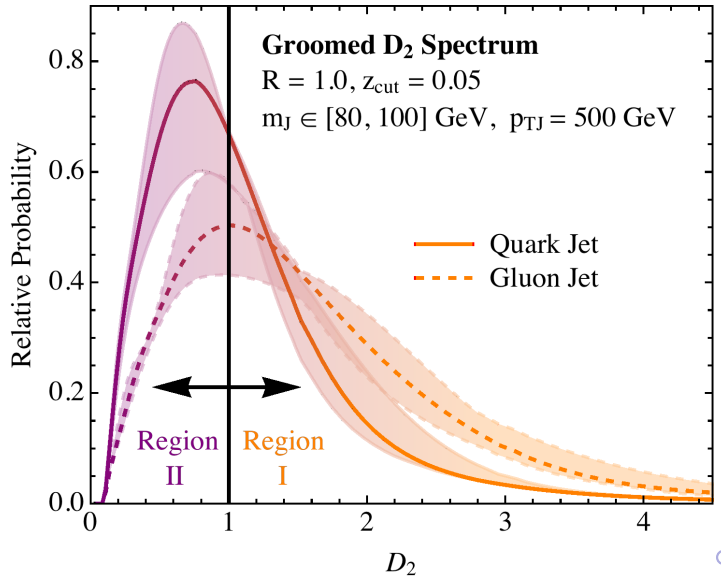
More Sophisticated Calculations



More Sophisticated Techniques

- Analytic calculations are a catalyst for further improvements in jet substructure.





Thanks!