Constructing Stable Observables with Energy Correlation Functions

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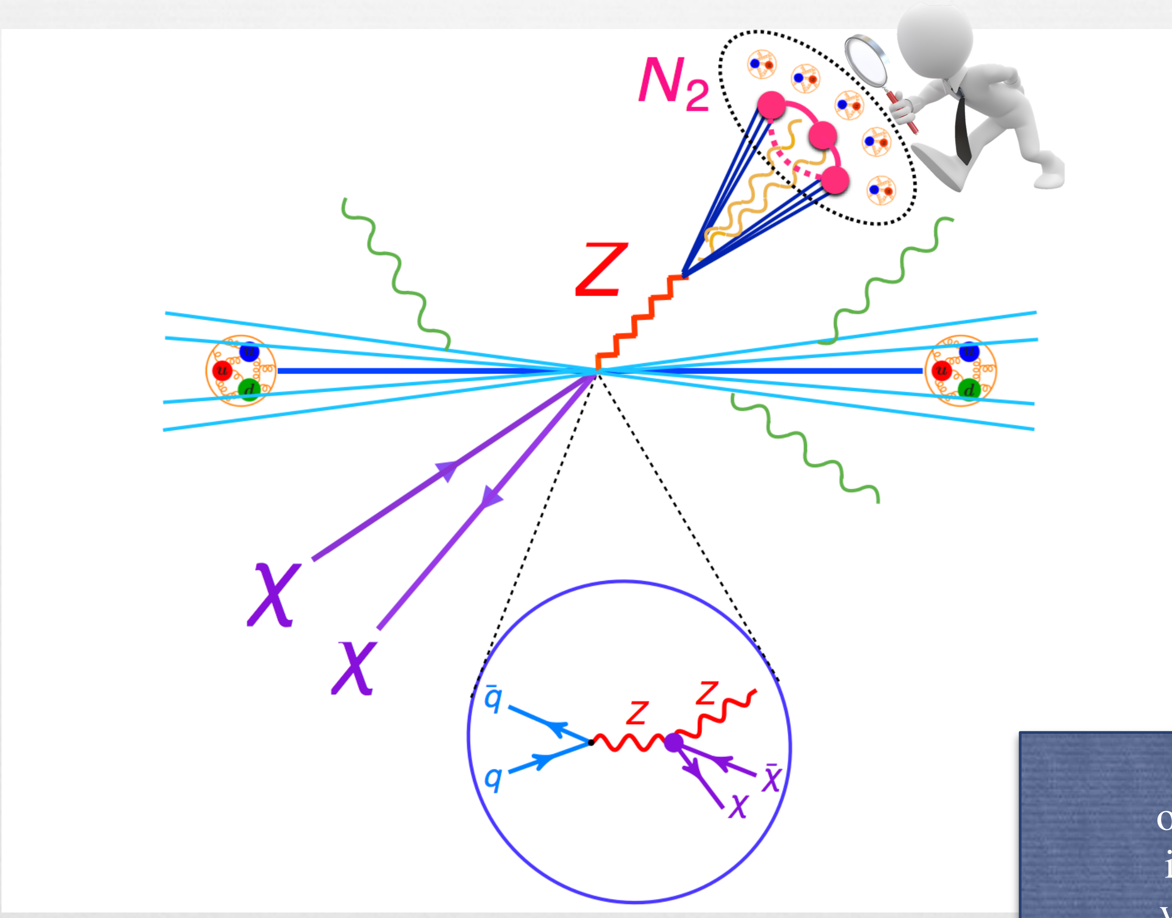
Based on arXiv:1609.07483

In collaboration with Ian Moult and Jesse Thaler

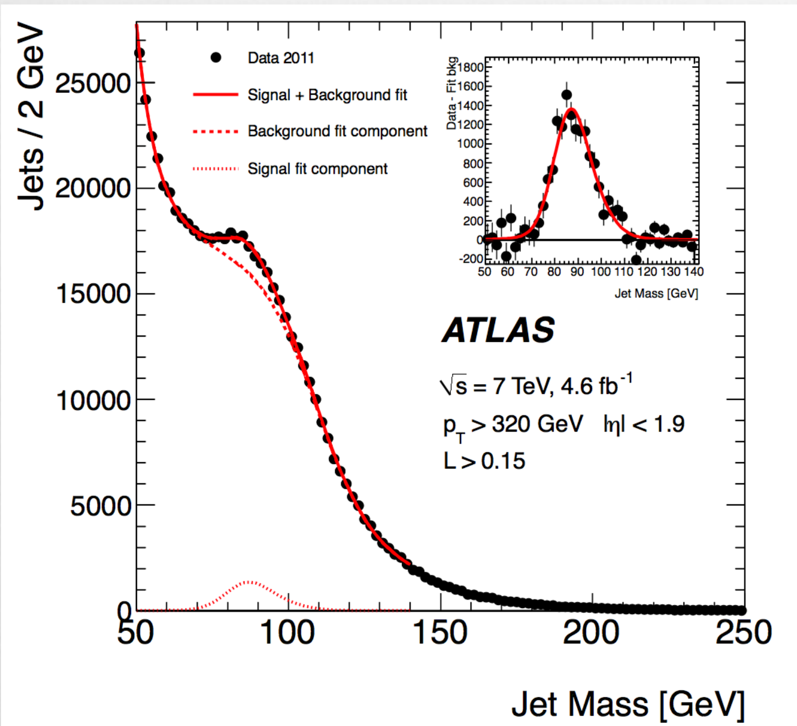
Jet Substructure

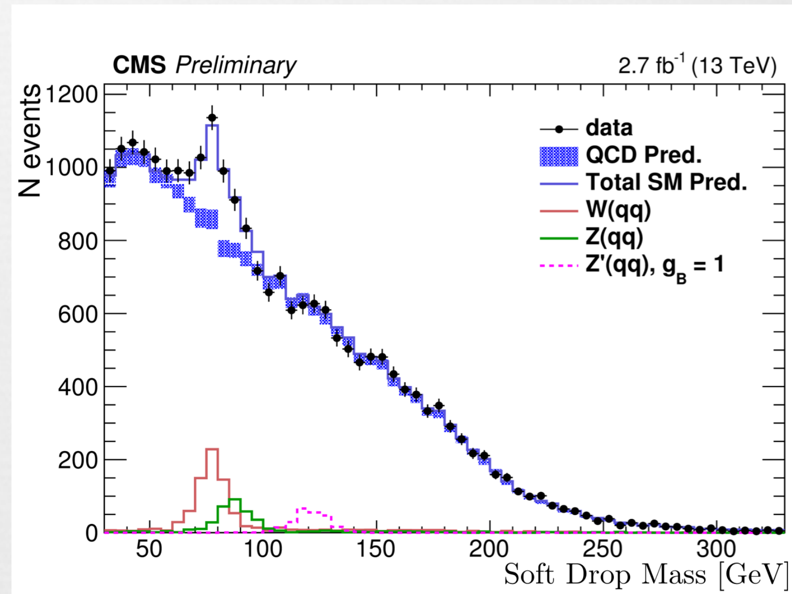


Jet substructure observables play an important role in a variety of searches, e.g. dark matter.


Absolute Performance
Stability

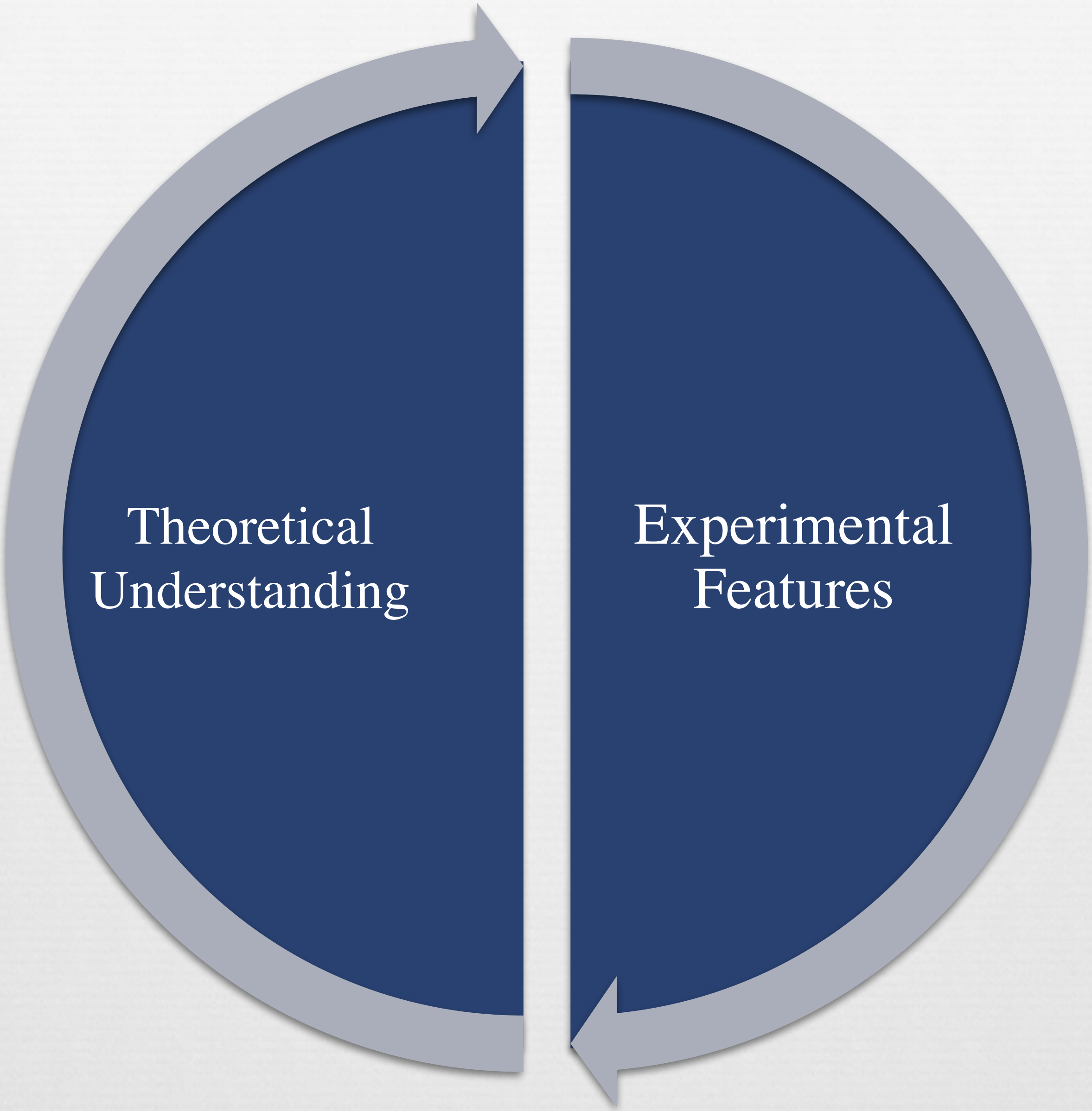
Stability in m_J and p_{TJ}

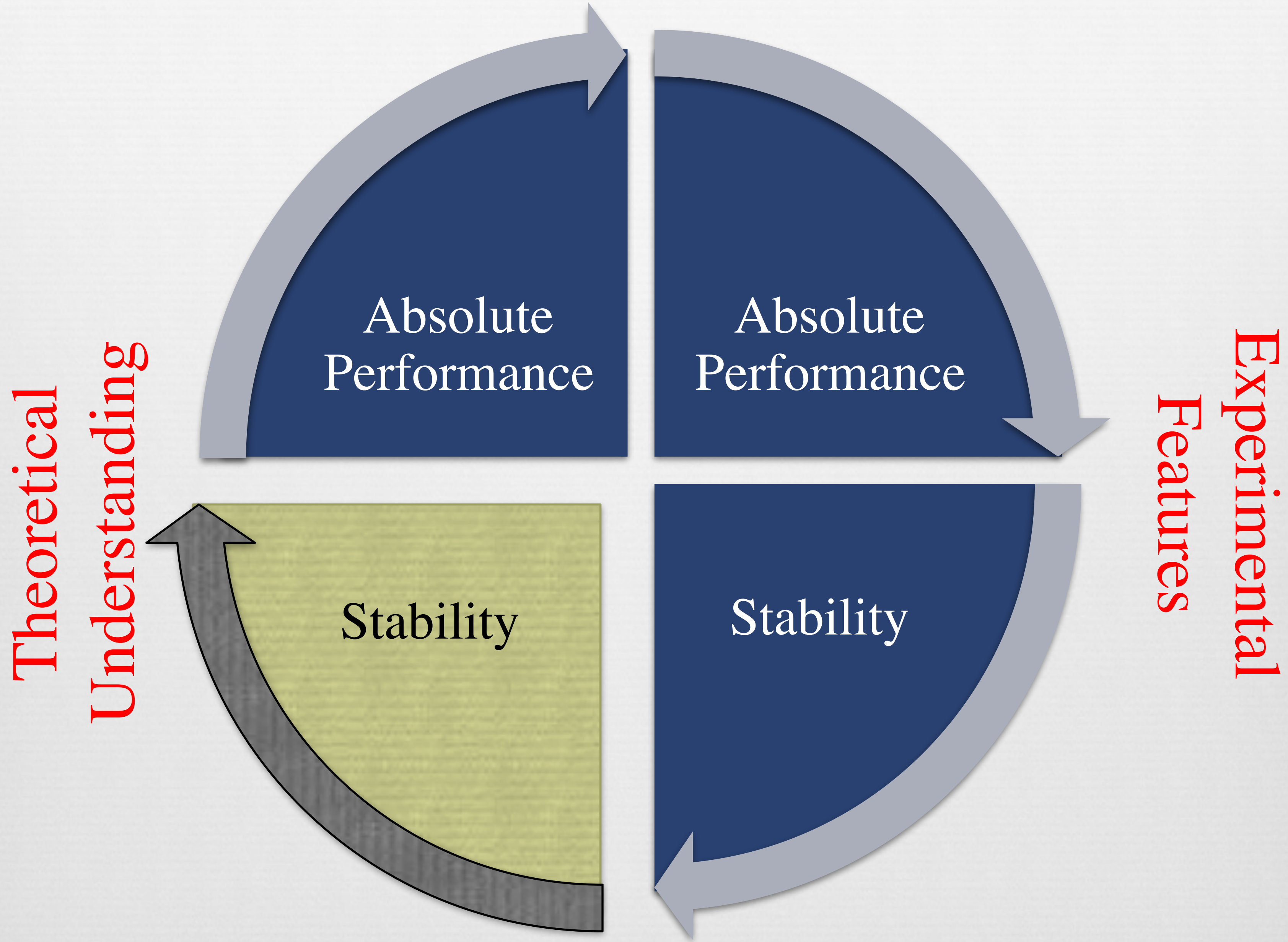




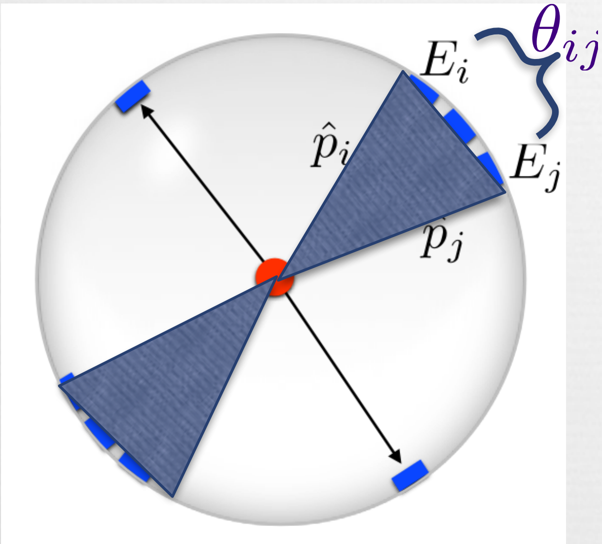
Use more stable substructure observables leads to improved performance. For example, DDT.

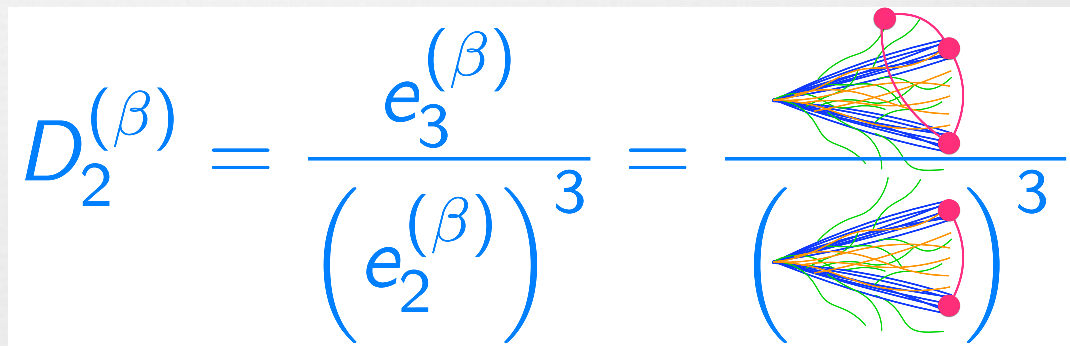
[Dolen, Harris, Marzani, Rappoccio, Tran 1603.00027]


Theoretical Understanding
Experimental Features


Absolute Performance
Absolute Performance
Stability
Stability
Theoretical Understanding
Experimental Features

Problem: Unstable Observables



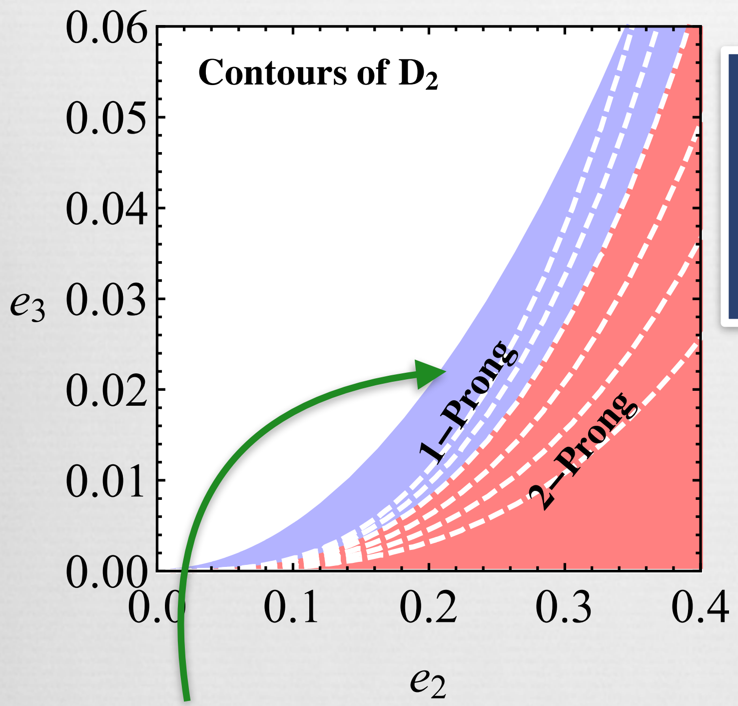


For definitions, see backup slides

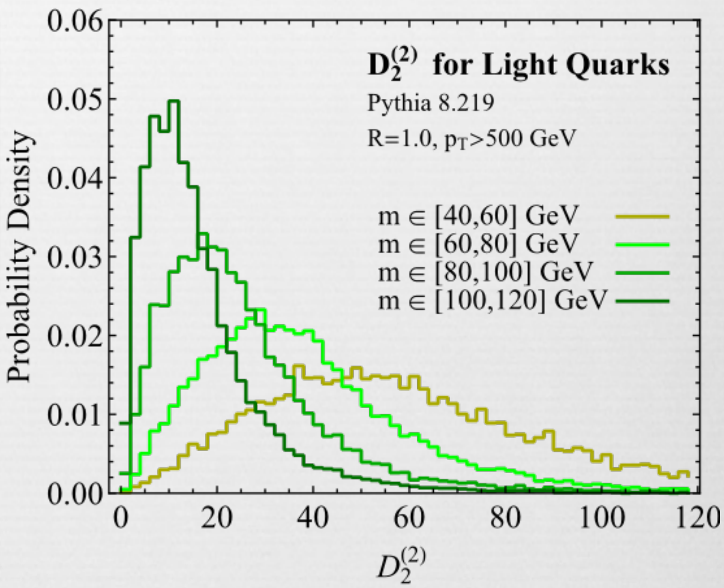
- D_2 is designed from power counting to optimize performance.

[Larkoski, Moult, Neill 1507.03018]

Problem: Unstable Observables



Can easily detect power law scaling with power counting!



$$D_2^{(2),\max} \sim \frac{e_3^{(2)}}{(e_2^{(2)})^3} \sim \frac{(e_2^{(2)})^2}{(e_2^{(2)})^3} \sim \frac{1}{(e_2^{(2)})} \sim \frac{p_T^2}{m_J^2}$$

No power law scaling means ``parametric stability"

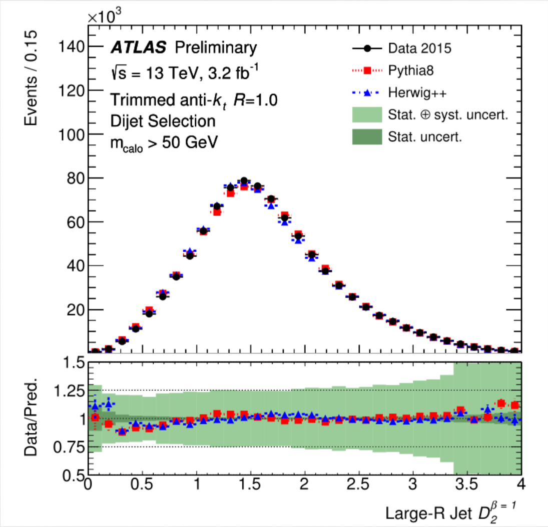
Stability

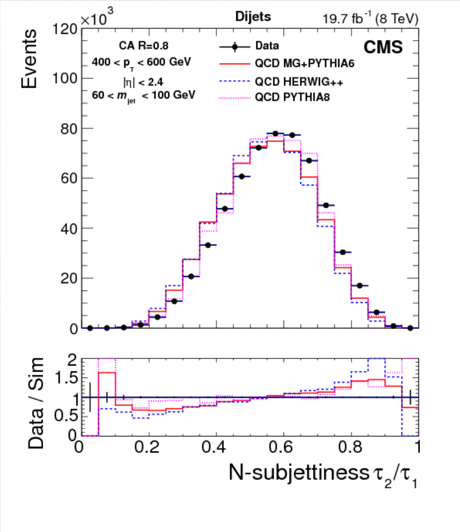
- There are multiple ways we can make stable observables:

Groom away soft radiation

Construct an intrinsically stable observable

R2D2 tagger



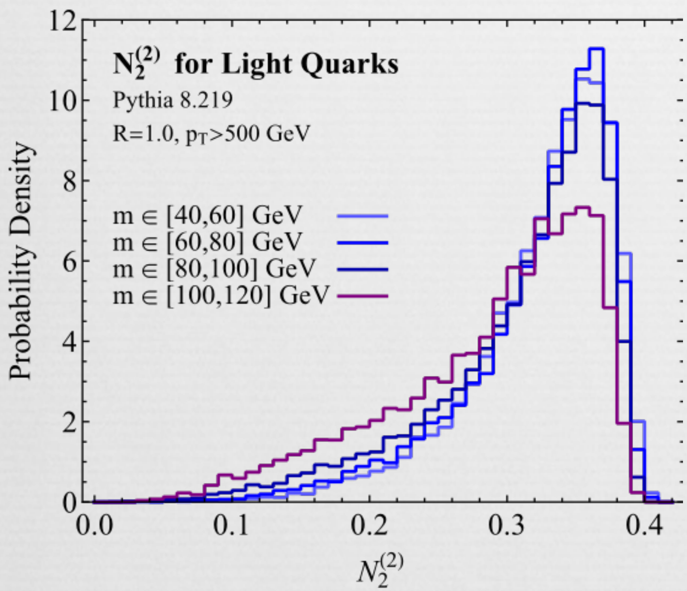


N-subjettiness

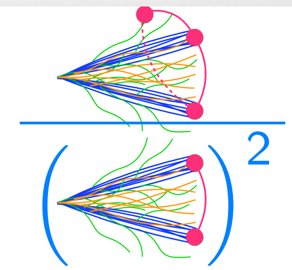
Further numerical instability can be removed by DDT.

Stability

- New energy correlation based observable N_2 parametrically stable <u>with</u> and <u>without</u> grooming!



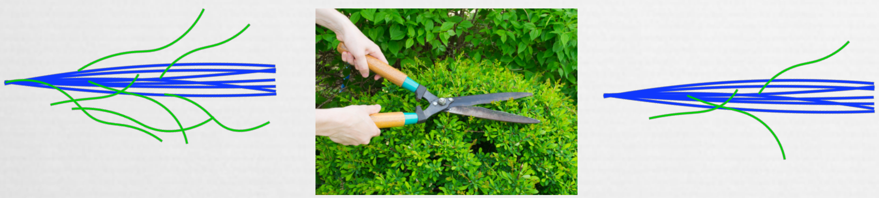
$$N_2^{(\beta)} = \frac{{}_2e_3^{(\beta)}}{\left(e_2^{(\beta)}\right)^2} =$$



Further numerical instability can be removed by DDT.

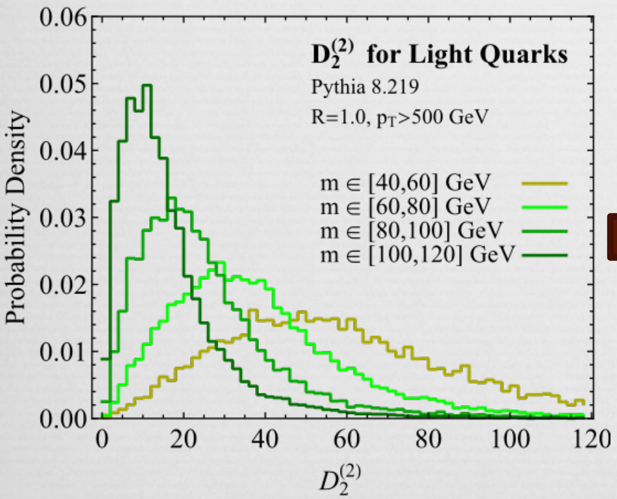
- N_2 power counts similarly as N-subjettiness, but avoids pathological issues with axes.

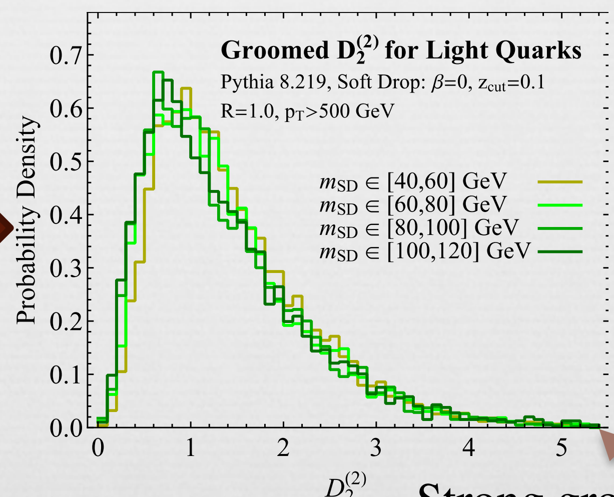
Strategy 1: Groom away soft radiation



- Softdrop
- Pruning
- Trimming
- Mass Drop
- …

- ATLAS used trimming to improve stability of D_2

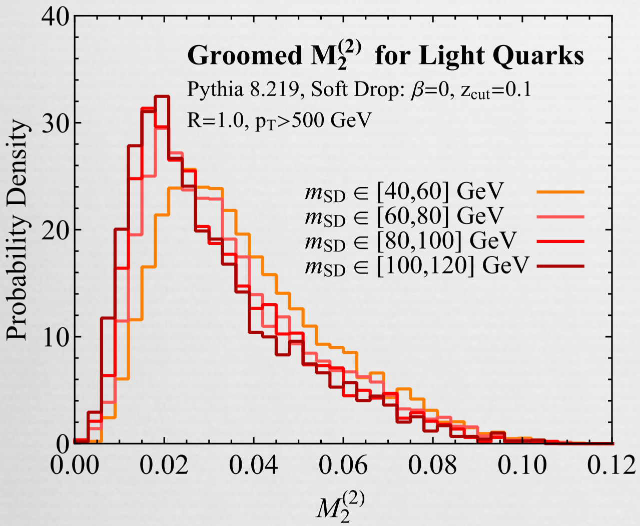




[Ellis, Vermilion, Walsh 0903.5081]
[Krohn,Thaler,Wang 0912.1342]
[Dasgupta, Fregoso, Marzani, Salam 1307.0007]
[Larkoski, Marzani, Soyez, Thaler 1402.2657]

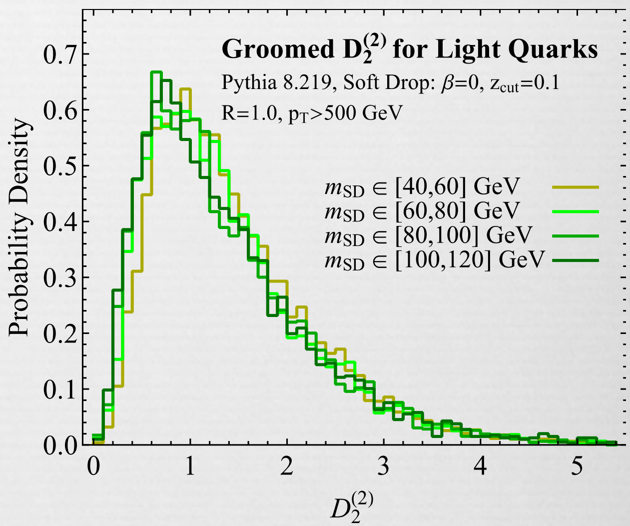
Strong grooming stabilizes the shape

Strategy 1: Groom away soft radiation



$$M_2^{(\beta)} = \frac{{}_1e_3^{(\beta)}}{(e_2^{(\beta)})}$$

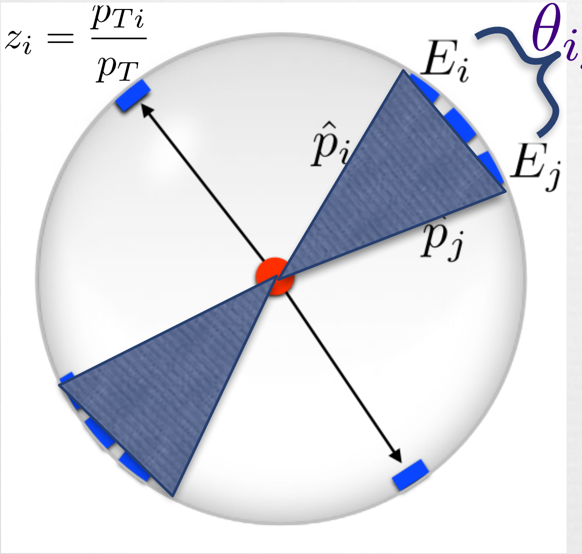
$$D_2^{(1,2)} = \frac{e_3^{(1)}}{(e_2^{(2)})^{3/2}}$$

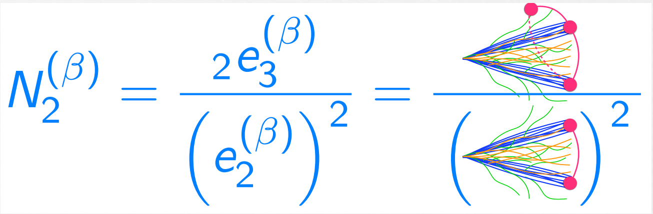


We can build more observables which are stable after grooming.

For detailed definitions, see backup slides

Strategy 2: Build a stable observable

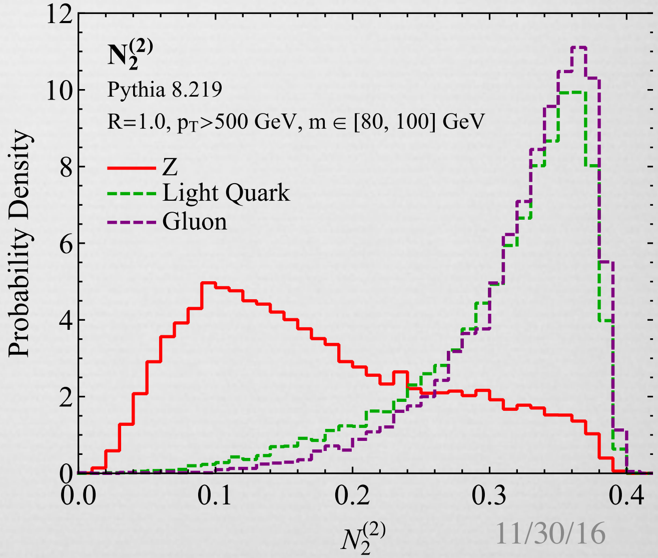




$$N_2^{(\beta)} = \frac{2e_3^{(\beta)}}{(e_2^{(\beta)})^2} = \frac{\sum_{i,j,k} z_i z_j z_k \min(\theta_{ij}^\beta \theta_{kj}^\beta, \theta_{ij}^\beta \theta_{ik}^\beta, \theta_{kj}^\beta \theta_{ik}^\beta)}{(\sum_{i,j} z_i z_j \theta_{ij}^\beta)^2}$$

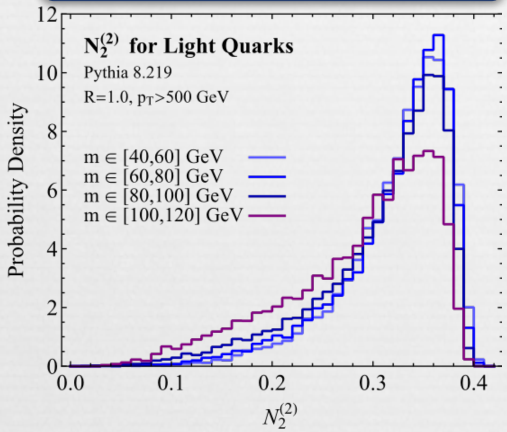
- Theoretically motivated for a good discrimination between 1 and 2-prong jets.
- Stable under changes of p_T and mass cuts!

Further numerical instability can be removed by DDT.



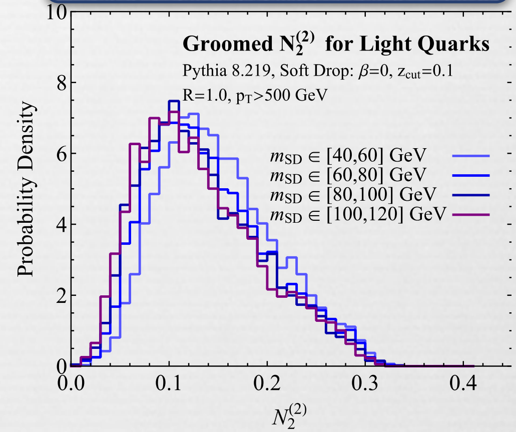
Strategy 2: Build a stable observable

Before Grooming



And everything in between!

After Grooming

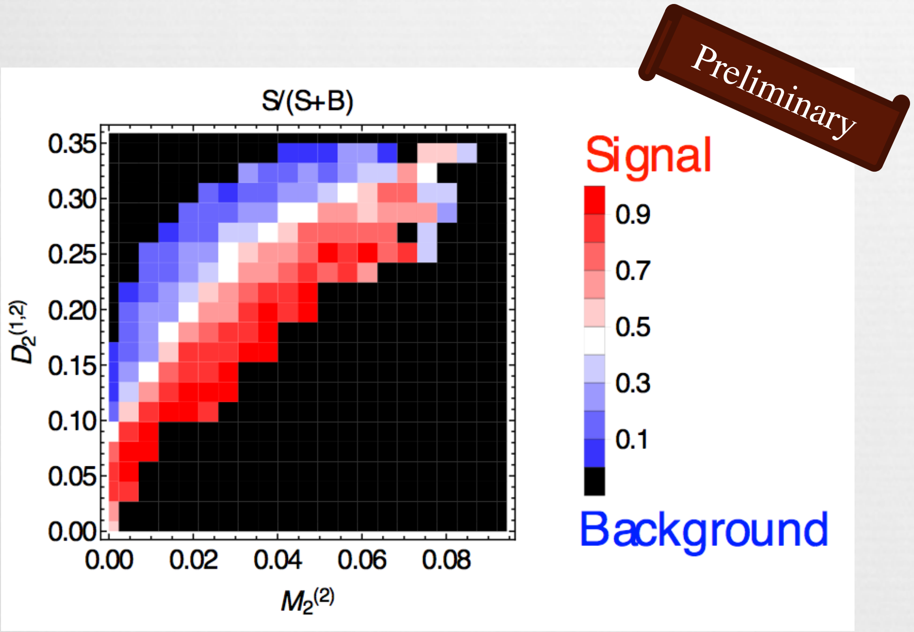


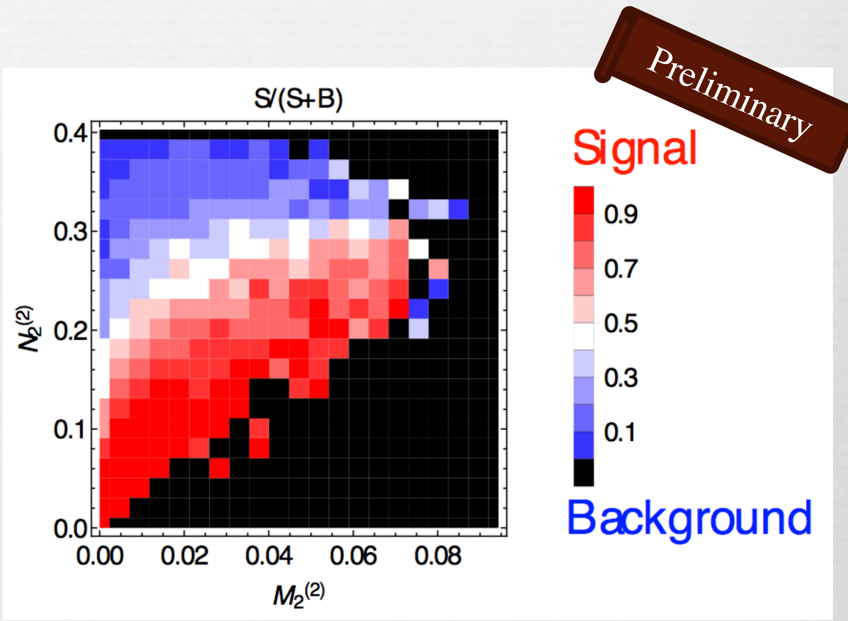
- Theoretically motivated for a good discrimination between 1 and 2-prong jets.
- Stable under changes of p_T and mass cuts!

Further instability can be removed by DDT.

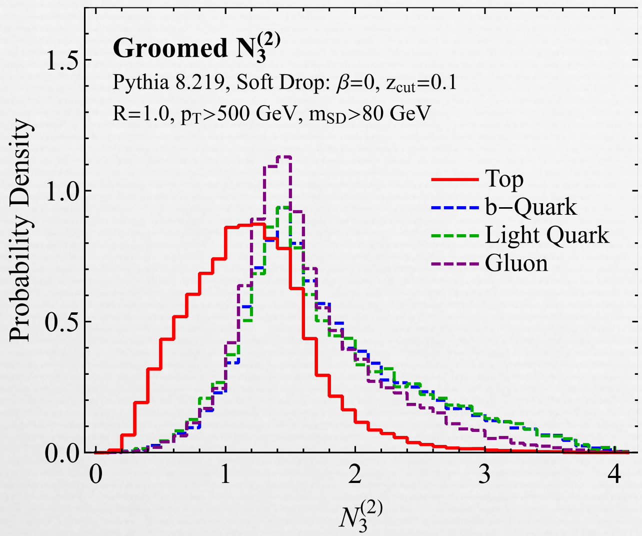
For power counting arguments, see backup slides

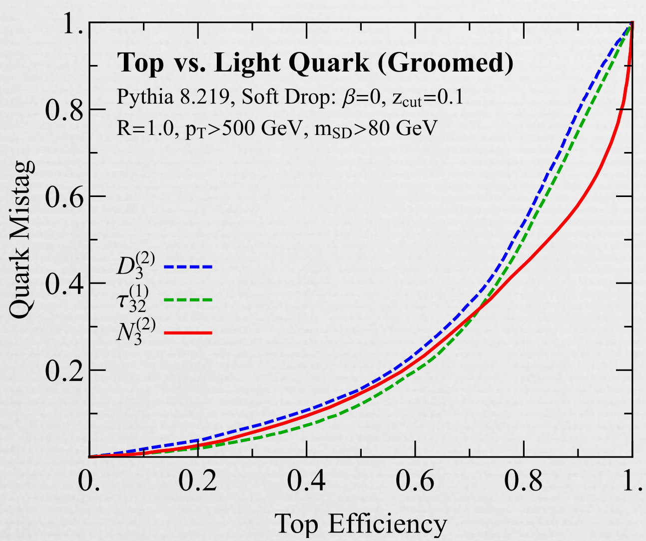
Looking ahead: Correlations





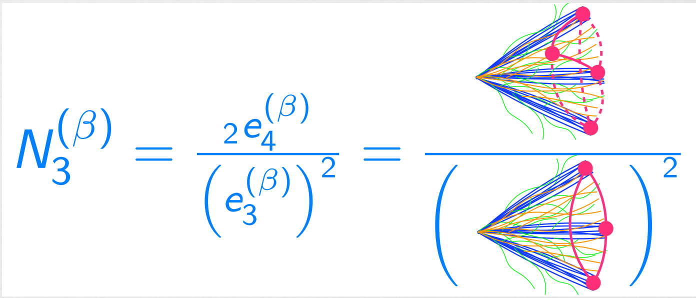
- Now we have 3 observables constructed from the same functions.
- Interesting to think about extending 1-D to 2-D observables.





Top Tagging

Extension of the same observables to 3 prong.



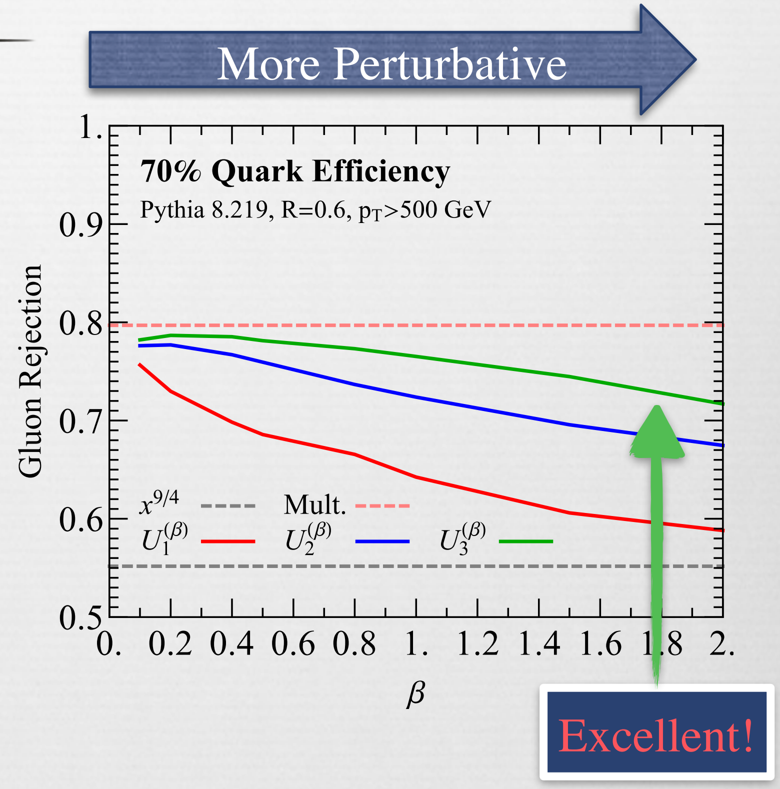
$$N_3^{(\beta)} = \frac{{}_2e_4^{(\beta)}}{(e_3^{(\beta)})^2}$$

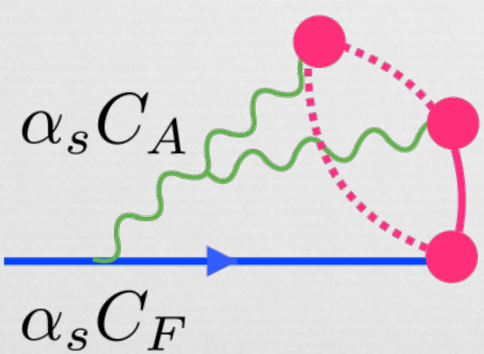
Quark/Gluon discrimination

Quarks and Gluons have different color factors, which allows for discrimination. Probing multiple emissions improves discrimination.

$$U_n^{(\beta)} = {}_1e_n^{(\beta)}$$

This observable is a measure of the ``number" of emissions!





Stability

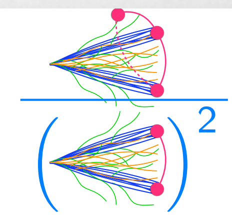
- We have the ability to construct observables with particular parametric features.
- Power counting is a useful diagnostic tool (see backup slides for CMS hybrid strategy).
- We focused on stability because it is of experimental significance.
- Experimental input is appreciated!

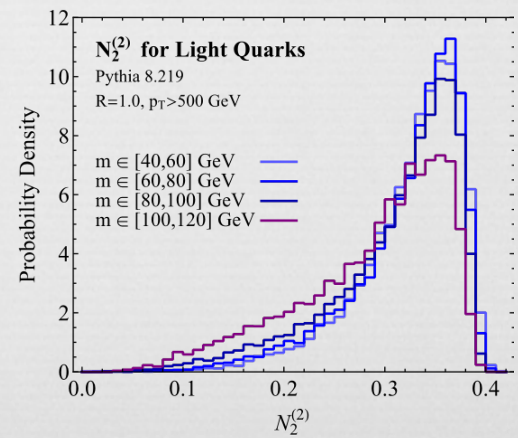
> All observables are available in fastjet contrib under EnergyCorrelator 1.2.0

Groom away soft radiation

Construct an intrinsically stable observable

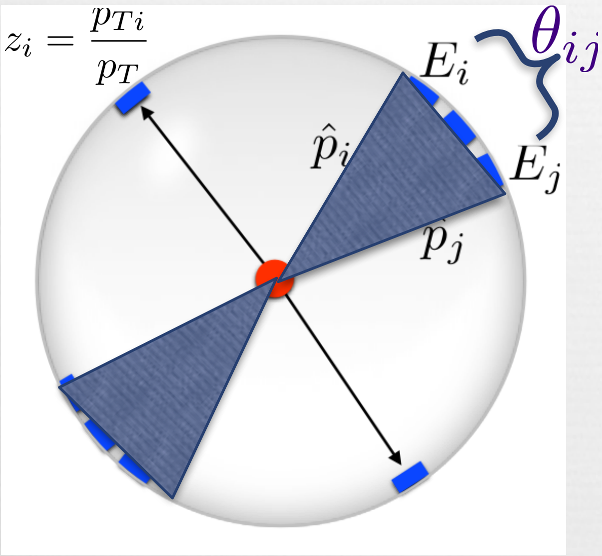
$$N_2^{(\beta)} = \frac{{}_2e_3^{(\beta)}}{\left(e_2^{(\beta)}\right)^2} =$$





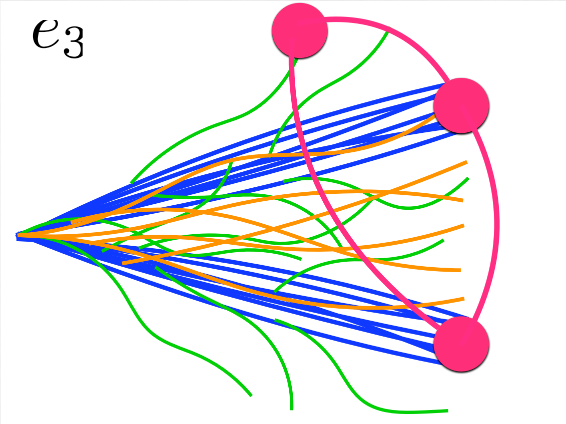
Backup Slides

Exploring Old Angles

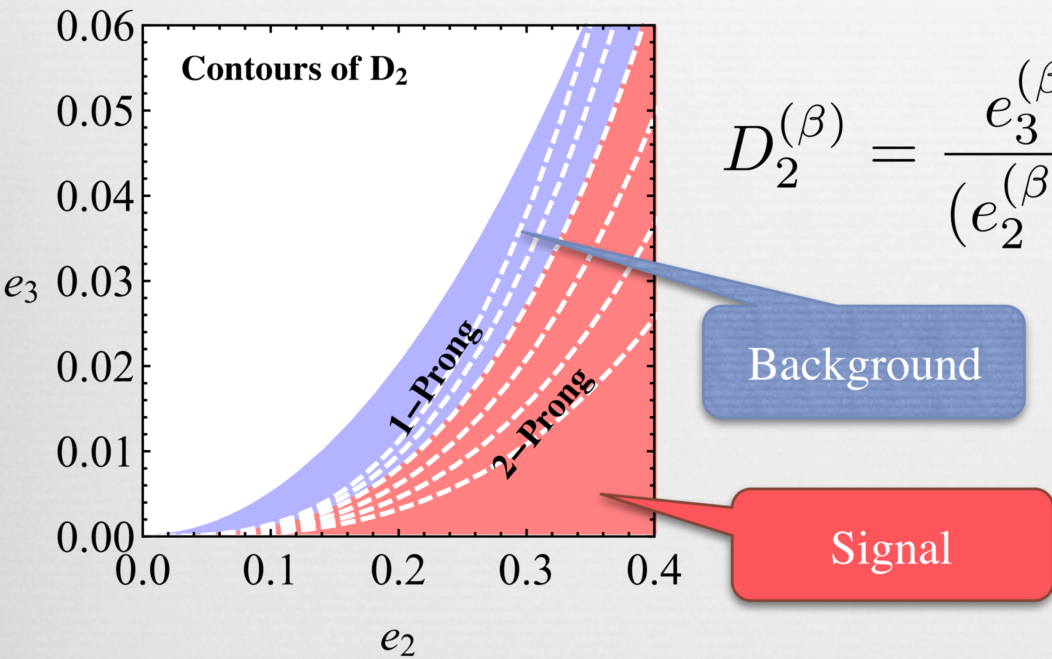


$$e_2^{(\beta)} = \sum_{i,j} z_i z_j \theta_{ij}^{\beta}$$

$$e_3^{(\beta)} = \sum_{i,j,k} z_i z_j z_k \theta_{ij}^{\beta} \theta_{kj}^{\beta} \theta_{ik}^{\beta}$$



D_2



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

Background:

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

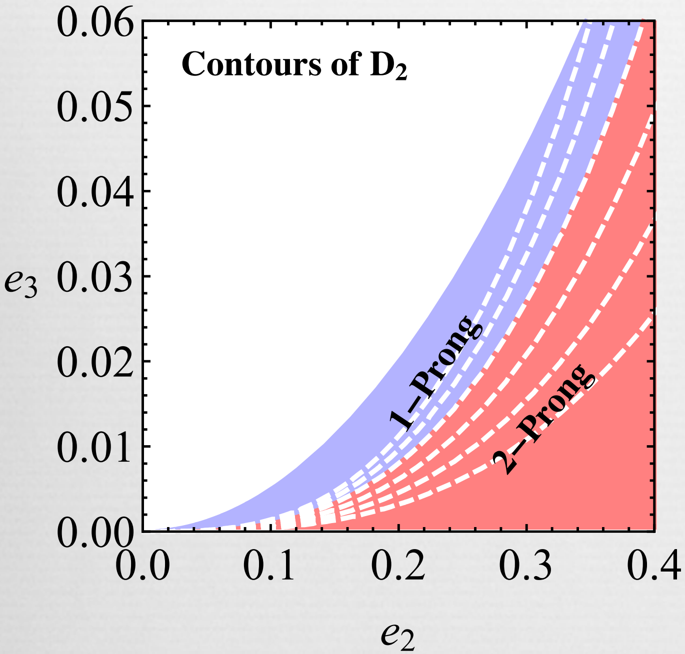
Signal:

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

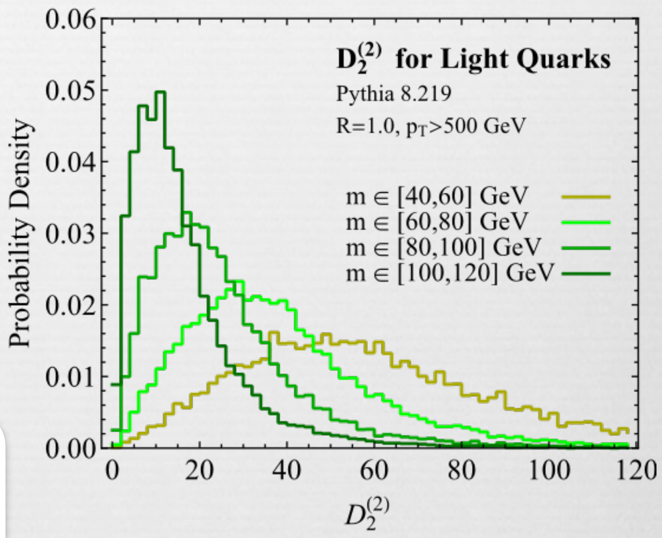
- From power counting, D_2 is the optimal observable obtained from the ``old'' energy correlation functions for 2-prong discrimination.

[Larkoski, Moult, Neill 1507.03018]

D_2



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

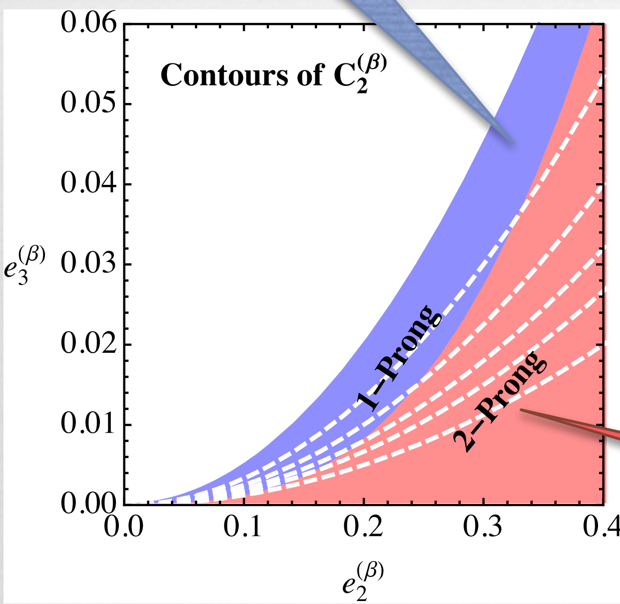


BUT:
D_2 is unstable!

- From power counting, D_2 is the optimal observables obtain from the ``old" energy correlation functions for 2-prong discrimination.
- Indeed it has been adopted at ATLAS.

[Larkoski, Moult, Neill 1507.03018]

C_2



Background

Signal

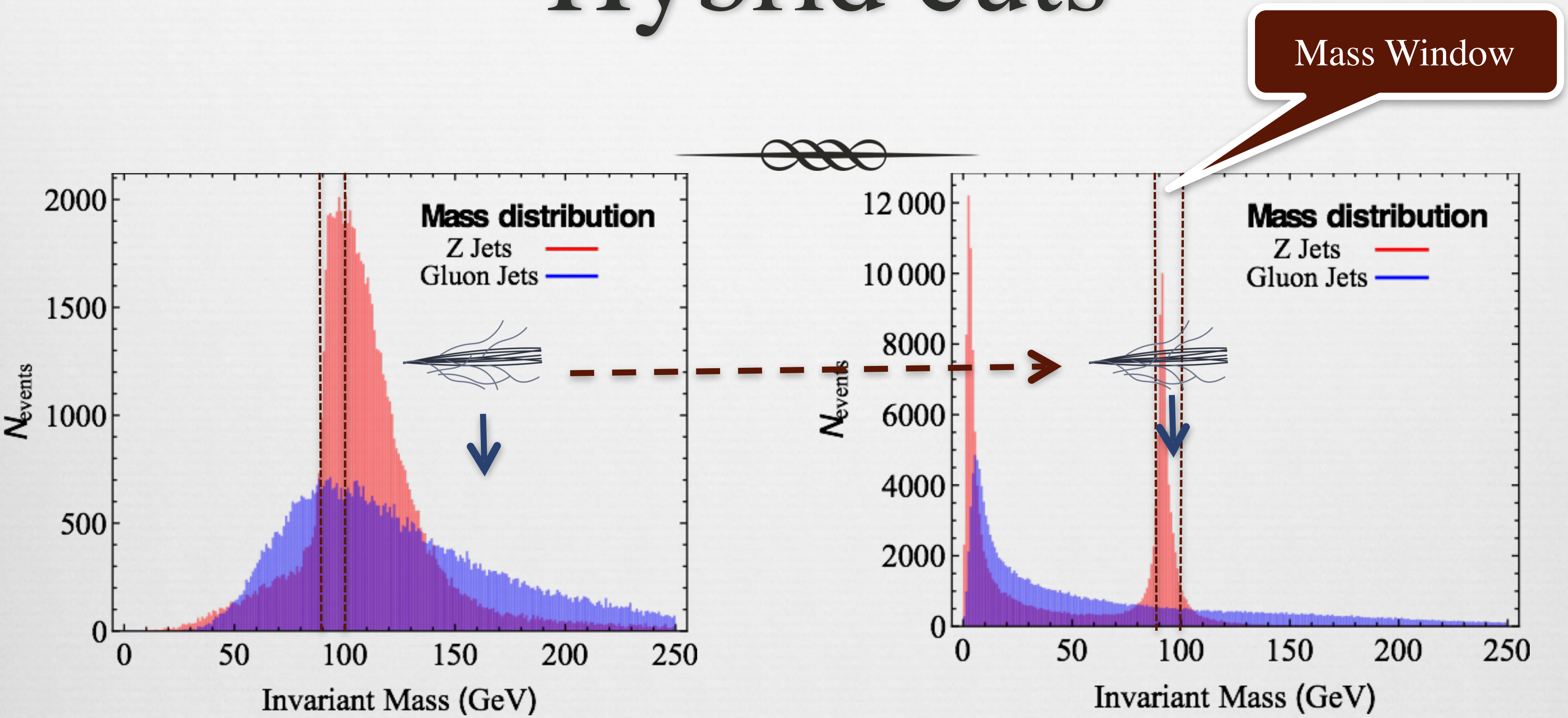
$$C_2^{(\beta)} = \frac{e_3^{(\beta)}}{(e_2^{(\beta)})^2}$$

BUT:
It can be shown from power counting that C_2 is not an optimal choice.

- It is used by CMS with a ``hybrid” cut.

[Larkoski, Thaler, Salam 1305.0007]

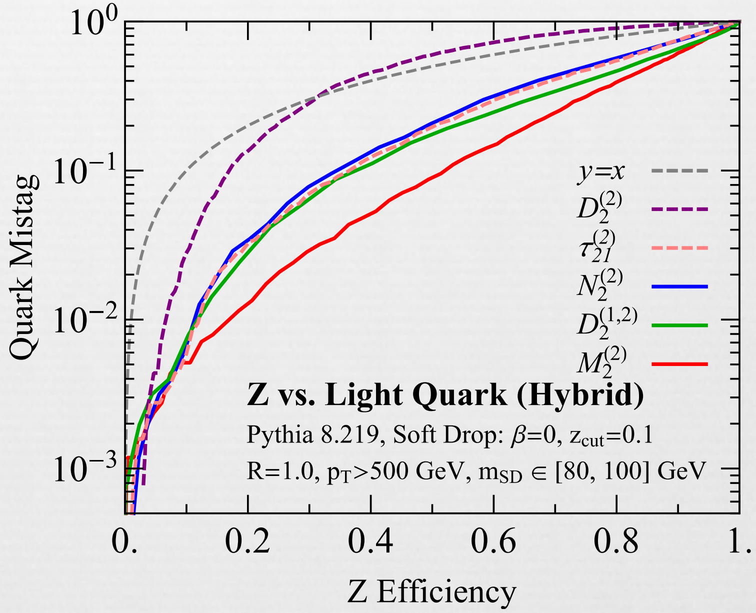
Hybrid cuts



- Strategy adopted by CMS, which makes C_2 perform well.
- Mass cut on the groomed mass.
- Effectively selects for higher mass.

Hybrid cuts

- Strategy adopted by CMS.
- Mass cut on the groomed mass.
- Effectively selects for higher mass.

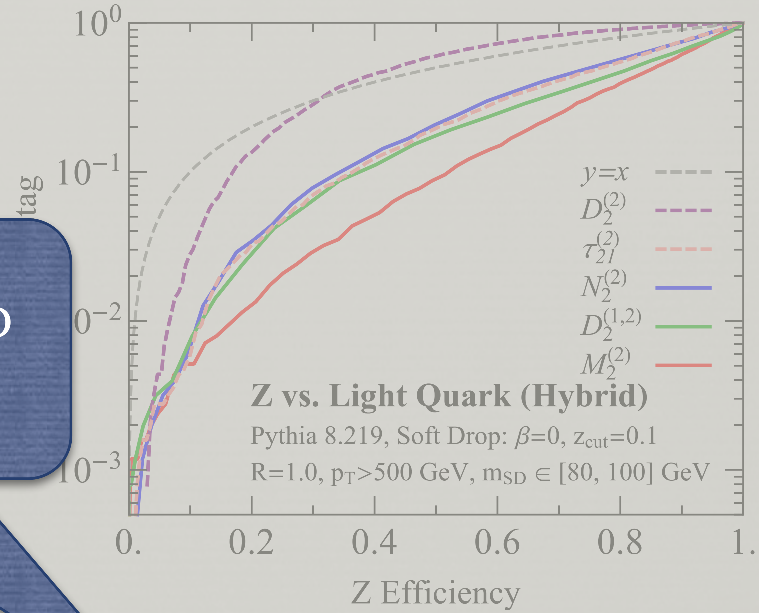


$$D_2^{(2),\text{max},} \sim \frac{P_{TJ}^2}{m_J^2} \qquad N_2^{(2),\text{max,peak}} \sim \text{const} \qquad M_2^{(2),\text{peak}} \sim \frac{m_J^2}{P_{TJ}^2}$$

Hybrid cuts

- Strategy adopted by CMS.
- Ma
  gro
- Effe
  higher mass.

Stable under standard AND hybrid cuts!

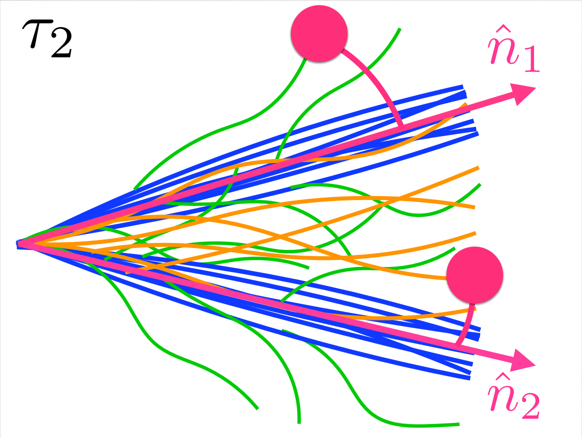


$D_2^{(2),\max,} \sim \frac{P_{TJ}^2}{m_J^2}$ $\quad N_2^{(2),\max,\text{peak}} \sim \text{const}$ $\quad M_2^{(2),\text{peak}} \sim \frac{m_J^2}{P_{TJ}^2}$

N-subjettiness

- N-subjettiness

$$\tau_{2,1} = \frac{\tau_2}{\tau_1}$$



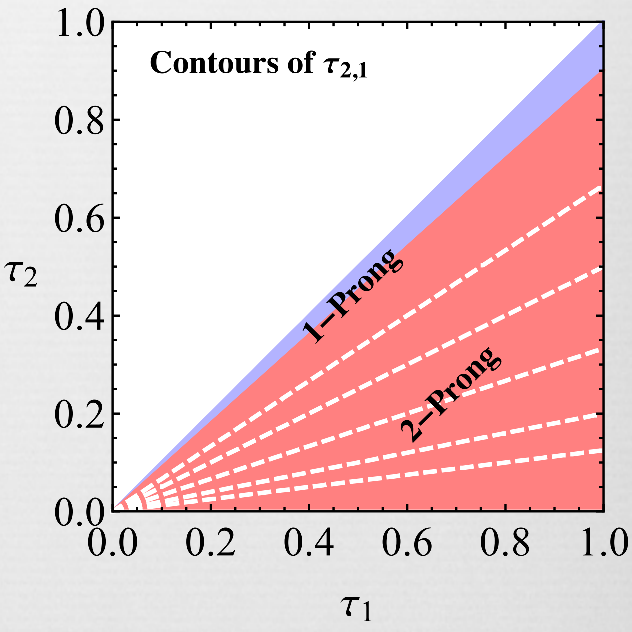
Background:

$\tau_2 \sim \tau_1$

Signal:

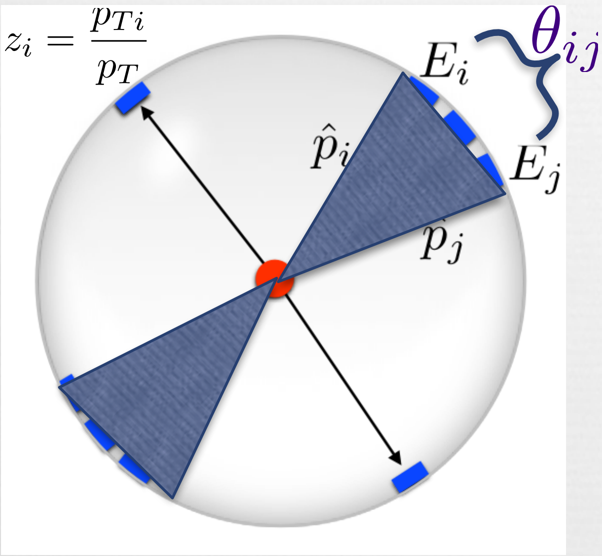
$\tau_2 < \tau_1$

BUT:
Axes are undefined in the unresolved limit.
Harder to calculate!



[Stewart, Tackmann, Waalewijn 1004.2489]
[Thaler, Van Tilburg 1011.2268]

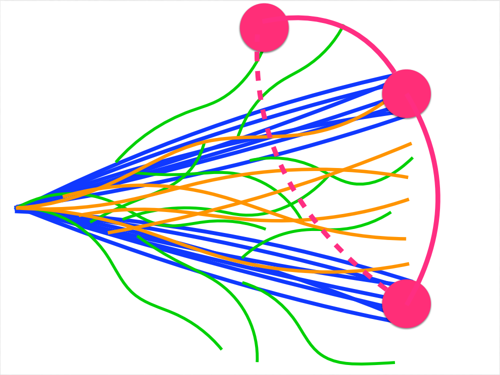
Exploring New Angles



$$e_2^{(\beta)} = \sum_{i,j} z_i z_j \theta_{ij}^{\beta}$$

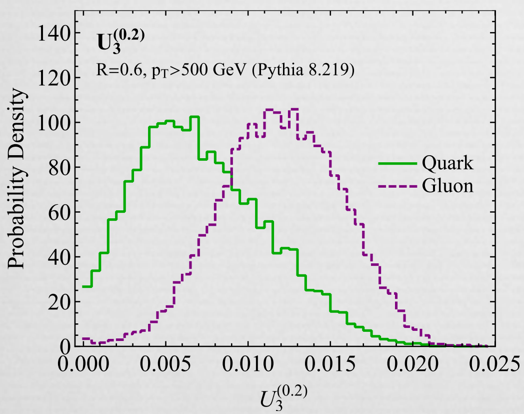
$${}_1e_3^{(\beta)} = \sum_{i,j,k} z_i z_j z_k \min(\theta_{ij}^{\beta}, \theta_{kj}^{\beta}, \theta_{ik}^{\beta})$$

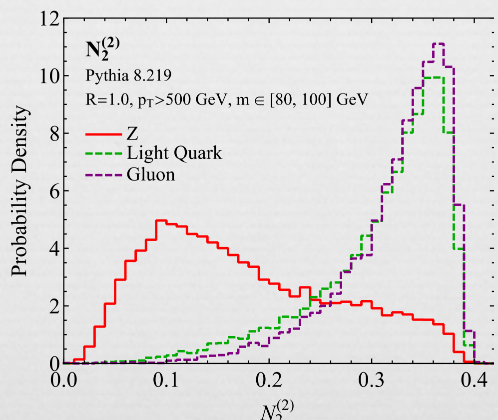
$${}_2e_3^{(\beta)} = \sum_{i,j,k} z_i z_j z_k \min(\theta_{ij}^{\beta}\theta_{kj}^{\beta}, \theta_{ij}^{\beta}\theta_{ik}^{\beta}, \theta_{kj}^{\beta}\theta_{ik}^{\beta})$$

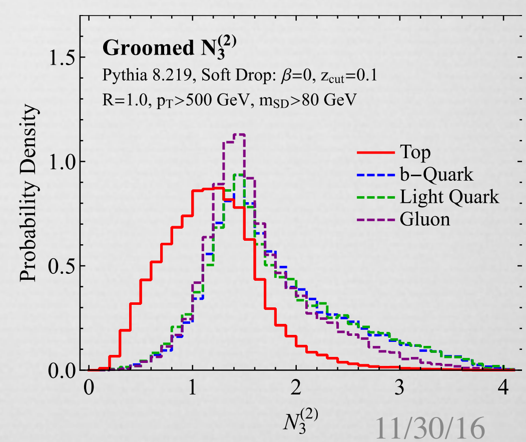


Observables of the Day

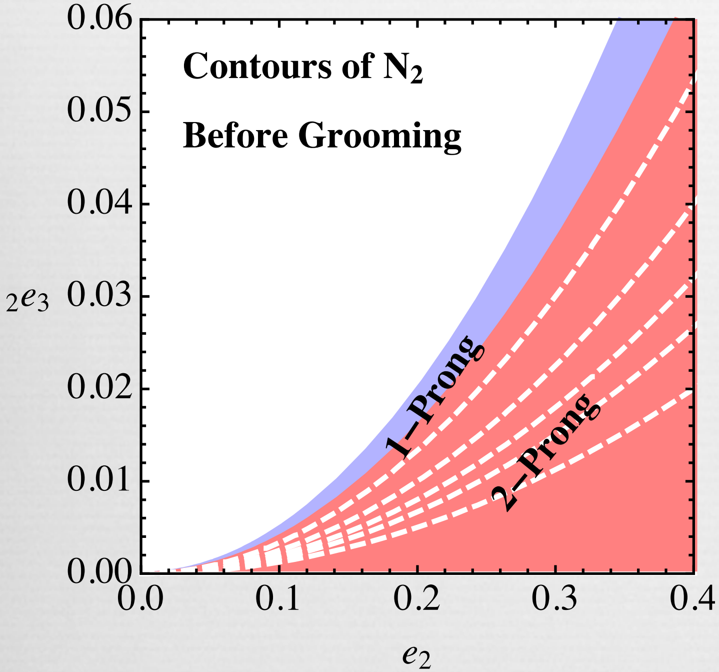
U_n → N_2, M_2, $D_2^{(1,2)}$ → N_3



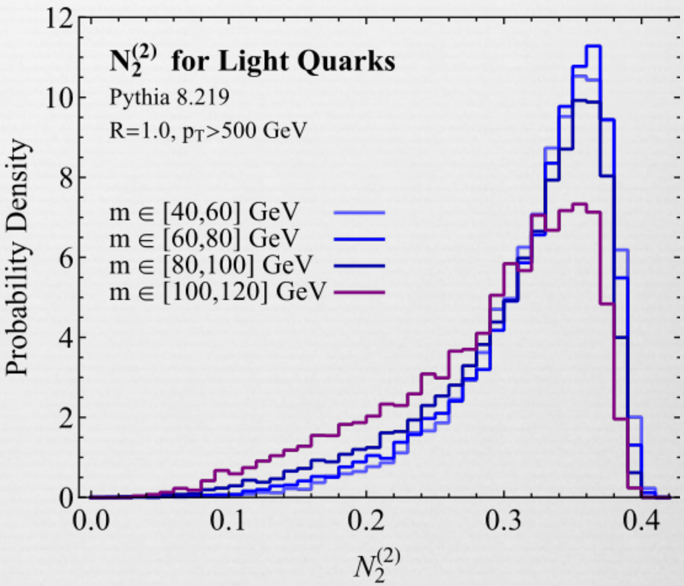




N_2



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



Background:

$$({}_2e_3^{(\beta)}) \sim (e_2^{(\beta)})^2$$

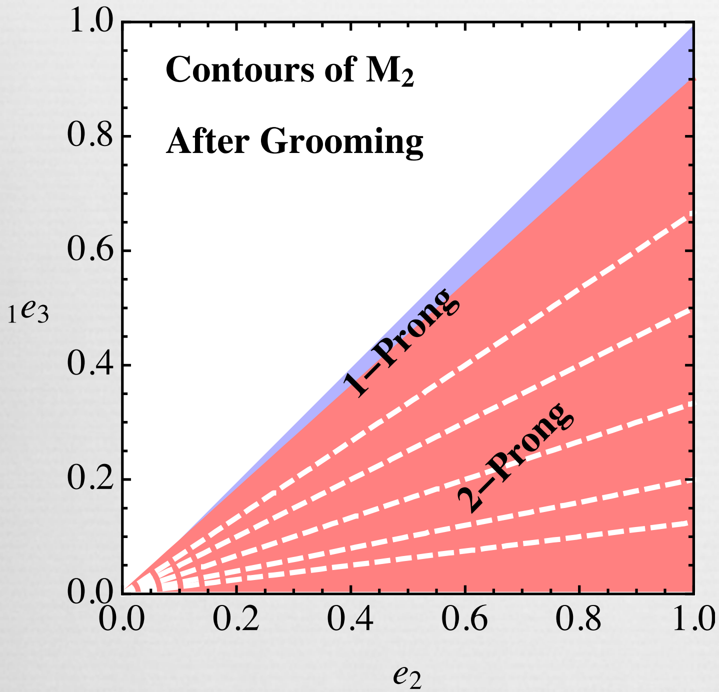
Signal:

$$({}_2e_3^{(\beta)}) < (e_2^{(\beta)})^2$$

- But most importantly, N_2 is stable!

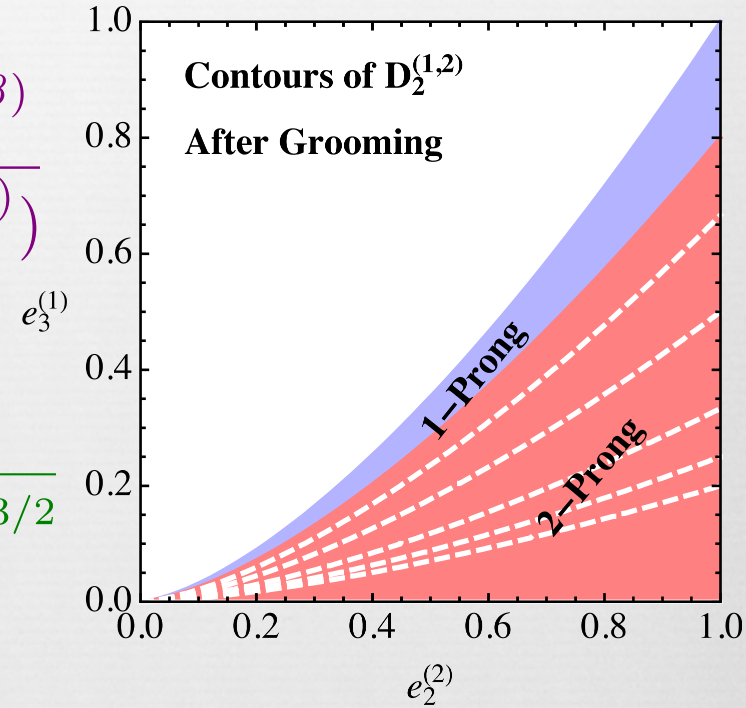
$$N_2^{(2),\max} \sim \frac{(e_2^{(\beta)})^2}{(e_2^{(\beta)})^2} \sim \text{const}$$

More Observables After Grooming



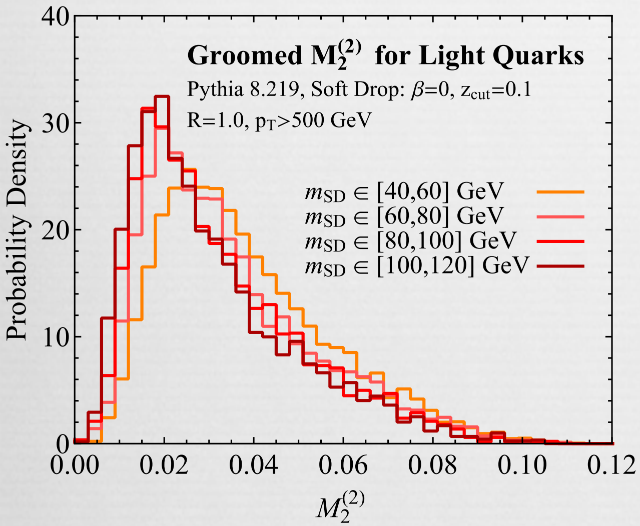
$$M_2^{(\beta)} = \frac{{}_1e_3^{(\beta)}}{\left(e_2^{(\beta)}\right)}$$

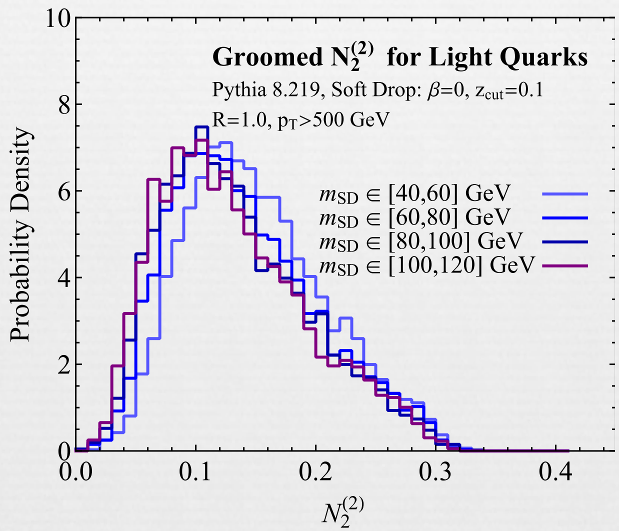
$$D_2^{(1,2)} = \frac{e_3^{(1)}}{\left(e_2^{(2)}\right)^{3/2}}$$

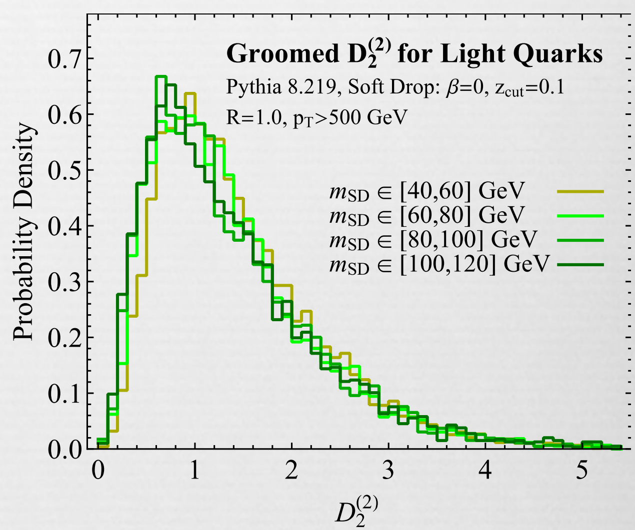


- New observables are stable after grooming!

Stability after Grooming

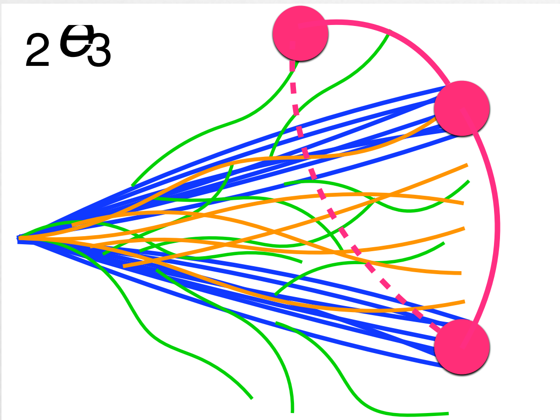


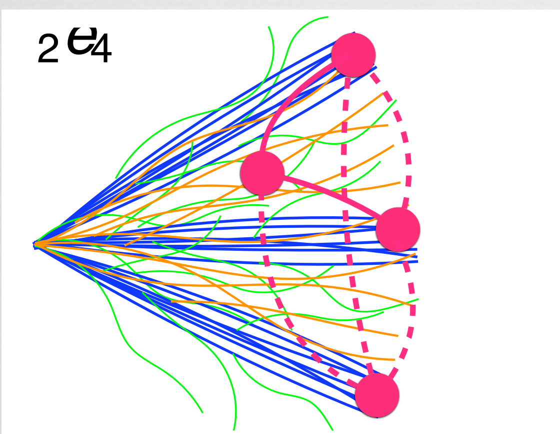


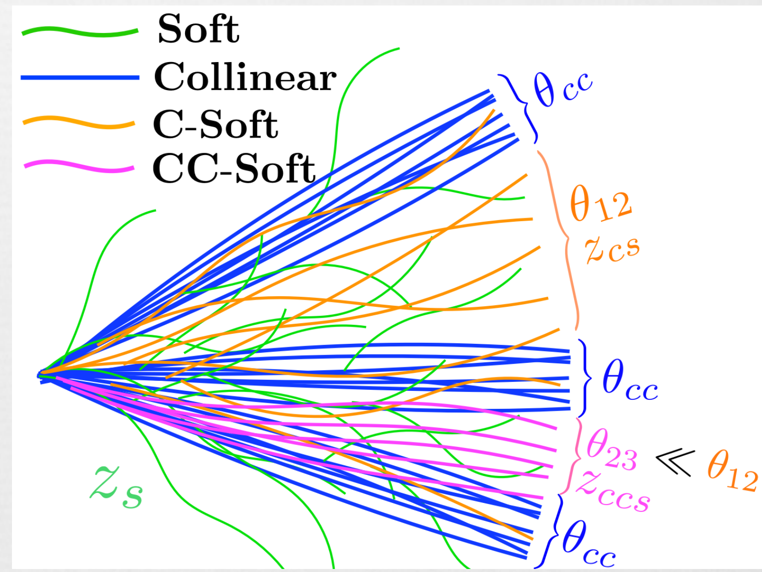


- Groomed observables are stable!

Build the same strategy for other searches:



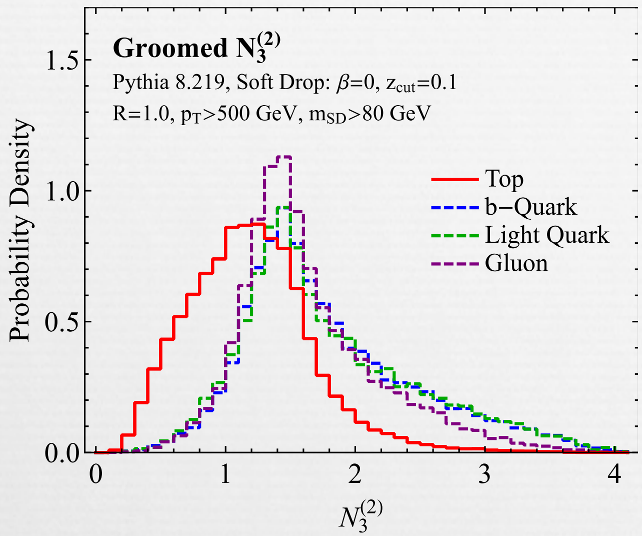


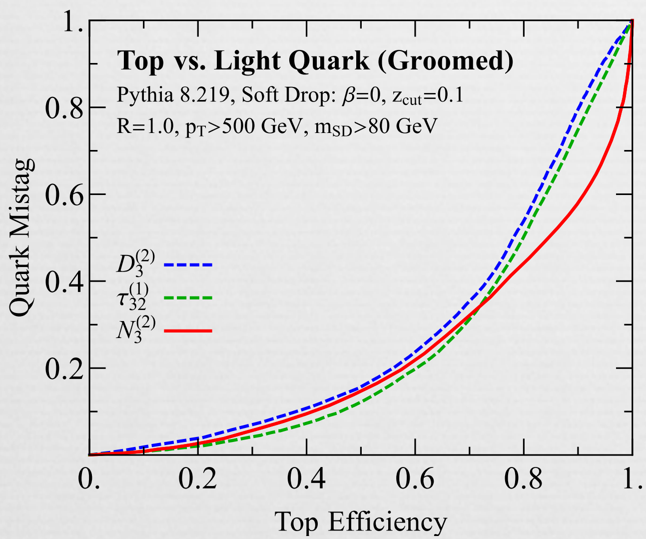


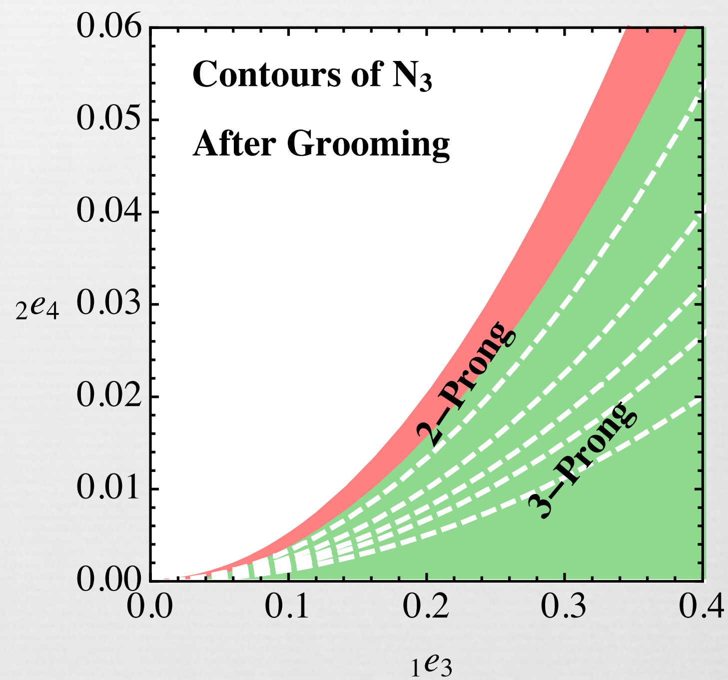
- Extending the generalized energy correlation functions from 2 prong, to 3 prong.

$$N_3^{(\beta)} = \frac{{}_2e_4^{(\beta)}}{(e_3^{(\beta)})^2}$$

Top Searches



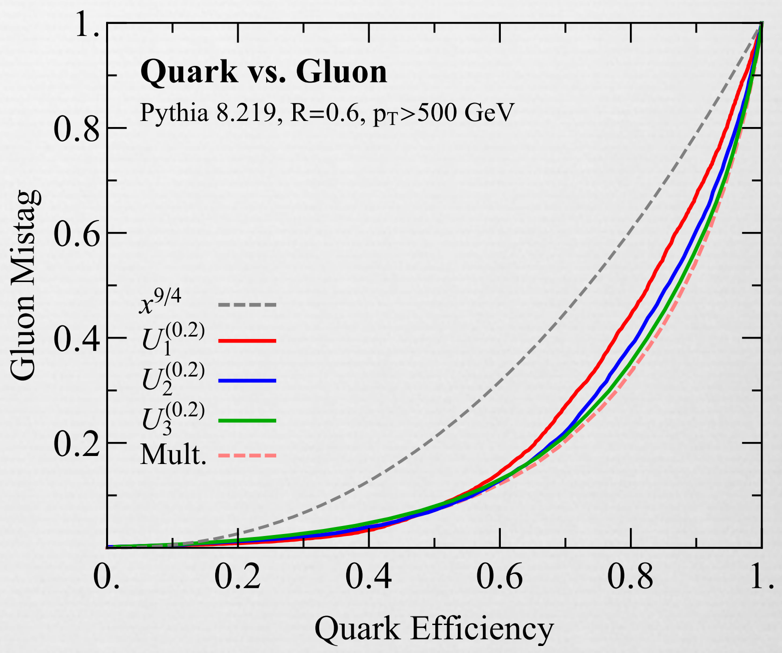




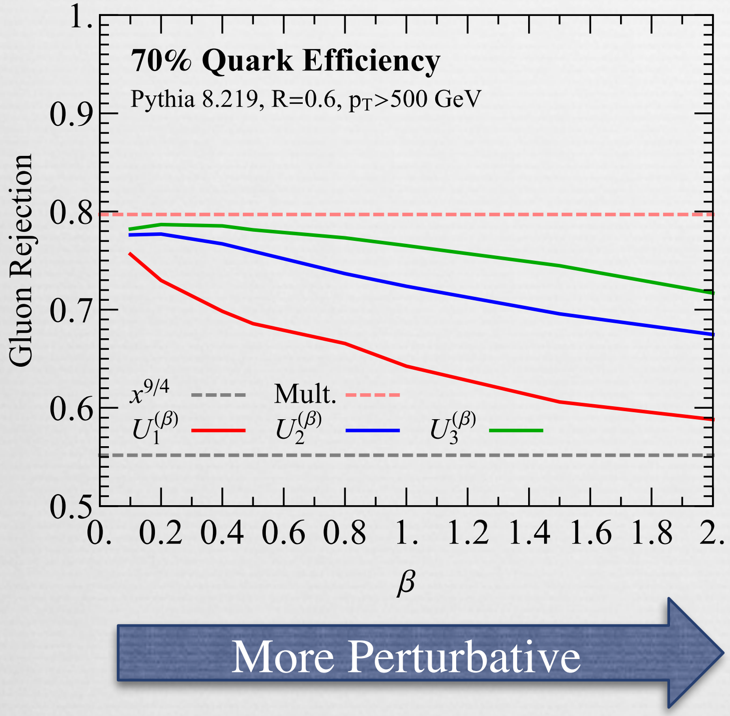
Quark/Gluon discrimination

- Beyond Casimir scaling by probing multiple emissions.
- U_n asymptotes to a measurement of multiplicity.

$$U_n^{(\beta)} = {}_1e_n^{(\beta)}$$



Quark/Gluon discrimination



$$U_n^{(\beta)} = {}_1e_n^{(\beta)}$$

- Small beta, small angles, non perturbative regime.
- Stability of U_3 as a function of beta is a great feature. High beta, more control.