Jets in Vacuum: Theory

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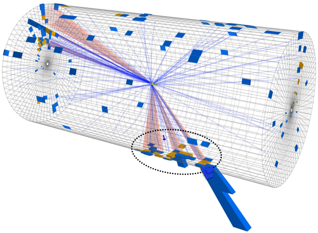


Outline

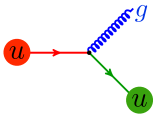
- Theoretical Aspects of Jets
  - Infrared and Collinear Safety and Jet Observables
  - Resummation
- From e^+e^- Event Shapes to Jets in pp
  - e^+e^- Event Shapes
  - Jets in pp
  - Groomed Observables

Why Jets?

QCD

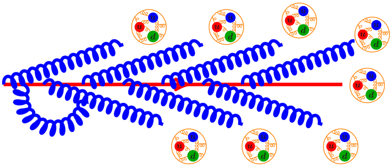
- QCD is an $SU(3)$ gauge theory:

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



- Microscopic degrees of freedom are quarks and gluons.

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

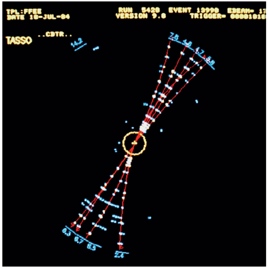


- Jets act as proxies for quarks and gluons.
- Jets are our probe of the underlying microscopic dynamics.

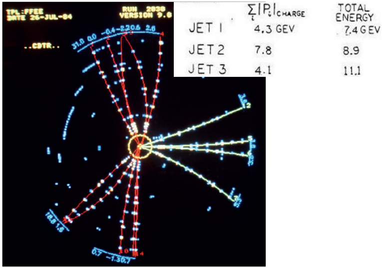
Jets at PETRA

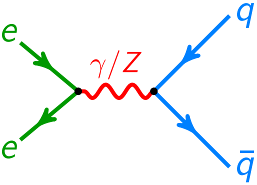
- Kinematics of jets used to infer gluon emission in hard scattering.

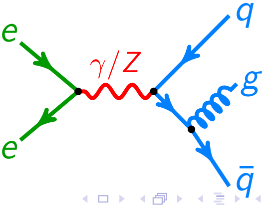
2-Jet Event



3-Jet Event



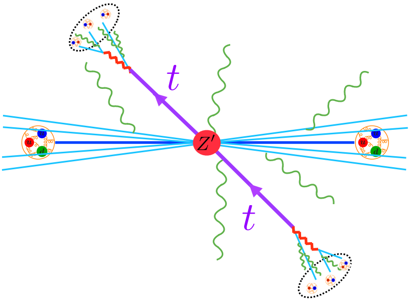




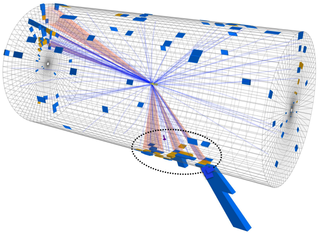
Jets at the LHC: Internal Structure

- 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



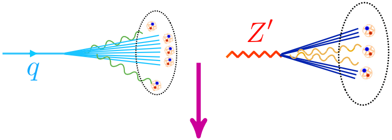
Event Display



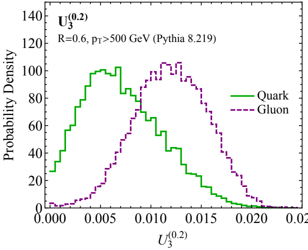
- Revolutionizes the types of questions we can/must ask about jets:
  $\Longrightarrow$ jets have substructure!

Jet Substructure

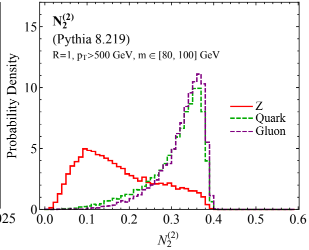
- Jet substructure: measure properties (charge, energy, etc) of radiation in a jet to extract information about its origin.



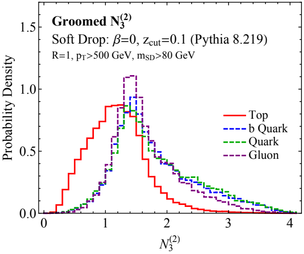
Quark vs. Gluon



$W/Z/H$ Tagging



Top Tagging

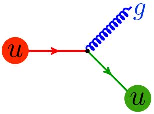


Infrared and Collinear Safety and Jet Observables

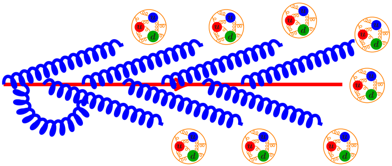
Perturbative Calculations

- We perform perturbative calculations in terms of quarks and gluons

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



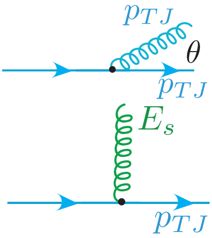
- But observables are measured on hadrons:



- For what observables is a perturbative calculation meaningful?

Non-Perturbative Corrections

- Non-perturbative corrections arise when you are sensitive to splittings with invariant mass $\sim \Lambda_{\mathrm{QCD}}$
- To have small invariant mass radiation can be either
  - Collinear: $m^2 \sim p_{TJ}^2\theta^2$
  - Soft: $m^2 \sim p_{TJ}E_s$



- Need observables to be well behaved in the soft and collinear limits.

Infrared and Collinear Safety

- Infrared and Collinear (IRC) Safety:

  An observable is infrared and collinear safe if it is insensitive to infinitesimally soft or exactly collinear emissions.

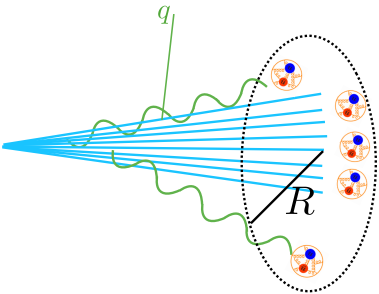
- Infrared and Collinear Safety implies that you get a finite answer at each order in perturbation theory.

- It does not mean that the answer is reliable!

- IRC safety is a primary guide in designing observables.

Infrared and Collinear Safety

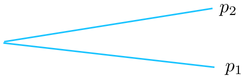
- What observables are Infrared and Collinear Safe:
  - Jet charge is not IRC safe.



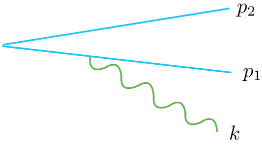
- An arbitrarily soft quark can carry charge away from the jet.
- Jet charge CANNOT be calculated in perturbation theory. A non-perturbative input function is required.
- Does NOT mean charge isn't interesting.

Infrared and Collinear Safety

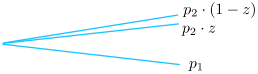
- What is Infrared and Collinear Safe:
  - Jet mass: $m_J^2 = \left(\sum_i p_i\right)^2$
- Consider a two-particle configuration that splits:



$$m^2 = (p_1 + p_2)^2 = 2p_1 \cdot p_2$$



$$m^2 = (p_1 + p_2 + k)^2 \simeq 2p_1 \cdot p_2$$

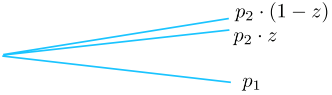


$$m^2 = (p_1 + p_2 \cdot z + p_2 \cdot (1-z))^2 = 2p_1 \cdot p_2$$

Infrared and Collinear Safety

- IRC safe observables are linear functions of energy.
- e.g. The observable $\sum_{i \in J} E_i^2$ is not IRC safe.

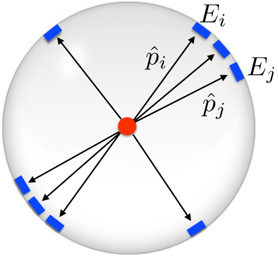
$$(E_2(1-z))^2 + (E_2 z)^2 \neq E_2^2$$



- Places strong constraints on perturbatively calculable observables.

Energy Correlation Functions

- Correlations of energies and angles are IRC safe.



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

- 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.

Generalized Energy Correlation Functions

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

General Energy Correlation Functions

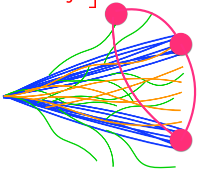
$${}_i e_j^{(\beta)} = \frac{1}{p_{TJ}^j} \sum_{1 \le n_1 < \cdots < n_j \le n} p_{Tn_1} p_{Tn_2} \ldots p_{Tn_j} \min\left(\prod_{s,t}^{i} R_{st}^{\beta}\right)$$

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

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

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

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

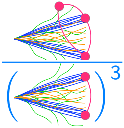


- Two particle correlation $e_2^{(2)}$ gives mass.

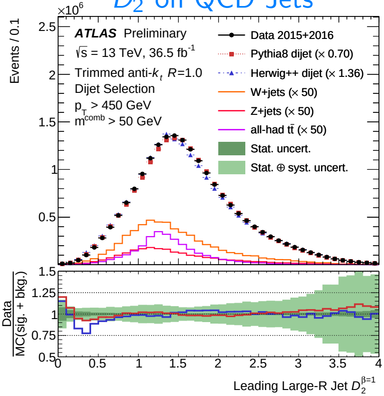
The Shape of Jets at the LHC: D_2

- D_2 distributions in ATLAS.

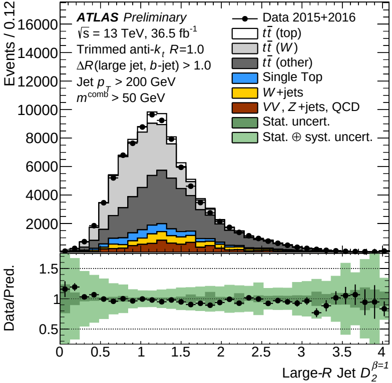
$$D_2^{(\beta)} = \frac{e_3^{(\beta)}}{\left(e_2^{(\beta)}\right)^3} =$$



D_2 on QCD Jets



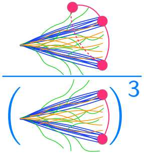
D_2 on W Jets



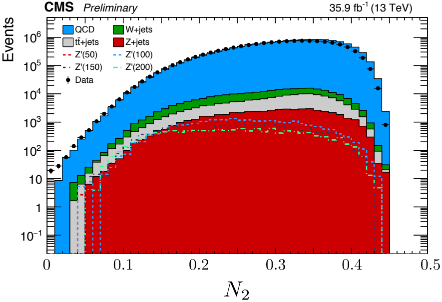
N_2 at CMS

- N_2 distributions in CMS.

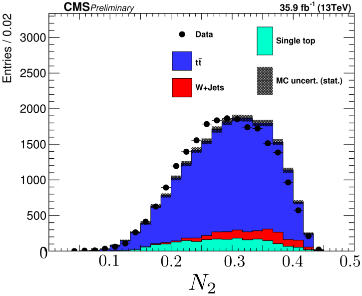
$$N_2^{(\beta)} = \frac{2\, e_3^{(\beta)}}{(e_2^{(\beta)})^2}$$



N_2 on QCD Jets



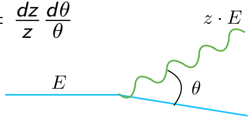
N_2 on W Jets



Resummation

A Standard QCD Calculation

- QCD has soft and collinear singularities: $P(z,\theta) = \frac{dz}{z}\frac{d\theta}{\theta}$



- We can try and compute the jet mass at lowest order (dropping all factors)

$$\frac{d\sigma}{dm_J^2} \sim \alpha_s C_F \int \frac{dz}{z}\frac{d\theta}{\theta}\delta\left(m_J^2 - z(1-z)\theta^2 p_{TJ}^2\right)$$

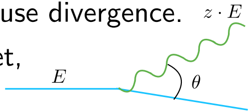
- Let $\tau = m_J^2/p_{TJ}^2$

$$\frac{d\sigma}{d\tau} \sim \alpha_s C_F \int \frac{dz}{z}\frac{d\theta}{\theta}\delta\left(\tau - z\theta^2\right)$$

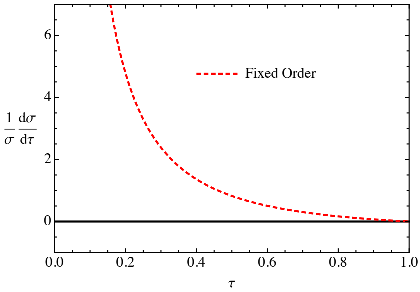
$$\sim \alpha_s C_F \frac{1}{\tau}\int_{\sqrt{\tau}} \frac{d\theta}{\theta} \sim \alpha_s C_F \frac{\log(\tau)}{\tau}$$

A Standard QCD Calculation

- Soft and collinear singularities, $P(z,\theta) = \frac{dz}{z}\frac{d\theta}{\theta}$, cause divergence.
- If one measures an observable $\tau = m_J^2/p_{TJ}^2$ on a jet,



$$\frac{d\sigma}{d\tau} = -\frac{2\alpha_s C_F}{\pi}\frac{\log\tau}{\tau}$$



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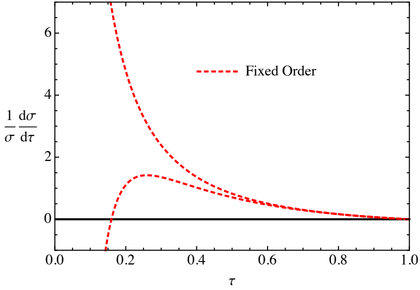
$$\frac{d\sigma}{d\tau} = -\frac{2\alpha_s C_F}{\pi}\frac{\log\tau}{\tau}\left(1 - \frac{\alpha_s C_F \log^2\tau}{\pi}\right)$$



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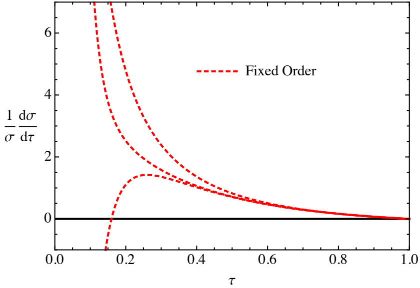

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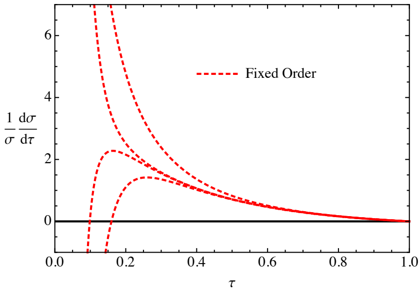

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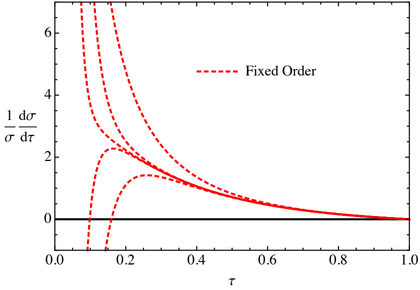

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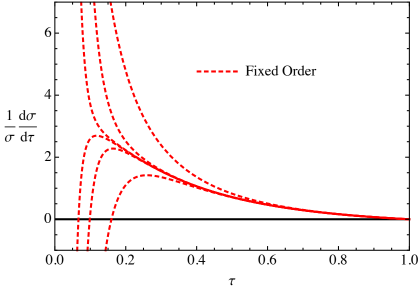

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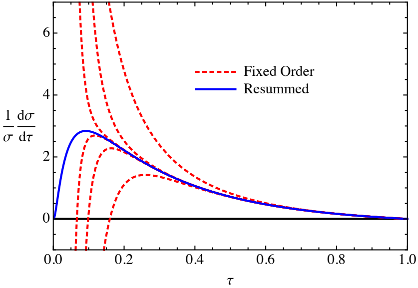
$$= -\frac{2\alpha_s C_F}{\pi}\frac{\log\tau}{\tau}\left(e^{-\frac{\alpha_s C_F}{\pi}\log^2\tau}\right)$$

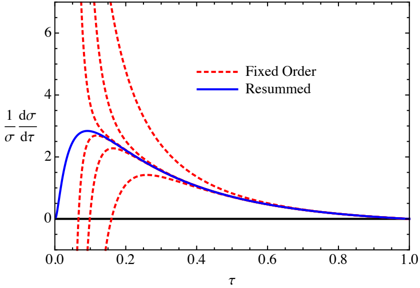


- All orders resummation necessary (powerful techniques exist).

Sudakov Form Factor

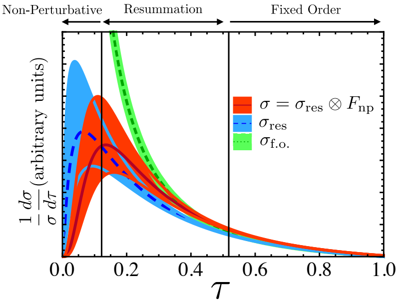
- This is a completely universal behavior.
- Exponential is referred to as Sudakov Form Factor. [Sudakov, 1954]
- Gives probability for no emissions between p_{TJ} and m_J.

$$\frac{d\sigma}{d\tau} = -\frac{2\alpha_s C_F}{\pi} \frac{\log \tau}{\tau} \left(e^{-\frac{\alpha_s C_F}{\pi} \log^2 \frac{m_J}{p_{TJ}}} \right)$$



Non-Perturbative Effects

- Even though mass is IRC safe, at small values, have non-perturbative corrections.

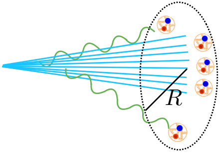


- For mass amount to a shift of the peak.
- Can be modelled by a shape function, or taken from Monte Carlo.

Logarithmic Counting

- Instead of counting orders in α_s (LO, NLO, ...) count logarithmic orders (LL, NLL, NNLL,...)
- Consider jet mass:

$$\sigma(m_J) = \int_0^{m_J} dm_J \frac{d\sigma}{dm_J}$$



$$\begin{aligned}\ln\sigma(m_J) = &\left(\frac{\alpha_s}{2\pi}\right)\left(G_{12}\log^2\frac{p_{TJ}}{m_J} + G_{11}\log\frac{p_{TJ}}{m_J}\right)\\ &+\left(\frac{\alpha_s}{2\pi}\right)^2\left(G_{23}\log^3\frac{p_{TJ}}{m_J} + G_{22}\log^2\frac{p_{TJ}}{m_J} + G_{21}\log\frac{p_{TJ}}{m_J}\right)\\ &+\left(\frac{\alpha_s}{2\pi}\right)^3\left(G_{34}\log^4\frac{p_{TJ}}{m_J} + G_{33}\log^3\frac{p_{TJ}}{m_J} + G_{32}\log^2\frac{p_{TJ}}{m_J} + \cdots\right)\\ &+\cdots\end{aligned}$$

LL $\sim \mathcal{O}(\alpha_s^{-1})$ | NLL $\sim \mathcal{O}(1)$ | NNLL $\sim \mathcal{O}(\alpha_s)$

$$\boxed{\log\frac{p_{TJ}}{m_J} \sim \frac{1}{\alpha_s}}$$

- Sum towers of logs: LL, NLL, NNLL, $\cdots$

What Should our Aim Be?

- Comparing Accuracy:
  - LL: "Calculations for Understanding"
  - NLL: Corrections $\mathcal{O}(\alpha_s)$ suppressed.
  - NNLL: Corrections $\mathcal{O}(\alpha_s^2)$ suppressed, reliable uncertainty estimates.

  $\Longrightarrow$ Data-Theory comparison!

$$\begin{aligned}\ln\sigma(m_J) = &\left(\frac{\alpha_s}{2\pi}\right)\left(G_{12}\log^2\frac{p_{TJ}}{m_J} + G_{11}\log\frac{p_{TJ}}{m_J}\right)\\ &+\left(\frac{\alpha_s}{2\pi}\right)^2\left(G_{23}\log^3\frac{p_{TJ}}{m_J} + G_{22}\log^2\frac{p_{TJ}}{m_J} + G_{21}\log\frac{p_{TJ}}{m_J}\right)\\ &+\left(\frac{\alpha_s}{2\pi}\right)^3\left(G_{34}\log^4\frac{p_{TJ}}{m_J} + G_{33}\log^3\frac{p_{TJ}}{m_J} + G_{32}\log^2\frac{p_{TJ}}{m_J} + \cdots\right)\\ &+\cdots\end{aligned}$$

LL $\sim\mathcal{O}(\alpha_s^{-1})$ | NLL $\sim\mathcal{O}(1)$ | NNLL $\sim\mathcal{O}(\alpha_s)$

- NNLL is now achievable for a select group of important observables.

Soft and Collinear Factorization

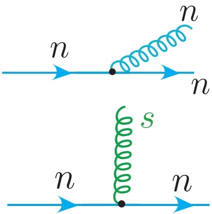
- A jet is by definition a collimated spray of radiation with $m_J \ll p_{TJ}$
- To have small invariant mass the jet can consist of radiation that is either

  - Collinear: $m_J^2 \sim p_{TJ}^2 \theta^2$

    $\implies \theta \sim \frac{m_J}{p_{TJ}}$

  - Soft: $m_J^2 \sim p_{TJ} E_s$

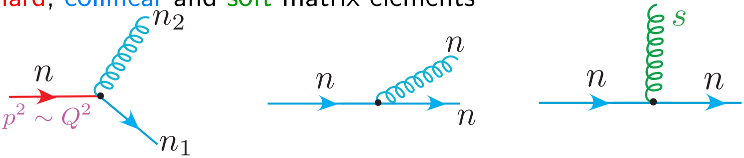
    $\implies E_s \sim \frac{m_J^2}{p_{TJ}}$

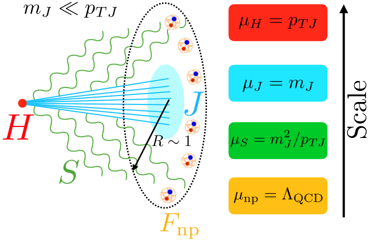


- Measuring a jet forces QCD into the soft and collinear limits.

Factorization

- It can be proven that we can write a cross section as a product of hard, collinear and soft matrix elements





$$\frac{d\sigma}{dm} = H(Q^2) \int dm^c dm^{\bar{c}} dm^s \delta\left(m - m^c - m^{\bar{c}} - m^s\right) J_{n_a}\left(m^c\right) J_{n_b}\left(m^{\bar{c}}\right) S(m^s)$$

Factorization and Renormalization

- Factorization allows cross section to be written as a product (convolution) of simple single scale functions:

$$\frac{d\sigma}{dm} = H(Q^2) \int dm^c dm^{\bar{c}} dm^s \delta\Big(m - m^c - m^{\bar{c}} - m^s\Big) J_{n_a}\Big(m^c\Big) J_{n_b}\Big(m^{\bar{c}}\Big) S(m^s)$$

- Each function can be easily computed by itself (often in an expanded limit).
- All logarithms predicted by renormalization group evolution:

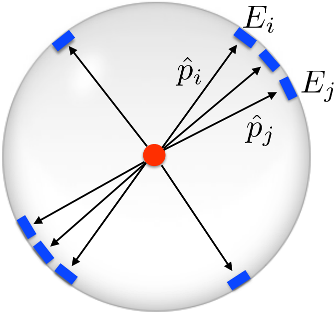
$$\frac{\mathrm{d}}{\mathrm{d}\log\mu} F(z;\mu,\nu) = \int \mathrm{d}z' \, \gamma_F^{\mu}(z - z';\mu,\nu) F(z';\mu,\nu)$$

- Anomalous dimensions can be computed to very high perturbative accuracy.

Jets in e^+e^-

Jets in e^+e^-

- Jets in e^+e^- are literally jets from the QCD vacuum.

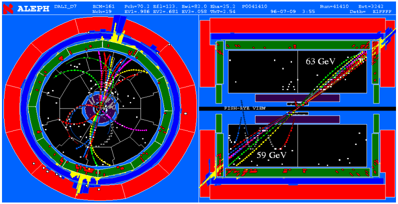


- Insert the current $J^\mu = \bar{q}\gamma^\mu q$ into the QCD vacuum.
  $\Longrightarrow$ exceptional theoretical control!

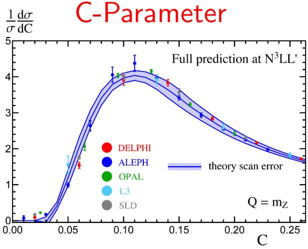
Jets at LEP

- Measured detailed distribution of radiation using event shapes.

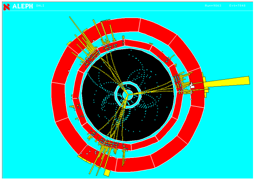
2-Jet Event

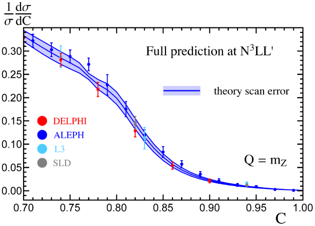


C-Parameter



3-Jet Event



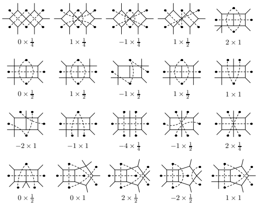


- Precise probe of QCD:
  $\alpha_s(M_Z) = 0.1123 \pm 0.0015$

[Hoang, Kolodrubetz, Mateu, Stewart]

Perturbative Accuracy

- State of the art for e^+e^- event shapes is 3 loops.
- Example of renormalization group boundary condition at 3 loops:



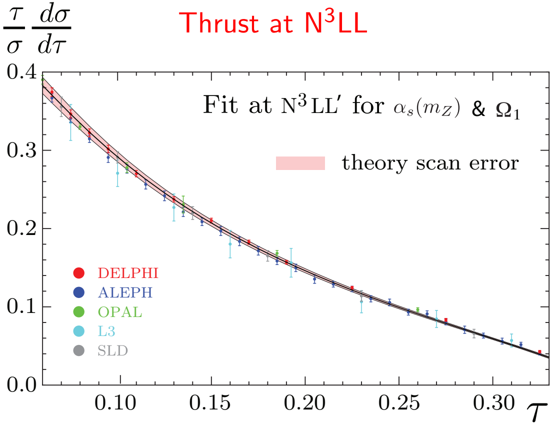
[Moult and Zhu]

$$
\begin{aligned}
c_1^{\mathrm{EEC}} &= -2C_F\zeta_2\,, \\
c_2^{\mathrm{EEC}} &= C_A C_F\left(\frac{2428}{81} - \frac{67}{3}\zeta_2 - \frac{154}{9}\zeta_3 + 10\zeta_4\right) \\
&\quad + C_F n_f\left(-\frac{328}{81} + \frac{10}{3}\zeta_2 + \frac{28}{9}\zeta_3\right)\,, \\
c_3^{\mathrm{EEC}} &= C_F C_A^2\left(\frac{5211949}{13122} - \frac{297481}{729}\zeta_2 - \frac{151132}{243}\zeta_3 + \frac{3649}{27}\zeta_4\right. \\
&\qquad\left. + \frac{1804}{9}\zeta_5 + \frac{1100}{9}\zeta_2\zeta_3 - \frac{3086}{27}\zeta_6 + \frac{928}{9}\zeta_3^2\right) \\
&\quad + C_F C_A n_f\left(-\frac{412765}{6561} + \frac{74530}{729}\zeta_2 + \frac{8152}{81}\zeta_3 - \frac{416}{27}\zeta_4 - \frac{184}{3}\zeta_5 + \frac{40}{9}\zeta_3\zeta_2\right) \\
&\quad + C_F^2 n_f\left(-\frac{42727}{486} + \frac{275}{9}\zeta_2 + \frac{3488}{81}\zeta_3 + \frac{152}{9}\zeta_4 + \frac{224}{9}\zeta_5 - \frac{80}{3}\zeta_3\zeta_2\right) \\
&\quad + C_F n_f^2\left(-\frac{256}{6561} - \frac{136}{27}\zeta_2 - \frac{560}{243}\zeta_3 - \frac{44}{27}\zeta_4\right)
\end{aligned}
$$

- Very sophisticated and well developed mathematical tools exist.

Theory Precision for Jets in Vacuum

- 1% uncertainty achieved for certain observables!



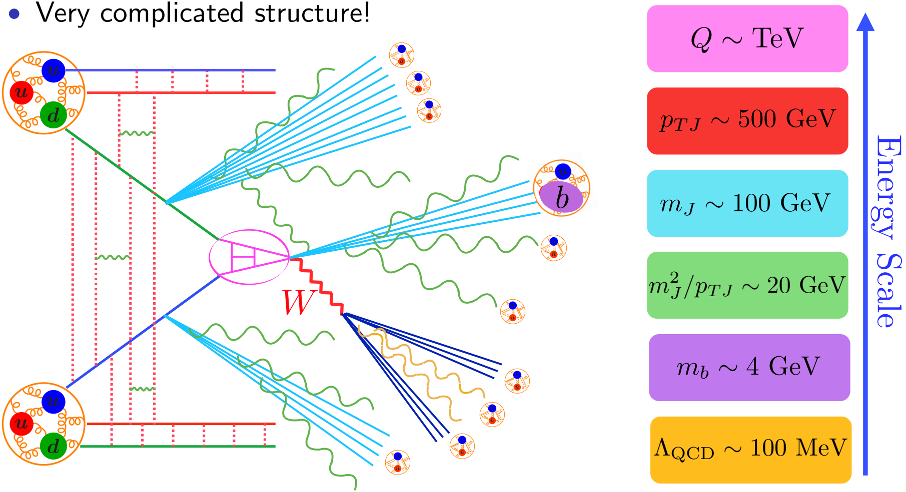
[Abbate, Fickinger, Hoang, Mateu, Stewart]

- Jets in true vacuum quite well understood.

Jets in pp

Proton-Proton Collisions

- Very complicated structure!

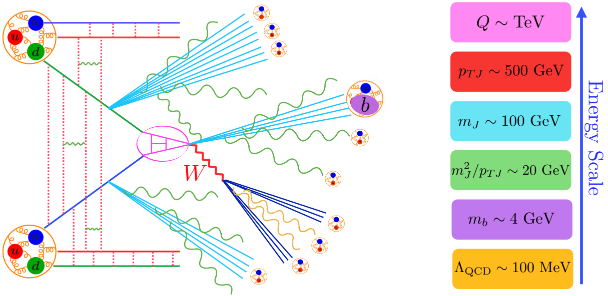


- Involves interactions at many hierarchical energy scales.

Proton-Proton Collisions

- Tractable due to factorization:

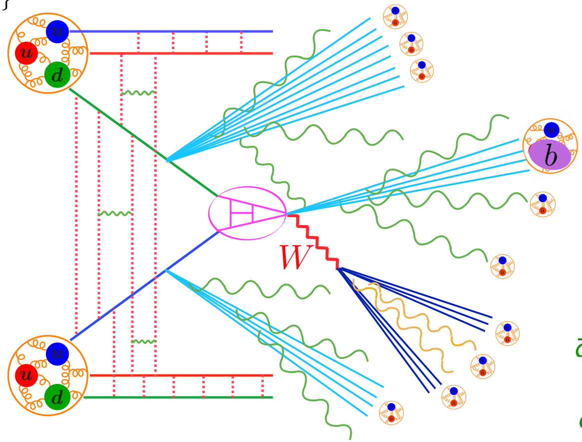
$$\frac{d\sigma}{d\mathcal{M}_1\cdots} = \sum_{\{\kappa\}} \mathrm{tr} H_\kappa \mathcal{I}\mathcal{I} J_{\kappa_i} \otimes \cdots \otimes J_{\kappa_j} S_{\kappa_s} \otimes f_{p/i} f_{p/j} \otimes f_{k\to H} \otimes \cdots \otimes f_{l\to H} \otimes F + \cdots$$

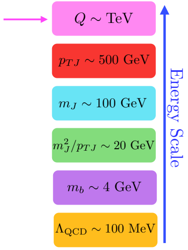


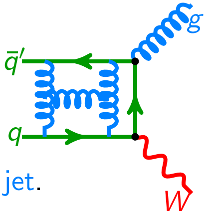
- $\frac{d\sigma}{d\mathcal{M}_1\cdots}$ written as a convolution of single scale objects.

Proton-Proton Collisions

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



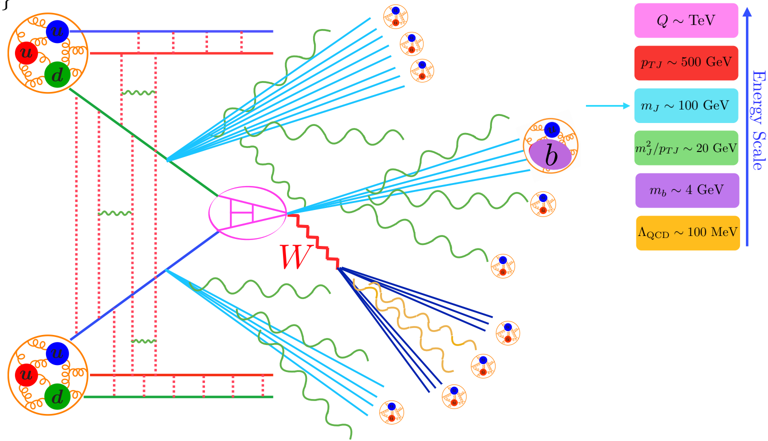




- H_κ: Describes underlying hard process. e.g. $q\bar{q}' \to W +$ jet.

Proton-Proton Collisions

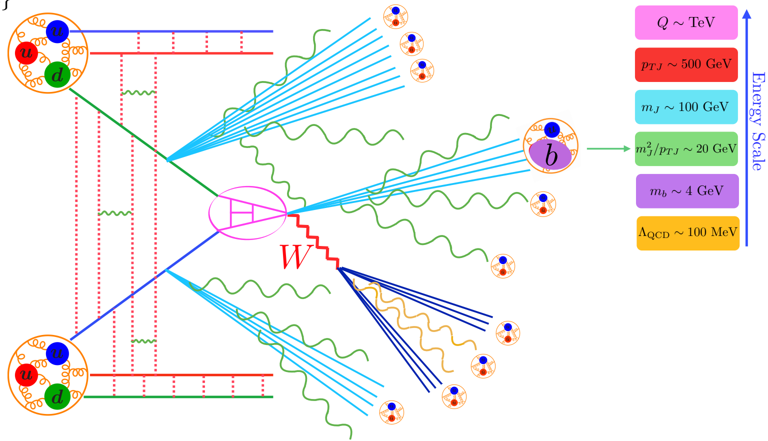
$$\frac{d\sigma}{d\mathcal{M}_1\cdots} = \sum_{\{\kappa\}} \mathrm{tr} H_\kappa \mathcal{I}\mathcal{I} J_{\kappa_i} \otimes \cdots \otimes J_{\kappa_j} S_{\kappa_s} \otimes f_{p/i} f_{p/j} \otimes f_{k\to H} \otimes \cdots \otimes f_{l\to H} \otimes F$$



- $\mathcal{I}\mathcal{I} J_{\kappa_i} \times \cdots \times J_{\kappa_j}$: Describe dynamics of collinear radiation (jets).

Proton-Proton Collisions

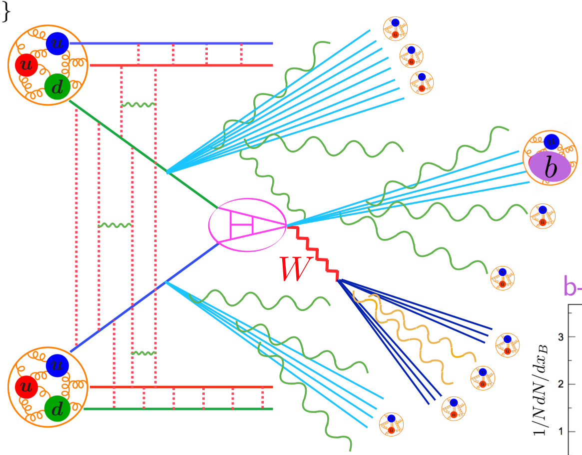
$$\frac{d\sigma}{d\mathcal{M}_1\cdots} = \sum_{\{\kappa\}} \mathrm{tr} H_\kappa \mathcal{I}\mathcal{I} J_{\kappa_i} \otimes \cdots \otimes J_{\kappa_j} S_{\kappa_s} \otimes f_{p/i} f_{p/j} \otimes f_{k\to H} \otimes \cdots \otimes f_{l\to H} \otimes F$$

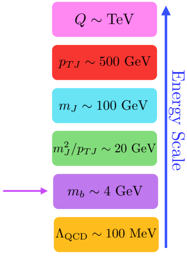


- S_{κ_s}, F: Describe low energy soft radiation.

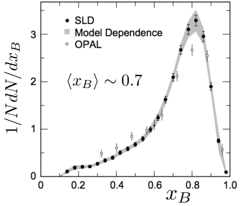
Proton-Proton Collisions

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





b-Fragmentation

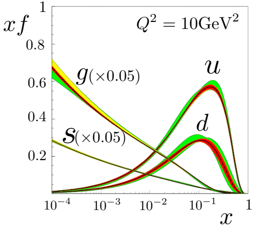


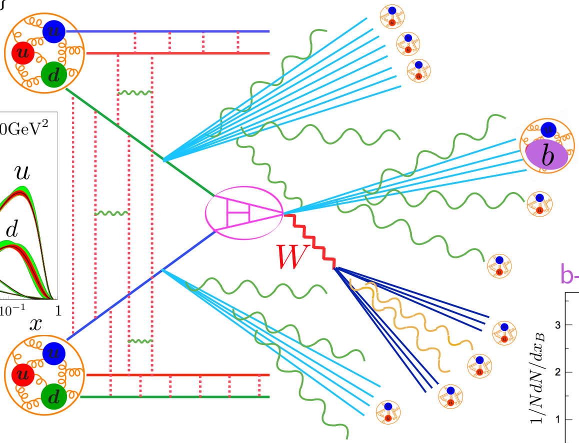
- $f_{k\to H}$: Describe fragmentation to identified hadrons.

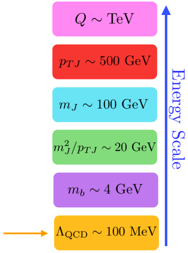
Proton-Proton Collisions

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

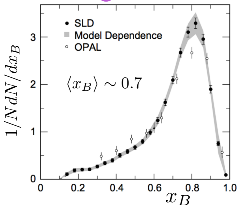
PDFs







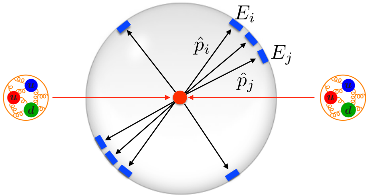
b-Fragmentation

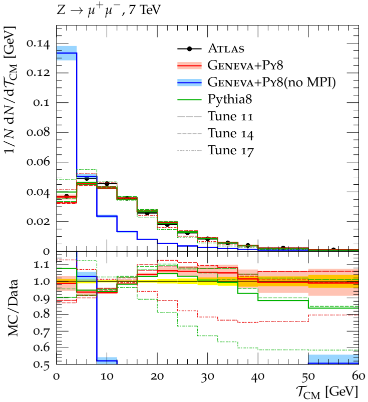


- $f_{p/i}, f_{p/j}$: PDFs describing incoming protons.

Underlying Event and MPI

- Global observables in *pp*:



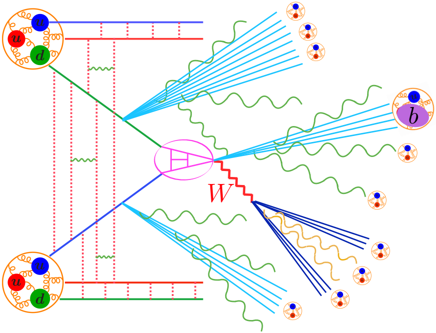


[Geneva Monte Carlo]

- Affected by Underlying Event (UE)/ Multiple Parton Interactions (MPI)

Underlying Event and MPI

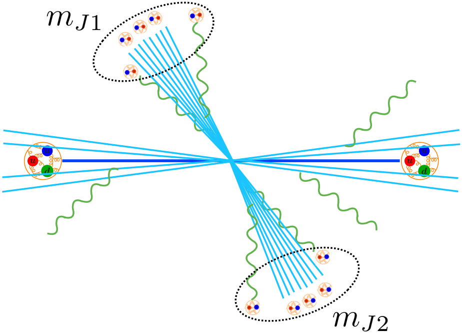
- Proton remnants interact. Can violate factorization into independent PDFs $f_{p/i}, f_{p/j}$



- MPI/UE is typically low energy uniform radiation
- Is in general non-perturbative. Options:
  - Models tuned to data implemented in standard Monte Carlos.
  - Minimize effects.

Jet Observables

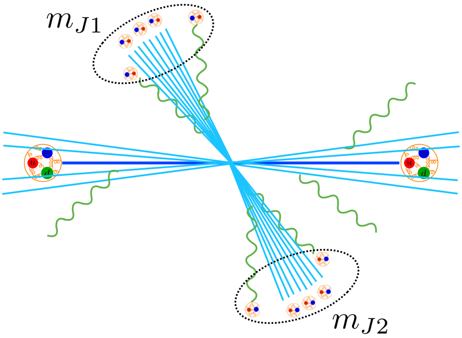
- Effects can be significantly minimized by measuring observables on jets themselves instead of entire event.



- Jet observables get smaller contamination from low energy UE/MPI

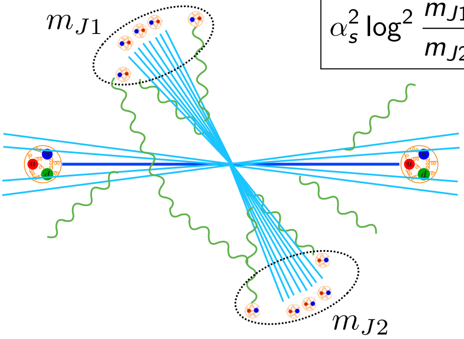
Non-Global Observables

- Most ($\sim$ all) measurements at the LHC make different measurements in different regions of phase space.



Non-Global Observables

- Most ($\sim$ all) measurements at the LHC make different measurements in different regions of phase space.
- In a non-abelian gauge theory, this introduces correlations:



$$\alpha_s^2 \log^2 \frac{m_{J1}}{m_{J2}} + \cdots$$

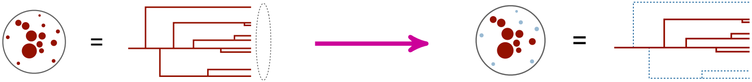
- Significantly complicates the structure.

How can we make a jet look like it is in e^+e^-?

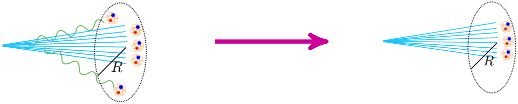
Grooming

[Larkoski, Marzani, Soyez, Thaler]
[Dasgupta, Fregoso, Marzani, Salam]

- Groomer are used to remove soft contamination.
- Soft Drop/ mMDT: Recurse through a Cambridge-Aachen clustering tree and remove particles that fail the condition: $\frac{\min[p_{Ti}, p_{Tj}]}{p_{Ti} + p_{Tj}} > z_{\text{cut}}$



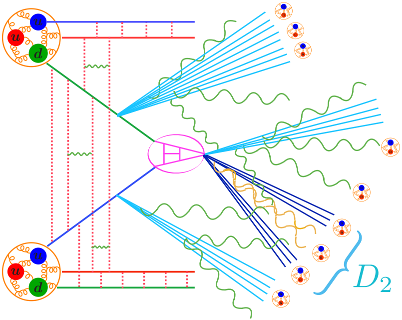
- Loosely speaking, reduces a jet to its collinear core.



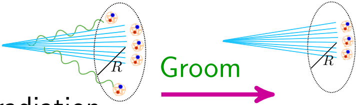
- Any IRC safe observable measured on a groomed jet is IRC safe.

Difficulties with *pp* Collisions

- Difficulties in QCD calculations for *pp*:



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

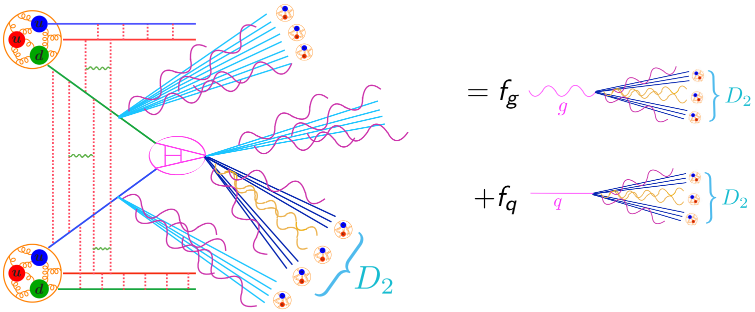


- All complications associated with soft radiation.
- Groomers remove soft radiation

  $\Longrightarrow$ Makes calculations simpler and more universal.

Grooming for *pp* Collisions

- Grooming removes all color correlations.



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

Groomed Observables

Precision Calculations with Grooming

- Groomed mass is a benchmark observable.
  $\Longrightarrow$ Motivates push to precision
- Groomed mass is theoretically well understood:
  - Simple structure ✓
  - Contamination is minimized ✓
- Formalized in all orders factorization theorem:

$$\frac{d\sigma^{\text{resum}}}{dm_J^2} = \sum_{k=q,\bar{q},g} D_k(p_T, z_{\text{cut}}, R) S_{C,k}(z_{\text{cut}} m_J^2) \otimes J_k(m_J^2)$$

sum over jet flavor

includes pdfs, emissions that were groomed away, out-of-jet radiation,...

collinear-soft radiation

hard collinear radiation

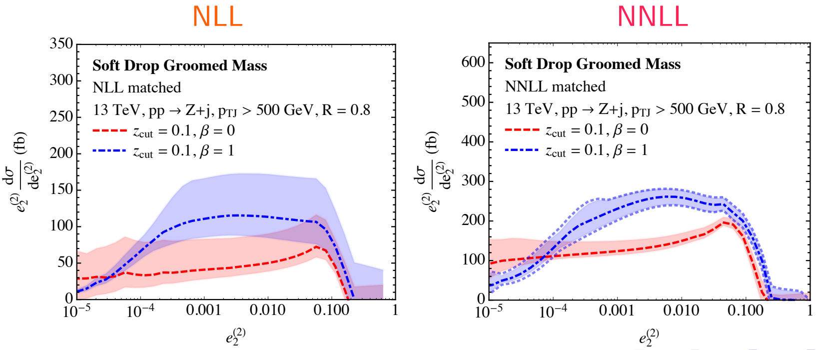
[Frye, Larkoski, Schwartz, Yan]

- Allows one to systematically compute to higher orders.

Soft Drop Jet Mass

- Factorization theorem allows one to immediately go to NNLL.
- First precision calculation of a jet substructure observable!

Soft Drop Mass $pp -> Z + j$

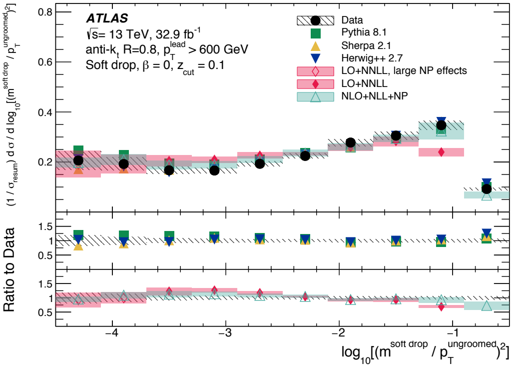


[Frye, Larkoski, Schwartz, Yan]

Soft Drop Jet Mass

- Measurement of the groomed jet mass in ATLAS:

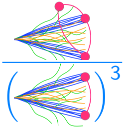
Soft Drop Mass in ATLAS



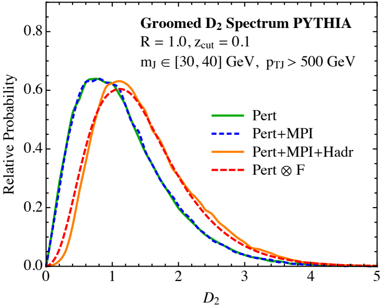
- Comparison of first principles QCD theory and data in pp environment.

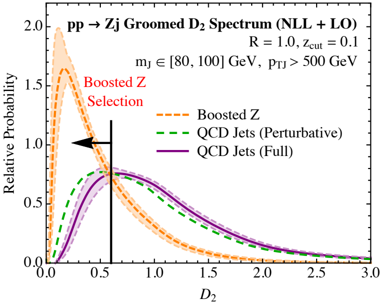
Groomed D_2

- Similar success with other more complicated observables.

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

Groomed D2



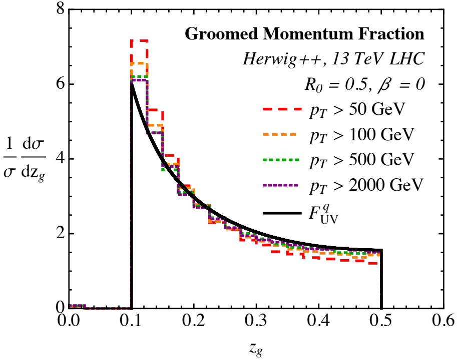


- MPI/Underlying Event completely negligible.
- Non-perturbative corrections are from hadronization within the jet.

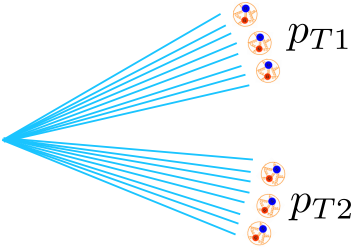
Momentum Asymmetry z_g

- Asymmetry on groomed jets: z_g.

z_g Distribution



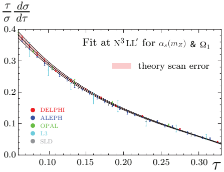
$$z_g = \frac{\min[p_{T1}, p_{T2}]}{p_{T1} + p_{T2}}$$



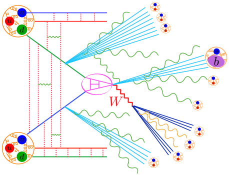
- Measures the splitting probability.

Summary

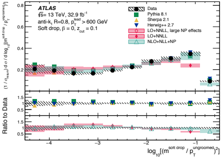
- IRC safe observables can be computed perturbatively to high accuracy.



- Understanding of jets in vacuum in pp difficult due to complex environment.



- Precision understanding regained by smart choice of observables.



Further Reading

- For a modern review of jets at the LHC (with 500+ references):

Jet Substructure at the Large Hadron Collider:
A Review of Recent Advances in Theory and Machine Learning

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(Dated: September 15, 2017)

Jet substructure has emerged to play a central role at the Large Hadron Collider (LHC), where it has provided numerous innovative new ways to search for new physics and to probe the Standard Model in extreme regions of phase space. In this article we provide a comprehensive review of state of the art theoretical and machine learning developments in jet substructure. This article is meant both as a pedagogical introduction, covering the key physical principles underlying the calculation of jet substructure observables, the development of new observables, and cutting edge machine learning techniques for jet substructure, as well as a comprehensive reference for experts. We hope that it will prove a useful introduction to the exciting and rapidly developing field of jet substructure at the LHC.

Thanks!