Probing the Core of QCD

Jesse Thaler

Boost 2015, Chicago — August 10, 2015
Textbook QCD: Universal Collinear Limit

\[ 2 \rightarrow n \approx 2 \rightarrow n-1 \times \left| \begin{array}{c} \frac{z}{1-z} \\ \theta \end{array} \right| 2 \]

\[ \int \frac{d\theta}{\theta} \, dz \, P(z) \]

Collinear singularity  Soft singularity

\[ P(z) \approx \frac{1}{z} \]
The Core of QCD

Basis for parton shower MC generators, PDF evolution, NLO subtractions, $k_t$ clustering, jet substructure intuition…

Measurable? Calculable?

Splitting Function

$I \rightarrow 2$

\[ \int \frac{d\theta}{\theta} dz P(z) \]

Collinear singularity Soft singularity

\[ P(z) \simeq \frac{1}{z} \]

IRC Unsafe
Jet substructure to probe universal singularity structure of gauge theories (e.g. QCD)

Today:

Sudakov Safety
[Andrew Larkoski, JDT, 1307.1699; my talk at Boost 2013]

Ingredients:

Soft Drop
[Andrew Larkoski, Simone Marzani, Gregory Soyez, JDT, 1402.2657; Simone’s talk at Boost 2014]

Standard Candles
[Andrew Larkoski, Simone Marzani, JDT, 1502.01719]
Outline

From Soft Drop to Splitting Functions

From Sudakov Safety to Standard Candles

From Theory to Experiment
From Soft Drop to Splitting Functions

From Sudakov Safety to Standard Candles

From Theory to Experiment
Measure Universal Singularity?

Angular-ordered tree (C/A)…
Measure Universal Singularity?

Angular-ordered tree (C/A)...

...gives splitting function?

\[ \int \frac{d\theta}{\theta} \, dz \, P(z) \]

\[ IR/C \text{ Unsafe} \]
Measure Universal Singularity?

Groomed angular-ordered tree...

...gives splitting function?

Soft Drop ($\beta = 0$, aka mMDT)

$z > z_{\text{cut}}$

$\int \frac{d\theta}{\theta} \, dz \, P(z)$

$Z_g \quad \text{IR Safe}$

C Unsafe

[Larkoski, Marzani, Soyez, JDT, 1402.2657]
[see also Butterworth, Davison, Rubin, Salam, 0802.2470; Dasgupta, Fregoso, Marzani, Salam, 1307.0007]
Measure Universal Singularity?

One prong jet...

\[ \theta_g = 0 \]

vs.

\[ z_g \quad l - z_g \]

\[ \theta_g = 0 \]

\[ z \quad \theta \]

\[ \int \frac{d\theta}{\theta} \quad dz \quad P(z) \]

Soft Drop \((\beta = 0, \text{aka mMDT})\)

\[ z > z_{cut} \]

energy threshold

IR Safe

C Unsafe

[see also Butterworth, Davison, Rubin, Salam, 0802.2470; Dasgupta, Fregoso, Marzani, Salam, 1307.0007]
How to calculate from first principles?

(see backup for how our elders addressed this in 1978)
From Soft Drop to Splitting Functions

From Sudakov Safety to Standard Candles

From Theory to Experiment

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1. Use Sudakov Form Factors

\[ Z_g \quad \text{IR Safe} \quad C \text{ Unsafe} \]

\[ Z_g \quad m > 0 \quad \text{IRC Safe} \]

Measure jet mass?

[Larkoski, JDT, 1307.1699]
1. Use Sudakov Form Factors

- $Z_g$  
  - IR Safe
  - C Unsafe

Measure jet mass?

- $Z_g^{m>0}$  
  - IRC Safe

$\Rightarrow$

Jet mass never zero!

- $Z_g$  
  - Sudakov Safe

[Larkoski, JDT, 1307.1699]
1. Use Sudakov Form Factors

Measure jet mass?

Jet mass never zero!

$Z_g \quad \text{IR Safe}

C \quad \text{Unsafe}

Z_g \quad m > 0 \quad \text{IRC Safe}

\Rightarrow

Z_g \quad \text{Sudakov Safe}

Jet mass distribution

Fixed $O(\alpha_s)$

$m=0$ singular

[Larkoski, JDT, 1307.1699]
1. Use Sudakov Form Factors

Measure jet mass?

Jet mass never zero!

$Z_g$ IR Safe
C Unsafe

$Z_g$ $m > 0$ IRC Safe

$Z_g$ Sudakov Safe

Jet mass distribution

Fixed $O(\alpha_s)$

m=0 singular

VS.

All $\alpha_s$ Orders (resummed logs)

m=0 suppressed

[Larkoski, JDT, 1307.1699]
I. Use Sudakov Form Factors

\[
\text{Want: } \quad p(u) = \frac{1}{\sigma} \frac{d\sigma}{du}
\]

Unsafe
I. Use Sudakov Form Factors

Unsafe

Want: \[ p(u) = \frac{1}{\sigma} \frac{d\sigma}{du} \]

Need: \[ p(u|s) = \frac{p(u,s)}{p(s)} \]

...with Safe companion

[Larkoski, Marzani, JDT, 1502.01719]
I. Use Sudakov Form Factors

Unsafe

Want: \[ p(u) = \frac{1}{\sigma} \frac{d\sigma}{du} \]

Need: \[ p(u|s) = \frac{p(u, s)}{p(s)} \]

...with Safe companion

Calculable...

Sudakov Safe

Insight:
\[
p(u) = \int ds \, p(s) \, p(u|s)
\]

Sudakov form factor
(all orders in $\alpha_s$)

Perturbative
(fixed order in $\alpha_s$)

Suppresses isolated singularities...

...at each perturbative order

[Larkoski, Marzani, JDT, 1502.01719]
2. Use Fragmentation Functions

\[
\frac{d\sigma}{d z_g} \sim F(z_g)
\]

Absorb singularities into universal function (just like PDFs!)

[Zg IR Safe C Unsafe]

[Larkoski, Marzani, JDT, 1502.01719]
2. Use Fragmentation Functions

\[ \frac{d\sigma}{dz_g} \sim F(z_g) - \frac{1}{2\epsilon} \frac{\alpha_s C}{\pi} F(z_g) + \frac{\alpha_s C}{\pi} \int \frac{d\theta}{\theta} P(z_g) \]

Absorb singularities into universal function (just like PDFs!)

[Larkoski, Marzani, JDT, 1502.01719]
2. Use Fragmentation Functions

\[ \frac{d\sigma}{dz_g} \sim F(z_g) - \frac{1}{2\epsilon} \frac{\alpha_s C}{\pi} F(z_g) + \frac{\alpha_s C}{\pi} \int \frac{d\theta}{\theta} P(z_g) \]

Absorb singularities into universal function (just like PDFs!)

\[ \text{renormalize} \]

\[ F(z_g) \Rightarrow F(z_g; \mu) \]

[Larkoski, Marzani, JDT, 1502.01719]
2. Use Fragmentation Functions

\[
\frac{d\sigma}{d\bar{z}_g} \sim F(\bar{z}_g) - \frac{1}{2\epsilon} \frac{\alpha_s C}{\pi} F(\bar{z}_g) + \frac{\alpha_s C}{\pi} \int \frac{d\theta}{\theta} P(\bar{z}_g)
\]

IR Safe
\[Z_g\]

C Unsafe

Absorb singularities into universal function (just like PDFs!)

\[F(\bar{z}_g) \rightarrow F(\bar{z}_g; \mu) \rightarrow \frac{d}{d\mu} \rightarrow P(\bar{z}_g)\]

[Larkoski, Marzani, JDT, 1502.01719]
A Standard Candle for Jets

\[ \frac{1}{\sigma} \frac{d\sigma}{dz_g} = \frac{P_i(z_g)}{\int_{z_{cut}}^{1/2} dz \ P_i(z)} + \ldots \]

\( z > z_{cut} \)

\( z_g \Rightarrow P(z) \)

\( \approx \) independent of \( \alpha_s \) (!)

\( \approx \) independent of jet \( p_T \) and radius

\( \approx \) same for quarks and gluons

calculable deviations from universality

(see backup for \( \beta \neq 0 \))

[Larkoski, Marzani, JDT, 1502.01719]
From Soft Drop to Splitting Functions

From Sudakov Safety to Standard Candles

From Theory to Experiment
Theory Calculation

Anti-\(k_t\): \(R = 0.5\); \(p_T > 150\) GeV
Soft Drop: \(\beta = 0\); \(z_{\text{cut}} = 0.1\)

\(p_T > 150\) GeV
\(z_{\text{cut}} = 0.1\)

**MLL:**
leading log plus running coupling

Uncertainties from 
\(\alpha_s\) scale variation and quark/gluon composition

(Likely an overestimate since normalization is not enforced and q/g composition is known)

[Thanks to Simone Marzani]
Parton Shower Simulation

\[
\frac{1}{\sigma} \frac{d\sigma}{d z_g}
\]

Theory (MLL)
Pythia 8.205
Herwig++ 2.6.3

Anti-\(k_t\): \(R = 0.5\); \(p_T > 150\) GeV
Soft Drop: \(\beta = 0\); \(z_{\text{cut}} = 0.1\)

\(p_T > 150\) GeV
\(z_{\text{cut}} = 0.1\)

MC:
LO QCD dijets out of the box

Particle level, default underlying event tune, no detector simulation

[Thanks to Andrew Larkoski, Alexis Romero]
Experimental Measurement

This slide intentionally blank
The Future is Open

CMS 2010 Data:

\( \approx 200k \) events with hardest jet \( p_T > 150 \) GeV, very low pileup

Accelerating science through (judicious) public data releases
Anti-\( k_t \): \( R = 0.5 \); \( p_T > 150 \text{ GeV} \)
Soft Drop: \( \beta = 0 \); \( z_{\text{cut}} = 0.1 \)
Ratio to Theory

Anti-$k_t$: $R = 0.5$; $p_T > 150$ GeV
Soft Drop: $\beta = 0$; $z_{\text{cut}} = 0.1$
Open Data Analysis

CMS 2010 Open Data

| Theory (MLL) | Pythia 8.205 | Herwig++ 2.6.3 |

Anti–$k_t$: $R = 0.5$; $p_T > 150$ GeV
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$p_T > 150$ GeV
$z_{cut} = 0.1$

CMS Open Data: Jet Primary Data Set with Particle Flow Candidates

Statistical uncertainties only, no unfolding, 58021 events

Using single jet triggers with $\approx 100\%$ efficiency, AK5 jet energy corrections with area subtraction, no PFC corrections

AOD $\rightarrow$ MOD format (MIT Open Data project)

More plots in backup slides

[Thanks to Sal Rappoccio, Aashish Tripathee, Wei Xue]

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Open Data Analysis

As nature intended:

Ratio to Data

CMS 2010 Open Data

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- Pythia 8.205
- Herwig++ 2.6.3

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Summary

From Soft Drop to Splitting Functions
Jet grooming to expose two-prong energy sharing “z”
Makes concrete what we already intuit from jet substructure

From Sudakov Safety to Standard Candles
All orders in $\alpha_s$ yields new insights into QFT
New way to measure the universal singularity structure of QCD

From Theory to Experiment
The future is now: idea + simulation + calculation + open data analysis
Can open data enhance theory/experiment interface?

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Backup Slides
3. Learn from Our Elders

Me: “φ is IRC unsafe”

My Elder: “We explicitly calculated \( \frac{d\sigma}{d\varphi} \) in 1978”

\[
\frac{2\pi}{\sigma_0} \frac{d\sigma}{d\varphi} = 1 + O(\alpha_s(Q^2)) + \frac{\alpha_s(Q^2)}{\pi} \left( \frac{16}{3} \ln \frac{3}{2} - 2 \right) \cos 2\varphi
\]

Lesson: Use IRC limit to resolve ambiguities

\[\text{[Pi, Jaffe, Low, 1978; Kramer, Schierholz, Willrodt, 1978]}\]
“Phase Diagram” for Observables

\[ \beta \rightarrow \infty \quad \text{No Change} \]

\[ \beta > 0 \quad \text{Sudakov Safe} \]

\[ \beta = 0 \quad \text{IRC Safe} \]

\[ \beta < 0 \quad \text{No Jet} \]

\[ \beta \rightarrow -\infty \]

\[ \sqrt{\frac{\alpha_s C_i}{\beta}} P_i(z_g) + \ldots \]

\[ \int_{z_{cut}}^{1/2} dz \bar{P}_i(z) + \ldots \]

\[ \frac{2\alpha_s C_i}{\pi |\beta|} \bar{P}_i(z_g) \log \frac{z_g}{z_{cut}} + \ldots \]

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[Larkoski, Marzani, JDT, 1502.01719]
**Additional $z_g$ Theory Plots**

**Groomed Momentum Fraction**

- **13 TeV LHC, $p_T > 2$ TeV**
  - $R_0 = 0.5$, $\beta = 0$, $z_{cut} = 0.05$
  - Colors: **Pythia 8**, **Herwig++**, **Sherpa**, **$F_{UV}^g$**

**Groomed Momentum Fraction**

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[Larkoski, Marzani, JDT, 1502.01719]
Additional $z_{\text{cut}}$ Values

$p_T > 150$ GeV

$z_{\text{cut}} = 0.05$

$z_{\text{cut}} = 0.2$

CMS 2010 Open Data

Theory (MLL)

Pythia 8.205

Herwig++ 2.6.3

Anti-$k_t$: $R = 0.5$; $p_T > 150$ GeV

Soft Drop: $\beta = 0$; $z_{\text{cut}} = 0.05$

Soft Drop: $\beta = 0$; $z_{\text{cut}} = 0.2$

58021 events
Additional \( p_{T\text{cut}} \) Values

\[ z_{\text{cut}} = 0.1 \]

\( p_T > 300 \) GeV

\( p_T > 600 \) GeV
All Particles vs. Track Only

$p_T > 150$ GeV

$z_{\text{cut}} = 0.05$

$z_{\text{cut}} = 0.1$

$z_{\text{cut}} = 0.2$

$p_T > 300$ GeV

$p_T > 600$ GeV
Applying Pseudo SoftKiller

**$p_T > 150 \text{ GeV}$**

$z_{\text{cut}} = 0.05$

$z_{\text{cut}} = 0.1$

$z_{\text{cut}} = 0.2$

**$p_T > 300 \text{ GeV}$**

**$p_T > 600 \text{ GeV}$**
CMS Corrected Jet $p_T$ Spectrum

![Graph showing CMS Corrected Jet $p_T$ Spectrum]

- Pythia 8.205
- Herwig++ 2.6.3
- Corrected
- Uncorrected

Anti-$k_t$: $R = 0.5$

Ratio to Data
CMS Jet Primary Data Set Triggers

**A.U.**

$A_{\Delta U}$

**Ratio**

$\text{Jet30U / 15U HNF}$

$\text{Jet50U / 30U}$

$\text{Jet70U / 50U}$

$\text{Jet100U / 70U}$

$\text{Jet140U / 100U}$

$\text{Anti-} k_t: R = 0.5$

**p_T (GeV)**

$10^0$ $10^1$ $10^2$ $10^3$ $10^4$ $10^5$ $10^6$ $10^7$ $10^8$ $10^9$ $10^{10}$ $10^{11}$

$0$ $50$ $100$ $150$ $200$ $250$ $300$ $350$ $400$ $450$ $500$ $550$ $600$ $650$ $700$ $750$ $800$ $850$ $900$ $950$ $1000$ $1050$ $1100$ $1150$ $1200$ $1250$ $1300$ $1350$ $1400$ $1450$ $1500$ $1550$ $1600$ $1650$ $1700$ $1750$ $1800$ $1850$ $1900$ $1950$ $2000$ $2050$ $2100$ $2150$ $2200$ $2250$ $2300$ $2350$ $2400$ $2450$ $2500$ $2550$ $2600$ $2650$ $2700$ $2750$ $2800$ $2850$ $2900$ $2950$ $3000$