Theoretical Progress in Dissecting Jets

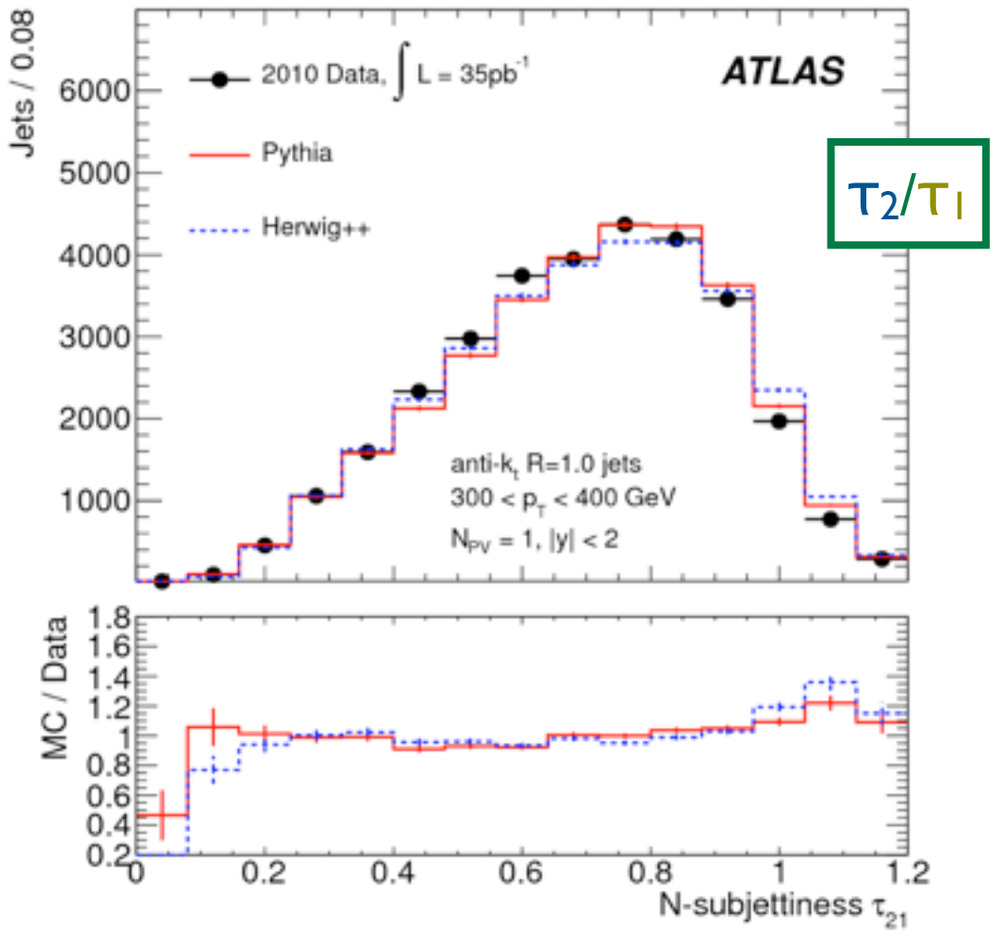
Calculations Past, Present, and Future

Jesse Thaler

Boost 2013, Flagstaff — August 12, 2013

Why Calculations?

Why not jet substructure from data/MC?



[ATLAS: CERN-PH-EP-2012-031]

Of course:

QCD calculations for controlling theory systematics

Today's Focus:

QCD calculations to build intuition (and breakdown biases) about jet substructure

Outline

(Calculations for Precision)

Unfinished Business from Boost 2012

Calculations for Insight

Back to Basics for Boost 2013

Calculations for Liberation

Thinking Beyond IRC Safety for Boost 2014

(Disclaimer: This is a personal view, not a comprehensive summary.)

Calculations for Precision

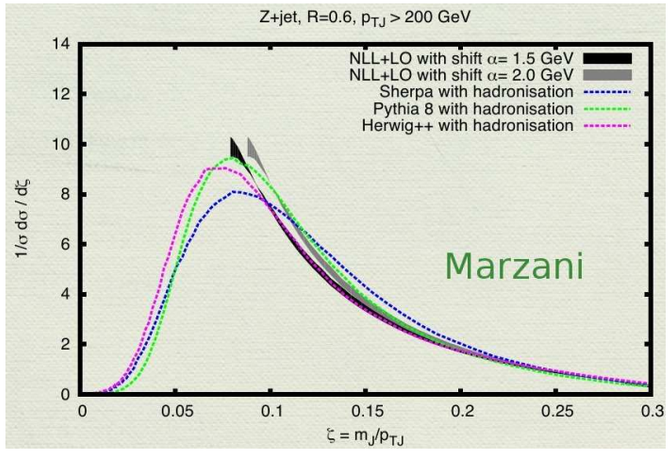
Unfinished Business from Boost 2012

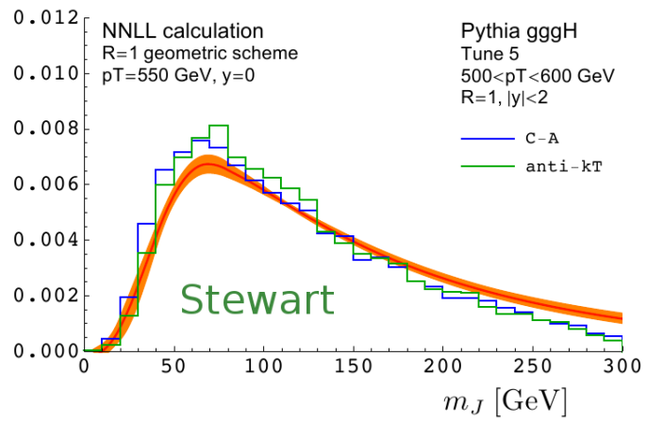
Key substructure observable: Jet Mass

Important theoretical progress!

[from 2012 summary by Salam]

Jet masses from two groups





Resummed jet masses compared to Monte Carlo showers

These results are a significant theory development of the workshop

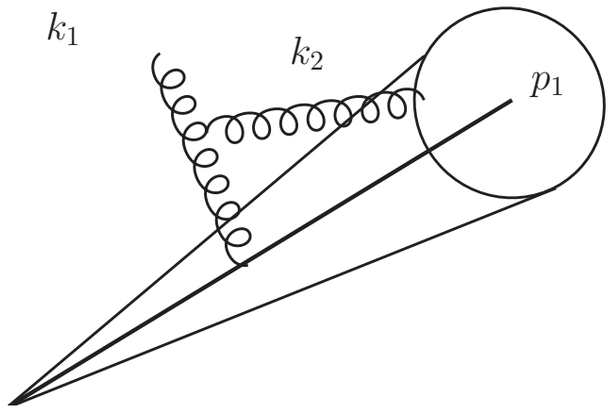
but, be aware of the fine print

Gavin Salam (CERN/Princeton/CNRS) Boost Theory Summary Boost 2012-07-27 14 / 33

The Fine Print

What is "the jet mass spectrum"?

Non-global Logarithms!



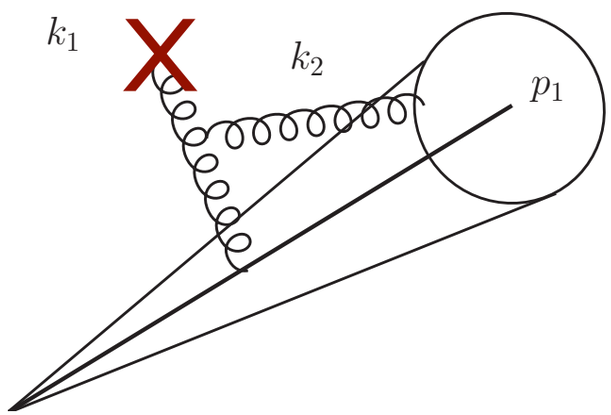
[figure from Marzani]

Inclusive Measurement:
Mass of any jet in an event?

Semi-Inclusive Measurement:
Mass of hardest jet in an event?

vs.

Exclusive:
Veto additional radiation



Exclusive Measurement:
Mass of hardest jet, restricting additional radiation?

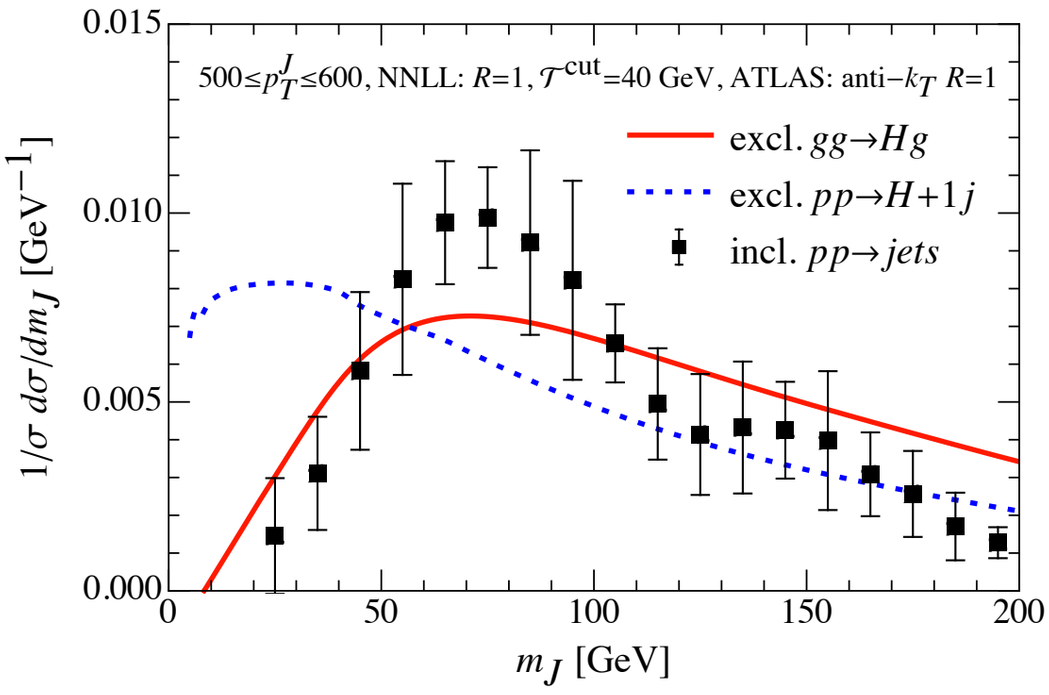
[see talk by Schabinger]

The Fine Print

What is "the jet mass spectrum"?

Inclusive (ATLAS data)
vs. Exclusive (NNLL calc)

(many important caveats to this plot)



[from Jouttenus, Stewart, Tackmann, Waalewijn]

Inclusive Measurement:
Mass of any jet in an event?

Semi-Inclusive Measurement:
Mass of hardest jet in an event?

vs.

Exclusive Measurement:
Mass of hardest jet,
restricting additional radiation?

[see talk by Schabinger]

Calculations for Precision

Unfinished Business from Boost 2012

Lesson: For high precision, need to correlate measurement and calculation

Option 1: Accept non-global complications

Option 2: Do more exclusive measurements

c.f. jet vetoes in precision Higgs cross sections

Option 3: Find observables less sensitive to soft physics

(see e.g. mMDT)

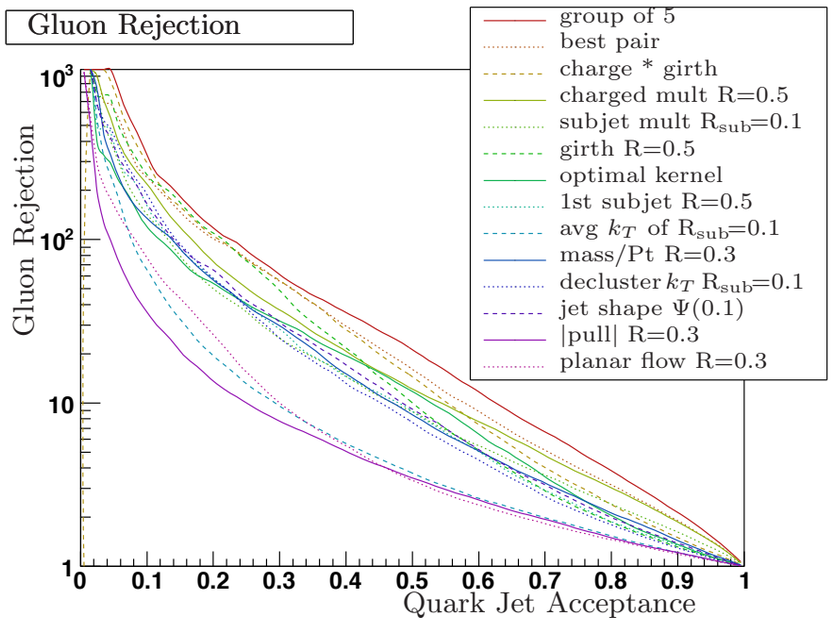
Calculations for Insight

Back to Basics for Boost 2013

Explosion of jet substructure methods/observables!

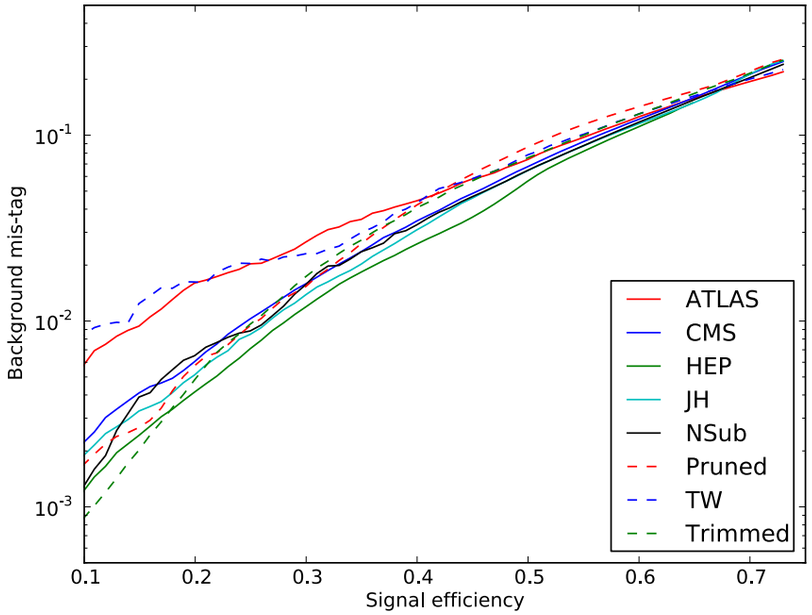
[see talks by Bertolini, Low, Lou, El Hedri, Tseng,
Larkoski, Waalewijn, Curtin, Cogan, Chien, Han, ...]

e.g. Quarks vs. Gluons



[from Gallicchio, Schwartz]

e.g. Boosted Tops



[from Boost 2011 Report]

To what extent do they probe the same/different physics?

Calculations for Insight

Back to Basics for Boost 2013

Maximize Discrimination Power?

Provably: Full matrix element method

[see talks by Soper (Shower Deconstruction) and Backovic (Template Overlap)]

Maximize Intuition?

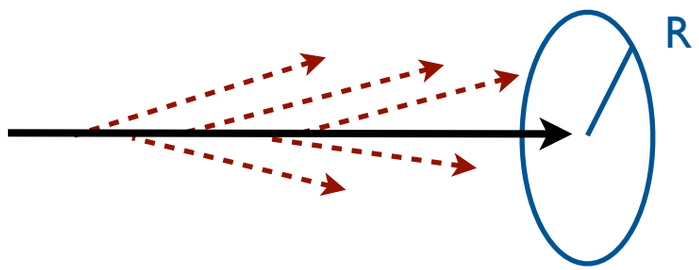
Focus on lowest-order analytic behavior

Show *why* observables are sensitive to desired physics

The Strongly-Ordered Limit

Basis for parton shower

Gluon Haze Surrounding...



...Eikonal Hard Quark/Gluon

In soft & collinear limit:

$$\mathcal{P} = \frac{2\alpha_s C}{\pi} \frac{dz}{z} \frac{d\theta}{\theta}$$

C = 4/3 (q), 3 (g)
z = Energy Fraction
θ = Splitting Angle

Uniform in logarithmic plane

The Strongly-Ordered Limit

Basis for parton shower

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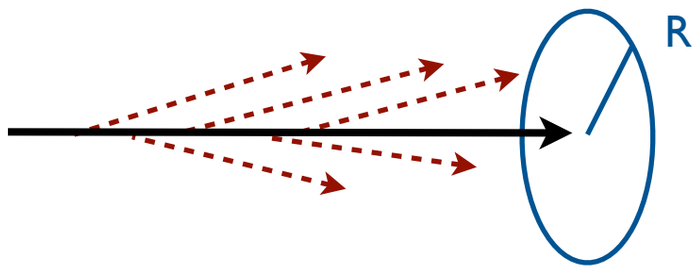

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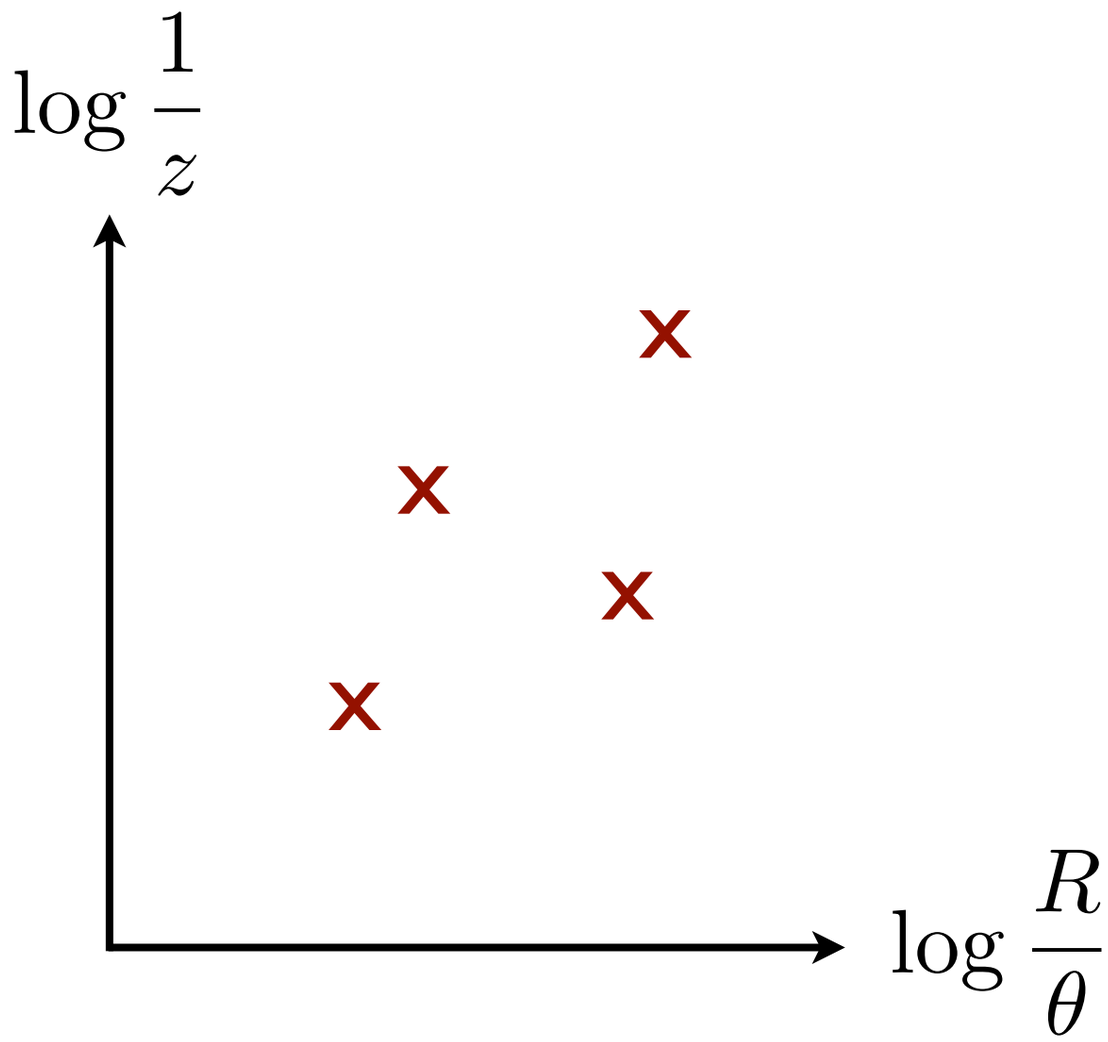

[variant of this plane likely to appear in talks by Salam, Marzani, Larkoski, me, ...]

The Strongly-Ordered Limit

Basis for parton shower

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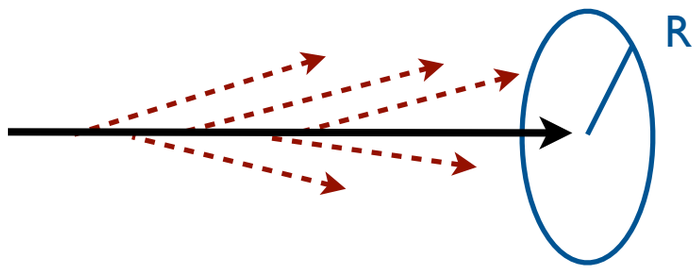

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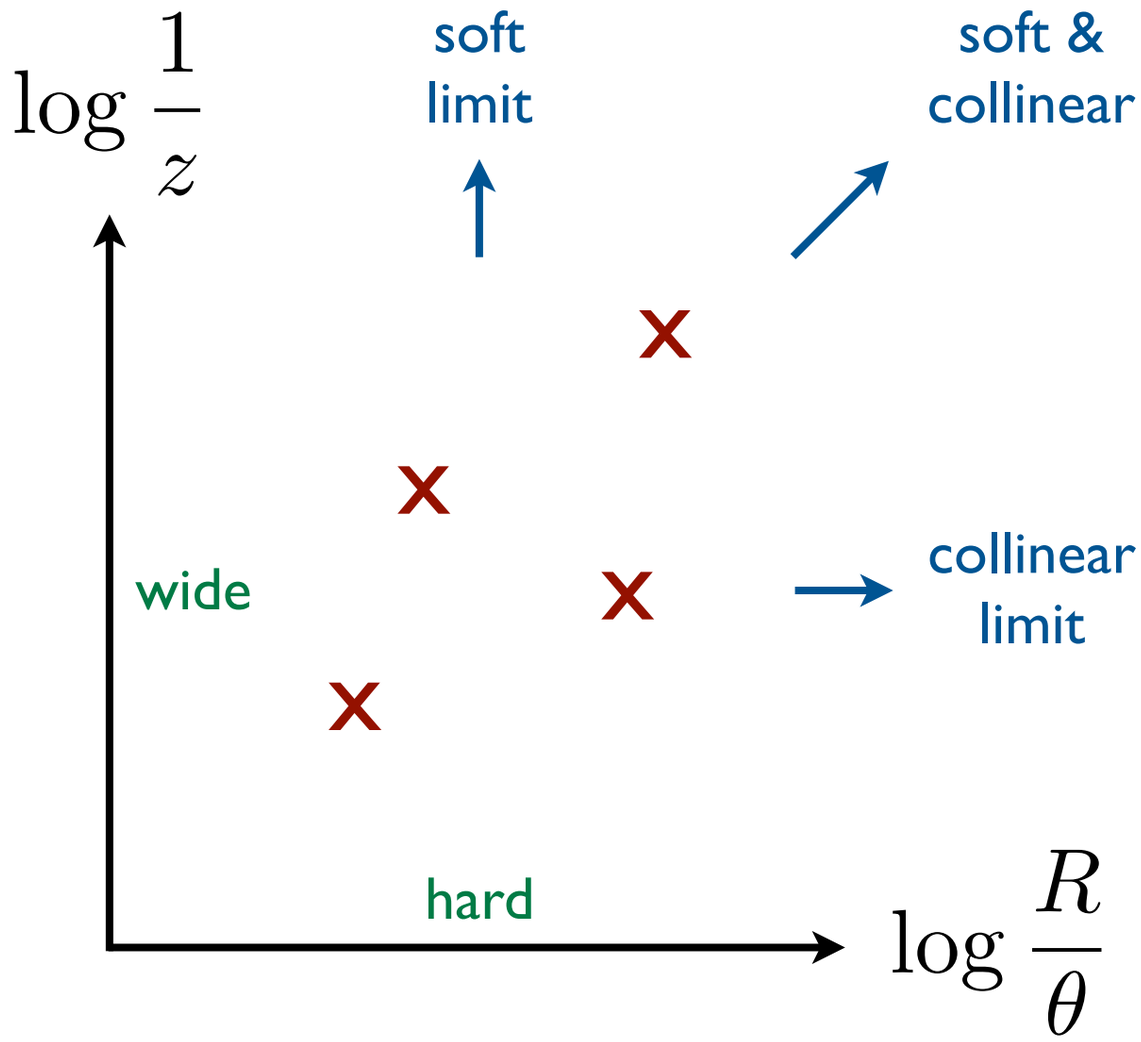

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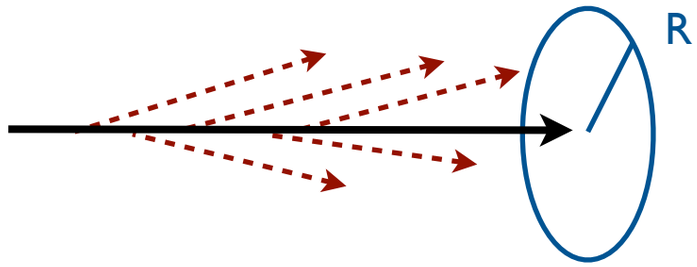
The Strongly-Ordered Limit

Basis for parton shower

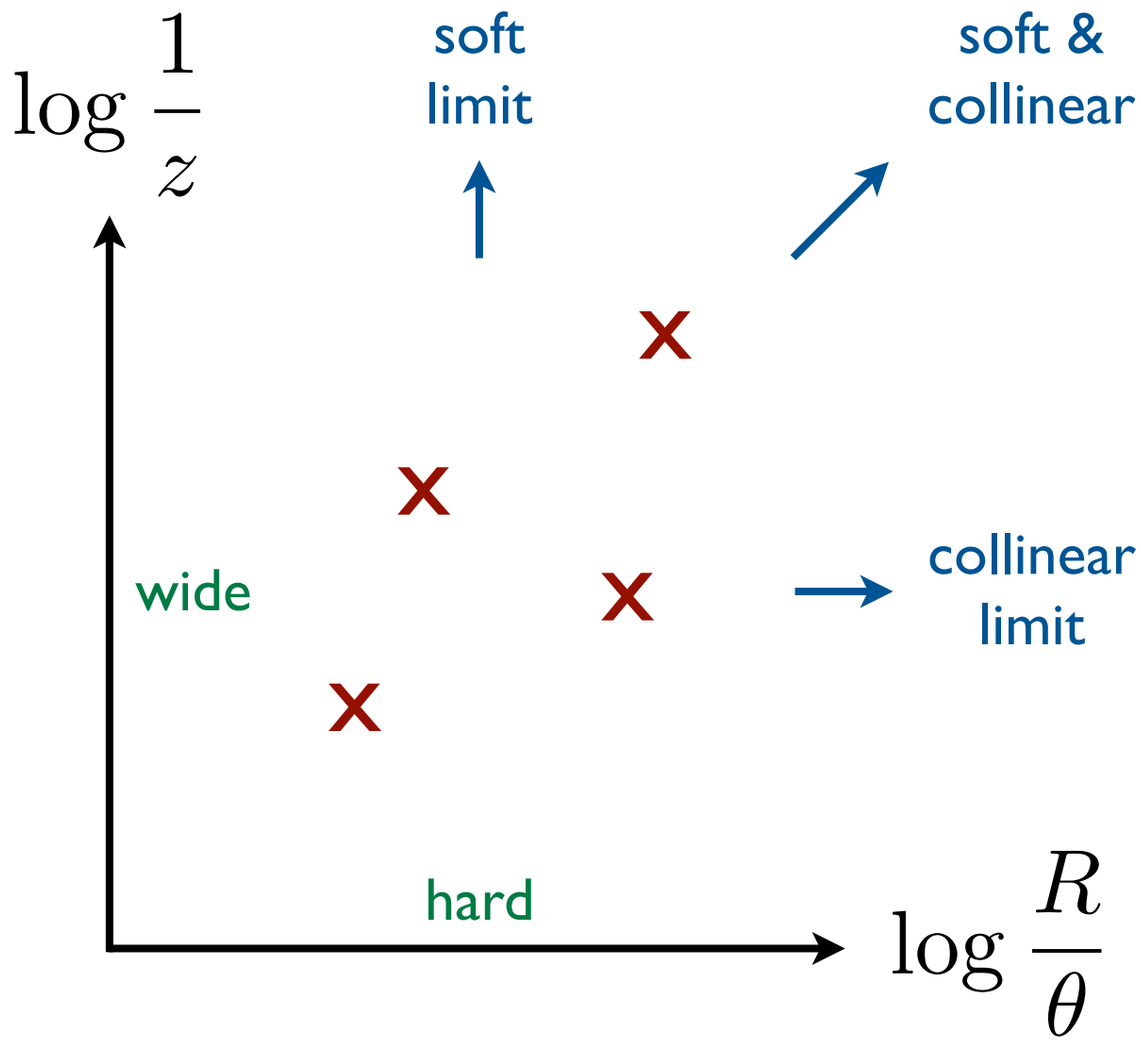


Immediate Observations:

Arbitrary emissions?
Captures (some) physics
at all orders in α_s

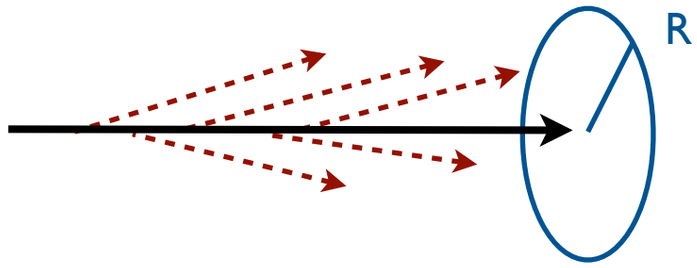
Soft/collinear singularities?
Logarithmic plane extends
up and to the right

IRC safe observables?
Smooth behavior in singular limit
(virtual contributions at infinity)



The Strongly-Ordered Limit

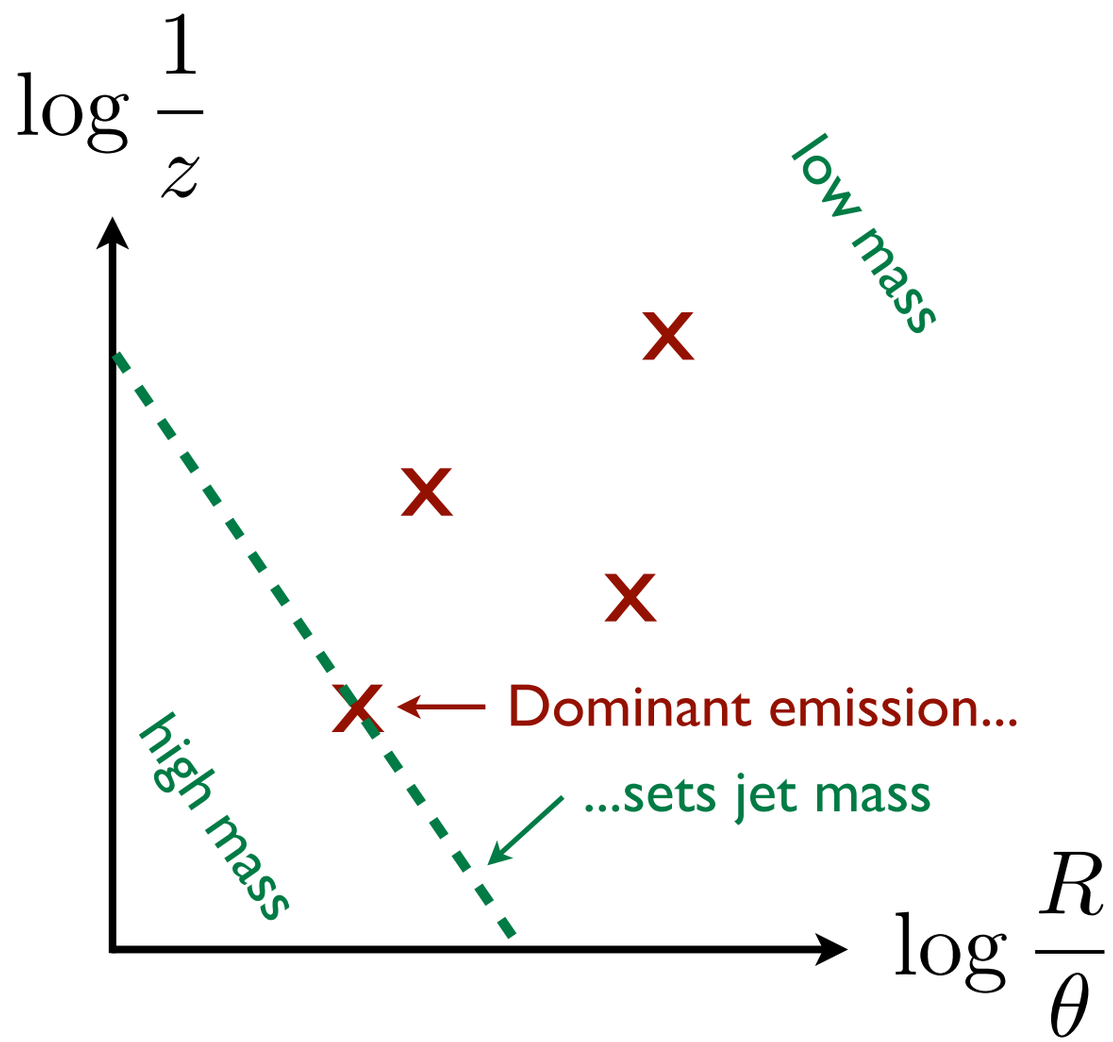
Basis for parton shower



Easy to Estimate Observables!

E.g. Jet Mass

$$m^2_{\text{jet}} \simeq E^2_{\text{jet}}\, z\, \theta^2$$



[see talk by Larkoski
for slower derivation]

The Strongly-Ordered Limit

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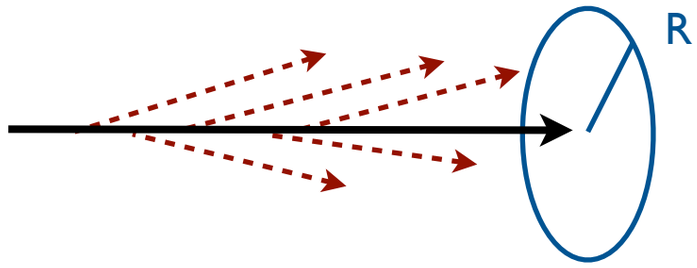

Easy to Estimate Observables!

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$$m^2_{\text{jet}} \simeq E^2_{\text{jet}}\, z\, \theta^2$$

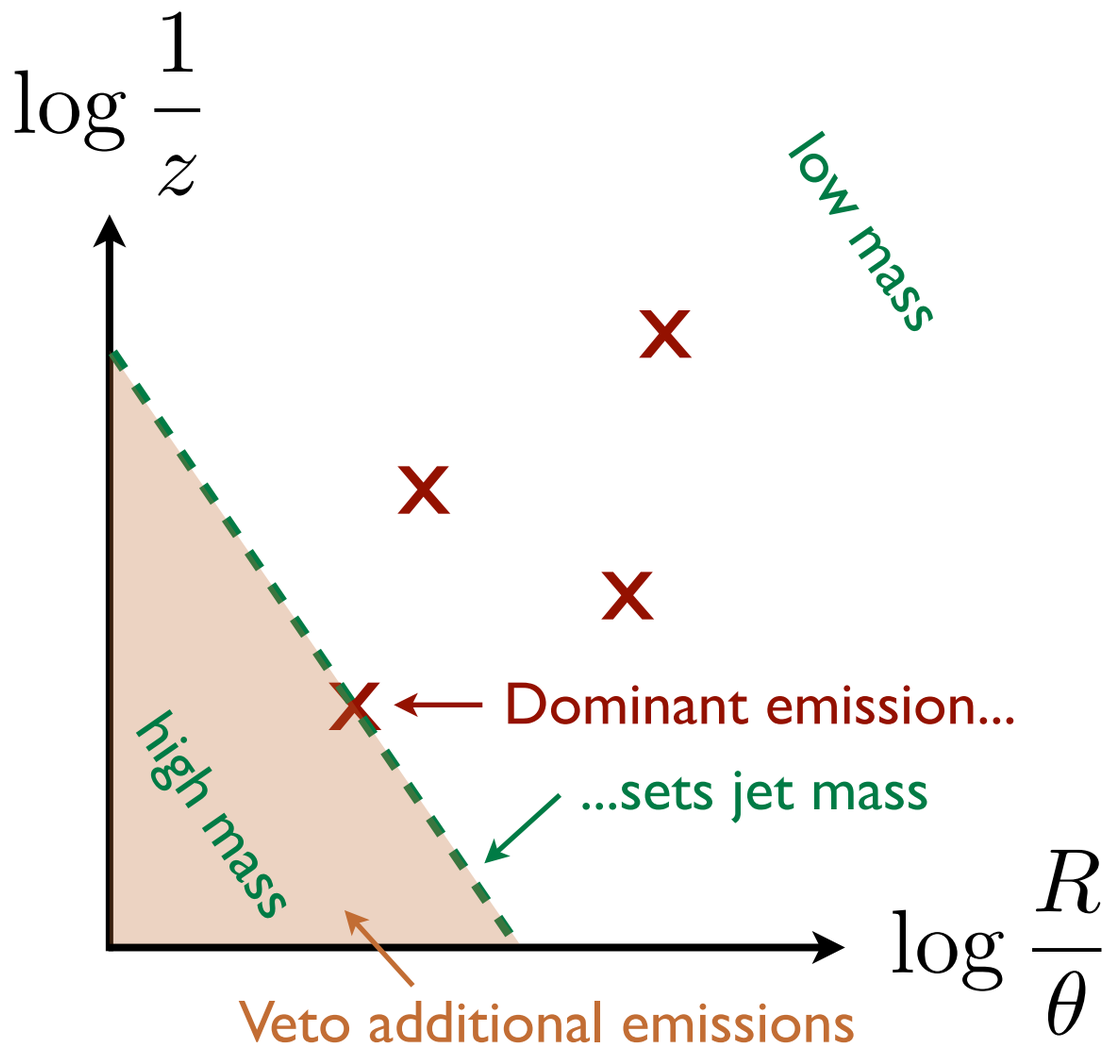
Sudakov Factor

(probability to get measurement below m_{max})

$$\Delta(m_{\text{max}}) = e^{-\frac{2\alpha_s C}{\pi}}$$

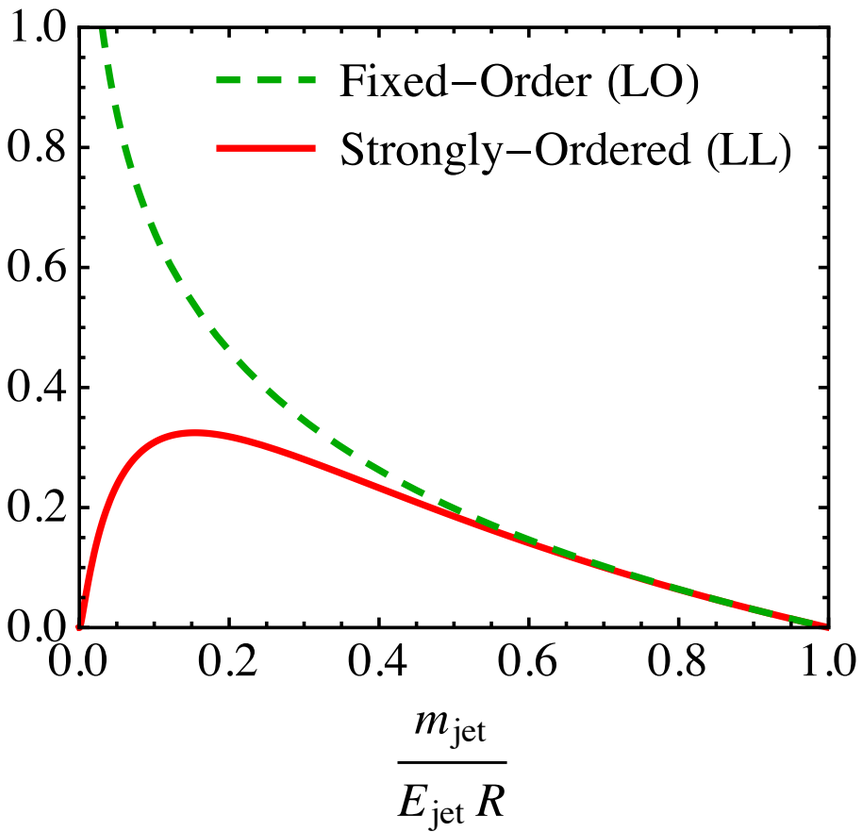
Normalized Cross Section

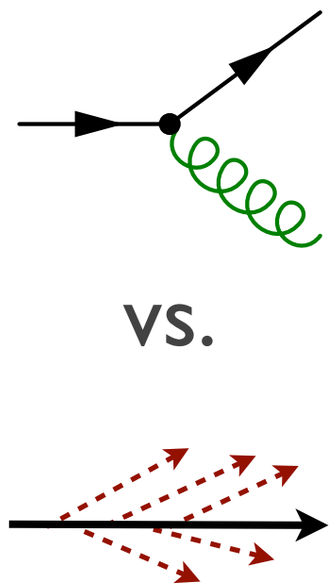
$$\frac{1}{\sigma}\frac{d\sigma}{dm} = \frac{d}{dm}\Delta(m)$$

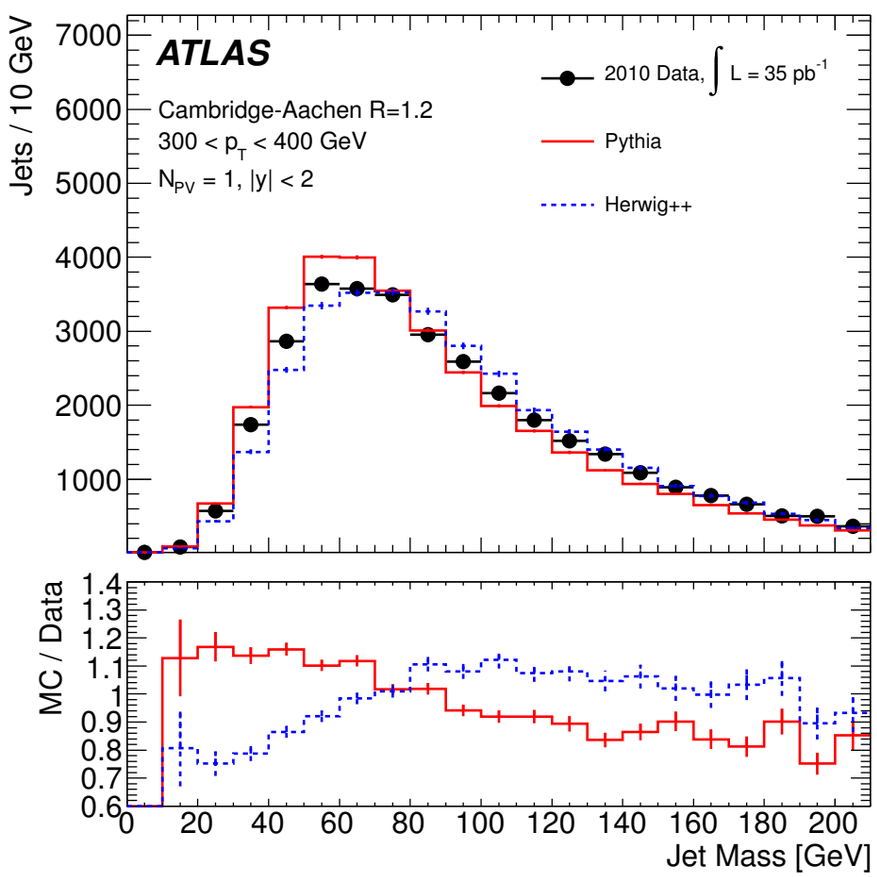


[see talk by Larkoski for slower derivation]

Better Starting Intuition than Fixed-Order





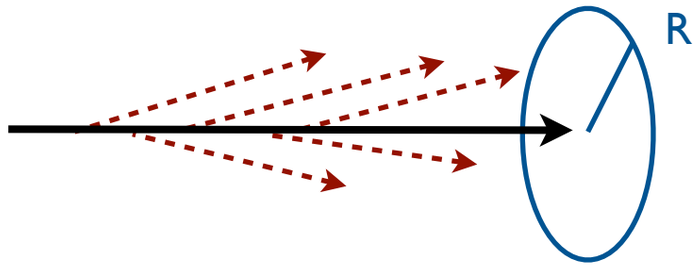


$$\frac{1}{\sigma}\frac{d\sigma}{dm} = \frac{d}{dm} e^{-\frac{2\alpha_s C}{\pi}}$$

[ATLAS: CERN-PH-EP-2012-031]

Realistic parton showers include additional effects (like running α_s)

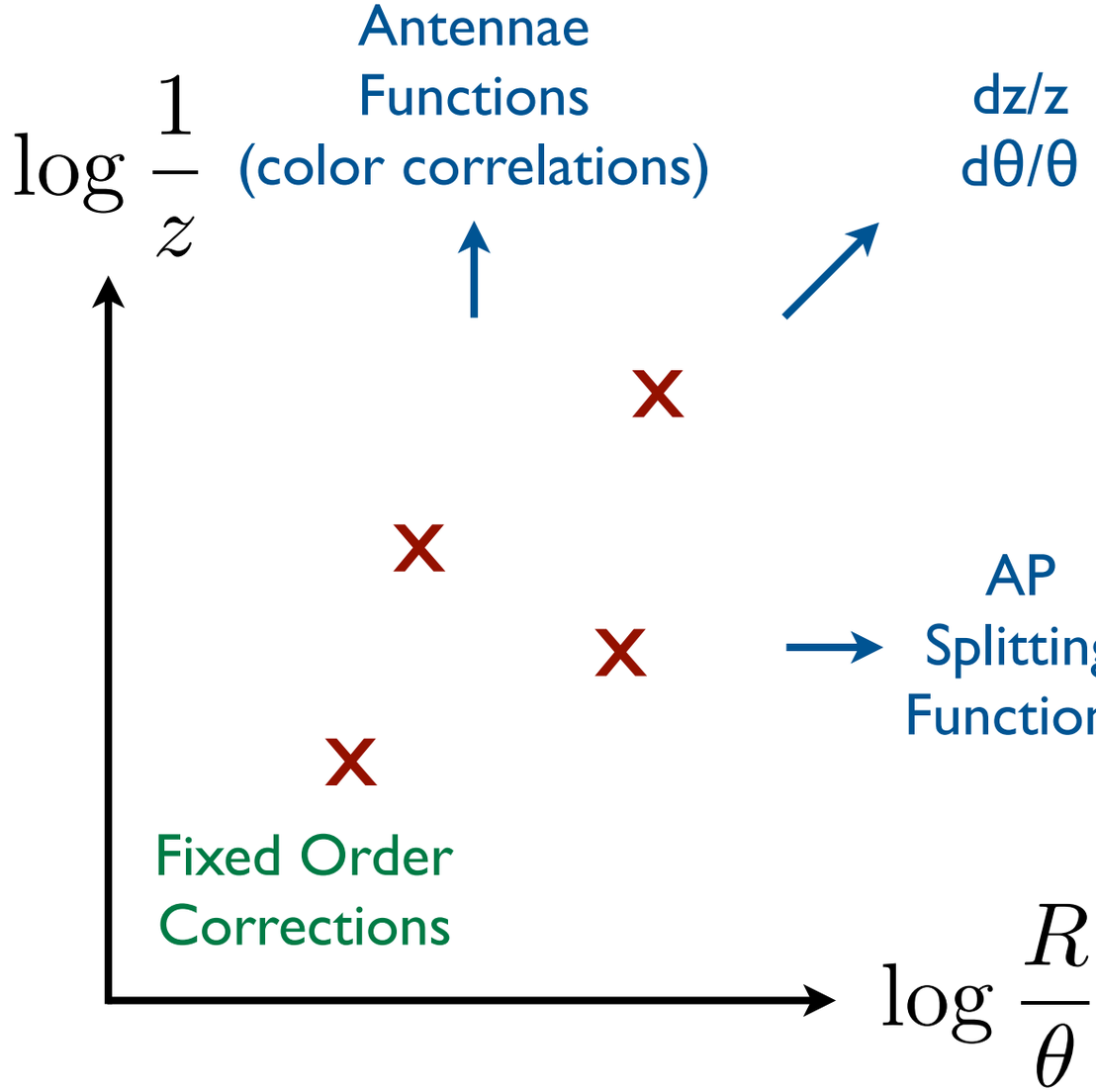
Systematically Improvable



Strongly-Ordered Limit:
Leading logarithmic terms
(i.e. $\alpha_s \log^2 m/E$)

Higher-Order Effects:
Running α_s, Multiple Emissions,
Full Splitting Functions,
Soft Color Correlations,
Fixed-Order Corrections,
Non-global Logarithms, ...

(Many effects already included in existing parton showers)



Quark/Gluon Discrimination is Hard

[see talk by Larkoski]

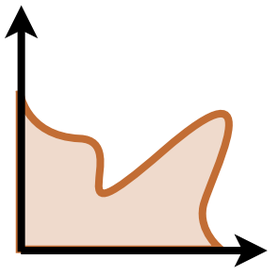
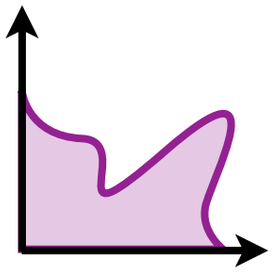
In soft & collinear limit...

$$\mathcal{P} = \frac{2\alpha_s C}{\pi} \frac{dz}{z} \frac{d\theta}{\theta}$$

C = 4/3 (q), 3 (g)
z = Energy Fraction
θ = Splitting Angle

...only difference between quarks and gluons is color factor.

At this order, all* observables has same discrimination power!

Quark Efficiency = x  ⇒  Gluon Mistag = $x^{9/4}$

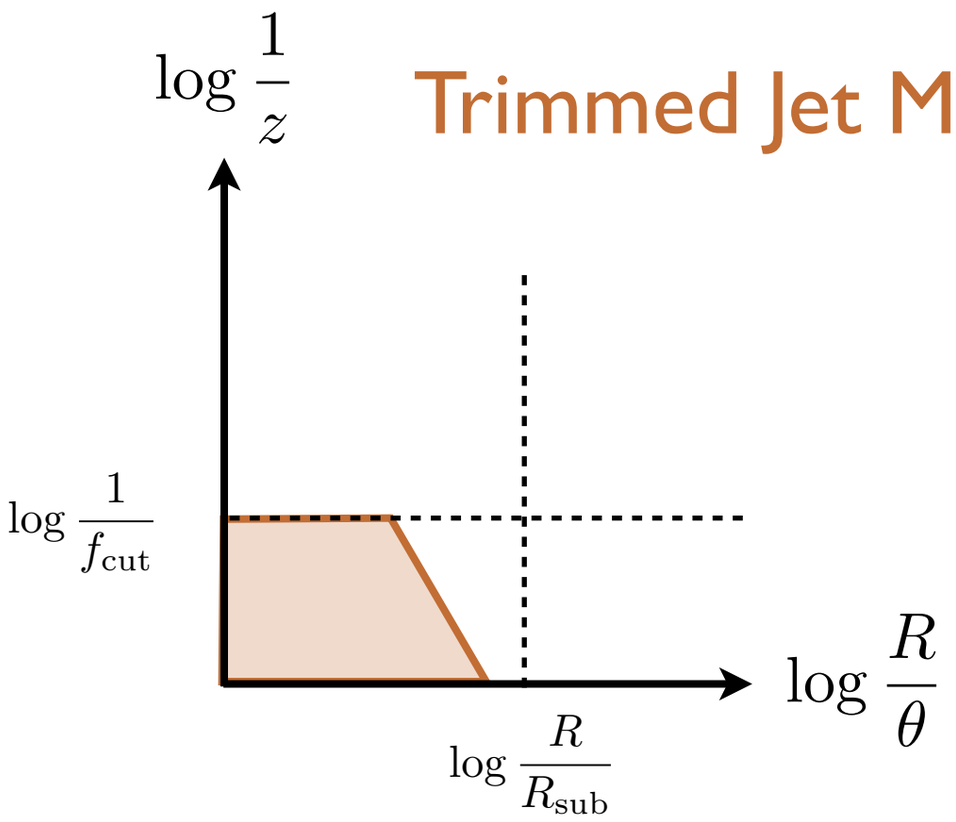
To improve discrimination, need to probe subleading structures (e.g. EEC)

[Larkoski, Salam, JDT]

Comparison of Jet Grooming Methods

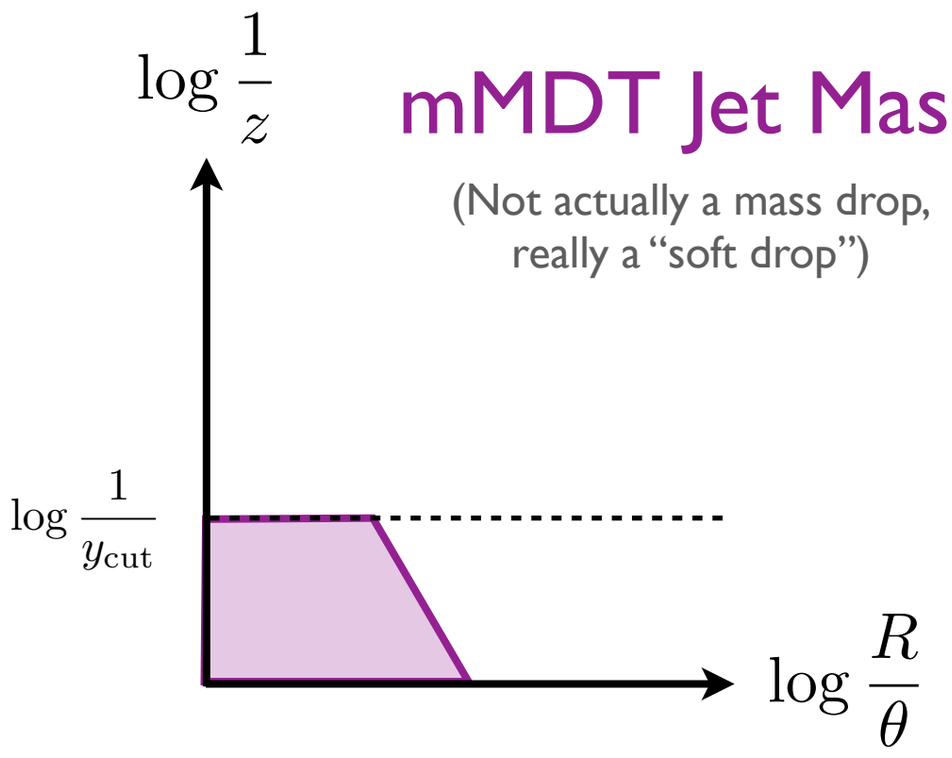
[see talks by Salam, Marzani]

Trimmed Jet Mass



mMDT Jet Mass

(Not actually a mass drop, really a "soft drop")



[Dasgupta, Fregoso, Marzani, Salam/Powling]

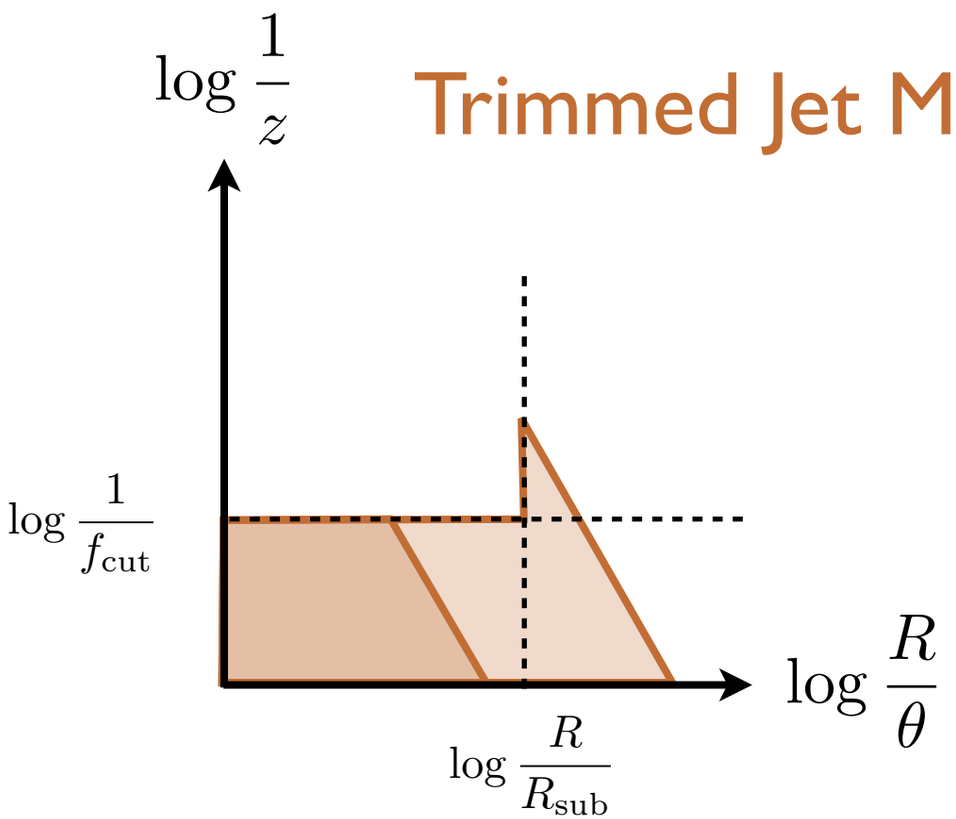
Need to be aware of differing behavior

Trimming: Sudakov double logs (but broadly applicable)

mMDT: "magical" analytic behavior (only for "2 parton" observables)

Comparison of Jet Grooming Methods

[see talks by Salam, Marzani]



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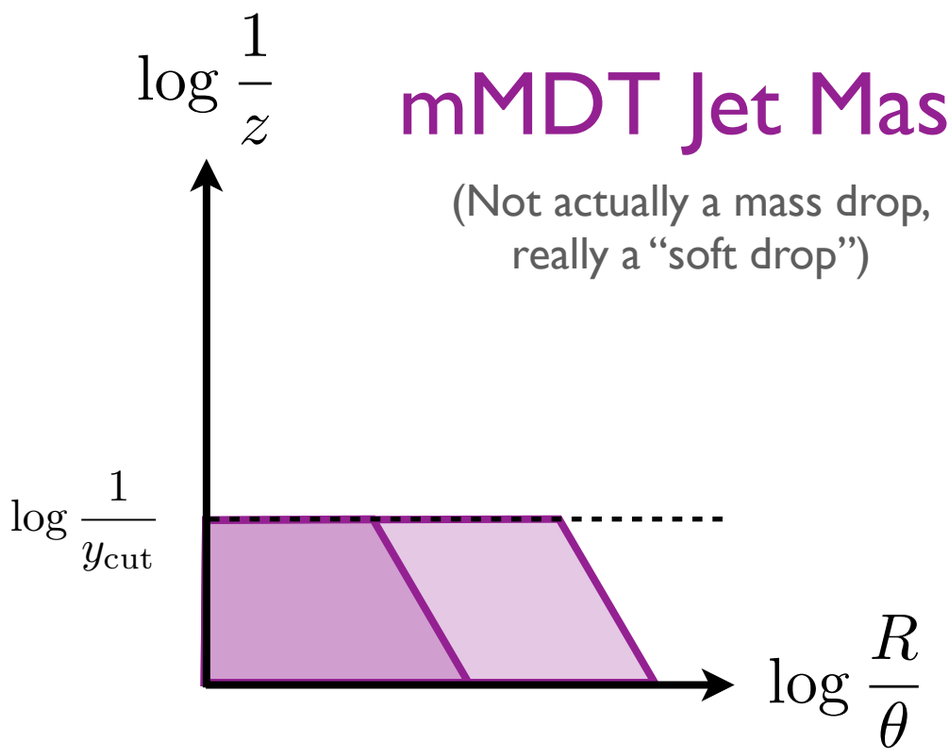

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Calculations for Insight

Back to Basics for Boost 2013

Lesson: Simple analytic methods can guide choice of observables

Boost 2013: "2 parton" (1-prong) observables

Expect Boost 2014: "3 parton" (2-prong) observables

Strongly-ordered limit can highlight degeneracy/differences

New Substructure Checklist:

- Identify Key Physics
- Construct (Clever) Observable
- Predict Discrimination with QCD
- Validate in Monte Carlo
- Test in Data

Calculations for Liberation

Thinking Beyond IRC Safety for Boost 2014

Original Subtitle on Indico:

"what can and what cannot be calculated?"

If you have asked me a year ago...

	Can?	Cannot?
Fixed-Order?	IRC Safe	IRC Unsafe
Resummation? [e.g. 2012 talk by Walsh]	Factorizable	Non-Factorizable

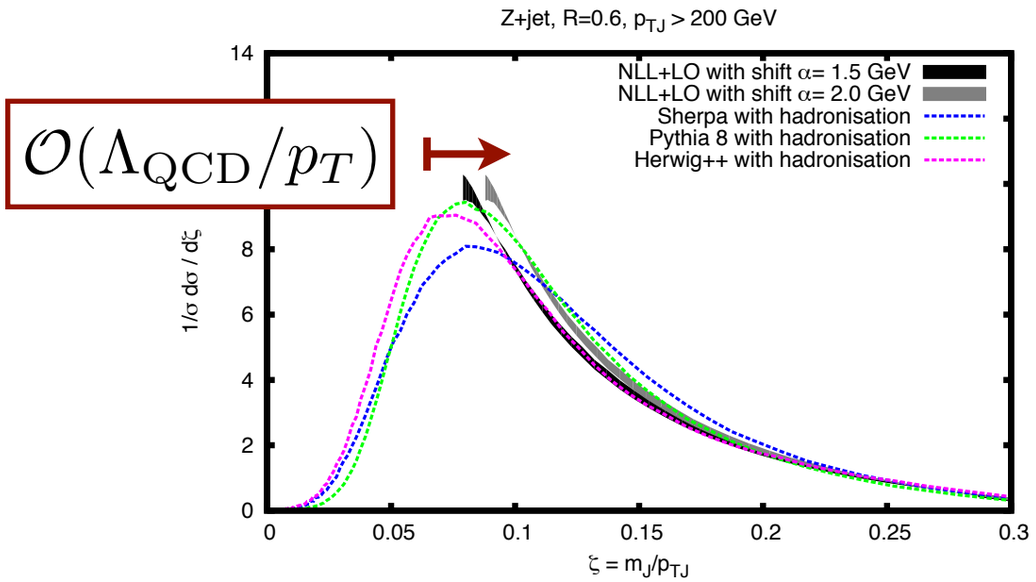
A More Nuanced Picture

	IRC Safe?	IRC Unsafe?
Perturbative Control?	Yes Order-by-order in α_s	
Non-Perturbative Input?		

IRC Safe ≠ No Non-Perturbative

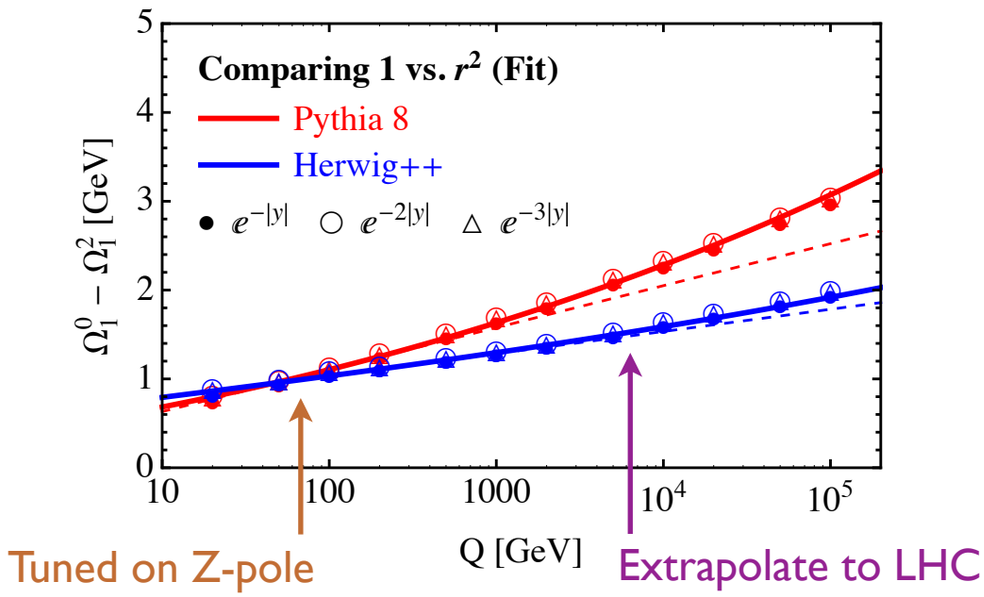
Reminders from Boost 2012

e.g. Power Corrections in Jet Mass



[Dasgupta, Khelifa-Kerfa, Marzani, Spannowsky, 2012 talk by Marzani]

Perturbative Evolution of NP Corrections



[Mateu, Stewart, JDT; 2012 talk by Mateu]

Non-perturbative input needed for precision calculations

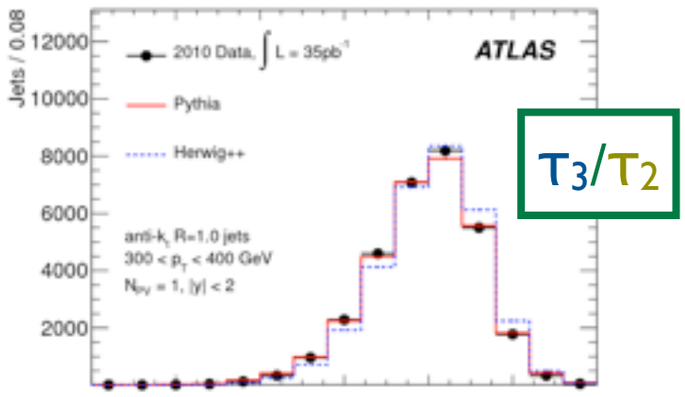
A More Nuanced Picture

	IRC Safe?	IRC Unsafe?
Perturbative Control?	Yes Order-by-order in α_s	
Non-Perturbative Input?	Yes: $(\Lambda/Q)^n$ e.g. Power Corrections ↑ Sometimes: Perturbative Handle	

Key: Assess *degree* of sensitivity to NP physics

Built from IRC Safe ≠ IRC Safe

[see talk by me]



Theorists tricked ATLAS to make an IRC unsafe measurement?

N-subjettiness: τ_1 is IRC Safe

τ_2 is IRC Safe

τ_3 is IRC Safe

Strictly Speaking: τ_2/τ_1 is IRC Unsafe

τ_3/τ_2 is IRC Unsafe

[observed by Soyez, Salam, Kim, Dutta, Cacciari]

Don't Panic: These (and others) are "Sudakov Safe"

Higher degree of sensitivity to NP physics, but still calculable

A More Nuanced Picture

	IRC Safe?	IRC Unsafe?
Perturbative Control?	Yes Order-by-order in α_s	Sometimes e.g. expansion in $\sqrt{\alpha_s}$
Non-Perturbative Input?	Yes: $(\Lambda/Q)^n$ e.g. Power Corrections ↑ Sometimes: Perturbative Handle	

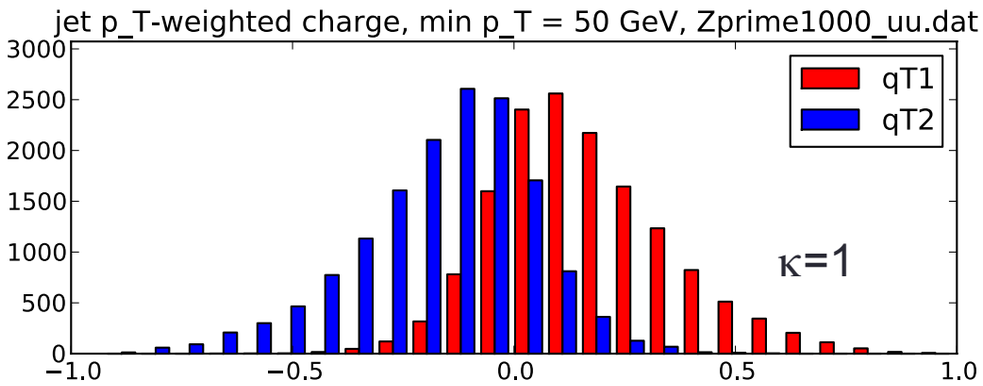
Key: Assess *degree* of sensitivity to NP physics

Jet Charge

Key development from Boost 2012

$$Q_\kappa^i = \frac{1}{E_{\text{jet}}} \sum_{j \in \text{jet}} Q_j (E_j)^\kappa$$

[Krohn, Lin, Schwartz, Waalewijn; 2012 talk by Schwartz]



$$Z' \to \bar{u} u$$

IRC Unsafe: Very sensitive to fragmentation of partons to charged hadrons

But still calculationally tractable!

We've seen this before...

Analogy with Parton Distribution Functions

PDFs: Fundamentally non-perturbative...

$$f_i(x) \Leftrightarrow \langle p|\overline{\psi}(y)\psi(0)|p\rangle$$

Measure at one scale...

...with perturbative DGLAP evolution

$$\mu\frac{d}{d\mu}f_i = \frac{\alpha_s}{2\pi}P_{i\to j}\otimes f_j$$

...RG evolve to higher scale

Same basic principle behind jet charge

(though more complicated evolution than PDF or fragmentation function)

New Application: Track-Based Observables

[See talk by Waalewijn]

A More Nuanced Picture

	IRC Safe?	IRC Unsafe?
Perturbative Control?	Yes Order-by-order in α_s	Sometimes e.g. Ratio Observables in $\sqrt{\alpha_s}$
Non-Perturbative Input?	Yes: $(\Lambda/Q)^n$ e.g. Power Corrections	Yes: $O(1)$ e.g. Track Functions

Sometimes:
Perturbative Handle

Key: Assess *degree* of sensitivity to NP physics

Calculations for Liberation

Thinking Beyond IRC Safety for Boost 2014

Lesson: There are analytic approaches for understanding IRC unsafe observables

should

"what ~~can and what cannot~~ be calculated?"

My old view: Onus on experimental community to use IRC-safe jet observables

Absolutely still the default

My evolving view: Onus on theory community to calculate other useful observables (or variants)

e.g. hadron multiplicity for quark vs. gluon

Summary

(Calculations for Precision)

Deep connection between what you measure and what you calculate

Calculations for Insight

Dominant physics often captured by strongly-ordered limit
Theory can guide choice of optimal observables (for a given purpose)
Discovery of magical observables like mMDT

Calculations for Liberation

If an observable works in data/MC, onus on theory to understand it
IRC safety is not a necessary condition for analytic understanding
Non-perturbative effects matter even for IRC safe observables
New insights when working to all orders in α_s
Key role of non-perturbative objects with perturbative evolution (c.f. PDFs)