Controlling Jets with SCET

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work with
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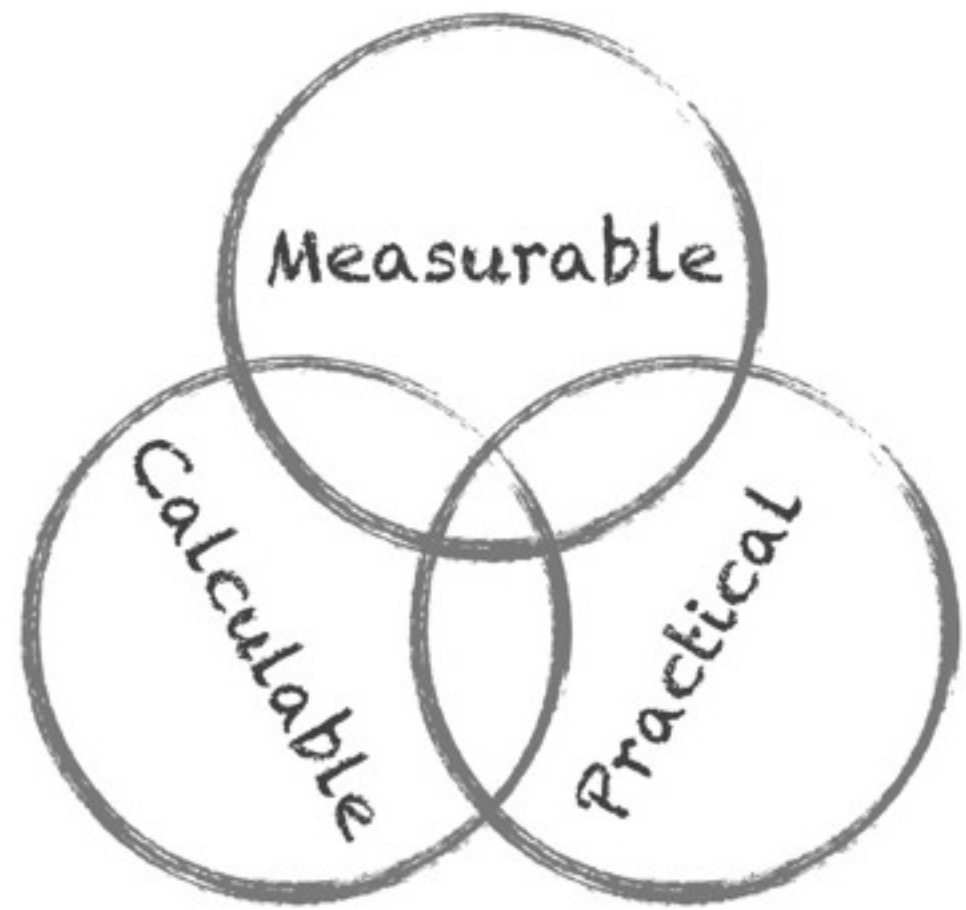
Outline

- Accessing jet structure
- Constructing an effective theory for jet structure
- Future Outlook

Calculable, Measurable, Predictable

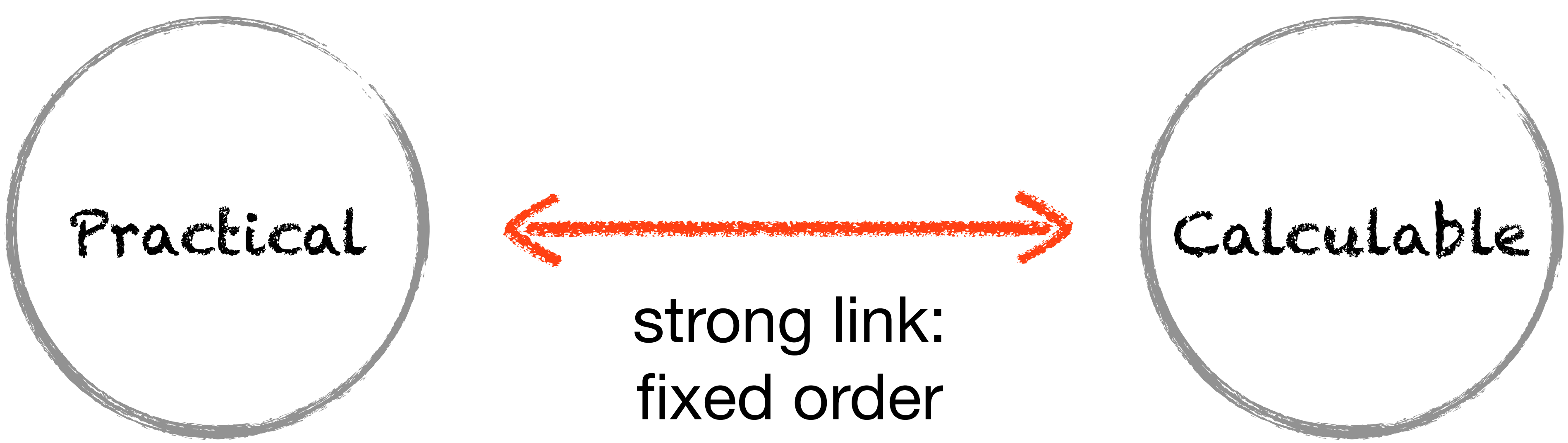
- Is jet substructure measurable?
  - Yes!
- Is jet substructure practical?
  - Yes!
- Is jet substructure calculable?
  - Kind of...



Calculable Approaches

Analytic approaches (pQCD & SCET, factorization and resummation)

- Pros: well controlled, provides accuracy, helps improve MC
- Cons: inclusive observables, currently limited to simple configurations, difficult to add a full range of physics



strong link:
fixed order
factorization and resummation
want jet substructure

Calculable Framework for Jet Substructure

- Calculation-friendly algorithms, observables

  Catani, Dokshitzer, Olsson, Turnock, Webber; Ellis, Soper;
  Dokshitzer, Leder, Moretti, Webber; Cacciari, Salam, Soyez; Bauer, Hornig, Tackmann

- Hard scattering for the LHC

  Everyone ever

- Merging between multijet processes

  Catani, Seymour; Catani, Krauss, Kuhn, Webber; Mangano + many MC authors

- Jet shapes and multijet events

  Ellis; Seymour; Berger, Sterman; Almeida, Lee, Perez, Sterman, Sung, Virzi;
  Ellis, Hornig, Lee, Vermilion, JW; Jouttenus, Stewart, Tackmann, Waalewijn + many event shapes authors

- Non-global logarithms

  Dasgupta, Salam, Rubin, Banfi, Khelifa-Kerfa, Marzani,
  Kelley, Schabinger, Schwartz, Zhu; Hornig, Lee, Stewart, JW, Zuberi

- Non-perturbative corrections and uncertainties

  Lee, Sterman; Dasgupta, Magnea, Salam; Hoang, Stewart; Bauer, Lee, Manohar, Wise

N-jettiness

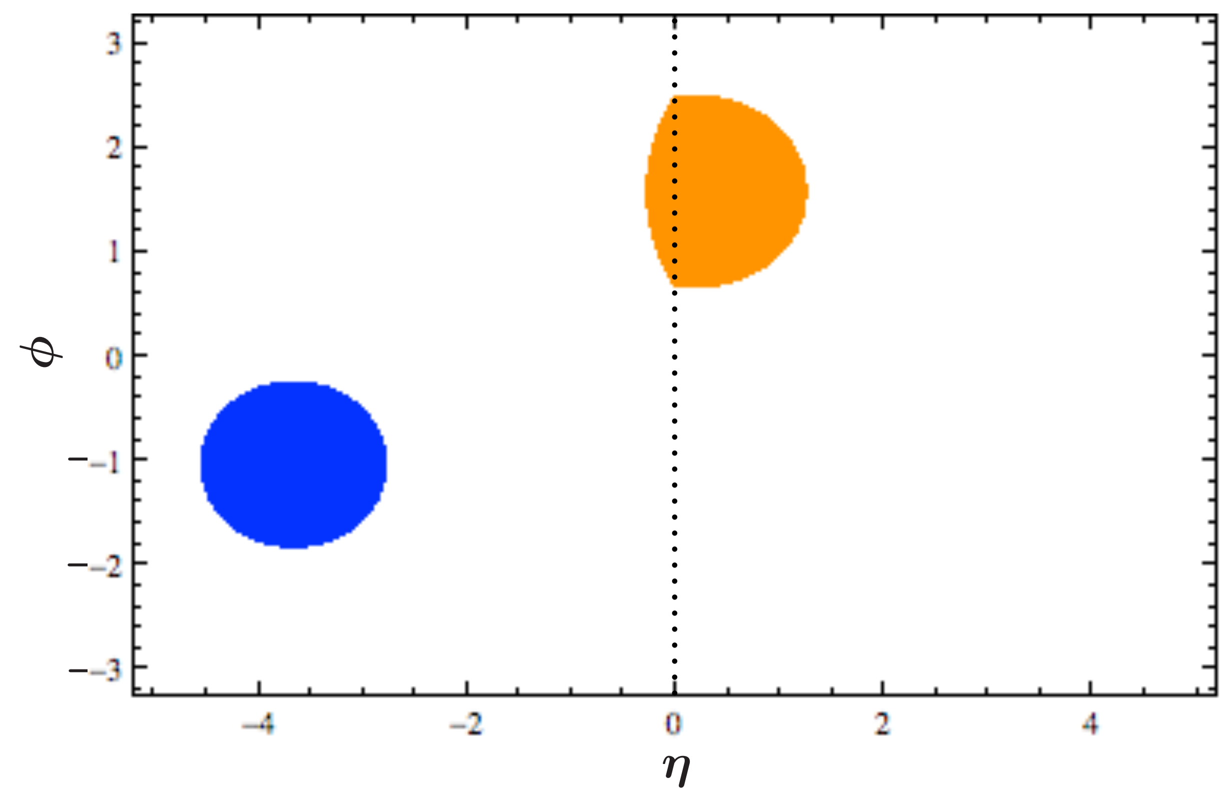
Stewart, Tackmann, Waalewijn
Jouttenus, Stewart, Tackmann, Waalewijn

for each jet:

$$\mathcal{T}_j = \sum_i n_j \cdot k_i$$

advantages:
inclusive over phase space
calculable
no boundary parameters

boundary regions for jets, beam

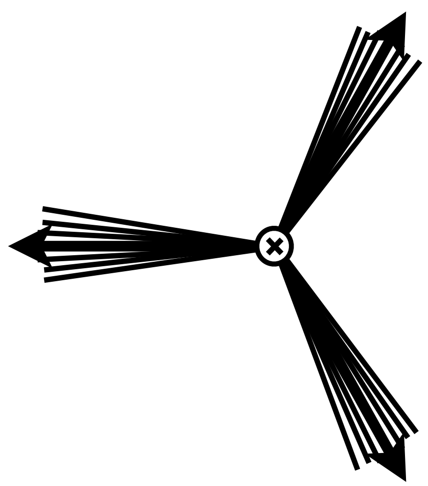


jet assignment depends only on particle direction

We will study a specific multijet configuration using N-jettiness

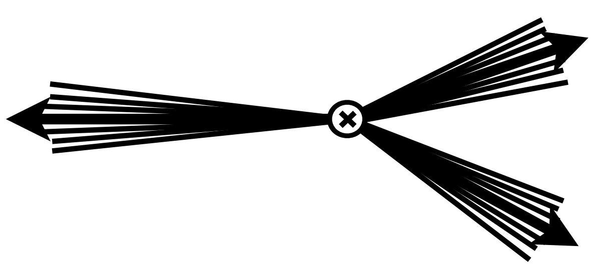
But the framework we use applies to other jet definitions and observables

Multi-jet and Multi-subjet Events

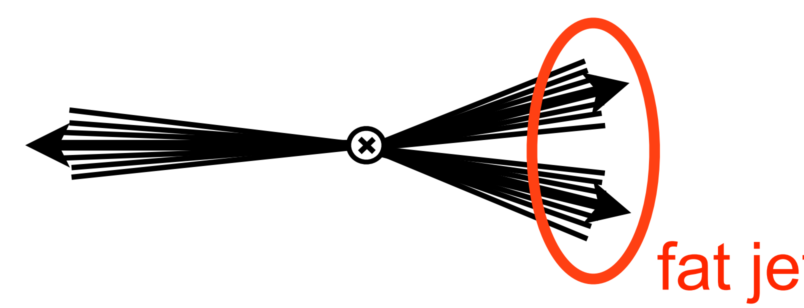


uncommon
well-separated
energetic
all scales ~Q

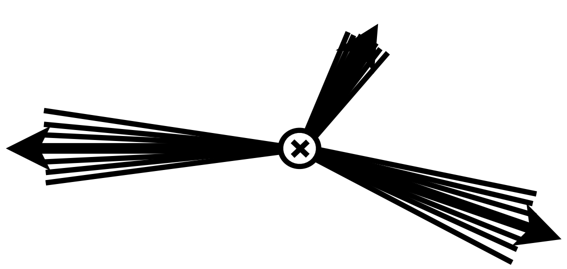
substructure limit:
2 jets merge



common
nearby jets
energetic
small dijet invariant mass t

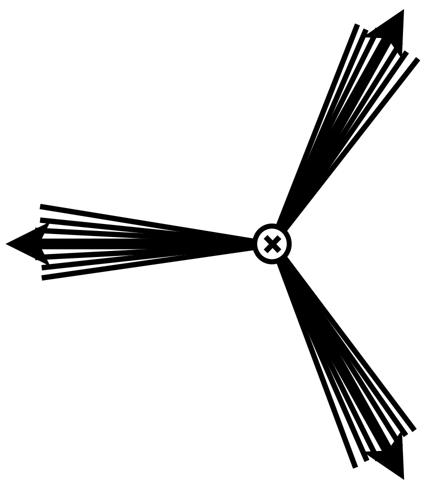


Can think about the
subjets as their own jets



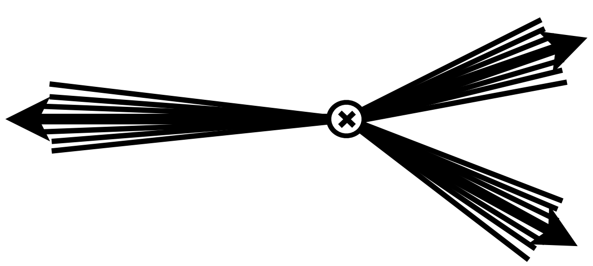
common
well-separated
hierarchy of jet energies
small dijet invariant masses

Multi-jet and Multi-subjet Events



uncommon
well-separated
energetic
all scales ~Q

scales:
center of mass energy
dijet invariant masses
jet masses
soft scales



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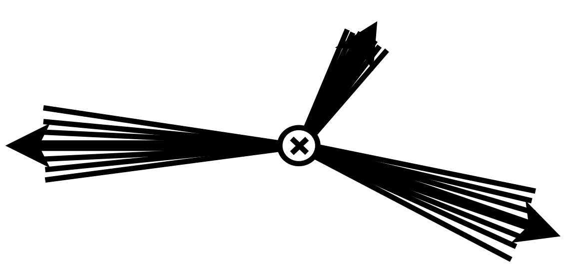

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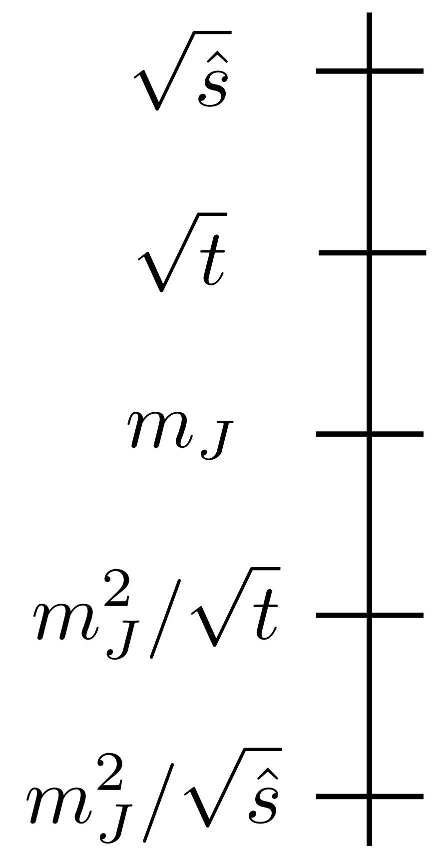
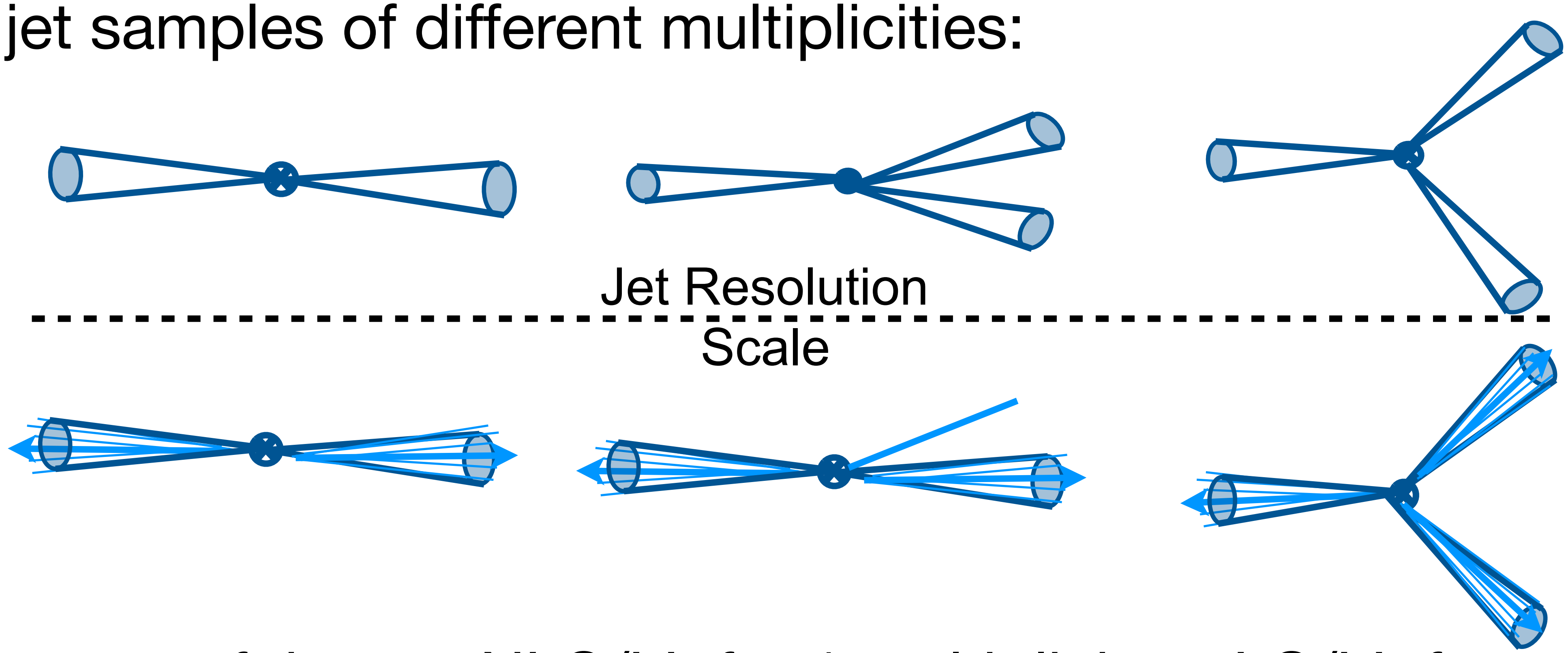


Multijets and Monte Carlo

- Merge jet samples of different multiplicities:



- Current state of the art: NLO/LL for 1 multiplicity + LO/LL for additional multiplicities

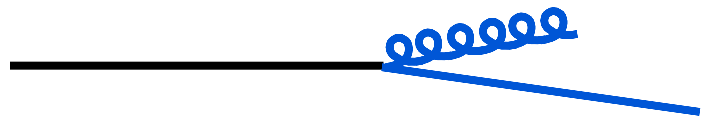
- Goal: NLO/LL for many multiplicities

GENEVA

Christian Bauer, Calvin Berggren, Nicholas Dunn, Andrew Hornig, Frank Tackmann, Jesse Thaler, Christopher Vermilion, Jonathan Walsh, Saba Zuberi

Modes for Jet Physics

collinear $p_c \sim Q(\lambda^2, 1, \lambda)$

n 

soft $p_s \sim Q(\lambda^2, \lambda^2, \lambda^2)$

n 

light-cone coords:

$$n_j = (1, \hat{n}_j)$$
$$\bar{n}_j = (1, -\hat{n}_j)$$

$$k = (\bar{n} \cdot k, n \cdot k, k_\perp)$$
$$= (k^-, k^+, k^\perp)$$

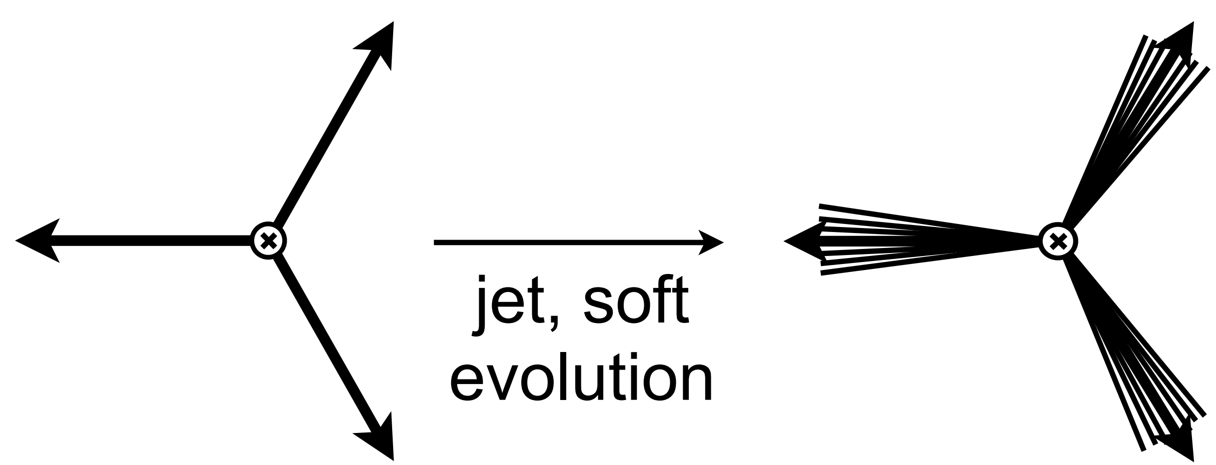
$\lambda \equiv \dfrac{p_\perp}{Q} \ll 1$: defines the power counting parameter in SCET

getting from QCD to SCET:

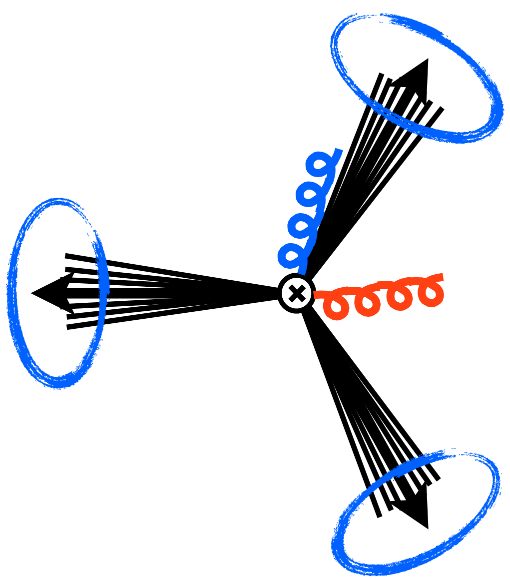
$$\sqrt{\hat{s}} \quad \frac{\text{QCD}}{\text{SCET}} \quad C_N(q_i)$$

N-jet operator

hard parton configuration



Factorization and Scales in Multijet Events



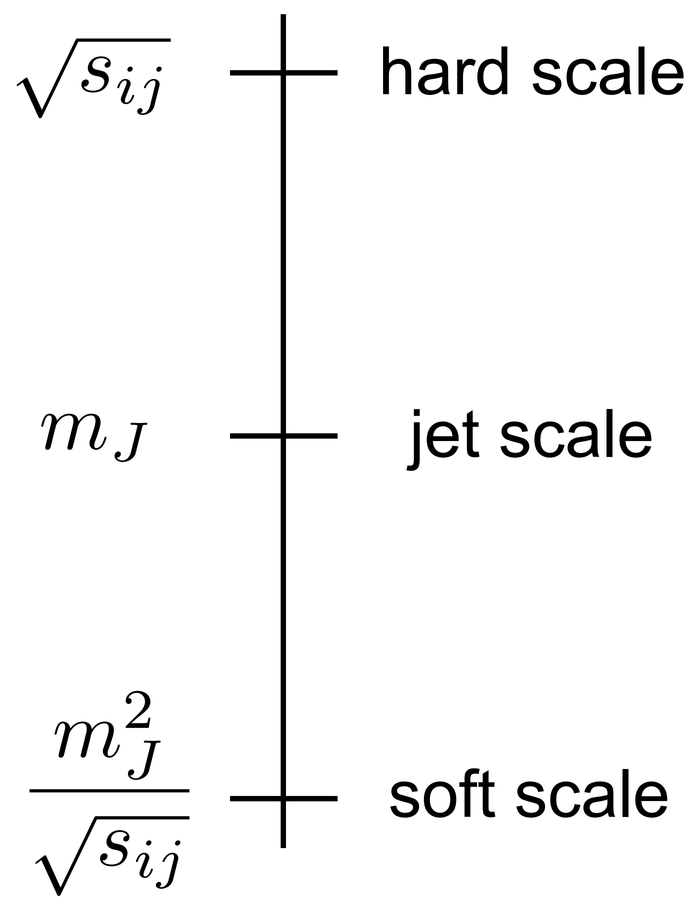
hard: $p_h \sim \sqrt{s_{ij}}(1,1,1)$ $\quad p_h^2 \sim s_{ij}$

collinear: $p_c \sim E_J(1,\lambda^2,\lambda)$ $\quad p_c^2 \sim E_J^2\lambda^2 \sim m_J^2$

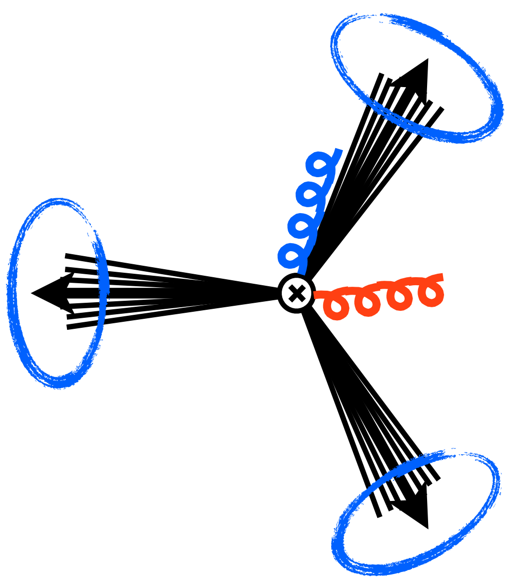
soft: $p_s \sim E_J(\lambda^2,\lambda^2,\lambda^2)$ $\quad p_s^2 \sim E_J^2\lambda^4 \sim m_J^4/E_J^2$

factorization theorem:

$$\frac{d\sigma}{d\mathcal{T}_i} = \frac{d\sigma^0}{d\Phi_3} H_3\, J_i \otimes S_3$$



Scales in Multijet Events



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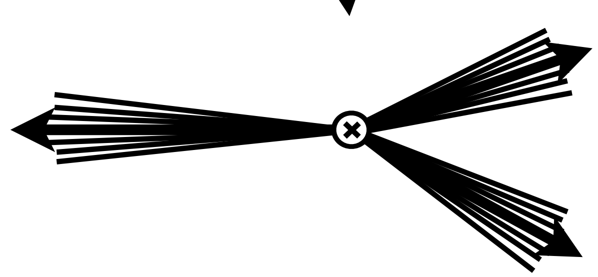
jet configuration changes



Hard scales become widely separated

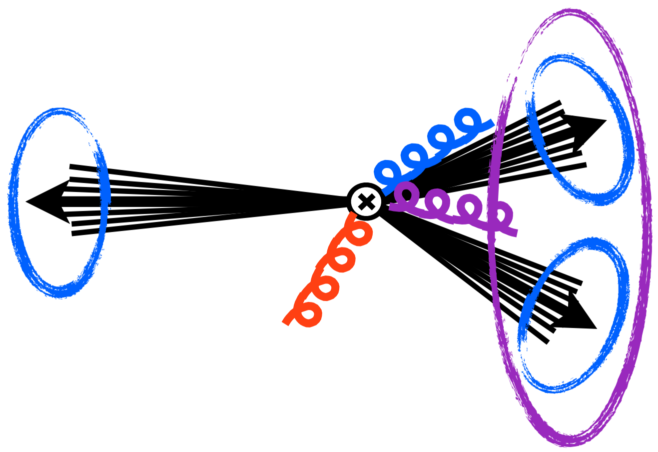
Cannot sum large logarithms in the hard function
- same problem in the soft function

Obtain large logs of small angles: $\ln n_i \cdot n_j$

For nearby jets, need a new mode for the dijet system and a new factorization theorem

$$\ln n_i \cdot n_j \ : \ \text{ninja}$$

Solution: Add a New Mode



culprits:
need additional hard scattering factorization
soft radiation between the dijets lives at a different scale

Hard scattering factorization solved by
Bauer, Schwartz
Baumgart, Marcantonini, Stewart

We will add a new collinear-soft (csoft) mode which contributes to the dijet system

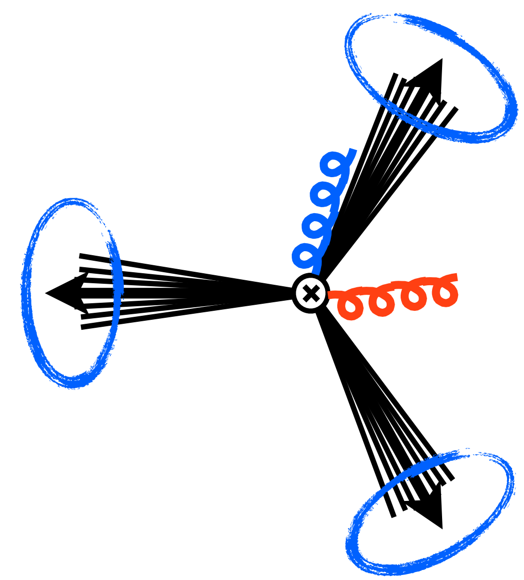
Build this new mode into a new version of SCET
SCET_+: an EFT for multijets with small dijet invariant masses
Also useful for jet substructure: nearby subjets

Why Collinear and Soft Modes?

$$\text{hard:} \quad p_h \sim \sqrt{s_{ij}}\,(1,1,1)$$

$$\text{collinear:} \quad p_c \sim E_J(1,\lambda^2,\lambda)$$

$$\text{soft:} \quad p_s \sim E_J(\lambda^2,\lambda^2,\lambda^2)$$



relate them to the observable:

$$\mathcal{T}_j(p) = n_j \cdot p$$

$$\mathcal{T}_j(p_c) = n_j \cdot p_c \sim E_J \lambda^2 \;+\; p_c^2 \sim E_J^2 \lambda^2 \;\Rightarrow\; p_c \sim E_J(1,\lambda^2,\lambda)$$

$$\mathcal{T}_j(p_s) = n_j \cdot p_s \sim E_J \lambda^2 \;+\; p_s^2 \sim E_J^2 \lambda^4 \;\Rightarrow\; p_s \sim E_J(\lambda^2,\lambda^2,\lambda^2)$$

asking for a given sized contribution to the observable
and certain kinematics (collinear, soft) fixes the scaling of the modes

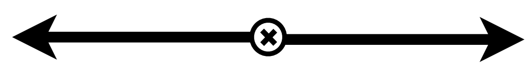
Modes with Nearby Jets: Hard Modes

Bauer, Schwartz
Baumgart, Marcantonini, Stewart

QCD

$\sqrt{s_{ij}}$ —— $C_2(q_i)$ hard: $p_h \sim \sqrt{s_{ij}}\,(1,1,1)$

O_2
2-jet operator



resolve 2 jets

Modes with Nearby Jets: Hard Modes

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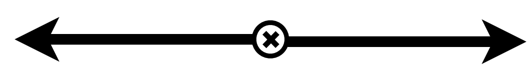


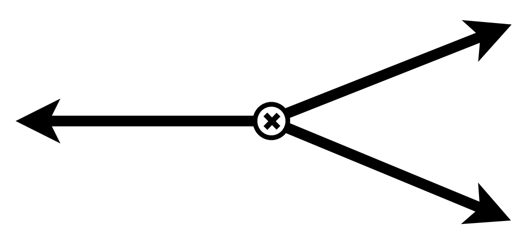
resolve 2 jets

$$\lambda = \frac{m_J^2}{Q^2}$$

$\sqrt{t}$ ——— $C_3(q_i)$ collinear: $p_c \sim E_J(1, \lambda_t^2, \lambda_t)$

$$\lambda_t = \frac{t}{Q^2}$$

O_3
3-jet operator



resolve 3 jets

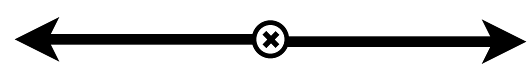
Modes with Nearby Jets: Hard Modes

Bauer, Schwartz
Baumgart, Marcantonini, Stewart

QCD

$\sqrt{s_{ij}}$ —— $C_2(q_i)$ hard: $p_h \sim \sqrt{s_{ij}}\,(1,1,1)$

O_2
2-jet operator



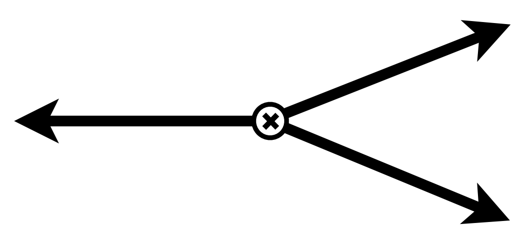
resolve 2 jets

$$\lambda = \frac{m_J^2}{Q^2}$$

$\sqrt{t}$ —— $C_3(q_i)$ collinear: $p_c \sim E_J(1, \lambda_t^2, \lambda_t)$

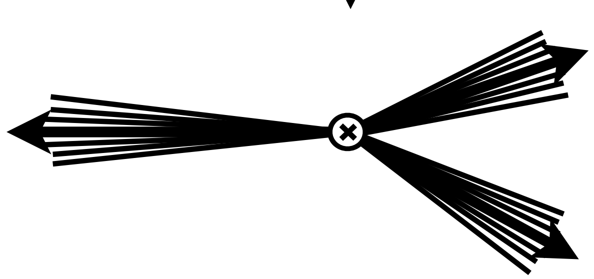
$$\lambda_t = \frac{t}{Q^2}$$

O_3
3-jet operator

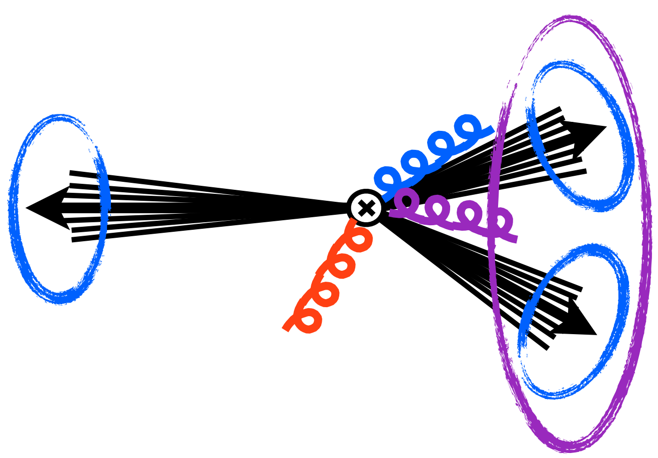


resolve 3 jets

↓ jet evolution



Modes with Nearby Jets: Collinear and Soft Modes



$\mathcal{T}_j(p) = n_j \cdot p$

collinear: $p_c \sim E_J(1, \lambda^2, \lambda)$

csoft: $p_{cs} \sim E_J \dfrac{\lambda^2}{\lambda_t^2}(1, \lambda_t^2, \lambda_t)$

soft: $p_s \sim E_J(\lambda^2, \lambda^2, \lambda^2)$

$$\lambda = \frac{m_J^2}{Q^2}$$

$$\lambda_t = \frac{t}{Q^2}$$

$$\mathcal{T}_j(p_c) = n_j \cdot p_c \sim E_J \lambda^2 \;\;\&\;\; p_c^2 \sim E_J^2 \lambda^2 \;\Rightarrow\; p_c \sim E_J(1, \lambda^2, \lambda)$$

$$\mathcal{T}_j(p_{cs}) = n_j \cdot p_{cs} \sim E_J \lambda^2 \;\;\&\;\; \frac{p_{cs}^+}{p_{cs}^-} \sim \lambda_t^2 \;\Rightarrow\; p_{cs} \sim E_J \frac{\lambda^2}{\lambda_t^2}(1, \lambda_t^2, \lambda_t)$$

$$\mathcal{T}_j(p_s) = n_j \cdot p_s \sim E_J \lambda^2 \;\;\&\;\; p_s^2 \sim E_J^2 \lambda^4 \;\Rightarrow\; p_s \sim E_J(\lambda^2, \lambda^2, \lambda^2)$$

Scales and the Factorization Theorem

Complete factorization in SCET+

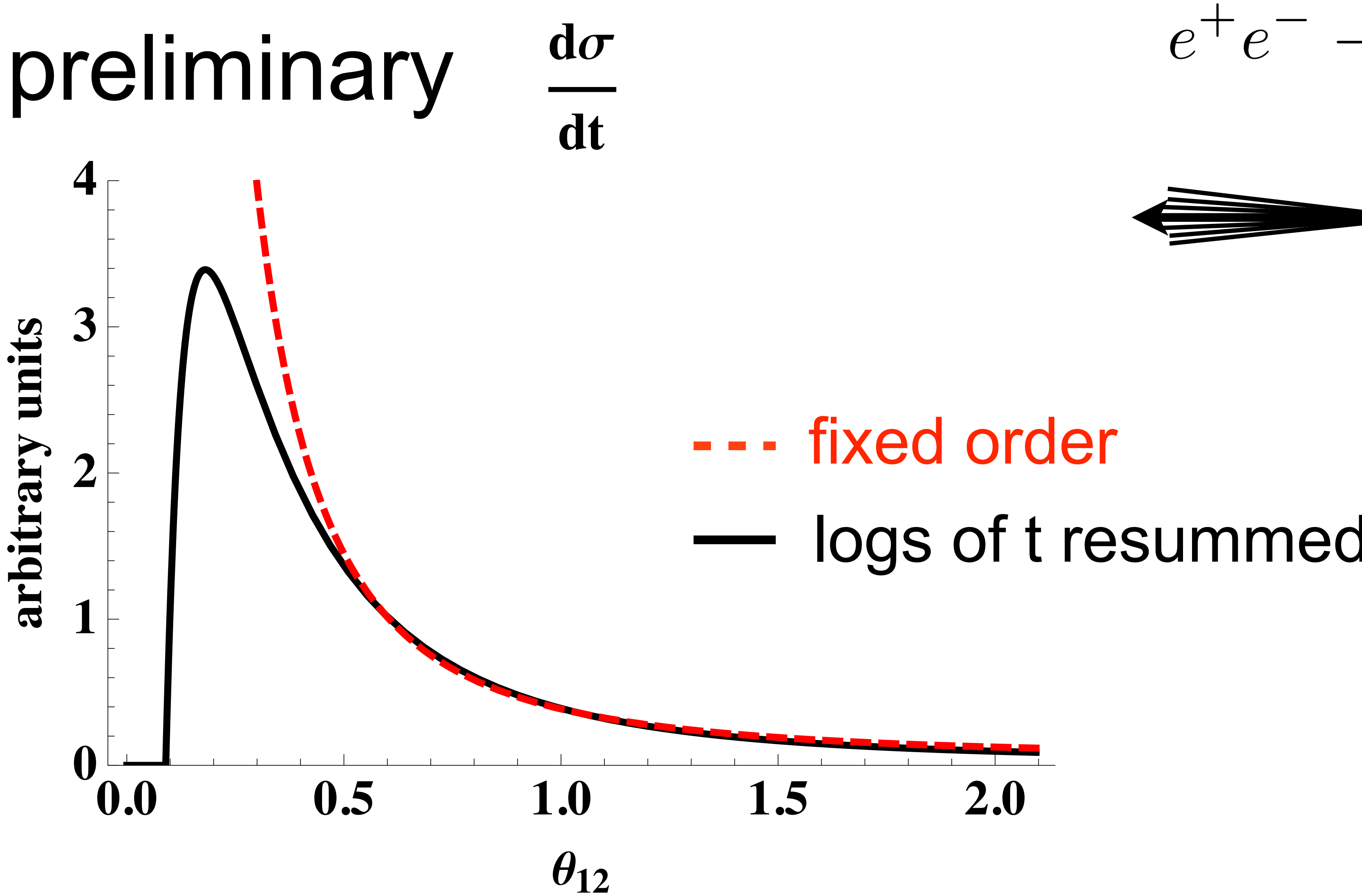
	Scale			
QCD				
———	$\sqrt{s_{ij}}$	hard 2 jet	$\longrightarrow$	$\ln \frac{\mu}{\sqrt{s_{ij}}}$
SCET O2				
———	$\sqrt{t}$	hard 3 jet	$\longrightarrow$	$\ln \frac{\mu}{\sqrt{t}}$
SCET+ O3				
———	m_J	jet	$\longrightarrow$	$\ln \frac{\mu}{m_J}$
soft+ S3				
———	$\frac{m_J^2}{\sqrt{t}}$	csoft	$\longrightarrow$	$\ln \frac{\mu}{m_J^2/\sqrt{t}}$
soft S2				
———	$\frac{m_J^2}{\sqrt{s_{ij}}}$	soft	$\longrightarrow$	$\ln \frac{\mu}{m_J^2/\sqrt{s_{ij}}}$

$$\frac{d\sigma}{d\mathcal{T}_i} = \frac{d\sigma^0}{d\Phi_3} H_2\, H_3^+\, J_i \otimes S_c \otimes S_2$$

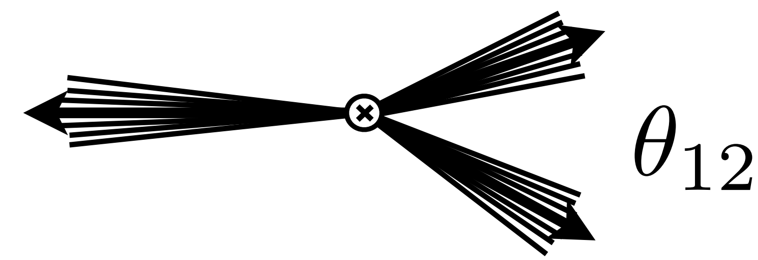
all functions
fully factorized
(one scale per function)

Resumming Kinematic Logs

preliminary



$e^+e^- \to 3$ jets



rate for jets with 3-jettiness less than a cutoff

$$Q\tau_3 < 0.1$$

Conclusions

- Worthwhile to access jet substructure through analytic approaches
- SCET developing more tools to describe realistic jets
- Have built an effective theory to describe nearby energetic jets
  - Applications for jet substructure

Factorization constraints on jet substructure algorithms,
JW & Zuberi, 1106.xxxx

- Goal is convergence with experimental measurements