Towards a Better Understanding of Jets

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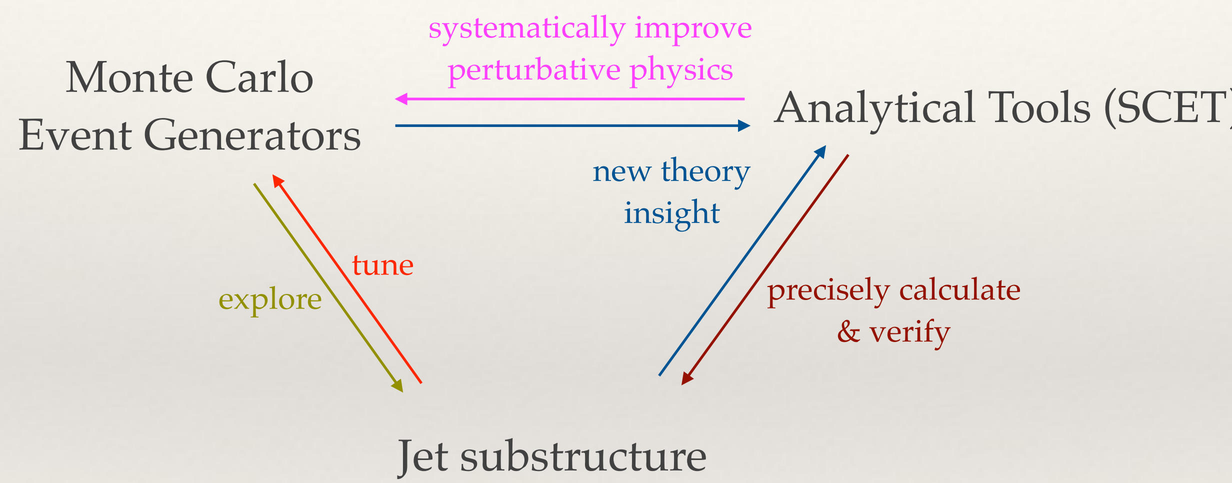
LANL
Jan 13, 2015

The Big Picture

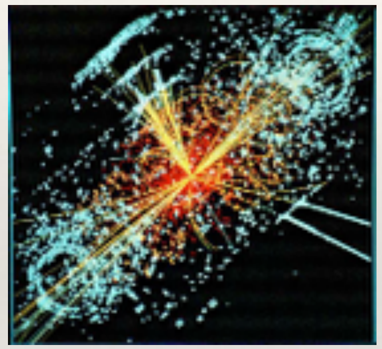


Outline

- Jets from SCET (progress in multijet observables)
- Jet Substructure from Event Generators (“Q-jets”)
- SCET from Jet Substructure (“Q-thrust” and NGLs)
- Event Generators from SCET (“GenEvA”)

What is a Jet?

- high-energy event:



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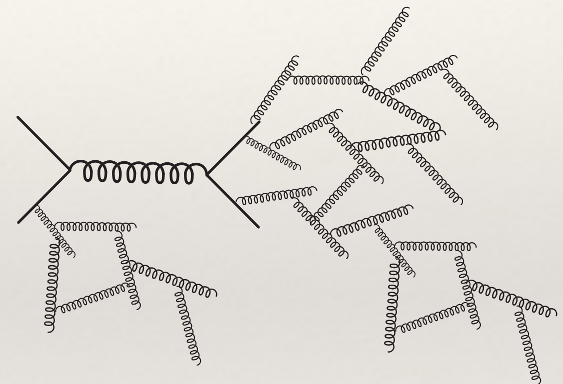
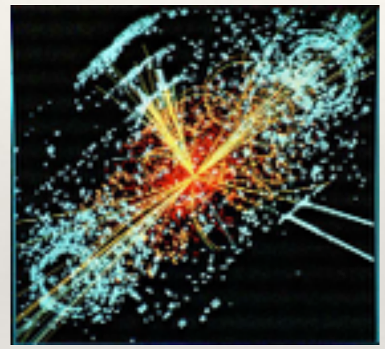
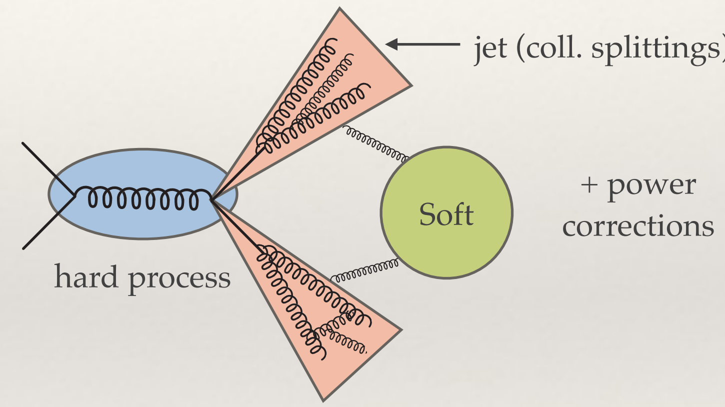


- organizing principle (beyond fixed-order calculation)?

What is a Jet?

- (soft & collinear) singularities → organize through *factorization*

 = 

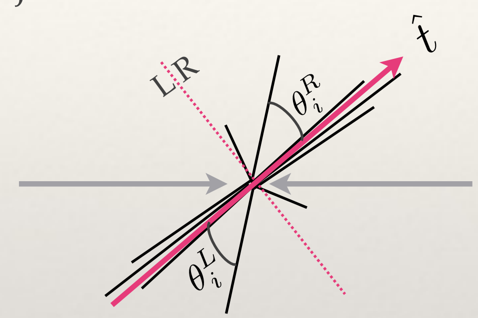
- can be achieved via Effective Field Theory (in particular, Soft-Collinear Effective Theory, or SCET)

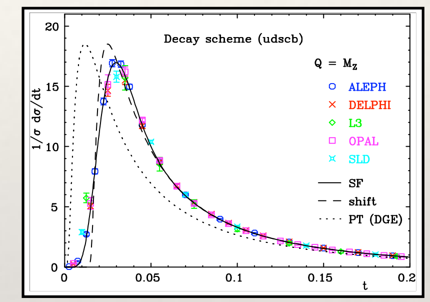
SCET and Thrust

- thrust measures "jettiness" of e^+e^- events:

$$\tau = \tau_L + \tau_R$$

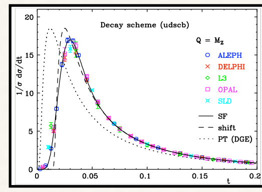
$$\tau_{L,R} = \sum_{i \in L,R} E_i \cos\theta_i^{L,R}$$





- small thrust $\Longrightarrow$ all particles close to thrust axis (very jetty)
- fixed order calculation not possible in this region:

$$\frac{1}{\sigma_0}\frac{d\sigma}{d\tau} = 1 + \alpha_s\left(a_{12}\frac{\ln\tau}{\tau} + a_{11}\frac{1}{\tau} + a_{10}\right) + \alpha_s^2\left(a_{23}\frac{\ln^3\tau}{\tau} + a_{22}\frac{\ln^2\tau}{\tau} + a_{21}\frac{\ln\tau}{\tau} + a_{20}\right) + \cdots$$

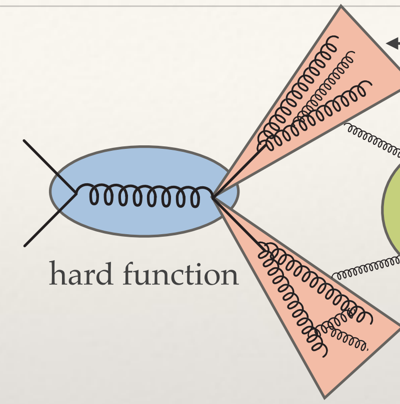


SCET and Thrust

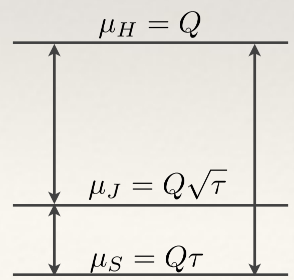
- factorization:

$$\frac{d\sigma}{d\tau} = H * J_n \otimes J_{\bar{n}} \otimes S_{n\bar{n}}$$

virtual (H), coll. real (J_n, $J_{\bar{n}}$), soft real ($S_{n\bar{n}}$)



- resummation:



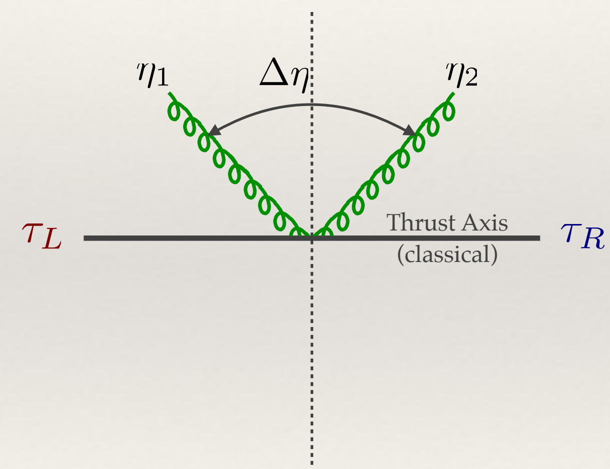
- matching:

$$(d\sigma)_{\text{matched}} = (d\sigma)_{\text{resummed}} + (d\sigma)_{\text{non-singular}}$$

Non-global Logs in Thrust

Dasgupta, Salam hep-ph/0104277
Kelley, Schwartz, Schabinger, Zhu 1105.3676
AH, Lee, Stewart, Walsh, Zuberi 1105.4628

- arise when separately measure L & R thrusts



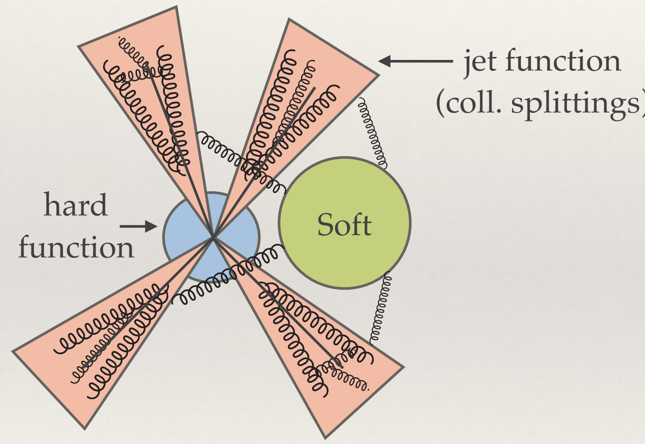
$$\alpha_s^2 C_F C_A \frac{\pi^2}{3} \ln^2 \frac{\tau_L}{\tau_R}$$

Multijet Events from SCET

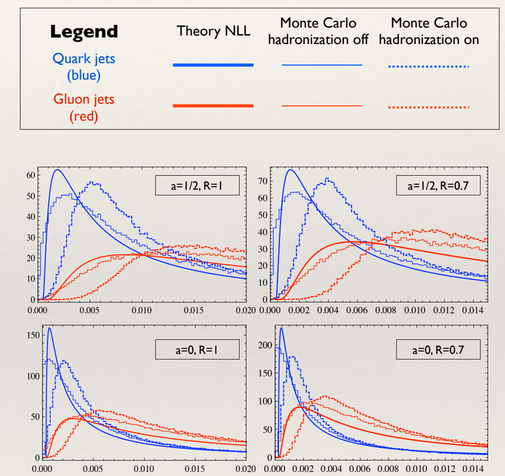
Ellis, AH, Lee, Vermilion, Walsh 1001.0014

- factorization:

$$\frac{d\sigma}{d\mathcal{O}} = H_N * J_1 \otimes \cdots J_N \otimes S_{1\cdots N}$$



- 3 jet events vs Pythia



- much more types of NGLs….
- currently extending to pp collisions with T. Mehen (involves soft function with p_T veto and rapidity cut)

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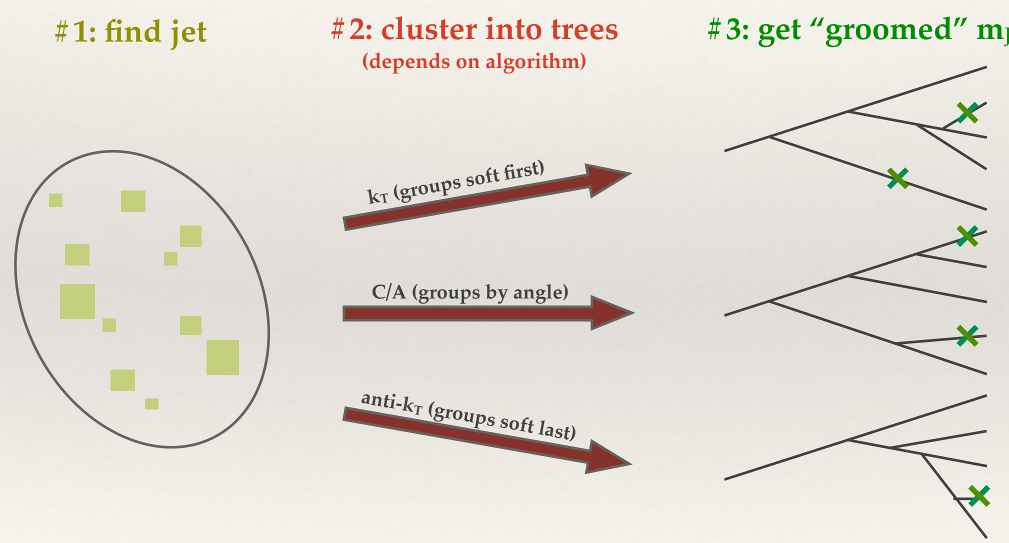
What is a "Q-Jet"?

- classical (deterministic) substructure analyses



"Mass Drop+Filter"
Butterworth, Davison, Rubin, Salam (0802.2470)

"Pruning"
Ellis, Walsh, Vermilion (0912.0033)

"Trimming"
Krohn, Thaler, Wang (0912.1342)

- Q-Jets: use "all" clusterings ⇒ mass distribution *for each jet*

Tree Weighting

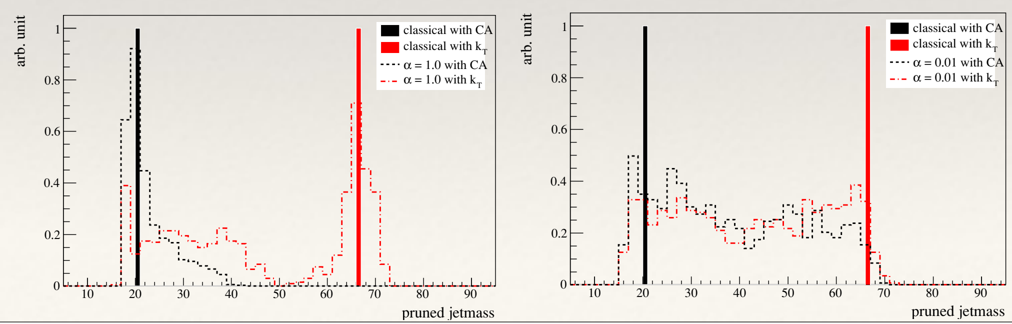
- can't sample all clusterings/"trees" (~10!-20!)
- instead, sample around kT-like (or CA-like) randomly:

weight for particle pair (ij)

$$\omega_{ij}^{(\alpha)} \equiv \exp\left\{-\alpha \frac{(d_{ij} - d^{\min})}{d^{\min}}\right\} \quad \text{where} \quad d_{ij} = \begin{cases} d_{\mathrm{k_T}} \equiv \min\{p_{Ti}^2, p_{Tj}^2\}\Delta R_{ij}^2 \\ d_{\mathrm{C/A}} \equiv \Delta R_{ij}^2 \end{cases}$$

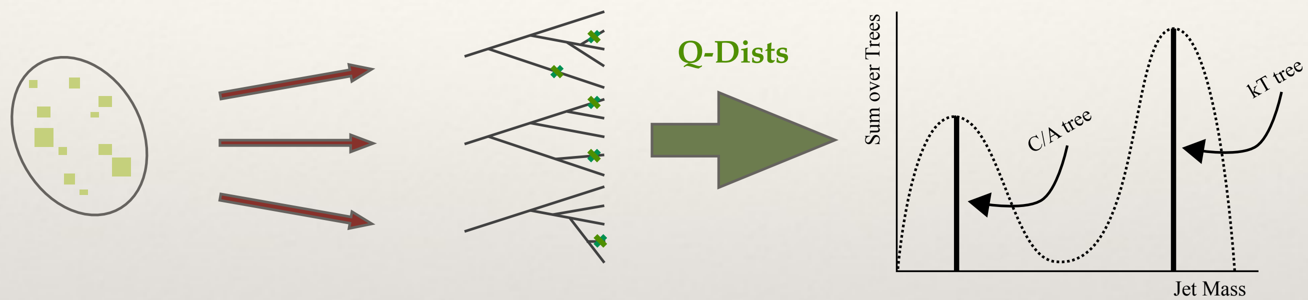
"rigidity" parameter

- this gives distribution for each jet (stable after ~10-100 trees)



New Observables from Q-jets

- different for different algorithms :

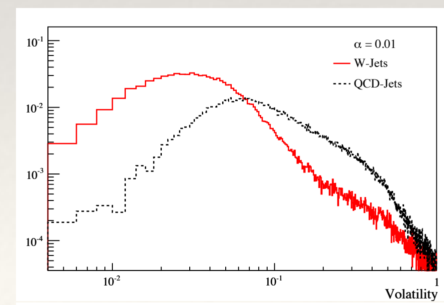


- Variation larger for QCD jets (no real m_J scale)

$\Rightarrow$ "Volatility":

$$\mathcal{V} = \Gamma / \langle m \rangle$$

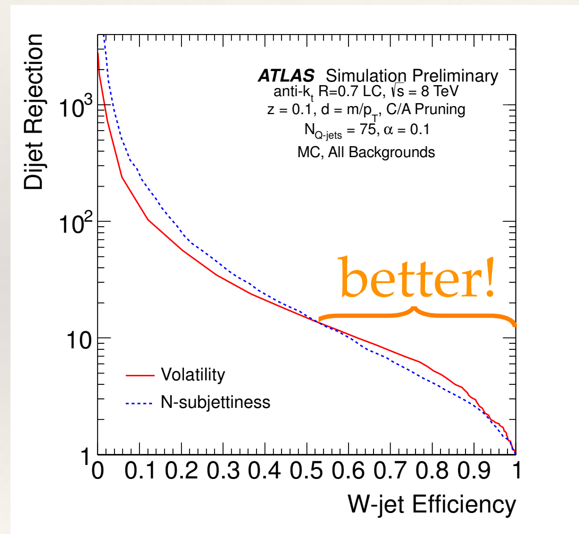
$$\Gamma \equiv \sqrt{\langle m^2 \rangle - \langle m \rangle^2}$$

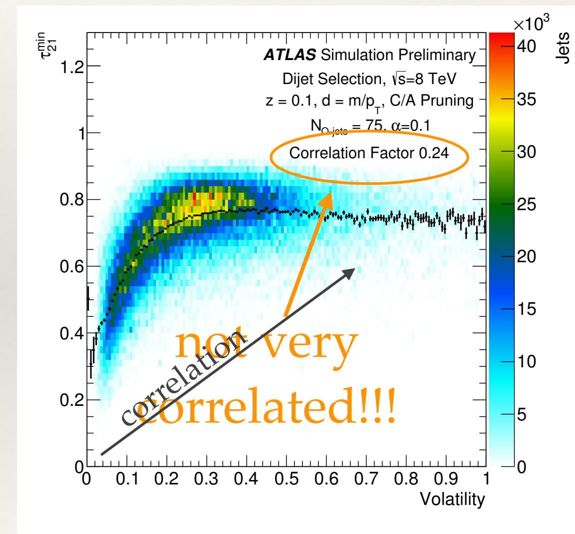


Experimental Success of Volatility

- compare to standard candle (N-subjettiness):

Thaler, Tilburg 1011.2268

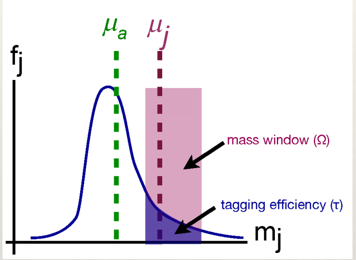




- BOOST2013 working groups: understand correlations

Statistical Improvement

- standard measurements have Poisson production and binomial tagging
- instead, weighted tagging based off Q-jet overlap



- in general, we find $\frac{1}{\sqrt{N}} \leq \left(\frac{\delta N_T}{N_T}\right)^Q \leq \frac{1}{\sqrt{\epsilon N}}$

  classical (binomial) tagging

  Poisson limit

- found ~25% improvement on both S/δB and δm/m measurements!

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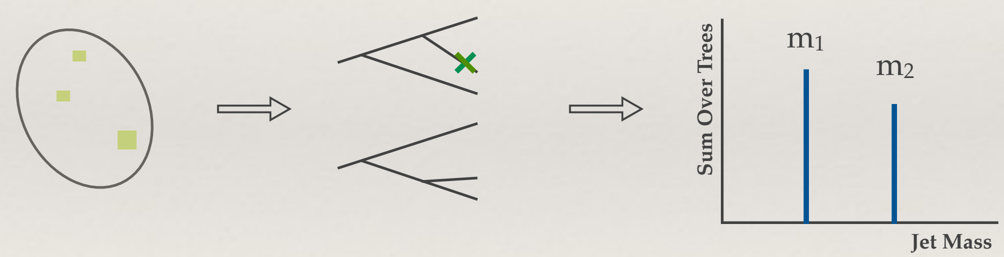
Q-Jet Volatility Calculation (?)

- non-trivial mass Q-dists require at least O(10) particles

  $\Rightarrow$ need $O(\alpha^{10})$ calculation….



- also not well-suited for SCET (V $\rightarrow$ 0 not "jetty")

Why are Q-Jets different?

- 2 reasons:
  1. NOT deterministic
  2. NOT energy-flow variable (event/jet shape)

     (depends on clustering, not just particle 4-momenta)

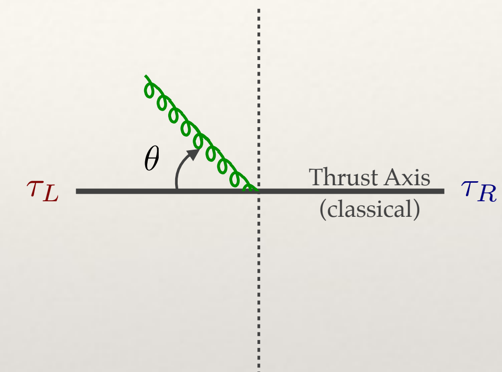
- Can we disentangle these two properties???

Q-Thrust

- cluster L, R with some probability:

$$\delta(\tau_L - k^+/Q)\underbrace{\Theta\left(\theta < \frac{\pi}{2}\right)}_{\to P_L(\theta)}$$

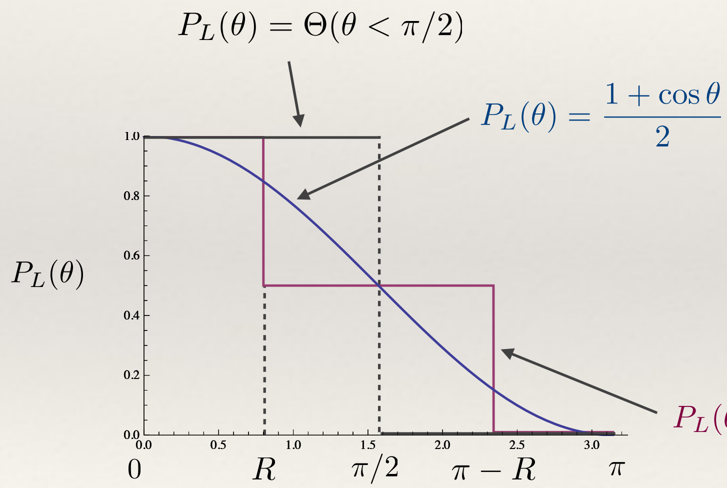
$$+\delta(\tau_R - k^-/Q)\underbrace{\Theta\left(\theta > \frac{\pi}{2}\right)}_{\to P_R(\theta)}$$

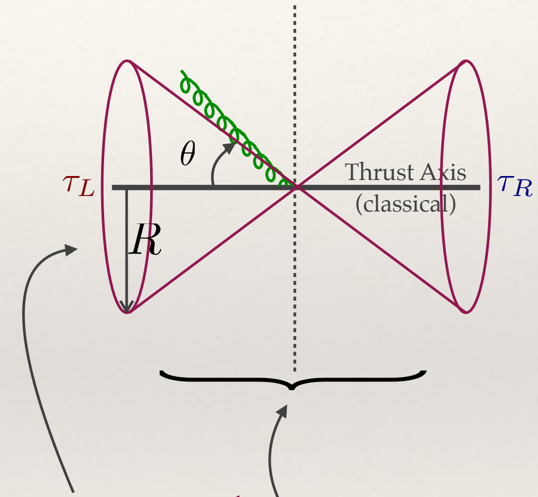


- disentangle Q-Jets / N-subjettiness (un)correlation???
  1. non-deterministic (like traditional Q-Jets)
  2. *but* now energy-flow / shape var

Q-Thrust

- Examples:



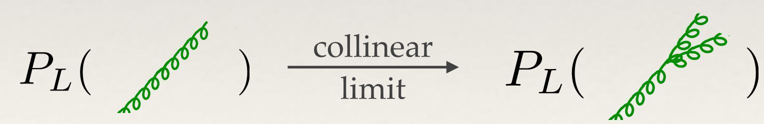


$P_L(\theta) = \Theta(\theta < R) + \frac{1}{2}\Theta(R < \theta < \pi - R)$

"double step function"

Q-Thrust

- definition for higher orders - IR safety:
  - must use clustering!
  - IR safety requires (in collinear limit):
    - before splitting:
    - after splitting:



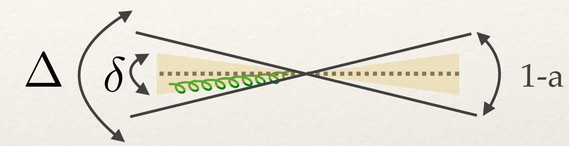
2 Loop Results

"fuzzy" region ~ 1 - a

clustering size ~ δ < 1 - a

clustering region ~ Δ > 1 - a

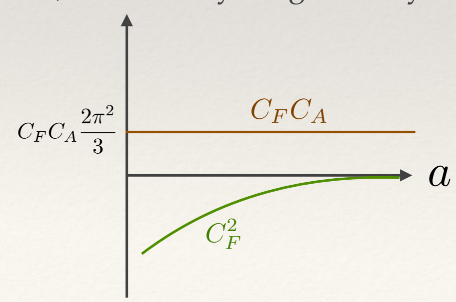
$$a \equiv \tan^2 \frac{R}{2}$$



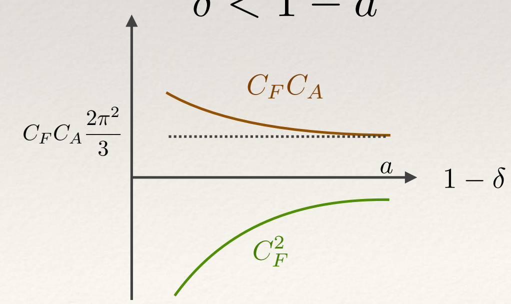
- Cancellation of NGLs:

$$\delta = 1 - a$$

(cluster everything in fuzzy region)



$$\delta < 1 - a$$



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Overview of Event Generation

- Loops
- Logs
  - shower (LL)
  - QCD resummation
  - SCET
- Legs
  - -Madgraph
  - -Alpgen
  - -AMEGIC++
  - -calchep

} MC@NLO, POWHEG

} CKKW, MLM

} GenEvA (v0.1), MENLOPS = 1 NLO + many LO + PS

GenEvA (v1.0) = many NLO + PS

Bauer, Berggren, Dunn, AH, Tackmann, Vermilion, Walsh, Zuberi 1211.7049

MC@NLO: Frixione, Webber
POWHEG: Nason et al

CKKW: Catani, Krauss, Kuhn, Webber
MLM: Mangano

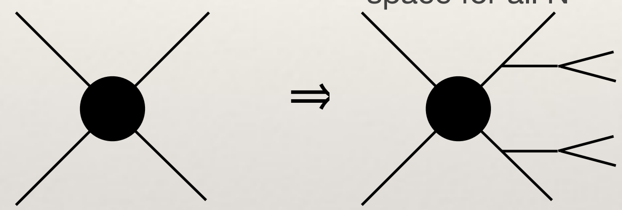
GenEvA v0.1: Bauer, Tackmann, Thaler
MENLOPS: Hamilton, Nason; Hoche, Krauss, Schonherr, Siegert

The Parton Shower (PS)

- LO for lowest multiplicity, higher mult. filled w/ parton splittings

start w/ 2-2 ME
2 partons/jets

showering fills
N-body phase
space for all N

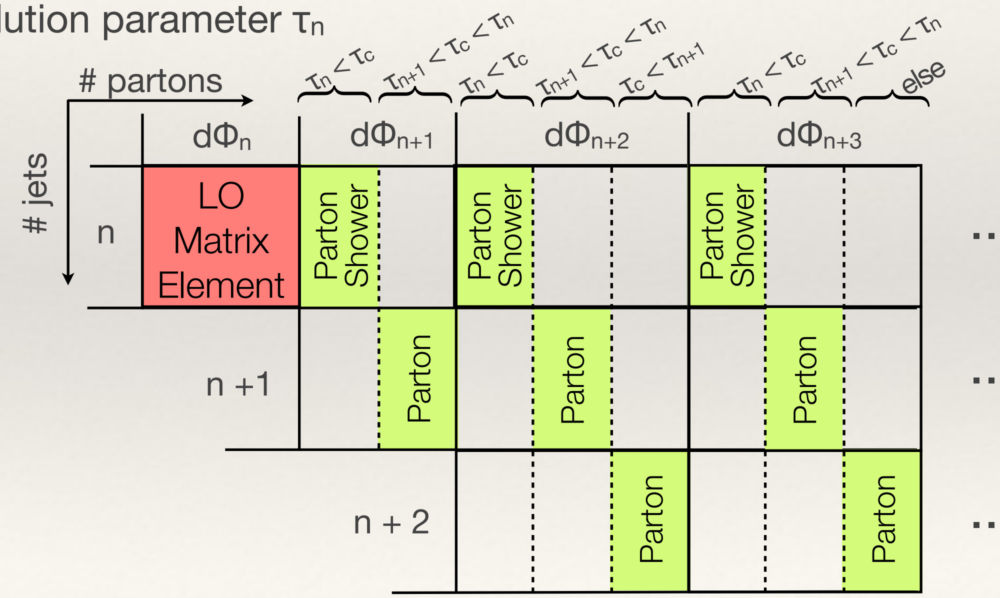


- simple phase-space picture

$d\Phi_n$	$d\Phi_{n+1}$	$d\Phi_{n+2}$	$d\Phi_{n+3}$
LO Matrix Element	Parton Shower	Parton Shower	Parton Shower

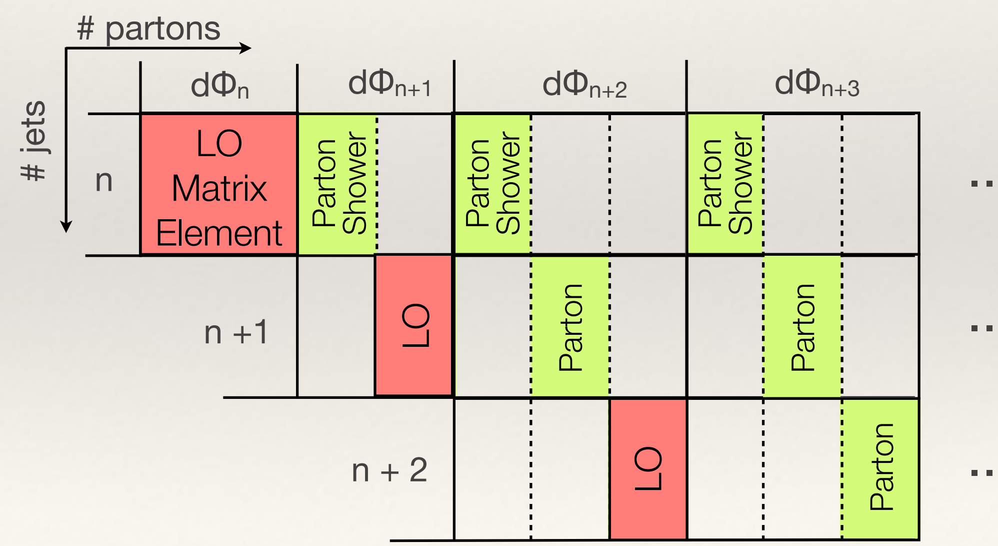
The Parton Shower (PS)

- beyond tree level, will need partons ≠ jets!!
- need resolution parameter τ_n



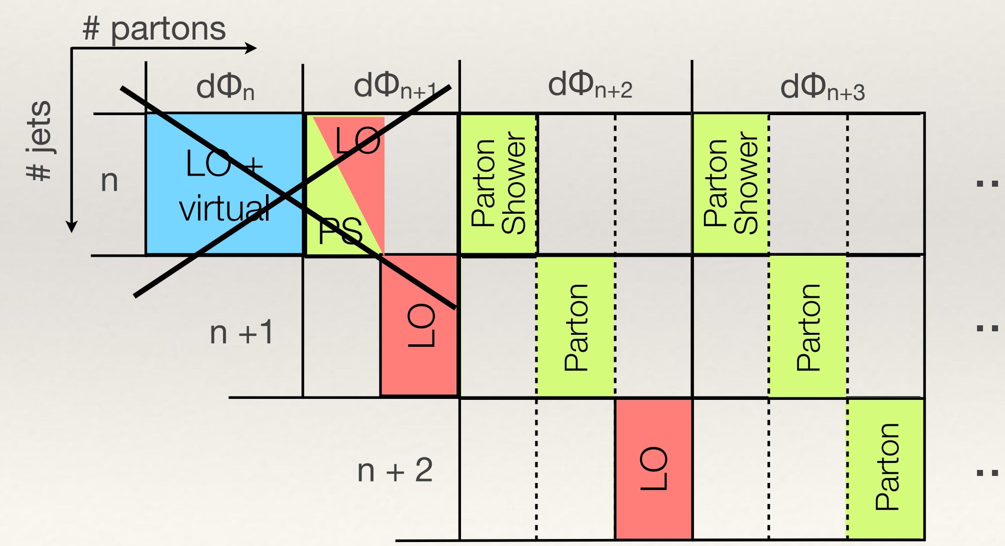
How to Merge LO + PS (e.g., CKKW/MLM)

- multiple LO Matrix Elements



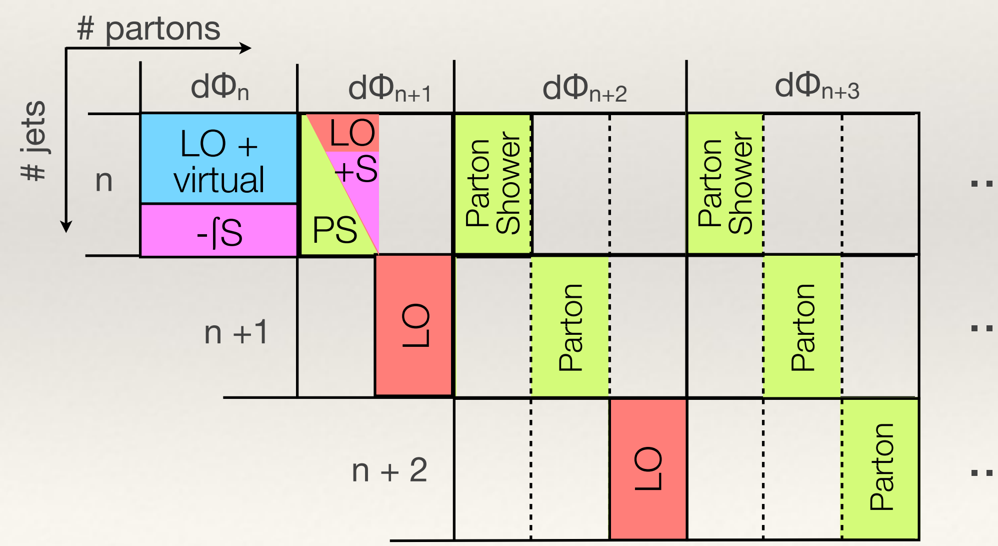
NLO + PS
(MC@NLO, POWHEG)

- add virtual corrections?
- rows are IR-safe, finite quantities, but not columns!



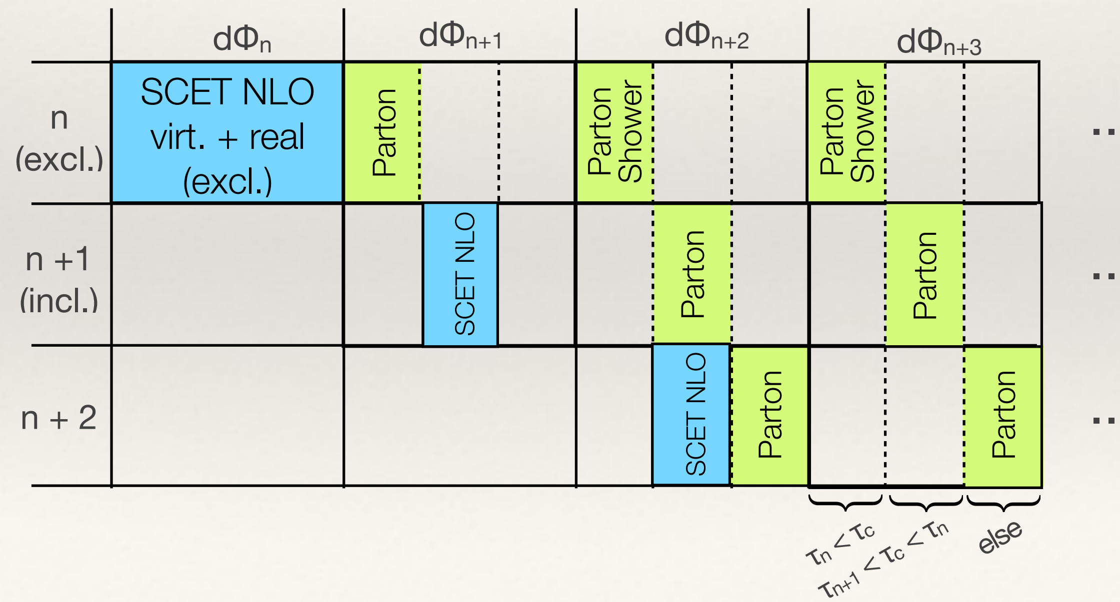
NLO + PS
(MC@NLO, POWHEG)

- need some "subtraction":

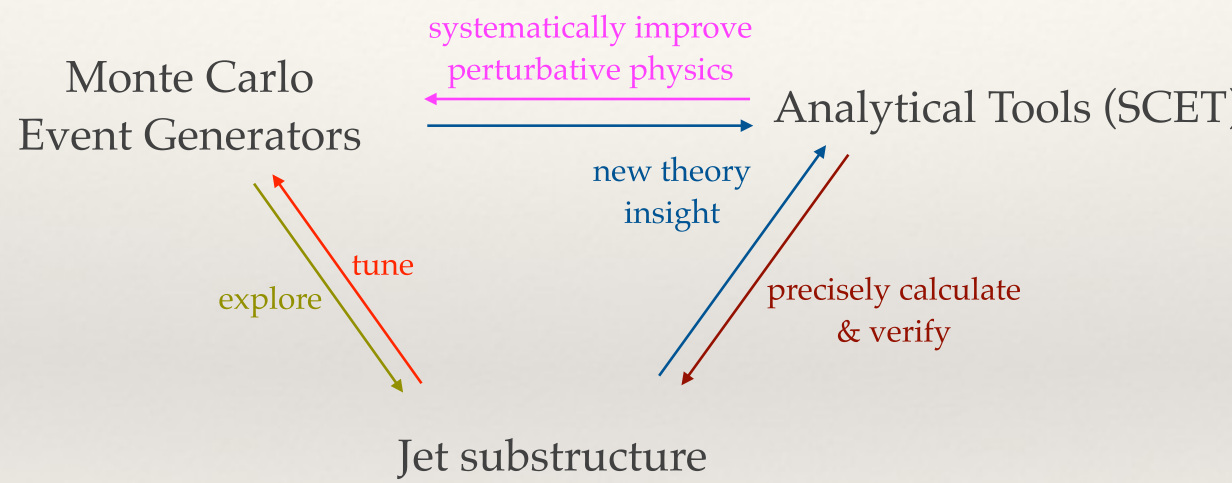


GenEvA (many NLO + PS)

- Can't simply extend this idea to multiple NLO ⇒ use SCET:



Summary



multijets with jet shapes
Q-jets
Q-thrust & NGLs
GenEvA