# Improving Event Generators with SCET

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work in progress
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# Outline

- Review Monte Carlos
- Introduce SCET
- Schematic of SCET approach
- Some Results
- Error Analysis
- Conclusions

# Monte Carlos

- What are the uncertainties in Monte Carlo programs?
  - Why do Pythia, Herwig, Ariadne, Sherpa, etc. all give different results?
  - Errors are estimated by comparing programs and fitting to data

- Can they be systematically improved?
  - What approximations are being used?
  - Which approximations can be improved upon, which cannot?

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# Monte Carlos

Factorization lets us separate:

1. Hard Matrix Element
2. Parton Shower
3. Hadronization

- SM
- RS/Compositeness
- Little Higgs
- MSSM
- Non-standard SUSY
- Higgless
- UED
- Twin Higgs

Events

# Parton Shower

- Emission **probability** given by splitting functions

$$\mathrm{d}\sigma^{(n+1)} = \int \mathrm{d}\sigma^{n} P_{ab}$$

- Probability of no-emission given by Sudakov Factor

$$\Delta = e^{-\quad P_{ab}}$$

- Valid in the limit $p_T^{(1)} \gg p_T^{(2)} \gg \cdots \gg p_T^{(n)}$

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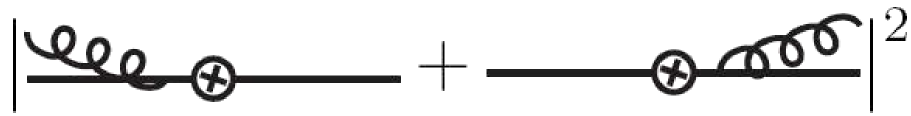
# Parton Shower

Replaces the quantum matrix element



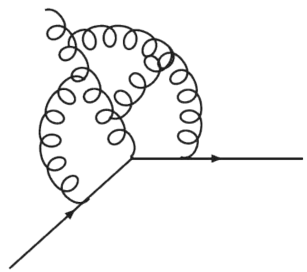
With a classical approximation

- Drops Interference
- Breaks gauge invariance

# Matrix Elements

How do we do an accurate calculation in QCD?

Loops:



$$\sim \left(\frac{\alpha_s}{\pi}\right)^3 \log^6 \frac{p_i}{p_j}$$

- Can we resum large logarithims, but keep finite pieces?
- What do we do with IR divergences?
- How do we combine with parton shower to get events?
- Exactly what effective field theories are good for!

# SCET Approach

- Match to QCD at hard scale Q.
  - Uses as much QCD as possible
  - Finite matching at $N^nLO$

Hard Matrix Elements

- Run using RGE
  - Anomalous dimensions to $N^nLL$

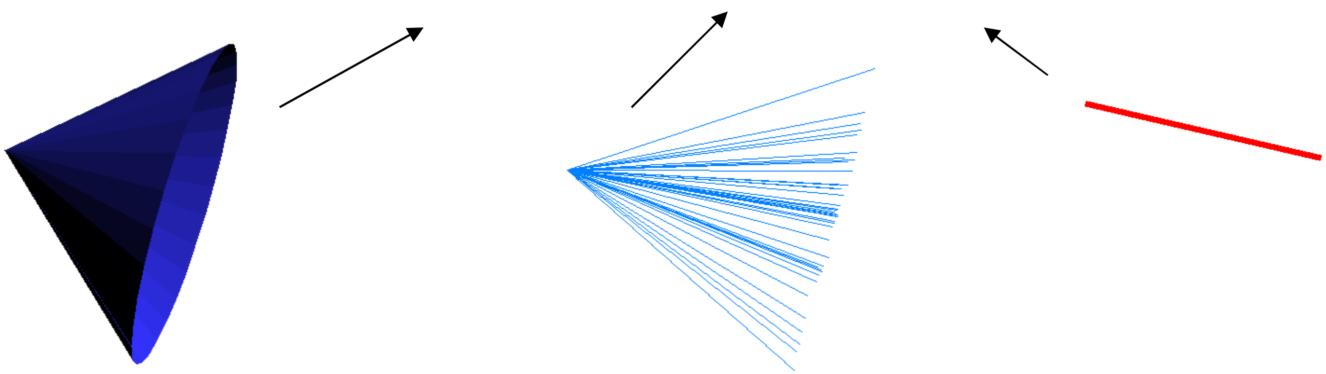
Parton Shower

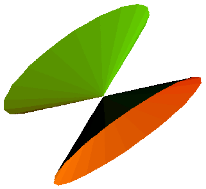
- Match across emission threshold
  - Power corrections can be included

# Intro to SCET

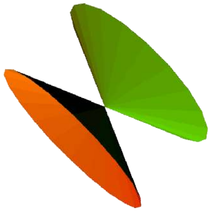
- Fields are collinear or soft
  - Colliner fields in direction $n^\mu$ have $p_T < \lambda(\bar{n} \cdot p)$
  - Natural objects are jets

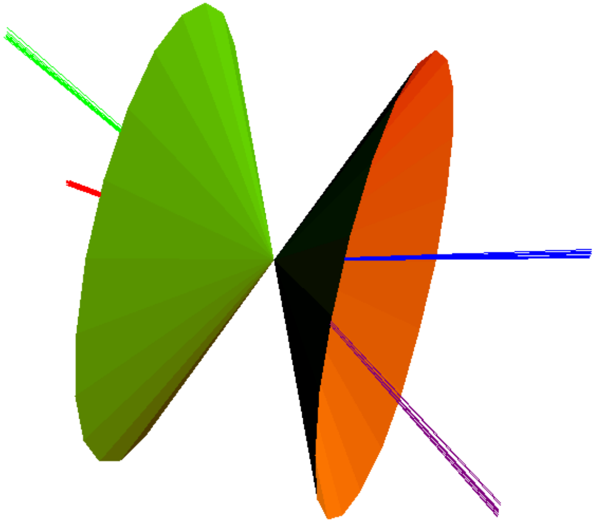
$$\chi_n = W_n \xi_n$$





# SCET





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# Match

- Match at scale Q

$$\langle \mathrm{QCD} | q\bar{q} \rangle = \mathcal{C}_2 \langle \mathcal{O}_2 | q\bar{q} \rangle$$

$$\langle \mathrm{QCD} | q\bar{q}g \rangle = \mathcal{C}_2 \langle \mathcal{O}_2 | q\bar{q}g \rangle + \mathcal{C}_3 \langle \mathcal{O}_3 | q\bar{q}g \rangle$$

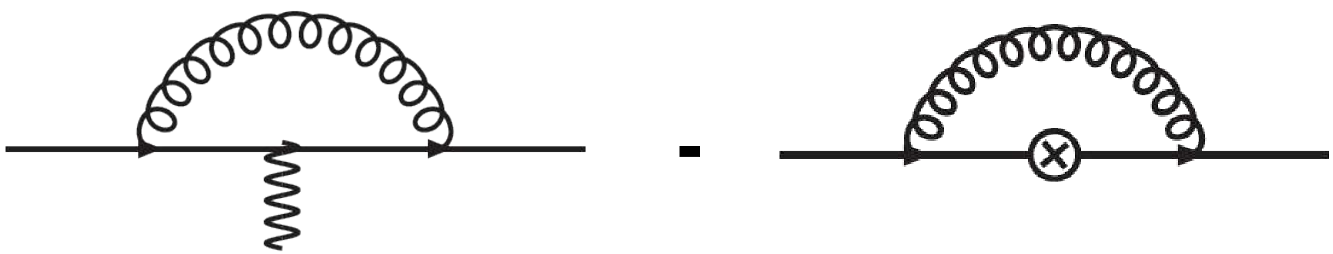
$$\Rightarrow \mathcal{O}_2 = \bar{\chi}_{\bar{n}} \Gamma \chi_n$$

$$\boxed{\mathcal{O}_3 = \mathrm{QCD} - \mathcal{O}_2} = \bar{\chi}_{\bar{n}} \Gamma \not{n} \not{A} \chi_n$$

$$\mathcal{C}_2(Q) = \mathcal{C}_3(Q) = 1$$

# Match

Higher order matching is finite



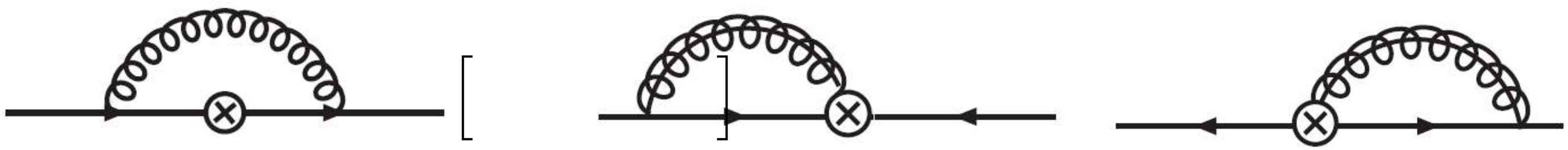
= finite

- IR divergences are the same in SCET and QCD
- UV divergences are different, but removed with counterterms

$$\Rightarrow \quad \mathcal{C}_2 = 1 + \frac{\alpha_s}{4\pi}\left[ 8 - \frac{\pi^2}{6} \right]$$

# Run

## Calculate anomalous dimensions



$$\gamma_2 = \frac{\alpha_s C_F}{4\pi}\left[\log\frac{\mu^2}{Q^2} + \frac{3}{2}\right] + \alpha_s^2\left(b_1 \log\frac{\mu^2}{Q^2} + b_2\right) + \cdots$$

LL

NLL

NNLL

$$\gamma_3 = \frac{\alpha_s}{\pi}\left[(C_F + C_A)\log\frac{\mu^2}{Q^2} + C_F\left(\frac{3}{2}\right)\log u + C_A\left(\frac{11}{6}\log\frac{st}{Q^4}\right) + \frac{n_f}{6}\right] + \cdots$$

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# Solve RGE

- Solve RGE for Wilson Coefficients

$$\mathcal{C}_n(\mu) = \mathcal{C}_n(Q)\Pi_n(Q,\mu)$$

$$\Pi_n(Q,\mu) = e^{\left(\frac{d\mu}{\mu}\gamma_n\right)}$$

$$2\Pi_2(Q,\mu) = e^{-\frac{d\mu}{\mu}\frac{\alpha_s}{\pi}\left(\frac{3}{2}-\log\frac{\mu^2}{Q^2}\right)} = \Delta(Q,\mu)$$

- Reproduce Sudakov factors from LO Running
- Systematically improvable to NLL, NNLL, . . .

# Emissions

- Emissions given by matrix elements in SCET

$$\left|\langle \mathcal{O}_2 | q\bar{q}g \rangle\right|^2 = \frac{s}{t}\frac{u^2+1}{(u-1)^2} \rightarrow \frac{1}{t}\frac{1+z^2}{1-z} = P_{qq}$$

- Reproduces parton shower at leading order
- Can be improved with power corrections, in principle

# 3-jet matching

- Interpolates between QCD and Parton Shower

$$\mathcal{O}_3 = \mathrm{QCD} - \mathcal{O}_2$$

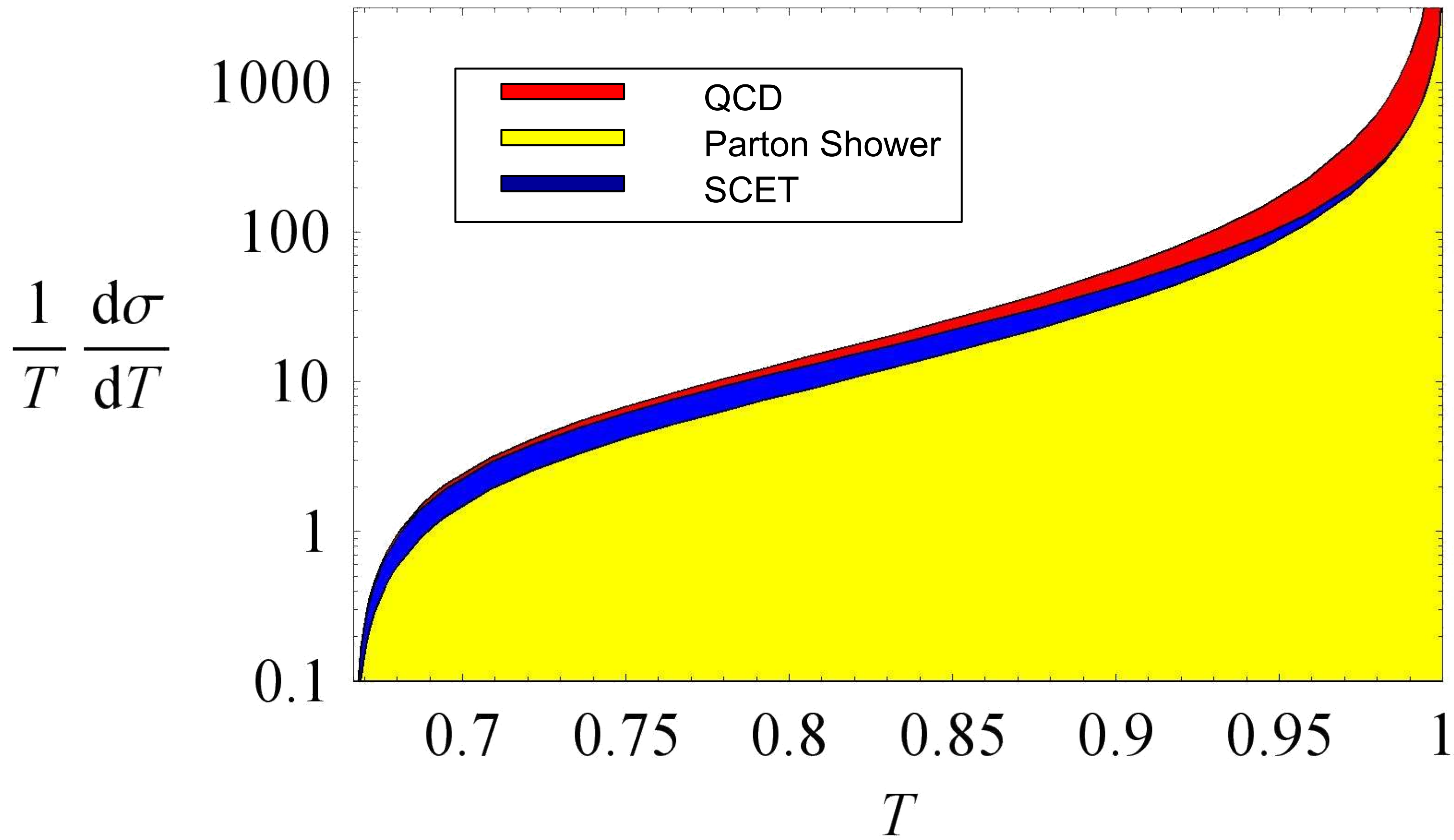
$$d\sigma = |\mathcal{C}_2 \langle \mathcal{O}_2 \rangle + \mathcal{C}_3 \langle \mathcal{O}_3 \rangle|^2$$
$$= |\Pi_2 \langle \mathrm{QCD} \rangle + (\Pi_2 - \Pi_3) \langle \mathcal{O}_2 \rangle|^2$$

$$p_T \sim Q \Rightarrow \Pi_2 \sim \Pi_3 \sim 1$$

$$p_T \ll Q \Rightarrow QCD \sim \mathcal{O}_2$$

# Results

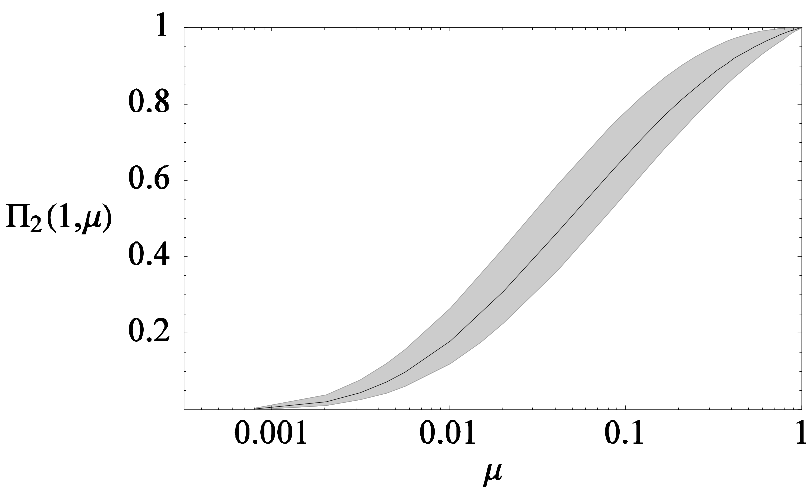
Thrust Distribution $e^+e^- \to q\bar{q}g$



# Errors

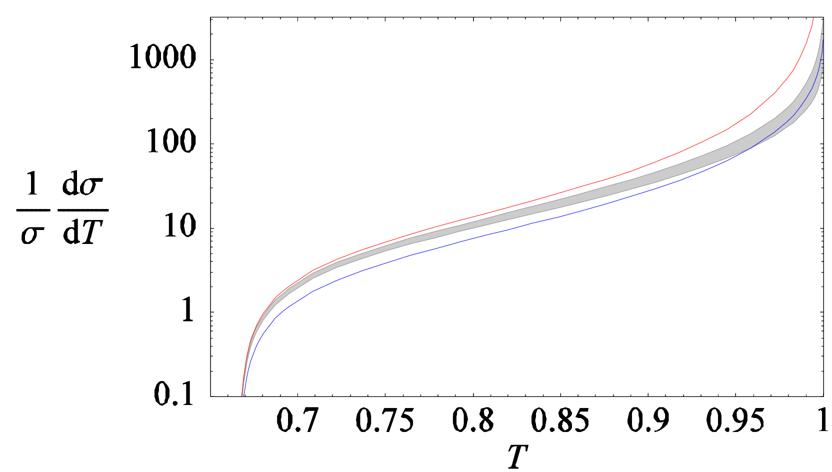
- Errors can be estimated by next-to-leading order effects

$$2\gamma_2 = \frac{\alpha_s C_F}{4\pi}\left[\log\frac{-\mu^2}{Q^2} \pm \frac{\alpha_s C_F}{4\pi}\frac{3}{2}\right] \pm \alpha_s^2\left(b_1 \log\frac{\mu^2}{Q^2} + b_2\right) + \cdots$$




Error in Sudakov factor

Error in thrust distribution



# Conclusions

•SCET provides a consistent framework to study jet distributions

•Matching to QCD and running can be improved systematically

•Matching and Showering naturally combined

•Power corrections can be included too, but may be unproductive.

•Errors can be estimated and included in Monte Carlo event generators