TeVJet: a general framework for the calculation of jet observables in NLO QCD

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Overview

- Introduction - the Dipole Subtraction Method
- TeVJet Design
- New calculations - including new processes
- PhaseSpace class - integrable singularities
- Example results
- Summary & Outlook

The Dipole Subtraction Method

The problem is that different terms must be integrated over different phase space volumes. The general idea is to write the NLO contribution as:

$$\begin{aligned}\sigma^{\mathrm{NLO}} &= \int_{\mathrm{m+1}} d\sigma^{\mathrm{R}} + \int_{\mathrm{m}} d\sigma^{\mathrm{V}} + \int_{\mathrm{m}} d\sigma^{\mathrm{C}} \\ &= \int_{\mathrm{m+1}} \left[d\sigma^{\mathrm{R}} - d\sigma^{\mathrm{A}}\right] + \int_{\mathrm{m+1}} d\sigma^{\mathrm{A}} + \int_{\mathrm{m}} d\sigma^{\mathrm{V}} + \int_{\mathrm{m}} d\sigma^{\mathrm{C}}\end{aligned}$$

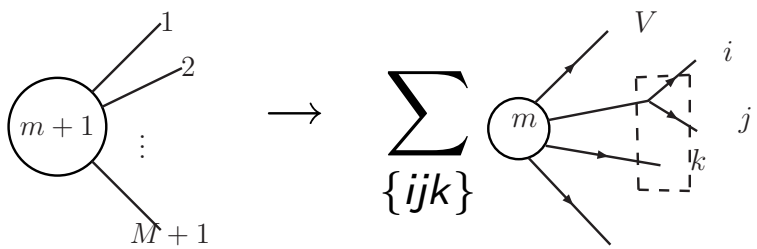
Where the 'subtraction term' can be easily integrated analytically and combined with the virtual and collinear terms:

$$\begin{aligned}\sigma^{\mathrm{NLO}} &= \int_{\mathrm{m+1}} \left[d\sigma^{\mathrm{R}}(p) - d\sigma^{\mathrm{A}}(p)\right] + \int_{\mathrm{m}} \left[d\sigma^{\mathrm{V}}(p) + d\sigma^{B}(p) \times \mathbf{I}\right] \\ &\quad + \int_0^1 dx \int_{\mathrm{m}} d\sigma^{\mathrm{B}}(xp) \times (\mathbf{P} + \mathbf{K})(x)\end{aligned}$$

The subtraction term

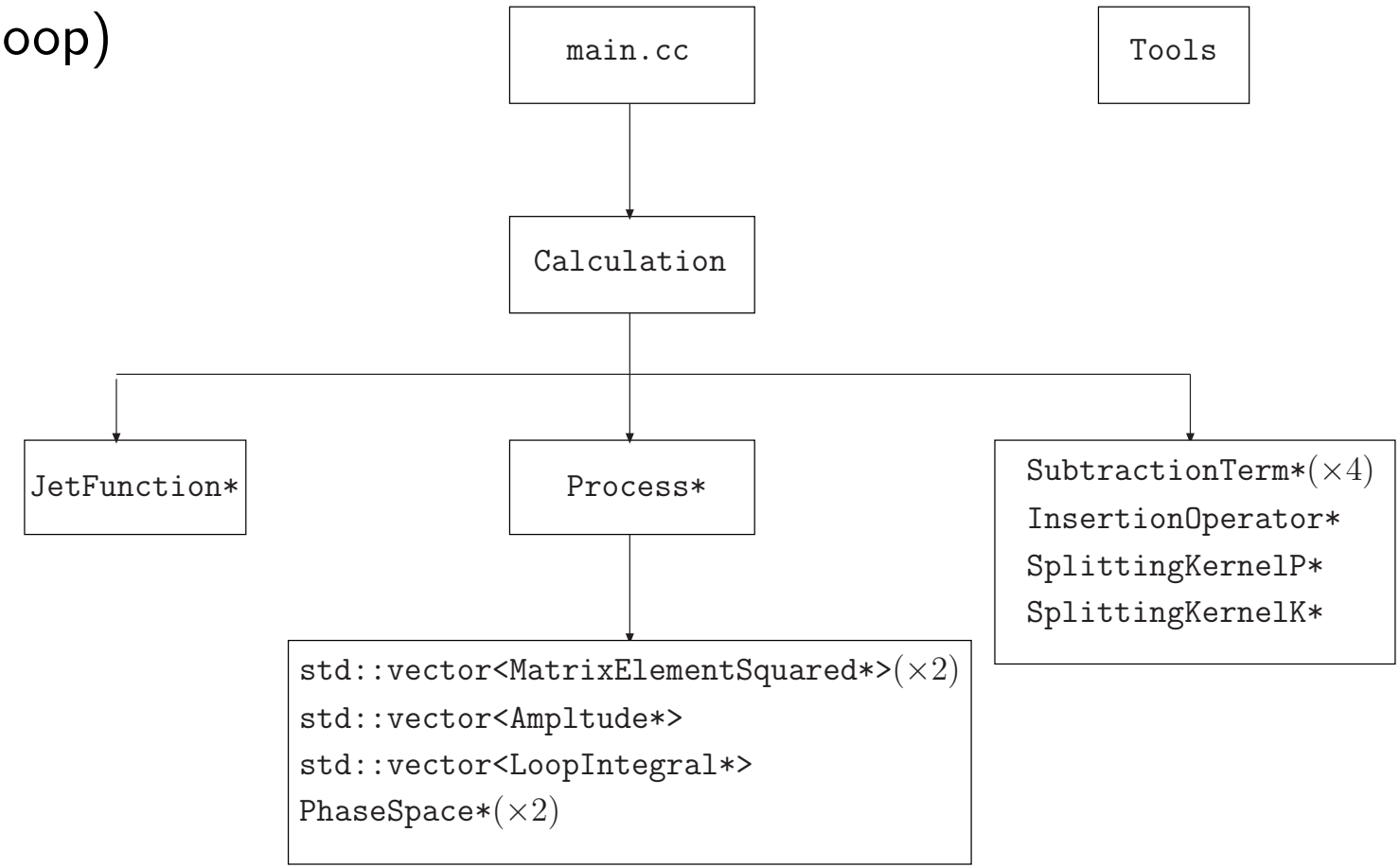
Need to construct a subtraction term that:

- Matches the divergences of the Real $|\mathcal{M}|^2$.
- Smoothly extrapolates away from these singular regions such that it obeys a factorisation over the whole of phase space.
- Must be simple enough to be analytically integrable (in d dimensions) over the one parton subspace containing the divergence [Phase Space constraints].



TeVJet Design - structure of the code

Aim: automate construction of all process-independent parts
(user still has to construct process-dependent matrix elements:
– Born, including colour and spin projections
– NLO tree
– NLO loop)



TeVJet Design - example main program


```
//standard lib headers
#include <iostream>
#include <cmath>

//my lib headers that are always needed
#include "Tools.h"
#include "Calculation.h"
#include "JetFunction.h"
#include "Process.h"

//process specific user headers
#include "ProcEEto3jet.h"
#include "UserEEto3jet.h"

int main(int argc, char** argv) {

  long           seed = 12345;
  std::string filename="EEto3jet_12345";

  //set the SM parameters
  TeVJet::Tools::getInstance()->setEWconvention(3);
  TeVJet::Tools::getInstance()->setWmass(80.41);
  TeVJet::Tools::getInstance()->setZmass(91.188);
  TeVJet::Tools::getInstance()->setGfermi(1.16639*pow(10,-5));
  TeVJet::Tools::getInstance()->setAlphasMZ(0.118);

  //set some parameters
  int       Nborn = 1000;//no of 'events'
  int       Nvirt = 1000;
  int       Nreal = 1000;

  double CMenergy = TeVJet::Tools::getInstance()->getZmass();//GeV
  bool       useZ = false;

  double Ebeam1   = CMenergy/2;
  double Ebeam2   = CMenergy/2;

  double fren = 1.0;

  TeVJet::Process     * proc;
  TeVJet::JetFunction * jet;
```



```
  //process specific stuff
  proc = new TeVJet::ProcEEto3jet(CMenergy,useZ);
  jet  = new TeVJet::UserEEto3jet(filename,CMenergy,useZ);
  //process specific ends

  TeVJet::Calculation calc(proc,jet);
  //user can set stuff here
  calc.setNborn(Nborn);
  calc.setNreal(Nreal);
  calc.setNvirt(Nvirt);
  calc.setSeed(seed);
  calc.setEbeam1(Ebeam1);
  calc.setEbeam2(Ebeam2);

  calc.setRenScaleFactor(fren);

  //initialize stuff
  calc.Initialize();

  //calculate born level
  calc.BornLoop();

  //if required calculate NLO contribution
  if(calc.m_proc->DoNLO()){
    calc.RealLoop();
    calc.VirtLoop();
    if(calc.m_proc->HadronBeams()){
      calc.ConvLoop();
    }
  }

  delete jet;
  jet=0;
  delete proc;
  proc=0;

  return 0;
}
```

How to include a new process

- Need to write a class which inherits from the Process class
- This includes the (usual) process-dependent information:
  - Square of the matrix elements for the Born level and real diagrams:

$$|\mathcal{M}_{m;a,\ldots}|^2 =_{m;a,\ldots} \langle 1,\ldots,m;a,\ldots|1,\ldots,m;a,\ldots\rangle_{m;a,\ldots}. \quad (1)$$

  - The Born level Amplitude projected onto the helicity space of each external gluon
  - The necessary colour algebra to calculate the colour correlated Born Level amplitude for each combination of emitter and spectator:

$$|\mathcal{M}^{I,J}_{m;a,\ldots}|^2 =_{m;a,\ldots} \langle 1,\ldots,m;a,\ldots|\mathbf{T}_I.\mathbf{T}_J|1,\ldots,m;a,\ldots\rangle_{m;a,\ldots}, \quad (2)$$

  - The 1-loop renormalized Amplitude
- Also need to know the scales (μ_R, μ_F) etc.

Matrix Element Squared

The user must provide code to return $|\mathcal{M}|^2$ for each sub-process which contributes to the Born level and real terms.

- TeVJet links to the HELAS library which can be used to calculate these
- This could be fully automated (c.f. MADGRAPH) in future

Born level Amplitude

Recall that in the soft and collinear limits the factorization is not exact - there are colour and spin correlations.

- In order to match the soft limits TeVJet requires user to provide the necessary colour algebra to calculate the colour-correlated amplitude for all emitters/spectators:

$$|\mathcal{M}^{I,J}_{m;a,\ldots}|^2 = {}_{m;a,\ldots}\langle 1,\ldots,m;a,\ldots|\mathbf{T}_I.\mathbf{T}_J|1,\ldots,m;a,\ldots\rangle_{m;a,\ldots}, \tag{3}$$

- For the collinear limits TeVJet needs the Born level amplitude projected onto the spin space of each external gluon, i.e $\mathcal{A}^\mu$ where

$$\mathcal{A} = \epsilon^*_\mu \mathcal{A}^\mu \tag{4}$$

- This could also be fully automated in future.

1-loop Amplitude

- Using dimensional regularization the renormalized one-loop matrix element in the $\overline{\mathrm{MS}}$ scheme is typically of the form

$$|\mathcal{M}|^2_{1-loop} = \frac{\alpha_S}{2\pi}\frac{1}{\Gamma(1-\epsilon)}\left(\frac{4\pi\mu^2}{Q^2}\right)^{\epsilon}\left\{\frac{A}{\epsilon^2}+\frac{B}{\epsilon}+C+\mathcal{O}(\epsilon)\right\}, \tag{5}$$

  where μ is the dimensional regularization scale (which we set equal to the renormalization scale throughout), and Q is some scale relevant to the process..
- The convention in `TeVJet` is to extract a factor of

$$\frac{1}{\Gamma(1-\epsilon)}\left(\frac{4\pi\mu^2}{Q^2}\right)^{\epsilon}, \tag{6}$$

  from the insertion operator and the one-loop matrix element.
- The user must provide the reference scale Q and the finite part of the 1-loop amplitude with this pre-factor extracted.
- In the future this could be the only process-dependent input required for a new process.

Phase space generation

The phase space generation in TeVJet uses the dipole phase space factorization:

$$d\Pi_{m+1}(\{p\}; Q) = d\Pi_m(\{\tilde{p}\}; Q) \cdot \mathcal{J}\, dydzd\phi$$

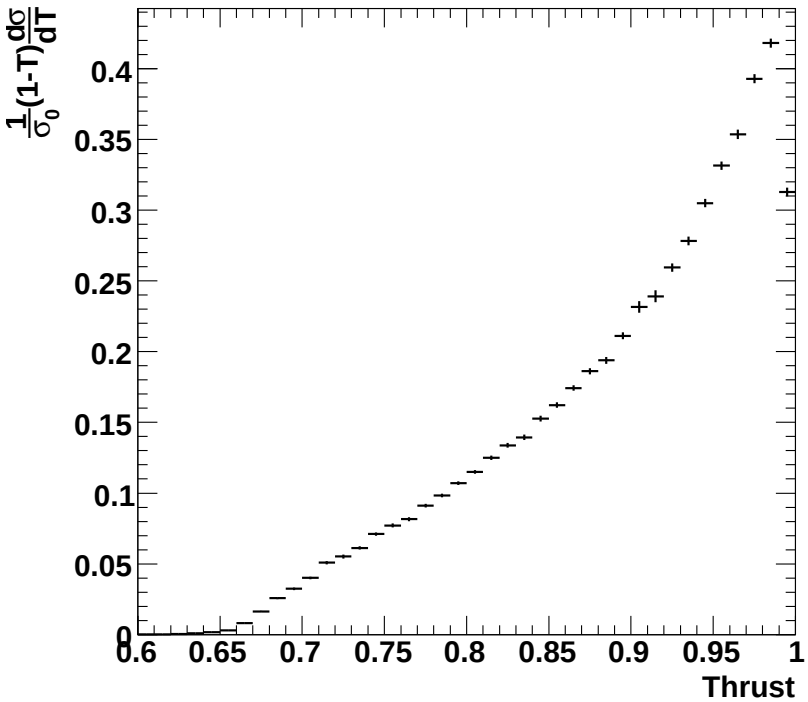
to generate an $m+1$ body configuration from an m body configuration.

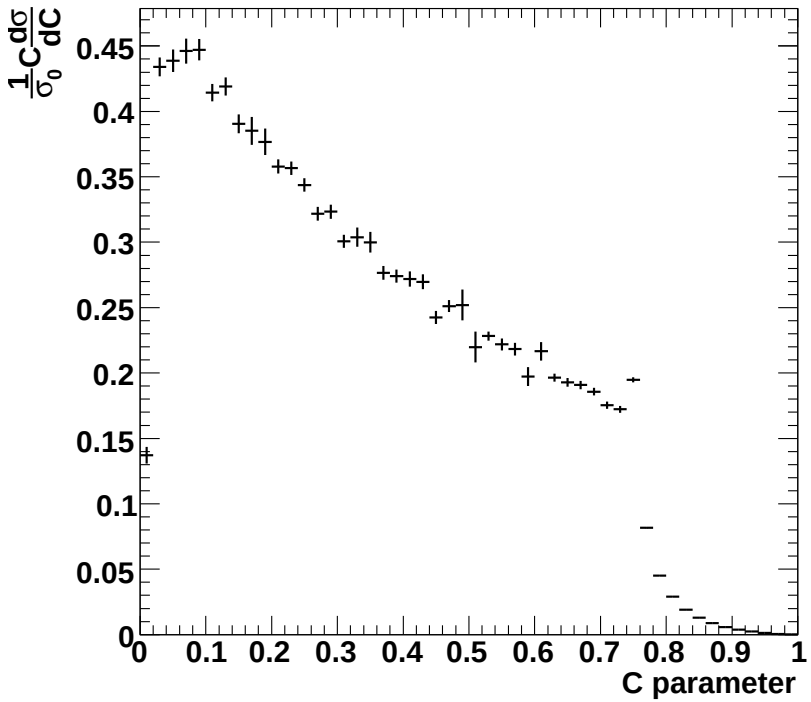
- The 'real minus subtraction term' typically contains (integrable) square-root singularities in the dipole variables as $y \longrightarrow 0$ and $z \longrightarrow 0, 1$
- TeVJet uses a multichannel phase space generation introducing a Jacobian factor of the form

$$\mathcal{J} = \frac{8\sqrt{y_{ij,k}}\sqrt{\widetilde{z}_i(1-\widetilde{z}_i)}}{\sqrt{\widetilde{z}_i} + \sqrt{1-\widetilde{z}_i}}, \tag{7}$$

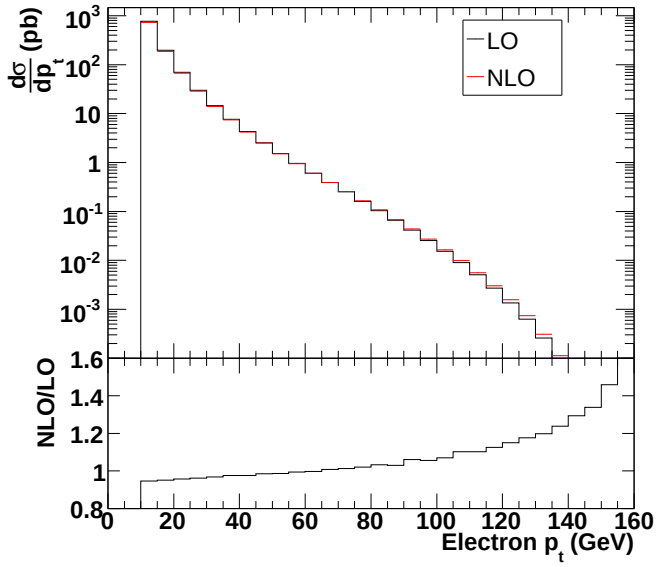
for each channel.

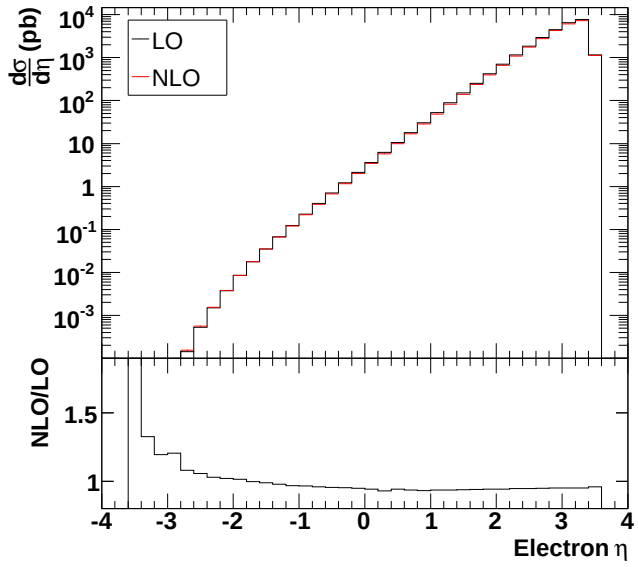
TeVJet Results - 3jet event shapes

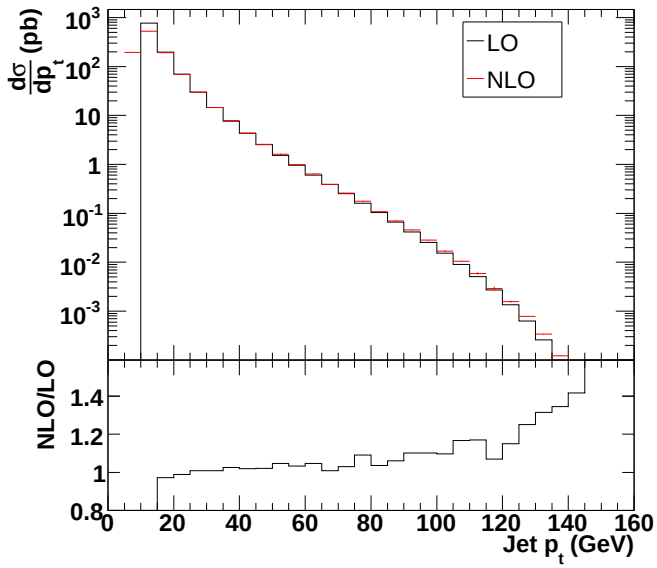


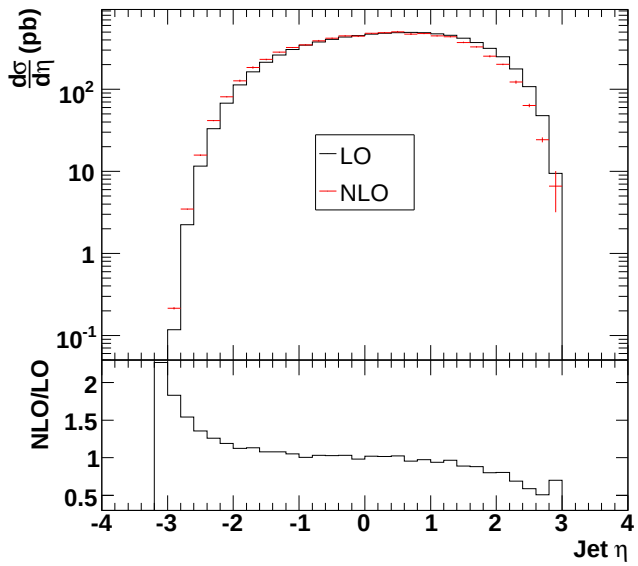


TeVJet Results - $ep \longrightarrow e + 1\text{jet}$









Summary & Outlook

- TeVJet is a direct implementation of the dipole subtraction method
- Inclusion of new processes fairly straight forward
- Could be made easier by full automation of Matrix element and Amplitude code (colour algebra)
- Full working version for the case of massless particles
- Currently including all mass effects ($pp \longrightarrow t\bar{t}$ cross section in progress)