Chris White, Nikhef

Higgs Boson Production with Multiple Hard Jets

In collaboration with J. Andersen, V. Del-Duca

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Overview

How can we reliably estimate multijet final states?

- Traditional methods for calculating jets.
- Higgs physics at the LHC.
- New technique for calculating Higgs + multijets.
- Example results and outlook.

Summary of Methods for Final State Jets

Exact

- Use standard perturbation theory at LO, NLO...
- Best thing to do, but very difficult.
- Limited to small numbers of final state partons and low orders in α_S.

Approximate

- Combine tree level matrix elements (e.g. from MADGRAPH) with parton showers.
- Get more realistic final states.
- However, only soft / collinear enhanced radiation included (low p_t).

- We know that parton showers are insufficient in some processes.

$\rightarrow$ Can we instead estimate hard radiation in the final state?

New method

- Will now introduce our new technique.
- Aim: estimate hard jets in the matrix element.
- Will start with a known factorisation formula for hard jet emission (FKL).
- Can be modified to include known features of the perturbation expansion.
- Will apply this to Higgs boson production via GGF.
- Can validate approximate matrix elements by comparing to known results at low orders in α_S.

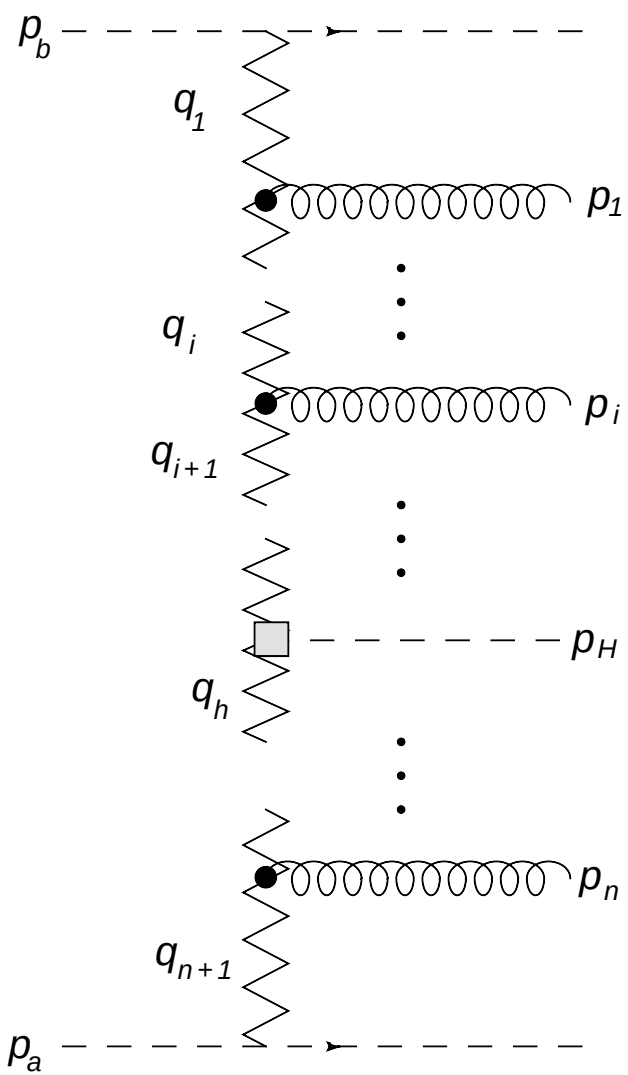
FKL Factorisation - Overview

- In a particular kinematic limit (MRK), particular Feynman diagrams dominate the matrix element (Fadin, Kuraev & Lipatov).
- These correspond to the process:

$$\alpha + \beta \to \alpha + \beta + ng,$$

  where α, $\beta \in \{q, \bar{q}, g\}$.
- The sum of such diagrams gives a factorised expression for the matrix element in terms of:
  1. Impact factors for the incoming jets and additional particles (e.g. Higgs, W bosons).
  2. Modified emission vertices for the outgoing gluons.
  3. Propagators for the (virtual) exchanged gluons.
  4. Leading virtual corrections.
- Let's look at this for Higgs production...

FKL factorisation



- The FKL formula:

$$
\begin{aligned}
i\mathcal{M}^{ab\to abj_1\ldots j_n}_{\mu_1\ldots\mu_n} &= 2s(g_s)^{n+2} \\
&\times \left(\prod_{i=1}^{n_1+1} \frac{1}{q_i^2} \exp[\hat{\alpha}(q_i^2)(y_{i-1}-y_i)]\right) \\
&\times \left(\prod_{i=1}^{n_1} C_{\mu_i}(q_{i-1},q_i)\right) C_H(q_{n_1+1},q_{n_1+2}) \\
&\times \left(\prod_{i=n_1+2}^{n+1} \frac{1}{q_i^2} \exp[\hat{\alpha}(q_i^2)(y_{i-1}-y_i)]\right) \\
&\times \left(\prod_{i=n_1+2}^{n} C_{\mu_i}(q_{i-1},q_i)\right)
\end{aligned}
$$

FKL - Comments

Advantages

- Factorised form - can be applied at any order in α_S.
- Gives exclusive multijet final states with hard jets.
- Some virtual corrections built in - collinear singularities cancelled.

Disadvantages

- Only works in a certain kinematic limit (MRK)
- Does not approximate matrix element well outside this limit.
- MRK kinematics not a good approximation for the Tevatron or LHC.

- Solution: Use FKL as a starting point. Modify to build in extra features.

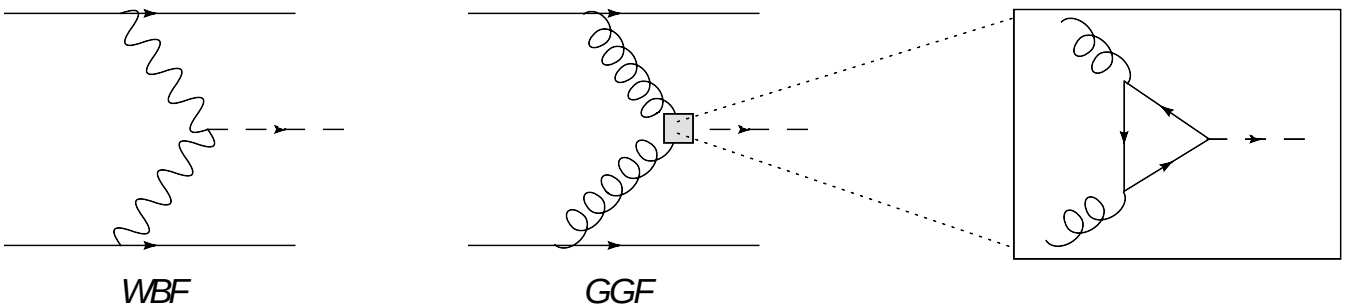
Improved Description

- We construct approximate matrix elements from the FKL formula with the following prescription:

1. Impose 4-momentum conservation at emission vertices.
2. Use full dependence on virtual momenta instead of transverse components.
3. Impose gauge invariance of Lipatov vertex ($k \cdot C = 0$) over all of phase space.

- These modifications significantly affect the FKL description.
- Physically motivated, and beyond any logarithmic order in $\hat{s}/t$.

Higgs Production at the LHC

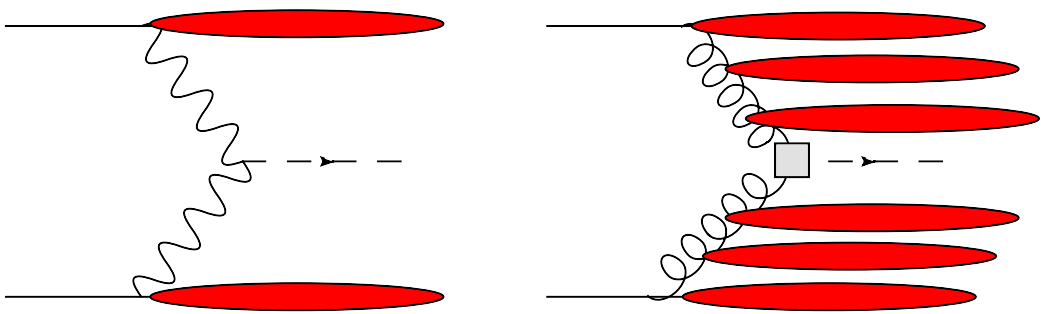


- Two main production modes - both can be used as a discovery channel.
- WBF - measure coupling of h to vector bosons. Is it the SM Higgs?
- GGF - measure nature of fermion coupling. CP even or odd?
- Can use cuts to separate processes.

$\Rightarrow$ Need a detailed understanding of both production modes.

WBF & GGF - Differences

- No exchange of colour in WBF - QCD radiation limited mainly to incoming partons.
- Colour octet exchange in GGF - get lots of QCD radiation in central rapidity region.



- Understanding of jet pattern in GGF crucial for:
  1. Measurement of coupling of h to fermions.
  2. Efficient background reduction of GGF w.r.t WBF.

Implementation

- Have calculated GGF matrix elements using the modified FKL description.
- Factorised form - can be efficiently implemented in a numerical code.
- We produced a Monte Carlo implementation of our technique.
- Generates events (with any number of final state partons) weighted by the approximated matrix elements.
- To investigate how good the new approximate matrix elements are, can compare to exact perturbation theory.
- I.e. expand approximate results order by order in α_S, and compare with known tree level results for *hjj* and *hjjj* (MADGRAPH).

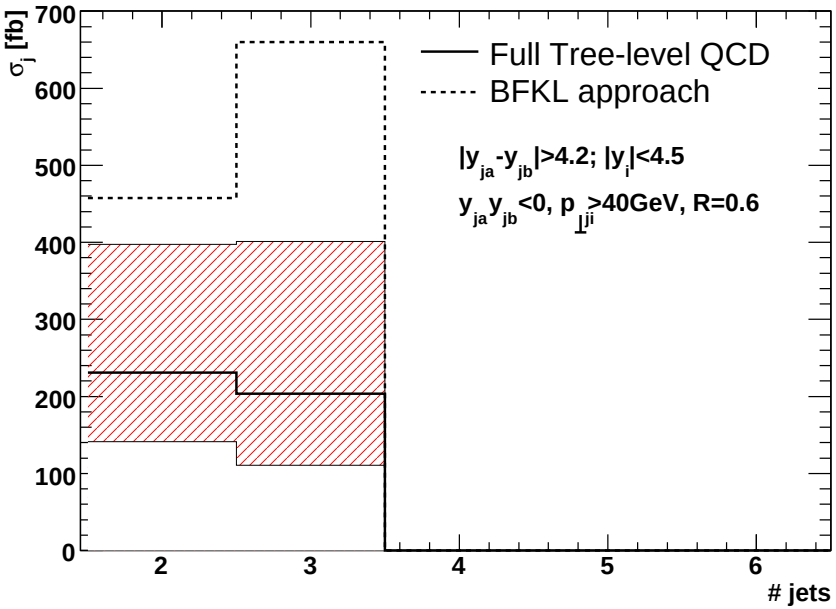
Results

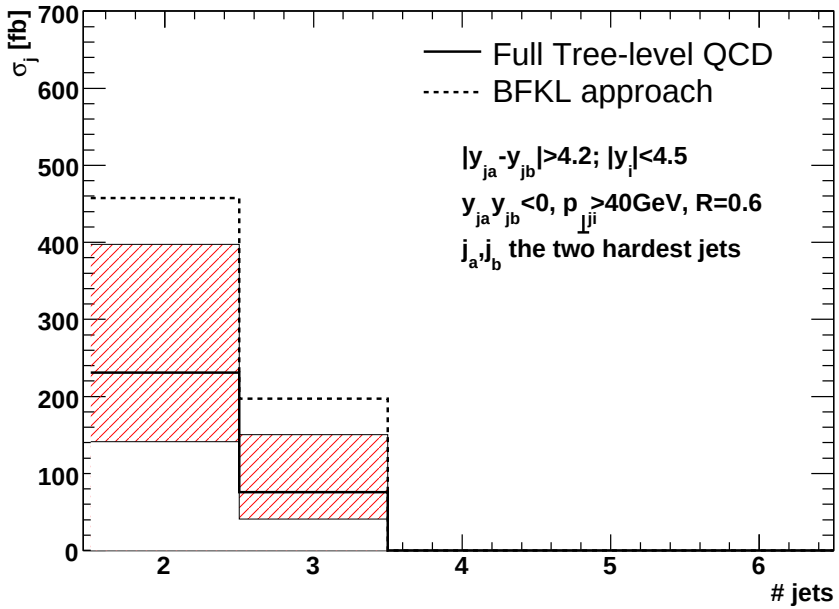
- Will show results for *WBF cuts*, designed to reduce the GGF process.
- This has been widely studied in the literature with other techniques (Zeppenfeld et. al.).

$p_{c_\perp}, p_{d_\perp}, p_{j_\perp}$	> 40 GeV	$y_c \cdot y_d$	< 0
$\lvert y_j \rvert$	< 4.5	$\lvert y_c - y_d \rvert$	> 4.2

- But results are representative of those obtained for other cuts.
- First show traditional BFKL results, before the new approach...

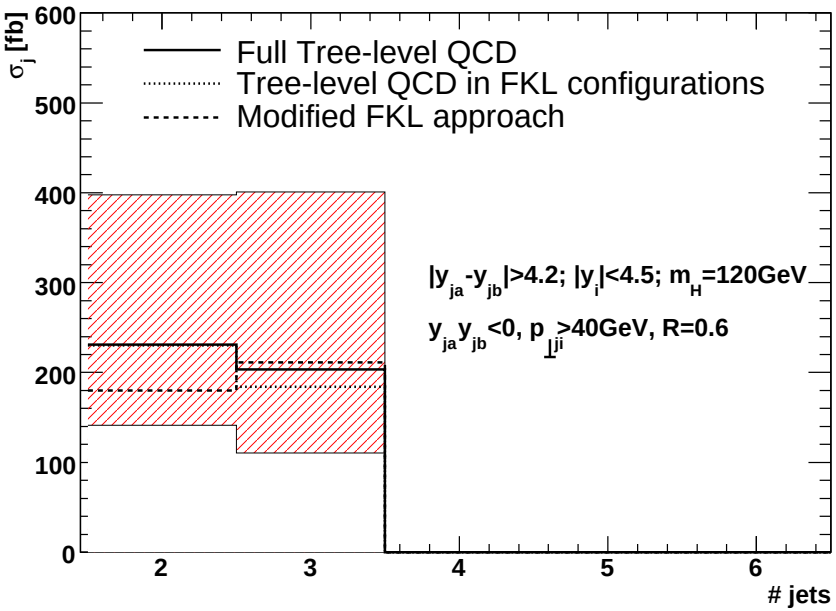
BFKL comparison

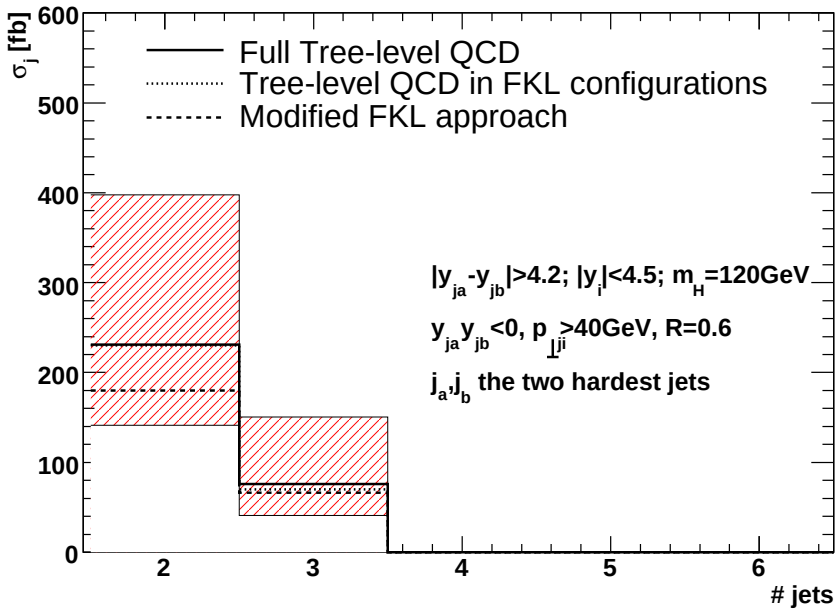




- The BFKL description with 4-momentum conservation is shown.
- Does not work well.

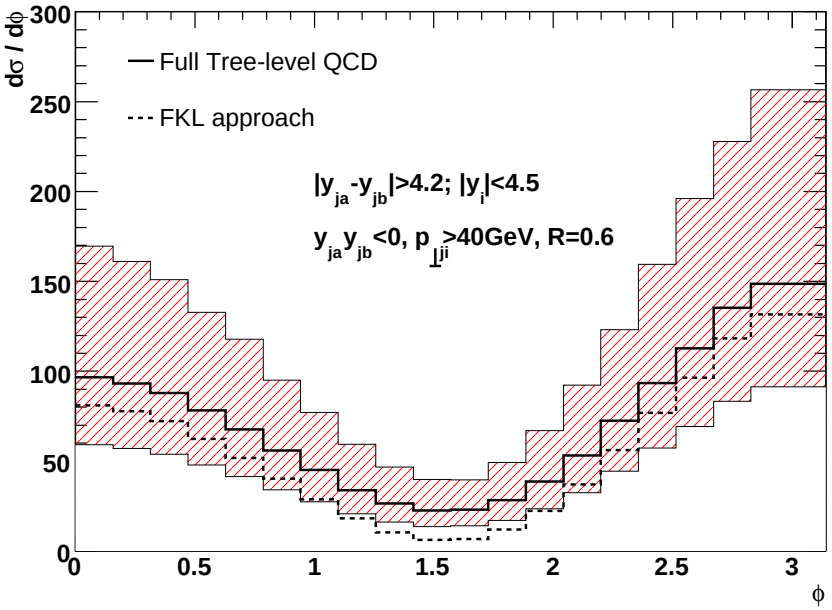
Improved description

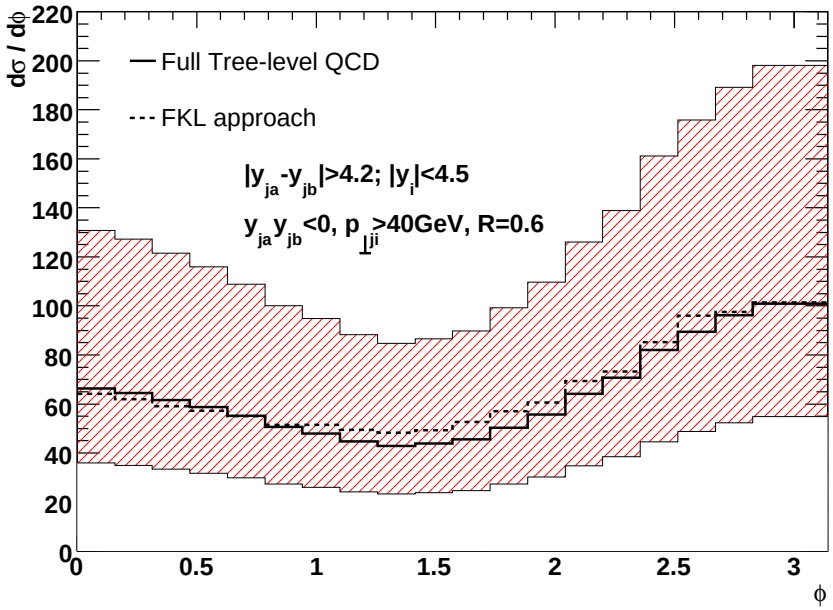




- Approximation is well within scale variation!
- Can also check differential distributions...

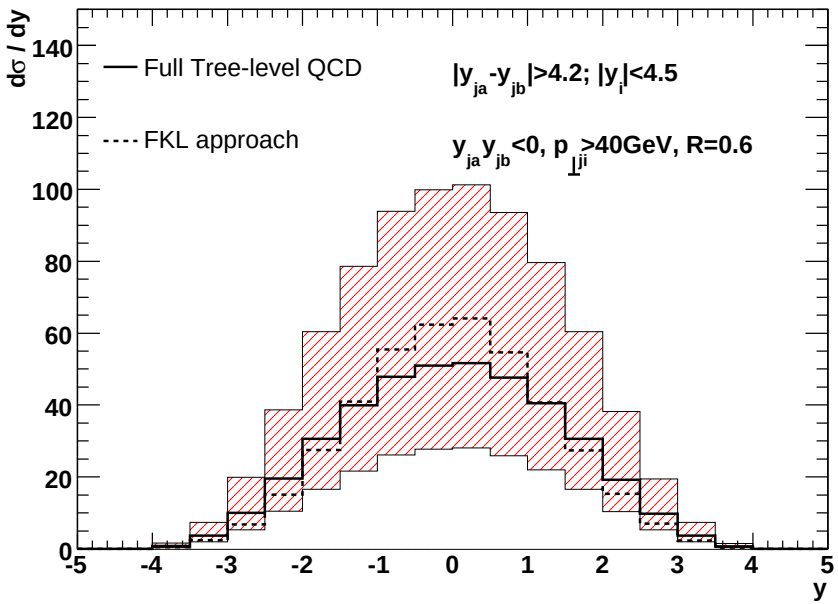
Azimuthal angle between tagging jets

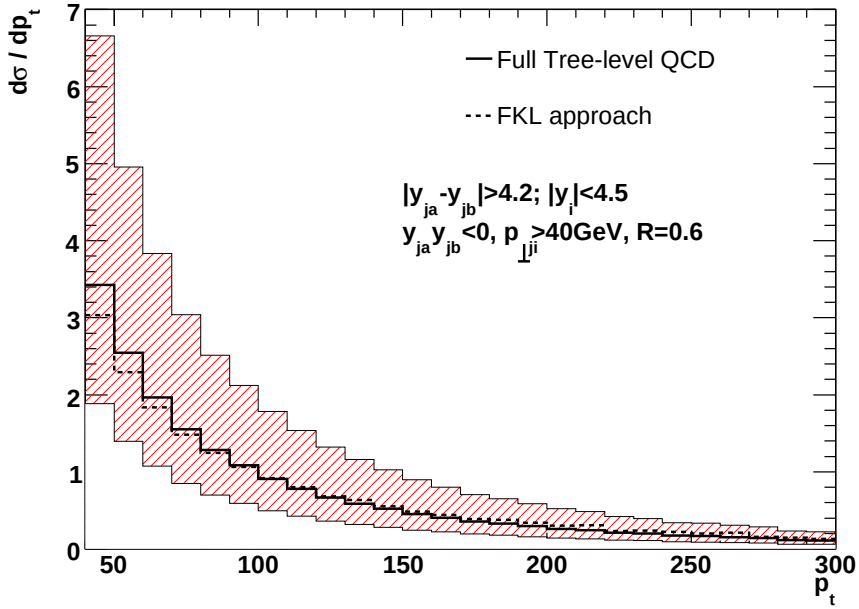




- Intimately related to CP nature of Higgs boson.

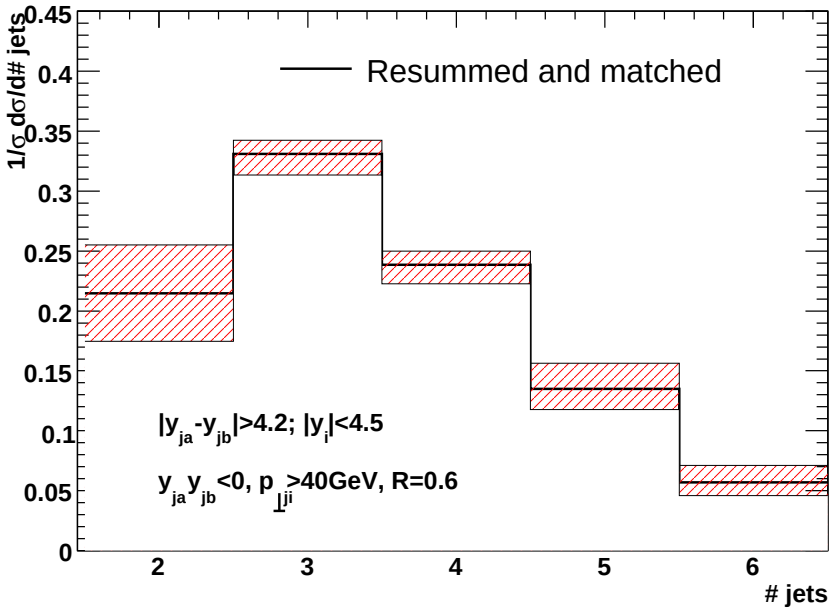
Properties of third parton in *hjjj*

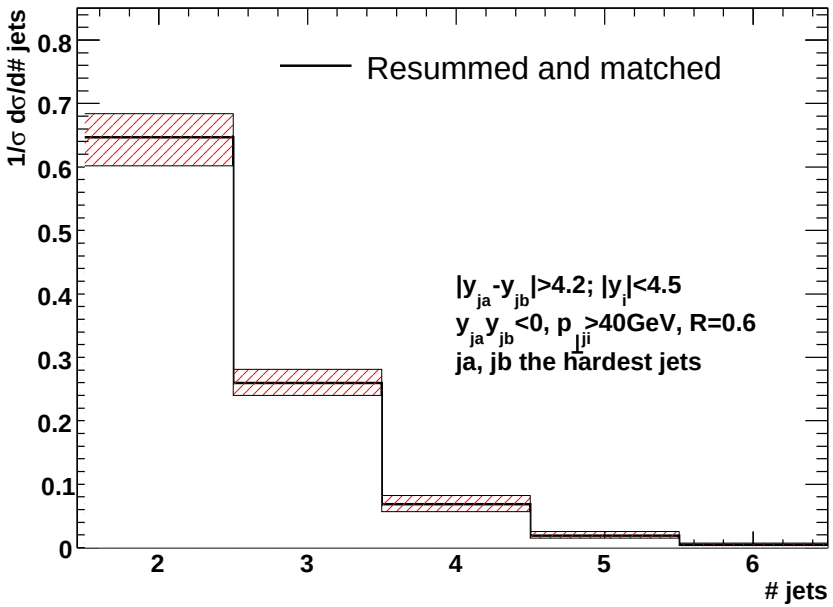




- Approximate matrix elements are working well.
- Can now turn on full resummation i.e. look at effect of multiple hard jets.

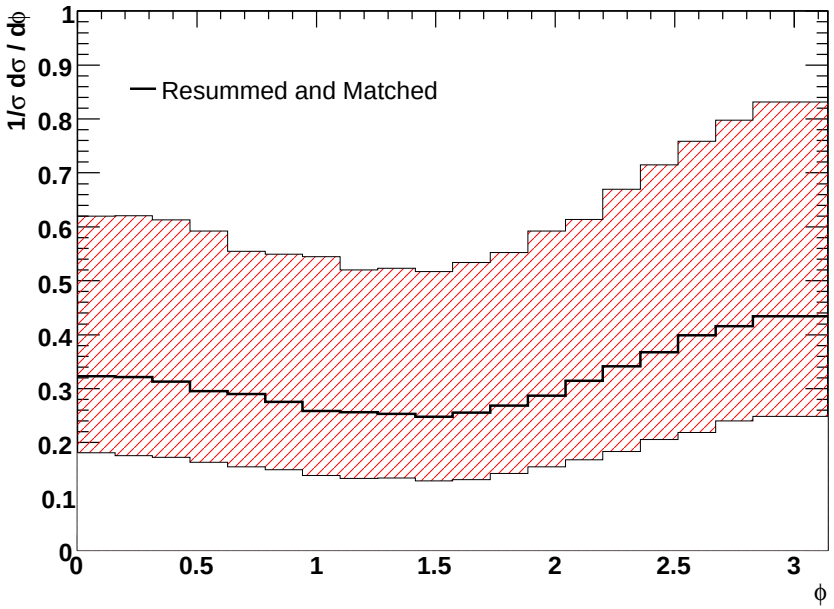
Number of hard jets

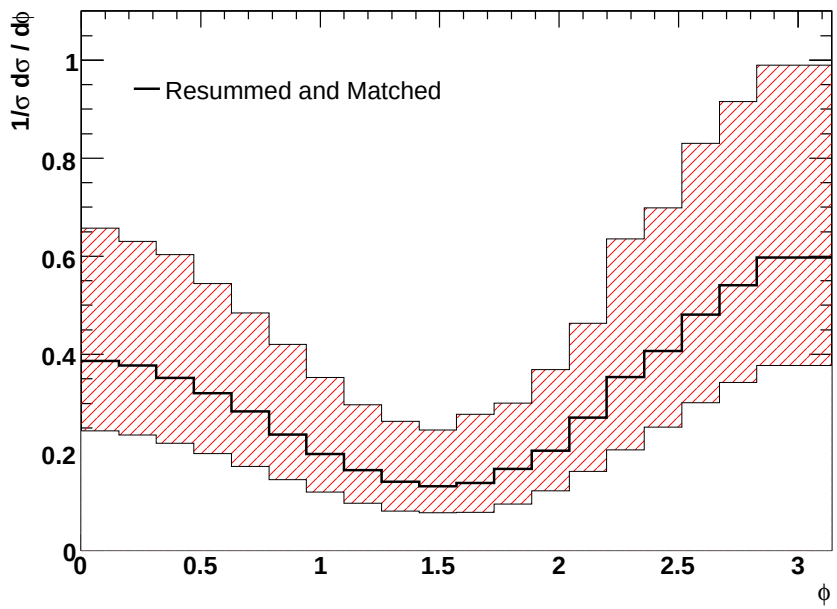




- Tagging on hardest jets reduces impact of further radiation.
- Still significant number of events with many hard partons.

Azimuthal correlation





- Measureable correlation sensitive to cuts.

Conclusions

- Have devised a new technique for approximating matrix elements with multiple final state hard partons.
- Useful for estimating final state jet topology, rather than the jet substructure which is better estimated by a parton shower.
- Uses FKL factorisation as a starting point, with modifications to include known features of perturbation theory.
- So far applied to Higgs production.
- Code available for simulating Higgs + multijet events.

Outlook

- More detailed Higgs phenomenology in progress.
- Can extend technique to other processes (e.g. W / Z + jets, pure multijet).
- Underlying approximation (FKL factorisation) can be systematically improved.
- Interfacing to parton showers for a more complete description of final states.