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Higgs Boson Production with Multiple Hard Jets

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SMLHC Workshop - UCL

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.

- Events at the LHC will be dominated by multijet final states.
- These arise from QCD radiation.
- In some processes, measurable properties are sensitive to this radiation. Number of jets? Hard or soft?
- Need to be able to calculate Feynman diagrams with lots of quark and gluon legs.
- Let's review existing methods...

Fixed Order Perturbation Theory

Why not just calculate all the Feynman diagrams?

- In principle, can write down Feynman diagrams at any order of α_S and calculate them.
- Real and virtual contributions are both singular, but singularities cancel when added together.
- However, calculational complexity increases stupendously with:
  1. Increasing order in the coupling constant (number of diagrams grows factorially).
  2. Number of external parton legs (number of scales in the problem increases).
- Only very low orders in α_S are known for most processes...

Parton Shower Techniques

- Can use parton showers to simulate extra radiation.
- Based on a known factorisation of matrix elements in the *soft* and *collinear* limit.
- Shower is applied to each external leg.
- Get final states with many particles.
- Can couple to hadronisation / detector simulations etc.
- Accurate only if jets are soft - can increase accuracy by including higher order tree level matrix elements.

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

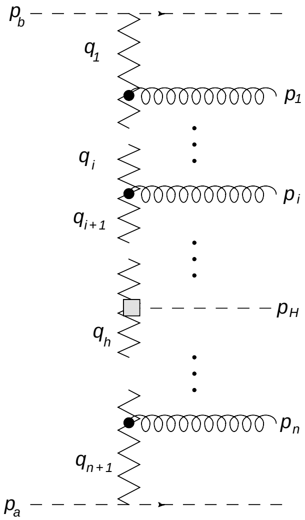
- In a particular kinematic limit (MRK), particular Feynman diagrams dominate the matrix element (Fadin, Kuraev & Lipatov).
- These correspond to the process:

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

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:

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

FKL - Comments

- Formally applies only in a certain high energy limit (MRK):

$$y_1 \ll y_2 \ll \ldots y_n; \quad k_{1\perp} \sim k_{2\perp} \sim \ldots k_{n\perp}.$$

- Jets strongly ordered in rapidity, but not in transverse momentum (so "hard").
- Resums (includes at each order in α_S) leading logarithms in $\hat{s}/t$.
- In the traditional implementation of this formula, one replaces the virtual gluon 4 -momenta:

$$q_i \rightarrow q_{i\perp}$$

  and ignores any contributions which are subleading in $\ln(\hat{s}/t)$.
- Can also ignore 4-momentum conservation at LL order.
- This is known as BFKL after Balitski, Fadin, Kuraev & Lipatov.
- Will see later how this performs for Higgs production - description is not good at LHC.

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.

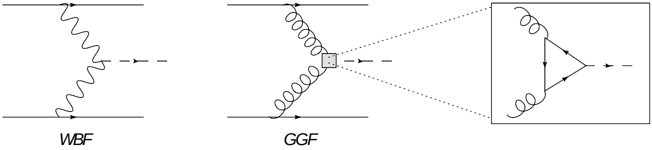
Improved Description - Comments

- Energy-momentum conservation is an obvious piece of physics, and should be included.
- Has been considered before, but makes numerical implementation mandatory.
- Use of full 4-momenta corresponds to including known singularity structure of amplitude, rather than shifting poles outside the MRK limit.
- Gauge invariance leads to local positivity of the Lipatov vertex ($-C.C > 0$), thus removes spurious negative contributions due to gauge-violating terms.
- These corrections are not just NLL...

Improved Description - More Comments

- Conservation of energy implements subleading corrections to FKL, but also phase space of emitted gluons.
- Thus goes beyond any logarithmic order in $\hat{s}/t$.
- Likewise, so does the use of full virtual momenta.
- Resulting matrix elements are much closer to fixed order perturbation theory than to the original FKL description.
- Will validate approximation by looking at a particular process (Higgs boson production via gluon-gluon fusion).
- Let's briefly review some aspects of Higgs physics at the LHC...

Higgs Production at the LHC

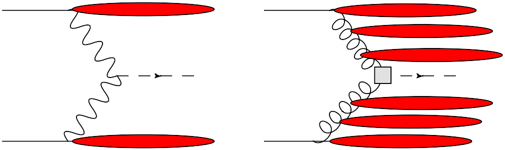


- Two main production modes - both can be used as a discovery channel.
- WBF - measure coupling of h to vector bosons. Is it the SM Higgs?
- GGF - measure nature of fermion coupling. CP even or odd?
- Can use cuts to separate processes.

$\Rightarrow$ 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).

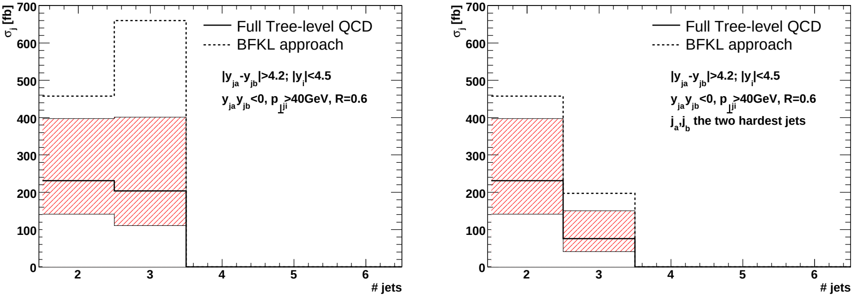
Results

- 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

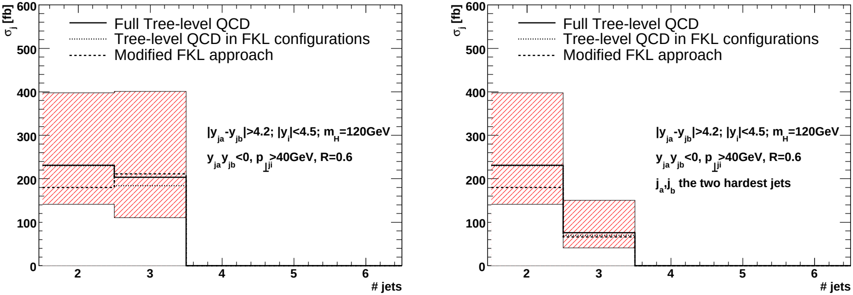
- But results are representative of those obtained for other cuts.
- First show traditional BFKL results, before the new approach...

BFKL comparison



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

Improved description

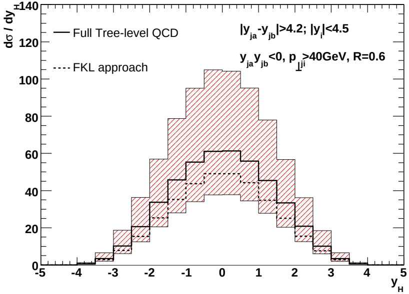


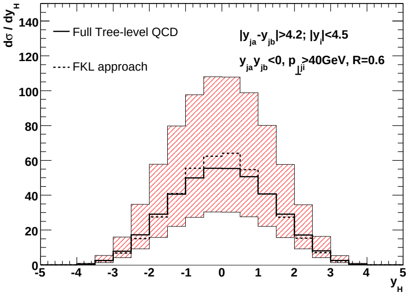
- Approximation is well within scale variation!

Comments

- Total cross-sections are well estimated by the new technique.
- However, this is only part of the story.
- Can also check differential distributions at fixed order...

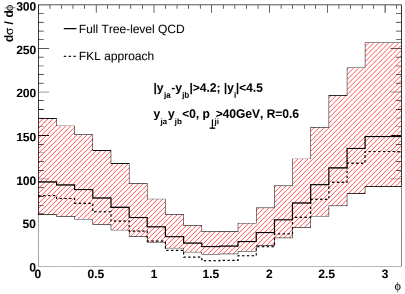
Rapidity of Higgs boson

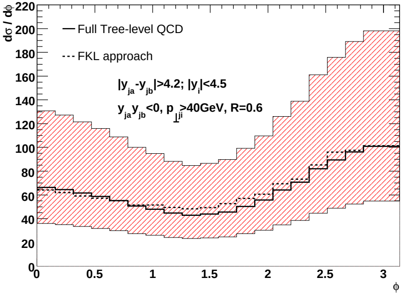




- Shown for *hjj* (left) and *hjjj* (right).

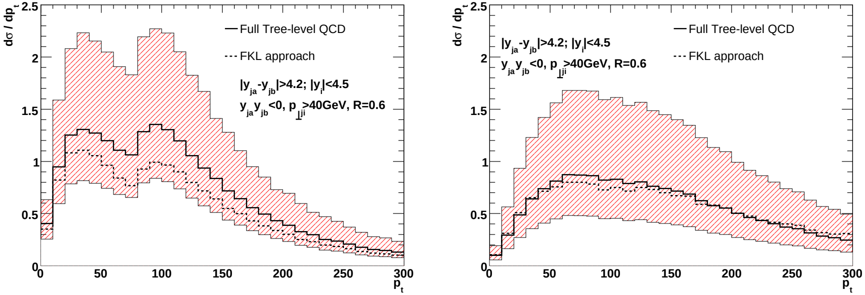
Azimuthal angle between tagging jets





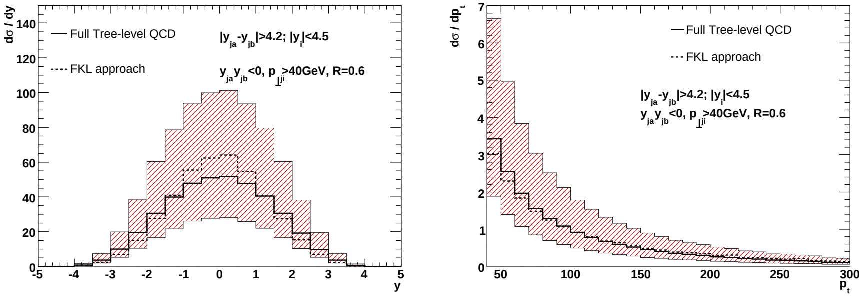
- Intimately related to CP nature of Higgs boson.

Transverse momentum of Higgs boson



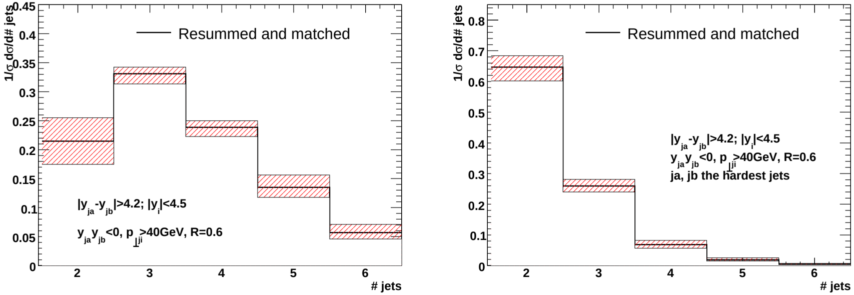
- Shape change due to azimuthal correlation...

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

- We have already seen that the azimuthal angle distirubiton has a pronounced shape at fixed order.
- Related to CP nature of Higgs-fermion coupling.
- Whether or not it can be measured depends strongly on the extent of QCD radiation.
- Introduce (Zeppenfeld et. al.):

$$A_\phi = \frac{\sigma(\phi_{j_a j_b} < \pi/4) - \sigma(\pi/4 < \phi_{j_a j_b} < 3\pi/4) + \sigma(\phi_{j_a j_b} > 3\pi/4)}{\sigma(\phi_{j_a j_b} < \pi/4) + \sigma(\pi/4 < \phi_{j_a j_b} < 3\pi/4) + \sigma(\phi_{j_a j_b} > 3\pi/4)}$$

- $|A_\phi = 0|$ for completely uncorrelated jets, and 1 for completely correlated.
- $A_\phi \sim 0$ for WBF.
- In GGF, $A_\phi > 0$ for CP even (scalar) Higgs and < 0 for CP odd (pseudoscalar).

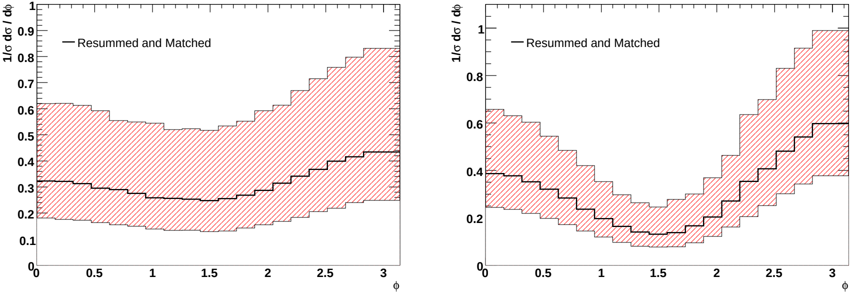
A_ϕ values

Inclusive cuts	A_ϕ
LO 2-jet	0.456
Resummed, $=$ 2-jet	0.444
LO 3-jet	0.203
Resummed	0.123

Hardest cuts	A_ϕ
LO 2-jet	0.456
Resummed, $=$ 2-jet	0.436
LO 3-jet	0.374
Resummed	0.372

- Cuts can efficiently be used to increase the observed correlation.
- E.g. jet vetoes, tagging jet choice.

Azimuthal correlation



- Distributions confirm the numbers on the previous slide...

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.