All-order corrections in production of (gluon fusion) Higgs boson plus jets

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Zürich
January 9, 2000

The impact of higher order corrections. . .

- Significant perturbative corrections
  . . . also from **hard** emissions

  S. Höcker: Incl. H@NNLO: Significant contribution from multi jet states (unless **vetoed**)
  L. Reina: Ass. $W/Z + b\bar{b}$: Estimate of ren. scale uncertainty larger at NLO than at LO, except if extra jets are **vetoed**

  ⋮

- Propose to **calculate to all orders** the source of these large corrections, in order to **stabilise the perturbative calculation** rather than removing the contributions by vetoes (sensitive to HO corrections).
- **Flexible** implementation necessary for realistic analyses

What, Why, How?

What?

Develop a framework for reliably calculating many-parton rates inclusively (both real and virtual corrections to create ensemble of $2, 3, 4, \ldots$ parton rates) in a flexible way (jets, W+jets, Higgs+jets,...) **without relying on soft/collinear approximation of parton shower**

Why?

$(n+1)$-jet rate not necessarily small compared to n-jet rate
Need inclusive perturbative corrections for realistic jet studies

How?

Factorisation of QCD Amplitudes in the High Energy Limit.
New Technique. Validation. Use $H+$dijet as example.

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Previous studies of Higgs Boson plus jets

Necessary to understand multi-emission topologies in order to cleanly extract WBF signal (c. jet veto, angular dist. of jets,. . .)

- hjj@full NLO: Increase in cross section over LO estimate of factors 1.2-1.3 or 1.7-1.8 depending on cuts (note: discussion of K-factors not really useful for a multi-scale problem).

  J. Campbell, K. Ellis, G. Zanderighi

- hjj@LO+parton showers: Focus on effects of soft and collinear radiation to all orders. Find significant effects beyond NLO.

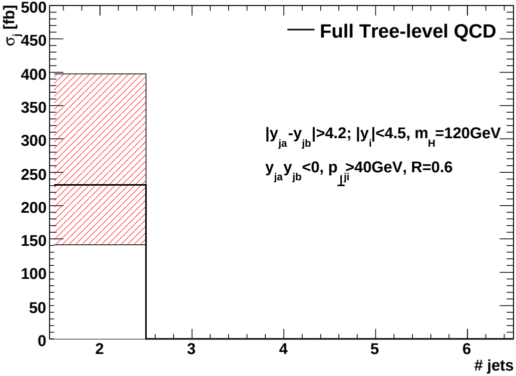
  V. Del Duca, G. Klämke, D. Zeppenfeld, M.L. Mangano, M. Moretti, F. Piccinini, R. Pittau, A.D. Polosa

Will focus on **developing a framework** which captures a part of the **perturbative series to all orders** (**not relying** on soft and collinear factorisation) - and **compare it order by order** to the full result where known.

All Order Resummation Necessary?

Are tree-level (or generally fixed order) calculation always sufficient?

Higgs Boson plus *n* jets at the LHC at leading order



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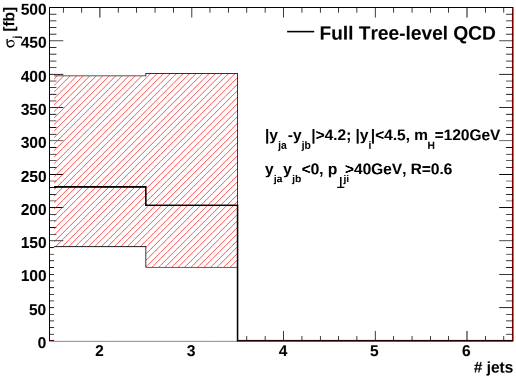

Indication that we need to go further! However, fixed order tools **exhausted** (full $2 \to 3$ with a massive leg at two loops **untenable!**).

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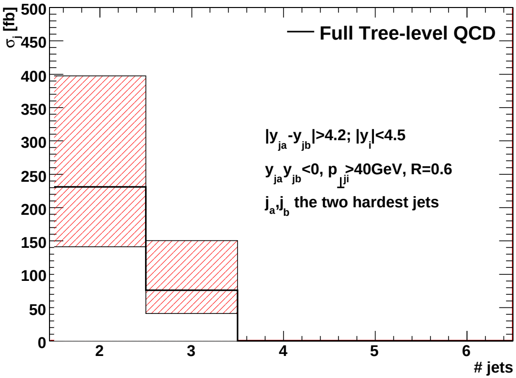

Could require that the two jets passing the cuts are also the two hardest jets. This reduces the three-jet phase space and the higher order corrections. Sensitivity to pert. corrections?

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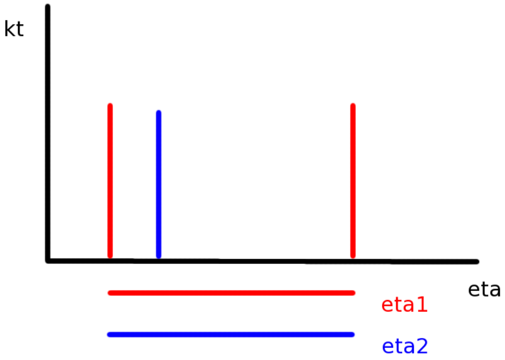

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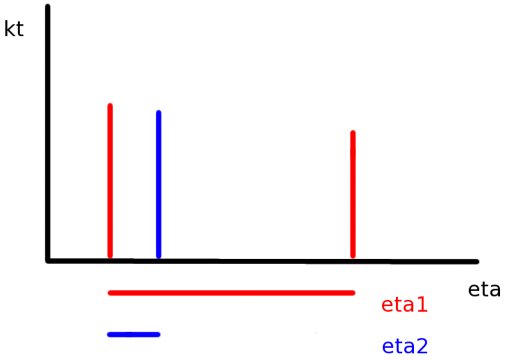

Rapidity span between hardest jets very sensitive to small perturbative corrections

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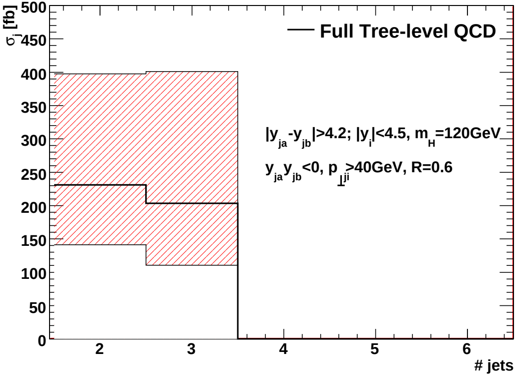

The method we develop will be applicable to both set of cuts, but crucially will allow a **stabilisation** of the perturbative series by **resummation**

Factorisation of QCD Matrix Elements

It is **well known** that QCD matrix elements **factorise** in certain kinematical limits:
Soft limit $\rightarrow$ **eikonal approximation** $\rightarrow$ enters all parton shower (and much else) resummation.

Like all good limits, the eikonal approximation is applied **outside its strict region of validity**.

Will discuss the **less well-studied factorisation** of scattering amplitudes in a different kinematic limit, better suited for describing perturbative corrections from **hard parton emission**

This factorisation only **becomes exact** in a region **outside** the reach of any collider. . . **also** control sub-asympt. terms

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Regge and High Energy Factorisation of Amplitudes

In the High Energy Limit, $2 \to 2$ **scattering amplitudes** are **dominated** by the ***t*-channel exchange** of the particle of the **highest spin** allowed by the scattering theory

$$\mathcal{M}^{p_a p_b \to p_1 p_2} \xrightarrow{\text{Regge limit}} \hat{s}^{\hat{\alpha}(\hat{t})}\ \gamma(\hat{t})$$

Regge (1959)

$\hat{s} = (p_a + p_b)^2, \hat{t} = (p_a - p_1)^2$, Regge limit: $\hat{s} \to \infty, \hat{t}$ fixed.

Multi-particle generalisation?

$$\mathcal{M}^{p_a p_c \to p_{a'} p_b p_{c'}} \xrightarrow{\text{Multi Regge limit}} \hat{s}_1^{\hat{\alpha}(\hat{t}_1)}\ \hat{s}_2^{\hat{\alpha}(\hat{t}_2)}\ \gamma(\hat{t}_1, \hat{t}_2, \frac{s_{12}}{s_1 s_2})$$

MRK: $\hat{s}_{12}, \hat{s}_1, \hat{s}_2 \to \infty, t_1, t_2$ fixed

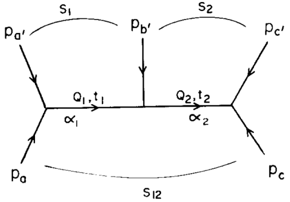
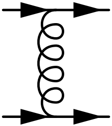
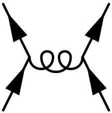
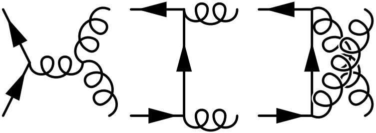


Fig. 2.1. Five-particle diagram showing notation.

Brower, DeTAR, Weis (1974)

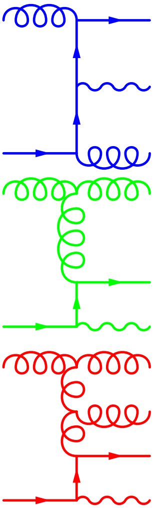
High Energy Factorisation - t–channel dominance

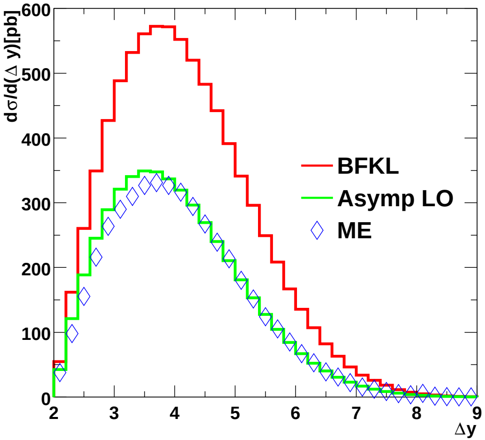
Process	Diagrams	$\overline{\sum}\lvert\mathcal{M}\rvert^2/g^4$
$qq' \to qq'$		$\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$
$q\bar{q} \to q'\bar{q}'$		$\frac{4}{9}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$
$q\bar{q} \to gg$		$\frac{32}{27}\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}} - \frac{8}{3}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$

High Energy Limit: $\lvert\hat{t}\rvert$ fixed, $\hat{s} \to \infty$

t–channel dominance

Example: W+n-jet production at the LHC



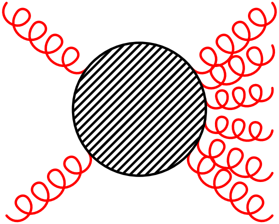


$$\Delta y = y_{j_2} - y_{j_1}, y_W, y_{j_2} \geq 1, y_{j_1} \leq -1$$

V. Del Duca, F. Maltoni, W.J. Stirling, JRA

The Possibility for Predictions of n-jet Rates

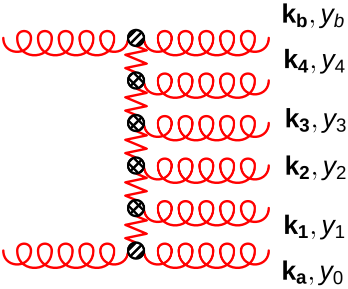
The Power of Reggeisation



High Energy Limit

$$\xrightarrow{\qquad}$$

$$|\hat{t}| \quad \text{fixed}, \qquad \hat{s} \to \infty$$



$$\mathcal{A}^R_{2\to 2+n} = \frac{\Gamma_{A'A}}{q_0^2}\left(\prod_{i=1}^{n} e^{\omega(q_i)(y_{i-1}-y_i)}\frac{V^{J_i}(q_i,q_{i+1})}{q_i^2 q_{i+1}^2}\right) e^{\omega(q_{n+1})(y_n-y_{n+1})}\frac{\Gamma_{B'B}}{q_{n+1}^2}$$

$q_i = \mathbf{k}_a + \sum_{l=1}^{i-1} \mathbf{k}_l$

LL: Fadin, Kuraev, Lipatov; NLL: Fadin, Fiore, Kozlov, Reznichenko

Maintain (at LL) terms of the form

$$\left(\alpha_s \ln \frac{\hat{s}_{ij}}{|\hat{t}_i|}\right)$$

to all orders in α_s.

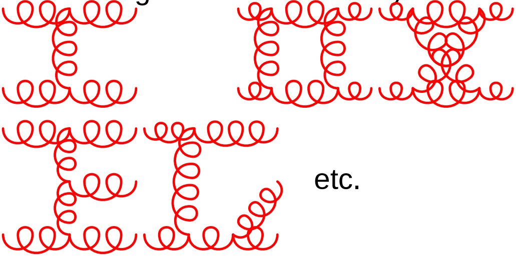
At LL only gluon production; at NLL also quark–anti-quark pairs produced.

Approximation of any-jet rate possible.

FKL at Leading Logarithmic Accuracy

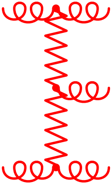
Fadin, Kuraev, Lipatov

Which diagrams contribute beyond lowest order?



etc.

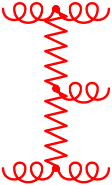
All these contributions can be calculated using **effective vertices** and propagators for the **reggeized gluon**.

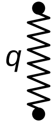


General form proved using s-channel unitarity and a set of bootstrap relations NLL: Fadin, Fiore, Kozlov, Reznichenko

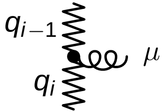
FKL formalism (Fadin, Kuraev, Lipatov)

FKL: Identification of the **dominant contributions** to the **perturbative series** for processes with two large (perturbative) and disparate energy scales $\hat{s} \gg |\hat{t}|$ ($\hat{s}$: E^2_{cm}, $\hat{t}$: $p^2_\perp$)





$$\frac{1}{q^2}\exp\left(\hat{\alpha}(q)\Delta y\right)$$



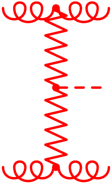
$$C^\mu_L(q_{i-1}, q_i)$$

$$C^\mu_L(q_{i-1}, q_i) = \left[-(q_i + q_{i+1})^{\mu_i} + p^\mu_a \left(\frac{q_i^2}{k_i.p_1} + 2\frac{k_i.p_b}{p_a.p_b}\right) - p_b\left(\frac{q^2_{i+1}}{k_i.p_b} + 2\frac{k_i.p_a}{p_a.p_b}\right)\right]$$

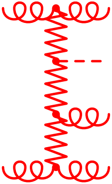
(note $C^\mu k_\mu = 0$. Subasymptotic controlled by requirement of gauge invariance). Framework exact in the limit of Multi Regge Kinematic (MRK)

$$y_0 \gg y_1 \gg \ldots \gg y_n, \quad |k_{i\perp}| \approx |k_{j\perp}|, \quad q_i^2 \approx q_j^2$$

Higgs Boson plus $n \geq 2$ jets in the HE limit

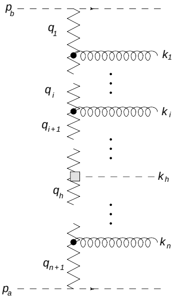


Extract the effective GG-Higgs Boson vertex using Hgggg-amplitudes (also checks factorisation)



Only four diagrams contribute to the process Higgs Boson plus 3 jets in the High Energy Limit!

The Scattering Amplitude



$$
\begin{aligned}
i\mathcal{M}_{\mathrm{HE}}^{ab\to p_0\ldots p_j h p_{j+1} p_n} &= 2i\hat{s} \\
&\cdot \left(i g_s f^{a d_0 c_1} g_{\mu_a \mu_0} \right) \\
&\cdot \prod_{i=1}^{j} \left(\frac{1}{q_i^2} \exp[\hat{\alpha}(q_i^2)(y_{i-1} - y_i)] \left(i g_s f^{c_i d_i c_{i+1}} \right) C_{\mu_i}(q_i, q_{i+1}) \right) \\
&\cdot \left(\frac{1}{q_h^2} \exp[\hat{\alpha}(q_i^2)(y_j - y_h)] C_H(q_{j+1}, q_h) \right) \\
&\cdot \prod_{i=j+1}^{n} \left(\frac{1}{q_i^2} \exp[\hat{\alpha}(q_i^2)(y'_{i-1} - y'_i)] \left(i g_s f^{c_i d_i c_{i+1}} \right) C_{\mu_i}(q_i, q_{i+1}) \right) \\
&\cdot \frac{1}{q_{n+1}^2} \exp[\hat{\alpha}(q_{n+1}^2)(y'_n - y_b)] \left(i g_s f^{b d_{n+1} c_{n+1}} g_{\mu_b \mu_{n+1}} \right)
\end{aligned}
$$

Have: **exact** result in the **very exclusive limit** of **infinite separation** between **all particles**

Want: **inclusive** cross sections. . .

Improving the Framework

Start again from the FKL amplitudes:

$$i\mathcal{M}_{\mathrm{HE}}^{ab\to p_0\cdots p_j h p_{j+1} p_n} = 2i\hat{s}\cdots\prod_{i=1}^{j}\left(\frac{1}{q_i^2}\exp[\hat{\alpha}(q_i^2)(y_{i-1}-y_i)]\left(ig_s f^{c_i d_i c_{i+1}}\right)C_{\mu_i}(q_i,q_{i+1})\right)\cdots$$

Result exact in the MRK limit. Control the sub-asymptotic behaviour by imposing

1. Position of Divergences
2. Gauge invariance (also in sub-MRK region)

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The full scattering amplitude is divergent for several momentum configurations, for which the use of MRK approximations of invariants would render the amplitude finite. However, we choose to re-instate several of these divergences by using **the full momentum dependence of all invariants**.

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1. Position of Divergences
2. Gauge invariance (also in sub-MRK region)

Using full expression for propagators **automatically takes into account the dominant source of NLL corrections** to *any* logarithmic accuracy. NLL corrections to Lipatov Vertex C^{μ} starts to address the dependence on longitudinal momenta between two neighbouring partons. We can restore the **full** propagator between all gluons.

Improving the Framework

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Result exact in the MRK limit. Control the sub-asymptotic behaviour by imposing

1. Position of Divergences
2. Gauge invariance (also in sub-MRK region)

Choose form of Lipatov vertex satisfying $C^\mu k_\mu = 0$. The gauge dependent terms are suppressed in the HE limit (and thus not controlled by such considerations), but we are seeking a form which works **everywhere**. Requirement of Gauge invariance severely constrains the sub-asymptotic terms.

Improving the Framework

Start again from the FKL amplitudes:

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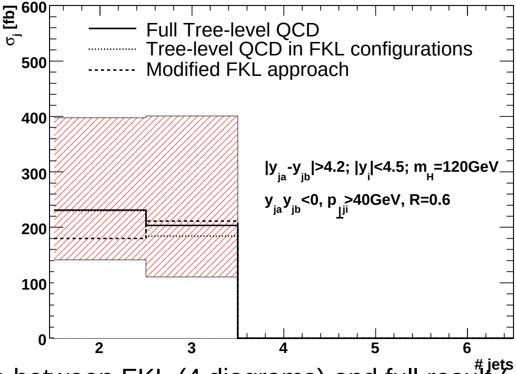
Result exact in the MRK limit. Control the sub-asymptotic behaviour by imposing

1. Position of Divergences
2. Gauge invariance (also in sub-MRK region)

These two **constrains the subasymptotic** form of the amplitude (and obviously does not alter the asymptotic form). Approximates the full results well where known. **Sufficiently simple** to allow an **all-order resummation**.

Comparison between FKL and Full Matrix Element



Difference between FKL (4 diagrams) and full result (~10^3 diagrams) is much less than the renormalisation and factorisation scale uncertainty. Repair with matching corrections.

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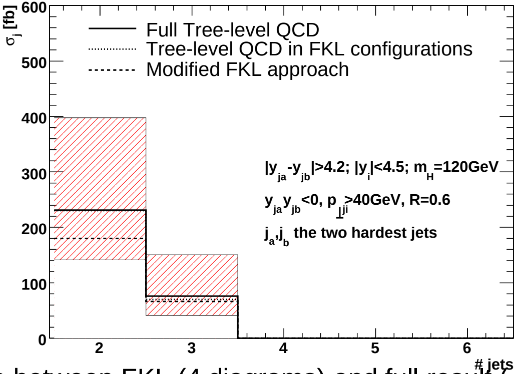
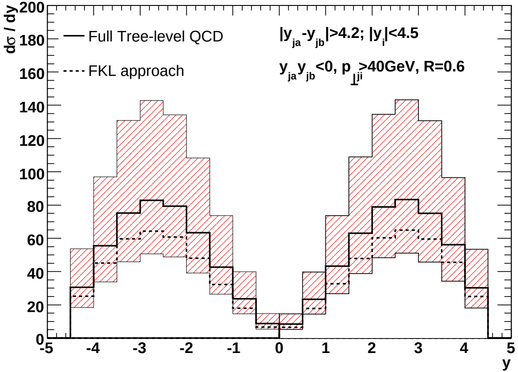


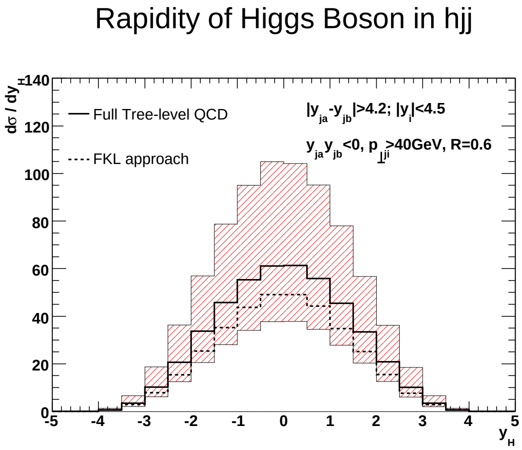
Difference between FKL (4 diagrams) and full result (10^3 diagrams) is much less than the renormalisation and factorisation scale uncertainty. Repair with matching corrections.

Fixed Order Comp^n: FKL vs Full Matrix Element

Rapidities of forward/backward jet in hjj

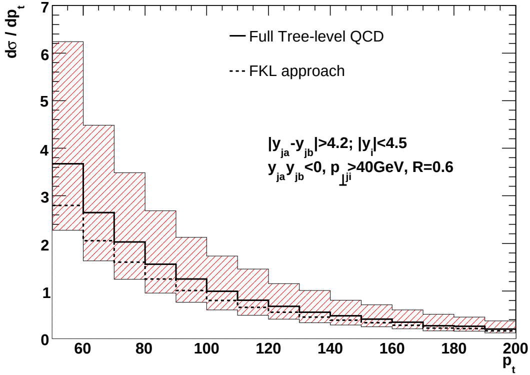


Fixed Order Comp^n: FKL vs Full Matrix Element



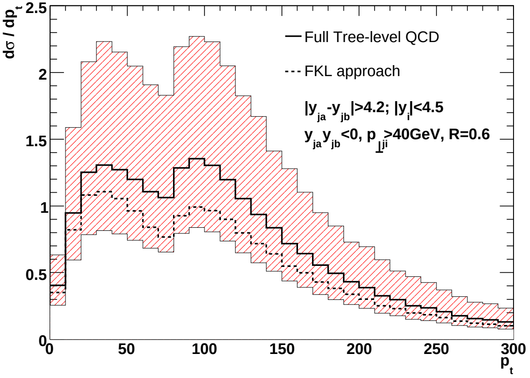
Fixed Order Comp^n: FKL vs Full Matrix Element

Transverse momentum of jets in hjj



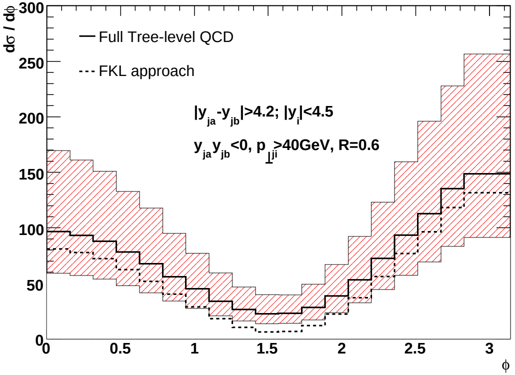
Fixed Order Comp^n: FKL vs Full Matrix Element

Transverse momentum of Higgs Boson in hjj



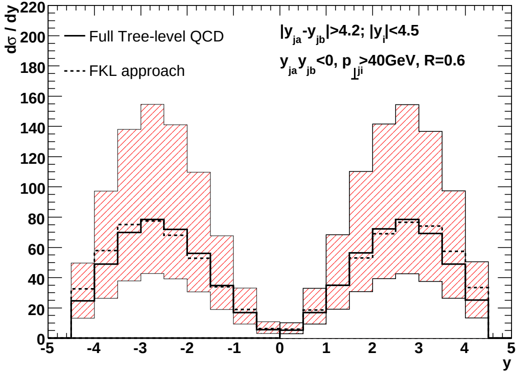
Fixed Order Comp^n: FKL vs Full Matrix Element

Azimuthal angle between jets in hjj



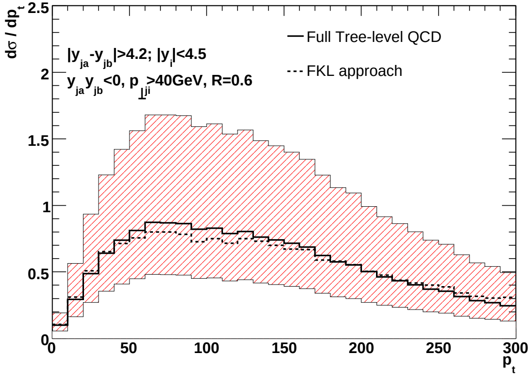
Fixed Order Comp^n: FKL vs Full Matrix Element

Rapidities of forward/backward jet in hjjj



Fixed Order Comp^n: FKL vs Full Matrix Element

Transverse momentum of Higgs Boson in hjjj



Beyond validation. . .

Have so far demonstrated that the terms we can take into account reproduce the full tree level results to within $10 - 25\%$ where ever these are known - and reproduce distributions.

Can calculate this approximation for the tree-level Higgs Boson plus *n*-parton amplitude, and include also the corresponding virtual corrections. Can thereby form the inclusive *any*-parton sample (i.e. LO: only H+2 partons, NLO: H+2 and H+3 partons, . . .)

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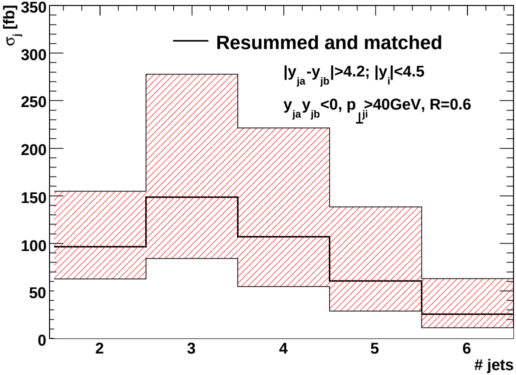
FKL All Order Resummation Incl. Matching

$$\sigma_{hjj}^{LO} : 230\text{fb}; \; \sigma_{hjj}^{\text{resummed+matched}} : 435\text{fb} \; (K = 1.9)$$



Can sum over *n*-parton inclusive samples (both real and virtual contributions included). Matching to the tree level *n*-parton matrix elements.

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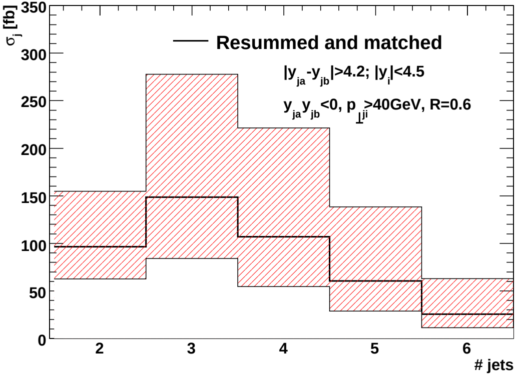

Significant jet activity - 10% – 20% increase in inclusive cross section compared to NLO

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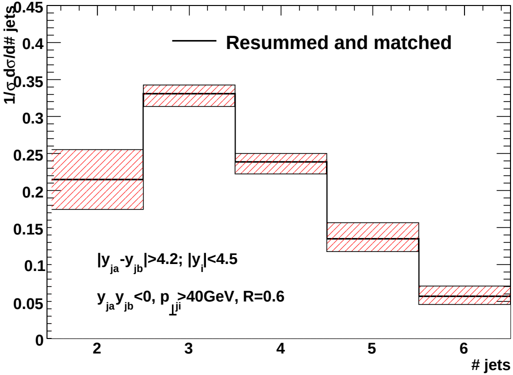
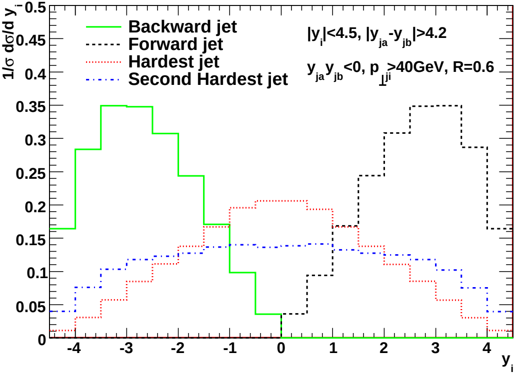


Significant jet activity - relative jet counts stable against scale variation

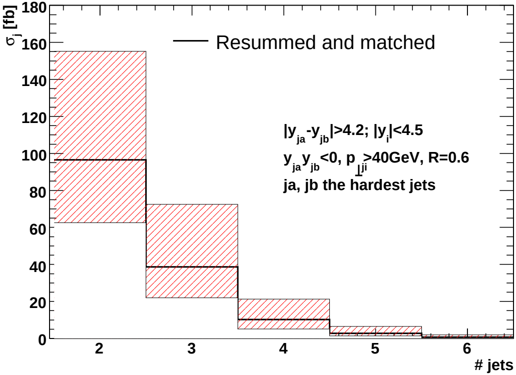
Rapidities of jets



Rapidities of forward/backward jet similar to LO distributions; hardest and next-to-hardest jets much more central (as expected)

FKL All Order Resummation Incl. Matching

σ_{hjj}^{LO} : 230fb; $\sigma_{hjj}^{\text{resummed+matched}}$: 149fb ($K = 0.65$)



Most events are rejected because of the central jet activity - cross section reduced compared to NLO value

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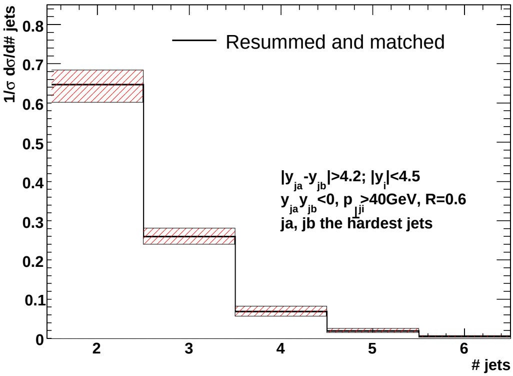

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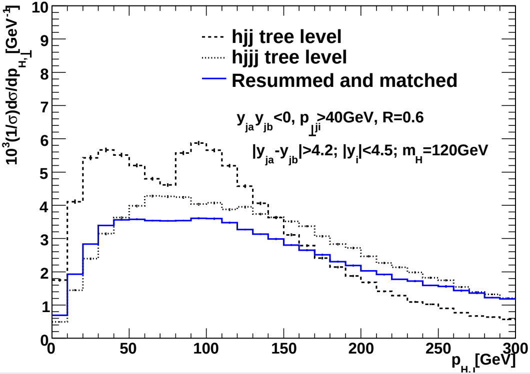
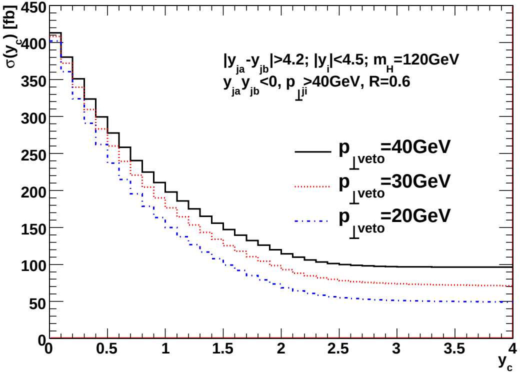
Transverse Momentum Spectrum of the Higs Boson



Strong features of Higgs boson transverse momentum spectrum (caused by strong azimuthal correlation coupled with cuts on jets) disappears at higher orders.

Central rapidity jet veto



$$\forall j \in \{\text{jets with } p_{j\perp} > p_{\perp,\text{veto}}\} \setminus \{a,b\} \ : \ \left| y_j - \frac{y_a + y_b}{2} \right| > y_c$$

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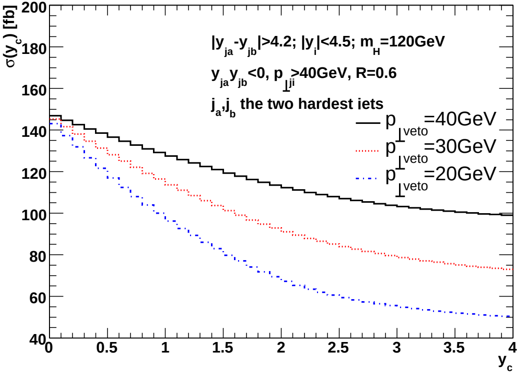

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Azimuthal decorrelation

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

Results from lowest order:
$A_\phi > 0$ (CP-even), $A_\phi \approx 0$ (CP-blind), $A_\phi < 0$ (CP-odd)

Inclusive cuts	A_ϕ	Hardest cuts	A_ϕ
LO 2-jet	0.456	LO 2-jet	0.456
Resummed, $=$ 2-jet	0.437	Resummed, $=$ 2-jet	0.436
LO 3-jet	0.203	LO 3-jet	0.374
Resummed	0.133	Resummed	0.372

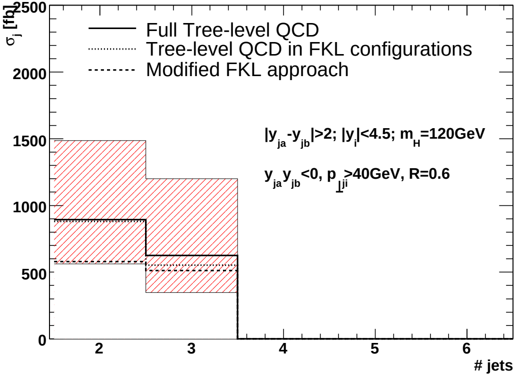
Significant azimuthal decorrelation from higher orders real radiation - most stable when hardest jets used for tagging (since multi-jet ecents in this case are practically vetoed)

Summary

Summary

- Emerging framework for the study of processes with multiple hard jets
- Working implementation, including matching to the known fixed order results; public code available: http://andersen.web.cern.ch/andersen/MJEV
- Impact many studies: jet correlations,. . .
- Les Houches Interface to study effects of showering

Relaxed Rapidity Cuts



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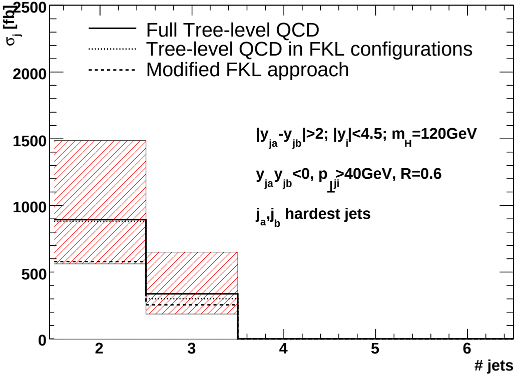

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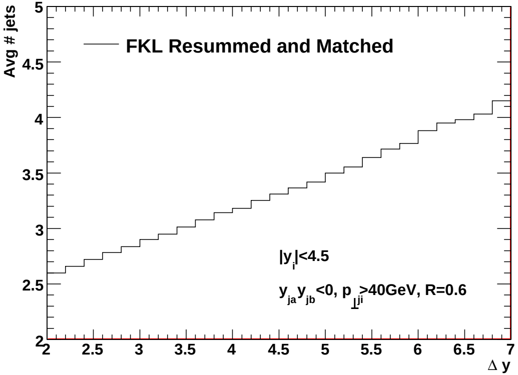

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