All-Order Multi-jet Predictions with **H**igh **E**nergy **J**ets

Jeppe R. Andersen
in collaboration with J.M. Smillie

HO10
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Overview

- We need (hard) perturbative at higher orders than at previous colliders in order to reliably describe the complicated final states
- Build framework (HEJ: High Energy Jets)
- Applications to H+jets, W+jets, pure jets

At colliders until now, **two separate** effects have ensured the suppression of hard radiative corrections:

1. increasing powers of the coupling
2. fast decrease of pdfs as the light-cone momentum fractions x are increased

$$\sigma_{ab\to 1\cdots N} = \int \prod_{i=1}^{N} \left(\frac{\mathrm{d}^2\mathbf{p}_{\perp i}\ \mathrm{d}y_i}{(2\pi)^3\ 2} \right) (2\pi)^4 \delta^2 \left(\sum_{i=1}^{N} \mathbf{p}_{\perp i} \right) \frac{1}{\hat{s}^2}$$
$$\times\, x_1 f_1(x_1, Q_1^2)\ x_2 f_2(x_2, Q_2^2)\ \left|\mathcal{M}_{ab\to 1\cdots N}\right|^2$$

$$x_1 = \frac{1}{\sqrt{s}} \sum_{1}^{N} p_{i\perp} \exp(y_i) \quad x_2 = \frac{1}{\sqrt{s}} \sum_{1}^{N} p_{i\perp} \exp(-y_i)$$

If/when two jets are created far apart in rapidity, then the phase space suppression for additional central jets is exponentially small

$$x_1 = \frac{1}{\sqrt{s}} \sum_1^N p_{i\perp} \exp(y_i) \quad x_2 = \frac{1}{\sqrt{s}} \sum_1^N p_{i\perp} \exp(-y_i)$$

This situation can arise as a result of

1. event selection cuts (H+dijets, decay of TeV-scale resonances)
2. naturally because of dominance by qg initial state (W/Z+3,4,...jets)

Why Hjj, The Problem, The Solution

Why study Higgs Boson production in Association with Dijets?

The distribution in the **azimuthal angle** between the **two** jets in *Hjj* allows for a **clean extraction** of CP properties

The Problem

... in a region of phase space where the **perturbative corrections are large**.

How do we deal with events with **three or more** jets?

The Solution

By constructing an azimuthal observable, which takes into account the **information from all the jets** of the event!

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Which Scalar?

Once/if a scalar is discovered, it is important to determine whether this is the **Higgs Boson** of the **Standard Model** (or something else).

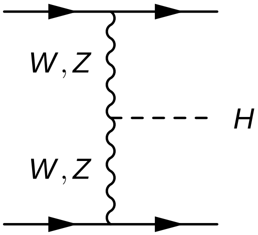
Measure the **strength** and **Lorentz structure** of the Higgs boson couplings:

1. **production mechanism** (independent of the Higgs decay channel)

or

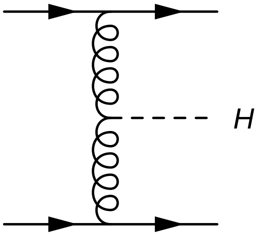
2. detailed study of the Higgs boson **decay products** (independent on the production mechanism)

Higgs Couplings through Azimuthal Correllations

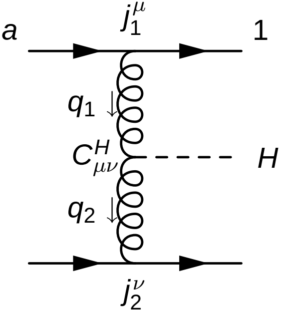


Considerations for Weak Boson Fusion

Higgs Couplings through Azimuthal Correllations



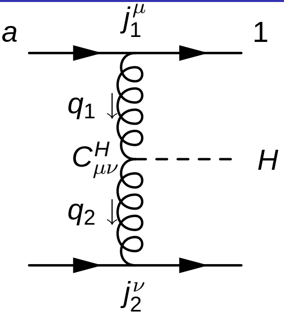
. . . and gluon fusion (Higgs coupling to gluons through top loop)



$$\mathcal{M} \propto \frac{j_1^\mu\, C^H_{\mu\nu}\, j_2^\nu}{t_1\, t_2}, \qquad j_1^\mu = \overline{\psi}_1 \gamma^\mu \psi_a$$

$$C_H^{\mu\nu} = a_2\, (q_1 q_2 g^{\mu\nu} - q_1^\nu q_2^\mu) + a_3\, \varepsilon^{\mu\nu\rho\sigma}\, q_{1\rho}\, q_{2\sigma}.$$

Higgs Couplings through Azimuthal Correllations



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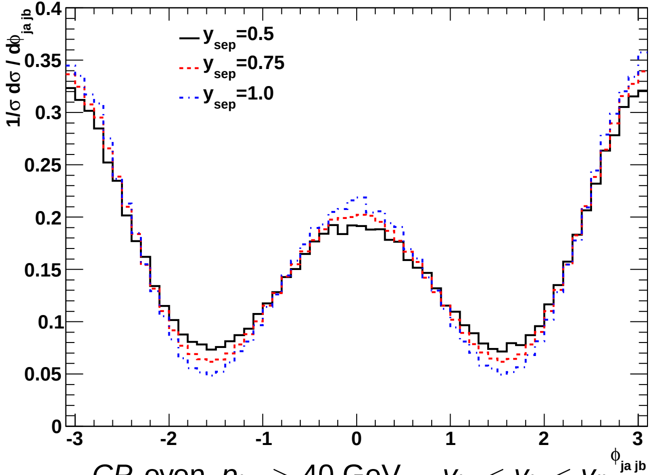
Take e.g. the term $\varepsilon^{\mu\nu\rho\sigma} \, q_{1\rho} \, q_{2\sigma}$: for $|p_{1,z}| \gg |p_{1,x,y}|$ and for small energy loss (i.e. $p_{a,e} \sim p_{1,e}$):

$$\left[j_1^0 \, j_2^3 - j_1^3 \, j_2^0 \right] (\mathbf{q}_{1\perp} \times \mathbf{q}_{2\perp}) \, .$$

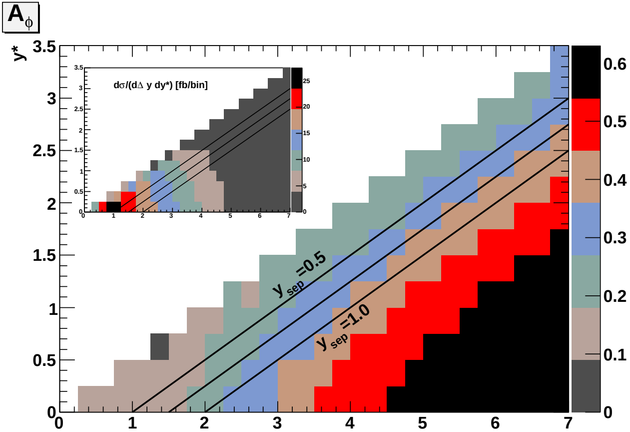
In this limit, the azimuthal dependence of the propagators is also suppressed: $|\mathcal{M}|^2$:sin$^2(\phi)$ **(CP-odd)**, cos$^2(\phi)$ **(CP-even)**.

Azimuthal distribution



CP-even, $p_{j\perp} > 40$ GeV, $\quad y_{ja} < y_h < y_{jb}$,
$|y_{j_a,j_b}| < 4.5, \min\left(|y_h - y_{j_a}|, |y_h - y_{j_b}|\right) > y_{\mathrm{sep}}$.

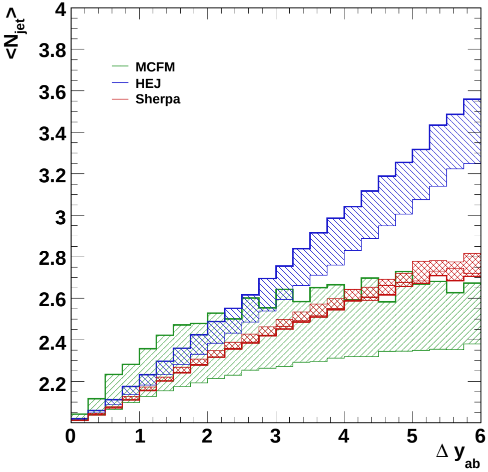
Signature and Cross Section



$$\Delta y = |y_{j_a} - y_{j_b}|, \quad y^* = y_h - \frac{y_{j_a}+y_{j_b}}{2}.$$

Rapidity separation between the jets and the Higgs Boson **enhance the azimuthal correlation**.

Increasing Rapidity Span → Increasing Number of Jets



All models show a clear increase in the number of hard jets as the rapidity span increases.

How to extract the *CP*-structure of the Higgs boson coupling from events with **three or more** jets?

2 hardest jets?

J.R. Andersen, J. Campbell, S. Höche, arXiv:1003.

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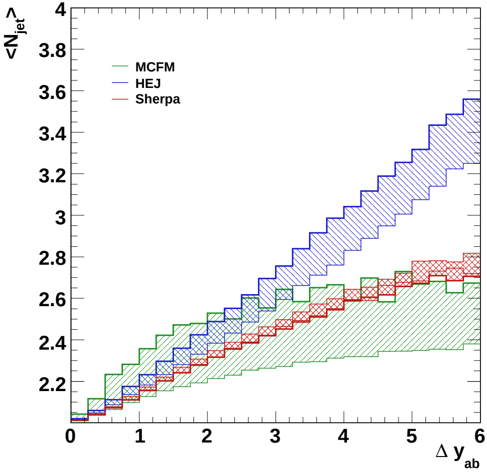

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2 hard jets furthest apart in rapidity?

J.R. Andersen, J. Campbell, S. Höche, arXiv:1003.

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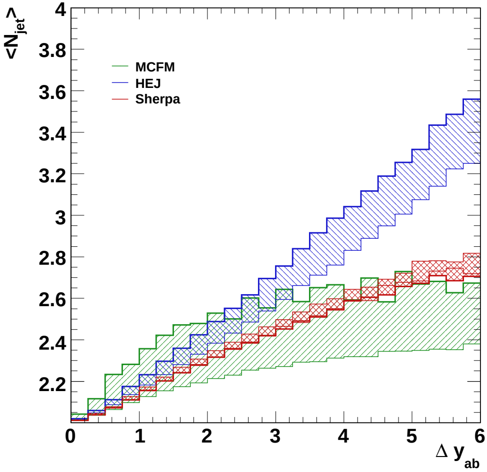

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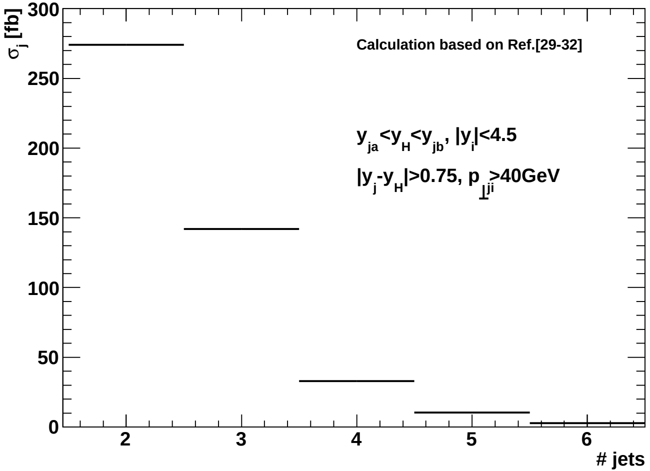
Significant washing out of the azimuthal correlation observed at tree-level *hjj*

J.R. Andersen, J. Campbell, S. Höche, arXiv:1003.

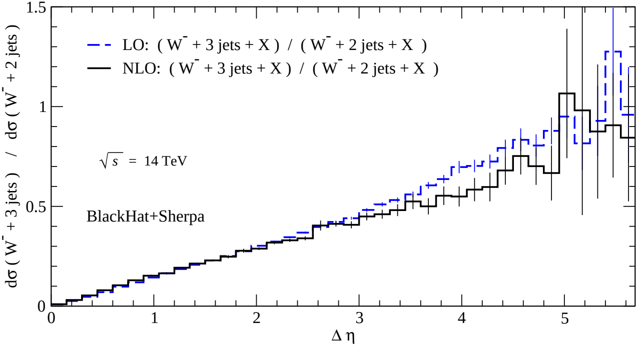
Many Jets!



Calculation based on all-order approximant to the *n*-particle matrix element, which reproduces the exact result in the limit of large invariant mass between all particles.

JRA&C.D. White, JRA&J.M. Smillie

W+Multiple Jets @ NLO

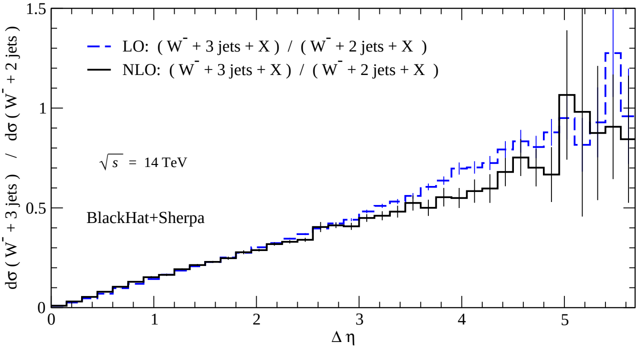


BlackHat, arXiv:0912.4927

The inclusive 3-jet rate is large compared to the inclusive 2-jet rate, even for normal rapidity spans obviously, the inclusive 3-jet rate “ought to” be smaller than the inclusive 2-jet rate.

The large contribution from real radiative corrections to W+dijets is not revealed by the inclusive K-factor (actually less than one)

W+Multiple Jets @ NLO



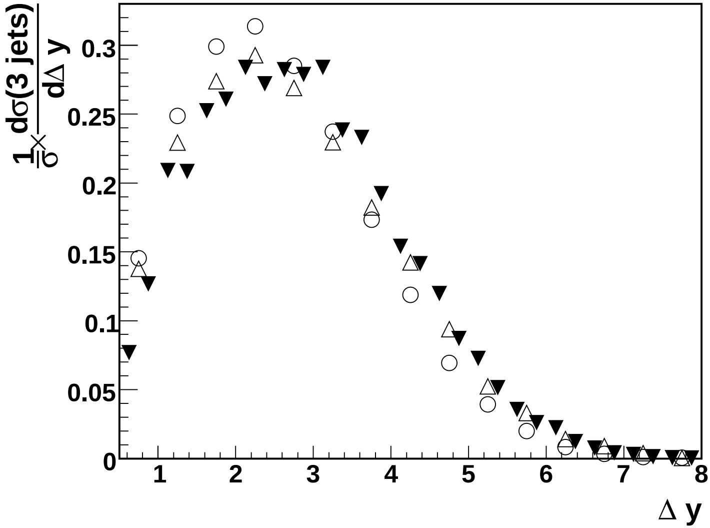
BlackHat, arXiv:0912.4927

All calculational methods and processes will agree on the opening of phase space as Δy increases

The mechanism for emission **differ** between processes (WBF vs. GF) and calculational methods (full NLO, shower, . . .). Can be **tested against data!**

$1/\sigma\ d\sigma/d\Delta y$

JRA, M. Campanelli, J. Campbell, V. Ciulli, J. Huston, P. Lenzi, R. Mackeprang, arXiv:1003.1241



$\Delta y \approx 2 - 3$ (where σ_{3j}/σ_{2j} is already very large) is not “tail of distribution”!

HEJ (High Energy Jets)

Goal (inspired by the great Fadin & Lipatov)

Sufficiently **simple** model for hard radiative corrections that the all-order sum can be evaluated explicitly (completely exclusive)

but. . .

Sufficiently **accurate** that the description is relevant

Resummation and Matching

Consider the **perturbative expansion** of an observable

$$R = r_0 + r_1\alpha_s + r_2\alpha^2 + r_3\alpha^3 + r_4\alpha^4 + \cdots$$

Fixed order pert. QCD will calculate a fixed number of terms in this expansion. r_n may contain **logarithms** so that $\boldsymbol{\alpha_s}$ **ln($\cdots$)** is large.

$$\begin{aligned} R &= r_0 + \left(r_1^{LL}\ln(\cdots) + r_1^{NLL}\right)\alpha_s + \left(r_2^{LL}\ln^2(\cdots) + r_2^{NLL}\ln(\cdots) + r_2^{SL}\right)\alpha_s^2 + \cdots \\ &= r_0 + \sum_n r_n^{LL}(\alpha_s\ln(\cdots))^n + \sum_n r_n^{NLL}\alpha_s(\alpha_s\ln(\cdots))^n + \text{sub-leading terms} \end{aligned}$$

Need simplifying assumptions to get to all orders - useful **iff** the terms really do describe **the dominant part** of the **full pert. series**. **Matching** combines **best of both worlds**:

$$R = r_0 + r_1\alpha_s + r_2\alpha^2 + \left(r_3^{LL}\ln^3(\cdots) + r_3^{NLL}\ln^2(\cdots) + r_3^{SL}\right)\alpha^3 + \cdots$$

Factorisation of QCD Matrix Elements

It is **well known** that QCD matrix elements **factorise** in certain kinematical limits:
Collinear limit enters all parton shower (and much else) resummation.

Like all good limits, this 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**

Factorisation only **becomes exact** in a region **outside** the reach of any collider. . .

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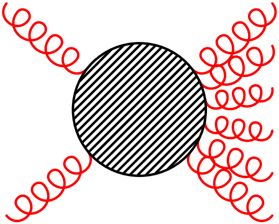
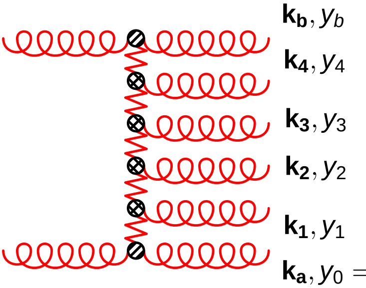
The Possibility for Predictions of n-jet Rates

The Power of Reggeisation



High Energy Limit

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



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

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

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.

Comparison of 3-jet scattering amplitudes

Universal behaviour of scattering amplitudes in the HE limit:

$$\forall i \in \{2,\ldots,n-1\} : y_{i-1} \gg y_i \gg y_{i+1}$$
$$\forall i,j : |p_{i\perp}| \approx |p_{j\perp}|$$

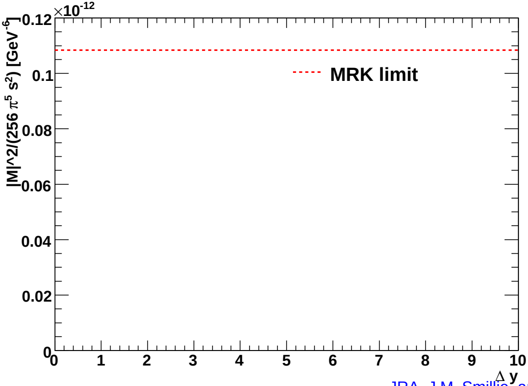
$$\left|\overline{\mathcal{M}}^{MRK}_{gg\to g\cdots g}\right|^2 = \frac{4\,s^2}{N_C^2-1}\,\frac{g^2\,C_A}{|p_{1\perp}|^2}\left(\prod_{i=2}^{n-1}\frac{4\,g^2 C_A}{|p_{i\perp}|^2}\right)\frac{g^2\,C_A}{|p_{n\perp}|^2}.$$
$$\left|\overline{\mathcal{M}}^{MRK}_{qg\to qg\cdots g}\right|^2 = \frac{4\,s^2}{N_C^2-1}\,\frac{g^2\,C_F}{|p_{1\perp}|^2}\left(\prod_{i=2}^{n-1}\frac{4\,g^2 C_A}{|p_{i\perp}|^2}\right)\frac{g^2\,C_A}{|p_{n\perp}|^2},$$
$$\left|\overline{\mathcal{M}}^{MRK}_{qQ\to qg\cdots Q}\right|^2 = \frac{4\,s^2}{N_C^2-1}\,\frac{g^2\,C_F}{|p_{1\perp}|^2}\left(\prod_{i=2}^{n-1}\frac{4\,g^2 C_A}{|p_{i\perp}|^2}\right)\frac{g^2\,C_F}{|p_{n\perp}|^2},$$

Allow for analytic resummation (BFKL equation).
However, how well does this actually approximate the amplitude?

Comparison of 3-jet scattering amplitudes

Study just a slice in phase space:

40GeV jets in Mercedes star (transverse) configuration. Rapidities at $-\Delta y, 0, \Delta y$.



JRA, J.M. Smillie, arXiv:0908.2786

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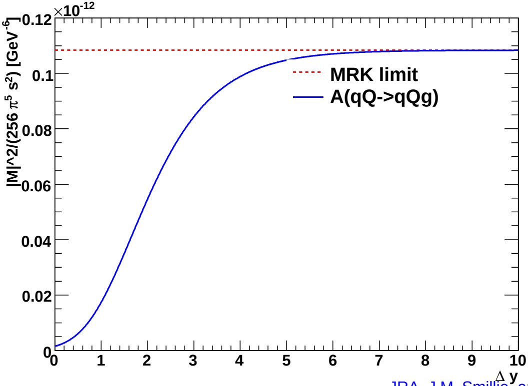

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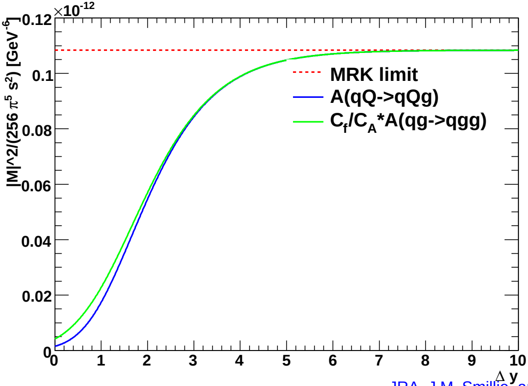

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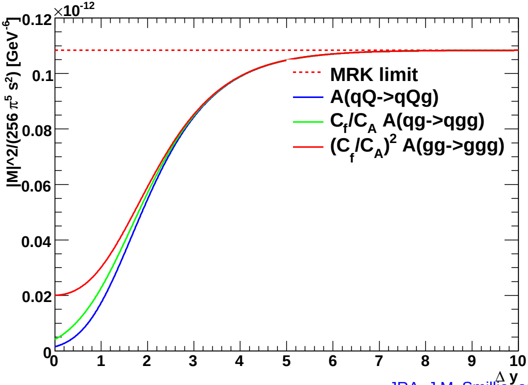

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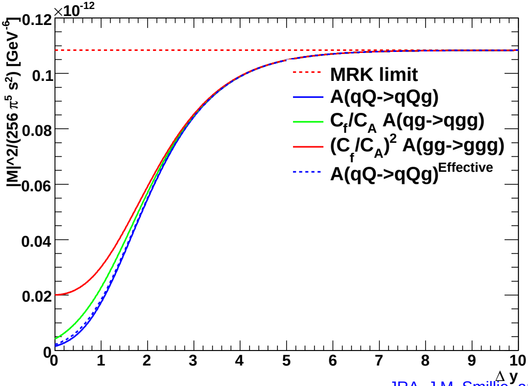


JRA, J.M. Smillie, arXiv:0908.2786

1) Inspiration from Fadin&Lipatov: dominance by t-channel
2) No kinematic approximations in the position of these poles (denominator)
3) Accurate definition of currents (coupling through t-channel exchange)
4) Gauge invariance. Not just asymptotically.

Scattering of qQ-Helicity States

Start by describing quark scattering. Simple matrix element for $q(a)Q(b) \to q(1)Q(2)$:

$$M_{q^-Q^-\to q^-Q^-} = \langle 1|\mu|a\rangle \frac{g^{\mu\nu}}{t} \langle 2|\nu|b\rangle$$

t-**channel factorised**: Contraction of (local) currents across t-channel pole

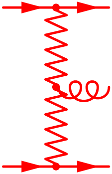
$$\left|\overline{\mathcal{M}}^t_{qQ\to qQ}\right|^2 = \frac{1}{4\,(N_C^2-1)}\ \left\|S_{qQ\to qQ}\right\|^2 \cdot \left(g^2\ C_F\ \frac{1}{t_1}\right) \cdot \left(g^2\ C_F\ \frac{1}{t_2}\right).$$

Extend to $2 \to n \ldots$

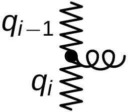
J.M.Smillie and JRA: arXiv:0908.2786

Building Blocks for an Amplitude

Identification of the **dominant contributions** to the **perturbative series** in the limit of well-separated particles

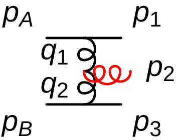


$$\frac{1}{q^2}\exp\left(\hat{\alpha}(q)\Delta y\right)$$

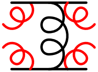


$$V^\mu(q_{i-1},q_i)$$

$$j^\nu = \overline{\psi}\gamma^\nu\psi$$



$$\begin{aligned} V^\rho(q_1,q_2) = &- (q_1+q_2)^\rho \\ &+ \frac{p_A^\rho}{2}\left(\frac{q_1^2}{p_2\cdot p_A} + \frac{p_2\cdot p_B}{p_A\cdot p_B} + \frac{p_2\cdot p_n}{p_A\cdot p_n}\right) + p_A \leftrightarrow p_1 \\ &- \frac{p_B^\rho}{2}\left(\frac{q_2^2}{p_2\cdot p_B} + \frac{p_2\cdot p_A}{p_B\cdot p_A} + \frac{p_2\cdot p_1}{p_A\cdot p_1}\right) - p_B \leftrightarrow p_3. \end{aligned}$$

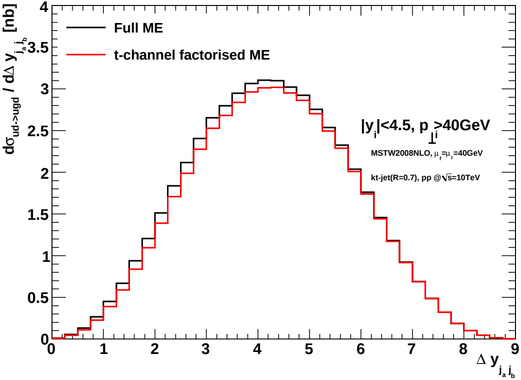


Building Blocks for an Amplitude

$p_g \cdot V = 0$ can easily be checked (gauge invariance)
The approximation for $qQ \to qgQ$ is given by

$$
\begin{aligned}
\left|\overline{\mathcal{M}}^{t}_{qQ\to qgQ}\right|^2 = &\frac{1}{4\,(N_C^2-1)}\ \left\|S_{qQ\to qQ}\right\|^2 \\
&\cdot\ \left(g^2\ C_F\ \frac{1}{t_1}\right)\cdot\ \left(g^2\ C_F\ \frac{1}{t_2}\right) \\
&\cdot\left(\frac{-g^2 C_A}{t_1 t_2}\ V^{\mu}(q_1,q_2)V_{\mu}(q_1,q_2)\right).
\end{aligned}
$$

3 Jets @ 10 TeV



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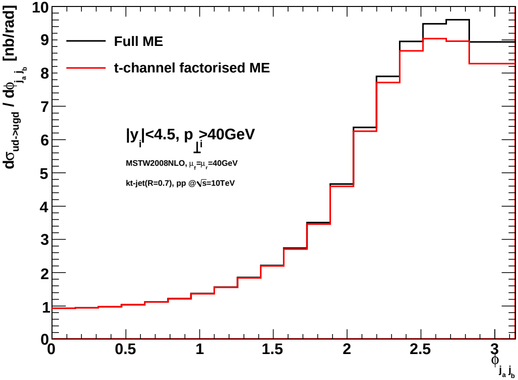

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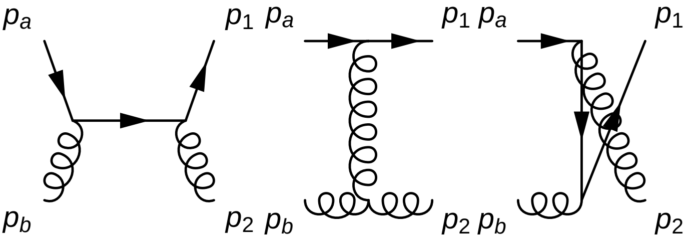
Quark-Gluon Scattering

“What happens in $2 \to 2$-processes with gluons? Surely the t-channel factorisation is spoiled!”



Direct calculation ($q^- g^- \to q^- g^-$):

$$M = \frac{g^2}{\hat{t}} \times \frac{p_{2\perp}^*}{|p_{2\perp}|} \left(t^2_{ae} t^b_{e1} \sqrt{\frac{p_b^-}{p_2^-}} - t^b_{ae} t^2_{e1} \sqrt{\frac{p_2^-}{p_b^-}} \right) \langle b|\sigma|2\rangle \ \times \langle 1|\sigma|a\rangle.$$

Complete t-channel factorisation!

J.M.Smillie and JRA

Quark-Gluon Scattering

For the helicity choices where a qQ-channel exists, the t-channel current generated by a gluon in qg scattering is that of a quark, but with a colour factor

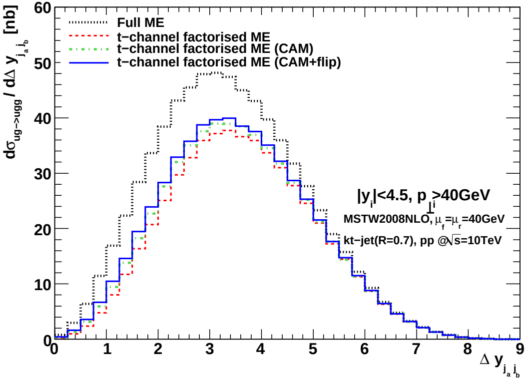
$$\frac{1}{2}\left(C_A - \frac{1}{C_A}\right)\left(\frac{p_b^-}{p_2^-} + \frac{p_2^-}{p_b^-}\right) + \frac{1}{C_A}$$

instead of C_F. Tends to C_A in MRK limit.

Similar results for e.g. $g^+g^- \to g^+g^-$. **Exact, complete** t-channel **factorisation**.

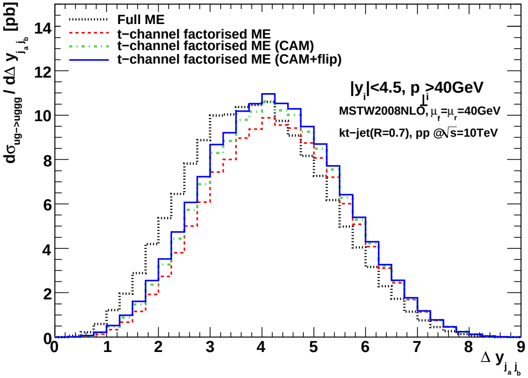
By using the formalism of **current-current scattering**, we get a better description of the t-channel pole than by using just the kinematic limit.

Quark-Gluon Scattering



J.M.Smillie and JRA

Quark-Gluon Scattering



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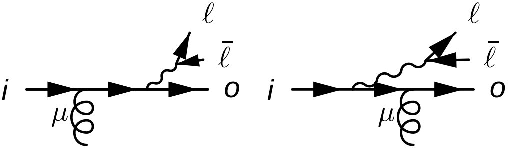
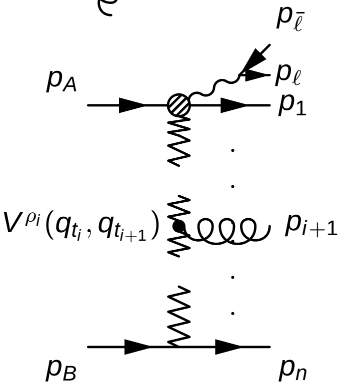
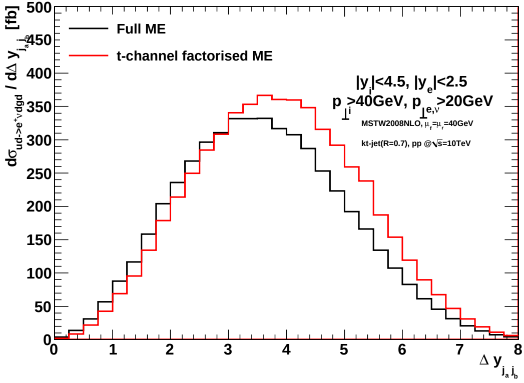
W+Jets

Two currents to calculate for $W + jets$:



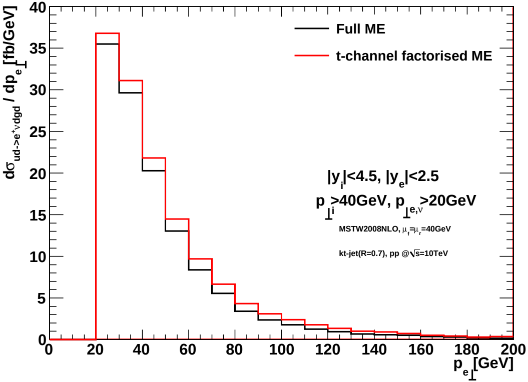


W+ 3 Jets @ LHC



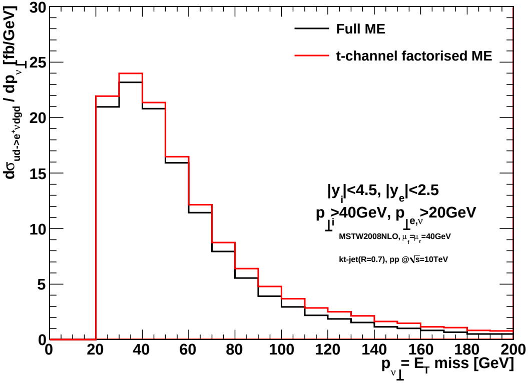
J.M.Smillie and JRA: arXiv:0908.2786

W+ 3 Jets @ LHC



J.M.Smillie and JRA: arXiv:0908.2786

W+ 3 Jets @ LHC



J.M.Smillie and JRA: arXiv:0908.2786

Performing the Explicit Resummation

Soft divergence from real radiation:

$$\left|\mathcal{M}_{\mathrm{HE}}^{p_a p_b \to p_0 p_1 p_h p_2}\right|^2 \xrightarrow{\mathbf{p}_1^2 \to 0} \left(\frac{4 g_s^2 C_A}{\mathbf{p}_1^2}\right) \left|\mathcal{M}_{\mathrm{HE}}^{p_a p_b \to p_0 p_h p_2}\right|^2$$

Integrate over the soft part $\mathbf{p}_i^2 < \lambda^2$ of phase space in $D = 4 + 2\varepsilon$ dimensions

$$\int_0^\lambda \frac{\mathrm{d}^{2+2\varepsilon}\mathbf{p}\ \mathrm{d}y_1}{(2\pi)^{2+2\varepsilon}\ 4\pi} \left(\frac{4 g_s^2 C_A}{\mathbf{p}^2}\right) \mu^{-2\varepsilon}$$
$$= \frac{4 g_s^2 C_A}{(2\pi)^{2+2\varepsilon} 4\pi} \Delta y_{0h} \frac{\pi^{1+\varepsilon}}{\Gamma(1+\varepsilon)} \frac{1}{\varepsilon} (\lambda^2/\mu^2)^\varepsilon$$

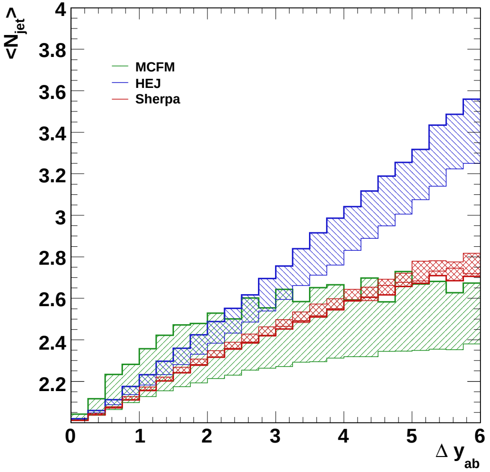
Pole in ε cancels with that from the virtual corrections

$$\hat{\alpha}(t) = -\frac{g_s^2 C_A \Gamma(1-\varepsilon)}{(4\pi)^{2+\varepsilon}} \frac{2}{\varepsilon} \left(\mathbf{q}^2/\mu^2\right)^\varepsilon .$$

All-Orders and Regularisation

- Have prescription for $2 \to n$ matrix element, including virtual corrections: Lipatov Ansatz $1/t \to 1/t \exp(-\omega(t)\Delta y_{ij})$
- Organisation of cancellation of IR (soft) divergences is easy
- Can calculate the sum over the n-particle phase space explicitly ($n \sim 30$) to get the all-order corrections (just as if one had provided all the $N^{30}LO$ matrix elements and a regularisation procedure)
- **Match** to n-jet tree-level where known

J.M. Smillie, JRA arXiv:0908.2786, arXiv: 0910:5113

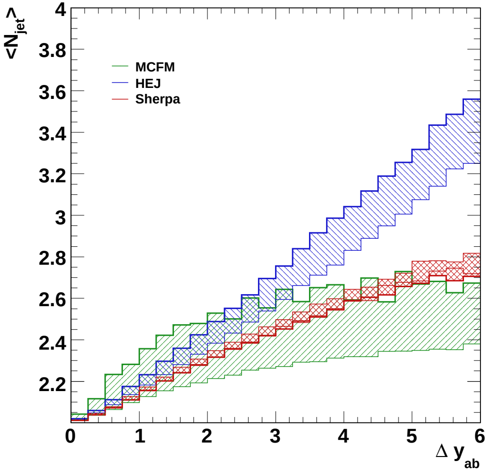


All models show a clear increase in the number of hard jets as the rapidity span increases.

How to extract the *CP*-structure of the Higgs boson coupling from events with **three or more** jets?

2 hardest jets?

J.R. Andersen, J. Campbell, S. Höche, arXiv:1003.



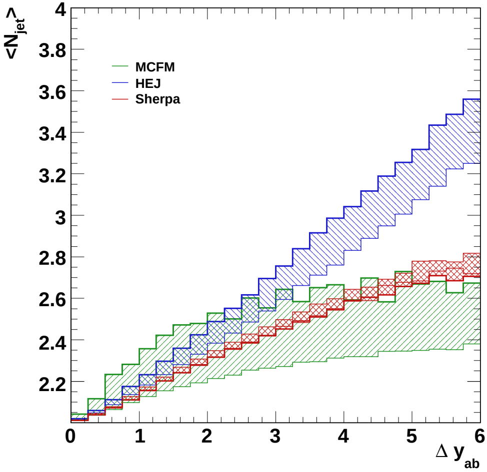
All models show a clear increase in the number of hard jets as the rapidity span increases.

How to extract the *CP*-structure of the Higgs boson coupling from events with **three or more** jets?

2 hard jets furthest apart in rapidity?

J.R. Andersen, J. Campbell, S. Höche, arXiv:1003.

Increasing Rapidity Span → Increasing Number of Jets



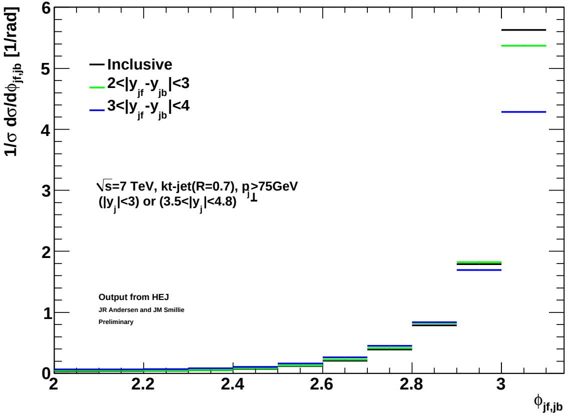
All models show a clear increase in the number of hard jets as the rapidity span increases.

How to extract the *CP*-structure of the Higgs boson coupling from events with **three or more** jets?

Significant washing out of the azimuthal correlation observed at tree-level *hjj*

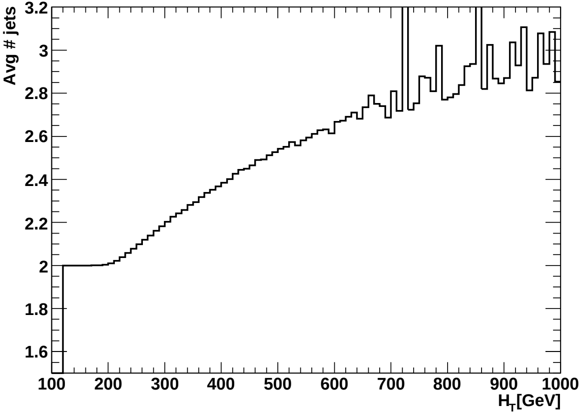
J.R. Andersen, J. Campbell, S. Höche, arXiv:1003.

Azimuthal correlations in dijets



Evolution should be measurable with dijets already in this years data

Dominance of Multi-Jets in Tails Too. W+dijets



Hard, radiate corrections are important for the description of the tails also in e.g. H_t.

Outlook and Conclusions

Conclusions

- Emerging framework for the study of processes with multiple hard jets
- For each number of particles n, the approximation to the matrix element (real and virtual) is sufficiently simple to allow for the all-order summation to be constructed as an explicit sum over n-particle final states (exclusive studies possible)
- Resummation based on approximation which really does capture the behaviour of the scattering processes at the LHC
- Matching will correct the approximation where the full matrix element can be evaluated