Hard Jets and Higgs Bosons

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NExT PhD Workshop

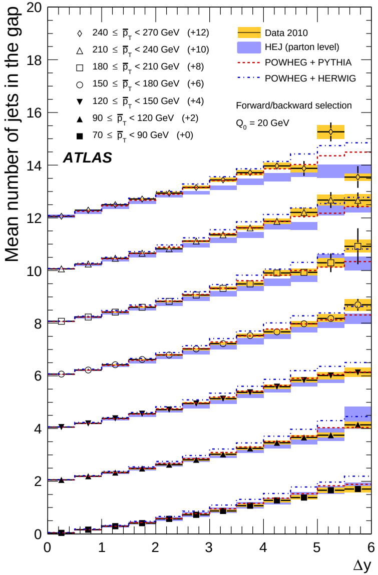
The Interesting Challenge of the Weak Boson Fusion

Two drivers for multi-jet production:

- large ratio of transverse scales (shower resummation)
- Colour exchange over a range in rapidity

The description of the gluon fusion contribution to *hjj* for large rapidity/invariant mass separated jets is very challenging.
The challenges can be studied first for other processes (dijets, W+dijets,...) to verify the quality of the theoretical description there, before applying it to H+dijets.

ATLAS: Study of Further Jet Activity in Dijet Events



CERN-PH-EP-2011-100

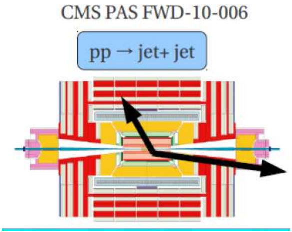
Note the two “drivers” of jet production were **not** cleanly separated. (cut on $\bar{p}_t$ induces large p_t-hierarchy on forward/backward jet, besides the hierarchy between large $\bar{p}_t$ and Q_0, the general jet scale)

HEJ slightly undershoots the jet activity when large ratios of transverse scales are imposed (shower region).

Very good agreement in the most important regions of phase space

Obviously **beyond** NLO (more than one extra jet **on average** at $\Delta y \geq 3$!)

CMS: Simultaneous prod. of central and forward jet

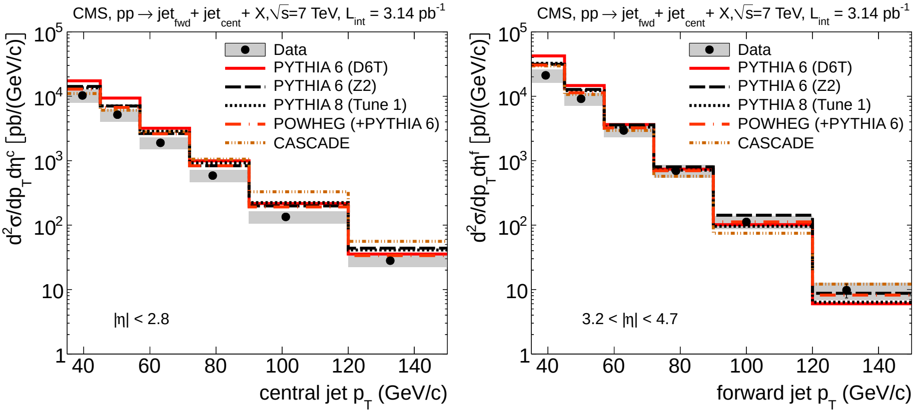


Jets: anti-kt, R=.5, $p_t > 35$GeV

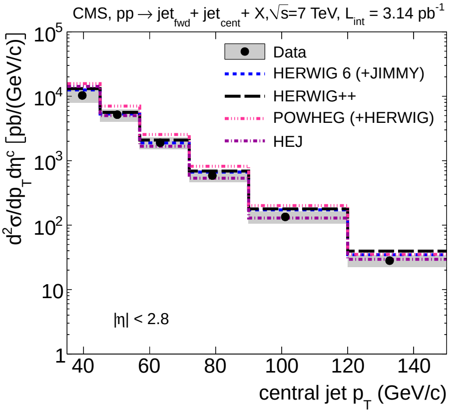
$$\begin{aligned} \text{central} &: |\eta| < 2.8 \\ \text{forward} &: 3.2 < |\eta| < 4.7 \end{aligned}$$

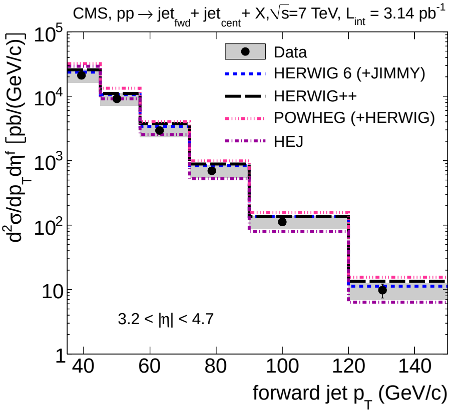
(not particularly large rapidity spans, typically 1 unit).
Measure the p_t-spectrum of the central and the forward jet. Any difference is obviously due to additional radiation.

Comparison to Theory, I



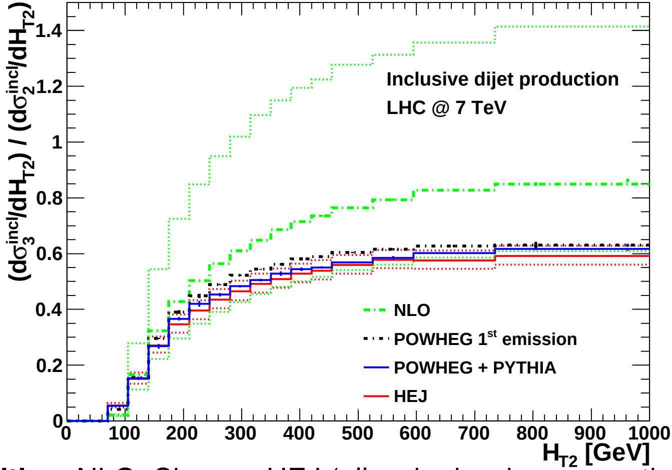
Comparison to Theory, II





Predictions for ratio of Inclusive Jet Rates vs. H_{T2}

S. Alioli, E. Re, J.M. Smillie, C. Oleari, JRA; arXiv:1202.1475

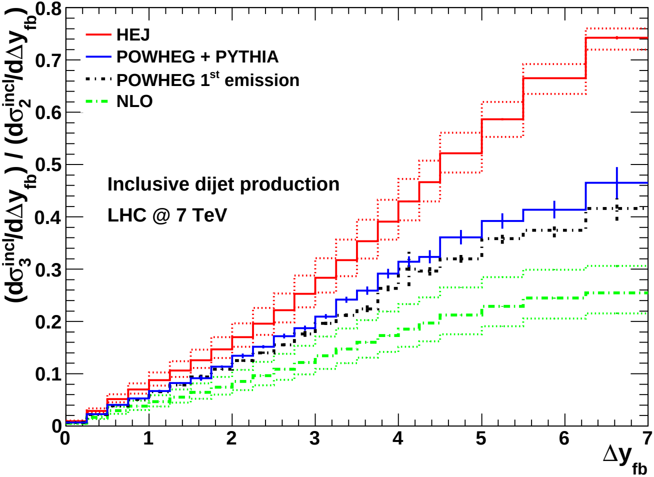


Similarities: NLO+Shower, HEJ (all-order hard resummation)

Difference: NLO

Ratio of Inclusive Jet Rates vs. Rapidity

S. Alioli, E. Re, J.M. Smillie, C. Oleari, JRA; arXiv:1202.1475



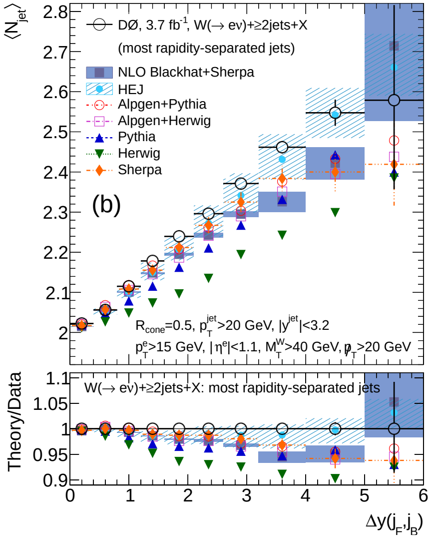
Clear differences: NLO, POWHEG, HEJ

Summary of dijet study

Simple set of cuts, combined with a **exclusive dijet-analyses** can discriminate clearly between the **mechanisms of perturbative corrections** implemented in NLO, POWHEG (NLO+Shower) and High Energy Jets.

D0: W+Jets arXiv:1302.6508

D0 measurement of the average number of jets when requiring just a W in association with two jets. Pure test of the rapidity or large m_{jj}-driver of emissions (no large p_t-hierarchy imposed).



CP Properties of Higgs-Boson Couplings from Hjj through Gluon Fusion

Stabilising the Extraction against Higher Order Corrections

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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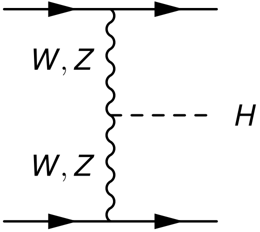
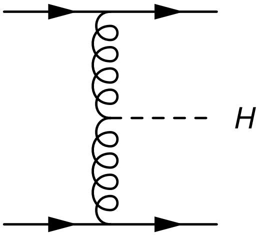
Higgs Couplings through Azimuthal Correllations



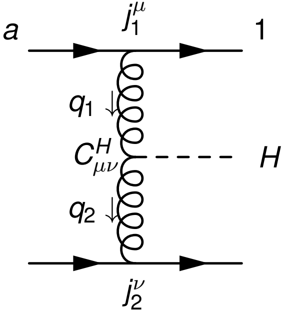
Considerations for Weak Boson Fusion

Higgs Couplings through Azimuthal Correllations



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

Higgs Couplings through Azimuthal Correllations



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

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

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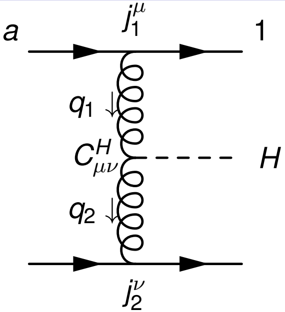

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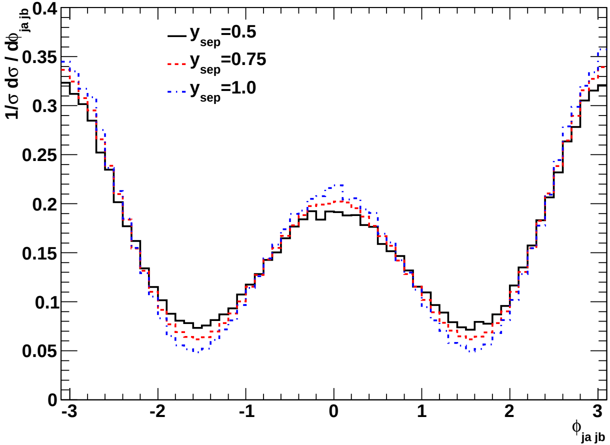
Take e.g. the term $\varepsilon^{\mu\nu\rho\sigma} \; q_{1\rho} \; q_{2\sigma}$: for $|p_{1,z}| \gg |p_{1,x,y}|$ and for small energy loss (i.e. $p_{a,e} \sim p_{1,e}$):

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

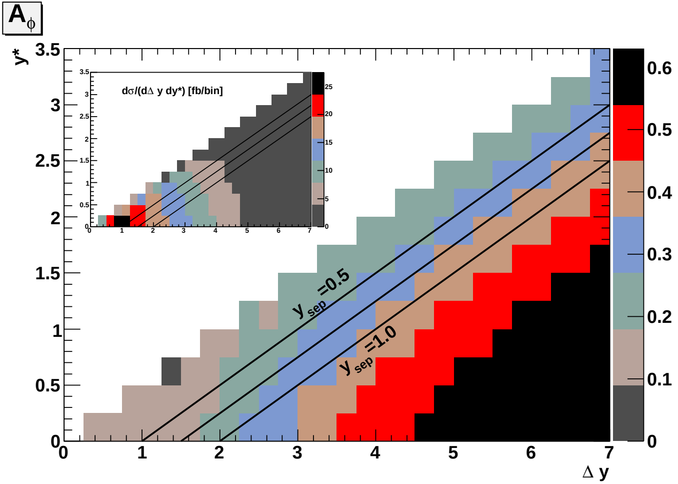
In this limit, the azimuthal dependence of the propagators is also suppressed: $|\mathcal{M}|^2$:$\sin^2(\phi)$ **(CP-odd)**, $\cos^2(\phi)$ **(CP-even)**.

Azimuthal distribution



JRA, K. Arnold, D. Zeppenfeld (JHEP 1006 (2010) 091)

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

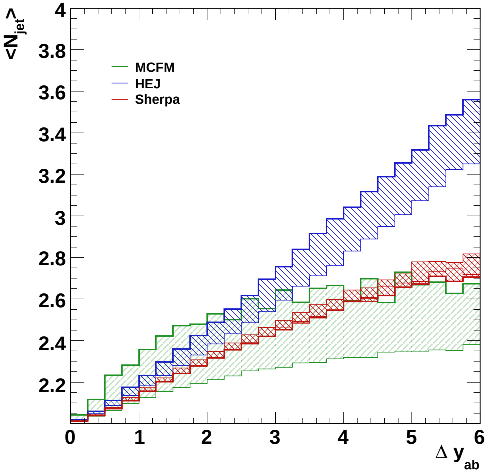


$$\Delta y = |y_{j_a} - y_{j_b}|, \quad y^* = y_h - \frac{y_{j_a}+y_{j_b}}{2}.$$

JRA, K. Arnold, D. Zeppenfeld

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

Increasing Rapidity Span → Increasing Number of Jets



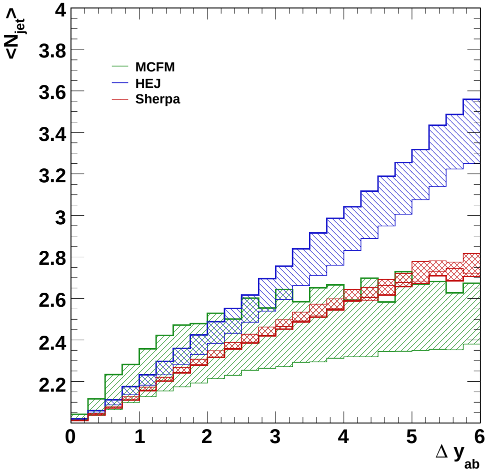
J.R. Andersen, J. Campbell, S. Höche, arXiv:1003.1241

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?

Increasing Rapidity Span → Increasing Number of Jets



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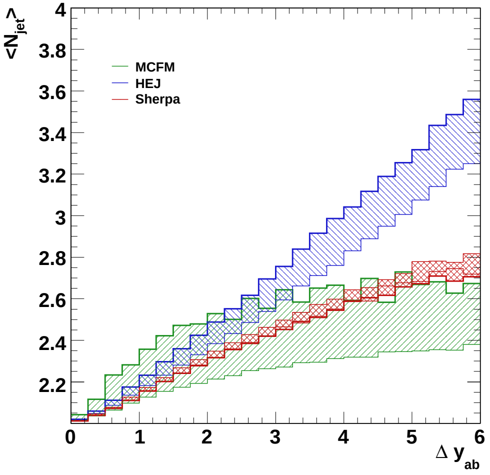
2 hard jets furthest apart in rapidity?

J.R. Andersen, J. Campbell, S. Höche, arXiv:1003.1241



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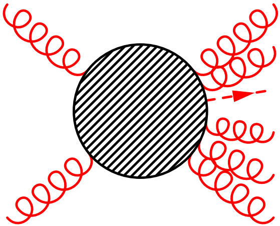
Significant washing out of the azimuthal correlation observed at tree-level *hjj*

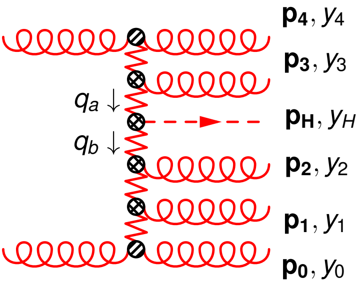
J.R. Andersen, J. Campbell, S. Höche, arXiv:1003.1241

Develop Insight Into the Perturbative Corrections



High Energy Limit $\longrightarrow$

$|p_{\perp,i}|$ fixed, $\hat{s}_{ij} \to \infty$

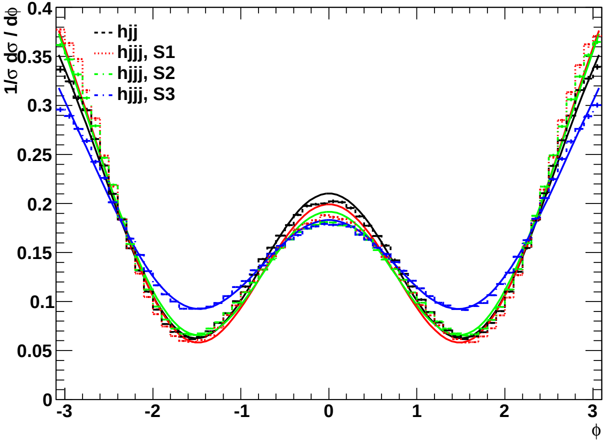


$$\left|\mathcal{M}_{gg\to g\cdots ghg\cdots g}\right|^2 \to \frac{4\hat{s}^2}{N_C^2-1}\left(\prod_{i=1}^{j}\frac{C_A\, g_s^2}{\mathbf{p}_{i\perp}^2}\right)\frac{|C^H(\mathbf{q}_{a\perp},\mathbf{q}_{b\perp})|^2}{\mathbf{q}_{a\perp}^2\ \mathbf{q}_{b\perp}^2}\left(\prod_{i=j+1}^{n}\frac{C_A\, g_s^2}{\mathbf{p}_{i\perp}^2}\right)$$

$$C^H(\mathbf{q}_{a\perp},\mathbf{q}_{b\perp}) = -i\,\frac{\alpha_s}{3\pi v}\,\mathbf{q}_{a\perp}\cdot\mathbf{q}_{b\perp}, \quad y_0 < \cdots < y_j < y_H < y_{j+1} < y_n$$

The **High Energy Limit** tells us to investigate the **azimuthal angle** between the **sum of the jet vectors** either side in rapidity of the Higgs Boson!

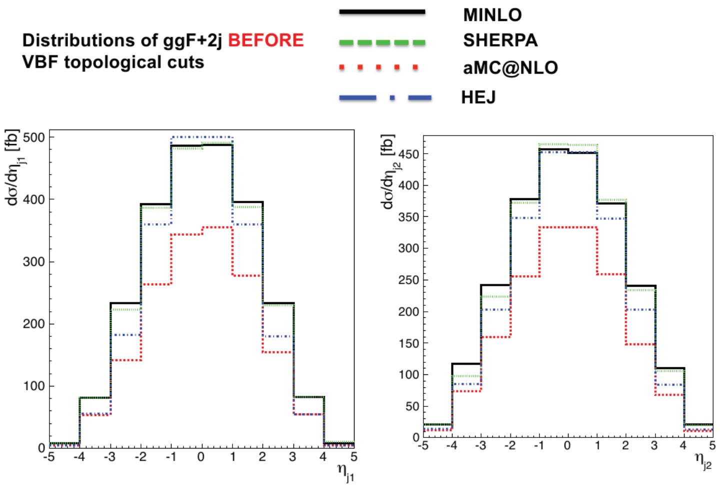
And It Even Works!



JRA, K. Arnold, D. Zeppenfeld, arXiv:1001.3822

Three subsamples of tree-level three-jet events: two jets on same side of the Higgs boson parallel (S1), perpendicular (S2) or anti-parallel (S3). Azimuthal correlation almost unchanged from hjj.

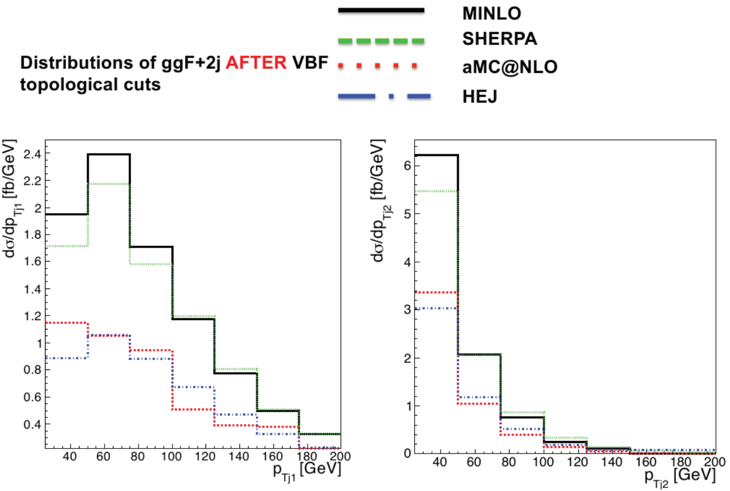
Comparison of Predictions



MINLO, Sherpa & HEJ all agree at central jet rapidities; aMC@NLO 25-30% lower

Comparison of Predictions

Distributions of ggF+2j AFTER VBF topological cuts



factor 2 difference between aMC@NLO and Sherpa/MINLO, smaller differences between MINLO, Sherpa

recall Sherpa is H+2@LO, aMC@NLO & MINLO are H+2@NLO

Conclusions

- The LHC probes hard (=jets) perturbative corrections beyond pure NLO
  …already at 7TeV!
- ***High Energy Jets**** provides a new approach to the perturbative description of LHC physics
  …and compares favourably to data in several analyses
  …already in its present, first iteration (several improvements foreseen in the theoretical description)

* http://cern.ch/hej