QCD at High Energies

Challenges and Opportunities

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QCD at the Highest Energies - Outline

Why QCD at the highest energies is (highly) non-trivial

…despite $\alpha_s(Q^2) \to 0$ for $Q^2 \to \infty$

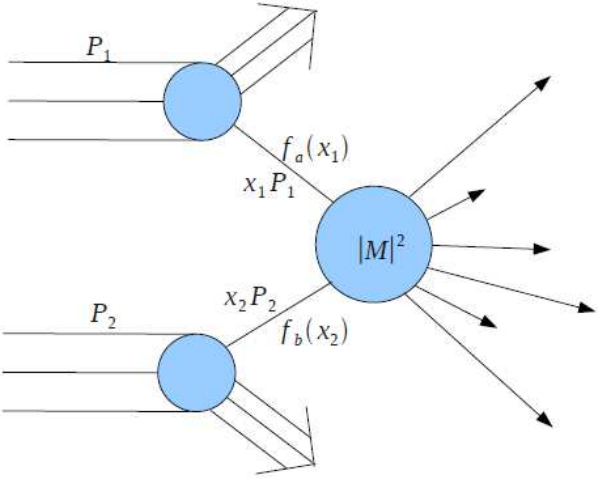
Special Opportunities at High Energy

The necessity of overcoming difficulties:
Measurements of the characteristics of the Higgs Boson couplings

The Perturbative Description

Elements of the Perturbative Picture:

- Proton collision at energy $\sqrt{S}$
- **Perturbative** collision of two partons
- The hard scattering matrix element $|\mathcal{M}|^2$ is calculated as a **series** in α_s.

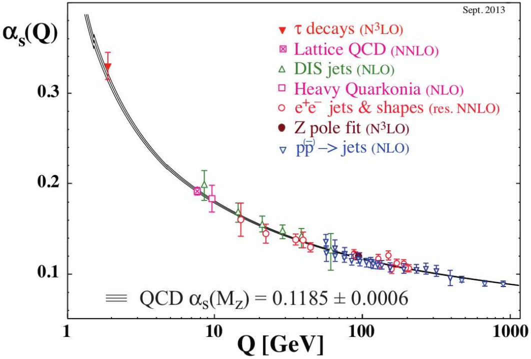


Running of α_s

The QCD coupling decreases as the scale increases.

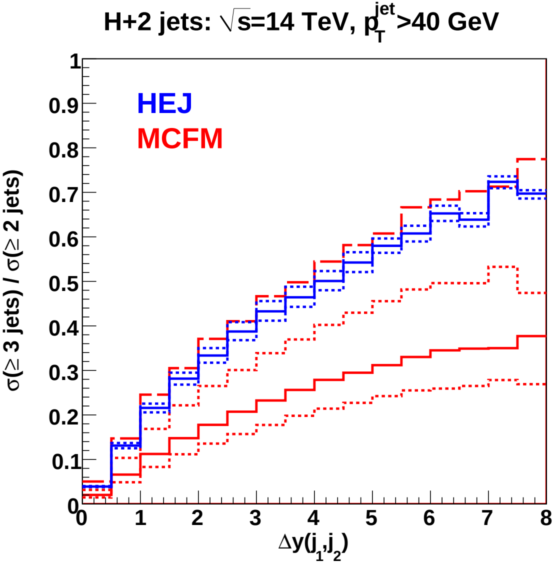
"Unfortunately" this does not lead to trivial corrections as the collision energy is increased:

The proton collision centre of mass energy is not the relevant scale for evaluating the perturbative coupling:
DIS: Q^2 measured from scattered electron; e^+e^-: Z mass; jets: transverse momenta



A Measure of the Impact of Higher Order Corrections

A measure of the significance of higher order perturbative corrections:
Require e.g. a Higgs boson and two jets at born level.
Calculate NLO. How frequently do we find 3 jets?
$\Delta y \approx \ln \hat{s}/p_\perp^2$.



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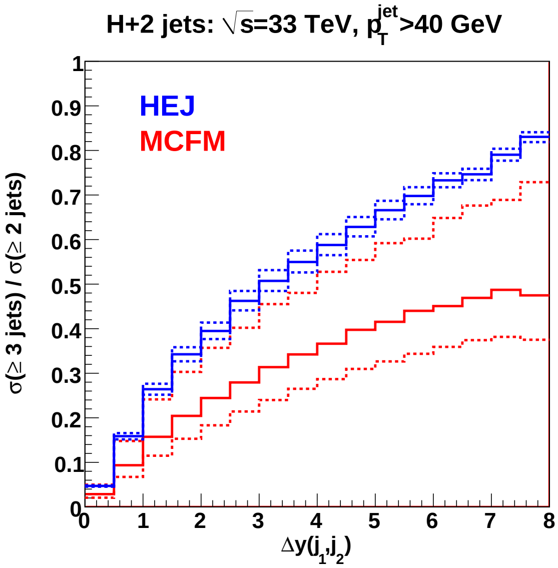

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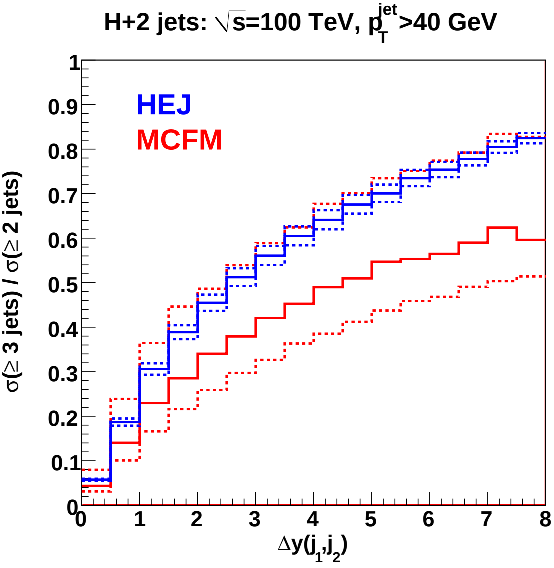

Why Hjj, The Problem, The Solution

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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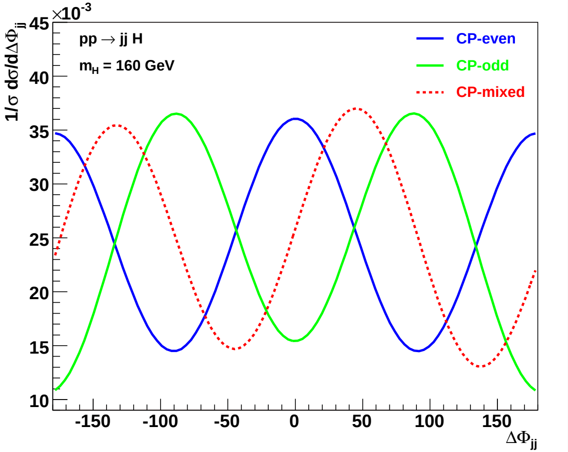
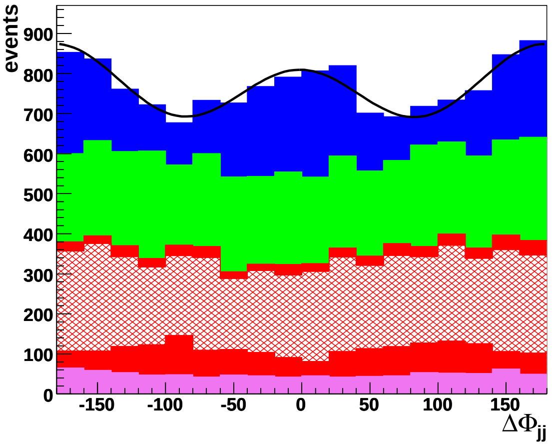
Distribution of Azimuth between Jets



Klaemke, Zeppenfeld

The SM Higgs boson has CP-even couplings to gluons - let us entertain the possibility of direct CP-violation in the H-sector and ask ourselves if we could measure an admixture.

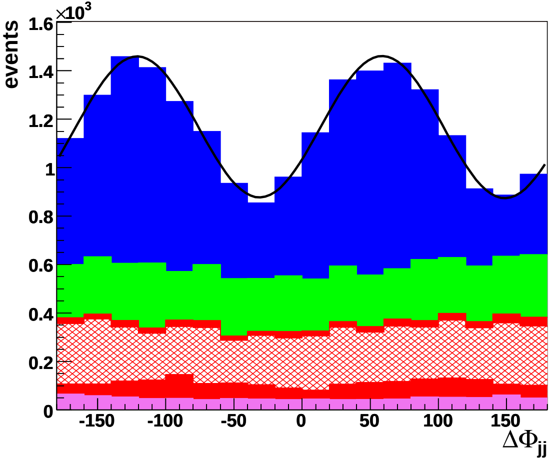
Azimuthal distribution, Standard Model



Klaemke, Zeppenfeld

Backgrounds (WBF, top+jets, other) are mostly flat - signature remains strong.

Azimuthal distribution, CP-mixture



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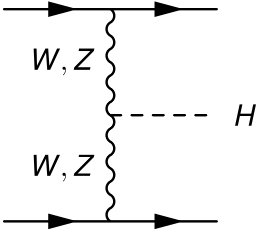
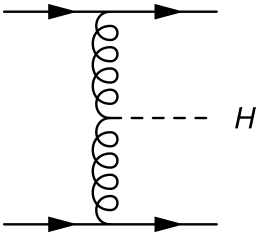
Higgs Couplings through Azimuthal Correllations



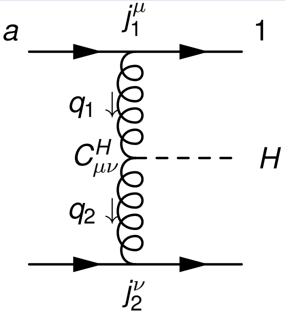
Considerations for Weak Boson Fusion

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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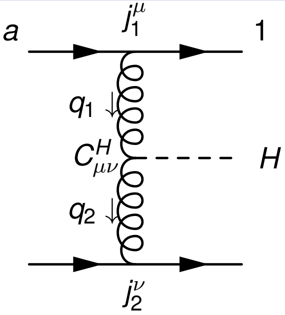

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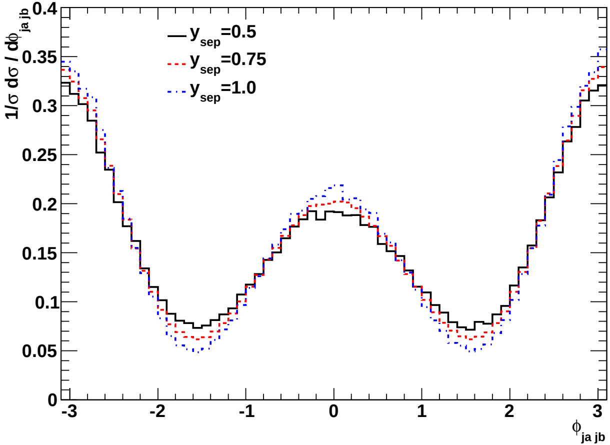
Take e.g. the term $\varepsilon^{\mu\nu\rho\sigma} \, q_{1\rho} \, q_{2\sigma}$: for $|p_{1,z}| \gg |p_{1,x,y}|$ and for small energy loss (i.e. $\overline{\psi}_1 \gamma^\mu \psi_a \to 2p_a, \overline{\psi}_2 \gamma^\mu \psi_b \to 2p_b, p_{a,e} \sim p_{1,e}$):

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

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)**.

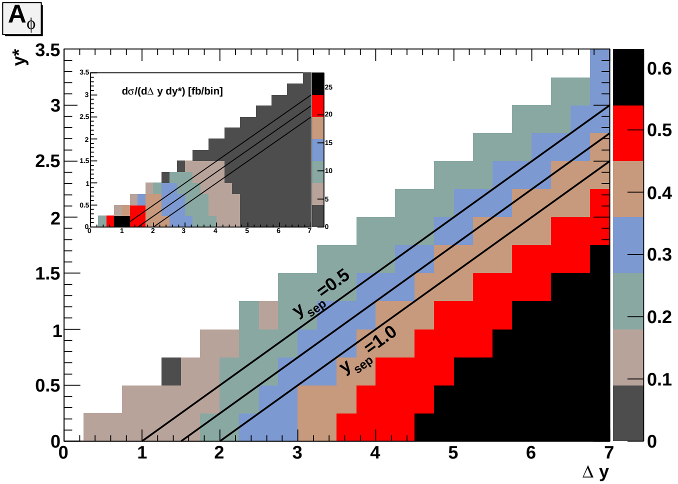
Azimuthal distribution



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

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

Signature and Cross Section

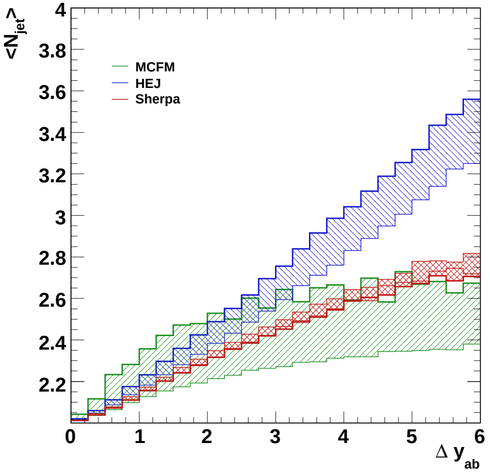


$$\Delta y = |y_{j_a} - y_{j_b}|, \quad y^* = y_h - \frac{y_{j_a}+y_{j_b}}{2}.$$

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.

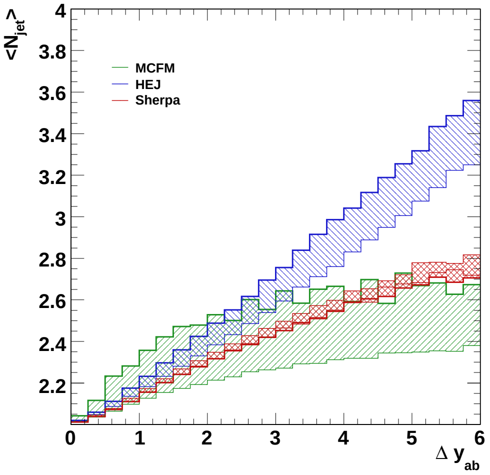
How to extract the *CP*-structure of the Higgs boson coupling from events with **three or more** jets?

Need reliable calculation and better understanding of the perturbative series

Scattering Amplitudes at High Energies

…and their implementation in High Energy Jets

Increasing Rapidity Span → Increasing Number of Jets



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

Please recall this plot when I discuss the results of the ATLAS study of $\langle N_{\text{jets}} \rangle$

h+dijets (at least 40GeV).

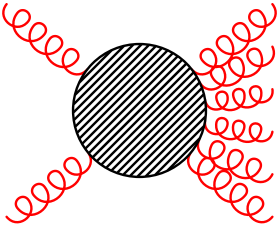
Δy_{ab}: Rapidity difference between most forward and backward hard jet

Compare NLO (green), CKKW matched shower (red), and High Energy Jets (blue).

Very **important to understand effect** for purpose of **applying cuts in analysis** (invariant mass etc.), and for extracting *CP-properties* of the Higgs boson coupling.

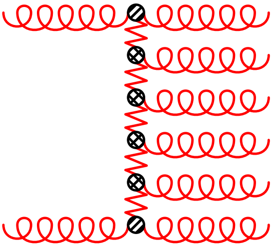
Similar behaviour in pure dijet, W+dijet,. . .

can be studied already



High Energy Limit $\longrightarrow$

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



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

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

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

At LL only gluon production; at NLL also quark–anti-quark pairs produced. Approximation of any-jet rate possible.

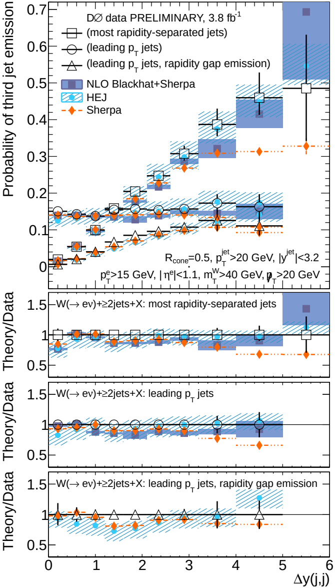
Skip forward the exciting improvements brought by HEJ, the fixed-order matching, the sub-leading corrections,. . . we arrive at a formalism of relevance to present day collisions.

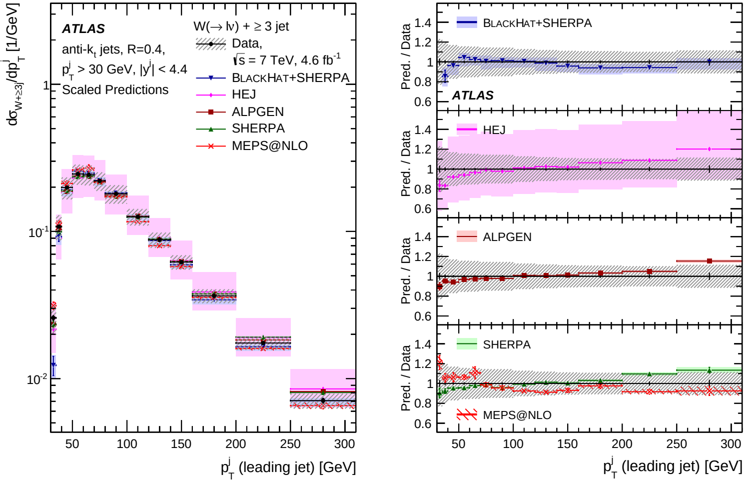
D0: W+Jets Phys. Rev. D 88, 092001

D0 measurement of the probability of at least one additional jet when requiring just a *W* in association with two jets. Probability measured vs. rapidity separation of

1. the two most rapidity separated jets
2. the two hardest (in pt) jets
3. the two hardest (in pt) jets, counting additional jets only in the rapidity interval between the two hardest jets

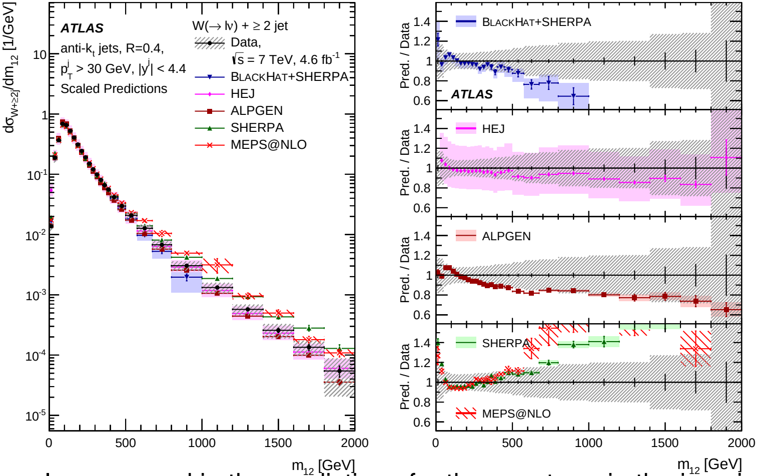
Good agreement between data and HEJ for all observables - effects will be even more pronounced at the LHC.





For standard p_t-based observables, all predictions give a reasonable description (NLO is very good, NLL corrections improve HEJ).

ATLAS: W+DiJets



There is a large spread in the predictions for the spectrum in the invariant mass between the two hardest jets. Here, the terms systematically dealt with in HEJ are important, and HEJ gives a good description.

Note: hjj interesting for $m_{jj} > 400 - 600$GeV.

Conclusions

- Hadron colliders probes hard (=jets) perturbative corrections beyond pure NLO . . . already at 1.96, 7, 8,. . . TeV!
- ***High Energy Jets****** provides a new approach to the perturbative description of proton collider physics
  . . . and compares favourably to data in several analyses
  . . . several ongoing improvements in the formal accuracy of the perturbative approximations

* http://cern.ch/hej