Higgs Boson plus Dijets: CP Properties and jet veto effects

Radiative Corrections to (H/W/Z+)Multi-Jets

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Soft Gluons and New Physics
November 2, 2010

Multiple ($\geq$ 2) hard jets...

Smaller number of jets solved satisfactory (?) already...(POWHEG, MC@NLO, NNLO,...)

Special radiation pattern from **current-current** scattering

Look into **higher order corrections beyond** “inclusive K-factor”

Concentrate on the **hard, perturbative corrections** relevant for a description of the final state **in terms of jets**.

Goal

Build framework for **all-order summation** (virtual+real emissions). Exact in another limit than the usual soft&collinear. Better suited for describing **radiation relevant for multi-jet** production.

Insight

Can use the insight gained from studying the relevant limit to **guide and improve** analyses: *CP*-properties of the Higgs-boson couplings

The Challenge, The Solution, Status

The Challenge (fka Problem), (in trivial statements)

Hard emission is less suppressed at **increasing collider energies**.
New problem for the LHC-era (W+jets, H+jets, . . .)
NLO gets the **one** hard emission right, but **one may not be sufficient**.
Parton shower does **many emissions**, but **not the hard ones**.
PS+matching is **good at Tevatron**, but **sufficient at LHC?**

The Solution

High Energy Jets (HEJ): What it is; what it is **not**

Status

What **HEJ** can do for you
What $1fb^{-1}$@7TeV can tell us about our perturbative tools

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Prerequisites for the discussion

Observables

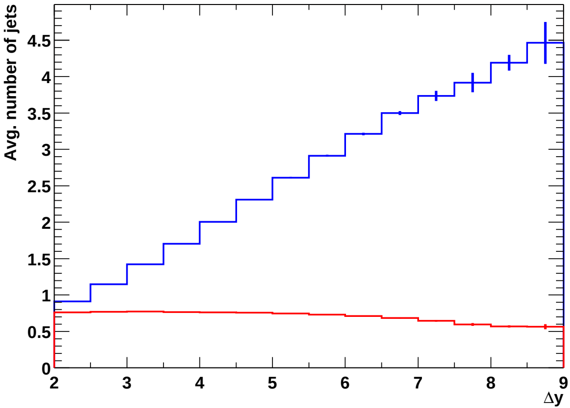
Focus on the final state in terms of jet count and configuration (not the jet substructure).

The obtained description is **fully exclusive**. Concentrate the discussion on a few of the many possible observables, which capture the relationship between the **increasing phase space** (for increasing Δy between most forward and most backward hard jet) and the **amount of hard radiation**:

$$\frac{\sigma_{N+1}}{\sigma_N}, \langle \#\text{jets} \rangle, \ldots \text{vs. } \Delta y.$$

Δy "large" can arise as a **result of specific phase space cuts** (H+dijets), **or naturally** ((W, Z, H+)multiple jets, especially from qg final state)
Hard **radiative corrections** also **dominant in other corners** of phase space! Large Ht…

The Challenge: $\langle \#\text{jets} \rangle$ vs. Δy



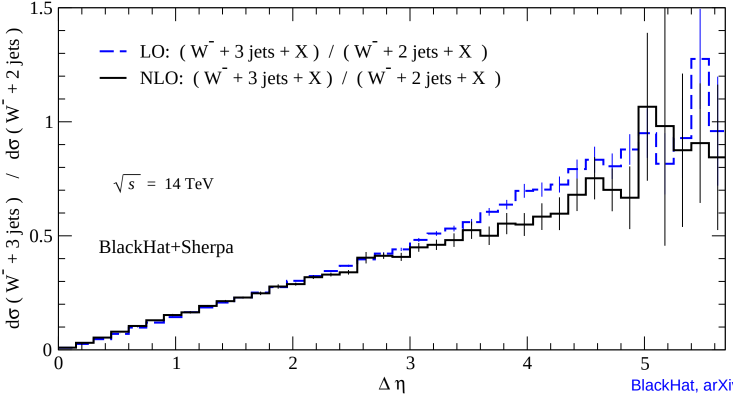
Red: Average number of central ($|y| < 1$) jets.

JRA, V. Del Duca, F. Maltoni, W.J. Stirling, hep-ph/0105146

Basic observation of increasing phase space for hard emissions with increasing Δy is the motivation for e.g. BFKL resummation.

However, don't just take *my* word for it...

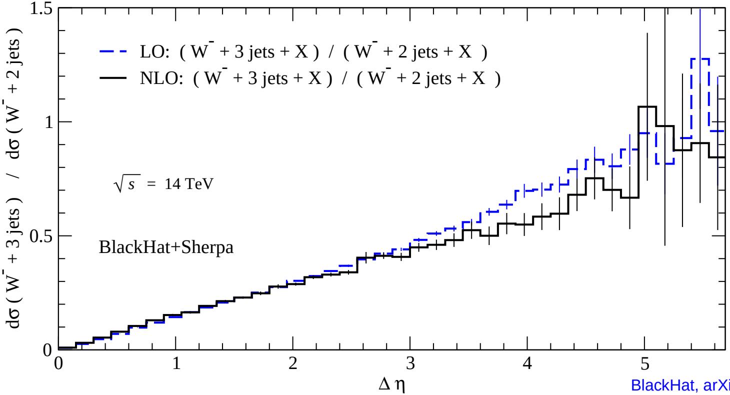
W+Multiple Jets @ NLO



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)



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!

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

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**.

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

Will focus on application of the formalism in H+dijets and pure jets

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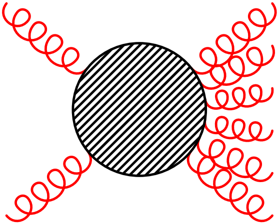
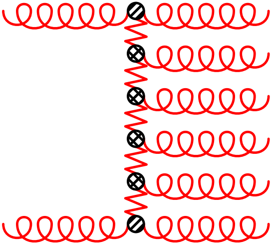


High Energy Limit

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



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

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

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

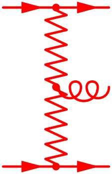
Maintain (at LL) terms of the form

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

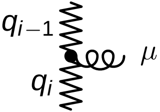
to all orders in α_s.

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

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

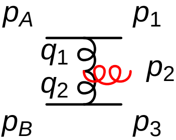


$$\frac{1}{q^2}\exp\left(\hat{\alpha}(q)\Delta y\right)$$

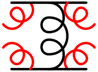


$$V^{\mu}(q_{i-1}, q_i)$$

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



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



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

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.

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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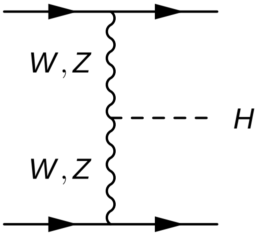
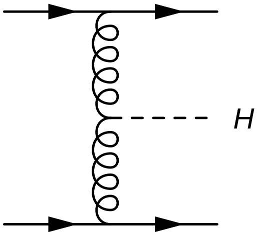


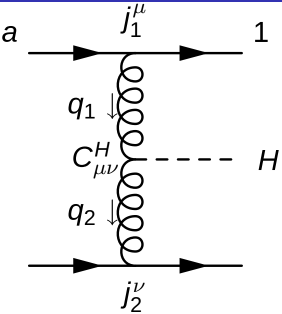
Considerations for Weak Boson Fusion

Higgs Couplings through Azimuthal Correllations



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

Higgs Couplings through Azimuthal Correllations



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

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

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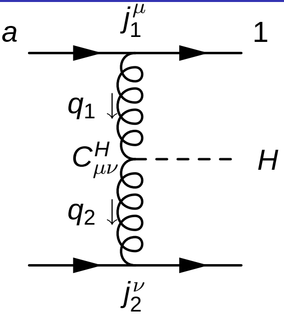

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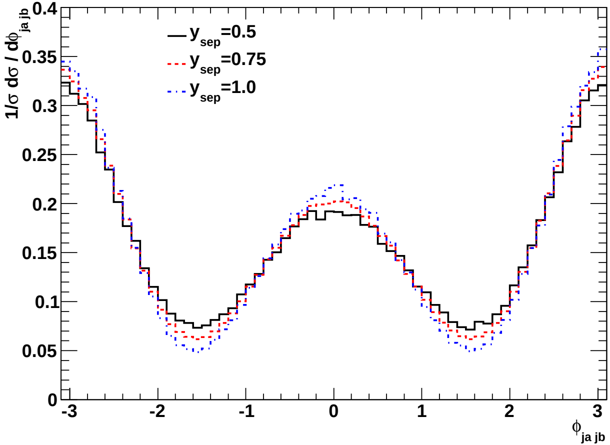
Take e.g. the term $\varepsilon^{\mu\nu\rho\sigma} \, q_{1\rho} \, q_{2\sigma}$: for $|p_{1,z}| \gg |p_{1,x,y}|$ and for small energy loss (i.e. $p_{a,e} \sim p_{1,e}$):

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

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)**.

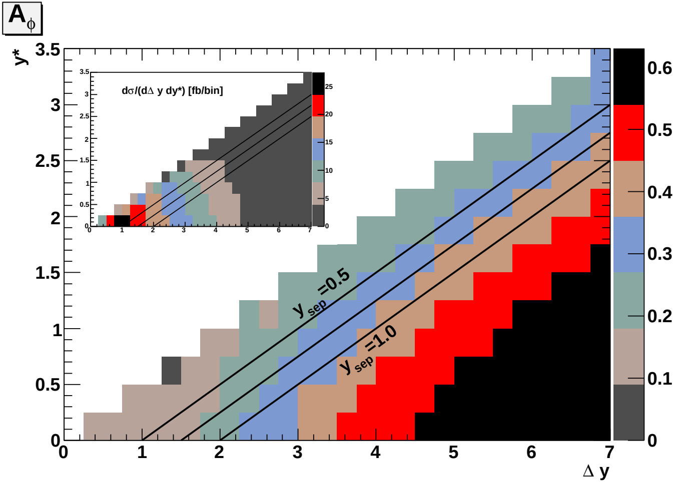
Azimuthal distribution



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

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

Signature and Cross Section

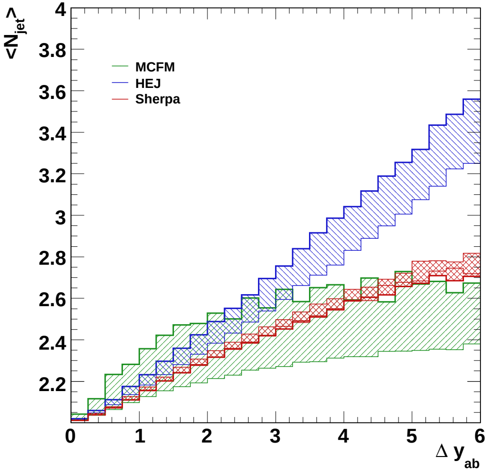


$$\Delta y = |y_{j_a} - y_{j_b}|, \quad y^* = y_h - \frac{y_{j_a} + y_{j_b}}{2}.$$

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?

2 hardest jets?

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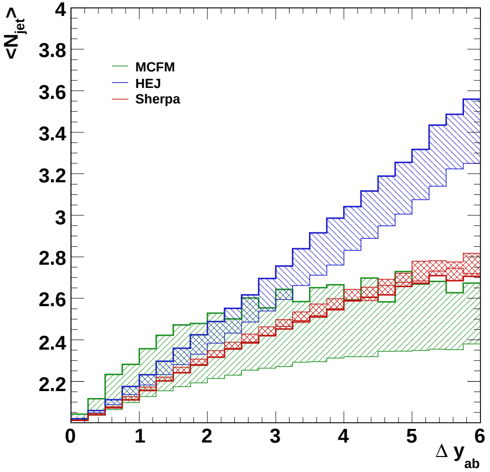

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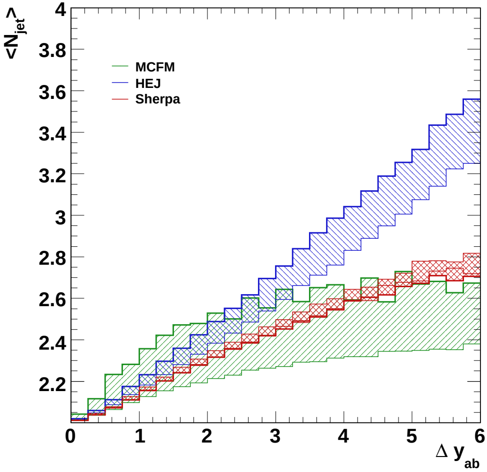
2 hard jets furthest apart in rapidity?

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



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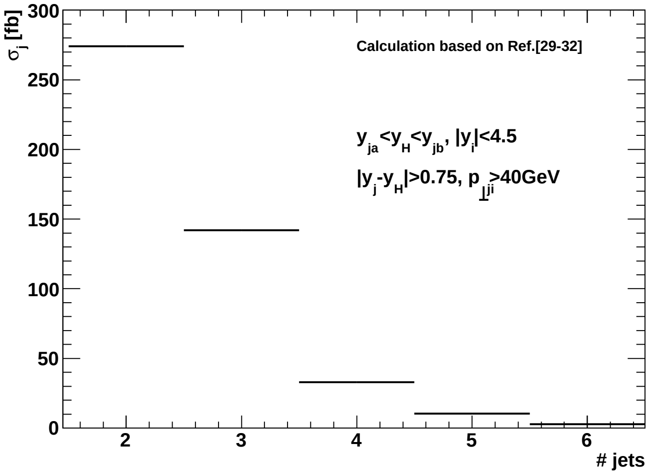
Significant washing out of the azimuthal correlation observed at tree-level *hjj*

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

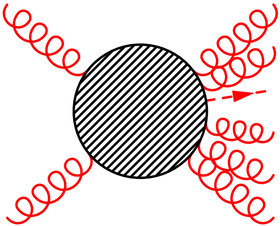
Many Jets!



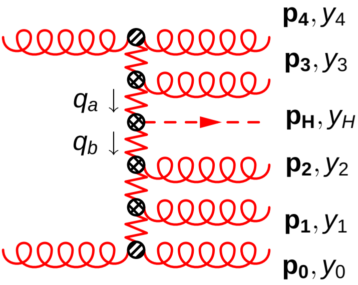
Calculation based on all-order approximant to the *n*-particle matrix element, which reproduces the exact result in the limit of large invariant mass between all particles.

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

Develop Insight Into the Perturbative Corrections



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

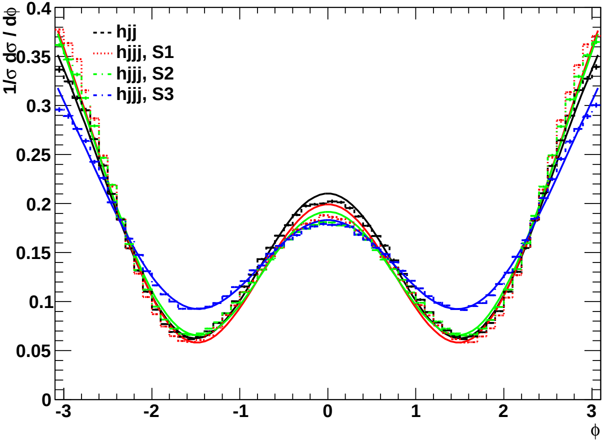


$$\left|\mathcal{M}_{gg\to g\cdots ghg\cdots g}\right|^2 \to \frac{4\hat{s}^2}{N_C^2-1}\left(\prod_{i=1}^{j}\frac{C_A\,g_s^2}{\mathbf{p}_{i\perp}^2}\right)\frac{|C^H(\mathbf{q}_{a\perp},\mathbf{q}_{b\perp})|^2}{\mathbf{q}_{a\perp}^2\ \mathbf{q}_{b\perp}^2}\left(\prod_{i=j+1}^{n}\frac{C_A\,g_s^2}{\mathbf{p}_{i\perp}^2}\right)$$

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

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!

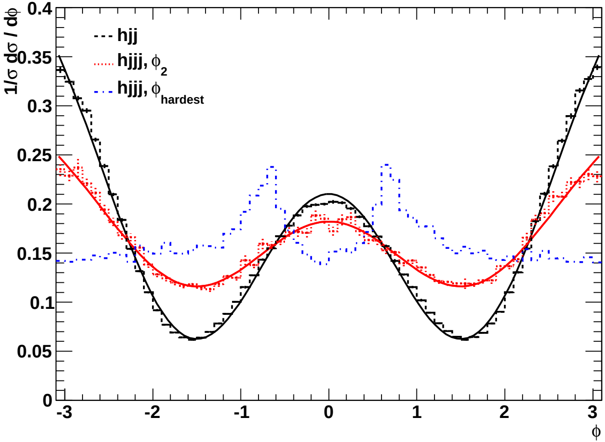
And It Even Works!



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.

...Much Better Than The Alternative

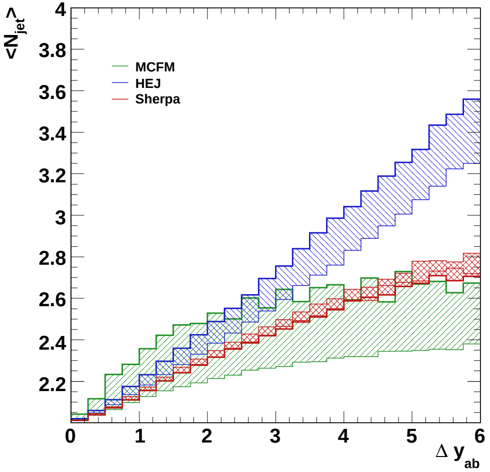


JRA, K. Arnold, D. Zeppenfeld, arXiv:1001.3822

Two hardest jets on one side, and the softest on the other (all above 40GeV - $1/3$ of inclusive 3-jet cross section). Using **just the two hardest** jets gives **unsatisfactory** result.

Insight from HE limit allow us to construct an observable for the extraction of the CP properties, which is extremely stable against perturbative corrections.

Increasing Rapidity Span → Increasing Number of Jets



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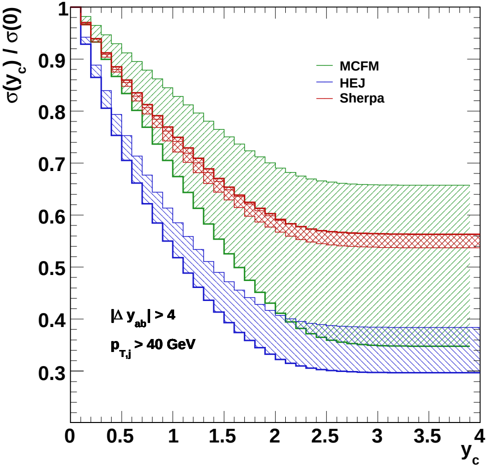
What is the impact of a central jet veto?
Can be used to separate contribution from gluon fusion and weak boson fusion
note very small interference!.

Effect of Central Jet Veto



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

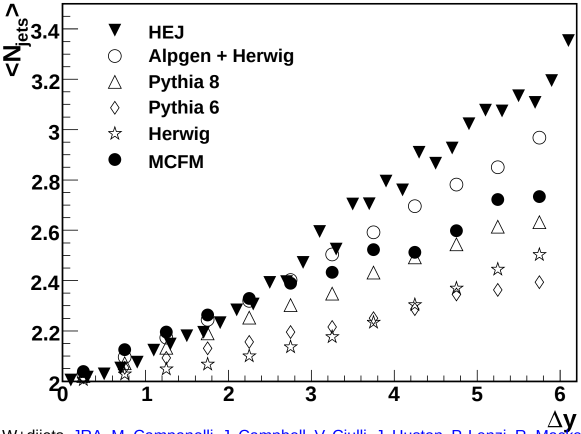
$$\forall j \in \{\text{jets with } p_{j\perp} > 40\text{GeV}\} \setminus \{a, b\} \; : \; \left| y_j - \frac{y_a + y_b}{2} \right| > y_c$$

What Early Data Can Tell Us

Radiation pattern “universal” for processes with colour exchange in t-channel

Look at W+jets, or simply pure jets. . .

What can $1fb^{-1}$ tell us about our perturbative tools



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

$1fb^{-1}$@7TeV could be enough to tell the predictions apart!

Obviously, similar results for pure dijets with much less data

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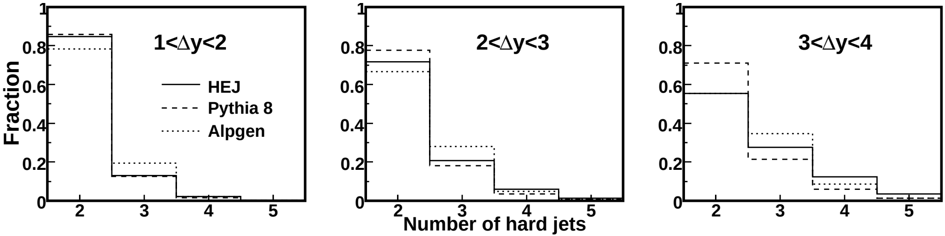

Many handles to distinguish the predictions from various perturbative approaches using early data

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

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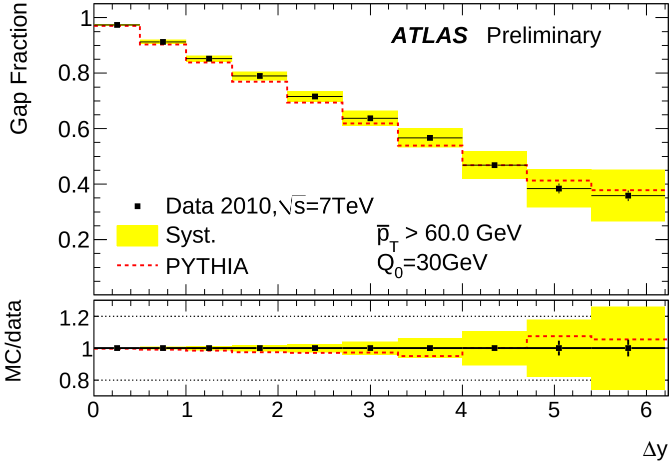
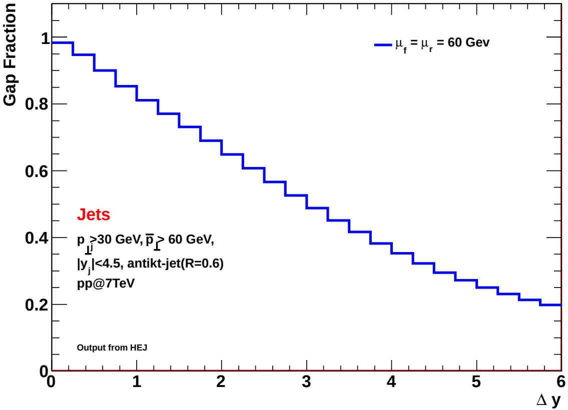
LHC Data Has Arrived!



ATLAS-CONF-2010-085

. . . and we have the predictions too!



HEJ

Caveat: Need to ensure the analysis is identical to the one applied by ATLAS before comparing numbers directly

Conclusions

- The insight gained from studying the **High Energy Limit** useful for constructing a **very robust** extraction of the **CP properties of the Higgs boson couplings**
- . . . and for constructing an **all-order approximation** to the perturbative corrections to **all hard processes with at least two jets** (current-current scattering)
- Study highlights **differences** in current **theoretical descriptions of high-energy collisions**
- **early data** will investigate the importance of taking into account all-order hard corrections