# Hard Jets and Higgs Bosons

## HEJ: All-Order Perturbative Corrections to Hard Multi-Jet Processes

Jeppe R. Andersen

IPPP, Durham University

Edinburgh, Jan 16 2013

# Overview of Talk

## Elements of Proton Collisions

**Hard scattering**, **shower**, **matching to fixed order**
multiple interactions, underlying event. . .

**Jets** to the rescue!

## Multi-Jet Predictions

Why we **must** care about HO corrections (in some situations). . .
A new approach to multiple, wide-angle emissions from the **hard scattering**:

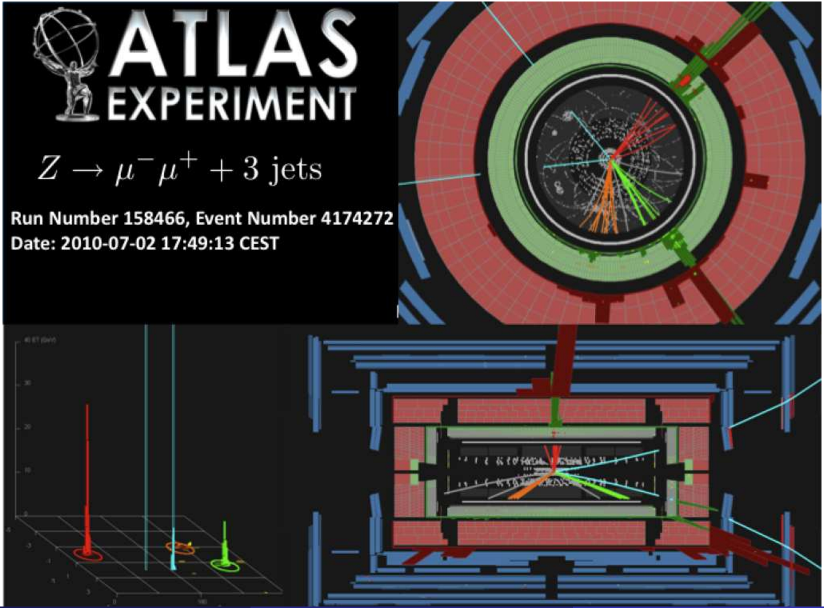
**High Energy Jets**

Merging with **shower**. **Predictions** for dijets, $W$+jets, $H$+jets,. . .

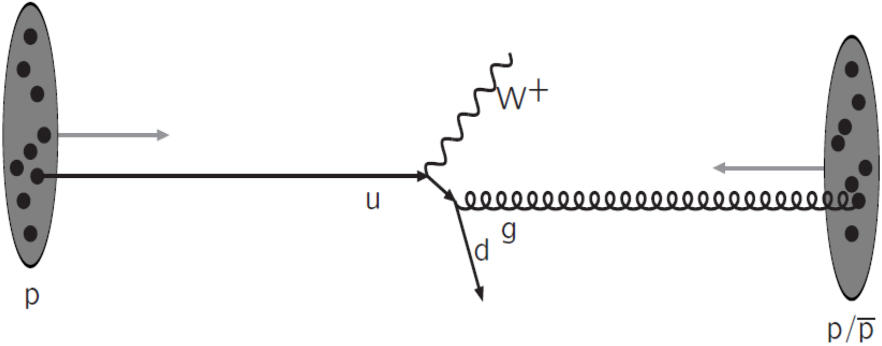
## Theory vs. Data

Results of **first data** compared to HEJ
Hard, higher order effects beyond NLO

# A Real pp-Collision

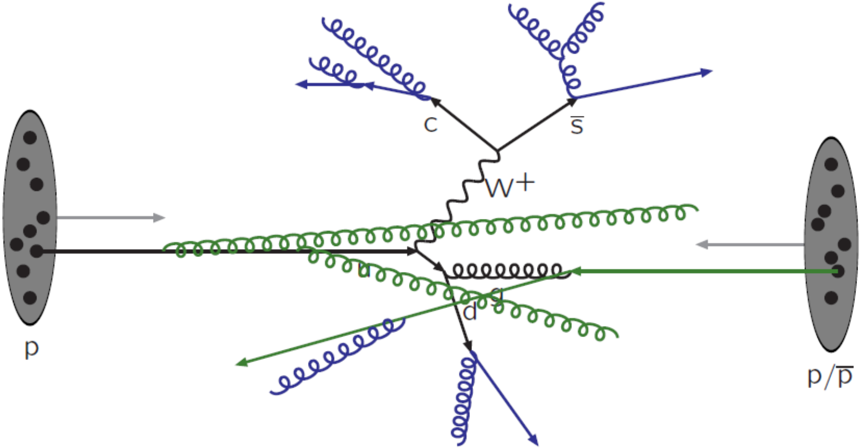


# The Theoretical Description, I*)



*)Drawing by R. Corke

# The Theoretical Description, II$^*$)



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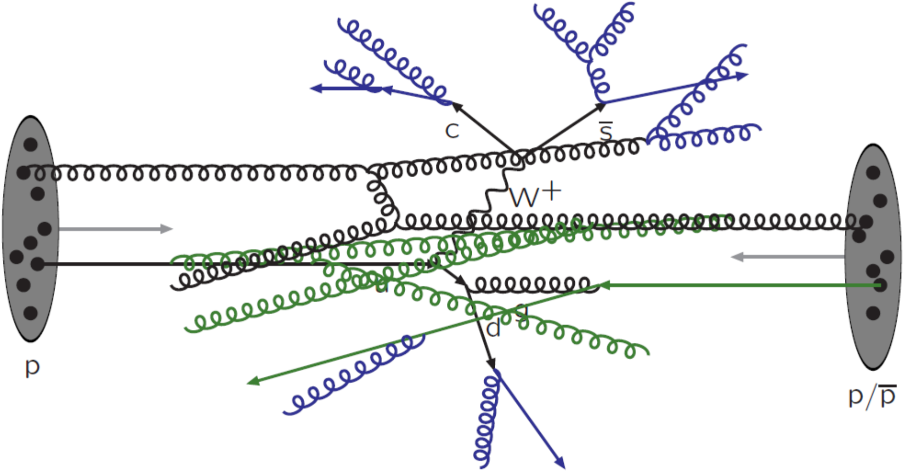
$^*$)Drawing by R. Corke

# The Theoretical Description, III$^*$)



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# Jet (algorithms) to the Rescue!

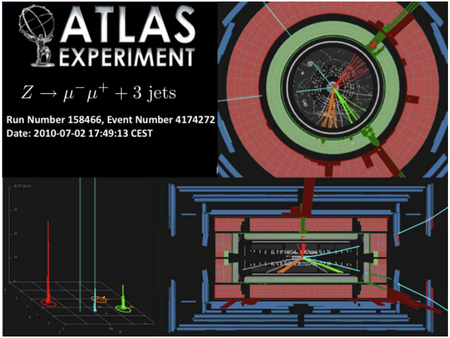
Depending on the question we want to answer, we **may not need** to describe all the **stages of the collision**.

The notion of jets allow us to **compare pure perturbation theory** (few partons) to **experimental observation** (many hadrons)

Transverse Momentum

Rapidity: $y = \ln \frac{E+p_z}{E-p_z}$

still need to ensure (relative) insensitivity to underlying event, multiple interactions. . . ask questions only about relatively hard jets ($p_\perp > 30$ GeV?)



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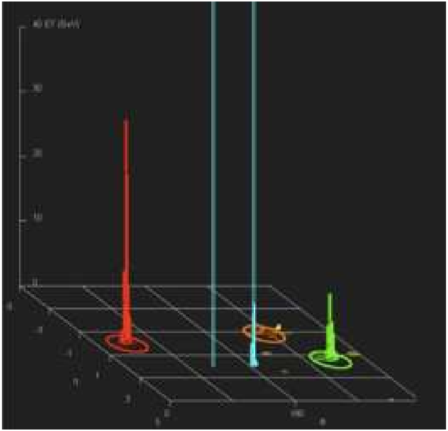
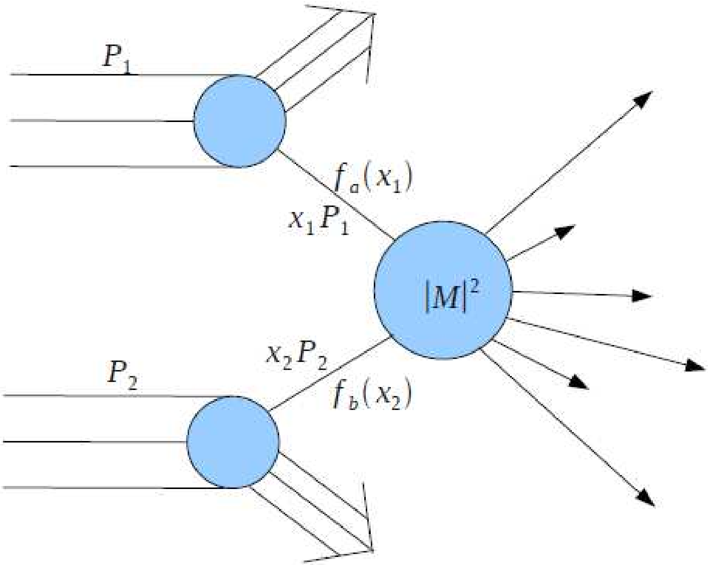


Obviously need the jet algorithms to be well-defined both experimentally (many discrete hits) and theoretically (probing singularity structure). Use fastjet!

# The Perturbative Description



# Why Study Multi-jet Observables?

## We don't have a choice!

1. Many BSM (e.g. SUSY) particles will have *decay chains* involving the production of jets (e.g. 4 jets + $\not{p}_T$). Calculation of signal is easy (one process), SM contribution is very hard (several processes).
2. All LHC processes involves QCD-charged particles; sometimes the (n+1)-jet cross section is as large as the n-jet cross section!
3. It is a challenge we cannot ignore !

# Jets at the LHC

## The age old hunt. . .

Effects beyond NLO DGLAP?
. . . apart from the obvious soft and collinear regions (shower profile)
Do we need more than NLO DGLAP to describe the hard jet events at the LHC?

## The News

The data collected in 2010 already show effects beyond **NLO** DGLAP. . .

1. for some observables based on **hard jets**
2. in certain regions of phase space

# Scope of this talk

**Will not** discuss several interesting effects:

- jet broadening (shower profiles)
- impact of underlying event on the jet energy

⋮

These are (well?) described by a tunable shower MC.

**Will instead** focus on the description of the **hard event**, and in particular on observables not well described by **NLO** DGLAP.

*Which regions of phase space receive large corrections from hard perturbative corrections (= additional jet activity)*

Compare the description of hard jet activity from NLO, NLO+shower, High Energy Jets.
Dijets, W+Dijets, H+Dijets; Similarities in Jet Activity

## 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.

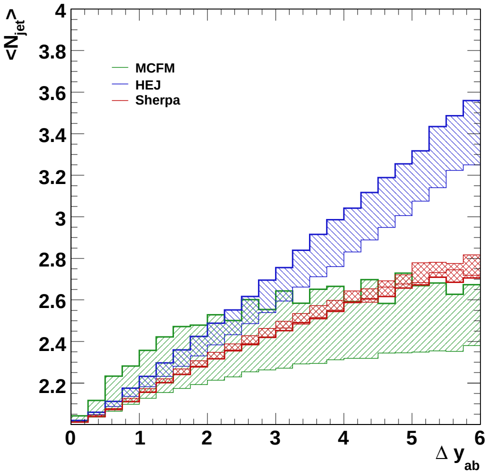
## Insight

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

# Drivers of Emission

1. Collinear ( jet profile)
2. Soft ($p_t$-hierarchies)
3. Opening of phase space (semi-hard emissions - not related to a divergence of $|M|^2$).
   Think (e.g.) multiple jets of fixed $p_t$, with increasing rapidity span (span=max difference in rapidity of two hard jets=$\Delta y$).
   ***All*** calculations will agree that number of additional jets increases - but the amount of radiation will differ (wildly) - e.g. due to **limitations** on the **number** (NLO) or **hardness** (shower) of additional radiation **allowed by theoretical assumptions**.

# Increasing Rapidity Span → Increasing Number of Jets



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

h+dijets (at least 40GeV). $\Delta y_{ab}$: Rapidity difference between most forward and backward hard jet

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

**All** models show a clear increase in the number of hard jets as the rapidity span $\Delta y_{ab}$ increases.

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

# 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:
**Collinear limit** → enters many resummation formalisms, parton showers. . . .

Like all good limits, the collinear 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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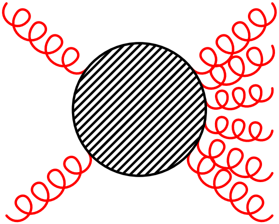
# The Possibility for Predictions of *n*-jet Rates

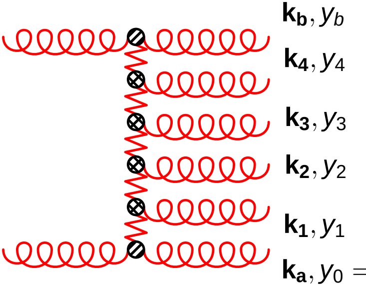
## The Power of Reggeisation



**High Energy Limit**

$\longrightarrow$

$|\hat{t}|$ 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

Maintain (at LL) terms of the form

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

to all orders in $\alpha_s$.

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:

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

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

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

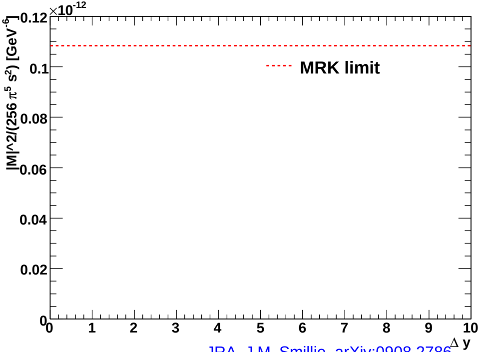
$$\left|\overline{\mathcal{M}}^{MRK}_{qQ\to qg\cdots Q}\right|^2 = \frac{4\,s^2}{N_C^2-1}\,\frac{g^2\,C_F}{|p_{1\perp}|^2}\left(\prod_{i=2}^{n-1}\frac{4\,g^2 C_A}{|p_{i\perp}|^2}\right)\frac{g^2\,C_F}{|p_{n\perp}|^2},$$

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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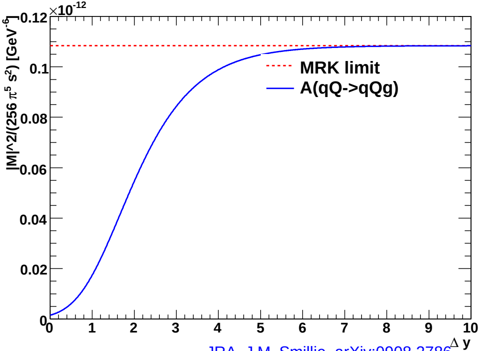

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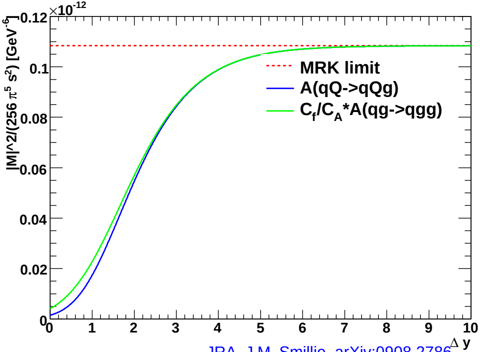

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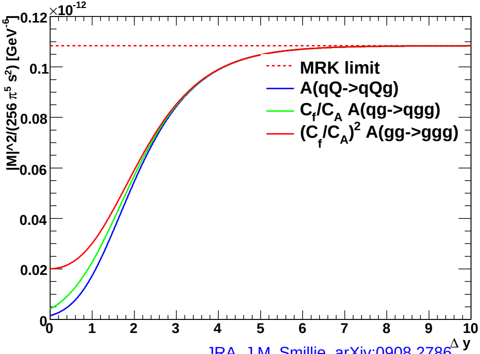

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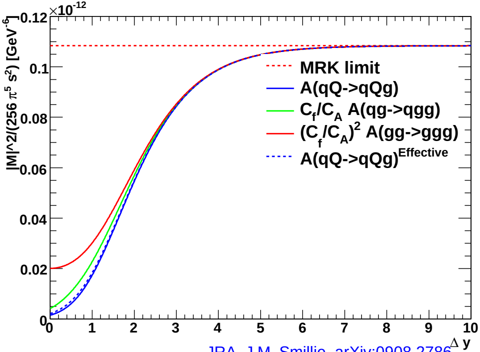


JRA, J.M. Smillie, arXiv:0908.2786

High Energy Jets (HEJ):

1) Inspiration from Fadin&Lipatov: dominance by $t$-channel
2) No kinematic approximations in invariants (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 $q(a)Q(b) \rightarrow q(1)Q(2)$:

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

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

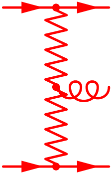
$$\left|\overline{\mathcal{M}}^t_{qQ\rightarrow qQ}\right|^2 = \frac{1}{4\,(N_C^2-1)}\ \left\|S_{qQ\rightarrow qQ}\right\|^2 \\ \cdot\ \left(g^2\ C_F\ \frac{1}{t_1}\right) \\ \cdot\ \left(g^2\ C_F\ \frac{1}{t_2}\right).$$

Extend to $2 \rightarrow n$ ...

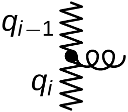
J.M.Smillie and JRA: arXiv:0908.2786

# Building Blocks for an Amplitude

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

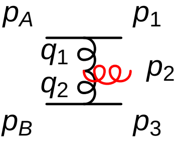


$$\frac{1}{q^2}\exp\left(\hat{\alpha}(q)\Delta y\right)$$

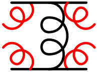


$$V^\mu(q_{i-1},q_i)$$

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



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



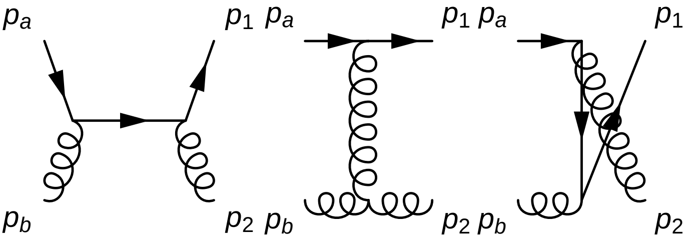
# Building Blocks for an Amplitude

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

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

# Quark-Gluon Scattering

> “What happens in 2 → 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

The $t$-channel current generated by a gluon in qg scattering is that genersated by 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 BFKL kinematic limit.

# All-Orders, Regularisation, etc.

- 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 (by merging $m$-parton momenta to $n$ hard jet-momenta) where this can be evaluated in reasonable time
- Resummation of HEJ recently merged with a **parton shower** (Ariadne)

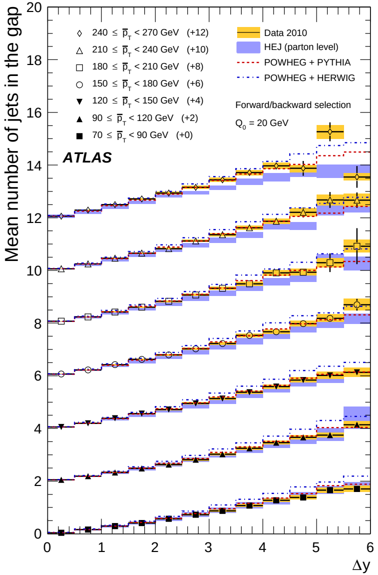
# Comparison to data

Two drivers for multi-jet production:

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

The LHC has the energy to explore the second mechanism.
Several interesting studies already with the first (2010) year of data!

# ATLAS: Study of Further Jet Activity in Dijet Events



CERN-PH-EP-2011-100

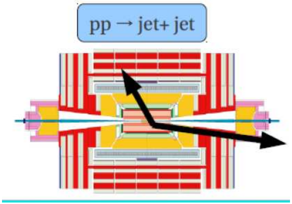
This Atlas analysis did not cleanly separate the two “drivers” of jet production. (cut on $\bar{p}_t$ induces large $p_t$-hierarchy on forward/backward jet, besides the hierarchy between large $\bar{p}_t$ and $Q_0$, the general jet scale)

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



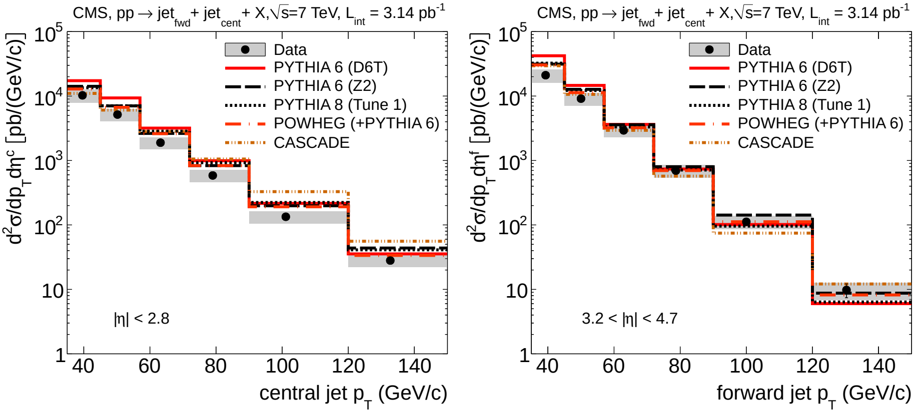
CMS PAS FWD-10-006

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

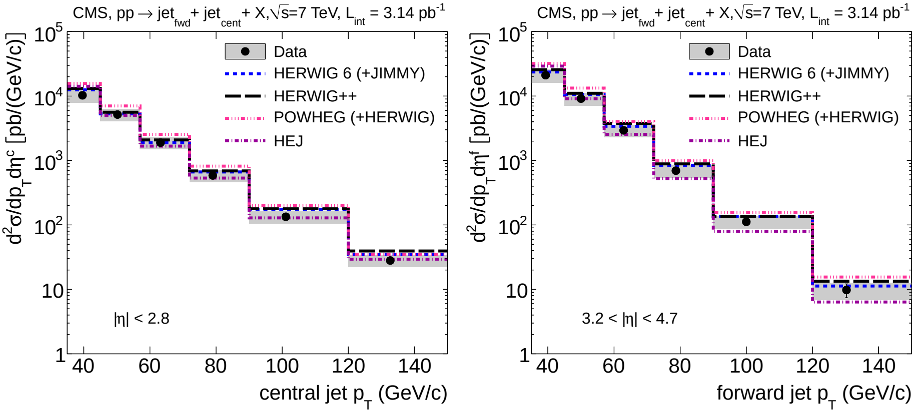
$$\begin{aligned} \text{central} &: |\eta| < 2.8 \\ \text{forward} &: 3.2 < |\eta| < 4.7 \end{aligned}$$

(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

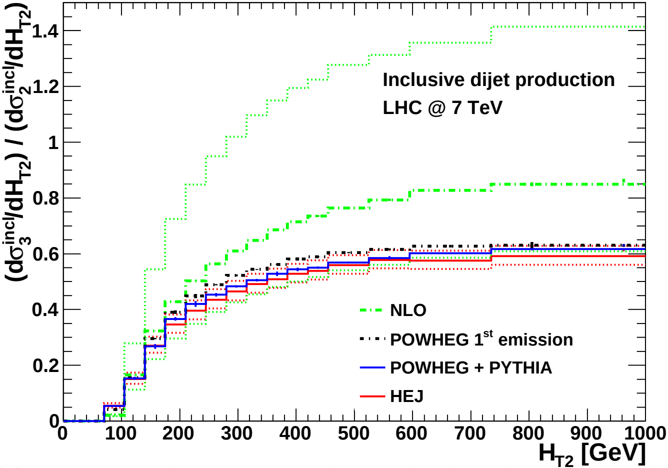


# Comparison to Theory, II



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

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

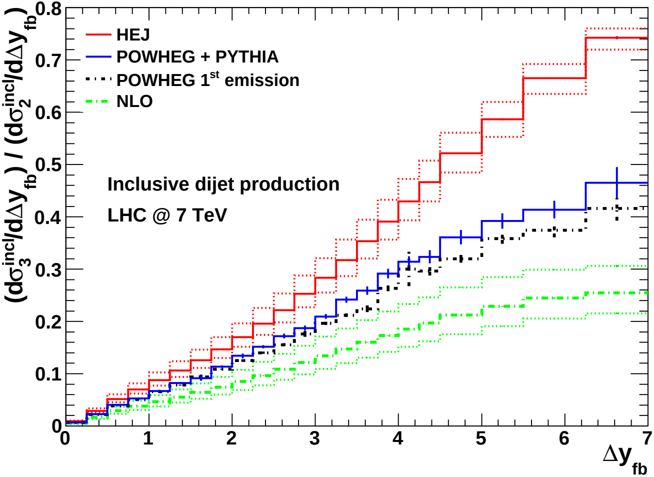


**Similarities**: NLO+Shower, HEJ (all-order hard resummation)

**Difference**: NLO

# Ratio of Inclusive Jet Rates vs. Rapidity

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



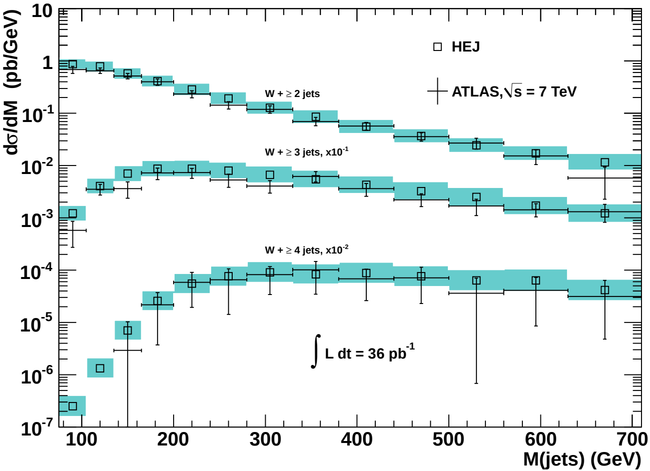
Clear differences: NLO, POWHEG, HEJ

# Summary of dijet study

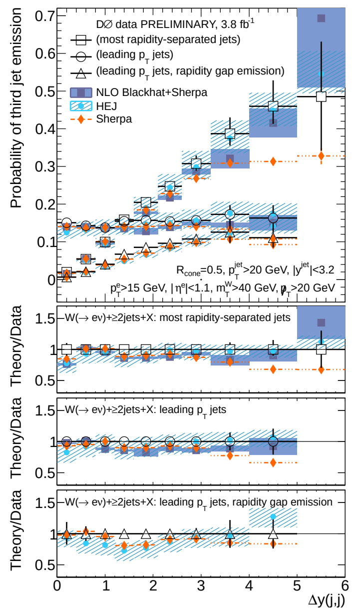
**Simple set of cuts**, combined with a **exclusive dijet-analyses** can discriminate clearly between the **mechanisms of perturbative corrections** implemented in NLO, POWHEG (NLO+Shower) and High Energy Jets.

# W+Jets

T. Hapola, J.M. Smillie, JRA (JHEP 1209 (2012) 047)



# D0: W+Jets


DØ data PRELIMINARY, 3.8 fb$^{-1}$
(most rapidity-separated jets)
(leading $p_T$ jets)
(leading $p_T$ jets, rapidity gap emission)
NLO Blackhat+Sherpa
HEJ
Sherpa
Probability of third jet emission
$R_{cone}$=0.5, $p_T^{jet}$>20 GeV, $|y^{jet}|$<3.2
$p_T^e$>15 GeV, $|\eta^e|$<1.1, $m_T^W$>40 GeV, $\not{E}_T$>20 GeV
W(→ eν)+≥2jets+X: most rapidity-separated jets
W(→ eν)+≥2jets+X: leading $p_T$ jets
W(→ eν)+≥2jets+X: leading $p_T$ jets, rapidity gap emission
Theory/Data
Theory/Data
Theory/Data
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.5
1
1.5
0
1
2
3
4
5
6
Δy(j,j)

# 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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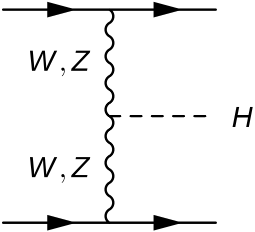
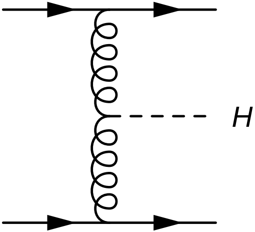
# Higgs Couplings through Azimuthal Correllations



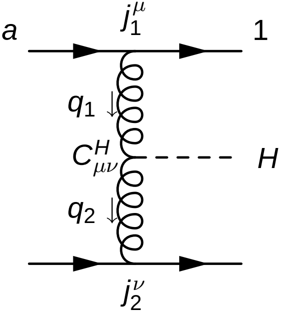
Considerations for Weak Boson Fusion

# Higgs Couplings through Azimuthal Correllations



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

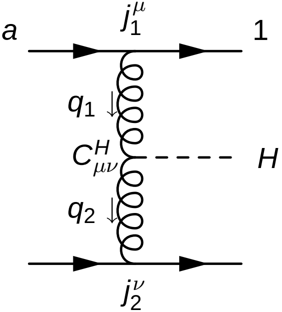
# Higgs Couplings through Azimuthal Correllations



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

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

# Higgs Couplings through Azimuthal Correllations



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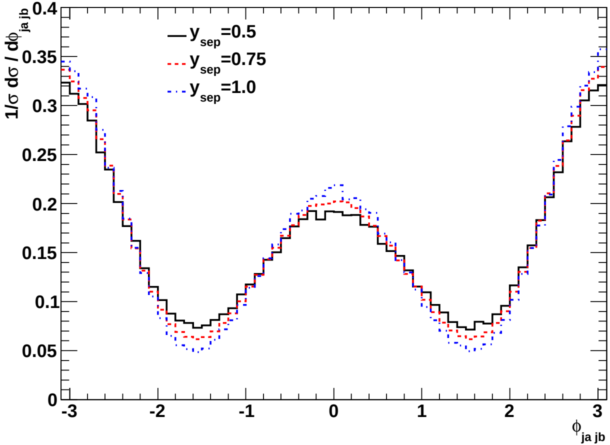
Take e.g. the term $\varepsilon^{\mu\nu\rho\sigma} \, q_{1\rho} \, q_{2\sigma}$: for $|p_{1,z}| \gg |p_{1,x,y}|$ and for small energy loss (i.e. $p_{a,e} \sim p_{1,e}$):

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

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)**.

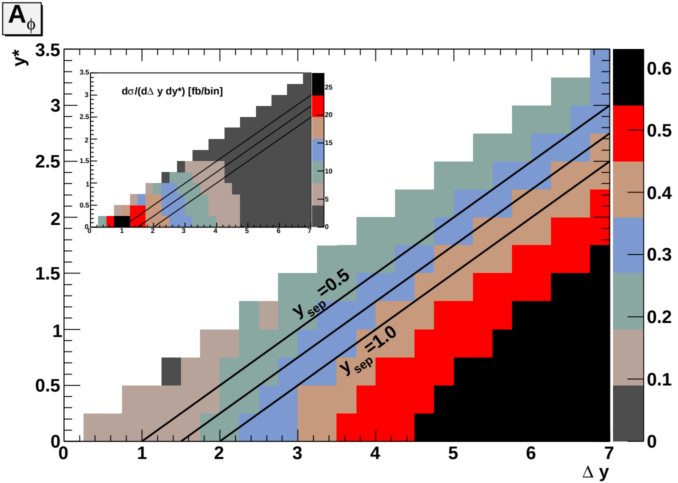
# Azimuthal distribution



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

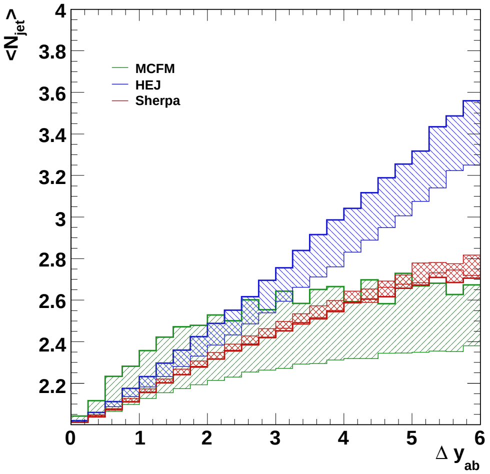


$$\Delta y = \left|y_{j_a} - y_{j_b}\right|, \quad y^* = y_h - \frac{y_{j_a}+y_{j_b}}{2}.$$

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



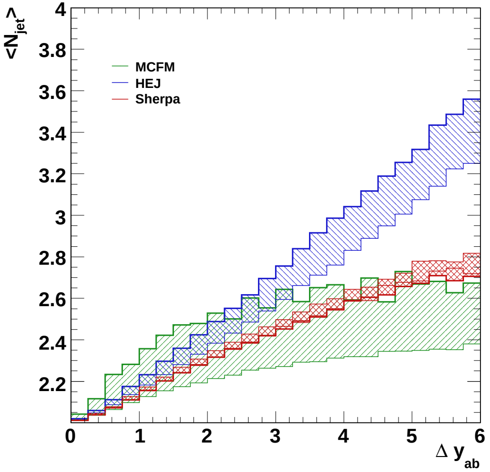
J.R. Andersen, J. Campbell, S. Höche, arXiv:1003.1241

**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



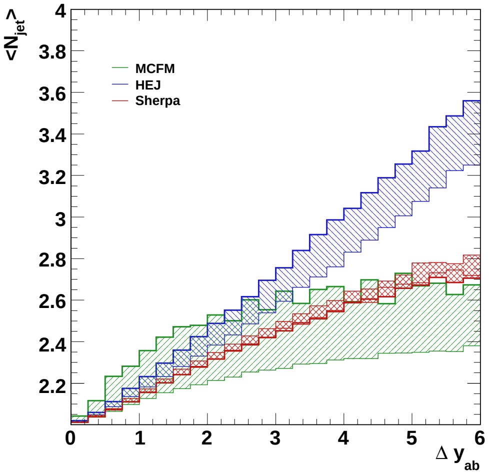
**All** models show a clear increase in the number of hard jets as the rapidity span increases.

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:1003.1241

# Increasing Rapidity Span → Increasing Number of Jets



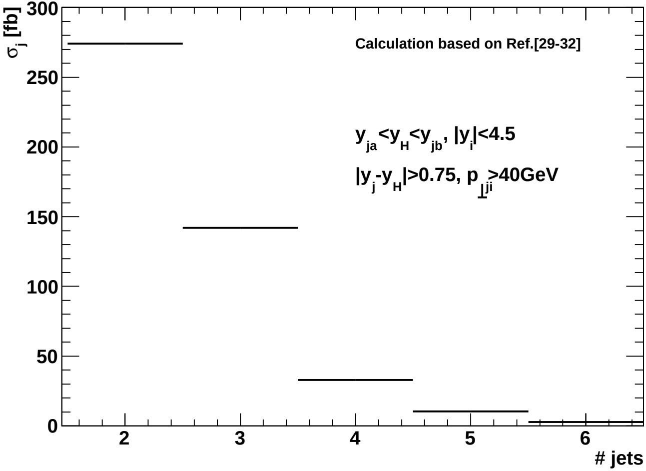
**All** models show a clear increase in the number of hard jets as the rapidity span increases.

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

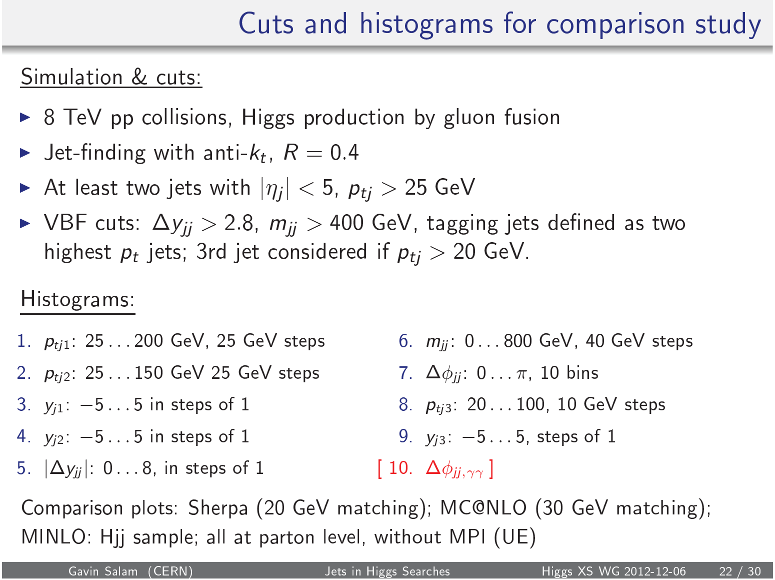
Significant washing out of the azimuthal correlation observed at tree-level *hjj*

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

# Many Jets!


$\sigma_j$ [fb]
300
250
200
150
100
50
0
2
3
4
5
6
# jets
Calculation based on Ref.[29-32]
$y_{ja}<y_H<y_{jb}$, $|y_i|<4.5$
$|y_j-y_H|>0.75$, $p_{\perp ji}>40$GeV

# Excess or not?



## Cuts and histograms for comparison study

Simulation & cuts:

- 8 TeV pp collisions, Higgs production by gluon fusion
- Jet-finding with anti-$k_t$, $R = 0.4$
- At least two jets with $|\eta_j| < 5$, $p_{tj} > 25$ GeV
- VBF cuts: $\Delta y_{jj} > 2.8$, $m_{jj} > 400$ GeV, tagging jets defined as two highest $p_t$ jets; 3rd jet considered if $p_{tj} > 20$ GeV.

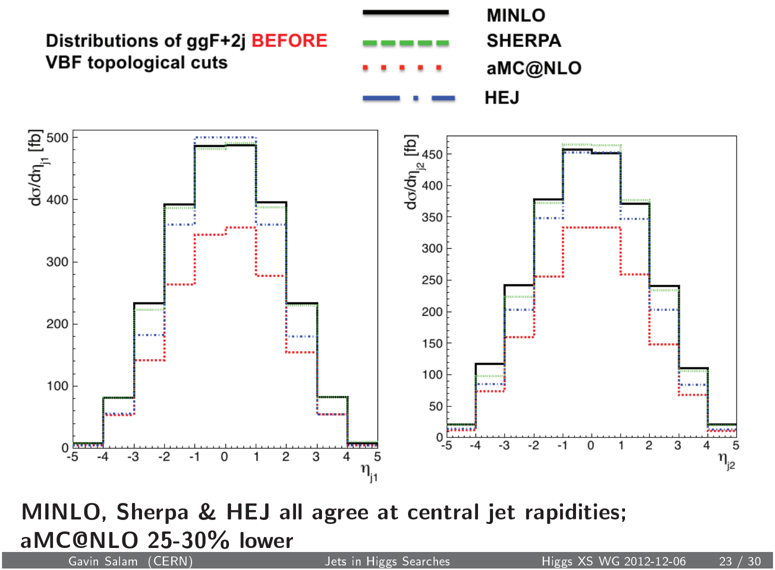
Histograms:

1. $p_{tj1}$: $25 \ldots 200$ GeV, 25 GeV steps
2. $p_{tj2}$: $25 \ldots 150$ GeV 25 GeV steps
3. $y_{j1}$: $-5 \ldots 5$ in steps of 1
4. $y_{j2}$: $-5 \ldots 5$ in steps of 1
5. $|\Delta y_{jj}|$: $0 \ldots 8$, in steps of 1
6. $m_{jj}$: $0 \ldots 800$ GeV, 40 GeV steps
7. $\Delta\phi_{jj}$: $0 \ldots \pi$, 10 bins
8. $p_{tj3}$: $20 \ldots 100$, 10 GeV steps
9. $y_{j3}$: $-5 \ldots 5$, steps of 1

[ 10. $\Delta\phi_{jj,\gamma\gamma}$ ]

Comparison plots: Sherpa (20 GeV matching); MC@NLO (30 GeV matching); MINLO: Hjj sample; all at parton level, without MPI (UE)

# Excess or not?

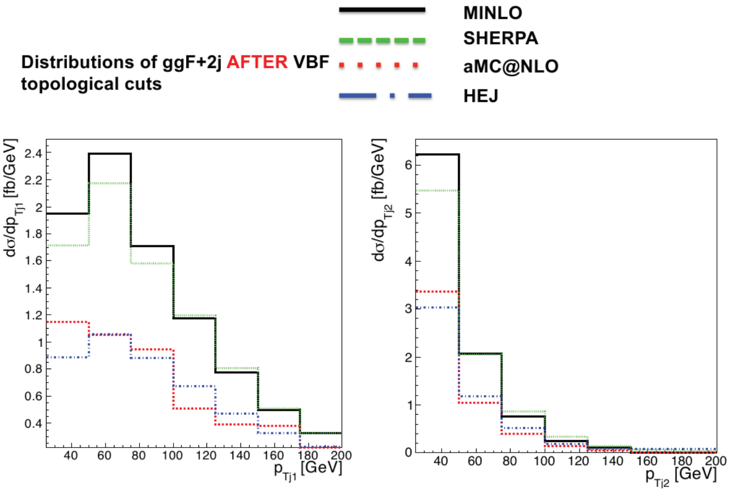


Distributions of ggF+2j **BEFORE** VBF topological cuts

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

Gavin Salam (CERN) Jets in Higgs Searches Higgs XS WG 2012-12-06 23 / 30

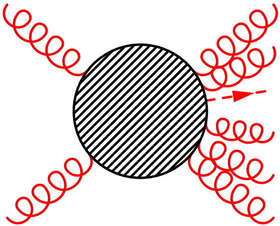
# Excess or not?


Distributions of ggF+2j AFTER VBF topological cuts

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

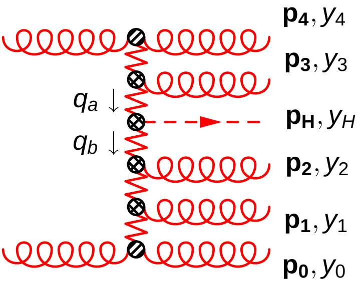
recall Sherpa is H+2@LO, aMC@NLO & MINLO are H+2@NLO

# Develop Insight Into the Perturbative Corrections



**High Energy Limit** $\longrightarrow$

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

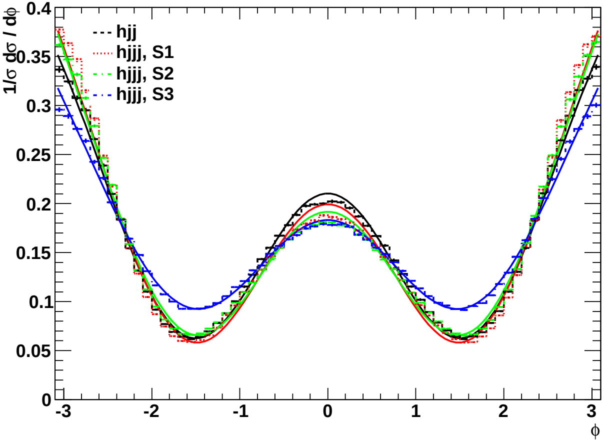


$$\left|\mathcal{M}_{gg\to g\cdots ghg\cdots g}\right|^2 \to \frac{4\hat{s}^2}{N_C^2-1}\left(\prod_{i=1}^{j}\frac{C_A\, g_s^2}{\mathbf{p}_{i\perp}^2}\right)\frac{|C^H(\mathbf{q}_{a\perp},\mathbf{q}_{b\perp})|^2}{\mathbf{q}_{a\perp}^2\ \mathbf{q}_{b\perp}^2}\left(\prod_{i=j+1}^{n}\frac{C_A\, g_s^2}{\mathbf{p}_{i\perp}^2}\right)$$

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

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!

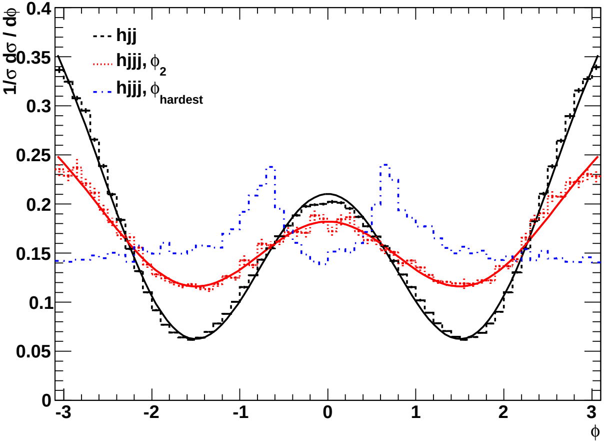
# And It Even Works!



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 Any 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.

# 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)