Jets, Jets, Higgs & Jets

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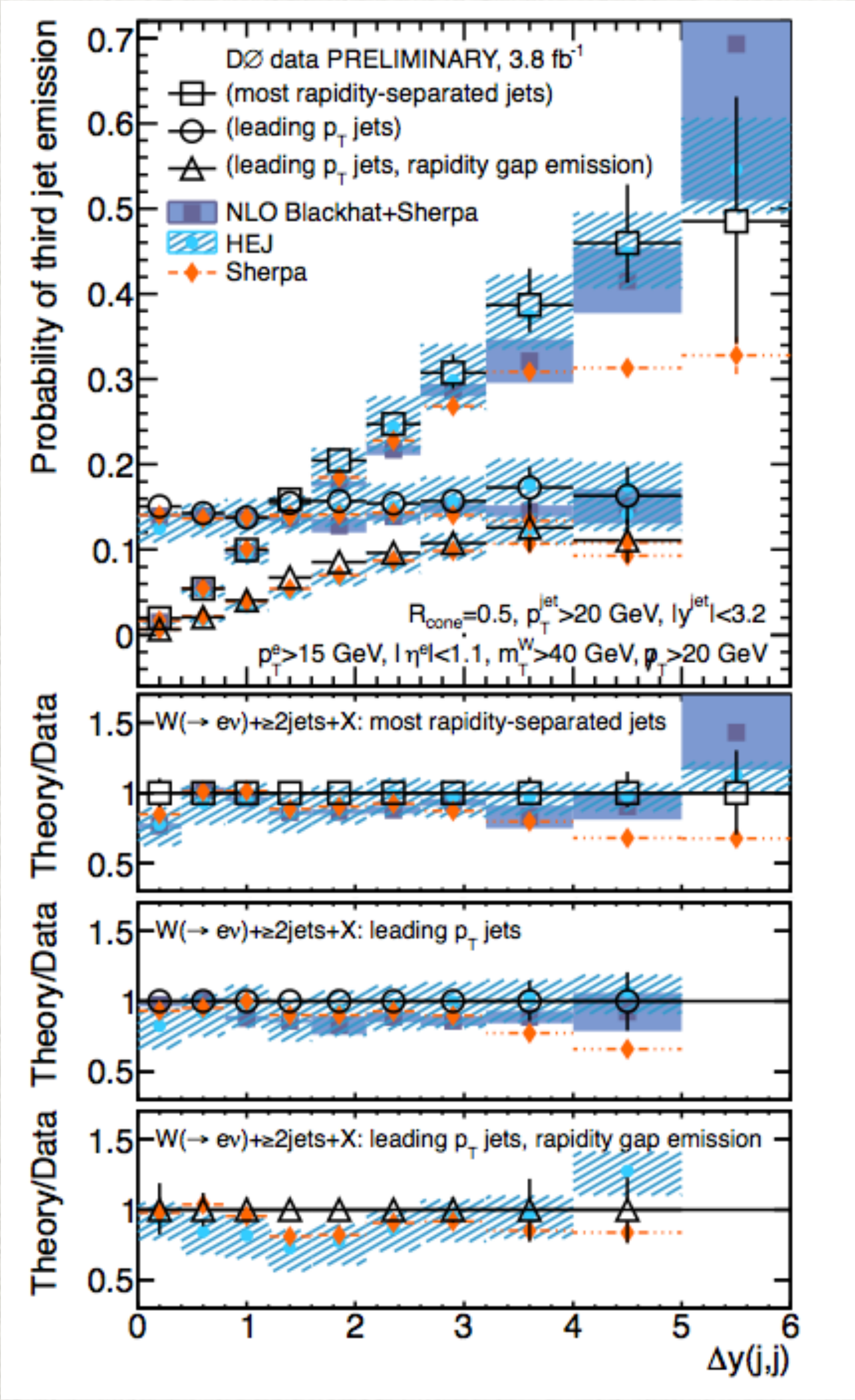
Mostly HEJ = with J. Andersen, T. Hapola, J. Medley
(+ J. Cockburn, H. Brooks)

UCL Seminar **24 Jan 2014**

Outline

- Introduction
- High Energy Jets
- Recent Jet Results
- Higgs Plus Jets



D0 arXiv:1302.6508

Why Study Jets?

- Complex Standard Model Process

  Therefore complex test of tools

- Test models of jet vetoes etc. here before Higgs

- IF new physics is hiding, need precision to find it

- Many tools available... with different strengths

Higher Orders

- Already seen (n+1)-jet rates are not small

  e.g. ATLAS Z+jets

  $$\frac{\text{(n+1)-jet rate}}{\text{n-jet rate}} \approx 0.2,\ n=1,\ldots,6\ (!)$$

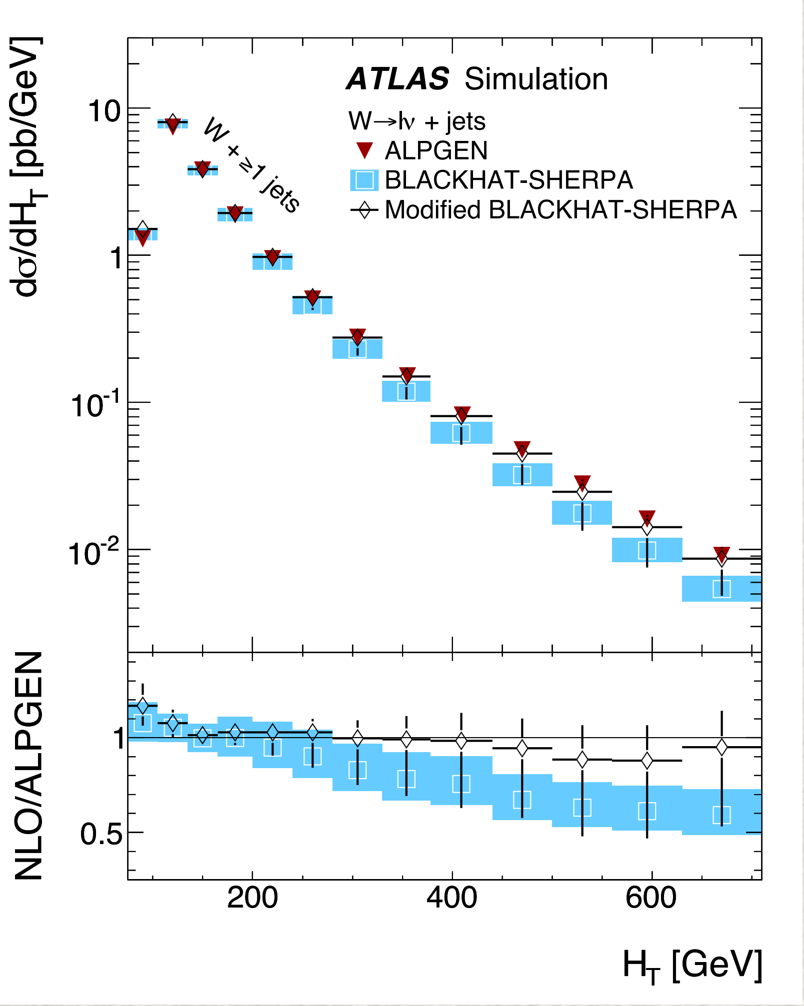
  Rises to 0.3 after VBF cuts!

arXiv:1304.7098

- NLO is only one more emission

  Consistently need to combine orders

  to describe data



ATLAS W+jets arXiv:1201.1276

Merging Higher Orders

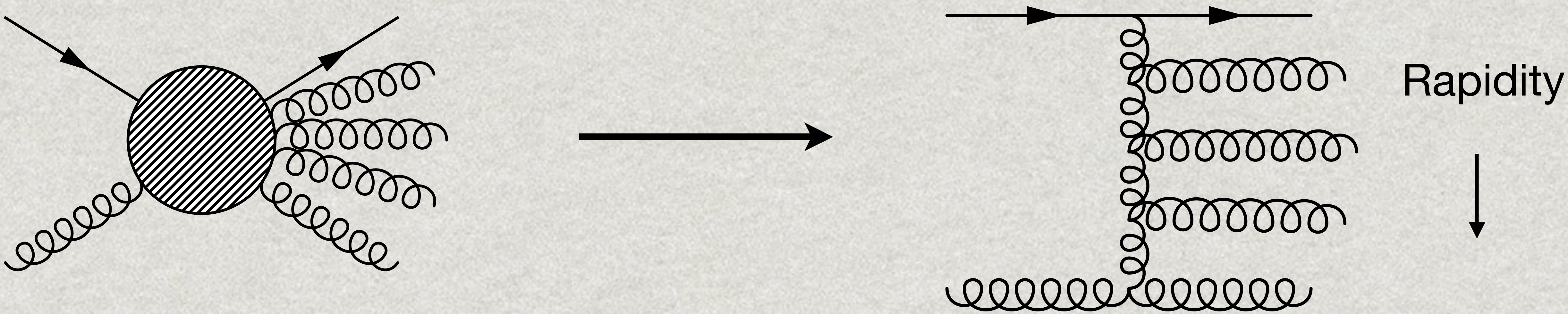
- NLO + Parton Shower: POWHEG, MC@NLO
- New approaches available to merge NLO at different orders. Lönnblad & Prestel (UNLOPS), Plätzer
- Alternatively: calculate all-orders in the first place!
- High Energy Jets provides systematic description of hard, wide-angle emissions at all orders
- Price: have to approximate the matrix element

High Energy Limit

- The High Energy (Multi-Regge) limit is:

$$s_{ij} \to \infty, \quad |p_{\perp_i}| \sim |p_{\perp_j}|, \quad i, j = 1, ..., n$$

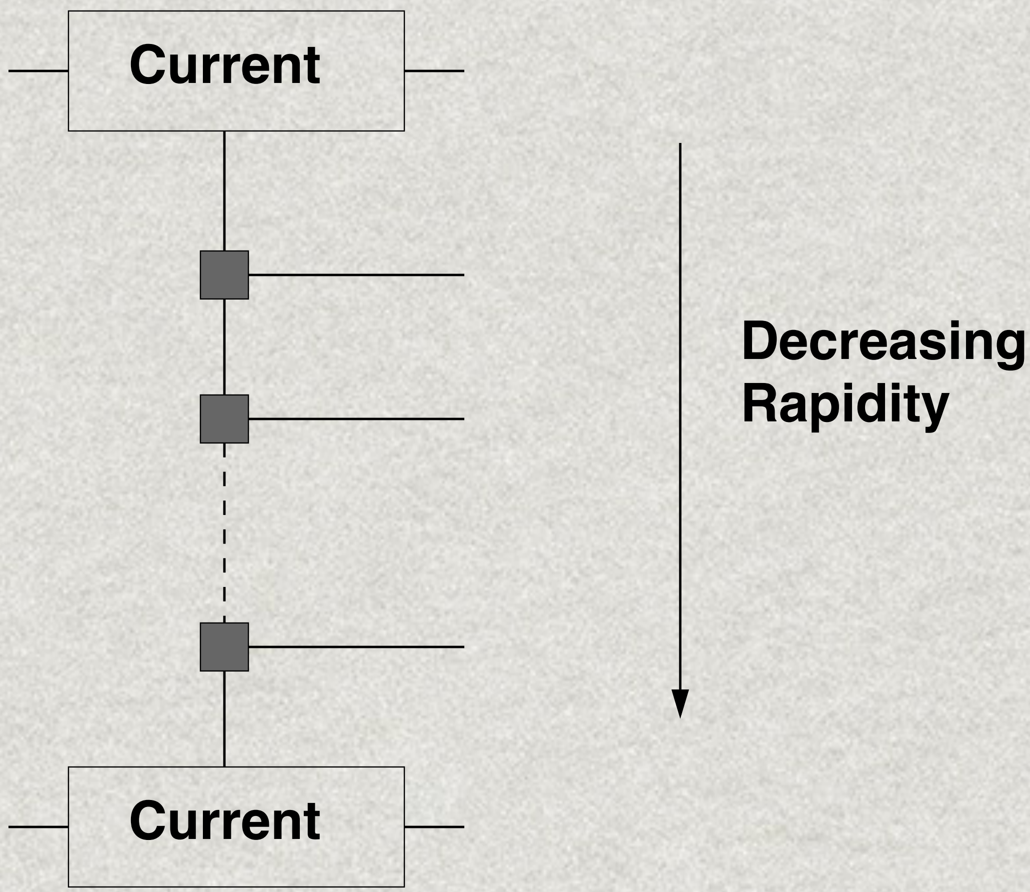
In practice, particles spread out in rapidity



- Dominant Momentum Configurations in HE limit correspond to those which would allow maximum t-channel gluon exchanges:
- Other orderings are logarithmically suppressed.

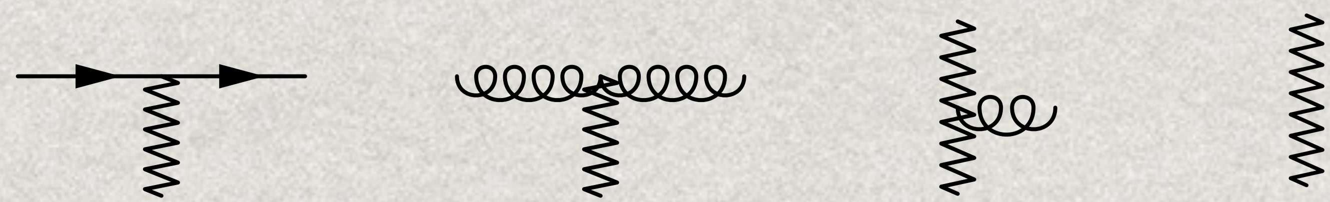
A HEJ Amplitude

- <u>All</u> scattering amplitudes factorise in this limit
  ⇒ Can exploit this to build a simple approximation.



- A HEJ amplitude is structured:

current-current
x product-of-emissions

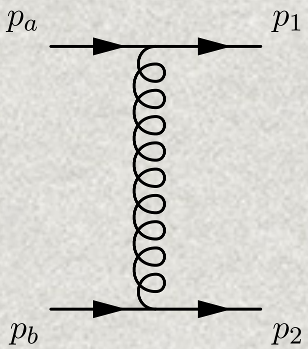


Applies to loop diagrams too (needed to regulate soft).

Pieces I: Currents

Pieces independent of rest of chain - pick convenient processes

- Incoming quarks: straight-forward



$$\frac{8g_s^4}{9}\frac{|j^\mu(p_a,p_1)\cdot j_\mu(p_b,p_2)|^2}{\hat{t}^2}$$
$$= \frac{4g_s^4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$$

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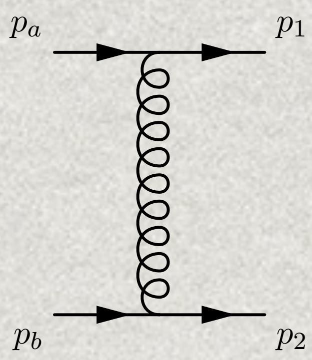
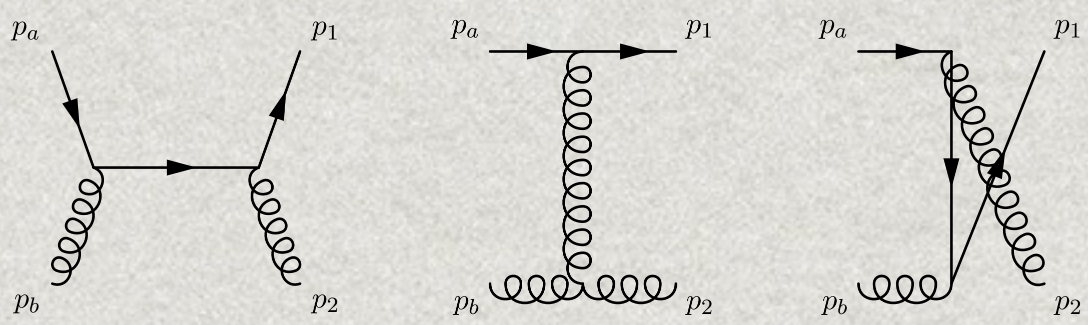


$$\frac{8g_s^4}{9}\frac{|j^\mu(p_a,p_1)\cdot j_\mu(p_b,p_2)|^2}{\hat{t}^2}$$
$$=\frac{4g_s^4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$$

- Incoming gluons: surprisingly so!



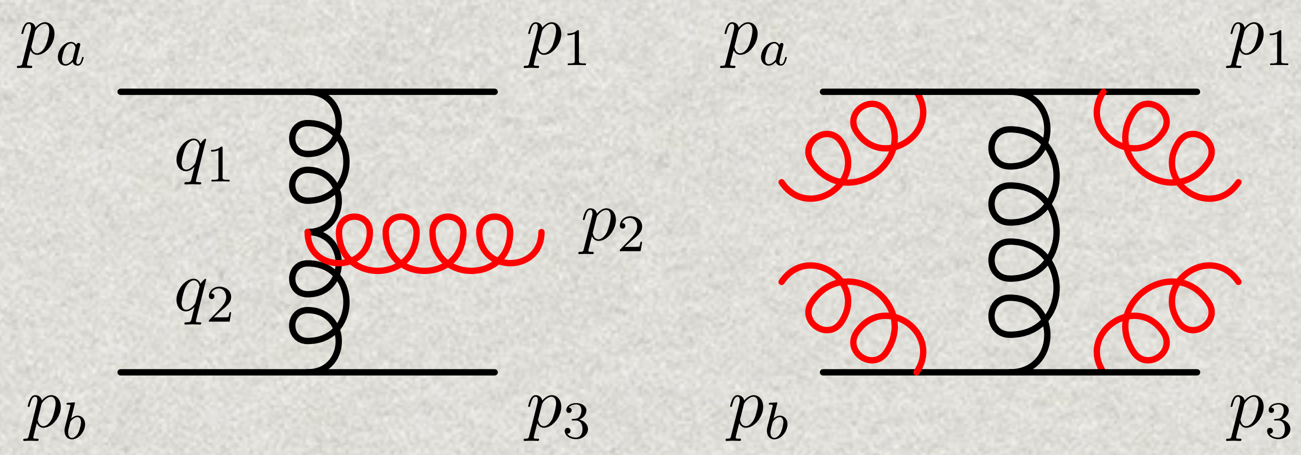
- <u>Exact</u> result: $\frac{g_s^4 C_{CAM}}{6}\;\frac{|j^\mu(p_a,p_1)\cdot j_\mu(p_b,p_2)|^2}{\hat{t}^2}$

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

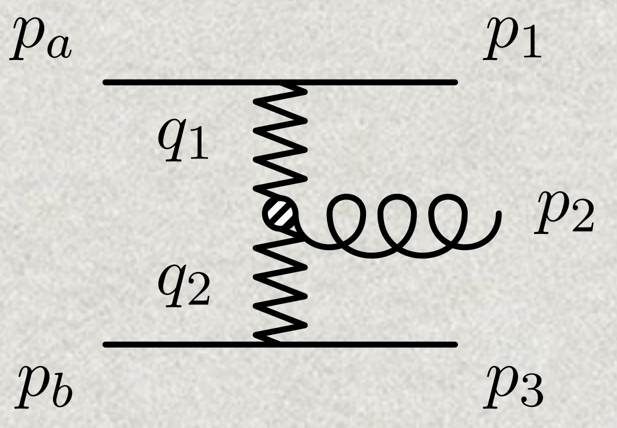
- Only t-pole remains explicitly

Pieces II: Emission Vertices

- Use qQ → qgQ



- In HE limit, colour factors combine to give



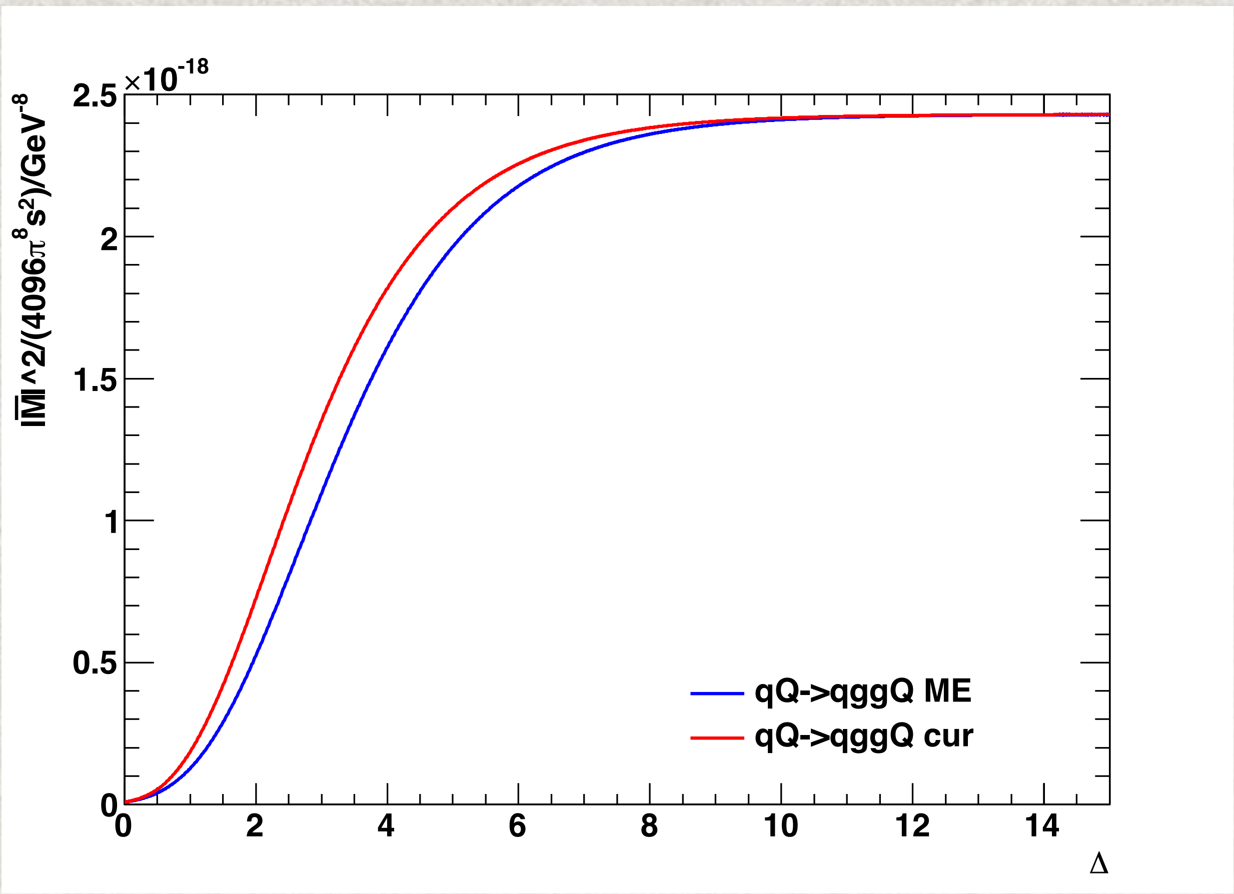
$$\mathcal{A}_{qQ\to qgQ} = g_s^3\ \mathcal{C}_g\ \varepsilon_\rho^*\ \frac{j^\mu(p_a,p_1)\cdot j_\mu(p_b,p_3)}{q_1^2 q_2^2}\ V^\rho(q_1,q_2)$$

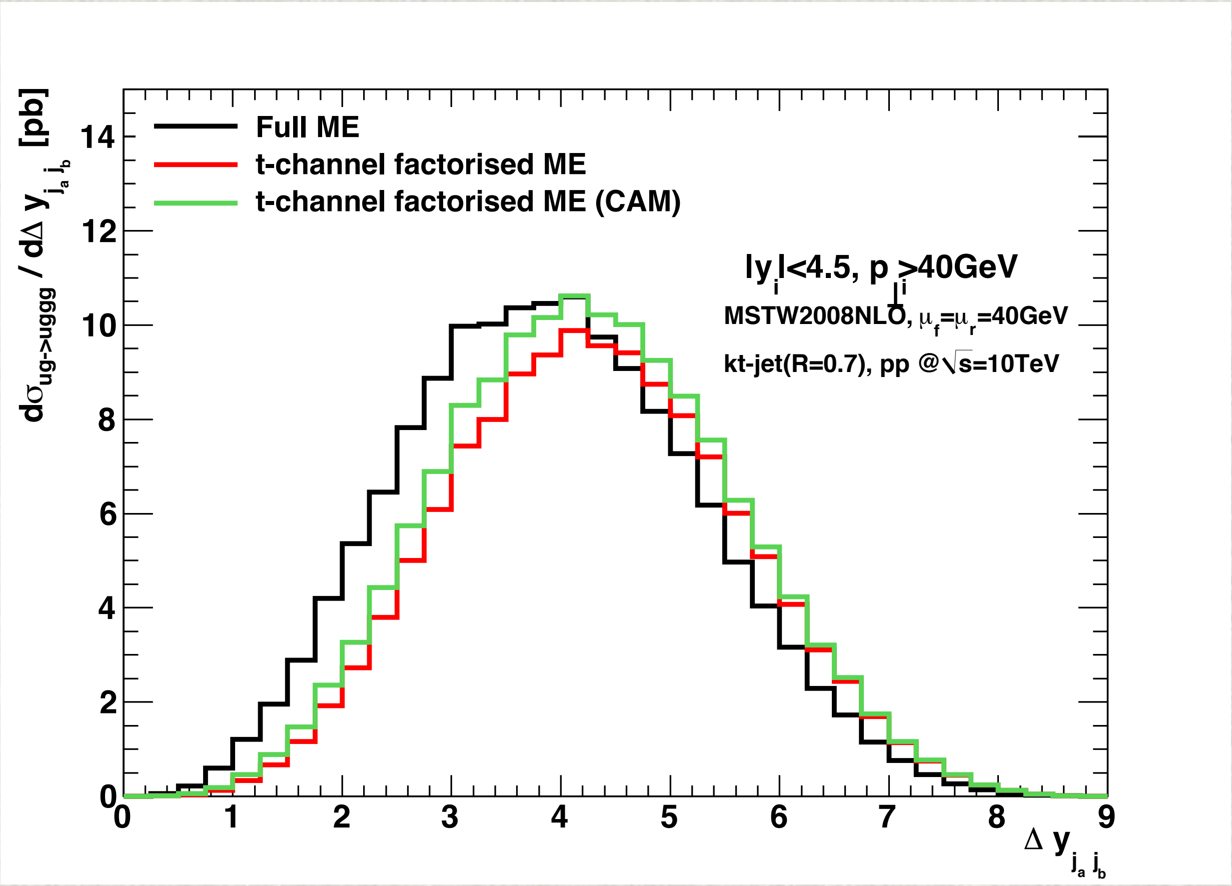
$$\begin{aligned} V^\rho(q_1,q_2) = &-(q_1+q_2)^\rho \\ &+ \frac{p_a^\rho}{2}\left(\frac{q_1^2}{p_2\cdot p_a} + \frac{p_2\cdot p_b}{p_a\cdot p_b} + \frac{p_2\cdot p_3}{p_a\cdot p_3}\right) + p_a \leftrightarrow p_1 \\ &- \frac{p_b^\rho}{2}\left(\frac{q_2^2}{p_2\cdot p_b} + \frac{p_2\cdot p_a}{p_b\cdot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

Gauge invariant in *all* of phase space.

Andersen & JMS arXiv:0908.2786

Does It Work?



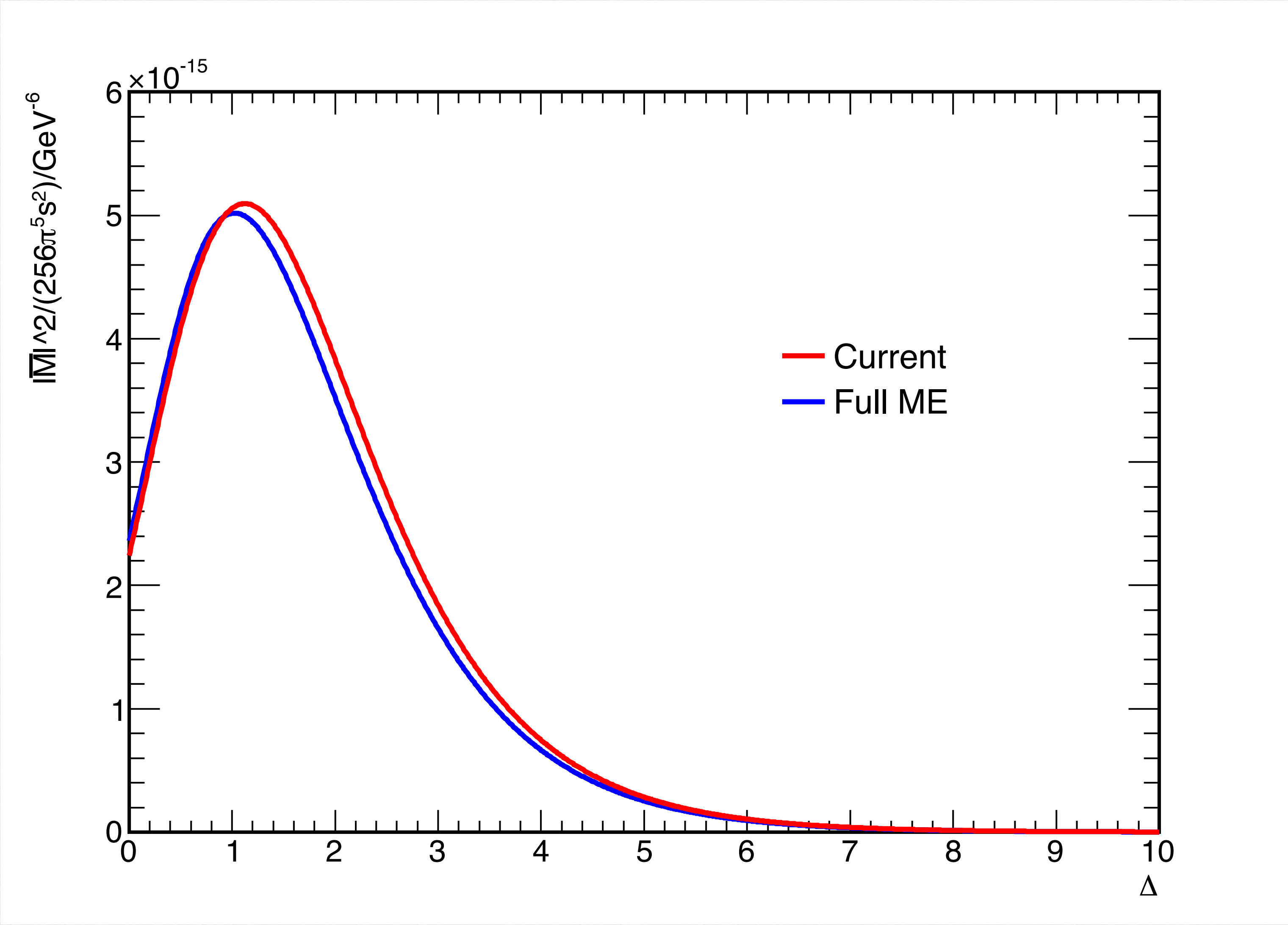


$qQ \to qggQ$

$qg \to qggg$

Even when it's not supposed to!

Gluon now pulled forward of both quarks:



us → usg

Pieces III: Regulation

Last part is to regulate divergences when $p_i \to 0$

HE limit of virtual corrections is given by the Lipatov Ansatz

$$= \frac{1}{t_i} \exp[\hat{\alpha}(q_i)(y_{i-1} - y_i)]$$

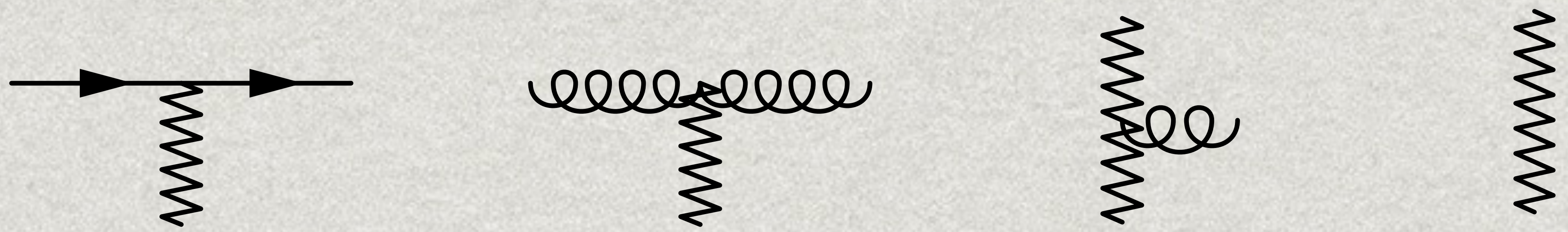
$$\hat{\alpha}(q_i) = \alpha_s \; C_A \; t_i \int \frac{d^{2+2\epsilon} k_\perp}{(2\pi)^{2+2\epsilon}} \frac{1}{k_\perp^2 (q_i - k)_\perp^2}$$

$$\to -g_s^2 C_A \; \frac{\Gamma(1-\varepsilon)}{(4\pi)^{2+\varepsilon}} \frac{2}{\varepsilon} \left(\mathbf{q}^2/\mu^2\right)^\varepsilon$$

Proved to next-to-leading log

Fadin, Fiore, Kozlov & Reznichenko: hep-ph/0602006

Assembly



Build fully-flexible Monte Carlo from these

Match to exact LO if cluster into 2, 3 or 4 jets

Add missing momentum configurations for 2,3 & 4j

Publicly available at

http://cern.ch/hej

Jets, W+jets, Higgs+jets, HEJ+ARIADNE

In a Nutshell:

- High Energy Jets describes QCD emissions at large s_{ij}

  ⇒ Captures hard jet production

$$s_{ij} = 2p_{Ti}p_{Tj}\left(\cosh(y_i - y_j) - \cos(\phi_i - \phi_j)\right)$$

- Opposite limit to a parton shower, which sums large contributions at small s_{ij}

  ⇒ Good at jet substructure, underestimates rate/hardness

- Can combine both (but not straight-forward).

Andersen, Lönnblad & JMS arXiv:1104.1316

Early Jet Results

ATLAS: gap fraction

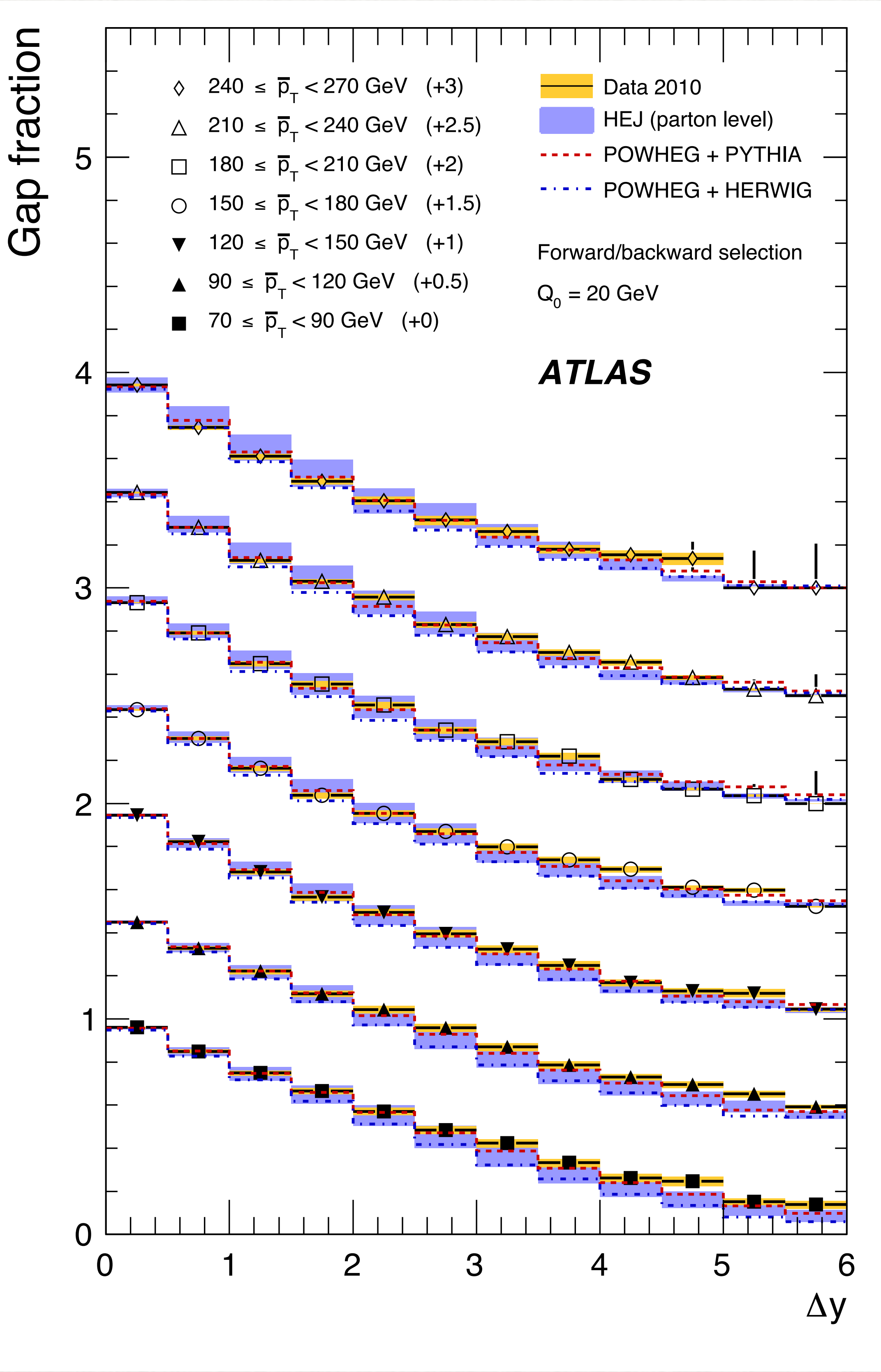
$$\text{Gap Fraction} = \frac{\sigma(\text{no jets in gap})}{\sigma(\text{2j inclusive})}$$

$\bar{p}_T$ = average p_T of tagging jets

Tagging = most forward/ backward

Good agreement with POWHEG+PYTHIA & HEJ

arXiv:1107.1641



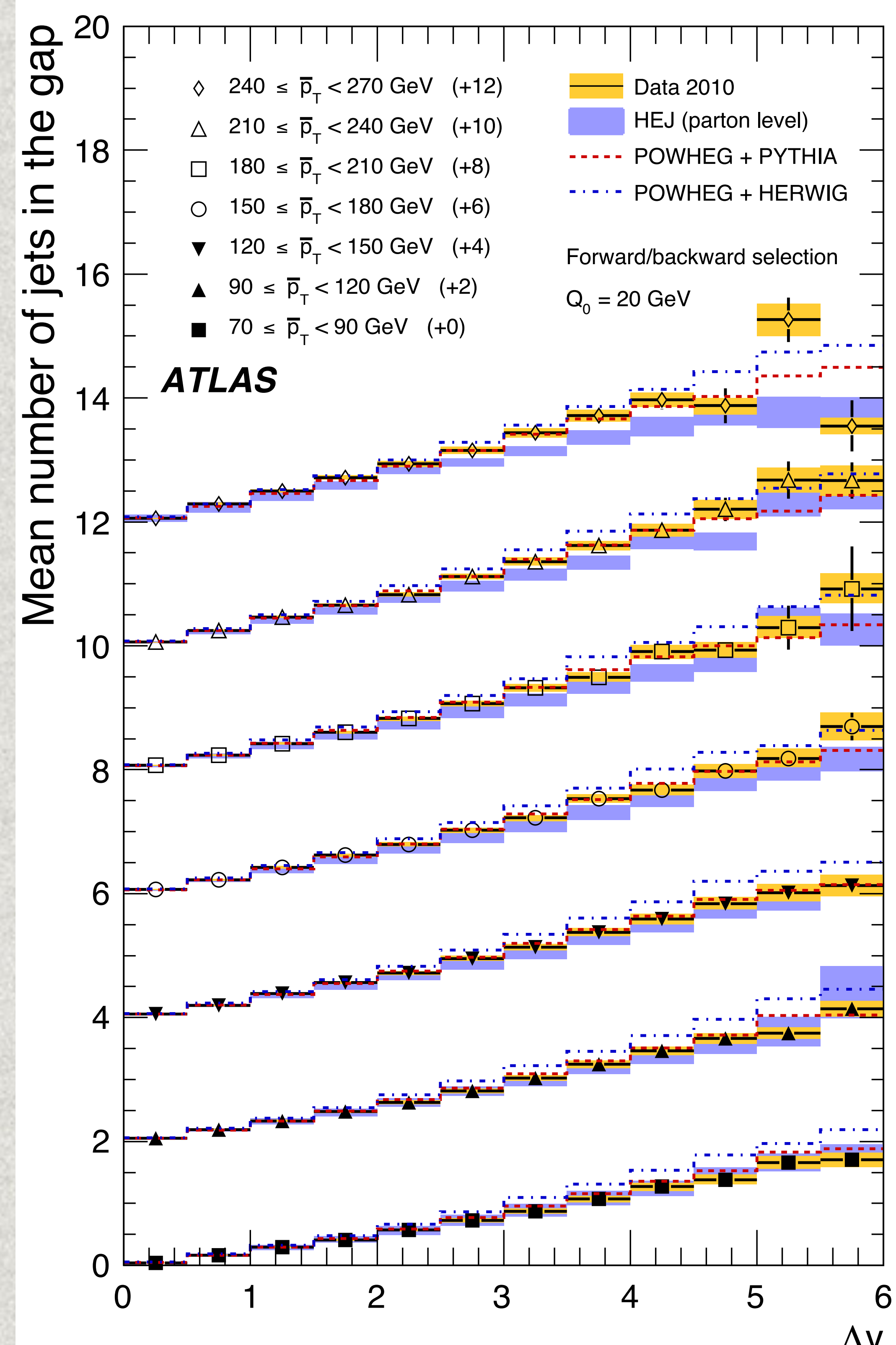
ATLAS: jet veto analysis

Now, average number of additional jets.

More than one extra jet on average for $\Delta y > 3$
Clearly beyond NLO!

Tagging = most forward/
backward

Still good agreement



arXiv:1107.1641

ATLAS: gap fraction

$$\text{Gap Fraction} = \frac{\sigma(\text{no jets in gap})}{\sigma(\text{2j inclusive})}$$

Now, tagging jets are leading p_T

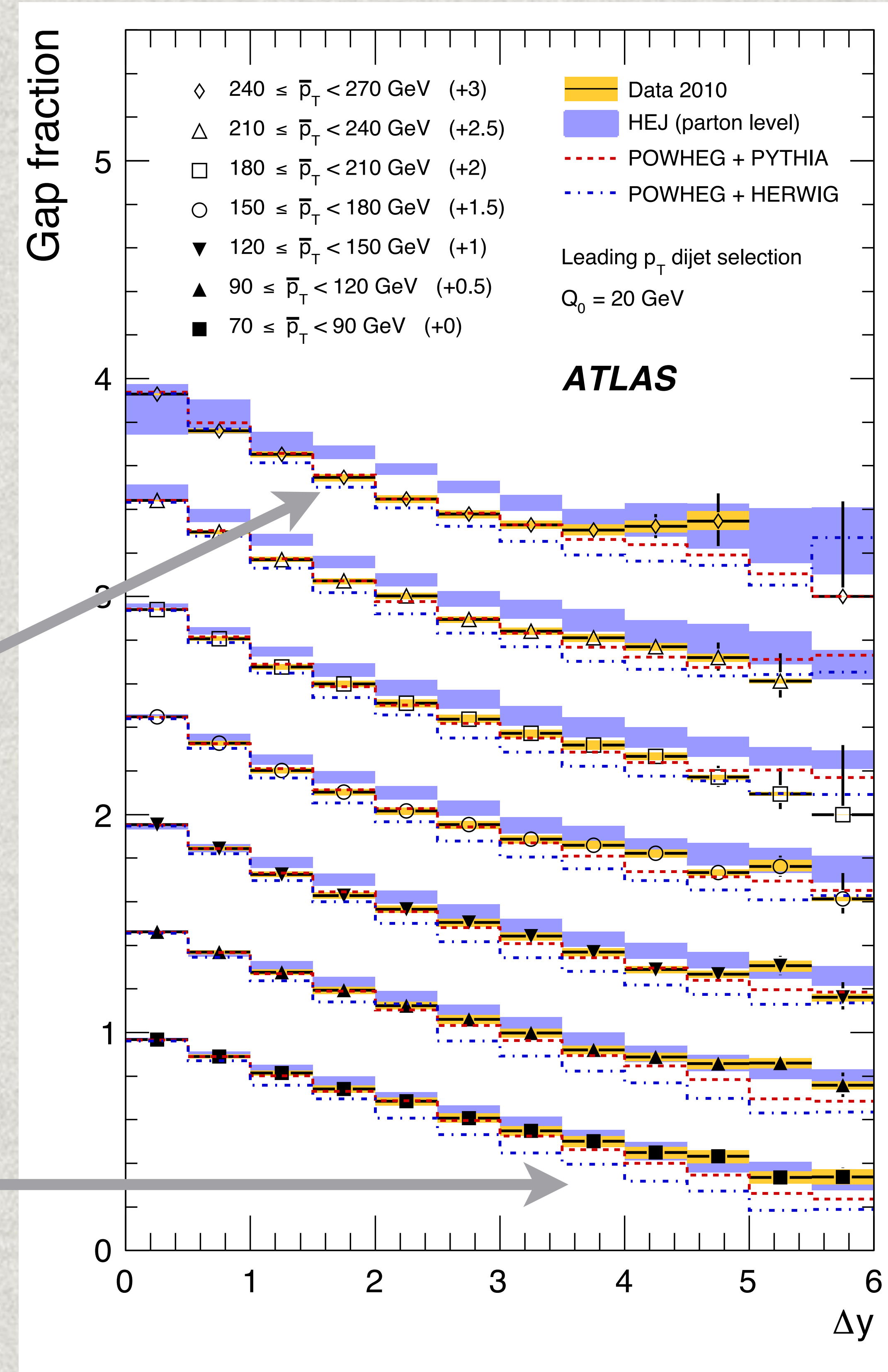
Hierarchy in p_T (up to factor 10!)

p_T evolution not in HEJ

Evolution in rapidity

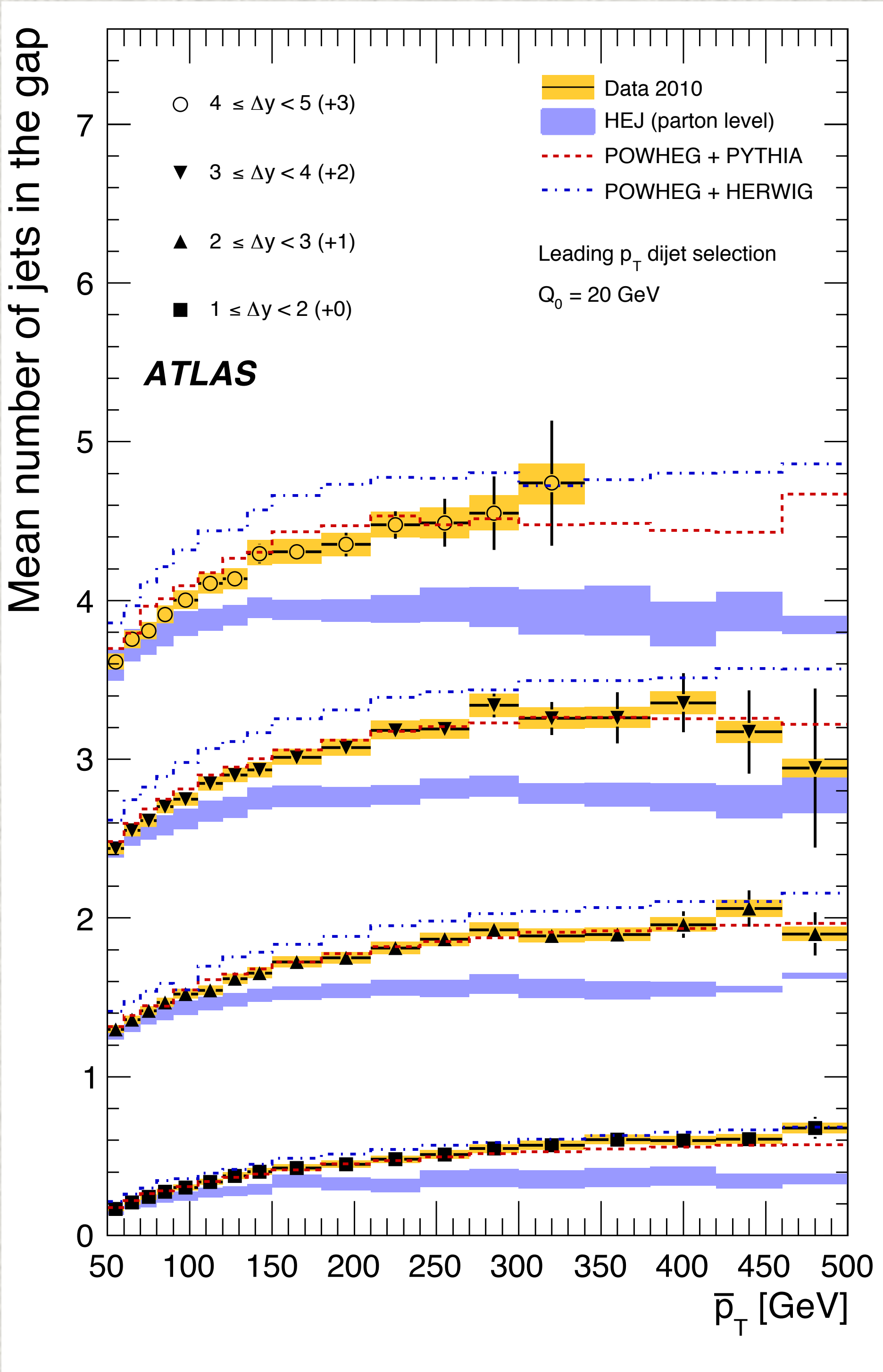
HEJ description good,

POWHEG undershoots



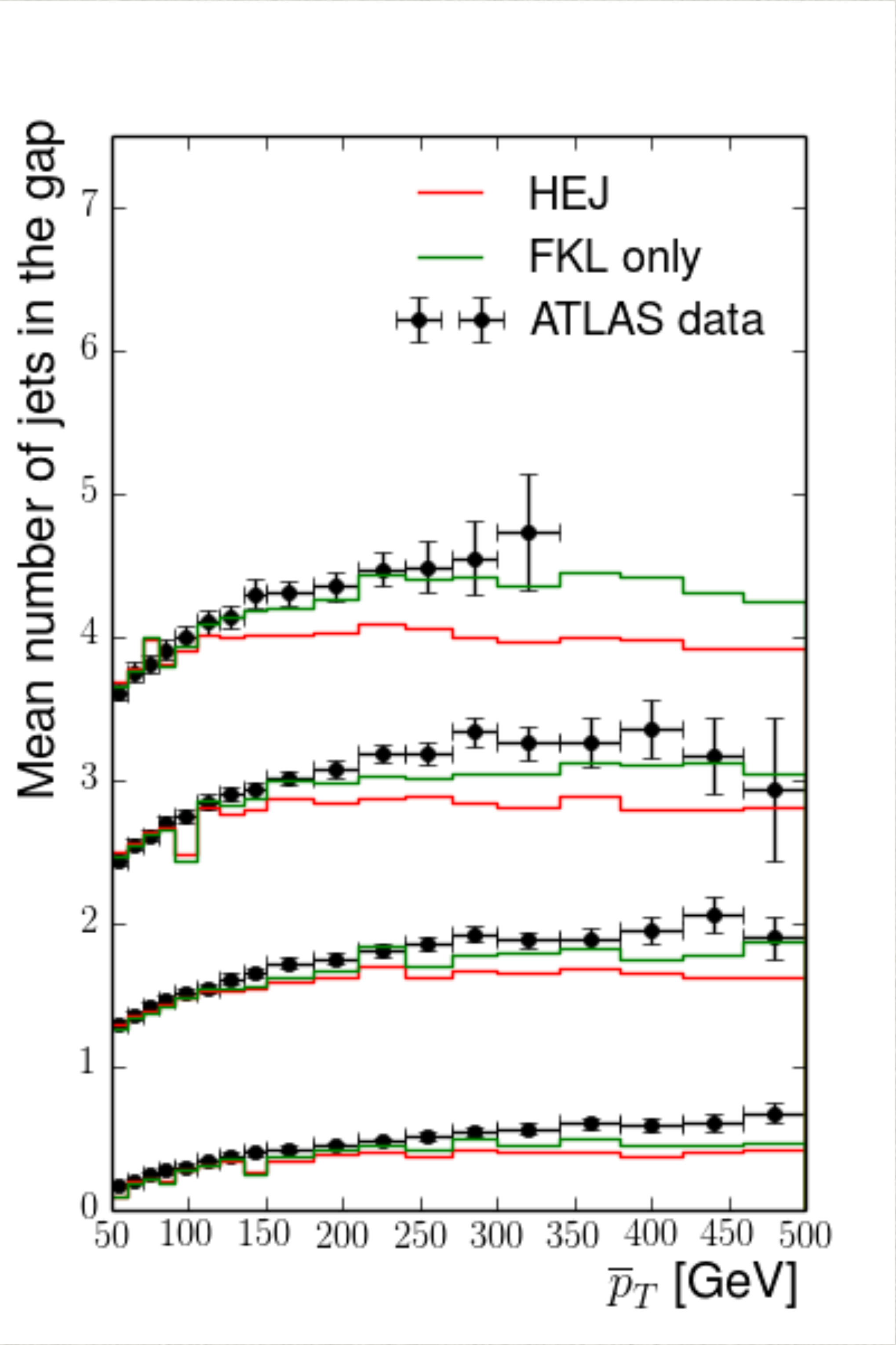
arXiv:1107.1641

ATLAS: What we now know!



Turning off matching (green) improves HEJ description

No resummation included in the matching and it dominates the cross section at large p_T

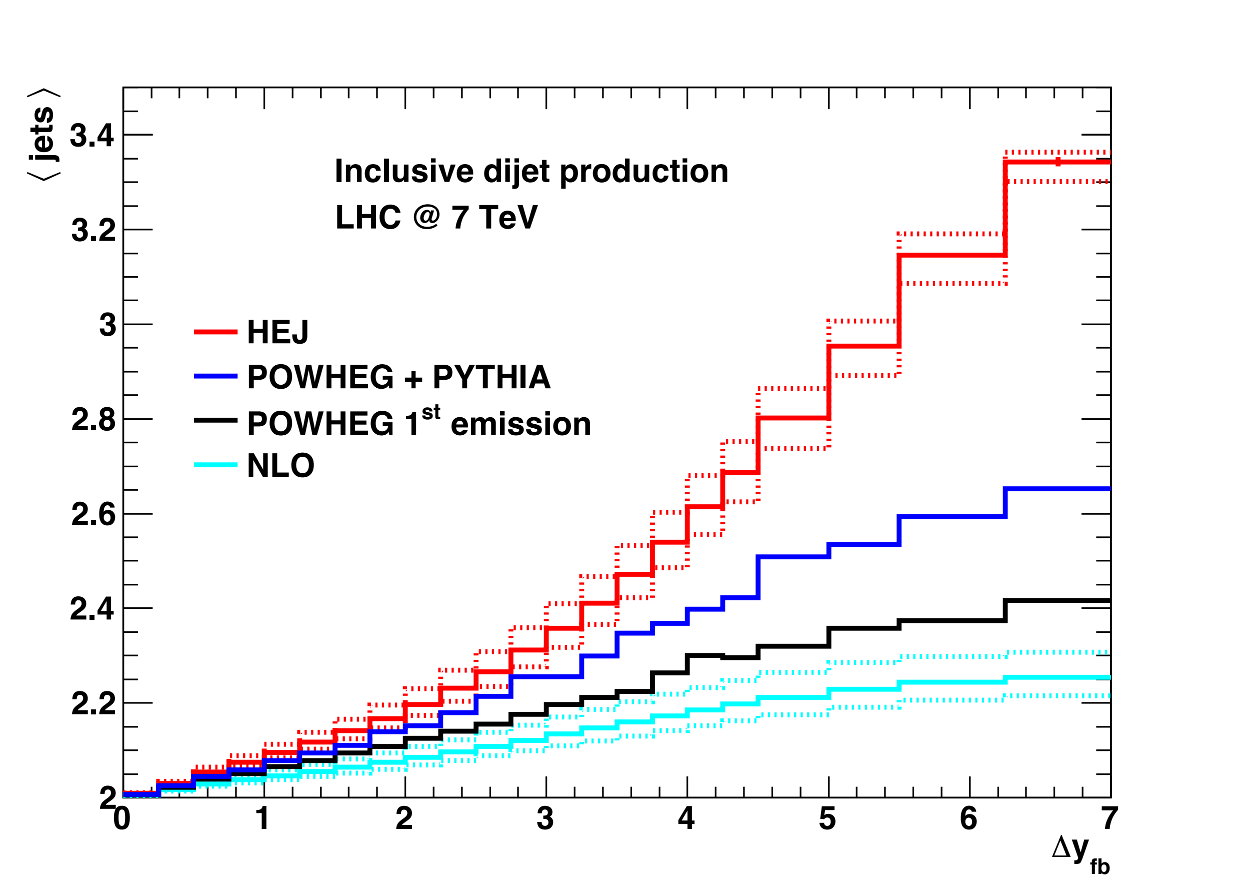


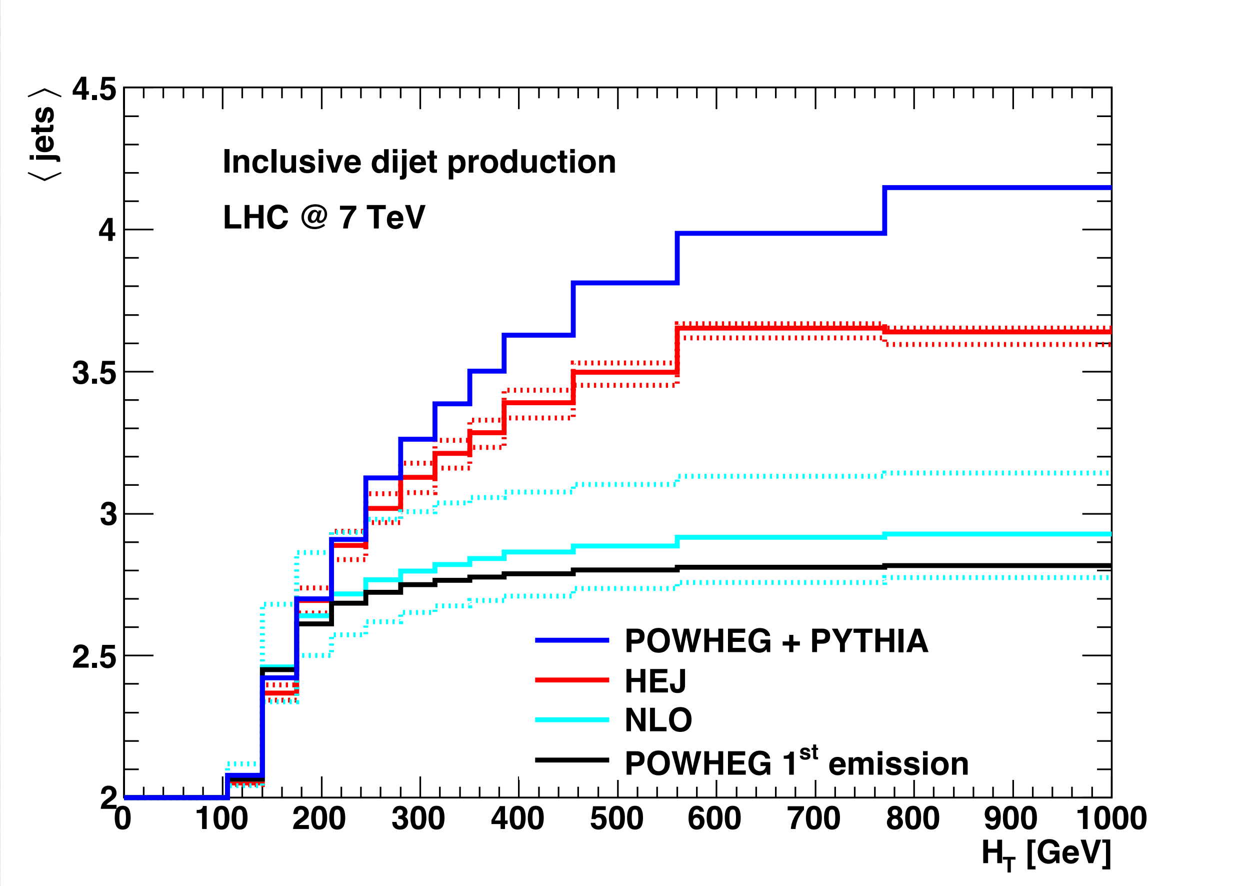
arXiv:1107.1641

DiJet Comparison

POWHEG+PYTHIA and HEJ gave very similar predictions

Can they be distinguished?





$$p_{T,j} > 35 \text{ GeV}, \; p_{T,j1} > 45 \text{ GeV}, \; |y_j| < 4.7$$

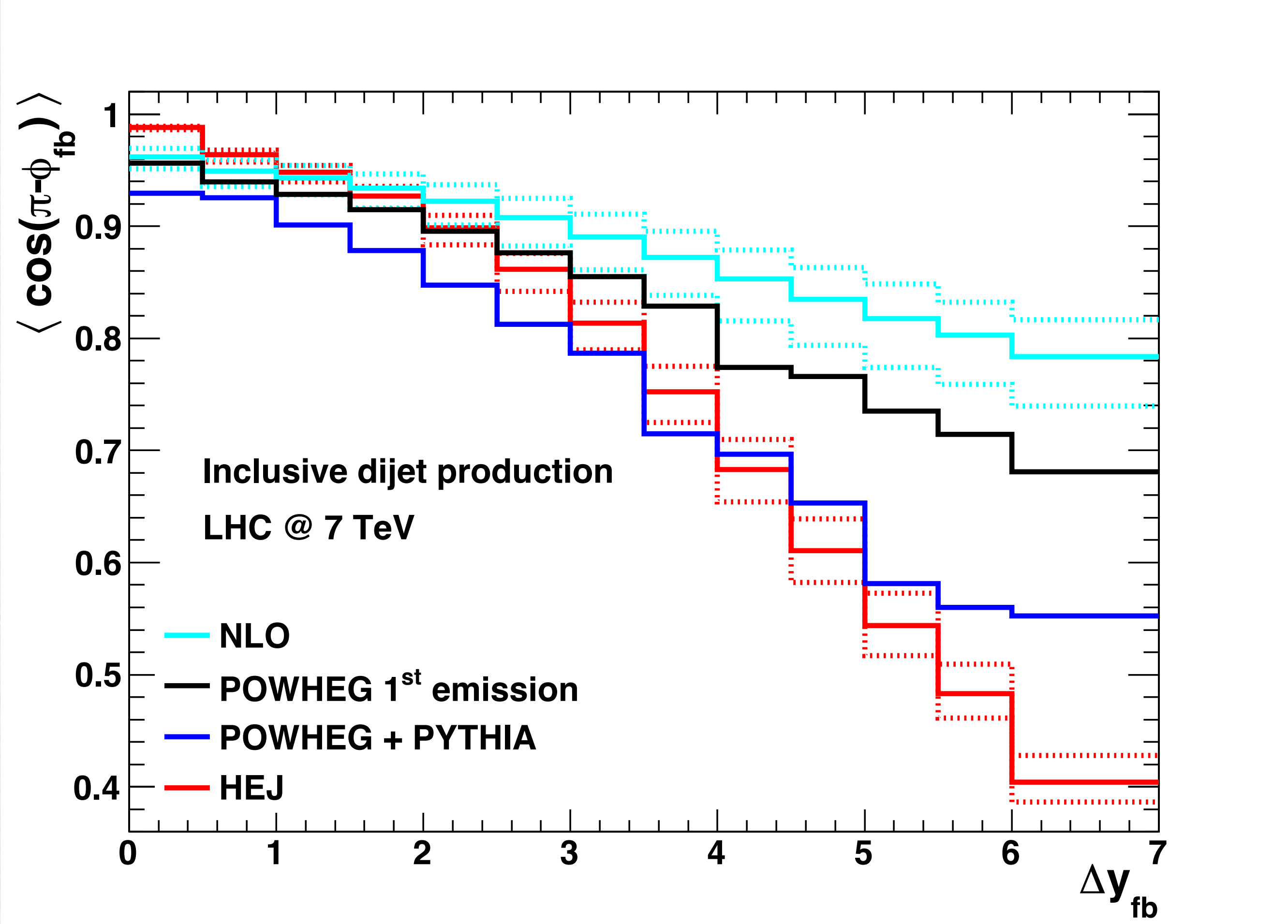
Choose cuts which do not induce p_T hierarchy

Alioli, Andersen, Oleari, Re & JMS arXiv:1202.1475

DiJet Comparison

Other variables show little difference, e.g. $\cos(\phi_{fb})$

ϕ_{fb} = azimuthal angle between forward and backward jet

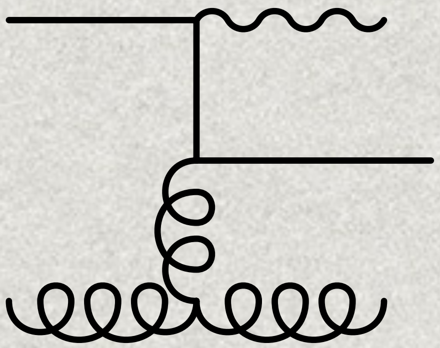


Azimuthal decorrelation gives measure of extra radiation

Alioli, Andersen, Oleari, Re & JMS arXiv:1202.1475

Recent W+jets Results

Extension to Ws

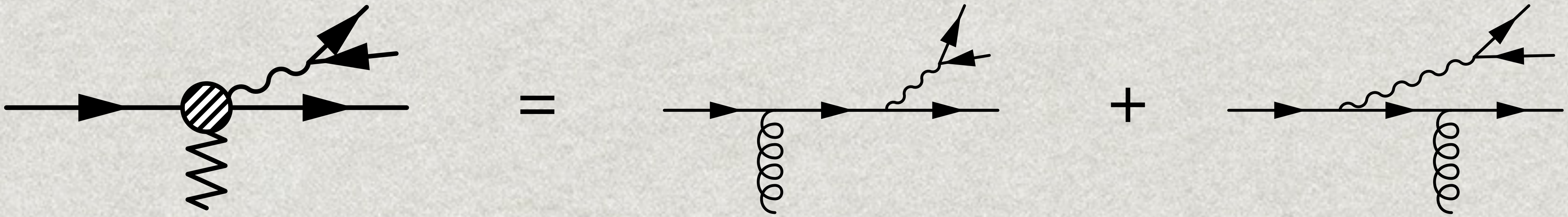


qg-channel dominant for W+nj at LHC

Treated in HE limit before, with constraint on decays

Andersen, Del Duca, Maltoni & Stirling: hep-ph/0105146

In HEJ:

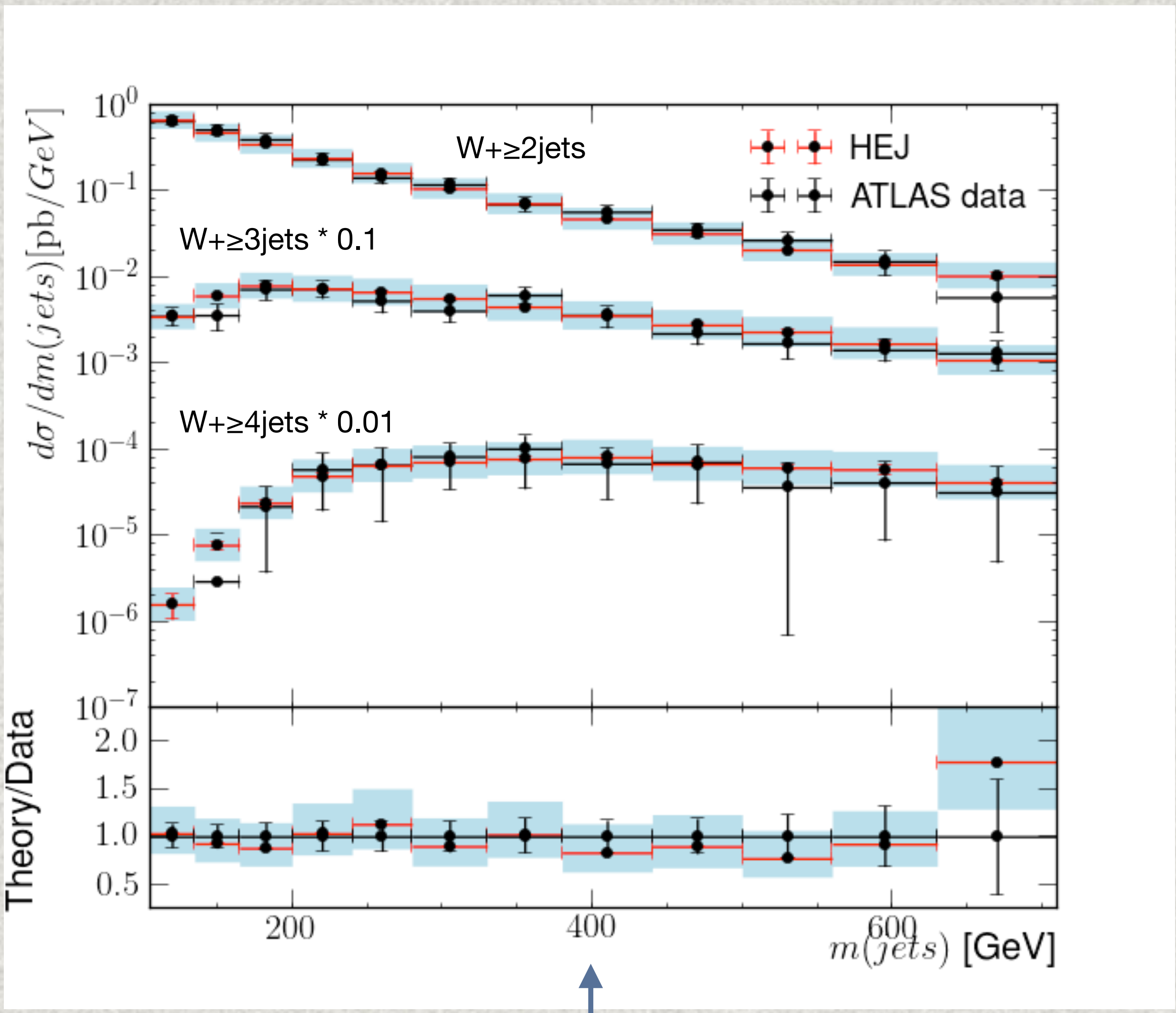


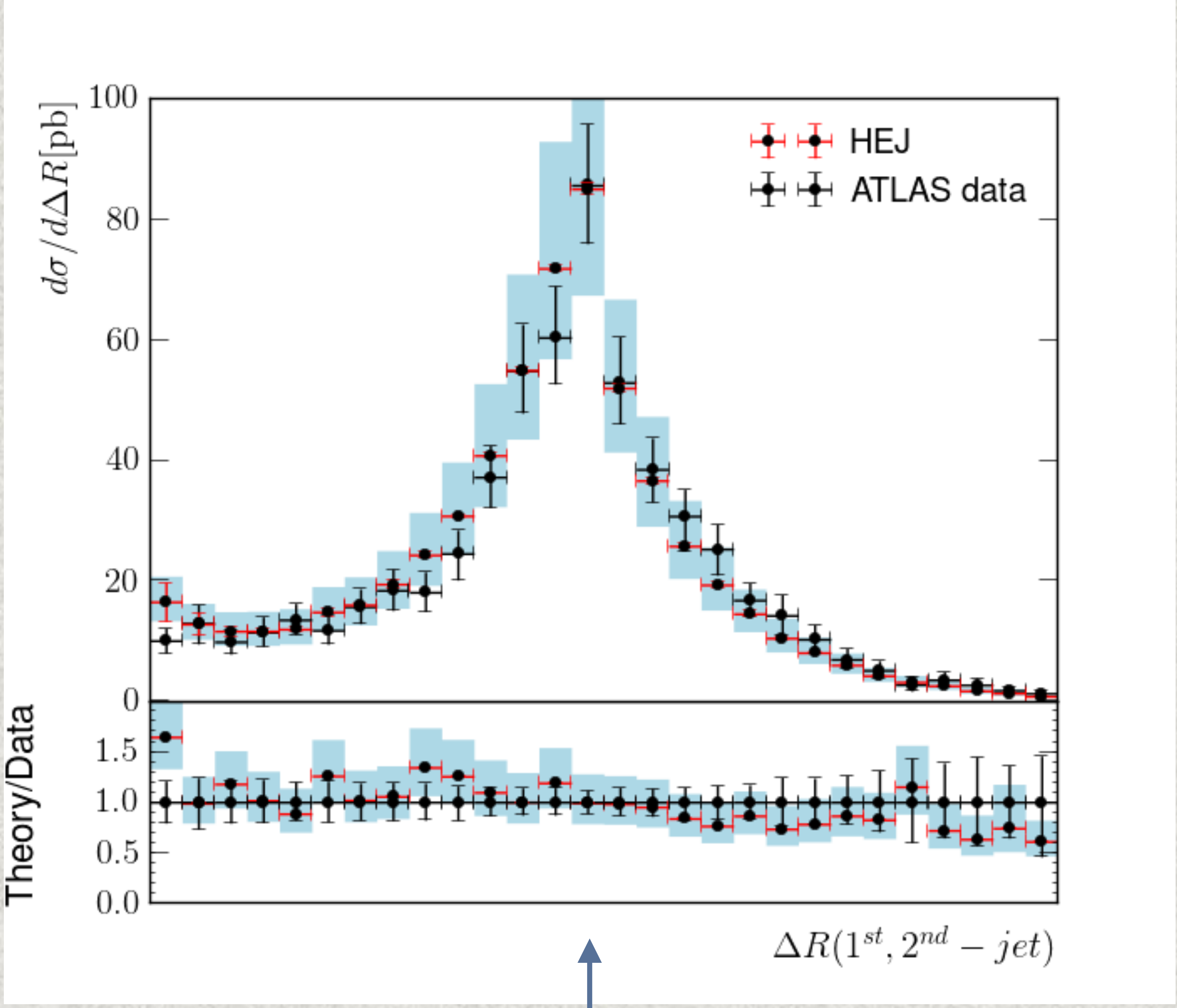
No constraints on decay products of W (or Z/γ^*)

Andersen, Hapola & JMS arXiv:1206.6763

ATLAS W+dijets

HEJ again gives good description:





Note large impact of higher orders!

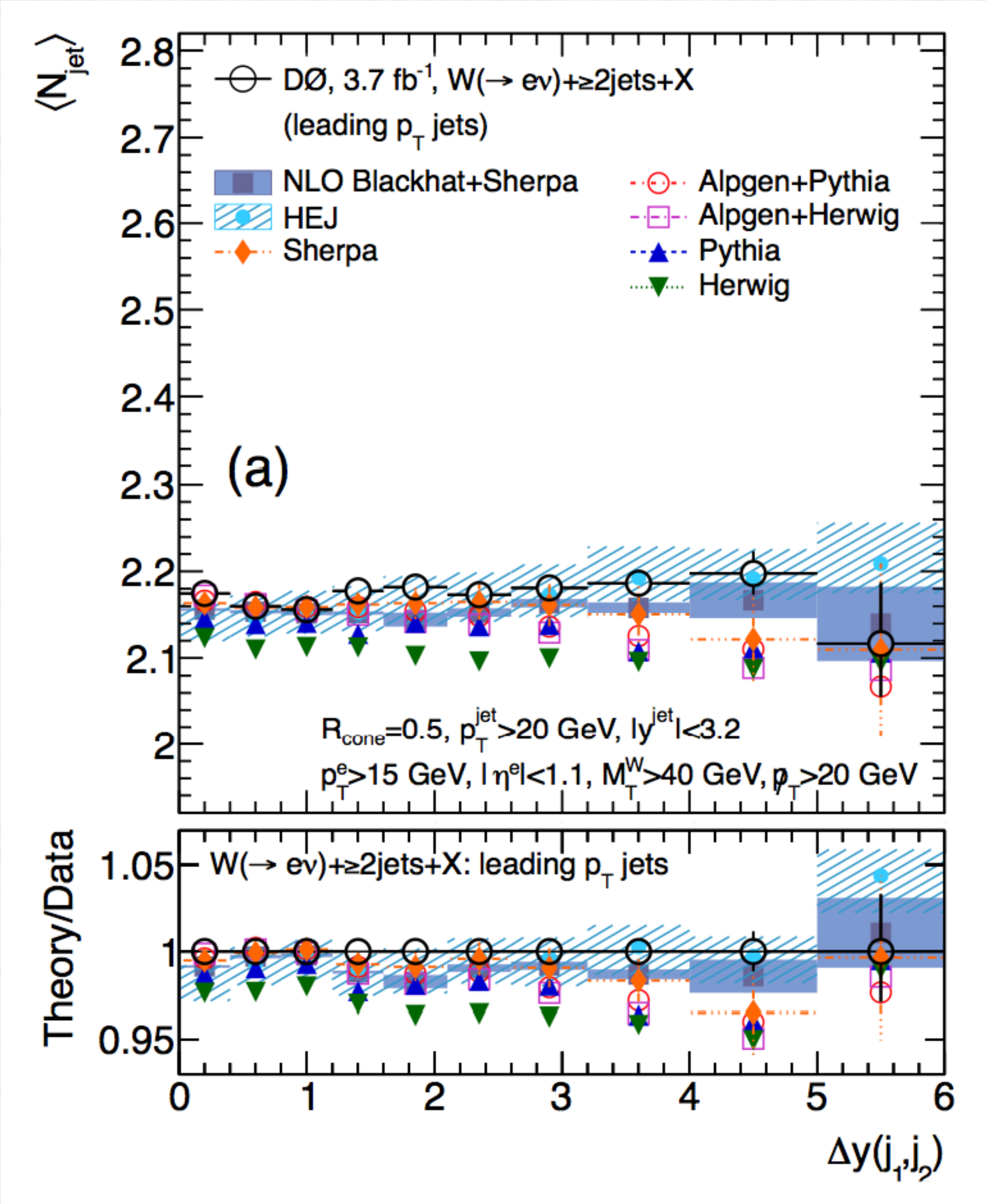
Traditionally very hard to describe (testing ground for state-of-the-art) HEJ gives good description

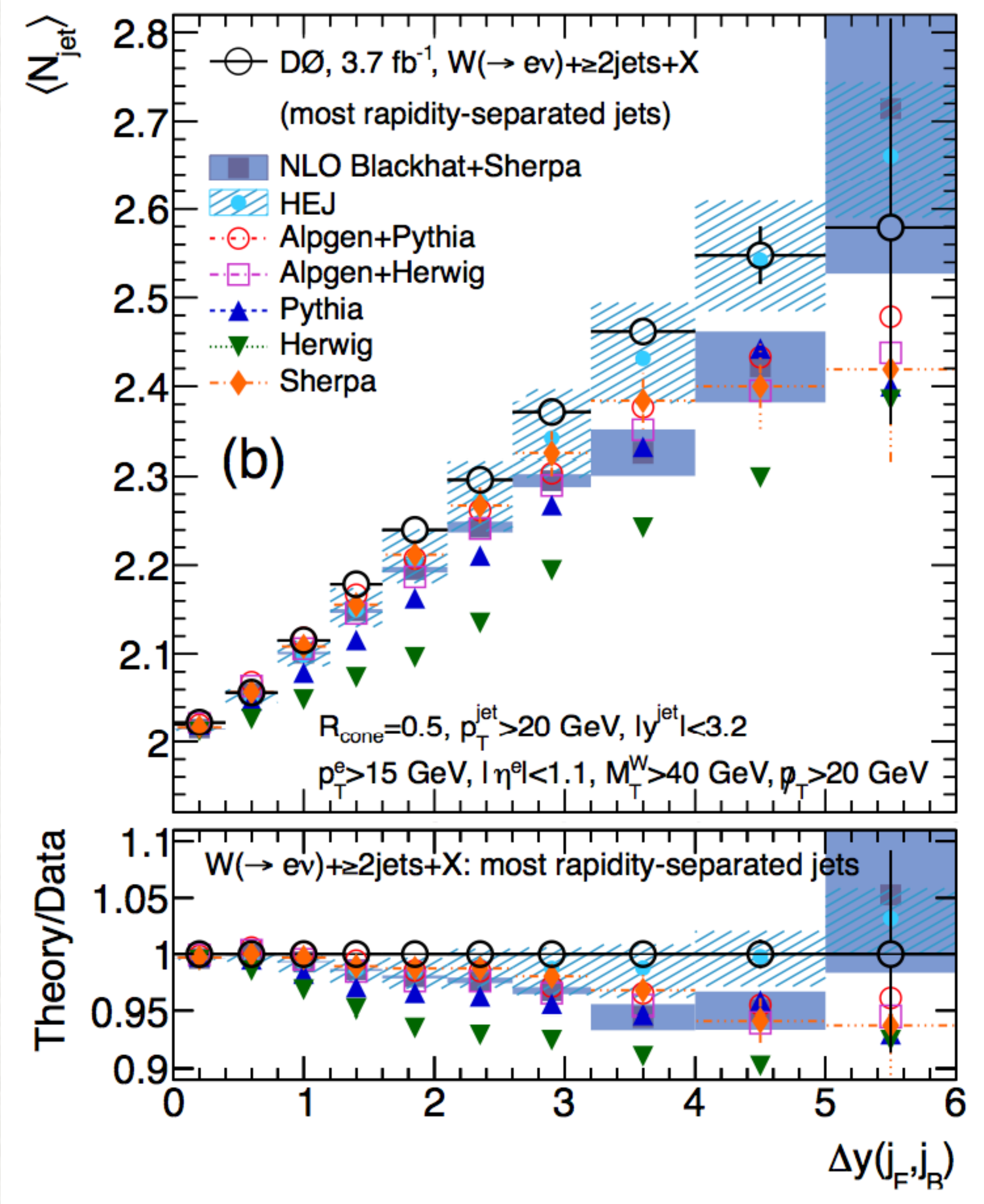
ATLAS (2010) data arXiv:1201.1276

Andersen, Hapola & JMS arXiv:1206.6763

D0 W+Jets

Really thorough analysis: 40 observables!





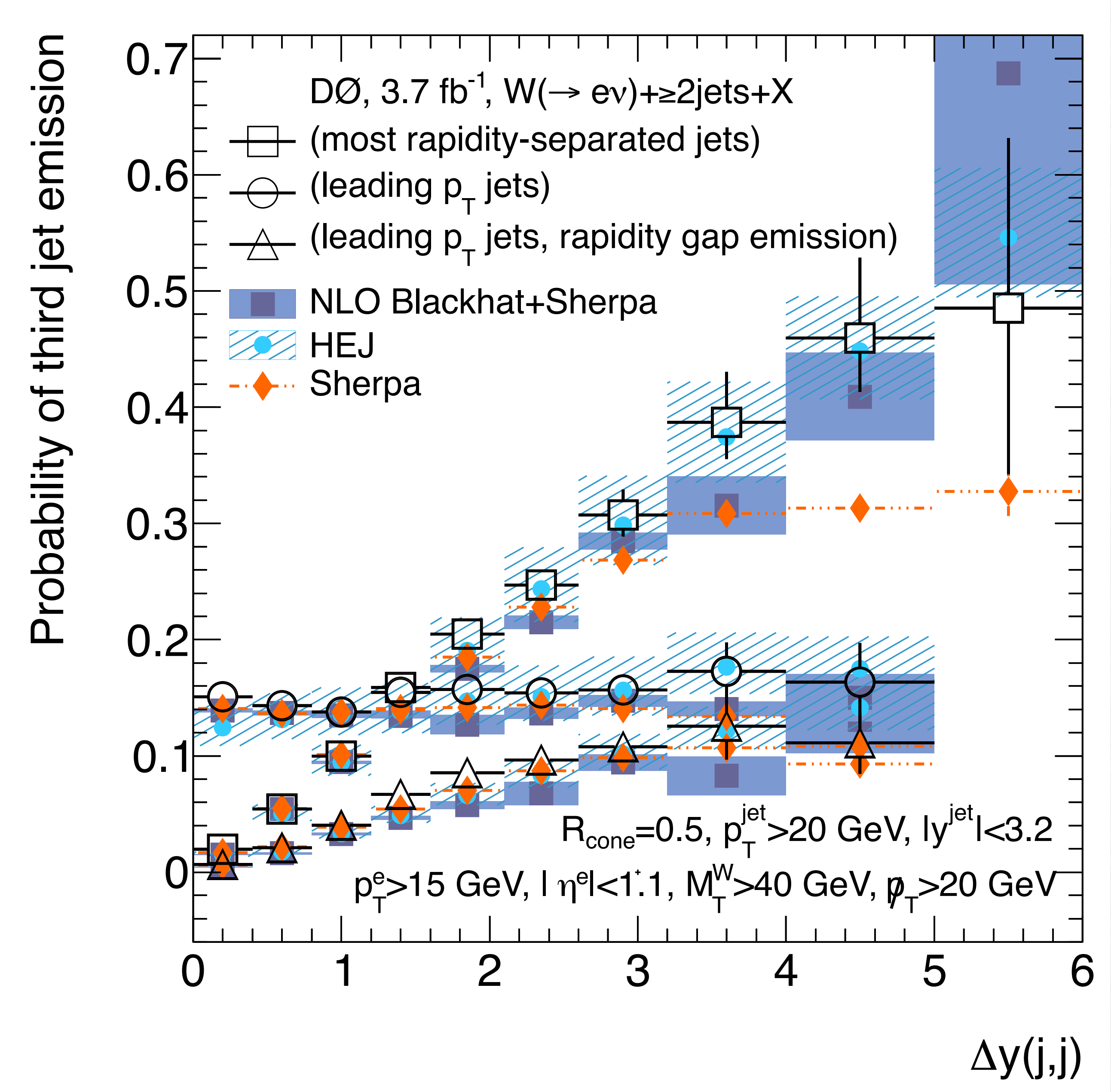
This is the difference between:

Leading Jets — Most forward/backward Jets

arXiv:1302.6508

D0 W+Jets

Probability of third jet emission versus Δy of:



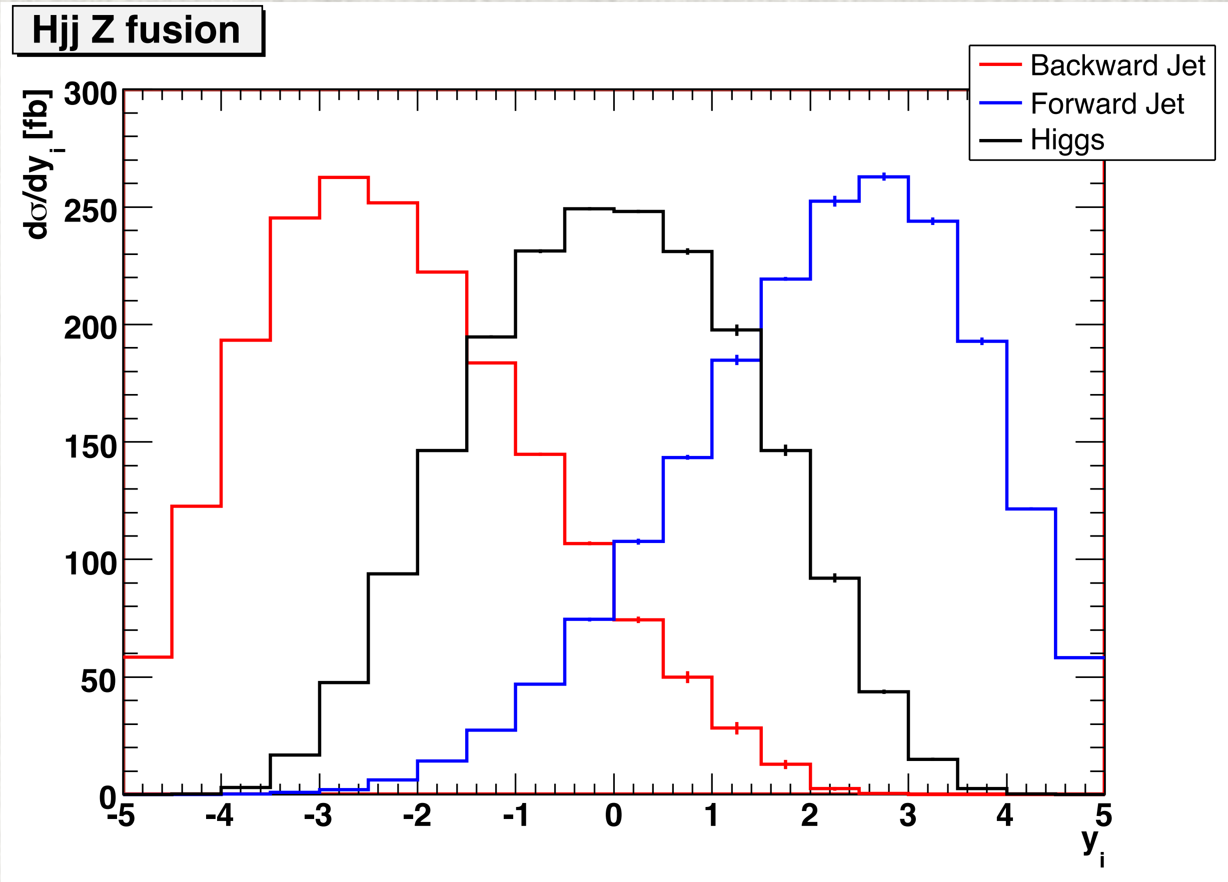
- Most forward/backward Jets
- Hardest Jets
- Hardest Jets, counting only jets between

arXiv:1302.6508

Higgs Plus Dijets

Higgs Plus Dijets

- Vector Boson Fusion is 2nd largest production channel
- Key opportunity to study VVH vertex
- Use distinctive topology to select events



Here:

$$p_{T,j} > 20 \text{ GeV}, \;\; |\eta_j| \leq 5,$$
$$R_{jj} > 0.6$$

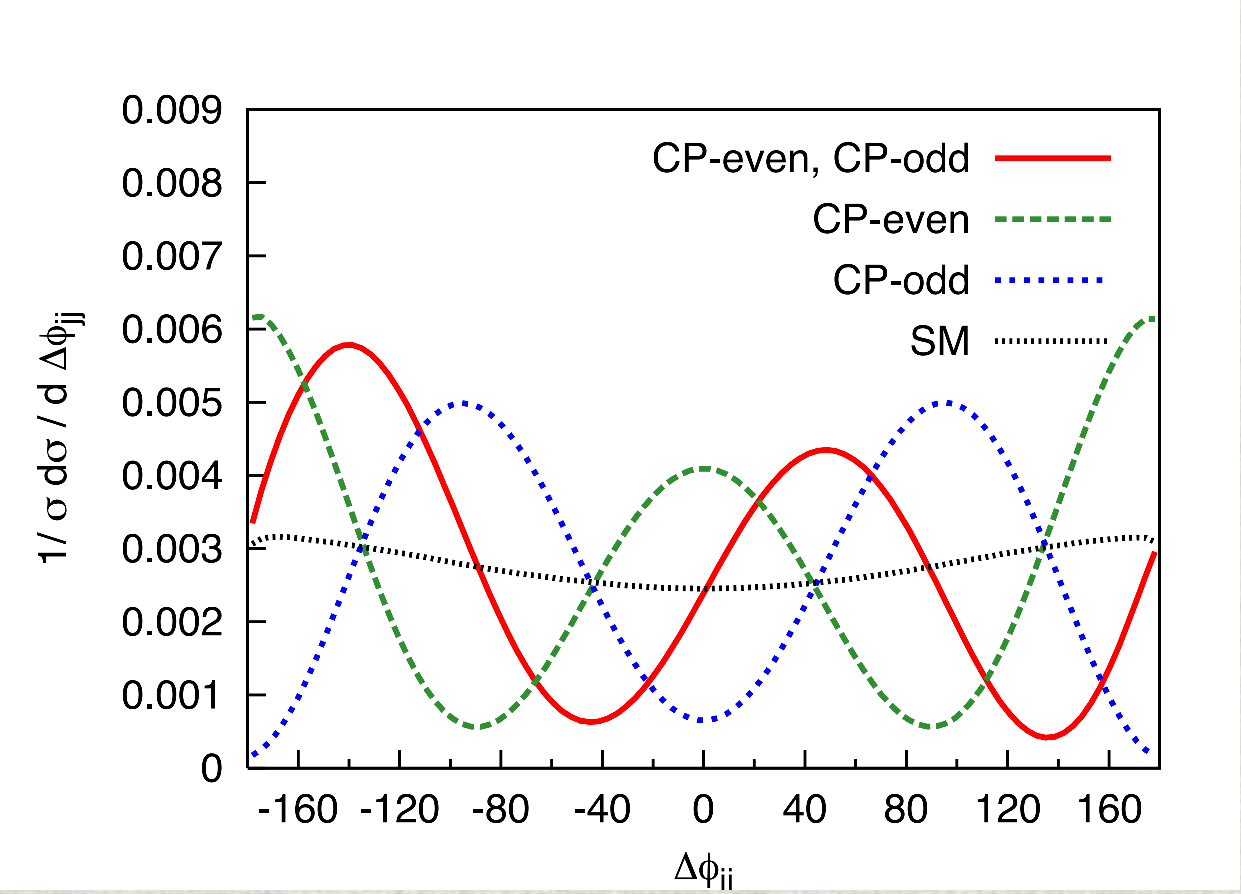
Higgs Plus Dijets

Typical "VBF" cuts:

$$p_{T,j} > 25\ \text{GeV},\ |\eta_j| \le 5,\ |\Delta\eta_{jj}| > 2.8,\ m_{jj} > 400\ GeV$$

Puts us right into the difficult region!

Want to use azimuthal angle between jets to study CP structure of the vertex:

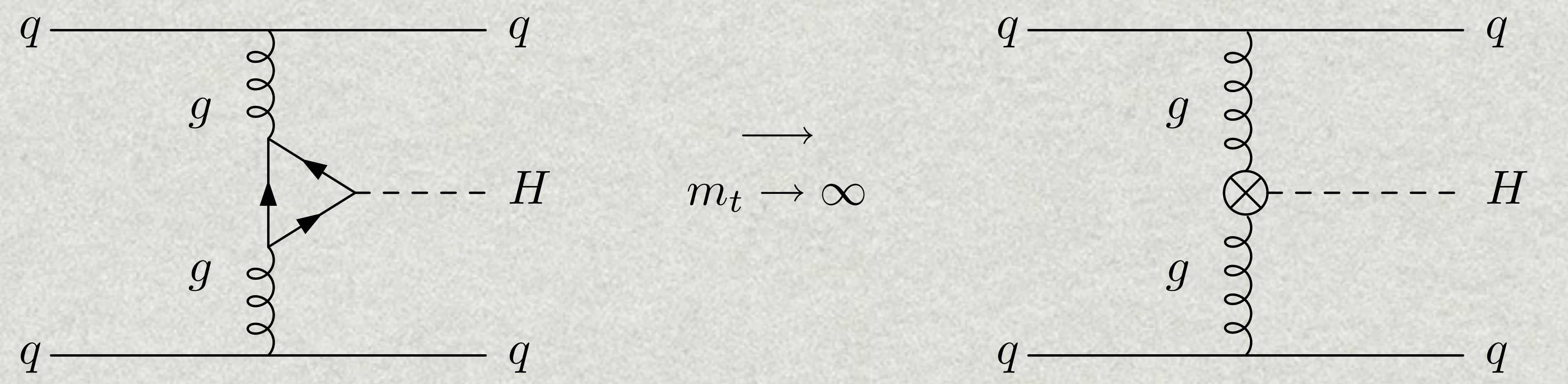


HE limit tells you how to extend to n jets

Andersen, Arnold & Zeppenfeld arXiv:1001.3822

Figy, Hankele, Klämke & Zeppenfeld hep-ph/0609075

Higgs Plus Jets



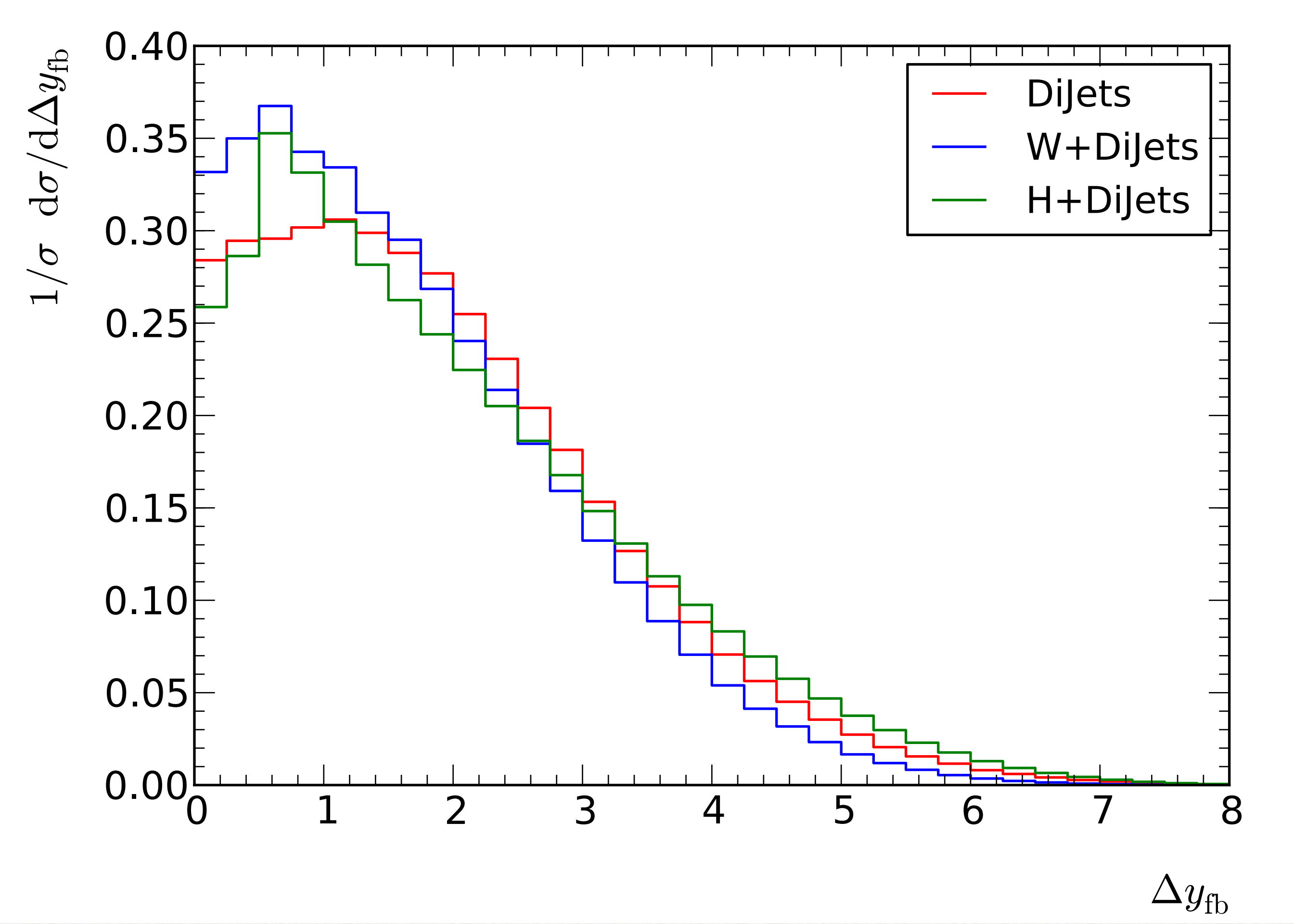
In heavy top-mass limit: $V_{Hgg}(p^\mu, q^\nu) = \frac{i\alpha_s}{3\pi v}(p \cdot q g^{\mu\nu} - p^\nu q^\mu)$

- Different CP structure so can contaminate study.
- Interesting to study in own right
- Gluons expected to radiate more
  $\therefore$ use a "jet veto" between tagged jets to separate

Multi-Jet Descriptions

To extract couplings cleanly, need to separate Weak Boson Fusion and Gluon-Gluon Fusion (ideally both!)

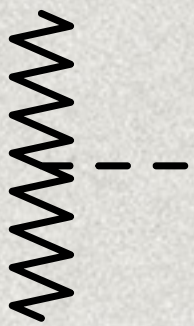
From now on, will focus on Gluon-Gluon Fusion.



Jet radiation patterns universal across processes.

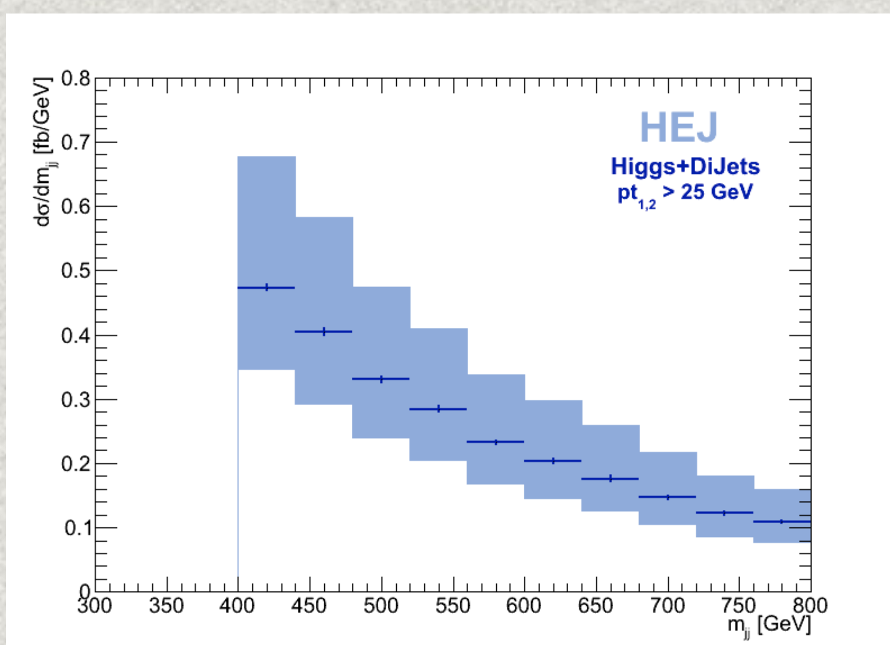
Use existing data to test descriptions.

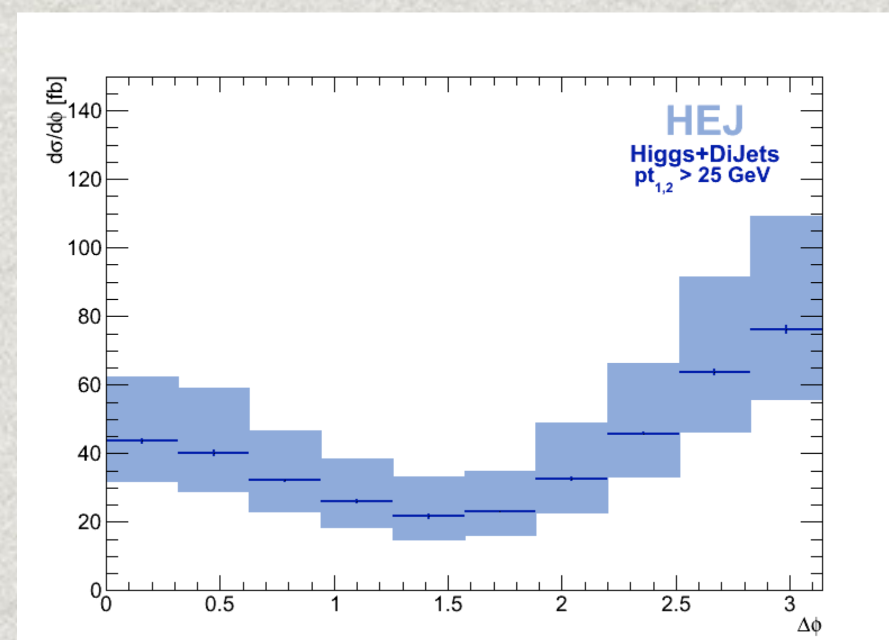
Higgs in HEJ



$$\frac{j^\mu j_\mu}{\hat{t}} \rightarrow \frac{j^\mu j^\nu}{q_1^2\ q_2^2}\left(g_{\mu\nu}\ q_1 \cdot q_2 - q_{1_\nu} q_{2_\mu}\right)$$

Insert this in the gluon chain according to rapidity



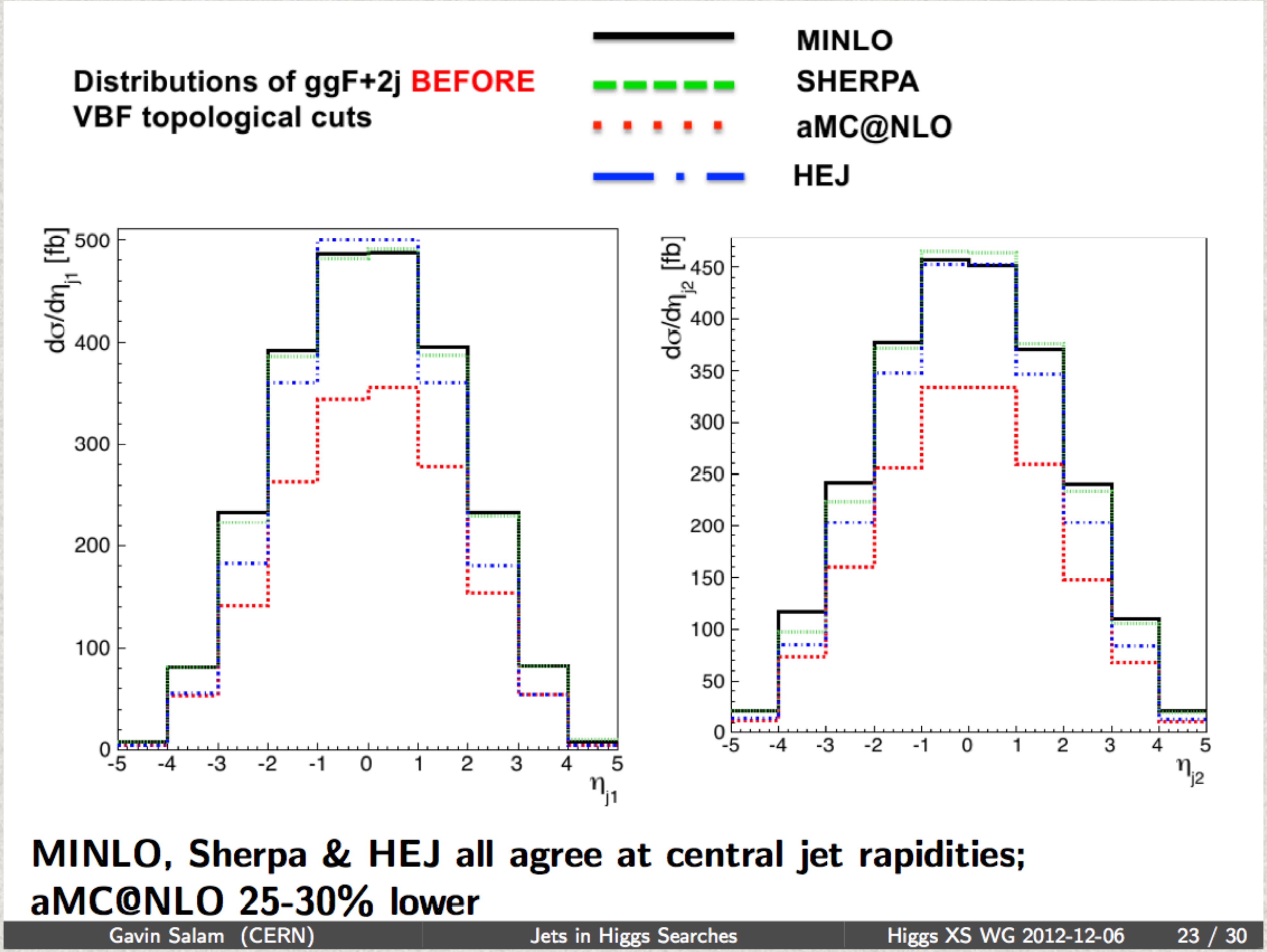


Now also includes one un-ordered gluon emission

Andersen, Hapola & JMS (to appear)

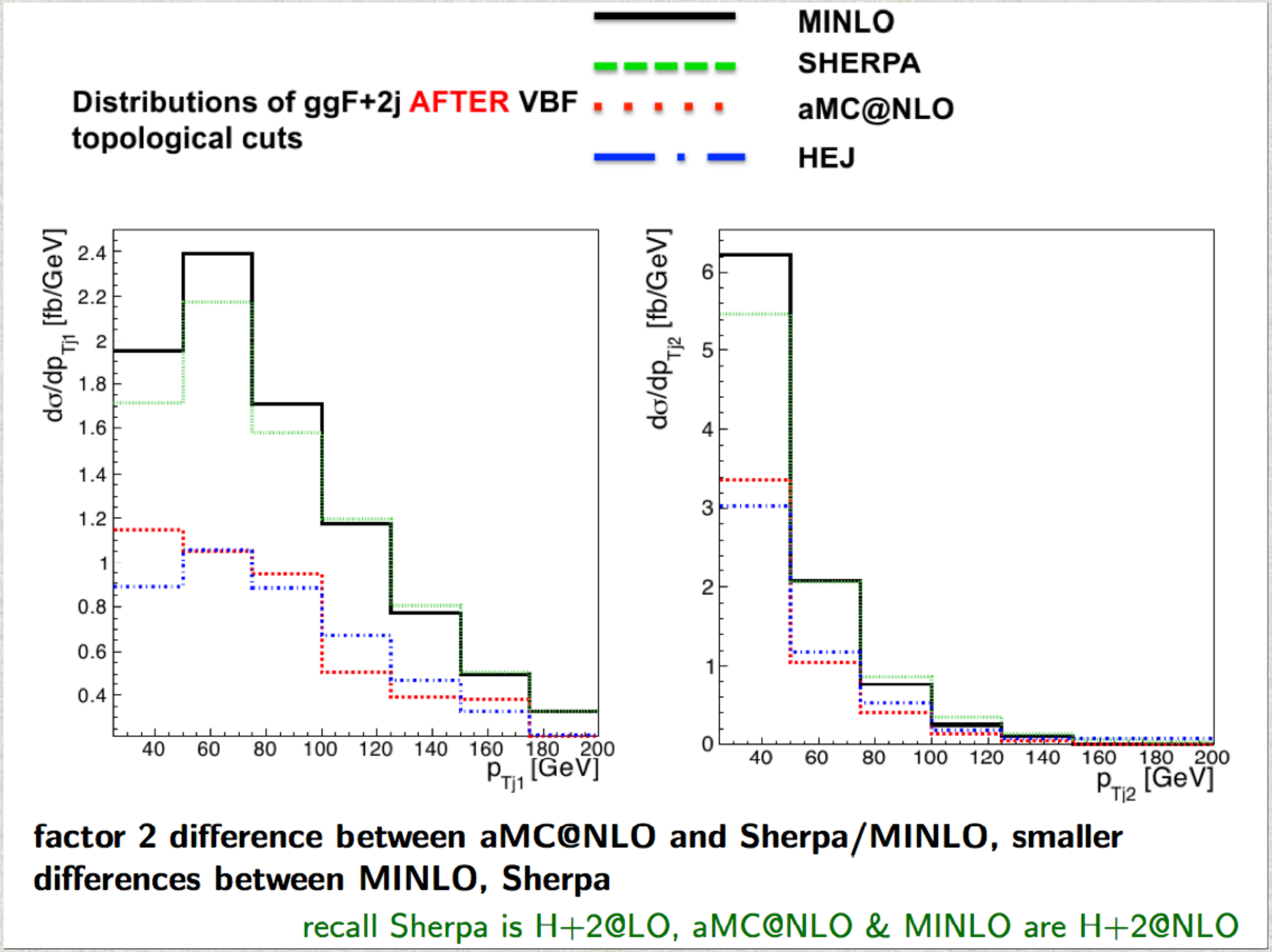
Higgs XS WG Studies

Gavin Salam's Dec 2012 Talk:

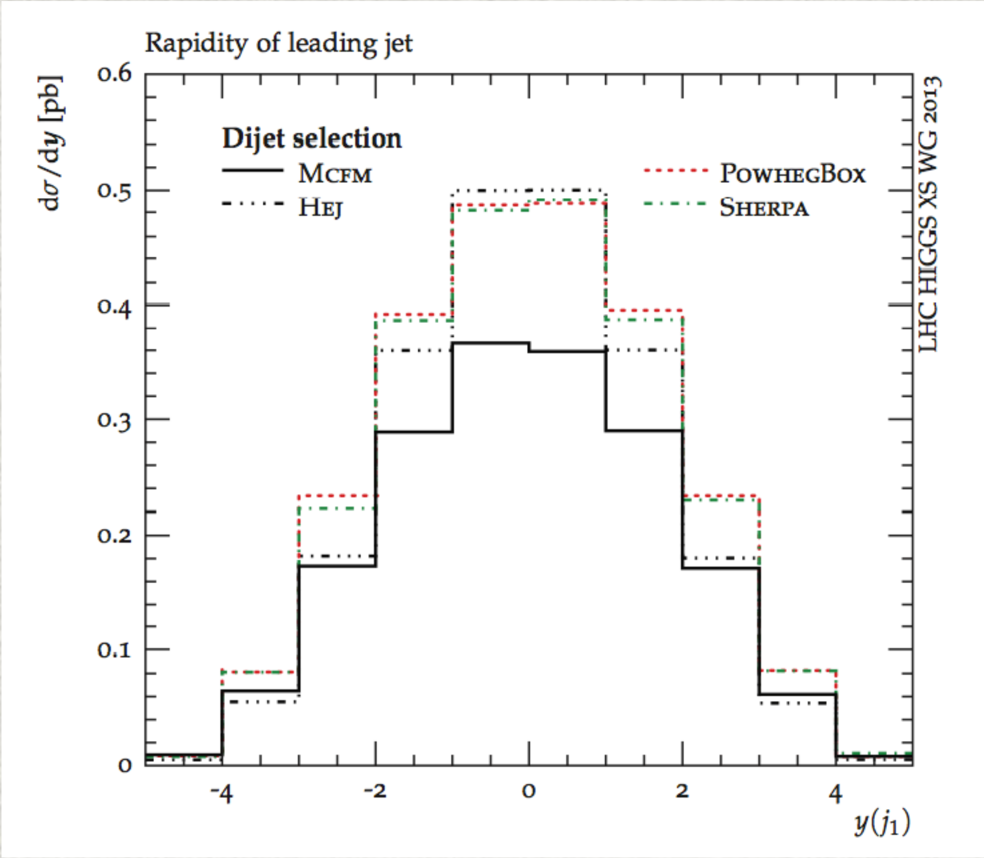


Higgs XS WG Studies

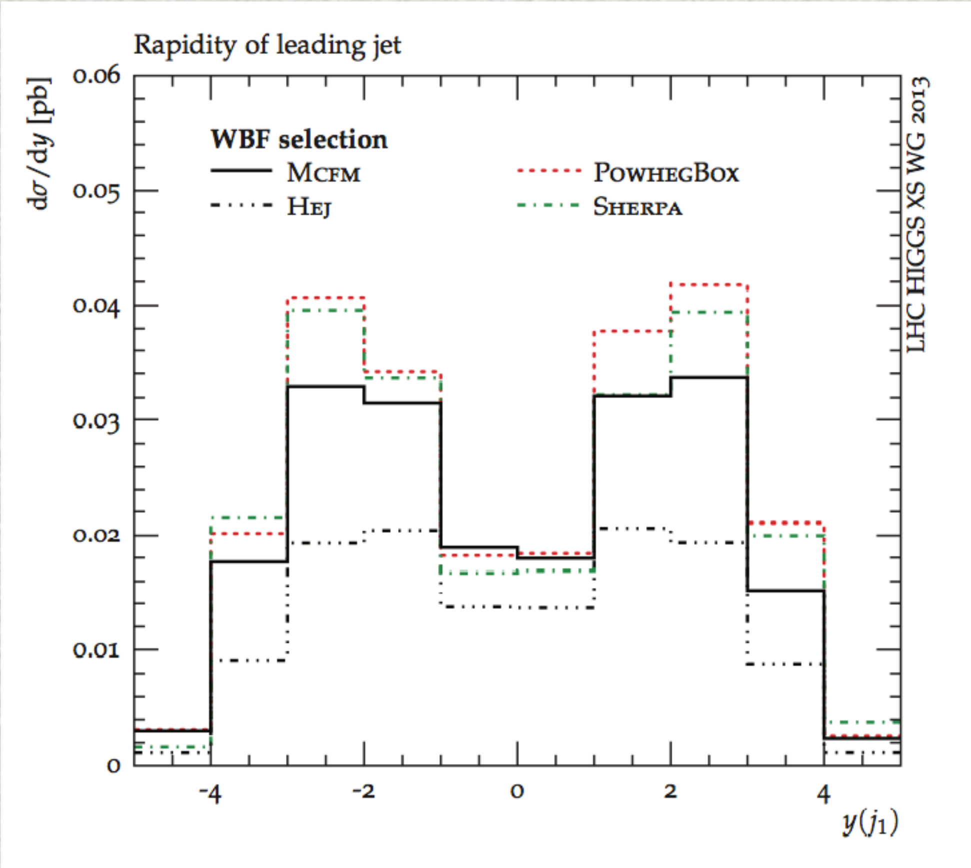
Gavin Salam's Dec Talk:



Higgs XS WG YR3 2013



+VBF cuts



- Difference in shape expected
- Impact on cross section:
  About 10% for MCFM, POWHEG & SHERPA; 6% for HEJ
- 2 effects: if well-separated jets, will typically emit a (harder) jet in between; otherwise Regge-suppression

See update in this year’s LH proc

Summary

* Hard QCD radiation feature of LHC collisions
* Data has clearly shown effects beyond pure NLO
* Flexible MC description from HEJ
  Built from HE properties of amplitudes
* Lots of interesting physics in jet data with important applications to Higgs+Jets studies

http://cern.ch/hej