Jets, Jets, Higgs & Jets

Jenni Smillie

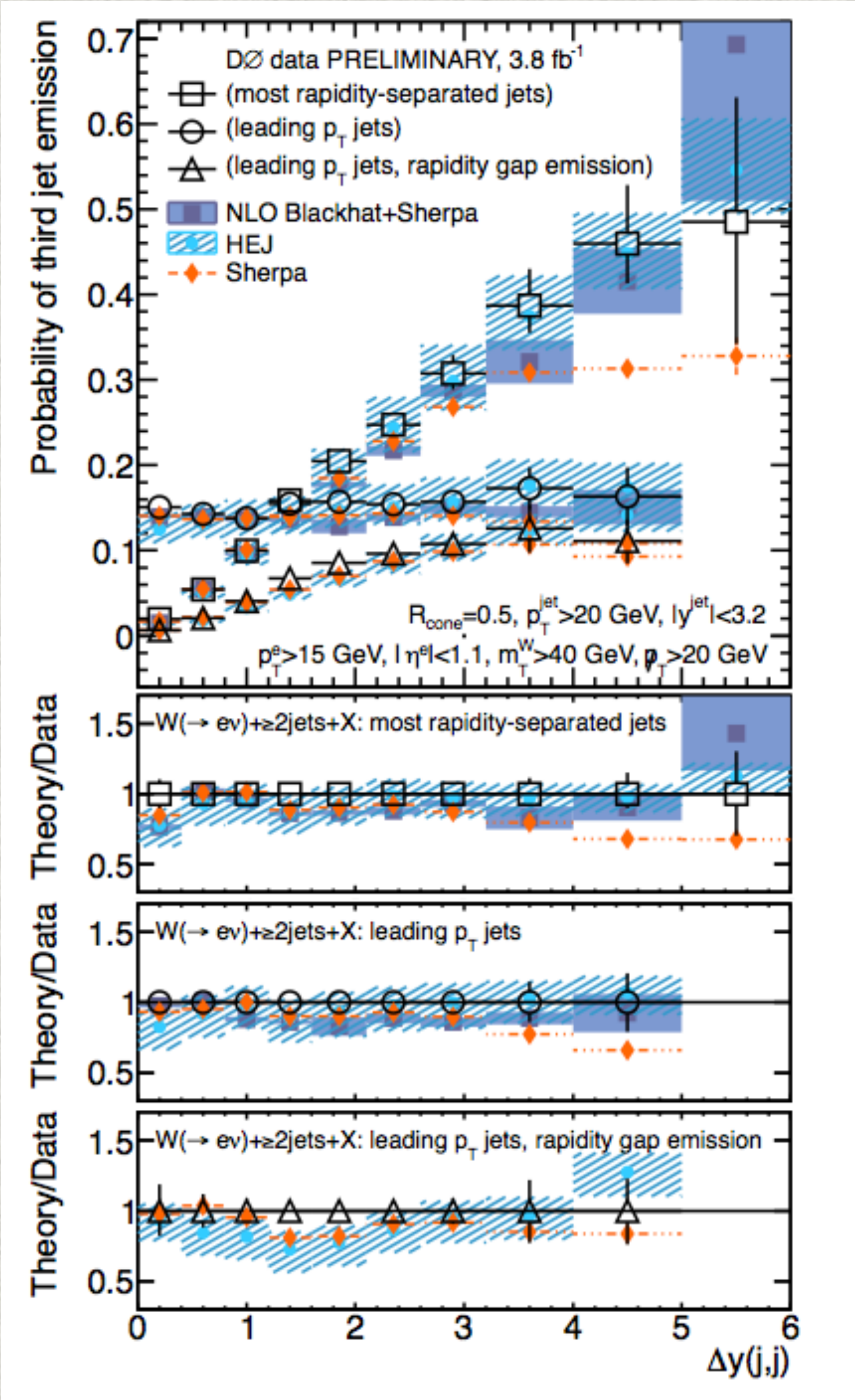
Higgs Centre for Theoretical Physics
Edinburgh

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

Birmingham Seminar **6 May 2015**

Outline

- Introduction
- High Energy Jets
- Comparisons to Data
- Higgs Plus Jets



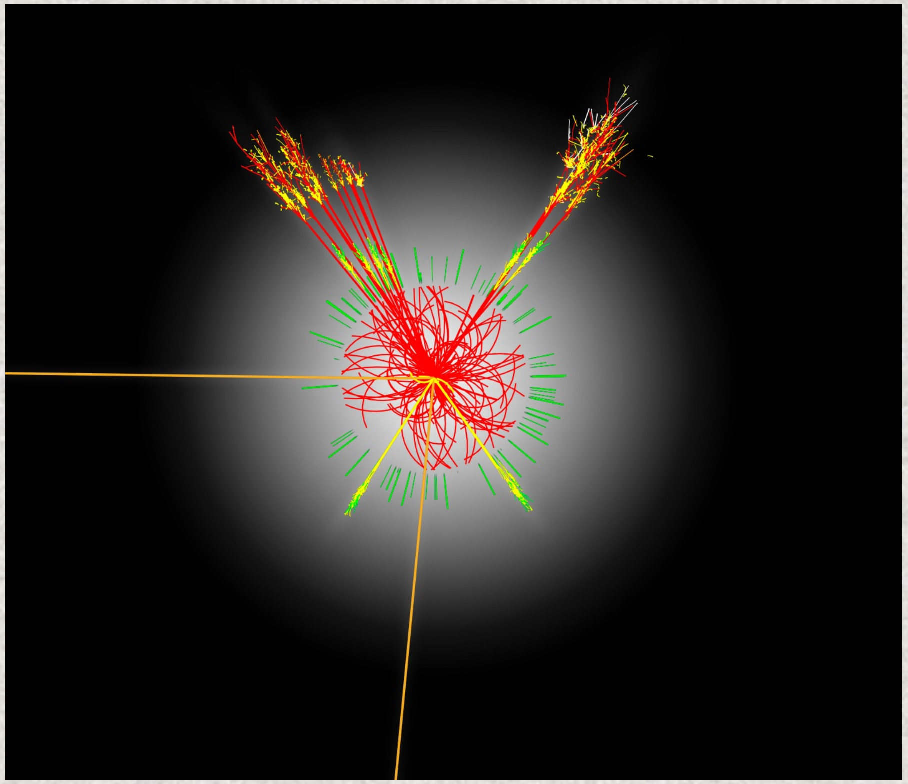
D0 arXiv:1302.6508

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

Scales

- In this talk will concentrate on hard-scattering matrix element - high scale



ATLAS Experiment © 2014 CERN

- Will neglect underlying event and shower effects - low scale
- Very interesting physics, but not today!

Higher Orders

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

  e.g. ATLAS Z+jets

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

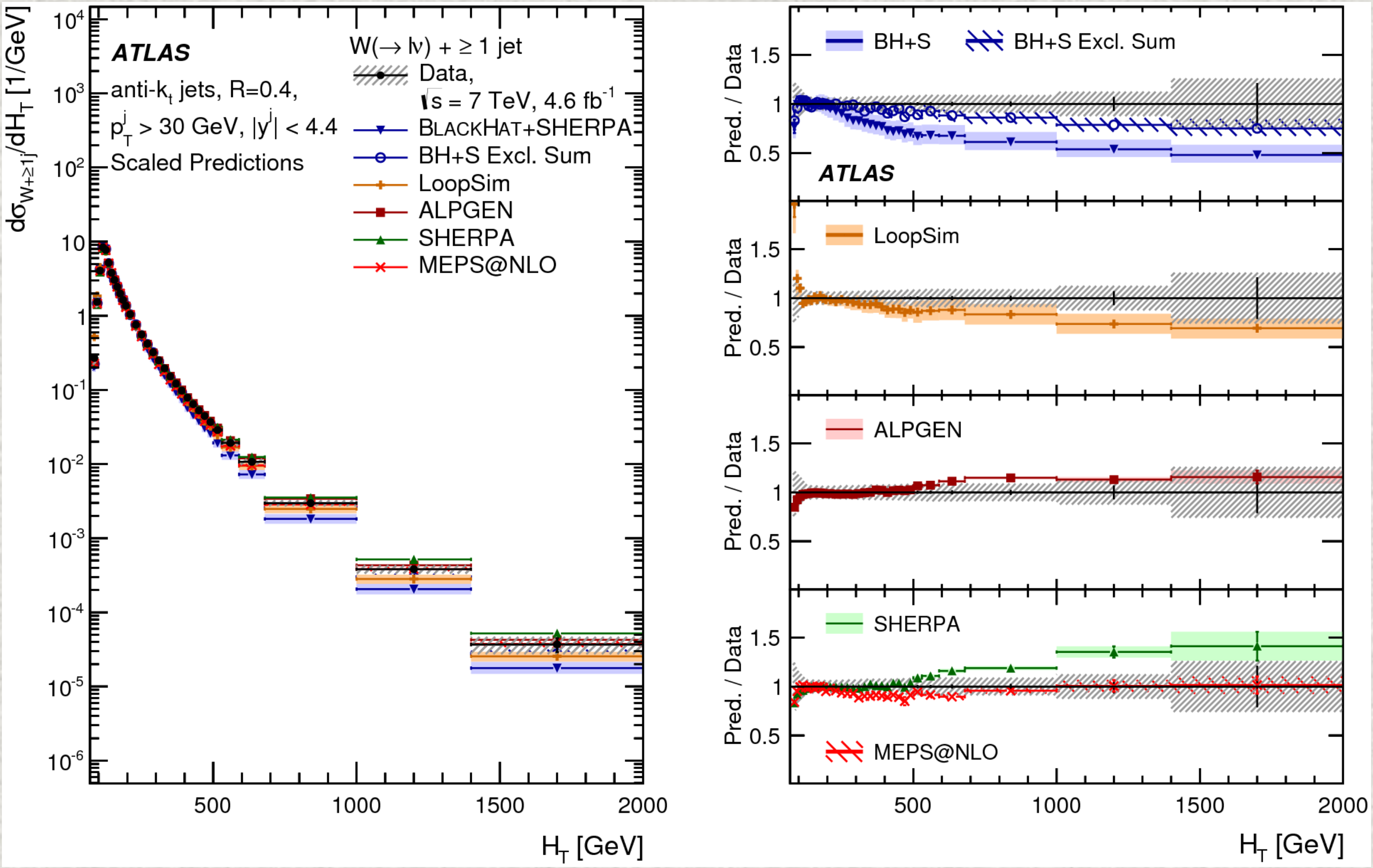
  Rises to 0.3 after VBF cuts!

arXiv:1304.7098

ATLAS W+jets arXiv:1409.8639

- NLO is only one more emission

  Consistently need to combine orders to describe data



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

What is “all-order”?

$$
\begin{aligned}
\sigma = \quad & \alpha_s^2 \left(a_2(s^2/t^2) + b_2\right) \\
& + \alpha_s^3 \left(a_3(s^2/t^2) \log(s/t) + b_3(s^2/t^2) + c_3\right) \\
& + \alpha_s^4 \left(a_4(s^2/t^2) \log^2(s/t) + b_4(s^2/t^2) \log(s/t) + ...\right) \\
& + ...
\end{aligned}
$$

- LO = first line

What is “all-order”?

$$\begin{aligned}\sigma = \quad & \alpha_s^2 \left(a_2(s^2/t^2) + b_2\right) \\ & + \alpha_s^3 \left(a_3(s^2/t^2)\log(s/t) + b_3(s^2/t^2) + c_3\right) \\ & + \alpha_s^4 \left(a_4(s^2/t^2)\log^2(s/t) + b_4(s^2/t^2)\log(s/t) + ...\right) \\ & + ...\end{aligned}$$

- LO = first line
- NLO = first two lines

What is “all-order”?

$$\begin{aligned}\sigma = \quad & \alpha_s^2 \left(a_2(s^2/t^2) + b_2\right) \\ & + \alpha_s^3 \left(a_3(s^2/t^2)\log(s/t) + b_3(s^2/t^2) + c_3\right) \\ & + \alpha_s^4 \left(a_4(s^2/t^2)\log^2(s/t) + b_4(s^2/t^2)\log(s/t) + ...\right) \\ & + ...\end{aligned}$$

- LO = first line
- NLO = first two lines
- Leading-log = the ‘a’-terms

What is "all-order"?

$$
\begin{aligned}
\sigma = \quad & \alpha_s^2 \left(a_2(s^2/t^2) + b_2\right) \\
& + \alpha_s^3 \left(a_3(s^2/t^2)\log(s/t) + b_3(s^2/t^2) + c_3\right) \\
& + \alpha_s^4 \left(a_4(s^2/t^2)\log^2(s/t) + b_4(s^2/t^2)\log(s/t) + ...\right) \\
& + ...
\end{aligned}
$$

- LO = first line
- NLO = first two lines
- Leading-log = the 'a'-terms
- In practice, merge LO and LL

ATLAS: jet veto analysis

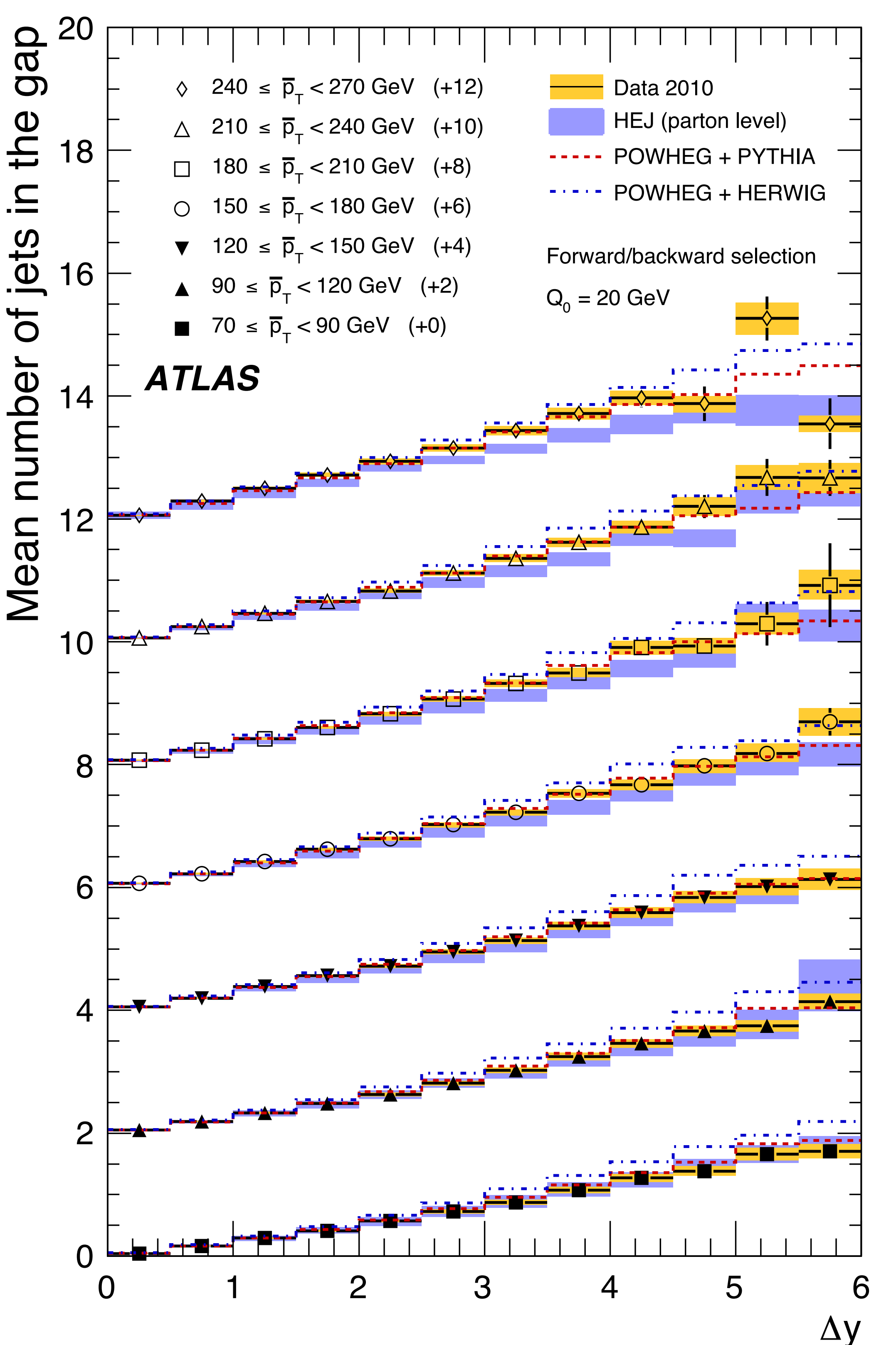
Plot average number of additional jets.

More than one extra jet on average for $\Delta y > 3$

Clearly beyond NLO!

Tagging = most forward/backward

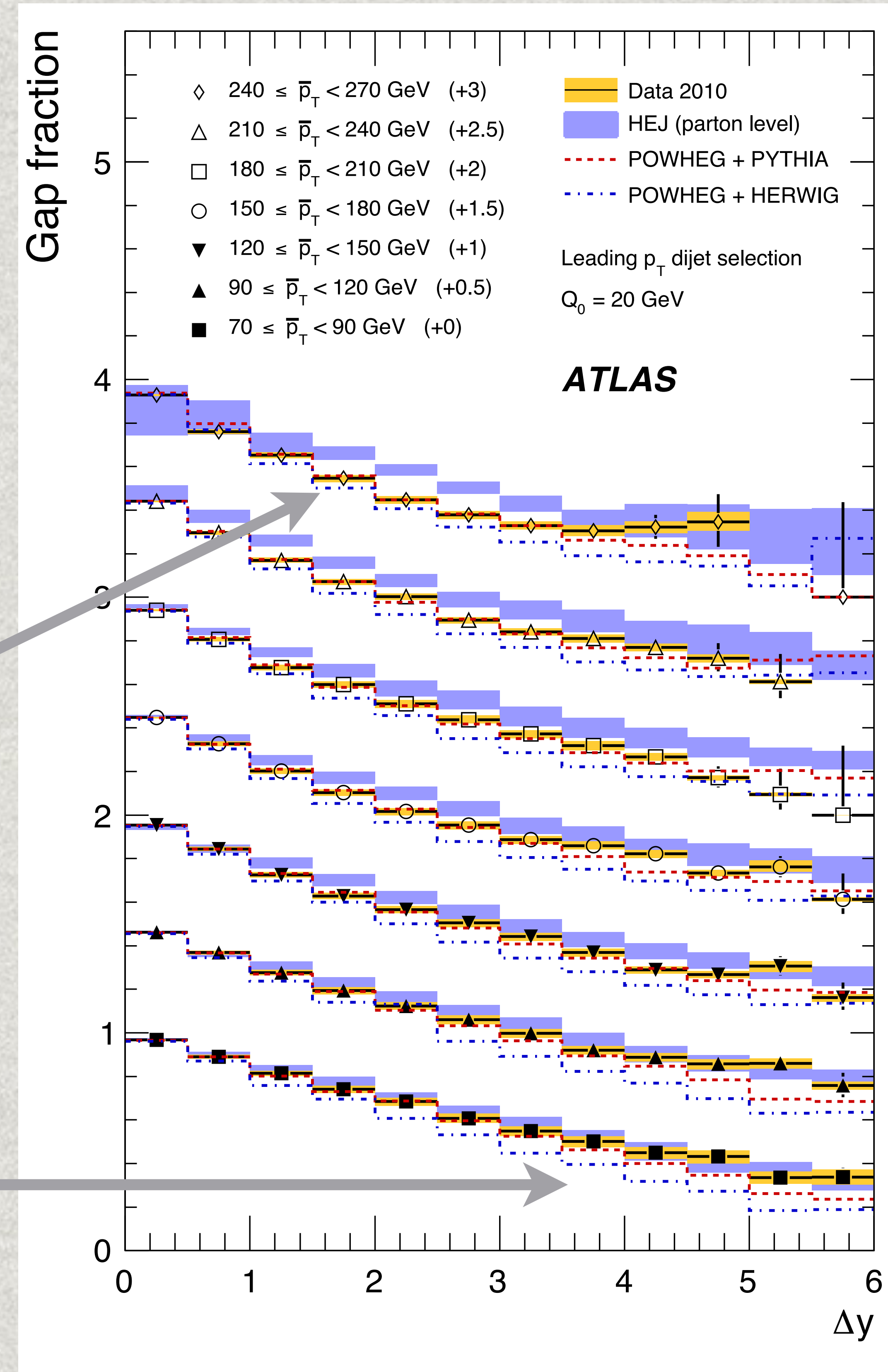
Good agreement with POWHEG+PYTHIA & HEJ



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

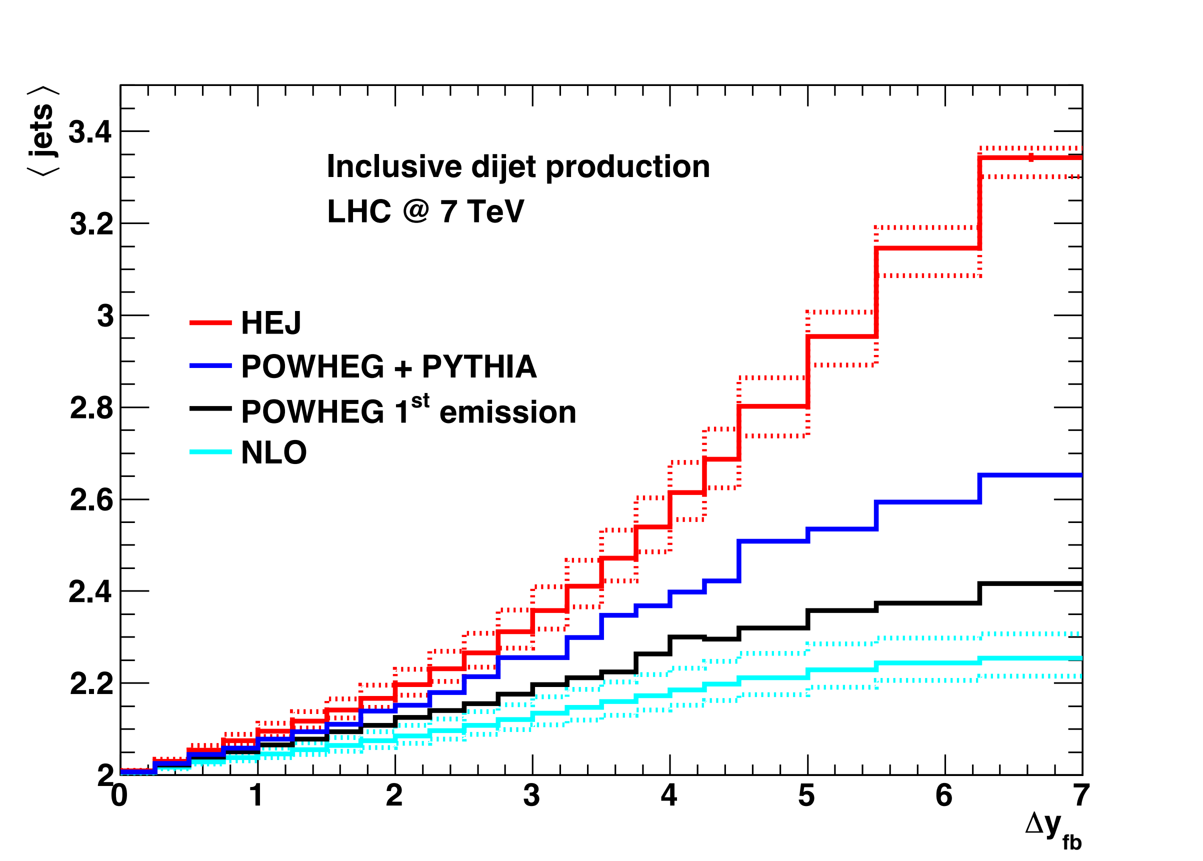
DiJet Comparison

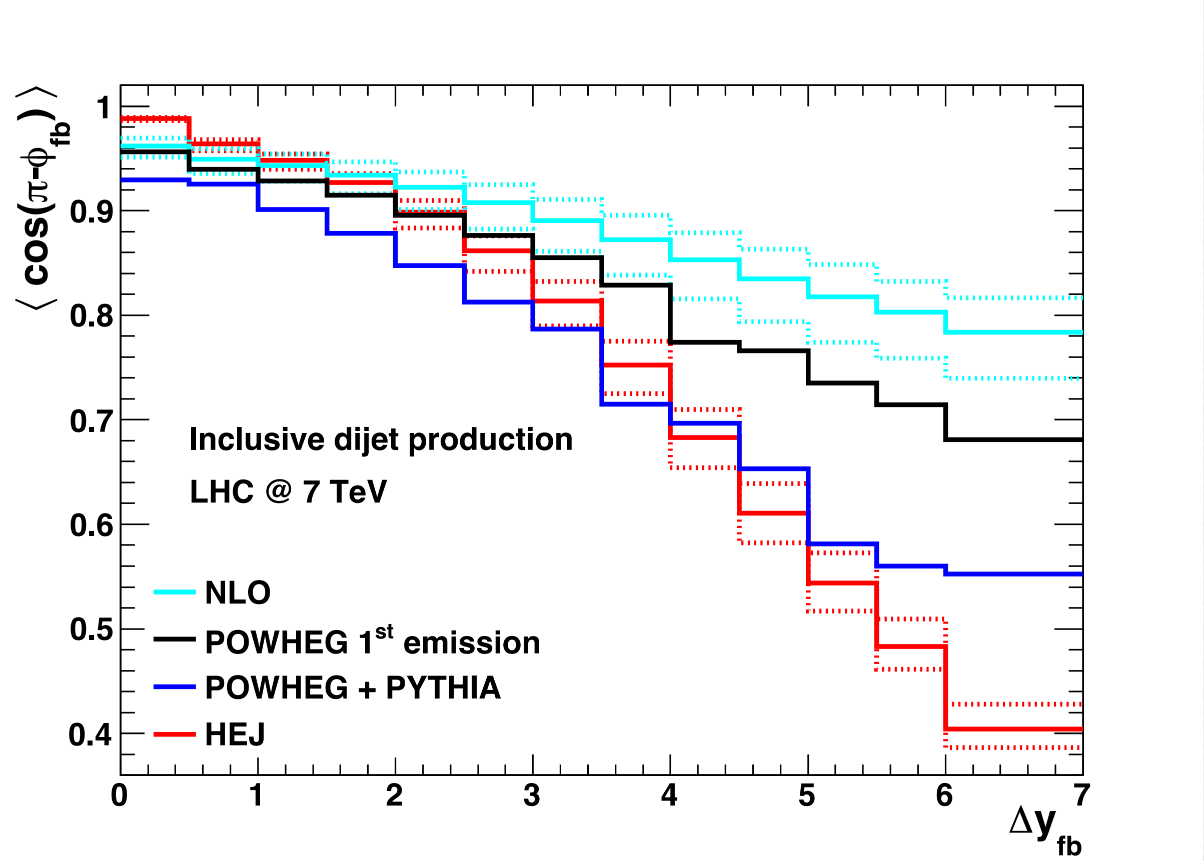
POWHEG+PYTHIA and HEJ gave very similar predictions

Can they be distinguished?

Choose cuts which do not induce p_T hierarchy

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





In some cases, yes,... others, no.

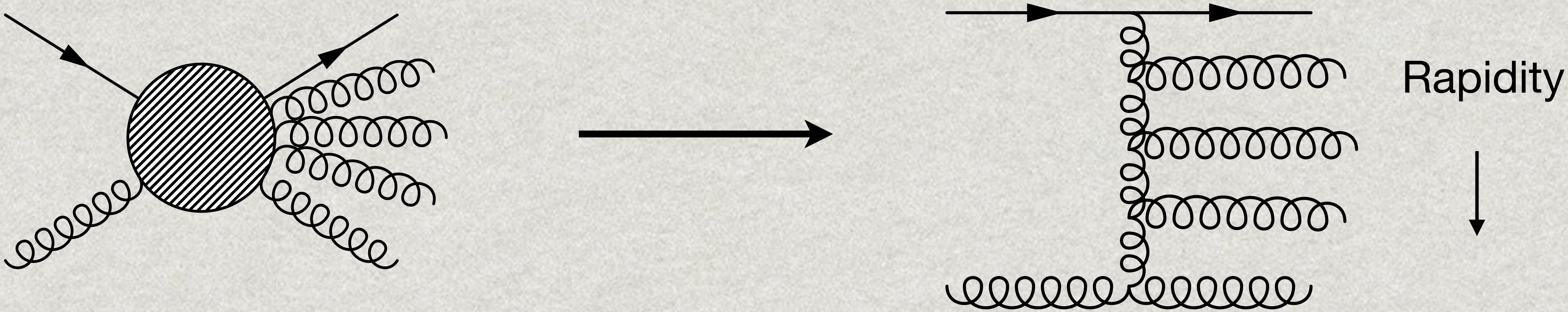
Alioli, Andersen, Oleari, Re & JMS arXiv:1202.1475

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

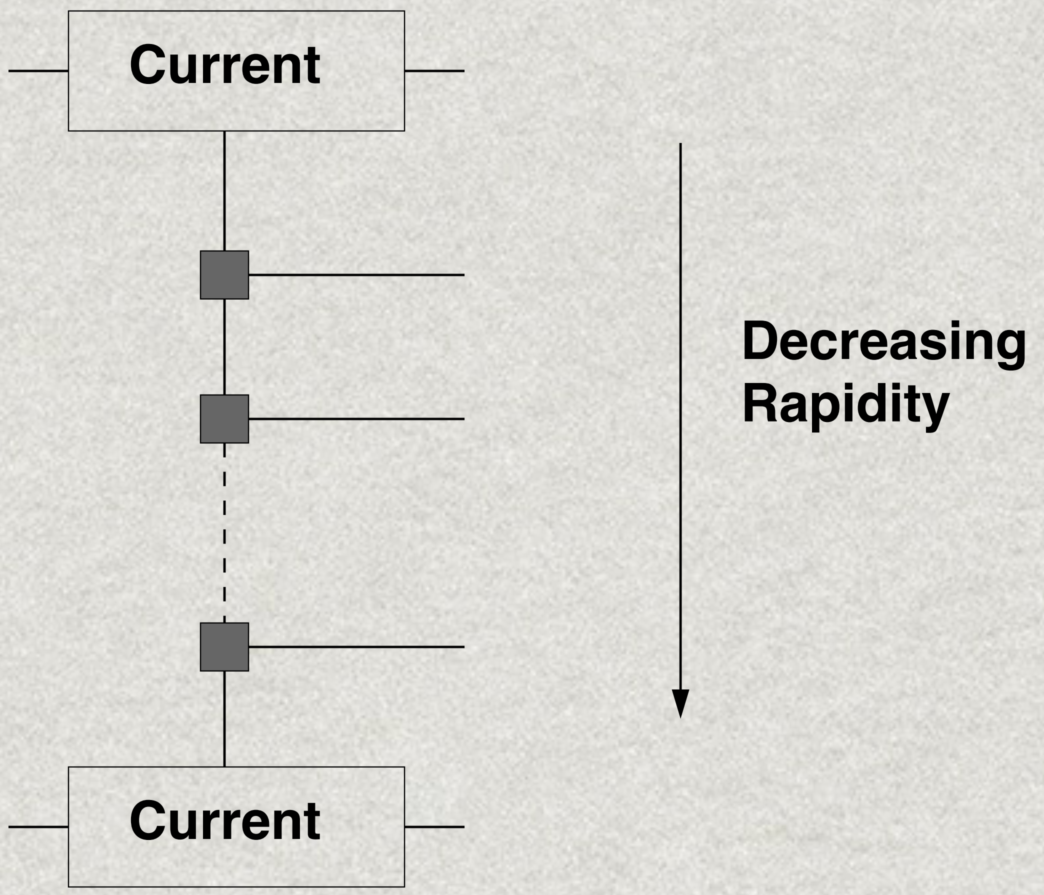


- Dominant Momentum Configurations in HE limit correspond to those which would allow maximum t-channel gluon exchanges:

- Other orderings are logarithmically suppressed.

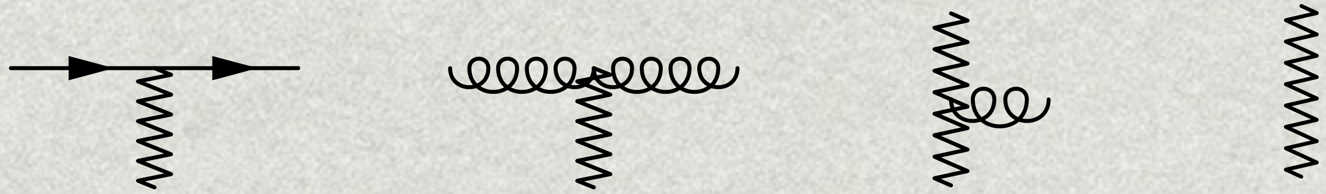
A HEJ Amplitude

- All 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

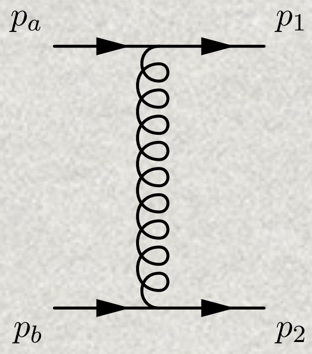


Applies to loop diagrams too (needed to regulate soft).

Pieces I: Currents

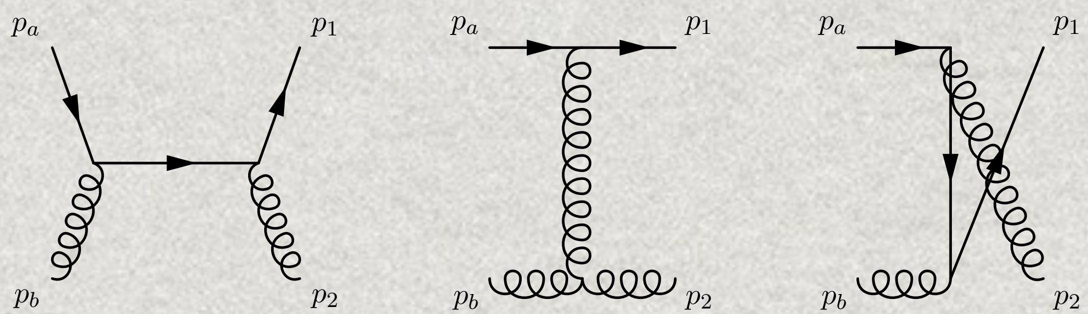
Pieces independent of rest of chain - pick convenient processes to derive them

- Incoming quarks: straight-forward



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

- Incoming gluons: surprisingly so!



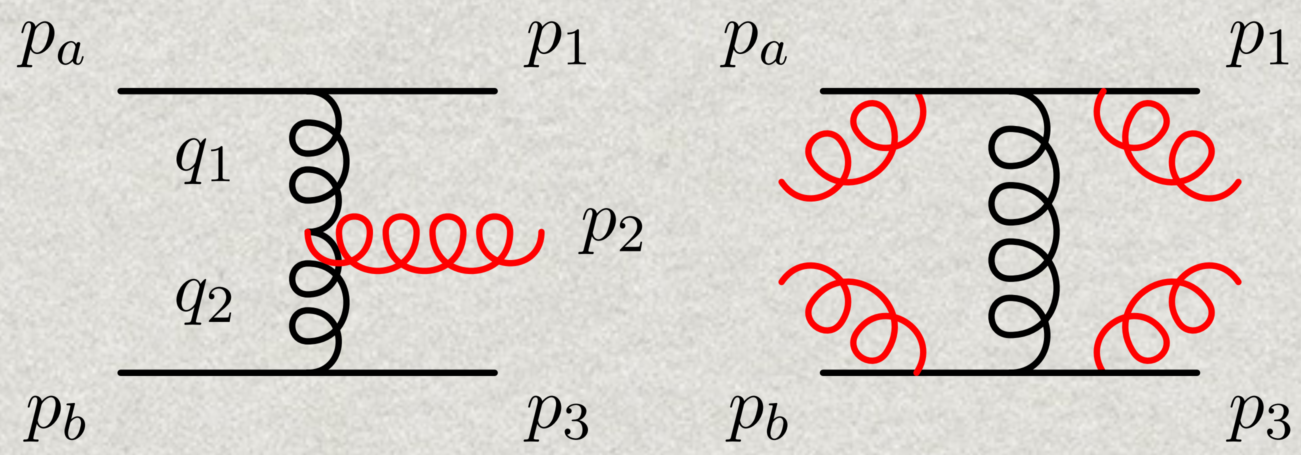
- Exact result: $\frac{g_s^4 C_{CAM}}{6}\frac{|j^\mu(p_a,p_1)\cdot j_\mu(p_b,p_2)|^2}{\hat{t}^2}$

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

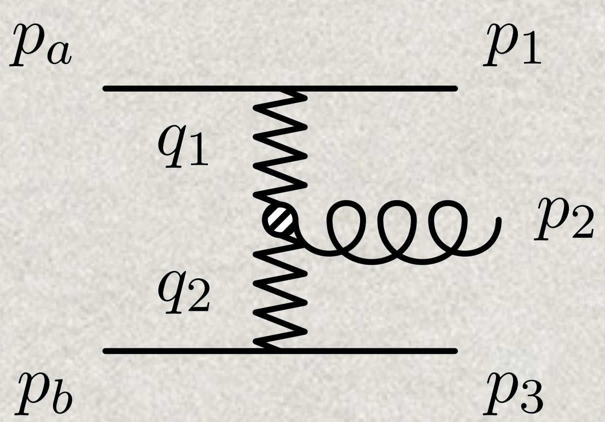
- Only t-pole remains explicitly

Pieces II: Emission Vertices

- Use qQ → qgQ



- In HE limit, colour factors combine to give



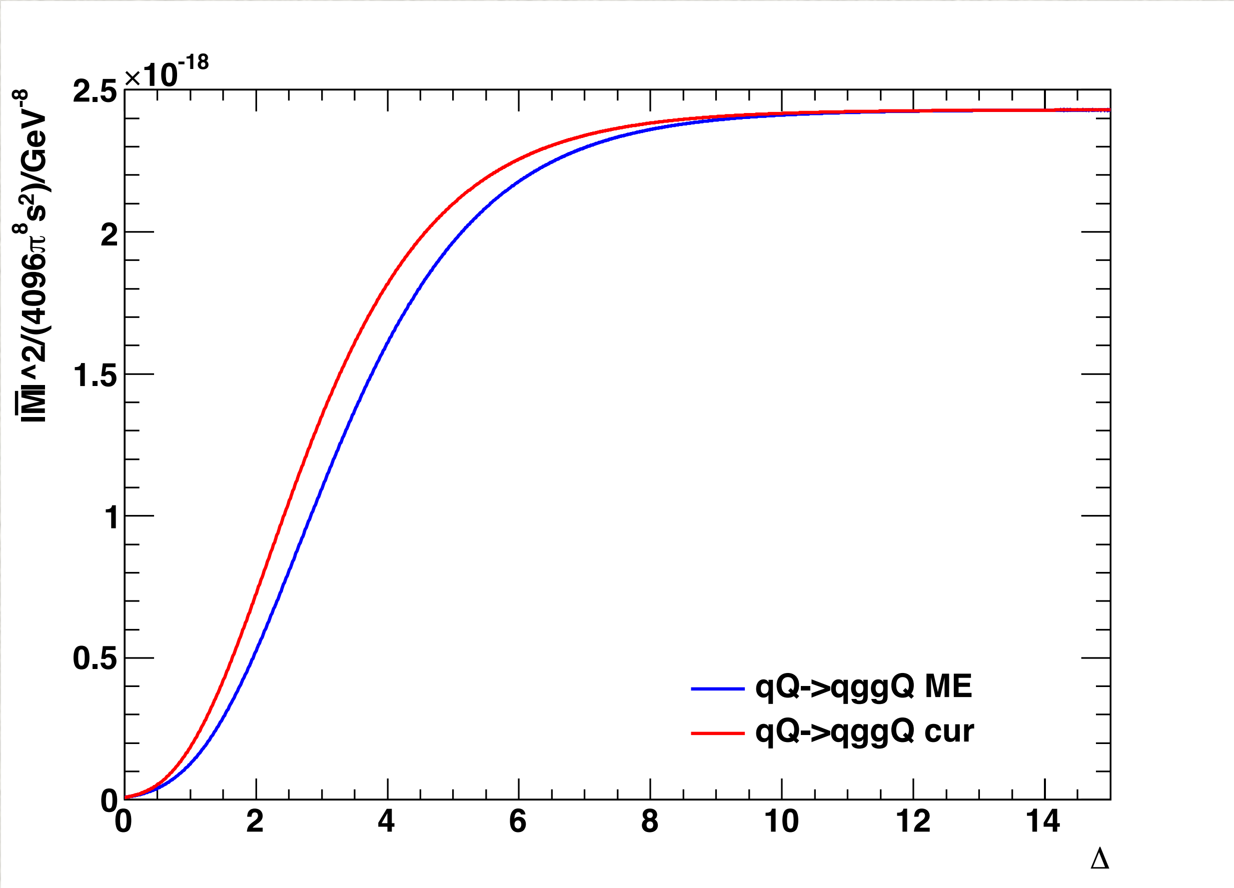
$$\mathcal{A}_{qQ\to qgQ} = g_s^3\ \mathcal{C}_g\ \varepsilon_\rho^*\ \frac{j^\mu(p_a,p_1)\cdot j_\mu(p_b,p_3)}{q_1^2 q_2^2}\ V^\rho(q_1,q_2)$$

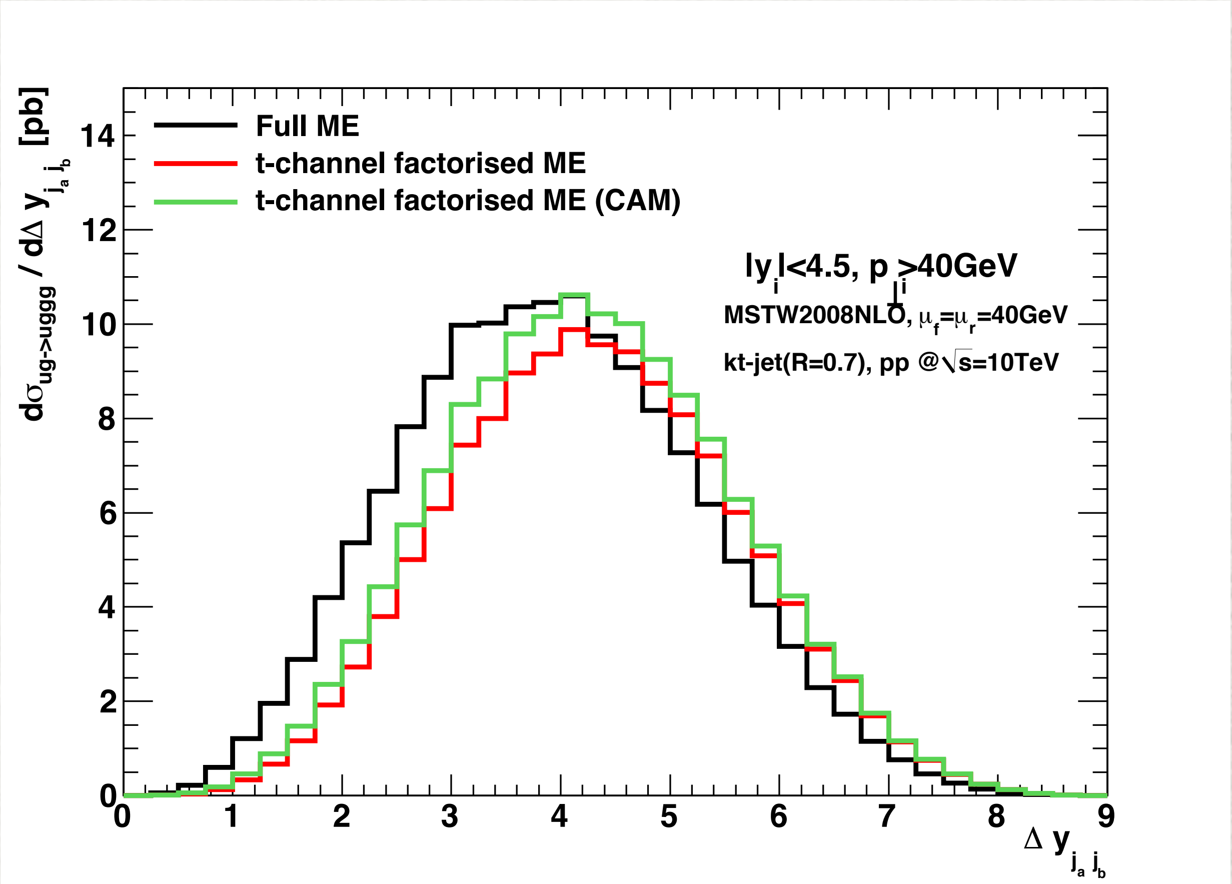
$$V^\rho(q_1,q_2) = -(q_1+q_2)^\rho + \frac{p_a^\rho}{2}\left(\frac{q_1^2}{p_2\cdot p_a}+\frac{p_2\cdot p_b}{p_a\cdot p_b}+\frac{p_2\cdot p_3}{p_a\cdot p_3}\right)+p_a\leftrightarrow p_1 - \frac{p_b^\rho}{2}\left(\frac{q_2^2}{p_2\cdot p_b}+\frac{p_2\cdot p_a}{p_b\cdot p_a}+\frac{p_2\cdot p_1}{p_b\cdot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

Gauge invariant in *all* of phase space.

Andersen & JMS arXiv:0908.2786

Does It Work?



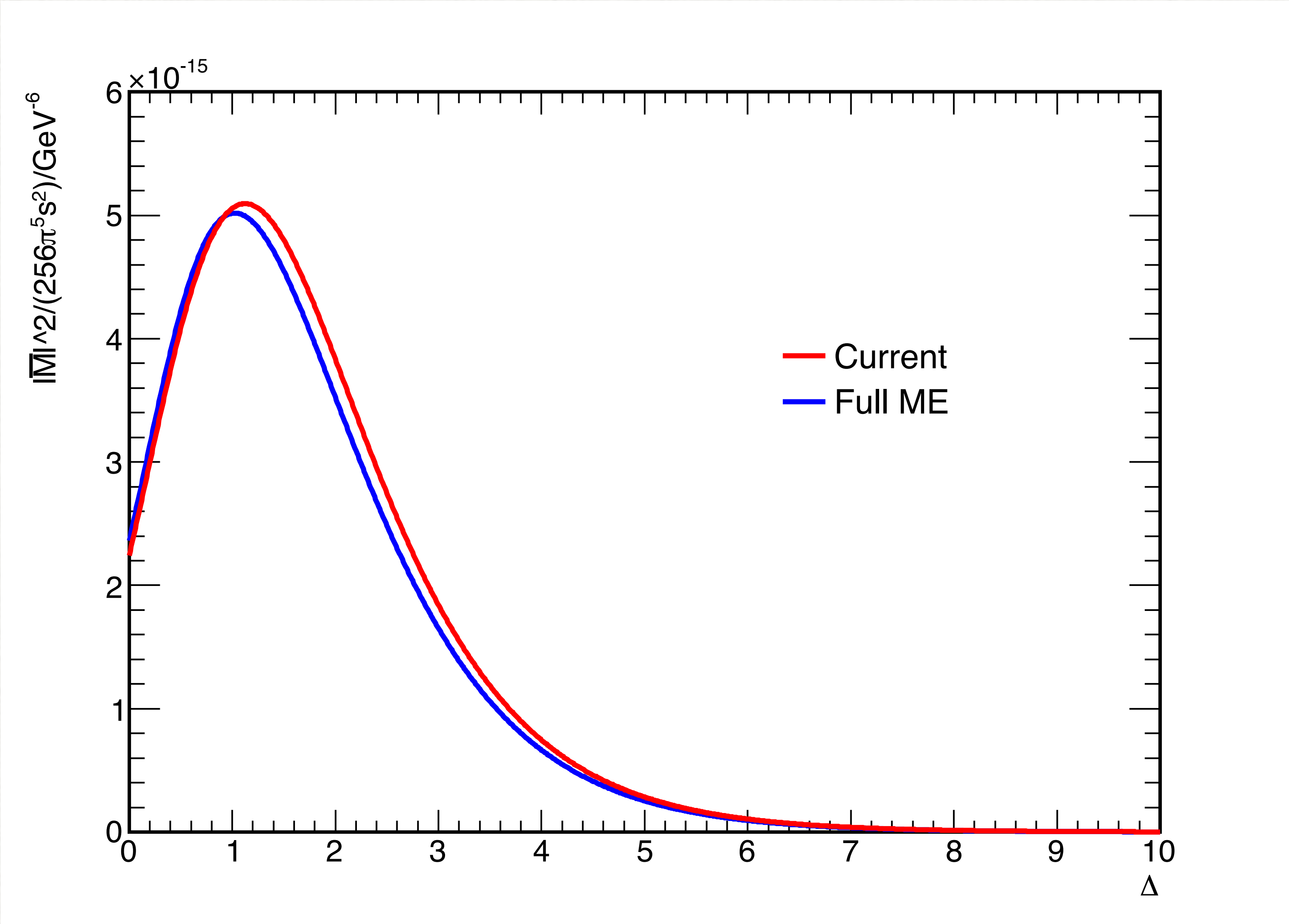


$qQ \rightarrow qggQ$

$qg \rightarrow qggg$

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

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

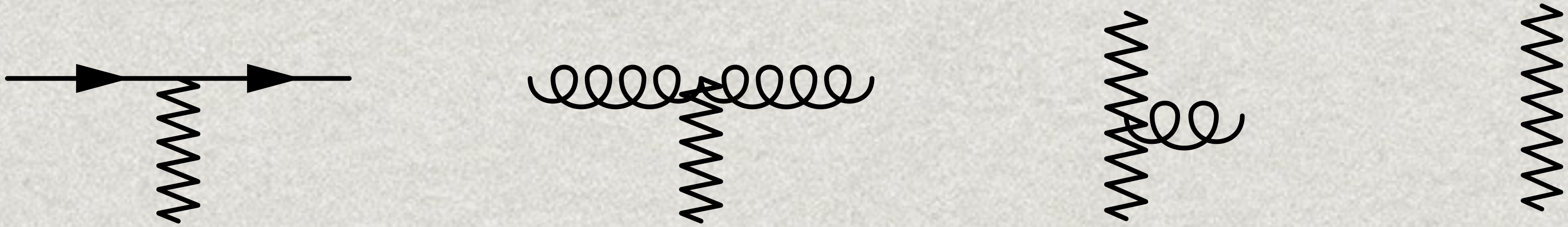
$$\hat{\alpha}(q_i) = \alpha_s \; C_A \; t_i \int \frac{d^{2+2\epsilon} k_\perp}{(2\pi)^{2+2\epsilon}} \frac{1}{k_\perp^2 \, (q_i - k)_\perp^2}$$

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

Proved to next-to-leading log

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

Assembly



Build fully-flexible Monte Carlo from these

Merge with exact LO if cluster into 2, 3 or 4 jets

Add missing momentum configurations for 2,3 & 4j

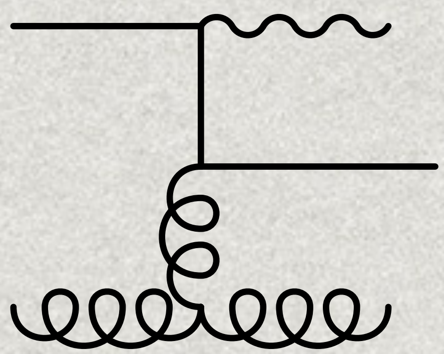
Publicly available at

http://cern.ch/hej

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

Extension to Ws

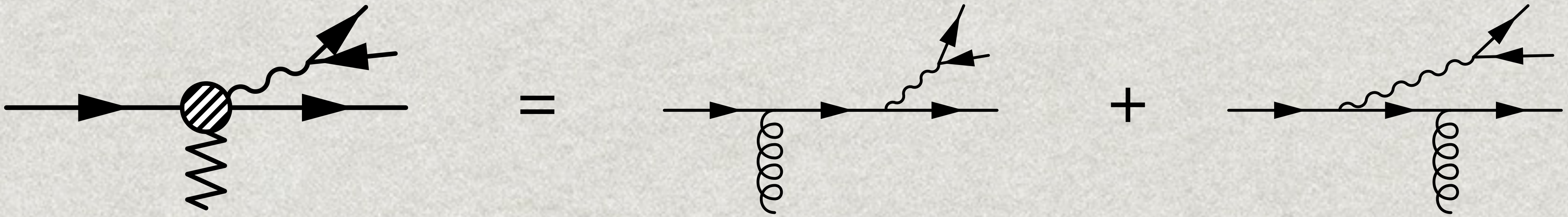
qg-channel dominant for W+nj at LHC



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

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

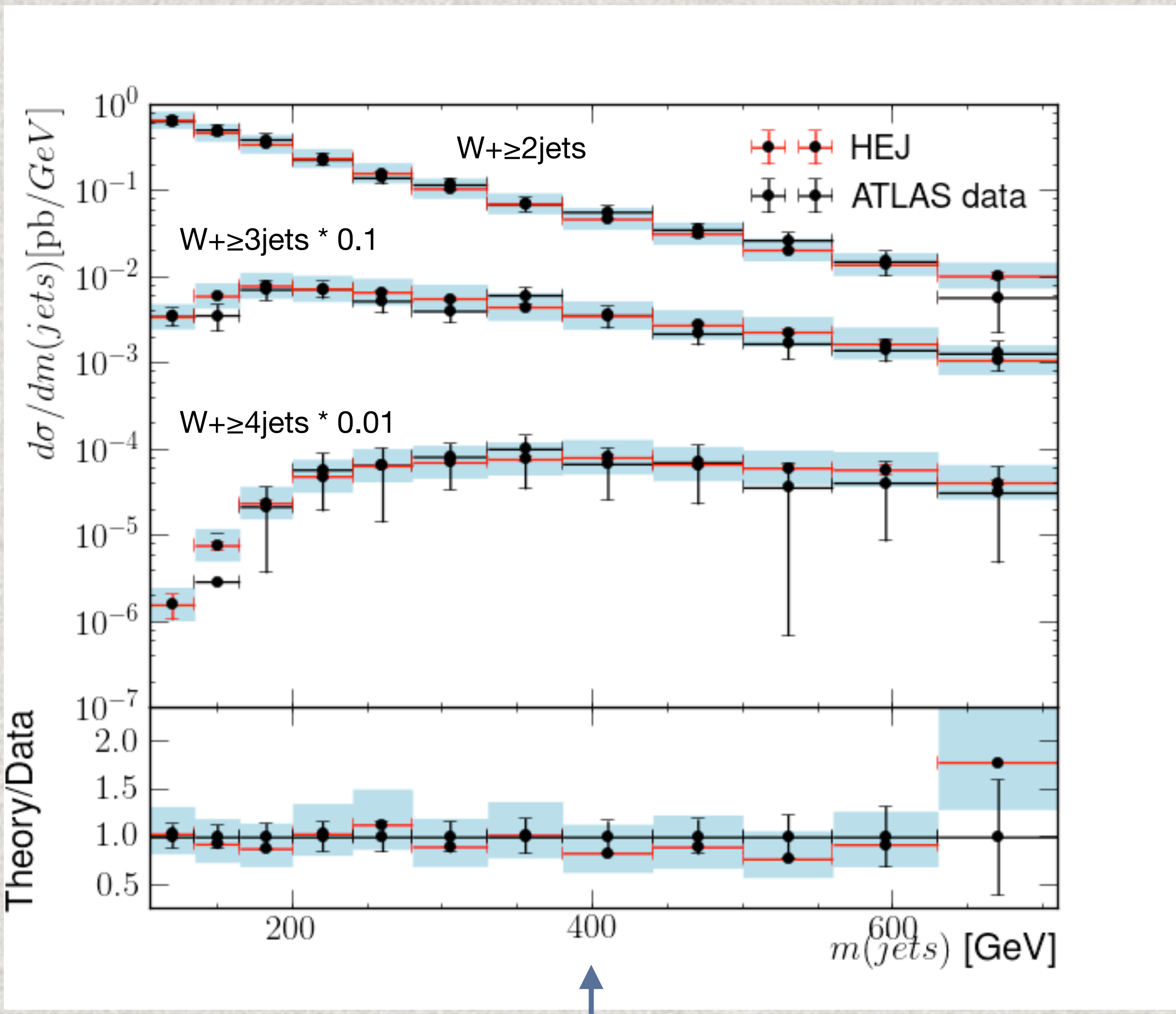
- Can combine both (but not straight-forward).

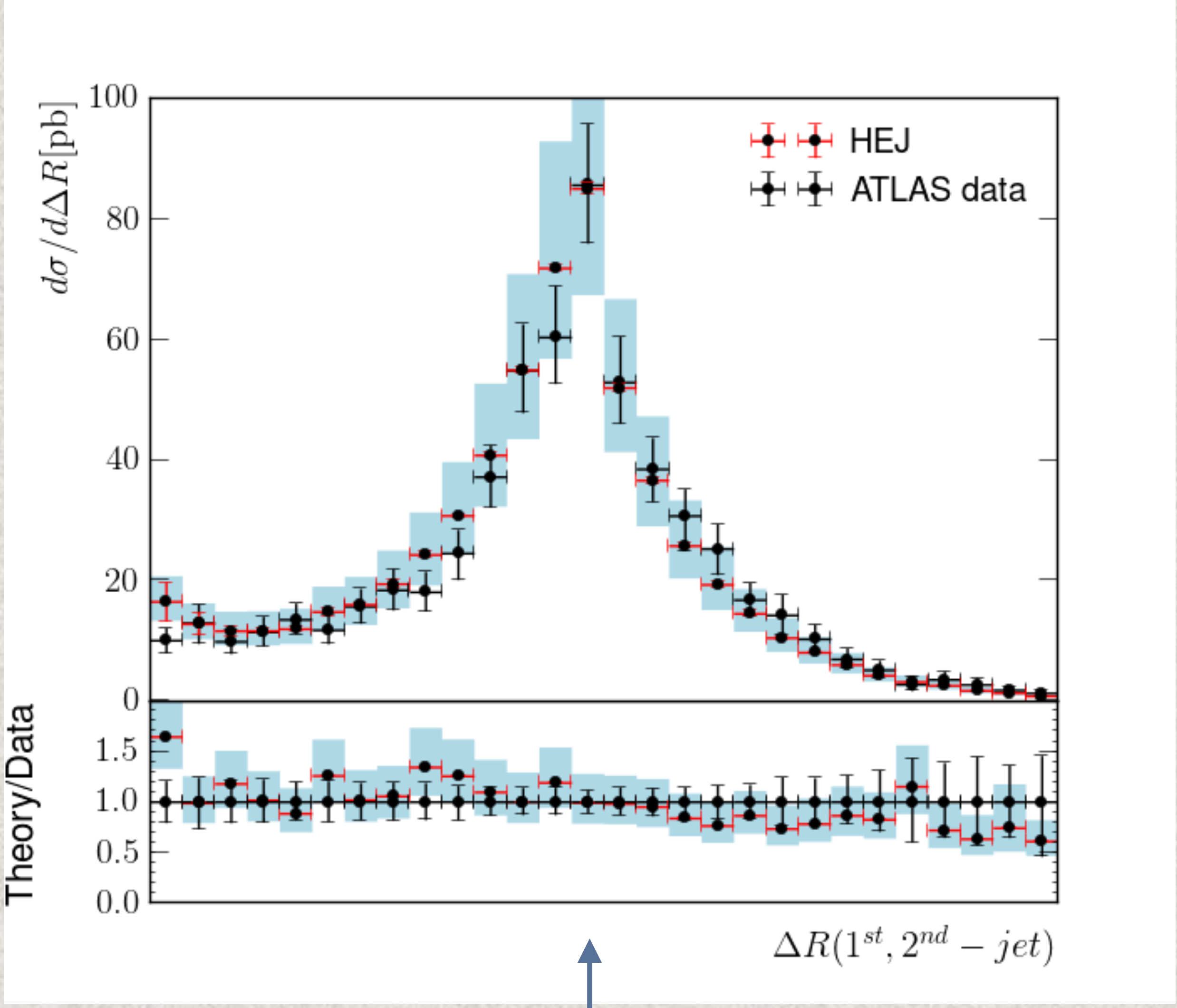
Andersen, Lönnblad & JMS arXiv:1104.1316

More Results

ATLAS 2010 W+dijets

HEJ again gives good description:





Note large impact of higher orders!

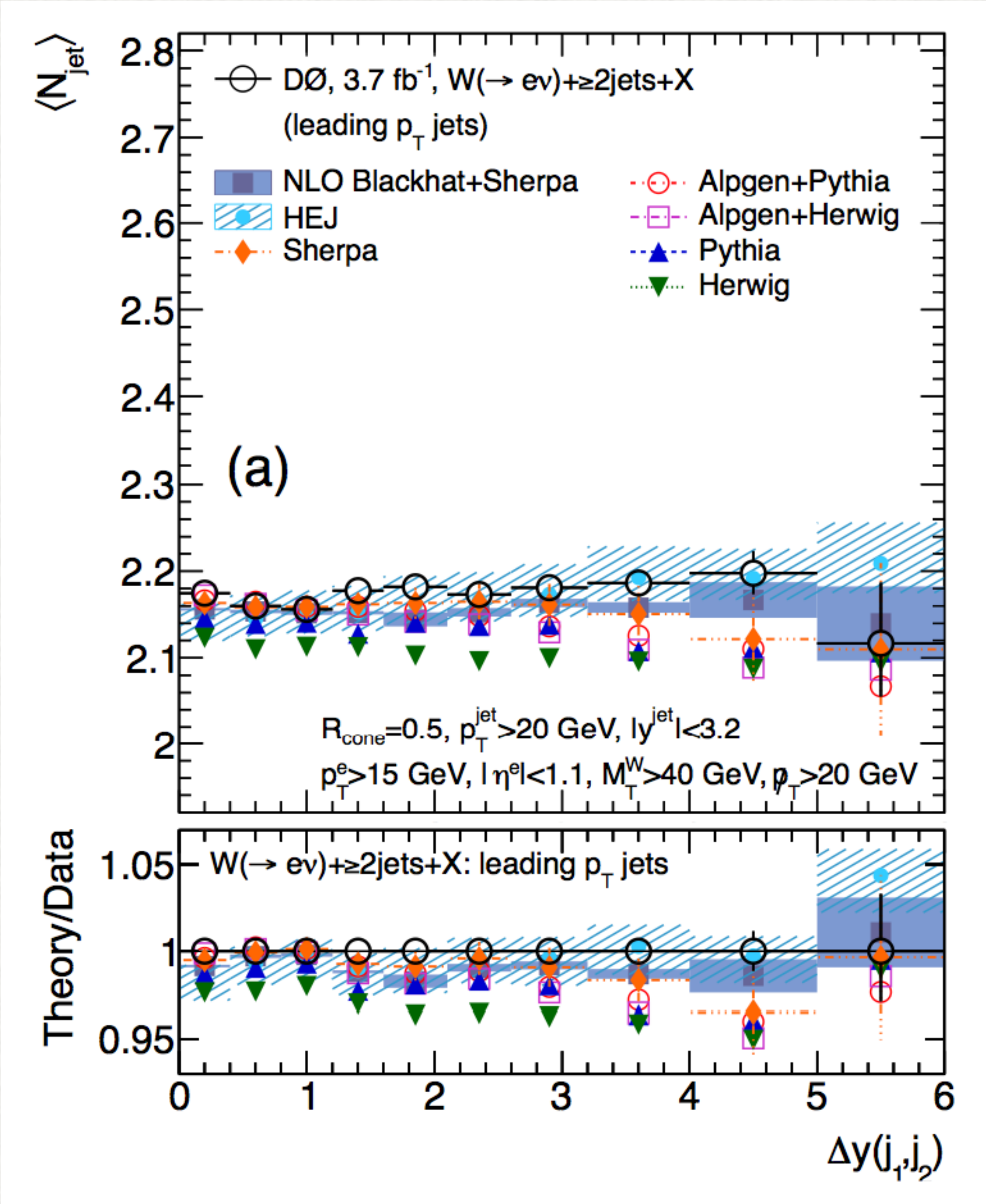
Traditionally very hard to describe (testing ground for state-of-the-art) HEJ gives good description

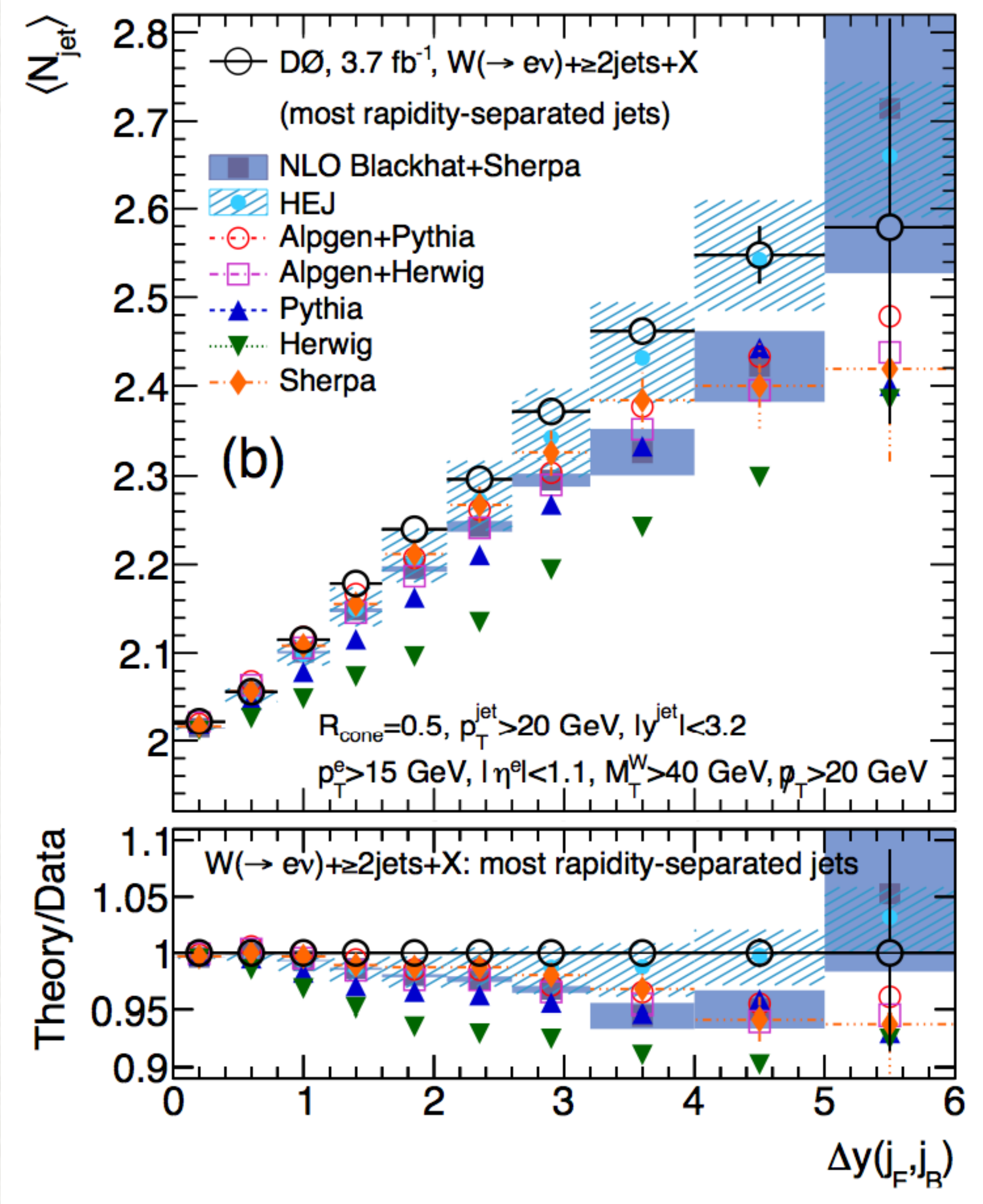
ATLAS (2010) data arXiv:1201.1276

Andersen, Hapola & JMS arXiv:1206.6763

D0 W+Jets

Really thorough analysis: 40 observables!





This is the difference between:

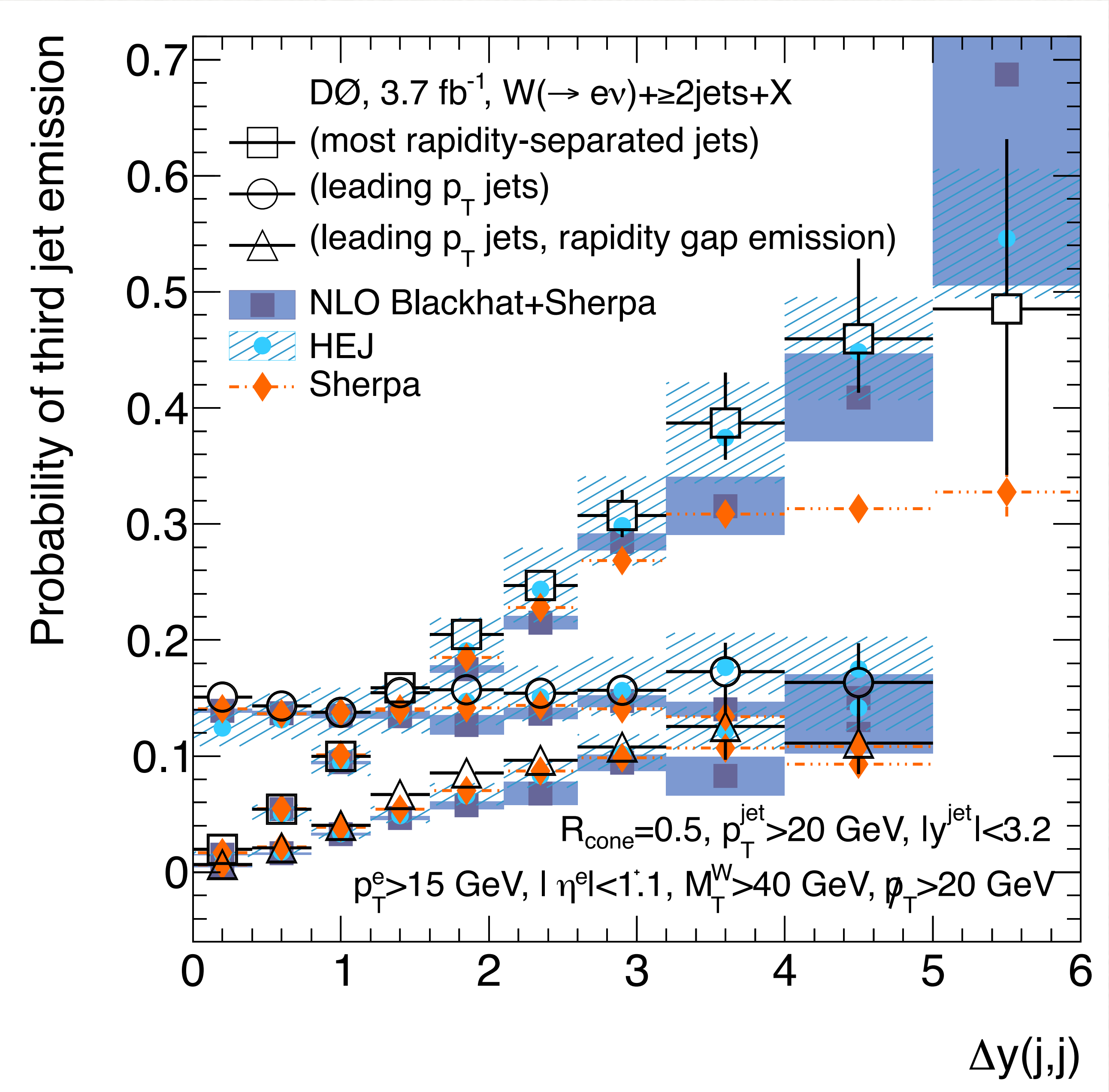
Leading Jets

Most forward/backward Jets

arXiv:1302.6508

D0 W+Jets

Probability of third jet emission versus Δy of:

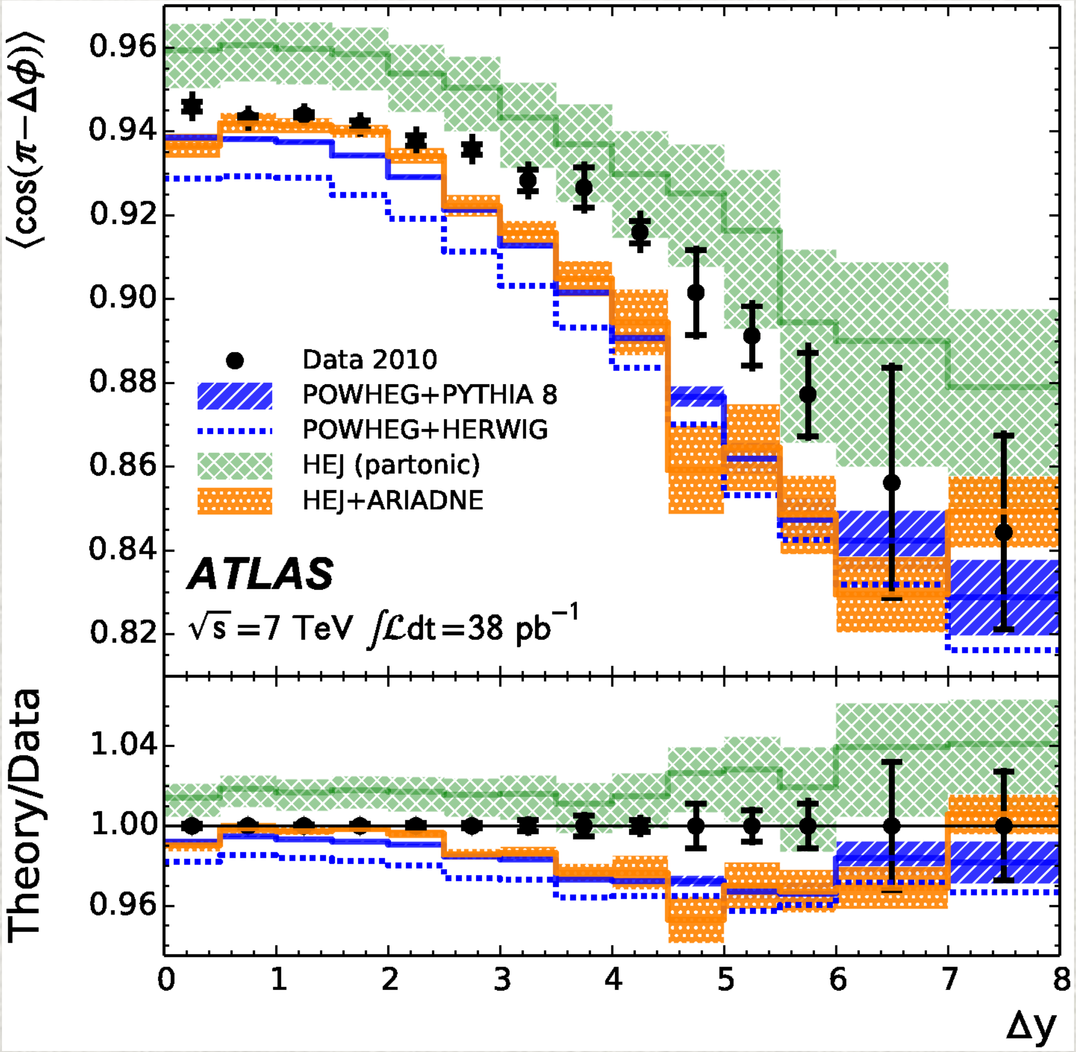


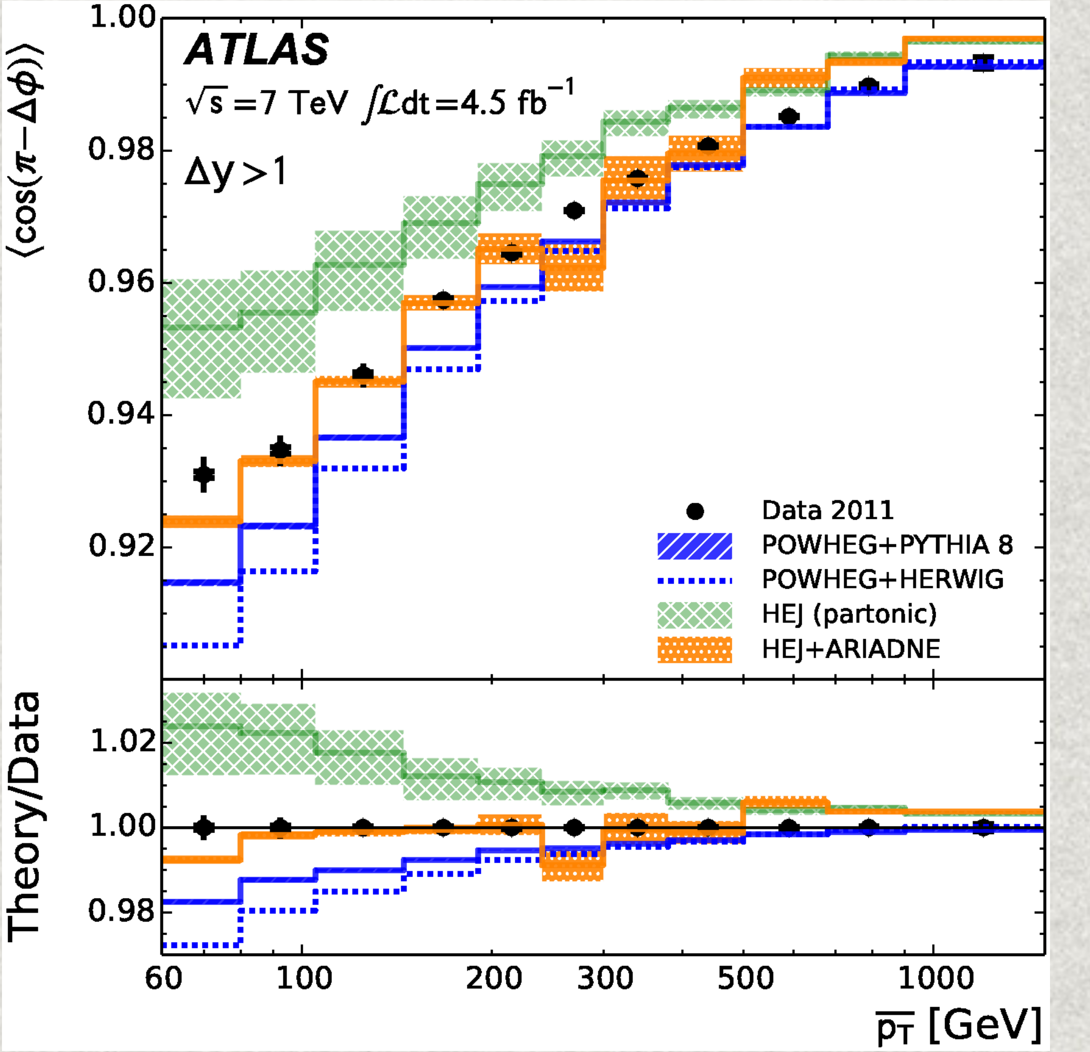
- Most forward/backward Jets
- Hardest Jets
- Hardest Jets, counting only jets between

arXiv:1302.6508

How you choose 2 jets matters!!

ATLAS jet veto update





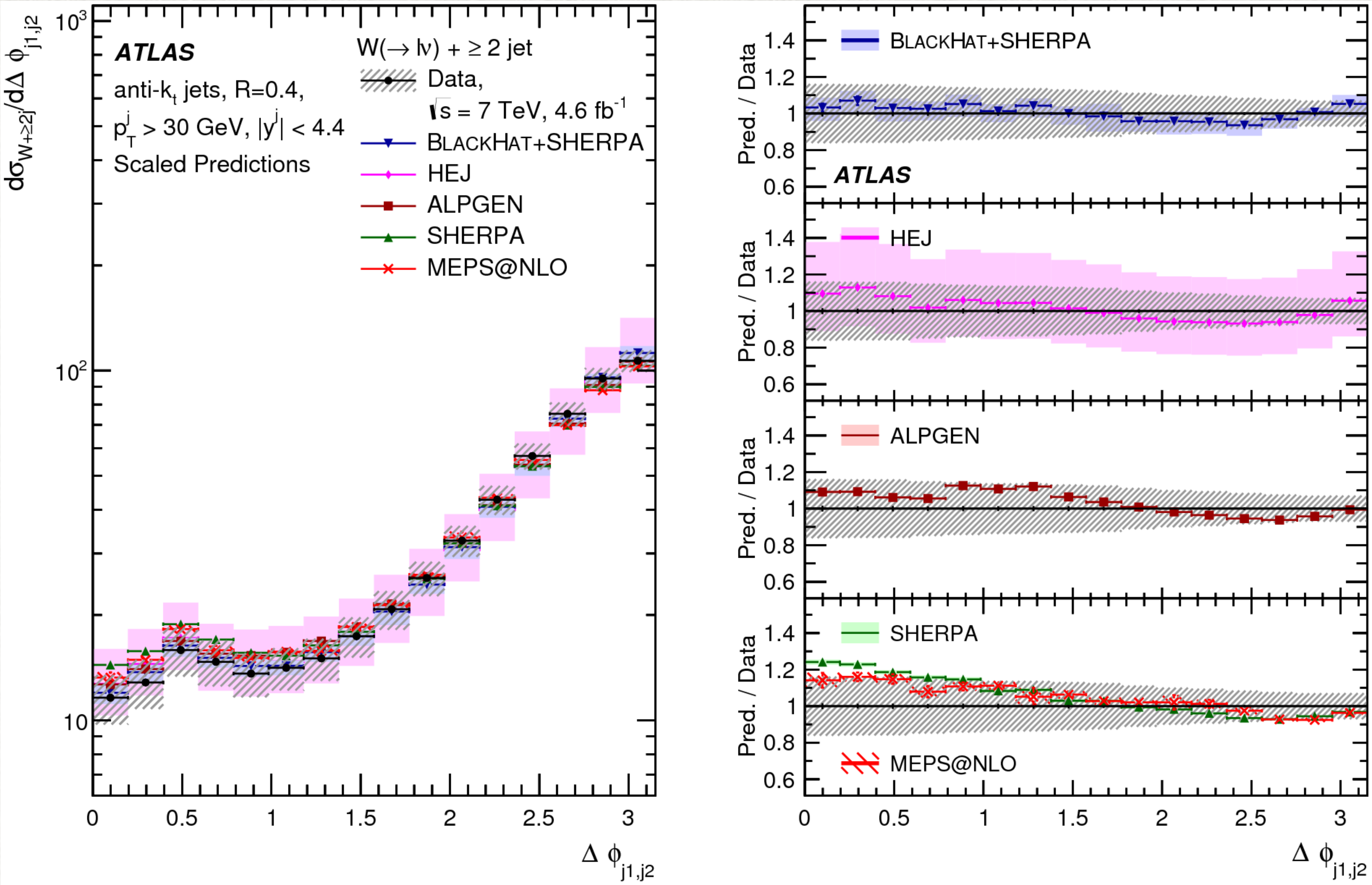
arXiv:1407.5756

$\langle\cos(\pi-\Delta\phi)\rangle$ measures angular decorrelation

Large impact of shower in this set-up

$$\overline{p_T} > 50\ (60)\ \text{GeV}, \quad Q_0 > 20\ (30)\ \text{GeV}, \quad |y_j| < 4.4\ (2.4)$$

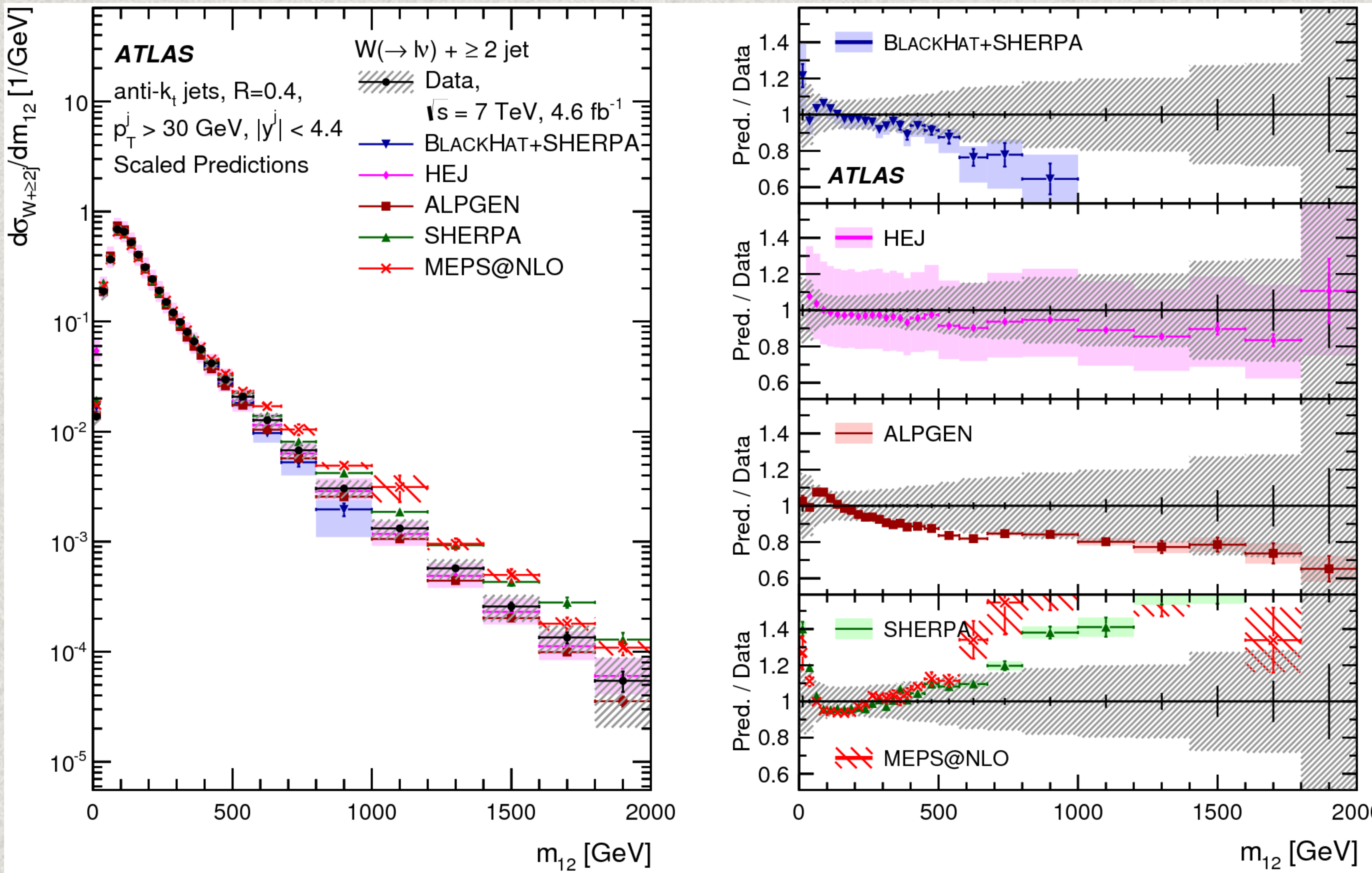
ATLAS 2011 W+Jets



Many interesting distributions studied up to 5 jets

arXiv:1409.8639

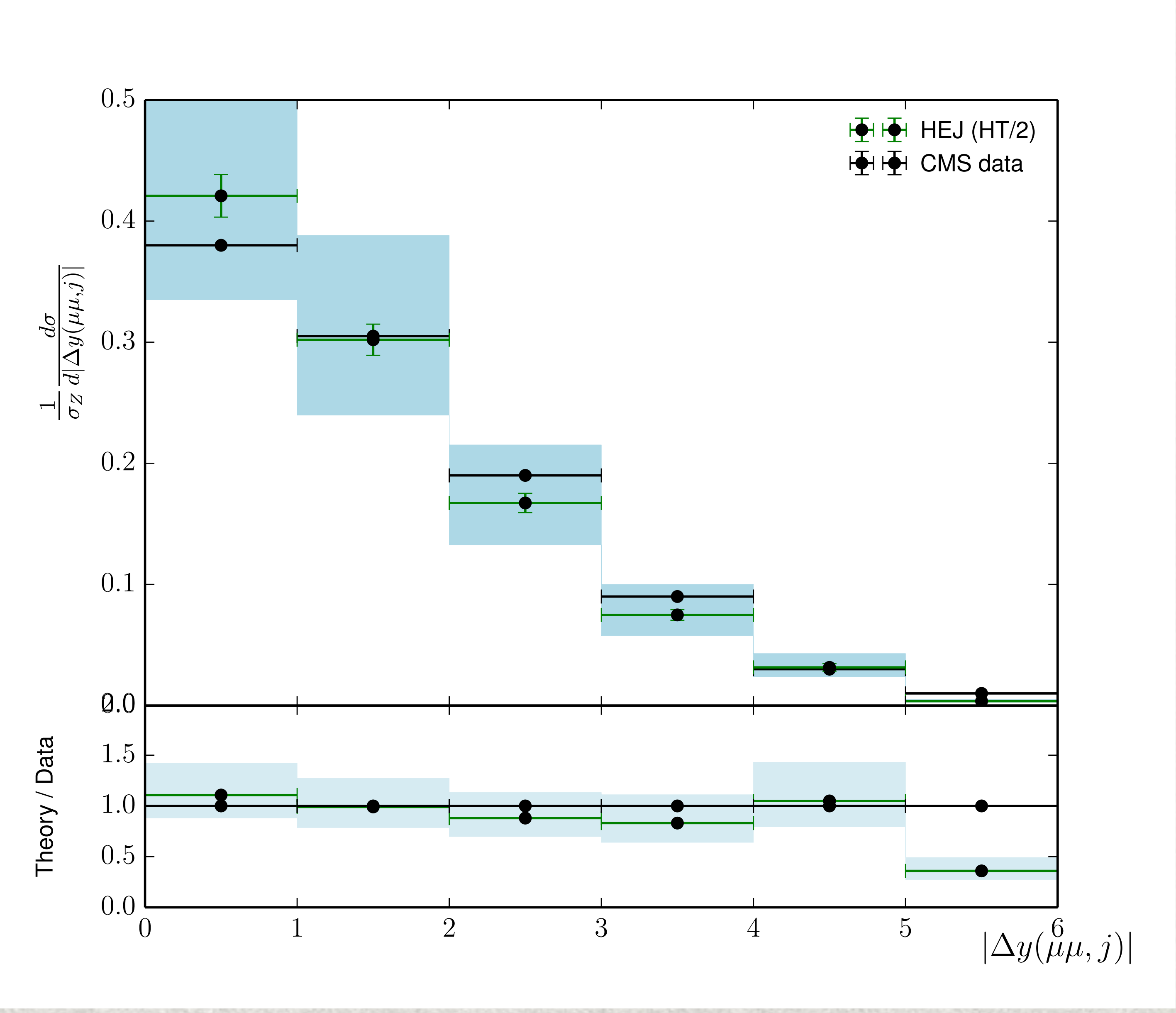
ATLAS 2011 W+Jets



Clearly illustrates the improvement at large invariant mass

arXiv:1409.8639

CMS 2011 Z+Jets



Mass window: $60\ \text{GeV} < m_{\mu\mu} < 120\ \text{GeV}$

HEJ = PRELIMINARY

Data from CMS PAS FSQ-13-003

Higgs Plus Dijets

Higgs Plus Dijets

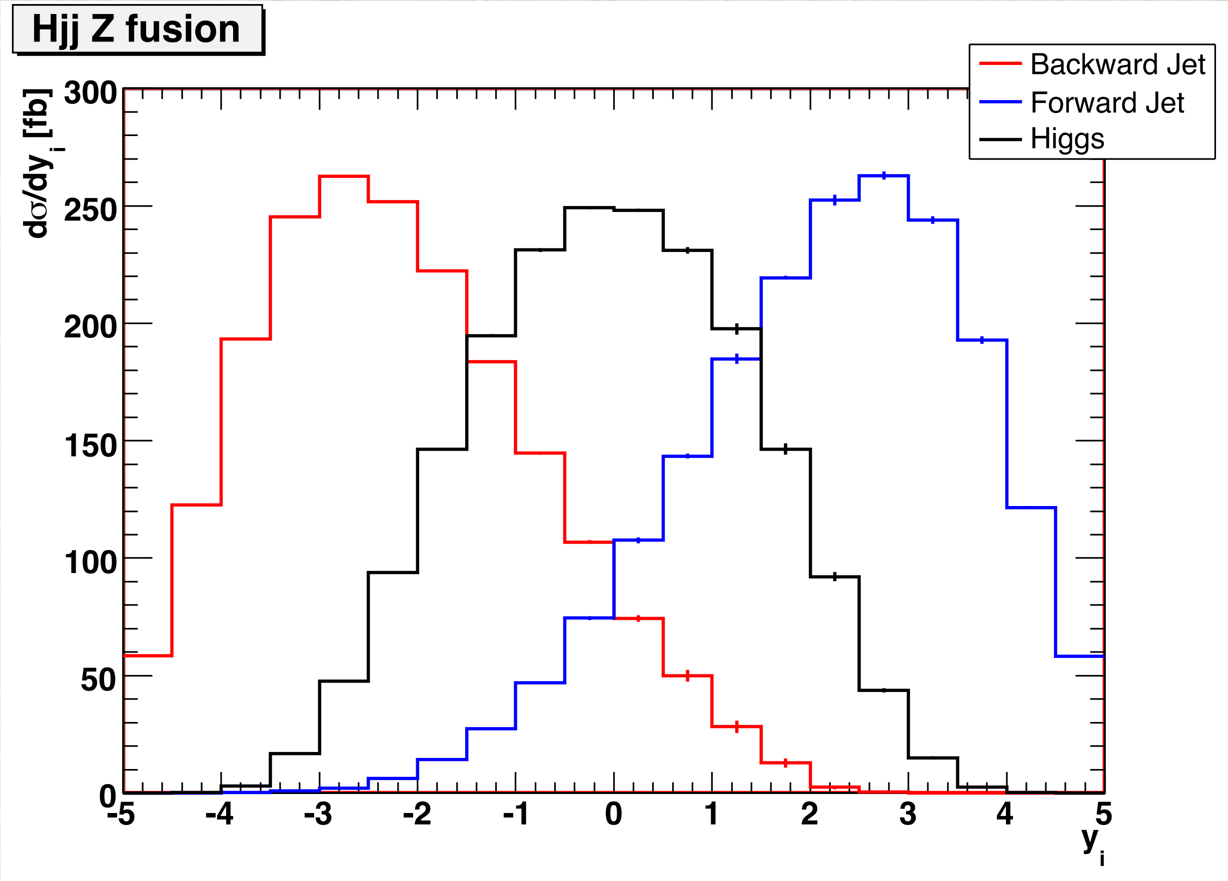
- Vector Boson Fusion is 2nd largest production channel

- Key opportunity to study VVH vertex

- Use distinctive topology to select events

Here:

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



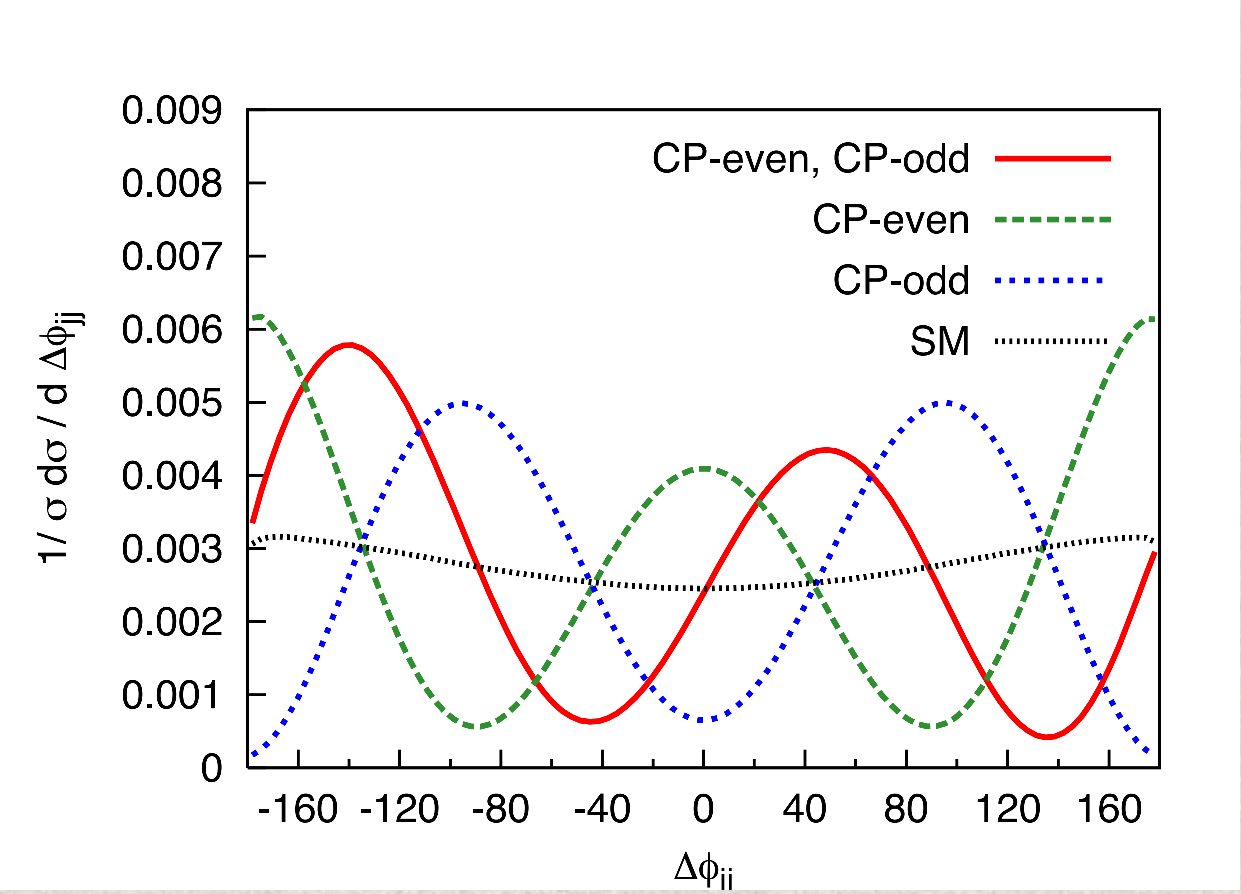
Higgs Plus Dijets

Typical “VBF” cuts:

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

Puts us right into the difficult region!

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

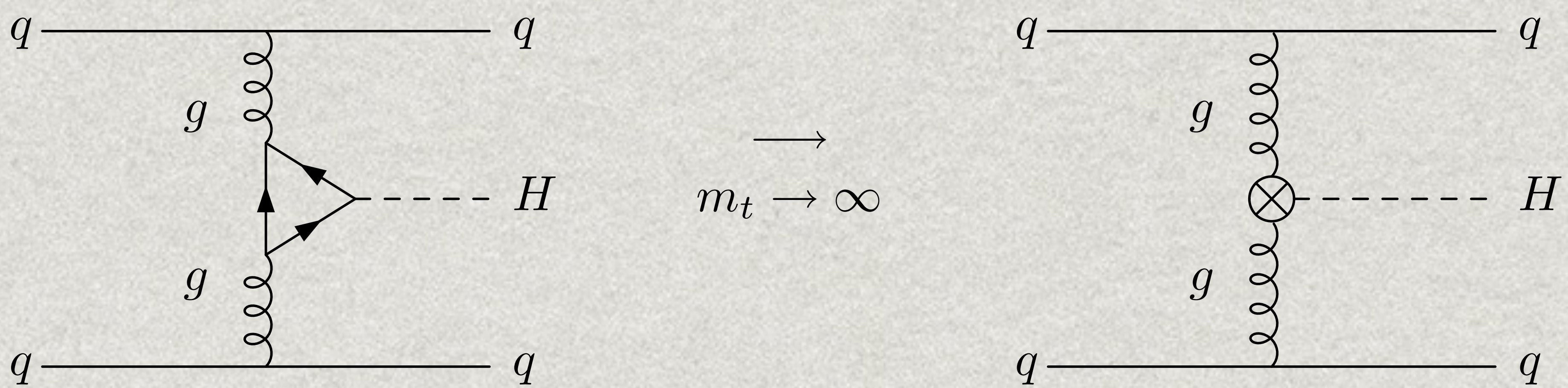


HE limit tells you how to extend to n jets

Andersen, Arnold & Zeppenfeld arXiv:1001.3822

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

Higgs Plus Jets



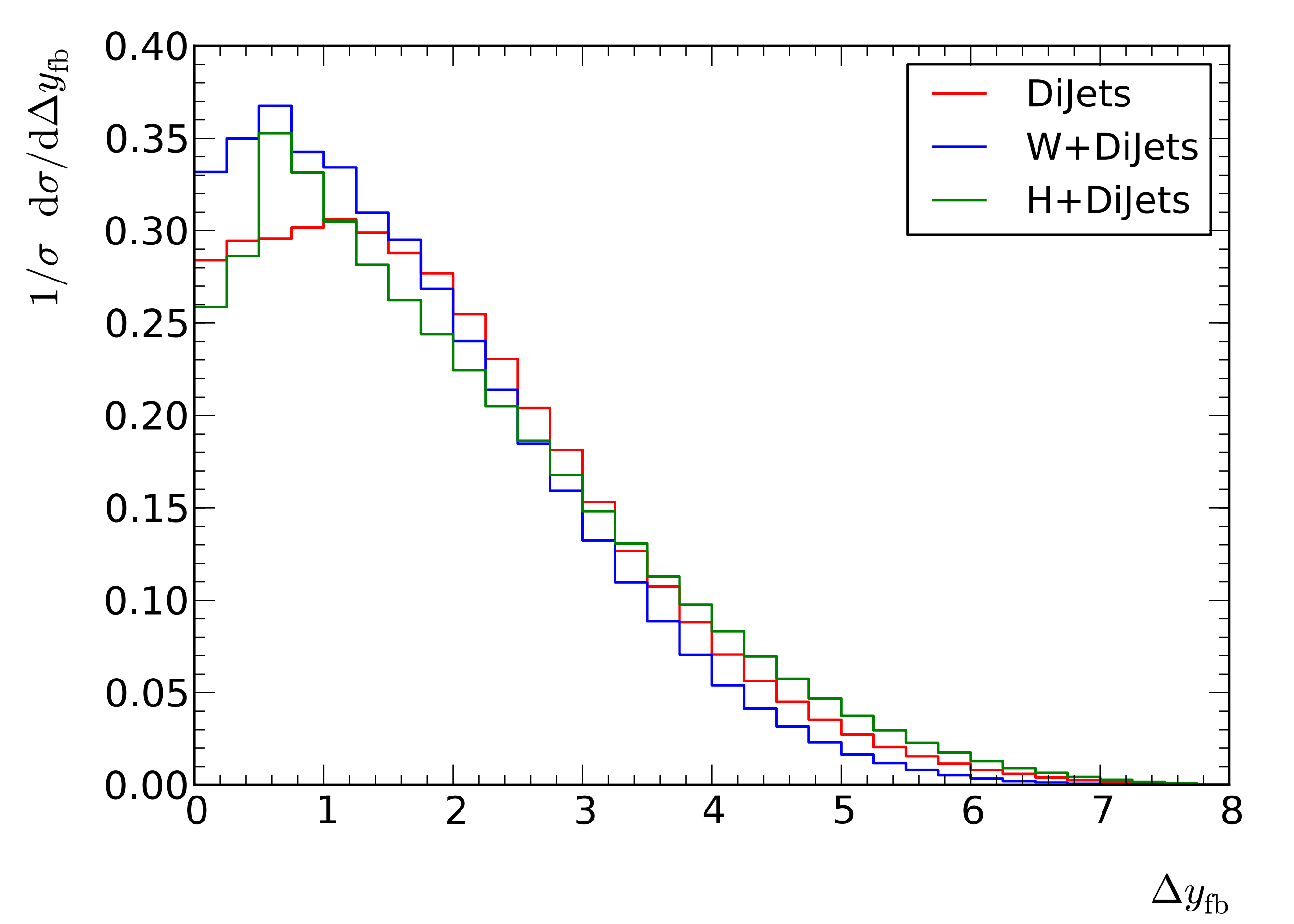
In heavy top-mass limit: $V_{Hgg}(p^\mu, q^\nu) = \frac{i\alpha_s}{3\pi v}(p \cdot q g^{\mu\nu} - p^\nu q^\mu)$

- Different CP structure so can contaminate study.
- Interesting to study in own right
- Gluons expected to radiate more
  ∴ 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!)

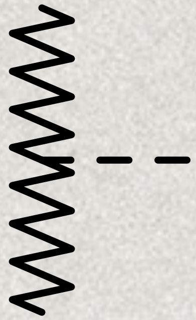
From now on, will focus on Gluon-Gluon Fusion.



Jet radiation patterns universal across processes.

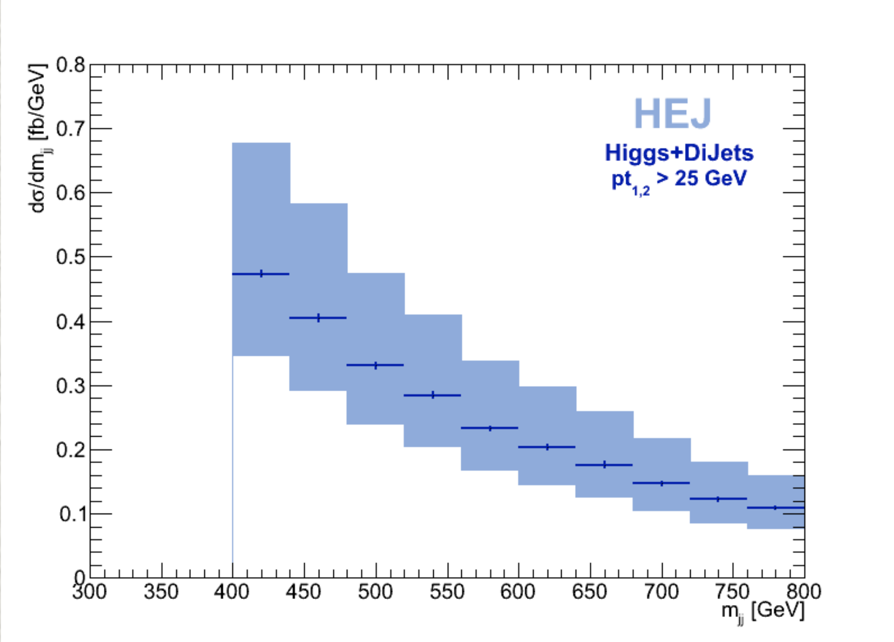
Use existing data to test descriptions.

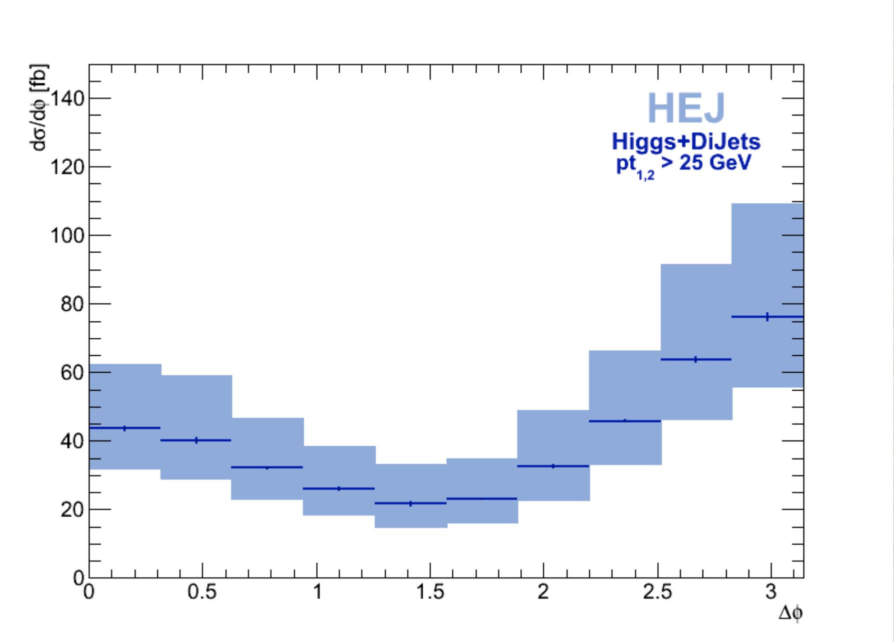
Higgs in HEJ



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

Insert this in the gluon chain according to rapidity

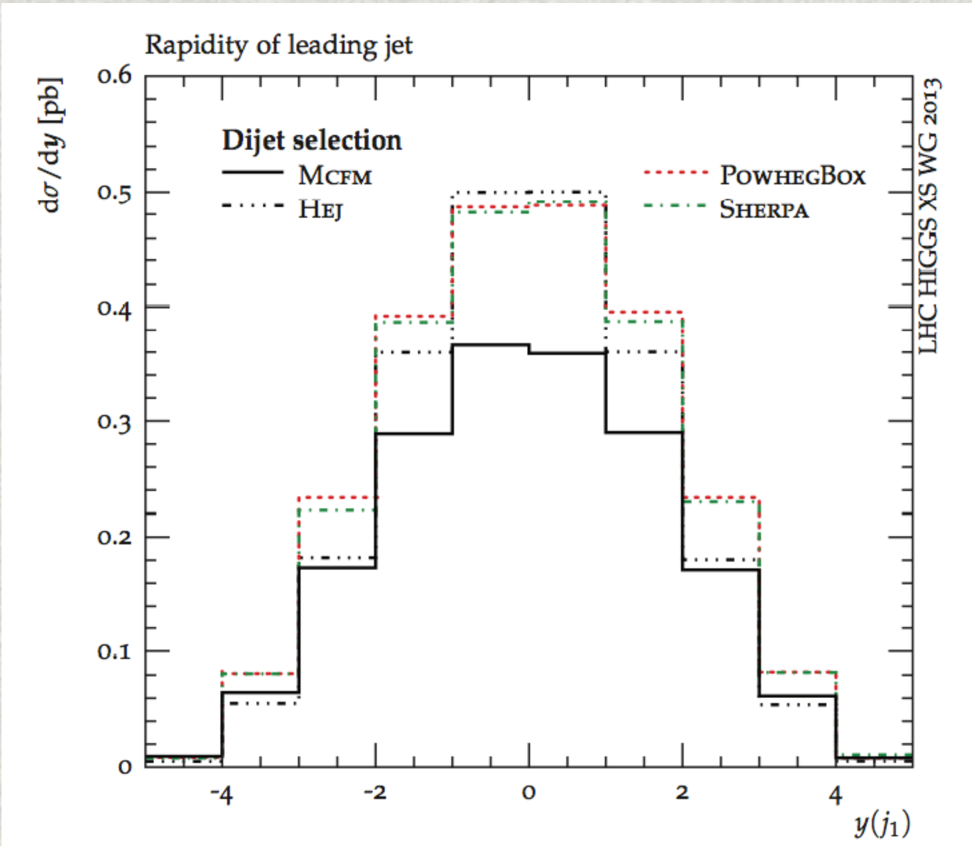




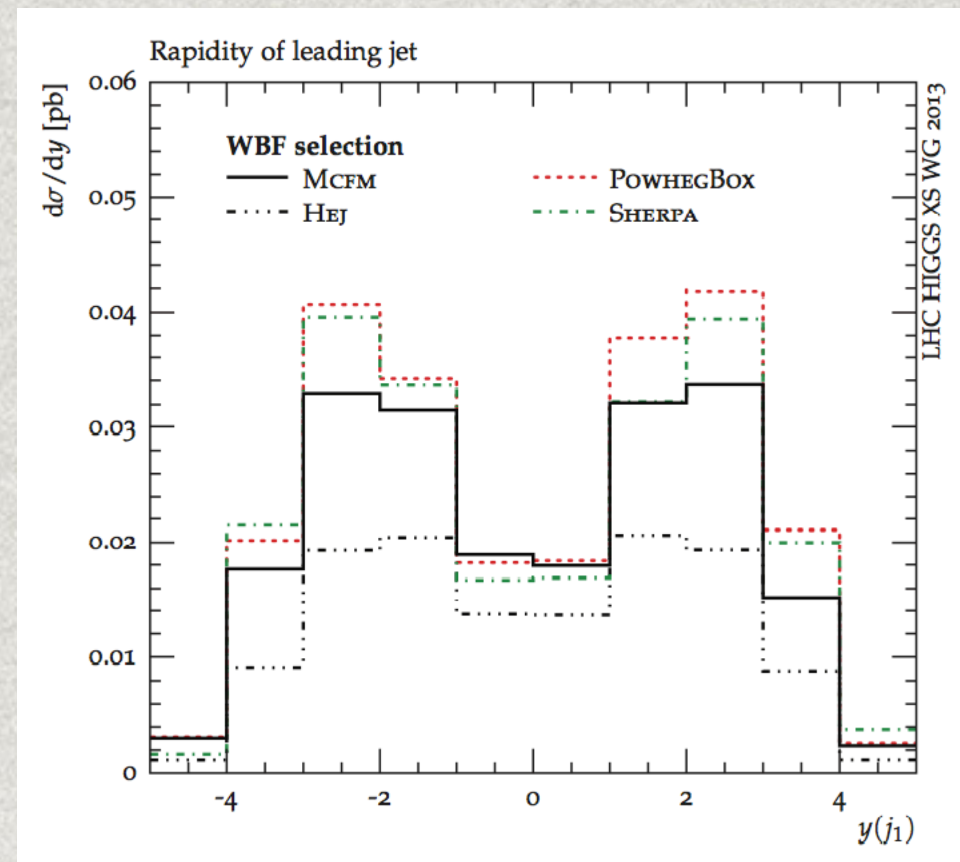
Now also includes one un-ordered gluon emission

Andersen, Hapola & JMS (to appear)

Higgs XS WG YR3 2013

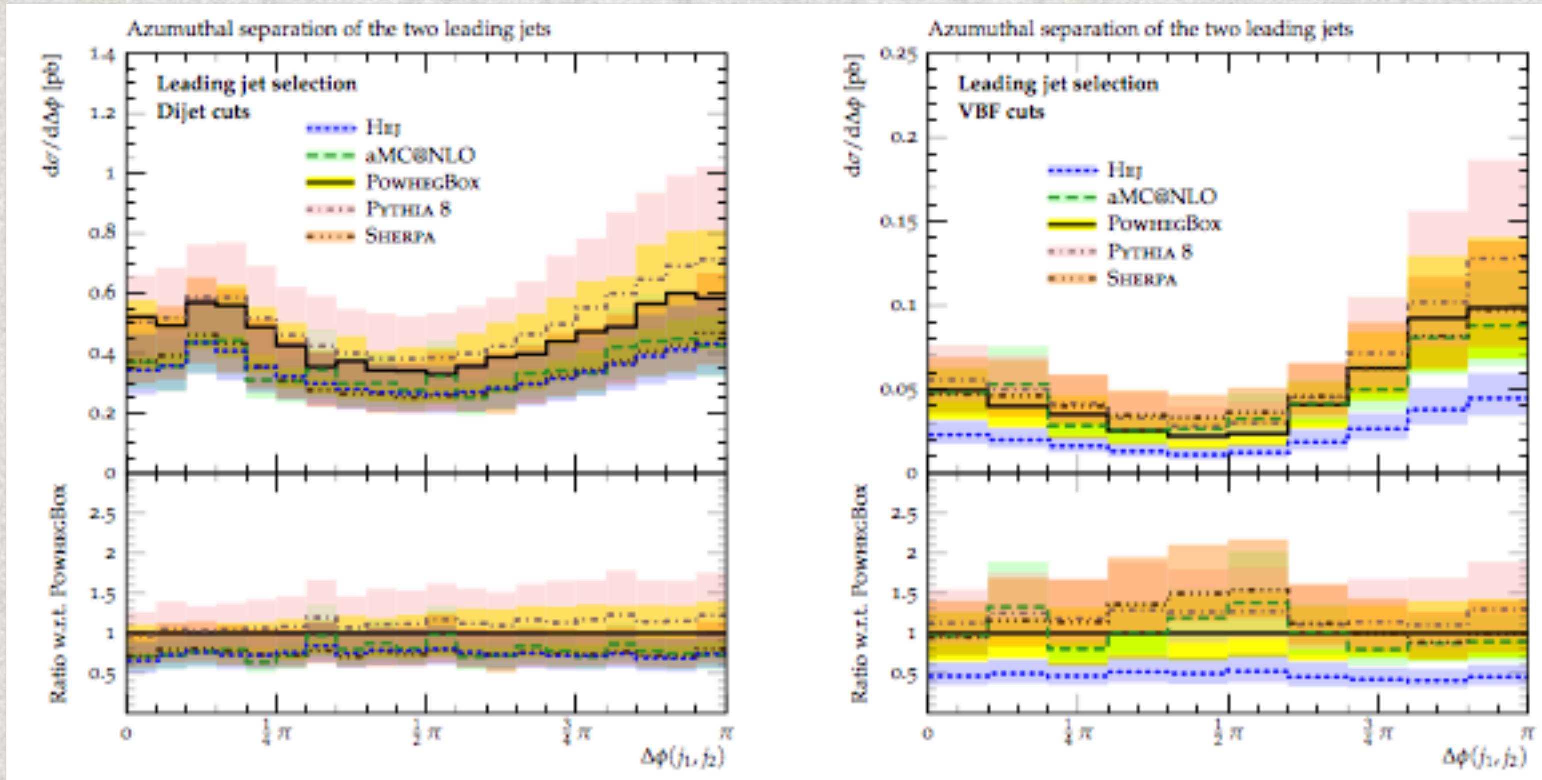


+VBF cuts



- 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

Variation in Theory



Cross sections in the forward-backward selection

Generator	σ_{dijet} [pb]	σ_{dijet} [pb] $y_{j_{\text{bw}}} < y_h < y_{j_{\text{fw}}}$	σ_{VBF} [pb]	σ_{VBF} [pb] $y_{j_{\text{bw}}} < y_h < y_{j_{\text{fw}}}$	σ_{VBF} [pb] $y_{j_{\text{bw}}} < y_{j_3} < y_{j_{\text{fw}}}$
HEJ	$1.053^{+0.374}_{-0.253}$	$0.384^{+0.130}_{-0.089}$	$0.103^{+0.044}_{-0.028}$	$0.086^{+0.035}_{-0.022}$	$0.0585^{+0.0323}_{-0.0190}$
aMC@NLO	$1.106^{+0.316}_{-0.272}$	$0.512^{+0.147}_{-0.127}$	$0.183^{+0.058}_{-0.047}$	$0.163^{+0.050}_{-0.041}$	$0.0796^{+0.0237}_{-0.0198}$
POWHEGBOX	$1.426^{+0.328}_{-0.415}$	$0.658^{+0.199}_{-0.214}$	$0.197^{+0.068}_{-0.068}$	$0.177^{+0.060}_{-0.061}$	$0.0878^{+0.0472}_{-0.0394}$
PYTHIA 8	$1.590^{+0.612}_{-0.385}$	$0.716^{+0.282}_{-0.175}$	$0.220^{+0.093}_{-0.055}$	$0.195^{+0.082}_{-0.049}$	$0.0726^{+0.0288}_{-0.0173}$
SHERPA	$1.073^{+0.462}_{-0.225}$	$0.499^{+0.229}_{-0.099}$	$0.218^{+0.102}_{-0.052}$	$0.189^{+0.091}_{-0.045}$	$0.1129^{+0.0656}_{-0.0296}$

Les Houches 2013
arXiv:1405.1067

See update at this year's Les Houches workshop!

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