The University of Manchester

# Measurements of W+jets production (jet vetoes, jet multiplicity, and others) at DØ

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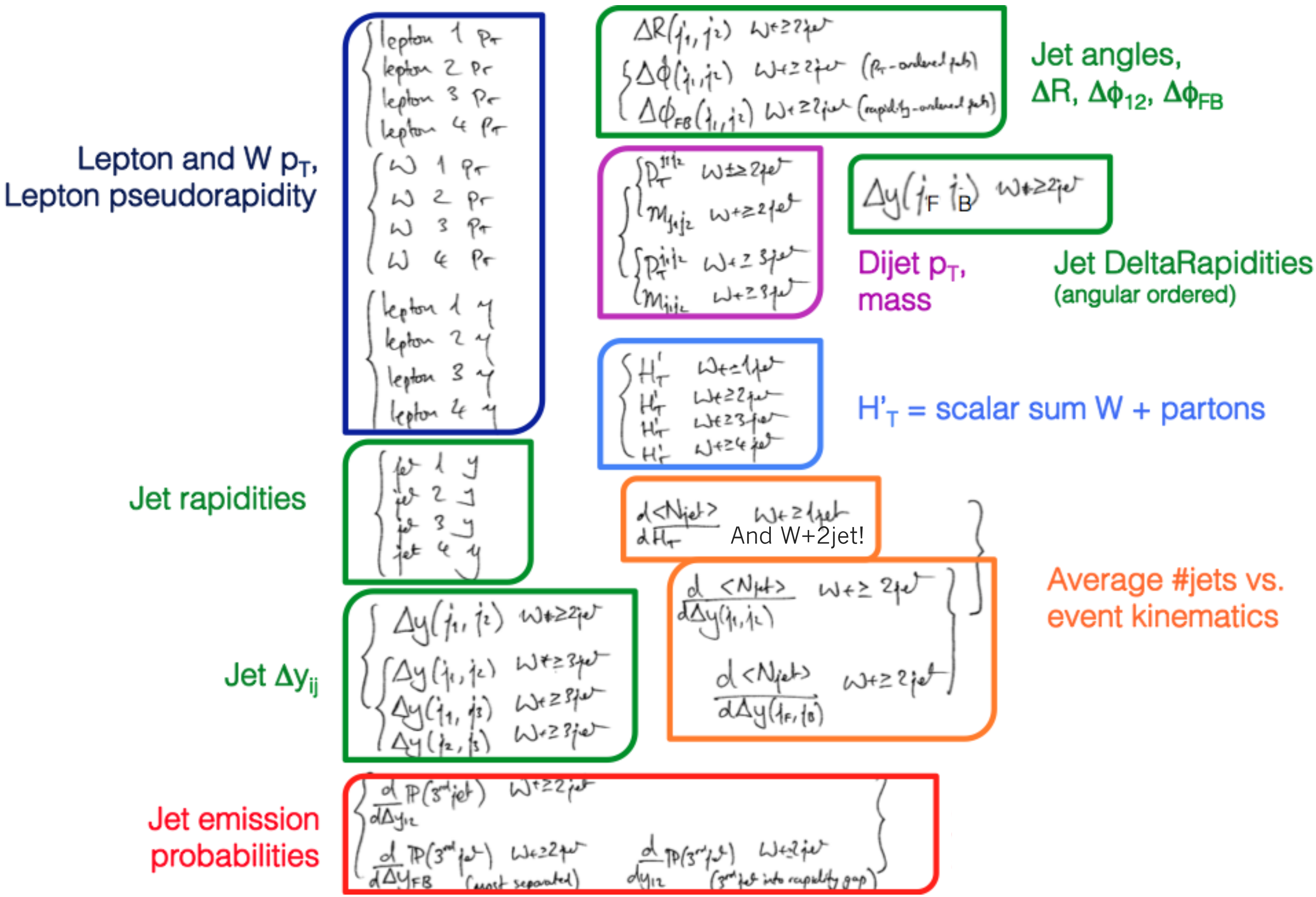
IPPP Jet Vetoes Workshop, Durham, July 17th—19th 2013

# W+jets: what we measure

arXiv:1302.6508 [hep-ex]



40 distributions in total: 33 cross-section, 7 jet veto/multiplicity measurements



# W(eυ)+jets selection criteria



Use 3.7 fb$^{-1}$ dataset of proton-antiproton collisions at $\sqrt{s}$=1.96 TeV

## Electron candidate

$p_T$>15 GeV, |η|<1.1, $Z(e^+e^-)$ mass veto

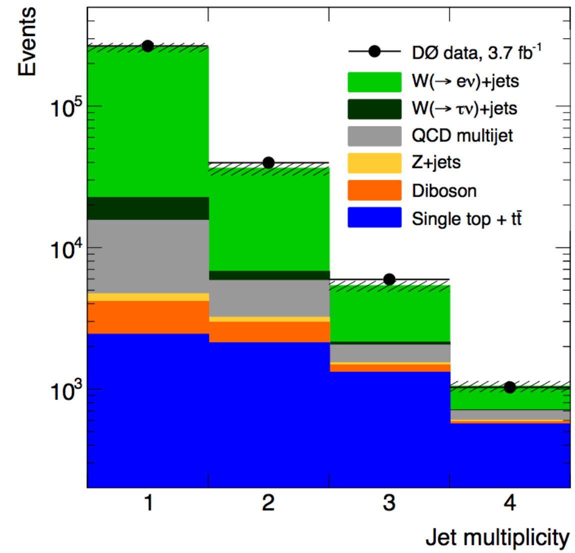
## W boson candidate

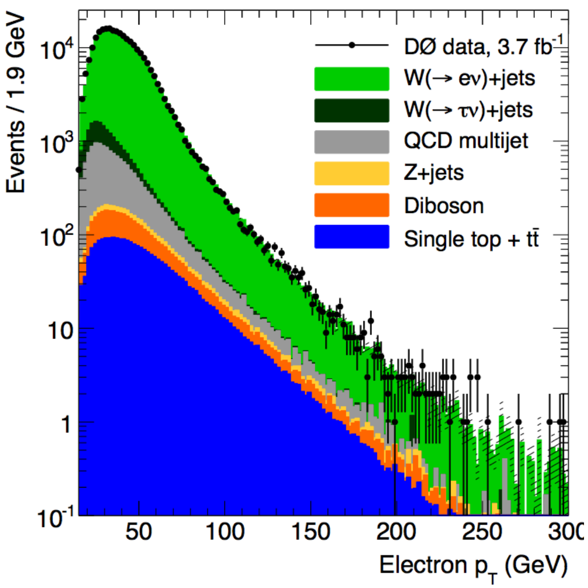
MET>20 GeV, $m_T(W)$>40 GeV

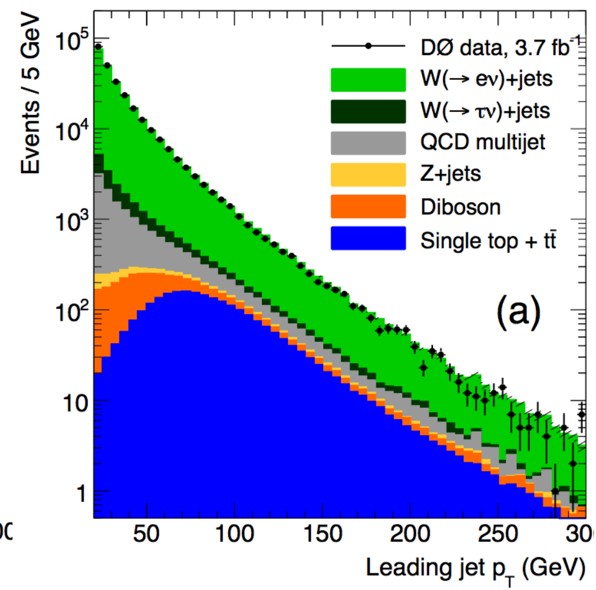
## Jet selection

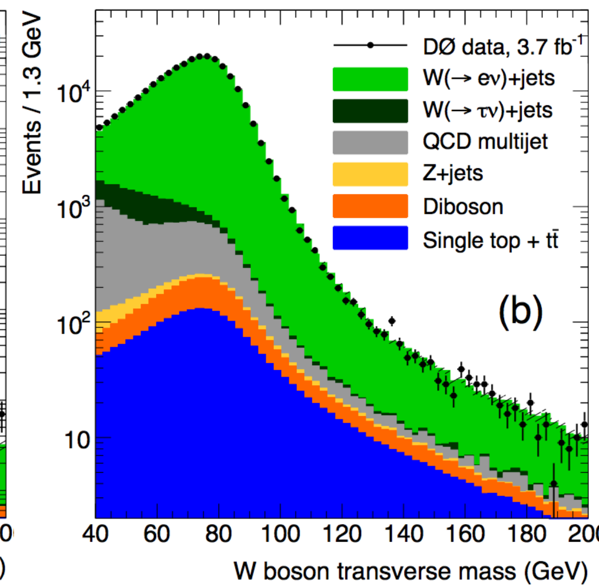
$E_T$>20 GeV, $|y_j|$<3.2, vertex confirmation

DØ RunII midpoint cone algorithm R=0.5



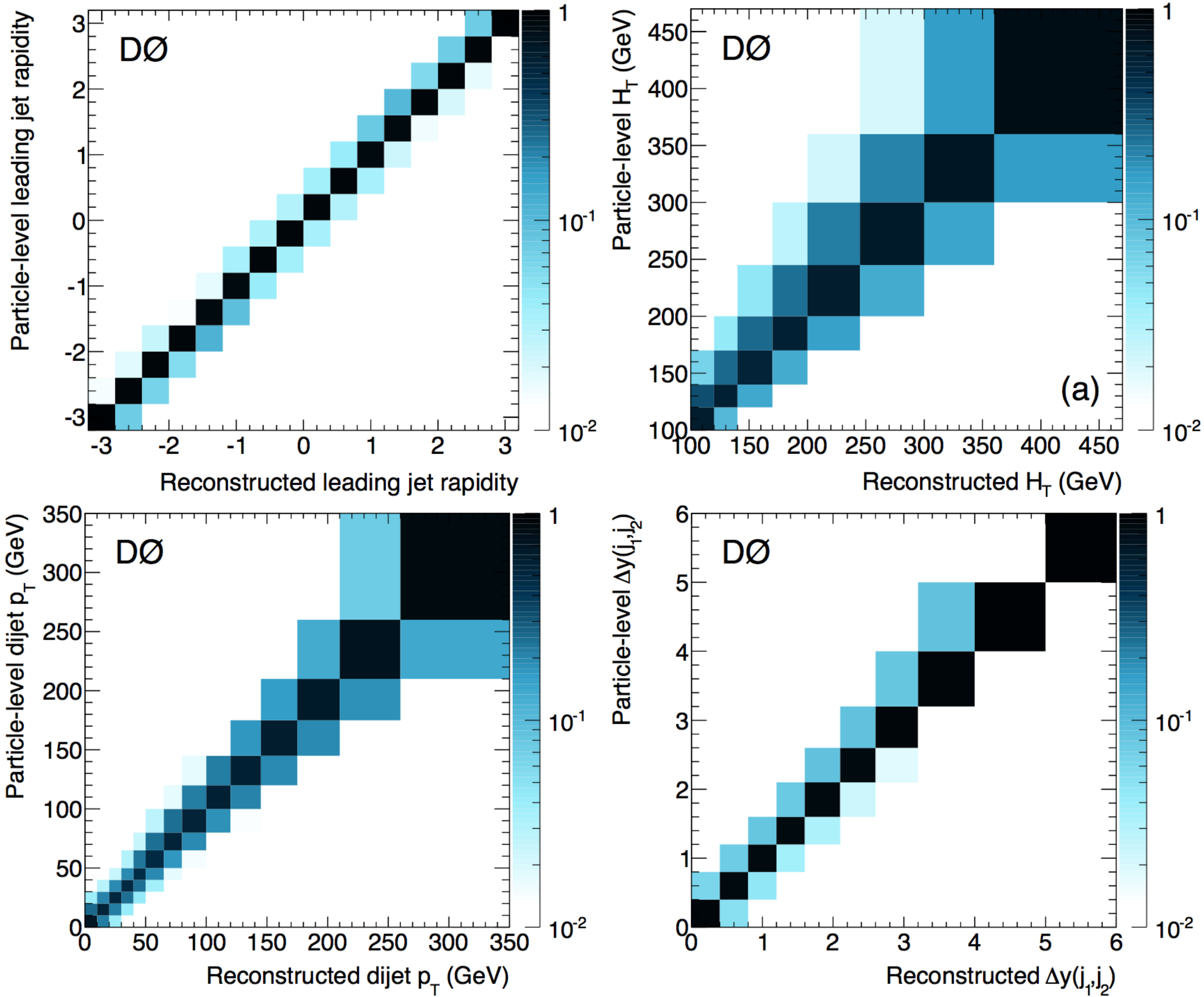



# Unfolding of data to particle-level



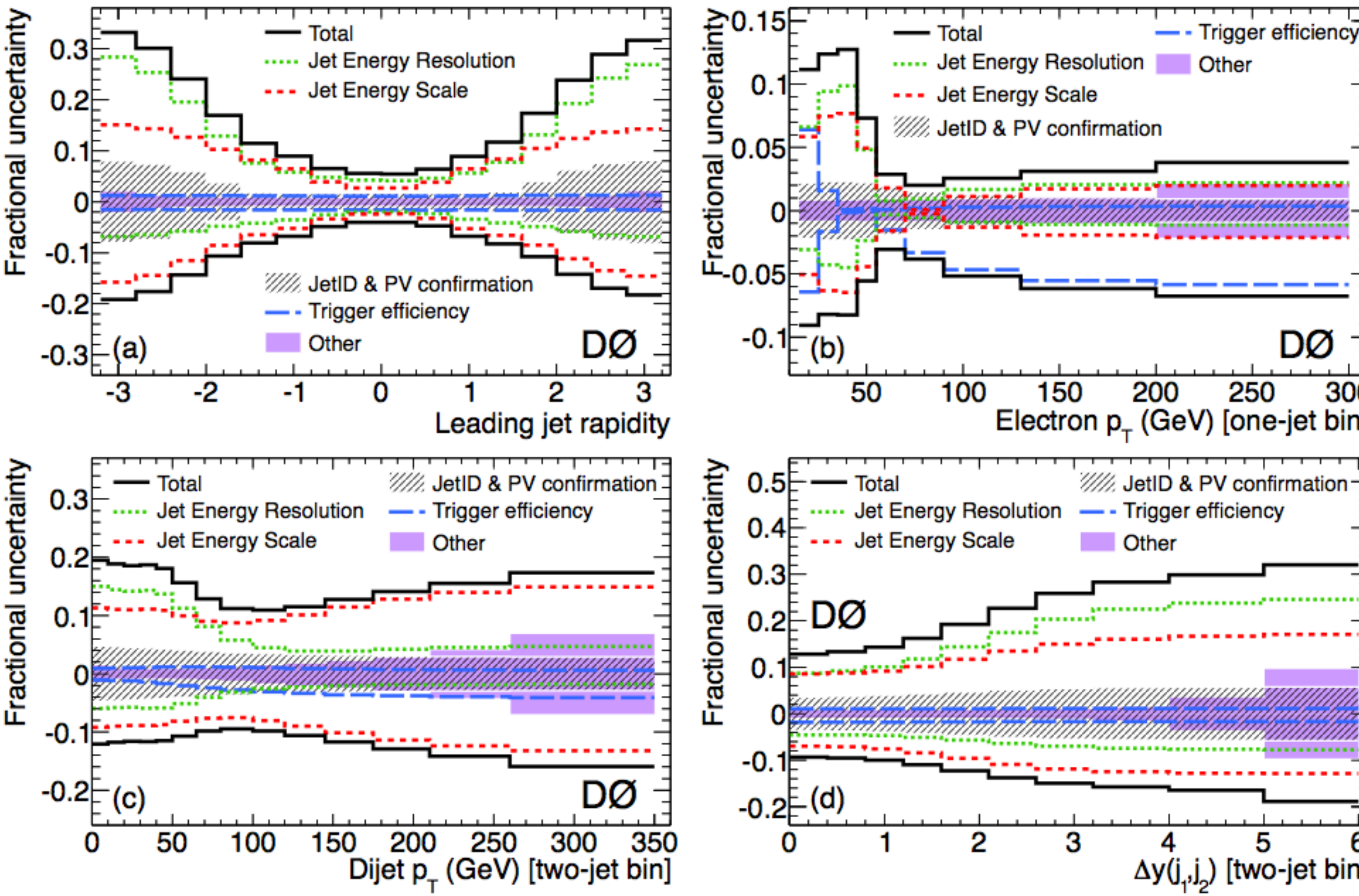
Unfold all distributions to particle level using regularised SVD approach (takes into account migration effects)




Example detector response matrices

# Systematic uncertainties

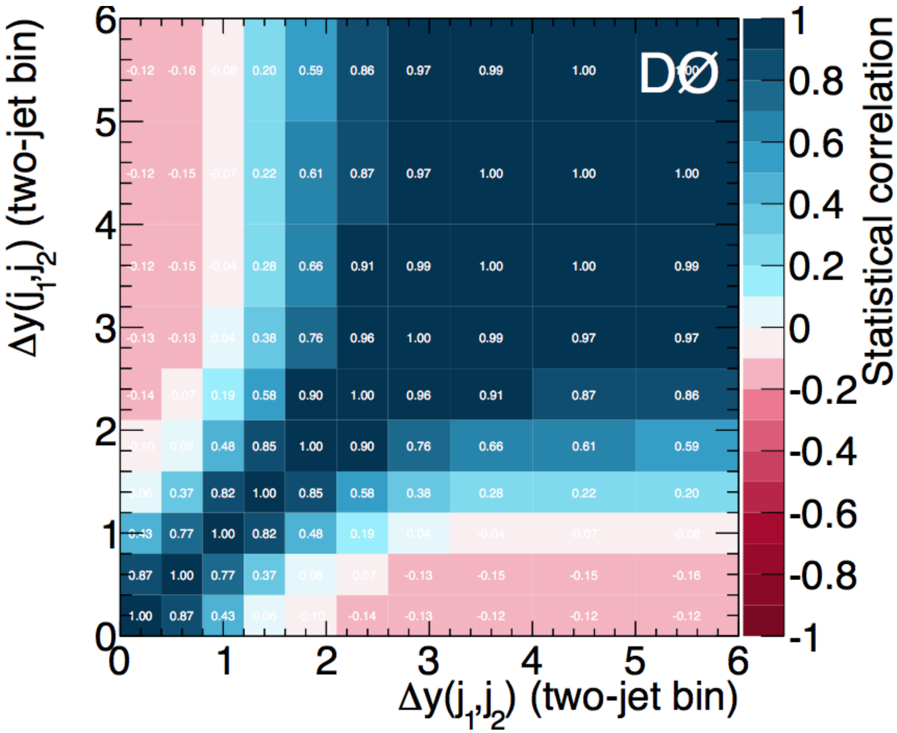


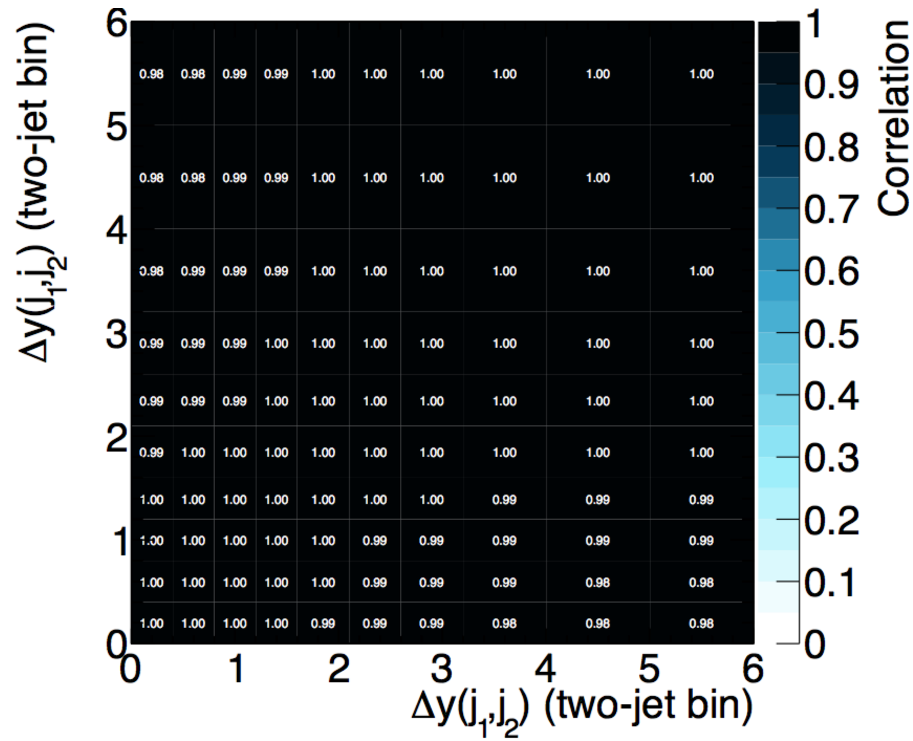


# Statistical and systematic correlations



Statistical and systematic correlations in unfolded measurements determined and documented (EPAPS and HEPDATA) along with measurements for purposes of constraining theory-data fits

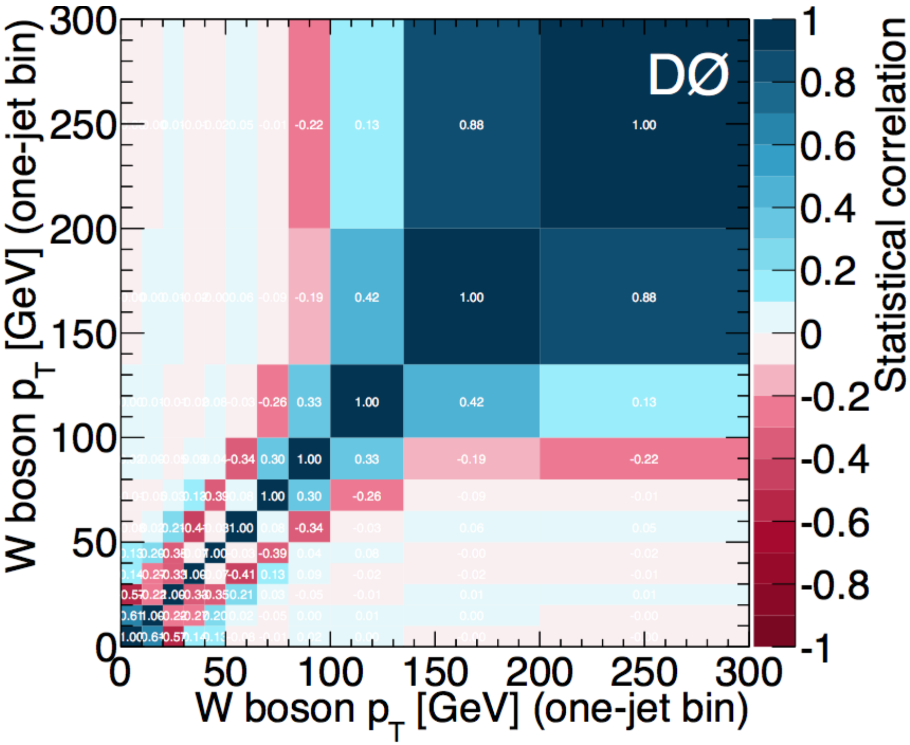


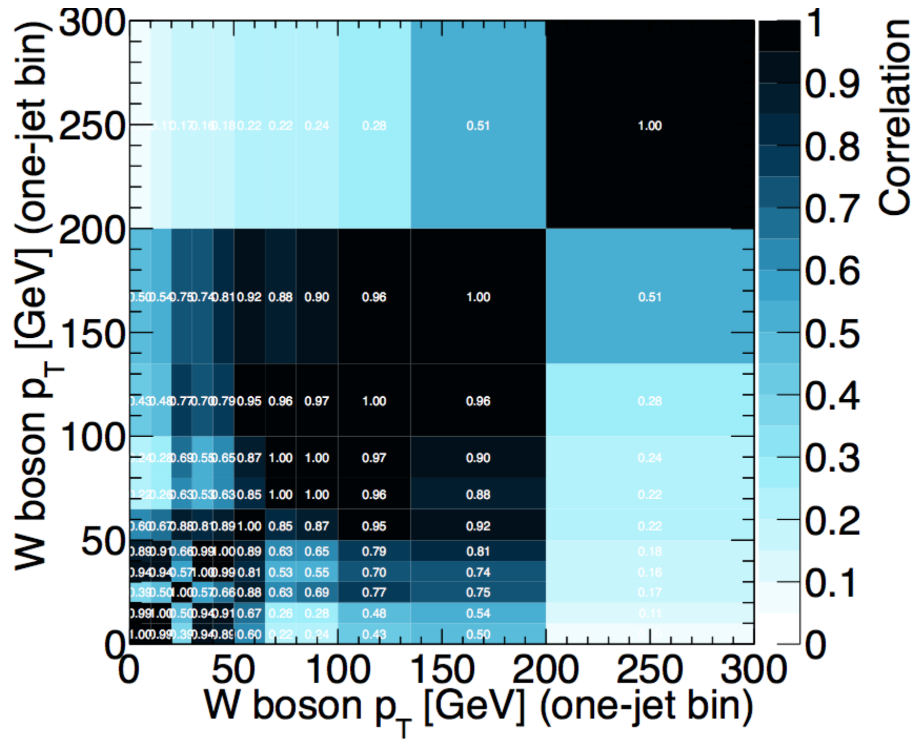



# Statistical and systematic correlations



**Statistical and systematic correlations in unfolded data determined**
Documented in EPAPS and HEPDATA along with measurements for purposes of constraining theory-data fits



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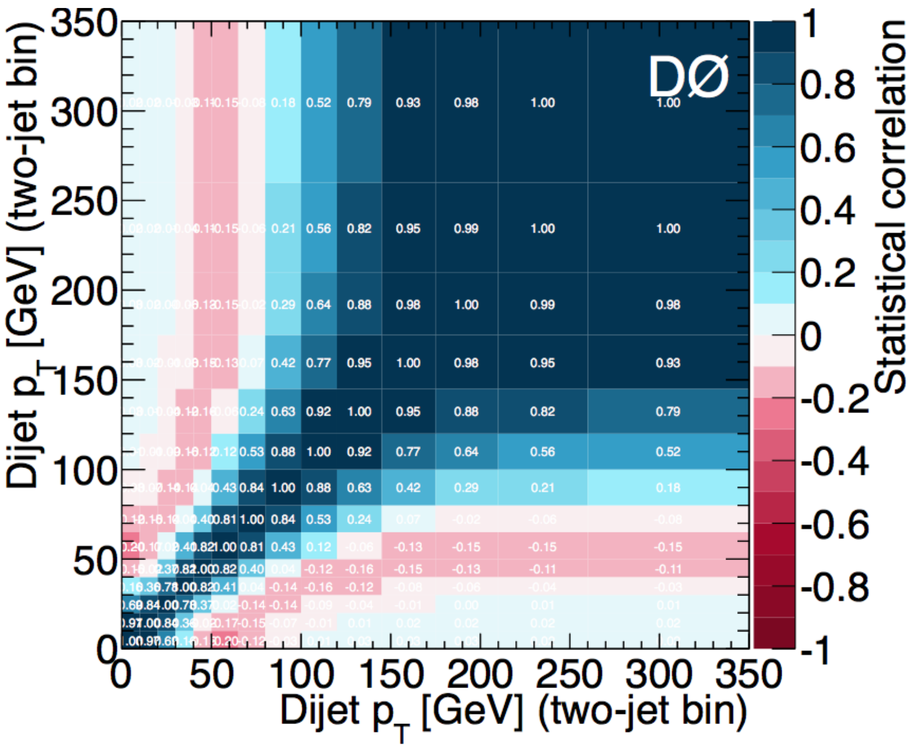
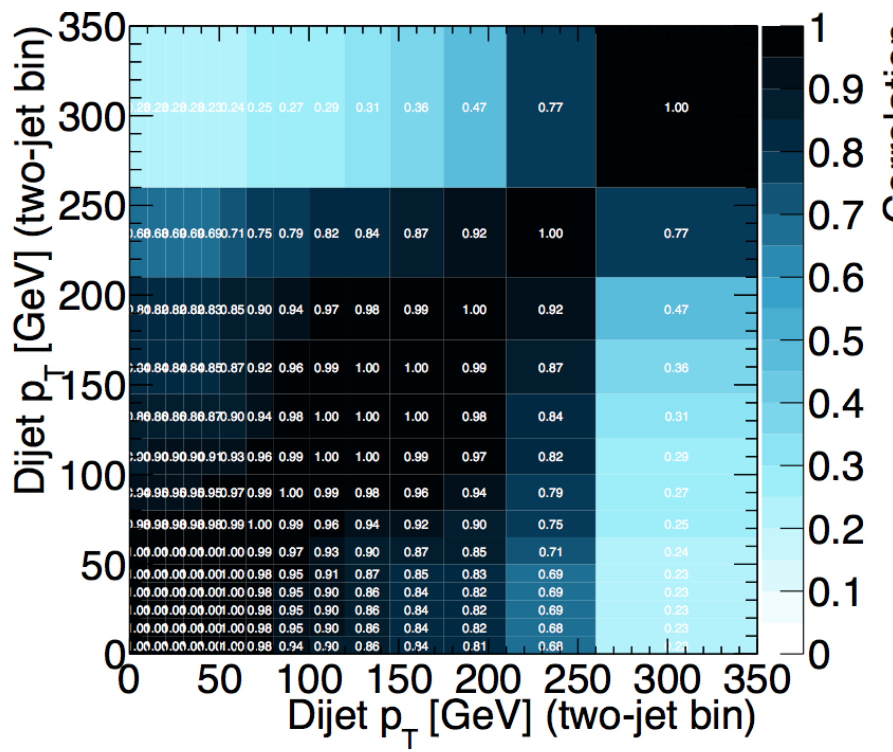


# Comparisons with theory



Unfolded results compared to various theory predictions:

- Parton-Shower MC:
  - **Pythia 6.425 (Perugia 2011) [CTEQ5L]**
  - **Herwig 6.520 (+Jimmy) [CTEQ6L1]**
- Matrix-Element Parton-Shower matched MC:
  - **Alpgen 2.414+Pythia (Perugia 2011) [CTEQ5L]**
  - **Alpgen 2.414+Herwig(+Jimmy) [CTEQ6L1]**
  - **Sherpa v1.4.0 [CT10]**
- NLO+MEPS pQCD predictions from:
  - **Blackhat+Sherpa [MSTW 2008 NLO, $\mu_F=\mu_R=0.5H_T$]**
- All-order resummation predictions from:
  - **High Energy Jets (HEJ)** **(applicable to W+≥2jet observables only)** **[MSTW 2008 NLO, $\mu_F=\mu_R=\max\{p_{Tj}\}$]**

# Non-perturbative corrections



**Experimental measurements corrected to 'particle-level'**

Apply non-perturbative corrections to fixed order parton-level calculations to bring them in line with data

Non-perturbative corrections take into account correction for:

- Jet algorithm differences (SIScone←→Midpoint)
- Underlying event and hadronisation effects

Corrections derived from Sherpa 1.4.0; symmetric uncertainty from recalculating Sherpa results with Lund string fragmentation

S. Höche, F. Krauss, M. Schonherr and F. Siegert, J. High Energy Phys. 09, 49 (2012)

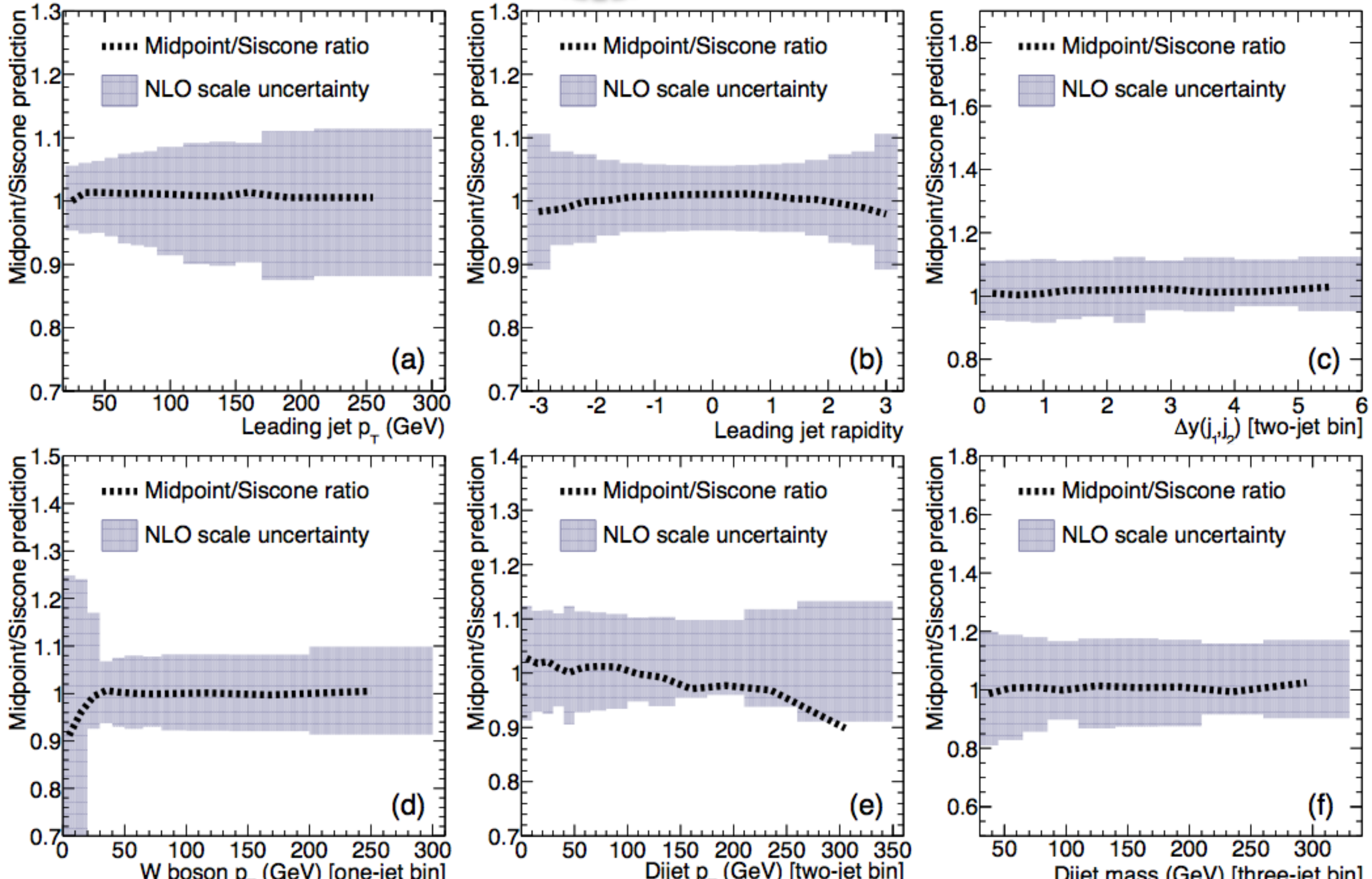
- **When corrections larger than 50%, fixed order predictions not displayed in comparison to data.**
- **All correction factors (for jet algorithm & UE+hadronisation effects) public in EPAPS and HEPDATA.**

# Jet algorithm corrections (npQCD)



## Examples of typical correction factors for Midpoint/Siscone

$$\text{total correction} = \frac{\sigma^{\text{Midpoint}}_{\text{particle}}}{\sigma^{\text{siscone}}_{\text{particle}}} \times \frac{\sigma^{\text{siscone}}_{\text{particle}}}{\sigma_{\text{parton}}} = \frac{\sigma^{\text{Midpoint}}_{\text{particle}}}{\sigma_{\text{parton}}}$$



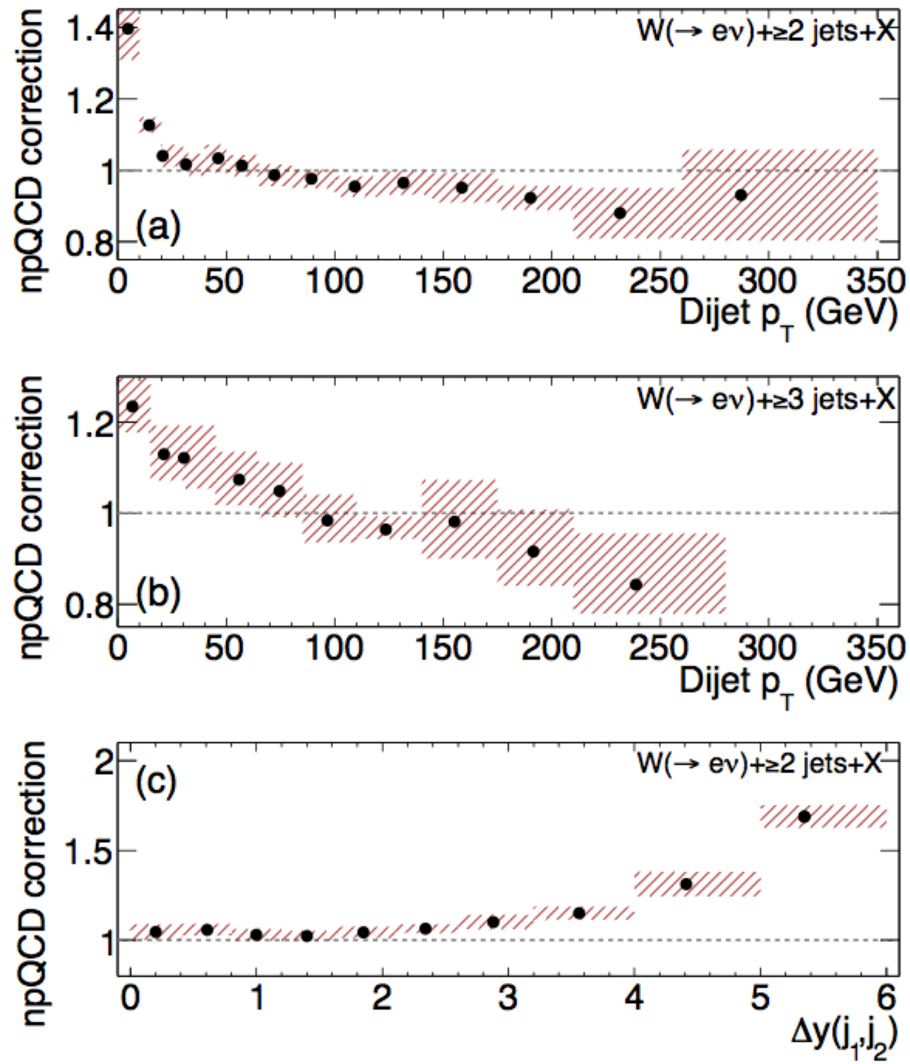
# Total npQCD correction (largest examples)



**Total npQCD correction usually small.**

Examples of observables where large corrections sometimes seen shown to the right (with uncertainties)

$$\text{total correction} = \frac{\sigma^{\text{Midpoint}}_{\text{particle}}}{\sigma^{\text{siscone}}_{\text{particle}}} \times \frac{\sigma^{\text{siscone}}_{\text{particle}}}{\sigma_{\text{parton}}} = \frac{\sigma^{\text{Midpoint}}_{\text{particle}}}{\sigma_{\text{parton}}}$$

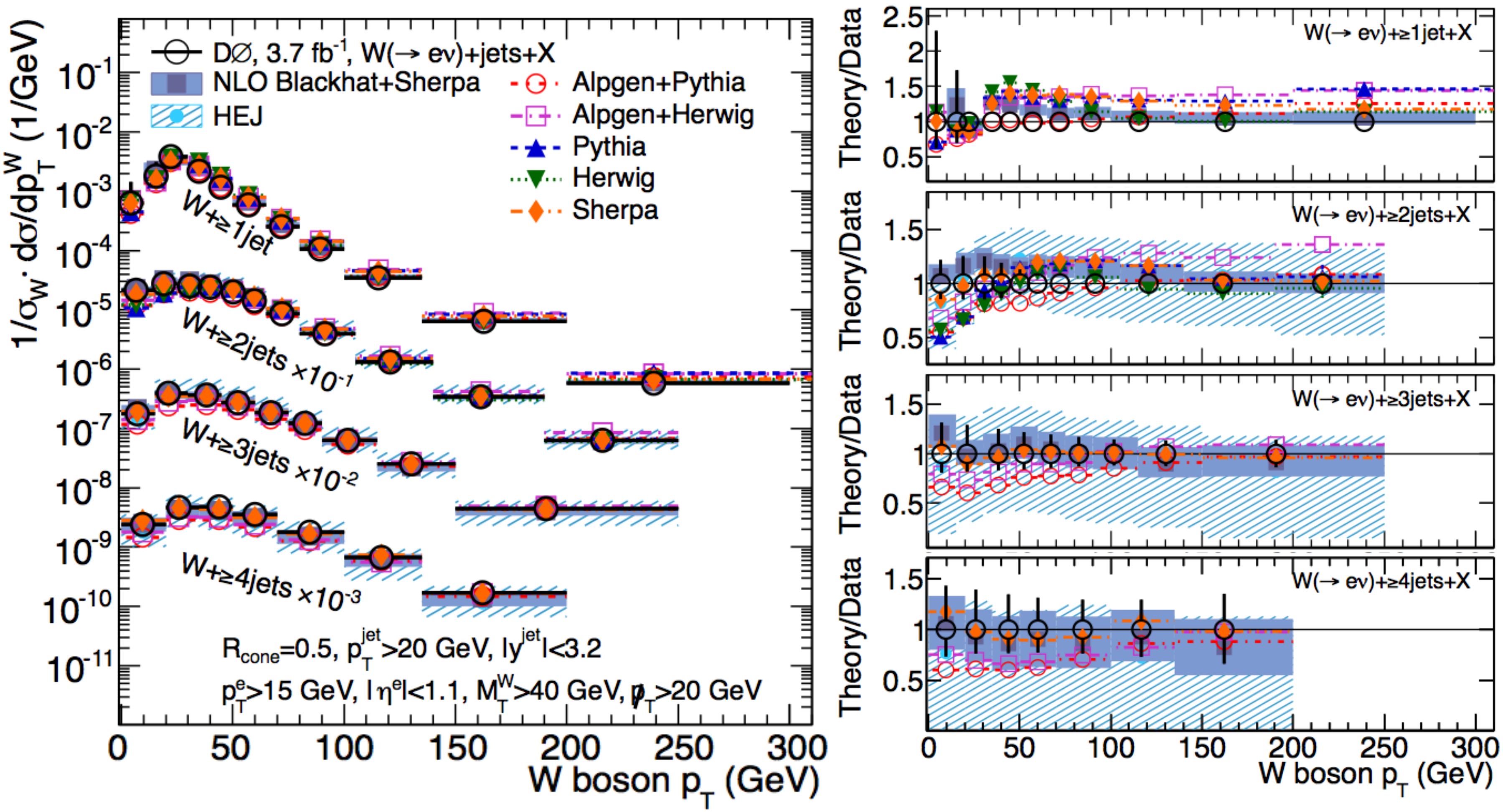


# W boson $p_T$



Lepton $p_T$ analogue, but includes missing energy vector.

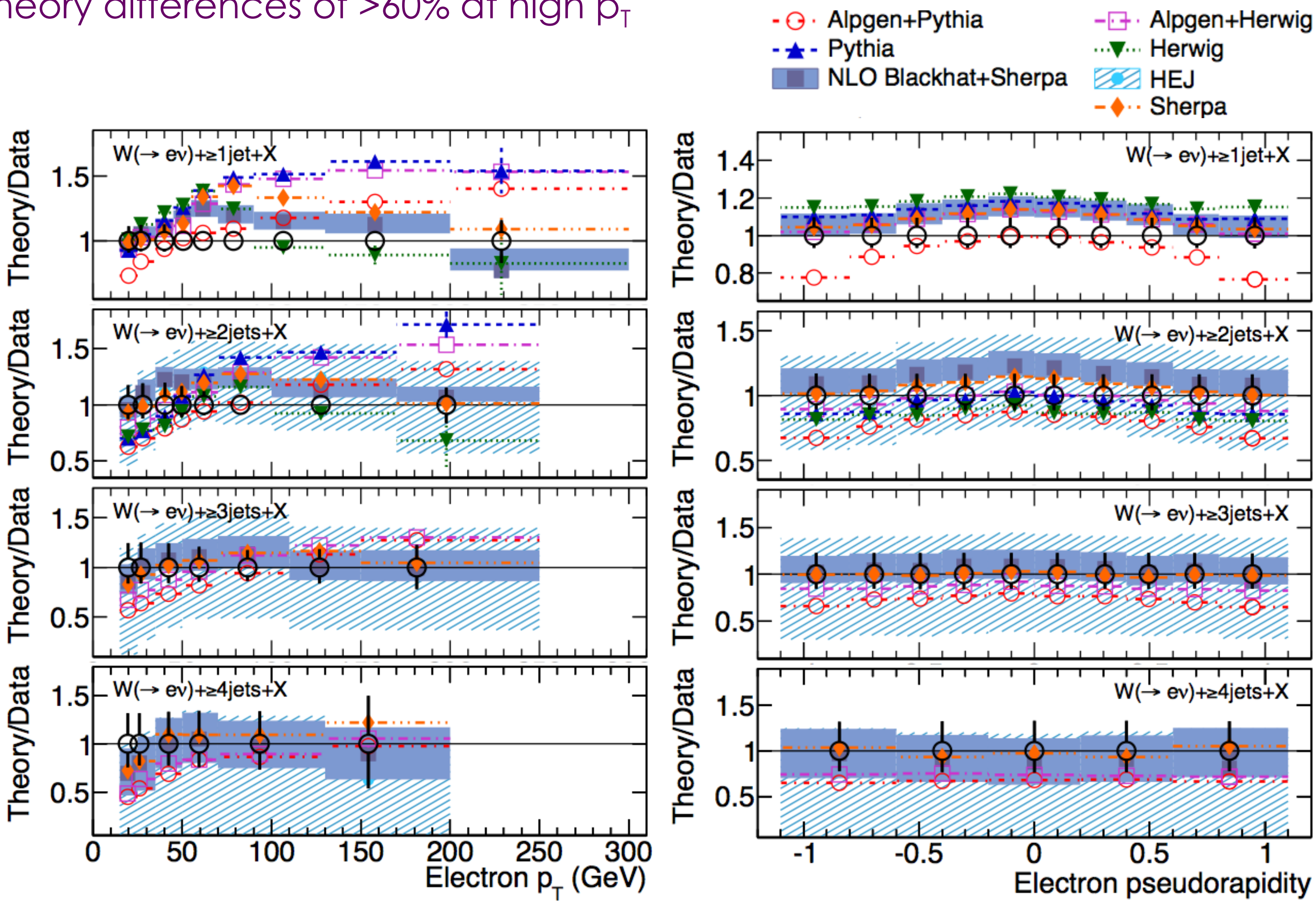
Agreement between data and NLO
Various theoretical predictions still show relatively large variation



# Lepton $p_T$ and pseudorapidity



Wide range of shapes in $p_T$ description:
theory differences of >60% at high $p_T$

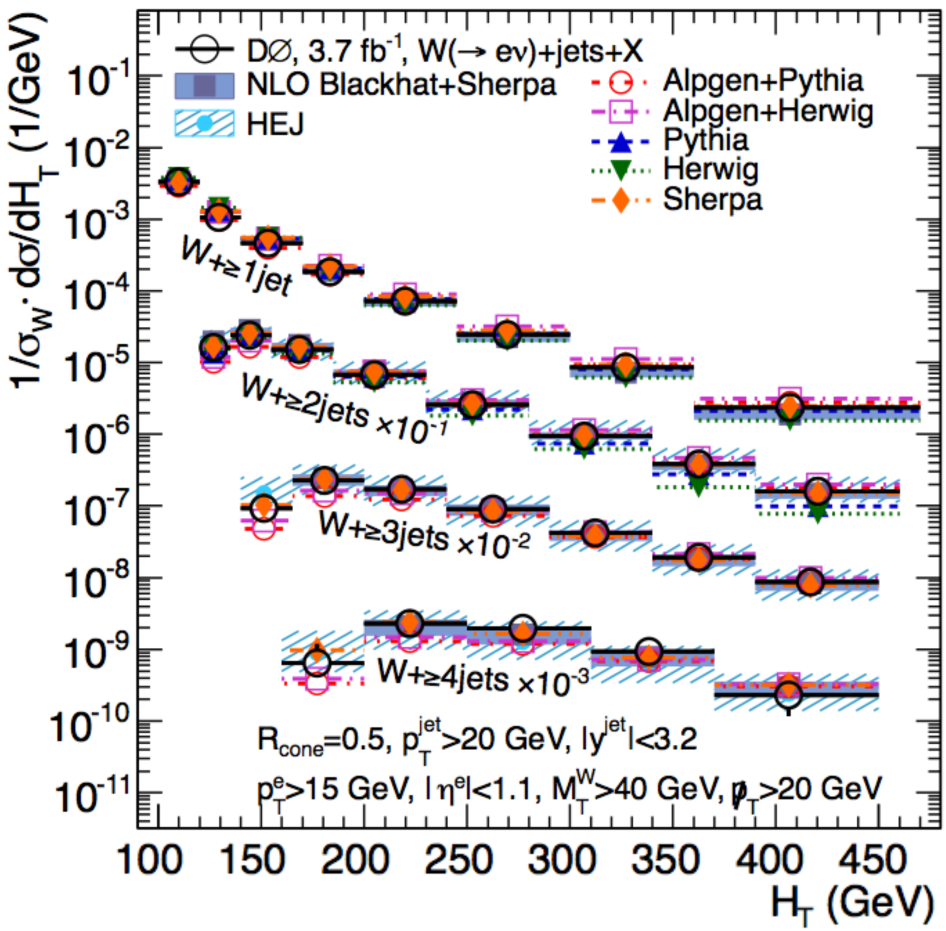


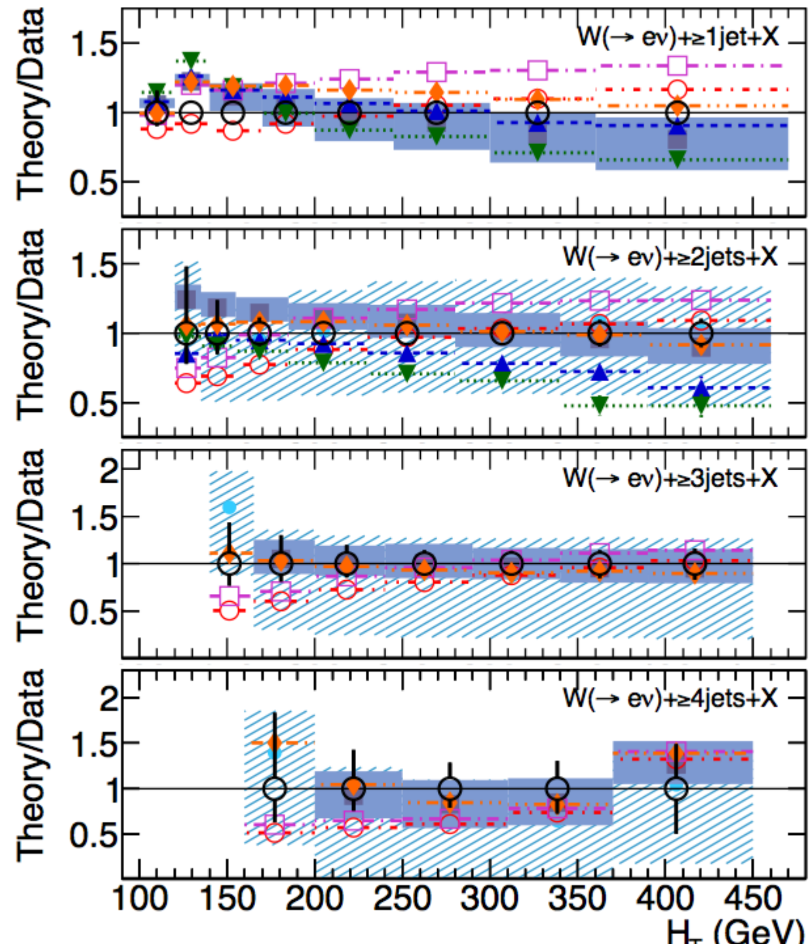
# Event $H_T$



$H_T$: scalar sum of the W boson and jet transverse energies

Higher order corrections important at high $H_T$ (even at Tevatron).



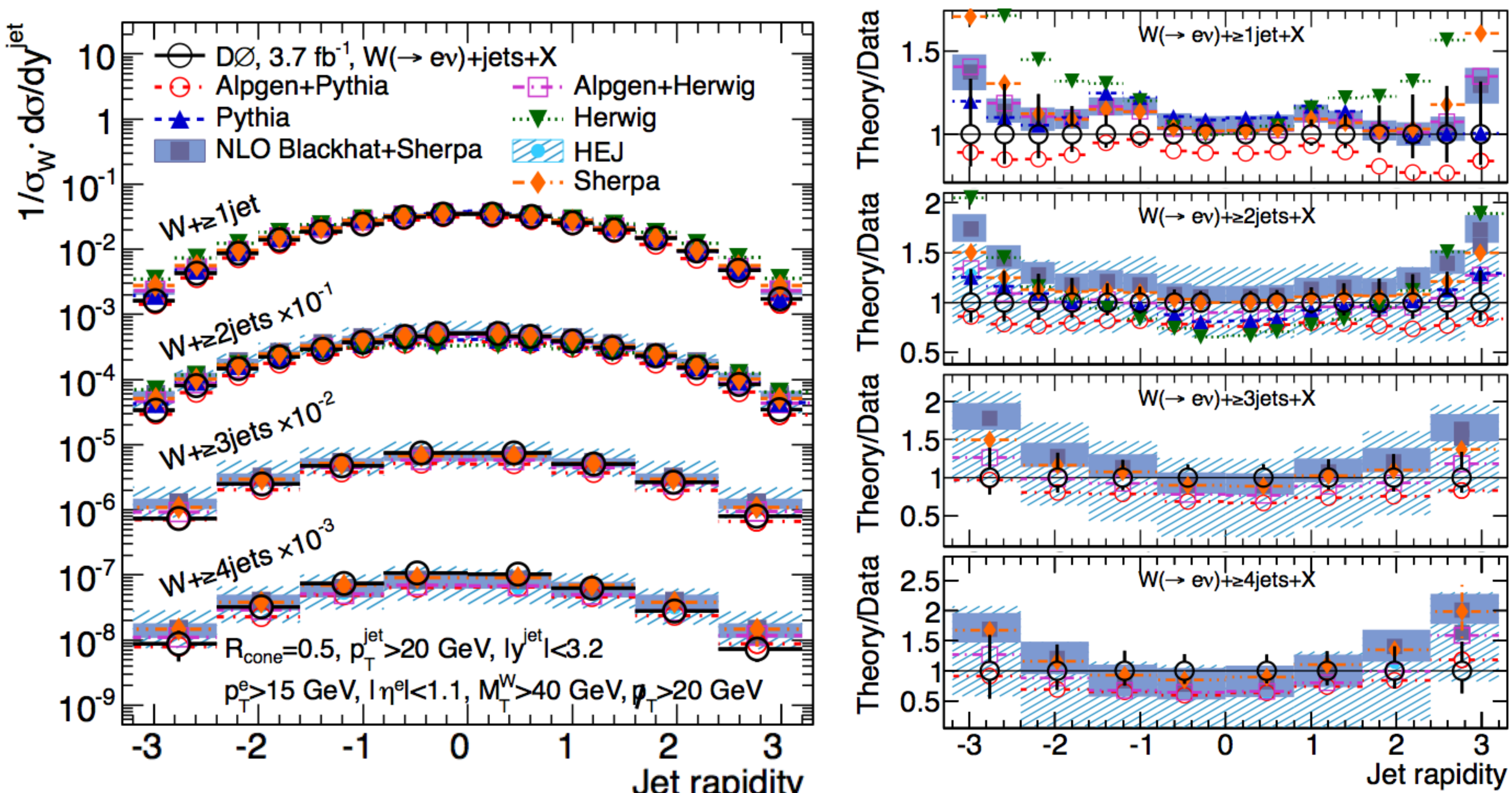



# Jet rapidities



Wide variation in predictions for high rapidity jet rates in different theoretical approaches…

Notable overestimation of rates at high rapidity from NLO/Sherpa

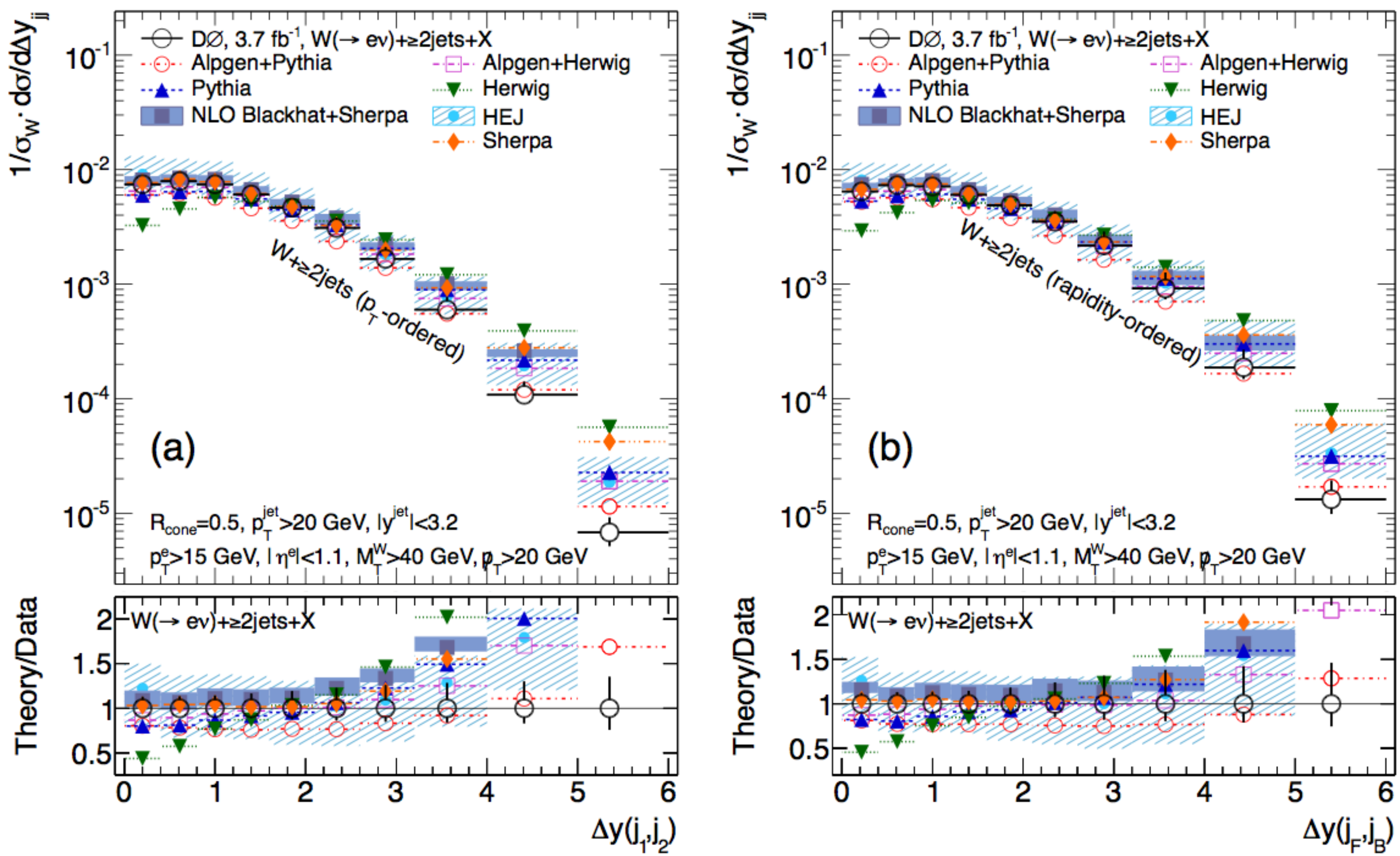


# Dijet rapidity separation [two-jet bin]



Separation between highest $p_T$ jets (left) & most rapidity-separated jets (right)

Trend for overestimation of highly rapidity-separated jet rate

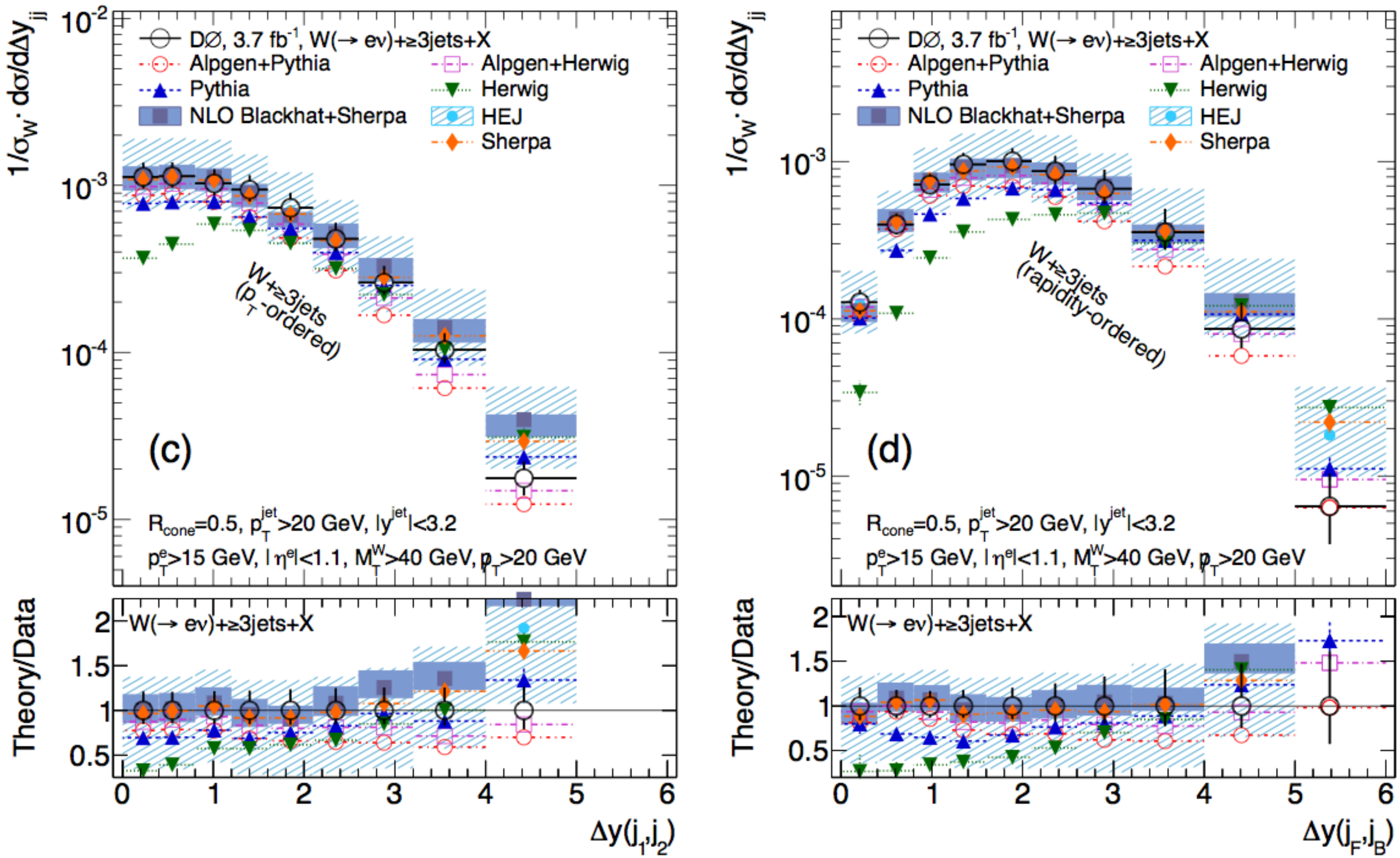


# Dijet rapidity separation [three-jet bin]



Separation between highest $p_T$ jets (left) & most rapidity-separated jets (right)

Trend for overestimation of highly rapidity-separated jet rate

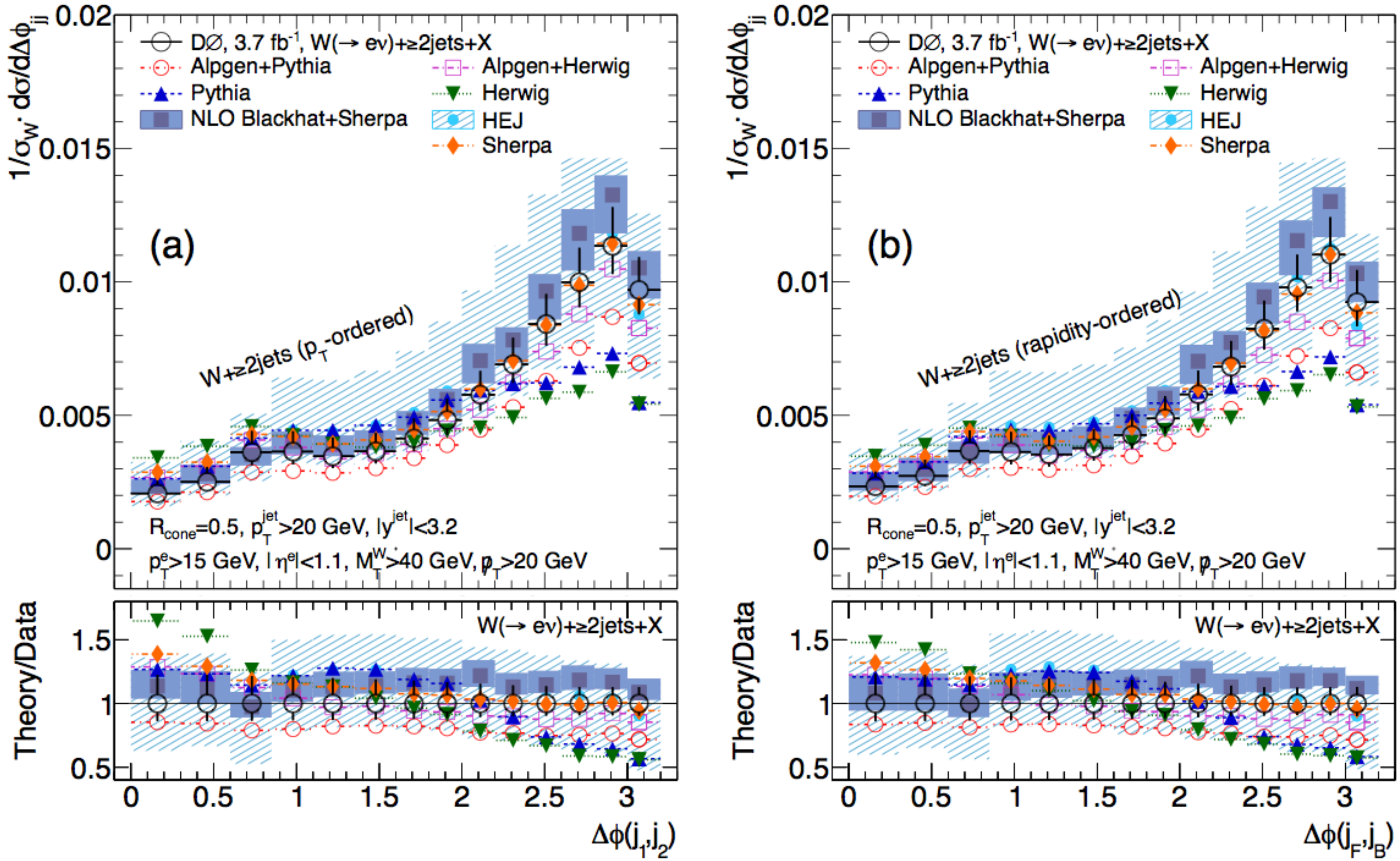


# Dijet azimuthal angle separation



Sensitive to soft radiation emissions, input to MC tuning

PS MC's in particular give more collinear emissions and significantly reduced high $\Delta\varphi$ emissions than observed in data

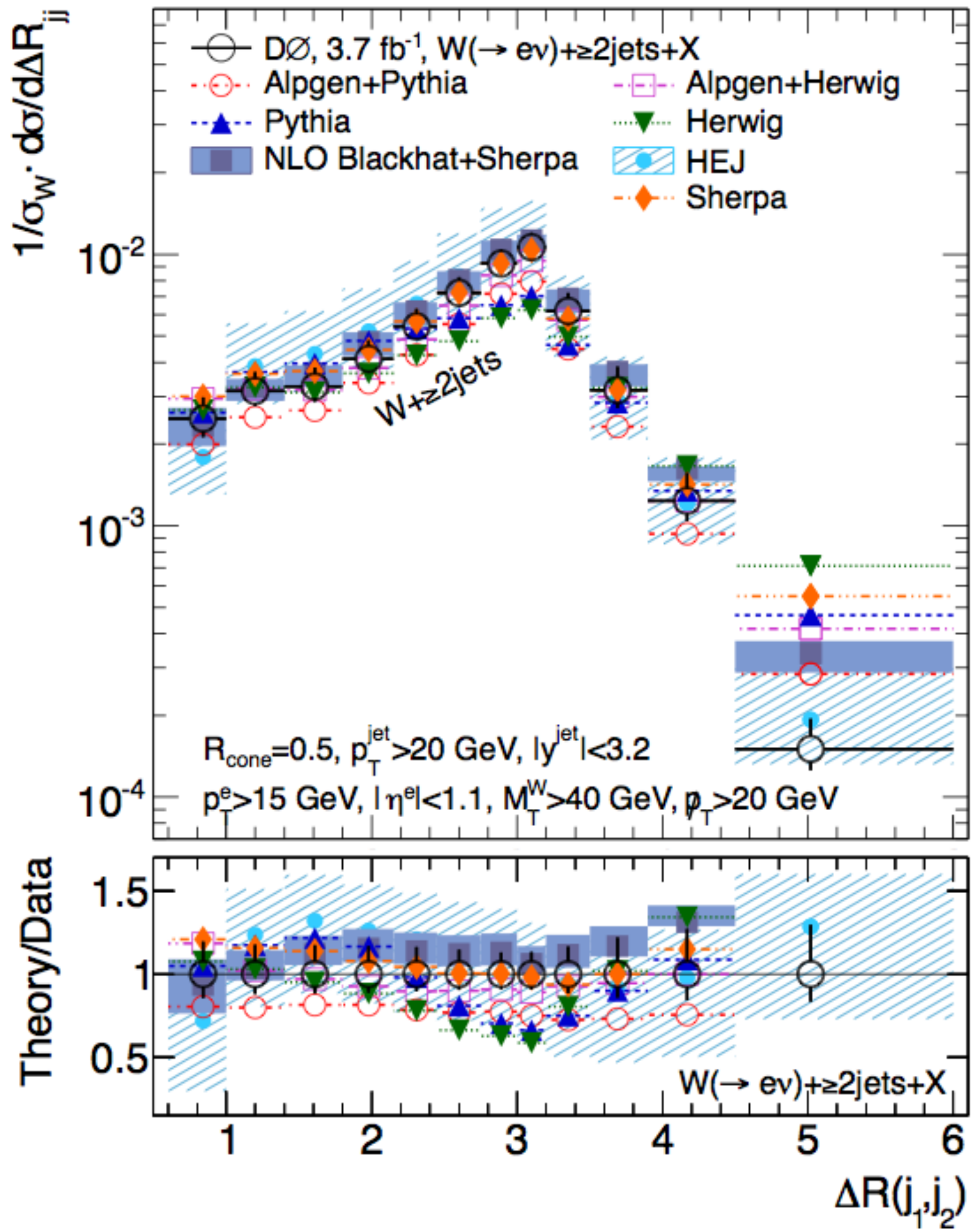


# Dijet opening angle



Spatial opening angle ΔR defined in (true) rapidity and azimuthal angle space

Large shape variations observed, and large (>50%) divergences between various theoretical descriptions

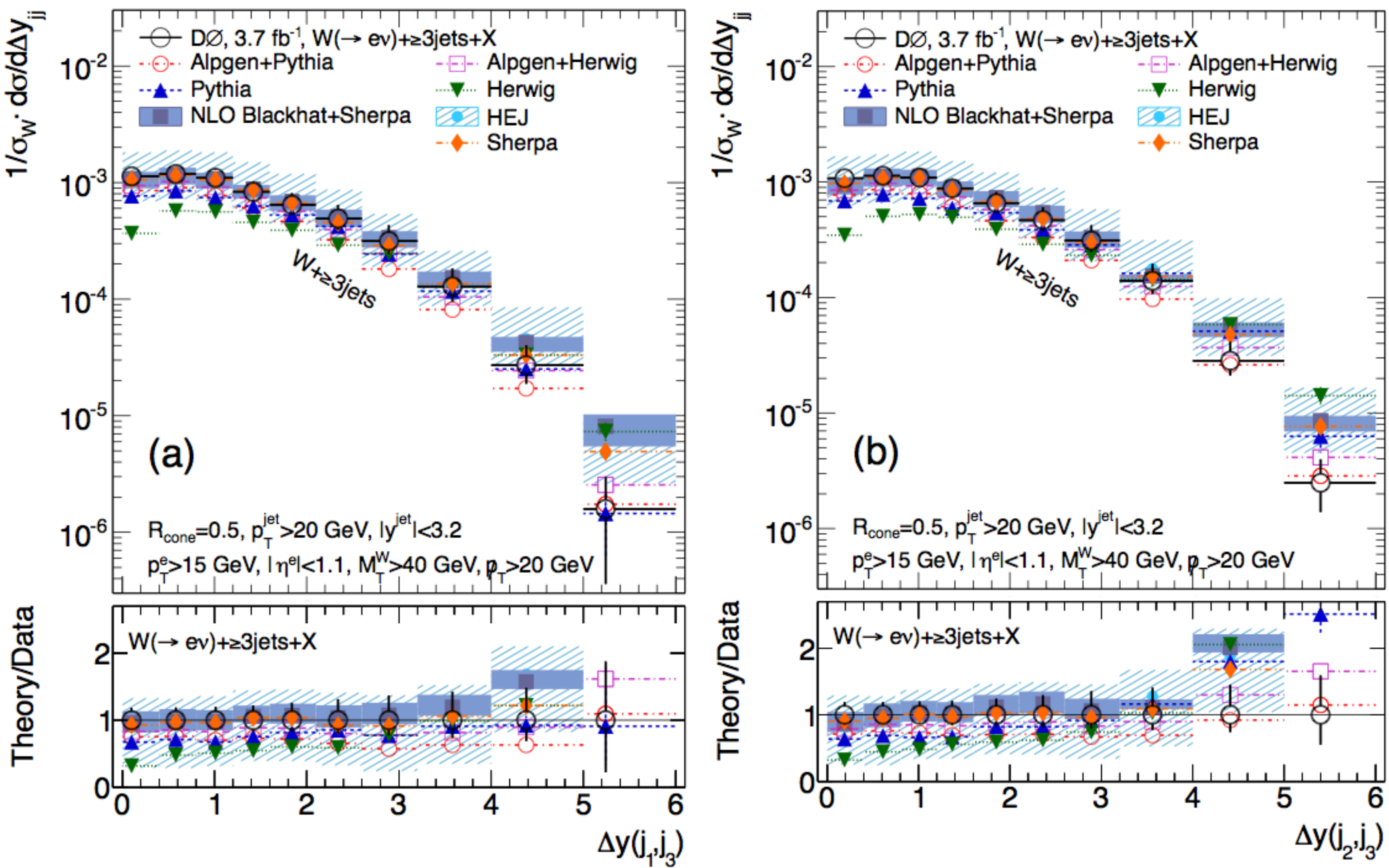


# First/second-third jet rapidity separation



Test rapidity separation between first-third and second-third jet pairings.

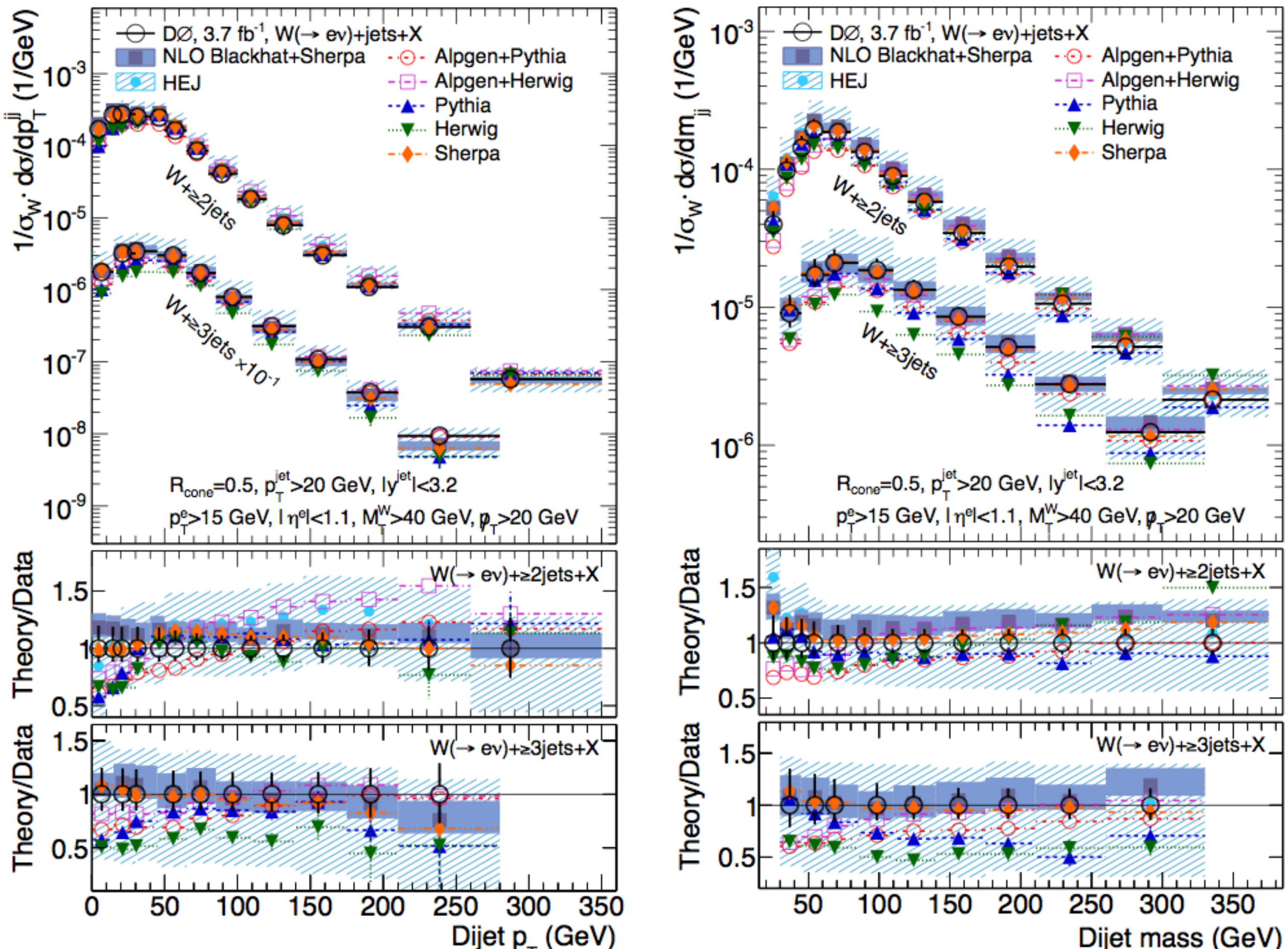
Tuning, in particular constraining QCD radiation modelling in MC



# Dijet $p_T$/mass



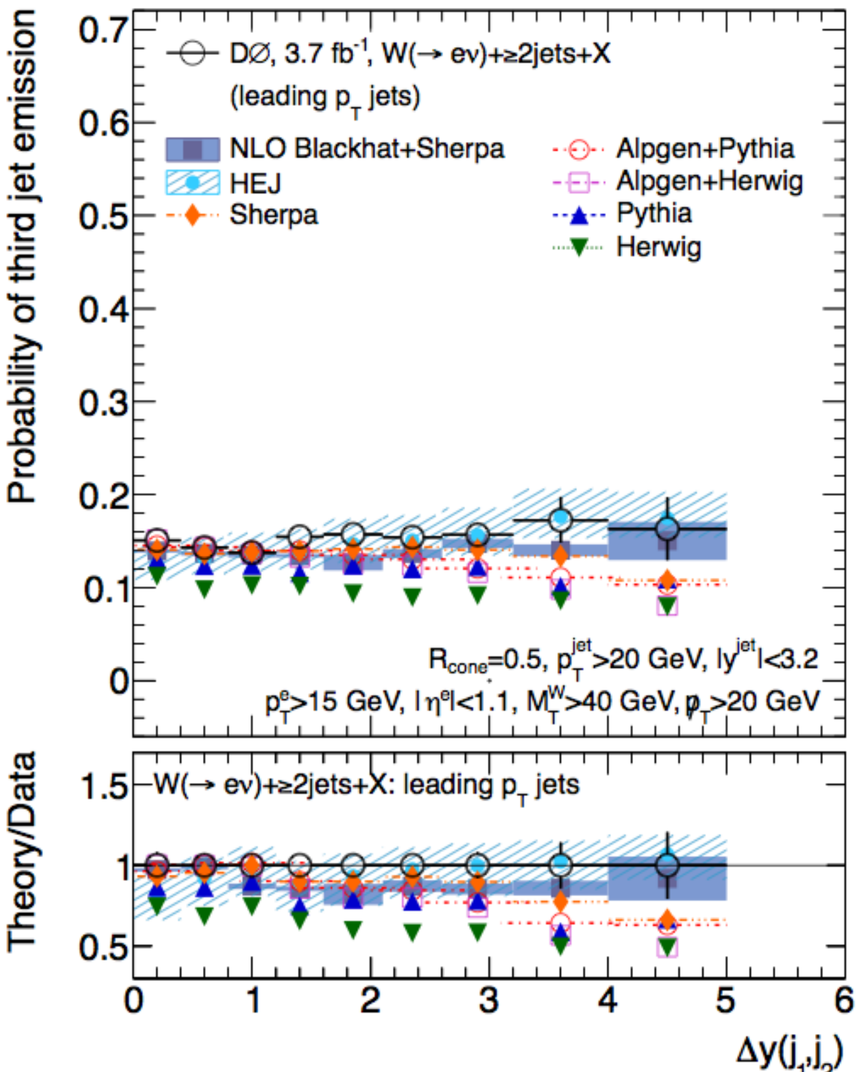
NLO tends to overestimate rate at high dijet mass, PS/MEPS predictions vary widely



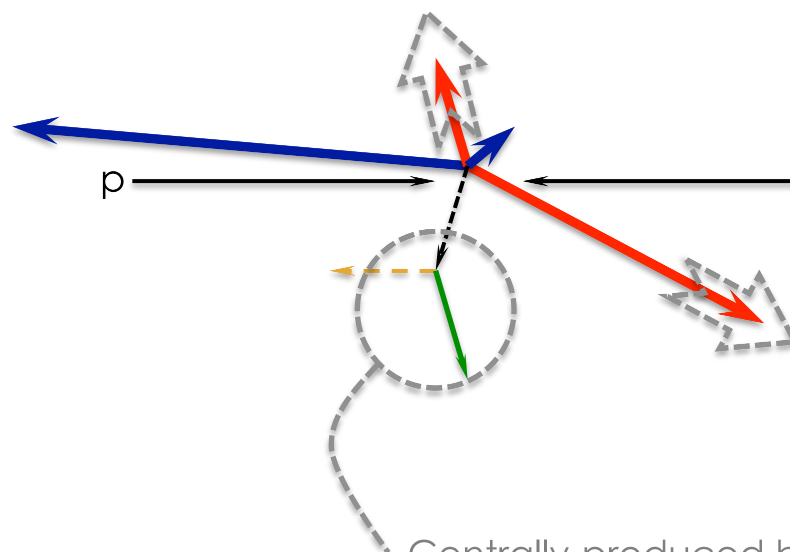
# Third jet emission probabilities (W+2j)



Study radiation emissions into rapidity interval between two energetic jets in events with a W boson (important for jet vetoes)




Two highest $p_T$ jets not necessarily creating largest rapidity gap; additional jet emission permitted to occur at *any* rapidity



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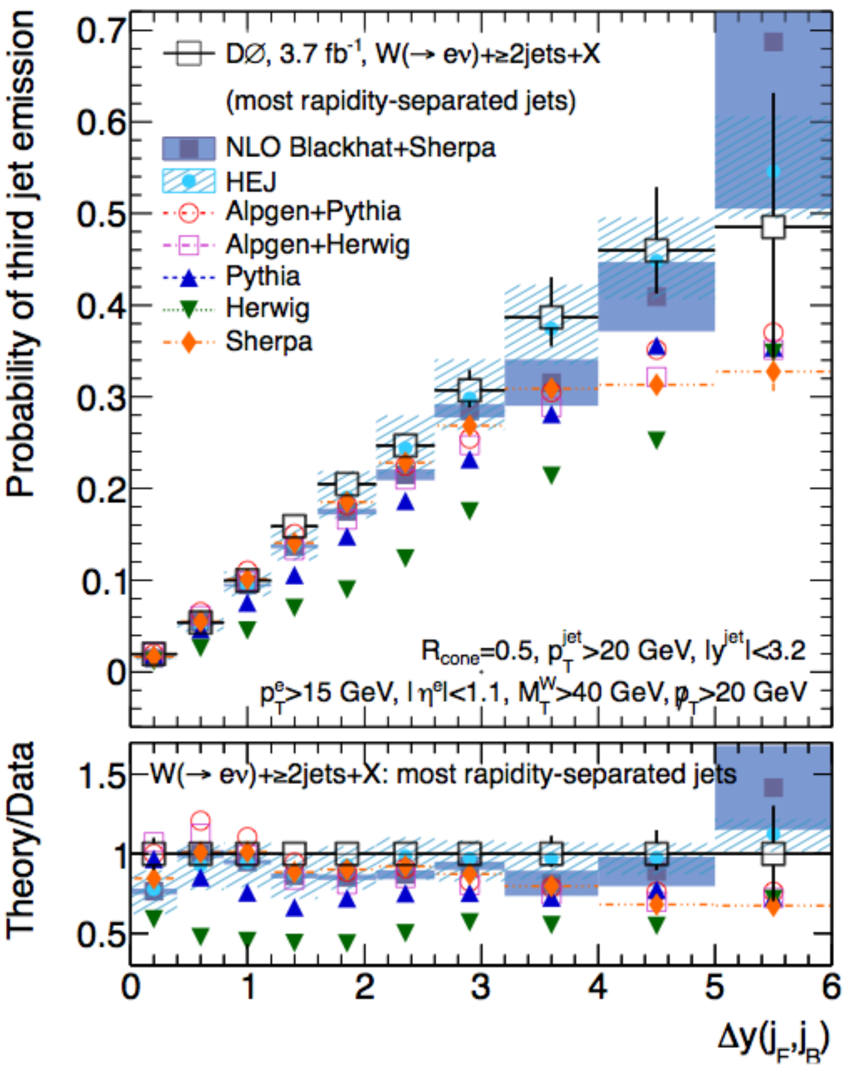
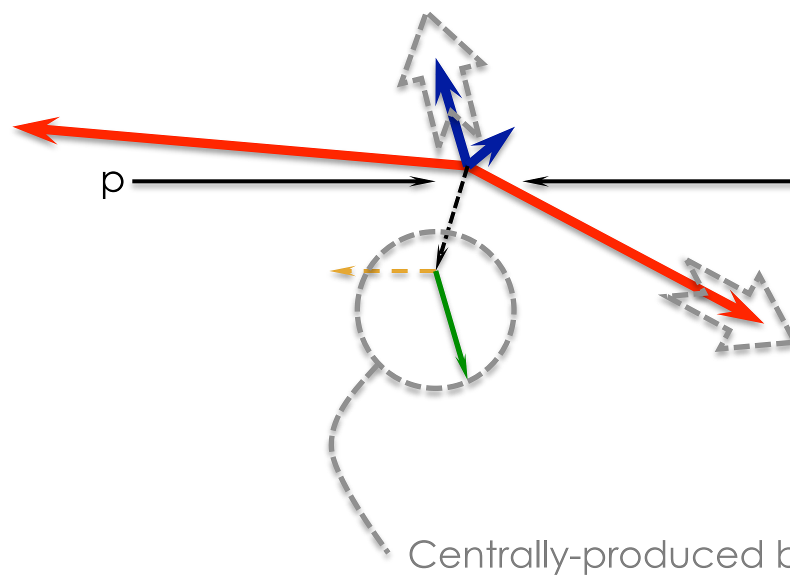



Two most rapidity-separated jets define largest rapidity gap; additional jet emission occurs inside gap by construction



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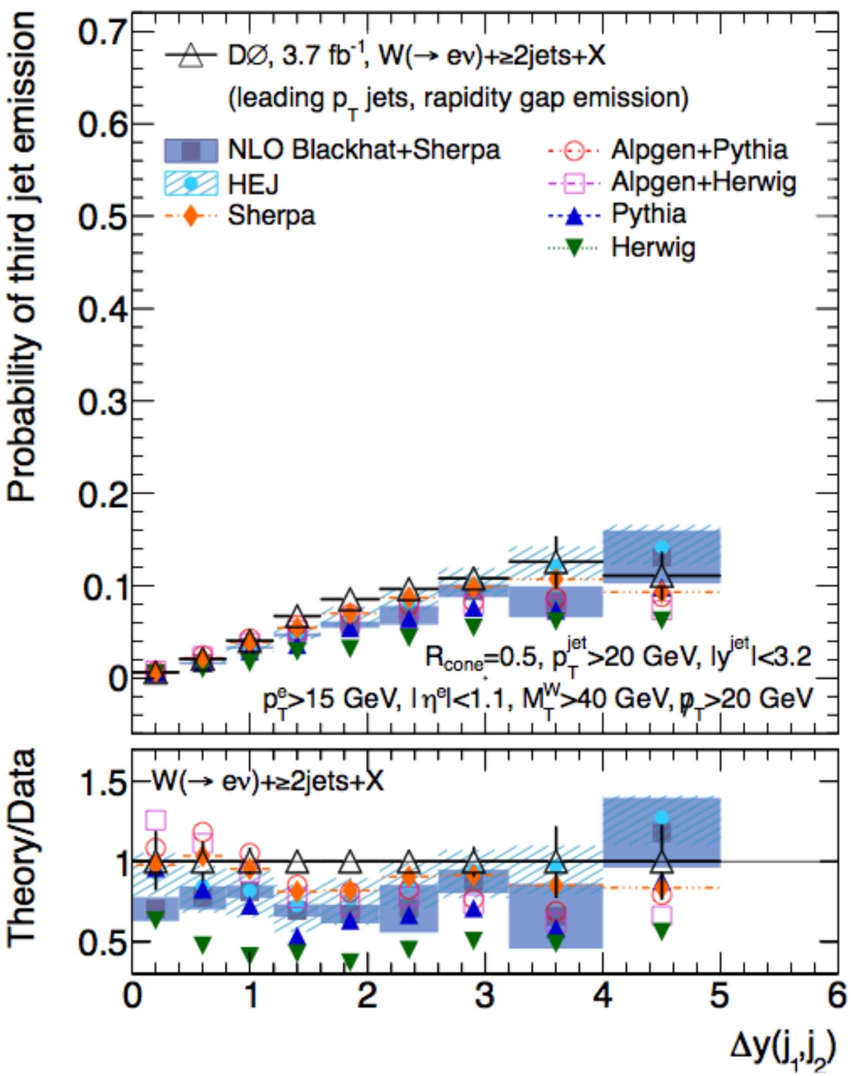
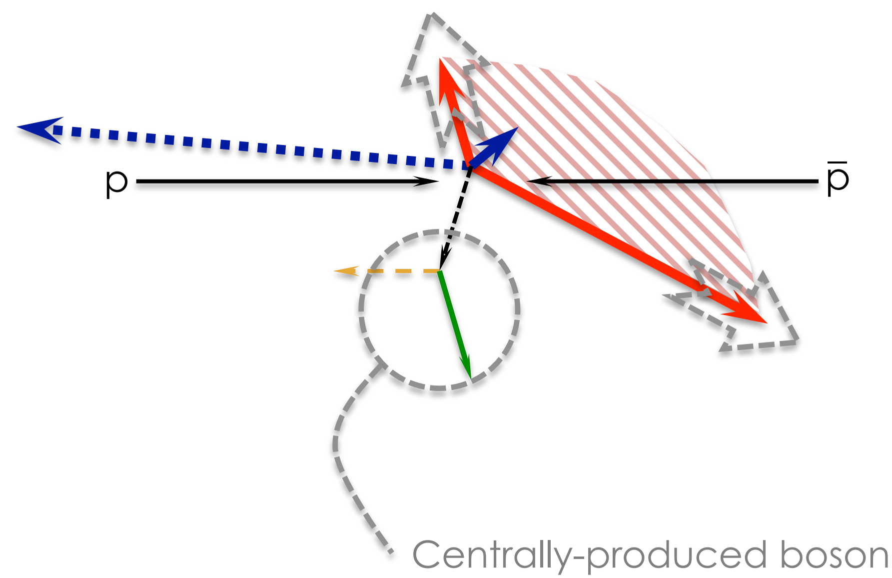



Two highest $p_T$ jets not necessarily creating largest rapidity gap, but additional radiation only counted if it occurs in the rapidity gap

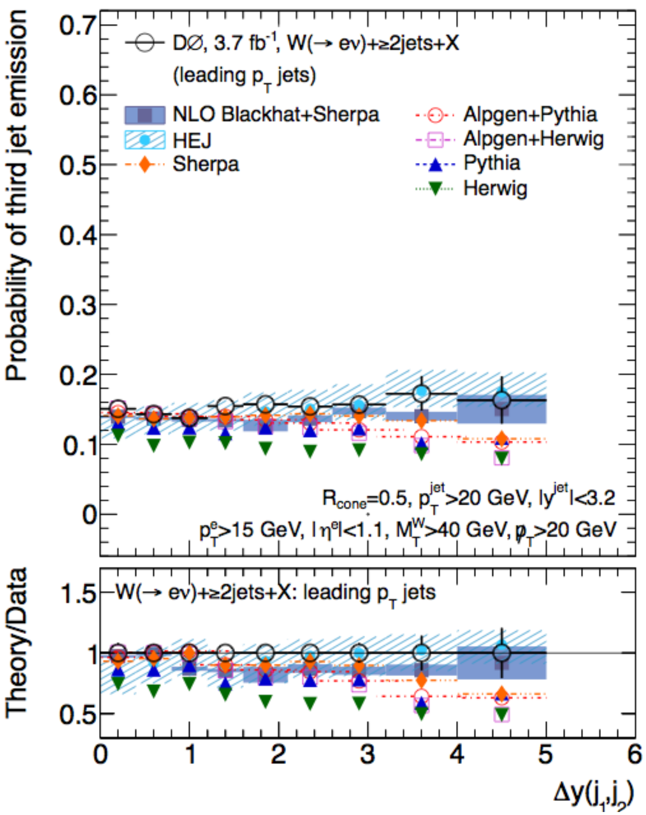


# Third jet emission probabilities (W+2j)

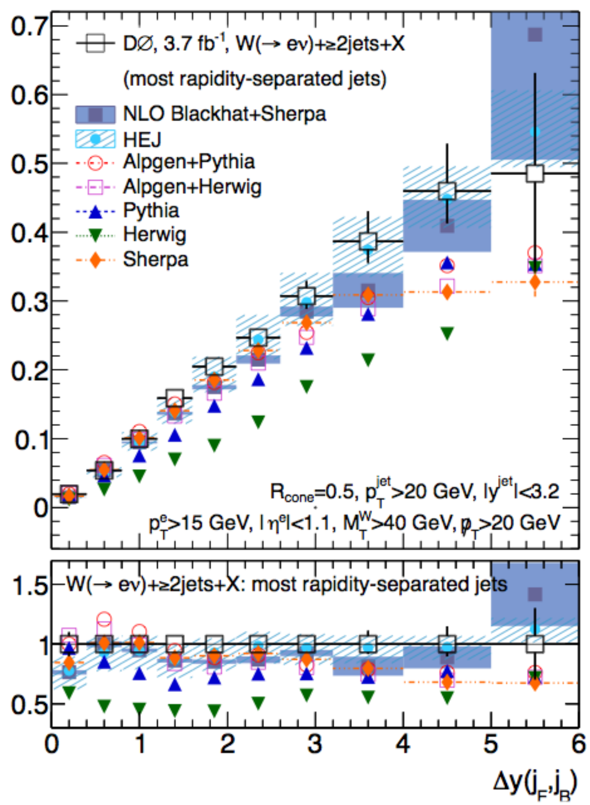


Radiation emissions into rapidity interval between two energetic jets in events with a W boson

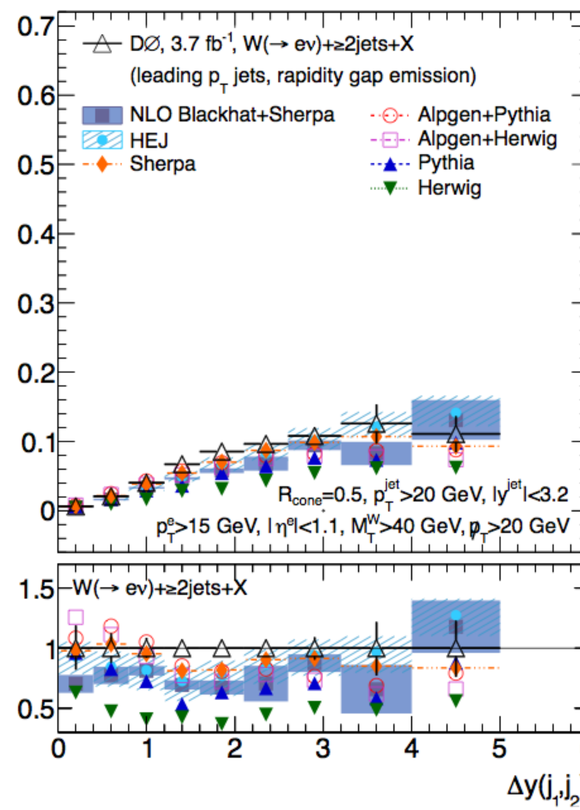
Rapidity separation between the two highest $p_T$ jets




Rapidity separation between the two most rapidity-separated jets



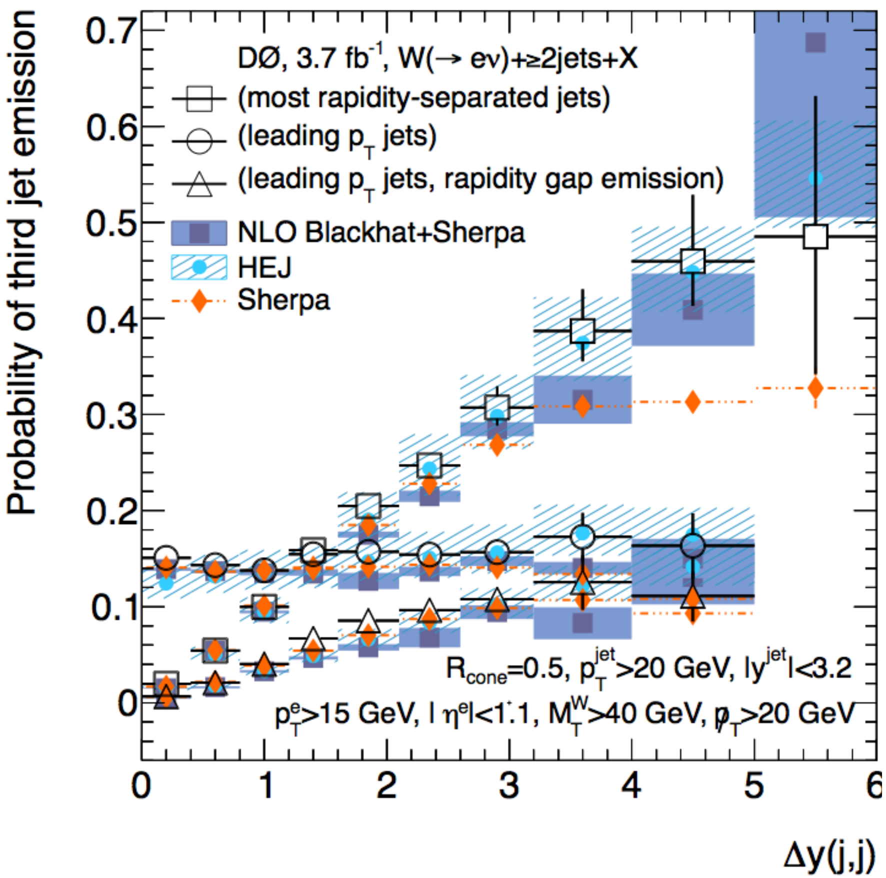

Rapidity separation between the highest $p_T$ jets with requirement that third jet be emitted in *between* the first two in rapidity

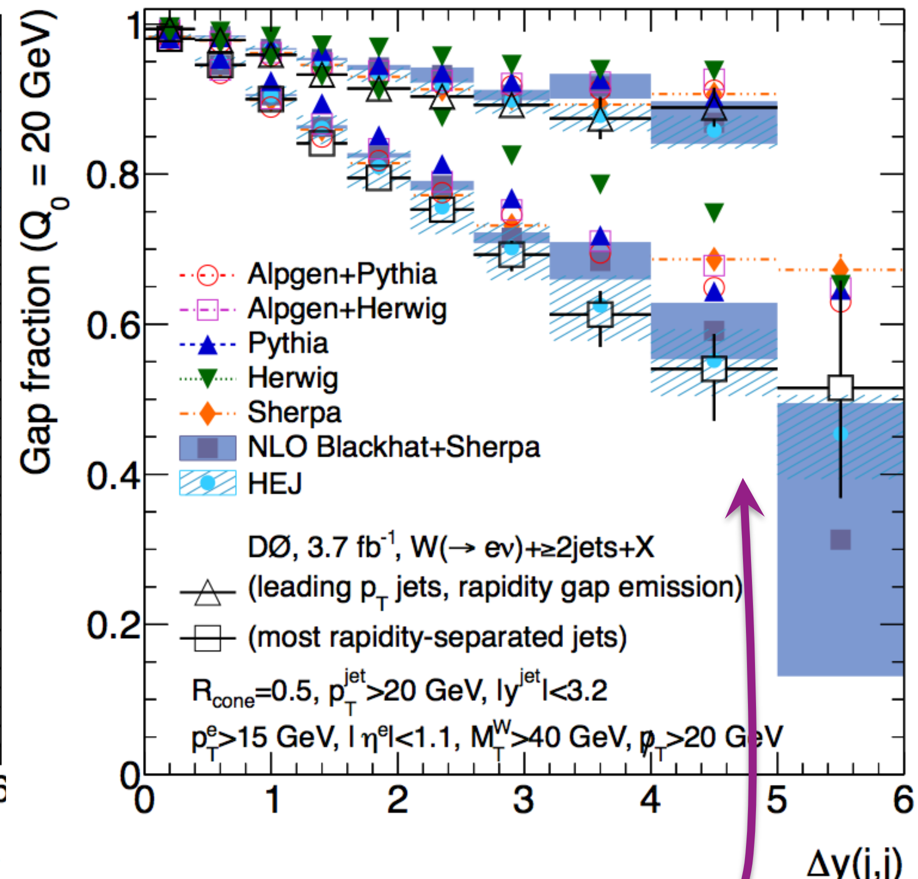


# Gap fraction vs. rapidity gap size



Third jet emission probability can be re-interpreted as gap fraction, with veto scale $Q_0$=20 GeV




"What fraction of V+dijet events, with rapidity gap Δy, have no jets ($p_T$>20 GeV) emitted into this gap?"

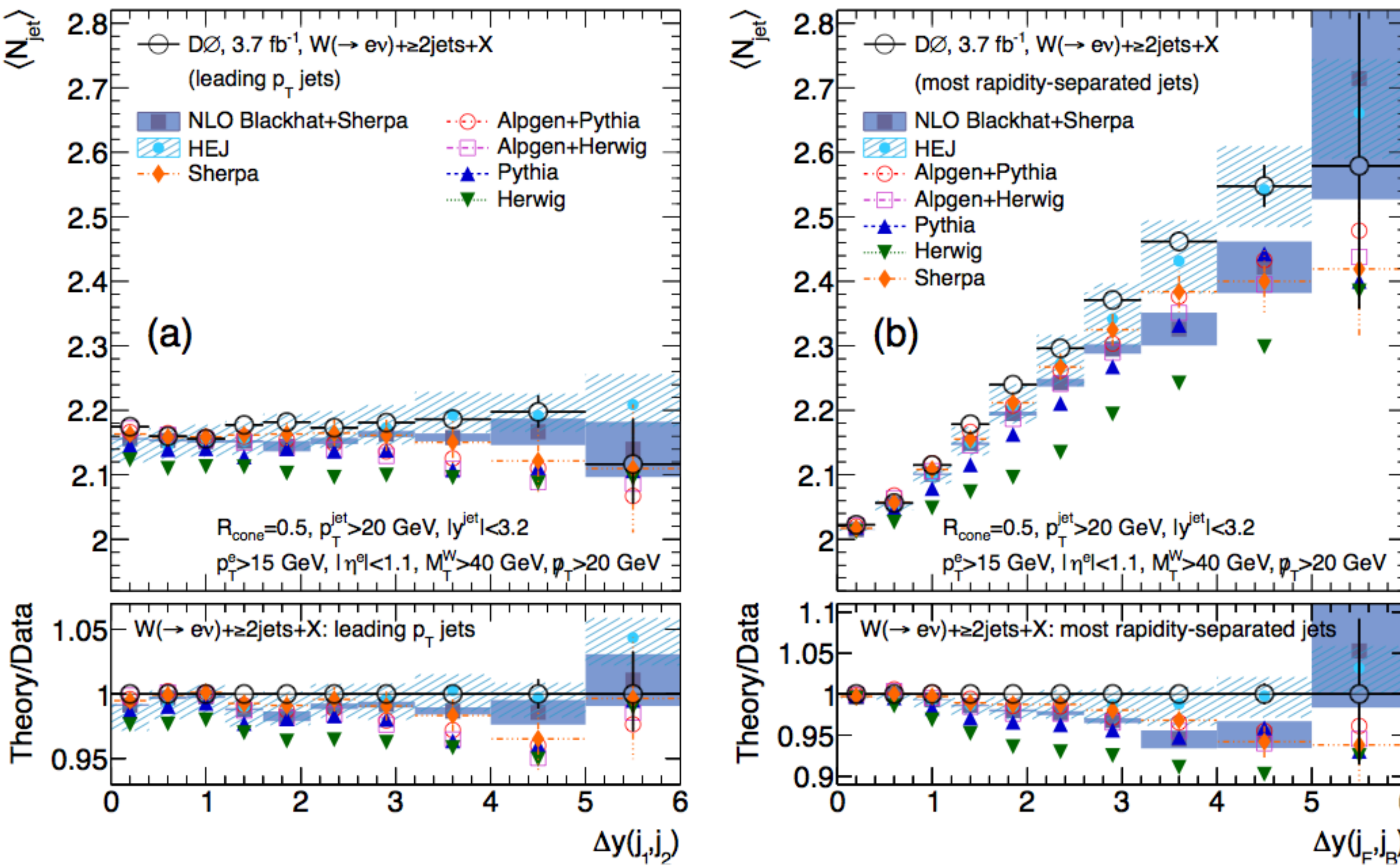
**Was first study of jet veto dynamics in vector boson plus jet final states.**

# Average jet multiplicity vs. Δy



Studied as a function of dijet rapidity separation in two configurations:

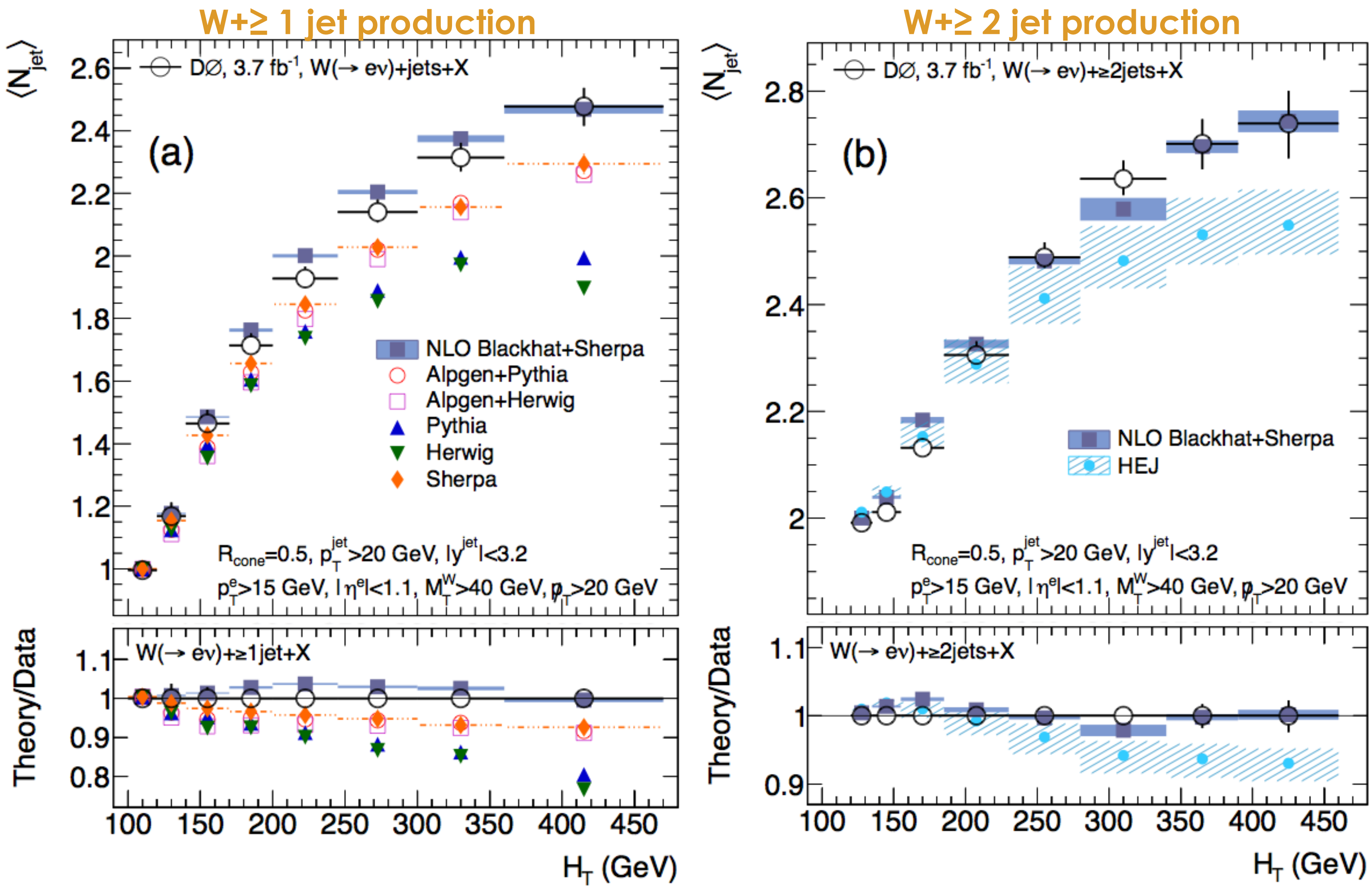
- between the two highest $p_T$ jets
- between the two most rapidity-separated ($p_T$>20 GeV) jets



# Average jet multiplicity vs. $H_T$



Dependence of average jet multiplicity in W+jet events on sum of transverse energies of boson and jets $\langle N_{\rm jet}\rangle_{\rm Blackhat} = n + \left(d\sigma^{\rm NLO}_{n+1} + d\sigma^{\rm LO}_{n+2}\right)/d\sigma^{\rm NLO}_{n}$



# Conclusions



**Detailed measurements of W+jets production at the Tevatron available for 40 new unfolded distributions**

- Data more precise than spread of theoretical predictions, often smaller than NLO scale uncertainties
- Statistical and systematic correlations on unfolded measurements, snd all results and npQCD correction factors documented in EPAPS/HEPDATA

Discrepancies exist between theoretical calculations and data in several kinematic regions, notably high jet rapidity and angular separation of jets.

Data can distinguish between large variations in MC approaches can provide input to tuning.

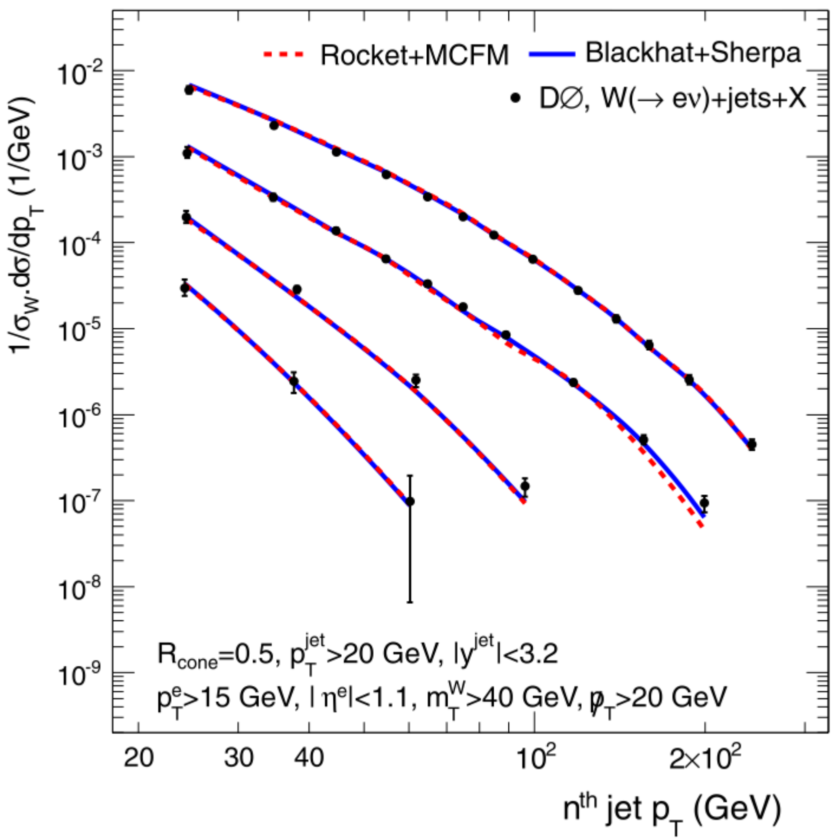
NLO and HEJ performing well in jet veto / multiplicity observables, but run into limitations at large angle, high $H_T$ respectively.

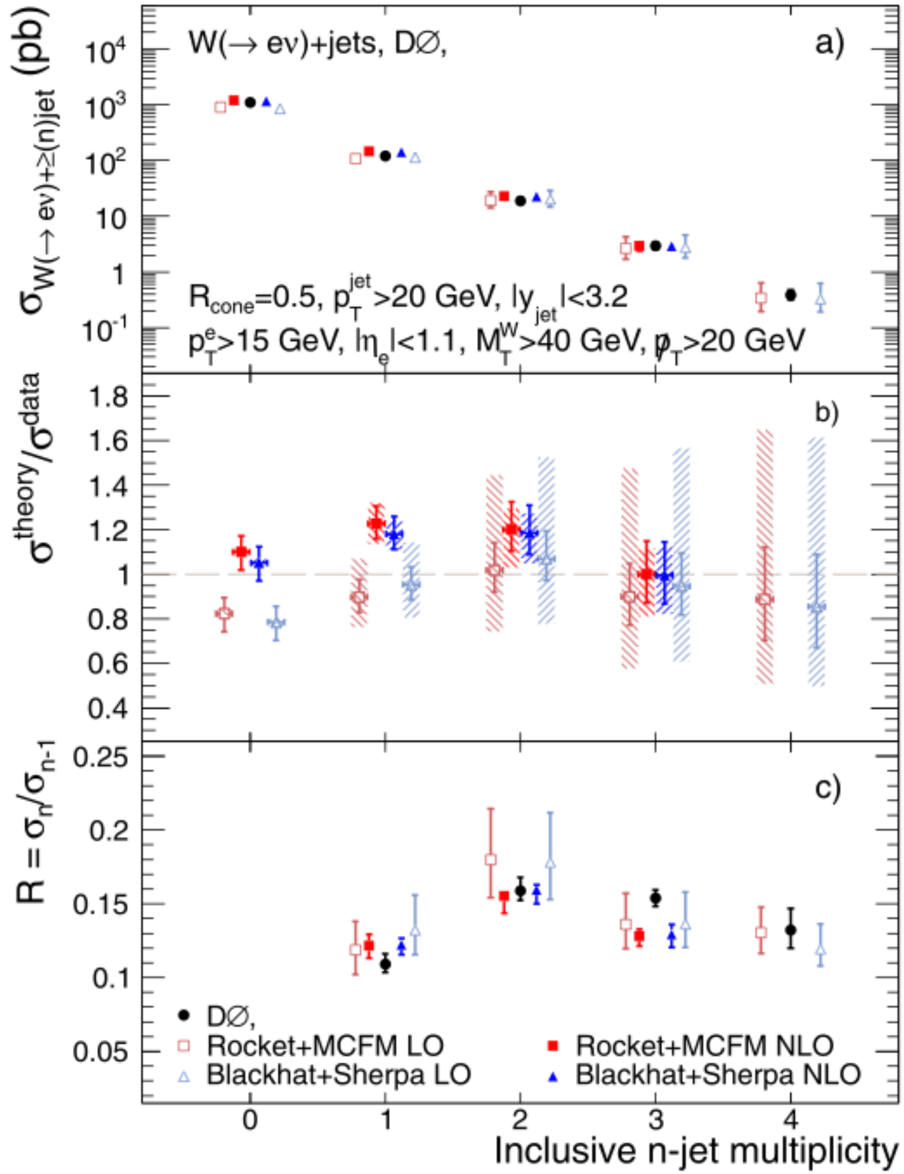
# Additional material

# Previous DØ W+jets measurement



Differential jet $p_T$ and inclusive n-jet cross-sections studied in **arXiv:1106.1457, Phys. Lett. B 705 (2011) 200-207**



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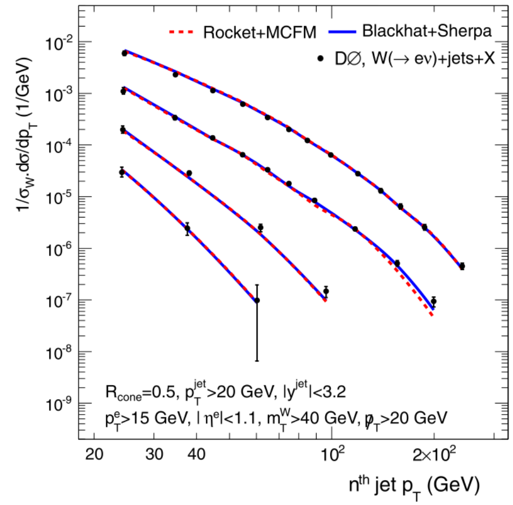
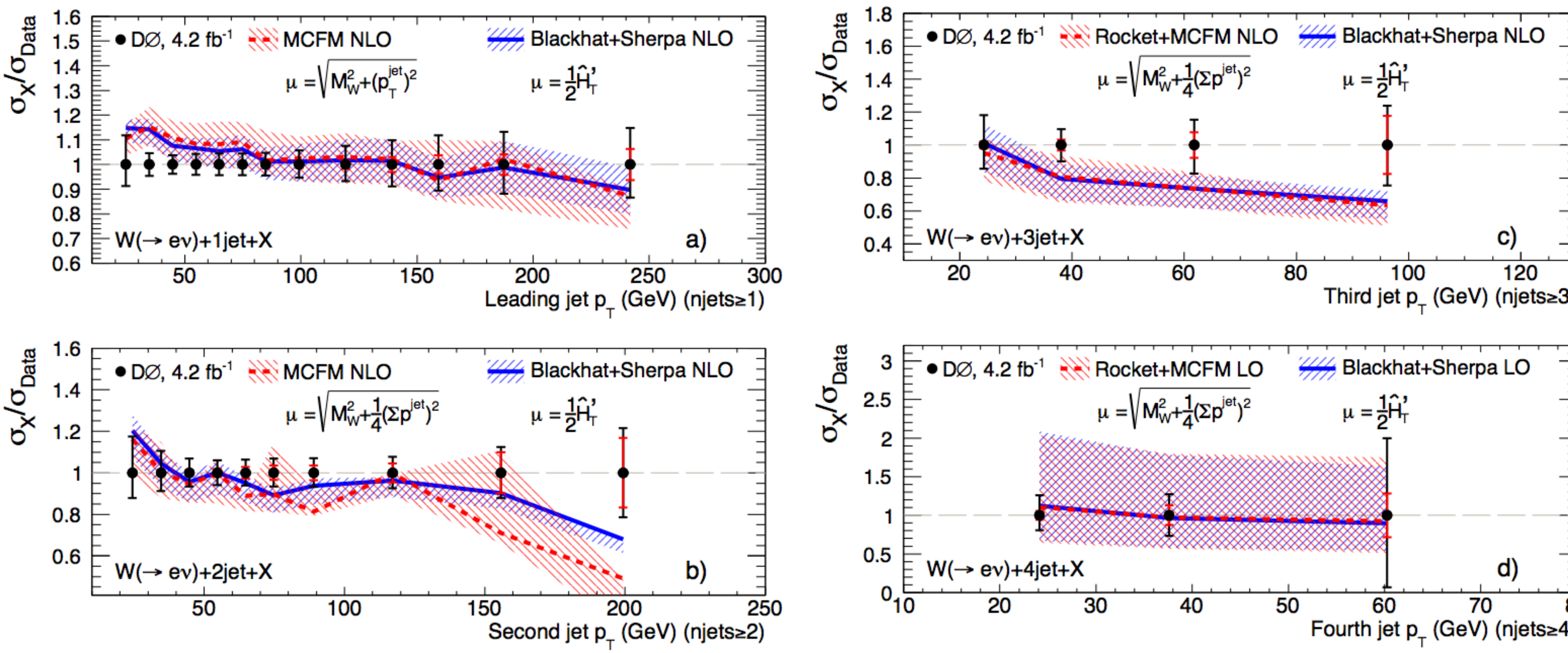
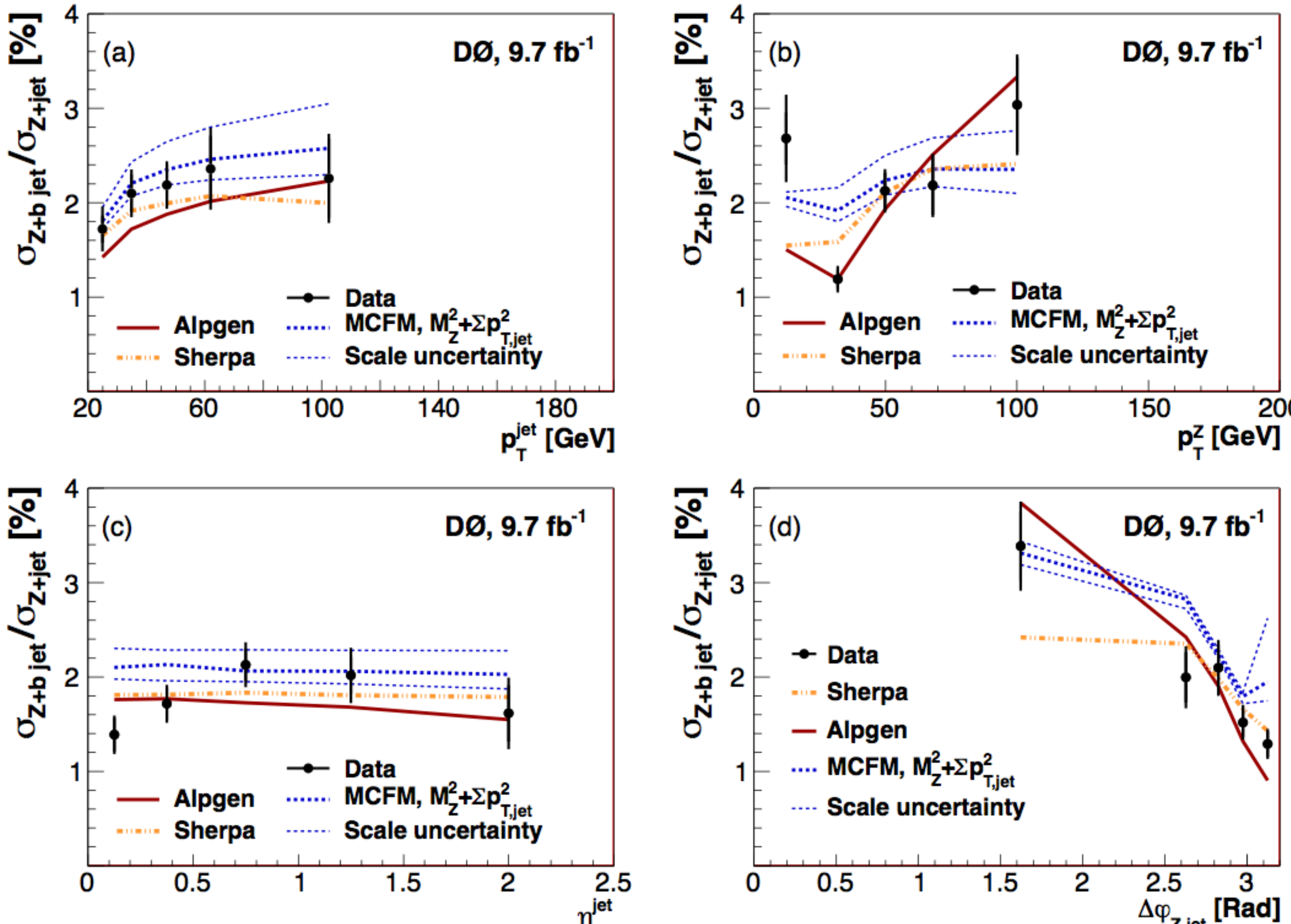


# Z+b/Z+jets differential measurement



New DØ measurement extends differential studies to study of Z pT, and azimuthal angle between Z and b-jet. **arXiv:1301.2233**



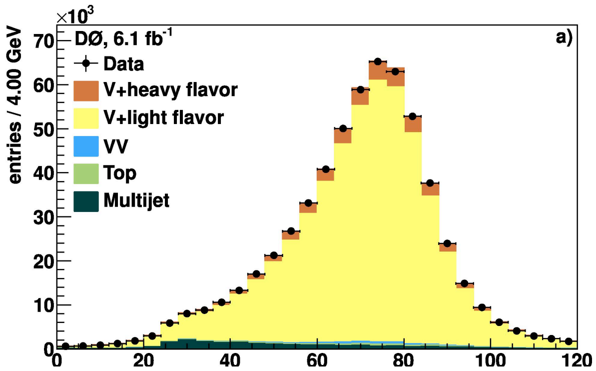
# W+b production

arXiv:1210.0627 [hep-ex]

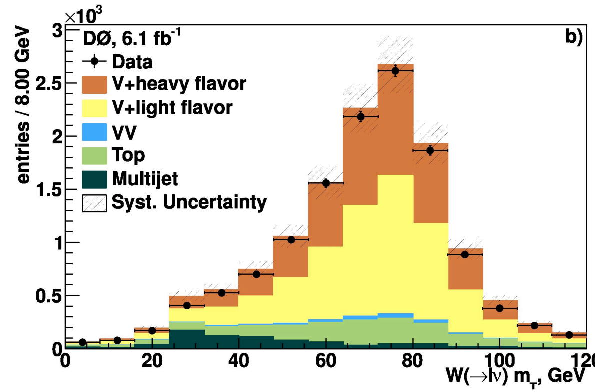


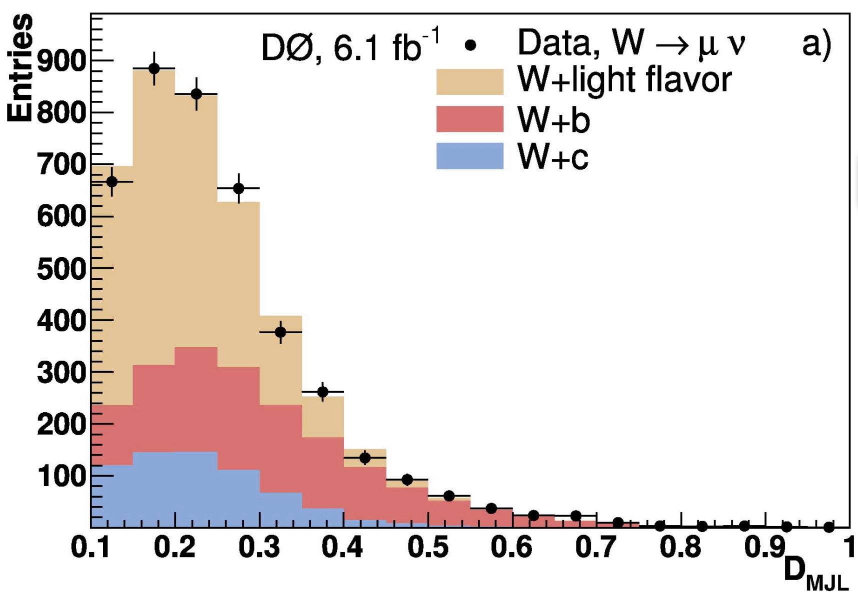
Excess of W+b production over NLO observed previously by CDF (1.9 $fb^{-1}$)

Use b-jet identification to reject dominant W+light flavour backgrounds




Before and after b-jet identification




Use discriminant based MVA b-tagging output and vertex mass to extract b-component of data

$$\sigma(W+b+X) = 1.05 \pm 0.03\ (\text{stat.}) \pm 0.12\ (\text{syst.})\text{pb}$$

Theory

$$\text{MCFM NLO} = 1.28^{+0.40}_{-0.33}\ (\text{scale})$$
$$\pm 0.06\ (\text{PDF})^{+0.09}_{-0.05}\ (m_b)\ \text{pb}$$
$$\text{Sherpa} = 1.08\ \pm 0.03(\text{stat.})\text{pb}$$
$$\text{MADGRAPH5} = 1.44\ \pm 0.02(\text{stat.})\text{pb}$$