# Recent Developments in Sherpa

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## Sherpa features

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- MENLOPS for POWHEG + CKKW
- Cluster hadronisation model
- Hadron and $\tau$ decays
- QED radiation from hard leptons and hadron decays in the YFS approach
- Multiple parton interactions

## Introduction

### Sherpa features

- POWHEG matching for NLO + parton shower
- MENLOPS for POWHEG + CKKW
- Cluster hadronisation model
- Multiple parton interactions

# Current versions

## Sherpa 1.2.3

- Released Dec 2010
- First POWHEG implementation in Sherpa
- First public MENLOPS code

## Sherpa 1.3.0

- To be released this(?) week
- More processes in POWHEG and MENLOPS approach
- Minor updates of hadronisation model + new tune

## Sherpa 2.0

- New model for soft inclusive QCD
  $\Rightarrow$ Minimum Bias
  $\Rightarrow$ Underlying Event
- Inclusive hard decays
- No definite time scale yet, $\mathcal{O}$(months)

## Basic ingredients

### Catani-Seymour dipole subtraction for NLO calculations

- Real emission and virtual MEs separately divergent
- Divergences cancel ⇒ Subtraction using Catani-Seymour dipoles
- Automated implementation of real and integrated subtraction terms in Sherpa
  Gleisberg, Krauss (2007)

↓ ↓

### ME level NLO calculations

- Only interface to the virtual matrix element is necessary (e.g. via Binoth Les Houches accord)
- Born, real emission, real/integrated subtraction, phase space done by Sherpa

→ Daniel's talk about state-of-the-art application in "Blackhat+Sherpa"

### NLO matched with parton shower

- Automated POWHEG implementation (again: "only" virtual ME needed)
  Höche, Krauss, Schönherr, FS (2010)
- MENLOPS on top of POWHEG:
  Höche, Krauss, Schönherr, FS (2010)
  Tree-level ME accuracy for final state multiplicities beyond NLO (instead of shower approximation)

## POWHEG: Features

Höche, Krauss, Schönherr, FS (2010)

### Cross section at NLO accuracy in $\alpha_s$

- Each event weighted with $\bar{\mathrm{B}} = \mathrm{B} + \mathrm{V} + \mathrm{I} + \int(\mathrm{R} - \mathrm{S})$ instead of B
- Integration of real emission phase space done by Monte-Carlo sampling
  $\Rightarrow$ Currently only weighted events

### Radiation pattern of first emission according to real ME

- Same principle as matrix element corrections in parton showers
- Simplified summary:
  - Weight with which to correct first emission generated by POWHEG generator (with splitting kernels based on the CS dipole terms)

$$w \;=\; \left(\frac{\mathrm{R}}{\mathrm{B}}\right) \Big/ \left(\frac{8\pi\,\alpha_s\mathcal{K}}{2\,p_i p_j}\right)$$

  - Replace splitting kernels in POWHEG generator $\mathcal{K} \;\rightarrow\; \max(w)\mathcal{K}$
  - Accept POWHEG emission with probability $\frac{w}{\max(w)}$
- $Z/H$ splitting implemented for the case $\mathrm{B} \rightarrow 0$

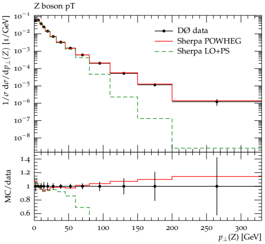
## Validation of total cross sections

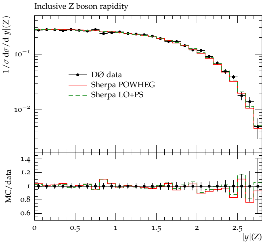
| | | $e^+e^- \to$ hadrons | | $e^+p \to e^+ + j + X$ | |
|---|---|---|---|---|---|
| | | $E_{\rm cms}$ = 91.2 GeV | | $E_{\rm cms}$ = 300 GeV, $Q^2 >$ 150 GeV$^2$ | |
| $\mu = \mu_R = \mu_F$ | Factor | POWHEG | NLO | POWHEG | NLO |
| $\sqrt{Q^2}$ | 1/2 | 30179(18) | 30195(20) | 3906(9) | 3908(10) |
| | 1 | 29411(17) | 29416(18) | 4047(10) | 4050(11) |
| | 2 | 28680(16) | 28697(18) | 4180(10) | 4188(11) |

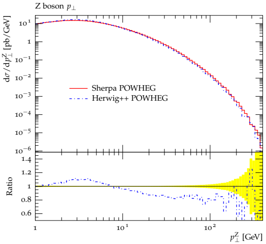
| | | $p\bar{p} \to W^+ + X$ | | $p\bar{p} \to Z + X$ | | $pp \to h + X$ | |
|---|---|---|---|---|---|---|---|
| | | $E_{\rm cms}$ = 1.8 TeV, $m_{\ell\nu} >$ 10 GeV | | $E_{\rm cms}$ = 1.96 TeV, $66 < m_{\ell\ell} < 116$ GeV | | $E_{\rm cms}$ = 14 TeV, $115 < m_{\tau\tau} < 125$ GeV | |
| $\mu = \mu_R = \mu_F$ | Factor | POWHEG | NLO | POWHEG | NLO | POWHEG | NLO |
| $m_{\ell\nu}/m_{\ell\ell}$ | 1/2 | 1235.4(5) | 1235.1(1.0) | 243.96(14) | 243.84(16) | 2.3153(13) | 2.3130(13) |
| | 1 | 1215.0(5) | 1214.9(9) | 239.70(13) | 239.59(16) | 2.4487(12) | 2.4474(13) |
| | 2 | 1201.4(5) | 1202.0(9) | 236.72(13) | 236.77(15) | 2.5811(13) | 2.5786(13) |
| $m_\perp$ | 1/2 | 1231.0(5) | 1230.3(1.0) | 243.00(14) | 243.06(16) | 2.2873(13) | 2.2869(14) |
| | 1 | 1211.8(5) | 1211.7(9) | 239.01(13) | 238.96(15) | 2.4255(12) | 2.4231(19) |
| | 2 | 1198.8(5) | 1199.3(9) | 236.23(13) | 236.13(14) | 2.5623(13) | 2.5620(14) |

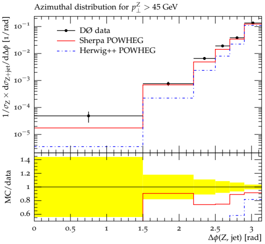
Cross sections in pb for various processes as calculated in the POWHEG framework and in a conventional fixed order NLO calculation (both in Sherpa).

## POWHEG Drell-Yan lepton pair production



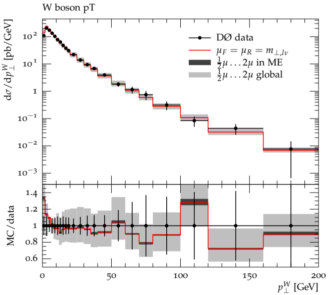



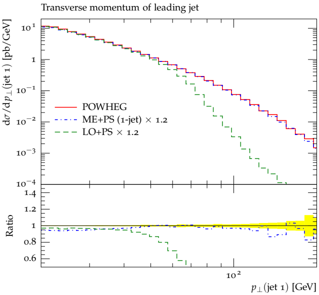



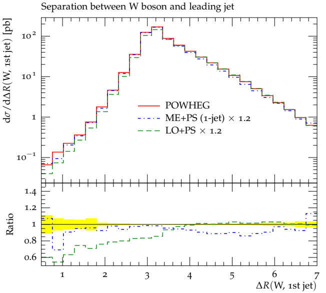




- [Sherpa $\geq$ 1.2.3]
- Virtual ME built-in, or from BlackHat, or from MCFM
- Good description of inclusive observables, agreement with Herwig++
- For anything beyond NLO (e.g. $\Delta\phi(Z, j) \to 0$) only shower approximation $\Rightarrow$ differences between both programs

# POWHEG $W$ boson production

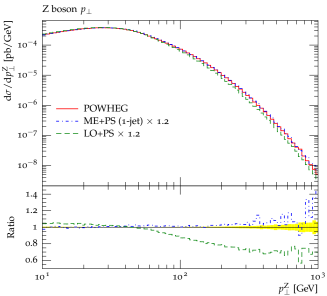


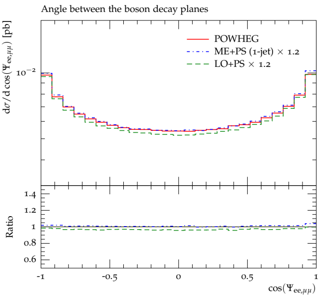



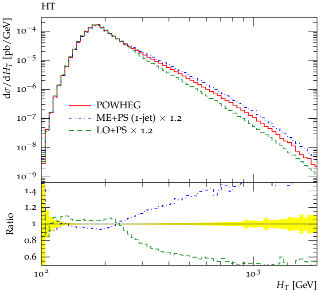




- [Sherpa $\geq$ 1.2.3]
- Virtual ME built-in, or from BlackHat, or from MCFM
- Comparison of POWHEG to ME+PS with up to 1 jet and LO+PS, all in Sherpa: agreement between POWHEG and ME+PS except for $K = 1.2$ global factor
- Scale variations in ME only are negligible compared to global scale variations

# POWHEG $Z$ pair production

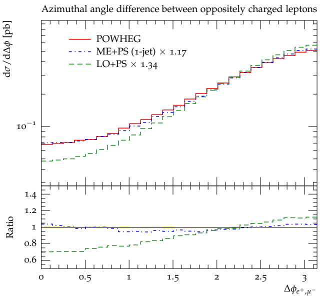


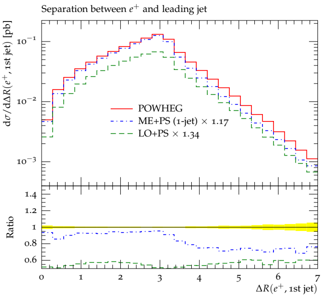



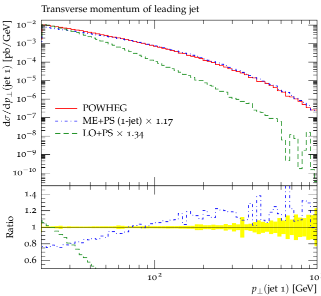




- [Sherpa $\geq$ 1.2.3]
- Virtual ME from MCFM
- Comparison of POWHEG to ME+PS with up to 1 jet and LO+PS, all in Sherpa
- $K$-factor $K \approx 1.2$
- Otherwise agreement between POWHEG and ME+PS(1) in inclusive observables, but differences when sensitive to higher-order contributions, like $H_T$

# POWHEG $W^+W^-$ production

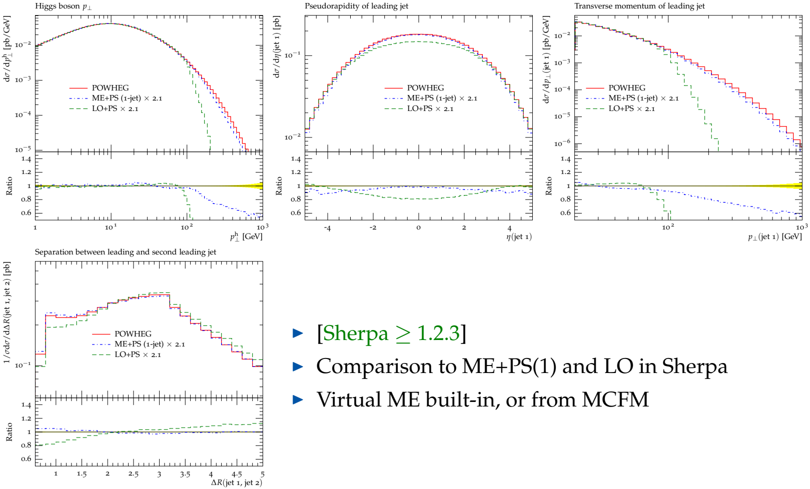



- [Sherpa $\geq$ 1.2.3]
- Virtual ME from MCFM
- global $K$-factor $K \approx 1.34$ for pure shower run, $K \approx 1.17$ for ME+PS(1)

# POWHEG $gg \to H \to \tau\tau$




- [Sherpa ≥ 1.2.3]
- Comparison to ME+PS(1) and LO in Sherpa
- Virtual ME built-in, or from MCFM

## Other Higgs processes

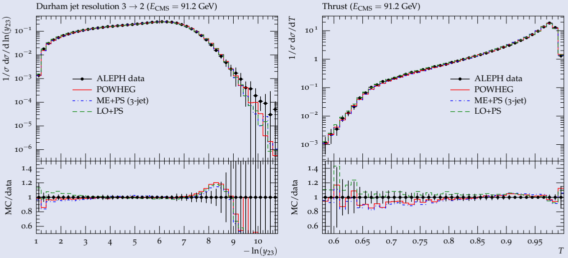
### Gluon-gluon fusion

- $gg \to H \to \tau\tau$ [Sherpa $\geq$ 1.2.3]
- $gg \to H \to \gamma\gamma$ [Sherpa $\geq$ 1.3.0]
- $gg \to H \to WW \to \ell\ell\nu\nu$ [Sherpa $\geq$ 1.3.0]
- $gg \to H \to ZZ \to \ell\ell\ell\ell$ [Sherpa $\geq$ 1.3.0]

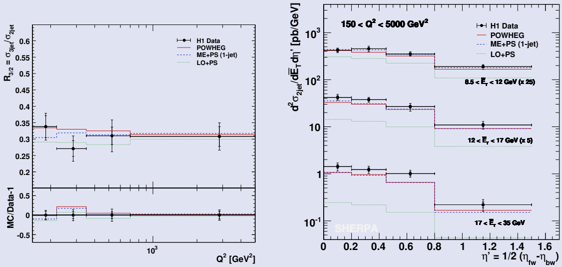
### Associated VH production

- $W[\to \ell\nu]H[\to WW \to \ell\ell\nu\nu]$ [Sherpa $\geq$ 1.3.0]
- $Z[\to \ell\ell]H[\to WW \to \ell\ell\nu\nu]$ [Sherpa $\geq$ 1.3.0]

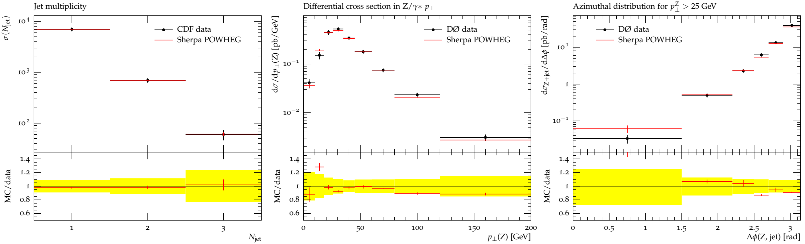
# Jet production in $e^+e^-$ collisions

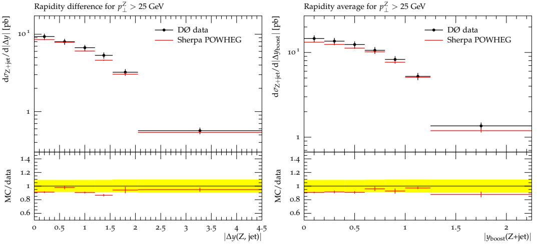



# Deep-inelastic lepton-nucleon scattering



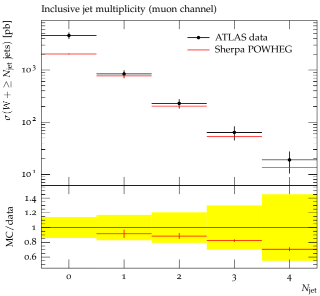
## Sneak preview: $Z + 1$jet

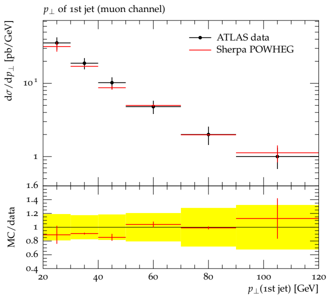


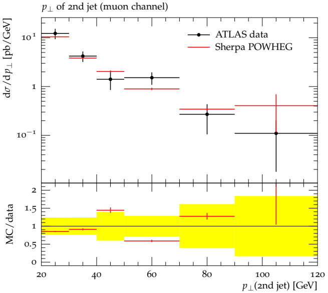




- Virtual ME from BlackHat
- Comparison to measurements from CDF and DØ
- PRELIMINARY, work in progress!

## Sneak preview: $W$ + 1jet

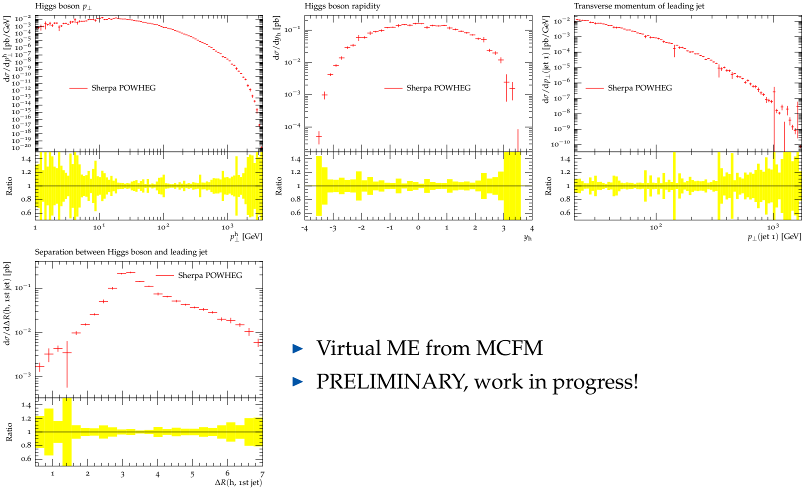



- Virtual ME from BlackHat
- Comparison to ATLAS W+jets measurements
- PRELIMINARY, work in progress!

# Sneak preview: $gg \to H + 1$jet




- Virtual ME from MCFM
- PRELIMINARY, work in progress!

# What is MENLOPS?

Hamilton, Nason (2010), Höche, Krauss, Schönherr, FS (2010)

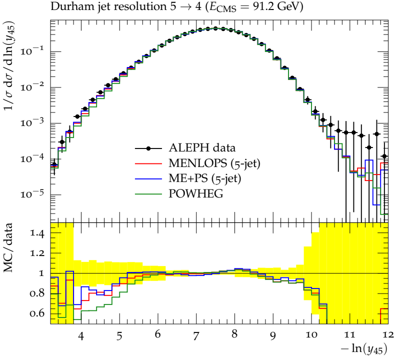
## Motivation

- POWHEG:
  - NLO accuracy for inclusive observables
  - LO accuracy for "+1 jet"
  - shower approximation for "+2, 3, ... jets"
- Can one do better especially for the high multiplicities?
- We already know how to get LO accuracy for "+1, 2, 3, 4, 5 jets": CKKW-like ME+PS merging
- Combination of ME+PS and POWHEG: MENLOPS
  - NLO accuracy for inclusive observables
  - LO accuracy for observables sensitive to the first $n$ jets (with $n$ up to $\approx 5$, depending on the process)

## Availability

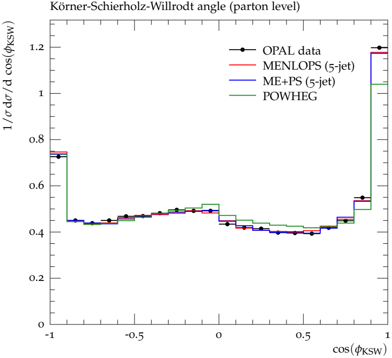
- First public availability in Sherpa 1.2.3
- Possible for all processes which are available in Sherpa's POWHEG

# MENLOPS: Comparison to LEP results for $e^+e^- \to$ hadrons




Jet resolution where 5 jets are clustered into 4 jets

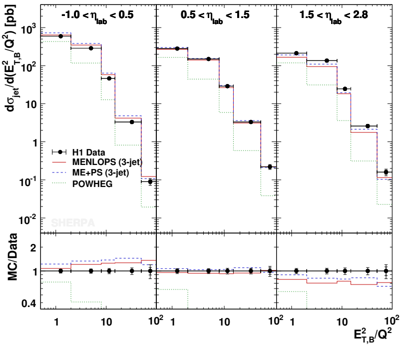
Eur. Phys. J. C35 (2004), 457-486




KSW Angle built from momenta of four most energetic jets

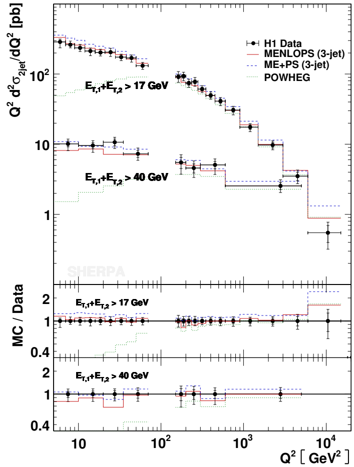
arXiv:hep-ex/0101044

# MENLOPS: Comparison to HERA results for Deep-Inelastic lepton-nucleon Scattering




Inclusive jet cross section as function of transverse energy in Breit frame

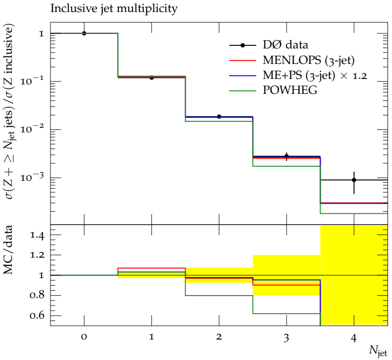
arXiv:hep-ex/0206029




Dijet cross section as function of $Q^2$

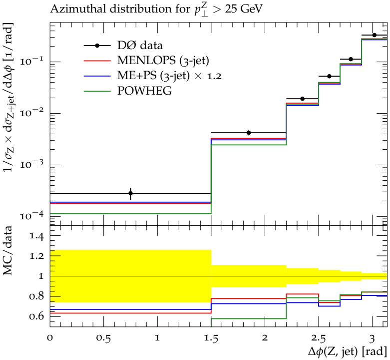
arXiv:hep-ex/0010054

# MENLOPS: Comparison to Tevatron results for $pp \to \ell\ell$




Inclusive jet multiplicity

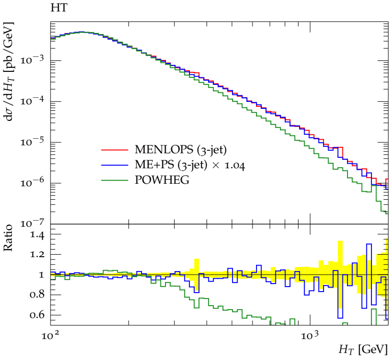
arXiv:hep-ex/0608052



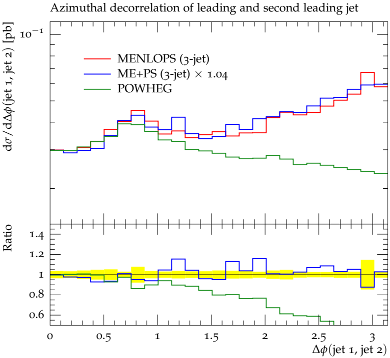

Azimuthal separation of lepton pair and leading jet

arXiv:0907.4286

# MENLOPS: Predictions for $W^+W^-$ production at LHC




Scalar sum of missing $E_T$ and transverse momenta of jets and leptons




Azimuthal decorrelation between leading and second leading jet

## MPI tuning to LHC data

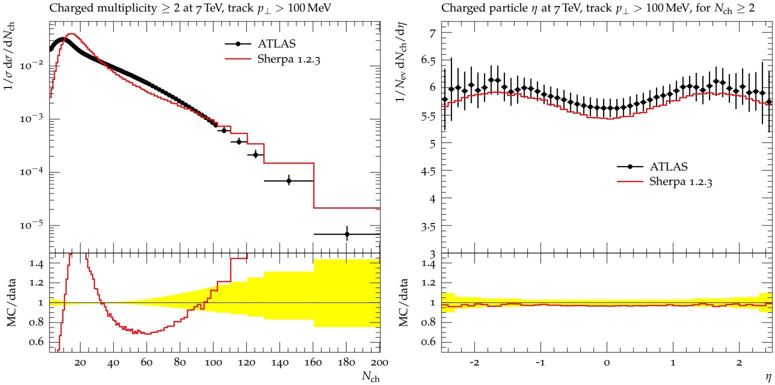
### Sherpa 1.2.3 default MPI tune

- MPI tuned using cteq66 PDF
- Main input: Particle level distributions from Atlas measurements
- Tevatron UE measurements also included, but with smaller weight
- Rivet used for all analyses
- Generator response interpolated and minimised using Professor
- Main Sherpa contact for tuning: Hendrik Hoeth
  (thanks to Hendrik also for most of the plots in the following)

### Tuned parameters

- Secondary QCD $2 \to 2$ scattering cutoff $p_\perp^{\rm min}$ and its energy dependence exponent
- Scale factor for non-diffractive cross section
- Proton matter distribution: Gaussian parameters (mean and width)
- Intrinsic $k_\perp$ (mean and width)

# Results for LHC @ 7 TeV (arXiv:1012.5104)




- MinBias events
- Sherpa simulation not inclusive enough
- Diffraction and soft QCD missing

⇒ Can it describe MB at all? Reasonable agreement in some distributions

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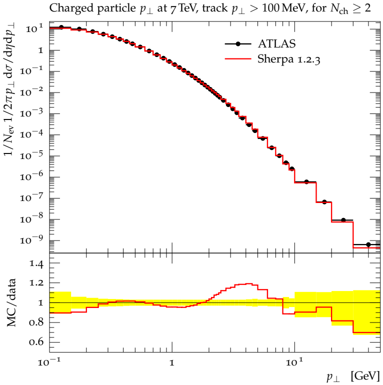


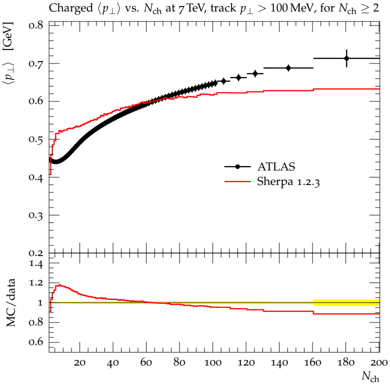


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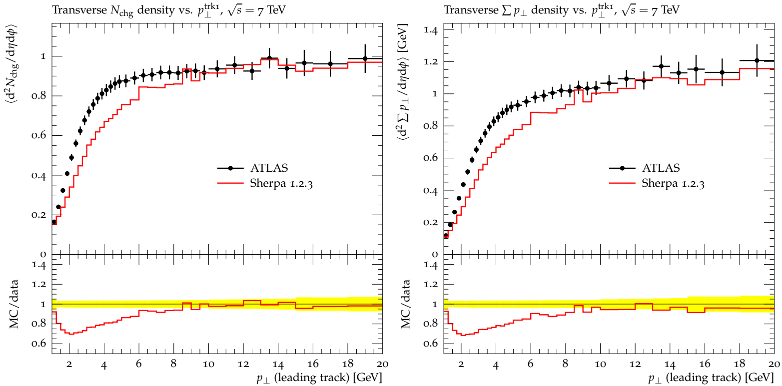


- Underlying Event measurement
- Sherpa's $p_\perp^{\text{min}}(7000) \approx 3.5$ GeV
  $\Rightarrow$ Turn-on effect in most plots up to $p_\perp^{\text{lead}} \approx 6$ GeV

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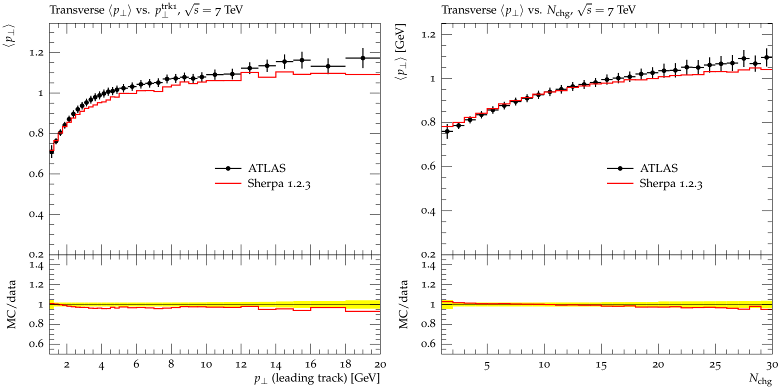


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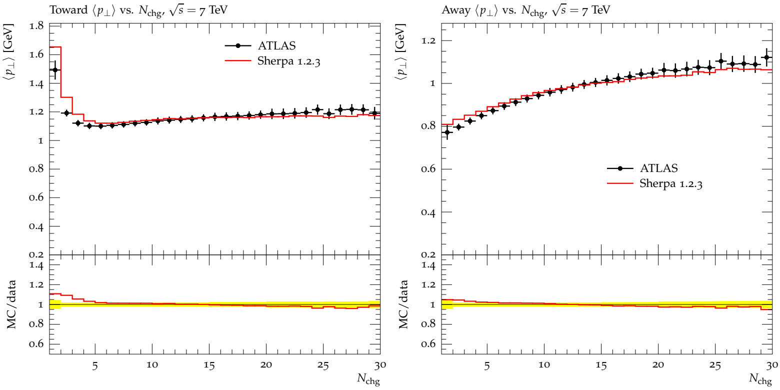


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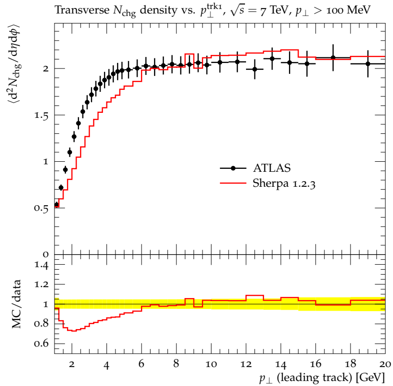


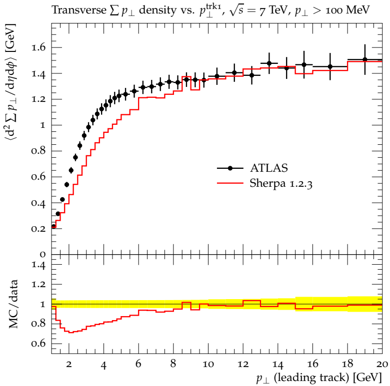


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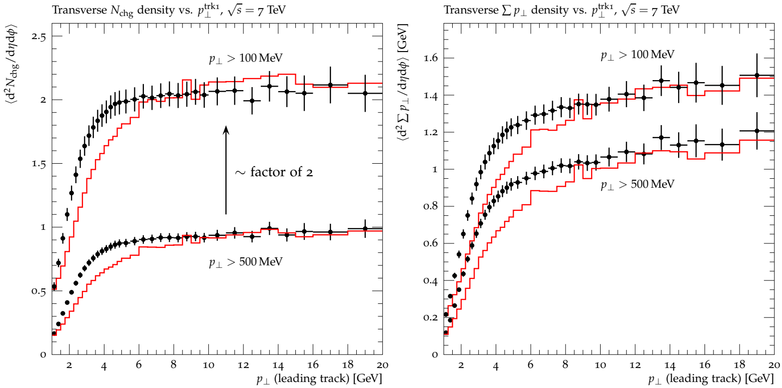


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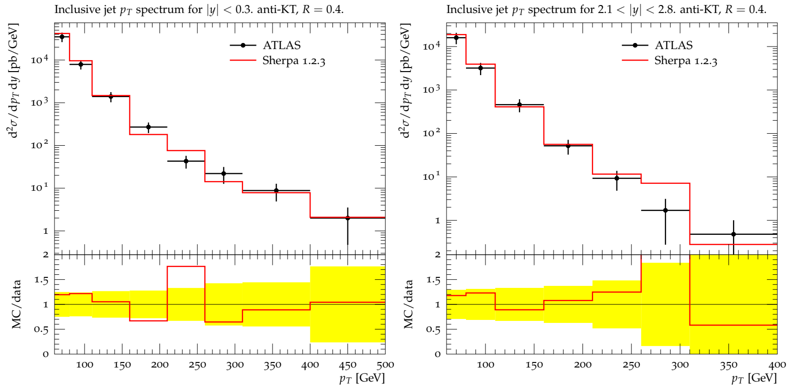
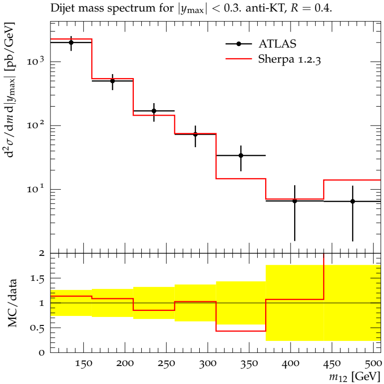
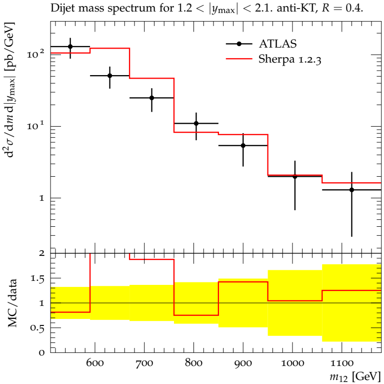



- Inclusive jet cross sections
- Nice agreement even in total cross section!

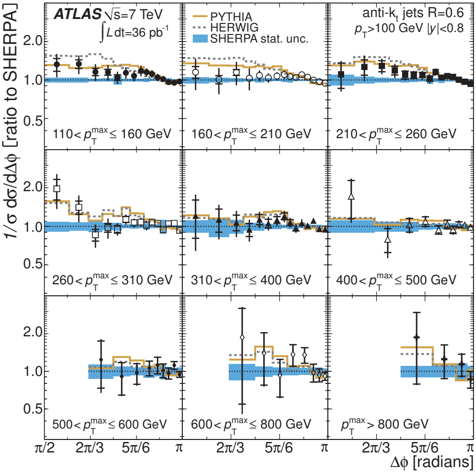
# Results for LHC @ 7 TeV (arXiv:1009.5908)



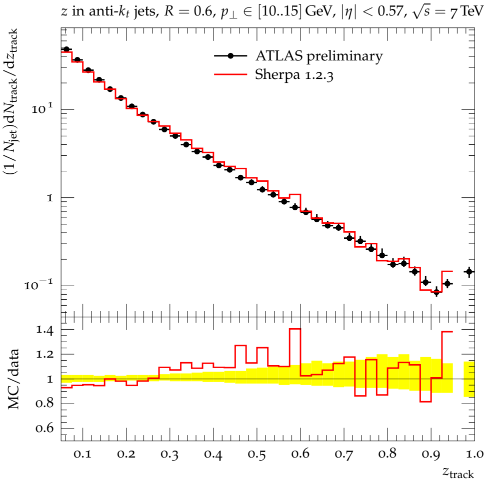

- Dijet mass

## Results for LHC @ 7 TeV (arXiv:1102.2696)



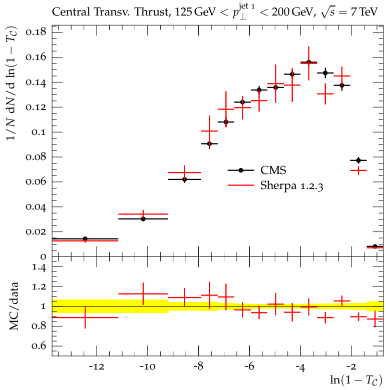

- Azimuthal decorrelations (figure from arXiv:1102.2696)
- Sensitive to multi-jet events

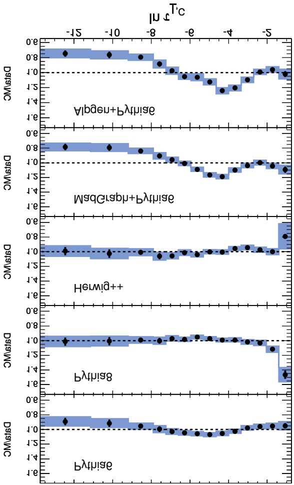
## Results for LHC @ 7 TeV (ATLAS-CONF-2010-049)




- Fragmentation in anti-kt jets

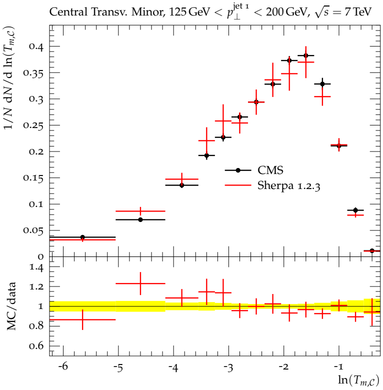
# Results for LHC @ 7 TeV (arXiv:1102.0068)

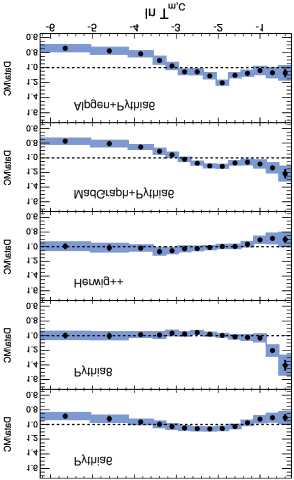



- Event shapes measured by CMS
- Large disagreement in comparison to ME+PS by MadGraph and Alpgen
- First look with Sherpa looks reasonable

## Results for LHC @ 7 TeV (arXiv:1102.0068)




- Event shapes measured by CMS
- Large disagreement in comparison to ME+PS by MadGraph and Alpgen
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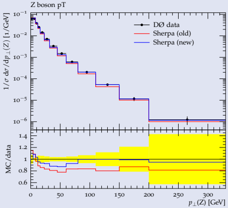
## Hadronisation update

### Recent changes for Sherpa 1.3.0

- Bugfixes in hadronisation for $z$ distribution in gluon splitting during cluster formation
- Shower parameter changed:
  Pre-factor for $\alpha_s$ scale from NLL arguments and comparison to Tevatron data for $Z\ p_\perp$ (e.g. arXiv:1006.0618)

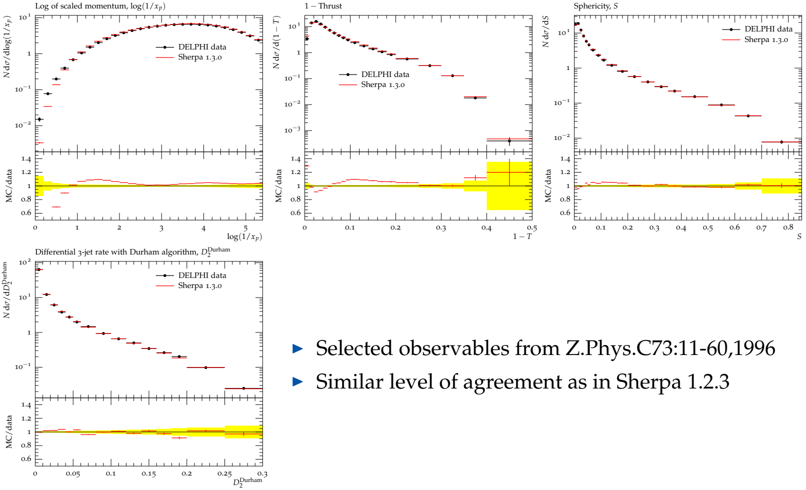
$\Rightarrow$ New hadronisation tune necessary




### Hadronisation tune using LEP data

- Shower infrared cut-off $p^2_{\perp,\mathrm{min}}$
- Parameters of cluster fragmentation
  - `PT^2_0`, `PT_MAX`
  - `DECAY_OFFSET`, `DECAY_EXPONENT`
  - `STRANGE_FRACTION`, `BARYON_FRACTION`
  - `P_{QS}/P_{QQ}`

# Preliminary results for Sherpa to-be-1.3.0




- Selected observables from Z.Phys.C73:11-60,1996
- Similar level of agreement as in Sherpa 1.2.3

## Summary

- Sherpa developments in perturbative physics:
  - Automated POWHEG implementation
  - Multitude of processes with simple colour structure
  - Preliminary results for more complicated processes: $W/Z/H$+1jet
  - Implementation of MENLOPS on top of POWHEG restores LO accuracy for higher jet multiplicities
- Tuning of non-perturbative aspects of event generation:
  - Sherpa 1.2.3 was first version to come with a default tune to LHC data
  - Used mainly corrected data from Atlas, and also Tevatron measurements
  - New hadronisation tune after bug fixes and model changes

## Outlook

- POWHEG will be available for more processes especially in the Higgs sector in imminent Sherpa 1.3.0 release
- Finalise validation of POWHEG for $W/Z/H$+1jet
- Version 2.0 will bring new physics modules, e.g. for soft inclusive QCD
- Long term goal: CKKW merging for different jet multiplicities at NLO