Parton Showers since LEP

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Outline

- Status at end of LEP
- From LEP to the LHC
- At the LHC
- The Future

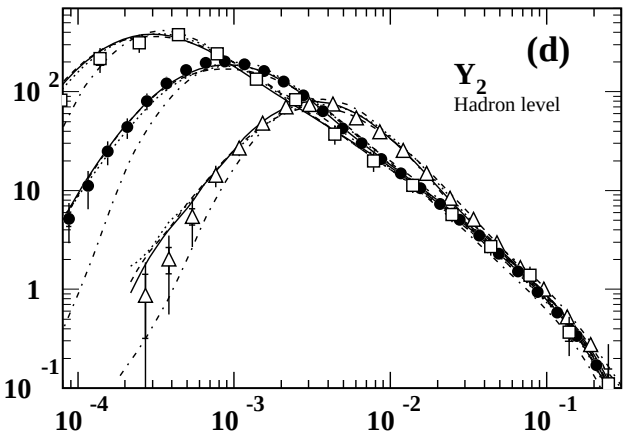
LEP

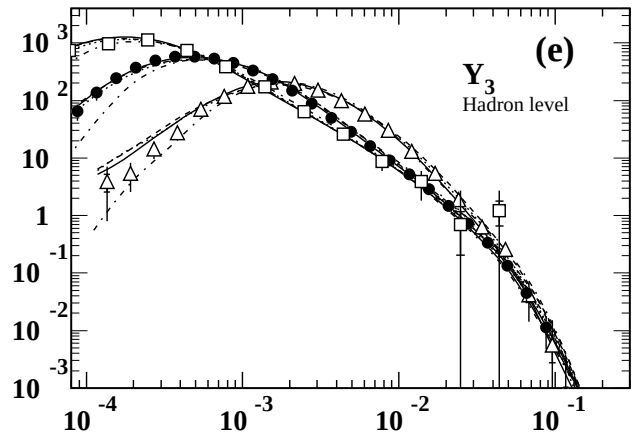
- LEP was when event generators came of age.
- Better understanding of QCD.
- Increased computer performance.
- Went hand-in-hand to give a very good description of the LEP data.
- The workhorses were PYTHIA(JETSET) and HERWIG.

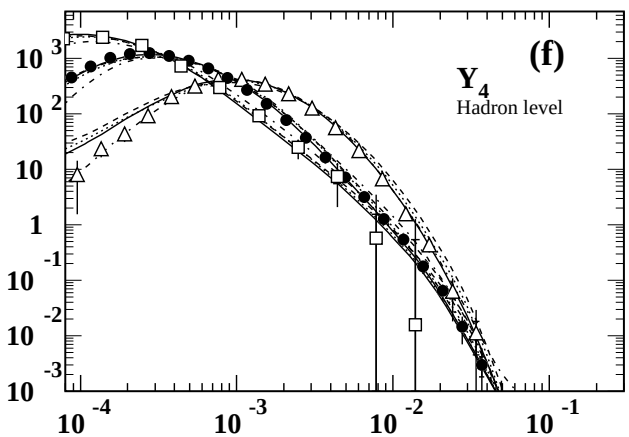
LEP

- Used leading-order matrix elements for $e^+e^- \to q\bar{q}$, together with matching of one hard gluon emission.
- String (PYTHIA) or cluster (HERWIG) model used for hadronization.
- The alternative dipole shower of ARIADNE (+PYTHIA hadronization) often provide the best agreement with the data.
- Older generators with worse parton-shower algorithms (non-coherent) and hadronization models (independent fragmentation) were often used only to show there were models which couldn't describe the data.

LEP Jet Resolution

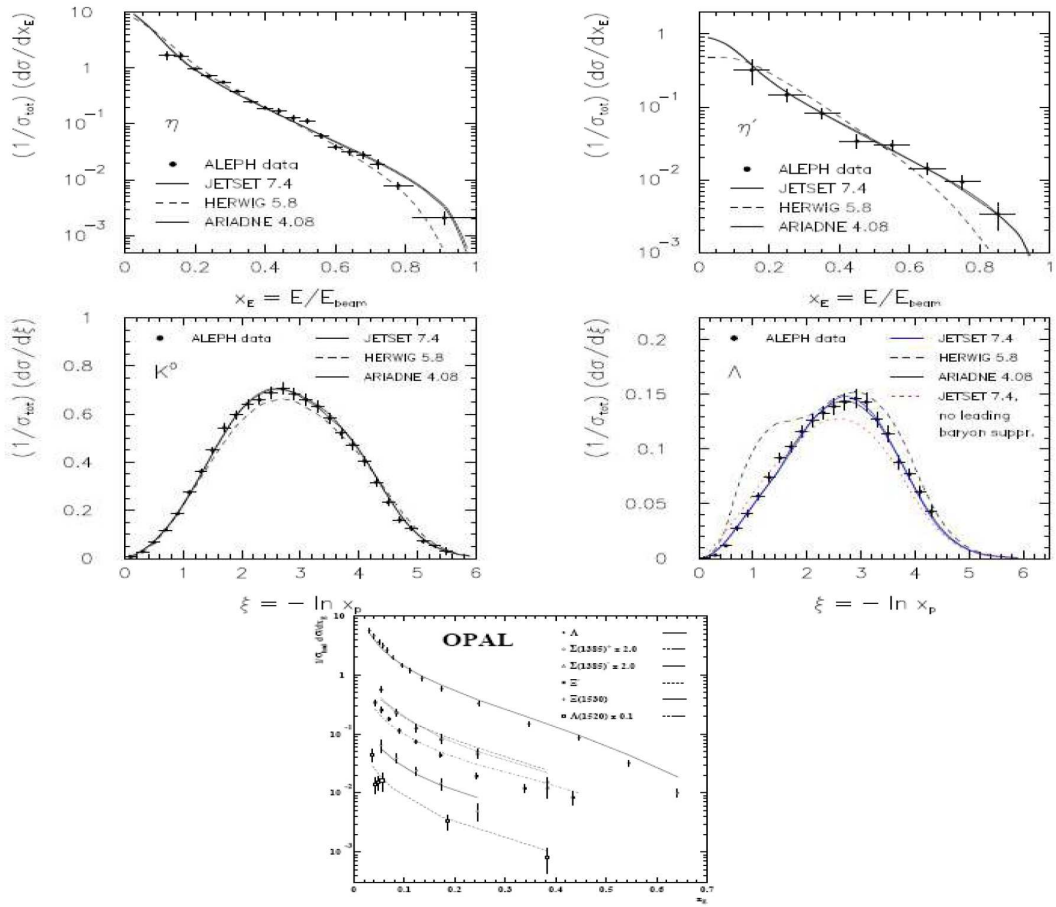






JADE/OPAL Eur.Phys.J.C17:19-51,2000

LEP Identified Particle Spectra



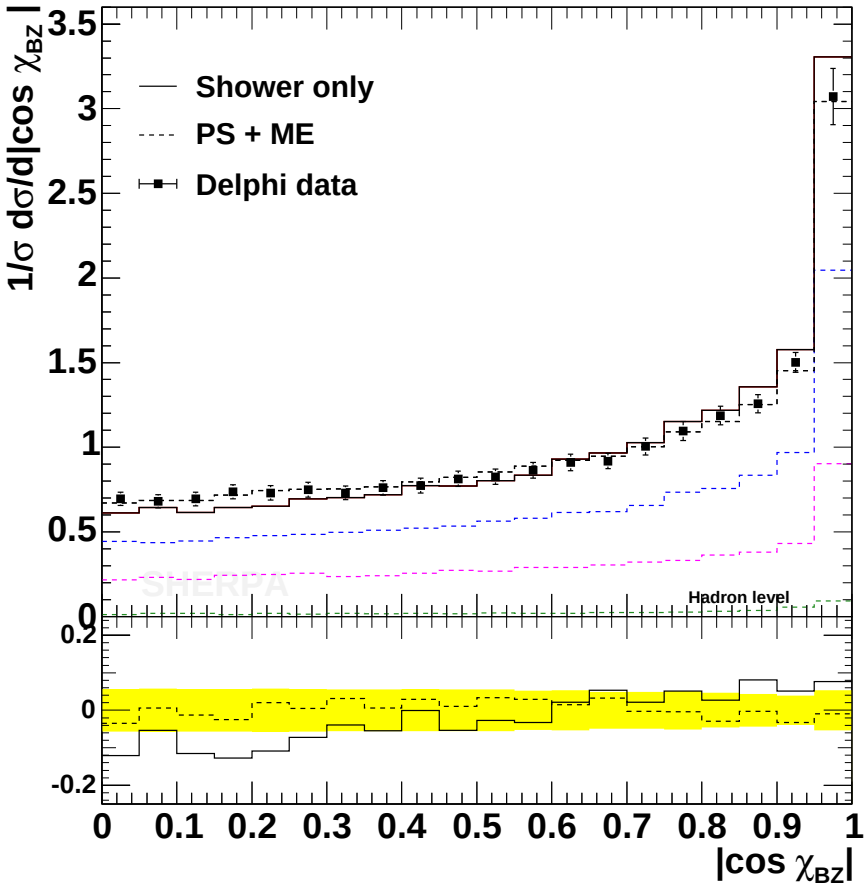
LEP

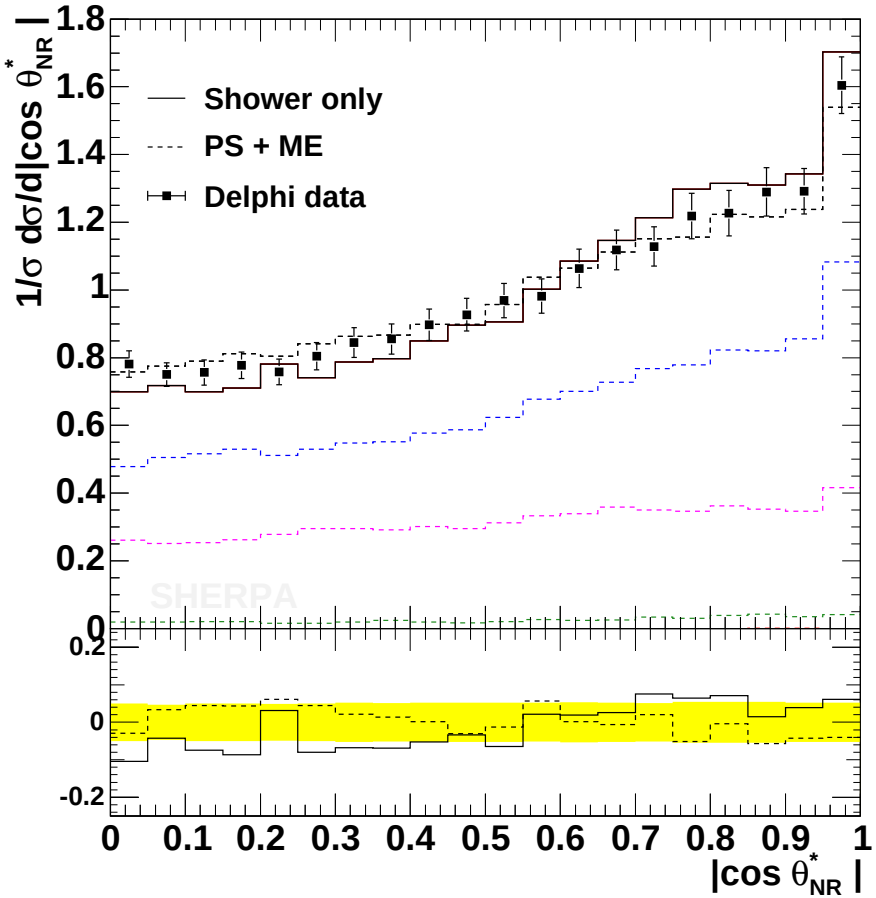
- In general good agreement for event shapes, jet rates etc.
- The description of meson spectra was generally good.
- However in all simulations baryon production has issues.
- At LEP II interest in colour reconnection between the W decay products and Bose-Einstein correlations.

LEP 4 jet

- At LEP there was also interest in 4 jet production.
- At the time couldn't describe the 4th jet using the available matching procedures.
- However the 4th jet had sufficient energy that it wasn't completely within the parton-shower regime.
- Led to the development of the CKKW (Catani, Krauss, Kuhn and Webber JHEP 0111 (2001) 063) approach to merge the shower with many jets at leading order.

LEP 4 jet





Schälicke, Krauss JHEP 0507 (2005) 018

From LEP to LHC: Higher Orders

- After end of LEP the main physics focus of event generator development was the inclusion of higher order corrections.
- Matching to NLO (NLO normalisation and 1st emission)
  - MC@NLO (Frixione, Webber JHEP 0206 (2002) 029)
  - POWHEG (Nason JHEP 0411 (2004) 040)
  - KrkNLO (S. Jadach, et. al. JHEP 1510 (2015) 052)
- Merging at NLO (NLO normalisation for multiple emissions)
  - MINLO (Hamilton, Nason JHEP 1006 (2010) 039, Hamilton, Nason, Zanderighi JHEP 1210 (2012) 155)
  - FxFx Frederix, Frixione JHEP 1212 (2012) 061
  - Sherpa (Höche, Krauss, Schonherr, Siegert JHEP 1304 (2013) 027)
  - UMEPS(Lönnblad, Prestel JHEP 1303 (2013) 166)
  - + Herwig 7.1 in prep based on (Plätzer JHEP 1308 (2013) 114) + ...
- First processes at NNLO (Hamilton, Nason, Oleari, Zanderighi JHEP 1305 (2013) 082), ...

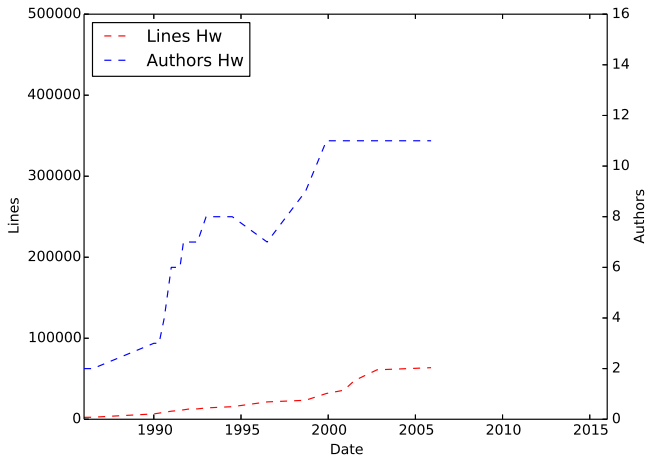
From LEP to LHC: New Algorithms

- Motivated by matching/merging development of new parton-shower algorithms
  - Improved AO (Gieseke, Stephens, Webber JHEP 0312 (2003) 045)
  - PYTHIA p_T (Sjöstrand, Skands, Eur.Phys.J. C39 (2005) 129-154)
  - Catani-Seymour based SHERPA (Schumann, Krauss JHEP 0803 (2008) 038), Herwig++ (Plätzer, Gieseke JHEP 1101 (2011) 024)
  - Antenna Based (Giele, Kosower, Skands Phys.Rev. D78 (2008) 014026)
  - DIRE (Höche, Prestel Eur.Phys.J. C75 (2015))
  - GenEvA (Bauer, Tackmann,Thaler JHEP 0812 (2008) 010)

From LEP to LHC: New Programs

- At the end of LEP the existing FORTRAN generators needed to be rewritten to allow physics improvements and long term development:
  - HERWIG redeveloped as Herwig++ and then Herwig7;
  - PYTHIA → Pythia 8;
  - Sherpa developed from scratch;

  all in C++.



- New generation of event generators which are the workhorses at the LHC, together with specialized programs for the calculation of hard processes in the various merging schemes.

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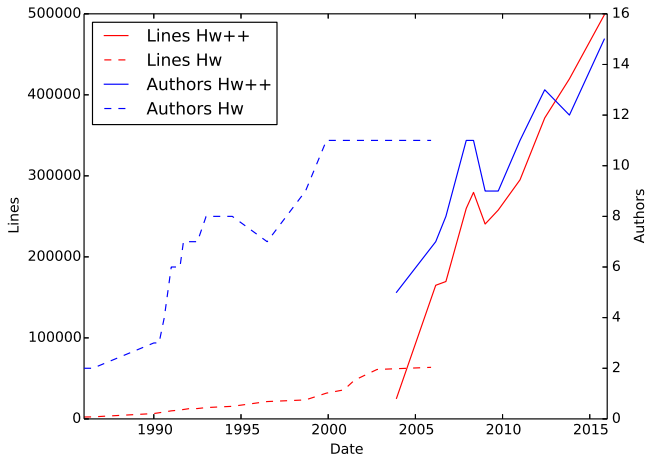

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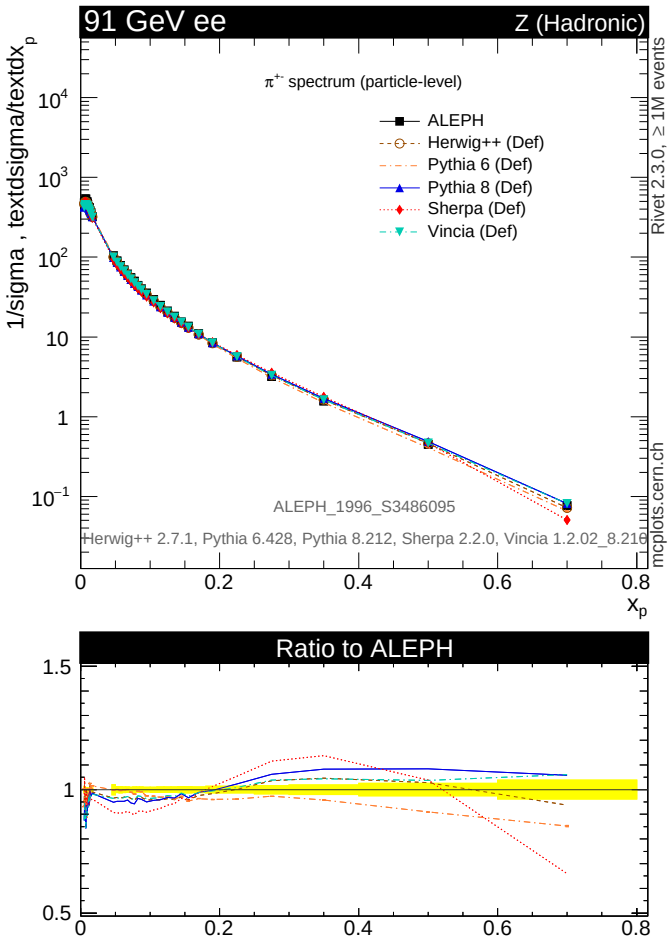
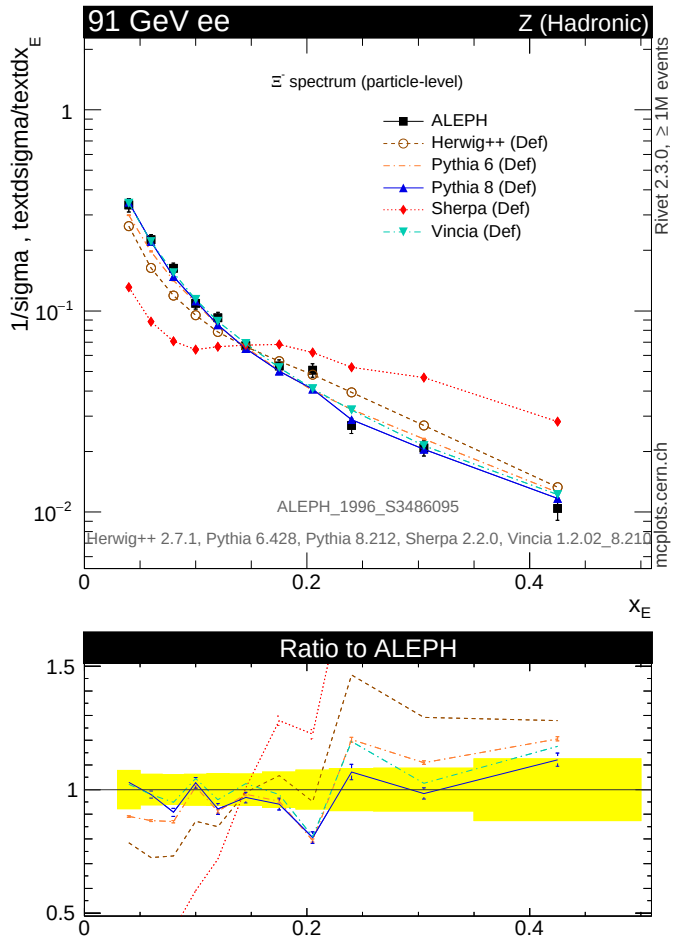
From LEP to LHC

- A lot of development in the last 15 years.
- Motivation was to describe the results of the LHC.
- However describing LEP data is still important and all the new shower algorithms are still developed, testing and tuned using data from e^+e^- collisions.
- Many things, particularly relating to the production of specific hadrons are hard, if not impossible, to measure in the more complicated hadron–hadron environment.

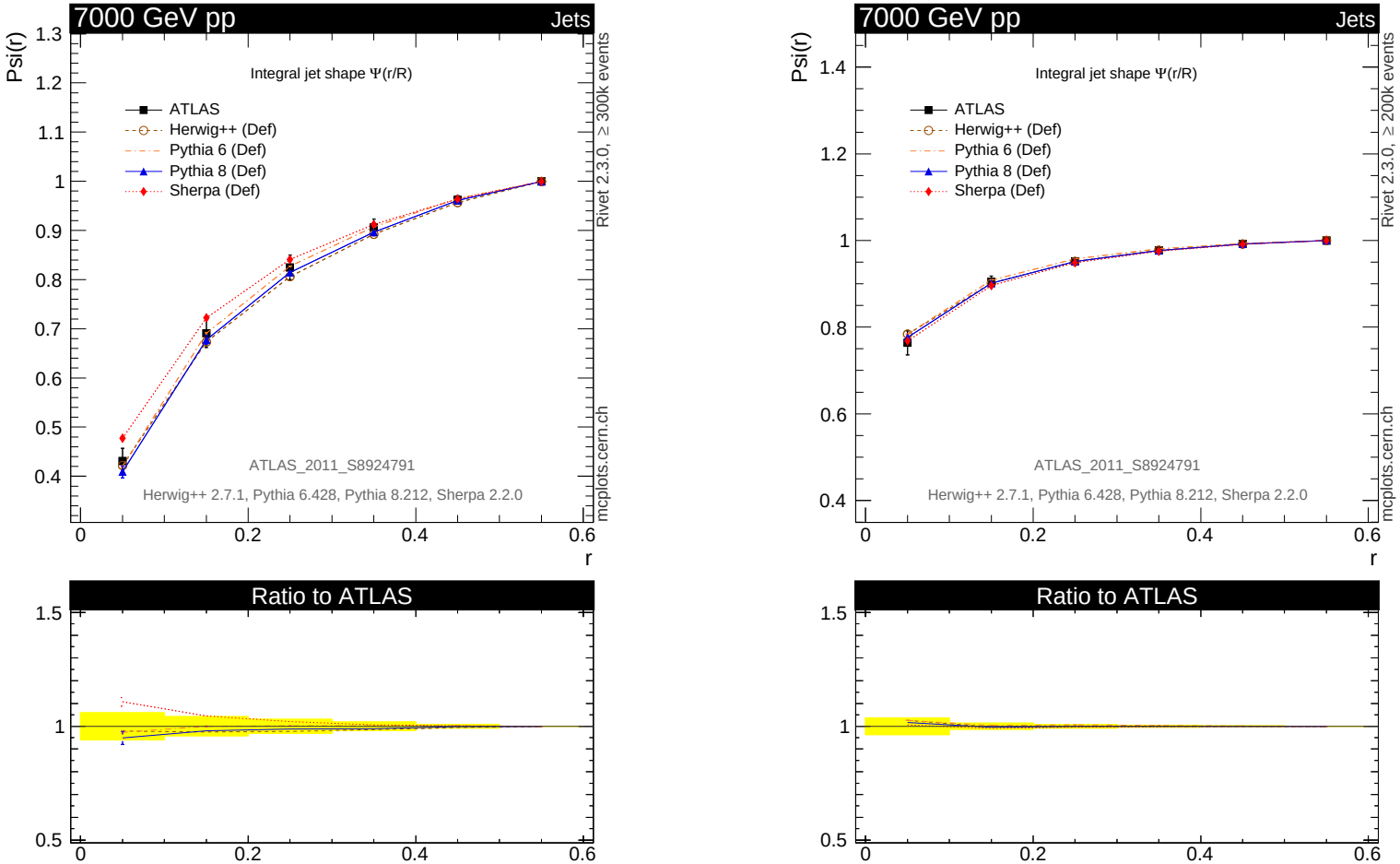
From LEP to LHC: Identified Particle Spectra





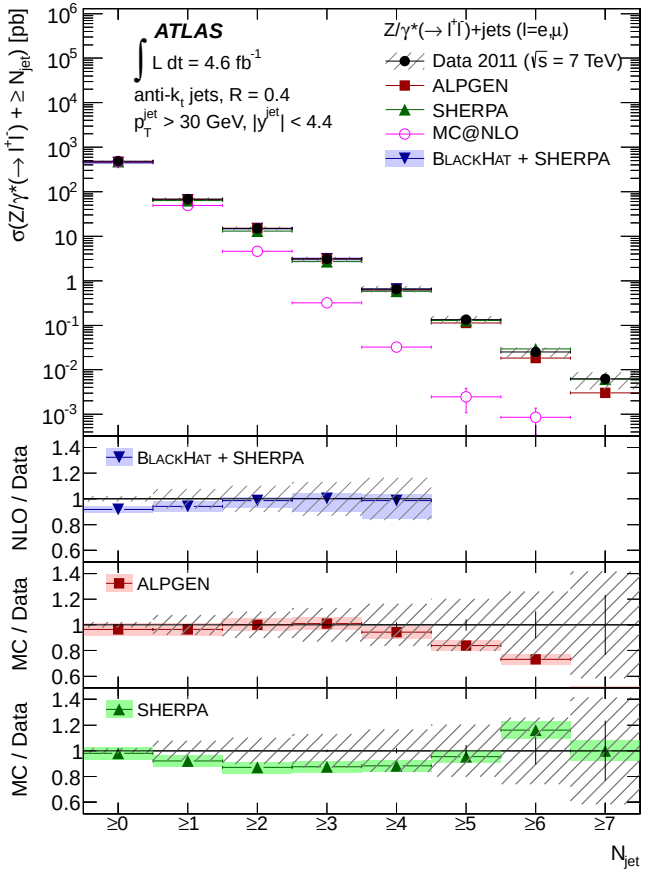
Plots from MCplots

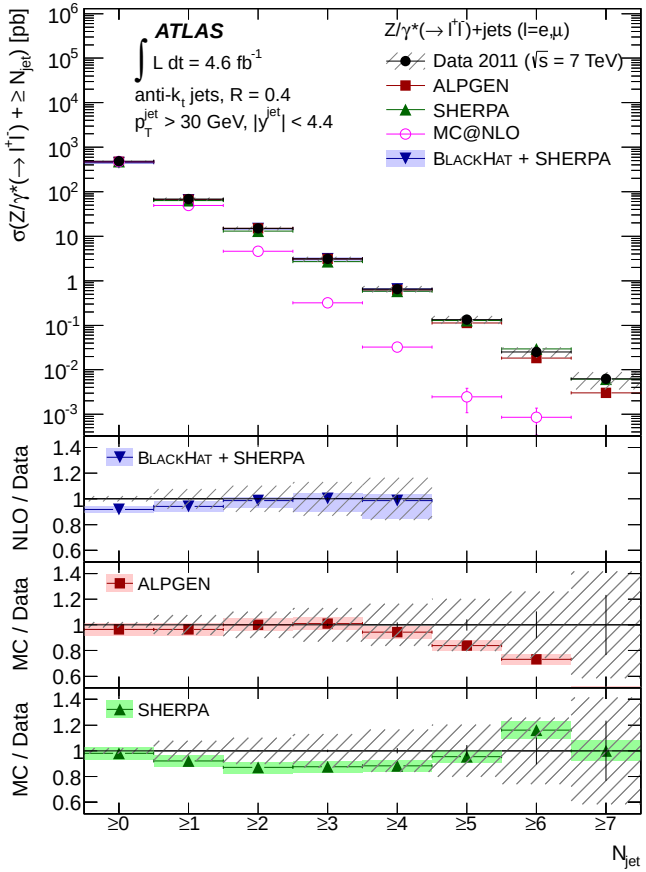
At the LHC: ATLAS Jet Shapes



Plots from MCplots

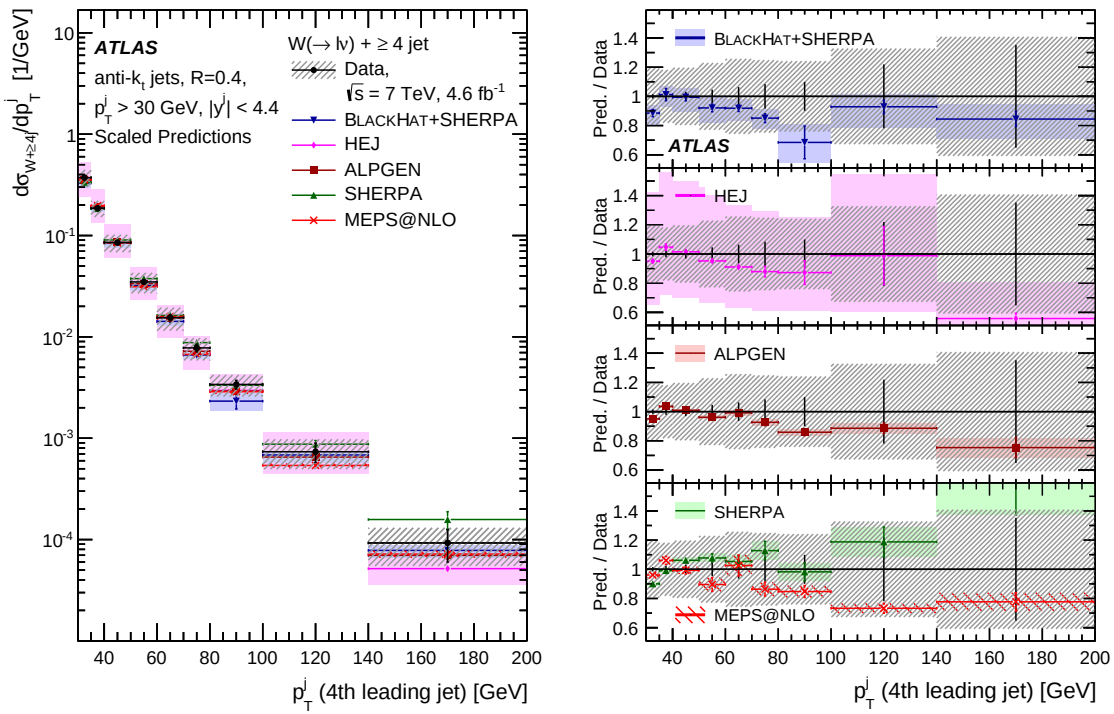
At the LHC: ATLAS Z+jets





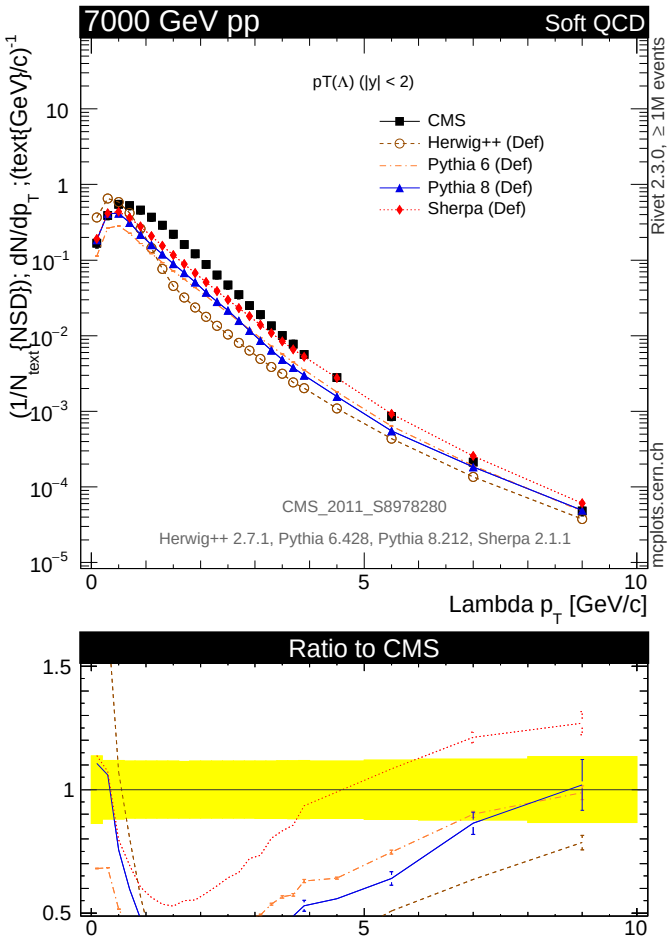
ATLAS JHEP 1307 (2013) 032

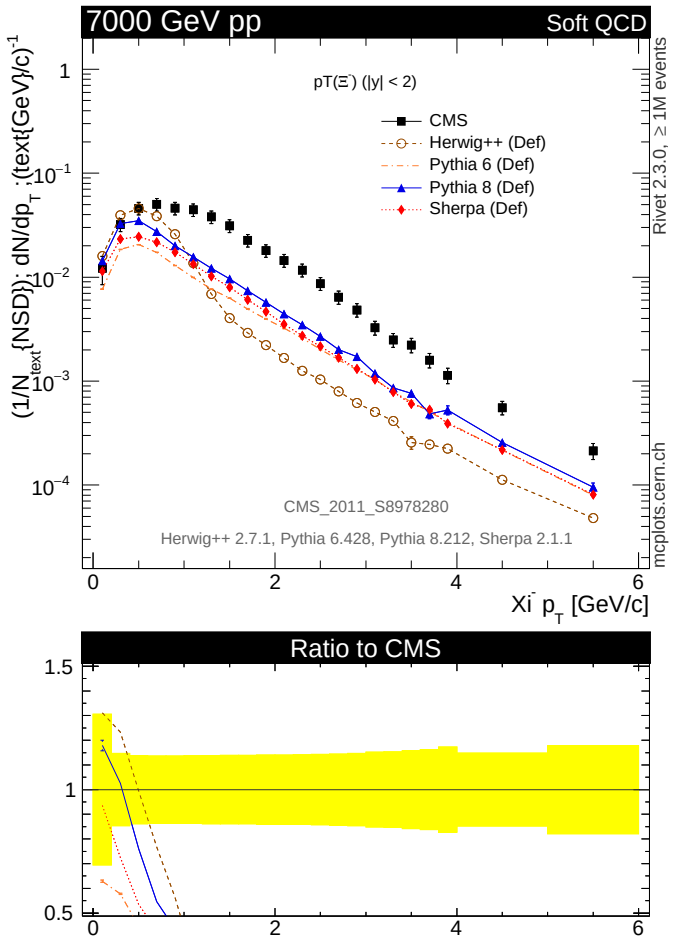
At the LHC: ATLAS W+jets



ATLAS Eur.Phys.J. C75 (2015) no.2, 82

At the LHC: Baryons



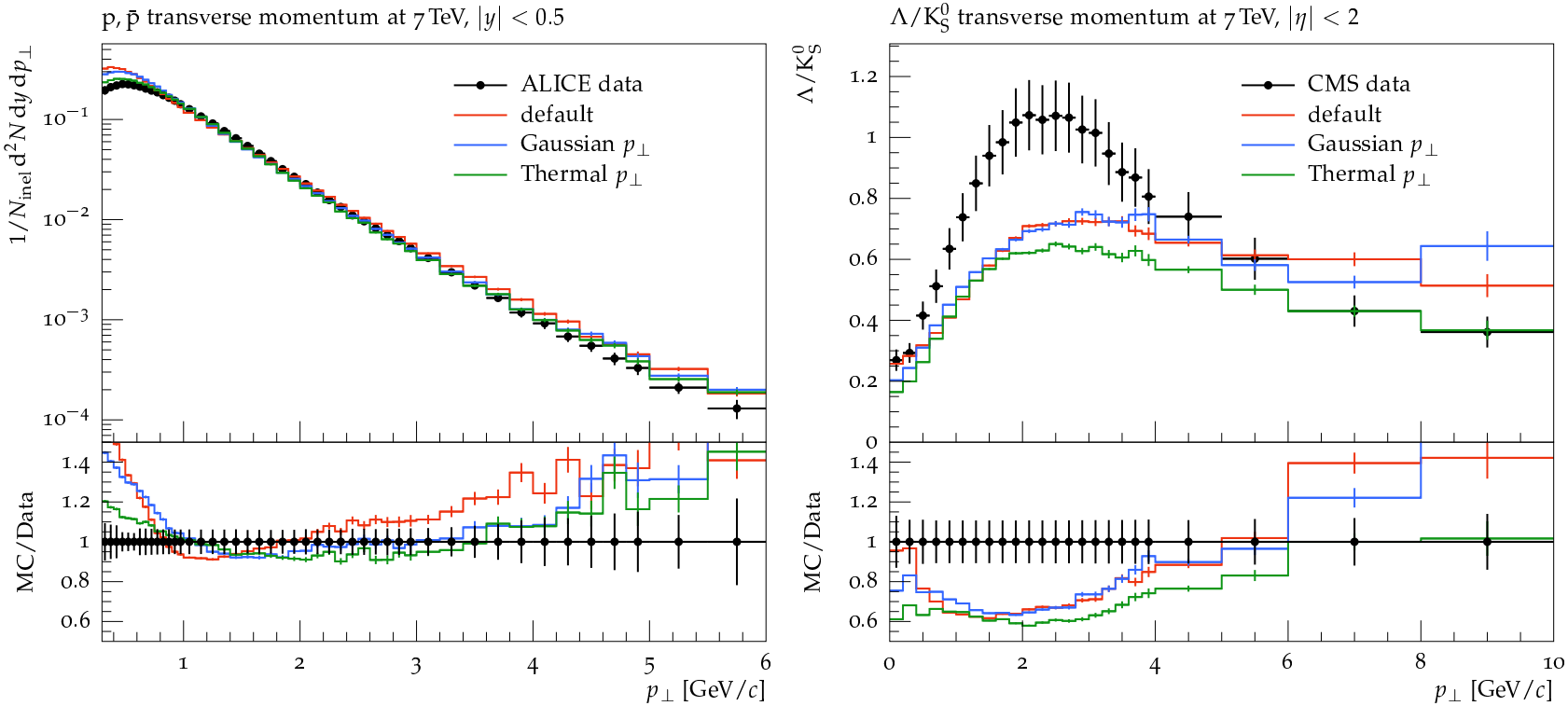


Plots from MCplots

At the LHC: Baryons

- Standard assumption of universality was that we could develop the hadronization models using e^+e^- data and then apply them in hadron–hadron collisions.
- Have always needed additional non-perturbative modeling of the underlying event and colour reconnection.
- In the more complex environment of the LHC clear other things are going on, or colour reconnection is much more complicated, and we need better modeling of non-perturbative effects.
- Some new ideas, e.g. (Fischer, Sjöstrand arXiv:1610.09818)

At the LHC: Baryons

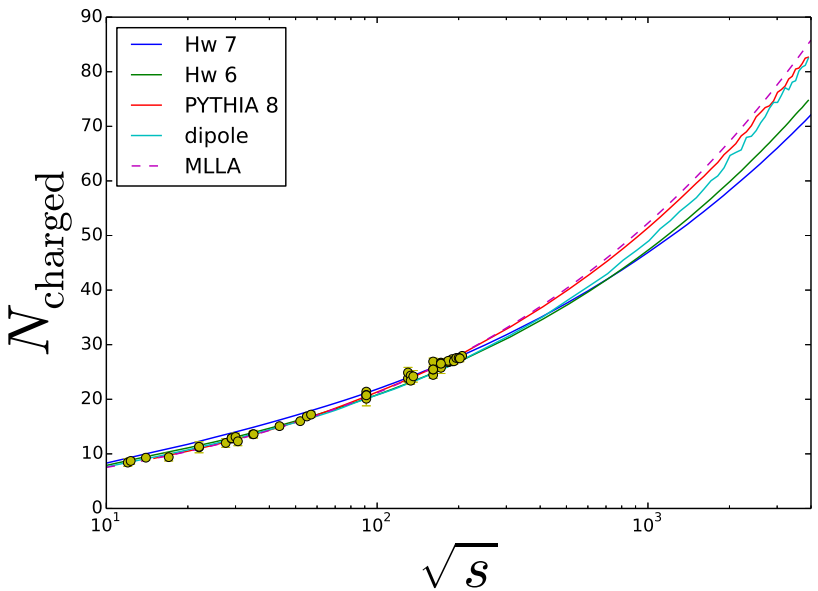


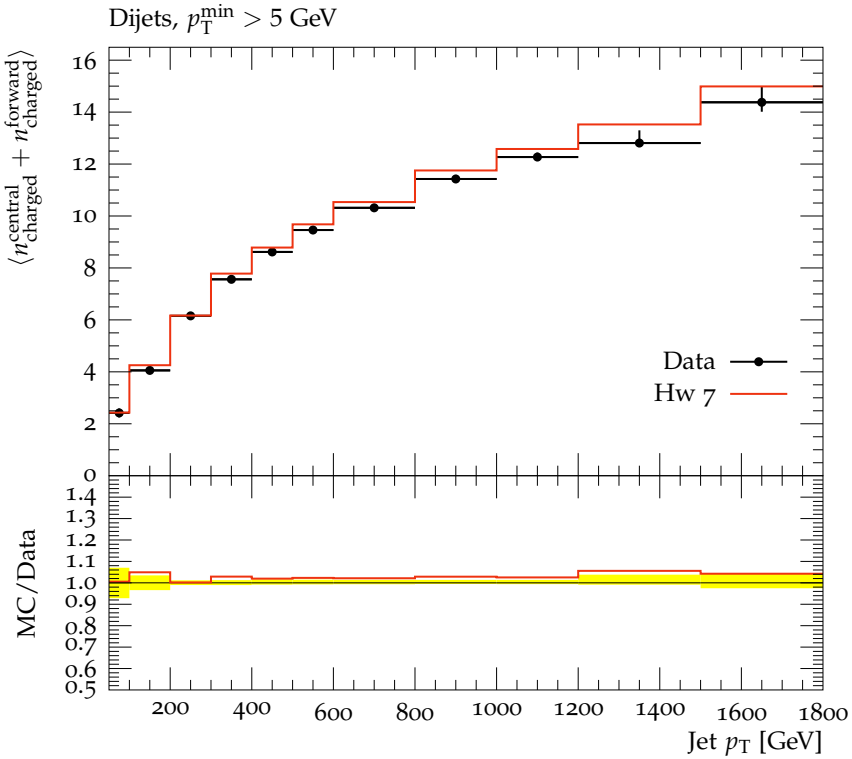
Plots from (Fischer, Sjöstrand arXiv:1610.09818)

Interplay

- In the development of the event generators there is obviously a lot of interplay between e^+e^- and hadronic collisions.
- However given the different environment and observables, jet algorithms etc this is usually a bit indirect.
- Some things like fragmentation functions are measured in both e^+e^- and hadron–hadron.
- Even there in e^+e^- the primary process is quark production while at the LHC in many cases gluon production dominates.

Interplay: N_{charged}

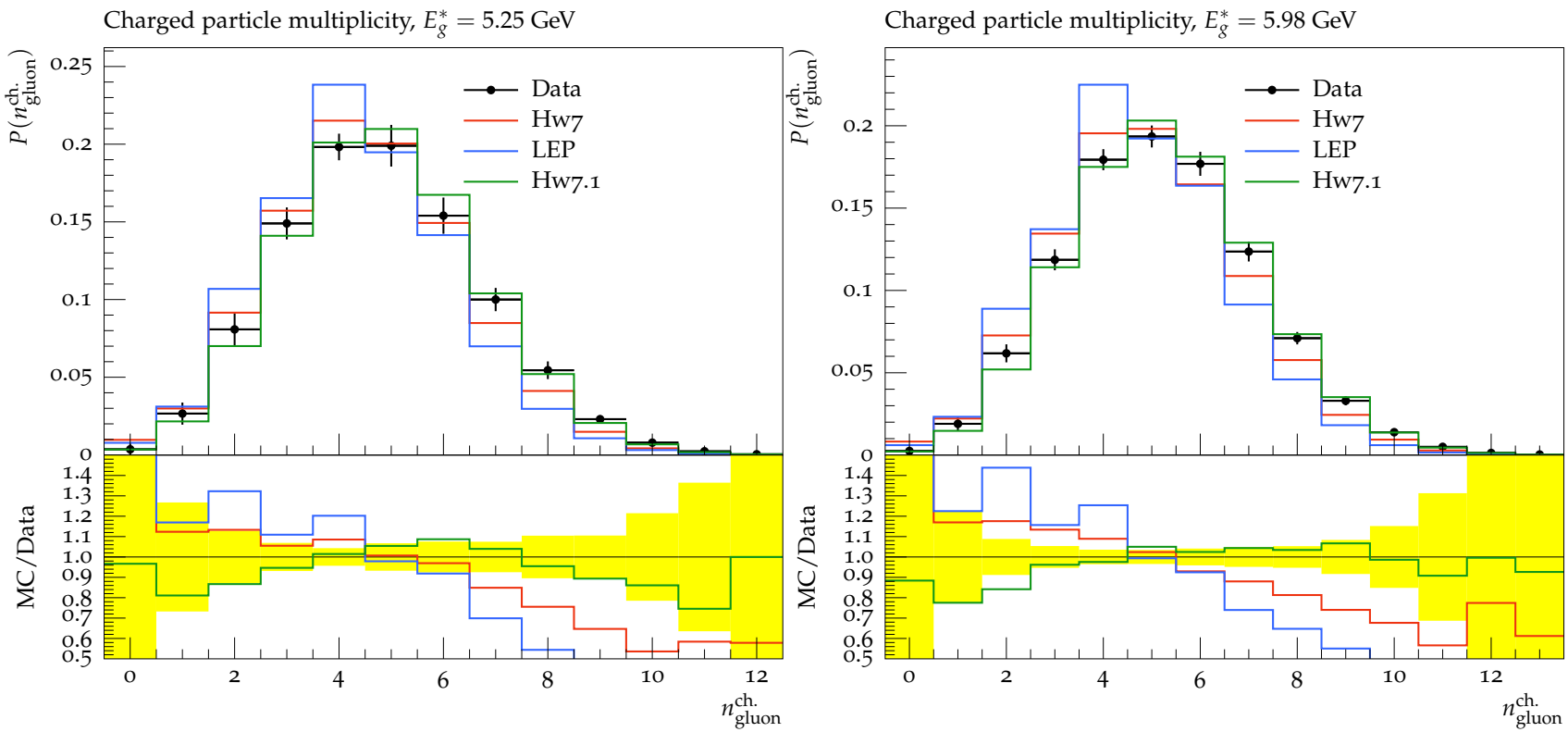




(Siodmok, Reichelt, PR in preparation)

Even here differences, at LEP all charged particles, LHC charged particles with $p_T > 5\,\text{GeV}$ in a jet

Interplay: Gluon jets



OPAL Phys.Rev. D69 (2004) 032002

(Siodmok, Reichelt, PR in preparation)

Future

- There will continue to be developments as the LHC progresses.
- If we look at the progress in the last 15 years it will be surprising if at least NNLO for the important processes, with NLO matching of additional multiplicities, will be the default.
- Given the much simpler environment in e^+e^- collisions it may be possible to go further for e^+e^- collisions.

Accuracy of the shower

- For the first time in many years more work on the accuracy of the parton-shower algorithms.
- Needed as we go to higher accuracy for the matrix elements.
- $1/N_c$ (Plätzer, Sjödahl JHEP 1207 (2012) 042), (Nagy, Soper, JHEP 1507 (2015) 119)
- Subleading logs (Li, Skands, arXiv:1611.00013)
- This is the area where there is probably the greatest potential for improvement.
- If we can consistently improve the logarithmic accuracy.

Conclusions

- There clearly are some event generator issues that a future e^+e^- collider can address.
- Not entirely clear to me what these are/should be.
- For the moment I think its much ($\rightarrow \infty$) more important to focus on the LHC.
- The issues for the LHC which are (most) important at the moment aren't relevant for the e^+e^-.
- Any improvements in higher order or log accuracy will also be relevant in e^+e^-.
- Other things will need new developments in non-perturbative models.