Monte Carlo tools and NLO Monte Carlo Simulations

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Outline

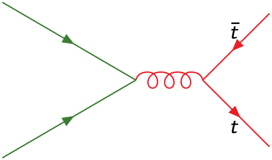
- Basics of Event Generation
- Hard Processes and Higher Orders
- Non-perturbative physics
- More Logs?
- The Future

Basics of Event Generation

- Monte Carlo event generators combine:
  - hard perturbative QCD calculations;
  - approximate QCD evolution from high to low energy scales using the parton shower;
  - perturbative multiple parton scattering models of the underlying event;
  - non-perturbative models of the hadronization process;
  - simulations of hadron decays;

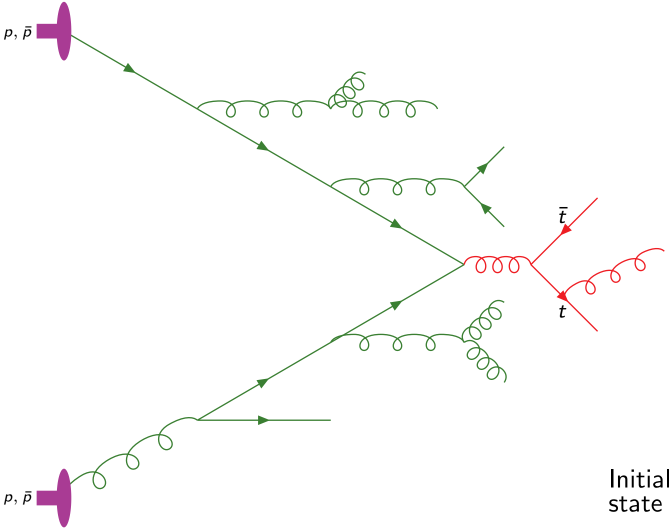
  to provide simulations of complete events.
- They are essential tools that both encapsulate the current theoretical understanding of hadronic collisions and produce simulated events which can be compared with data.

A Monte Carlo Event



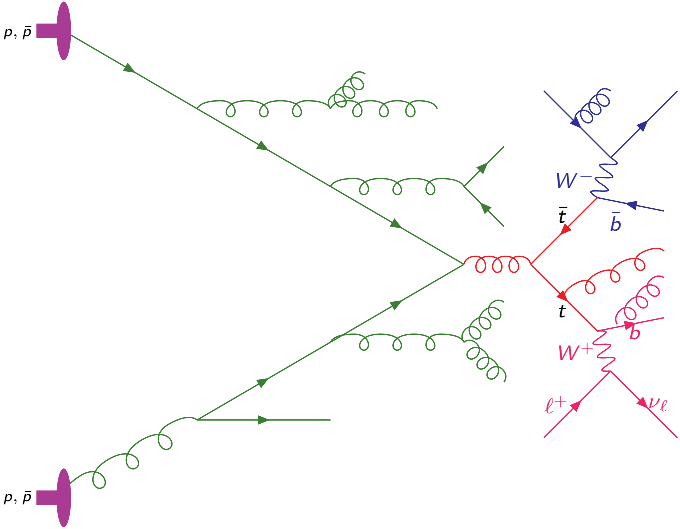
Hard Process, now usually calculated at NLO

A Monte Carlo Event



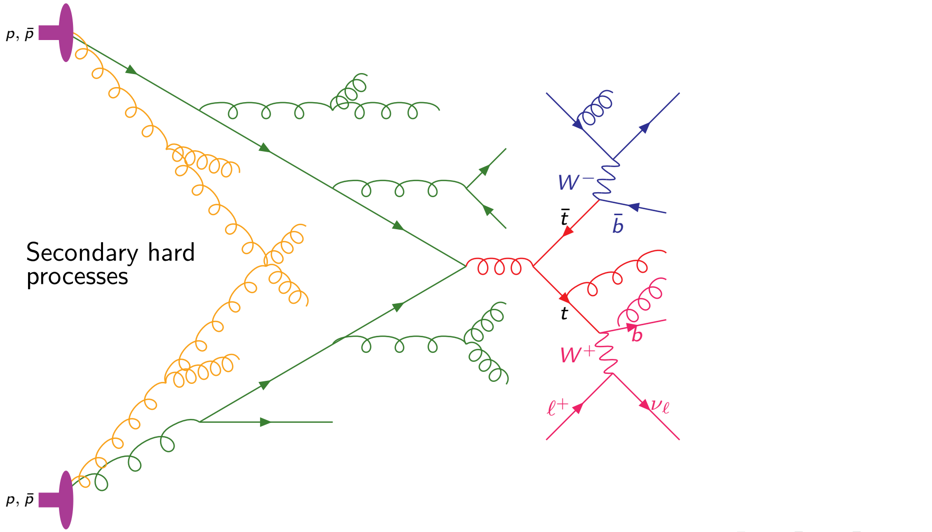
Initial- and final-state parton shower

A Monte Carlo Event

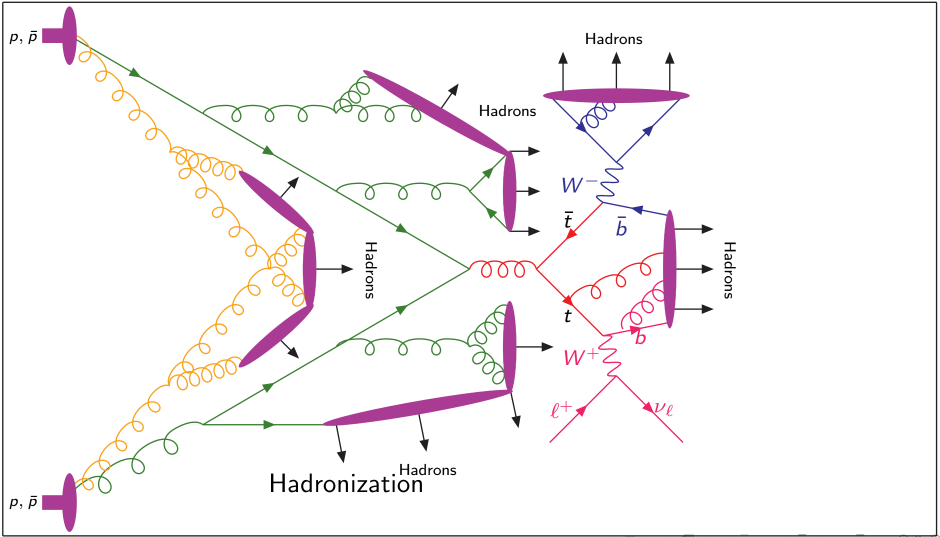


Perturbative decays of heavy particles

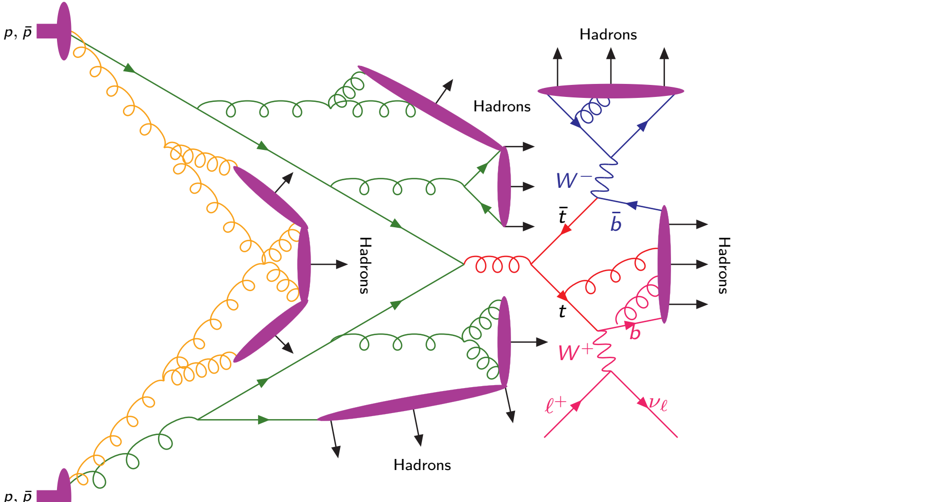
A Monte Carlo Event



A Monte Carlo Event



A Monte Carlo Event



Hadron Decays

Last 15 years

- Before we go on and consider recent developments its worth thinking about how much things have changed over the last 15 years.
- At the end of LEP
  - Main programs were FORTRAN HERWIG6 and PYTHIA6.
  - Parton showers with matching to the first hard emission for simple processes such as $e^+e^- \to q\bar{q}$ and Drell-Yan.
  - Cluster or string model for hadronization.
  - The alternative dipole shower of ARIADNE (+PYTHIA hadronization) also available.

From LEP to LHC: Higher Orders

- Focus of event generator development has been the inclusion of additional hard emissions and higher-order corrections.
- Multiple emissions at LO, CKKW (Catani, Krauss, Kuhn and Webber JHEP 0111 (2001) 063) and numerous variants.
- 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, (+Zanderighi) JHEP 1006 (2010) 039, 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 (Bellm et.al. arXiv:1705.06700, Plätzer JHEP 1308 (2013) 114) + ...
- 1st processes at NNLO (Hamilton, Nason, Oleari, Zanderighi JHEP 1305 (2013) 082), ...

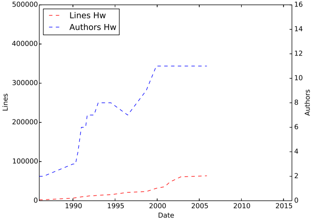
From LEP to LHC: New Algorithms

- 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)
- These developments have been possible due to improved understanding of QCD, automation of NLO calculations, and faster computers.

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 specialised programs for the calculation of hard processes in the various merging schemes.

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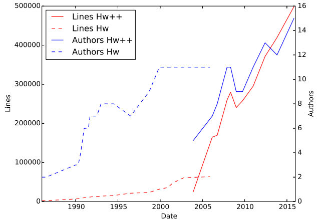

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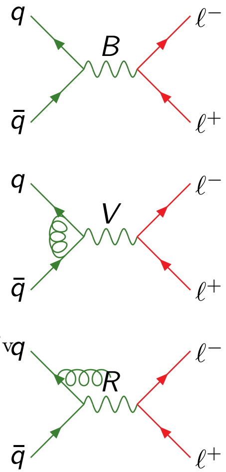
Hard Processes and Higher Orders



- NLO simulations rearrange the NLO cross section formula.

$$
\begin{aligned}
\mathrm{d}\sigma &= B(v)\mathrm{d}\Phi_v + (V(v) + C(v,r))\mathrm{d}\Phi_r\mathrm{d}\Phi_\mathrm{v} \\
&\quad + (R(v,r) - C(v,r))\mathrm{d}\Phi_v\mathrm{d}\Phi_r
\end{aligned}
$$

- Either choose $C(v,r)$ to be the shower approximation.

$$
\begin{aligned}
\mathrm{d}\sigma &= B(v)\mathrm{d}\Phi_v + (V(v) + C_\mathrm{shower}(v,r))\mathrm{d}\Phi_r\mathrm{d}\Phi_\mathrm{v} \\
&\quad + (R(v,r) - C_\mathrm{shower}(v,r))\mathrm{d}\Phi_v\mathrm{d}\Phi_r
\end{aligned}
$$

MC@NLO, Frixione and Webber

- First practical approach for combining NLO calculations and the parton shower.

Hard Processes and Higher Orders

- A alternative rearrangement (POWHEG, Nason) is

$$\mathrm{d}\sigma = \bar{B}(v)\mathrm{d}\Phi_v \left[\Delta_R^{(\mathrm{NLO})}(0) + \Delta_R^{(\mathrm{NLO})}(p_\perp)\frac{R(v,r)}{B(v)}\mathrm{d}\Phi_r\right],$$

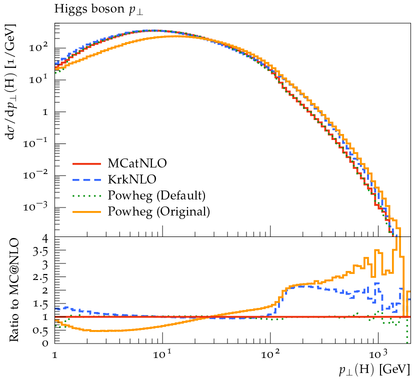
where

$$\begin{aligned}\bar{B}(v) &= B(v) + V(v) + \int \left[R(v,r) - C(v,r)\right]\mathrm{d}\Phi_r, \\ \Delta_R^{(\mathrm{NLO})}(p_\perp) &= \exp\left[-\int \mathrm{d}\Phi_r \frac{R(v,r)}{B(v)}\theta(k_\perp(v,r) - p_\perp)\right].\end{aligned}$$

- Looks more complicated but has the advantage that it is independent of the shower and only generates positive weights.

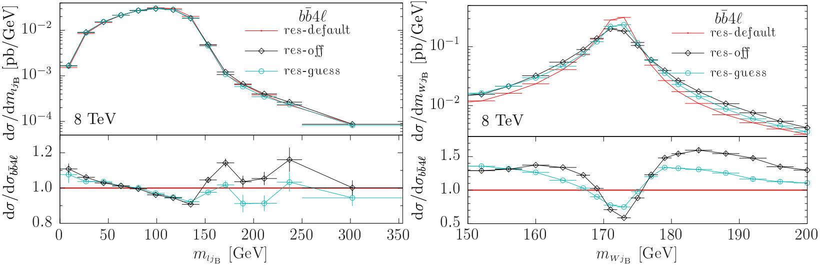
KrKNLO

- Define new PDFs in a Monte Carlo scheme.
- NLO corrections implemented by reweighting.



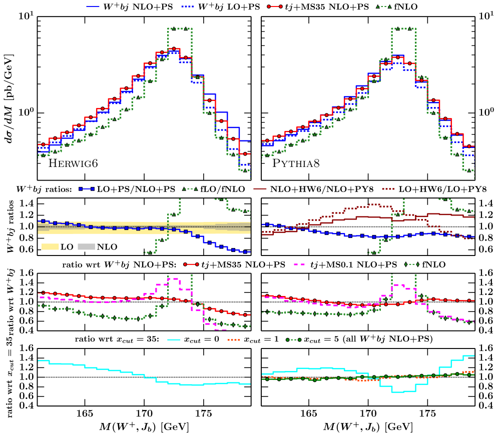
from 1607.06799 Jadach et.al.

Off-Shell Particles



from Eur.Phys.J. C76 (2016) no.12, 691 Jezo et.al.

Off-Shell Particles

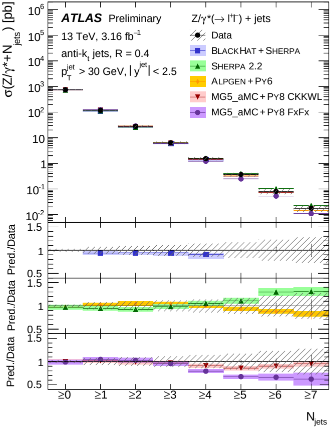


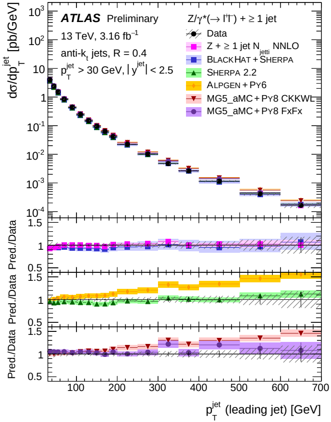
from JHEP 1606 (2016) 027 Frederix et.al

Higher Multiplicities

- Now a range of both LO and NLO techniques available for merging many jet multiplicities.
- Leading-order merging is widely used in LHC analyses, NLO is starting to be used more.
- Mainly the built-in MEPSNLO in Sherpa and FxFx using MadGraph5 aMC@NLO

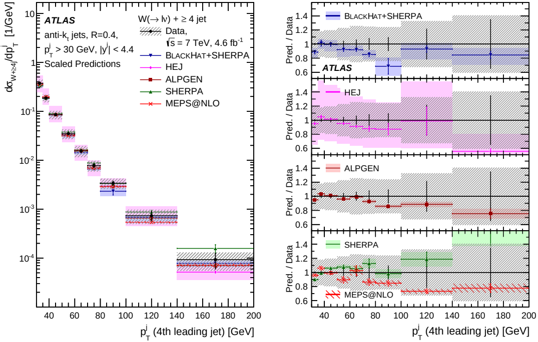
At the LHC: ATLAS Z+jets



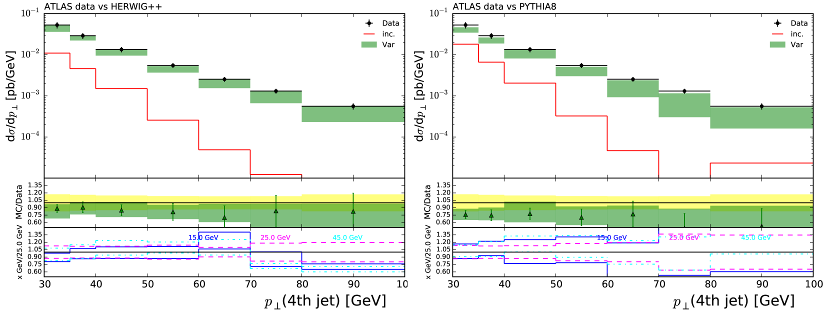


ATLAS-CONF-2016-046

At the LHC: ATLAS W+jets

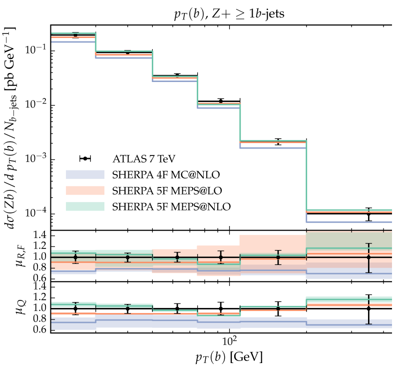


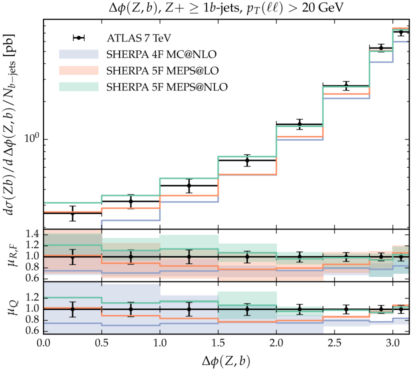
FxFx Merging



from JHEP 1602 (2016) 131 Frederix et.al.

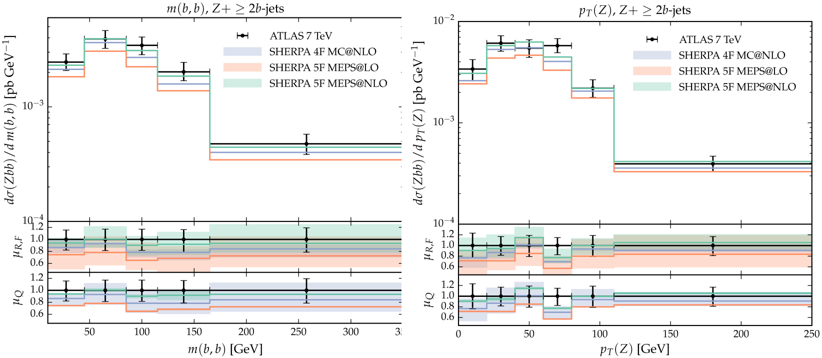
Merging with bottom quarks





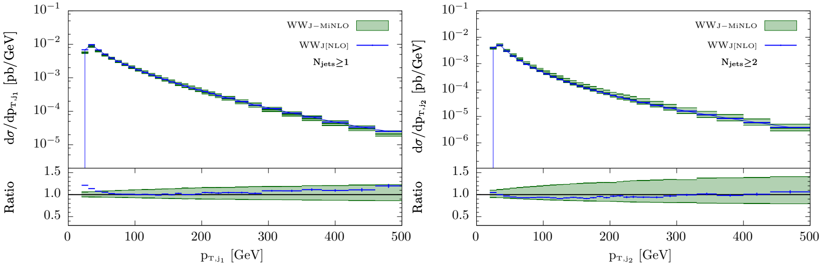
from 1612.04640 Krauss, Napoletano, Schumann

Merging with bottom quarks



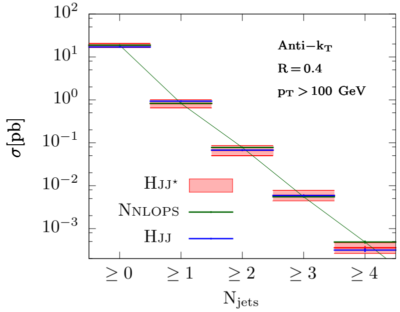
from 1612.04640 Krauss, Napoletano, Schumann

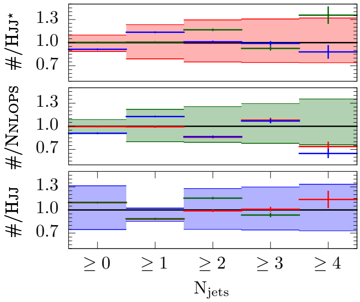
Merging W^+W^- and W^+W^-+jet with MINLO



JHEP 1609 (2016) 057 Hamilton et.al.

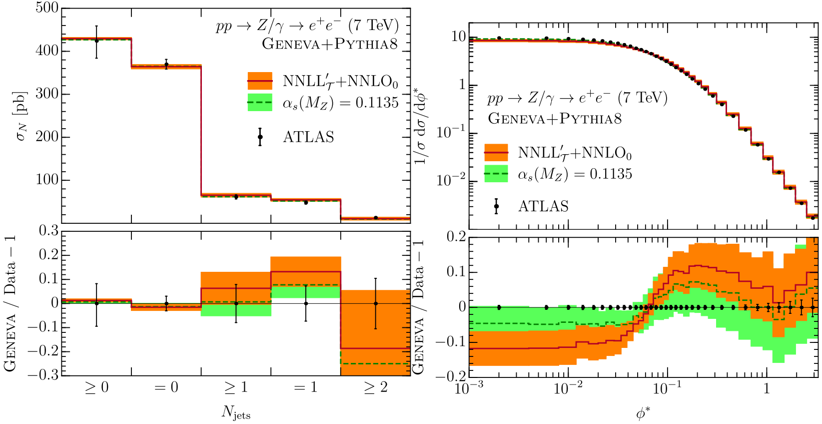
Extending MINLO





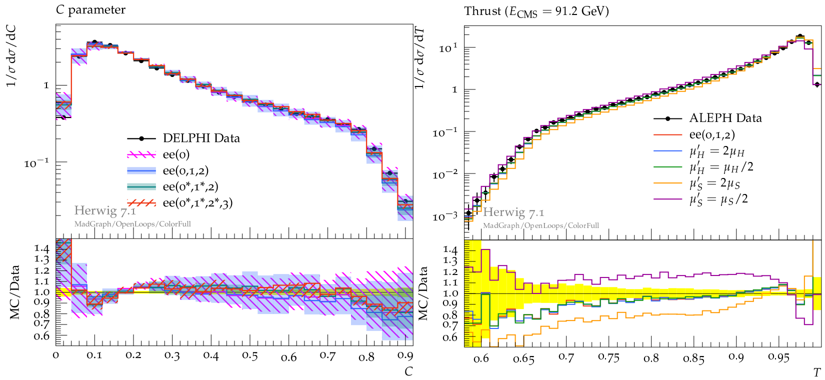
JHEP 1605 (2016) 042 Frederix and Hamilton

GENEVA



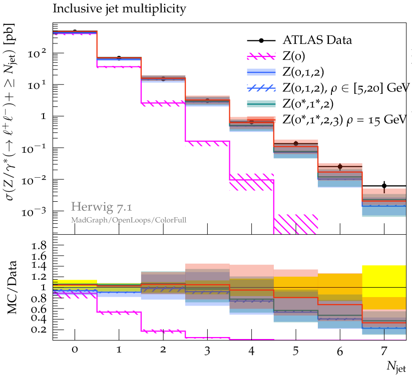
Include NNLL resummation of specific event shape, in this case 0-jettiness $\mathcal{T}_0$ (a.k.a. beam thrust) from Phys.Rev. D92 (2015) no.9, 094020 Alioli et. al.

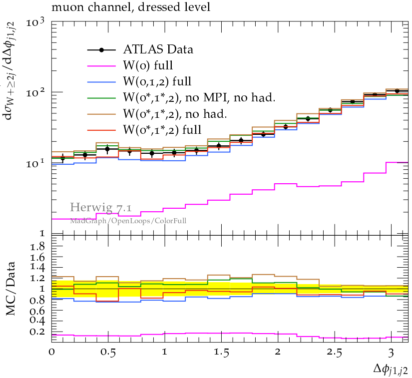
Herwig 7.1



Bellm et.al. arXiv:1705.06919. Main new feature multi-jet NLO merging (Bellm, Gieseke, Pläter arXiv:1705.06700).

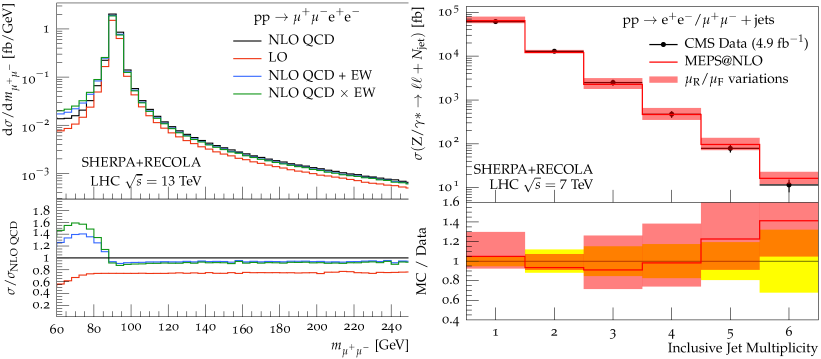
Herwig 7.1





Bellm et.al. arXiv:1705.06919. Main new feature multi-jet NLO merging (Bellm, Gieseke, Pläter arXiv:1705.06700).

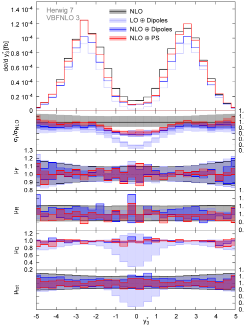
EW corrections



from Biedermann, Bräuer, Denner, Pellen, Steffen Schumann, Thompson 1704.05783

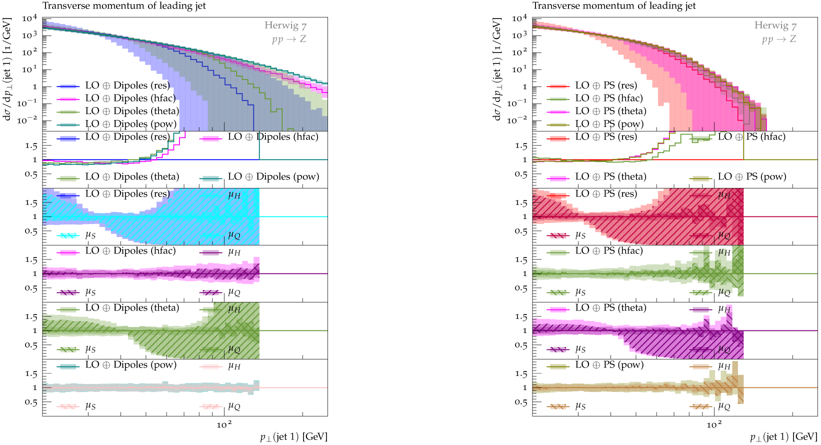
Uncertainties

- As the accuracy of simulations improves it is important that we can assess the uncertainties.
- Still in its infancy.
- Need to disentangle which are uncertainties are perturbative and which are from tuning to data.
- Lot of work at Les Houches 2015 and subsequently.



from 1605.07851 Rauch and Plätzer

Uncertainities

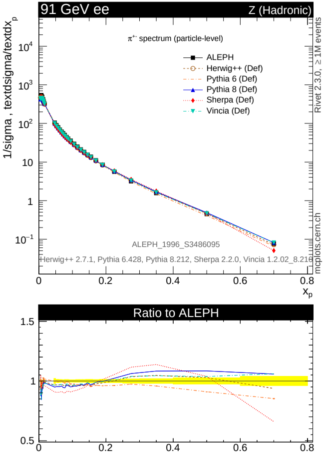


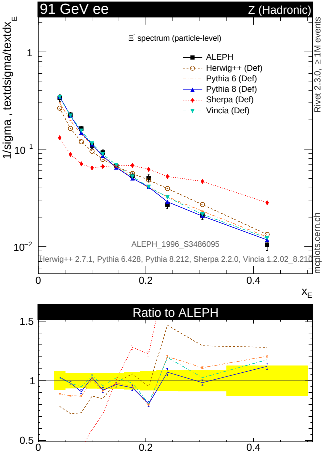
Eur.Phys.J. C76 (2016) no.12, 665 Bellm et.al.

Non-perturbative Physics

- 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 clearly 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)

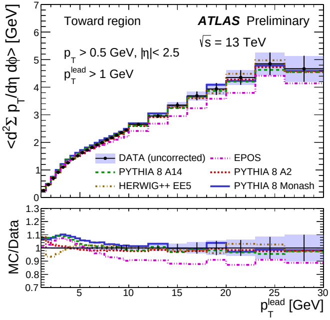
From LEP to LHC: Identified Particle Spectra

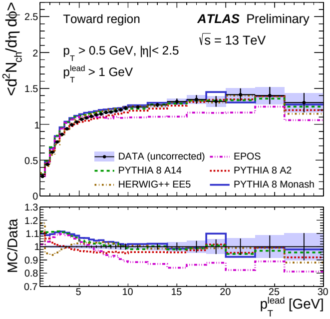




Plots from MCplots

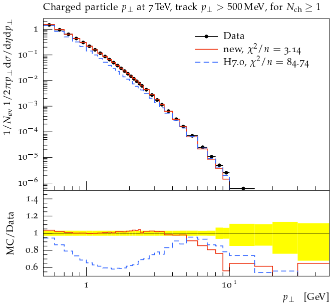
Underlying Event

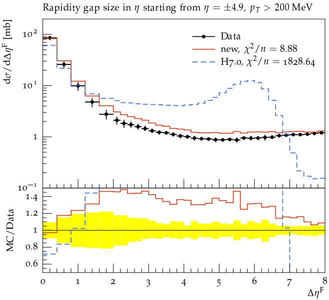




from ATL-PHYS-PUB-2015-019

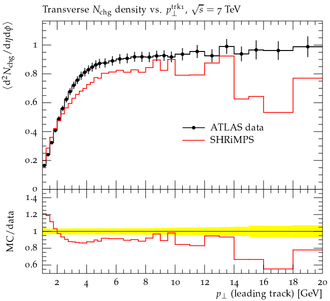
Soft and diffractive scattering in Herwig

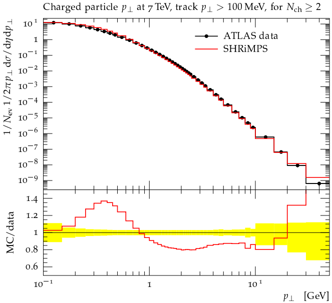




New model including a diffractive component from 1612.04701 Stefan Gieseke, Frashër Loshaj, Patrick Kirchgaeßer

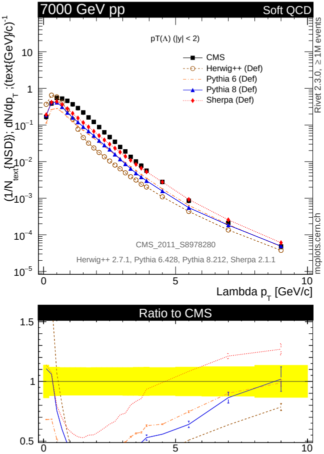
SHRiMPS

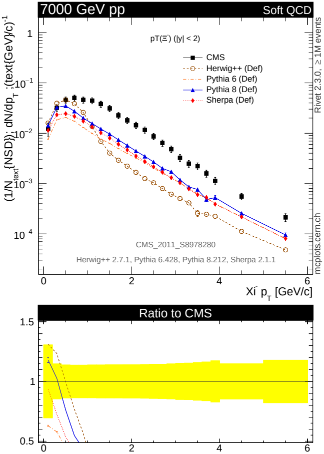




New model in SHERPA. Based on the model by Khoze, Martin, and Ryskin (KMR). Plots from Krauss, Zapp in 1612.04701 LHC Forward Physics Working Group.

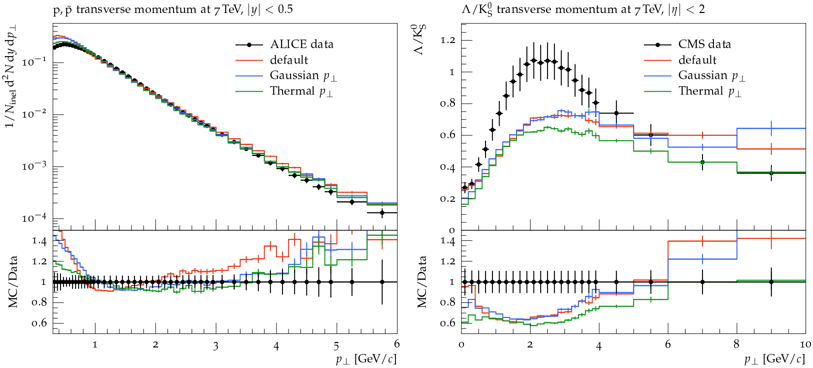
At the LHC: Baryons





Plots from MCplots

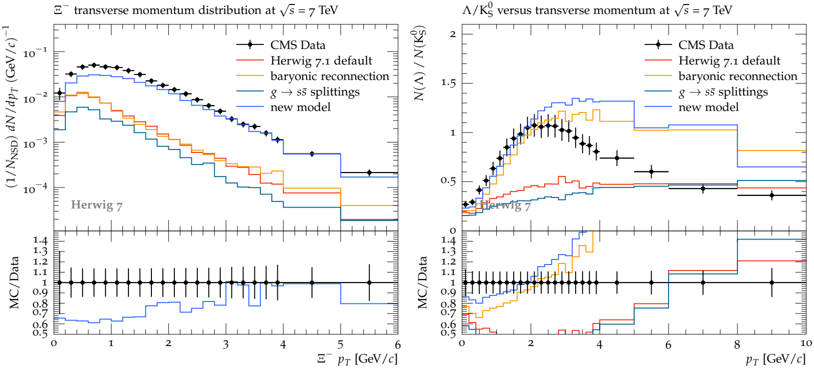
At the LHC: Baryons



Plots from Fischer, Sjöstrand arXiv:1610.09818.

Clearly work still needed to describe baryon production in particular.

At the LHC: Baryons

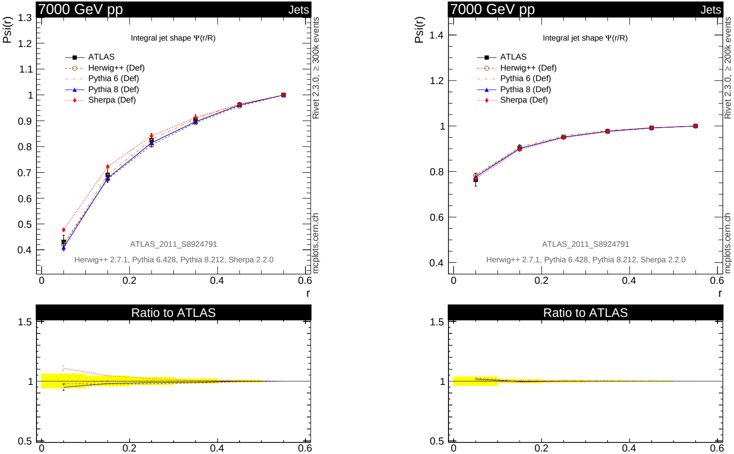


Plots from Gieseke, Kirchgaeßer, Plätzer Eur.Phys.J. C78 (2018) no.2, 99

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.
- This is the area where there is probably the greatest potential for improvement.
- If we can consistently improve the logarithmic accuracy.

At the LHC: ATLAS Jet Shapes

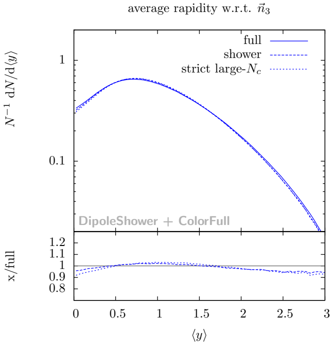


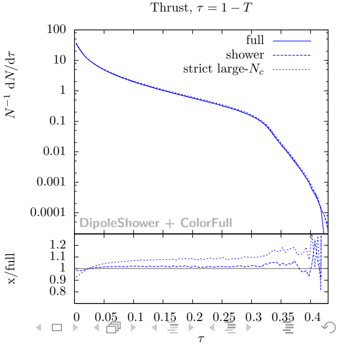
Plots from MCplots

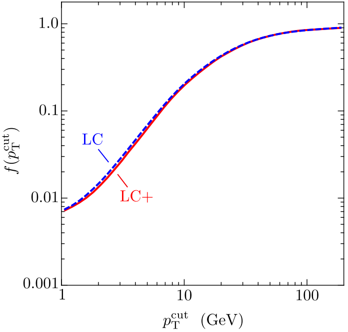
ATLAS Eur.Phys.J. C75 (2015) no.2, 82

Subleading $1/N_c$

- Plätzer, Sjödahl JHEP 1207 (2012) 042, Ángeles Martnez et.al. arXiv:1802.08531
- Nagy, Soper, JHEP 1507 (2015) 119

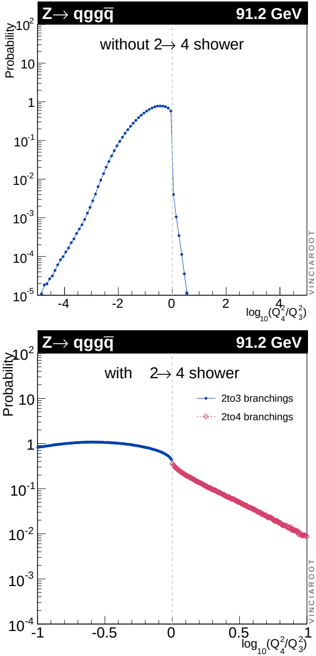




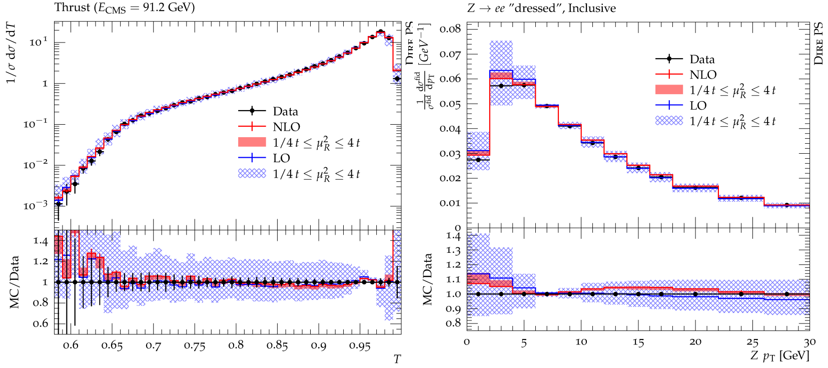


Subleading-Logs

- Subleading collinear logs via including higher order splitting functions in antenna formalism Li, Skands, arXiv:1611.00013
- DIRE higher order splitting functions in dipole formalism Höche, Prestel Phys.Rev. D96 (2017) no.7, 074017, arXiv:1805.03757, (+Krauss) JHEP 1710 (2017) 093



Subleading-Logs

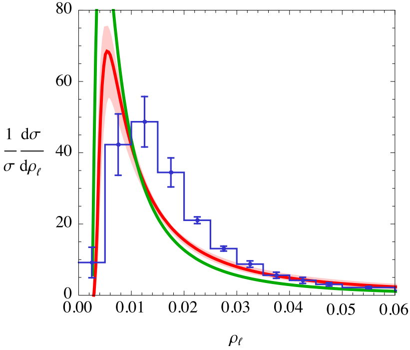


from Höche, Krauss, Prestel arXiv:1705.00982

Non-Global Logs

- Big problem with going to higher logarithmic accuracy are the non-global soft logs.
- Not even clear we can treat these correctly in analytic calculations.
- Let alone a numerical simulation
- Recent progress in SCET

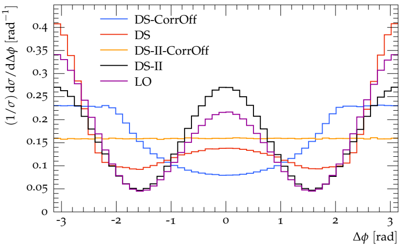
  Becher et. al. JHEP 1611 (2016) 019, JHEP 1612 (2016) 018



Light-hemisphere mass taken from Becher et. al. JHEP 1612 (2016) 018

Are we really as accurate as we think?

- Recent work Dasgutpa et.al. arXiv:1805.09327 looking at the accuracy of two dipole-type showers for FSR.
- Issues with leading (double) logarithms at sub-leading N_c and next-to-leading (single) logarithms at leading N_C.
- Mainly relating to the treatment of recoil in these showers.
- Spin correlations also often neglected.



$qq \to qqh^0$ via $gg \to h^0$ with $q \to qg$ splittings from the parton shower from PR and Webster arXiv:1807.01955.

What's actually being used

- Looking at yesterday's talks and recent Higgs papers experiments are mainly using
  - POWHEG-BOX, and improved variants MInLO, NNLOPS, etc
  - MG5aMC@NLO, with MC@NLO or Fx-Fx etc

  mainly interfaced to Pythia 8, sometime Herwig++(7)
- Problem that the more sophisicated approach in general the more CPU time it needs.
- For the generator community issues with new CPU architectures, negative weights, and run times which will need to be addressed.

Conclusions

- Event generators have matured as sophisticated implementations of state-of-the-art QCD calculations over the last 15 years.
- Aided by advances in understanding QCD, computing and automation of fixed-order calculations.
- Provide impressive agreement with LHC data.
- Still a lot of ongoing work needed to describe the unprecedented amount and accuracy of data from the LHC.
- Clearly work now needed on the "neglected" parts of the simulation, i.e. subleading logs and non-perturbative models.