Monte Carlo Generators

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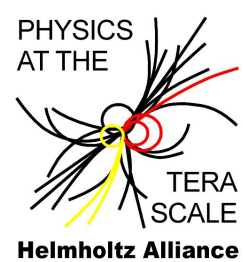


Anti outline

What this is *not* about:

- Tree level ME MCs.
- FeynRules. BSM.
- Multi-leg NLO MC programs aka “Les Houches list”.
- Automatized NLO.
- Completely new developments
  (e.g. WHIZARD, Geneva)

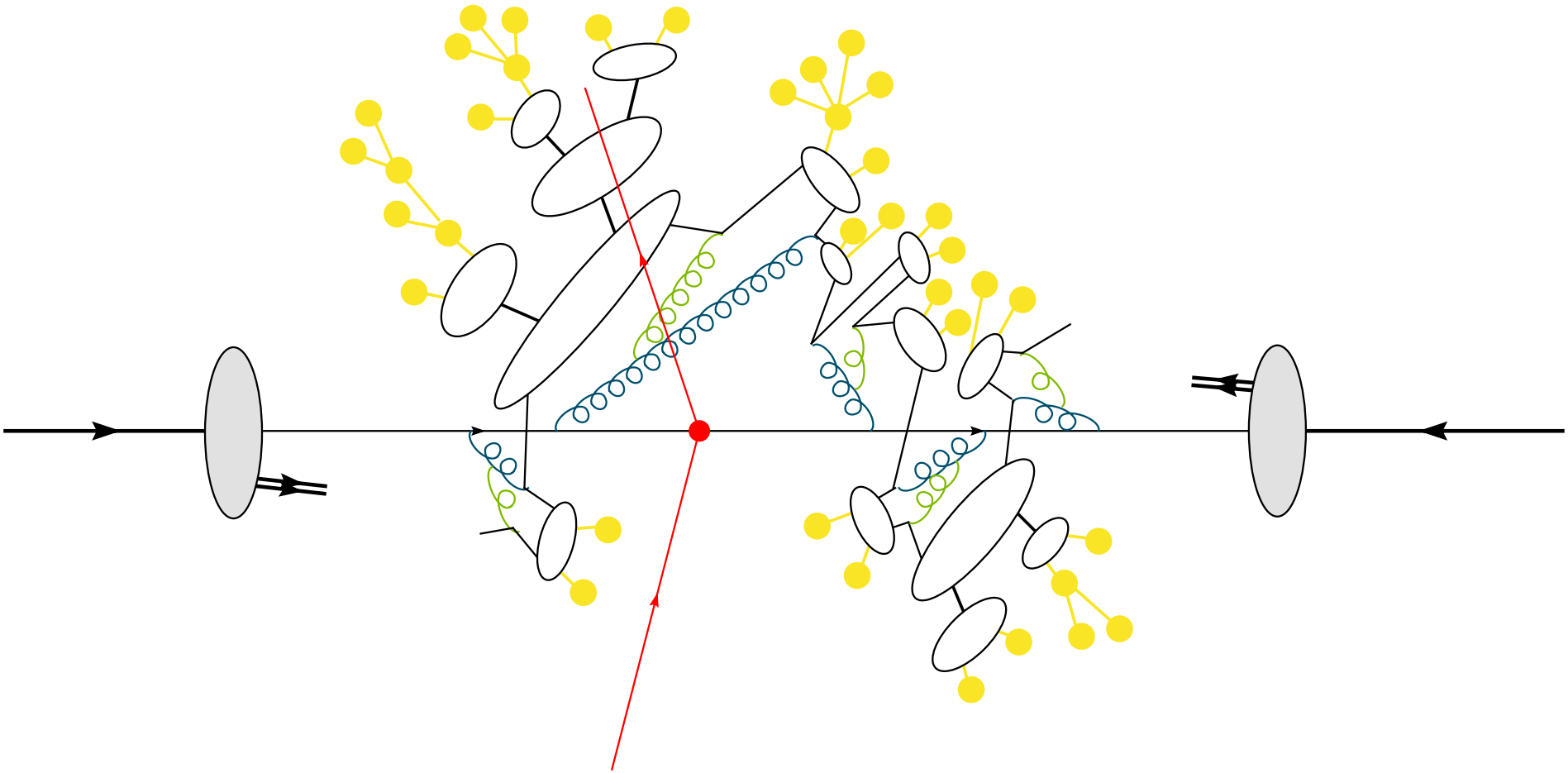
Apologies.

Focus on ‘workhorses’:
multi purpose hadron level event generators.

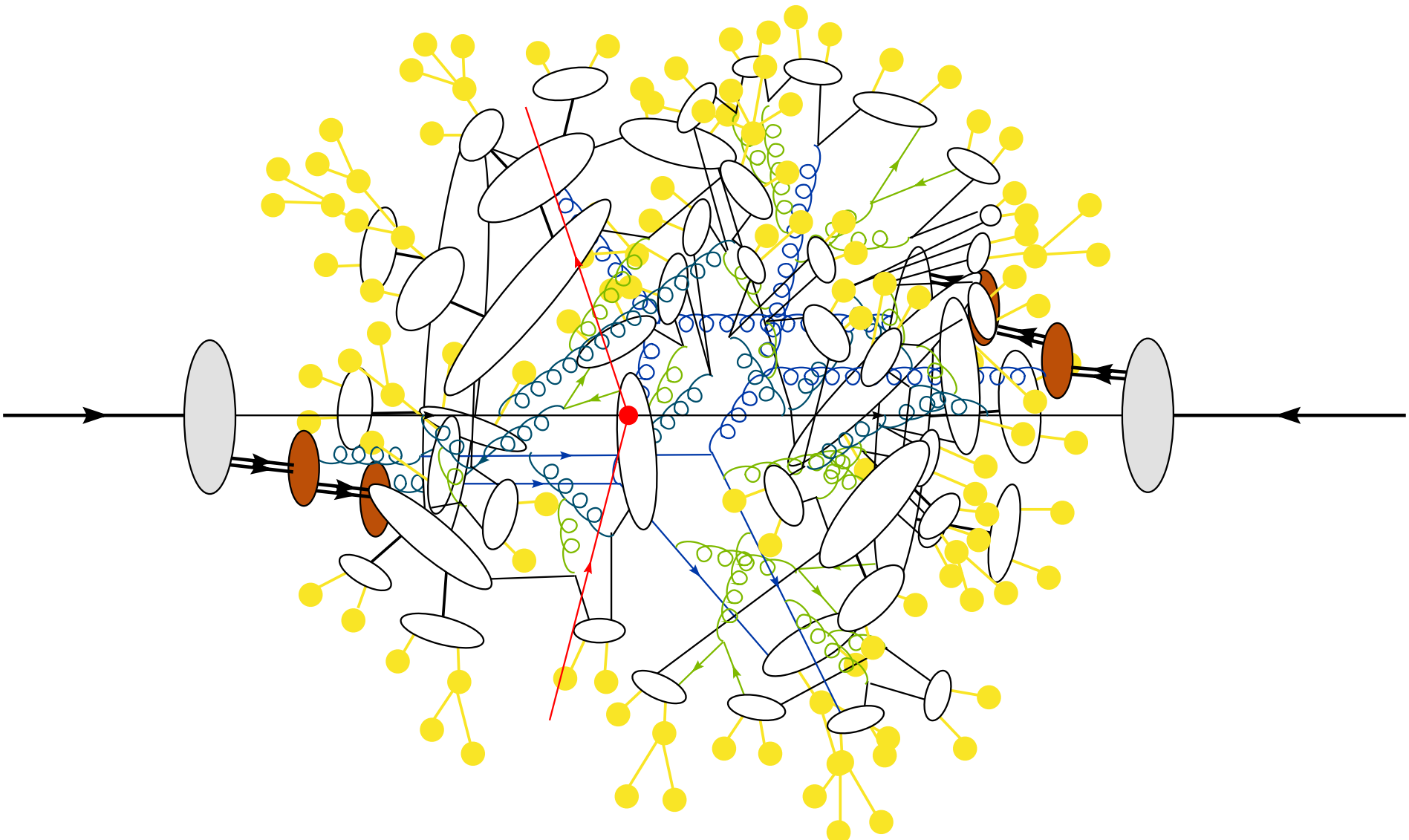
Next Generation MC programs

- Old programs: Pythia, Herwig (Fortran).
- New programs for the LHC era have been developed
  - Herwig++
  - Pythia8
  - Sherpa
- Pythia8 and Herwig++ now recommended as better options wrt old programs.

pp Event Generator



pp Event Generator



Outline

- State-of-the-Art.
  - Tree level.
  - Parton showers.
  - Multijet.
  - NLO.
  - MinBias/UE
  - Non perturbative physics.
- Outlook.
- Future of MC development.

Hard processes (tree level)

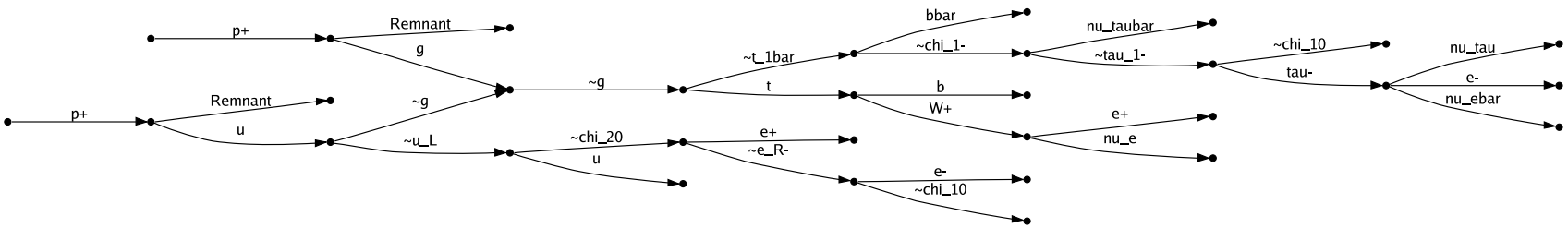
Herwig++:
Important $2 \to 2$ SM processes, many at NLO.
Many BSM processes, decays with full spin correlations.
Anything else via LHEF.

Sherpa:
All tree level processes via AMEGIC++, COMIX, built–in ME generators. New models via FeynRules.

Pythia:
Many processes built–in.
Pythia 8.1 can link back to Pythia 6.4 processes. Rest via LHEF.

Hard processes (tree level)

Example event, only MSSM hard process.
Full cascade decay chain w/ spin correlations



MSSM, UED, RS included in Herwig++ (since 2.1).

[Martyn Gigg, Peter Richardson, EPJC **51** (2007) 989]

Finite width effects and 3 body decays (since 2.3)

[M.A. Gigg, P. Richardson, arXiv:0805.3037]

All automatically built.
Inclusive or exclusive process specification.

Hard processes (tree level)

Works.

Parton showers

Herwig++

- New parton shower variables introduced for Herwig++

[SG, P. Stephens and B. Webber, JHEP **0312** (2003) 045]

- More under development $\rightarrow$ dipole shower, based upon Catani–Seymour dipoles.

[SG, S. Plätzer, JHEP **1101** (2011) 024]

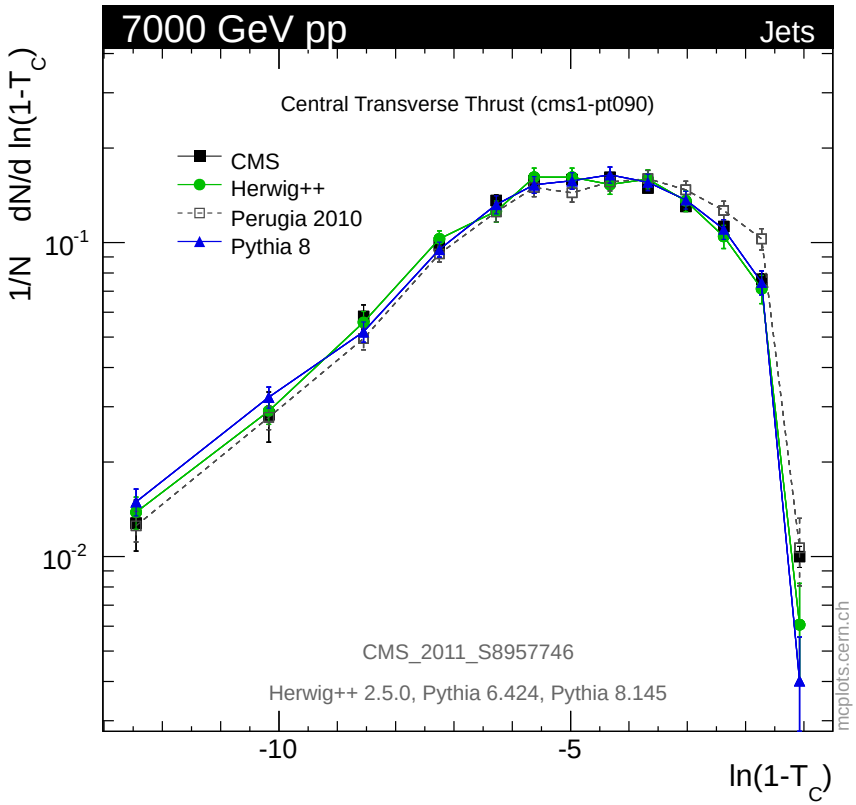
Sherpa

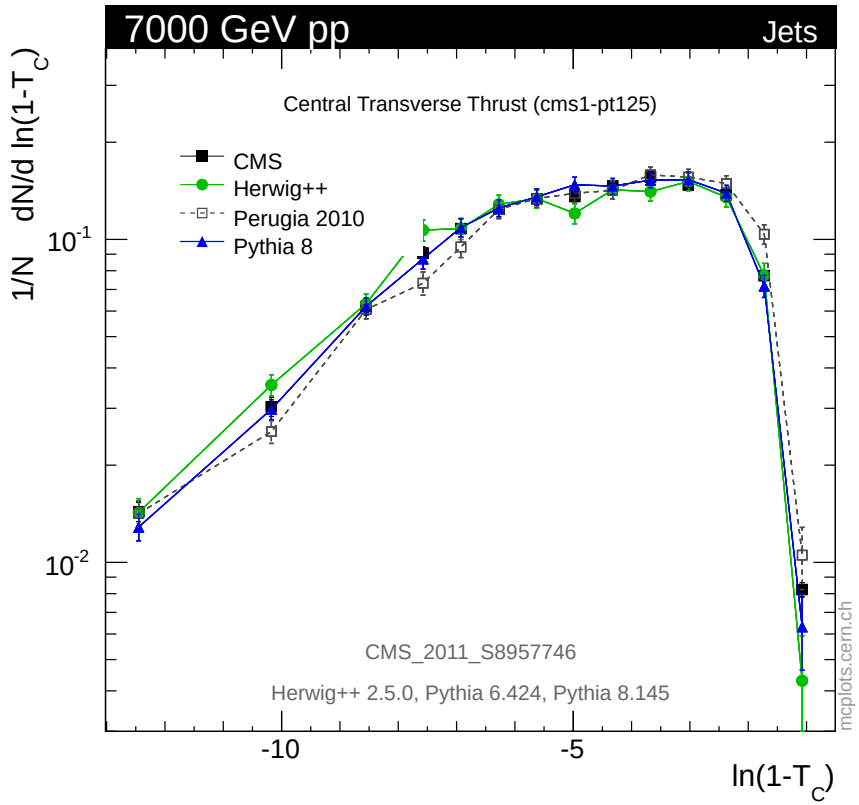
- CS-Shower default by now,
- always matched via CKKW (see later).

Pythia

- p_T ordered shower (simple matching).
- Interleaved with Multiple partonic interactions.

Transverse thrust

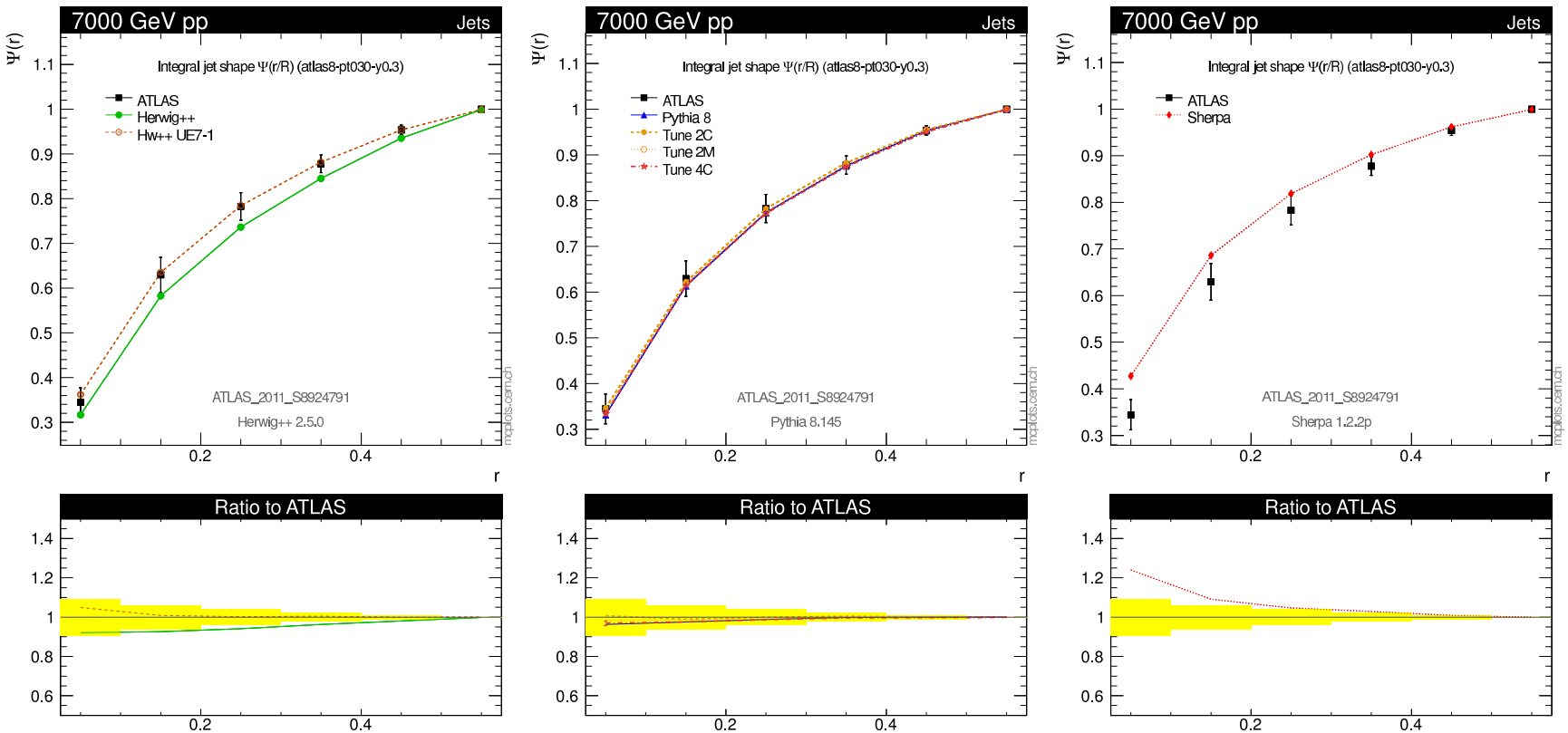




[mcplots.cern.ch]

Integral jet shapes

not too hard, central ($30 < p_T/\text{GeV} < 40; 0of < |y| < 0.3$)

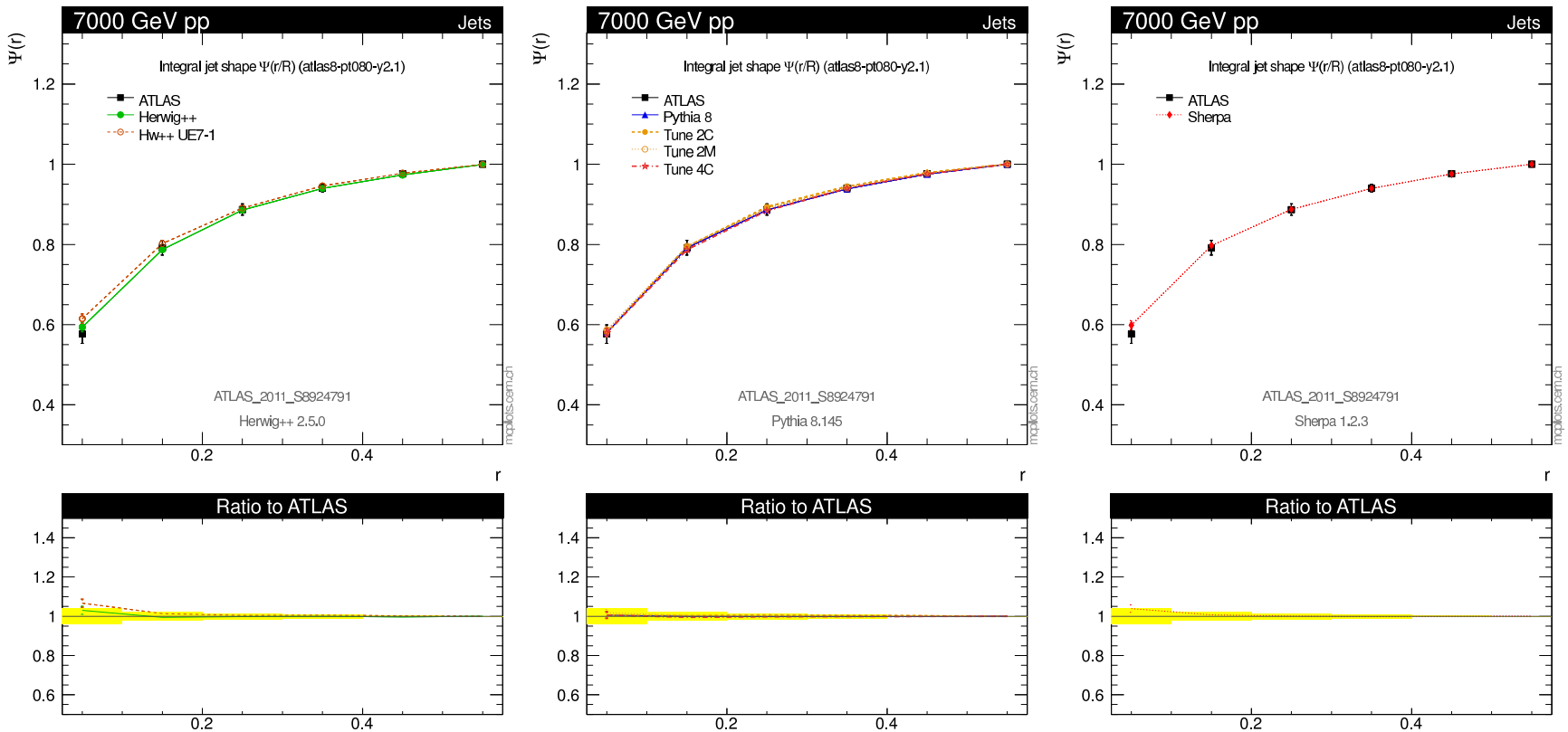


[mcplots.cern.ch]

Deviations due to UE → tuning

Integral jet shapes

harder, more forward ($80 < p_T/\text{GeV} < 110; 1.2 < |y| < 2.1$)

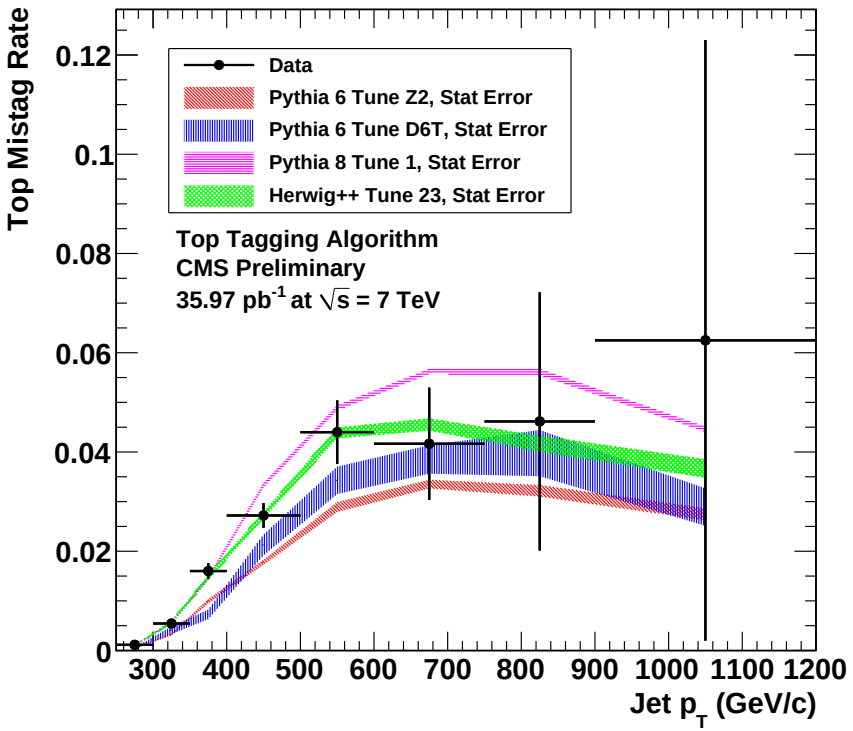


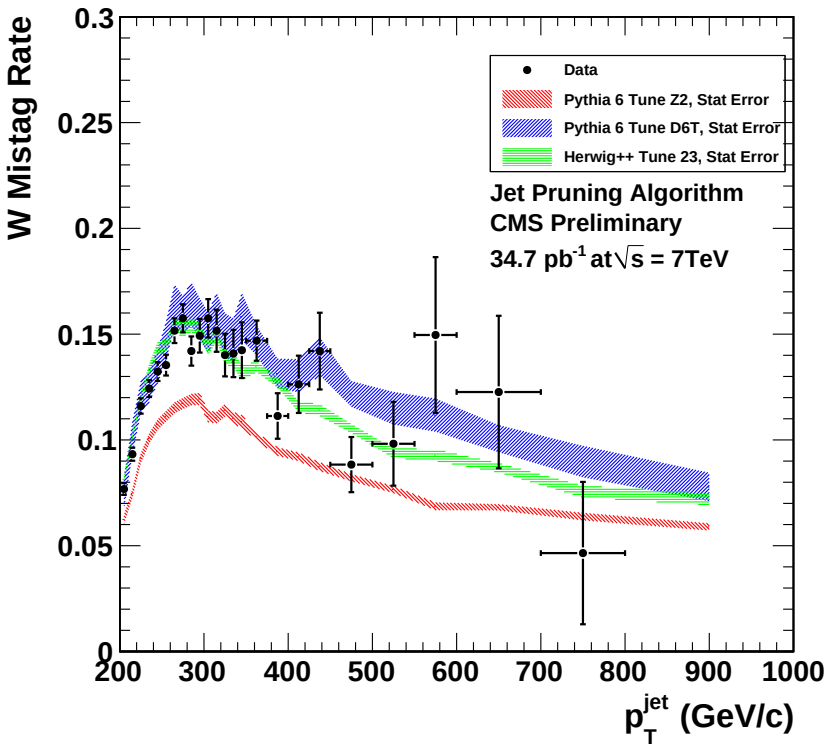
[mcplots.cern.ch]

Deviations due to UE → tuning

Integral jet shapes

Jet substructure in CMS. *t* and *W* tagging from jet substructure.





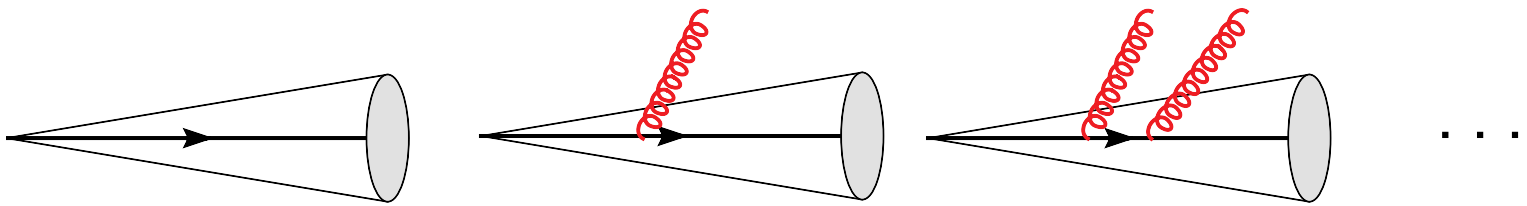
[CMS PAS JME-10-013]

Integral jet shapes

Jet substructure very well predicted by parton showers.

Matching tree level ME and parton showers

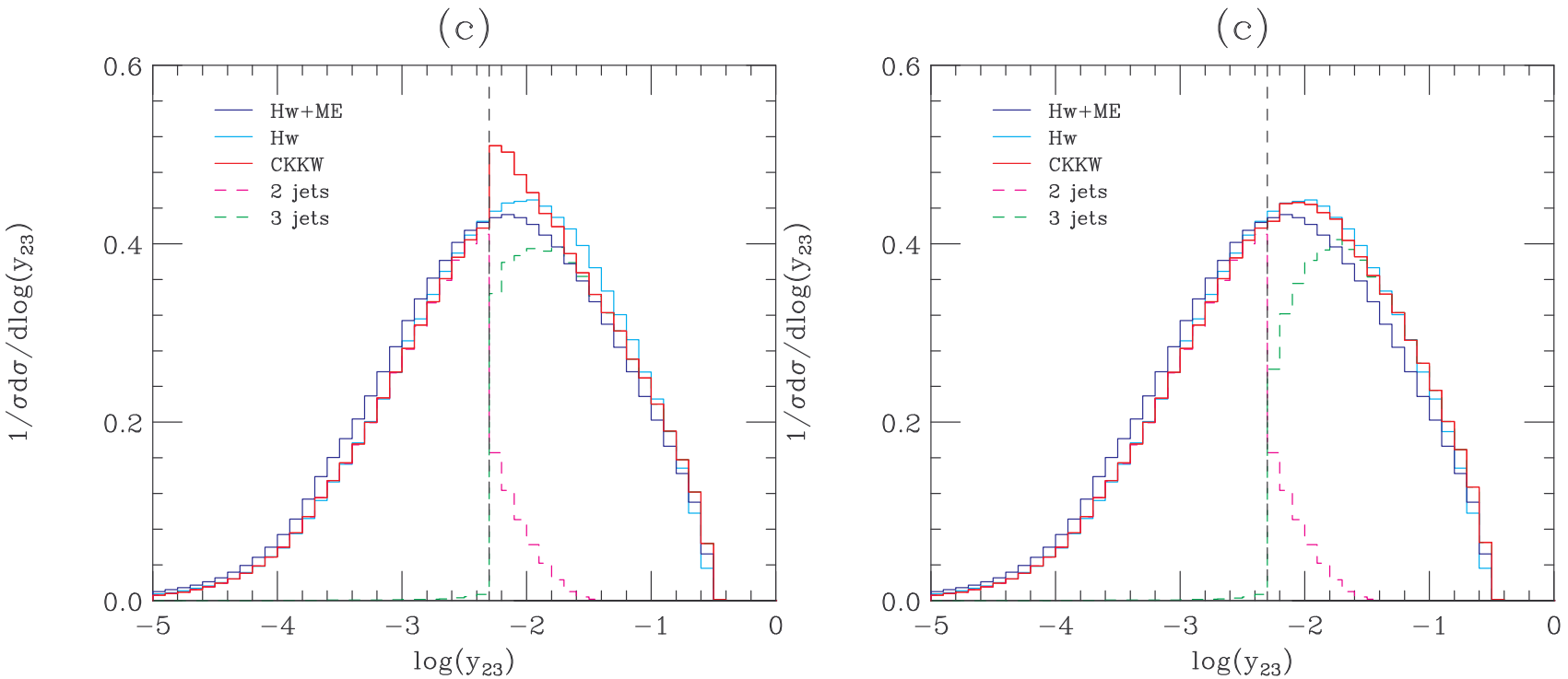
- Problem: have multiple tree level MEs for $X + 0, 1, \ldots n$ jets.



- Jets well separated and *inclusive*.
- Merge this into one exclusive multijet sample.
- Idea: use Sudakov form factors to disallow "+ anything softer" (which is normally inside an inclusive ME).
- That's done in the CKKW(-L) approach. Catani, Krauss, Kuhn, Webber, JHEP 0111:063,2001, Krauss JHEP 0208:015,2002, L. Lönnblad, JHEP 0205:046,2002, Gleisberg, Höche, Winter, Schälicke, Schumann.
- Alternative: MLM matching. M.L. Mangano
- Systematic study and comparison of implementations.

  J. Alwall, S. Höche, F. Krauss, N. Lavesson, L. Lönnblad, F. Maltoni, M.L. Mangano, M. Moretti, C.G. Papadopoulos, F. Piccinini, S. Schumann, M. Treccani, J. Winter, M. Worek, EPJC53:473-500,2008.

Matching tree level ME and parton showers



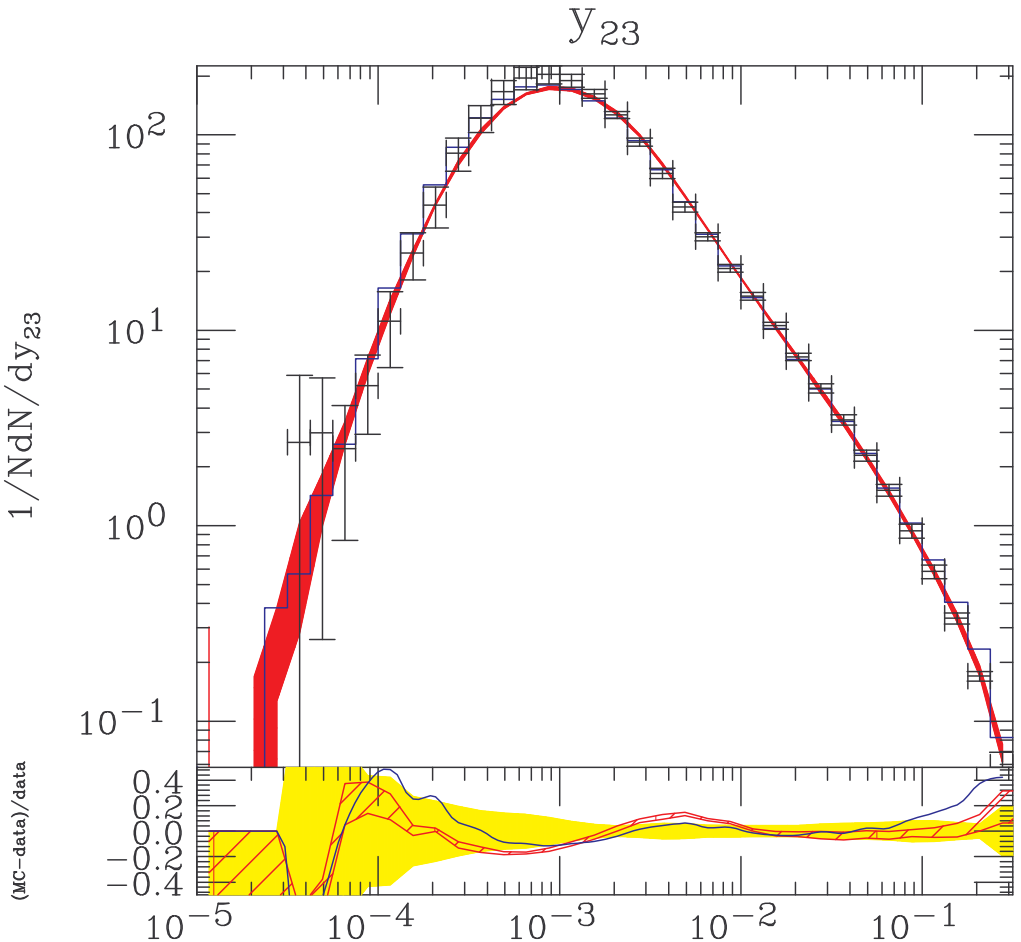
K. Hamilton, P. Richardson, J. Tully, JHEP 0911:038,2009.

Parton level merging for illustration.

Instabilities at Q_{ini} removed. Truncated showers important.

Matching tree level ME and parton showers

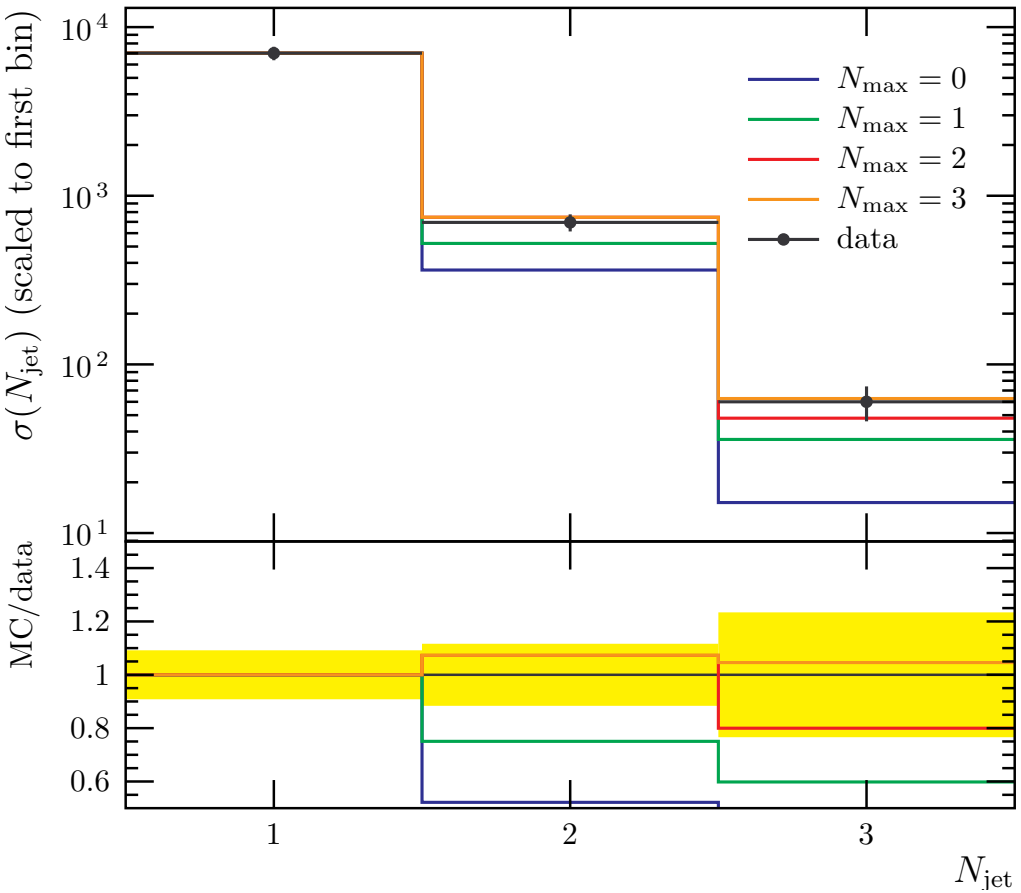
Hadron level with matching uncertainty band vs OPAL.



K. Hamilton, P. Richardson, J. Tully, JHEP 0911:038,2009.

Matching tree level ME and parton showers

Sherpa CS shower, matched with $Z^0 + N_{\text{jet}}$ jets vs CDF data.



S. Höche, F. Krauss, S. Schumann, F. Siegert, JHEP 0905:053,2009.

Reached remarkable stability wrt Q_{ini} variation.

Matching tree level ME and parton showers

A lot of progress with PS+ME merging. Very stable.

MC@NLO

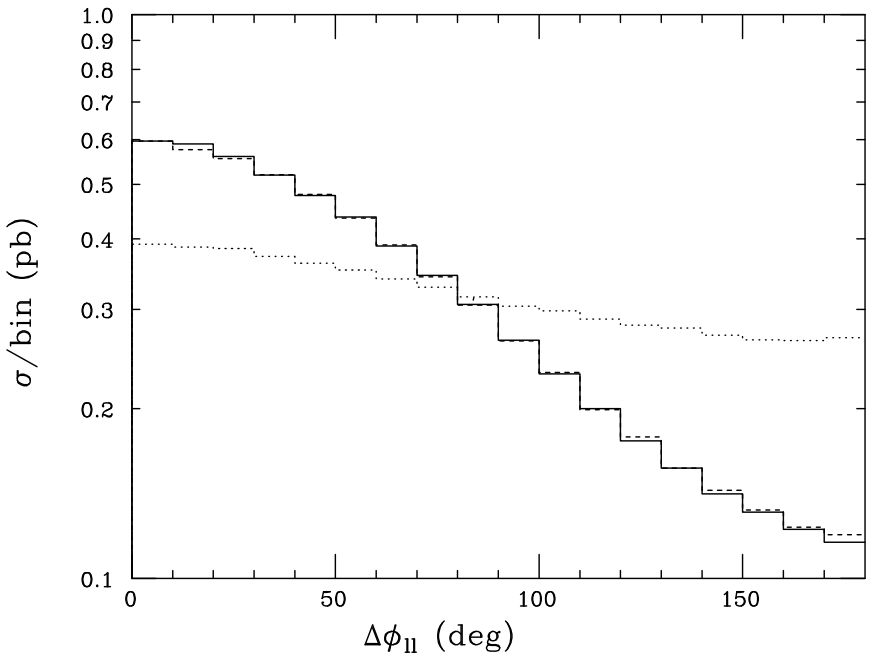
- Introduced 2002 Frixione, Webber, JHEP 0206:029,2002 [hep-ph/0204244].
- Extended to heavy quarks

  Frixione, Nason, Webber, JHEP 0308:007,2003 [hep-ph/0305252].
- further extensions to many processes (single top etc.)
- MC@NLO customised to use with HERWIG.
- Some processes in Herwig++ as well
  $e^+e^- \to$ jets, DY, W', h^0 decay

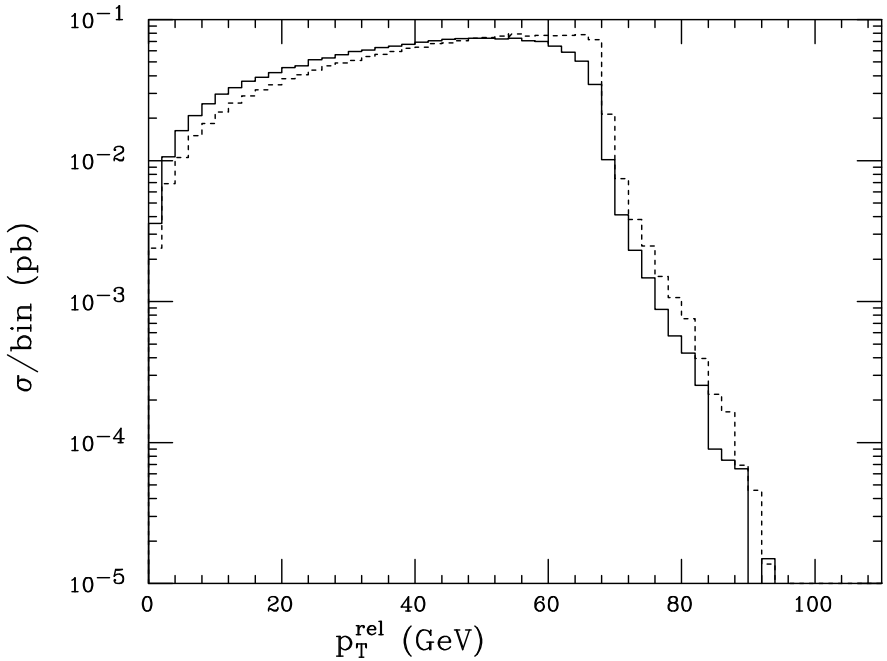
  Latunde–Dada 0708.4390, 0903.4135, Latunde–Dada, Papaefstatiou, 0901.3685.
- MC@NLO package adopted to Herwig++ as well.

  S. Frixione, F. Stoeckli P. Torrielli and B.R. Webber, 1010.0568.

Examples with Herwig++ (solid) Herwig6 (dash)



$h^0 \to WW \to l\nu l\nu$,
(no spin corr dotted)



$t\bar{t}$, $p_t(b)$ rel to t (right).

S. Frixione, F. Stoeckli P. Torrielli and B.R. Webber, 1010.0568.

POWHEG

- Alternative proposed by P. Nason.
- Modified Sudakov FF for first emission.
- Angular ordered Parton Shower tricky (see below).
- *Truncated Shower* adds in missing radiation afterwards.
- Finally evolution with 'ordinary' Parton Shower.

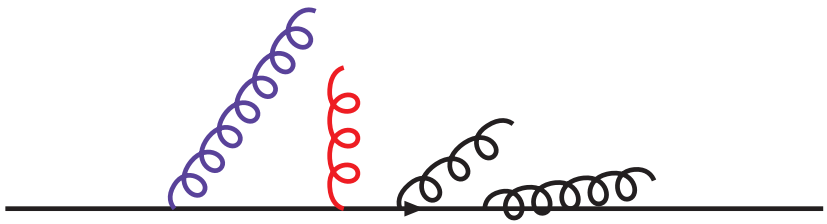
[Nason, hep-ph/0409146; Nason, Ridolfi hep-ph/0606275]

Systematically extended.

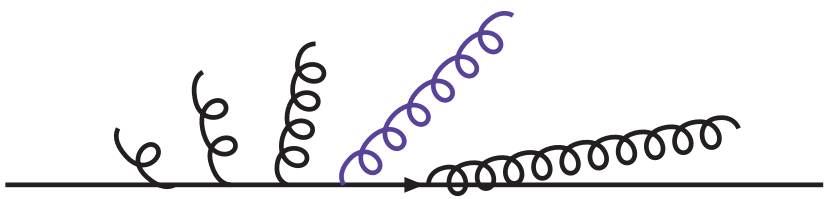
- `POWHEG` formulation independent of the event generator implementation (with caveats).
- Worked out for different subtraction schemes.

[Frixione, Nason, Ridolfi, 0707.3081, 0707.3088; Frixione, Nason, Oleari, 0709.2092]

Angular ordered showers and POWHEG



$p_\perp$ ordered shower. Angular ordering from additional vetos.



Angular ordered shower. Some softer emissions before hardest one.

Need truncated showers.

POWHEG in Herwig++

- First implementation of method for e^+e^- annihilation

  [O. Latunde–Dada, SG, B. Webber, hep-ph/0612281]

- Many more processes now available with release:
  DY $(\gamma^*/Z^0/W^\pm), h^0, h^0Z^0, h^0W^\pm, W^+W^-, W^\pm Z^0, Z^0Z^0$

  [K. Hamilton, P. Richardson and J. Tully, 0806.0290, 0903.4345, Hamilton, JHEP 1101:009]

- Finished, out with next release: VBF, $\gamma\gamma$

  [D'Errico, Richardson, 1106.2983, 1106.3939]

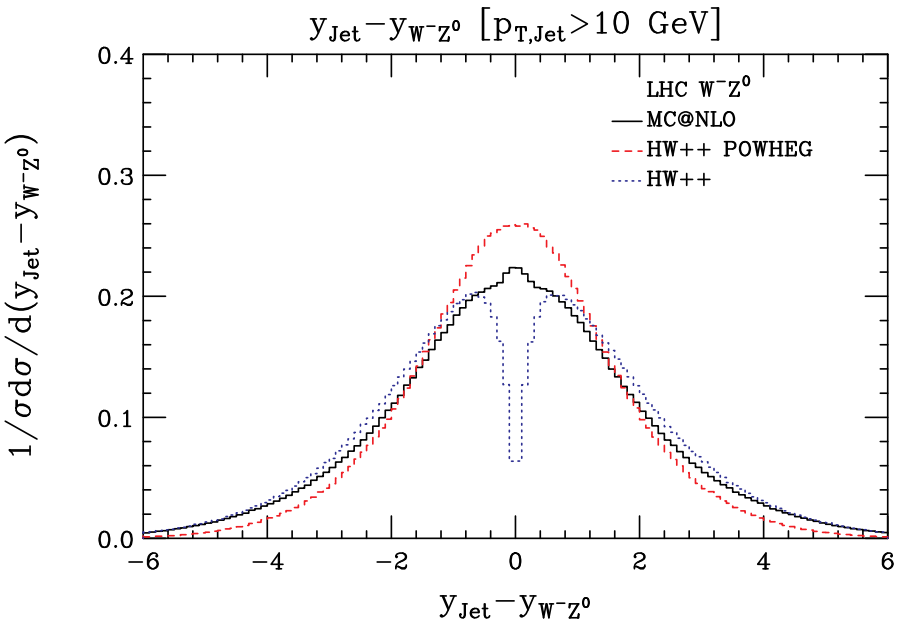
- and with contributed code:
  $e^+e^- \to \text{jets}, t\bar{t}, t-\text{decay}, W', h^0-\text{decay}$

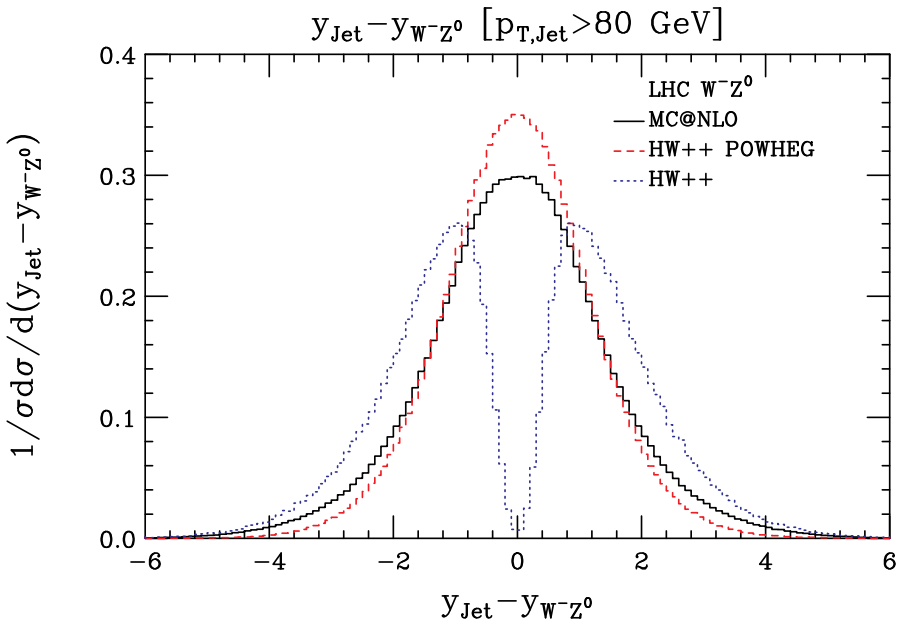
  [O. Latunde-Dada, 0812.3297, Eur. Phys. J. C **58**, 543 (2008)]

  [A. Papaefstathiou and O. Latunde-Dada, JHEP **0907**, 044]

- includes full truncated showers.
- Interface to PowhegBox straightforward.
- More processes underway (SUSY pair prod. . .).

POWHEG in Herwig++ with full truncated shower.

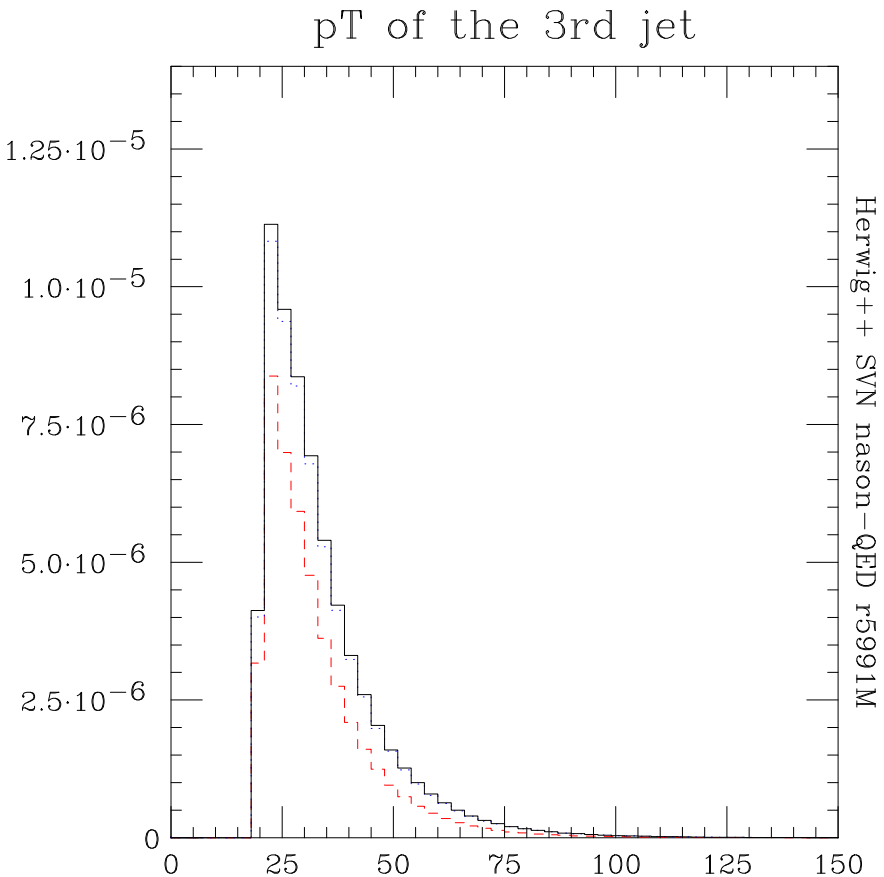


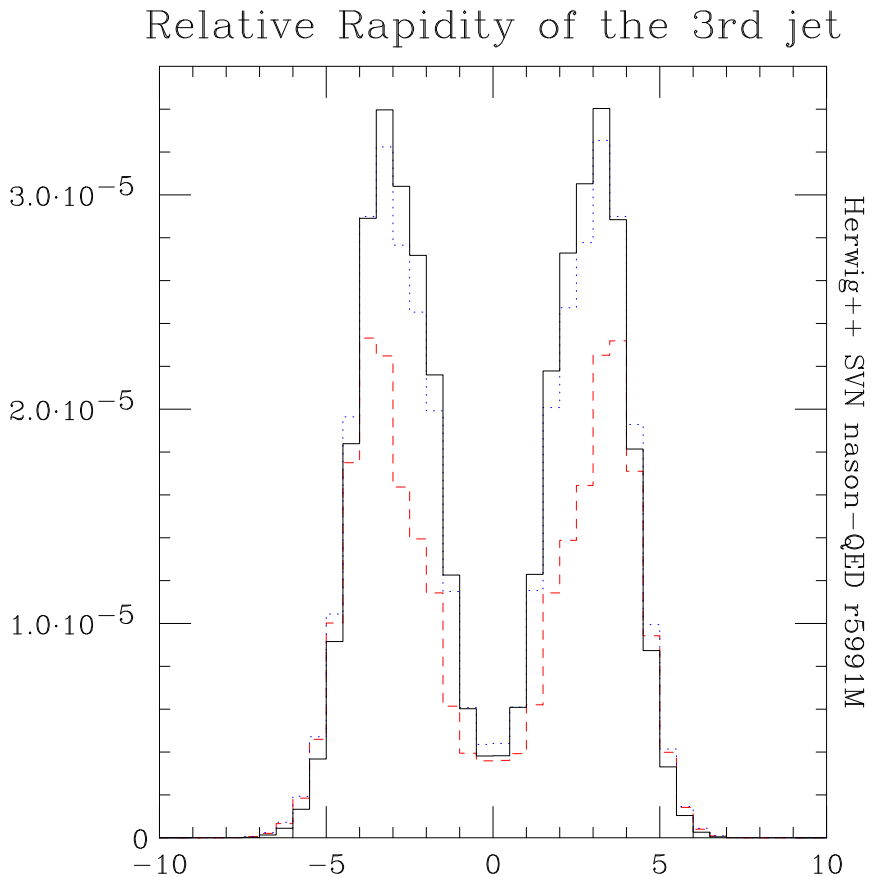


[K. Hamilton, JHEP 1101:009]

VV production. Phase space of radiated gluon.

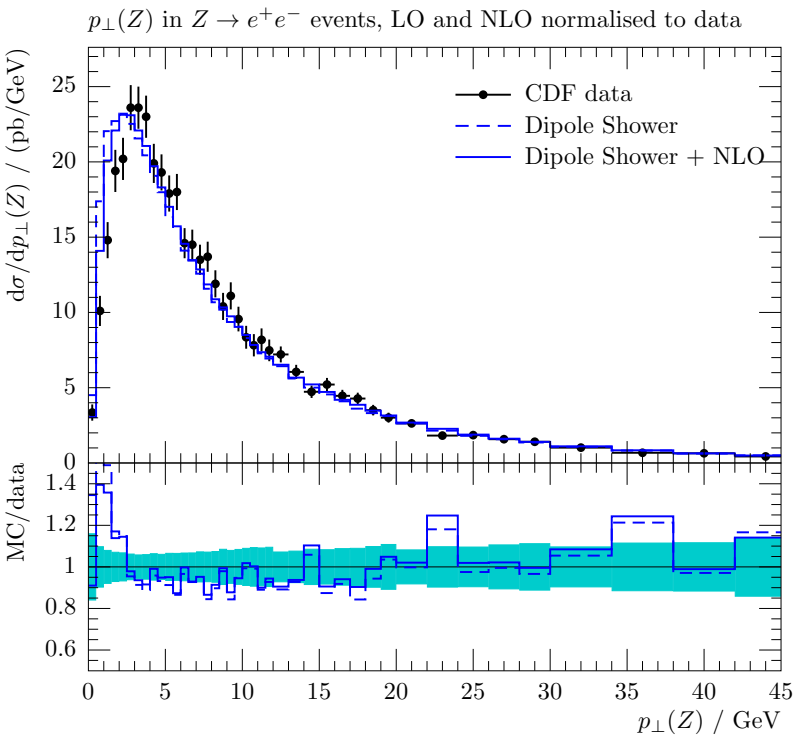
Higgs production in VBF. (POWHEG, MEC, LO+PS)

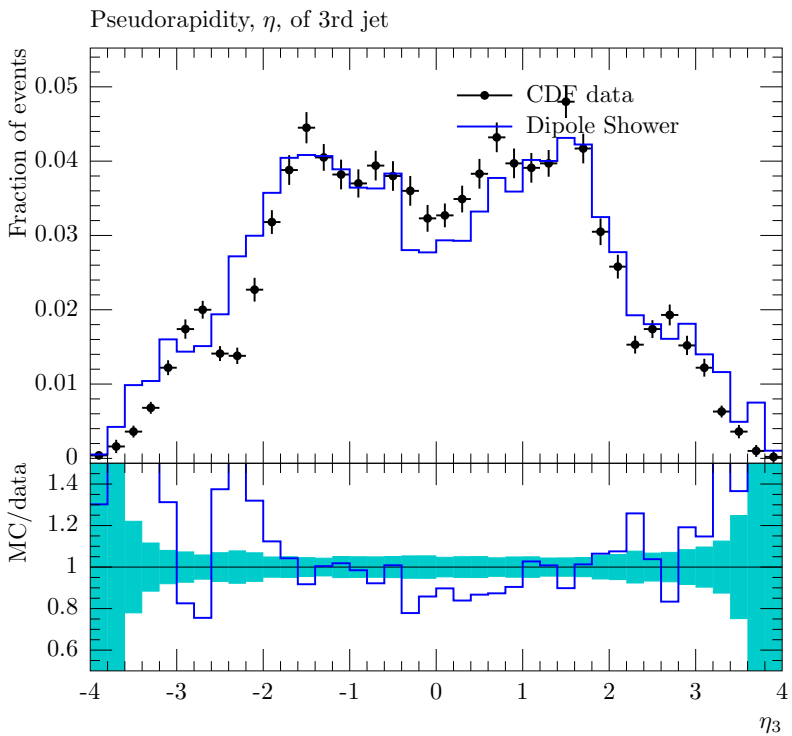




[L. D'Errico, P. Richardson 1106.2983]

Towards simple interface to NLO programs and automated matching. POWHEG– and MC@NLO-like.



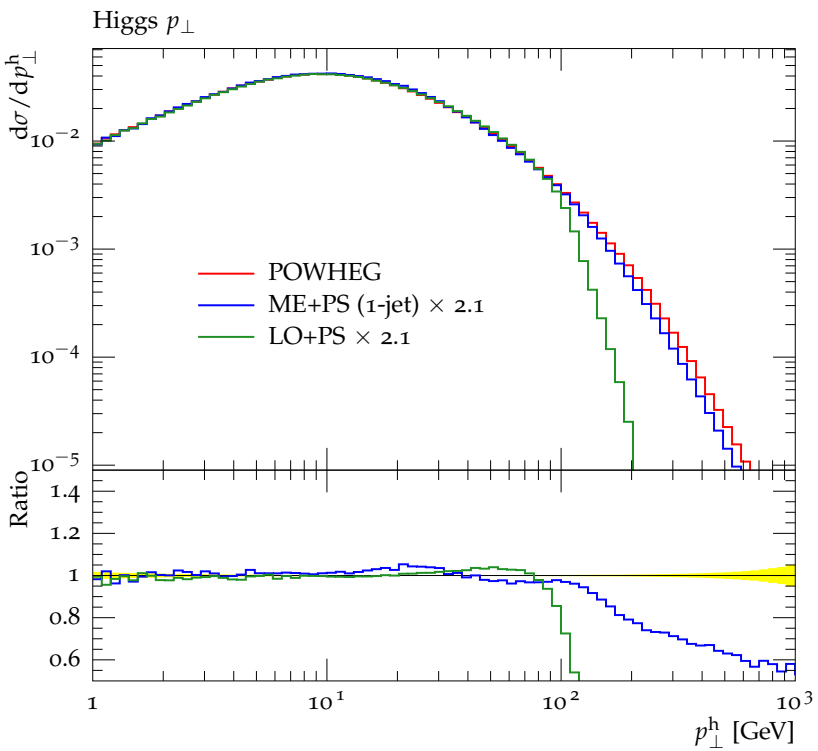


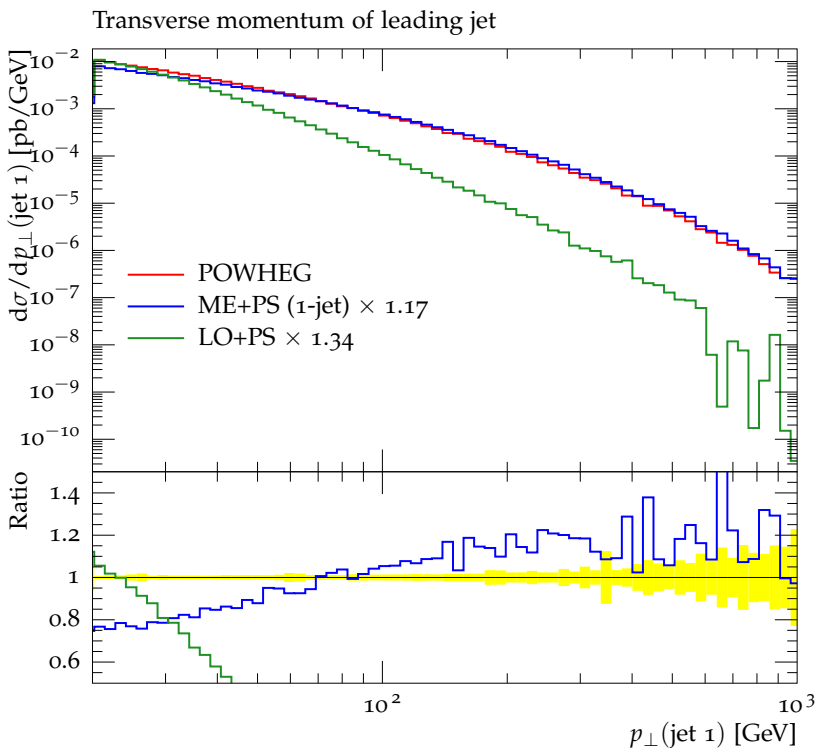
Proof-of-concept

[S. Plätzer, SG, 1109.6256]

NLO in Sherpa

- Automated POWHEG matching approach.
- Only virtuals needed → Binoth Les Houches Accord.

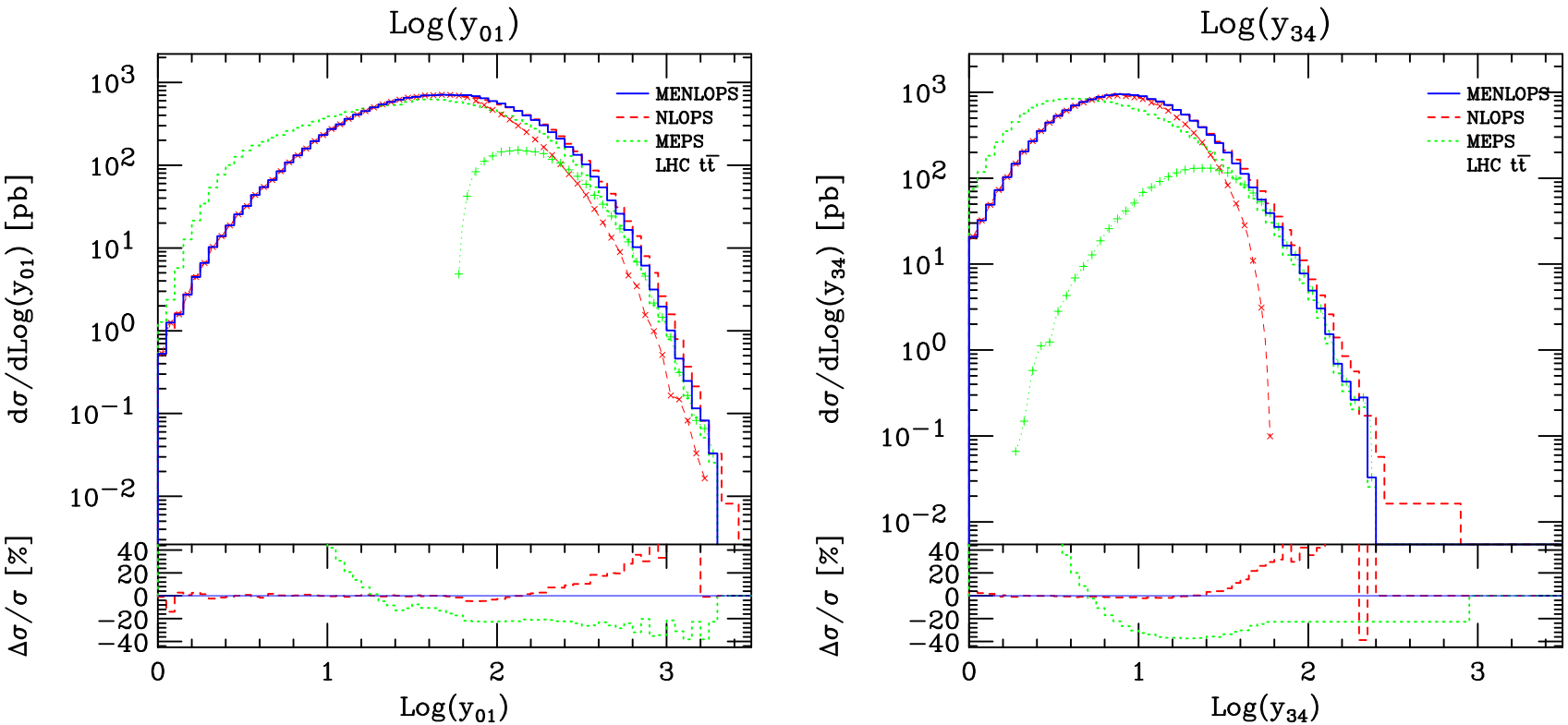




[Hoeche, Krauss, Schönherr, Siegert, JHEP 1104:024]

$gg \to h^0$ (left) WW+jets (right)

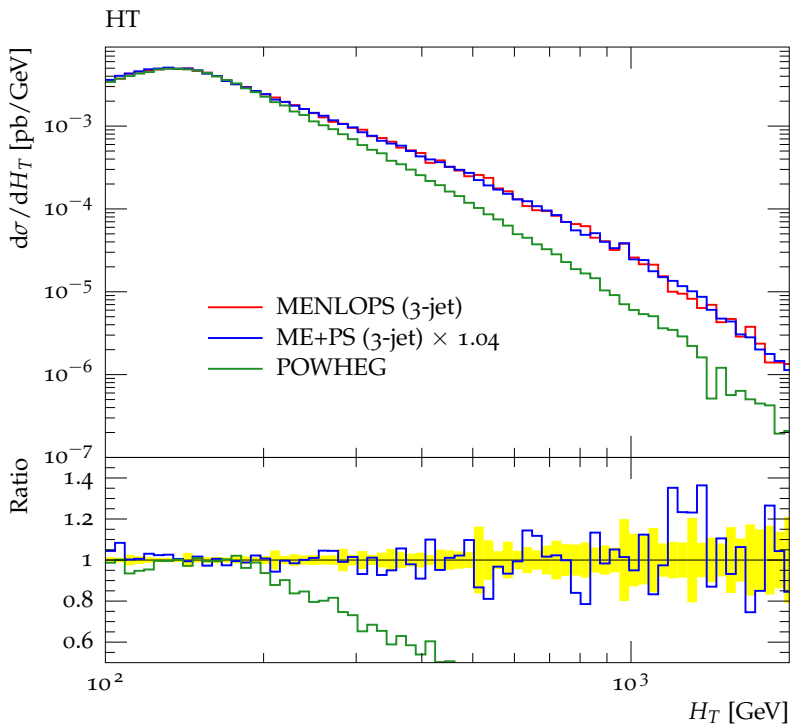
ME+PS merging with lowest multiplicity at NLO.

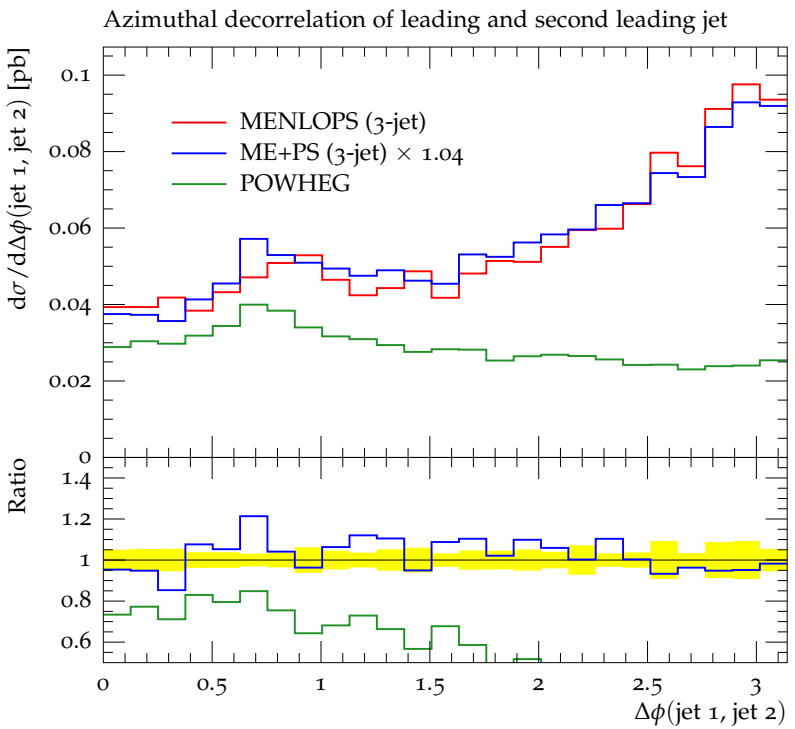


Test generic method with Pythia. y_{nm} in $t\bar{t}$+jets

[Hamilton, Nason, JHEP 1006:039]

ME+PS merging with lowest multiplicity at NLO.

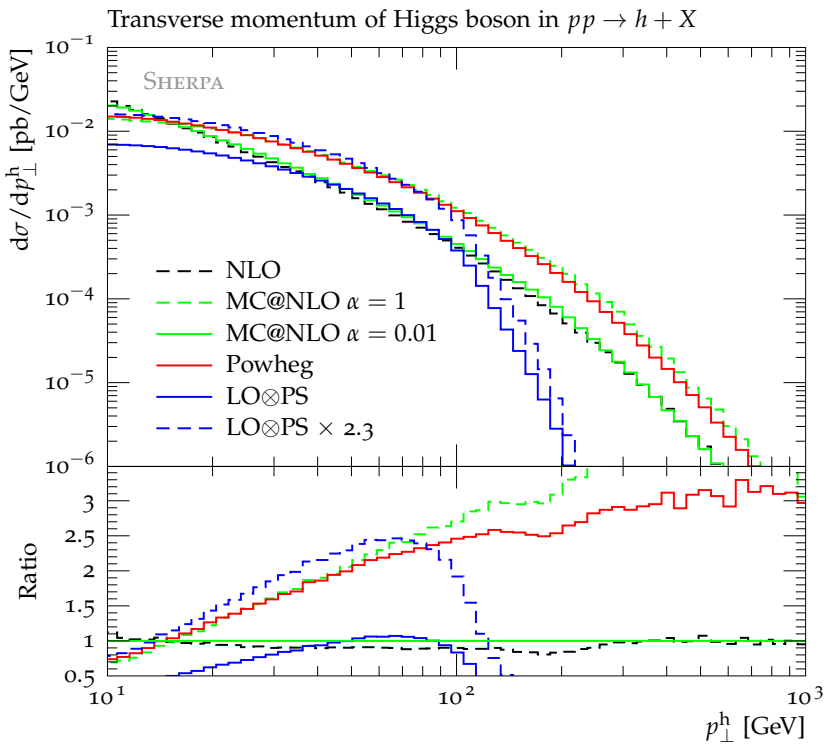


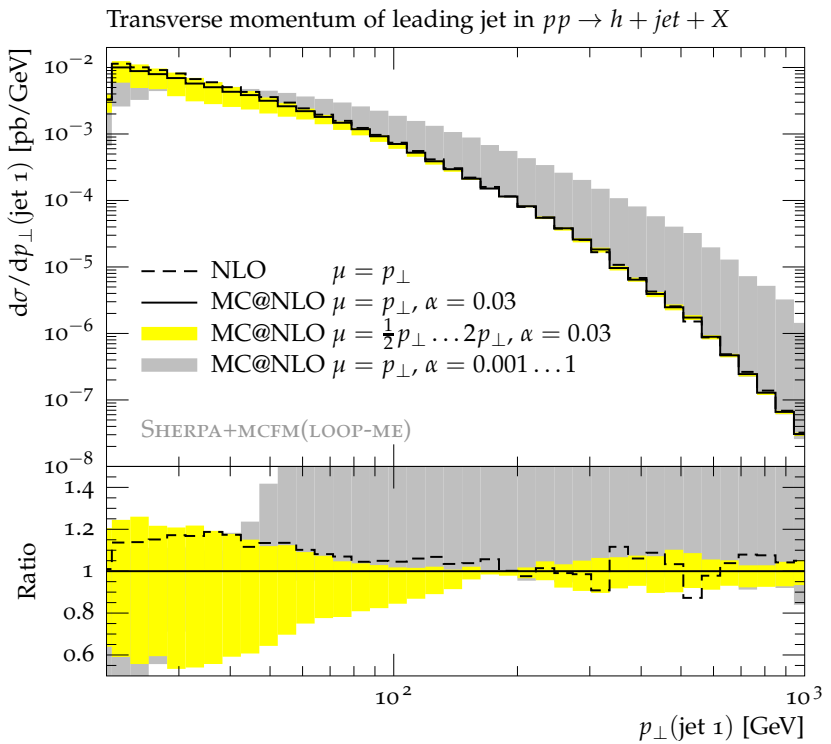


WW+jets implementation in Sherpa.

[Hoeche, Krauss, Schönherr, Siegert, 1009.1127]

Uncertainties in NLO matching





[Hoeche, Krauss, Schönherr, Siegert, 1111.1220]

$\alpha \to$ available Phase space for PS resummation.

Matching NLO+parton shower

- Tremendous effort.
- MC@NLO and POWHEG available for many processes.
- Implementation increasingly automatized.
- Complements huge effort of multi-leg NLO computations.
- Big discrepancies (at times), need to be understood better.

Min Bias/Underlying Event

Herwig++

MPI model with independent hard processes, showers and colour reconnection. Min bias without integrated diffraction.

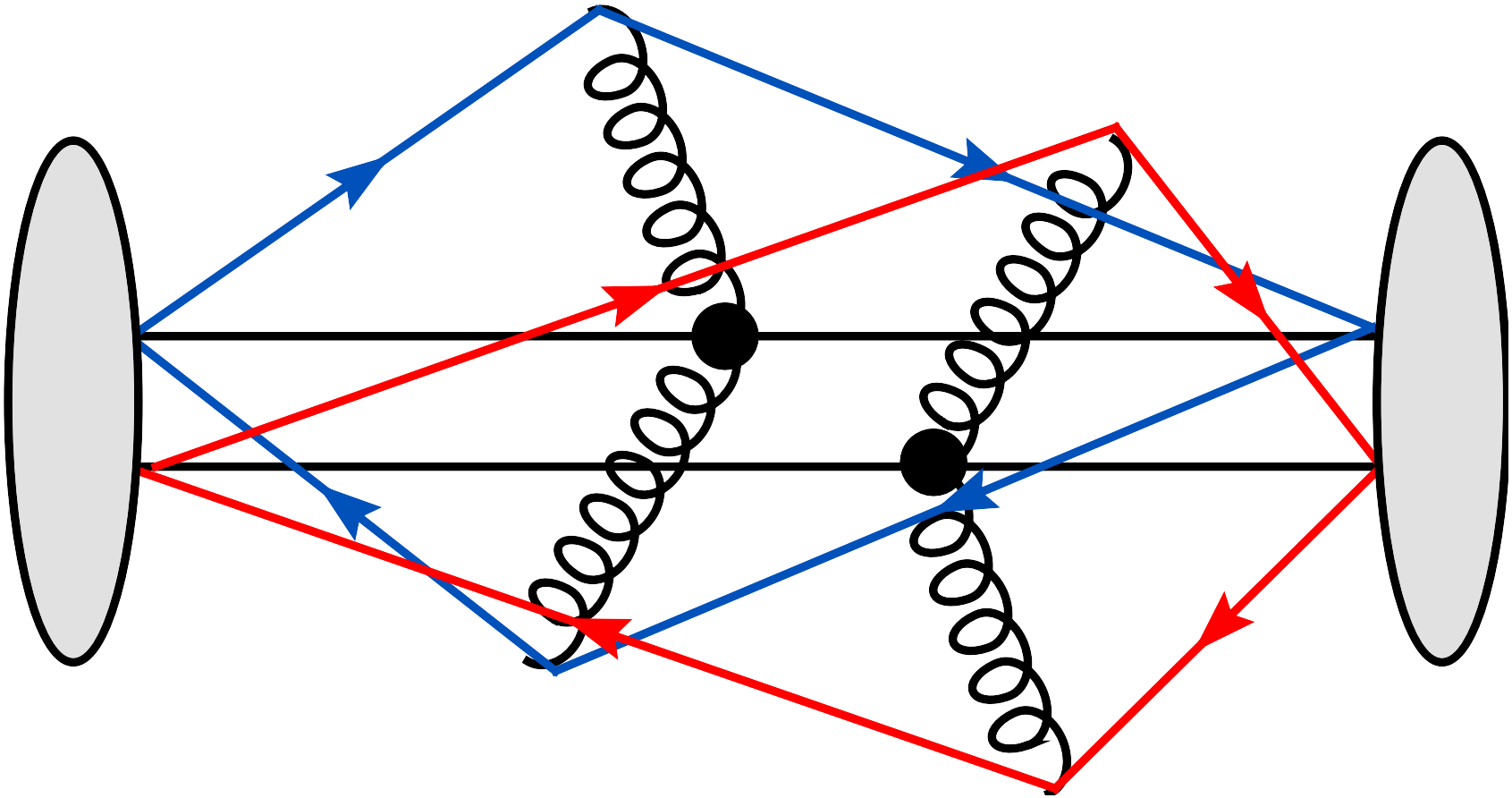
Pythia

MPI interleaved with showering. Many tune families.

Sherpa

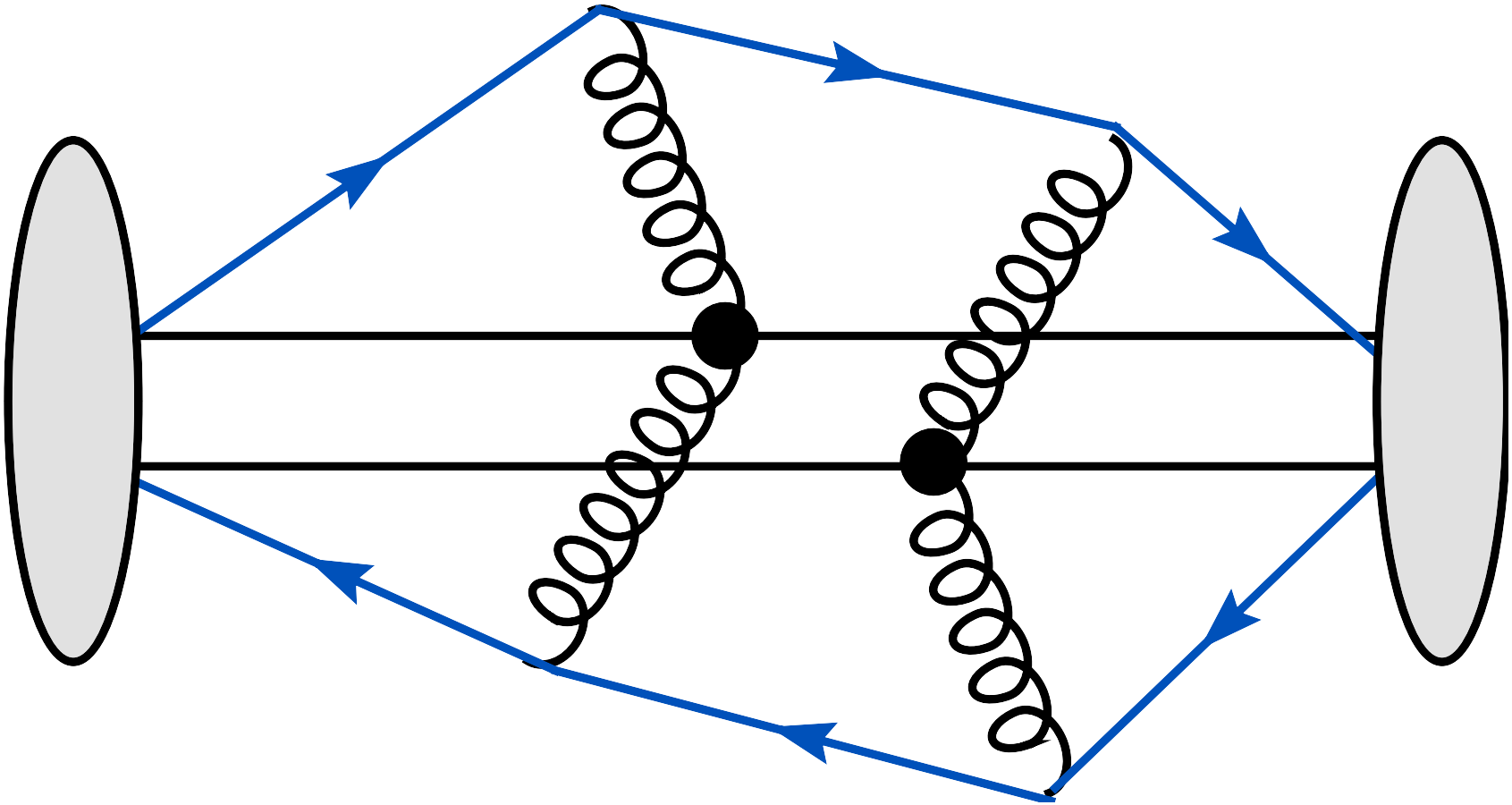
MPI model with independent hard processes. New model with integrated diffraction under development.

Colour reconnection at hadron colliders



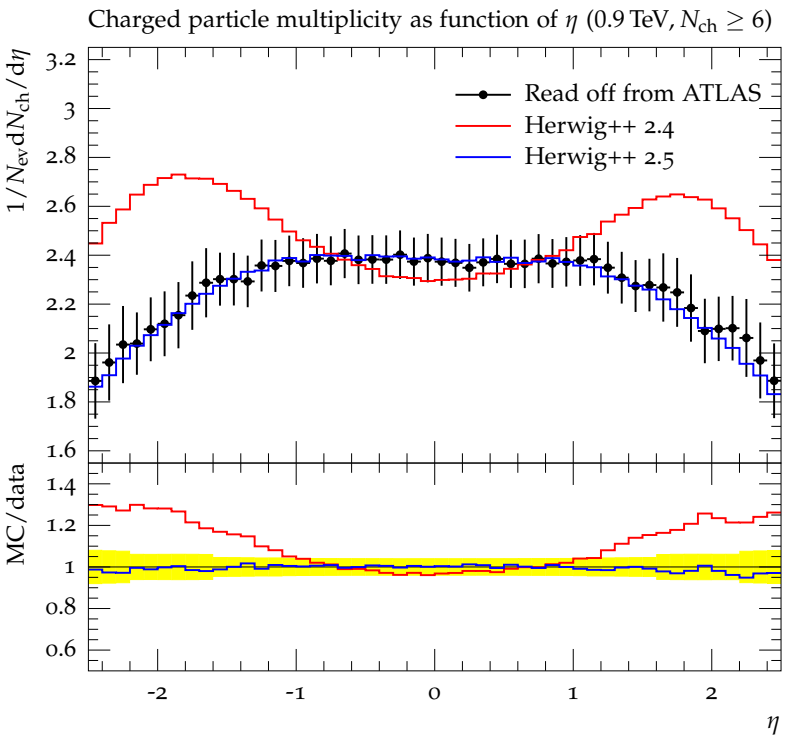
- Colour preconfinement
- Shorten colour string/lower mass clusters.

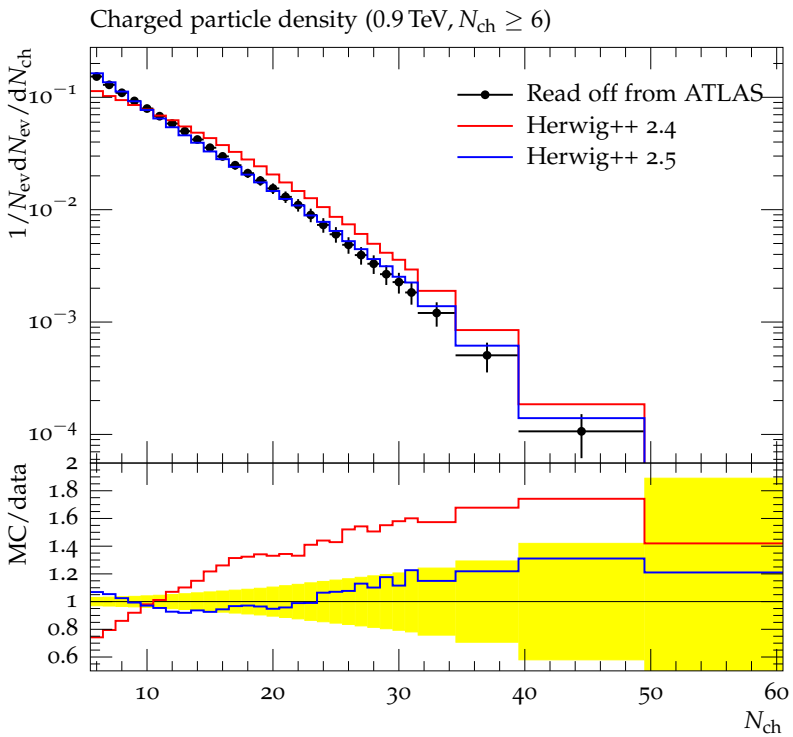
Colour reconnection at hadron colliders



- Colour preconfinement
- Shorten colour string/lower mass clusters.

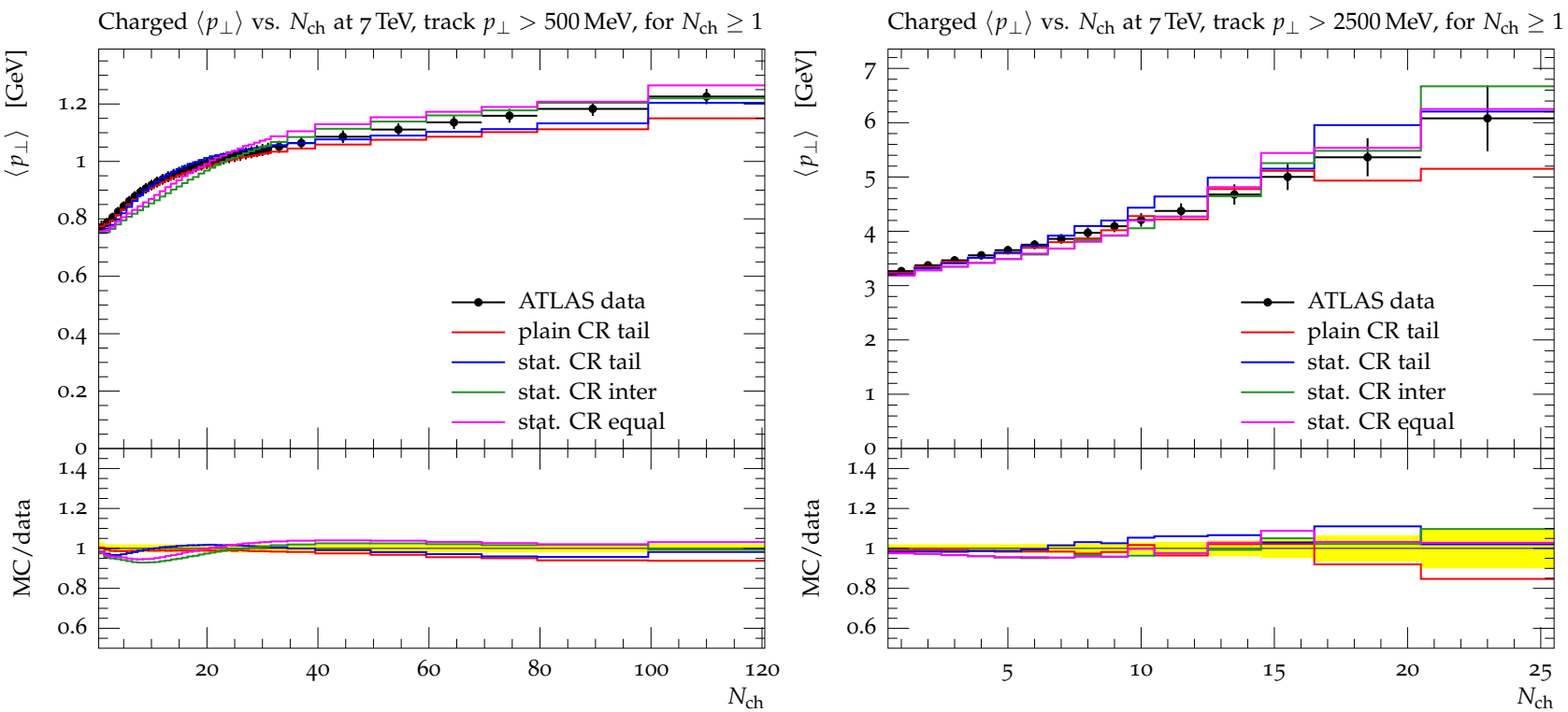
Colour reconnection model vital.





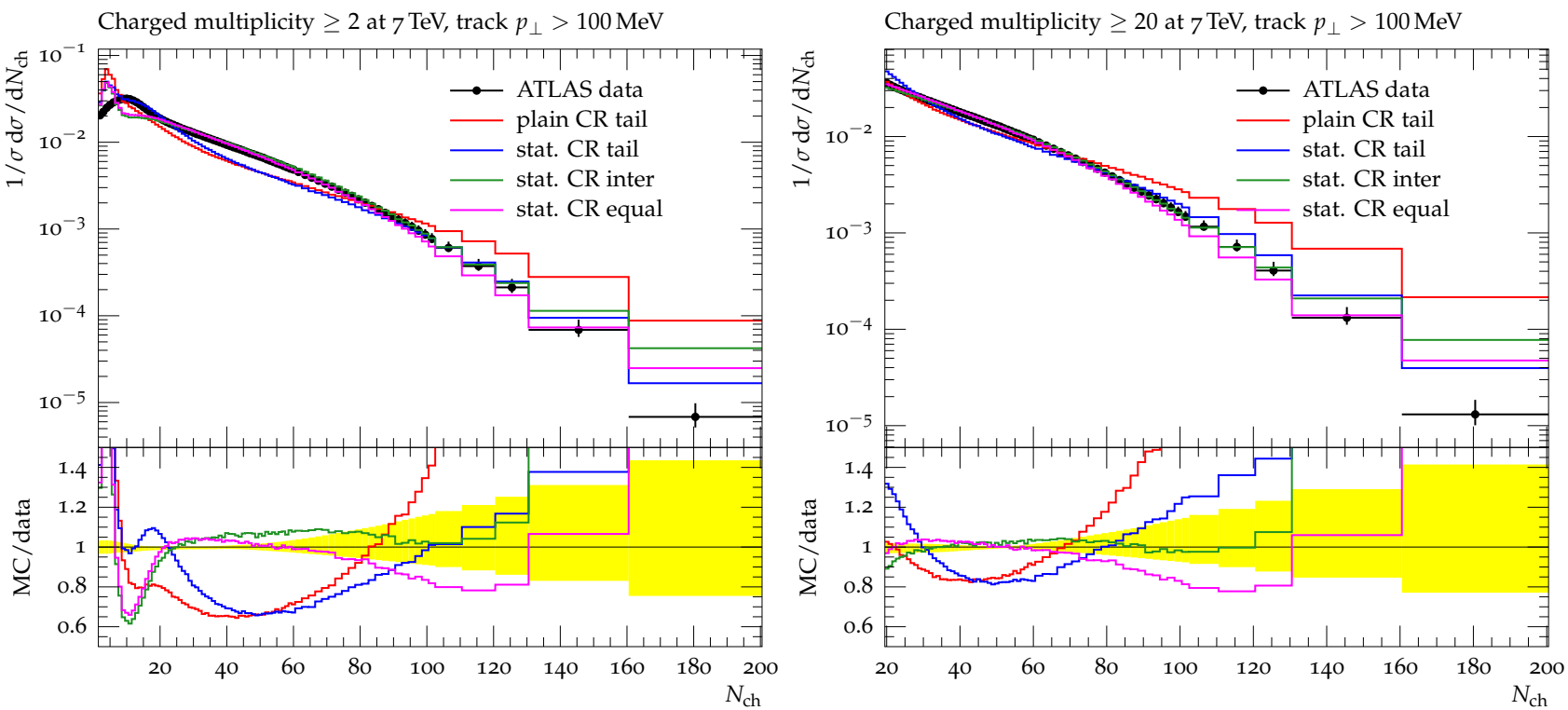
Model tuned to MinBias

$\langle p_\perp \rangle$ vs N_{ch}



Model tuned to MinBias

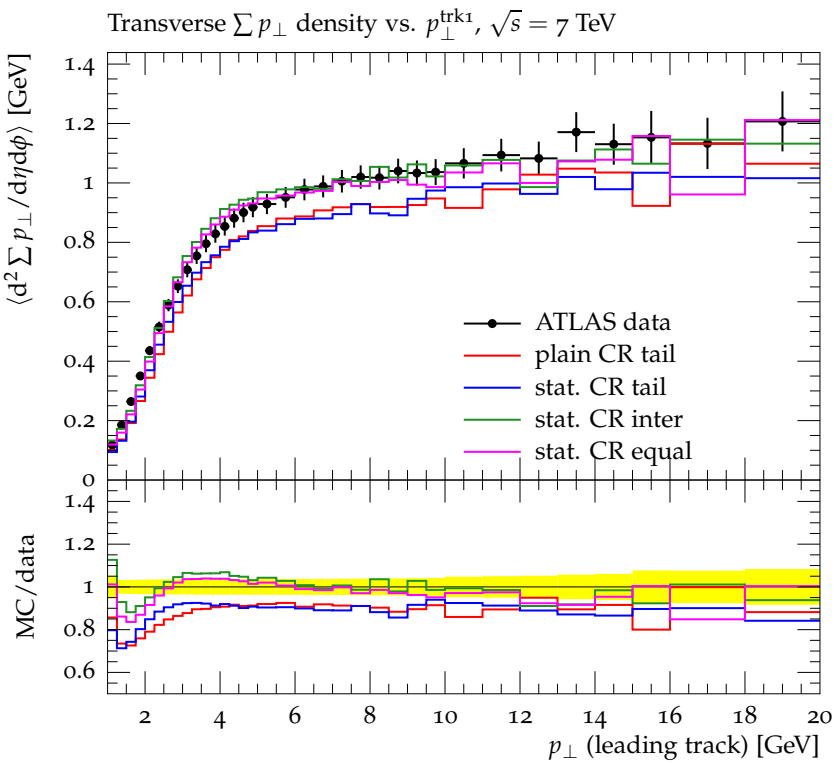
Charged multiplicity

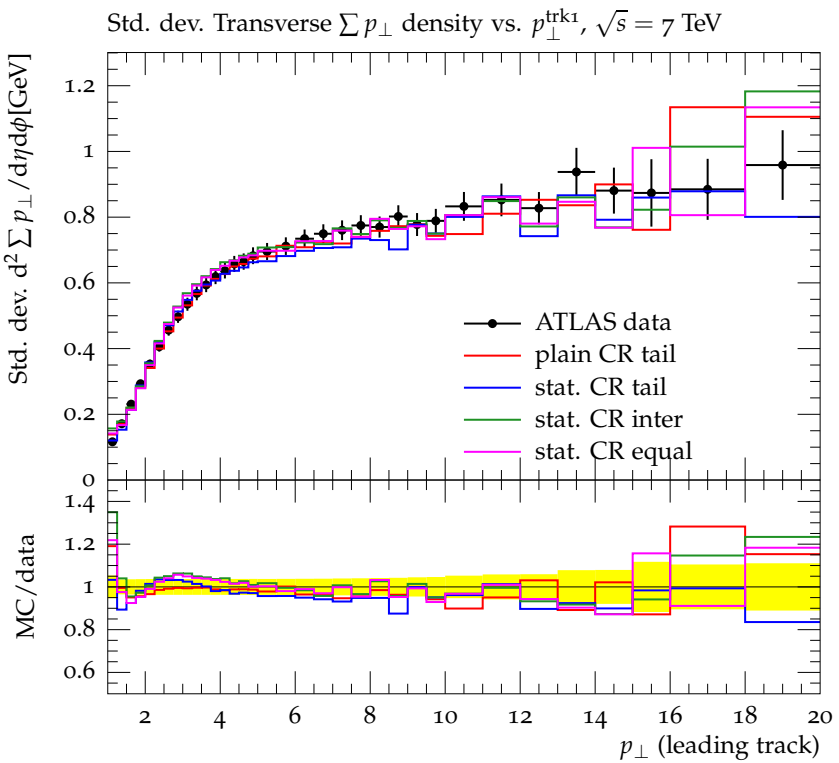


Some Results

Underlying Event results (not tuned to this).

Transverse $\sum p_\perp$

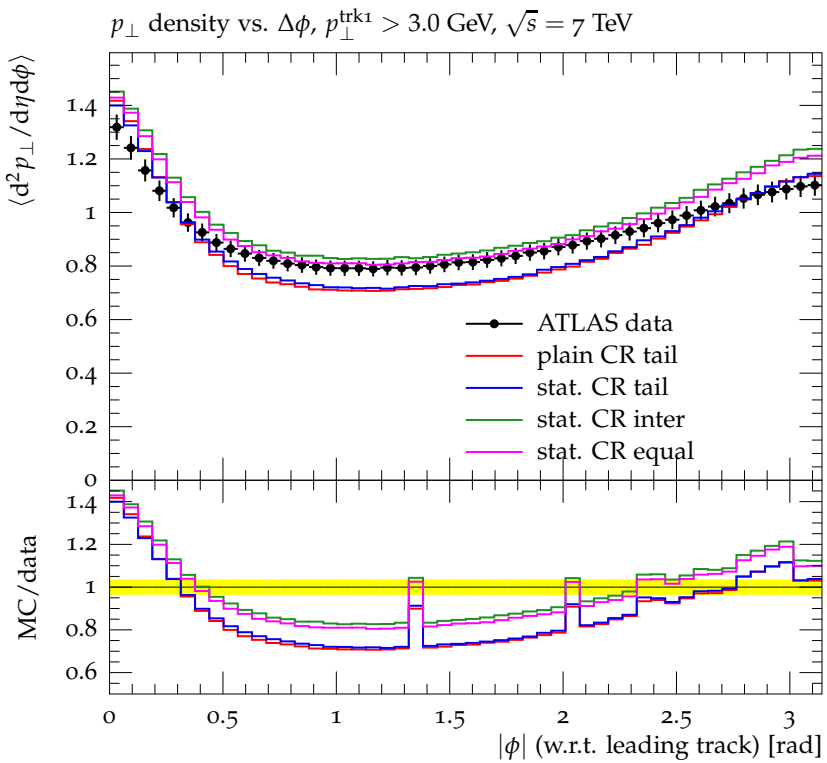


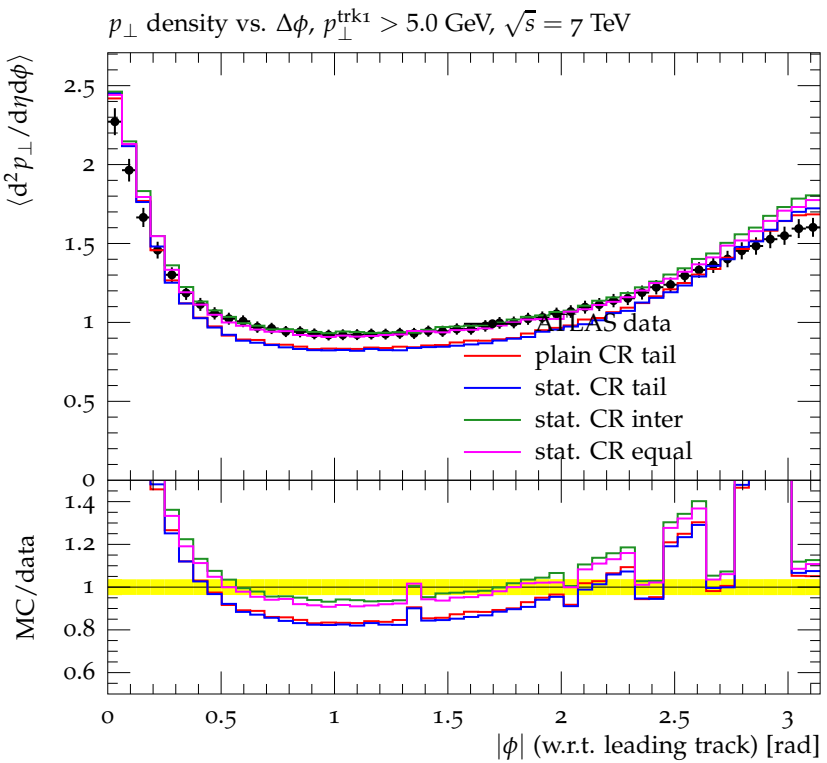


Some Results

Underlying Event results (not tuned to this).

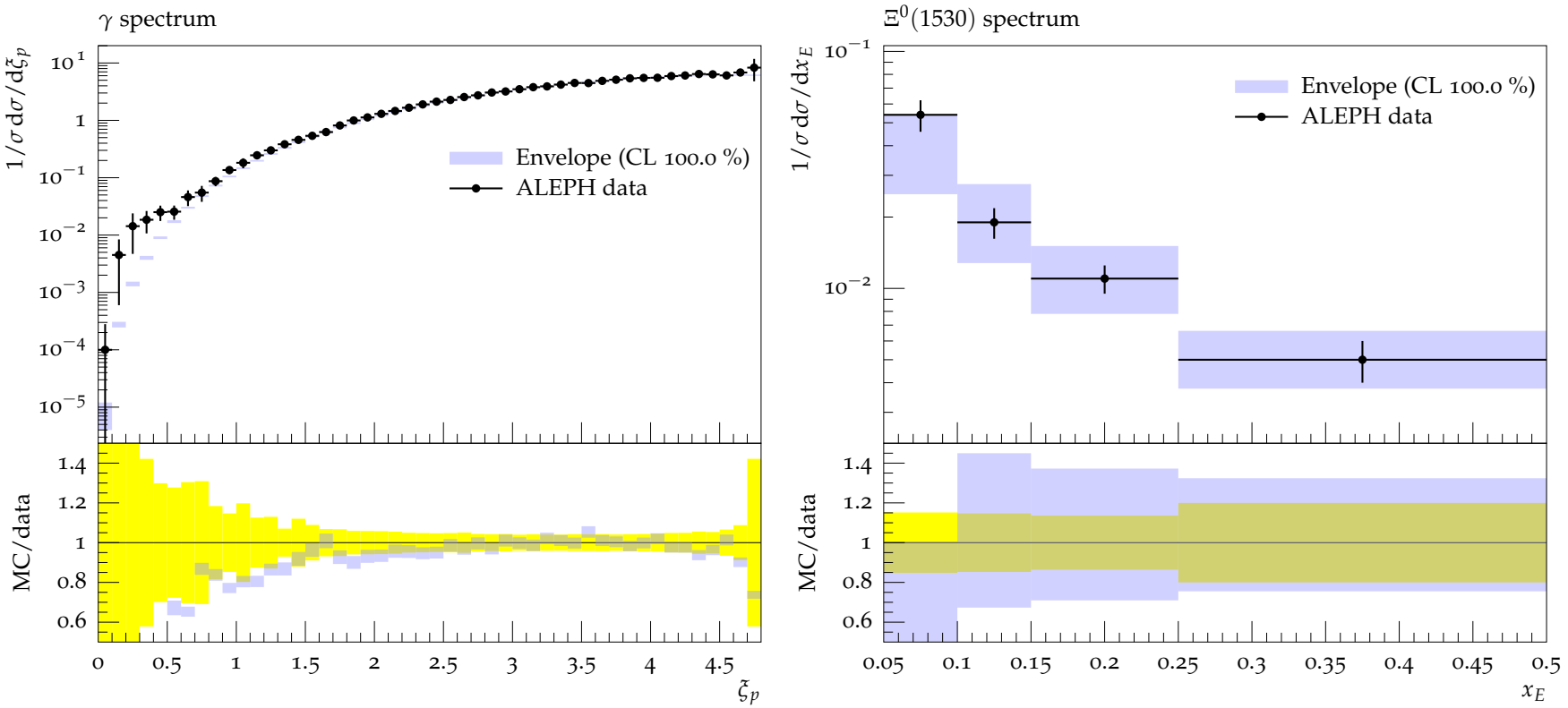
$p_\perp$ vs $\Delta\phi$ (ratio plots broken!)





Hadronization

MC errors from 'Eigentunes' quantifyable → PROFESSOR.



Extreme cases of observables with high/low sensitivity to hadronization parameters.

[D.E.Winn]

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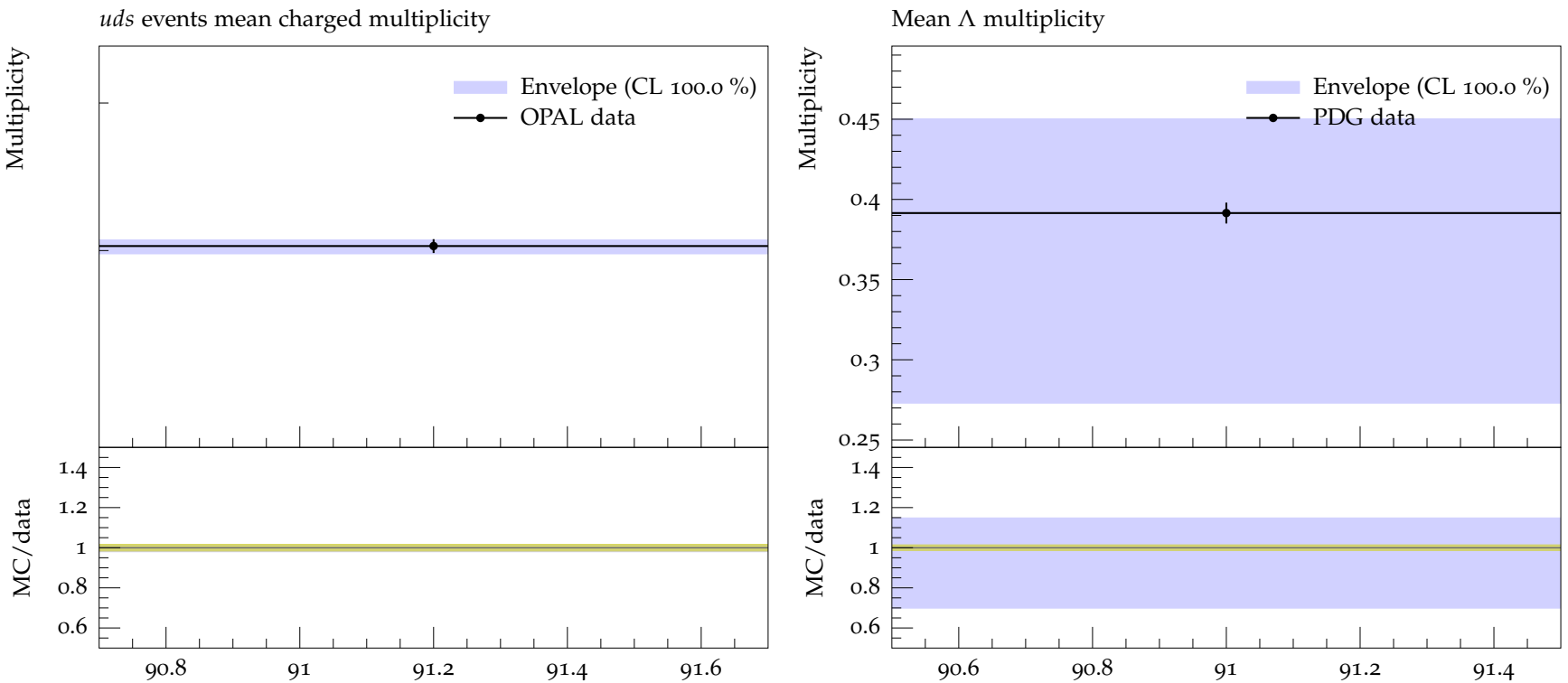

Extreme cases of observables with high/low sensitivity to hadronization parameters.

[D.E.Winn]

Non-perturbative physics

- Min Bias/UE still developed. Big effects.
- Hadronization only partly constrained by perturbative models. Room for (significant) improvement?

Validation/Quality control

MCs now use RIVET and PROFESSOR for tuning/validation.

[A. Buckley et.al., 1003.0694]

[A. Buckley, H. Hoeth, H. Lacker, E. v. Seggern, EPJ **C65** (2010) 331]

Possible to keep eye on $\sim$ 1000s of plots from $\sim$ 100 available analyses from PETRA, LEP, HERA, RHIC, Tevatron, LHC. (Automatized)

Really multi–purpose.

Status summary

- NLO widely available.
- Multiple hard jets via matching/merging.
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- Three completely new event generators established during the last decade.

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- Multi-leg NLO matched with parton shower.
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MC authors active in many fields.

Scenario I — small group (example)

- Contribute and study NLO processes one-by-one.
- Development in a few modules.
- Keep up with data, partial tuning.

Scenario II — big group (example)

- Keep up with data, tuning effort, consult experiments.
- Big NLO effort, incorporate "Les Houches list" and more in few years.
- Understand problems with discrepancies beyond NLO.
- Matching schemes for several NLO multi-leg processes.
- NNLO matching.

- New developements in MinBias, sophisticated inclusion of diffraction, precision tool, synergies with UHECR physics.

- Continued development of NP physics (hadronization/decays). Live up to new precision standards, raised by LHC data.

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- Theory $\longrightarrow$ MC $\longleftarrow$ Experiment.
  Indispensable tool for LHC and beyond.

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- Real infrastructure needed for day-to-day work —
  user support, software maintenance and performance,
  presence at workshops in different research areas.
- Long working cycle:
  theory/tech development $\rightarrow$ implementation $\rightarrow$
  experiments $\rightarrow$ data $\rightarrow$ theory $\ldots$
- Long term effort.