Monte Carlo Event Generators

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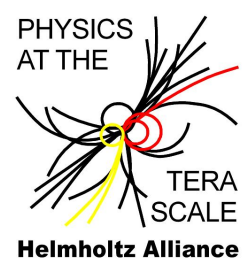
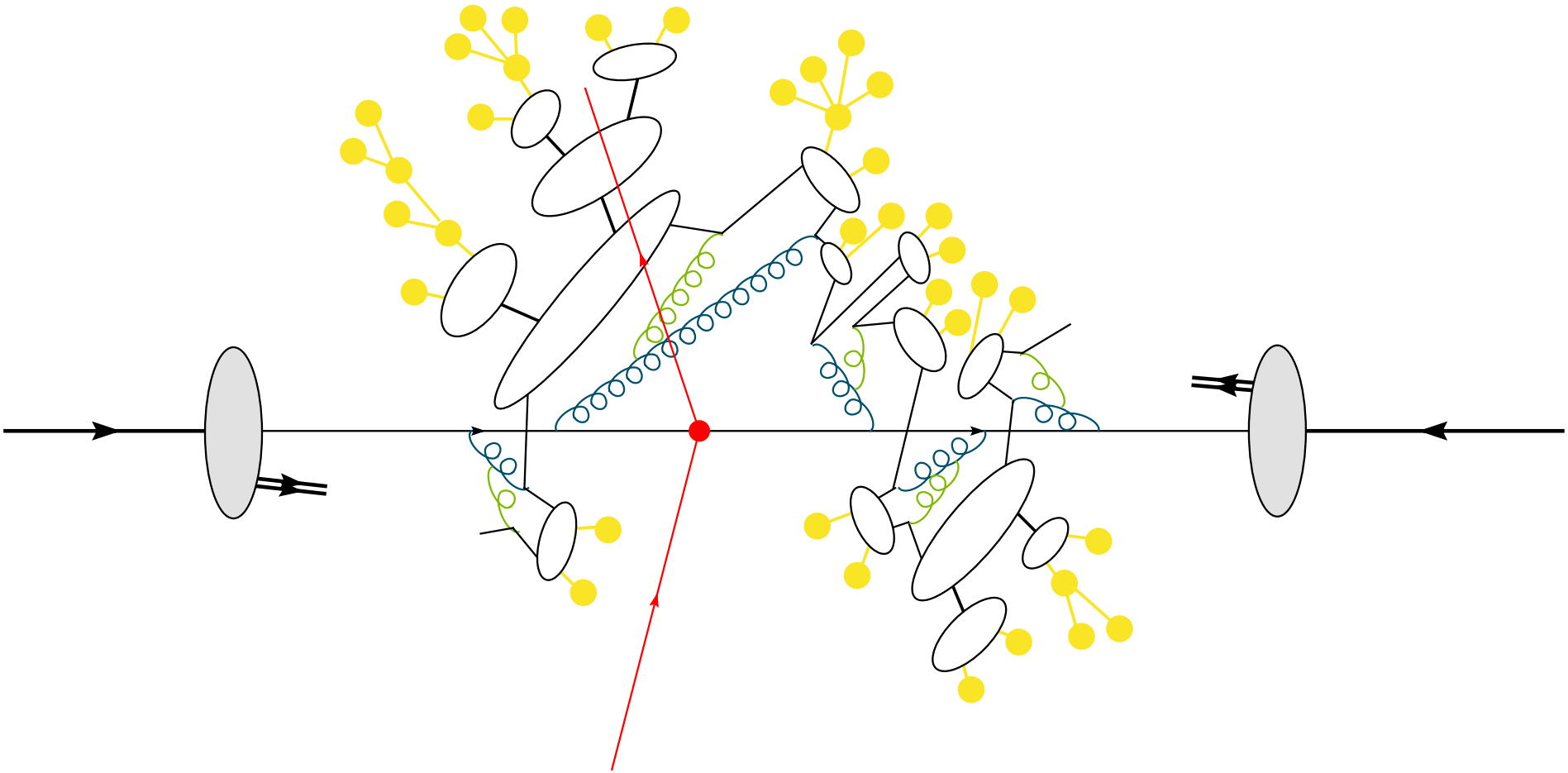
Ringberg Workshop *New Trends in HERA Physics*
25-28 September 2011



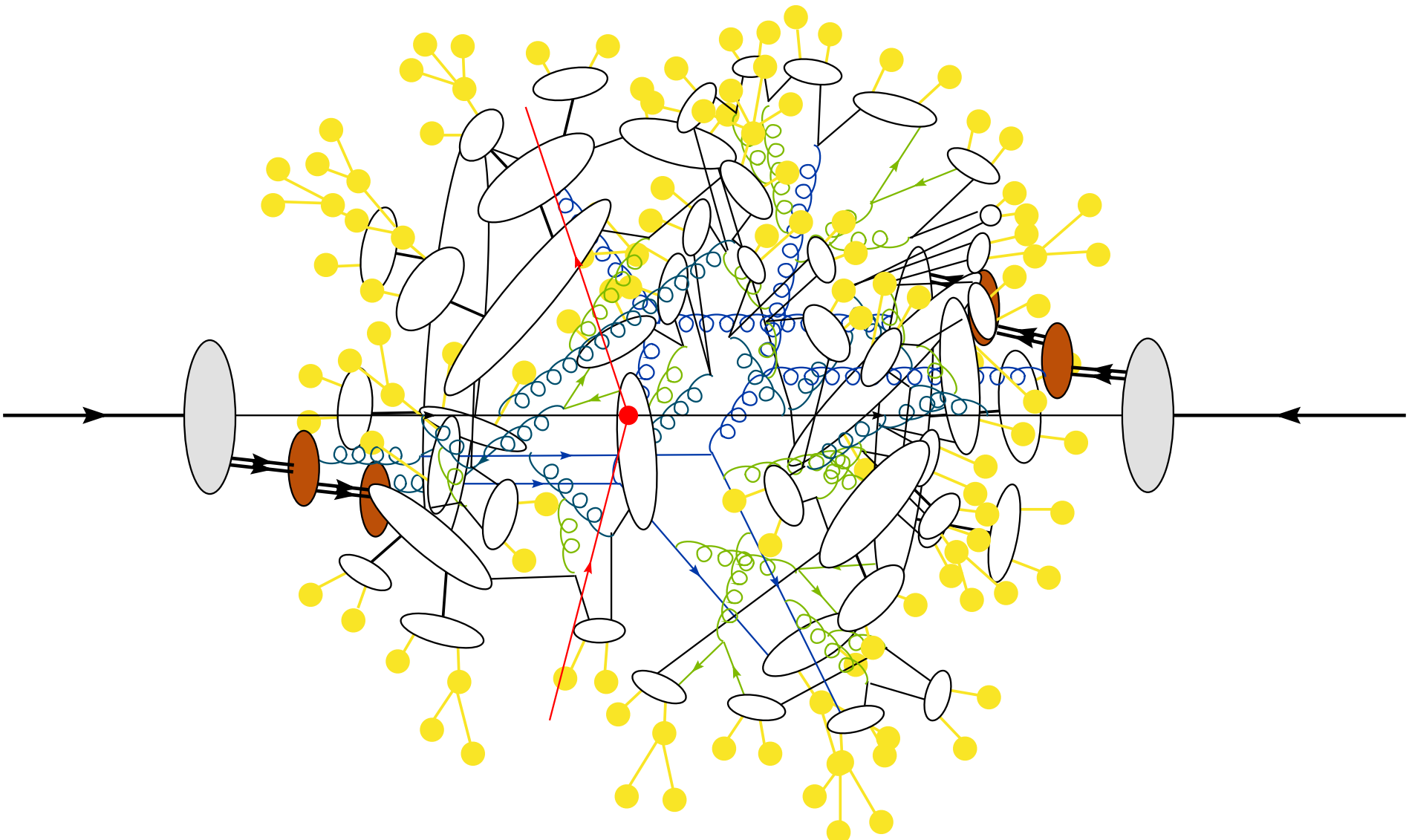
Outline

- Mostly newer developments.
- New generators (Herwig++/Pythia8/Sherpa) (biased ;).
- Emphasis on NLO and Underlying event.

pp Event Generator



pp Event Generator



Hard processes (tree level)

Processes at Born level (out of the box)

- Hadron collider
  QCD $2 \to 2$, $t\bar{t}$, MinBias
  $(\gamma, Z^0) \to \ell^+\ell^-$, $W^\pm \to \ell^\pm \nu_\ell$, $(Z^0, W^\pm) + \text{jet}$
  W^+W^-, $W^\pm Z^0$, Z^0Z^0, $W^\pm\gamma$, $Z^0\gamma$
  h^0, $h^0 + W^\pm$, $h^0 + Z^0$, $h^0 + \text{jet}$, qqh^0 (VBF), $t\bar{t}h^0$
  $\gamma + \text{jet}$, $\gamma\gamma$
- DIS
  NC/CC/Photoproduction, $\gamma p \to$ jets.
- $e^+e^-/\gamma\gamma$
  $e^+e^- \to Z^0$, $e^+e^- \to q\bar{q}$, $e^+e^- \to \ell^+\ell^-$, $e^+e^- \to W^+W^-$,
  $e^+e^- \to Z^0h^0$, $e^+e^- \to h^0e^+e^-$, $e^+e^- \to h^0\nu_e\bar{\nu}_e$.
  $\gamma\gamma \to W^+W^-$, $\gamma\gamma \to f\bar{f}$.

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  QCD $2 \to 2$, $t\bar{t}$, MinBias
  $(\gamma, Z^0) \to \ell^+\ell^-$, $W^\pm \to \ell^\pm \nu_\ell$, $(Z^0, W^\pm)$ + jet
  W^+W^-, $W^\pm Z^0$, Z^0Z^0, $W^\pm\gamma$, $Z^0\gamma$
  h^0, $h^0 + W^\pm$, $h^0 + Z^0$, h^0 + jet, qqh^0 (VBF), $t\bar{t}h^0$
  γ + jet, $\gamma\gamma$
- DIS
  NC/CC/Photoproduction, $\gamma p \to$ jets.
- $e^+e^-/\gamma\gamma$
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  $\gamma\gamma \to W^+W^-$, $\gamma\gamma \to f\bar{f}$.

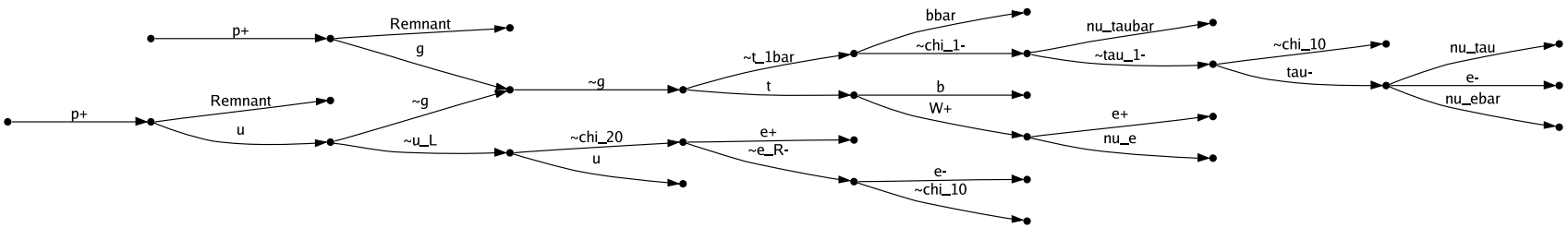
Also at NLO with POWHEG matching (more details later).

Hard processes (tree level)

- BSM processes
  - MSSM.
  - Extra Dimensions.
  - More under construction.
  - Hard process and up to 3 body decays created automatically from model file.
  - Allows for simulation of full spin correlations.
- Anything else via `LesHouchesFileReader`.

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)

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.

Parton showers

Herwig++

- New parton shower variables introduced for Herwig++

  [SG, P. Stephens and B. Webber, JHEP **0312** (2003) 045 [hep-ph/0310083]]

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

  [SG, S. Plätzer, 0909.5593]]

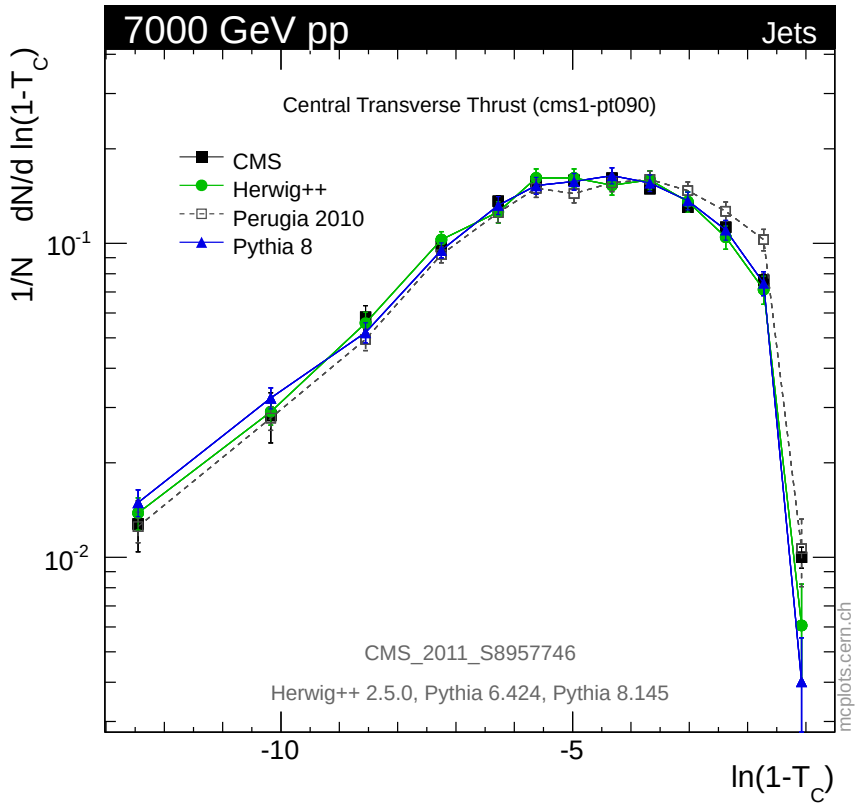
Sherpa

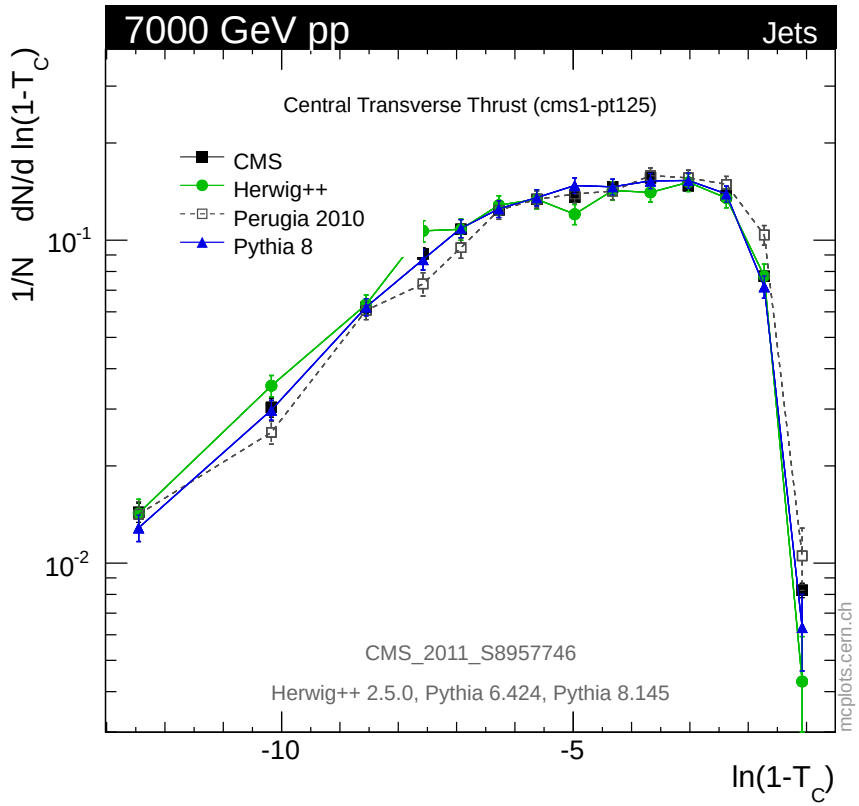
- CS-Shower default by now, always matched via CKKW (see later).

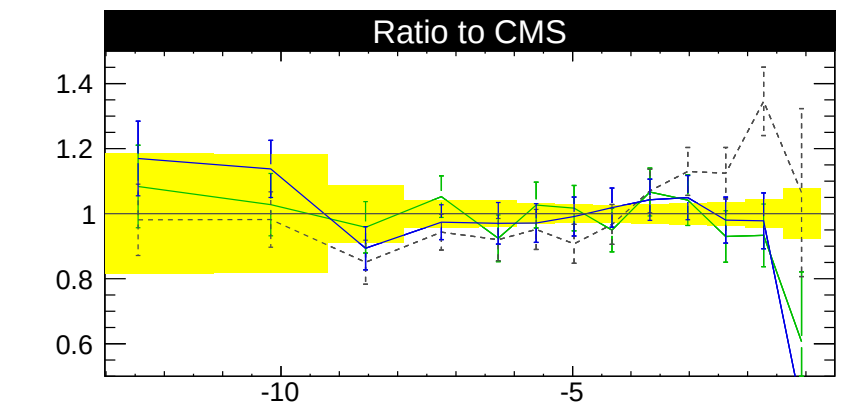
Pythia

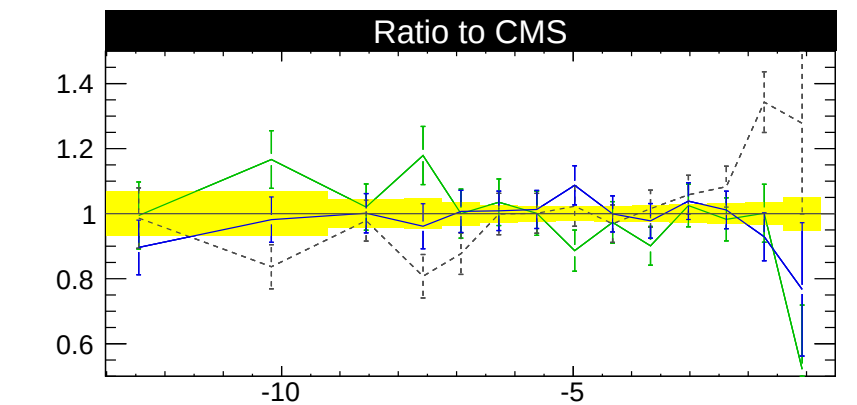
- p_T ordered shower (simple matching).
- Interleaved with Multiple partonic interactions.

Transverse thrust



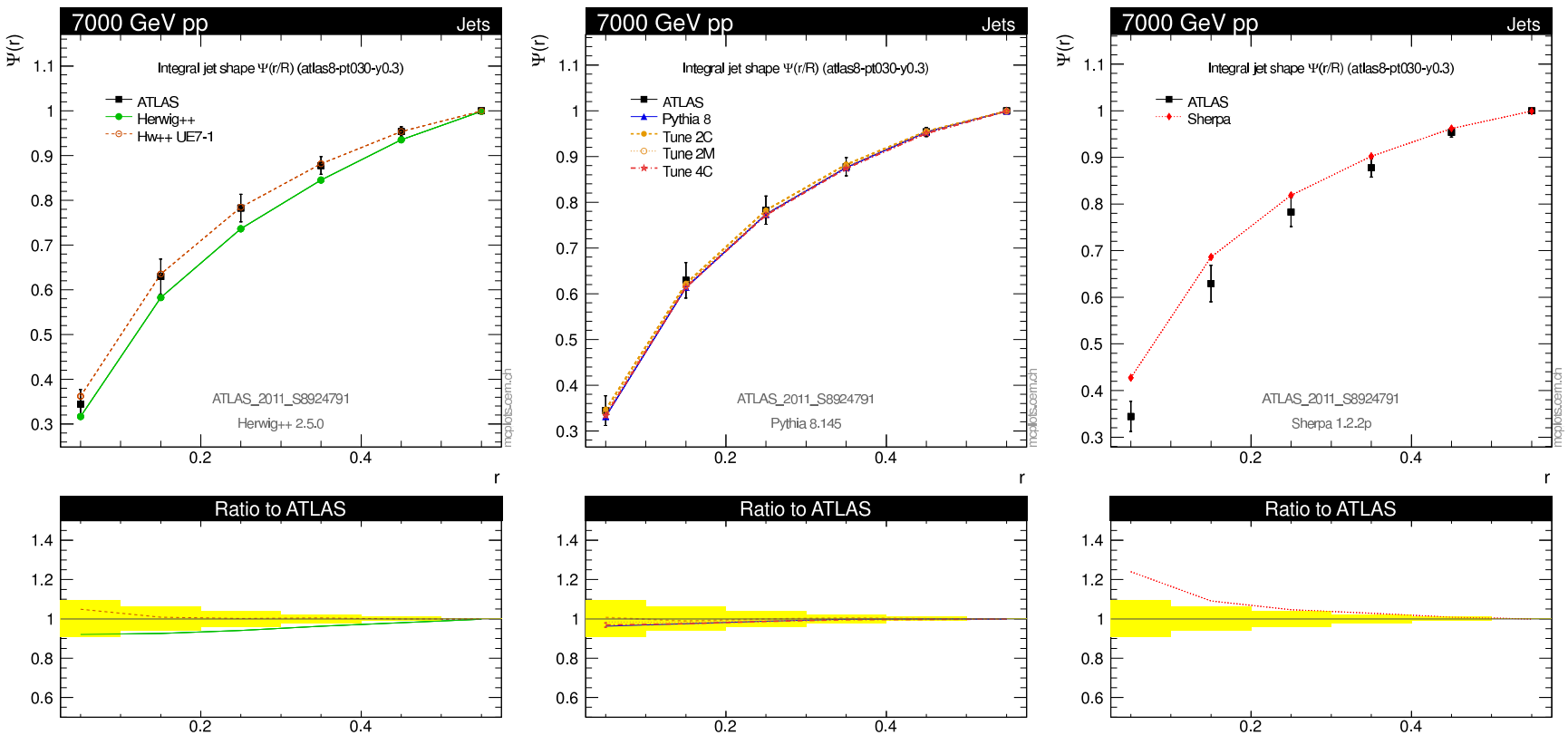






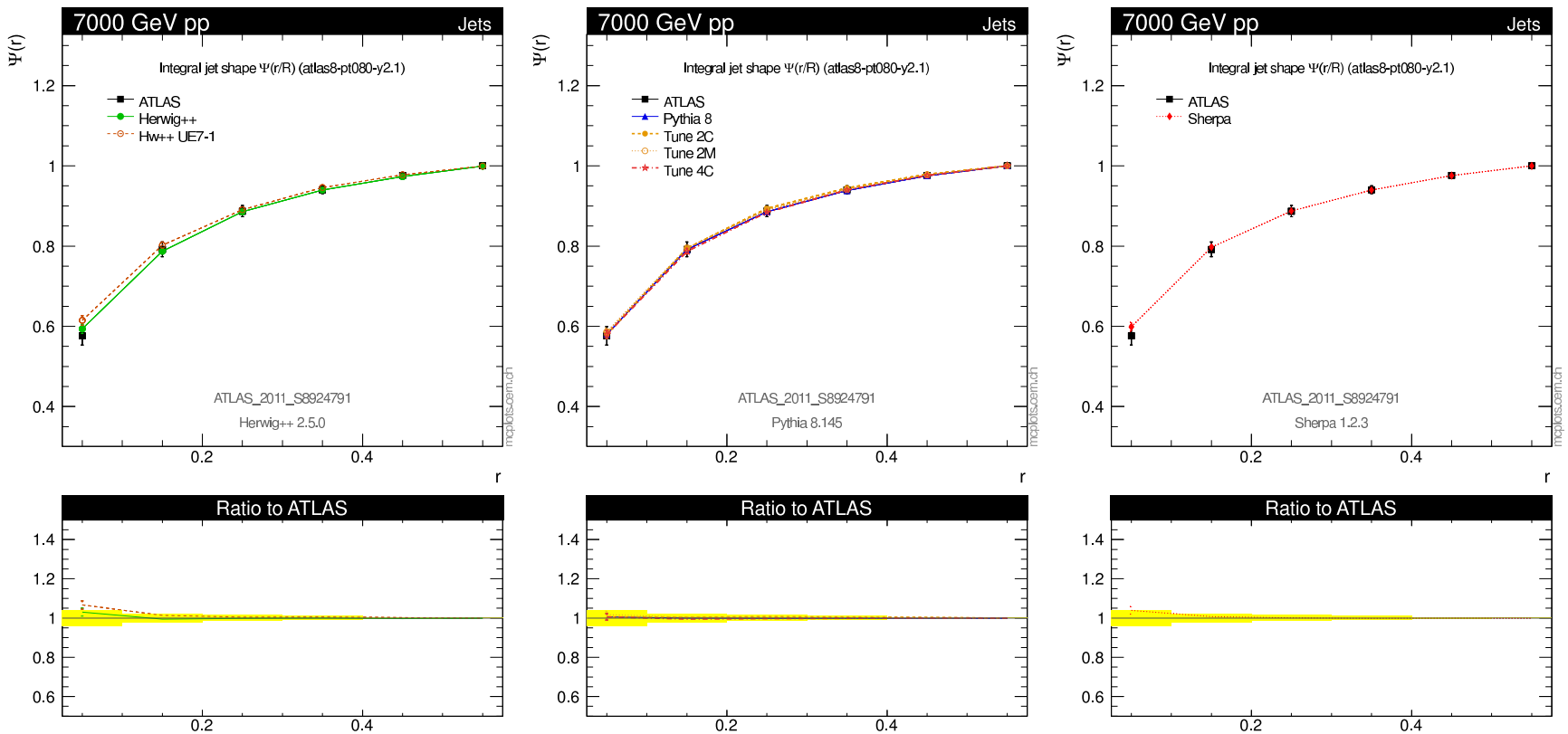
Integral jet shapes

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



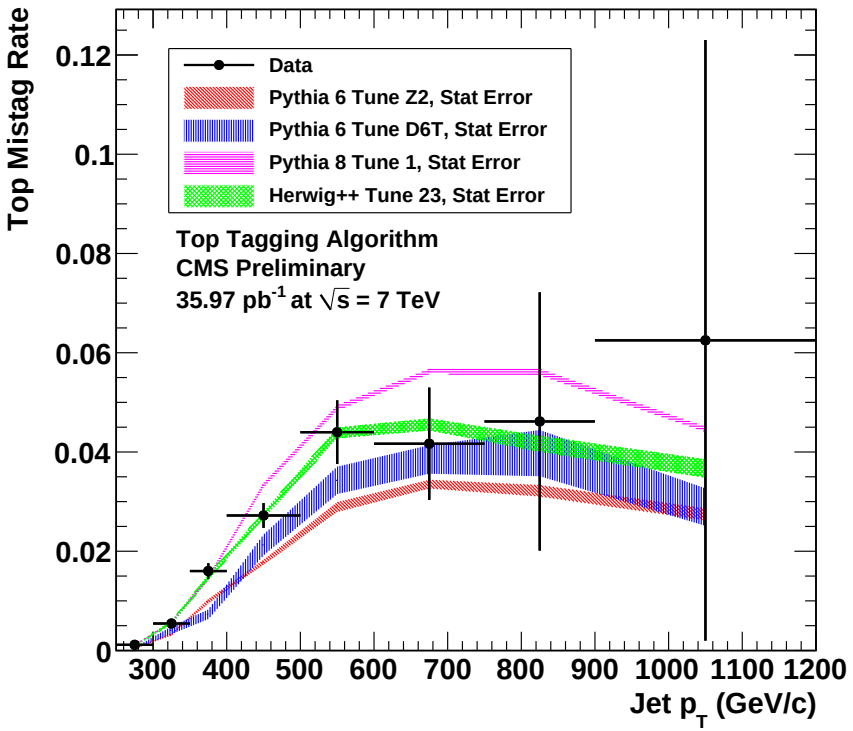
Integral jet shapes

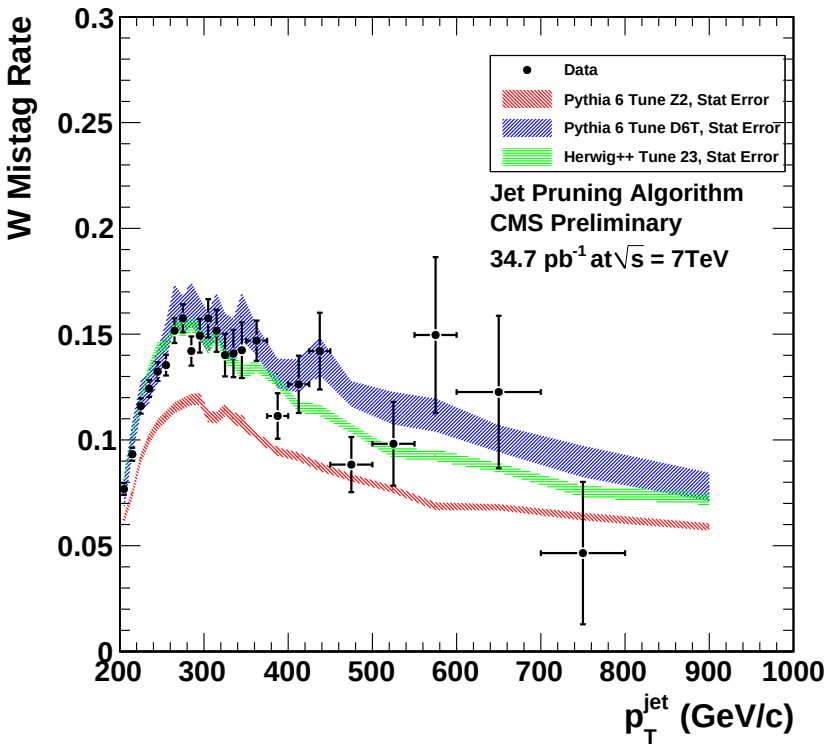
harder, more forward ($80 < p_T/\text{GeV} < 110; 1.2 < |y| < 2.1$)



Integral jet shapes

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



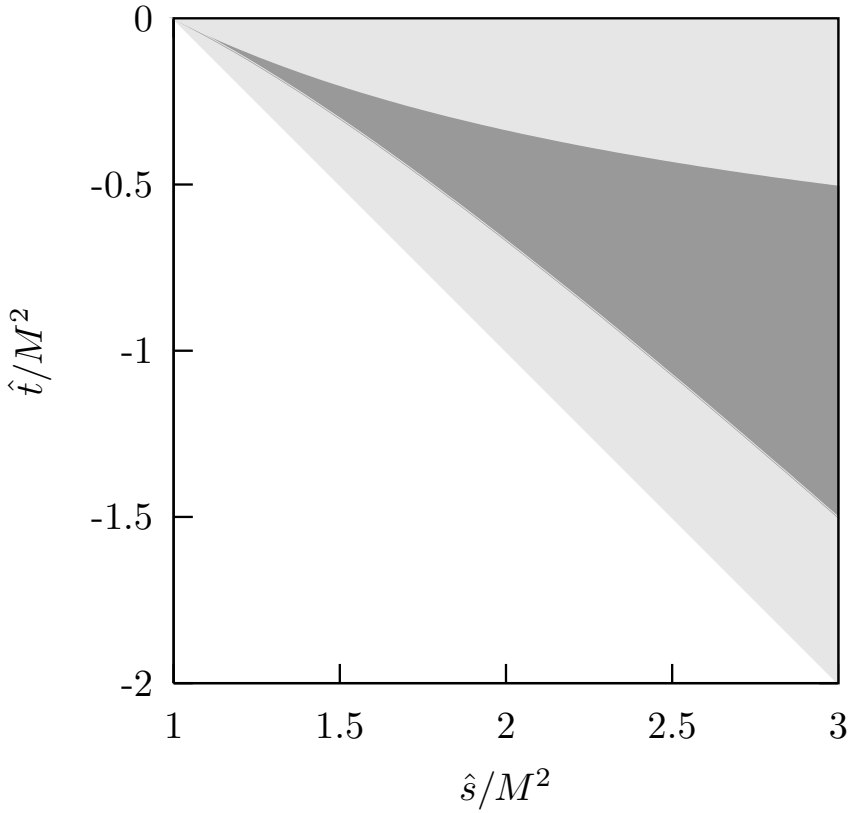


[CMS PAS JME-10-013]

Matrix element corrections

Hard ME correction (e.g. in DY)

- Light: collinear/soft regions.
- Dark: Dead region, filled with extra hard emissions — not accessable by parton shower.
- To be complemented by soft matrix element corrections.

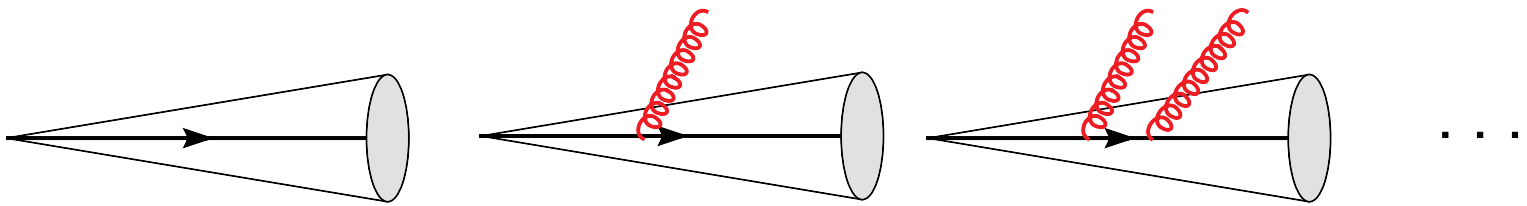


Also for $V^* \to q\bar{q}$, t–decay (2.0)
$gg \to h^0$ (2.2),

Simplest matching.

Matching tree level ME and parton showers

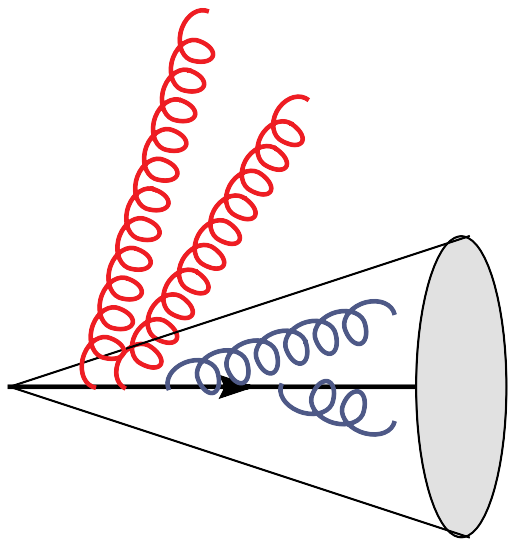
- Problem: have multiple tree level MEs for $X + 0, 1, \ldots n$ jets.



- 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. L"onnblad, 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

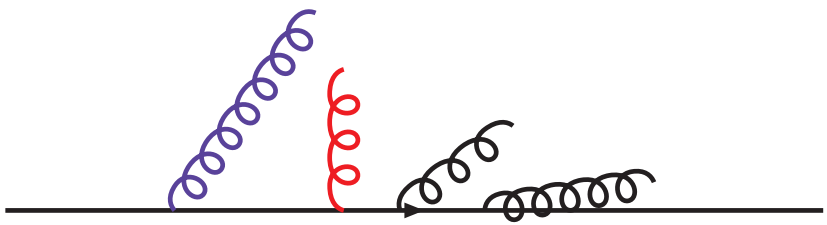
- Separates ME and parton shower at intermediate scale Q_{ini}.
- Parton shower fills region below Q_{ini}.
- All emissions resolvable above Q_0.



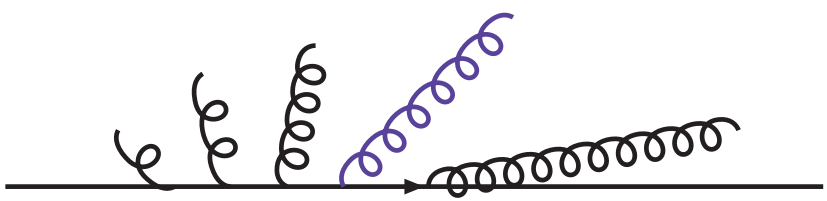
Merges ME and parton shower at scale Q_{ini}.

Matching tree level ME and PS — trouble?

Hard emission, to be complemented by parton shower.



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



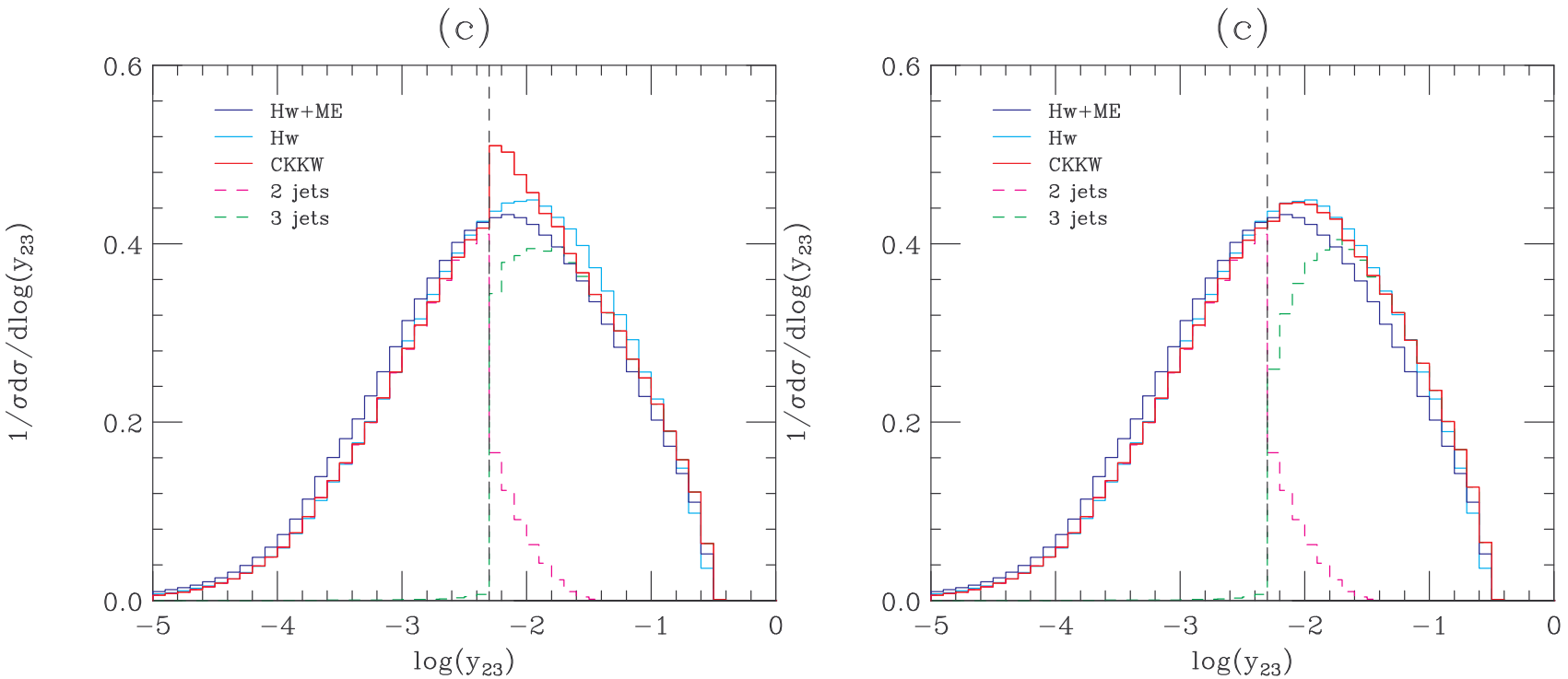
Angular ordered shower. Some softer emissions before hardest one.

Potential holes in phase space $\longrightarrow$ *truncated showers*.

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

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

Matching tree level ME and parton showers

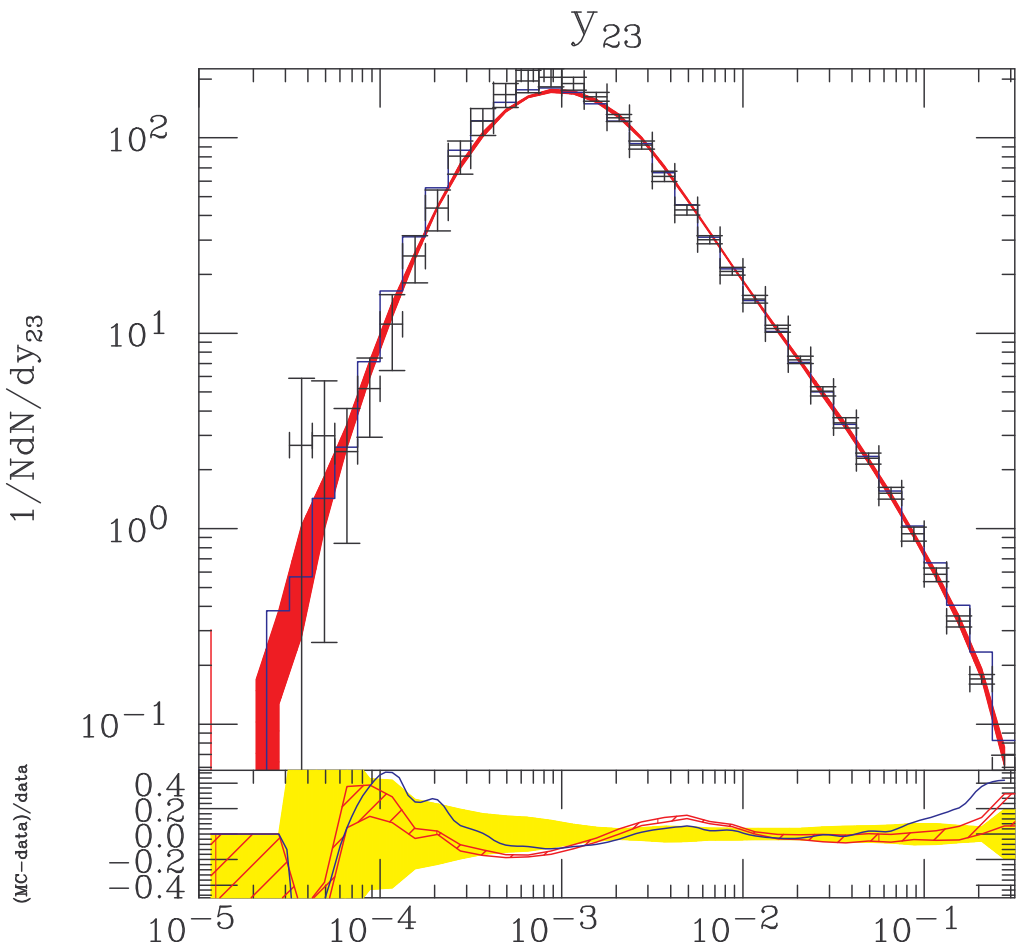


K. Hamilton, P. Richardson, J. Tully, JHEP 0911:038,2009.

Parton level merging for illustration.

Instabilities at Q_{ini} removed.

Matching tree level ME and parton showers

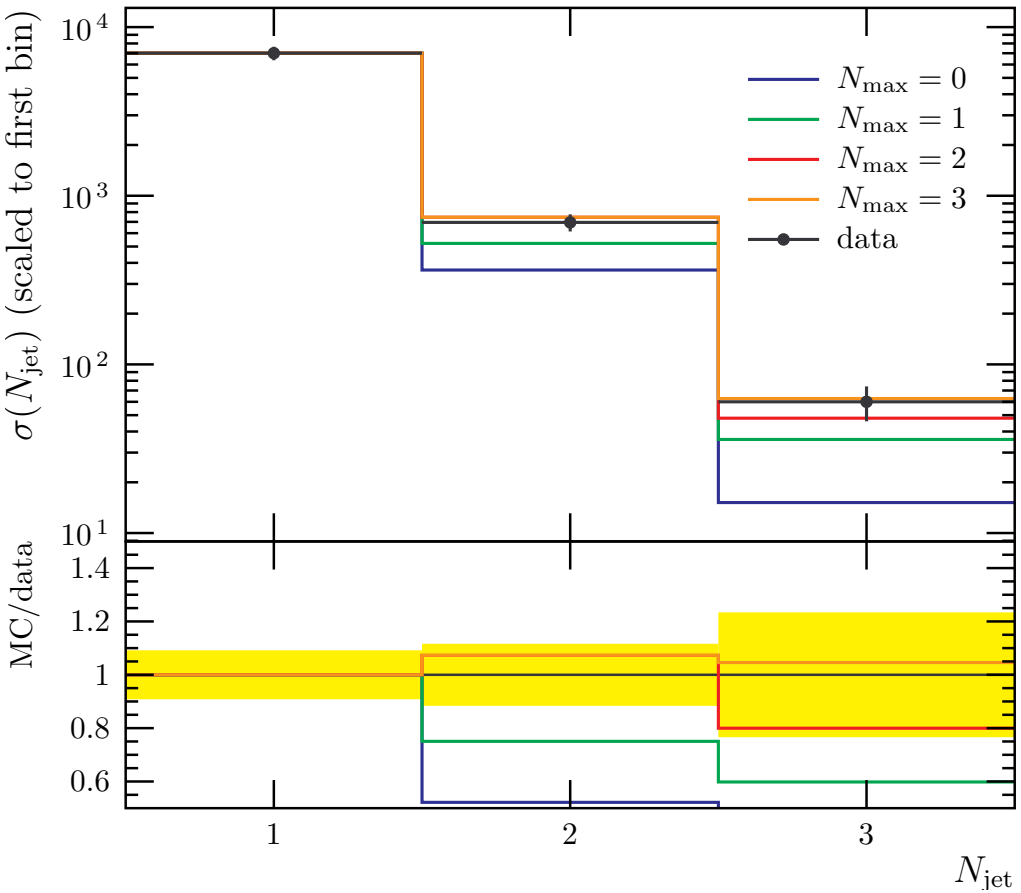


K. Hamilton, P. Richardson, J. Tully, JHEP 0911:038,2009.

Hadron level with matching uncertainty band vs OPAL.

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 MC and NLO

$$\langle O \rangle_{\text{MC@NLO}} = O(0) \left[B + \bar{V} + \int_0^1 dx \, \frac{P(x) - A(x)}{x} \right] + \int dx \, O(x) \frac{R(x) - P(x)}{x} \, .$$

Observations/remarks:

- Events with n and $n+1$ legs are seperately finite. No cancellation of large weights.
- NLO result can be recovered strictly upon expansion in powers of α (with parton shower emission).
- Interface to MC program very well defined.
- Dropping $\mu \to 0$ is only a power correction.

Matching MC and NLO

$$\langle O \rangle_{\text{MC@NLO}} = O(0) \left[B + \bar{V} + \int_0^1 dx \, \frac{P(x) - A(x)}{x} \right] + \int dx \, O(x) \frac{R(x) - P(x)}{x} \, .$$

Three types of matching

1. MC@NLO (classic, Frixione and Webber).
2. Simpler: parton shower with $P(x) = A(x)$.
3. Or, also simpler, $P(x) = R(x)$.

Matching MC and NLO

$$\langle O\rangle_{\text{MC@NLO}} = O(0)\left[B+\bar{V}+\int_0^1 dx\,\frac{P(x)-A(x)}{x}\right] + \int dx\,O(x)\,\frac{R(x)-P(x)}{x}\,.$$

1. Classic MC@NLO (Frixione and Webber)
   - $A(x) =$ FKS subtraction terms
   - $P(x)$ and phase space specific for HERWIG.
   - Generic, calculate once and for all.
     (Usually, $A(x)$ and $P(x)$ factorize off B.)
   - New for every process.

Matching MC and NLO

$$\langle O \rangle_{\text{MC@NLO}} = O(0) \left[B + \bar{V} + \int_0^1 dx \, \frac{P(x) - A(x)}{x} \right] + \int dx \, O(x) \frac{R(x) - P(x)}{x} \, .$$

2. 'Custom' parton shower
e.g. with Catani–Seymour subtraction kernels

- CS subtraction already used in many NLO calculations.
- $P(x) = A(x)$, so terms vanish.
- $R(x) - A(x)$ already in NLO parton level program.

$\Rightarrow$ (almost) no need to modify NLO calculation!

Matching MC and NLO

$$\langle O\rangle_{\text{MC@NLO}} = O(0)\left[B+\bar{V}+\int_0^1 dx\,\frac{P(x)-A(x)}{x}\right] + \int dx\,O(x)\frac{R(x)-P(x)}{x}\,.$$

3. Simpler in a different way, $P(x) = R(x)$
   - $R(x) - A(x)$ now only needed as integral available in NLO parton level program.
   - No $n+1$ body events.
   - ≥ 1 PS emission from $R(x)$ as splitting kernel $\rightarrow$`POWHEG`.
   - Positive weights (terms $\neq 0$ are $\sigma^{\text{incl}}_{\text{NLO}}$).
   - Further emissions from (truncated) standard PS.

MC@NLO

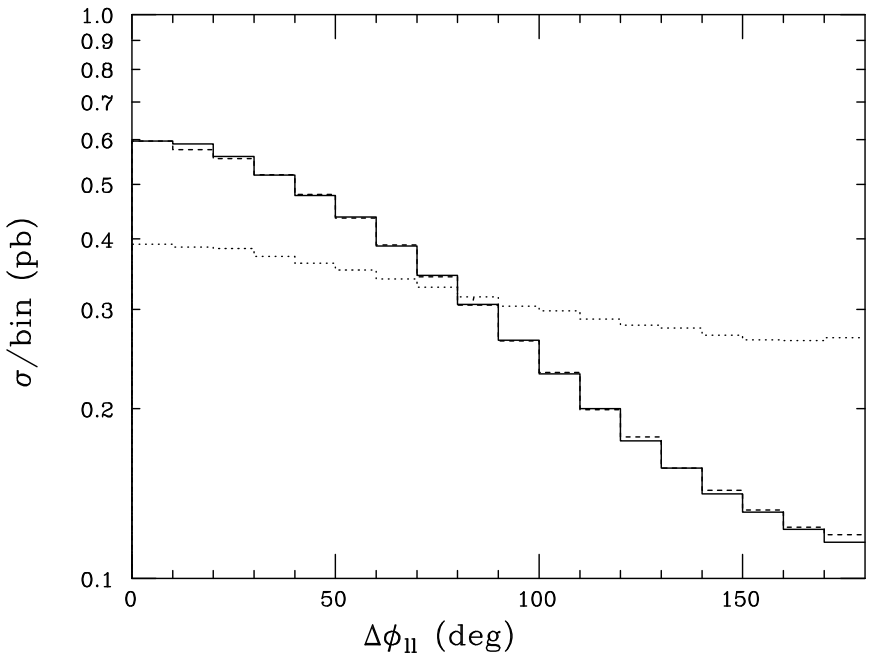
- Introduced 2002 Frixione, Webber, JHEP 0206:029,2002 [hep-ph/0204244].
- Extended to heavy quarks

  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

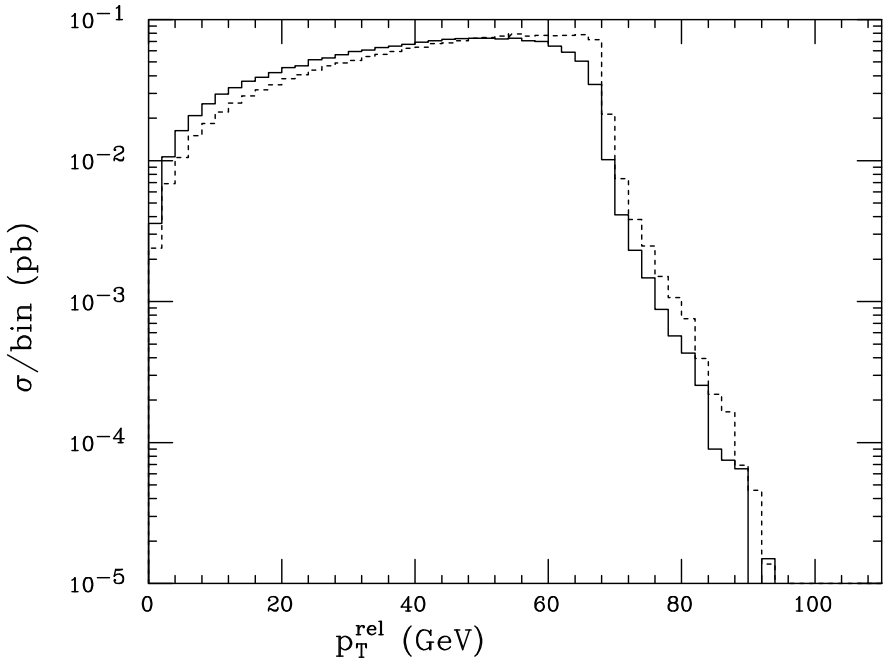
  Latunde–Dada 0708.4390, 0903.4135, Latunde–Dada, Papaefstatiou, 0901.3685.
- MC@NLO package adopted to Herwig++ as well.

  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.

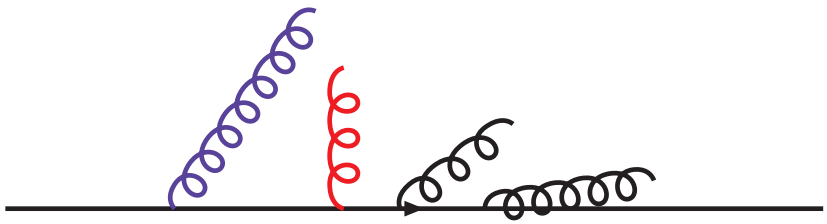
[Nason, hep-ph/0409146; Nason, Ridolfi hep-ph/0606275]

Recently systematically extended.

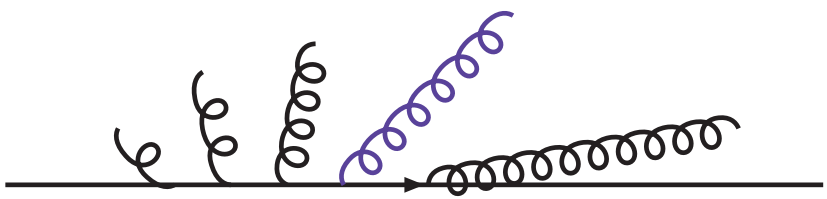
- `POWHEG` formulation independent of the event generator implementation.
- Worked out for different subtraction schemes.

[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]

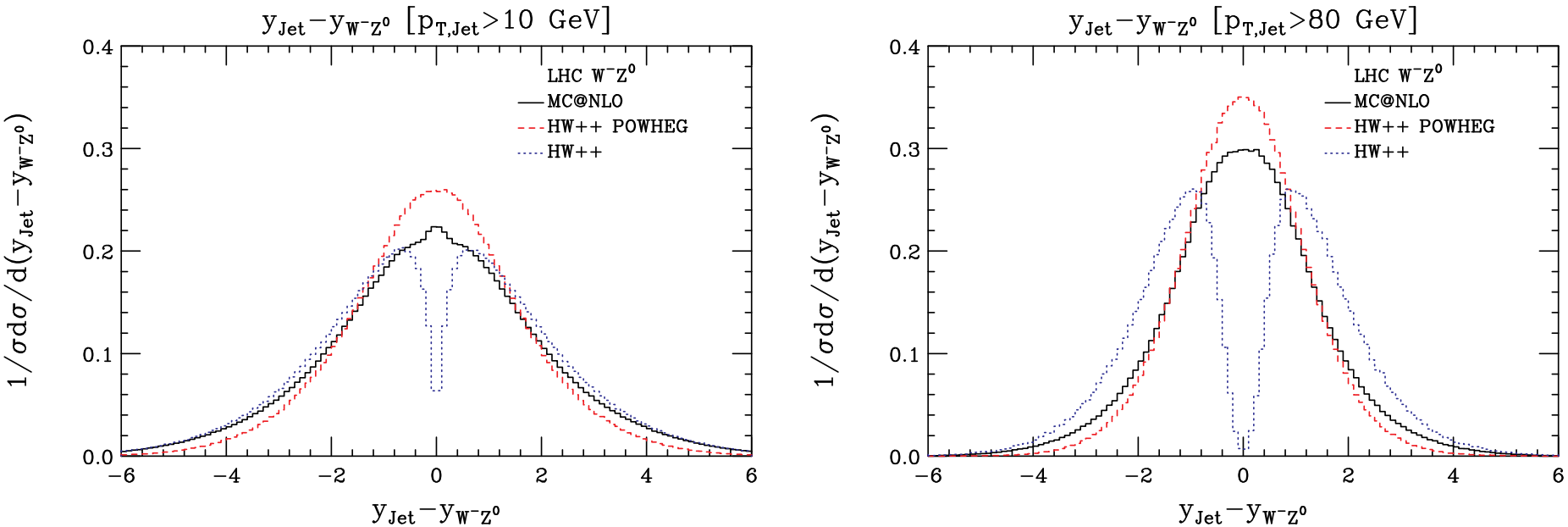
- and with contributed code:
  $e^+e^- \to \text{jets}, t\bar{t}, t-\text{decay}, W', h^0-\text{decay}$

  [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. . .).

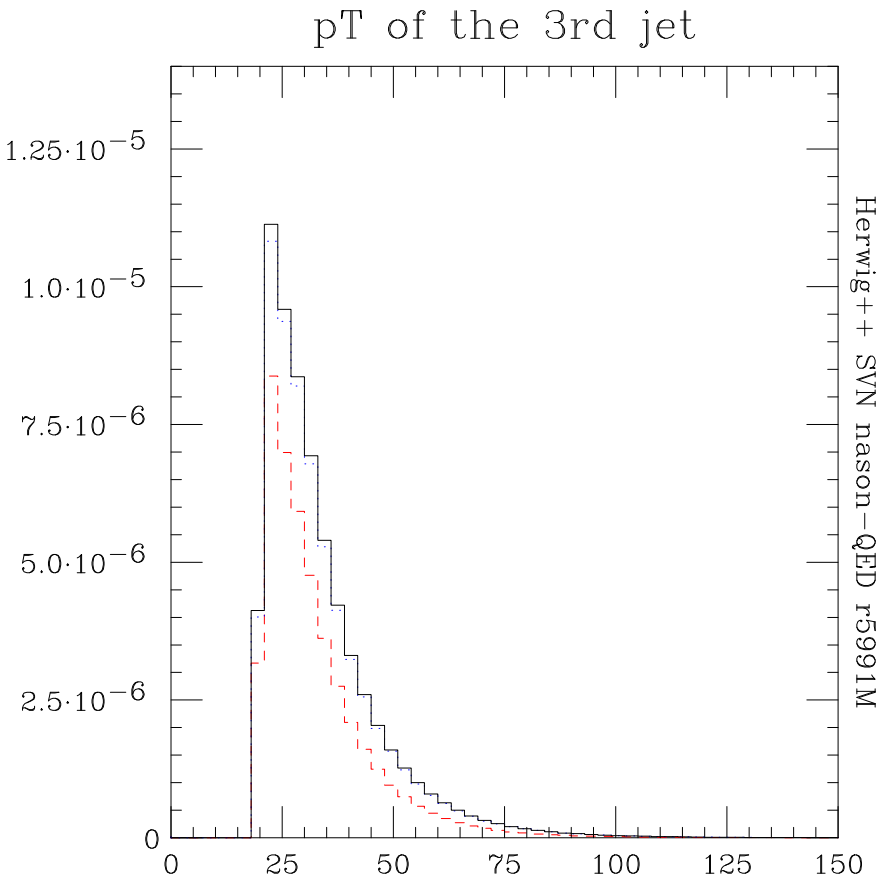
POWHEG in Herwig++ with full truncated shower.

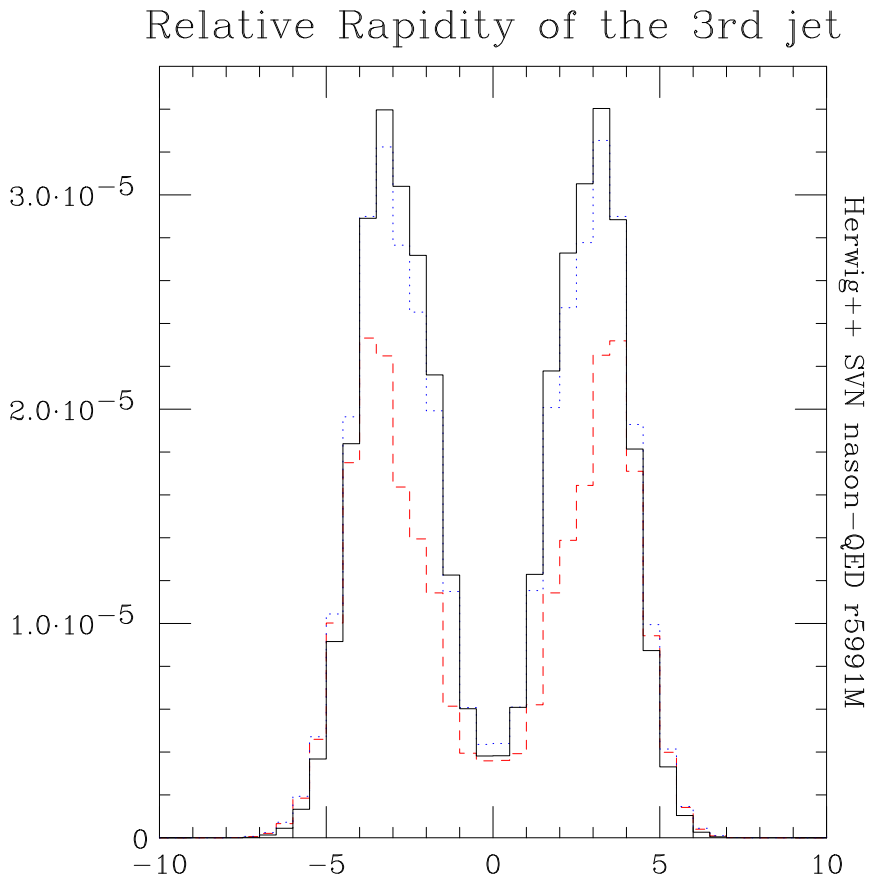


[K. Hamilton, JHEP 1101:009]

VV production. Phase space of radiated gluon properly filled.

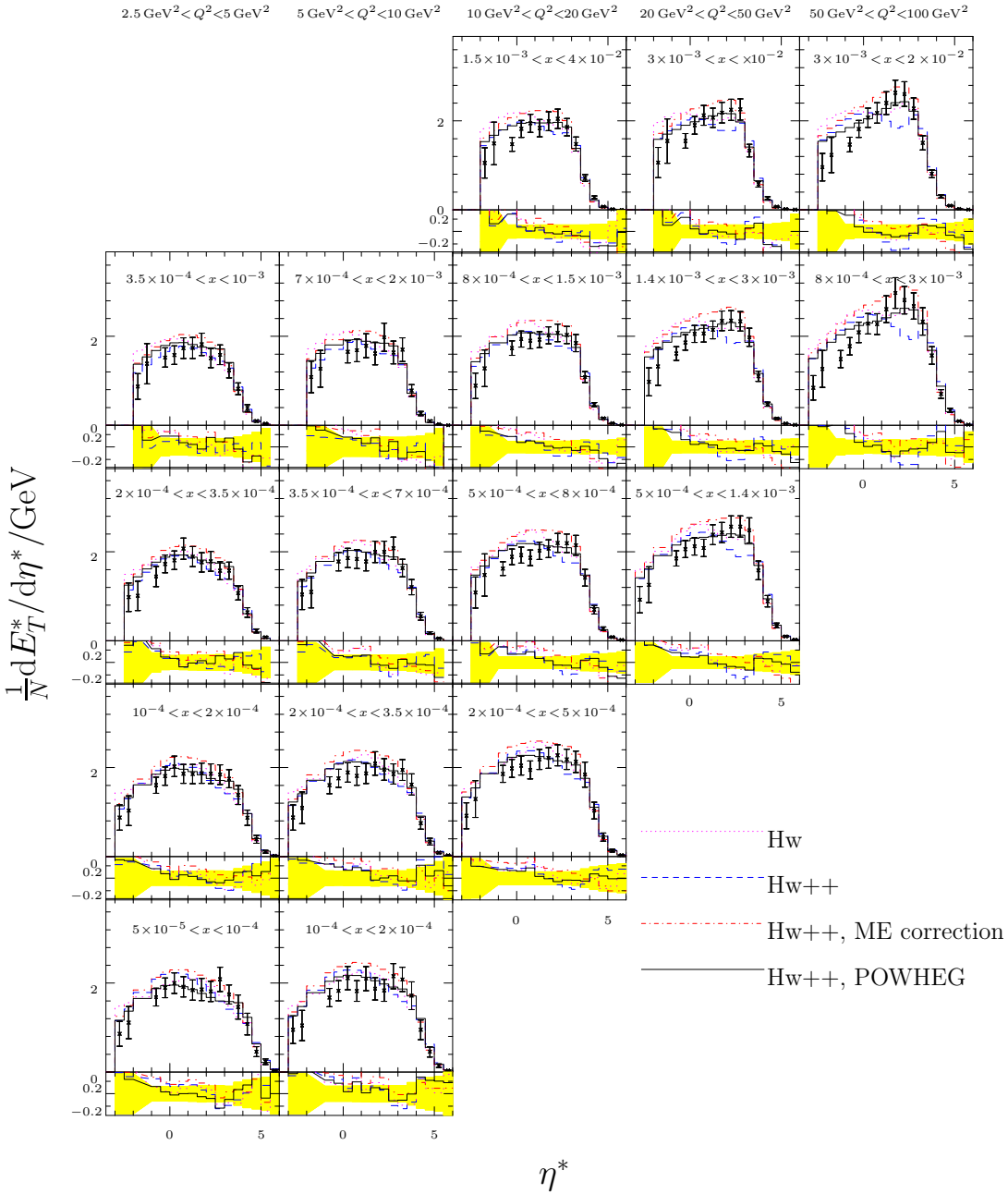
Higgs production in VBF. (POWHEG, MEC, LO+PS)





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

POWHEG in Herwig++

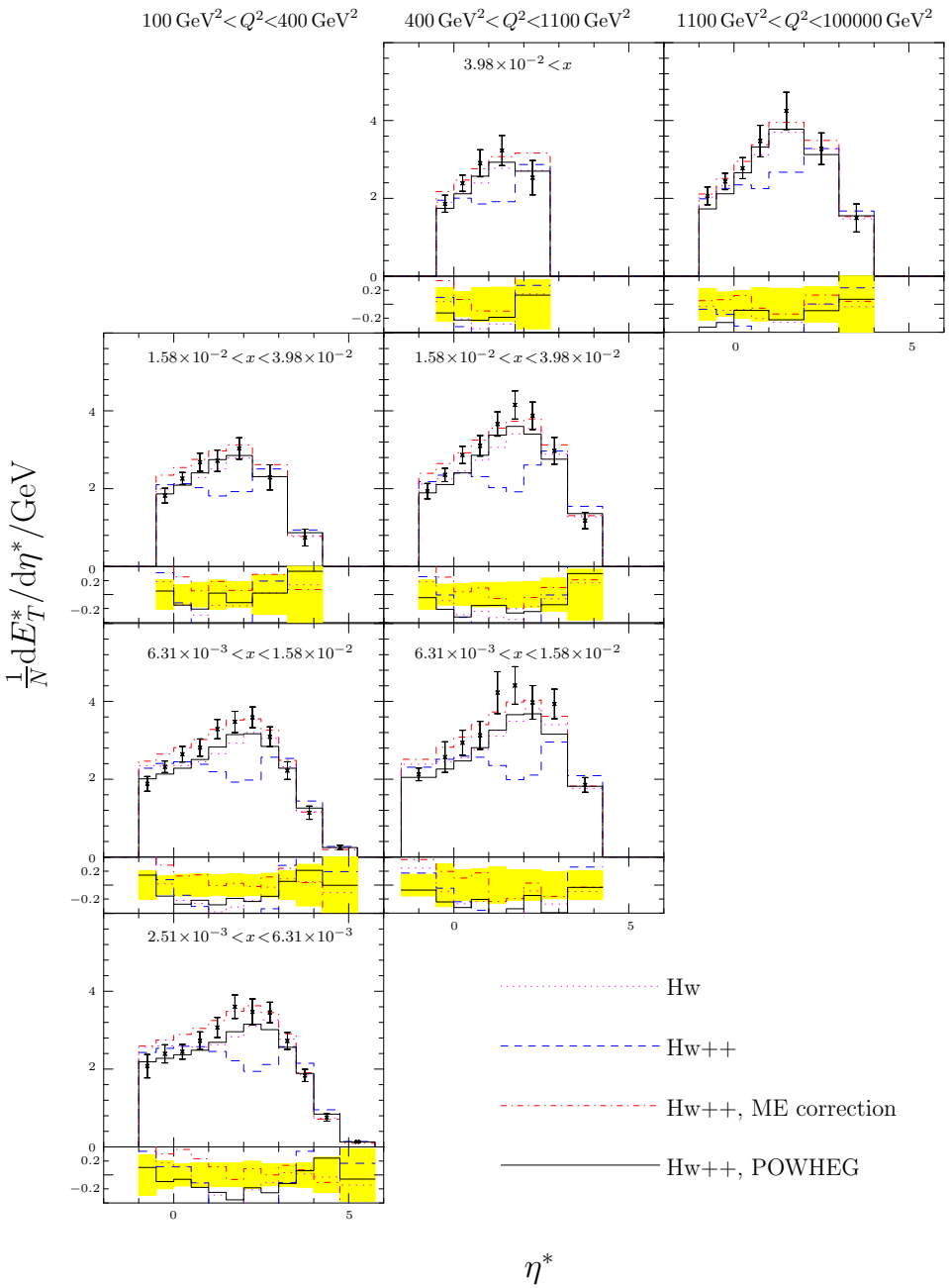


DIS transverse Energy vs H1 Data

[H1, EPJC 12 (2000) 595]

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

POWHEG in Herwig++



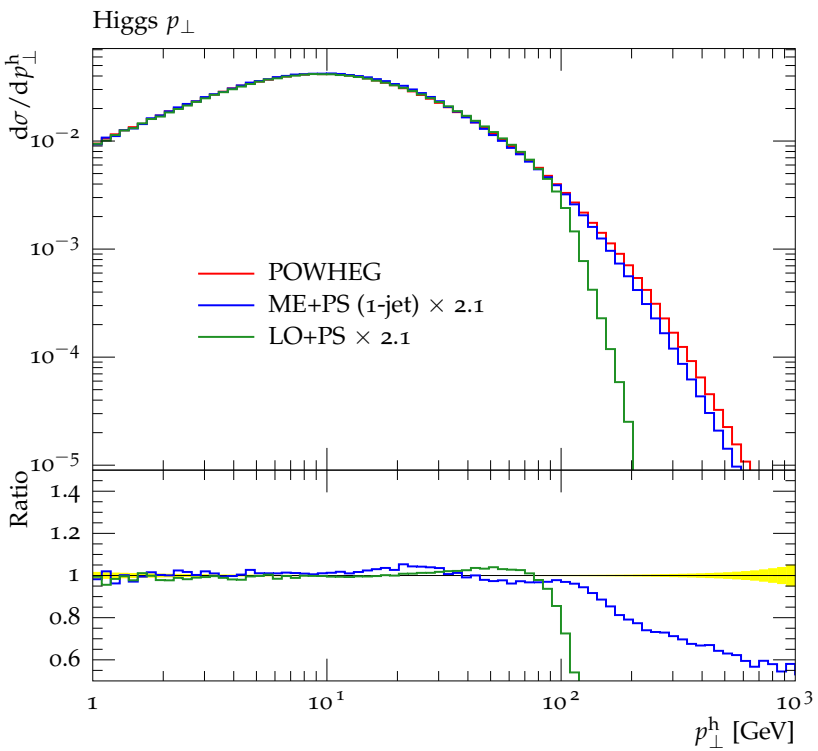
DIS transverse Energy vs H1 Data

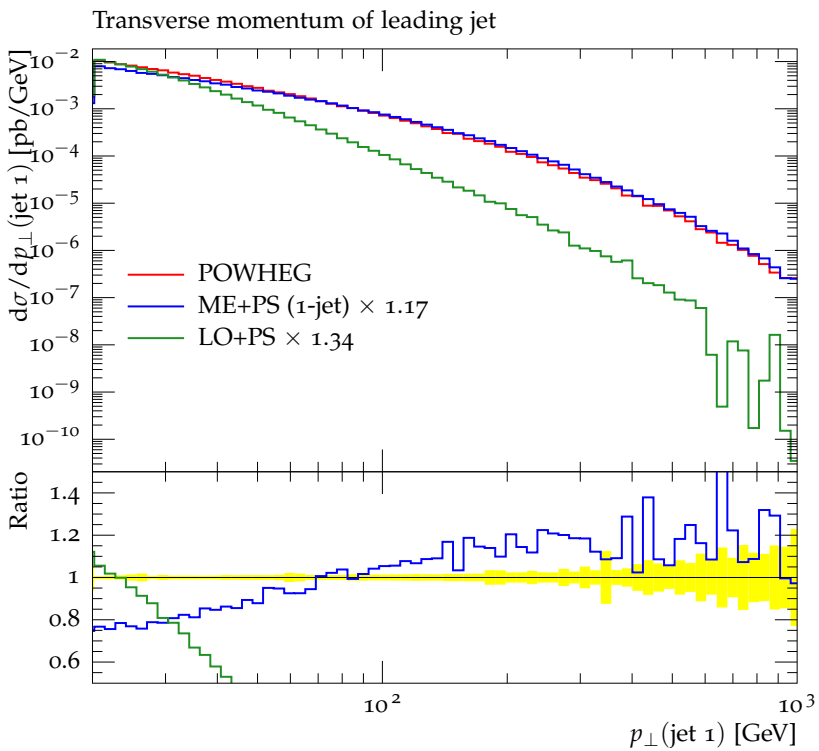
[H1, EPJC 12 (2000) 595]

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

NLO in Sherpa

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



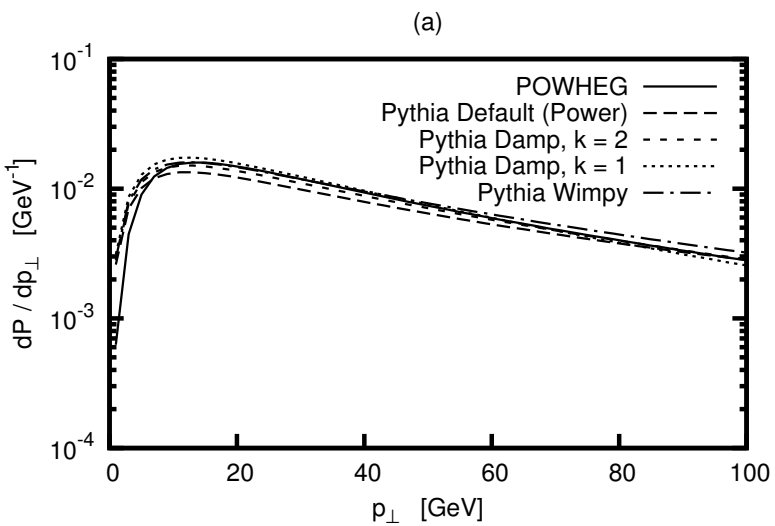


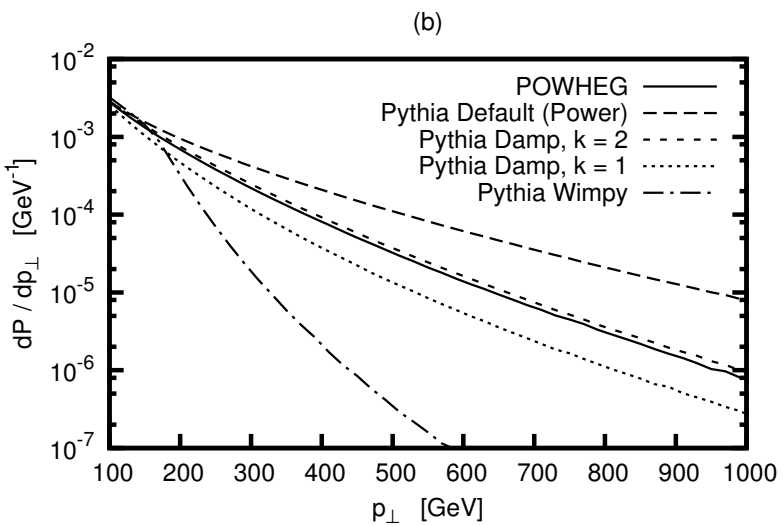
[Hoeche, Krauss, Schönherr, Siegert, JHEP 1104:024]

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

NLO in Pythia

- p_T-ordered shower $\rightarrow$ no truncated showers for POWHEG.
- Variants in phase space coverage more versatile. Interpolation between $1/p_t^2$ and $1/p_t^4$.

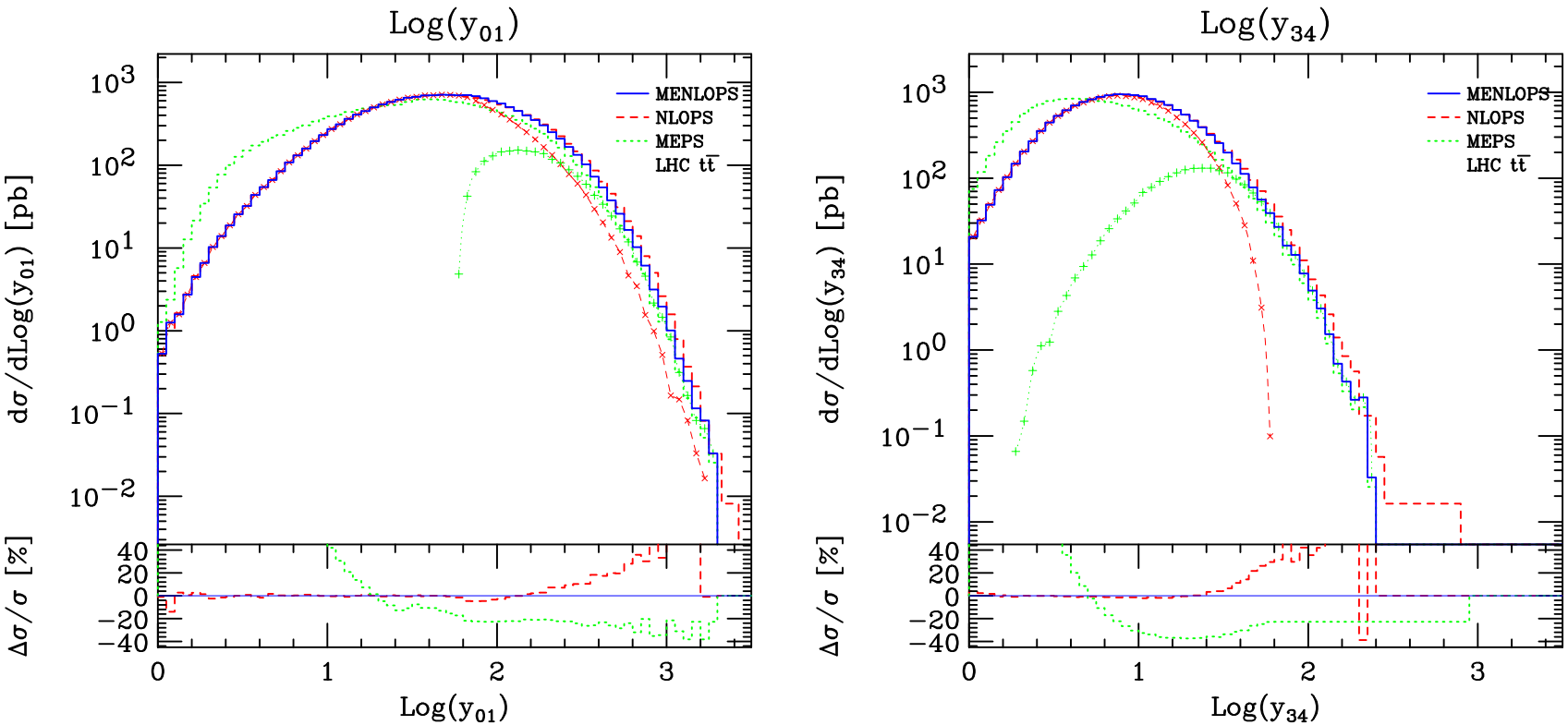




First emission off $t\bar{t}$ pair.

[R. Corke, T. Sjöstrand, EPJC69:1 (2010)]

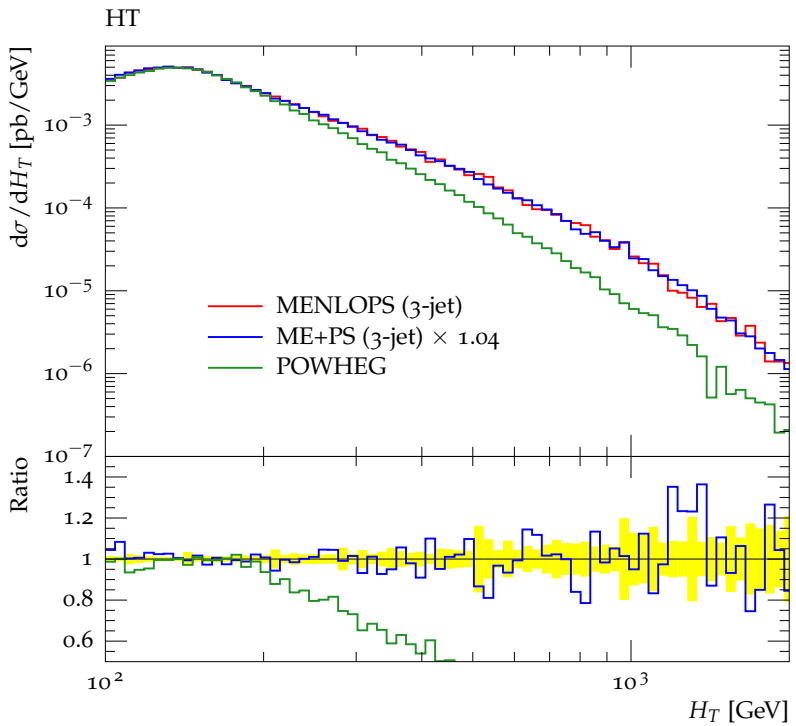
ME+PS merging with lowest multiplicity at NLO.

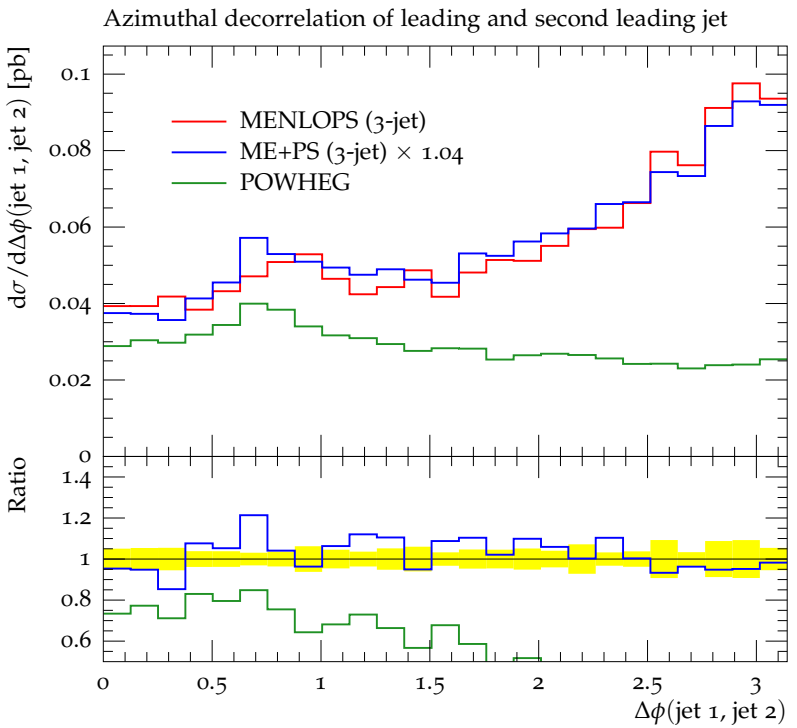


Test generic method with Pythia. y_{nm} in $t\bar{t}$+jets

[Hamilton, Nason, JHEP 1006:039]

ME+PS merging with lowest multiplicity at NLO.



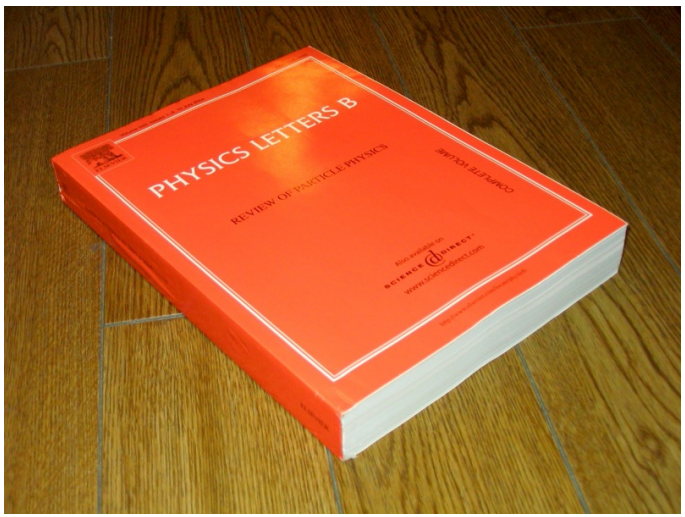


WW+jets implementation in Sherpa.

[Hoeche, Krauss, Schönherr, Siegert, 1009.1127]

Decays

- Herwig++ decays quite sophisticated
  - Specialized decayers for majority of channels. Mesons *and* baryons.
  - Up to 5-body decays.
  - Spin correlations.
  - Running widths.
  - Photon radiation off charged hadrons.



$\sim$ 500 particles and $\sim$ 6500 decay modes included.

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  - Up to 5-body decays.
  - Spin correlations.
  - Running widths.
  - Photon radiation off charged hadrons.
- Sherpa
  - Similar level of sophistication.
  - - less decay modes.
  - + Mixing in B decays with interference.
- Pythia
  - No spin correlations.
  - Relies on EvtGen.
  - Photons from PHOTOS.
  - τ decays from TAUOLA.

Min Bias/Underlying Event

Herwig++

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

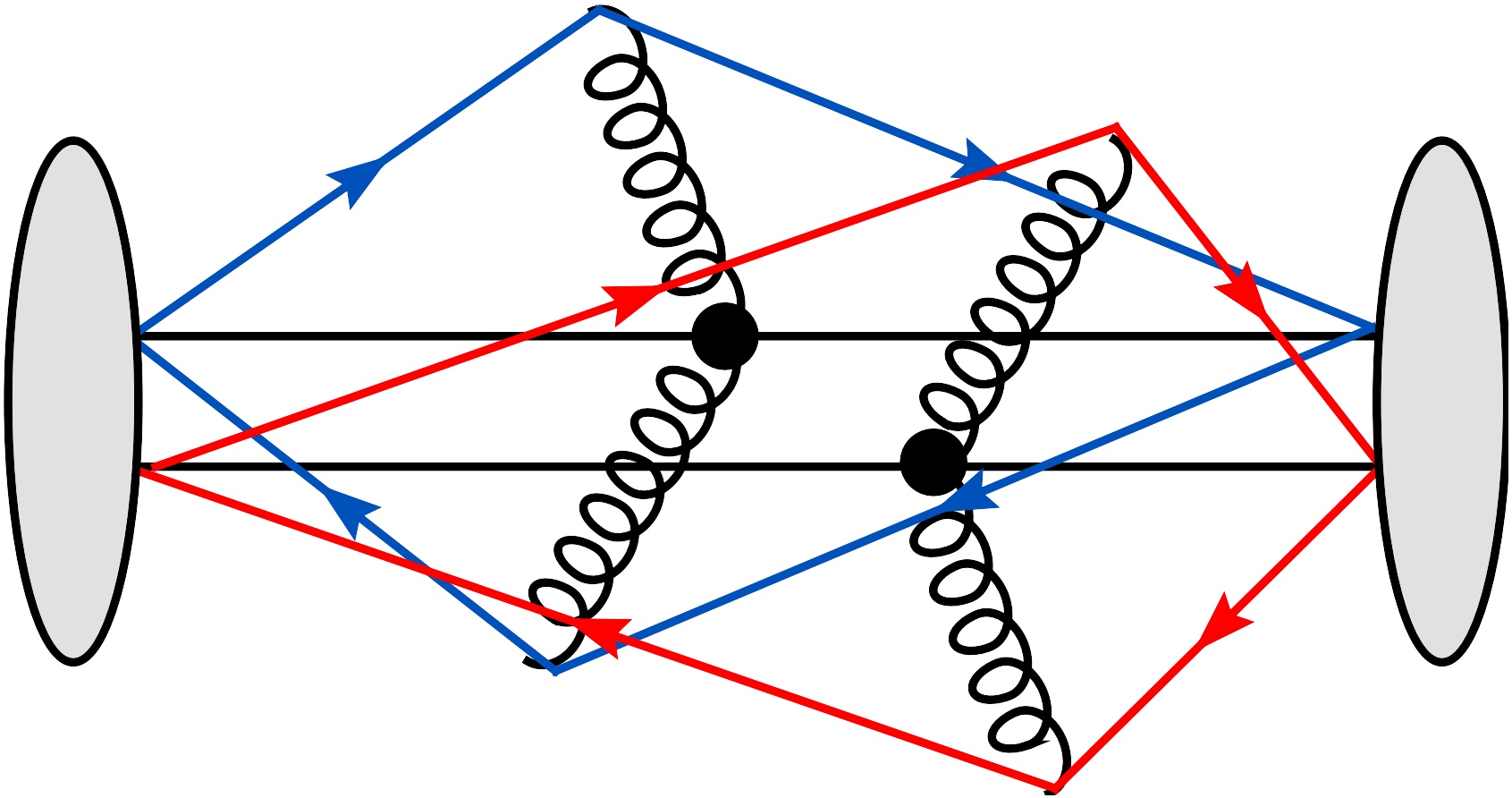
Pythia

MPI interleaved with showering. Many tune families.

Sherpa

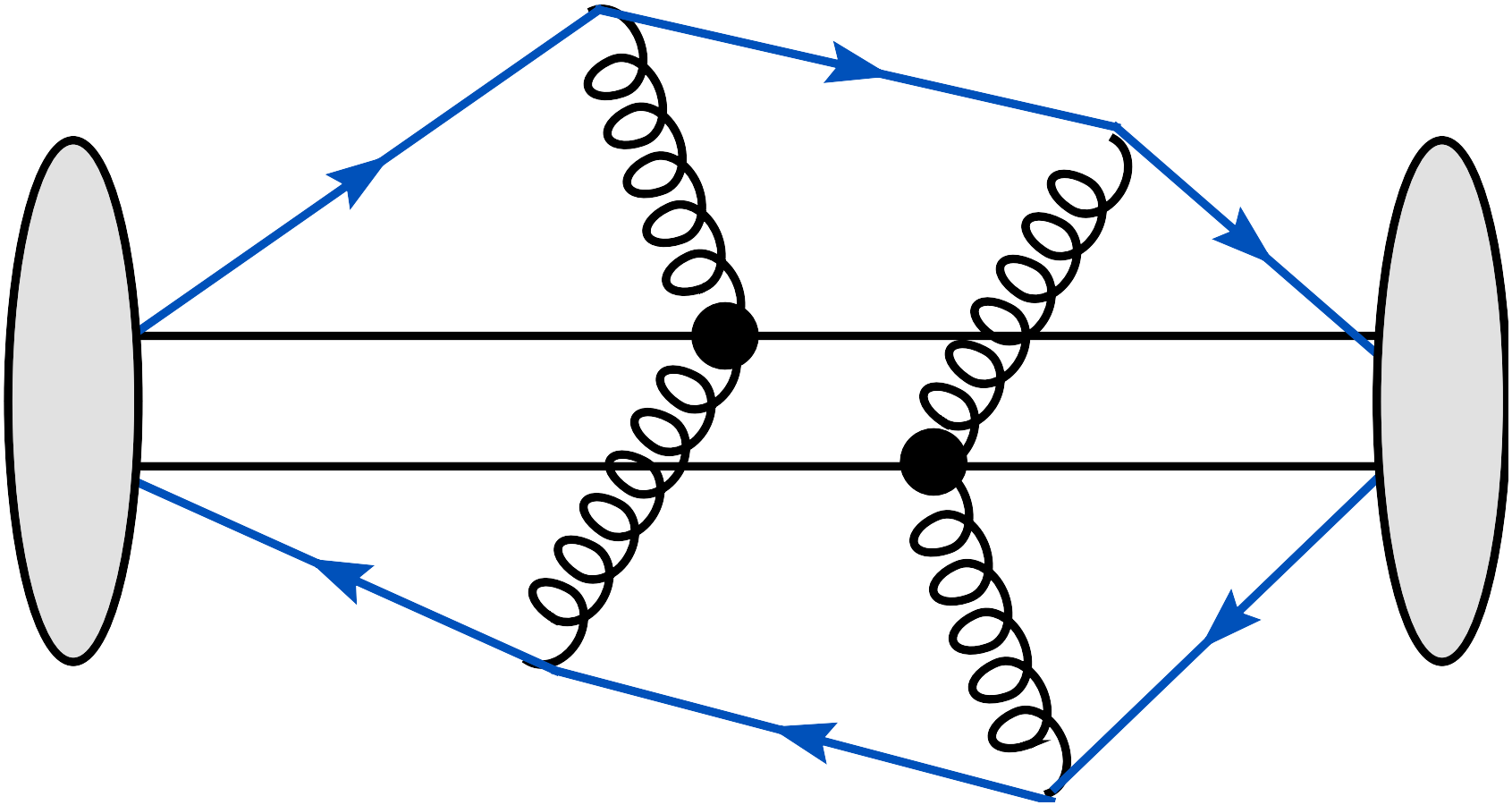
MPI model with independent hard processes. New model with integrated diffraction under development.

Colour reconnection at hadron colliders



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

Colour reconnection at hadron colliders



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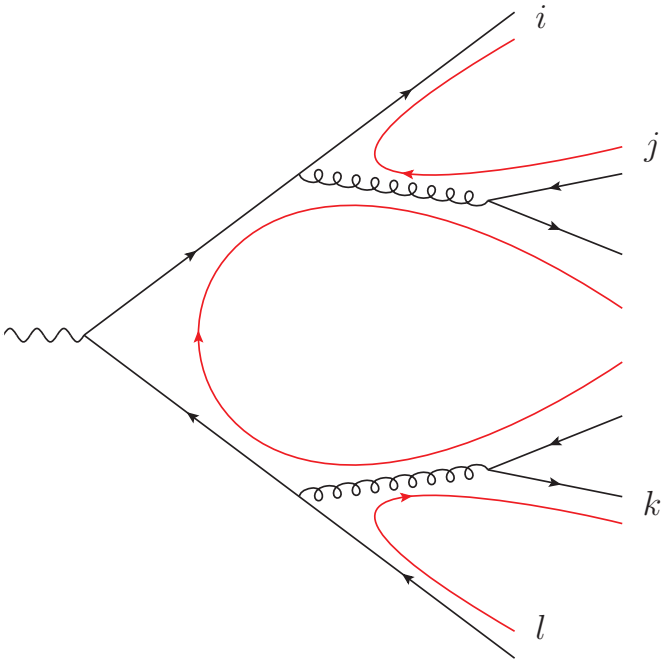
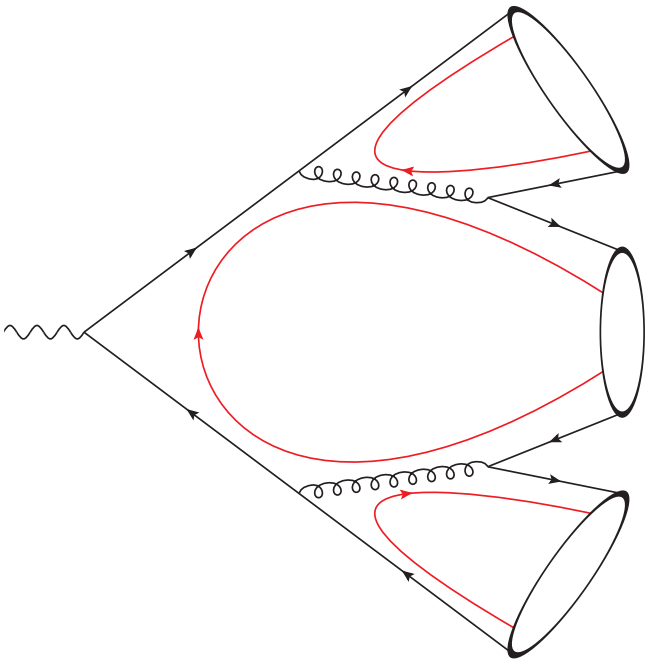
Colour reconnection (CR) in Herwig++



Extend cluster hadronization:

- QCD parton showers provide *pre-confinement* $\Rightarrow$ colour-anticolour pairs

Colour reconnection (CR) in Herwig++



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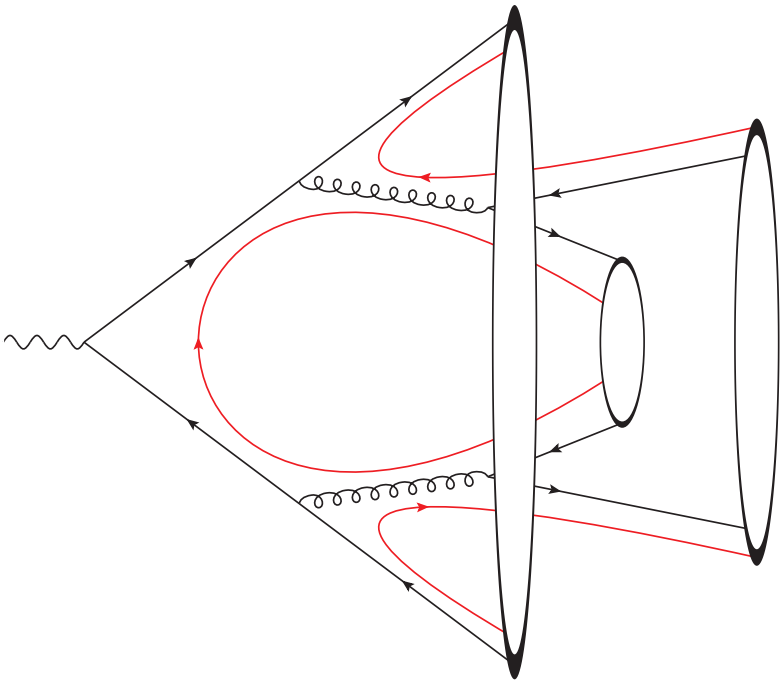

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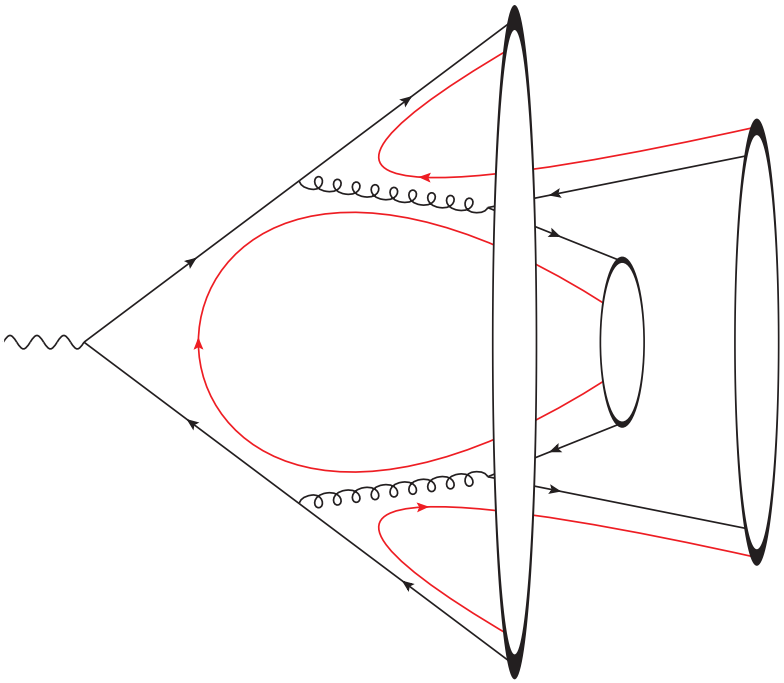
Colour reconnection (CR) in Herwig++



Extend cluster hadronization:

- QCD parton showers provide *pre-confinement* $\Rightarrow$ colour-anticolour pairs
- $\rightarrow$ *clusters*
- CR in the cluster hadronization model: allow *reformation* of clusters, *e.g.* $(il)+(jk)$

- Allow CR if the cluster mass decreases,

$$M_{il}+M_{kj}<M_{ij}+M_{kl},$$

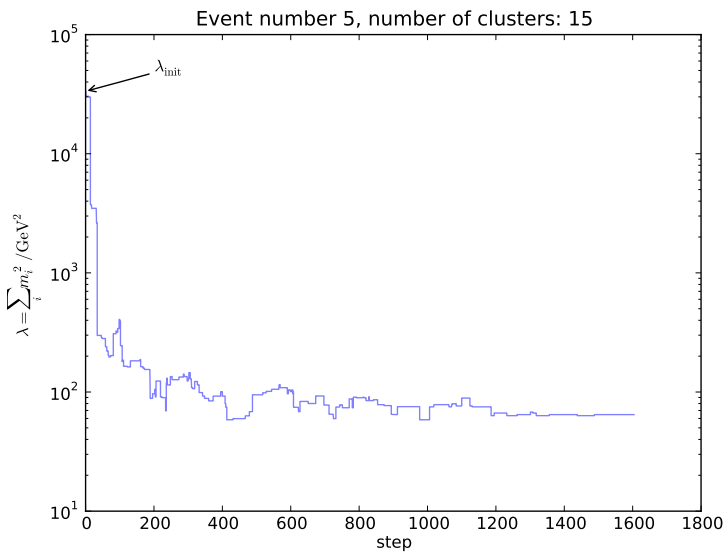
- Accept alternative clustering with probability p_{reco} (model parameter) $\Rightarrow$ this allows to switch on CR smoothly

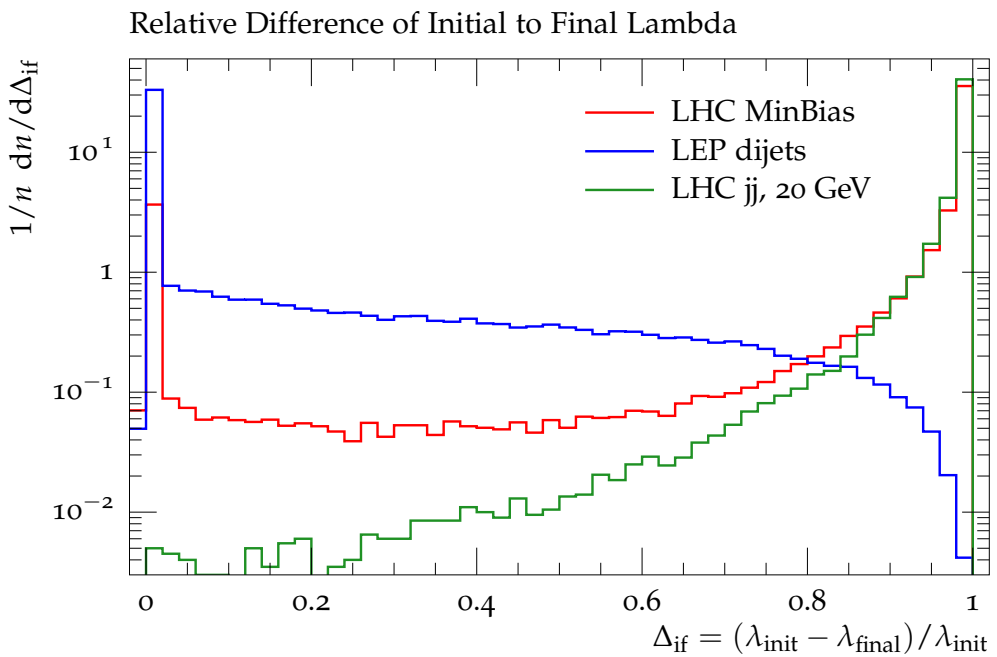
Also works with colour minimization based on Metropolis algorithm.

[SG, C. Röhr, A. Siodmok, in progress]

$$\lambda = \sum_{\text{clusters}} m^2_{\text{cluster}}$$

Very significant changes in event structure.

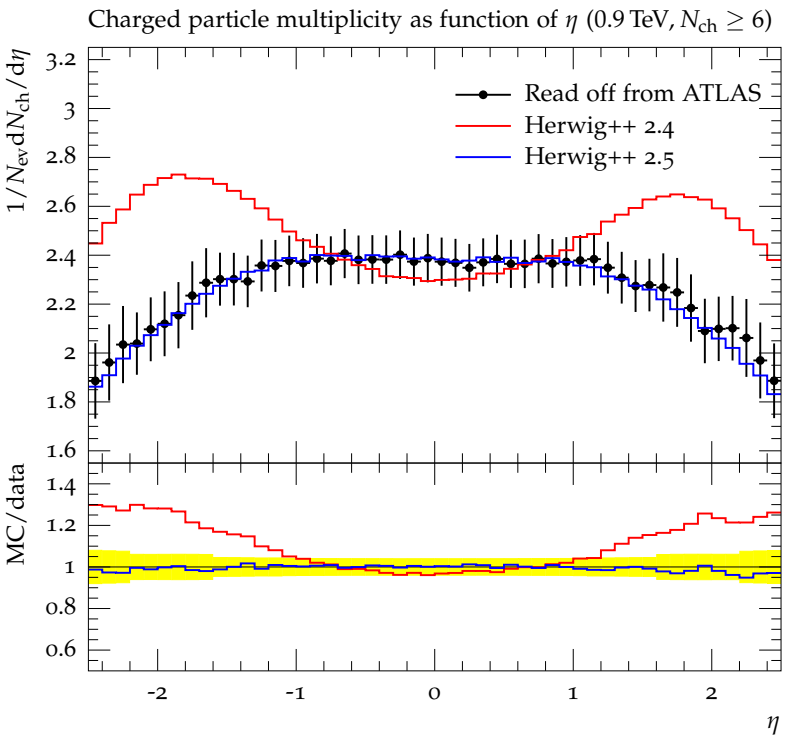


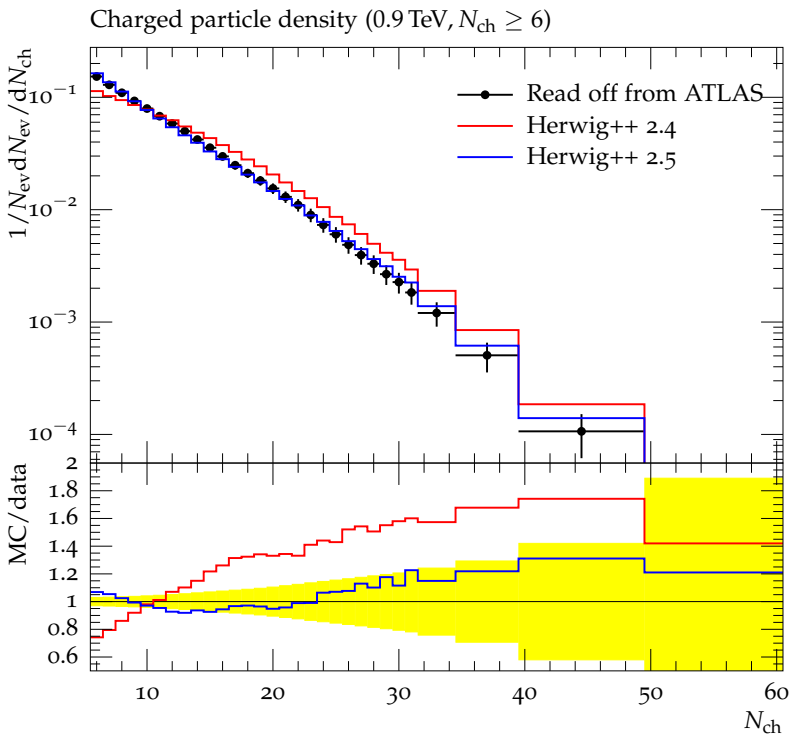


In almost all (hard) hadronic collisions.

Min Bias/Underlying Event in Herwig++

New colour reconnection model vital.



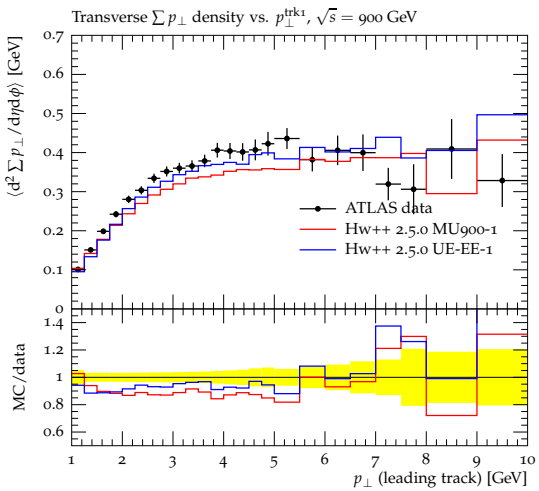


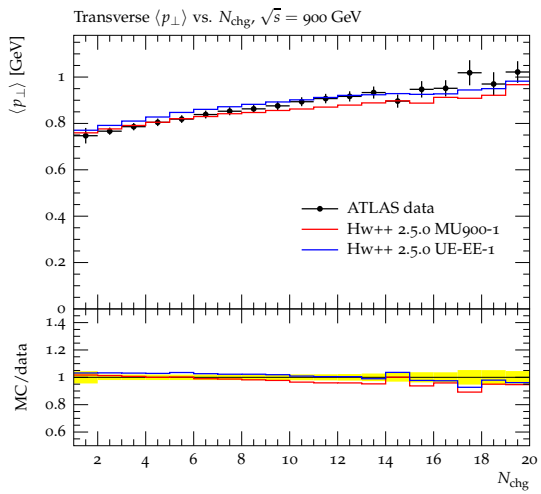
Min Bias/Underlying Event in Herwig++

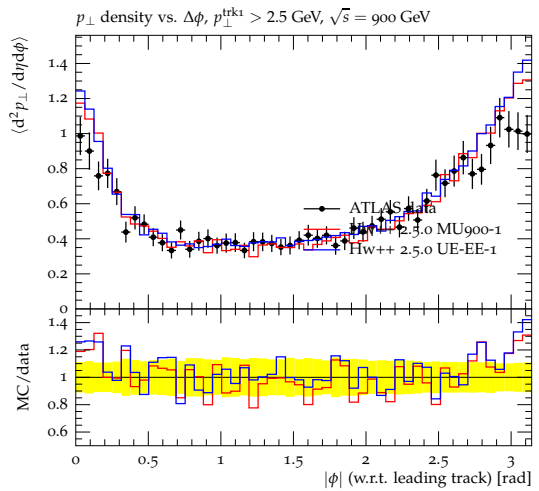
Tunes with only one energy dependent parameter possible

$\sqrt{s}$ dependence usually tricky.

LHC 900 GeV







Min Bias/Underlying Event in Herwig++

Tunes with only one energy dependent parameter possible
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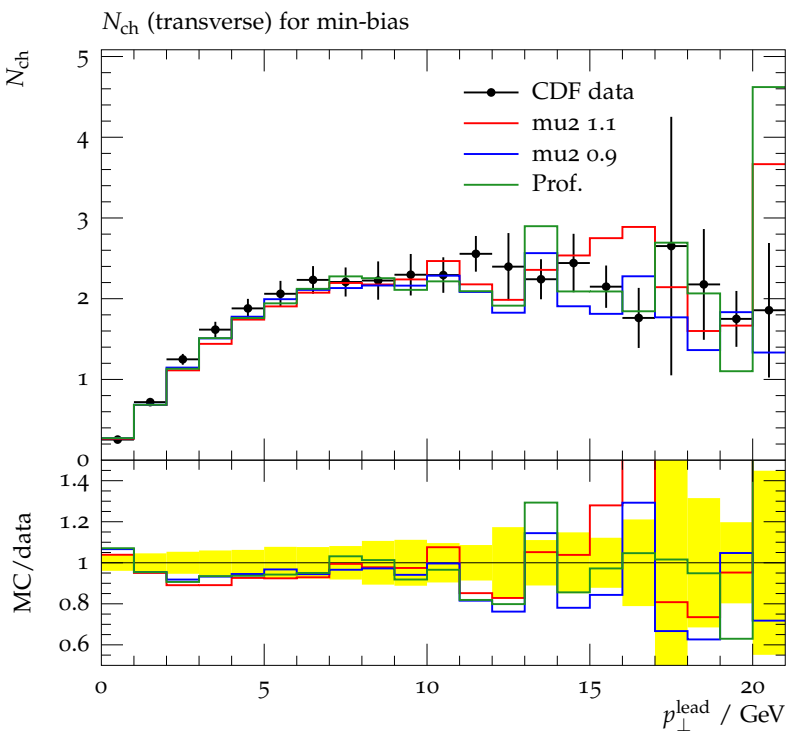
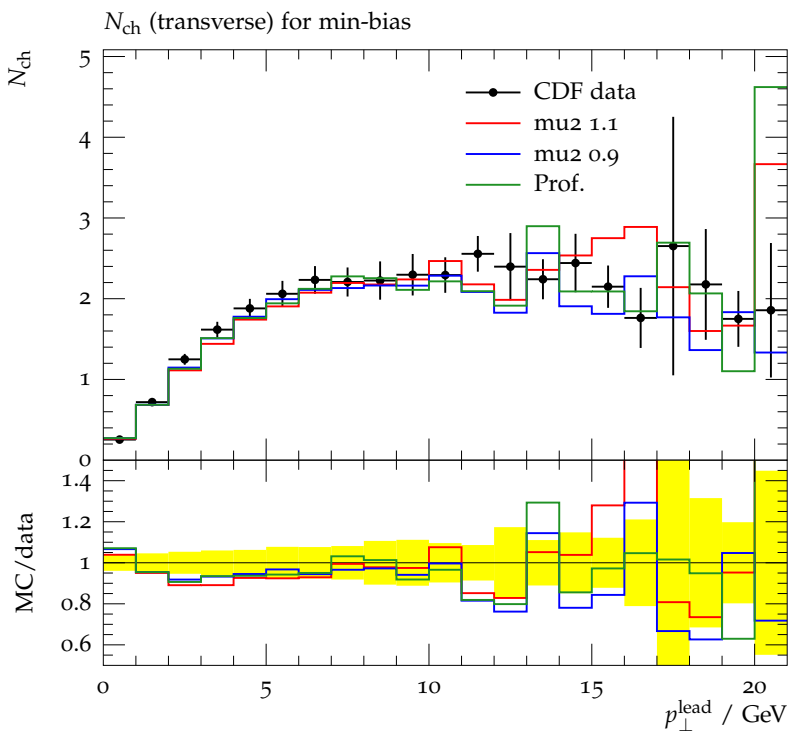
CDF Run I





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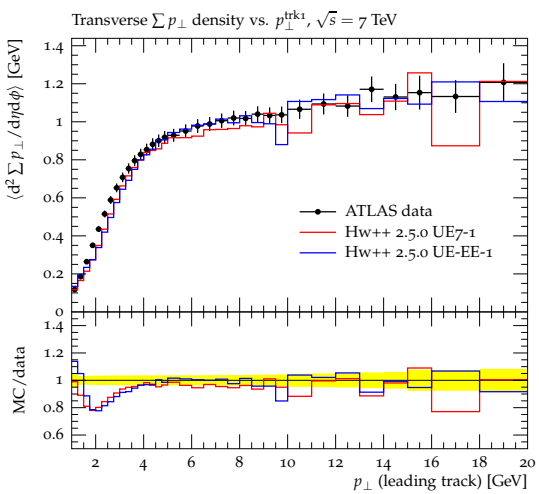
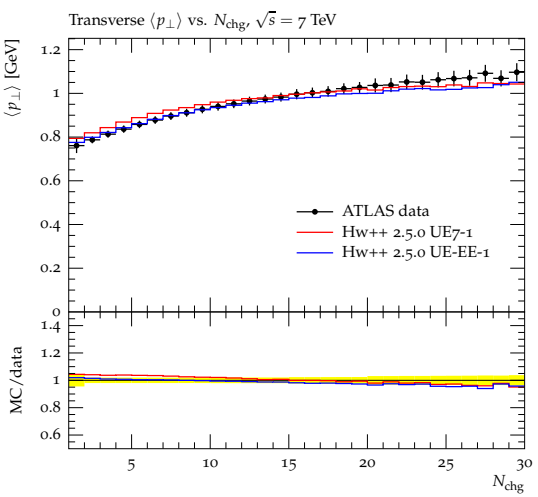
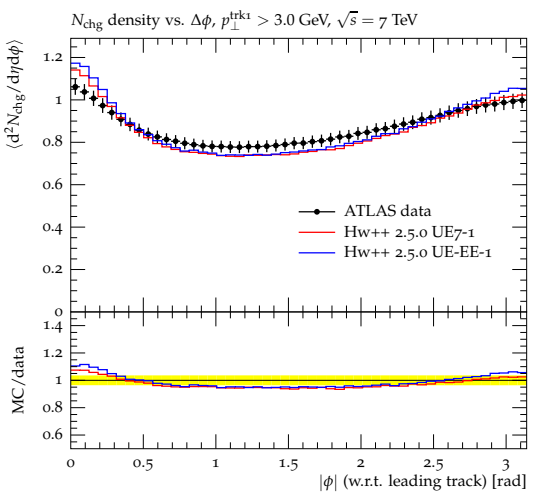
LHC 7 TeV



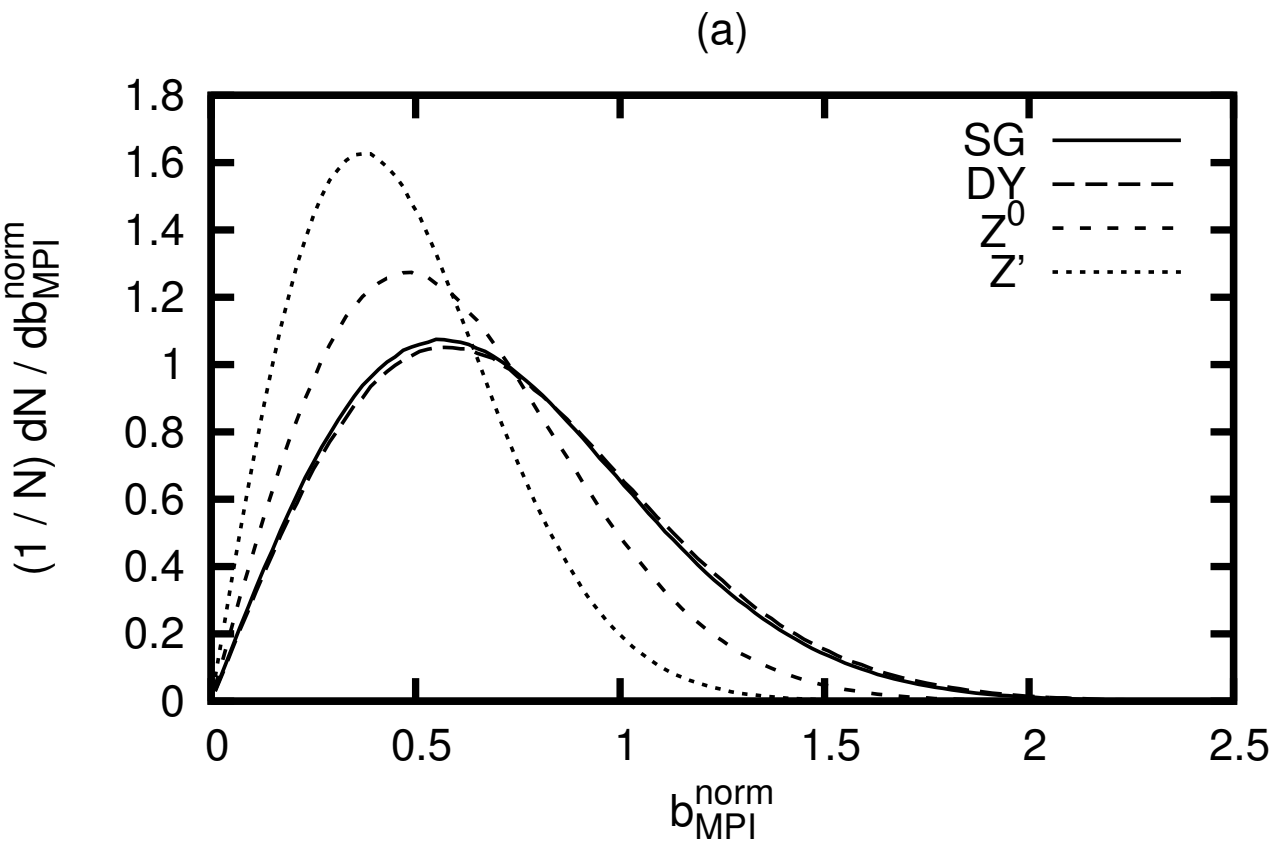




Min Bias/Underlying Event in Pythia

New development: x dependent matter distribution, i.e. Gaussian with x dependent width $a(x) = a_0(1 + a_1 \log 1/x)$.
$\rightarrow$ harder scattering more central.

[Corke, Sjöstrand, JHEP 1105:009]



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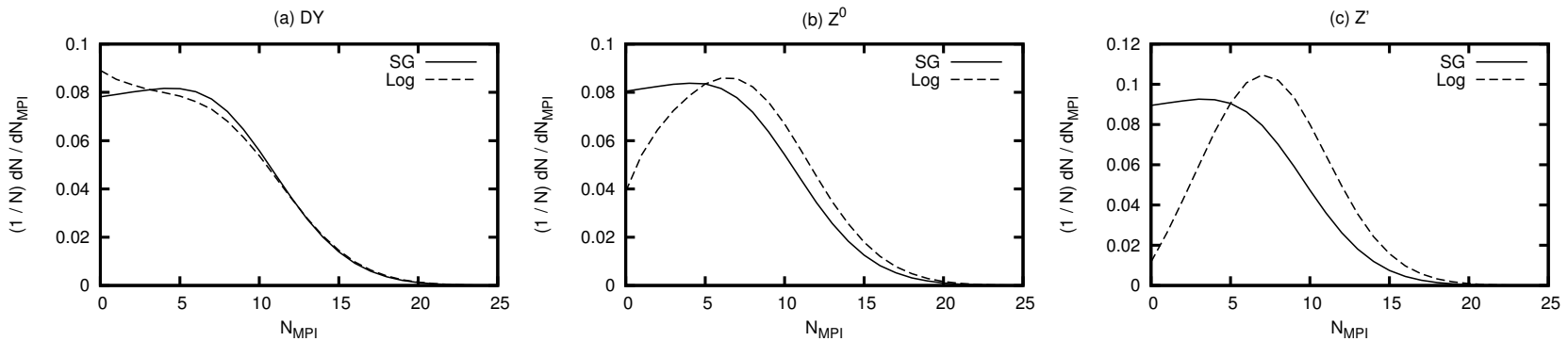

Results in $\langle N_{MPI} \rangle$ dependent on hardness.

Conclusion

- Tremendous amount of new developements in parton shower MCs.
- Parton showers well established.
- NLO for *many, many* processes available.
- MENLOPS NLO matching with many (tree) legs to become available as best of all worlds.
- New LHC results lead to new developments in MB/UE simulation. Good tunes available by now.
- Good first round of LHC data well described.