Herwig 7

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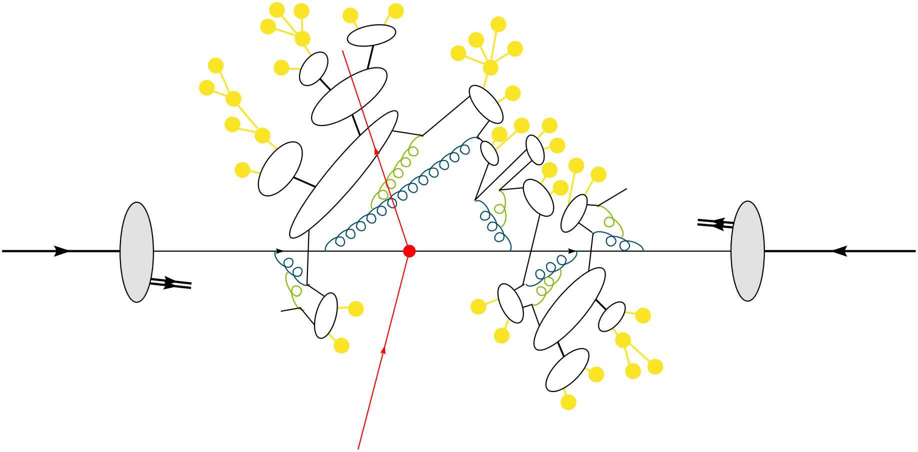
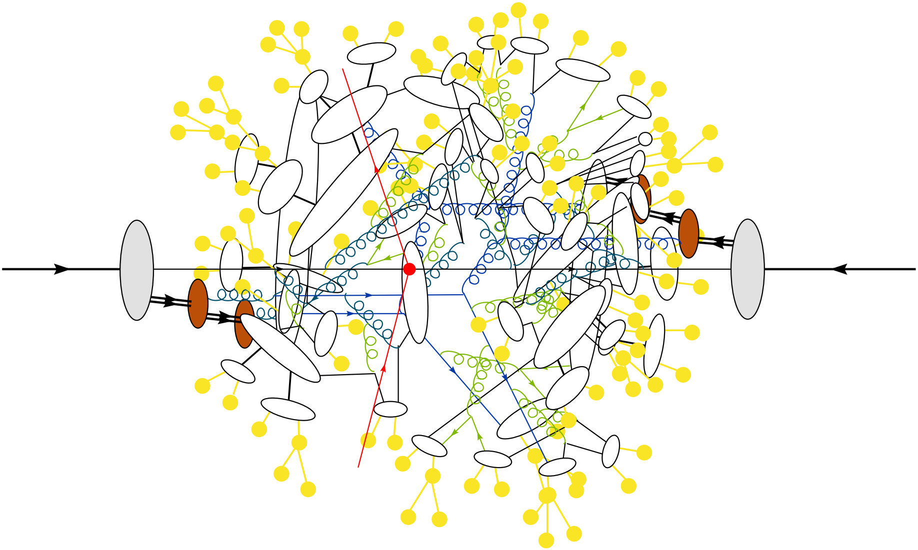
MCEGs for future ep and eA colliders
Regensburg, 22–23 Mar 2018

pp Event Generator



pp Event Generator



Recent History of Herwig

- HERWIG 6.5 last Fortran (2002), minor updates 2013.

  [Corcella et.al., hep-ph/0204123]

- Herwig++ 1.0. First C++ version, e^+e^- only.

  [SG, A. Ribon, P. Stephens, M.H. Seymour, B.R. Webber, JHEP 0402 (2004) 005]

- Herwig++ 2.0β– Herwig++ 2.7

  [SG et.al., Herwig++ 2.0 β Release Note, hep-ph/060206]

  [SG et al., Herwig++ 2.0 Release Note, hep-ph/0609306]

  [M. Bähr et al., Herwig++ 2.1 Release Note. 0711.3137]

  [M. Bähr et al., Herwig++ 2.2 Release Note. 0804.3053]

  [M. Bähr et al., Herwig++ 2.3 Release Note. 0812.0529]

  [SG et al., Herwig++ 2.5 Release Note. 1102.1672]

  [J. Bellm et al., Herwig++ 2.7 Release Note. 1310.6877]

  from simple *pp* collisions up to fully-fledged LHC event generation. Many 'in-house' NLO matched calculations.

- Now,

$$\tau(\text{Herwig++}) \approx \tau(\text{fHERWIG}) \gtrsim 15\,\text{years} .$$

Matrix elements and parton showers

Want best of both worlds.

Parton shower for soft+collinear radiation (intra jet).

Hard, large angle radiation from matrix elements (hard jets).

Higher accuracy from higher orders,
mostly NLO QCD corrections.

Herwig 7

New major release Herwig++ 3.0 aka Herwig 7.

Evolution of fHERWIG/Herwig++ subsumed as “7 > 6.5”.
“Better than fHERWIG in every aspect plus more”.

“NLO for all hard processes.”

[J. Bellm *et.al.*, Eur.Phys.J. C76 (2016), 196]

[Herwig 7.1 Release Note, arXiv:1705.06919]

Matchbox in Herwig 7

- Workinghorse of all NLO efforts in Herwig 7.
- Interfaces to various programs.
- Formalism and code to generate matched/merged events.

What's in Matchbox?

- Matching/merging formalism completely generic.
- Two showers
  - Angular ordered shower.
  - Catani–Seymour dipoles.
- Two matching formalisms
  - MC@NLO like.
  - POWHEG like.
- Many interfaces to (automatic) NLO programs.
- Automatic CS subtraction terms.
- Improved phase space.

ME Interfaces to Herwig

Everything pre-installed and called internally from Herwig!

- Amplitude level
  - Hand-coded MEs
  - Hjet++ [F. Campanario, T. Figy, S. Plätzer, M. Sjödahl]
  - MadGraph5 [MadGraph, SG, S. Plätzer, J. Bellm]
  - Colour correlations with ColourFull [S. Plätzer, M. Sjödahl]
- Squared amplitude level
  - GoSam [GoSam & J. Bellm, SG, S. Plätzer, C. Reuschle]
  - OpenLoops [OpenLoops & J. Bellm, SG, S. Plätzer]
  - NJet [NJet & S. Plätzer]
  - VBFNLO [VBFNLO & J. Bellm, SG, S. Plätzer]
- Some ME already built-in
  - Important SM processes
  - BSM internally with specified model
  - UFO interface
  - Spin correlations in 2- and 3-body decays.

[M. Gigg, P. Richardson, EPJ C51 (2007) 989]

Two parton showers

Angular ordered shower

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

- Angular ordering from $\tilde{q}$
- Phase space somewhat focused on collinear region
- No full coverage
- Colour coherence by construction

Dipole shower

[S. Plätzer, SG, EPJC72 (2012) 2187]

- Catani-Seymour dipoles
- NLO Matching inspired
- evolution in $p_\perp$
- full phase space
- Colour coherence

$\times$ two NLO matching schemes.

Merging with dipole shower.

Intrinsic systematic studies of parton shower uncertainties within one framework. [J. Bellm *et.al.*, EPJC76 (2016) 665]

Example results

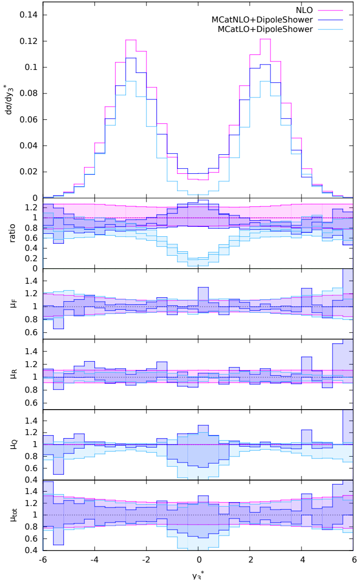
Not many serious studys of DIS with LHC-era event generators

Not many HERA results available in Rivet

Would give important insights also for current LHC studies

Use VBF-type processes as template for DIS type physics

VBF example



$W^+W^- + 2$jets NLO (VBFNLO+Herwig 7):

- $y^* = y_3 - \frac{y_1+y_2}{2}$
- Shower mostly forward.
- μ_R, μ_F ren./factorization scales.
- μ_Q shower scale.
- All varied by factor 2.

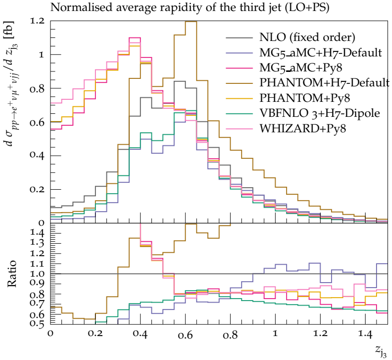
Extrapolation between central (hard) and forward (shower) region.

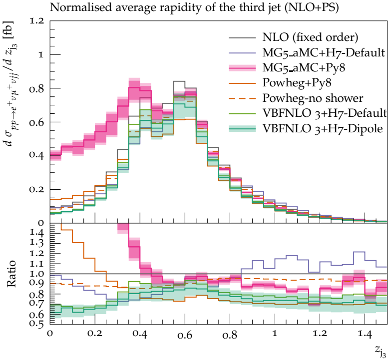
[M. Rauch, S. Plätzer, EPJC 77 (2017) 293]

VBF example

3rd jet in W^+W^+jj

$z_3 = \frac{|y_3 - \frac{y_1+y_2}{2}|}{|y_2-y_1|}$, $z_3 = 1/2$: alignment with tagging jet.





[VBSCAN (M. Rauch), to appear]

Unitarized Merging

New approach in Herwig++/Matchbox. [S. Plätzer, JHEP 1308 (2013) 114]

Idea: Approximation of Sudakov "$\Delta \approx 1 - \int BP$" violates parton shower unitarity. Replace BP by full LO matrix element also in reweighting of events.

Leads to unified NLO matching and (LO/NLO)-merging prescription [J. Bellm, SG, S. Plätzer, EPJC 2018]

Unitarized Merging

Consider parton shower acting on Born ME,

$$PS[B_0] = \Delta_\mu^0 B_0 + PS[P_1\, \Delta_0^1\, B_0]\ ,$$

iterate once,

$$PS[B_0] = \Delta_\mu^0 B_0 + \Delta_\mu^1\, P_1\, \Delta_1^0 B_0 + PS[P_2\, \Delta_2^1\, P_1\, \Delta_1^0\, B_0]\ ,$$

replace

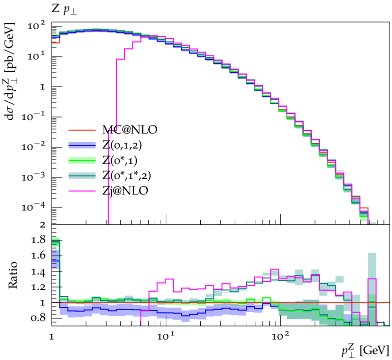
$$P_1\, B_0 \to \frac{\alpha_S(q_1)}{\alpha_S(q_0)} B_1\ ,$$

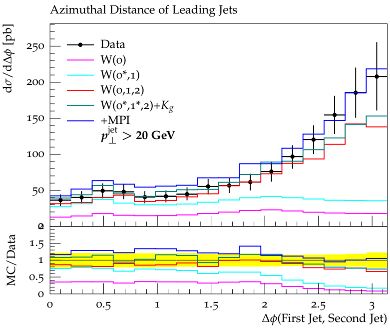
etc., but induces unitarity violation in Sudakov weights, so

$$\Delta_\mu^1 \approx 1 - P_1 B_0 \to 1 - \frac{\alpha_S(q_1)}{\alpha_S(q_0)} B_1\ .$$

Unitarized Merging

Z+jets, W+jets.



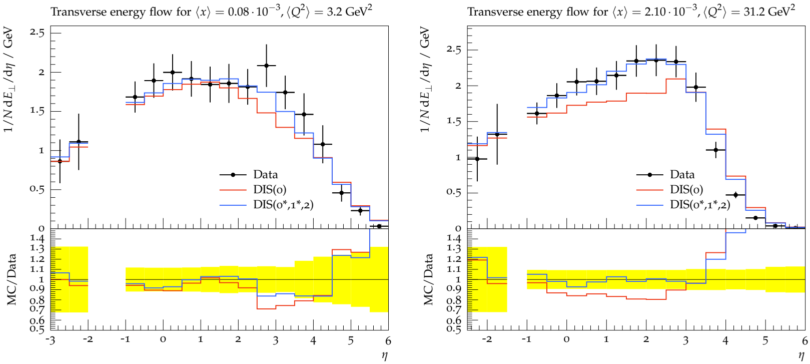


[J. Bellm, SG, S. Plätzer, EPJC 2018]

$Z(0^*, 1^*, 2) \to$ Zj@NLO in hard region. Soft region very stable.
$W(0^*, 1^*, 2)$ describes jet correlations. Still large MPI content.

Merging in DIS

$eq \to eq$ at LO and with NLO-merging vs H1 data.



[H1, EPJC12 (2000) 595]

Stabilization with higher orders.

MPI model

Multiple partonic interactions will become important in photo production events ($Q^2 \to 0$).
(Note: no photon pdf in latest LHAPDF!)

In Herwig:
hard MPI = multiple QCD $2 \to 2$ processes
soft MPI = production of soft particles (flat in y, narrow in $p_\perp$)
soft diffraction (with a hard tail...)

Good results for Min Bias and UE observables.

[M. Bähr, SG, M.H. Seymour, JHEP 0807 (2008) 076]

[SG, C. Röhr, A. Siodmok, EPJC72 (2012) 2225]

[SG, F. Loshaj, P. Kirchgaeßer, EPJC77 (2017) 156]

[SG, P. Kirchgaeßer, S. Plätzer, EPJC78 (2018) 99]

Overlap function

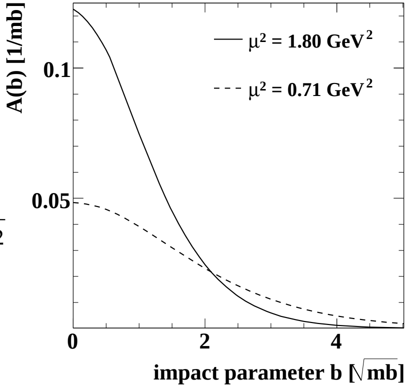
$$A(b) = \int \mathrm{d}^2\vec{b}' G_A(|\vec{b}'|) G_B(|\vec{b} - \vec{b}'|)$$

$G(\vec{b})$ from electromagnetic FF:

$$G_p(\vec{b}) = G_{\bar{p}}(\vec{b}) = \int \frac{\mathrm{d}^2\vec{k}}{(2\pi)^2} \frac{\mathrm{e}^{i\vec{k}\cdot\vec{b}}}{(1+\vec{k}^2/\mu^2)^2}$$

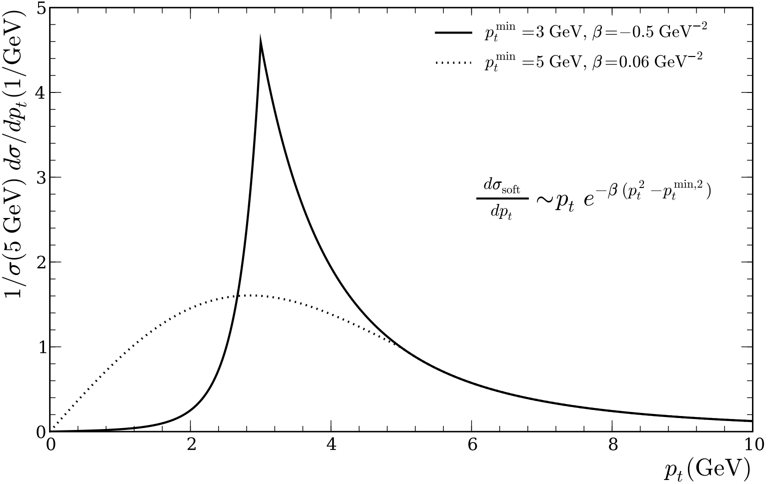
But μ^2 *not fixed* to the *electromagnetic* $0.71\,\mathrm{GeV}^2$.
Free for colour charges.

$\Rightarrow$ Two main parameters: $\mu^2, p_t^{\mathrm{min}}$.



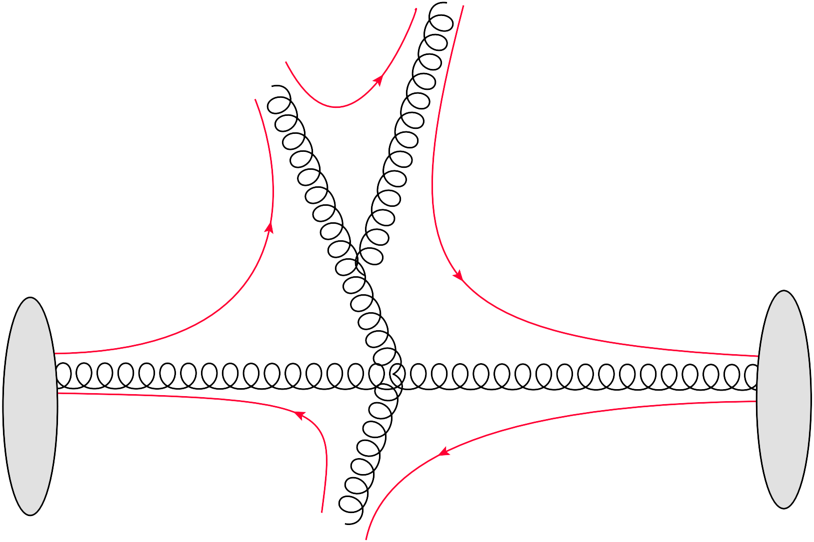
Extending into the soft region

Continuation of the differential cross section into the soft region $p_t < p_t^{\min}$ (here: p_t integral kept fixed)



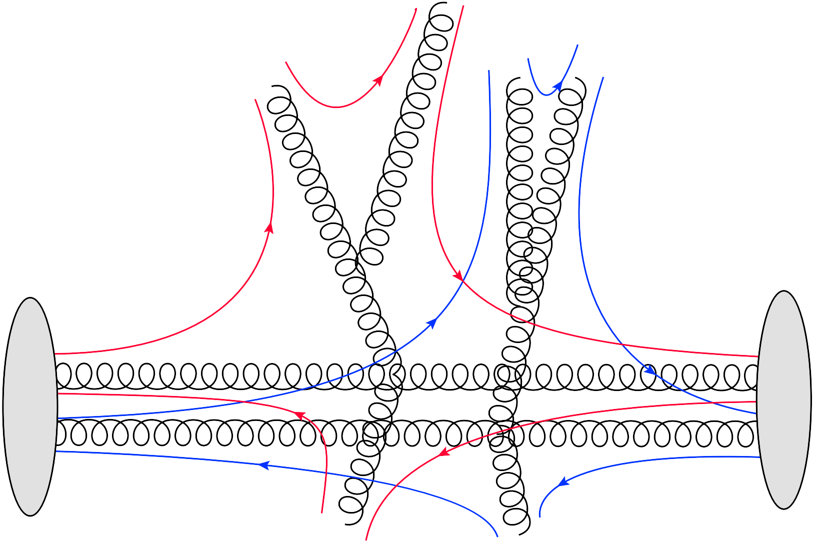
Colour Reconnection — idea

Two uncorrelated hard interactions



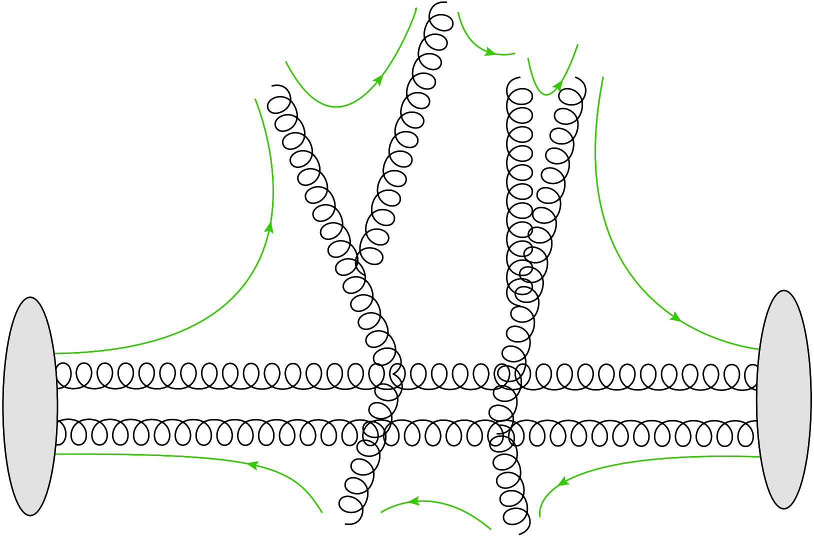
Colour Reconnection — idea

Two uncorrelated hard interactions



Colour Reconnection — idea

Possible rearrangement of colour lines with P_{reco}.



Diffractive final states

Strictly low mass diffraction only. Allow M^2 large nonetheless.

M^2 power-like, t exponential (Regge).

$$pp \to \text{(baryonic cluster)} + p \; .$$

Hadronic content from cluster fission/decay $C \to hh \ldots$
Cluster may be quite light. If very light, use directly

$$pp \to \Delta + p \; .$$

Also double diffraction implemented.

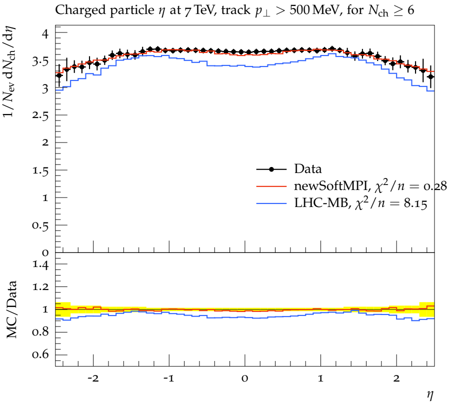
$$pp \to \text{(cluster)} + \text{(cluster)} \qquad pp \to \Delta + \Delta \; .$$

Technically: new MEs for diffractive processes set up.

Tuned results

ATLAS Min Bias 7 TeV.

[ATLAS, New.J.Phys. 13 (2011) 053033]

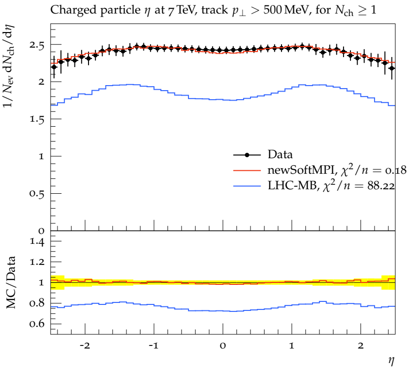


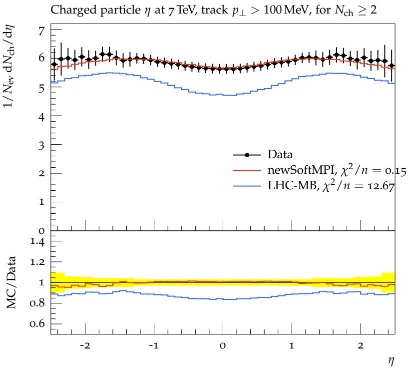
Similar to previous results, “harder part of Min Bias”.

H7

ATLAS Min Bias 7 TeV.

[ATLAS, New.J.Phys. 13 (2011) 053033]

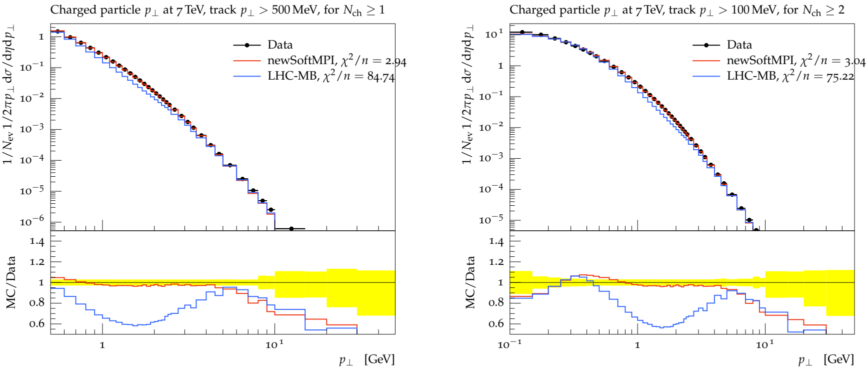




Also soft rates well described.

ATLAS Min Bias 7 TeV.

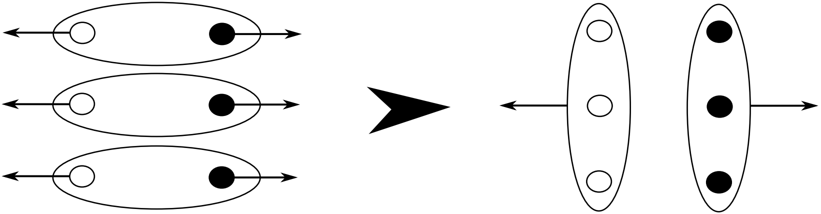
[ATLAS, New.J.Phys. 13 (2011) 053033]



Tails? Still within 1σ.

Rapidity based colour reconnection

Colour singlets not only from $q\bar{q}$ but also from qqq states



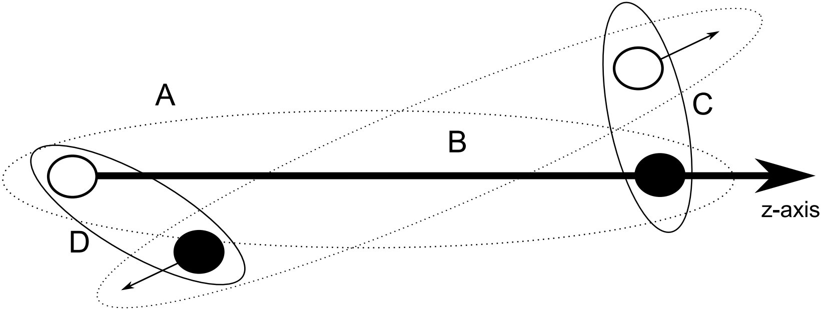
But, baryonic clusters would typically be much heavier

$$M_{ijk} + M_{lmn} > M_{il} + M_{jm} + M_{kn}$$

would always/often be reconnected into mesonic clusters.

Rapidity based colour reconnection

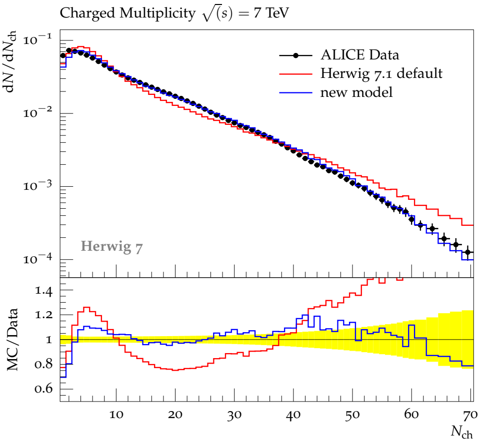
“Closeness” of quarks not based on invariant mass but on proximity in momentum space.



Consider other quarks’ movement based on their rapidity in reference clusters’ CM frame.

Results

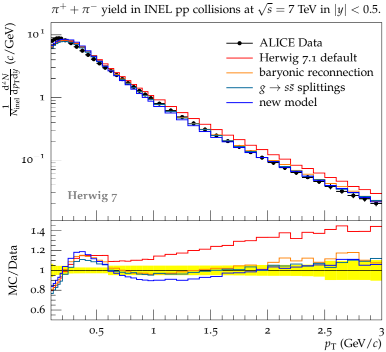
[ALICE, EPJ C75 (2015) 226]

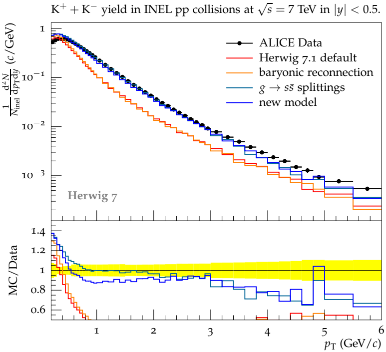


Idea seems to work.

Results

[ALICE, EPJ C75 (2015) 226]

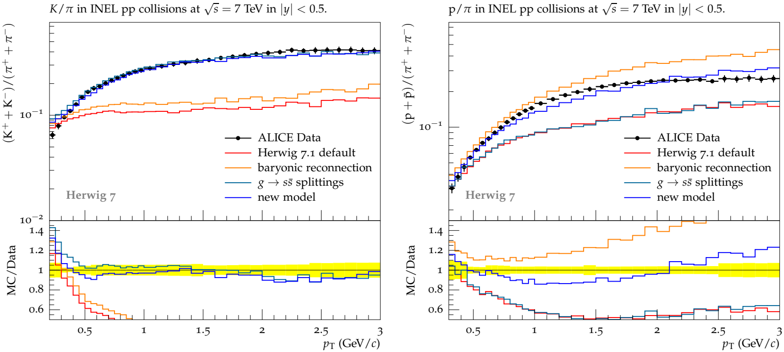




Strangeness difficult. $g \to s\bar{s}$ splitting.

Results

[ALICE, EPJ C75 (2015) 226]



Ratios much improved.

Conclusions

Today's event generators are very sophisticated tools.

NLO, Matching, Merging, MPI well under control

DIS still immature, but huge potential ($\rightarrow$ VBF)

First steps with ion collisions are being made

Monte Carlo
training studentships

3-6 month fully funded studentships for current PhD students at one of the MCnet nodes. An excellent opportunity to really understand and improve the Monte Carlos you use!

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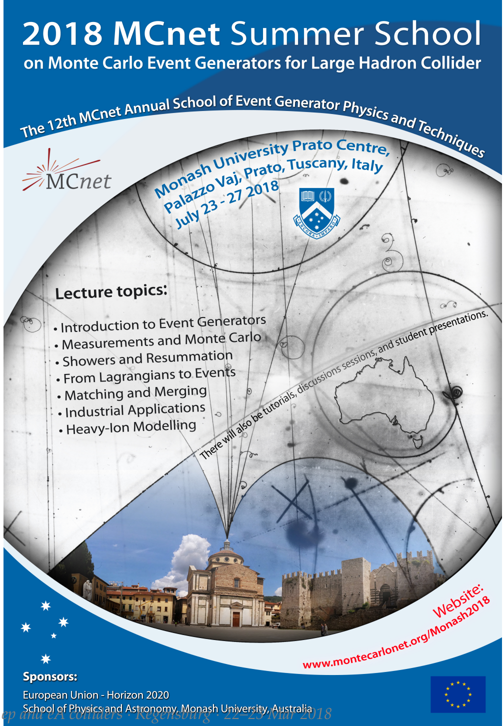
Herwig
Sherpa
MadGraph
"Plugin" – Ariadne+HEJ
CEDAR – Rivet+Professor
+Contur+hepforge+...


2018 MCnet Summer School
on Monte Carlo Event Generators for Large Hadron Collider
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Extra Slides

Matching MC and NLO on one slide

Solution: subtract doubly counted terms.

$$\langle O\rangle_{\text{NLO}} = BO(0) + \bar{V}O(0) + \int_0^1 dx\, \frac{O(x)R(x) - O(0)A(x)}{x}$$

$$\langle O\rangle_{\text{PS}} = BO(0)\left[1 - \int_\mu \frac{dx}{x}P(x)\right] + \int_\mu dx\, O(x)B\frac{P(x)}{x}$$

Matching MC and NLO on one slide

Solution: subtract doubly counted terms.

$$\langle O\rangle'_{\mathrm{NLO}} = BO(0) + \bar{V}O(0) + \int_0^1 dx\,\frac{O(x)R(x) - O(0)A(x)}{x}$$
$$+ \int_\mu \frac{dx}{x}P(x) - \int_\mu dx\,O(x)B\frac{P(x)}{x}$$

Matching MC and NLO on one slide

Solution: subtract doubly counted terms.

$$\langle O\rangle'_{\rm NLO} = BO(0) + \bar{V}O(0) + \int_0^1 dx\,\frac{O(x)R(x) - O(0)A(x)}{x} + \int_\mu \frac{dx}{x}P(x) - \int_\mu dx\,O(x)B\frac{P(x)}{x}$$

Result (“MC@NLO master formula”)

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

Note: $(O(0)B \otimes$ parton shower) adds back subtracted terms
$\Rightarrow$ NLO result is exactly reproduced after parton shower.

“Classic” MC and NLO

Implemented as subtractive matching in MC@NLO package

[Frixione, Webber, JHEP 0206:029,2002.]

[Frixione, Nason, Webber, JHEP 0308:007,2003.]

With modified Sudakov form factor as POWHEG/POWHEG-box

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

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

Both methods/packages used with Herwig++ as well.

Number of processes implemented independently into Herwig++ with truncated shower.

In view of “NLO revolution”: *can we go beyond?*