# LHC Event Generation with general-purpose Monte Carlo tools

(Fully exclusive modeling of high-energy collisions)

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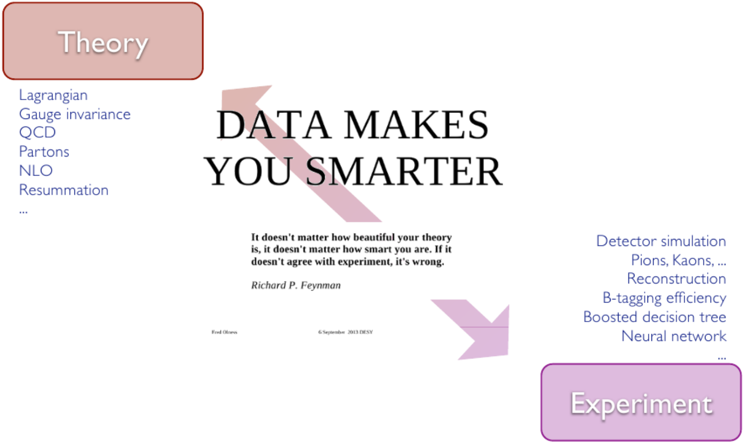

Theory
Lagrangian
Gauge invariance
QCD
Partons
NLO
Resummation
...
DATA MAKES
YOU SMARTER
It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong.
Richard P. Feynman
Fred Olness
6 September 2013 DESY
Detector simulation
Pions, Kaons, ...
Reconstruction
B-tagging efficiency
Boosted decision tree
Neural network
...
Experiment

# Motivation

**Theory**

Lagrangian
Gauge invariance
QCD
Partons
NLO
Resummation
...


Detector simulation
Pions, Kaons, ...
Reconstruction
B-tagging efficiency
Boosted decision tree
Neural network
...

**Experiment**

# General-purpose Monte Carlo

- Monte Carlo simulations are used by all experimental collaborations both to compare their data and theoretical predictions, and in data analysis.
- Unfortunately they are often treated as black boxes ...
  *J. D. Bjorken*
  *"But it often happens that the physics simulations provided by the the MC generators carry the authority of data itself. They look like data and feel like data, and if one is not careful they are accepted as if they were data."*
- It's important to understand the assumptions and approximations involved in these simulations.
- It is important to understand what is inside the programs to be able to answer the following type of questions.
  - Is the effect I'm seeing due to different models, or approximations, or is it a bug?
  - Am I measuring a fundamental quantity or merely a parameter in the simulation code?

# What do parton shower event generators do?

- An “event“ is a list of particles (pions, protons, ...) with their momenta.
- The MCs generate events.
- The probability to generate an event is proportional to the (approximate!) cross section for such an event.
- Calculate Everything $\sim$ solve QCD $\rightarrow$ requires compromise!
- Improve lowest-order perturbation theory, by including the ”most significant“ corrections $\rightarrow$ complete events (can evaluate any observable you want)

## The Workhorses: What are the Differences?

*All offer convenient frameworks for LHC physics studies, but with slightly different emphasis*:
**PYTHIA:** Successor to JETSET (begun in 1978). Originated in hadronization studies: Lund String.
**HERWIG:** Successor to EARWIG (begun in 1984). Originated in coherence studies: angular ordering parton shower. Cluster model.
**SHERPA:** Begun in 2000. Originated in ”matching” of matrix elements to showers: CKKW.

# What do parton shower event generators do?

**2012 J.J. Sakurai Prize for Theoretical Particle Physics Recipient**

The 2012 Sakurai Prize is awarded to:

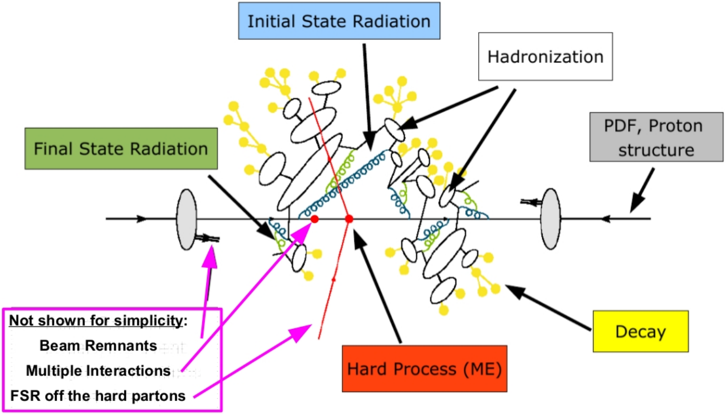
- Guido Altarelli (Universita di Roma Tre)
- Torbjorn Sjostrand (Lund University)
- Bryan Webber (University of Cambridge)

for key ideas leading to the detailed confirmation of the Standard Model of particle physics, enabling high energy experiments to extract precise information about quantum chromodynamics, electroweak interactions, and possible new physics.

I won't be able to cover details and include all references... one reference:

"General-purpose event generators for LHC physics", MC authors [arXiv:1101.2599]


Next MCnet school: Summer 2014 Manchester, UK




taken from Stefan Gieseke©

The general approach is the same in different programs but the models and approximations used are different.

**Herwig++:**

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, $\gamma p \to \text{jets}$.
- $e^+e^- / \gamma\gamma$
  $e^+e^- \to Z^0$, $e^+e^- \to q\bar{q}$, $e^+e^- \to \ell^+\ell^-$, $e^+e^- \to W^+W^-$,
  $e^+e^- \to Z^0h^0$, $e^+e^- \to h^0e^+e^-$, $e^+e^- \to h^0\nu_e\bar{\nu}_e$.
  $\gamma\gamma \to W^+W^-$, $\gamma\gamma \to f\bar{f}$.

Hard process and up to 3 body decays created automatically from model file.
Rest via LHEF (Les Houches Accord, transfers info on processes, cross sections, parton-level events).

# Hard processes - it is not a LO "Monte Carlo"

**Herwig++:**

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, $\gamma p \to \text{jets}$.
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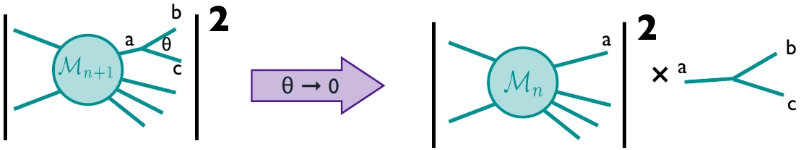
  $\gamma\gamma \to W^+W^-$, $\gamma\gamma \to f\bar{f}$.

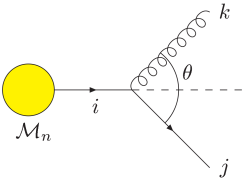
Also at NLO with POWHEG matching

**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.

- The hard subprocess, by definition, involves large momentum transfers and therefore the partons involved in it are violently accelerated.
- The accelerated coloured partons will emit QCD radiation in the form of gluons leading to parton showers.
- In principle, the showers represent higher-order corrections to the hard subprocess. However, it is not feasible to calculate these corrections exactly. Instead, an approximation scheme is used, in which the dominant contributions are included in each order.
- These dominant contributions are associated with collinear parton splitting or soft (low-energy) gluon emission.
- The conventional parton-shower formalism is based on collinear factorization



- In the collinear limit the cross section for a process factorizes:




$$d\sigma_{n+1} \approx d\sigma_n \frac{\alpha_S}{2\pi} \frac{d\theta^2}{\theta^2} dz\, d\phi\, P_{ji}(z,\phi)$$

  - $P_{ji}$ is the splitting function.
  - In the collinear limit $\frac{d\theta^2}{\theta^2} = \frac{dQ^2}{Q^2} = \frac{dk_\perp^2}{k_\perp^2} = \frac{dq^2}{q^2}$

- The Sudakov Form Factor: Probability of not emitting resolvable radiation

$$\Delta_i(q_1^2, q_2^2) = \exp\left\{ -\int_{q_2^2}^{q_1^2} \frac{dq^2}{q^2} \frac{\alpha_S}{2\pi} \int_{Q_0^2/q^2}^{1-Q_0^2/q^2} dz \int_0^{2\pi} d\phi\, P_{ji}(z,\phi) \right\} .$$

- The dominant region of phase space is the one where radiation is strongly ordered in evolution variable $q$.
- Many choices of $q$ are equivalent for collinear-enhanced contributions but they differ in soft gluon emission, which is also enhanced.
- Within the conventional parton-shower formalism, based on collinear factorization, it was shown that the soft region can be correctly described by using the angle of the emissions (Herwig) as the ordering variable (rather than the virtuality - old PYTHIA) leading to an angular-ordered parton shower.

Events with 2 hard (> 100 GeV) jets and a soft 3rd jet (∼ 10 GeV)

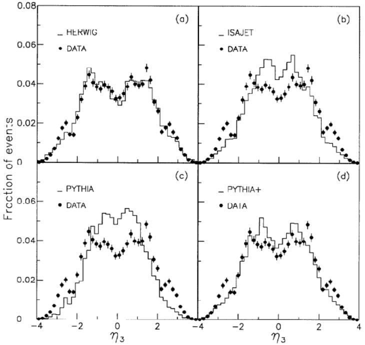


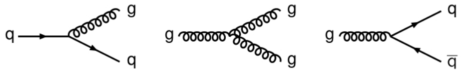

FIG. 13. Observed $\eta_3$ distribution compared to the predictions of (a) HERWIG; (b) ISAJET; (c) PYTHIA; (d) PYTHIA+.

F. Abe *et al.* [CDF Collaboration], Phys. Rev. D **50** (1994) 5562.

Best description with angular ordering.

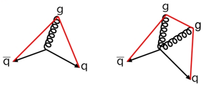
# Parton Shower - Not at all unique!

Some (more or less clever) choices still to be made.
**Standard shower** language of $a \to bc$ successive branchings



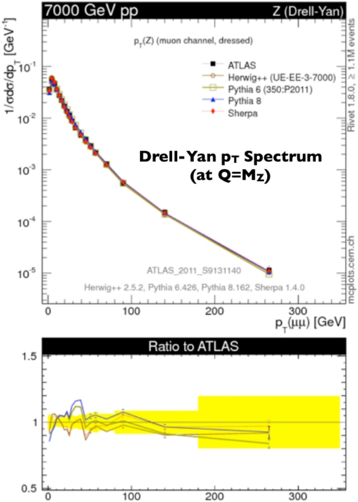

- $q$ evolution variable can be $\theta$ (Herwig), $Q^2$(old Pythia), $p_\perp$, ...
- Choice of $q_{min}$ scale not fixed.
- Integration limits, available parton shower phase space.
- Massless partons become massive. How?
- Initial-state showers to increase the Monte Carlo efficiency the backward evolution is used.

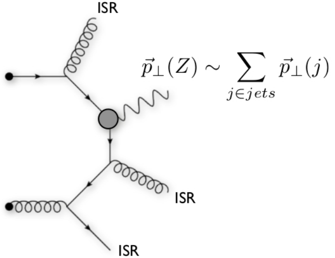
**Dipole shower**: dipole splitting is a $2 \to 3$




In this framework one can get the correct logarithmic structure for both soft and collinear emissions without angular-ordering requirement. First ARIADNE, now also available in SHERPA, Herwig++, VINCIA.

ATLAS: arXiv:1107.2381, CMS: arXiv:1110.4973



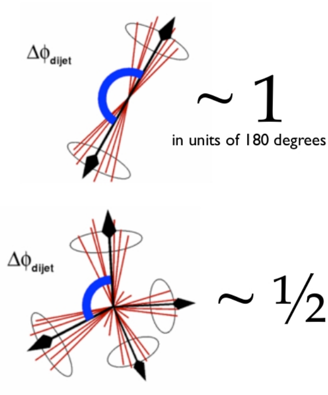




**Particularly sensitive to**

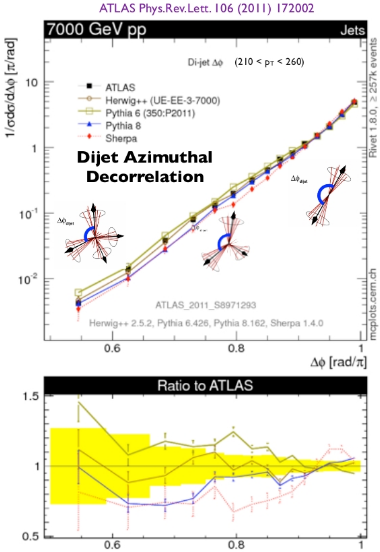
1. $\alpha_s$ renormalization scale choice
2. Recoil strategy (color dipoles vs global vs …)
3. FSR off ISR (ISR jet broadening)

Non-trivial result that modern GPMC shower models all reproduce it ~ correctly

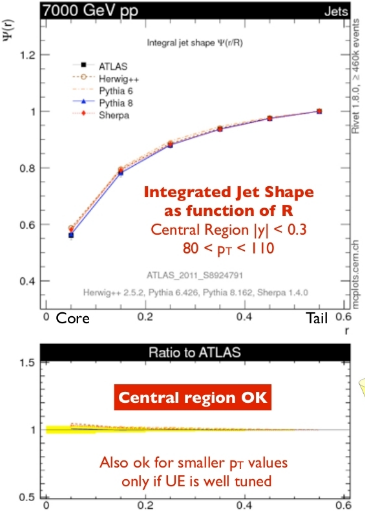
*Note: old PYTHIA 6 model (Tune A) did not give correct distribution, except with extreme $\mu_R$ choice (DW, D6, Pro-Q2O)*

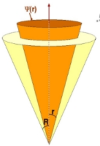


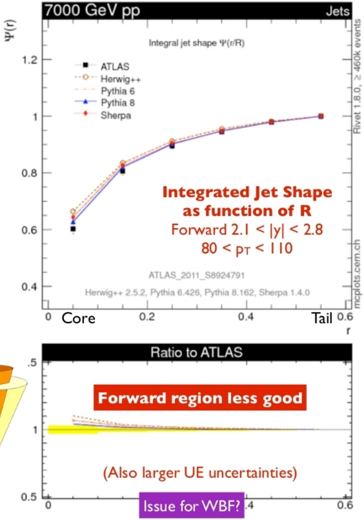
Δφ dijet
~ 1
in units of 180 degrees
Δφ dijet
~ ½

ATLAS Phys.Rev.Lett. 106 (2011) 172002
7000 GeV pp
Jets
Di-jet Δφ (210 < pT < 260)
ATLAS
Herwig++ (UE-EE-3-7000)
Pythia 6 (350:P2011)
Pythia 8
Sherpa
Dijet Azimuthal Decorrelation
1/σdσ/dΔφ [π/rad]
Rivet 1.8.0, ≥ 257k events
ATLAS_2011_S8971293
Herwig++ 2.5.2, Pythia 6.426, Pythia 8.162, Sherpa 1.4.0
mcplots.cern.ch
Δφ [rad/π]
Ratio to ATLAS

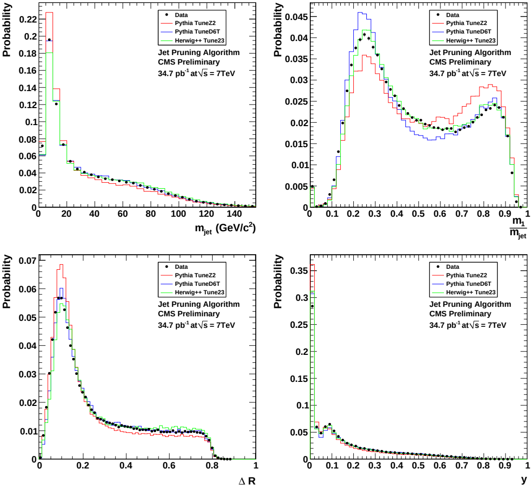

7000 GeV pp
Jets
Integral jet shape Ψ(r/R)
ATLAS
Herwig++
Pythia 6
Pythia 8
Sherpa
Integrated Jet Shape
as function of R
Central Region |y| < 0.3
80 < pT < 110
ATLAS_2011_S8924791
Herwig++ 2.5.2, Pythia 6.426, Pythia 8.162, Sherpa 1.4.0
Rivet 1.8.0, ≥ 460k events
mcplots.cern.ch
Ψ(r)
Core
Tail
r
Ratio to ATLAS
Central region OK
Also ok for smaller pT values
only if UE is well tuned


Ψ(r)
r
R


7000 GeV pp
Jets
Integral jet shape Ψ(r/R)
ATLAS
Herwig++
Pythia 6
Pythia 8
Sherpa
Integrated Jet Shape
as function of R
Forward 2.1 < |y| < 2.8
80 < pT < 110
ATLAS_2011_S8924791
Herwig++ 2.5.2, Pythia 6.426, Pythia 8.162, Sherpa 1.4.0
Rivet 1.8.0, ≥ 460k events
mcplots.cern.ch
Ψ(r)
Core
Tail
r
Ratio to ATLAS
Forward region less good
(Also larger UE uncertainties)
Issue for WBF?

Jet pruning/filtering designed to isolate new physics through hard internal jet structure but also a good probe of final state parton shower.

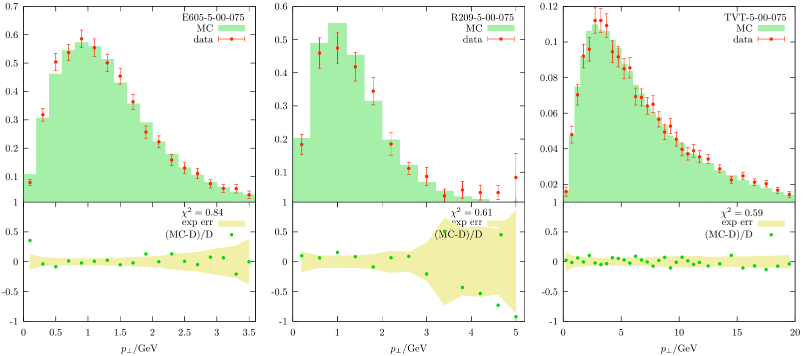
[CMS-PAS-JME-10-013]



## One example: "Non-perturbative gluon emission model"

Primordial $k_T$ from soft, non-perturbative gluons

Allow for very soft gluon radiation (all cutoffs, masses $\rightarrow \epsilon$).




Get good description of DY $p_T$ spectrum (38.8, 62 and 1800 GeV) using only small Gaussian primordial $k_T \sim 0.4$ GeV , (allowed by Heisenberg), not $> 2$ GeV.

[S. Gieseke, M. Seymour, AS, JHEP 06 (2008) 001]

# Parton shower - developments

**Herwig++**

- New parton shower variables in Herwig++ (still angular-ordered).
- Dipole shower, based upon Catani-Seymour dipoles.

**Sherpa**

- Catani-Seymour Shower default by now, also matched via CKKW (see later).

**Pythia 8**

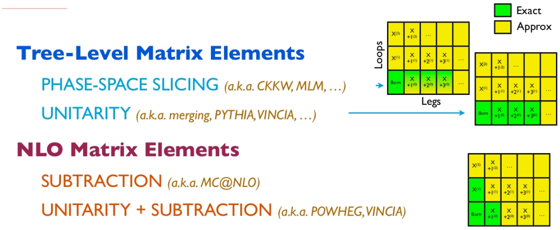
- $p_\perp$ ordered shower based on dipole showering.
- Interleaved with Multiple partonic interactions.

## IR Safe Summary (ISR/FSR):

- LO + showers generally in good O(20%) agreement with LHC (modulo bad tunes, pathological cases)
- Room for improvement: Quantification of uncertainties is still more art than science.
- Bottom Line: perturbation theory is solvable. Expect progress for example: NLO Parton Shower - Cracow group S. Jadach at al.

# Matching the shower to fixed order matrix elements

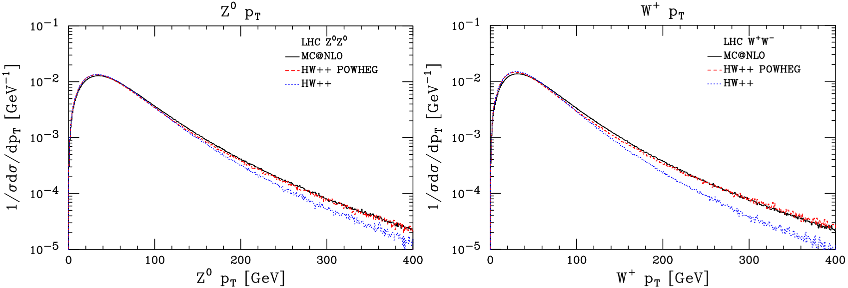
- Much of the research in Monte Carlo simulations in recent years has involved matching the shower to fixed order matrix elements at both:




  - Leading order to matrix elements with higher multiplicities to improve the simulation of events with many hard jets
  - NLO to improve the overall normalization and description of the hardest jet in the event
- There are many improvements in MC to include both types of approach: Powheg method, MC@NLO, Cracow Method, CKKW, CKKW-L...

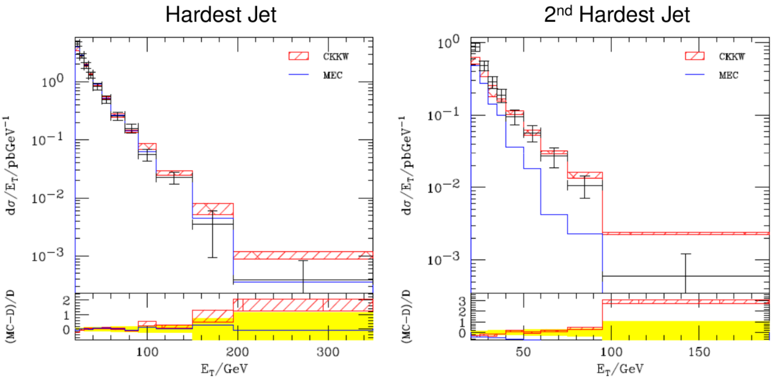
[For recent updates see: MC generators and future challenges, a joint ATLAS/CMS/LPCC workshop `https://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=212260`]

Example:



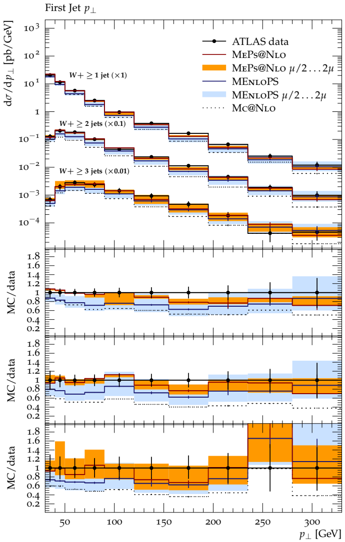

[K. Hamilton, JHEP 1101:009]

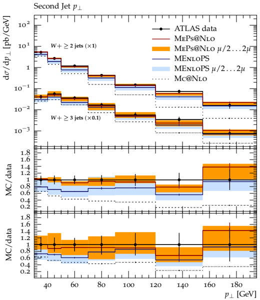
# $p_T$ of jets in Z+jets at the Tevatron

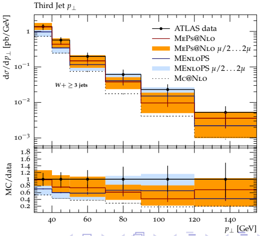



Herwig++ compared to data from CDF
Phys.Rev.D77:011108,2008

# Sherpa


First Jet $p_\perp$
dσ/dp⊥ [pb/GeV]
ATLAS data
MEPs@NLO
MEPs@NLO μ/2...2μ
MENLOPS
MENLOPS μ/2...2μ
MC@NLO
W+ ≥ 1 jet (×1)
W+ ≥ 2 jets (×0.1)
W+ ≥ 3 jets (×0.01)
MC/data
p⊥ [GeV]


Second Jet $p_\perp$
dσ/dp⊥ [pb/GeV]
ATLAS data
MEPs@NLO
MEPs@NLO μ/2...2μ
MENLOPS
MENLOPS μ/2...2μ
MC@NLO
W+ ≥ 2 jets (×1)
W+ ≥ 3 jets (×0.1)
MC/data
p⊥ [GeV]


Third Jet $p_\perp$
dσ/dp⊥ [pb/GeV]
ATLAS data
MEPs@NLO
MEPs@NLO μ/2...2μ
MENLOPS
MENLOPS μ/2...2μ
MC@NLO
W+ ≥ 3 jets
MC/data
p⊥ [GeV]

# Matching the shower to fixed order matrix elements

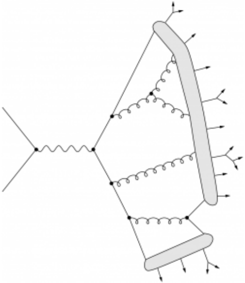
**Herwig++** MC@NLO and native implementation of Powheg method for many processes. Matchbox provides a framework to automatically assemble NLO calculations. MLM support. Modified CKKW merging with full truncated showering.

**Pythia** CKKW-L: via Les Houches files. POWHEG: done for ISR (via LHEF), in progress for FSR. MC@NLO: in progress, UNLOPS

**Sherpa** Multijet-merging at NLO: MENLOPS with up to 6-8 final state particles at leading order. Merging fully automatic, no interfaces, no files exchanged etc. MC@NLO and more...

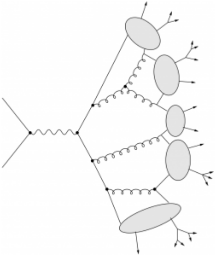
- Hadronization is a transition from the partonic "final" state to the actual hadronic final state.
- Non-perturbative regime ⇒ hadronization cannot be calculated from first principles, but has to be modeled.
- Model of hadronization should not depend on specifics of hard scattering process.
- The two most commonly used model classes (both inspired by QCD):

Lund String:



- Used in: Pythia

Cluster:

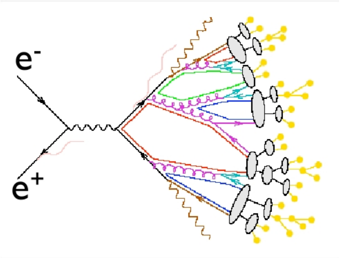


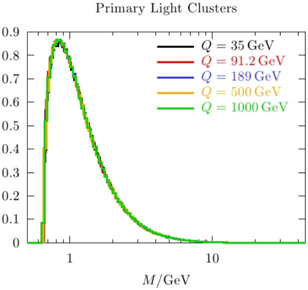
- Used in: Herwig++, Sherpa

- Models tuned mainly to the LEP data (clean environment).

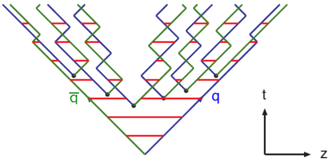
# Hadronization - cluster model

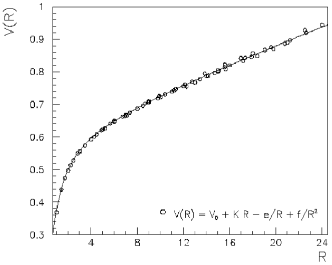
- The structure of the parton shower evolution, leads naturally to the clustering in phase-space of color-singlet parton pairs (preconfinement)
- Planar approximation: gluon = colour-anticolour pair
- Mass spectrum of colour-singlet pairs asymptotically independent of the nature and scale of the hard subprocess and depends only on $Q_0$ and the fundamental QCD scale $\Lambda$

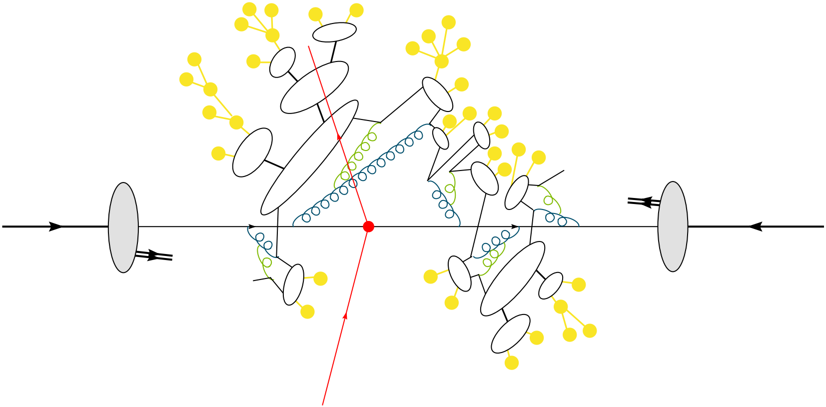


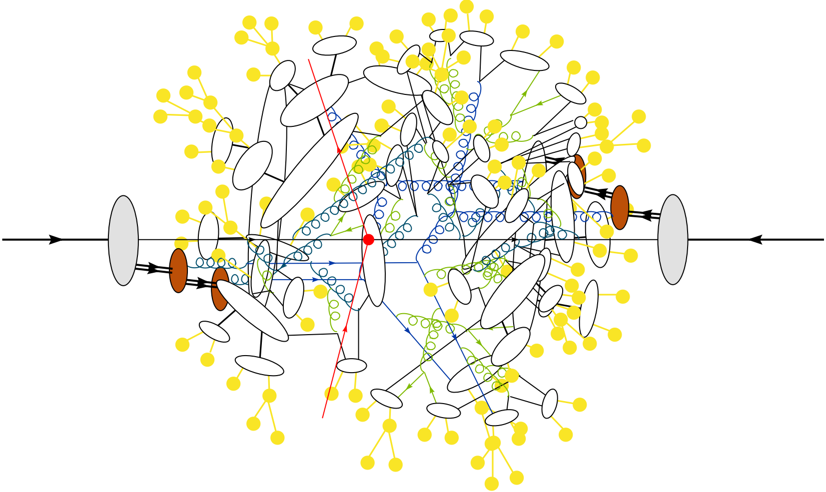



- The string model is based on the assumption of linear confinement.
- From lattice QCD ⇒ the color confinement potential of a quark-antiquark grows lineary with their distance $V(r) \sim kr$, with $k \sim 0.2$ GeV
- This is modeled with a string with uniform tension $k$
- When quark-antiquark are too far apart, it becomes energetically more favorable to break the string by creating a new qq pair in the middle.







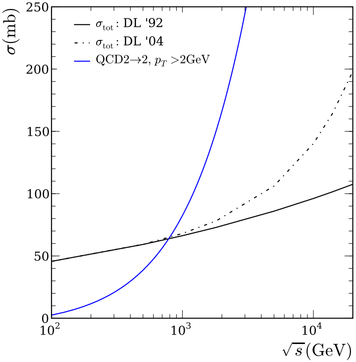
**Herwig++** MPI model with independent hard processes, showers and colour reconnection. Min bias without integrated diffraction.

**Pythia** MPI interleaved with showering. MPI ordered in $p_T$. Many tune families.

**Sherpa** MPI model with independent hard processes. New model - Shrimps with integrated diffraction under development.

Inclusive hard jet cross section in pQCD:

$$\sigma^{\text{inc}}(s, p_t^{\text{min}}) = \sum_{i,j} \int_{p_t^{\text{min}\,2}} \mathrm{d}p_t^2 \int \mathrm{d}x_1 \mathrm{d}x_2 \; f_i(x_1, Q^2)\, f_j(x_2, Q^2) \; \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2}$$




$\sigma^{\text{inc}} > \sigma_{\text{tot}}$ eventually

Interpretation:

- $\sigma^{\text{inc}}$ counts all partonic scatters in a single *pp* collision
- more than a single interaction

$$\sigma^{\text{inc}} = \langle n_{\text{dijets}} \rangle \sigma_{\text{inel}}$$

- direct evidence: measurement of momentum imbalance in multijet events at CERN ISR, $\gamma + 3$ jet at TVT.

# MPI model basics (Herwig++)

Assumptions:

- the distribution of partons in hadrons factorizes with respect to the b and x dependence ⇒ average number of parton collisions:

$$
\begin{aligned}
\bar{n}(\vec{b}, s) &= L_{\text{partons}}(x_1, x_2, \vec{b}) \otimes \sum_{ij} \int \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2} \\
&= \sum_{ij} \frac{1}{1+\delta_{ij}} \int \mathrm{d}x_1 \mathrm{d}x_2 \int \mathrm{d}^2\vec{b}' \int \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2} \\
&\quad \times D_{i/A}(x_1, p_t^2, |\vec{b}'|) D_{j/B}(x_2, p_t^2, |\vec{b} - \vec{b}'|) \\
&= \sum_{ij} \frac{1}{1+\delta_{ij}} \int \mathrm{d}x_1 \mathrm{d}x_2 \int \mathrm{d}^2\vec{b}' \int \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2} \\
&\quad \times f_{i/A}(x_1, p_t^2) G_A(|\vec{b}'|) f_{j/B}(x_2, p_t^2) G_B(|\vec{b} - \vec{b}'|) \\
&= A(\vec{b}) \sigma^{\text{inc}}(s; p_t^{\min}) \,.
\end{aligned}
$$

- at fixed impact parameter b, individual scatterings are independent (leads to the Poisson distribution)

Average number of parton collisions

$$\bar{n}(b,s) = A(b) \cdot \sigma^{\mathrm{inc}}(s, p_t^{\mathrm{min}})$$

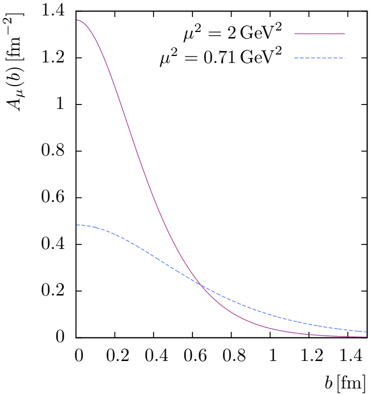
$$A(b,\mu) = \int \mathrm{d}^2b'\; S_A(\mathbf{b}')\; S_B(\mathbf{b}-\mathbf{b}')$$

$S(\mathbf{b})$ from electromagnetic FF:

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

But $\mu^2$ *not fixed* to the *electromagnetic* $0.71\,\mathrm{GeV}^2$.

Free for colour charges.



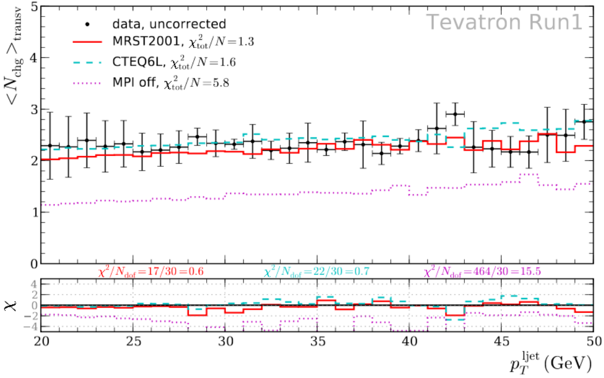

⇒ Two main parameters: $\mu^2$ and $p_t^{\mathrm{min}}$

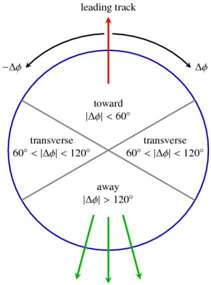
Pythia: Few functions including x-depended overlap

[Corke, Sjostrand, JHEP 1105:009], Richard's talk from MPI2010

# Semi hard underlying event

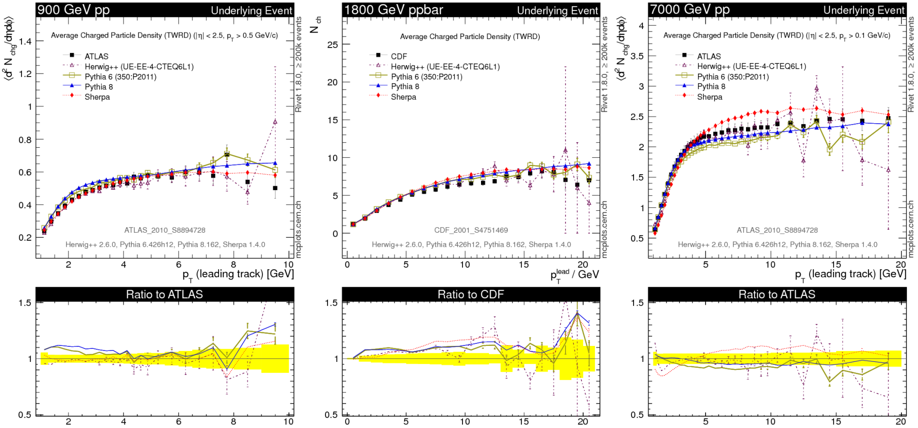
Good description of Run I Underlying event data ($\chi^2 = 1.3$).



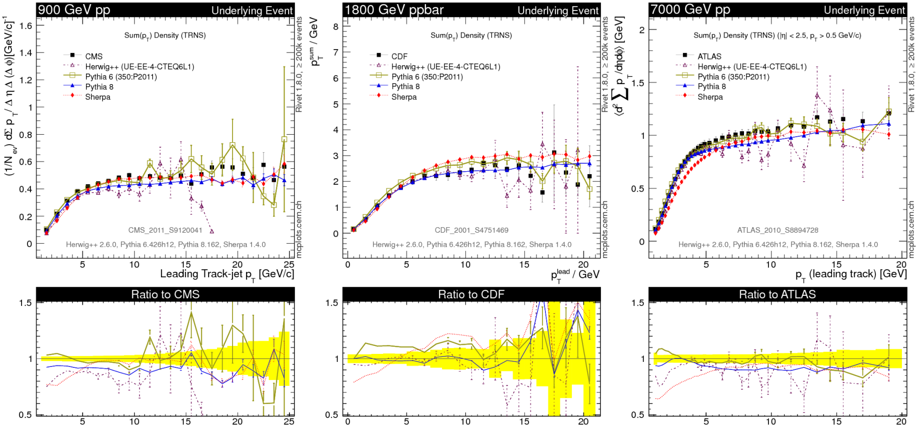




Only $p_T^{ljet} > 20$GeV.

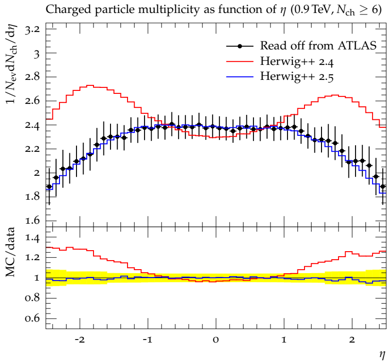
# UE measurements - Energy Overview

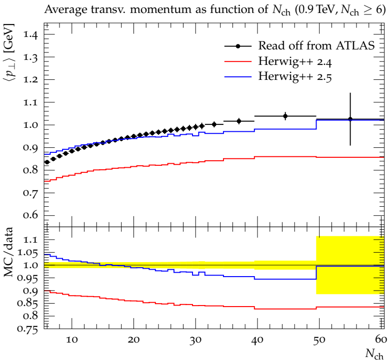


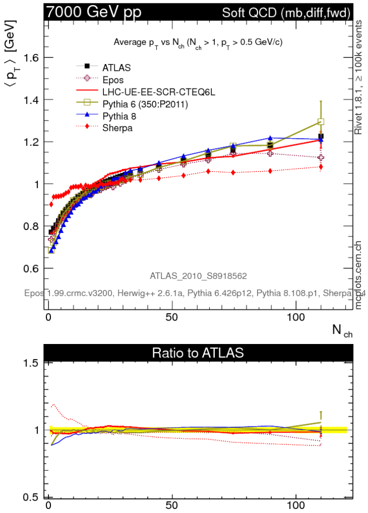
# UE measurements - Energy Overview



New data triggered new developements for example Colour Reconnection in Herwig++[Gieseke, Röhr, AS, EPJC 72 (2012)]:

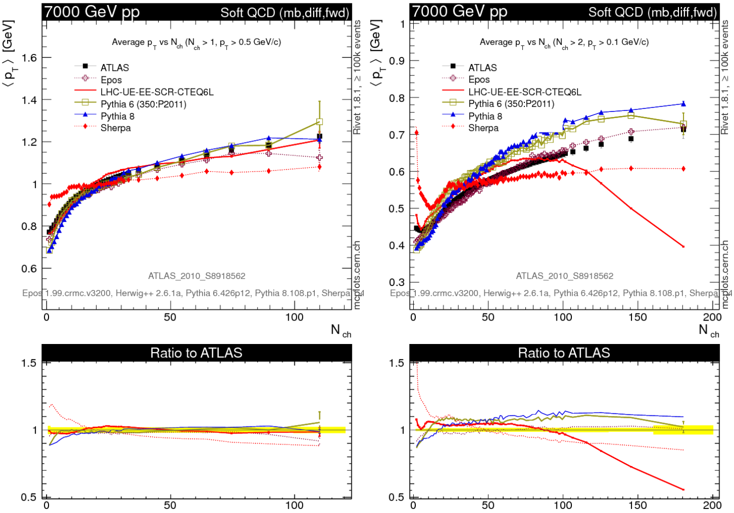





Need of the colour reconnection.

# MinBias ATLAS




Need of the colour reconnection. MB 7000 TeV, problem at low $p_T$, high Nch
Epos seems to describe MB data but fails to describe UE data.

- Not-too-soft not-too-high-multiplicity physics under good control.
- The parameters are carefully tuned, do not change them.
- Use recent tunes.
- Plots: mcplots.cern.ch (and mcplots-dev.cern.ch less stable but more recent results)
- more MinBias/UE models on the market
  - Cosmic ray models:
    - Epos, QGSJET, SIBYLL
  - Small-$x$:
    - DIPSY
  - Shrimps new model in Sherpa
- Recommended to use at least two different models (not tunes) in your analysis.
- More recent results/developements: MPI@LHC 2012, Workshop on Multi-Parton Interactions at the LHC:

  `https://indico.cern.ch/conferenceDisplay.py?confId=184925`

# Summary

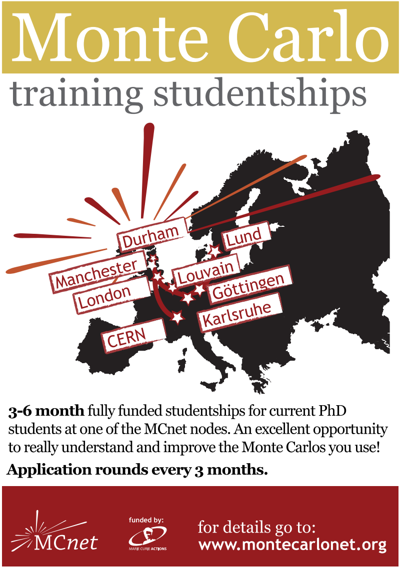
- Tremendous amount of new developements in parton shower MCs.
- Parton showers well established.
- NLO for many, many processes available.
- New LHC results lead to new developments in MB/UE simulation. Good tunes available by now.
- Minimum bias/underlying event/diffraction under constant improvement (DIPSY, new MPI model Shrimps in Sherpa, improvements in Pythia and Herwig)!
- Good first round of LHC data well described...
- ... but still a lot space for improvements.


Next MCnet school: Summer 2014 Manchester, UK

# The Road Ahead

- Event generators crucial since the start of LHC studies.
- Qualitatively predictive already 25 years ago
- Quantitatively steady progress, continuing today:
  - continuous dialogue with experimental community,
  - more powerful computational techniques and computers,
  - new ideas.
- As LHC needs to study more rare phenomena and more subtle effects, generators must keep up by increased precision.

# MCnet Short-term studentships




MC*net* projects

Pythia
Herwig
Sherpa
MadGraph
Ariadne
CEDAR

Thank you for the attention!

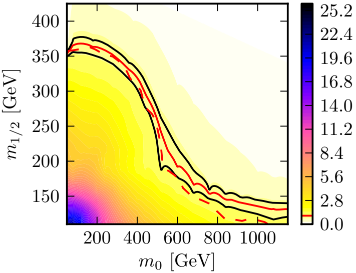
LHC data on jets plus missing energy provide powerful to test SUSY models (CMSSM studied). "New Constraints on Gauge Mediation and Beyond from LHC SUSY Searches at 7 TeV"

[M. J. Dolan, D. Grellscheid, J. Jaeckel, V. Khoze, P. Richardson arXiv:1104.0585]

Steps:

1. New physics model
2. Herwig++
3. Rivet implementation of ATLAS analysis
4. Exclusion!

Consistency check[1]:




1

[1] 95% confidence level exclusion limit in the $(m_0, m_{\frac{1}{2}})$ plane for $\tan\beta = 3$, $A_0 = 0$ and $\mu > 0$ in the CMSSM. The solid red line is the result using our signal simulations (the solid black lines show the effect of varying the factorization and renormalisation scales) whereas the dashed red line is the limit obtained by ATLAS. The colour scale shows the expected number of signal events normalised to the exclusion limit.

| Benchmark point | mediation scenario | $\sigma$/pb | | | | status |
| --- | --- | --- | --- | --- | --- | --- |
| | | A | B | C | D | ATLAS 35pb$^{-1}$ |
| ATLAS Limits | | 1.3 | 0.35 | 1.1 | 0.11 | |
| sps1a [13] | CMSSM | 2.031 | 0.933 | 1.731 | 0.418 | A,B,C,D |
| sps1b [13] | CMSSM | 0.120 | 0.089 | 0.098 | 0.067 | allowed |
| sps2 [13] | CMSSM | 0.674 | 0.388 | 0.584 | 0.243 | B,D |
| sps3 [13] | CMSSM | 0.123 | 0.093 | 0.097 | 0.067 | allowed |
| sps4 [13] | CMSSM | 0.334 | 0.199 | 0.309 | 0.144 | D |
| sps5 [13] | CMSSM | 0.606 | 0.328 | 0.541 | 0.190 | D |
| sps6 [13] | CMSSM (non-universal $m_{\frac{1}{2}}$) | 0.721 | 0.416 | 0.584 | 0.226 | B,D |
| sps7 [13] | GMSB ($\tilde{\tau}_1$ NLSP) | 0.022 | 0.016 | 0.023 | 0.015 | allowed |
| sps8 [13] | GMSB ($\tilde{\chi}_1^0$ NLSP) | 0.021 | 0.011 | 0.022 | 0.009 | allowed |
| sps9 [13] | AMSB | 0.019* | 0.004* | 0.006* | 0.002* | A,B,C,D |
| SU1 [14] | CMSSM | 0.311 | 0.212 | 0.246 | 0.143 | D |
| SU2 [14] | CMSSM | 0.009 | 0.002 | 0.010 | 0.001 | allowed |
| SU3 [14] | CMSSM | 0.787 | 0.440 | 0.637 | 0.258 | B,D |
| SU4 [14] | CMSSM | 6.723 | 1.174 | 7.064 | 0.406 | A,B,C,D |
| SU6 [14] | CMSSM | 0.140 | 0.101 | 0.115 | 0.074 | allowed |
| SU8a [14] | CMSSM | 0.251 | 0.174 | 0.197 | 0.120 | D |
| SU9 [14] | CMSSM | 0.060 | 0.046 | 0.053 | 0.040 | allowed |
| LM0 [15] | CMSSM | 6.723 | 1.174 | 7.064 | 0.406 | A,B,C,D |
| LM1 [15] | CMSSM | 2.307 | 1.108 | 1.808 | 0.458 | A,B,C,D |
| LM2a [15] | CMSSM | 0.303 | 0.201 | 0.241 | 0.139 | D |
| LM2b [15] | CMSSM | 0.260 | 0.180 | 0.205 | 0.123 | D |
| LM3 [15] | CMSSM | 1.155 | 0.504 | 1.113 | 0.270 | B,C,D |
| LM4 [15] | CMSSM | 0.783 | 0.432 | 0.699 | 0.260 | B,D |
| LM5 [15] | CMSSM | 0.202 | 0.138 | 0.179 | 0.109 | allowed |
| LM6 [15] | CMSSM | 0.127 | 0.094 | 0.099 | 0.068 | allowed |
| LM7 [15] | CMSSM | 0.062 | 0.013 | 0.072 | 0.006 | allowed |
| LM8 [15] | CMSSM | 0.189 | 0.099 | 0.194 | 0.082 | allowed |
| LM9a [15] | CMSSM | 0.238 | 0.029 | 0.358 | 0.015 | allowed |
| LM9b [15] | CMSSM | 0.075 | 0.017 | 0.088 | 0.009 | allowed |
| LM10 [15] | CMSSM | 0.003 | 0.000 | 0.003 | 0.000 | allowed |
| LM11 [15] | CMSSM | 0.358 | 0.223 | 0.311 | 0.166 | D |
| LM12 [15] | CMSSM | 0.037 | 0.008 | 0.043 | 0.004 | allowed |
| LM13 [15] | CMSSM | 2.523 | 0.904 | 2.289 | 0.331 | A,B,C,D |
| PGM1a [12] | pure GGM ($\tilde{\chi}_1^0$ NLSP) | 0.351 | 0.030 | 0.570 | 0.009 | allowed |
| PGM1b [12] | pure GGM ($\tilde{\chi}_1^0$ NLSP) | 0.373 | 0.032 | 0.625 | 0.014 | allowed |
| PGM2 [12] | pure GGM ($\tilde{\tau}_1$ NLSP) | 0.008* | 0.005* | 0.009* | 0.003* | allowed |
| PGM3 [12] | pure GGM ($\tilde{\tau}_1, \tilde{\chi}_1^0$ co-NLSP) | 0.140 | 0.103 | 0.121 | 0.086 | allowed |
| PGM4 [12] | pure GGM ($\tilde{\tau}_1$ NLSP) | 0.000 | 0.000 | 0.000 | 0.000 | allowed |

Table 1: Status of SUSY benchmark points. For each point the columns labelled A,B,C and D give the cross section for each of the signal regions used in the ATLAS analysis [3]. The last column shows which of the four regions the point is excluded by using the new data. In the GMSB scenerio the NLSP was taken to be stable on collider time scales. The starred cross sections are computed at leading-order values whereas all the other values are NLO.



Then automate and repeat...

## Cluster hadronization in a nutshell

- Nonperturbative $g \longrightarrow q\bar{q}$ splitting ($q = uds$) isotropically. Here, $m_g \approx 750$ MeV $> 2m_q$.
- Cluster formation, universal spectrum (see below)
- Cluster fission, until

$$M^p < M^p_{\max} + (m_1 + m_2)^p$$

where masses are chosen from

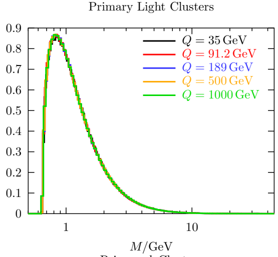
$$M_i = \left[ \left( M^P - (m_i + m_3)^P \right) r_i + (m_i + m_3)^P \right]^{1/P},$$

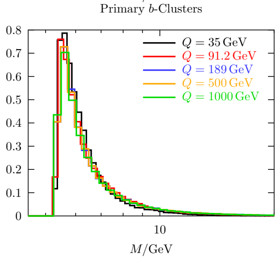
with additional phase space contraints. Constituents keep moving in their original direction.

- Cluster Decay

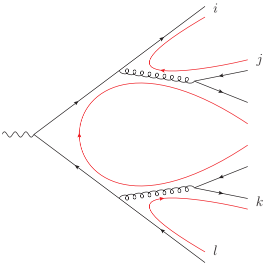
$$P(a_{i,q}, b_{q,j}|i,j) = \frac{W(a_{i,q}, b_{q,j}|i,j)}{\sum_{M/B} W(c_{i,q'}, d_{q',j}|i,j)}.$$

New in HERWIG++: Meson/Baryon ratio is parametrized in terms of diquark weight. In HERWIG the sum ran over all possible hadrons.



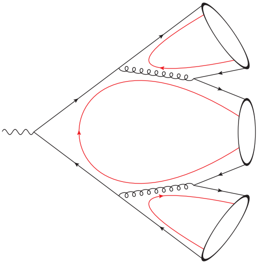
# Colour reconnection (CR) in Herwig++




Extending the hadronization model in Herwig(++):

- QCD parton showers provide *pre-confinement* $\Rightarrow$ colour-anticolour pairs form highly excited hadronic states, the *clusters*

# Colour reconnection (CR) in Herwig++



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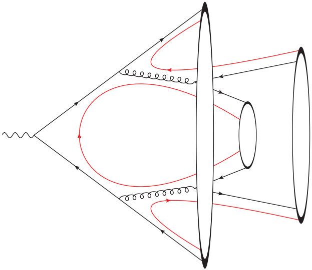

Extending the hadronization model in Herwig(++):

- QCD parton showers provide *pre-confinement* ⇒ colour-anticolour pairs form highly excited hadronic states, the *clusters*
- CR in the cluster hadronization model: allow *reformation* of clusters, *e.g.* $(il) + (jk)$
- Physical motivation: exchange of soft gluons during non-perturbative hadronization phase

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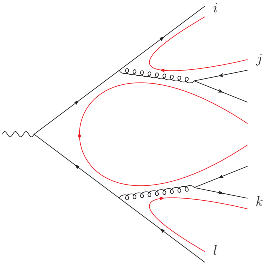


Extending the hadronization model in Herwig(++):

- QCD parton showers provide *pre-confinement* ⇒ colour-anticolour pairs form highly excited hadronic states, the *clusters*
- CR in the cluster hadronization model: allow *reformation* of clusters, *e.g.* $(il) + (jk)$
- Physical motivation: exchange of soft gluons during non-perturbative hadronization phase

## Implementation

- Allow CR if the cluster mass decreases,

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

  where $M_{ab}^2 = (p_a + p_b)^2$ is the (squared) cluster mass
- Accept alternative clustering with probability $p_{\mathrm{reco}}$ (model parameter) ⇒ this allows to switch on CR smoothly