LHC Event Generation with general-purpose Monte Carlo tools

(fully exclusive modeling of high-energy collisions)

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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?

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

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?

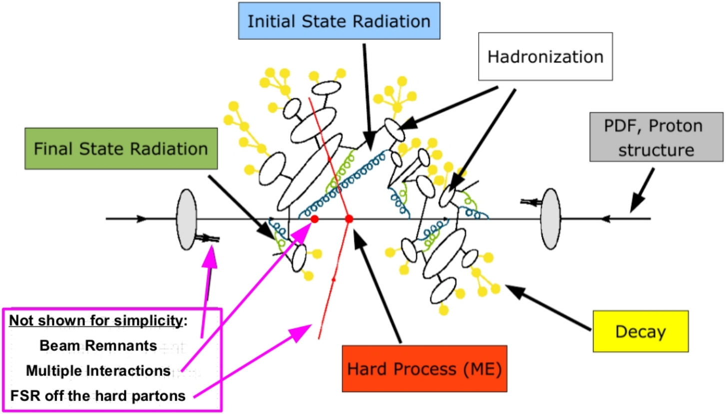
2012 J.J. Sakurai Prize for Theoretical Particle Physics Recipient

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.

Basics of Monte Carlo Generators



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

Also at NLO with POWHEG matching

Hard processes

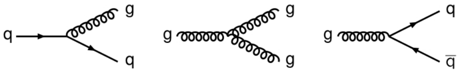
Sherpa:
All tree level processes via AMEGIC++, COMIX, built-in ME generators. New models via FeynRules.
Pythia:
Many processes built-in. Pythia 8.1 can link back to Pythia 6.4 processes. Rest via LHEF.

Parton Shower

- 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.
- 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.

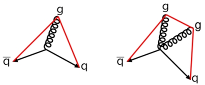
Parton Shower - Not at all unique!

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



- q evolution variable can be θ (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.

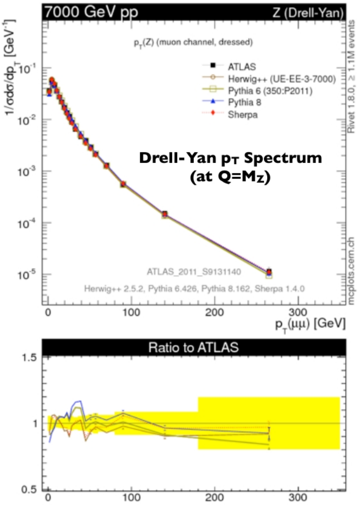
Dipole shower: dipole splitting is a $2 \to 3$

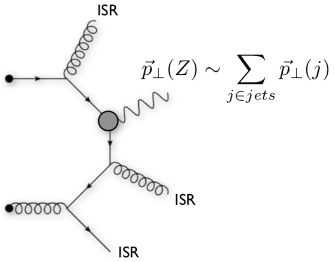


In this framework one can get the correct logarithmic structure for both soft and collinear emissions without angular-ordering requirement. First ARIADNE, now also available in SHERPA, Herwig++, VINCIA.

Parton Shower: Initial State:

ATLAS: arXiv:1107.2381, CMS: arXiv:1110.4973





Particularly sensitive to

1. α_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

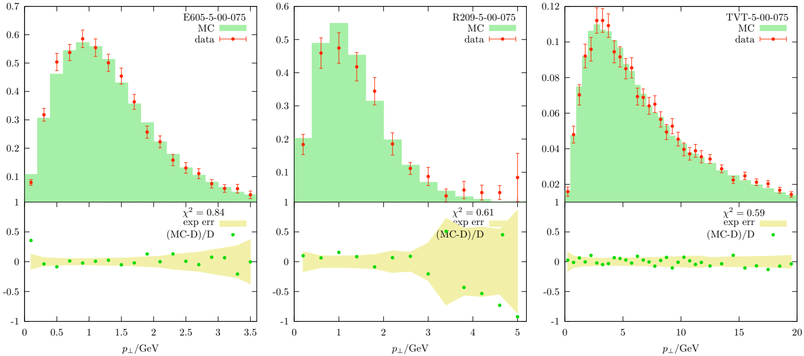
Note: old PYTHIA 6 model (Tune A) did not give correct distribution, except with extreme μ_R choice (DW, D6, Pro-Q2O)

Parton Shower: non-perturbative component

One example: “Non-perturbative gluon emission model”

Primordial k_T from soft, non-perturbative gluons

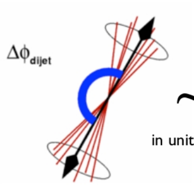
Allow for very soft gluon radiation (all cutoffs, masses $\to \epsilon$).



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.

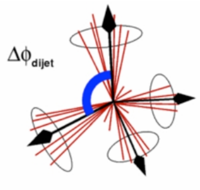
[S. Gieseke, M. Seymour, AS, JHEP 06 (2008) 001]

Parton Shower: Initial State



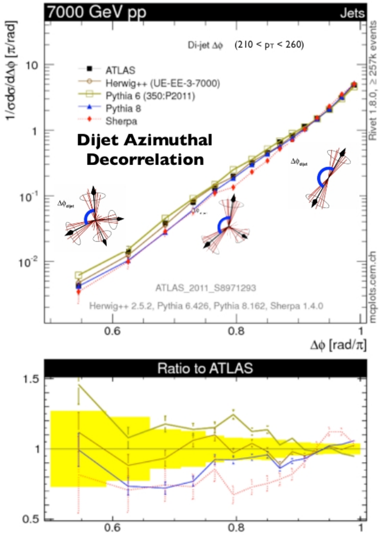
~ 1

in units of 180 degrees

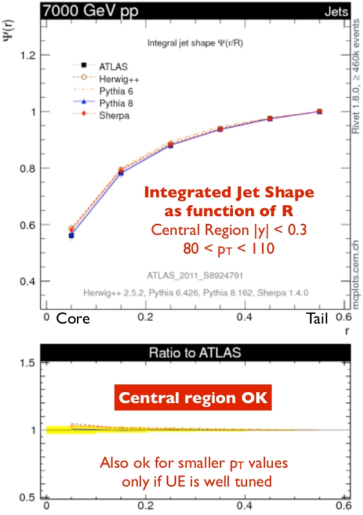


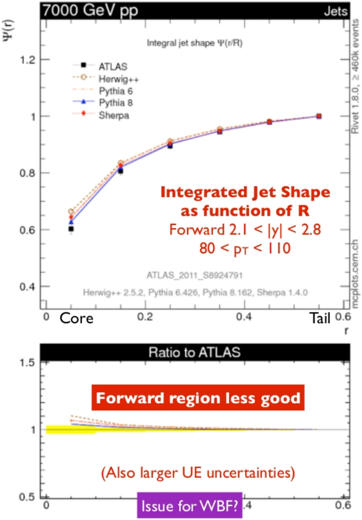
$\sim ½$

ATLAS Phys.Rev.Lett. 106 (2011) 172002



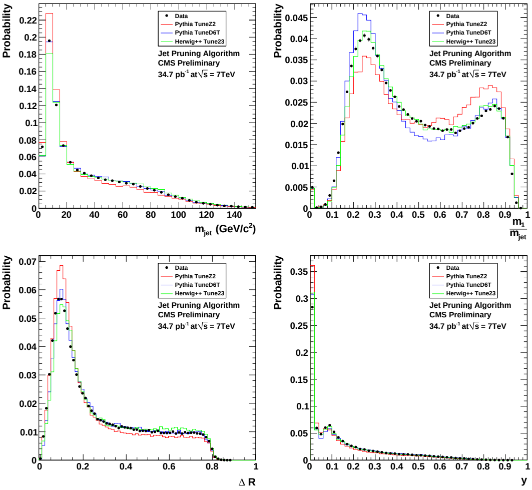
Parton Shower: Final State





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]



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

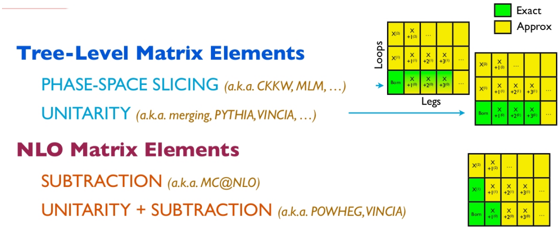
- $p_\perp$ ordered shower based on dipole showering.
- Interleaved with Multiple partonic interactions.

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:

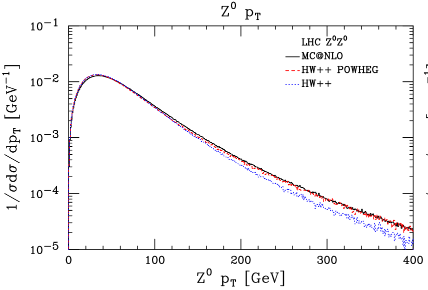


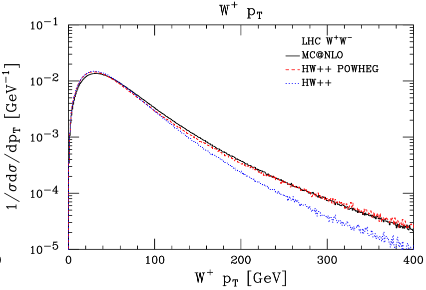
  - Leading order to matrix elements with higher multiplicities to improve the simulation of events with many hard jets
  - NLO to improve the overall normalization and description of the hardest jet in the event
- There are many improvements in MC to include both types of approach: Powheg method, MC@NLO,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

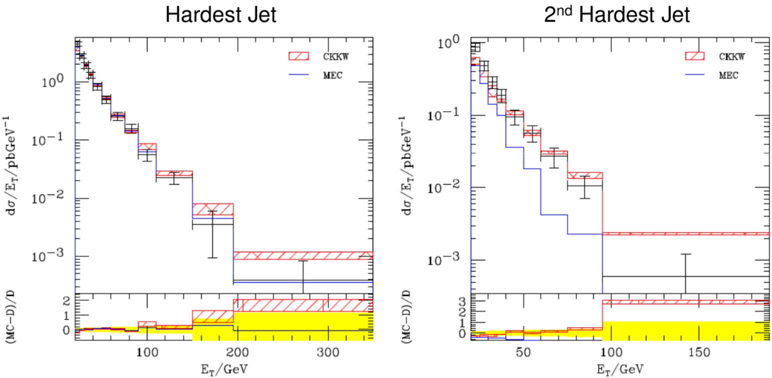
Example:





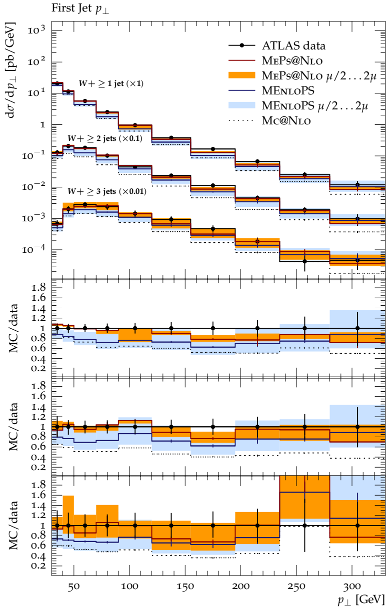
[K. Hamilton, JHEP 1101:009]

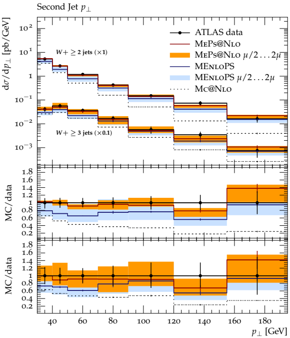
p_T of jets in Z+jets at the Tevatron

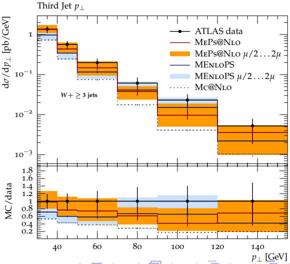


Herwig++ compared to data from CDF
Phys.Rev.D77:011108,2008

Also see talk M. Ćwiok.


First Jet $p_\perp$
$d\sigma/dp_\perp$ [pb/GeV]
ATLAS data
MEPs@NLO
MEPs@NLO $\mu/2\ldots2\mu$
MENLOPS
MENLOPS $\mu/2\ldots2\mu$
MC@NLO
$W+\geq 1$ jet ($\times 1$)
$W+\geq 2$ jets ($\times 0.1$)
$W+\geq 3$ jets ($\times 0.01$)
MC/data
$p_\perp$ [GeV]


Second Jet $p_\perp$
$d\sigma/dp_\perp$ [pb/GeV]
ATLAS data
MEPs@NLO
MEPs@NLO $\mu/2\ldots2\mu$
MENLOPS
MENLOPS $\mu/2\ldots2\mu$
MC@NLO
$W+\geq 2$ jets ($\times 1$)
$W+\geq 3$ jets ($\times 0.1$)
MC/data
$p_\perp$ [GeV]

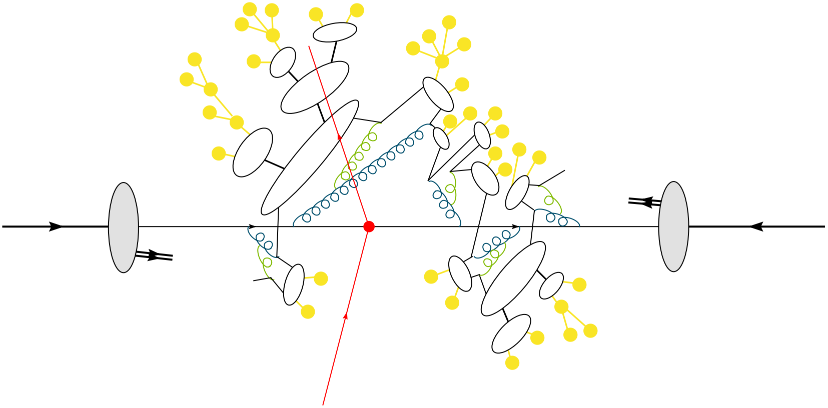

Third Jet $p_\perp$
$d\sigma/dp_\perp$ [pb/GeV]
ATLAS data
MEPs@NLO
MEPs@NLO $\mu/2\ldots2\mu$
MENLOPS
MENLOPS $\mu/2\ldots2\mu$
MC@NLO
$W+\geq 3$ jets
MC/data
$p_\perp$ [GeV]

Matching the shower to fixed order matrix elements

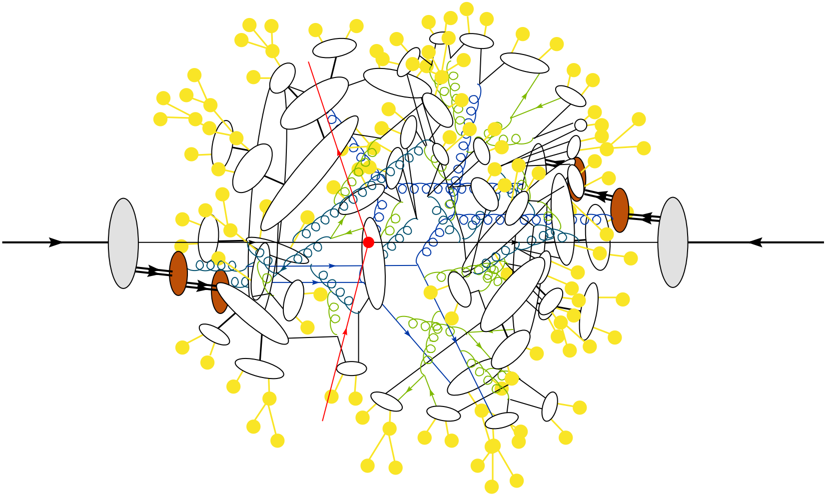
Herwig++ MC@NLO and native implementation of Powheg method for many processes. Matchbox provides a framework to automatically assemble NLO calculations. MLM support. Modified CKKW merging with full truncated showering.

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

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...



Multiple Partonic Interactions



Min Bias/Underlying Event

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

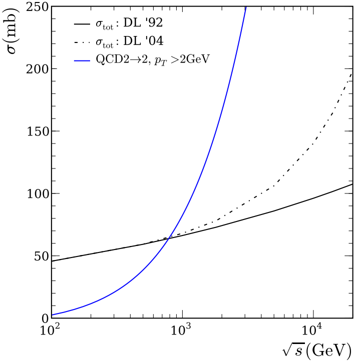
Pythia MPI interleaved with showering. MPI ordered in p_T. Many tune families.

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

MPI model basics

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:

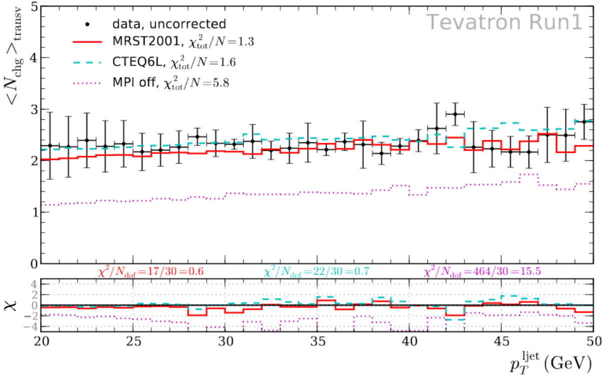
- σ^{inc} counts all partonic scatters in a single *pp* collision
- more than a single interaction

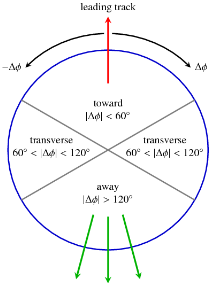
$$\sigma^{\text{inc}} = \langle n_{\text{dijets}} \rangle \sigma_{\text{inel}}$$

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

Semi hard underlying event

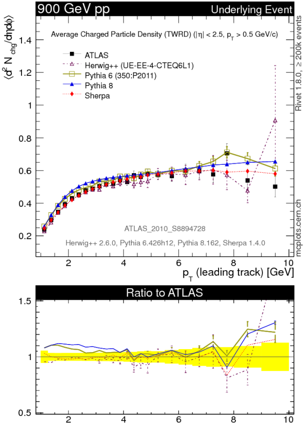
Good description of Run I Underlying event data ($\chi^2 = 1.3$).

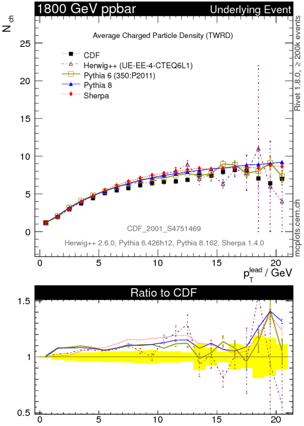


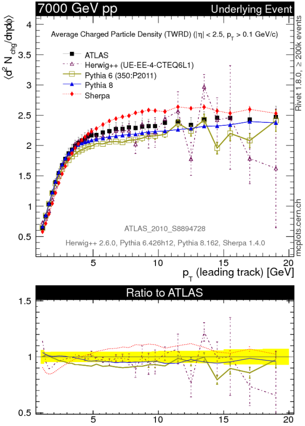


Only $p_T^{\rm ljet} > 20\,$GeV.

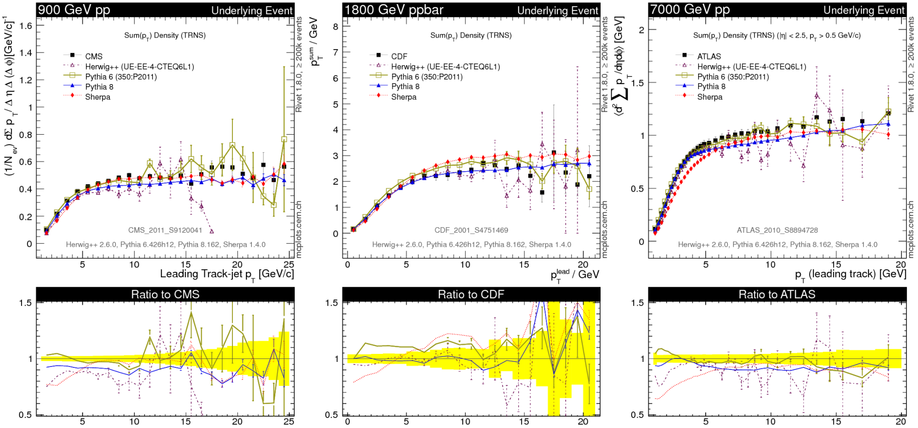
UE measurements - Energy Overview



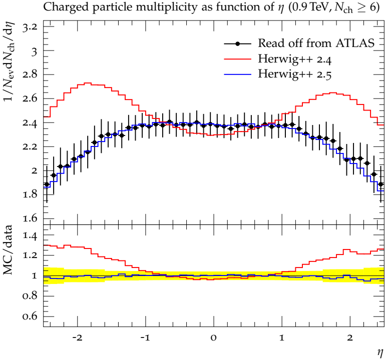


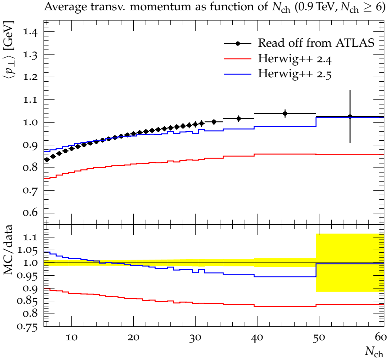


UE measurements - Energy Overview

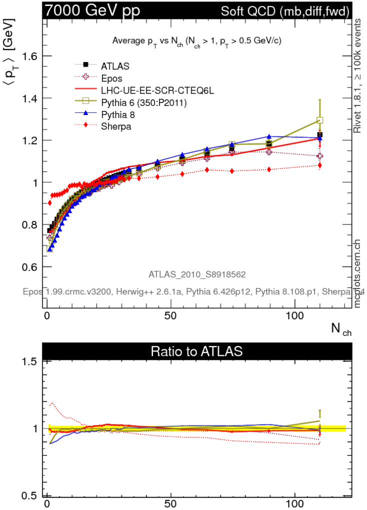


New data triggered new developements for example Colour Reconnection in Herwig++[Gieseke, Röhr, AS, EPJC 72 (2012)]:



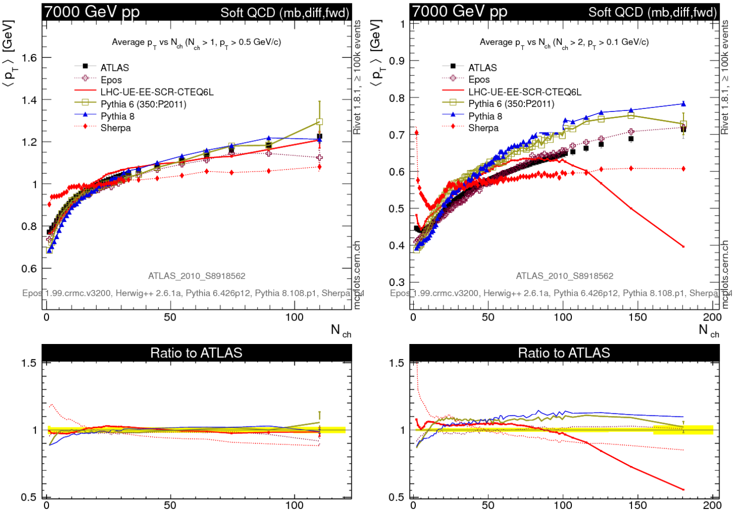


MinBias ATLAS



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.

Tuning remarks: tunes from mcplots-dev.cern.ch

Sherpa 1.4.0

1. default

Herwig++ 2.6.1a

1. LHC-UE-EE-4
2. LHC-UE-EE-4-CTEQ6L1
3. LHC-UE-EE-SCR-CTEQ6L

Pythia 8.170

1. default
2. default-CD
3. default-MBR
4. default-noFsr
5. default-noRap
6. early
7. tune-1
8. tune-2c
9. tune-2m
10. tune-4c
11. tune-4cx
12. tune-A2

Pythia 6.426p12

1. 350
2. 351
3. 352
4. 353
5. 354
6. 355
7. 356
8. 357
9. 358
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11. 360
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22. 375
23. 376
24. 377
25. 378
26. 379
27. a
28. ambt1
29. atlas-csc
30. d6t
31. default
32. dw
33. dwt
34. p0
35. p2010
36. p3
37. p6
38. phard
39. pnocr
40. pro-q2o
41. psoft
42. px
43. z1
44. z1-lep
45. z2
46. z2-lep

- 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
- 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.

Summary

- Some useful hard processes available. All the rest as well via LH interface.
- New parton shower working in IS, FS, t–decays, (SUSY particles).
- ME corrections in $e^+e^- \to q\bar{q}g$, DY, t–decay.
- ME+PS matching a la CKKW for $e^+e^- \to \mathrm{jets}$.
- MC@NLO type matching for $e^+e^- \to \mathrm{jets}$.
- pp simulations now possible in Herwig++. Many new features wrt old HERWIG.
- Hadronization ready.
- Much improved hadronic decayers.
- Spin correlations.
- Photon radiation in decays.
- First BSM (mostly MSSM) physics included.
- UA5 model for (simple) Underlying Event simulation.

Future of Herwig++

- ME+PS matching for hadronic interactions.
- NLO matching(s).
- More sophisticated Underlying event simulation.
- More BSM physics.
- More validation: Tevatron data (HERA photopruduction data?).

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.

Thank you for the attention!

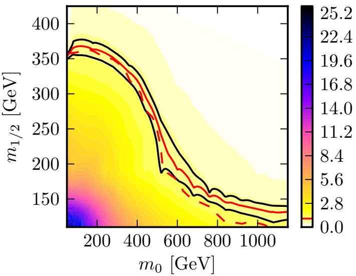
LHC data on jets plus missing energy provide powerful to test SUSY models (CMSSM studied). "New Constraints on Gauge Mediation and Beyond from LHC SUSY Searches at 7 TeV"

[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	σ/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...