Measurements useful for MC Tuning

James Robinson

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On behalf of the ATLAS, CMS, CDF and D0 collaborations

SM@LHC, Madrid April 8th-11th 2014

Introduction

Monte Carlo Simulations

Why Monte Carlo?

- Topology of collision events is complex
- Calculating cross-sections at hadron colliders relies on convolving
  - matrix elements (MEs) for the scattering process
  - corresponding parton distribution functions (PDFs)
- Monte Carlo simulations can relate these theoretical calculations to measurements

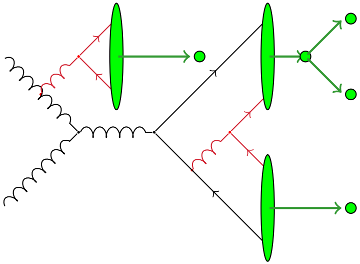
Monte Carlo predictions

- Outgoing partons fragment and hadronise (non perturbative)
- Radiation from initial and final-state partons together with MPI also important
- Non-perturbative effects described with phenomenological models

Models have free parameters with values that must be determined by fitting to data

Monte Carlo Event Structure

Historically, Monte Carlo generators factorised events into independent pieces



- **Matrix Element**: exact theoretical calculation up to stated accuracy (e.g. LO or NLO).
- Parton Shower: QCD radiation matched to the matrix element (bremsstrahlung).
- Hadronisation: Phenomenological models describing non-perturbative effects.

Interplay between ME and PS complicated at higher orders (eg. CKKW/MLM merging)

Challenges in describing data

Underlying event: any hadronic activity not associated with hard scattering process

- Unavoidable background in collision events
- Not well-predicted as non-perturbative effects dominate
- Need to ensure that measurements are not dependent on details of model used

Not possible to unambiguously assign particles to the hard scatter or UE

Typically modelled with

- Multiple parton interactions
- Initial/final-state radiation

Overlaid collisions within the same bunch crossing (pileup) also complicate measurements

History of Monte Carlo Tuning

Monte Carlo generators

- Majority of effort has been devoted to tuning PYTHIA 6
- LHC experiments have also tuned HERWIG +JIMMY and PYTHIA 8
- HERWIG++ and SHERPA have so far been tuned by authors

Tuning inputs

- Correcting measurements to well-defined kinematic region
- Important change in Tevatron → LHC transition (pioneered at ATLAS)

Professor/Rivet

- Automated tuning framework
- Generate lots of samples and use minimisation techniques to obtain best fit
- Strong support from LHC experiments

Experimental Areas

Underlying event

- Universality: studied in both jet events and Z events

Event and jet shapes

- Sensitive to collinear ISR/FSR

Colour coherence

- Sensitive to modelling of QCD correlations

Jet substructure

- Modelling of QCD branching

Jet vetoes

- Colour singlet/colour octet modelling

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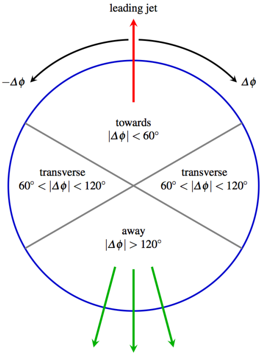
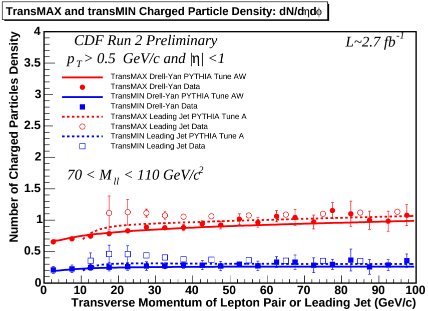
Underlying Event

CDF Data

CDF PRD 82 (2010) 034001

- Three azimuthal regions defined wrt leading object (eg. jet or vector boson)



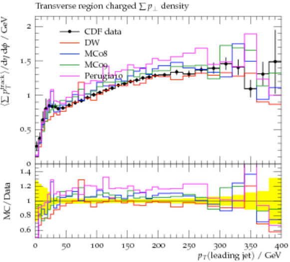


- Divide into trans-max and trans-min
- Underlying event activity very similar between Z-boson and jet events
- Transverse: depleted of QCD activity related to hard-scatter

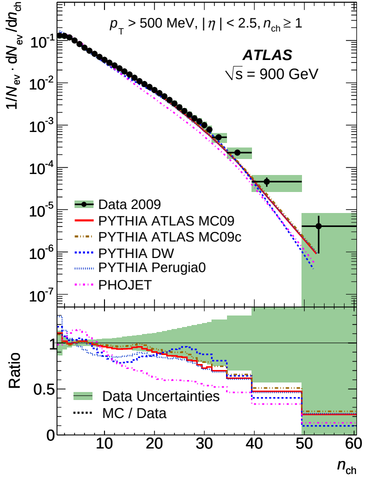
Pre-LHC tunes

ATLAS PLB 688 (2010) 21
ATLAS ATL-PHYS-PUB-2011-014

- Tunes agreed with CDF data

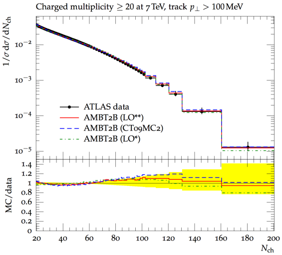


- ... but not with 900 GeV ATLAS data!



- Large deviations → new tunes needed

- UE no longer modelled as average to be subtracted from each event



- Separate charged+neutral components
- Much better agreement

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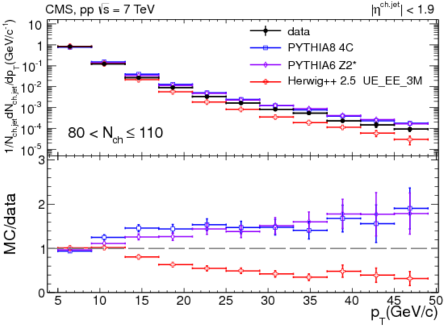
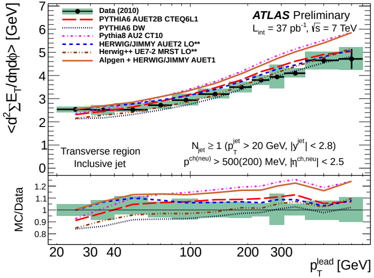
Underlying Event in Jets

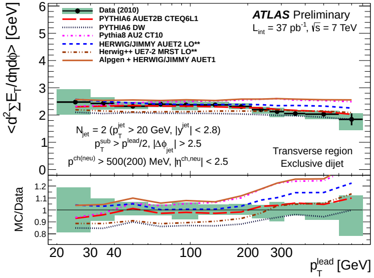
ATLAS ATLAS-CONF-2012-164

CMS EPJC 73 (2013) 2674

- Large discrepancies seen at high p_{T}





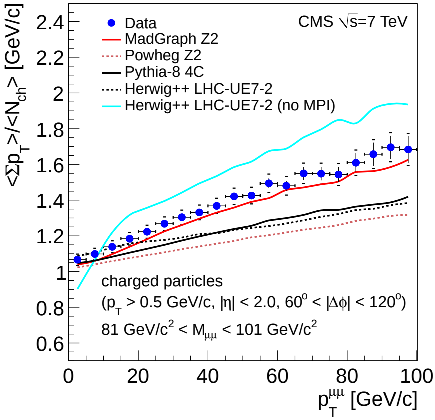


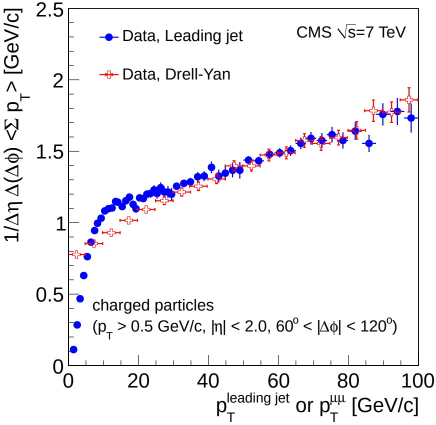
- Inclusive jet / exclusive dijet selections
- Study interplay of MPI and QCD radiation
- Flat $\sum p_{\mathrm{T}}$ in exclusive dijets $\rightarrow$ MPI independent of hard process
- **HERWIG++** better inclusive; **PYTHIA** exclusive

Underlying Event in Z-boson production

CMS EPJC 72 (2012) 2080

- Energy density in transverse region
- Sensitive to ISR and MPI (no QCD FSR)
- **HERWIG++**: MPI saturation (p_{T} > 40 GeV)

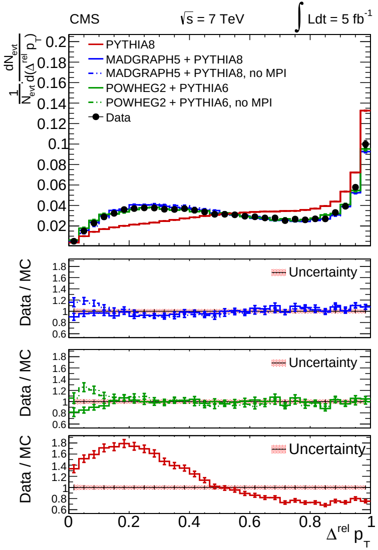




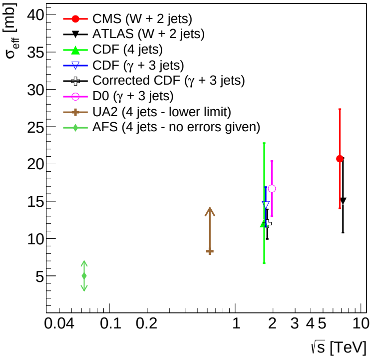
- UE well described by hadronic tunes $\rightarrow$ universality of MPI
- Z2 good with **MadGraph** (CTEQ6) but not **POWHEG** (CT10)

Double-parton scattering in W-boson+jets production

ATLAS NJP 15 (2013) 033038
CMS JHEP 03 (2014) 032



- Extract DPS component from final states
- Independent/simultaneous production (σ_{eff})



- Good agreement between LHC and Tevatron

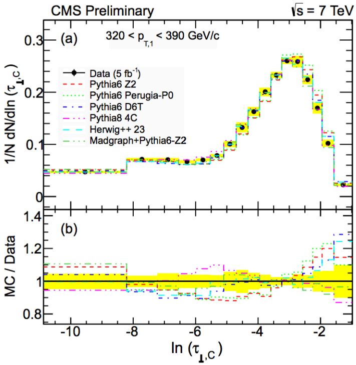
Event Shapes

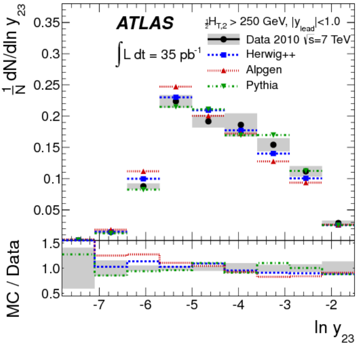
Event Shapes

See also talk by F. Stober

ATLAS EPJC 72 (2012) 2211
CMS CMS-PAS-SMP-12-022

- Test colour connection; ISR/FSR modelling





- Transverse thrust: $\tau_\perp = 1 - \max \frac{\sum_i |p_{\mathrm{T},i} \cdot \hat{n}_\mathrm{T}|}{\sum_i p_{\mathrm{T},i}}$
- MadGraph gives best agreement
- Not sensitive to MPI

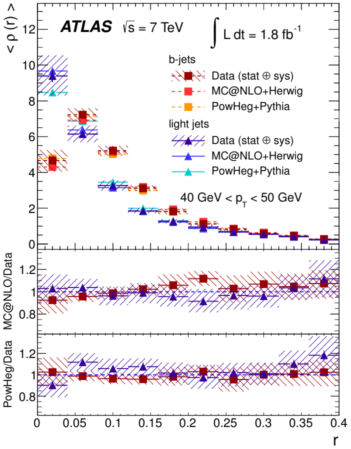
- Third jet resolution: $y_{23} = \frac{p^2_{\mathrm{T},3}}{(p_{\mathrm{T},1}+p_{\mathrm{T},2})^2}$
- PYTHIA/ALPGEN better than HERWIG++
- LO+PS gives reasonable description of multi-jet event shapes

Jet Shapes

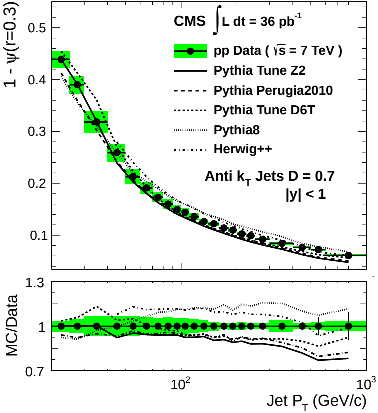
Jet Shapes

ATLAS EPJC 73 (2013) 2676
CMS JHEP 06 (2012) 160

- b-jets broader than light-quark jets
- POWHEG, MC@NLO both agree well



- $\psi = \sum_{r_i<r} p_{\mathrm{T}} / \sum_{r_i<R} p_{\mathrm{T}}$



- Large high p_{T} spread (Perugia2010 best)

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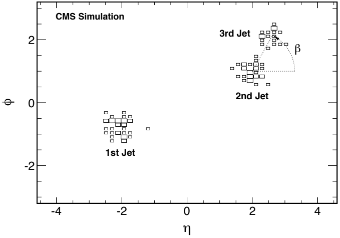
Colour Coherence

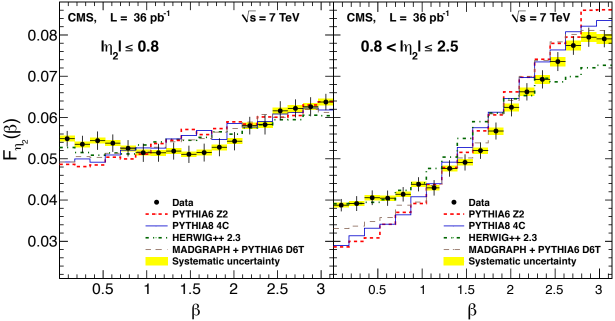
Colour Coherence

See also talk by F. Stober

CMS arXiv:1311.5815

- Emission of a coloured object depends on other coloured objects in the event.
- Direction of third jet emission gives information about colour coherence.
- No Monte Carlo describes the data well → colour coherence effects needed
- $\beta = \arctan\left(|\Delta\phi_{23}|/\Delta\eta_{23}\right)$



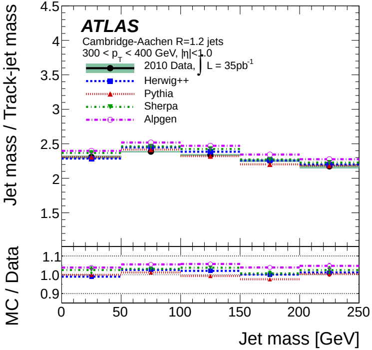


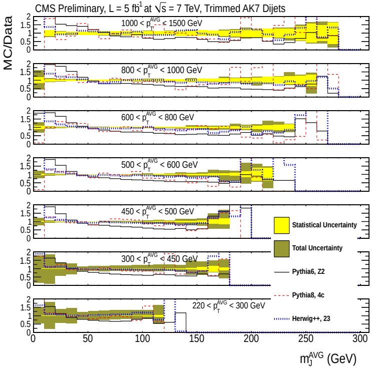
Jet Substructure

Boosted Jets

See also talk by G. Kasieczka

ATLAS JHEP 1205 (2012) 128
CMS JHEP 05 (2013) 090





- Substructure in boosted jets used to distinguish between QCD and heavy decays
- Undo jet clustering and look for a mass drop
- LO+PS Monte Carlo performs well

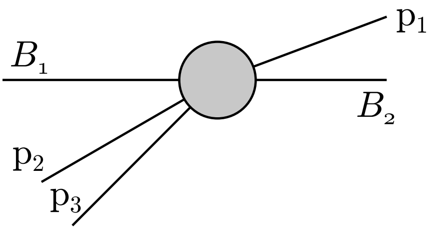
$k_\perp$ Splitting

See also talk by G. Kasieczka

ATLAS EPJC 73 5 (2013) 2432

$k_\perp$ algorithm

$$d_{ij} = \min\left(p_{\mathrm{T}i}^2, p_{\mathrm{T}j}^2\right)\frac{\Delta R_{ij}^2}{R^2} \qquad d_{iB} = p_{\mathrm{T}i}^2$$



- Look at iterative QCD branching in W + jets events ($\mathrm{W} \to \ell\nu$)
- Splitting scales $\sqrt{d_k}$ obtained by reversing algorithm

$k_\perp$ Splitting

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ATLAS EPJC 73 5 (2013) 2432

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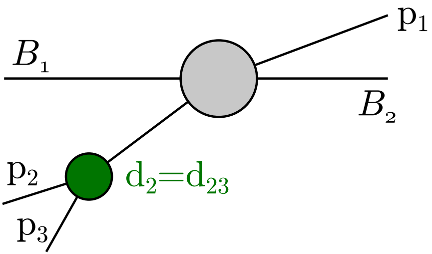

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ATLAS EPJC 73 5 (2013) 2432

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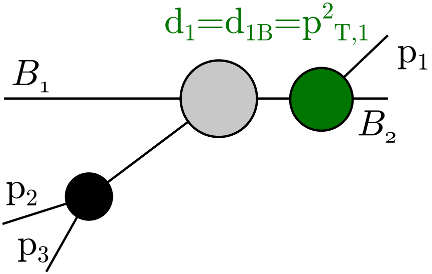

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ATLAS EPJC 73 5 (2013) 2432

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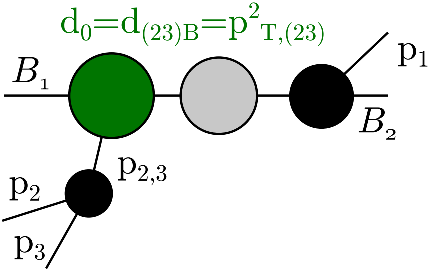

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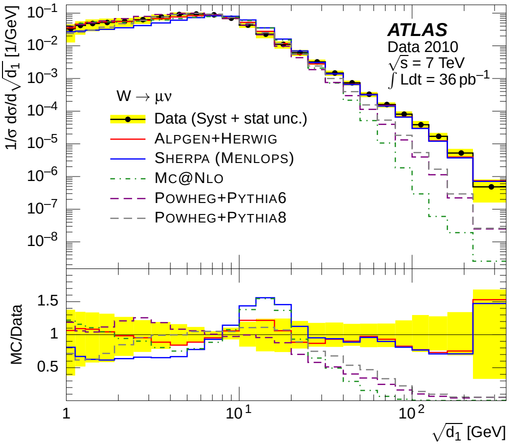
ATLAS EPJC 73 5 (2013) 2432



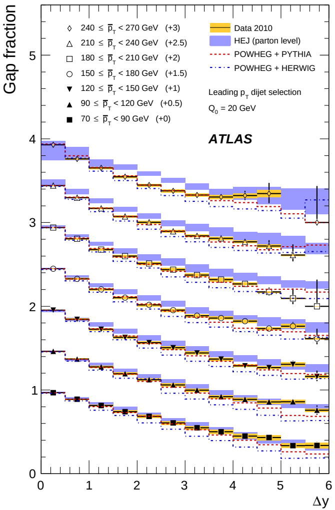
- Multi-leg (**ALPGEN +HERWIG** / **SHERPA**) exact tree level predictions
- Outperform NLO+PS (**POWHEG** / **MC@NLO**) in high p_T tails
- Even true for $\sqrt{d_0}$ for which they have the same formal accuracy

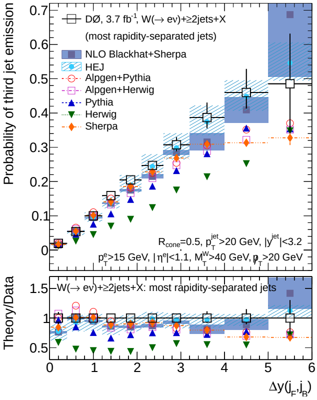
Jet Vetoes

Jet Vetoes

ATLAS JHEP 1109 (2011) 053

D0 PRD 88 092001 (2013)



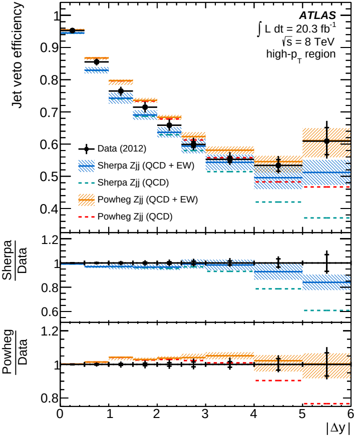


- Fraction of events with extra jet radiation
- Sensitive to BFKL/colour singlet effects
- **HEJ** performs well at large Δy

VBF Z +2J PRODUCTION

See also talk by G. Jones

ATLAS arXiv:1401.7610



- Direct test of ZWW coupling
- Only $\simeq 1\%$ of Z +2j cross-section
- Use jet veto to enhance
- Extract colour singlet component from colour octet background
- Benchmark for future weak-boson fusion studies

Summary

Summary

A large number of SM measurements have been made by LHC and Tevatron experiments

- impossible to discuss them all here
- dijet azimuthal decorrelations — **ATLAS** PRL 106 (2011) 172002; **CMS** PRL 106 (2011) 122003
- inclusive jet ratios — **ATLAS** EPJC (2013) 73 2509; **CMS** CMS-PAS-SMP-13-002
- event shapes in Z +jets — **CMS** PLB 722 (2013) 238–261
- V+jets — shown in talk by G. Chiodini yesterday

Monte Carlo generators have been remarkably successful in predicting experimental results

- experiments are providing distributions necessary for further Monte Carlo tuning work

Increased accuracy will be needed for LHC Run II (eg. differential Higgs analyses)

- improved modelling of low p_{T} processes has a large effect on precision measurements

Monte Carlo generator tuning is a complex but important area of study

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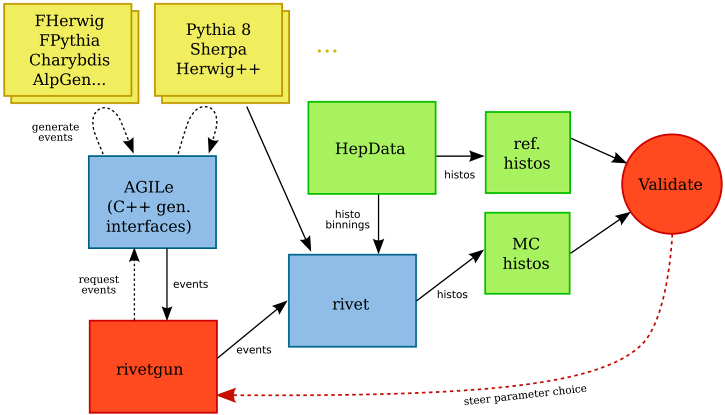
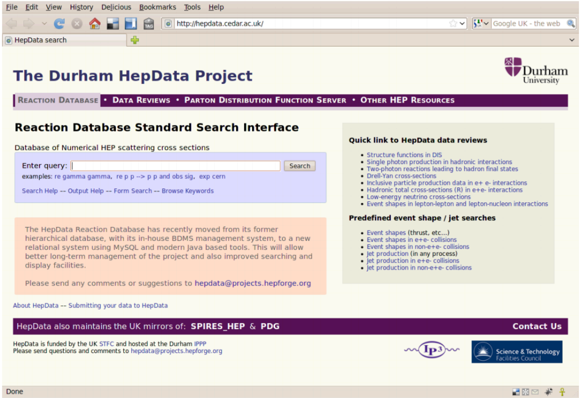
Backup

A complete validation/tuning system



Rivet/Professor workflow

Bundle reference data for standard analyses – mostly obtained direct from HepData



Monte Carlo histograms binned identically to reference data → automatic consistency.

Monte Carlo Parameters

There are lots of parameters:

- **PS**: t_{min}, α_s or Λ_{QCD}
- **Hadronisation**: depends strongly on model
  - **String**: string tension σ, Lund a and b params, baryon suppression, flavour params
  - **Cluster**: constituent masses, flavour params
- **UE**: interaction form factor params (Gaussian width/p(r,h)oton radii), p_{T}^{min}, colour reconnection params
- **CKKW/MLM**: ME/PS matching scale, factorization/renorm. scale

Can sometimes be tuned independently: e.g. kinematics, flavour, UE...depending on analyses

CDF Underlying Event – (slide 9)

CDF PRD 82 (2010) 034001

- PYTHIA 6.2 Tune A (CDF Run I UE)
- PYTHIA 6.2 Tune AW (CDF Run I UE+Z)
- PYTHIA 6.2 Tune DW (CDF Run I UE+Z+dijets)

Pre-LHC tunes – (slide 10)

ATLAS PLB 688 (2010) 21

- PYTHIA 6.421 ATLAS MC09
- PYTHIA 6.421 ATLAS MC09c
- PYTHIA 6.421 Tune DW (CDF Run I UE+Z+dijets)
- PYTHIA 6.421 Perugia0

ATLAS ATL-PHYS-PUB-2011-014

- PYTHIA 6.421 AMBT2B

Underlying Event in Jets – (slide 11)

CMS EPJC 73 (2013) 2674

- PYTHIA 6.424 Z2*
- PYTHIA 8.145 4C
- HERWIG++ 2.5 UE-EE-3M

ATLAS ATLAS-CONF-2012-164

- PYTHIA 6.425 AUET2B
- PYTHIA 6.421 DW
- PYTHIA 8.153 AU2
- HERWIG 6.5.20/JIMMY 4.31 AUET2
- HERWIG++ 2.5.1 UE7-2
- ALPGEN +HERWIG/JIMMY AUET1

Underlying Event in Z-boson production – (slide 12)

CMS EPJC 72 (2012) 2080

• MadGraph 5	Z2
• POWHEG	Z2
• PYTHIA 8	4C
• HERWIG++	LHC-UE7-2

Double-parton scattering in W-boson+jets production – (slide 13)

CMS JHEP 03 (2014) 032

- MadGraph 5+pythia 8 — Z2*
- powheg 2+pythia 6.425 — 4C
- pythia 8 — 4C

Event Shapes – (slide 15)

CMS CMS-PAS-SMP-12-022

PYTHIA 6.426	Z2
PYTHIA 6.426	Perugia0
PYTHIA 6.426	D6T (Tevatron)
PYTHIA 8.153	4C
HERWIG++ 2.5	23
MADGRAPH 5.1.5.7+PYTHIA 6.426	Z2

ATLAS EPJC 72 (2012) 2211

PYTHIA 6.423	Perugia 2010
HERWIG++ 2.4.2	unknown
ALPGEN 2.13+HERWIG 6.510/JIMMY 4.31	unknown

Jet Shapes – (slide 17)

ATLAS EPJC 73 (2013) 2676

- MC@NLO +HERWIG unknown
- POWHEG +PYTHIA unknown

CMS JHEP 06 (2012) 160

- PYTHIA 6.424 Z2
- PYTHIA 6.424 Perugia 2010
- PYTHIA 6.424 D6T
- PYTHIA 8.145 2C
- HERWIG++ 2.4.2 default

Colour Coherence – (slide 19)

CMS `arXiv:1311.5815`

• PYTHIA 6.422	Z2
• PYTHIA 8.145	4C
• HERWIG++ 2.4.2	default
• MADGRAPH 4+PYTHIA 6.422	D6T

Boosted Jets – (slide 21)

ATLAS JHEP 1205 (2012) 128

• PYTHIA 6.423	AMBT1
• HERWIG++ 2.4	unknown
• ALPGEN 2.13+HERWIG/JIMMY	unknown
• SHERPA 1.2.3	unknown

CMS JHEP 05 (2013) 090

• PYTHIA 6	Z2
• PYTHIA 8	4C
• HERWIG++	23

$k_\perp$ Splitting – (slide 23)

ATLAS EPJC 73 5 (2013) 2432

• ALPGEN 2.13+HERWIG 6.510/JIMMY 4.31	AUET1
• SHERPA 1.4.1	default
• MC@NLO 3.3.1	AUET1
• POWHEG 1.01+PYTHIA 6.425	AMBT1
• POWHEG 1.01+PYTHIA 8.165	AMBT1

Jet Vetoes – (slide 25)

ATLAS JHEP 1109 (2011) 053

• HEJ	n/a
• POWHEG PYTHIA 6	AMBT1
• POWHEG HERWIG	AUET1

DO PRD 88 092001 (2013)

• Blackhat+SHERPA	unknown
• HEJ	n/a
• ALPGEN 2.414+PYTHIA 6.425	Perugia 2011
• ALPGEN 2.414+HERWIG 6.520+JIMMY 4.31	unknown
• PYTHIA 6.425	Perugia 2011
• HERWIG 6.520+JIMMY 4.31	unknown
• SHERPA 1.4.0	default

VBF Z +2J PRODUCTION – (SLIDE 26)

ATLAS `arXiv:1401.7610`

- SHERPA 1.4.3 default
- POWHEG +PYTHIA 6 Perugia 2011