Recent Progress in Parton-Shower Event Generators

Graeme Nail

`graeme.nail@manchester.ac.uk`
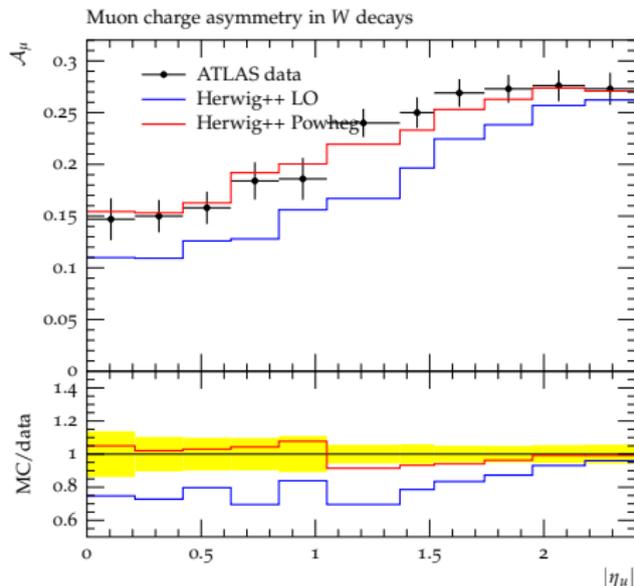
University of Manchester

The University of Manchester

MC*net*

Outline

Hard Scattering
NLO

NLO "recipe":

$$d\sigma_{NLO} = d\Phi_n B_n + d\Phi_n V_n + d\Phi_{n+1} R_{n+1}$$
$$= d\Phi_n B_n + d\Phi_n \left[V_n + d\Phi_1 S_n\right] + d\Phi_{n+1}\left[R_{n+1} - S_n\right]$$

- Virtual Corrections
- Real Corrections
- Subtraction terms

Muon charge asymmetry in W decays

Parton Shower Monte Carlos turn these into realistic predictions.

Hard Scattering

Overview

Matching	Merging
PS + FO for fixed multiplicity	PS + FO for several multiplicities Split phase space into hard and soft regions ■ Soft $\Rightarrow$ PS ■ Hard $\Rightarrow$ ME

|	ME	Matching	Merging	Shower
MADGRAPH5_aMC@NLO	MADGRAPH, BLHA	MC@NLO	FxFx	PYTHIA, HERWIG++ (Angular)
MATCHBOX/HERWIG++	MADGRAPH, BLHA	MC@NLO, POWHEG	UNLOPS	HERWIG++
POWHEG-BOX	Built-in, BLHA	POWHEG	MiNLO	All
POWHEL	HELAC-NLO	POWHEG	-	All
PYTHIA	Event Files	-	UNLOPS, NL^3	PYTHIA
SHERPA	COMIX, AMEGIC, BLHA	S-MC@NLO	MEPS@NLO	SHERPA (Dipole)
Gevena	Build-in + Resum	Geneva	Geneva	PYTHIA
HEJ	HEJ, MADGRAPH	-	HEJ+PS	Ariadne
Vincia	Built-in, MADGRAPH	Vincia	Vincia	Vincia, PYTHIA

BLHA: Blackhat, GoSam, NJet, OpenLoops, VBFNLO, ...
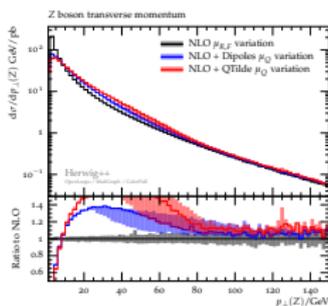
BSM support via UFO/FEYNRULES

Hard Scattering

Matching

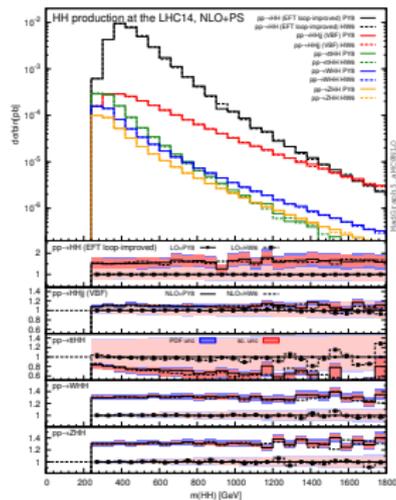High-degree of automation $\rightarrow$ lots of processes studies.
Need an assessment and understanding of our uncertainties.
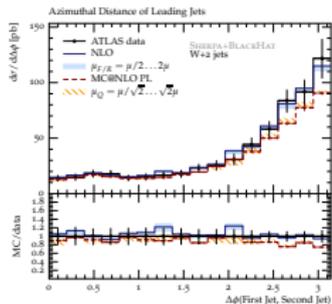
[Höche, Krauss, Schönherr, Siegert '12]

[Gieseke, Plätzer et al. - in progress]
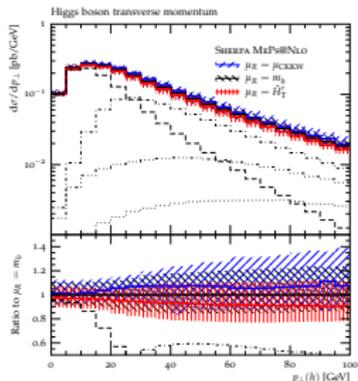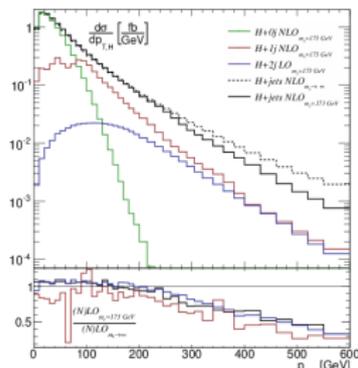

[Frederix et al. '14]

Hard Scattering
Merging

Minimise our dependence on the merging scale.

Merging at

- LO: Well understood
- NLO: Potential problems (inclusive cross-sections, how large?)

- FxFx, MEPS@NLO: Combine $\mathrm{MC@NLO}$'s of different multiplicities [Frixione, Frederix '12]   [Höche, Krauss, Schönherr, Siegert '12]
- MiNLO: Reproduce inclusive $pp \to X$ from $pp \to Xj$ with Sudakov factors [Hamilton, Nason, Oleari, Zanderighi '12]
- UNLOPS: Merge exclusive jet cross sections, constrain inclusive ones [Lönnblad, Prestel '12]   [Plätzer '12]
- Geneva: Combine NLOs with higher order resummation [Alioli et al. '13]
- Vincia: Lift iterated matrix element corrections to NLO [Skands et al. '13]

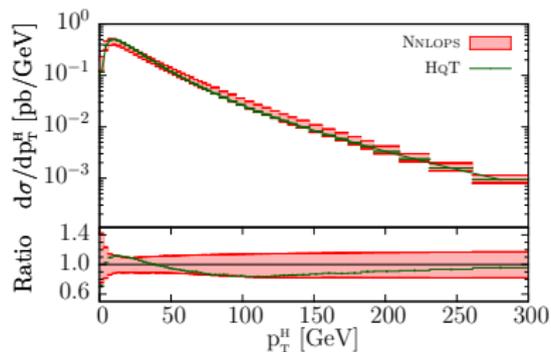
SHERPA, MEPS@NLO $gg \to H$
[Höche, Krauss, Schönherr '14]

SHERPA, MEPS@NLO $gg \to H$

Graeme Nail (Manchester)   Parton Shower Monte Carlo: Progress   SM@LHC, April 23, 2015   6 / 16

Hard Scattering
NNLO Matching

Proof of Concept for DY-type processes.

- Based on MiNLO [Hamilton, Nason, Re, Zanderighi '13]
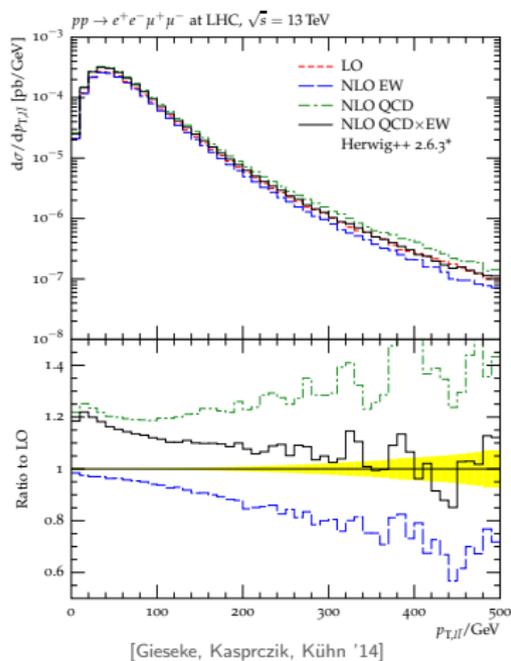- Based on UNLOPS [Höche, Li, Prestel '14]

Hard Scattering
EW Corrections

NLO EW $\sim$ NNLO QCD
Needed if we want sub 10% accuracy.

Factorised ansatz:
$(1 + \delta_{QCD})(1 + \delta_{EW}) \approx 1 + \delta_{QCD} + \delta_{EW}$

- Valid if both corrections are small
- QCD via POWHEG
- EW by reweighing

[Gieseke, Kasprczik, Kühn '14]

Shower
Overview

Showers resum large logarithms
Iterative implementation:

$PS[u(\phi_n), Q] = \Delta(\mu, Q)u(\phi_n) + P(q)\Delta(q, Q)\,PS[u(\phi_{n+1}), q]$

Shower	Construction	Recoil
HERWIG++	DGLAP (angular)	Global
	CS Dipoles	Local
PYTHIA 8	DGLAP (p_T)	Local
SHERPA	Antennae	Local
	CS Dipoles	Local
Ariadne	Antennae	Local
Cascade	CCFM	Global
Deductor	Nagy-Soper kernels	Local
KRKMC	DGLAP	Global
Vincia	Antennae	Local

Pin down differences, and cross-validate
uncertainties.

Other bits:

- Coherence
- EW
- Spin
- Subleading contributions

Ratio of jet masses, M_L^2/M_H^2

[Fischer, Gieseke, Plätzer, Skands '14]

Shower
Overview

Showers resum large logarithms
Iterative implementation:

$\mathsf{PS}[u(\phi_n), Q] = \Delta(\mu, Q)u(\phi_n) + P(q)\Delta(q, Q)\,\mathsf{PS}[u(\phi_{n+1}), q]$

Shower	Construction	Recoil
HERWIG++	DGLAP (angular)	Global
	CS Dipoles	Local
PYTHIA 8	DGLAP (p_T)	Local
SHERPA	Antennae	Local
	CS Dipoles	Local
Ariadne	Antennae	Local
Cascade	CCFM	Global
Deductor	Nagy-Soper kernels	Local
KRKMC	DGLAP	Global
Vincia	Antennae	Local

Pin down differences, and cross-validate
uncertainties.

Other bits:

- Coherence
- EW
- Spin
- Subleading contributions

[Christiansen, Sjöstrand '14]

Shower
Overview

Showers resum large logarithms
Iterative implementation:

$\mathrm{PS}[u(\phi_n), Q] = \Delta(\mu, Q)u(\phi_n) + P(q)\Delta(q, Q)\,\mathrm{PS}[u(\phi_{n+1}), q]$

Shower	Construction	Recoil
HERWIG++	DGLAP (angular)	Global
	CS Dipoles	Local
PYTHIA 8	DGLAP (p_T)	Local
SHERPA	Antennae	Local
	CS Dipoles	Local
Ariadne	Antennae	Local
Cascade	CCFM	Global
Deductor	Nagy-Soper kernels	Local
KRKMC	DGLAP	Global
Vincia	Antennae	Local

Pin down differences, and cross-validate
uncertainties.

Other bits:

- Coherence
- EW
- Spin
- Subleading contributions

$q \to qg + g \to q\bar{q}$ with $0.2 < z < 0.3$ and $0.3 < z' < 0.4$

gen-spin
gen-none
rec-spin
rec-none
gen-soft1
gen-all1
rec-soft1
rec-all1
gen-soft2
gen-all2
rec-soft2
rec-all2

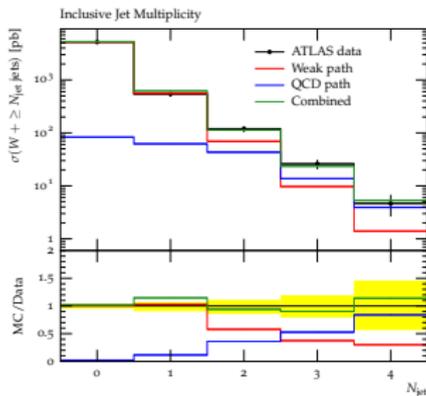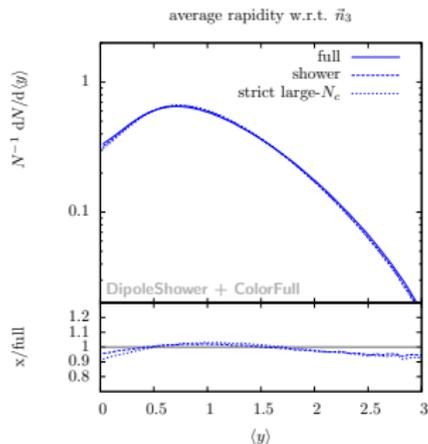$\Delta\phi$ [rad]

[Richardson - in progress]

Shower
Improvements

Colour-exact radiation patterns

$$D_{ij,k} \sim \frac{\langle \mathcal{M} | T_{ij} \cdot T_k | \mathcal{M} \rangle}{T_{ij}^2 |\mathcal{M}|^2}$$

- **First Emission** [Höche, Krauss, Schönherr, Siegert '11]
- **Several Emissions** [Plätzer, Sjödahl '11]

Electroweak:

- Include W, Z emission

  [Christiansen, Sjöstrand '14]

  [Krauss, Schönherr, Spannowsky '14]

- EW Sudakov logs unclear
  Different pattern to QCD logs

average rapidity w.r.t. $\vec{n}_3$

full
shower
strict large-N_c

DipoleShower + ColorFull

$N^{-1} \, \mathrm{d} N / \mathrm{d} \langle y \rangle$

x/full

$\langle y \rangle$

Inclusive Jet Multiplicity

ATLAS data
Weak path
QCD path
Combined

$\sigma(W + \geq N_{jet} \text{ jets})$ [pb]

MC/Data

N_{jet}

Shower
Uncertainties

Showers are perturbative objects. Can assess uncertainty through our scale dependence μ_F, μ_R, μ_Q. Analytic resummation: Scale compensation.

True for showers at LL. Showers more than LL, compensation less clear.

Need for cross-validation of different algorithms, and study of subleading effects.
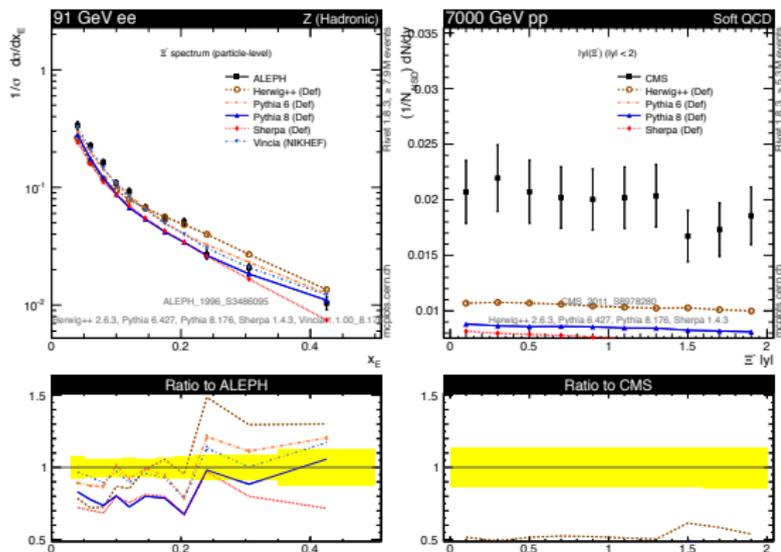Recoil procedure, starting scales, phase-space population, ...

[Höche, Krauss, Schönherr '14]

[Gieseke, Plätzer - in progress]
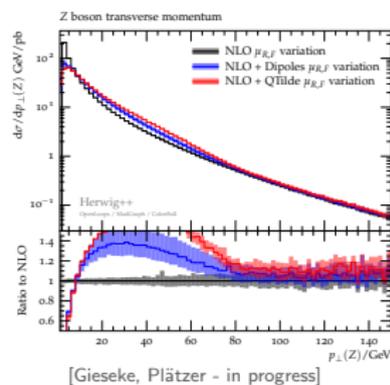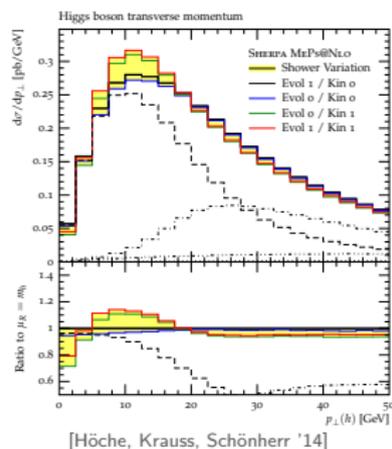
Hadronization
Overview

Strings (PYTHIA), Clusters (HERWIG++, SHERPA)

- Models developed for LEP.
- Little work in the past 10 years
- Cross-checks from Lattice
- Important for high-p_T physics
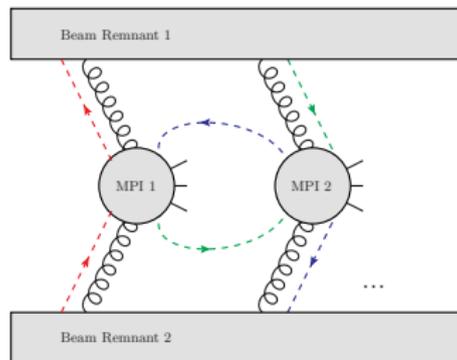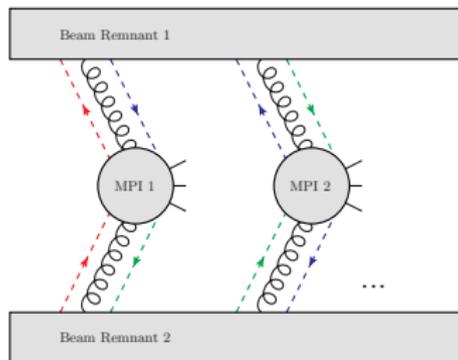- Data Driven ($\Rightarrow$ RIVET analyses)

Hadronization

Colour Reconnection
New Model of Beam Remnant and Colour Reconnection   [Christiansen, Skands - in progress]

Beam Remnant

- Conservation Laws (Flavour, Colour, Momentum)
- $SU(3)$ structure
- Example: $8 \otimes 8 = 27 \oplus \overline{10} \oplus 10 \oplus 8 \oplus 8 \oplus 1$
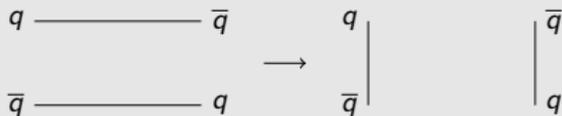

Colour reconnection allows us to reshuffle colour before hadronisation

- $SU(3)$ multiplet structure $\rightarrow$ allowed reconnections
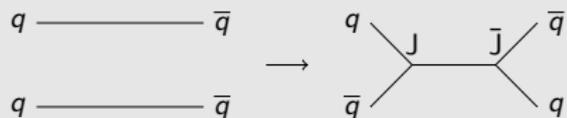- λ measure $\rightarrow$ preferred reconnections
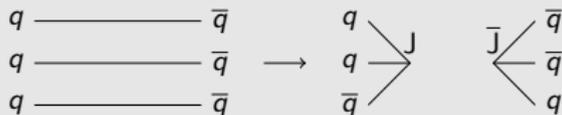
Hadronization

Colour Reconnection
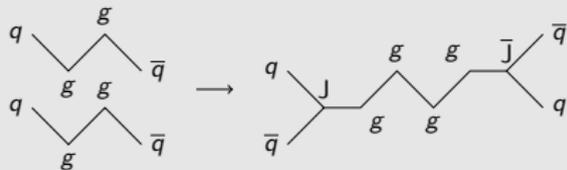
Hadronization

Colour Reconnection

$\Delta m_t = m_t(\text{default CR}) - m_t(\text{no CR})$

- No CR - unphysical, overestimates uncertainty?
- $m_t(\text{no CR})$ - may not give bound to m_t, underestimates uncertainty?

CR Model uncertainties turned out to be small at LEP2 (W mass measurements). Doesn't necessarily mean they'll be small for current efforts to measure top-mass. t is a coloured particle!

Model	$\mathbf{\Delta m_t^{rescaled}}$ [GeV]
Default	$+0.239$
Forced Random (Min)	-0.524
Move	$+0.239$
Swap	$+0.273$

$$m_t^{\max} - m_t^{\min} \simeq 0.8 \text{ GeV}$$

$\Delta m_t \approx 0.5 \text{ GeV}$ (for sophisticated models)

[Argyropoulos, Sjöstrand '14]

Outlook

Monte Carlos are important for the LHC Run-II and beyond.
Precision is not only higher order effects, but also understanding and controlling our uncertainties.

Need for

- EW-effects
- Improvements in Shower
- Improvements in Non-Perturbative

(Far) Future

- NNLO is at a *very* early stage.