

# Status of MC event generators

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SLAC NAL Theory Group



Workshop on LHC Physics

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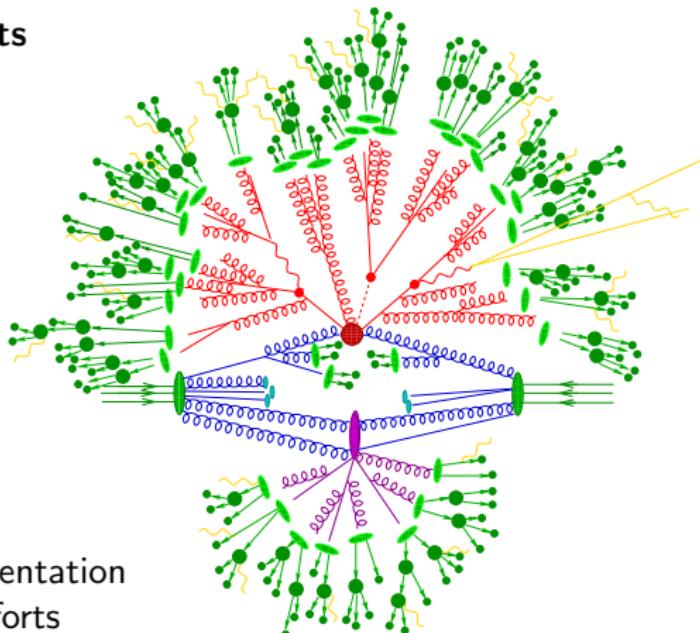


## Structure of simulated LHC events

- Hard interaction
- QCD evolution
- Secondary hard interactions
- Jet fragmentation
- Hadron decays
- Higher-order QED corrections

Much recent progress on hard QCD  
Benefits from “NLO revolution”

Improved models for MPI and fragmentation  
Combined with systematic tuning efforts



Three general-purpose tools with slightly different structure and emphasis

## Herwig

- Originated in coherent shower studies → angular ordered PS
- Front-runner in development of Mc@NLO and POWHEG
- Simple in-house ME generator & spin-correlated decay chains
- Original framework for cluster fragmentation

## Pythia

- Originated in hadronization studies → Lund string
- Leading in development of multiple interaction models
- Pragmatic attitude to ME generation → external tools
- Extensive PS development and earliest ME $\otimes$ PS matching

## Sherpa

- Started with PS generator APACIC++ & ME generator AMEGIC++
- Current MPI model and hadronization pragmatic add-ons
- Leading in development of automated ME $\otimes$ PS merging
- Automated framework for NLO calculations and Mc@NLO

**For more information, check out** [Buckley et al.] Phys.Rept.504(2011)145

For updates and news, go to <http://www.montecarlonet.org>



## Rivet [Buckley et al.] arXiv:0103.0694

- LHC-successor to HZTool  
Collection of exp. data & matching analysis routines
- Spirit: “Right MC describes everything at the same time”

## Professor [Buckley et al.] EPJC65(2010)331

- Tuning in multi-dimensional parameter space of MC
- Generate event samples at random parameter points  
Analyse them with Rivet  
Parameterize observables  
Minimize  $\chi^2$  and cross-check

## Tune comparisons

Deviation metrics per gen/tune and observable group:

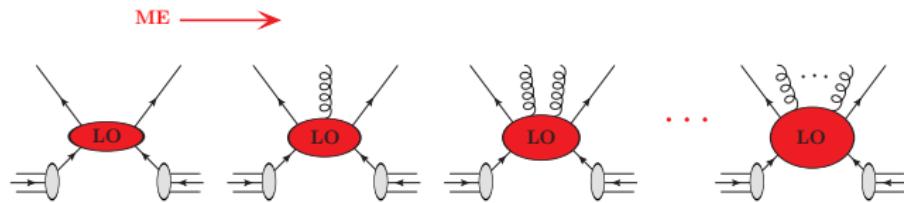
Gen	Tune	UE	Dijets	Multijets	Jet shapes	W and Z	Fragmentation	B frag
AlpGen	HERWIG6	—	1.83	5.36	2.48	0.91	—	—
	PYTHIA6-AMBT1	—	1.55	2.80	0.61	0.53	—	—
	PYTHIA6-D6T	—	1.38	2.67	2.31	1.67	—	—
	PYTHIA6-P2010	—	1.09	2.65	2.03	1.48	—	—
	PYTHIA6-P2011	—	1.12	2.60	0.48	0.24	—	—
	PYTHIA6-Z2	—	1.48	2.63	0.55	0.48	—	—
	PYTHIA6-profQ2	—	1.16	2.65	1.43	1.29	—	—
HERWIG	AUET2-CTEQ6L1	0.43	0.55	0.77	0.35	0.58	22.80	2.38
	AUET2-LOxx	0.25	0.71	0.60	0.39	0.88	22.13	2.29
Herwig++	2.5.1-UE-EE-3-CTEQ6L1	0.27	0.87	0.78	0.51	0.98	10.58	1.32
	2.5.1-UE-EE-3-MRSTLOxx	0.23	1.05	0.78	0.50	0.65	10.58	1.32
PYTHIA6	AMBT1	0.39	1.20	0.54	0.77	0.27	0.93	1.65
	AUET2B-CTEQ6L1	0.16	0.92	0.44	0.59	0.74	0.67	1.29
	AUET2B-LOxx	0.13	1.33	0.55	0.58	1.15	0.67	1.30
	D6T	0.58	0.79	0.50	0.56	1.25	0.36	2.63
	DW	0.81	0.78	0.61	0.56	1.33	0.36	2.63
	P2010	0.30	0.93	0.82	1.07	0.30	0.44	1.75
	P2011	0.12	0.89	0.67	1.02	0.53	0.43	2.13
Pythia8	ProfQ2	0.51	0.67	0.81	0.51	0.64	0.30	1.65
	Z2	0.18	0.94	0.73	0.80	0.30	0.95	2.78
Sherpa	4C	0.30	0.97	0.93	0.50	0.90	0.38	1.12
Sherpa	1.3.1	0.68	0.47	0.34	0.71	0.36	0.75	2.48

[LH'11 SM WG] arXiv:1203.6803 [hep-ph]

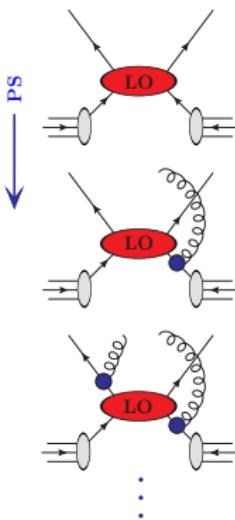
<http://rivet.hepforge.org/tunecmp/>



## High-multiplicity LO matrix elements

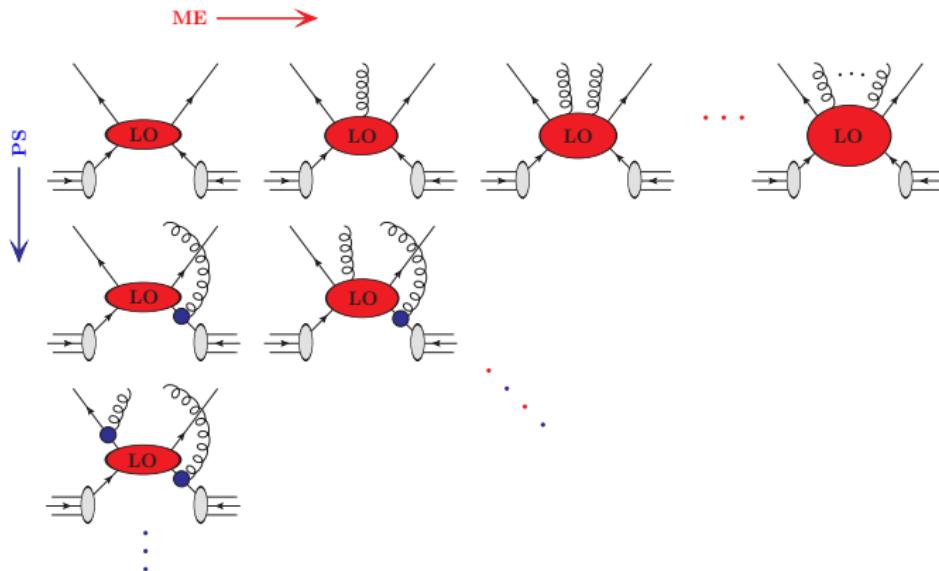


## Parton showers

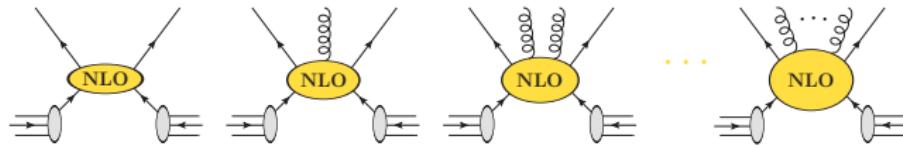


# Dictionary and Outline

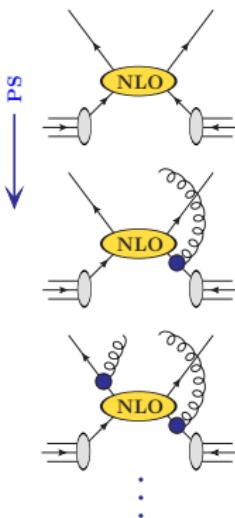
## Matrix-element parton-shower merging (ME $\otimes$ PS)



## High-multiplicity NLO matrix elements



## NLO matrix-element parton-shower matching



Plethora of tree-level tools on market  
**State of the art: Full automation**

- **Feynman diagrams**

- AMEGIC++ [Krauss et al.] JHEP02(2002)044
- CompHEP [Boos et al.] NIMA534(2004)250
- MADGRAPH [Alwall et al.] JHEP02(2011)128

- **Recursive techniques**

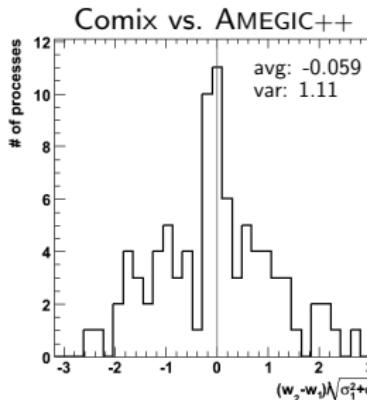
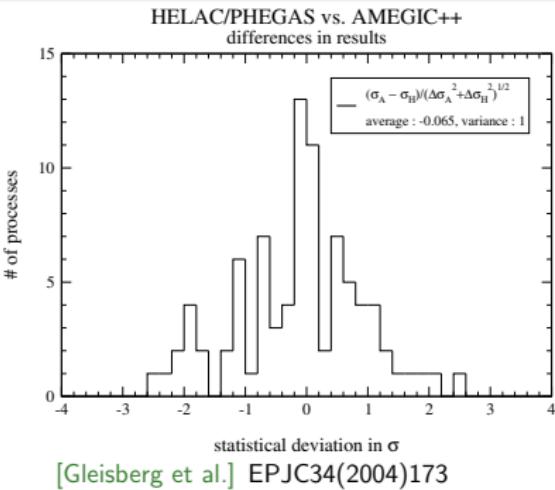
- Comix [Gleisberg,SH] JHEP12(2008)039
- HELAC [Kanaki,Papadopoulos] CPC132(2000)306
- O'Mega [Moretti,Ohl,Reuter] hep-ph/0102195

- **$\alpha$ -algorithm**

- ALPGEN [Mangano et al.] JHEP07(2001)003

LHEF output for passing events  
 to external MC HERWIG++ & PYTHIA

Useful plugins for NLO calculation  
 → Born, real emission & subtraction



$$\text{NLO prediction} \left\{ \begin{array}{l} B = \text{Diagram with two external lines and one internal loop} \\ V = \sum 2 \operatorname{Re} \left\{ \text{Diagram with two external lines and one internal loop} \right\} \\ R = \sum \text{Diagram with two external lines and one internal loop} \end{array} \right.$$

Singularities in  $V$  &  $R$  to be removed before MC-integration

$$\sigma^{NLO} = \int d\Phi_B (B + \tilde{V}) + \int d\Phi_R R = \int d\Phi_B \left[ (B + \tilde{V} + I^{(S)}) + \int d\Phi_{R|B} (R - D^{(S)}) \right]$$

### Commonly used subtraction techniques:

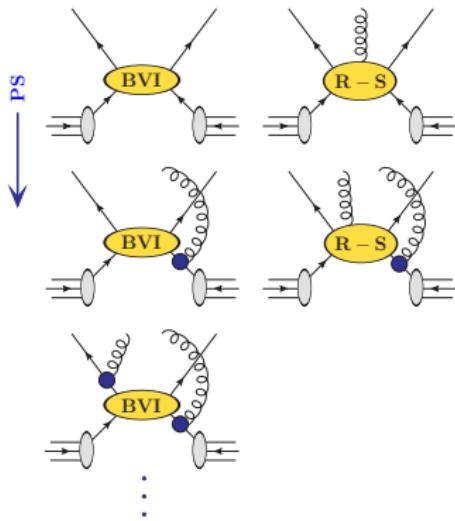
- **Dipole method** [Catani,Seymour] NPB485(1997)291  
[Catani,Dittmaier,Seymour,Trocsanyi] NPB627(2002)189, implemented in

- AMEGIC++ [Gleisberg,Krauss] EPJC53(2008)501, Comix [SH] colorful
- HELAC/PHEGAS [Czakon,Papadopoulos,Worek] JHEP08(2009)085 polarized
- MADDIPOLE [Frederix,Gehrmann,Greiner] JHEP09(2008)122, JHEP06(2010)096

- **FKS method** [Frixione,Kunszt,Signer] NPB467(1996)399, implemented in

- MADFKS [Frederix,Frixione,Maltoni,Stelzer] JHEP10(2003)009

Several other implementations, which are not part of automated tree-level tools



Assume parton shower with same structure as NLO-subtraction method  
 Expectation value of observable  $O$  to  $\mathcal{O}(\alpha_s)$  in PS approximation:

$$\langle O \rangle = \sum \int d\Phi_B B \left[ \Delta^{(PS)}(t_0) O(\Phi_B) + \sum \int_{t_0} d\Phi_{R|B}^{ij,k} K_{ij,k} \Delta^{(PS)}(t(\Phi_{R|B})) O(\Phi_R) \right]$$

where  $\Delta^{(PS)}(t) = \exp \left\{ - \int_t d\Phi_{R|B}^{ij,k} K_{ij,k} \right\}$

### Make this NLO-correct:

- Radiation pattern of R from ME correction

Correction weight  $w = D_{ij,k}^{(A)}/BK_{ij,k}$ , where  $D_{ij,k}^{(A)} \rightarrow$  dipole term

- Replace  $B \rightarrow \bar{B}^{(A)} = B + \tilde{V} + I^{(S)} + \sum \int d\Phi_{R|B}^{ij,k} \left[ D_{ij,k}^{(A)} - D_{ij,k}^{(S)} \right]$

- Add hard remainder function  $\int d\Phi_R H^{(A)}$ , where  $H^{(A)} = \left[ R - \sum D_{ij,k}^{(A)} \right]$

### Defines Mc@NLO algorithm [Frixione,Webber] JHEP06(2002)029

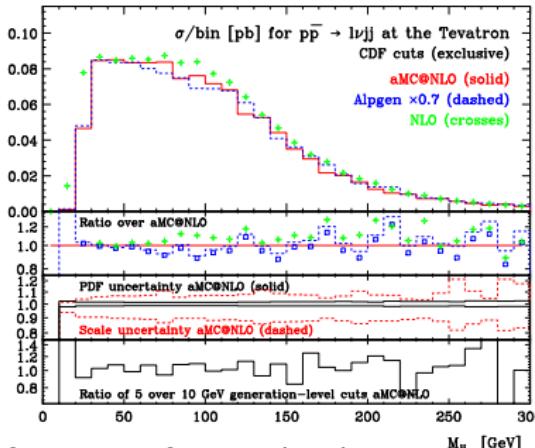
$$\begin{aligned} \langle O \rangle = & \sum \int d\Phi_B \bar{B}^{(A)} \left[ \bar{\Delta}^{(A)}(t_0) O(\Phi_B) \right. \\ & \left. + \sum \int_{t_0} d\Phi_{R|B}^{ij,k} \frac{D_{ij,k}^{(A)}}{B} \bar{\Delta}^{(A)}(t(\Phi_{R|B})) O(\Phi_R) \right] + \int d\Phi_R H^{(A)} O(\Phi_R) \end{aligned}$$

Standard method to combine NLO with MC    POWHEG almost identical

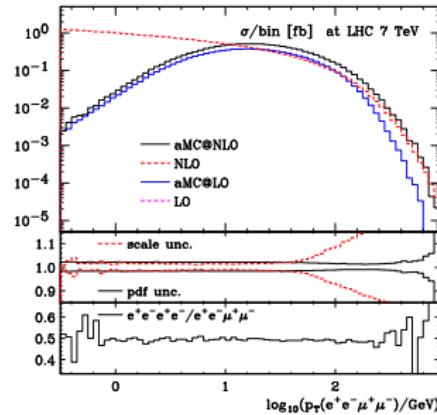
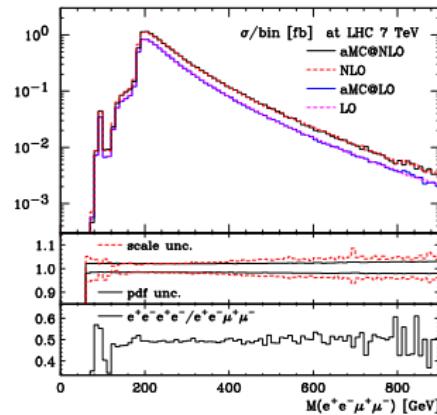
## Automated in aMc@NLO

Using MADFKS subtraction and fHERWIG PS  
Framework for convenient uncertainty estimate

- $t\bar{t}h$  PLB701(2011)427
- $W^\pm/Z + b\bar{b}$  JHEP09(2011)061
- 4 leptons JHEP02(2012)099
- $W^\pm + 2$  jets JHEP02(2012)048



[Frederix et al.] JHEP02(2012)048



[Frederix et al.] JHEP02(2012)099

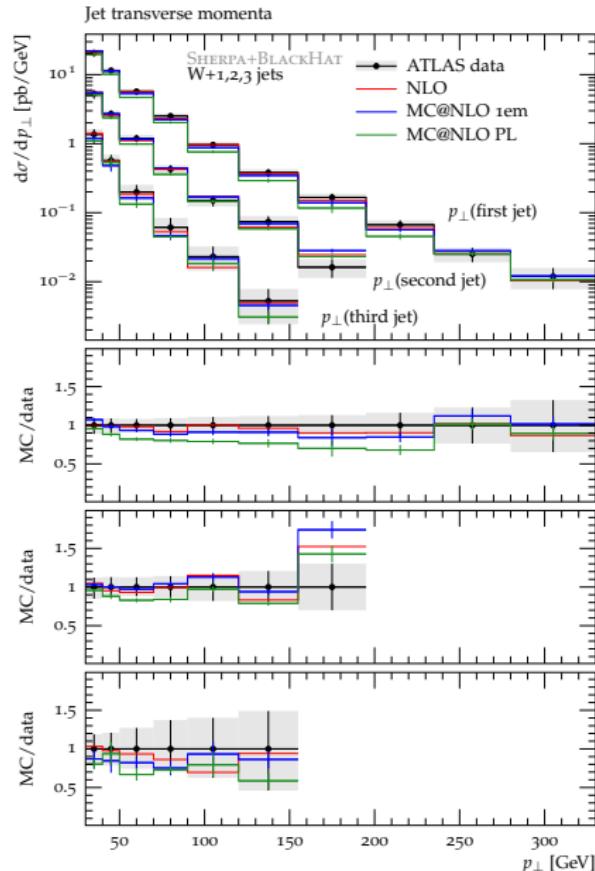
Substantial simplification of Mc@NLO  
if  $D_{ij,k}^{(A)} \rightarrow D_{ij,k}^{(S)}$   $\Rightarrow$  zero integral in  $\bar{B}^{(A)}$

**Works well in  $W+\leq 3$  jets  $\rightarrow$**

Automated for light partons

**Released with Sherpa 1.4.0**

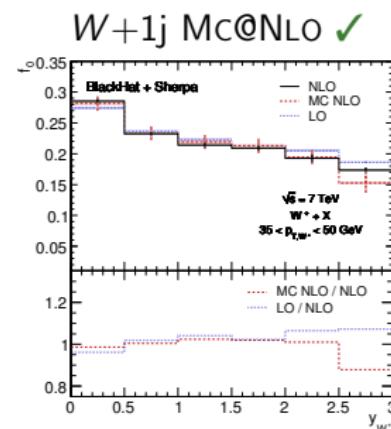
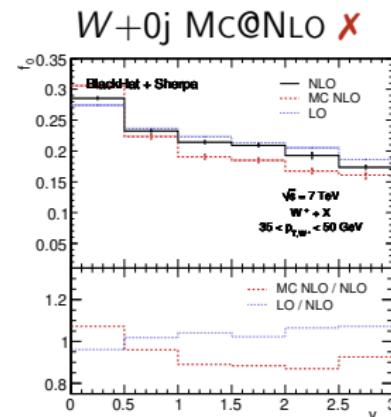
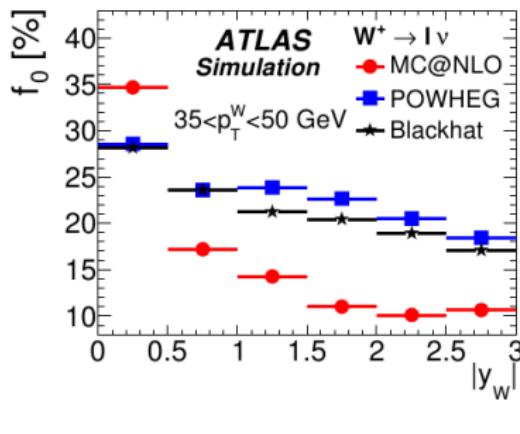
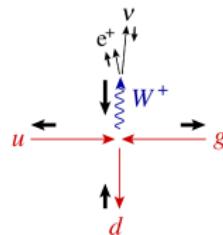
Resummation scale defined by  $\alpha_{\text{cut}}$   
will be changed to  $k_T$  in release 1.4.1  
now have  $k_T$ -integral of subtraction terms



## Which NLO-tool for what?

Example:  $\text{Mc@NLO} \leftrightarrow \text{POWHEG}$   
in  $W$ -polarization measurement

[ATLAS] arXiv:1203.2165



Originally  $D_{ij,k}^{(A)}$  defined by PS kernels  
+ soft suppression function (subleading color)

Use instead  $R_{ij,k}^{(A)} = D_{ij,k}^{(A)} / \sum D^{(A)} R$

→ Mc@NLO becomes POWHEG  
[Frixione,Nason,Oleari] JHEP11(2007)070

## Partially automated in POWHEGBox

[Alioli,Oleari,Nason,Re] JHEP06(2010)043

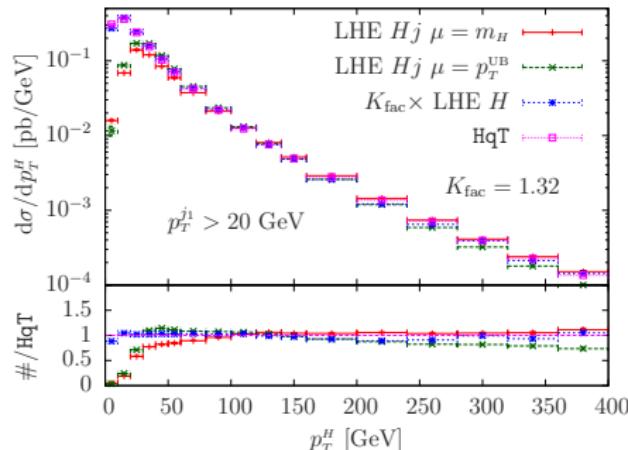
- FKS subtraction
- PYTHIA/fHERWIG PS

Extensive list of processes implemented  
Recent example:  $h+2$  jets in GF

POWHEGBOX originally aimed at providing framework only  
→ many contributors and rapid development

[Barzè,Bernaciak,Bagnaschi,Campbell,Ellis,Frederix,deGrassi,Jäger,Klasen,Kovarik,Melia,Moch,Montagna,Nicrosini,Piccinini,Reina,Ridolfi,Rontsch,Slavich,Uwer,Vicini,Wackerlo,Weydert,Williams,Zanderighi]

Now heading towards full automation using MADGRAPH & GO-SAM

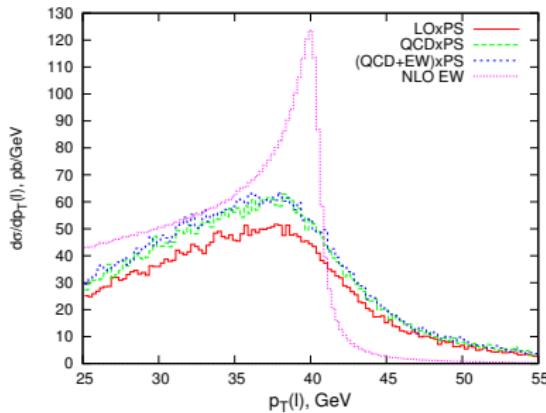


[Campbell,Ellis,Frederix,Nason,Oleari,Williams]  
arXiv:1202.5475 [hep-ph]

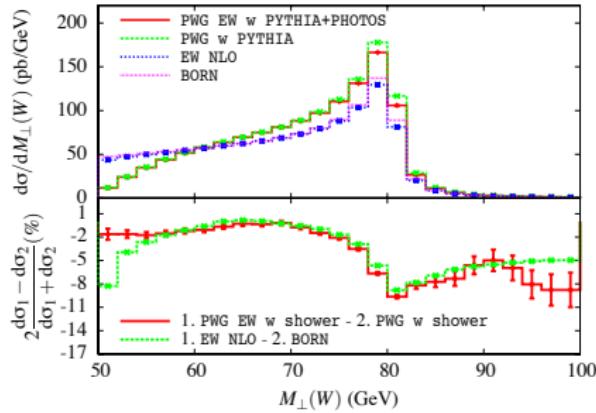
## EW corrections in the POWHEGBox

Single vector boson production → two different implementations:

- NLO QCD+EW  $\otimes$  QCD PS [Bernaciak,Wackeroth] arXiv:1201.4804 [hep-ph]
- NLO QCD+EW  $\otimes$  QCD+QED PS [Barzè et al.] JHEP04(2012)037



[Bernaciak,Wackeroth]  
arXiv:1201.4804 [hep-ph]



[Barzè, Montagna, Nason, Nicrosini, Piccinini]  
JHEP04(2012)037

## Some in-house implementations of POWHEG in HERWIG++

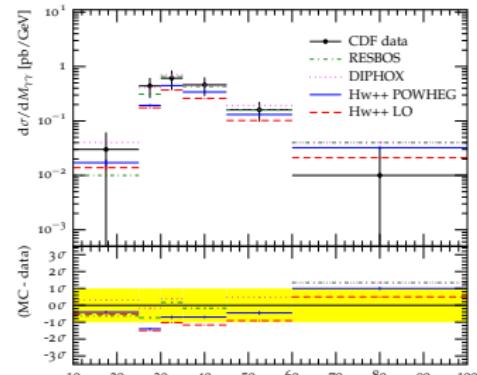
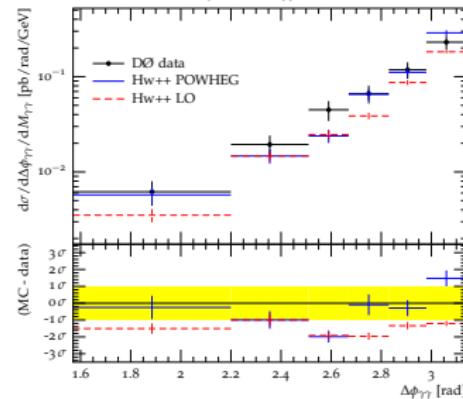
- Drell-Yan JHEP10(2008)015
- $W/Z + \text{Higgs}$  JHEP05(2009)112
- Higgs in GF JHEP04(2009)116
- DIS & VBF arXiv:1106.2983 [hep-ph]
- Diphoton JHEP02(2012)130

### Truncated PS always included!

While argued that necessary in principle truncated PS is **neglected** in POWHEGBox

Elegant solution for diphoton production:  
Split real-emission ME into QCD & QED  
parts using respective subtraction terms

$$R_{\text{QCD}}^{(A)} = R \frac{\sum D_{\text{QCD}}^{(A)}}{\sum D_{\text{QCD}}^{(A)} + \sum D_{\text{QED}}^{(A)}}$$

(a)  $50 \text{ GeV} < M_{\gamma\gamma} < 80 \text{ GeV}$ 

[d'Errico, Richardson] JHEP02(2012)130

**Controversy #1:** Mc@NLO radiation dip

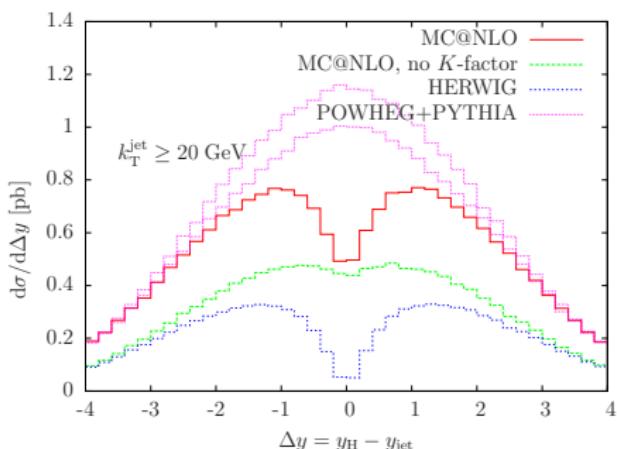
At large  $p_T$ , Mc@NLO cross section is

$$\frac{d\sigma}{d\Phi_R} = \sum_{ij,k} \left( \frac{\bar{B}_{ij\tilde{k}}^{(A)}}{B_{ij\tilde{k}}} - 1 \right) D_{ij,k}^{(A)} + R$$

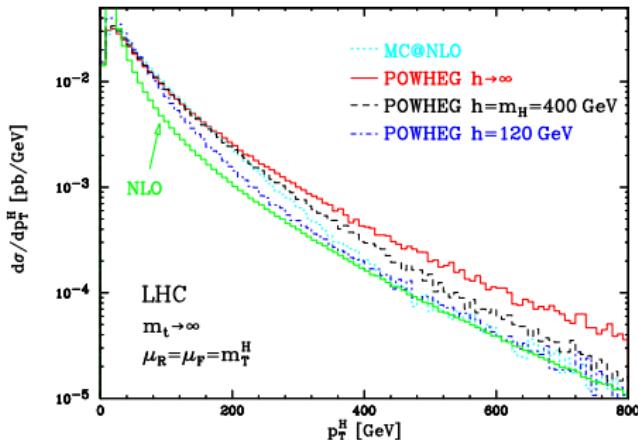
Formally,  $\bar{B}^{(A)}/B - 1$  is of order  $\alpha_s$

In practice this is often sizeable

→ Mc@NLO inherits MC dead zones



[Nason,Webber] arXiv:1202.1251 [hep-ph]



[Nason,Webber] arXiv:1202.1251 [hep-ph]

**Controversy #2:** What gets resummed  
 $D^{(A)}/H^{(A)}$  can be adjusted in

- functional form
- active phase space

POWHEG →  $D^{(A)}$  from damping  $R^{(A)}$

**Tuneable damping parameter  $h$**

Learn from analytic approaches

→  $h$  defined by resummation scale  $Q$

# Parton shower issues

SLAC

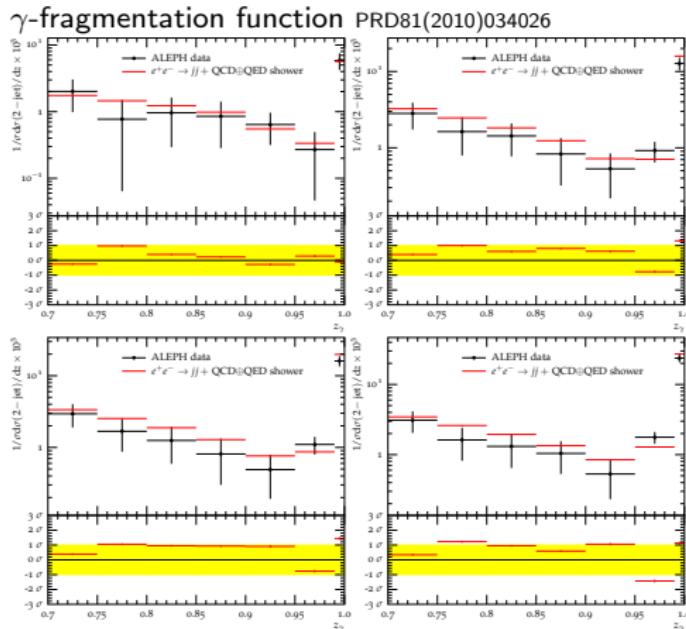
**Mc@NLO and POWHEG both rely on general-purpose MC for subsequent showering**

Kinematic effects & scale choices play a role → PS model affects accuracy of matched NLO result

**Need improved parton showers as part of general-purpose MC**

Various new implementations but few public codes on market

PS, Hadronization, & MPI linked  
→ combined tuning necessary!



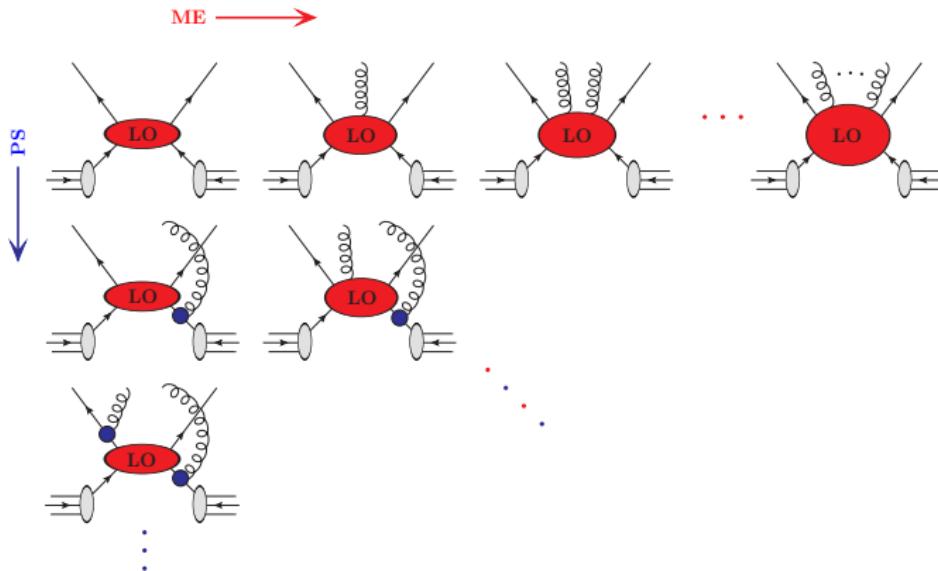
[Schumann,Sieger,SH] PRD81(2010)034026

Most promising progress with dipole-like parton showers

[Schumann,Krauss] JHEP03(2008)038, [Plätzer,Gieseke] JHEP01(2011)024

Sector showers interesting new alternative

[Giele,Kosower,Skands] PRD84(2011)054003, [Larkoski,Peskin] PRD81(2010)054010



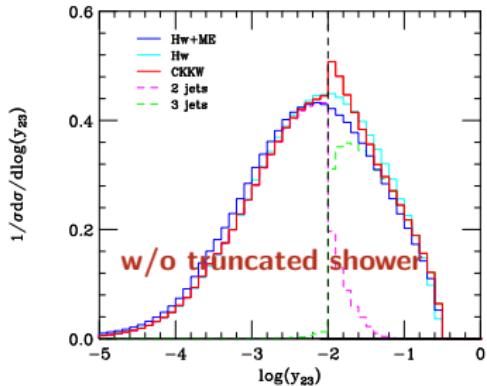
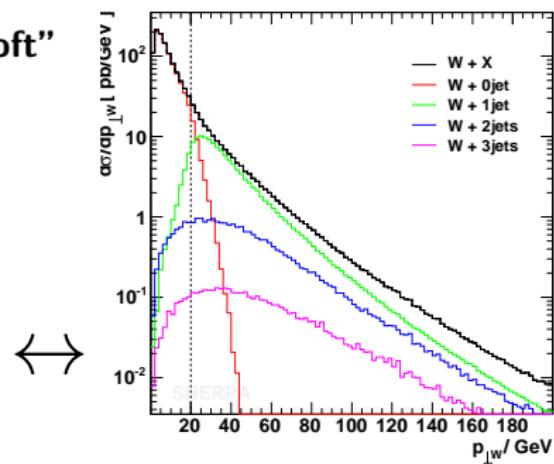
## Separate radiation into “hard” & “soft”

[Catani,Krauss,Kuhn,Webber] JHEP11(2001)063

[Krauss,Schumann,Siegert,SH] JHEP05(2009)053

- Real-emission ME in hard domain
- PS approximation in soft domain

need measure for “hard” & “soft”  
 → above / below critical value in  
 Jet criterion  $Q$  e.g.  $k_T$ -jet measure



If  $Q$  different from evolution variable  
 truncated showers needed to maintain  
 logarithmic accuracy of original PS

Only two implementations so far

- SHERPA JHEP05(2009)053
- HERWIG++ JHEP11(2009)038

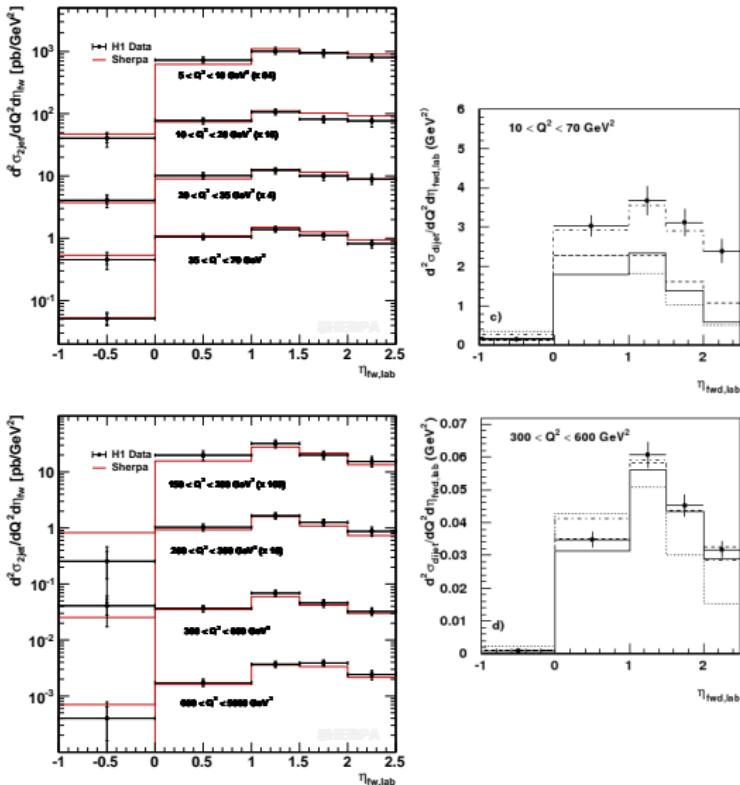
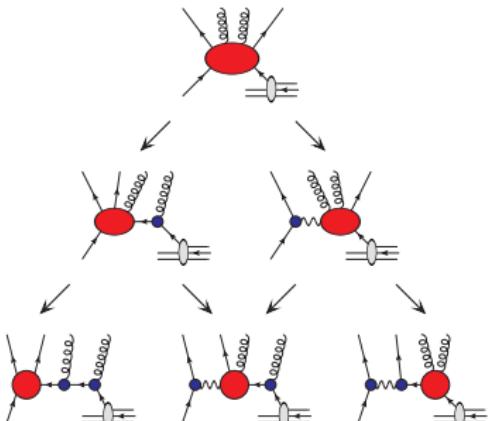
Requires intimate knowledge of PS

[Hamilton,Richardson,Tully] JHEP11(2009)038

## Lessons from DIS @ HERA:

Simulation often too focused  
on resonant contributions

Sometimes need be inclusive  
e.g. for low-mass Drell-Yan  
or photon & diphoton events

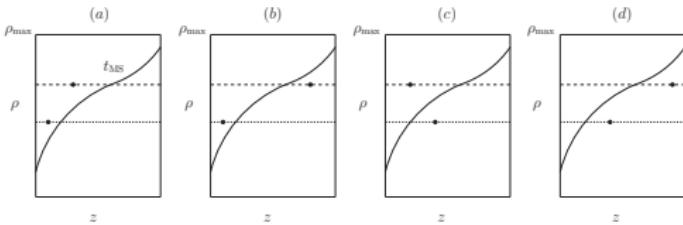


[Carli,Germann,SH] EPJC67(2010)73

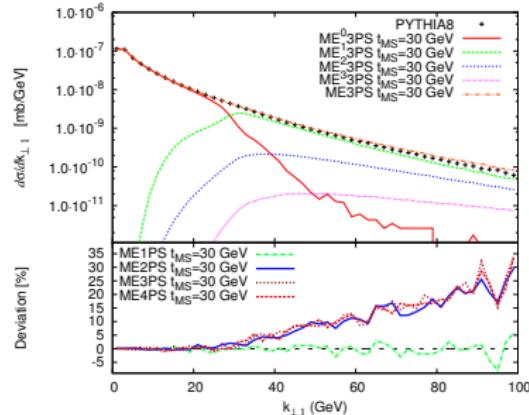
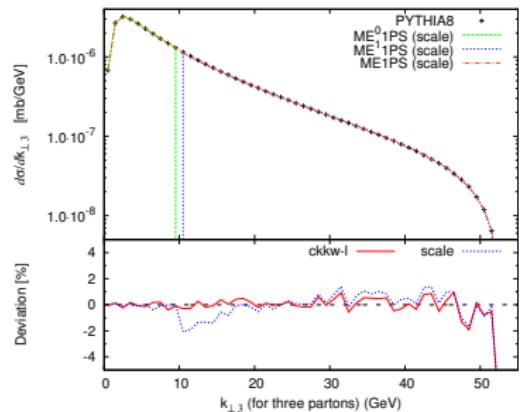
## New, promising merging approach

in Pythia 8 [Lönnblad, Prestel] JHEP03(2012)019

- CKKW-L like [Lönnblad] JHEP05(2002)046  
Works for interleaved showers
- Based on recasting jet criterion into hybrid of  $Q$  and PS evolution variable
- Alternative solution to truncated PS  
same formal accuracy in most regions
- Difficult to disentangle effects of phase-space separation analytically  
most likely not an issue in practice



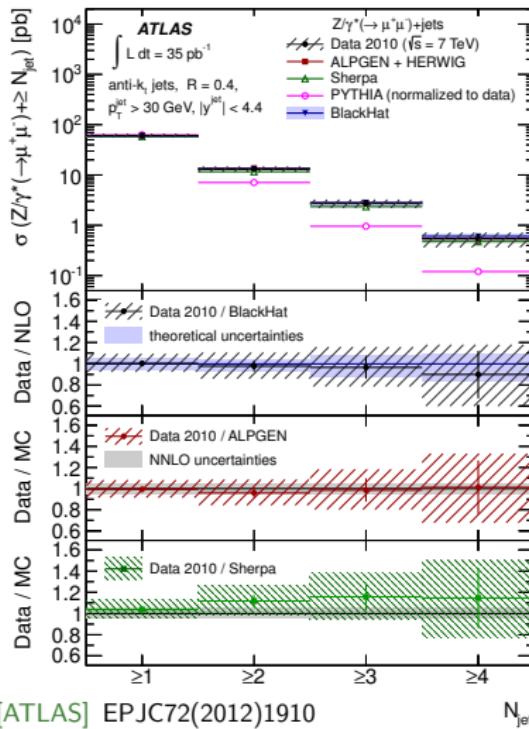
**Formal improvement over MLM method and suitable for all PS algorithms**



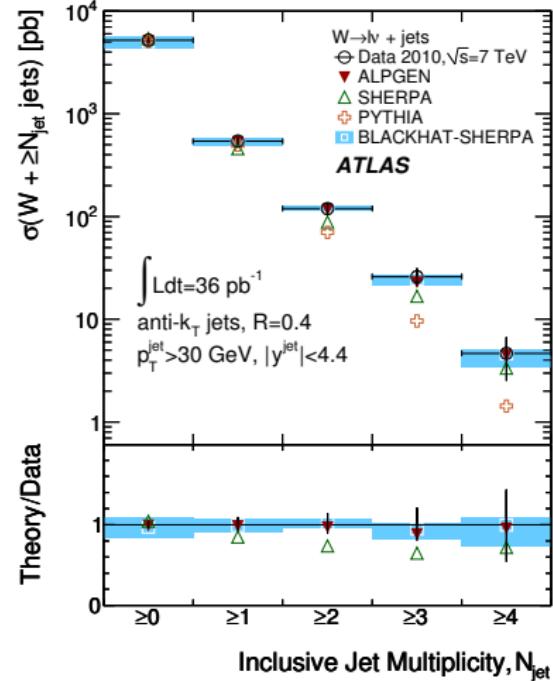
[Lönnblad, Prestel] JHEP03(2012)019

# Uncertainty estimates

Often good description of data with one approach or tool  
but not so good with another → **need systematic study of differences**



[ATLAS] EPJC72(2012)1910



[ATLAS] arXiv:1201.1276 [hep-ex]

# Uncertainty estimates

Need systematic quantification of hadronization & MPI uncertainties

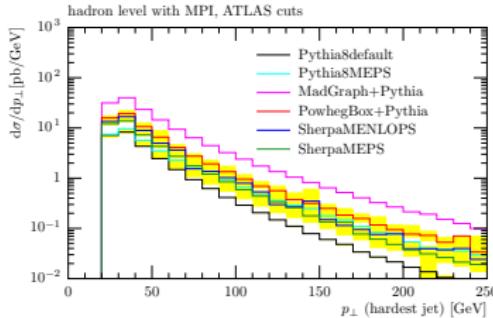
Instead of many different tunes,  
provide “error tunes” like PDF

→ Joint effort of theory and experiment

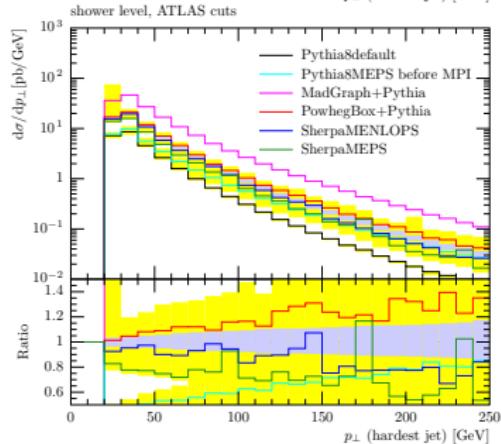
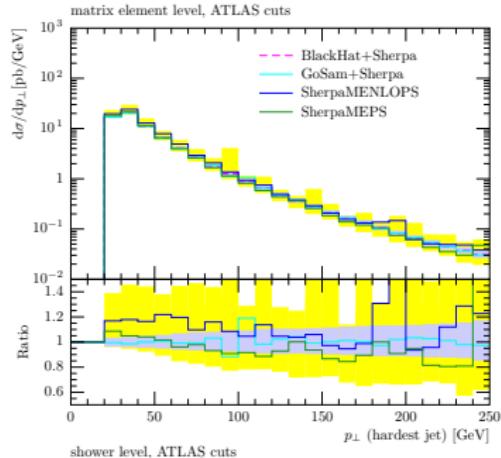
Need MC comparison at different levels  
and including full uncertainties

Pinpoint where tools could  
look alike and why they don't

→ Joint effort of theory and theory



[LH'11 SM WG] arXiv:1203.6803 [hep-ph]



# Minimum Bias

SLAC

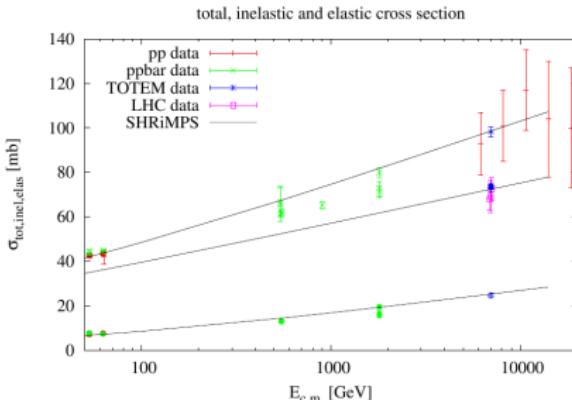
## New min bias generator based on KMR model in Sherpa 1.4.0

Optical theorem relates  $\sigma_{tot}$  to elastic forward scattering (Pomeron)

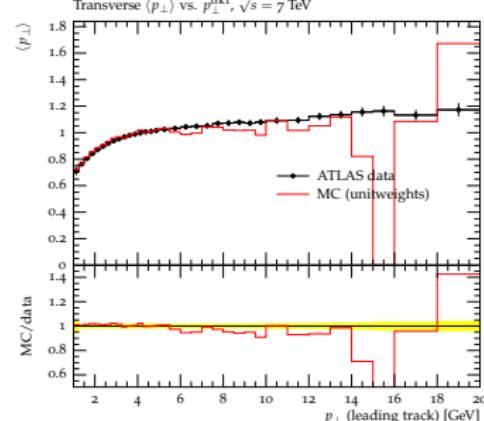
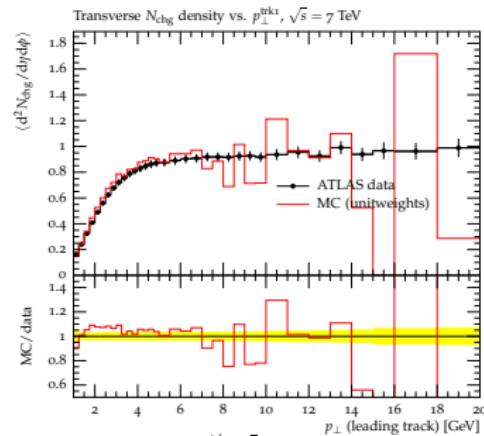
Elastic bare Pomeron exchange simulated as rapidity evolution

Rescattering in high density & strong coupling regime

Proton FF  $\leftrightarrow$  diffractive Eigenstates



[Hoeth,Khoze,Krauss,Martin,Ryskin,Zapp] SM@LHC'12



Exp. data: [ATLAS] PRD83(2011)112001

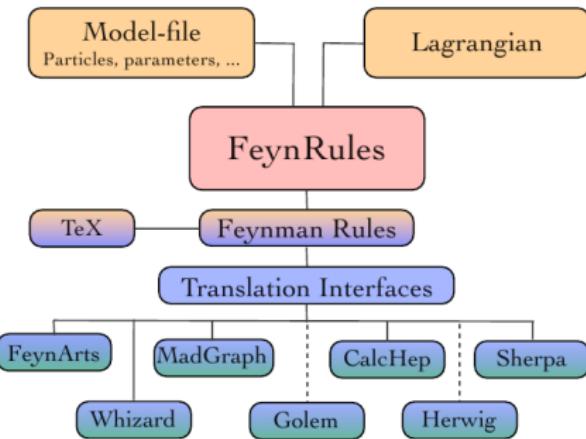
- HERWIG++, PYTHIA & SHERPA provide frameworks for event simulation
- Lots of progress to combine NLO tools with these general-purpose MC
- More systematic uncertainty studies needed

Tree-level ME generators suited for any physics model but implementing Feynman rules tedious and error-prone

## Automated by FeynRules

[Christensen,Duhr] CPC180(2009)1614

- Extract vertices from Lagrangian based on minimal information about particle content
- Write ME-generator specific output → universality and cross-checks



## Recent developments include:

- UFO** [Degrande,Duhr,Fuks,Grellscheid,Mattelaer,Reiter] CPC183(2012)1201  
Model files and Feynman rules → self-contained Python library
- ALOHA** [deAquino,Link,Maltoni,Mattelaer,Stelzer] arXiv:1108.2041 → MADGRAPH  
Automated implementation of arbitrary higher-dimensional operators
- Spin-3/2 particles and superfield formalism
- Counterterms for NLO ME generators

Multi-particle cuts and generalized unitarity simplify loop integration:

$$A_{loop} = \sum d_i \text{ (diagram)} + \sum c_i \text{ (diagram)} + \sum b_i \text{ (diagram)} + R + \mathcal{O}(\epsilon)$$

Cut-constructible part of virtual amplitude reduced to scalar integrals at integrand level → determine coefficients from tree amplitudes

[Ossola,Papadopoulos,Pittau] NPB763(2007)147, [Forde] PRD75(2007)125019

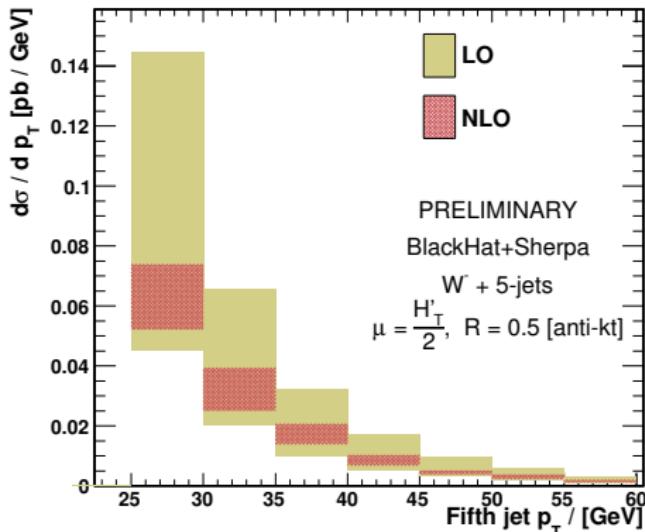
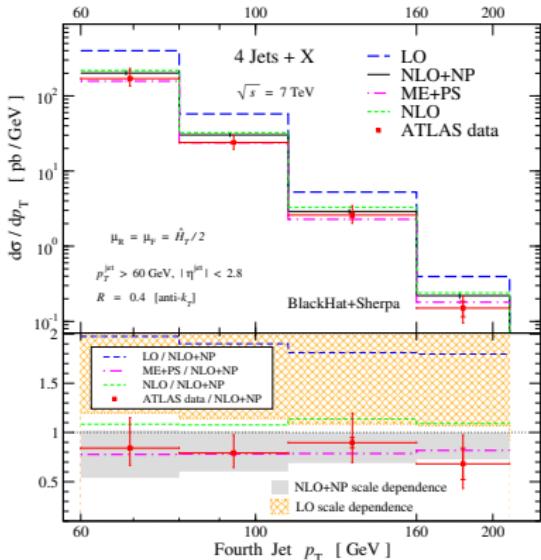
## Various (semi-)automated codes:

- BlackHat [Bern,Dixon,Febres-Cordero,Höche,Ita,Kosower,Maître,Ozeren]
- GoSam [Cullen,Greiner,Heinrich,Luisoni,Mastrolia,Ossola,Reiter,Tramontano]
- Helac-NLO [Bevilacqua,Czakon,Garzelli,van Hameren,Malamos,Papadopoulos,Pittau,Worek]
- MadLoop [Hirschi,Frerix,Frixione,Garzelli,Maltoni,Pittau]
- OpenLoops [Cascioli,Maierhöfer,Pozzorini]
- Rocket [Ellis,Giele,Kunszt,Melnikov,Zanderighi]
- & others [Badger,Lazopoulos,Giele,Kunszt, Winter,...]

Standalone programs, but also “loop engines” for MC@NLO & POWHEG  
Anticipate symbiotic relationship with tree-level tools → Binoth LH interface

# Automated NLO calculations

Example: BlackHat  $\oplus$  Comix



Four-jet production at 7 TeV LHC  
[BlackHat] arXiv:1112.3940 [hep-ph]

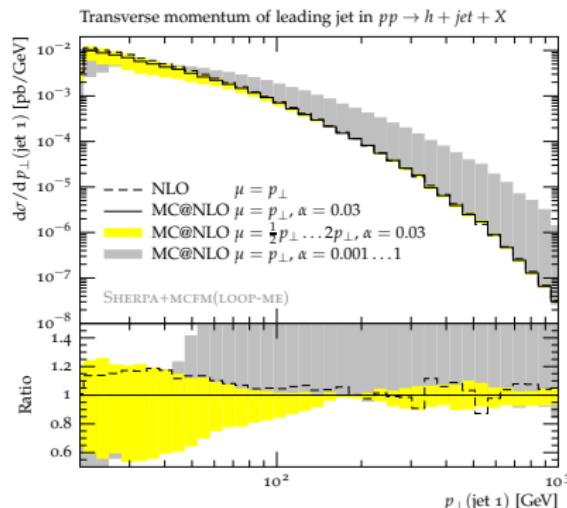
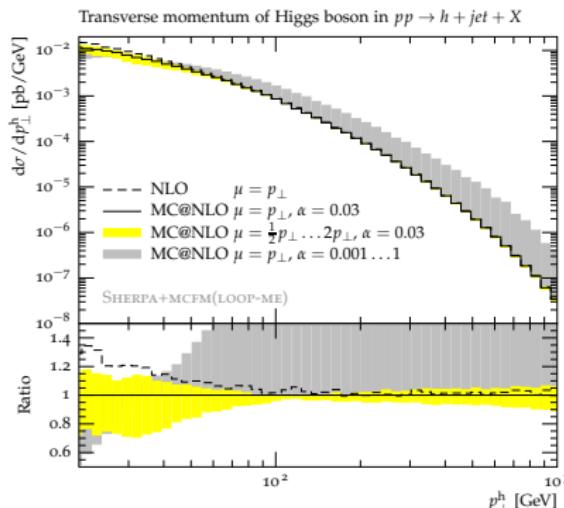
First results for  $W+5$  jets  
**Highly preliminary!** [BlackHat]

Jet multiplicity no more problem here  
But need to address other process types !

Increased parton multiplicity worsens problems

more QCD partons radiate more → higher chance to go wrong

**Exemplified this in  $pp \rightarrow h+j$  (GF)** [Krauss,Schönherr,Sieger,SH] arXiv:1111.1220 [hep-ph]



**Gray band  $\leftrightarrow$  POWHEG uncertainty due to varying  $D^{(A)}$**

Variation due to beyond-NLL effects? [Nason,Ridolfi] JHEP08(2006)077

Unlikely, as  $Q^2$  should really be  $\mathcal{O}(m_h)$  to avoid large spurious logs

[Banfi,Salam,Zanderighi] JHEP08(2004)062, [Bozzi,Catani,DeFlorian,Grazzini] NPB737(2006)73