Modern event generators for LHC physics

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West Coast ATLAS Forum

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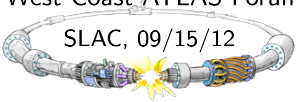
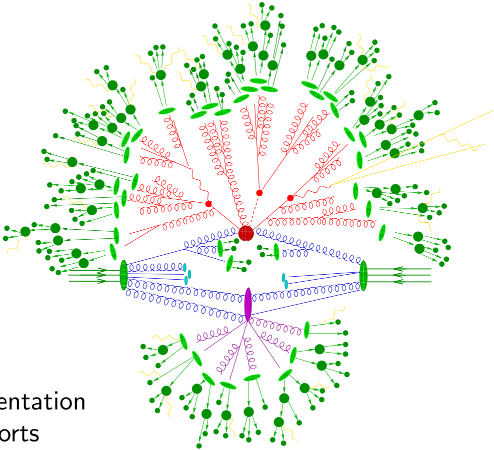


Structure of the simulation

- 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

Event generators for LHC physics

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⊗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⊗PS merging
- Automated framework for NLO calculations and MC@NLO

For more information, check out [Buckley et al.] arXiv:1101.2599
For updates and news, go to http://www.montecarlonet.org

Analysis and tuning tools

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.] arXiv:0907.2973

- Tuning in multi-dimensional parameter space of MC
- Generate event samples at random parameter points
  Analyse them with Rivet
  Parameterize observables
  Minimize χ^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
	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
Pythia8	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

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

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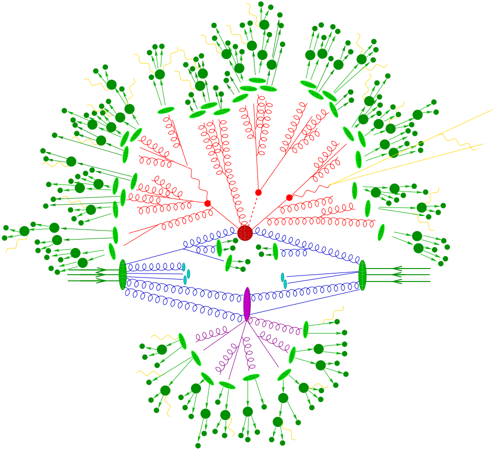
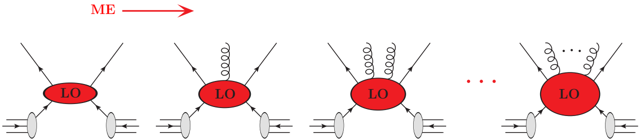
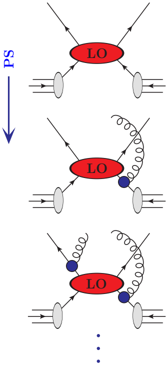


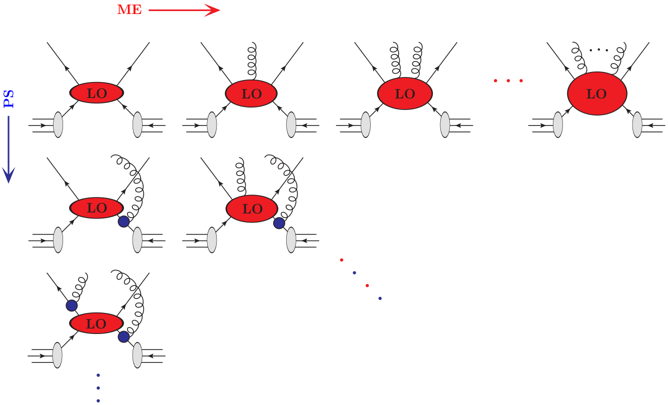
LO matrix elements



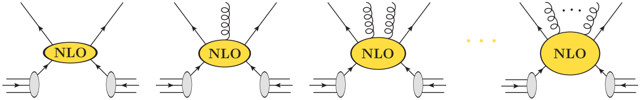
Parton showers



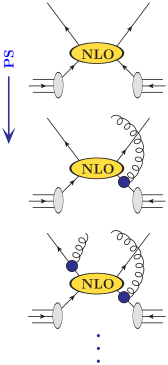
Matrix-element parton-shower merging (ME⊗PS)



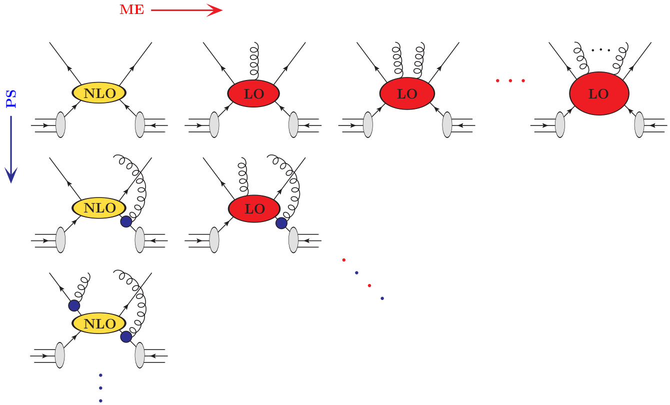
NLO matrix elements



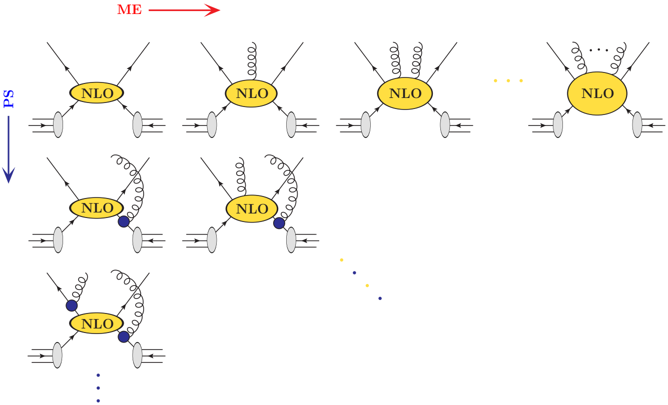
NLO matrix-element parton-shower matching



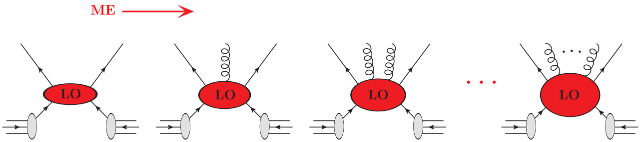
ME⊗PS combined with matching (MENLOPS)



Matrix-element parton-shower merging at NLO (ME⊗PS@NLO)



Matrix element tools



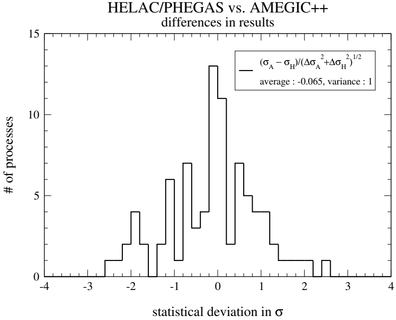
Plethora of tree-level tools on market

State of the art: **Full automation**

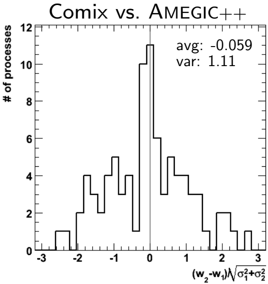
- **Feynman diagrams**
  - AMEGIC++ [Krauss et al.] hep-ph/0109036
  - CompHEP [Boos et al.] hep-ph/0403113
  - MADGRAPH [Alwall et al.] arXiv:1106.0522
- **Recursive techniques**
  - Comix [Gleisberg,SH] arXiv:0808.3674
  - HELAC [Kanaki,Papadopoulos] hep-ph/0002082
  - O'Mega [Moretti,Ohl,Reuter] hep-ph/0102195
- **α-algorithm**
  - ALPGEN [Mangano et al.] hep-ph/0206293

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

Useful plugins for NLO calculation
$\rightarrow$ Born, real emission & subtraction



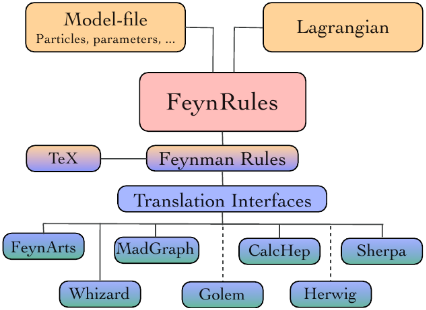
[Gleisberg et al.] hep-ph/0311273



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

Automated by FeynRules
[Christensen,Duhr] arXiv:0806.4194

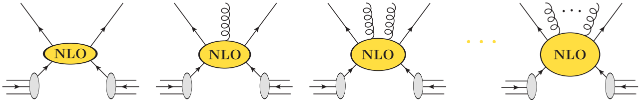
- Extract vertices from Lagrangian based on minimal information about particle content
- Write ME-generator specific output → universality and cross-checks



Recent developments include:

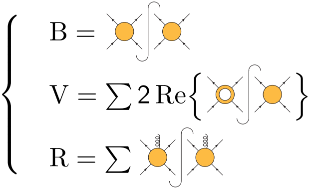
- UFO [Degrande,Duhr,Fuks,Grellscheid,Mattelaer,Reiter] arXiv:1108.2040
  Model files and Feynman rules → self-contained Python library
  ALOHA [deAquino,Link,Maltoni,Mattelaer,Stelzer] arXiv:1108.2041 → MadGraph
  Automated implementation of arbitrary higher-dimensional operators
- Spin-3/2 particles and superfield formalism

Matrix element tools for NLO



Matrix element tools for NLO

NLO prediction



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

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

Commonly used subtraction techniques:

- **Dipole method** [Catani,Seymour] hep-ph/9605323 [Catani,Dittmaier,Seymour,Trocsanyi] hep-ph/0201036, implemented in
  - AMEGIC++ [Gleisberg,Krauss] arXiv:0709.2881, Comix [SH] colorful
  - HELAC/PHEGAS [Czakon,Papadopoulos,Worek] arXiv:0905.0883 polarized
  - MADDIPOLE [Frederix,Gehrmann,Greiner] arXiv:0808.2128, arXiv:1004.2905
- **FKS method** [Frixione,Kunszt,Signer] hep-ph/9512328, implemented in
  - MADFKS [Frederix,Frixione,Maltoni,Stelzer] arXiv:0908.4272

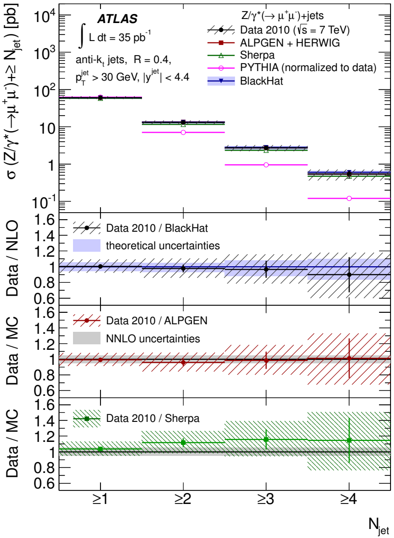
Several other implementations, which are not part of automated tree-level tools

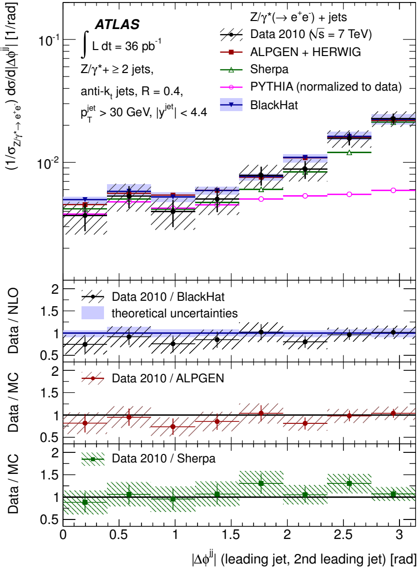
Many (semi-)automated programs to compute virtual
Based on different techniques for loop integration

- **Tensor reduction** [Denner,Dittmaier] hep-ph/0509141
  [Binoth,Guillet,Pilon,Heinrich,Schubert] hep-ph/0504267
  - Golem95 [Binoth,Cullen,Greiner,Guffanti,Guillet,Heinrich,Karg,Kauer,Reiter,Reuter]
  - MadGolem [Binoth,Goncalves Netto,Lopez-Val,Mawatari,Plehn,Wigmore]
  - OpenLoops [Cascioli,Maierhöfer,Pozzorini]
- **Generalized unitarity** [Bern,Dixon,Dunbar,Kosower] hep-ph/9409265 hep-ph/9708239
  [Ossola,Papadopoulos,Pittau] hep-ph/0609007, [Forde] arXiv:0704.1835
  - BlackHat [Bern,Dixon,Febres-Cordero,Ita,Kosower,Maître,Ozeren,SH]
  - GoSam [Cullen,Greiner,Heinrich,Luisoni,Mastrolia,Ossola,Reiter,Tramontano]
  - HelacNLO [Bevilacqua,Czakon,Garzelli,vanHameren,Kardos,Papadopoulos,Pittau,Worek]
  - MadLoop [Hirschi,Frederix,Frixione,Garzelli,Maltoni,Pittau]
  - NJet [Badger,Biedermann,Uwer,Yundin]
  - OpenLoops [Cascioli,Maierhöfer,Pozzorini]
  - Rocket [Ellis,Giele,Kunszt,Melnikov,Zanderighi]
- **Numerical integration** [Becker,Goetz,Reuschle,Schwan,Weinzierl] arXiv:1111.1733

Matrix element tools for NLO

Combination of BlackHat and SHERPA is pushing limits





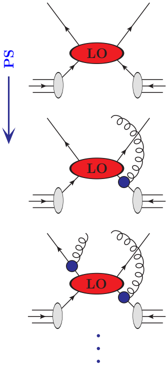
[ATLAS] arXiv:1111.2690

Fully automated NLO predictions with MadLoop

[Hirschi et al.]arXiv:1103.0621

	Process	μ	n_{lf}	LO	NLO
a.1	$pp \to t\bar{t}$	m_t	5	123.76 ± 0.05	162.08 ± 0.12
a.2	$pp \to tj$	m_t	5	34.78 ± 0.03	41.03 ± 0.07
a.3	$pp \to tjj$	m_t	5	11.851 ± 0.006	13.71 ± 0.02
a.4	$pp \to t\bar{b}j$	$m_t/4$	4	25.62 ± 0.01	30.96 ± 0.06
a.5	$pp \to t\bar{b}jj$	$m_t/4$	4	8.195 ± 0.002	8.91 ± 0.01
b.1	$pp \to (W^+ \to)e^+\nu_e$	m_W	5	5072.5 ± 2.9	6146.2 ± 9.8
b.2	$pp \to (W^+ \to)e^+\nu_e j$	m_W	5	828.4 ± 0.8	1065.3 ± 1.8
b.3	$pp \to (W^+ \to)e^+\nu_e jj$	m_W	5	298.8 ± 0.4	300.3 ± 0.6
b.4	$pp \to (\gamma^*/Z \to)e^+e^-$	m_Z	5	1007.0 ± 0.1	1170.0 ± 2.4
b.5	$pp \to (\gamma^*/Z \to)e^+e^- j$	m_Z	5	156.11 ± 0.03	203.0 ± 0.2
b.6	$pp \to (\gamma^*/Z \to)e^+e^- jj$	m_Z	5	54.24 ± 0.02	56.69 ± 0.07
c.1	$pp \to (W^+ \to)e^+\nu_e b\bar{b}$	$m_W + 2m_b$	4	11.557 ± 0.005	22.95 ± 0.07
c.2	$pp \to (W^+ \to)e^+\nu_e t\bar{t}$	$m_W + 2m_t$	5	0.009415 ± 0.000003	0.01159 ± 0.00001
c.3	$pp \to (\gamma^*/Z \to)e^+e^- b\bar{b}$	$m_Z + 2m_b$	4	9.459 ± 0.004	15.31 ± 0.03
c.4	$pp \to (\gamma^*/Z \to)e^+e^- t\bar{t}$	$m_Z + 2m_t$	5	0.0035131 ± 0.0000004	0.004876 ± 0.000002
c.5	$pp \to \gamma t\bar{t}$	$2m_t$	5	0.2906 ± 0.0001	0.4169 ± 0.0003
d.1	$pp \to W^+W^-$	$2m_W$	4	29.976 ± 0.004	43.92 ± 0.03
d.2	$pp \to W^+W^- j$	$2m_W$	4	11.613 ± 0.002	15.174 ± 0.008
d.3	$pp \to W^+W^+ jj$	$2m_W$	4	0.07048 ± 0.00004	0.1377 ± 0.0005
e.1	$pp \to HW^+$	$m_W + m_H$	5	0.3428 ± 0.0003	0.4455 ± 0.0003
e.2	$pp \to HW^+ j$	$m_W + m_H$	5	0.1223 ± 0.0001	0.1501 ± 0.0002
e.3	$pp \to HZ$	$m_Z + m_H$	5	0.2781 ± 0.0001	0.3659 ± 0.0002
e.4	$pp \to HZ j$	$m_Z + m_H$	5	0.0988 ± 0.0001	0.1237 ± 0.0001
e.5	$pp \to Ht\bar{t}$	$m_t + m_H$	5	0.08896 ± 0.00001	0.09869 ± 0.00003
e.6	$pp \to Hb\bar{b}$	$m_b + m_H$	4	0.16510 ± 0.00009	0.2099 ± 0.0006
e.7	$pp \to Hjj$	m_H	5	1.104 ± 0.002	1.036 ± 0.002

Parton showers



Parton showers are defined by

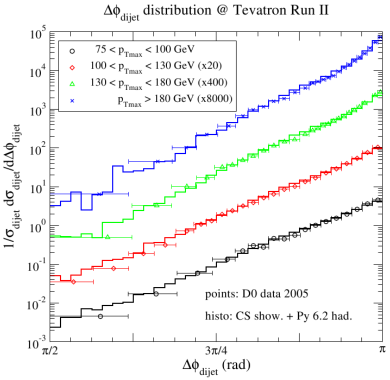
- Evolution & splitting variable
- Momentum mapping (recoil scheme)
- Splitting kernels

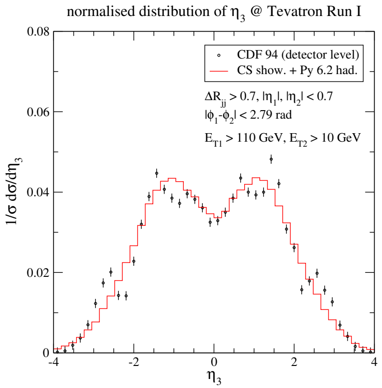
Publicly available programs and their characteristics:

	Evolution variable	Splitting variable	Coherence
Ariadne	dipole-$k_\perp^2$	Rapidity	$2 \to 3$ kernel
Herwig	$E^2\theta^2$	Energy fraction	AO
Herwig++	$(t - m^2)/z(1 - z)$	LC mom fraction	AO
Pythia 6.x	t	Energy fraction	Enforced
Pythia 8	$k_\perp^2$	LC mom fraction	Enforced
Sherpa 1.1.x	t	Energy fraction	Enforced
Sherpa 1.2.x	dipole-$k_\perp^2$	LC mom fraction	$2 \to 3$ kernel
(Vincia)	dipole-$k_\perp^2$	LC mom fraction	$2 \to 3$ kernel

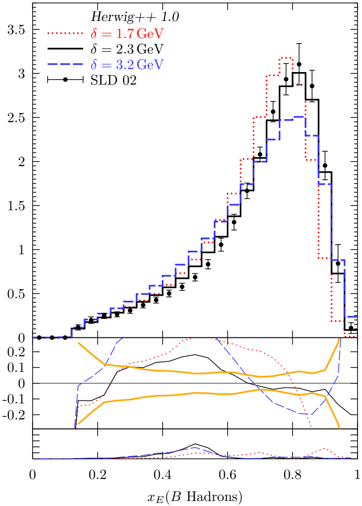
[Krauss,Schumann] arXiv:0709.1027

New PS developments based on Catani-Seymour subtraction formalism
Few model ambiguities, excellent approximation of higher-order real ME



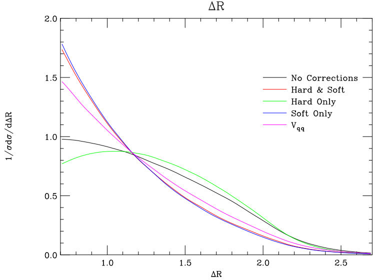


[Gieseke et al.] hep-ph/0311208
[Hamilton,Richardson] hep-ph/0612236

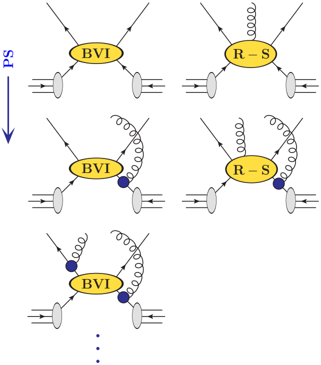


Many (not so recent) improvements on heavy flavor treatment in HERWIG++

- Reduction of dead region
- ME correction in $t \to Wb$ decays
- Extended quasi-collinear splitting functions



Matching NLO and PS



[Frixione,Webber] hep-ph/0204244

Differential event rate to $\mathcal{O}(\alpha_s)$ in PS

$$\frac{\mathrm{d}\sigma_{\mathrm{PS}}}{\mathrm{d}\Phi_n} = \mathrm{B}_n \left[\Delta_n^{(\mathrm{K})}(t_c, \mu_Q^2) + \int_{t_c}^{\mu_Q^2} \mathrm{d}\Phi_1 \, \mathrm{K}_n \, \Delta_n^{(\mathrm{K})}(t(\Phi_1), \mu_Q^2) \right]$$

K_n - sum of PS kernels for n-parton final state

Make this NLO-correct:

- Radiation pattern from ME corrected PS
  Correction weight $w_n = \mathrm{D}_n^{(\mathrm{A})}/\mathrm{B}_n\mathrm{K}_n$, where $\mathrm{D}_n^{(\mathrm{A})} \to$ dipole term
- Replace $\mathrm{B} \to \bar{\mathrm{B}}^{(\mathrm{A})} = \mathrm{B} + \tilde{\mathrm{V}} + \mathrm{I} + \int \mathrm{d}\Phi_1 \left(\mathrm{D}^{(\mathrm{A})} - S \right)$
- Add hard remainder function $\int \mathrm{d}\Phi_R \, \mathrm{H}^{(\mathrm{A})}$, where $\mathrm{H}^{(\mathrm{A})} = \left[R - \mathrm{D}^{(\mathrm{A})} \right]$

Differential event rate to $\mathcal{O}(\alpha_s)$ in matched calculation

$$\frac{\mathrm{d}\sigma_{\mathrm{NLOPS}}}{\mathrm{d}\Phi_n} = \bar{\mathrm{B}}_n^{(\mathrm{A})} \left[\Delta_n^{(\mathrm{A})}(t_c) + \int_{t_c} \mathrm{d}\Phi_1 \, \frac{\mathrm{D}_n^{(\mathrm{A})}}{\mathrm{B}_n} \, \Delta_n^{(\mathrm{A})}(t(\Phi_1)) \right] + \int \mathrm{d}\Phi_1 \, \mathrm{H}_n^{(\mathrm{A})}$$

MC@NLO and POWHEG differ only in choice of $\mathrm{D}^{(\mathrm{A})}$

Method 1 [Frixione,Webber] hep-ph/0204244

- Original algorithm formulated such that $\mathrm{D}_n^{(\mathrm{A})} \to \mathrm{D}_n^{(\mathrm{K})} = \mathrm{B}_n \mathrm{K}_n$,
  i.e. modified subtraction carried out with parton-shower approximation
- Exact only in collinear region
  Missing subleading colour terms in single-logarithmic divergences
- Solved by smoothly fading out real-emission correction in singly-soft region
  Need to correct for mismatch, but only affects unresolved gluons anyhow

Method 2 [SH,Krauss,Schönherr,Siegert] arXiv:1111.1220

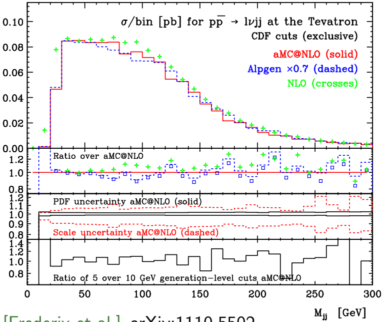
- Alternative solution employs $\mathrm{D}_n^{(\mathrm{A})} \to \mathrm{D}_n^{(\mathrm{S})} = \mathrm{S}_n$
  i.e. parton-shower evolution performed with NLO subtraction terms
- Leads to non-probabilistic Sudakov factor $\Delta_n^{(\mathrm{S})}$
  Requires modification of veto algorithm
- Exact cancellation of all divergences without additional smoothing
  Equivalent to one-step full colour parton shower algorithm

Method 1 automated in aMC@NLO

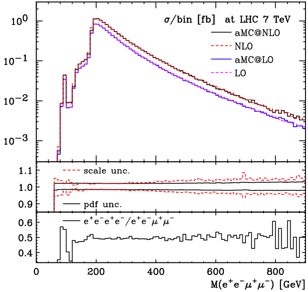
Using MADFKS subtraction and fHERWIG PS

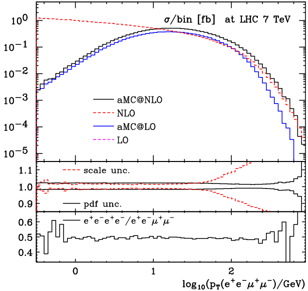
Framework for convenient uncertainty estimate

- $t\bar{t}h$ arXiv:1104.5613
- 4 leptons arXiv:1110.4738
- $W^{\pm}$+2 jets arXiv:1110.5502



[Frederix et al.] arXiv:1110.5502

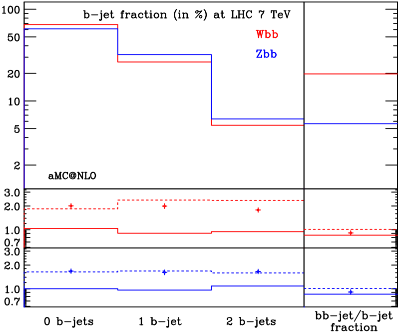


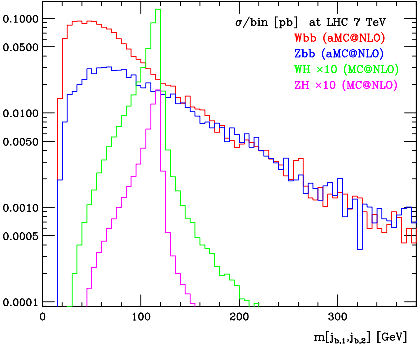


[Frederix et al.] arXiv:1110.4738

Method 1 automated in aMC@NLO

Applied to *Vbb* in 4-flavor scheme

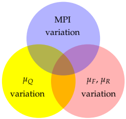




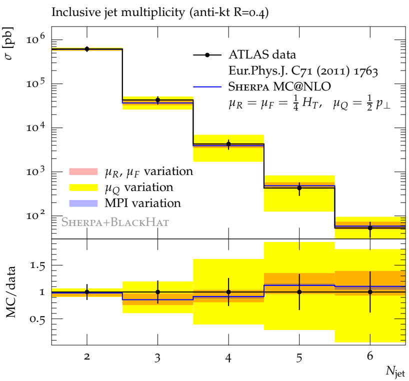
[Fredrix et al.] arXiv:1106.6019

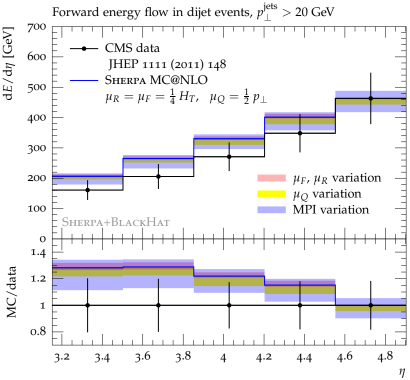
Method 2 automated in SHERPA

Allows to determine fixed-order and resummation scale uncertainty



[SH,Schönherr] arXiv:1208.2815





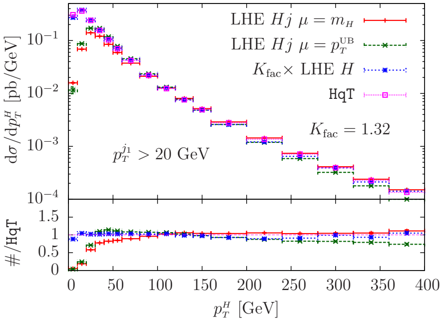
- Jet multiplicity $\rightarrow$ uncertainty due to choice of μ_Q^2
- Forward energy flow $\rightarrow$ major uncertainty from underlying event

$D^{(A)} \to R \Rightarrow$ MC@NLO $\to$ POWHEG
[Frixione,Nason,Oleari] arXiv:0709.2092

Partially automated in POWHEGBOX
[Alioli,Oleari,Nason,Re] arXiv:1002.2581

- FKS subtraction
- PYTHIA/fHERWIG PS

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



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

POWHEGBOX originally aimed at providing framework only
$\to$ 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,Wackeroth,Weydert,Williams,Zanderighi]

Heading towards full automation using MADGRAPH & GOSAM

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

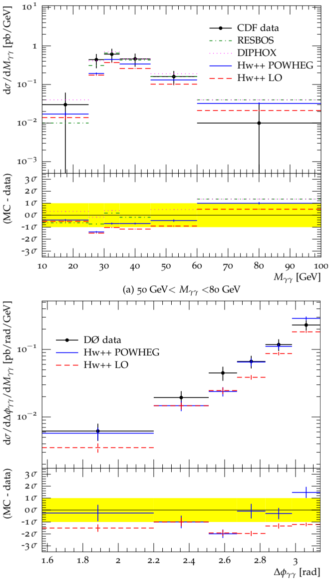
- Drell-Yan arXiv:0806.0290
- W/Z+Higgs arXiv:0903.4135
- Higgs in GF arXiv:0903.4345
- DIS & VBF arXiv:1106.2983
- Diphoton arXiv:1106.3939

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

$$R^{(A)}_{QCD} = R \frac{\sum D^{(A)}_{QCD}}{\sum D^{(A)}_{QCD} + \sum D^{(A)}_{QED}}$$



[d'Errico,Richardson] arXiv:1106.3939

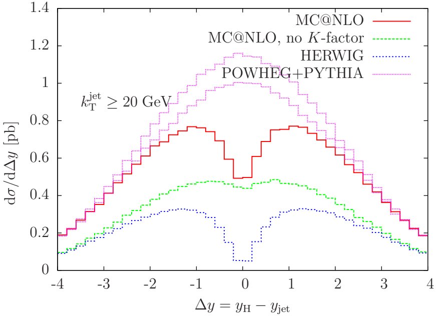
Controversial issue: What is resummed in POWHEG / MC@NLO?

$\mathrm{D}^{(\mathrm{A})}$/ $\mathrm{H}^{(\mathrm{A})}$ can be adjusted in functional form & active phase space

MC@NLO → a-priori choice / POWHEG → tuneable damping parameter h

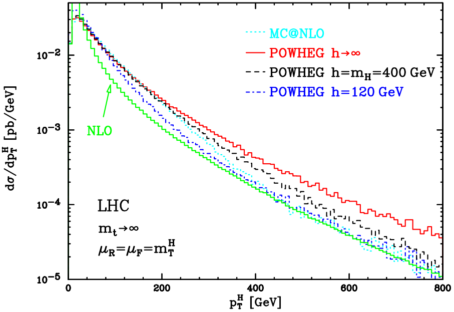
Why important? Two examples:

Limited phase-space coverage of PS → dead zones appear as "MC@NLO dip"



[Nason,Webber] arXiv:1202.1251

h not defined by resummation scale → disagreement with NLO in high-p_T tails



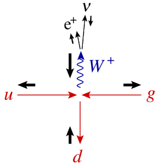
[Nason,Webber] arXiv:1202.1251

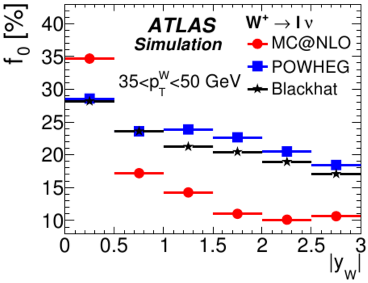
Usage issues

Which NLO-tool for what?

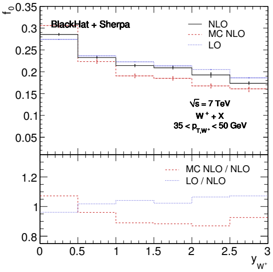
Example: MC@NLO ↔ POWHEG
in W-polarization measurement

[ATLAS] arXiv:1203.2165

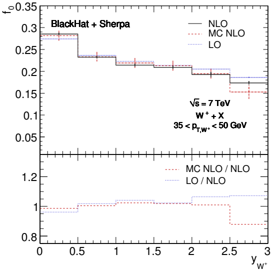




W+0j MC@NLO ✗



W+1j MC@NLO ✓



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

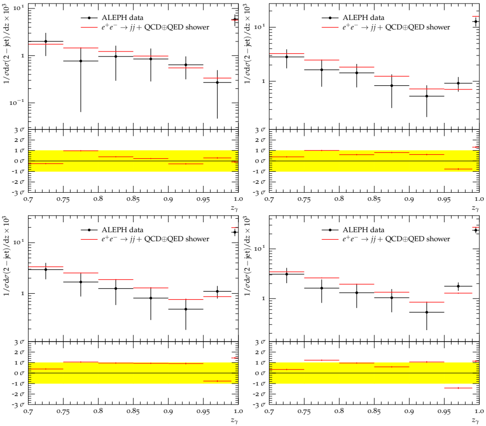
Kinematic effects & scale choices play a role → PS model affects accuracy of matched NLO result

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!

γ-fragmentation function arXiv:0912.3501



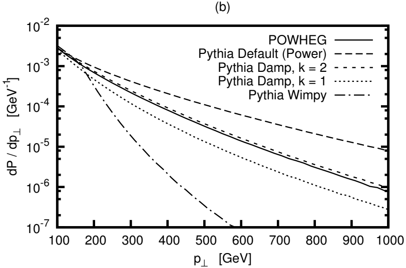
[Schumann,Siegert,SH] arXiv:0912.3501

Most promising progress with dipole-like parton showers
[Schumann,Krauss] arXiv:0709.1027, [Plätzer,Gieseke] arXiv:0909.5593

Sector showers interesting new alternative
[Giele,Kosower,Skands] arXiv:1102.2126, [Larkoski,Peskin] arXiv:0908.2450

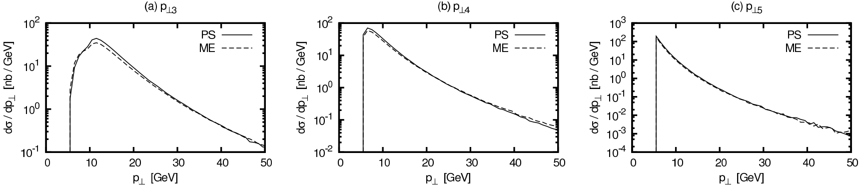
Efforts to bridge gap between "power" and "wimpy" showers in PYTHIA
by dampening factor $k^2\mu^2/(k^2\mu^2+p_T^2)$
Used for colored massive final states

Improved default PS alleviates matching to NLO simulation MC@NLO, POWHEG



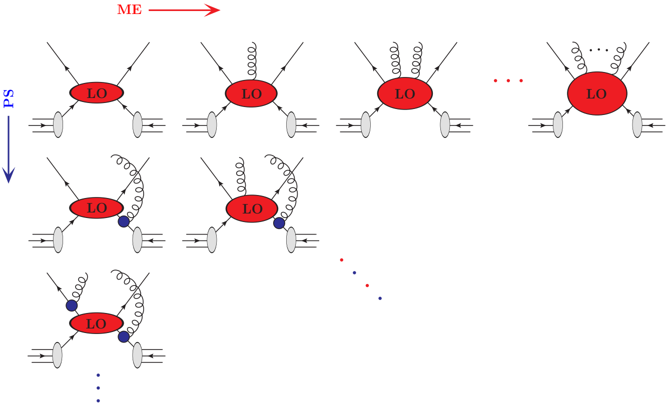
$t\bar{t}$+jets from [Corke,Sjöstrand] arXiv:1003.2384

Study of PS emission pattern in pure QCD yields good agreement with ME
large region of phase space usually well described → reduced systematics in matching



[Corke,Sjöstrand] arXiv:1011.1759

ME⊗PS merging

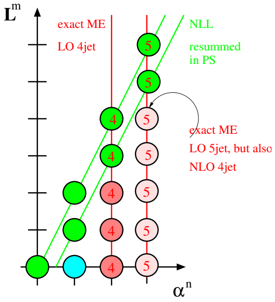


Prerequisites

- Jets defined with some IR-safe algorithm $\to$ k_T, anti-k_T, SISCone
- n-jet observable O to be described at some fixed order (LO or NLO)

Objectives

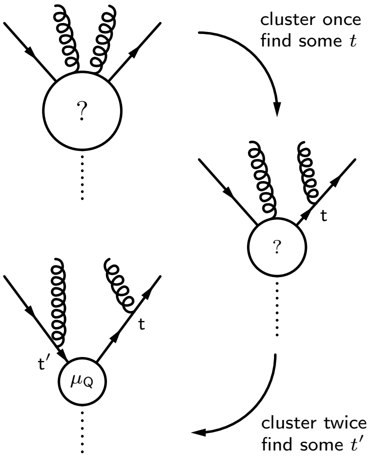
- In MC we can define jets using truth information
  $\to$ distance measure Q for theory, close to k_T
- Want multi-jet rates for $Q > Q_{\rm cut}$
  correct to given fixed order in α_s
  Current standard LO, first results for NLO
- Logarithmic accuracy of PS should be maintained



Parton-shower histories

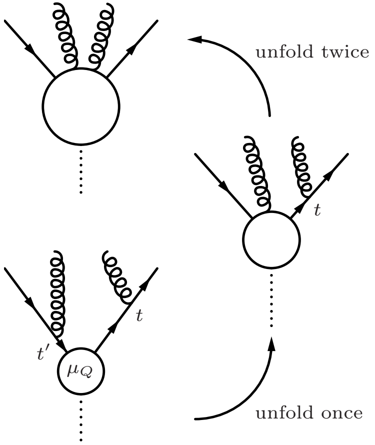
[André,Sjöstrand] hep-ph/9708390

- Start with some "core" process for example $e^+e^- \to q\bar{q}$
- This process is considered inclusive It sets the resummation scale μ_Q^2
- Higher-multiplicity ME can be reduced to core by clustering
- If we want to match ME & PS the correct clustering algorithm suggests itself
  - Identify most likely splitting according to PS emission probability
  - Combine partons into mother according to PS kinematics
  - Continue until core process



Truncated parton showers

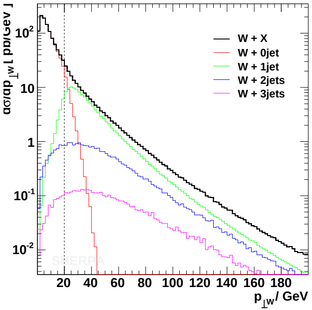
[Lönnblad] hep-ph/0112284
[Nason] hep-ph/0409146



- If higher-multiplicity ME can be clustered back to core that means it is included in the inclusive cross section
- Must compute Sudakov suppression corresponding to no-decay probability of each intermediate parton
  → make inclusive ME exclusive
- Here the merging methods differ most

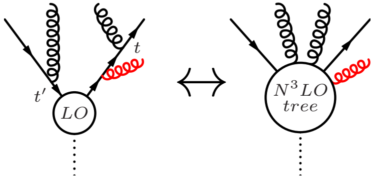
ME⊗PS merging

[Catani,Krauss,Kuhn,Webber] hep-ph/0109231



Basic idea

- Separate phase space into "hard" and "soft" region
- Matrix elements populate hard domain
- Parton shower populates soft domain
- Need criterion to define "hard" & "soft" $\rightarrow$ jet measure Q and corresponding cut, $Q_{\rm cut}$

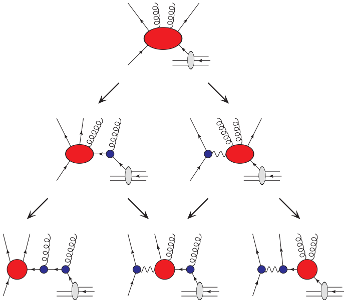


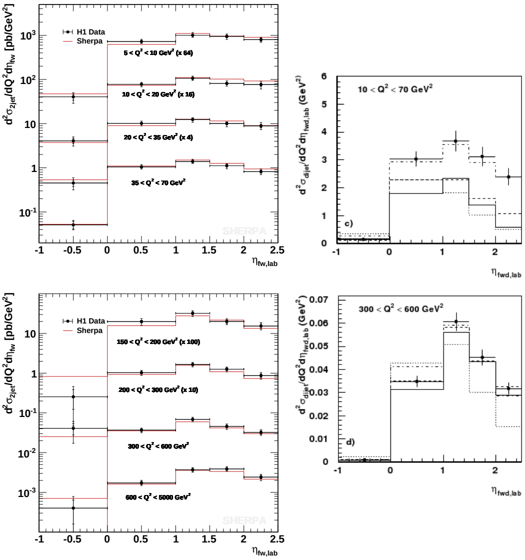
Method

- Start PS from core process
- Evolve until predefined branching $\leftrightarrow$ truncated parton shower
- Emissions that would produce additional hard jets lead to event rejection (veto)

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,Gehrmann,SH] arXiv:0912.3715

Need control of PS to do things correctly → only two techniques with

- Exact correspondence between clustering & PS evolution
- Sudakov form factors as defined in parton shower

[Lönnblad] hep-ph/0112284
[Lönnblad,Prestel] arXiv:1109.4829

CKKW-L (**Pythia 8**)

- Truncated showers generate suppression, but no emissions
- Jet criterion dynamically redefined during PS evolution
- Simple and easy to implement

[SH,Krauss,Schumann,Siegert] arXiv:0903.1219
[Hamilton,Richardson,Tully] arXiv:0905.3072

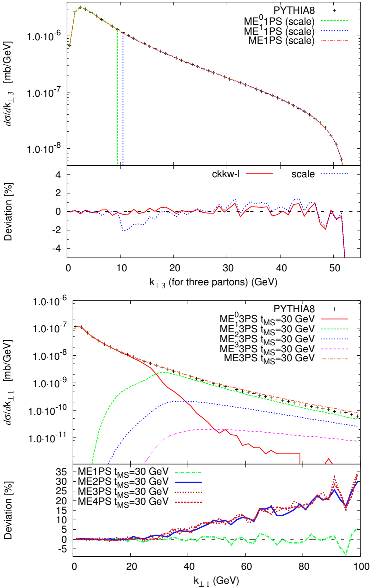
METS (**Herwig++** & **Sherpa**)

- Truncated parton showers generate emissions and suppression
- Accounts for mismatch between jet criterion and evolution variable
- Requires intimate knowledge of PS

CKKW-L in Pythia 8

[Lönnblad,Prestel] arXiv:1109.4829

- Set up for interleaved showers → combine with arbitrary MPI tunes
- Flexibility due to LHE event files from MadGraph, SHERPA, ...
- Released with PYTHIA 8
  Formal improvement over MLM
- Difficult to disentangle effects of phase-space separation analytically
  Probably not an issue in practice



[Lönnblad,Prestel] arXiv:1109.4829

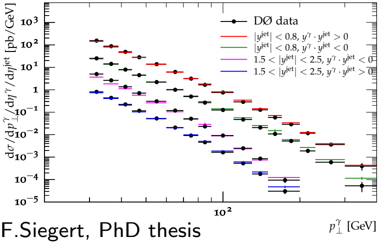
[Schumann,Siegert,SH] arXiv:0912.3501

“Democratic” model for γ’s

- Treat parton and γ equally
- Combine ME of various parton/γ multiplicity with
- Interleaved QCD⊕QED PS

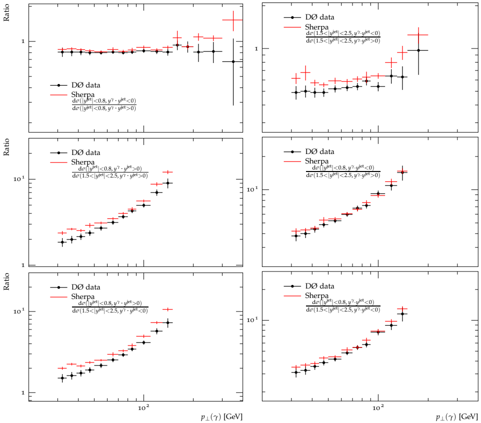
Photon p_T spectra arXiv:0804.1107

in regions of jet rapidity/orientation
scaled by 5, 1, 0.3 and 0.1 top to bottom



F.Siegert, PhD thesis

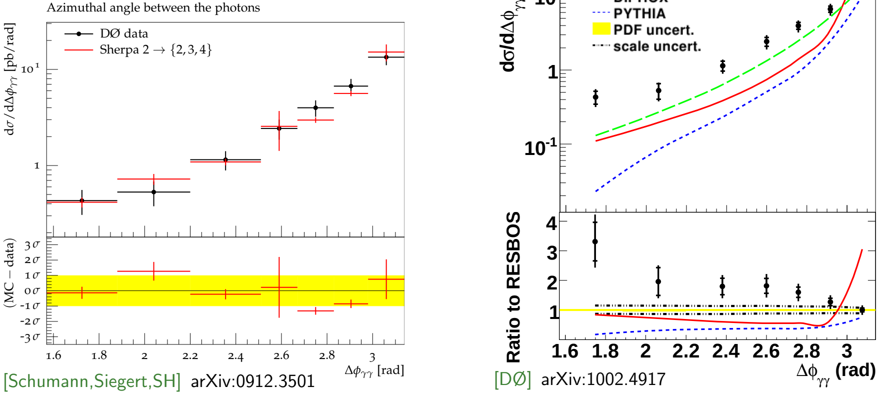
Ratio of photon p_T spectra arXiv:0804.1107
compare regions of jet rapidity/orientation



F.Siegert, PhD thesis

Di-photon production at DØ

$E_T^{\gamma 1} > 21$ GeV, $E_T^{\gamma 1} > 20$ GeV,
$|\eta^\gamma| < 0.9$, $E_T^{R=0.4} - E_T^\gamma < 2.5$ GeV



[Schumann,Siegert,SH] arXiv:0912.3501

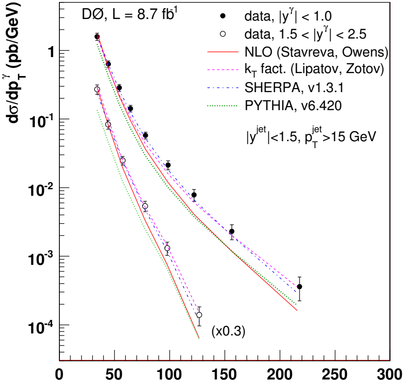
[DØ] arXiv:1002.4917

SHERPA prediction: Merged 2→{2,3,4}-jet/γ plus $gg \to \gamma\gamma$ box

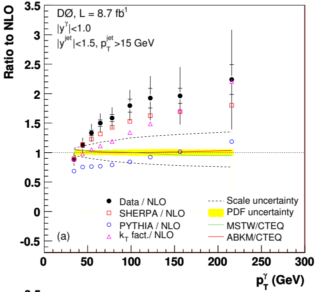
Z+b cross section [ATLAS] arXiv:1109.1403

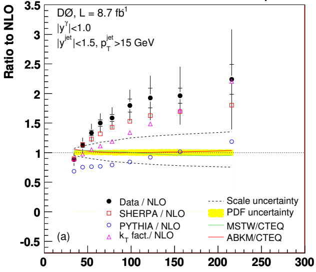
Experiment	$3.55^{+0.82}_{-0.74}(\mathrm{stat})^{+0.73}_{-0.55}(\mathrm{syst}) \pm 0.12(\mathrm{lumi})$ pb
MCFM	3.88 ± 0.58 pb
ALPGEN	2.23 ± 0.01 (stat only) pb
SHERPA	3.29 ± 0.04 (stat only) pb

DØ analysis of γ+bjet production



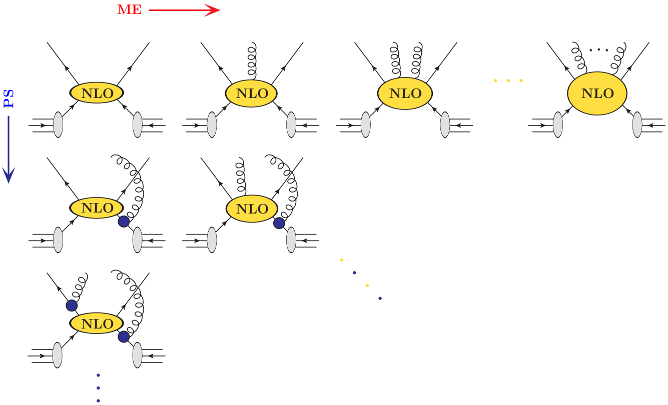
[DØ] arXiv:1203.5865





[DØ] arXiv:1203.5865

ME⊗PS merging at NLO



ME⊗PS merging at NLO

[Lavesson,Lönnblad] arXiv:0811.2912 [Lönnblad,Prestel] in preparation
[Gehrmann,SH,Krauss,Schönherr,Siegert] arXiv:1207.5030, arXiv:1207.5031

Basic idea: Define MC@NLO for higher parton multiplicity,
based on compound PS evolution kernel for $n+k$-particle final state

$$\tilde{\mathrm{D}}^{(\mathrm{A})}_{n+k} = \mathrm{D}^{(\mathrm{A})}_{n+k}\,\Theta(t_{n+k}-t_{n+k+1}) + \mathrm{B}_{n+k}\sum_{i=n}^{n+k-1}\mathrm{K}_i\,\Theta(t_i-t_{n+k+1})\Theta(t_{n+k+1}-t_{i+1})$$

t_i - nodal scales of parton emission in corresponding PS history

Extended modified subtraction, including $\mathcal{O}(\alpha_s)$ terms of truncated PS

$$\tilde{\mathrm{B}}^{(\mathrm{A})}_{n+k} = \left(\mathrm{B}_{n+k}+\tilde{\mathrm{V}}_{n+k}+\mathrm{I}_{n+k}\right) + \int \mathrm{d}\Phi_1\left(\tilde{\mathrm{D}}^{(\mathrm{A})}_{n+k}-\mathrm{S}_{n+k}\right)$$

$$\tilde{\mathrm{H}}^{(\mathrm{A})}_{n+k} = \mathrm{R}_{n+k} - \tilde{\mathrm{D}}^{(\mathrm{A})}_{n+k}$$

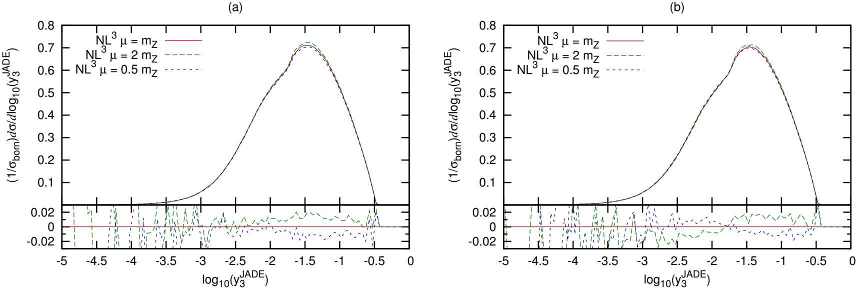
Otherwise arguments for ME⊗PS merging at LO go straight through!

Currently two techniques

- Explicit subtraction (**Pythia 8**)
- Shower veto (**SHERPA**)

ME⊗PS merging at NLO

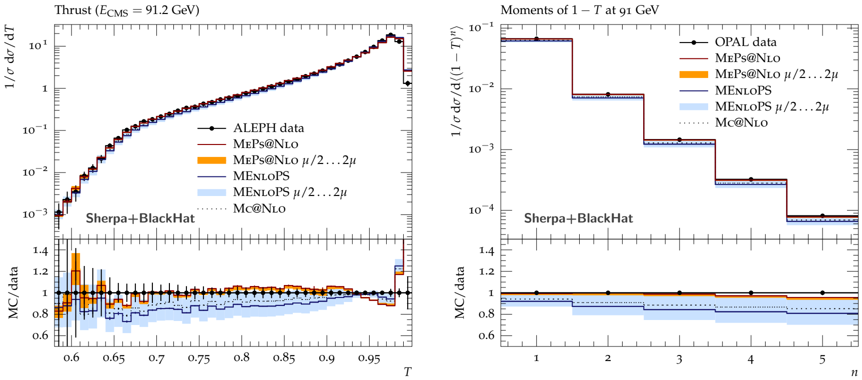
[Lavesson,Lönnblad] arXiv:0811.2912



- Durham k_T-jet resolution in $e^+e^- \to$hadrons at LEP
- MEPS@NLO with 2&3 jet PL at NLO /
  2 jet PL at NNLO & 3 jet PL at NLO

ME⊗PS merging at NLO

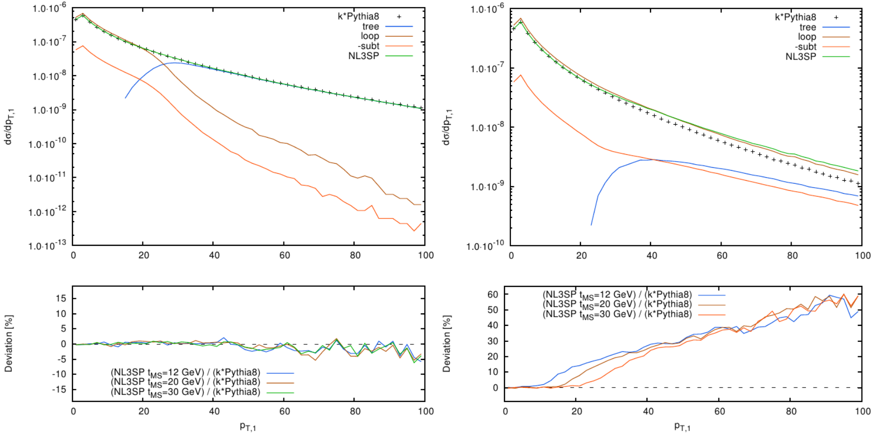
[Gehrmann,SH,Krauss,Schönherr,Siegert] arXiv:1207.5031



- MEPS@NLO with 2,3&4 jet PL at NLO plus 5&6 jet PL at LO
- MENLOPS with 2-6 jet PL at LO

ME⊗PS merging at NLO

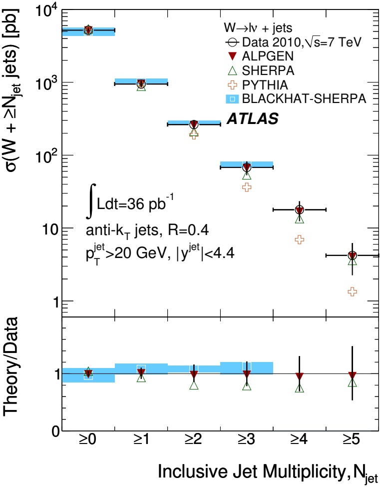
[Lönnblad,Prestel] ICHEP'12

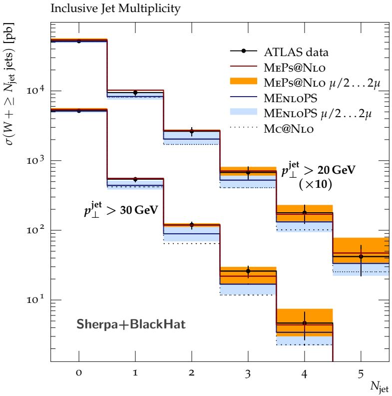


- Compare W+0-jet at NLO ↔ W+0,1-jet at NLO

ME⊗PS merging at NLO

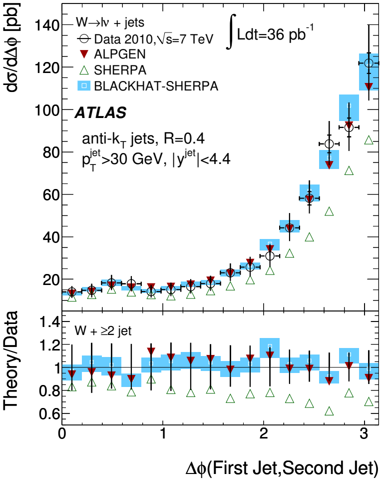
[ATLAS] arXiv:1201.1276
[SH,Krauss,Schönherr,Siegert] arXiv:1207.5030

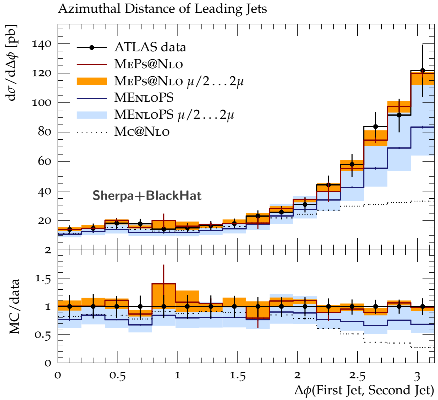




- MEPS@NLO with 0,1&2 jet PL at NLO plus 3&4 jet PL at LO
- MENLOPS with 0-4 jet PL at LO

[ATLAS] arXiv:1201.1276
[SH,Krauss,Schönherr,Siegert] arXiv:1207.5030

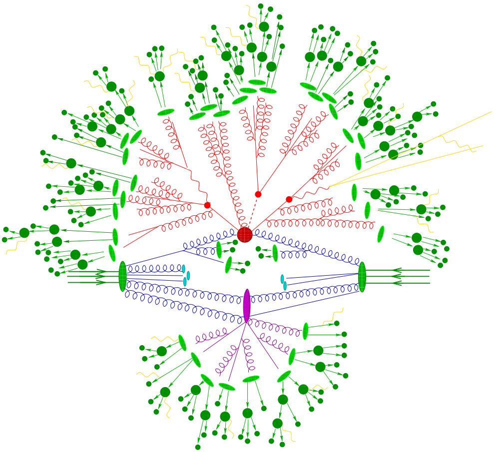




- MEPS@NLO with 0,1&2 jet PL at NLO plus 3&4 jet PL at LO
- MENLOPS with 0-4 jet PL at LO

Structure of the simulation

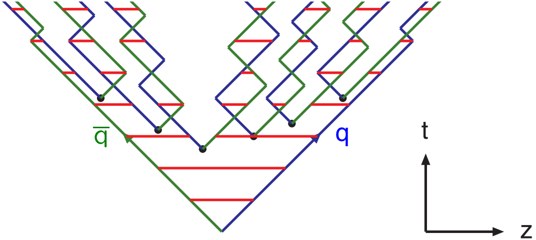
- Hard interaction
- QCD evolution
- Secondary hard interactions
- Jet fragmentation
- Hadron decays
- Higher-order QED corrections



[Andersson,Gustafson,Ingelman,Sjöstrand] PR97(1983)31

Lund string model of PYTHIA

- $e^+e^- \to q\bar{q} \Rightarrow$ QCD flux tube with constant $\mathrm{d}E/\mathrm{d}y$ $\leftrightarrow$ 
- New $q\bar{q}$-pairs created by tunneling
- Gluons are kinks on string $\to$ IR safe model
- Expanding string breaks into hadrons, then yo-yo modes
- Baryons modeled as quark-diquark pairs



Very well motivated, but many parameters, especially for baryon production

Hadronization models

[Webber] NPB238(1984)492
[Krauss,Winter] hep-ph/0311085

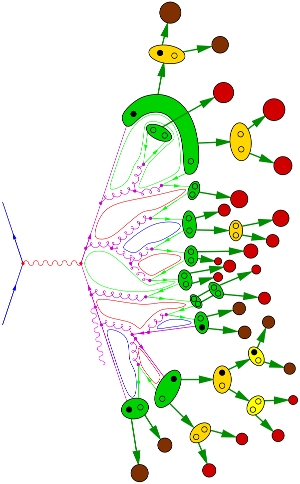
Cluster models of HERWIG++ & SHERPA

Naïve model

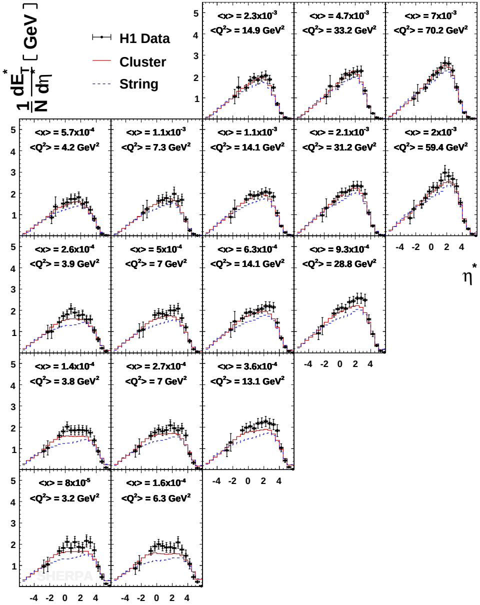
- After PS split gluons into $q\bar{q}$
- Color-adjacent pairs form primordial clusters
- Clusters decay into hadrons according to phase space
  $\rightarrow$ baryons & heavy quarks naturally suppressed

Improved model

- Heavy clusters decay into lighter ones
  C$\rightarrow$CC,
  C$\rightarrow$CH & C$\rightarrow$HH
- Leading particle effects missing
  $\rightarrow$ make model more string-like

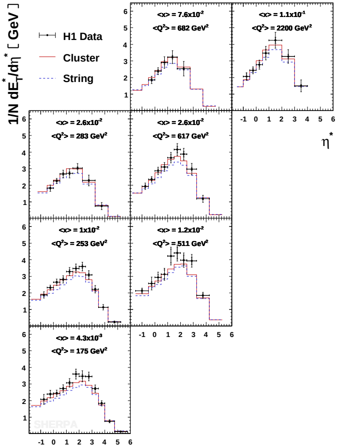


Hadronization uncertainties



Transverse energy flow in DIS

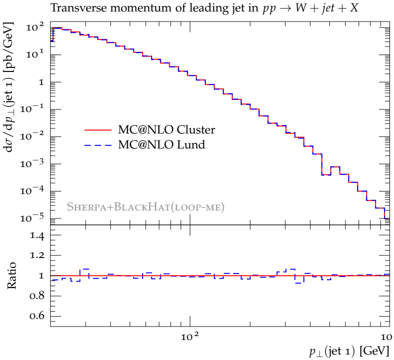
SHERPA cluster fragmentation vs. Lund string fragmentation

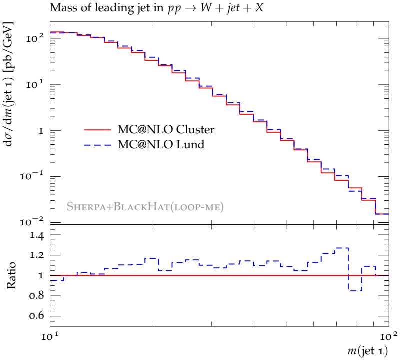


[Carli,Gehrmann,SH] arXiv:0912.3715

Hadronization uncertainties

[Krauss,Schönherr,Siegert,SH] arXiv:1111.1220

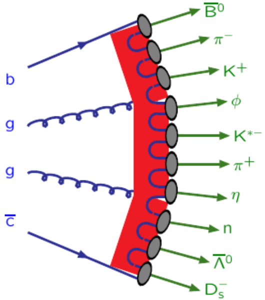


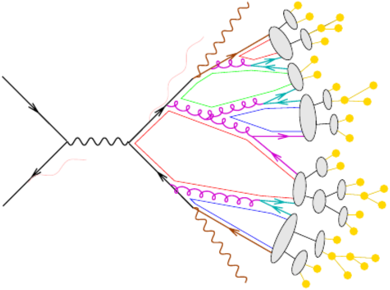


- MC@NLO for $pp \to h + j$ with SHERPA
- Lund string vs. Sherpa cluster fragmentation
- Correlated variation

String vs Cluster

[T.Sjöstrand, Durham'09]



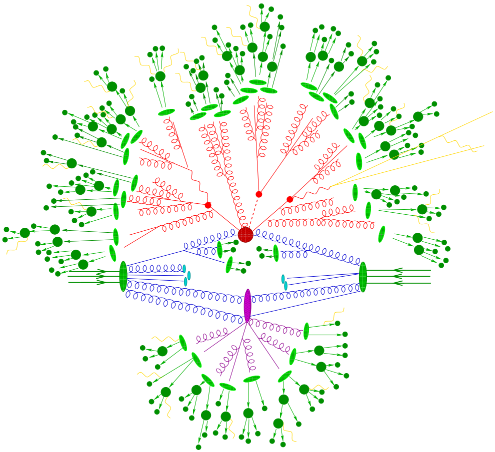


program	PYTHIA	HERWIG
model	string	cluster
energy–momentum picture	powerful	simple
	predictive	unpredictive
parameters	few	many
flavour composition	messy	simple
	unpredictive	in-between
parameters	many	few

"There ain't no such thing as a parameter-free *good* description"

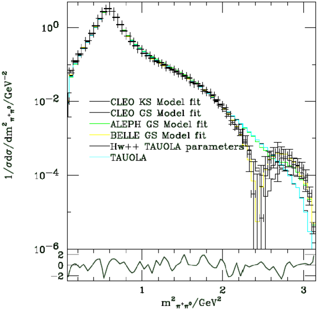
Structure of the simulation

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



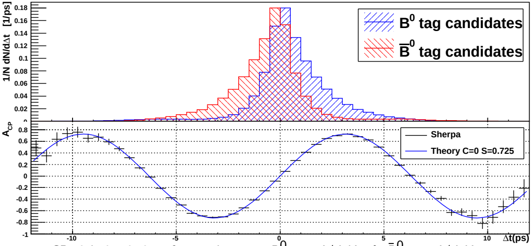
Secondary particle decays

- Previous generations of generators relied on external decay packages Tauola & EvtGen
- New generation programs Herwig++ & Sherpa contain at least as complete a description
- Spin correlations and B-mixing built in
- No interfacing issues



[Krauss,Siegert] in arXiv:0811.4622

[Grellscheid,Richardson] arXiv:0710.1951

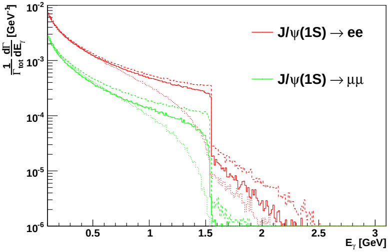


CP violation in interference between $B^0 \to J/\Psi K_S$ & $\bar{B}^0 \to J/\Psi K_S$

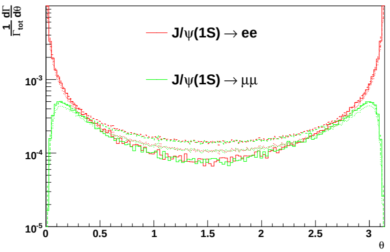
Photon radiation

[Yennie,Frautschi,Suura] AP13(1961)379

- Previous generations of generators relied on external package Photos to simulate QED radiation
- New generation programs Herwig++ & Sherpa have simulation of QED radiation built in



Total photon energy in J/ψ rest frame



Angular radiation pattern in ℓ^+-ℓ^- frame

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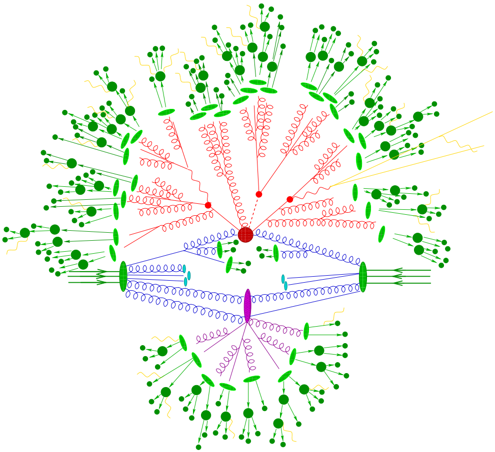
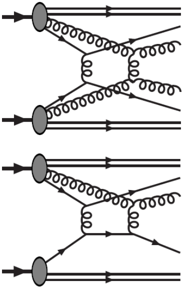


Multiple Parton Interactions

Same evolution variable, k_T, for ISR/FSR and MPI in PYTHIA
Interleave PS & MPI to arrive at more inclusive picture
[Sjöstrand,Skands] hep-ph/0408302, [Corke,Sjöstrand] arXiv:0911.1909

$$\frac{\mathrm{d}P}{\mathrm{d}p_T} = \frac{\mathrm{d}}{\mathrm{d}p_T} \exp\left\{ - \int_{p_T} \mathrm{d}\bar{p}_T \left(\frac{\mathrm{d}\mathcal{P}_{PS}}{\mathrm{d}\bar{p}_T} + \frac{\mathrm{d}\mathcal{P}_{MPI}}{\mathrm{d}\bar{p}_T} \right) \right\}$$

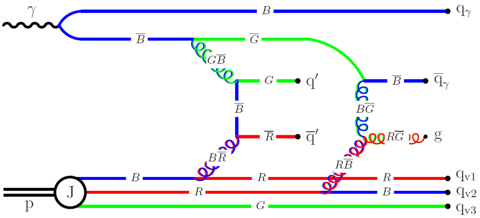


[Corke,Sjöstrand]
arXiv:0911.1909

Add rescattering $\rightarrow$ important at higher energies

	Tevatron		LHC	
	Min Bias	QCD Jets	Min Bias	QCD Jets
Normal scattering	2.81	5.09	5.19	12.19
Single rescatterings	0.41	1.32	1.03	4.10
Double rescatterings	0.01	0.04	0.03	0.15

- New models embed scatters into existing color topology
- Three different options for string drawing
  - At random
  - Rapidity ordered
  - String length optimized



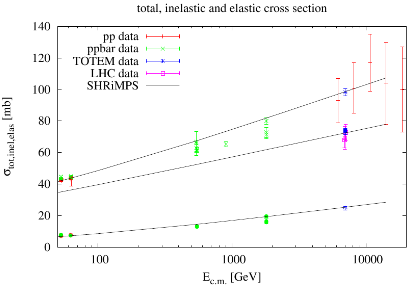
New generator based on KMR model in Sherpa 1.4.0

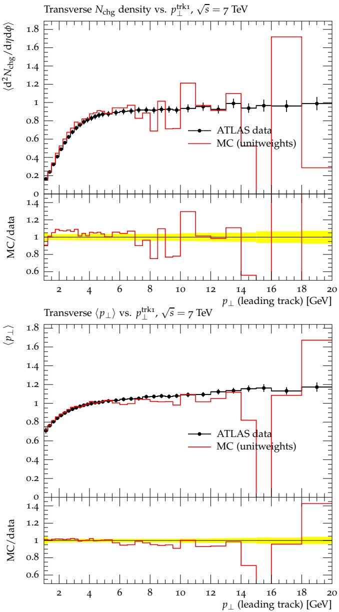
Optical theorem relates σ_{tot} to elastic forward scattering (Pomeron)

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] arXiv:1012.0791

Summary

- HERWIG++, PYTHIA & SHERPA provide frameworks for event simulation
- Lots of progress to combine NLO tools with these general-purpose MC
- Interesting new developments regarding inclusive QCD

- More systematic uncertainty studies needed
- Improved resummation needed if accuracy to be increased further
- High-energy effects may need to be included