Monte Carlo Development

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DESY

Warranty notice: This is a wide and very active field. I can't possibly cover all aspects and present all recent development in 20+ minutes, only representative examples. The proceedings will contain some more material.

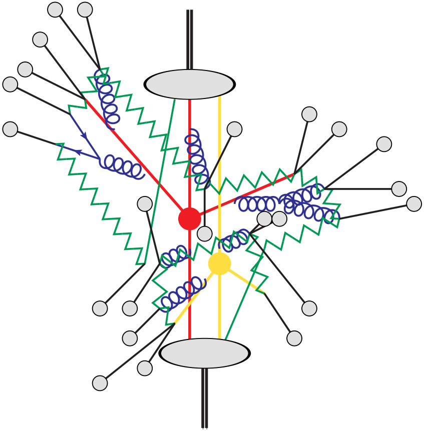
Overview.

Monte Carlo event generators:
Indispensable tools for experiments & phenomenologists.

Realistic, fully detailed simulation:
Spanning orders of magnitude in relevant energy scales.

Factorization dictates workflow:
Hard process.
Parton showers.
Multiple interaction models.
Hadronization models.

+ decays, QED radiation, other boring details.



Outline.

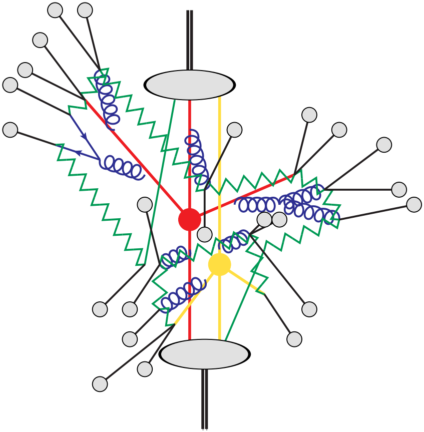
Hadronization models:
Limitations and needs.

Multiple interactions:
(not covered)

Shower development:
Uncertainties rule!

Hard scattering:
Higher orders.

Outlook:
Cross-feeding the steps.



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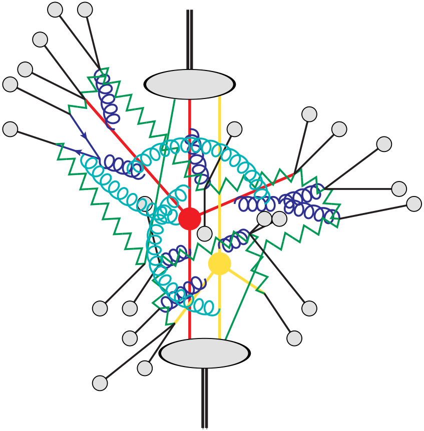

Hadronization Models.

The classic suspects: Strings (Pythia), Clusters (Herwig++, Sherpa).
Works at LEP, regard universal. **Little development** since 10 years.

This excludes colour reconnection, which should be seen from a different perspective.

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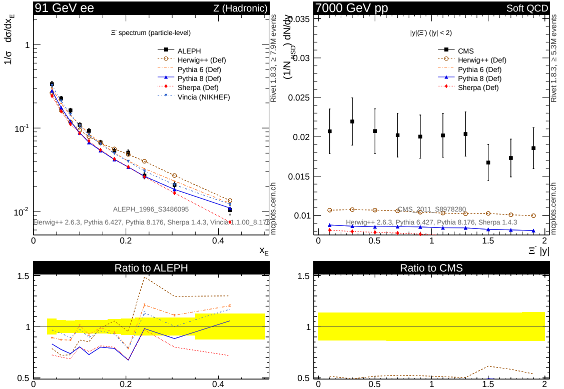
This excludes colour reconnection, which should be seen from a different perspective.

Works at LEP, **fails** elsewhere.

Does matter for high-$p_\perp$ physics: Jet energies, flavour tagging, ...

We need **much more** $\{e, p\}p$ **data.**

As Rivet analyses.



Showers: Overview.

Showers resum large logs.
But also fragment partons.

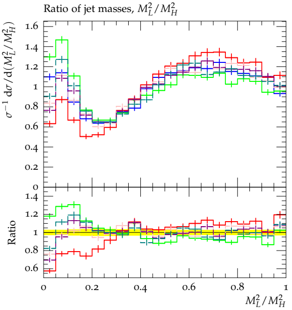
Typically iterative construction:

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

Shower	Construction	Recoil
Herwig++ angular	DGLAP	global
Herwig++ dipoles	CS dipoles	local
Pythia 8	DGLAP	local
Sherpa dipoles	CS dipoles	local
Sherpa antennae	antennae	local
Ariadne	antennae	local
Cascade	CCFM	global
Deductor	Nagy-Soper kernels	local
KRKMC	DGLAP	global
Vincia	antennae	local

Redundant? **No!**

Need to pin down differences, and cross-validate **uncertainties**.



[Gieseke, Fischer, SP, Skands '14]

Assess shower differences in a clean environment: Radiation patterns in four-jet events at LEP.

- Coherence properties.
- Push for subleading effects (avoid large scale hierarchy).

OPAL measurement in the pipeline!

Showers: Uncertainties.

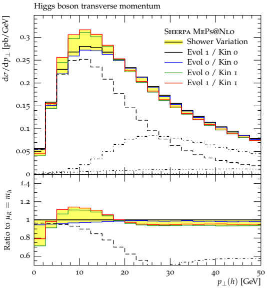
Showers are perturbative objects: Assess **genuine** perturbative uncertainties.
Three scales in the game: μ_R, μ_F, μ_Q. Analytic resummation: **Scale compensation.**

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

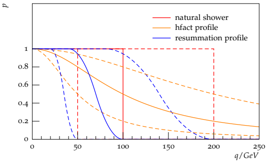
Need for **cross-validation**
of different algorithms.
$\rightarrow$ Subleading effects.

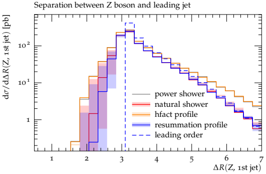
Recoils, definition of hard
scale, phase space
population, ...

also extensively addressed in Vincia
[Skands et al., '08-'14]



[Höche, Krauss, Schönherr '14]
see also [SP, Gieseke '09]
and [Höche, Schumann, Siegert '09]





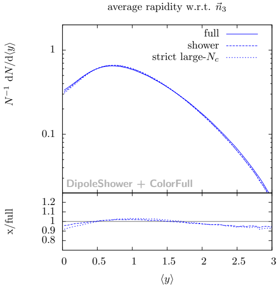
[SP – in progress '14]

Showers: Improvements.

Colour-exact radiation patterns:

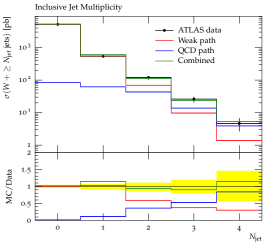
$$D_{ij,k} \sim \frac{\langle \mathcal{M} | \mathbf{T}_{ij} \cdot \mathbf{T}_k | \mathcal{M} \rangle}{\mathbf{T}_{ij}^2 |\mathcal{M}|^2}$$

- First emission for matching
  [Höche, Krauss, Schönherr, Siegert '11]
- Several emissions [SP, Sjödahl '11]



Electroweak effects:

- Include W, Z emission
  [Christiansen, Sjöstrand '14]
  [Krauss, Schönherr, Spannowsky '14]
- EW Sudakov logs unclear
  Different pattern than QCD logs.



Hard Scattering: Overview.

Two paradigms:

- (N)NLO **Matching**
- (N)LO **Merging**

N.B. NNLO matching requires NLO merging.

Matching combines shower and fixed order for a **fixed multiplicity**.

$$\mathrm{PS}[\mathrm{d}\sigma_{\mathsf{(N)NLO}} - \mathrm{d}\sigma_{\mathsf{PS,expanded}}] = \mathrm{d}\sigma_{\mathsf{(N)NLO}} + \mathcal{O}(\alpha_s^{1,2})$$

Pioneered by [Frixione, Webber '02] [Nason '04]

Merging combines shower and fixed order for **several multiplicities**.

- Divide phase space into hard and soft regions
- Supplement hard matrix elements by resummation
- Add vetoed shower on top

	ME	Matching	Merging	Shower
MadGraph5_aMC@NLO	MadGraph, BLHA	MC@NLO	FxFx	Pythia, Herwig++ (angular)
Matchbox/Herwig++	MadGraph, BLHA	MC@NLO, Powheg	UNLOPS	Herwig++ (angular,dipoles)
POWHEG-BOX	Builtin, 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 dipoles
Geneva	Builtin + Resum	Geneva	Geneva	Pythia
HEJ	HEJ, MadGraph	–	HEJ+PS	Ariadne
Vincia	Builtin, Madgraph	Vincia	Vincia	Vincia, Pythia

BLHA = GoSam, NJet, OpenLoops, VBFNLO

[full list of references → proceedings]

Hard Scattering: NLO Matching.

$$\mathrm{d}\sigma^{\text{matched}}_{\text{NLO}} =$$

$$\mathrm{d}\sigma_{\text{Born}}(\phi_n, Q)u(\phi_n)$$

$$+ \left(\mathrm{d}\sigma_{\text{Virtual}}(\phi_n, Q) + \int_1 \mathrm{d}\sigma_{\text{Sub}}(\phi_{n+1}, Q)\right) u(\phi_n)$$

$$- \mathrm{d}\sigma_{\text{Sub}}(\phi_{n+1}, Q)u(\phi_n) \qquad + \mathrm{d}\sigma_{\text{Real}}(\phi_{n+1}, Q)u(\phi_{n+1})$$

$$+ \mathrm{d}\sigma_{\text{Bridge}}(\phi_{n+1}, Q)\theta(\mu - q)\ u(\phi_n) \qquad - \mathrm{d}\sigma_{\text{Bridge}}(\phi_{n+1}, Q)\theta(\mu - q)\ u(\phi_{n+1})$$

$$+ P(\phi_n, q)\frac{\mathrm{d}\phi_{n+1}}{\mathrm{d}\phi_n}\theta(q - \mu)\ \mathrm{d}\sigma_{\text{Born}}(\phi_n, Q)u(\phi_n) \qquad - \mathrm{d}\sigma_{\text{Born}}(\phi_n, Q)P(\phi_n, q)\frac{\mathrm{d}\phi_{n+1}}{\mathrm{d}\phi_n}\theta(q - \mu)\ u(\phi_{n+1})$$

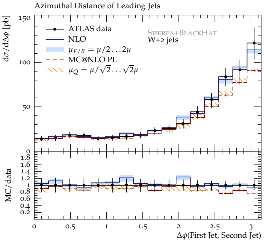
Auxialiary cross section below cutoff.

Here we did add a power correction $\mathcal{O}(\mu^2/Q^2)$ for IR safe observables.

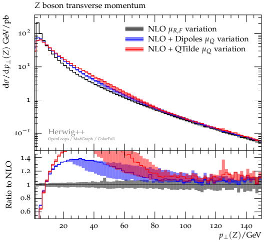
[see review by Webber and Nason & SP PhD thesis]

Hard Scattering: NLO Matching.

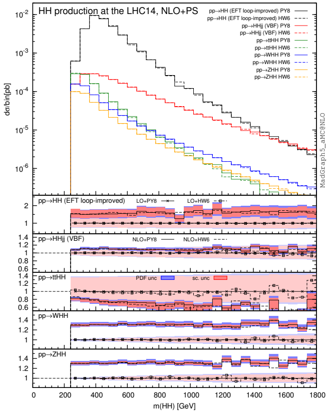
A large number of processes studied, thanks to automation. This does not mean that NLO is 'done'.
Again: Various algorithms. Need to assess and understand uncertainties.



[Höche, Krauss, Schönherr, Siegert '12]



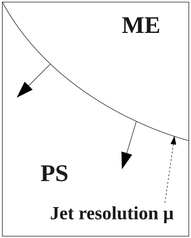
[Gieseke, SP et al. – in progress '14]



[Frederix et al. '14]

Hard Scattering: (N)LO Merging.

Cut phasespace according to jet measure on emission-by-emission basis.



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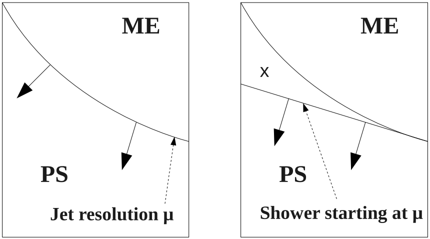

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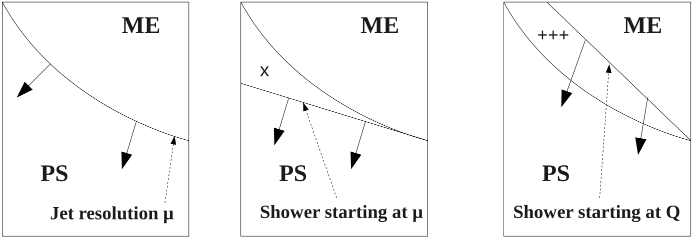

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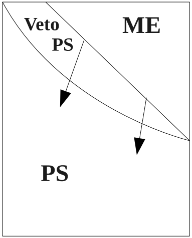

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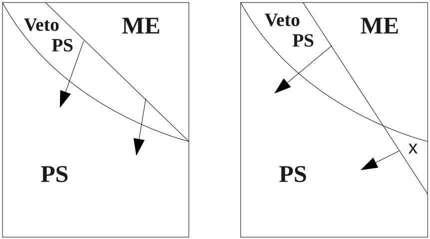

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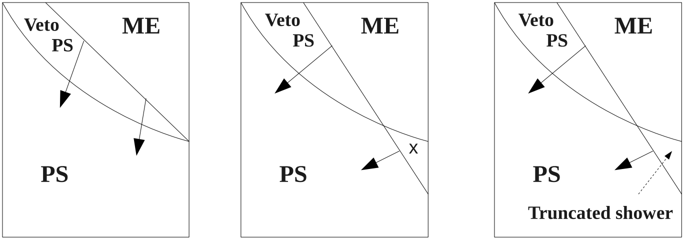
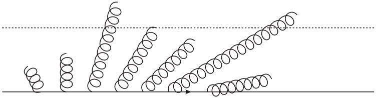
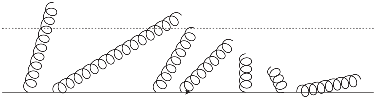
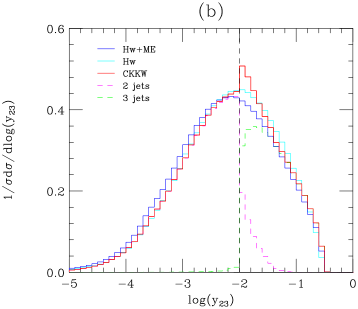


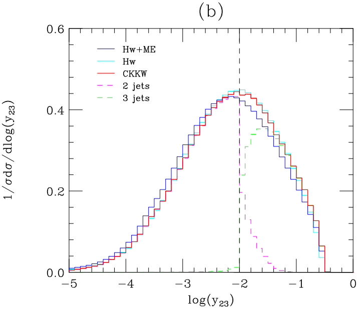
Truncated showers.

[Hamilton, Richardson, Tully '09] [Hoeche, Krauss, Schumann, Siegert '09]







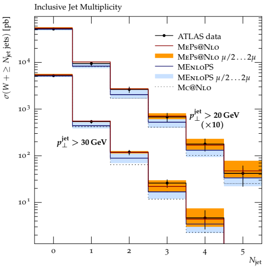


[Hamilton, Richardson, Tully '09]

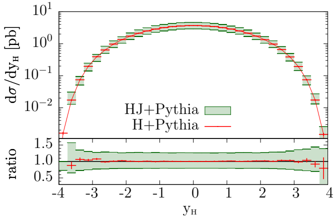
Hard Scattering: NLO Merging.

Name of the game: Minimize dependence on merging scale.
Well understood at LO, potential problems at NLO in inclusive cross sections.

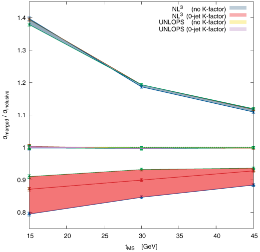
- FxFx, MEPS@NLO: Combine MC@NLO's of different multiplicities
  [Frixione, Frederix '12] [Höche, Krauss, Schönherr, Siegert '12]
- MiNLO: Reproduce inclusive $pp \to X$ from $pp \to Xj$ with Sudakov factors [Hamilton, Nason, Oleari, Zanderighi '12]
- UNLOPS: Merge exclusive jet cross sections, constrain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



Sherpa MEPS@NLO W+jets



MiNLO H+jets



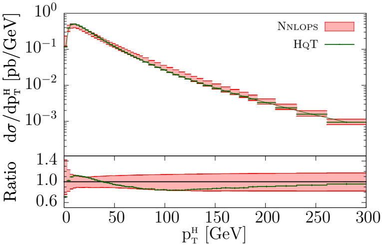
UNLOPS H+jets

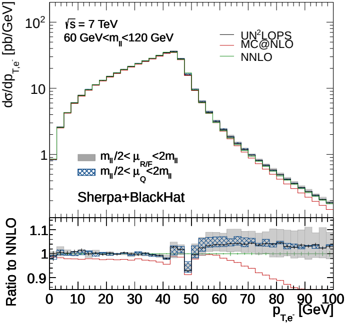
Much more processes looked at, thanks to automation.

Hard Scattering: NNLO Matching.

Proof-of-concept for DY-type processes.

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





Formally also NNLO: Merging of loop-induced contributions, e.g. $gg \to WW$

[Cascioli et al. '13]

Hard Scattering: EW Corrections.

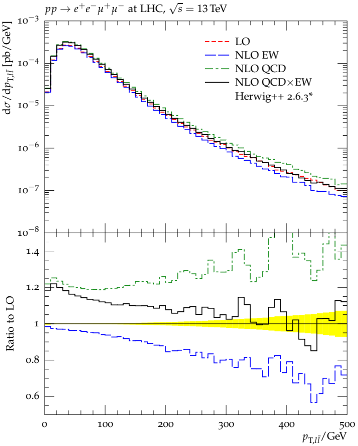
[Gieseke, Kasprczik, Kühn '14]

Electroweak corrections to diboson production @ LHC.

- Factorized ansatz to mixed corrections:

  $$(1 + \delta_{\mathrm{QCD}})(1 + \delta_{\mathrm{EW}}) \approx 1 + \delta_{\mathrm{QCD}} + \delta_{\mathrm{EW}}$$

- Valid if both corrections are small $\rightarrow$ use suitable cuts to supress phase space enhanced QCD corrections
- QCD corrections from builtin POWHEG cross sections
- EW corrections through $\hat{s}$, $\hat{t}$-dependent reweighting



Outlook.

Most manpower is currently going into higher-order improvements.
Showers need to match up this precision, especially for NNLO.

At this order, however, the simple factorization

cross section $\times$ emission probability

breaks down.

We need to include colour correlations, potentially spin correlations, both of which require **evolution of the amplitude**.

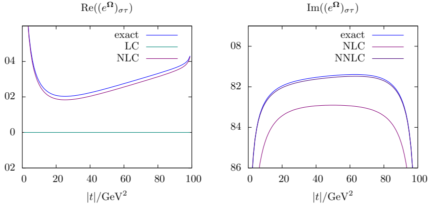
Need to pin down full colour evolution in showers in a practical way.

[Nagy, Soper '13] [SP '13]

Colour-rearranging soft-gluon amplitudes.
Vanish at leading colour!

(Approximate) handling of many legs derived.
Will enable new perspective on colour reconnection.

[SP '13-]



Summary.

MC tools play a major role for LHC physics and beyond.

Experimental accuracy, but also no evidence for new physics,
require increasing precision of these tools.

Precision not only means including higher orders,
but understanding and controlling uncertainties.

Rapid devlopment for the former, only starting to investigate the latter.

A clear need to improve showers, as well as non-perturbative issues.
Major challenge for the community.

Monte Carlo Development

Simon Plätzer

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