Introduction to Monte Carlo event generators
part III

Korinna Zapp

LIP (Lisbon), CERN

Münster 19. 10.–2. 11. 2016

Graduiertenkolleg 2149 Research Training Group

LIP FCT Fundação para a Ciência e a Tecnologia MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA CERN MCnet

Outline

Higher order corrections in event generators
- Next-to-leading order matrix elements
- Matrix element corrections
- NLO matching
- Multi-jet merging

MC event generators at work
- LEP: $e^+ + e^- \to$ jets
- LHC: Z + jets
- LHC: jets
- LHC: other processes

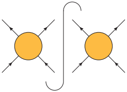
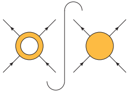
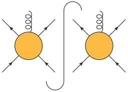
Other tools

Summary

Outline

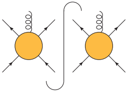
Next-to-leading order matrix elements

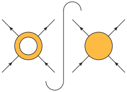
NLO calculation

- Born term: $\mathcal{B} =$ 
- Virtual terms: $\mathcal{V} = 2\,\mathrm{Re}\{$  $\}$
- Real terms: $\mathcal{R} =$ 

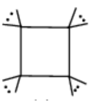
- UV divergences in $\mathcal{V}$ removed by renormalization procedure
- $\mathcal{V}$ and $\mathcal{R}$ both still infrared divergent
- IR divergences cancel between $\mathcal{V}$ and $\mathcal{R}$ (KLN theorem)
  $\rightarrow$ finite result for IR safe observables

Real and virtual correction

Real correction: $\mathcal{R} =$  $\Rightarrow$ tree-level, same technologies as for $\mathcal{B}$

Virtual correction: $\mathcal{V} =$ 

- reduce 1-loop matrix element to master integrals

$\mathcal{M}^{\text{1-loop}} = D$  $+ C$  $+ B$  $+ A$  $+ R$

- compute coefficients with tensor reduction or unitarity cuts
- problem: numerical stability, may need quad-precision

Cancellation of IR divergencies

NLO calculation

$$\langle O \rangle^{\mathrm{NLO}} = \int \mathrm{d}\Phi_N \Big[\mathcal{B}(\Phi_N) + \mathcal{V}(\Phi_N) \Big] \, O(\Phi_N) + \int \mathrm{d}\Phi_{N+1} \, \mathcal{R}(\Phi_{N+1}) \, O(\Phi_{N+1})$$

- IR divergences cancel between $\mathcal{V}$ and $\mathcal{R}$ (KLN theorem), but live in different phase spaces
  $\rightarrow$ IR divergences in $\mathcal{V}$ arise from integral over loop momentum
  $\rightarrow$ IR divergences in $\mathcal{R}$ arise from integral over soft-collinear external momentum
- subtraction method: construct universal integrable terms that reproduce $\mathcal{R}$ in the soft-collinear limit

Subtraction method

Frixione, Kunszt, Signer NPB467(1996); Catani, Seymour NPB485(1997)291; Kosower PRD57(1998)5410

$$\langle O \rangle^{\mathrm{NLO}} = \int d\Phi_N \Big[\mathcal{B}(\Phi_N) + \mathcal{V}(\Phi_N) + \mathcal{I}(\Phi_N) \Big] O(\Phi_N) + \int d\Phi_{N+1} \Big[\mathcal{R}(\Phi_{N+1})\, O(\Phi_{N+1}) - \mathcal{D}(\Phi_N \cdot \Phi_1)\, O(\Phi_N) \Big]$$

- subtraction method: construct universal integrable terms $\mathcal{D}$ that reproduce $\mathcal{R}$ in the soft-collinear limit
- holds for infrared-safe observables, i.e. $O(\Phi_{N+1}) \to O(\Phi_N)$ in IR limit
- assume phase space factorisation: $\Phi_{N+1} = \Phi_N \cdot \Phi_1$
- need to add $\int d\Phi_1 \mathcal{D}(\Phi_N \cdot \Phi_1) = \mathcal{I}(\Phi_N)$ back
  $\to$ cancels divergences in $\mathcal{V}$ (KLN)

$\Rightarrow$ integrands of both phase space integrals separately finite

Subtraction method

Frixione, Kunszt, Signer NPB467(1996); Catani, Seymour NPB485(1997)291; Kosower PRD57(1998)5410

$$\langle O \rangle^{\mathrm{NLO}} = \int \mathrm{d}\Phi_N \left[\mathcal{B}(\Phi_N) + \mathcal{V}(\Phi_N) + \mathcal{I}(\Phi_N) \right] O(\Phi_N) + \int \mathrm{d}\Phi_{N+1} \left[\mathcal{R}(\Phi_{N+1})\, O(\Phi_{N+1}) - \mathcal{D}(\Phi_N \cdot \Phi_1)\, O(\Phi_N) \right]$$

- subtraction method: construct universal integrable terms $\mathcal{D}$ that reproduce $\mathcal{R}$ in the soft-collinear limit
- holds for infrared-safe observables, i.e. $O(\Phi_{N+1}) \to O(\Phi_N)$ in IR limit
- assume phase space factorisation: $\Phi_{N+1} = \Phi_N \cdot \Phi_1$
- need to add $\int \mathrm{d}\Phi_1 \mathcal{D}(\Phi_N \cdot \Phi_1) = \mathcal{I}(\Phi_N)$ back
  $\to$ cancels divergences in $\mathcal{V}$ (KLN)

$\Rightarrow$ integrands of both phase space integrals separately finite

Subtraction method

Frixione, Kunszt, Signer NPB467(1996); Catani, Seymour NPB485(1997)291; Kosower PRD57(1998)5410

$$\langle O\rangle^{\rm NLO} = \int d\Phi_N \Big[\mathcal{B}(\Phi_N) + \mathcal{V}(\Phi_N) + \mathcal{I}(\Phi_N)\Big]\, O(\Phi_N) + \int d\Phi_{N+1}\, \Big[\mathcal{R}(\Phi_{N+1})\, O(\Phi_{N+1}) - \mathcal{D}(\Phi_N\cdot\Phi_1)\, O(\Phi_N)\Big]$$

- subtraction method: construct universal integrable terms $\mathcal{D}$ that reproduce $\mathcal{R}$ in the soft-collinear limit
- holds for infrared-safe observables, i.e. $O(\Phi_{N+1}) \to O(\Phi_N)$ in IR limit
- assume phase space factorisation: $\Phi_{N+1} = \Phi_N\cdot\Phi_1$
- need to add $\int d\Phi_1 \mathcal{D}(\Phi_N\cdot\Phi_1) = \mathcal{I}(\Phi_N)$ back
  $\to$ cancels divergences in $\mathcal{V}$ (KLN)

$\Rightarrow$ integrands of both phase space integrals separately finite

Subtraction method

Frixione, Kunszt, Signer NPB467(1996); Catani, Seymour NPB485(1997)291; Kosower PRD57(1998)5410

$$\langle O\rangle^{\mathrm{NLO}} = \int d\Phi_N \Big[\mathcal{B}(\Phi_N) + \mathcal{V}(\Phi_N) + \mathcal{I}(\Phi_N)\Big]\, O(\Phi_N) + \int d\Phi_{N+1} \Big[\mathcal{R}(\Phi_{N+1})\, O(\Phi_{N+1}) - \mathcal{D}(\Phi_N\cdot\Phi_1)\, O(\Phi_N)\Big]$$

- subtraction method: construct universal integrable terms $\mathcal{D}$ that reproduce $\mathcal{R}$ in the soft-collinear limit
- holds for infrared-safe observables, i.e. $O(\Phi_{N+1}) \to O(\Phi_N)$ in IR limit
- assume phase space factorisation: $\Phi_{N+1} = \Phi_N\cdot\Phi_1$
- need to add $\int d\Phi_1 \mathcal{D}(\Phi_N\cdot\Phi_1) = \mathcal{I}(\Phi_N)$ back
  $\to$ cancels divergences in $\mathcal{V}$ (KLN)

$\Rightarrow$ **integrands of both phase space integrals separately finite**

Subtraction method

- subtraction term for N particle process

$$\mathcal{D}(\Phi_N \cdot \Phi_1) = \mathcal{B}(\Phi_N) \otimes \mathcal{K}^{(\mathcal{S})}(\Phi_1)$$

$$\mathcal{I}(\Phi_N) = \int \mathrm{d}\Phi_1 \, \mathcal{B}(\Phi_N) \otimes \mathcal{K}^{(\mathcal{S})}(\Phi_1)$$

  with universal, i.e. process independent, kernel $\mathcal{K}^{(\mathcal{S})}(\Phi_1)$
- subtraction kernels can be used as splitting kernels in dipole shower
- need invertible phase space mapping $\Phi_{N+1} \longleftrightarrow \Phi_N \cdot \Phi_1$

Reminder and notation: the parton shower

- Sudakov form factor: no-splitting probability for dipole *ik*

$$\Delta_{ik}^{(\mathcal{K})}(t, t_0) = \exp\left\{ -\int_{t_0}^{t} \frac{\mathrm{d}t}{t} \int \mathrm{d}z \, \frac{\mathrm{d}\phi}{2\pi} \frac{\alpha_s}{2\pi} \mathcal{K}_{ik}(t, z, \phi) \right\}$$

- will replace $\frac{\mathrm{d}t}{t} \mathrm{d}z \frac{\mathrm{d}\phi}{2\pi} \longrightarrow \mathrm{d}\Phi_1$
- Sudakov form factor for emission off N particle configuration

$$\Delta_{N}^{(\mathcal{K})}(t, t_0) = \exp\left\{ -\int_{t_0}^{t} \mathrm{d}\Phi_1 \mathcal{K}_N(\Phi_1) \right\} \quad \text{with} \quad \mathcal{K}_N(\Phi_1) = \sum_{\{ik\}} \frac{\alpha_s}{2\pi} \mathcal{K}_{ik}(\Phi_1)$$

Reminder and notation: the parton shower

- consider first parton shower emission off Born configuration

$$
\mathrm{d}\sigma_{\mathrm{PS}}^{(\mathrm{LO})} = \mathrm{d}\Phi_N \mathcal{B}(\Phi_N) \times \underbrace{\left[\Delta_N^{(\mathcal{K})}(\mu_F^2, t_0) + \int_{t_0}^{\mu_F^2} \mathrm{d}\Phi_1 \, \mathcal{K}_N(\Phi_1) \Delta_N^{(\mathcal{K})}(\mu_F^2, t(\Phi_1)) \right]}_{=1 \quad \text{(unitarity of parton shower)}}
$$

- parton shower is unitary
- further emissions by recursion

Matrix element corrections

- parton shower not a good description for hard emissions
- form many processes $\mathcal{R} < \mathcal{B} \times \mathcal{K}_N$
- procedure: generate emission with parton shower and reject with probability $\mathcal{P} = \mathcal{R}/(\mathcal{B} \times \mathcal{K}_N)$

$$d\sigma_{\text{MEC}}^{(\text{LO})} = d\Phi_N \mathcal{B}(\Phi_N)$$

$$\times \underbrace{\left[\Delta_N^{(\mathcal{R}/\mathcal{B})}(\mu_F^2, t_0) + \int_{t_0}^{\mu_F^2} d\Phi_1 \, \frac{\mathcal{R}(\Phi_N \cdot \Phi_1)}{\mathcal{B}(\Phi_N)} \Delta_N^{(\mathcal{R}/\mathcal{B})}(\mu_F^2, t(\Phi_1)) \right]}_{=1}$$

where
$$\Delta_N^{(\mathcal{R}/\mathcal{B})}(t, t_0) = \exp\left\{ -\int_{t_0}^{t} d\Phi_1 \, \frac{\mathcal{R}(\Phi_N \cdot \Phi_1)}{\mathcal{B}(\Phi_N)} \right\}$$

Matrix element corrections

- cross section still LO
- first emission described by $\mathcal{R}$ (correct at order α_s)
- but: phase space constrained by μ_F^2
- "power shower": replace $\mu_F^2 \longrightarrow s$ and apply ME correction
- problem: generates wrong log
- extends resummation built into parton shower beyond region of its validity

NLO matching: Basic idea

- parton shower resums logarithms
  - fair description of collinear/soft emissions
  - jet evolution

where the logs are large

- matrix elements exact at given order
  - fair description of hard/large-angle emissions
  - jet production

where the logs are small

- adjust ("match") terms:
  - cross section at NLO accuracy & correct hardest emission in PS to exactly reproduce ME at order α_s ($\mathcal{R}$-part of the NLO calculation)
  - maintain (N)LL-accuracy of parton shower

review: Nason, Webber, Ann. Rev. Nucl. Part. Sci. 62 (2012) 187

NLO matching: Basic idea

- parton shower resums logarithms
  - fair description of collinear/soft emissions
  - jet evolution

where the logs are large

- matrix elements exact at given order
  - fair description of hard/large-angle emissions
  - jet production

where the logs are small

- adjust (“match”) terms:
  - cross section at NLO accuracy & correct hardest emission in PS to exactly reproduce ME at order α_s ($\mathcal{R}$-part of the NLO calculation)
  - maintain (N)LL-accuracy of parton shower

review: Nason, Webber, Ann. Rev. Nucl. Part. Sci. 62 (2012) 187

POWHEG

Nason, JHEP **0411** (2004) 040; Frixione, Nason, Oleari, JHEP **0711** (2007) 070

- promote ME correction to NLO accuracy by defining Born configuration with NLO weight — local K-factor

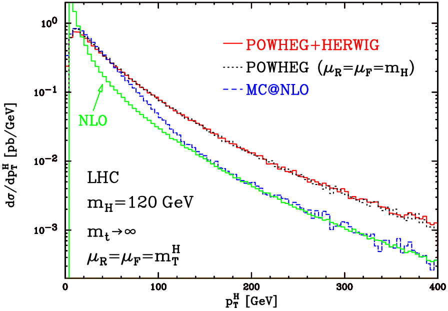
$$\bar{\mathcal{B}}(\Phi_N) = \mathcal{B}(\Phi_N) + \mathcal{V}(\Phi_N) + \mathcal{I}(\Phi_N) + \int \mathrm{d}\Phi_1 \left[\mathcal{R}(\Phi_N \cdot \Phi_1) - \mathcal{D}(\Phi_N \cdot \Phi_1)\right]$$

- integrates to NLO cross section
- radiation pattern like in ME correction

$$\mathrm{d}\sigma^{(\mathrm{NLO})}_{\mathrm{POWHEG}} = \mathrm{d}\Phi_N \bar{\mathcal{B}}(\Phi_N) \times \underbrace{\left[\Delta_N^{(\mathcal{R}/\mathcal{B})}(\mu_F^2, t_0) + \int_{t_0}^{\mu_F^2} \mathrm{d}\Phi_1 \frac{\mathcal{R}(\Phi_N \cdot \Phi_1)}{\mathcal{B}(\Phi_N)} \Delta_N^{(\mathcal{R}/\mathcal{B})}(\mu_F^2, t(\Phi_1))\right]}_{=1}$$

POWHEG

- pitfall, again: have to replace $\mu_F^2 \to s$ to fill entire phase space for first emission
  same implications as for MEC
- leads to formally sub-leading but numerically large deviations from NLO in distributions



Alioli, Nason, Oleari, Re, JHEP 0904 (2009) 002

POWHEG

- pitfall, again: have to replace $\mu_F^2 \to s$ to fill entire phase space for first emission
  same implications as for MEC
- leads to formally sub-leading but numerically large deviations from NLO in distributions
- $\mathcal{R}/\mathcal{B}$ generates sub-leading logs that get exponentiated
  not clear whether they should be exponentiated
- all configurations enhanced by local K-factor
  K-factor for inclusive production of X adequate for X + jet at large $p_\perp$?
- some $\mathcal{R}$ configurations cannot be generated by adding an extra emission to $\mathcal{B}$
- all events have positive weights

Improved POWHEG

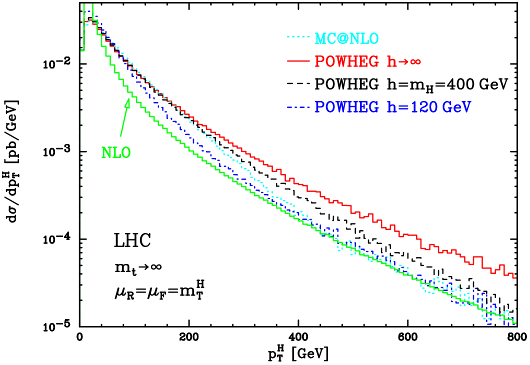
- split real-emission matrix element

$$\mathcal{R} = \mathcal{R}\left(\frac{h^2}{p_\perp^2 + h^2} + \frac{p_\perp^2}{p_\perp^2 + h^2}\right) = \mathcal{R}^{(S)} + \mathcal{R}^{(F)}$$

- can "tune" h to mimick NNLO or other (resummation) result
- differential event rate up to first emission

$$\mathrm{d}\sigma_{\mathrm{POWHEG}}^{(\mathrm{NLO})} = \mathrm{d}\Phi_N \bar{\mathcal{B}}^{(\mathcal{R}^{(S)})}\left[\Delta_N^{(\mathcal{R}^{(S)}/\mathcal{B})}(s, t_0) + \int_{t_0}^{s} \mathrm{d}\Phi_1 \frac{\mathcal{R}^{(S)}}{\mathcal{B}} \Delta_N^{(\mathcal{R}^{(S)}/\mathcal{B})}(s, t)\right] + \mathrm{d}\Phi_{N+1} \mathcal{R}^{(F)}(\Phi_{N+1})$$

Improved POWHEG



Alioli, Nason, Oleari, Re, JHEP 0904 (2009) 002

MC@NLO

Frixione, Webber, JHEP 0206 (2002) 029; Hoeche, Krauss, Schonherr, Siegert, JHEP 1209 (2012) 049

- divide $\mathcal{R}$ in IR-singular (soft) and IR-regular (hard) part

$$\mathcal{R} = \mathcal{R}^{(S)} + \mathcal{R}^{(H)} = \mathcal{D} + \mathcal{H}$$

- NLO weighted Born configuration simplifies

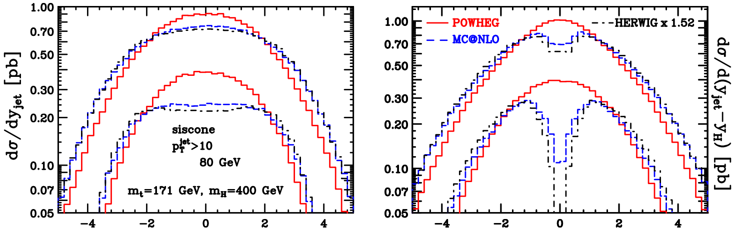
$$\bar{\mathcal{B}}^{(\mathcal{R}^{(S)})}(\Phi_N) \longrightarrow \tilde{\mathcal{B}}(\Phi_N) = \mathcal{B}(\Phi_N) + \mathcal{V}(\Phi_N) + \mathcal{I}(\Phi_N)$$

- use subtraction kernels as splitting kernels in PS $\mathcal{K}_N = \mathcal{D}$

$$\mathrm{d}\sigma^{(\mathrm{NLO})}_{\mathrm{MC@NLO}} = \mathrm{d}\Phi_N \tilde{\mathcal{B}}(\Phi_N) \left[\Delta_N^{(\mathcal{K})}(\mu_F^2, t_0) + \int_{t_0}^{\mu_F^2} \mathrm{d}\Phi_1 \, \mathcal{K}_N(\Phi_1) \Delta_N^{(\mathcal{K})}(\mu_F^2, t(\Phi_1)) \right] + \mathrm{d}\Phi_{N+1} \mathcal{H}(\Phi_{N+1})$$

MC@NLO

- only resummed parts modified with local K-factor
- process independent — no tuning of h
- makes high demands on parton shower:
  - parton shower must reproduce full IR structure
    problem with soft singularities in monopole showers
  - first emission must be full colour correct
  - parton shower has to fill phase space properly
- events can have negative weights



MC@NLO

- only resummed parts modified with local K-factor
- process independent — no tuning of h
- makes high demands on parton shower:
  - parton shower must reproduce full IR structure
    problem with soft singularities in monopole showers
  - first emission must be full colour correct
  - parton shower has to fill phase space properly
- events can have negative weights
- some formally sub-leading terms can become numerically large
  visible in some observables in processes with large NLO corrections
  can be cured by NLO multi-jet merging

Multi-jet merging: Basic idea

- parton shower resums logarithms
  - fair description of collinear/soft emissions
  - jet evolution

where the logs are large

- matrix elements exact at given order
  - fair description of hard/large-angle emissions
  - jet production

where the logs are small

- combine ("merge") both:
  results in "towers" of MEs with increasing number of jets evolved with PS
  - multi-jet cross sections at Born accuracy
  - maintain (N)LL accuracy of parton shower

Multi-jet merging: Basic idea

- parton shower resums logarithms
  - fair description of collinear/soft emissions
  - jet evolution

where the logs are large

- matrix elements exact at given order
  - fair description of hard/large-angle emissions
  - jet production

where the logs are small

- combine ("merge") both:
  results in "towers" of MEs with increasing number of jets evolved with PS
  - multi-jet cross sections at Born accuracy
  - maintain (N)LL accuracy of parton shower

Multi-jet merging: Basic idea

Problem: Overlap between ME and PS

- cross sections in fixed order perturbation theory are inclusive
- parton shower reproduces leading-log approximation of cross section

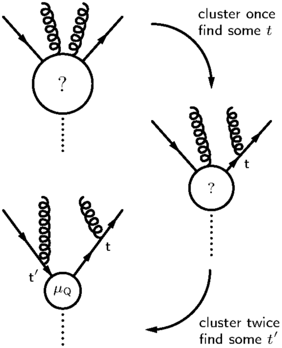
Solution

- introduce merging scale t_{MS} to divide phase space in
  - $t > t_{\text{MS}}$: hard regime to be populated by matrix elements
  - $t < t_{\text{MS}}$: soft/collinear regime to be populated by PS
- make matrix elements exclusive above t_{MS}
- restrict parton shower to radiate only below t_{MS}

Translating MEs to PS language: Parton shower histories

Andre, Sjostrand, Phys. Rev. D 57 (1998) 5767

- translate matrix element into branching sequence
- can be achieved by "running PS backwards"
  - identify most likely splitting according to PS emission probability
  - combine partons into mother according to PS kinematics
  - continue until core process is reached
- core process is considered inclusive
- it sets the resummation scale $t_{\max}$



MLM merging

Mangano, Moretti, Piccinini, Treccani, JHEP **0701** (2007) 013

MLM procedure

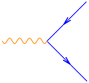
1. generate parton configuration from matrix element with $E_\perp > E_\perp^{\rm min}$ and angular separation $\Delta R_{jj} > R_{\rm min}$
2. shower event without restrictions on parton shower
3. cluster jets with cone radius $R_{\rm min}$ and $E_\perp > E_\perp^{\rm min}$
4. match partons and jets
5. reject event if not all partons and jets match or additional jets have been produced
6. add all accepted events

- works in practice
- theoretically not fully under control

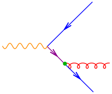
CKKW/CKKW-L merging

Catani, Krauss, Kuhn, Webber, JHEP **0111** (2001) 063 & Lonnblad, JHEP **0205** (2002) 046

- configurations generated by parton shower are exclusive
- e.g. jet rates in $e^+ + e^- \to$ jets
- Durham jet definition: relative transverse momentum $k_\perp > t_{\mathrm{MS}}$



$$\mathcal{P}_2(t_{\mathrm{MS}}) = [\Delta_{\mathrm{q}}(t_{\max}, t_{\mathrm{MS}})]^2$$



$$\mathcal{P}_3(t_{\mathrm{MS}}) = 2\Delta_{\mathrm{q}}(t_{\max}, t_{\mathrm{MS}}) \int_{t_{\mathrm{MS}}}^{t_{\max}} \frac{\mathrm{d}k_\perp^2}{k_\perp^2} \left[\int \mathrm{d}z \, \frac{\alpha_{\mathrm{s}}}{2\pi} \mathcal{K}_{\mathrm{q}}(k_\perp^2, z) \right.$$
$$\left. \times \, \Delta_{\mathrm{q}}(t_{\max}, k_\perp^2) \Delta_{\mathrm{q}}(k_\perp^2, t_{\mathrm{MS}}) \Delta_{\mathrm{g}}(k_\perp^2, t_{\mathrm{MS}}) \right]$$

- Sudakov factors prevent further emissions

Truncated & vetoed parton shower

- make ME exclusive by multiplying Sudakov factors
- can be done using analytic Sudakov factors (CKKW) or the parton shower (CKKW-L)

METS procedure

1. regularise matrix element with t_{MS} and generate configuration
2. cluster backwards until core process is reached
3. starting from t_{max} evolve until predefined branching $\leftrightarrow$ "truncated parton shower"
4. insert branching defined by matrix element
5. continue until t_0 is reached
6. emissions with $t > t_{\mathrm{MS}}$ lead to rejection of event $\leftrightarrow$ "veto"

Hoeche, Krauss, Schumann, Siegert, JHEP **0905** (2009) 053; Hamilton, Richardson, Tully, JHEP **0911** (2009) 038

LO merging in MC@NLO notation

- vetoed shower generates Sudakov form factor

$$\Delta_N^{(\mathcal{K})}(t_{\max}, t; > t_{\mathrm{MS}}) = \exp\left\{ - \int_{t_0}^{t} \mathrm{d}\Phi_1 \mathcal{K}_N(\Phi_1)\theta(t - t_{\mathrm{MS}}) \right\}$$

- expression for first emission

$$\mathrm{d}\sigma_{\mathrm{CKKW}} = \mathrm{d}\Phi_N \mathcal{B} \left[\Delta_N^{(\mathcal{K})}(t_{\max}, t_0) + \int_{t_0}^{t_{\max}} \mathrm{d}\Phi_1 \mathcal{K}_N \Delta_N^{(\mathcal{K})}(t_{\max}, t)\theta(t_{\mathrm{MS}} - t) \right]$$
$$+ \mathrm{d}\Phi_{N+1} \mathcal{B}_{N+1}(\Phi_{N+1}) \Delta_N^{(\mathcal{K})}(t_{\max}, t; > t_{\mathrm{MS}})\theta(t - t_{\mathrm{MS}})$$

- can add more matrix elements in the same way

Other techniques and approaches

UMEPS: unitary (process independent) multi-jet merging
Lonnblad, Prestel, JHEP 1302 (2013) 094 & Plätzer, JHEP 1308 (2013) 114

FxFx: MLM at NLO
Frixione, Frederix, JHEP 1212 (2012) 061

MEPS@NLO: process independent multi-jet merging at NLO
Höche, Krauss, Schönherr, Siegert JHEP 1304 (2013) 027 & JHEP 1301 (2013) 144

UNLOPS: UMEPS at NLO
Lönnblad, Prestel, JHEP 1303 (2013) 166 & Plätzer, JHEP 1308 (2013) 114

MiNLO: NLO+PS for Higgs and DY without merging cut
Hamilton, Nason, Oleari, Zanderighi, JHEP 1305 (2013) 082

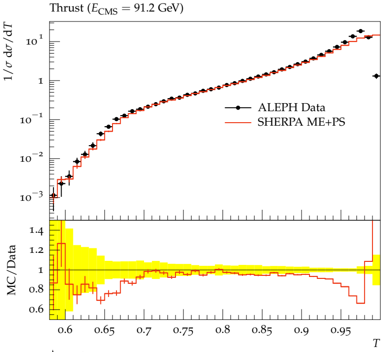
UN^{2}LOPS: UMEPS at NNLO for Higgs and Drell-Yan
Höche, Li, Prestel, Phys. Rev. D 91 (2015) no.7, 074015

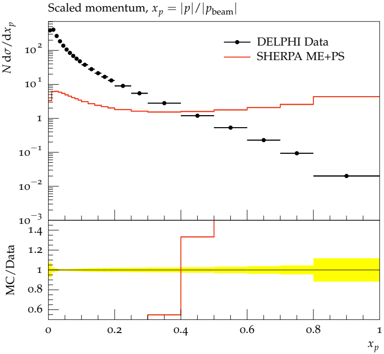
NNLOPS: MiNLO based NNLO+PS for Higgs and Drell-Yan
Hamilton, Nason, Re, Zanderighi, JHEP 1310 (2013) 222

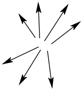
NLO QCD+EW: including multi-jet merging
Kallweit, Lindert, Maierhofer, Pozzorini, Schönherr, JHEP 1604 (2016) 021

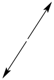
Outline

$e^+ + e^- \to$ jets at LEP



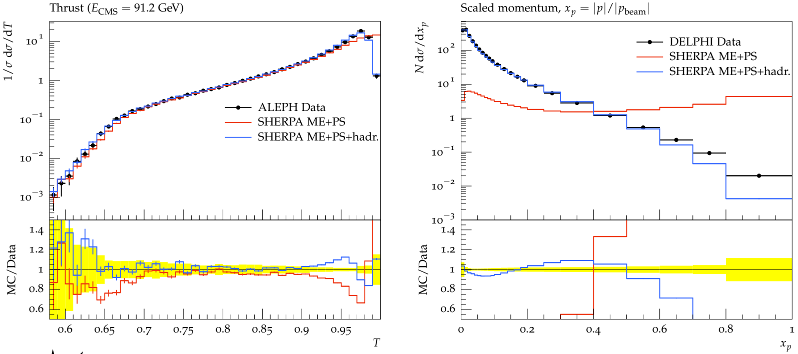


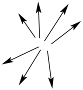




ALEPH, Eur. Phys. J. **C35** (2004) 457; DELPHI, Z. Phys. **C73** (1996) 11

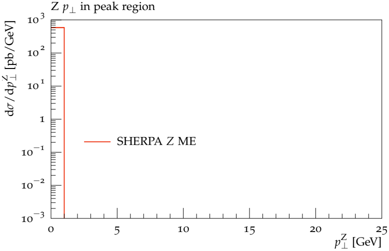
$e^+ + e^- \to$ jets at LEP

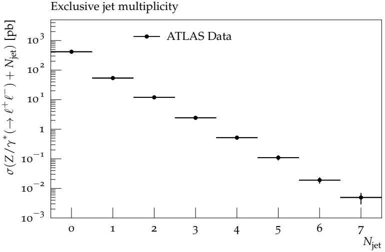


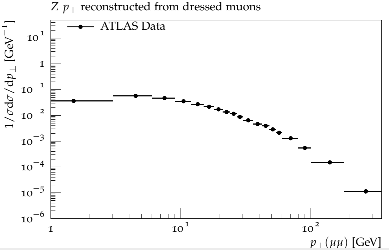


ALEPH, Eur. Phys. J. **C35** (2004) 457; DELPHI, Z. Phys. **C73** (1996) 11

Z + jets at LHC



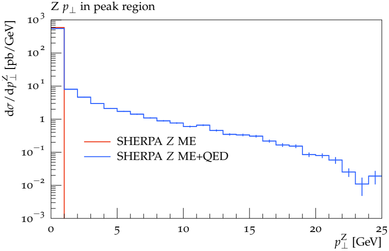


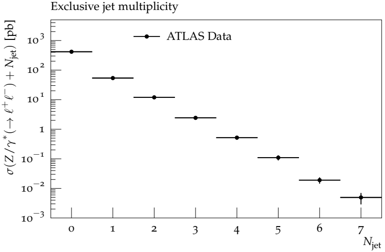


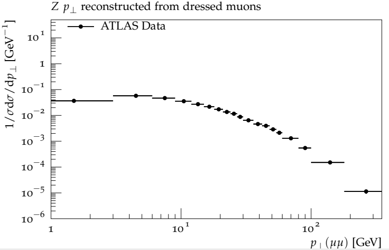
ATLAS, JHEP **1307** (2013) 032

ATLAS, Phys. Lett. B **705** (2011) 415

Z + jets at LHC



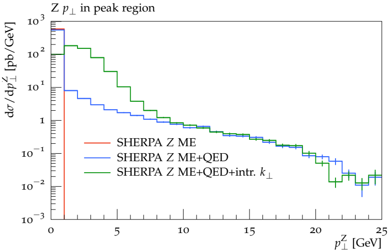


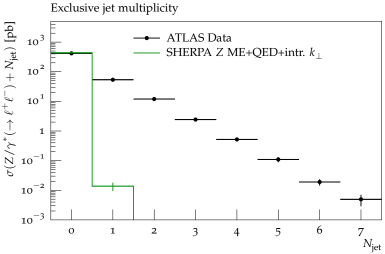


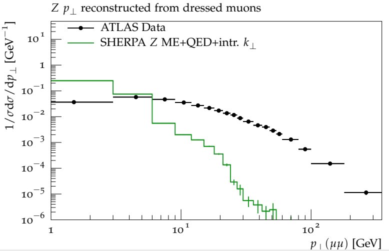
ATLAS, JHEP **1307** (2013) 032

ATLAS, Phys. Lett. B **705** (2011) 415

Z + jets at LHC



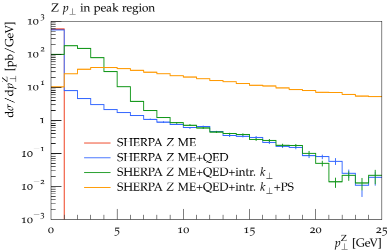


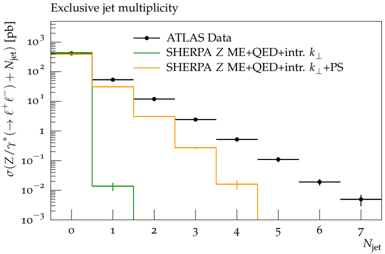


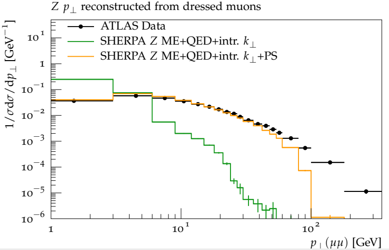
ATLAS, JHEP **1307** (2013) 032

ATLAS, Phys. Lett. B **705** (2011) 415

Z + jets at LHC



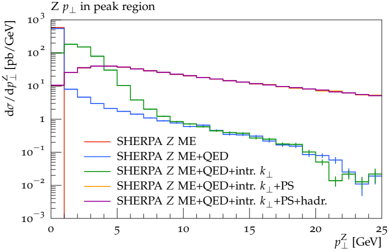


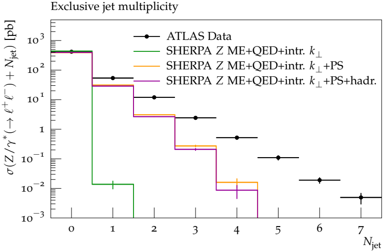


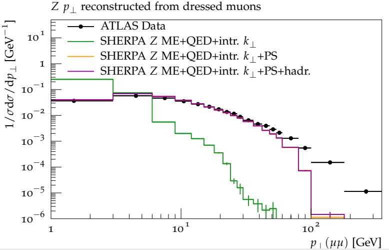
ATLAS, JHEP **1307** (2013) 032

ATLAS, Phys. Lett. B **705** (2011) 415

Z + jets at LHC



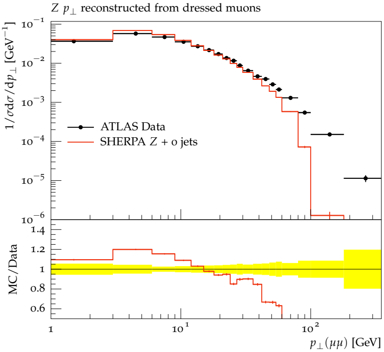


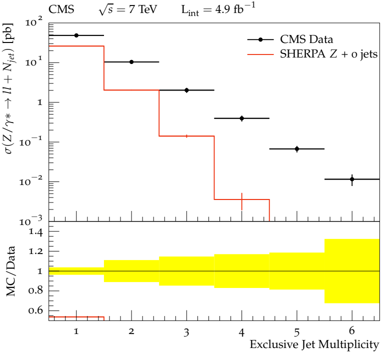


ATLAS, JHEP **1307** (2013) 032

ATLAS, Phys. Lett. B **705** (2011) 415

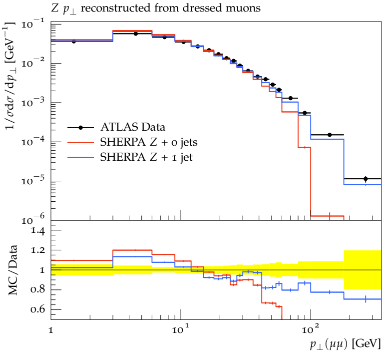
Now let's do LO multi-jet merging

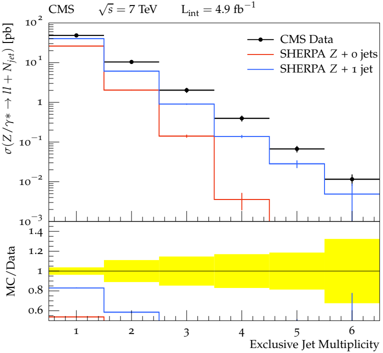




ATLAS, Phys. Lett. B **705** (2011) 415; CMS, Phys. Rev. D **91** (2015) no.5, 052008

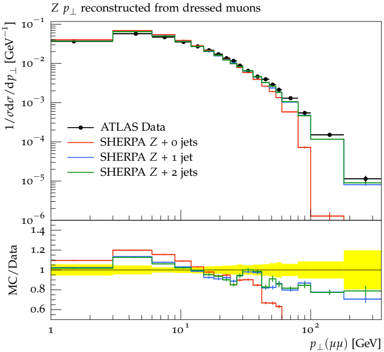
Now let's do LO multi-jet merging

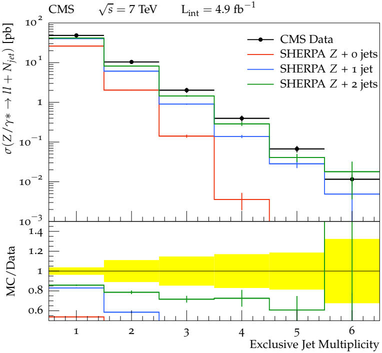




ATLAS, Phys. Lett. B **705** (2011) 415; CMS, Phys. Rev. D **91** (2015) no.5, 052008

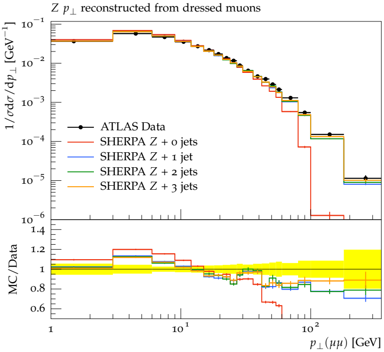
Now let's do LO multi-jet merging

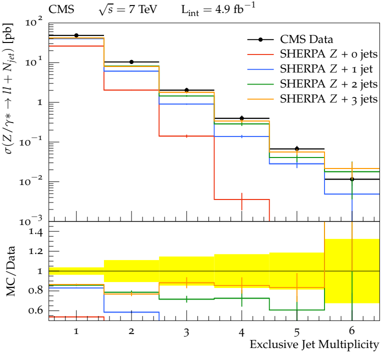




ATLAS, Phys. Lett. B **705** (2011) 415; CMS, Phys. Rev. D 91 (2015) no.5, 052008

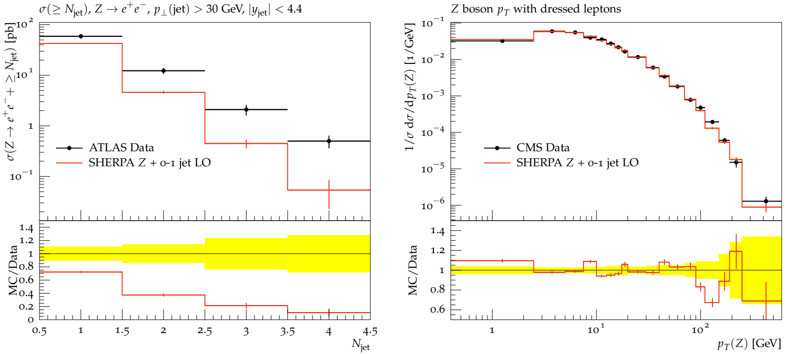
Now let's do LO multi-jet merging





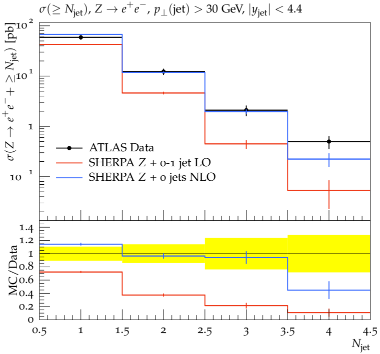
ATLAS, Phys. Lett. B **705** (2011) 415; CMS, Phys. Rev. D **91** (2015) no.5, 052008

Adding NLO corrections



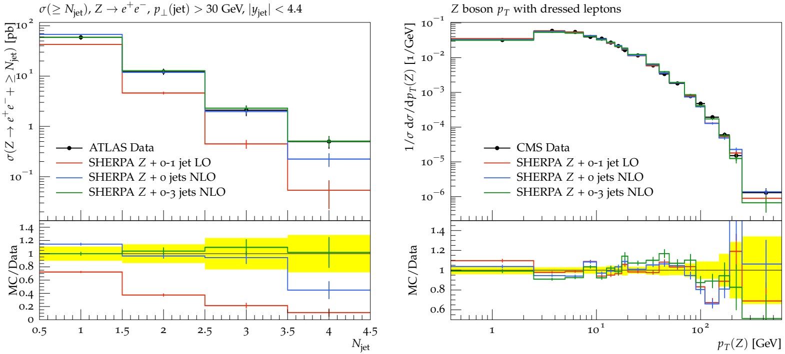
ATLAS, Phys. Rev. D **85** (2012) 032009; CMS, Phys. Rev. D **85** (2012) 032002

Adding NLO corrections



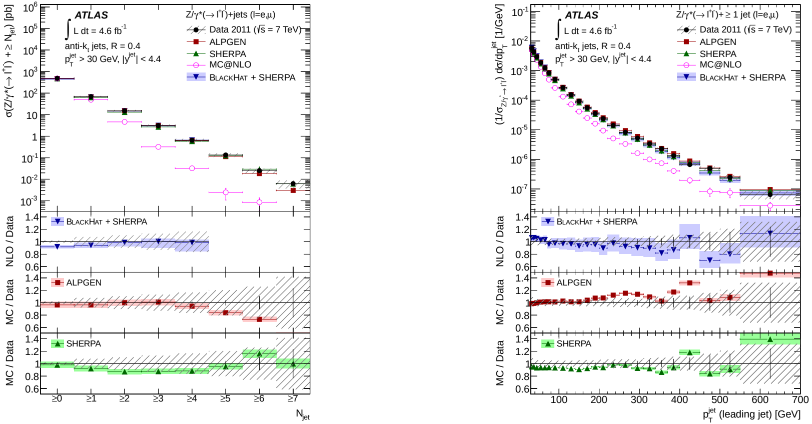
ATLAS, Phys. Rev. D **85** (2012) 032009; CMS, Phys. Rev. D **85** (2012) 032002

Adding NLO corrections



ATLAS, Phys. Rev. D **85** (2012) 032009; CMS, Phys. Rev. D **85** (2012) 032002

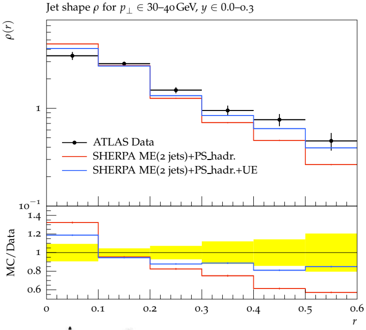
Different merging schemes

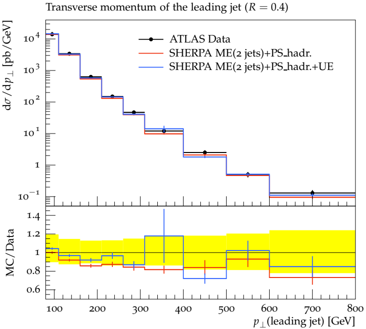


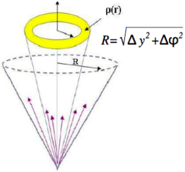
ATLAS, JHEP 1307 (2013) 032

- ALPGEN: LO with MLM merging
- SHERPA: LO with CKKW merging

Effect of underlying event

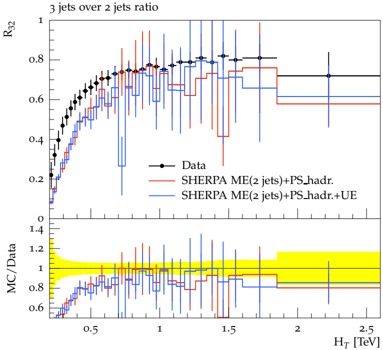


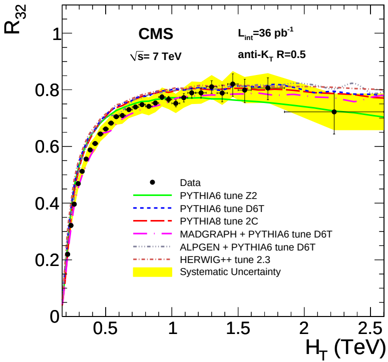




ATLAS, Phys. Rev. D 83 (2011) 052003 & Eur. Phys. J. C 71 (2011) 1763

Shower vs. matrix element

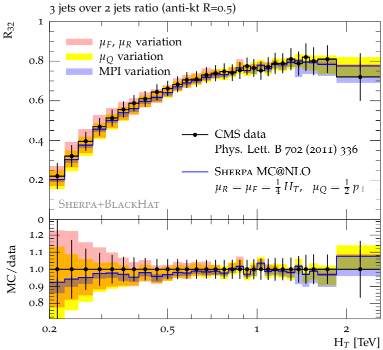


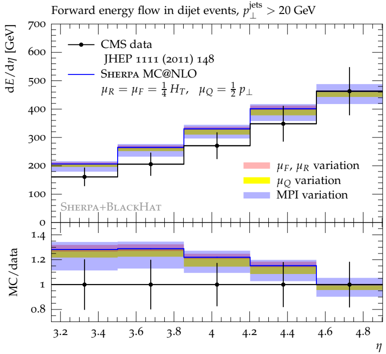


CMS, Phys. Lett. B 702 (2011) 336

- H_T: scalar sum of jet $p_\perp$'s
- jet $p_\perp > 50$ GeV

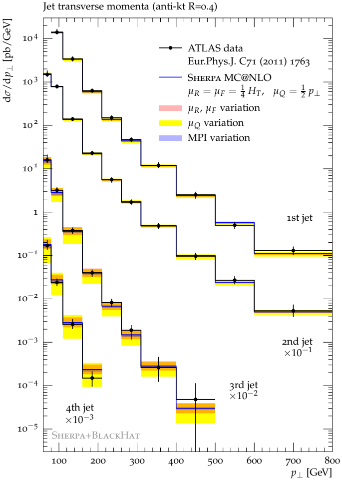
Theoretical uncertainties

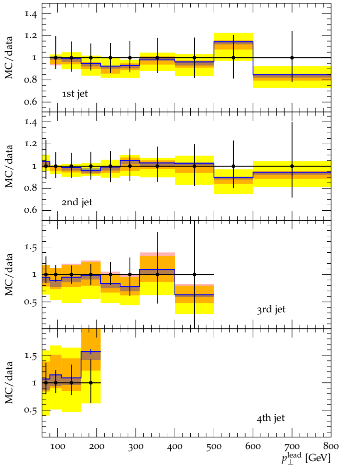




Hoeche, Schonherr, Phys. Rev. D 86 (2012) 094042

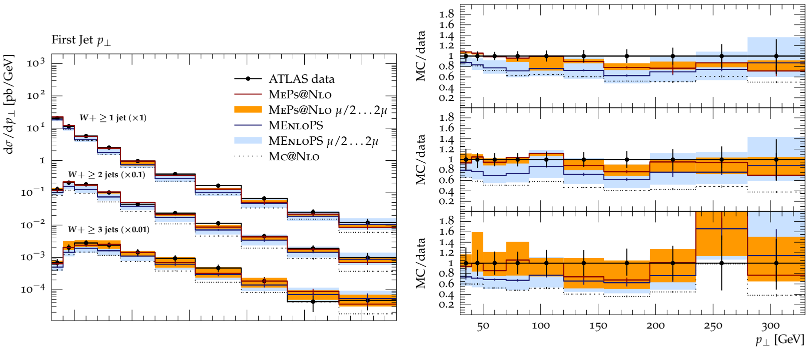
Theoretical uncertainties





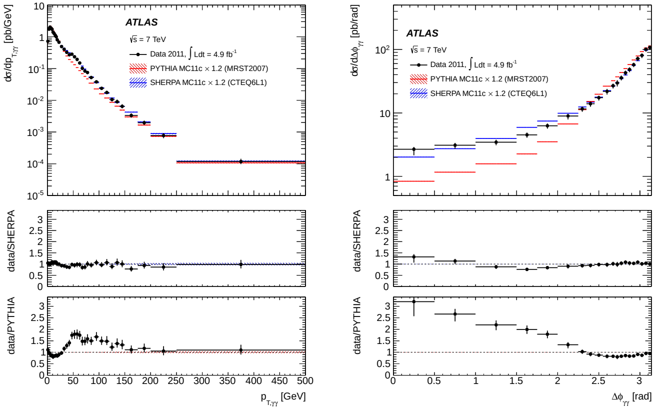
Hoeche, Schonherr, Phys. Rev. D 86 (2012) 094042

W+jets – NLO merging



Hoeche, Krauss, Schonherr, Siegert, JHEP 1304 (2013) 027

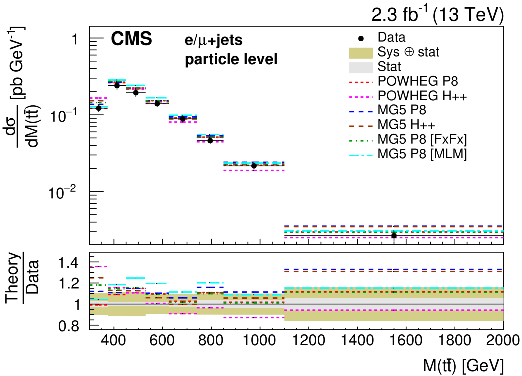
Diphotons



ATLAS, JHEP 1301 (2013) 086

- PYTHIA: di-photon ME + PS
- SHERPA: di-photon ME merged with up to 2 jets + PS

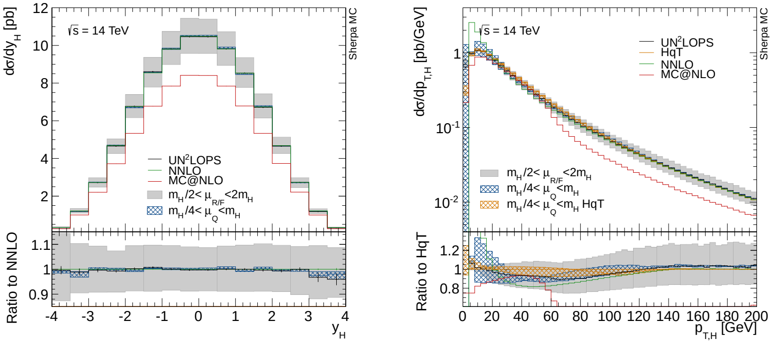
Top quark pairs



CMS, arXiv:1610.04191

MG5: MadGraph5_aMC@NLO (NLO matrix element generator including matching/merging); P8: PYTHIA8; H++: HERWIG++

Higgs – NNLO event generation



Höche, Li, Prestel, Phys. Rev. D **90** (2014) no.5, 054011

Outline

RIVET

http://rivet.hepforge.org

- HEP tool for analysing Monte Carlo events
- generator independent code due to “industry standard” for simulated events (HepMC)
- powerful library of predefined calculators (e.g. event shapes, jets, Z- finder,. . .)
- analyses are based on physical objects
  - final state hadrons
  - muons, electrons (dressed)
  - bosons reconstructed from particles
    rather than taken from event record
  - . . .
- allows for fair comparison with (unfolded) collider data

RIVET

- version 2.5 contains $\sim$ 350 Analyses (195 LHC)
- plugin system for new analyses
- lightweight histogramming (YODA), quite ok plotting
- exploration of BSM physics (UFO + Herwig7/Sherpa)

RIVET serves twofold purpose

- Monte Carlo validation and tuning
- data preservation

data are useless without detailed information about analysis

PROFESSOR

http://professor.hepforge.org

- phenomenological models in event generators have to be tuned to data
- many parameters $\rightarrow$ brute force doesn't work
- PROFESSOR procedure:
  1. random sampling: N parameter points in n-dimensional space
  2. run generator and fill histograms
  3. for each bin: use N points to fit interpolation (2$^{\text{nd}}$ or 3$^{\text{rd}}$ order polynomial)
  4. construct overall $\chi^2 \approx \sum_{\text{bins}} \frac{(\text{iterpolation} - \text{data})^2}{\text{error}^2}$
  5. numerically minimise

Other tools and standards

HepMC: generator independent event record for MC events

http://hepmc.web.cern.ch/hepmc/

LHAPDF: general purpose interpolator for evaluating PDFs from discretised data files, provides PDFs to MC generators

http://lhapdf.hepforge.org/

FASTJET: provides jet finding algorithms and related tools like taggers, used by RIVET http://www.fastjet.fr/

DELPHES/GEANT: detector simulation

http://cp3.irmp.ucl.ac.be/projects/delphes; http://geant4.web.cern.ch/geant4/

Binoth LHA/LHEF: standard for passing matrix element configurations between generators arXiv:1003.1643

PDG particle codes: system for numbering particles

many more . . .

Outline

Summary

- double counting has to be avoided when combining higher order matrix elements with each other and parton showers
- NLO ME + PS matching: POWHEG & MC@NLO
- merging of MEs of different multiplicity (combined with parton showers): different techniques available at LO and NLO

  MLM, CKKW(-L), MEPS@NLO, . . .
- MC event generators are controlled and quantitative tools
- MC generators essential for
  - interpretation of collider data
  - correction of detector effects
- additional tools are needed around generators, in particular RIVET for analysis and data preservation