TECHNISCHE UNIVERSITÄT DRESDEN

Fakultät Mathematik und Naturwissenschaften Institut für Kern- und Teilchenphysik

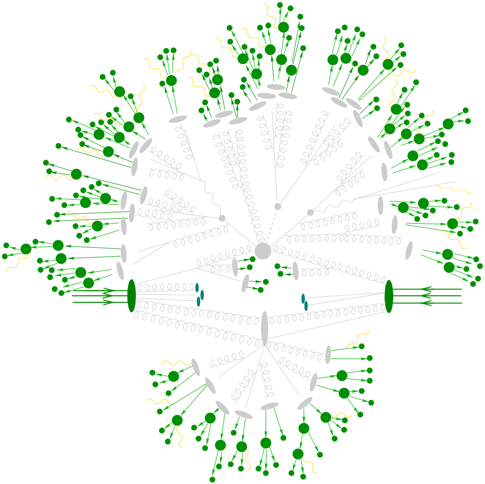
Modern event generation for the LHC

Features and caveats of the Sherpa event generator

Frank Siegert

Cavendish HEP Seminar, University of Cambridge, October 2015

Introduction: Monte-Carlo event generators



- We want:
  Simulation of $pp \to$ full hadronised final state
- MC event representation (e.g. $pp \to t\bar{t}H$ event)
- We know from first principles:
  - Hard scattering at fixed order in perturbation theory (**Matrix Element**)
  - Approximate resummation of QCD corrections to all orders (**Parton Shower**)
- Missing bits: Hadronisation/Underlying event (ignored today)

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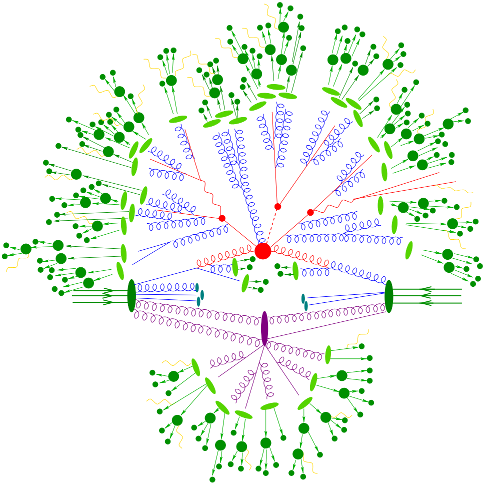

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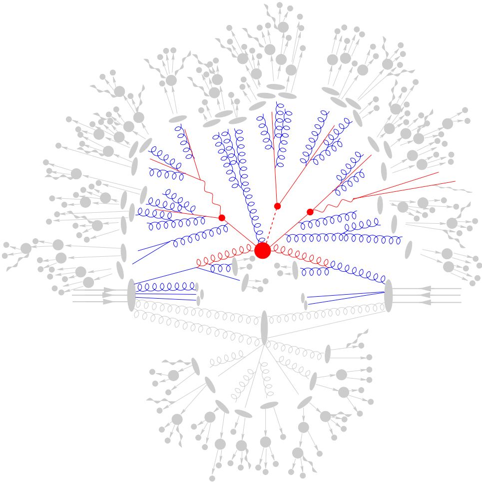

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Outline

- Introduction
- The parton shower approximation
- Correcting that approximation as far as possible:
  - NLO+PS matching (2002)
  - Tree-level ME+PS merging (2001)
  - ME+PS merging at NLO (2012)
- Practical considerations

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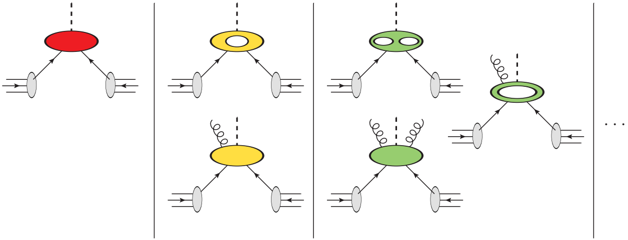
Perturbation Theory

- Cannot solve QCD and calculate $pp \to X$ exactly
- But can calculate parts of the perturbative series in α_s:



~ 1 ("LO") $\sim \alpha_s$ ("NLO") $\sim \alpha_s^2$ ("NNLO")

- Most precise calculations include $\mathcal{O}(\alpha_s^2)$ for some processes
- $\alpha_s^2 \approx 1\% \Rightarrow$ high enough precision, right?
- Why is that not always true?

From fixed order to resummation

- Predictions for inclusive observables calculable at fixed-order ($\rightsquigarrow$ KLN theorem for cancellation of infrared divergences)
- But if not inclusive $\to$ finite remainders of infrared divergences:

  logarithms of $\frac{\mu_{\text{cut}}^2}{\mu_{\text{hard}}^2}$ with each $\mathcal{O}(\alpha_s)$

  can become large and spoil convergence of perturbative series

  Examples:

  – Study certain regions of phase space, like $p_\perp^Z \approx 0$ @ DY
  – Making predictions for hadron-level final states: confinement at $\mu_{\text{had}} \approx 1$ GeV

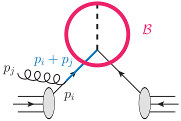
$\Rightarrow$ Need to resum the series to all orders

  – Problem: We are not smart enough for that.
  – Workaround: Resum only the logarithmically enhanced terms in the series

  $\to$ Parton Showers!

Construction of a parton shower

Universal structure at all orders



- Factorisation of QCD real emission for collinear partons (i,j):

$$\mathcal{R} \;\to\; \mathcal{D}_{ij}^{(\mathrm{PS})} \equiv \mathcal{B} \times \left[8\pi\alpha_s \, \frac{1}{2p_ip_j} \, \mathcal{K}_{ij}(p_i,p_j) \right]$$

- Factorisation of phase space element

$$\mathrm{d}\Phi_{\mathcal{R}} \;\to\; \mathrm{d}\Phi_{\mathcal{B}}\,\mathrm{d}\Phi_1 = \mathrm{d}\Phi_{\mathcal{B}}\;\mathrm{d}t\,\frac{1}{16\pi^2}\,\mathrm{d}z\,\frac{\mathrm{d}\phi}{2\pi}$$

with evolution variable $t \;\sim\; 2p_ip_j \;\sim\; \theta_{ij},\, k_\perp^{ij},\, Q_{ij}$

$\Rightarrow$ Differential branching probability: $\mathrm{d}\sigma_{ij}^{(\mathrm{PS})} \sim \mathrm{d}t\,\frac{\mathcal{D}_{ij}^{(\mathrm{PS})}}{\mathcal{B}} \sim \frac{\mathrm{d}t}{t}\,\frac{\alpha_s}{2\pi}\,\mathcal{K}_{ij}$

- $\mathrm{d}\sigma_{ij}^{(\mathrm{PS})}$ is universal and appears for each emission
- How do we get the resummed branching probability according to multiple such emissions?
  $\to$ Analogy to evolution of ensemble of radioactive nuclei:
  Survival probability at time t_1 depends on decay/survival at times $t < t_1$

Resummed branching probability

Radioactive decay

- Constant differential decay probability

$$f(t) = \text{const} \equiv \lambda$$

- Survival probability $\mathcal{N}(t)$

$$-\frac{\mathrm{d}\mathcal{N}}{\mathrm{d}t} = \lambda\,\mathcal{N}(t)$$

$$\Rightarrow \mathcal{N}(t) \sim \exp(-\lambda t)$$

- Resummed decay probability $\mathcal{P}(t)$

$$\mathcal{P}(t) = f(t)\,\mathcal{N}(t) \sim \lambda \exp(-\lambda t)$$

Parton shower branching

- Differential branching probability

$$f(t) \equiv \frac{\mathcal{D}_{ij}^{(\mathrm{PS})}}{\mathcal{B}}$$

- Survival probability $\mathcal{N}(t)$

$$-\frac{\mathrm{d}\mathcal{N}}{\mathrm{d}t} = f(t)\,\mathcal{N}(t)$$

$$\Rightarrow \mathcal{N}(t) \sim \exp\left(-\int_0^t \mathrm{d}t'\,f(t')\right)$$

- Resummed branching probability $\mathcal{P}(t)$

$$\mathcal{P}(t) = f(t)\,\mathcal{N}(t) \sim f(t)\exp\left(-\int_0^t \mathrm{d}t'\,f(t')\right)$$

Summary of main parton shower ingredients

- "Sudakov form factor" $\equiv$ Survival probability of parton ensemble:

$$\mathcal{N}(t) \sim \exp\left(-\int_0^t \mathrm{d}t'\, f(t')\right) \quad \rightarrow \quad \Delta(t',t'') = \prod_{\{ij\}} \exp\left(-\int_{t'}^{t''} \mathrm{d}t\, \frac{\mathcal{D}_{ij}^{(\mathrm{PS})}}{\mathcal{B}}\right)$$

- Evolution variable t: not time, but scale of collinearity from hard to soft
  $t \sim 2p_ip_j \sim$ e.g. angle θ, virtuality Q^2, relative transverse momentum $k_\perp^2$, ...
- Starting scale μ_Q^2 (time $t=0$ in radioactive decay) defined by hard scattering
- Cutoff scale related to hadronisation scale $t_0 \sim \mu_{\mathrm{had}}^2$
- Other variables (z, ϕ) generated directly according to $\mathrm{d}\sigma_{ij}^{(\mathrm{PS})}(t,z,\phi)$

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$\Rightarrow$ Differential cross section (up to first emission)

$$\mathrm{d}\sigma^{(\mathrm{B})} = \mathrm{d}\Phi_B \, \mathcal{B}$$

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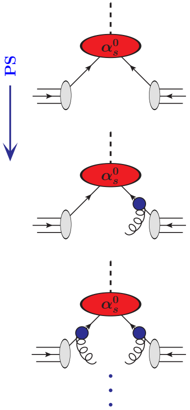
Example: pp $\to$ h+jets



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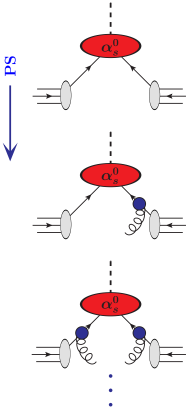

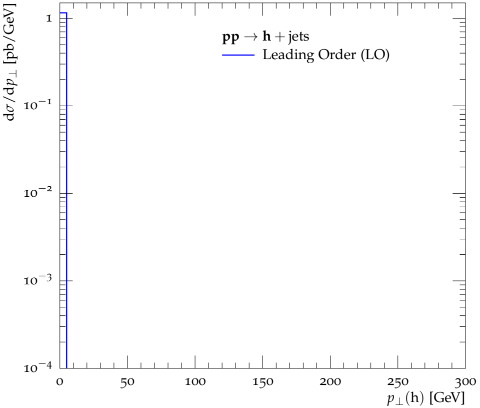

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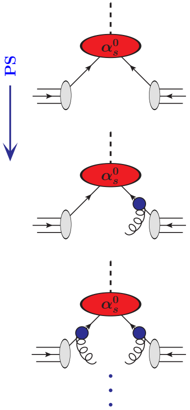

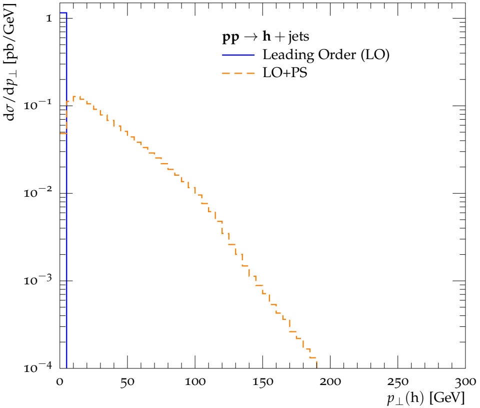

Parton shower improvements

Parton shower improvements: Classification

NLO+PS matching

- Parton shower on top of NLO prediction (e.g. inclusive W production)
- Objectives:
  - avoid double counting in real emission
  - preserve inclusive NLO accuracy

ME+PS@LO merging

- Multiple LO+PS simulations for processes of different jet multi (e.g. W, Wj, Wjj, . . .)
- Objectives:
  - combine into one inclusive sample by making them exclusive
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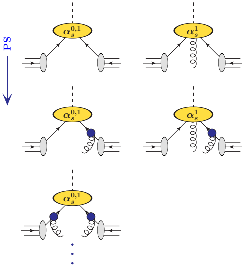
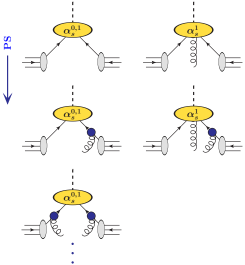


Basic idea

- "double-counting" between emission in real ME and parton shower for first emission
- ME is better than PS → subtract PS contribution first
- but: shower unitary → re-add "integrated" PS contribution with Born kinematics

NLO+PS matching in a nutshell



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Subtlety: NLO already contains subtraction

$$\mathrm{d}\sigma^{(\mathrm{NLO})} = \mathrm{d}\Phi_B \left[\mathcal{B} + \tilde{\mathcal{V}} + \sum_{\{ij\}} \mathcal{I}^{(\mathrm{S})}_{(ij)} \right] + \mathrm{d}\Phi_R \left[\mathcal{R} - \sum_{\{ij\}} \mathcal{D}^{(\mathrm{S})}_{ij} \right]$$

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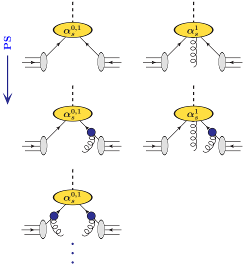

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Additional subtraction

- introduce additional (shower) subtraction terms $\mathcal{D}^{(\mathrm{A})}_{ij}$

$$\mathrm{d}\sigma^{(\mathrm{NLO\ sub})} = \mathrm{d}\Phi_B\ \bar{\mathcal{B}}^{(\mathrm{A})} + \mathrm{d}\Phi_R \left[\mathcal{R} - \sum_{\{ij\}} \mathcal{D}^{(\mathrm{A})}_{ij} \right]$$

$$\text{with } \bar{\mathcal{B}}^{(\mathrm{A})} = \mathcal{B} + \tilde{\mathcal{V}} + \sum_{\{ij\}} \mathcal{I}^{(\mathrm{S})}_{(ij)} + \sum_{\{ij\}} \int \mathrm{d}t \left[\mathcal{D}^{(\mathrm{A})}_{ij} - \mathcal{D}^{(\mathrm{S})}_{ij} \right]$$

- now apply PS resummation using $\mathcal{D}^{(\mathrm{A})}_{ij}$ as splitting kernels

Frixione, Webber (2002)

Master formula for NLO+PS up to first emission

$$\mathrm{d}\sigma^{(\mathrm{NLO+PS})} = \mathrm{d}\Phi_B\, \bar{\mathcal{B}}^{(\mathrm{A})} \left[\underbrace{\Delta^{(\mathrm{A})}(t_0, \mu_Q^2)}_{\text{unresolved}} + \underbrace{\sum_{\{ij\}} \int_{t_0}^{\mu_Q^2} \mathrm{d}t\, \frac{\mathcal{D}_{ij}^{(\mathrm{A})}}{\mathcal{B}} \Delta^{(\mathrm{A})}(t, \mu_Q^2)}_{\text{resolved, singular}} \right]$$

$$+ \; \mathrm{d}\Phi_R \underbrace{\left[\mathcal{R} - \sum_{\{ij\}} \mathcal{D}_{ij}^{(\mathrm{A})} \right]}_{\text{resolved, non-singular} \equiv \mathcal{H}^{(\mathrm{A})}}$$

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$$+ \;\mathrm{d}\Phi_R \underbrace{\Bigg[\mathcal{R} - \sum_{\{ij\}} \mathcal{D}_{ij}^{(\mathrm{A})} \Bigg]}_{\text{resolved, non-singular} \equiv \mathcal{H}^{(\mathrm{A})}}$$

- To $\mathcal{O}(\alpha_s)$ this reproduces $\mathrm{d}\sigma^{(\mathrm{NLO})}$
- Exact choice of $\mathcal{D}_{ij}^{(\mathrm{A})}$ distinguishes MC@NLO vs. POWHEG vs. S-MC@NLO vs. ...
- Resolved cases: Subsequent emissions can be generated by ordinary PS

Special cases: MC@NLO vs. S-MC@NLO

MC@NLO

Frixione, Webber (2002)

$\mathcal{D}^{(\mathrm{A})} = \mathcal{D}^{(\mathrm{PS})} =$ **PS splitting kernels**

- \+ Shower algorithm for Born-like events easy to implement
- – "Non-singular" piece $\mathcal{R} - \sum_{ij} \mathcal{D}_{ij}^{(\mathrm{A})}$ is actually singular:
  - – Collinear divergences subtracted by splitting kernels ✓
  - – Remaining soft divergences as they appear in non-trivial processes at sub-leading N_c ✗

Workaround: $\mathcal{G}$-function dampens soft limit in non-singular piece
$\Leftrightarrow$ Loss of formal NLO accuracy
but heuristically shown to be negligible

S-MC@NLO

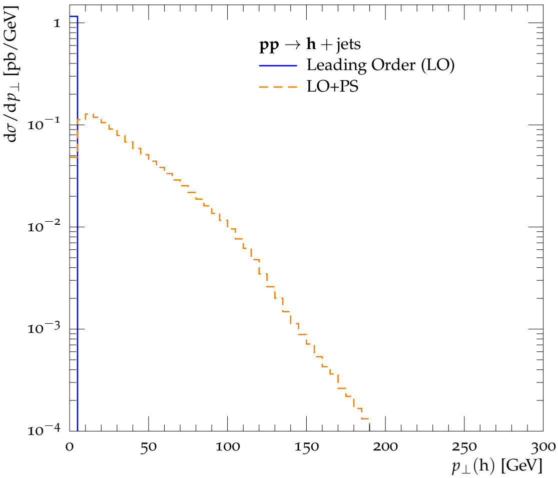
Höche, Krauss, Schönherr, FS (2011)

$\mathcal{D}^{(\mathrm{A})} = \mathcal{D}^{(\mathrm{S})} =$ **Subtraction terms**

- \+ "Non-singular" piece fully free of divergences
- – Splitting kernels in shower algorithm become negative

Solution: Weighted $N_C = 3$ one-step PS based on subtraction terms
$\Downarrow$
Used in SHERPA

Example: pp $\to$ h+jets



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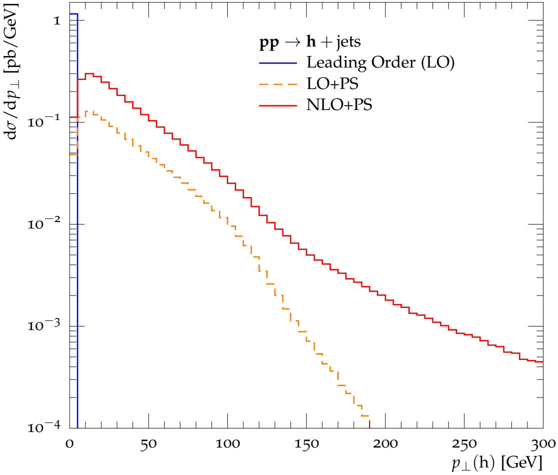

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NLO+PS matching

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ME+PS@LO merging

- Multiple LO+PS simulations for processes of different jet multi (e.g. W, Wj, Wjj, ...)
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Main idea

Catani, Krauss, Kuhn, Webber (2001)

Phase space slicing for QCD radiation in shower evolution

- Soft/collinear emissions $Q_{ij}(z,t) < Q_{\text{cut}}$

  $\Rightarrow$ Retained from parton shower $\quad \mathcal{D}_{ij}^{(\text{PS})} = \mathcal{B} \times \left[8\pi\alpha_s \, \frac{1}{2p_ip_j} \, \mathcal{K}_{ij}(p_i, p_j) \right]$

- Hard emissions $Q_{ij}(z,t) > Q_{\text{cut}}$
  - Events rejected $\rightsquigarrow$ Sudakov suppression
  - Compensated by events starting from higher-order ME regularised by Q_{cut}

  $\Rightarrow$ Splitting kernels replaced by exact real-emission matrix elements

$$\mathcal{D}_{ij}^{(\text{PS})} \quad \to \quad \mathcal{R}_{ij}$$

(But Sudakov form factors $\Delta^{(\text{PS})}$ remain unchanged)

Cross section up to first emission in ME+PS

$$\mathrm{d}\sigma = \mathrm{d}\Phi_B \, \mathcal{B} \Bigg[\underbrace{\Delta^{(\text{PS})}(t_0, \mu_Q^2)}_{\text{unresolved}} + \sum_{\{ij\}} \int_{t_0}^{\mu_Q^2} \mathrm{d}t \, \Delta^{(\text{PS})}(t, \mu^2) \times \Bigg(\underbrace{\frac{\mathcal{D}_{ij}^{(\text{PS})}}{\mathcal{B}} \, \Theta(Q_{\text{cut}} - Q_{ij})}_{\text{resolved, PS domain}} + \underbrace{\frac{\mathcal{R}_{ij}}{\mathcal{B}} \, \Theta(Q_{ij} - Q_{\text{cut}})}_{\text{resolved, ME domain}} \Bigg) \Bigg]$$

Translate ME event into shower language

Embedding existing emissions into PS evolution

- Preserve resummation features (logarithmic accuracy)
- Determine starting scales t for PS evolution

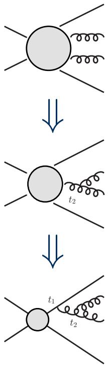
$\Rightarrow$ Shower picture of ME event needed!

Problem: ME only gives final state, no history

Solution: Backward-clustering (running the shower reversed), similar to jet algorithm:

1. Select last splitting according to shower probablities
2. Recombine partons using inverted shower kinematics $\rightarrow$ N-1 particles + splitting variables for one node
3. Reweight $\alpha_s(\mu^2) \rightarrow \alpha_s(p_\perp^2)$
4. Repeat 1 - 3 until core process ($2 \rightarrow 2$)

Example:



Truncated shower

- Shower each (external and intermediate!) line between determined scales
- “Boundary” scales: resummation scale μ_Q^2 and shower cut-off t_0

Features and shortcomings by example

Example

Diphoton production at Tevatron

- Measured by CDF Phys.Rev.Lett. 110 (2013) 101801
- Isolated hard photons
- Azimuthal angle between the diphoton pair

ME+PS simulation using SHERPA

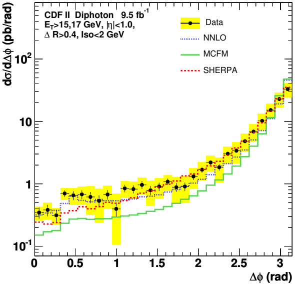
Höche, Schumann, FS (2009)

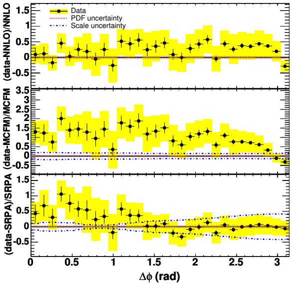
Conclusions

Shapes described very well even for this non-trivial process/observable for both:

- Hard region, e.g. $\Delta\Phi_{\gamma\gamma} \to 0$
- Soft region, e.g. $\Delta\Phi_{\gamma\gamma} \to \pi$

Scale variations high $\Rightarrow$ NLO needed





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  - combine into one inclusive sample
  - preserve NLO accuracy for jet observables

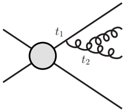
Concepts continued from ME+PS merging at LO

- For each event select jet multiplicity k according to its inclusive NLO cross section
- Reconstruct branching history and nodal scales $t_0 \dots t_k$
- Truncated vetoed parton shower, but with peculiarities (cf. below)

Differences for NLO merging

- For each event select type ($\mathbb{S}$ or $\mathbb{H}$) according to absolute XS
  $\Rightarrow$ Shower then runs differently
- $\mathbb{S}$ event:
  1. Generate MC@NLO emission at t_{k+1}
  2. Truncated "NLO-vetoed" shower between t_0 and t_k:
     First hard emission is only ignored, no event veto
  3. Continue with vetoed parton shower
- $\mathbb{H}$ event:
  (Truncated) vetoed parton shower as in tree-level ME+PS

Example: $k = 1$

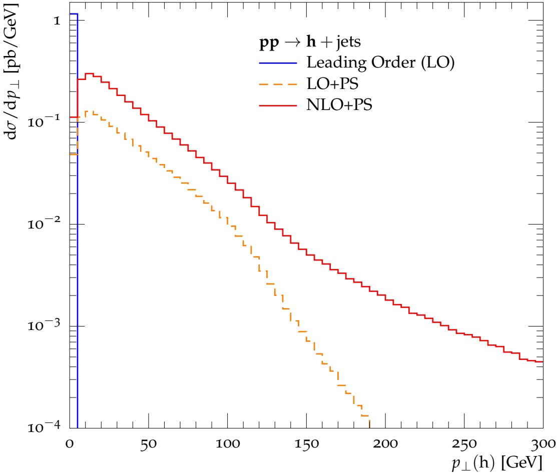


Master formula

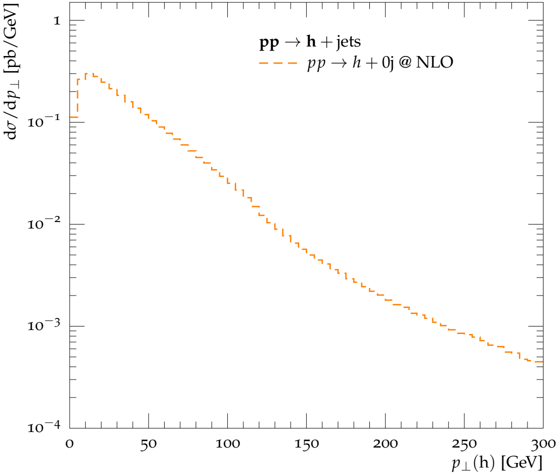
ME+PS@NLO prediction for combining NLO+PS samples of multiplicities n and $n+1$

$$
\begin{aligned}
d\sigma \;=\; & d\Phi_n\, \bar{\mathrm{B}}_n^{(\mathrm{A})} \left[\Delta_n^{(\mathrm{A})}(t_c, \mu_Q^2) + \int_{t_c}^{\mu_Q^2} d\Phi_1\, \frac{\mathrm{D}_n^{(\mathrm{A})}}{\mathrm{B}_n}\, \Delta_n^{(\mathrm{A})}(t_{n+1}, \mu_Q^2)\, \Theta(Q_{\mathrm{cut}} - Q_{n+1}) \right] \\
& + d\Phi_{n+1}\, \mathrm{H}_n^{(\mathrm{A})}\, \Delta_n^{(\mathrm{PS})}(t_{n+1}, \mu_Q^2)\, \Theta(Q_{\mathrm{cut}} - Q_{n+1}) \\
& + d\Phi_{n+1}\, \bar{\mathrm{B}}_{n+1}^{(\mathrm{A})} \underbrace{\left(1 + \frac{\mathrm{B}_{n+1}}{\bar{\mathrm{B}}_{n+1}^{(\mathrm{A})}} \int_{t_{n+1}}^{\mu_Q^2} d\Phi_1\, \mathrm{K}_n \right)}_{\text{MC counterterm} \,\to\, \text{NLO-vetoed shower}} \Delta_n^{(\mathrm{PS})}(t_{n+1}, \mu_Q^2)\, \Theta(Q_{n+1} - Q_{\mathrm{cut}}) \\
& \qquad \times \left[\Delta_{n+1}^{(\mathrm{A})}(t_c, t_{n+1}) + \int_{t_c}^{t_{n+1}} d\Phi_1\, \frac{\mathrm{D}_{n+1}^{(\mathrm{A})}}{\mathrm{B}_{n+1}}\, \Delta_{n+1}^{(\mathrm{A})}(t_{n+2}, t_{n+1}) \right] \\
& + d\Phi_{n+2}\, \mathrm{H}_{n+1}^{(\mathrm{A})}\, \Delta_{n+1}^{(\mathrm{PS})}(t_{n+2}, t_{n+1})\, \Delta_n^{(\mathrm{PS})}(t_{n+1}, \mu_Q^2)\, \Theta(Q_{n+1} - Q_{\mathrm{cut}}) \; + \; \ldots
\end{aligned}
$$

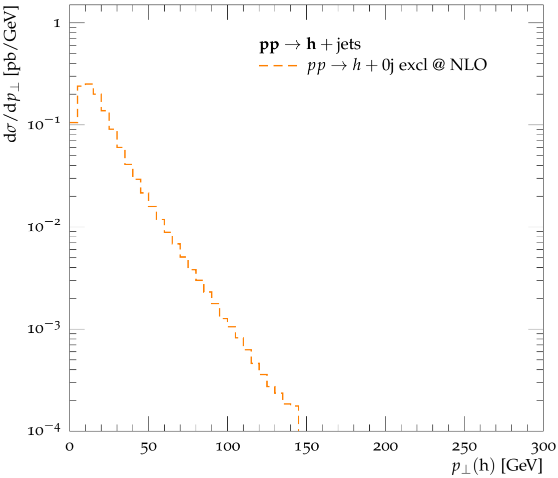
Example: pp $\rightarrow$ h+jets



Example: pp $\rightarrow$ h+jets



Example: pp $\to$ h+jets



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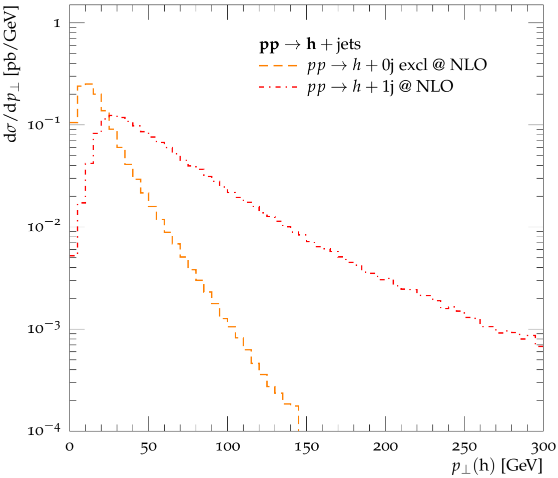
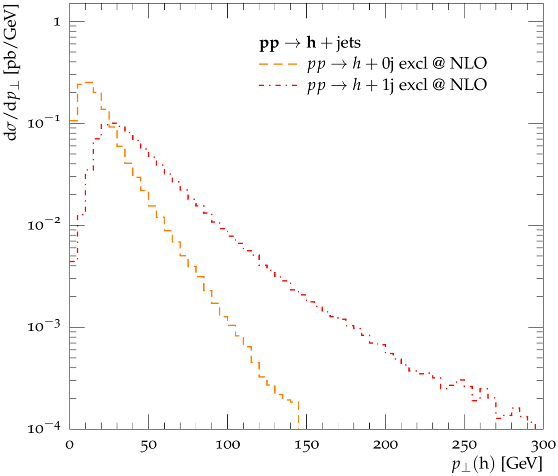
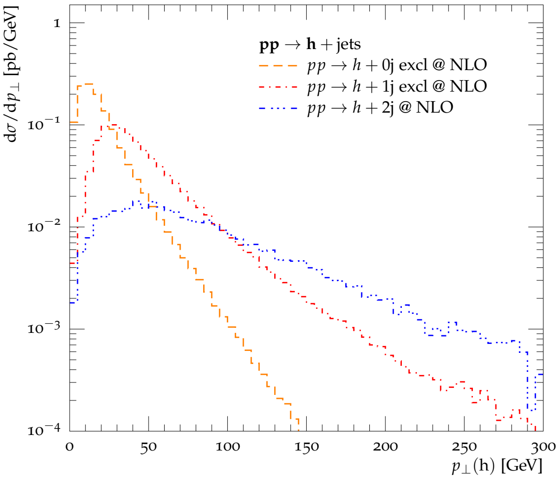


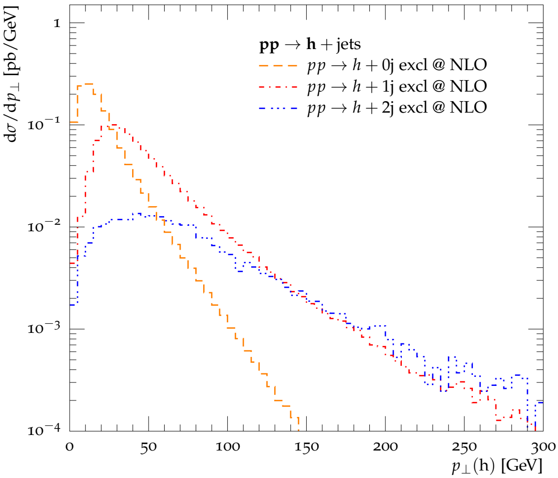
Example: pp $\to$ h+jets



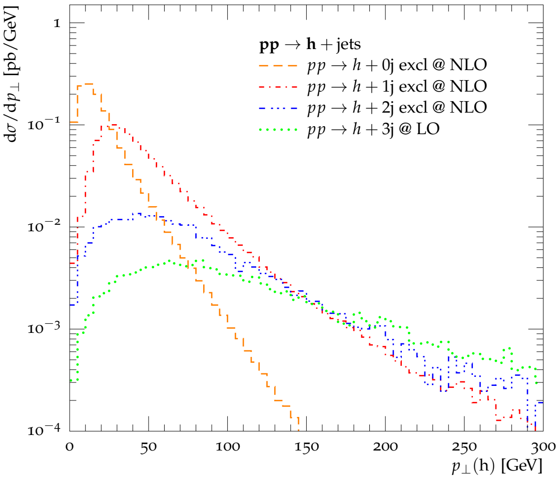
Example: pp $\rightarrow$ h+jets



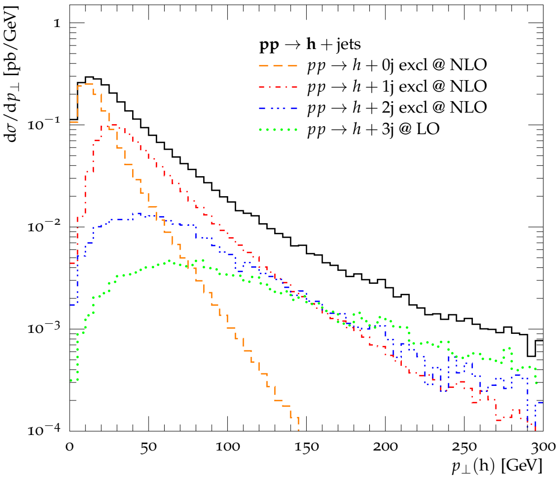
Example: pp $\to$ h+jets



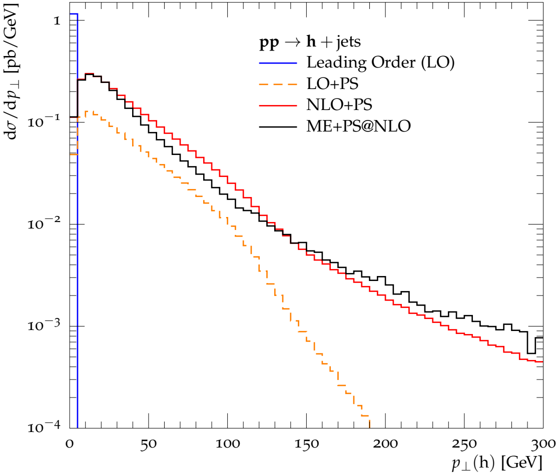
Example: pp $\to$ h+jets



Example: pp $\rightarrow$ h+jets

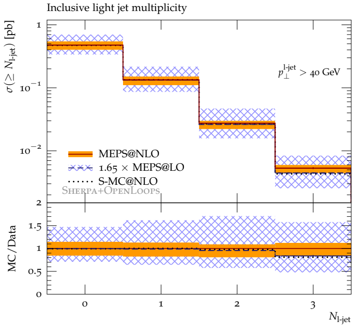


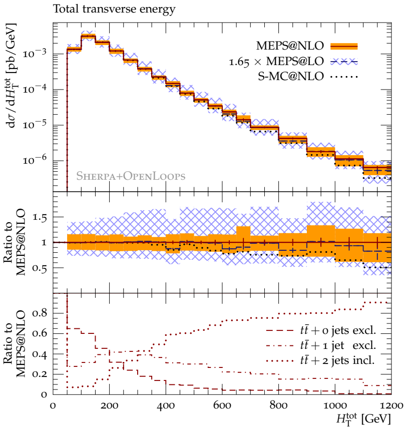
Example: pp $\to$ h+jets



Real world example: $t\bar{t}$ production

Höche, Krauss, Maierhöfer, Pozzorini, Schönherr, FS (2014)





- Uncertainty reduction from 79% to 19% in 2-jet bin
- Important BSM search selection: high total transverse energy
  → major reduction of theoretical uncertainties compared to tree-level merging

Practical considerations

Perturbative uncertainties

- Unknown higher-order corrections
- Estimated by scale variations
  $\mu_F = \mu_R = \frac{1}{2}\mu \ldots 2\mu$

Non-perturbative uncertainties

- Model uncertainties in hadronisation, hadron decays, multiple parton interactions, parton shower (evolution variable, kinematics reshuffling, infrared cut-offs)
- Estimated by variation of parameters/models within tuned ranges

Matching/merging uncertainties

- Arbitrariness of $\mathcal{D}^{(\mathrm{A})}$ and thus of the exponent in $\Delta^{(\mathrm{A})}$
  - Estimated by:
    - Variations of μ_Q^2 in MC@NLO
    - (Variation of $\mathcal{R}^r$ in POWHEG)
  - Reduced by merging with higher parton multiplicities
- Choice of merging cut

Scale vs. core scale

- Multi-jet matrix elements embedded into parton shower evolution
  $\Rightarrow$ Extra emissions should be evaluated with same $\alpha_s(p_\perp^{ij})$
- Remaining freedom: core process scales μ_R, μ_F

Global scale setting

(`SCALES` parameter)

- For multi-jet merged samples the `METS` setter has to be used to implement the above
- For simpler fixed-order or (N)LO+PS samples without merging:
  - `VAR` scale setter for arbitrary functions of parton level momenta
  - `FASTJET` scale setter to use jet momenta
  - custom definition by writing C++ code

Core process scale

(`CORE_SCALE` parameter)

- For use with the `METS` global scale setter
- Different options to define the core scale:
  - `VAR` core scale setter for arbitrary functions of parton level momenta
  - `DEFAULT` core scale setter for automatically taking into account type of core process (cf. next slide)

Core process in merged samples

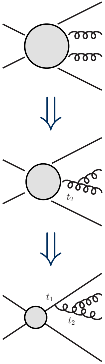
- Multi-jet merging based on core process + up to n partons
- Core process defined by user $\rightarrow$ unambigious?
  $\rightarrow$ two options to translate ME events into shower language:

"Exclusive" merging

(EXCLUSIVE_CLUSTER_MODE=1)

- Emission history identified by QCD clustering only
  $\Rightarrow$ core process as defined by user
- Most straightforward way of a shower history
- If core process contains partons, e.g. in electroweak V+2-jets production:
  parton level cuts for "core" jets necessary
- What if the event looks more like hard QCD with softer EW attached?

Example:



Core process in merged samples

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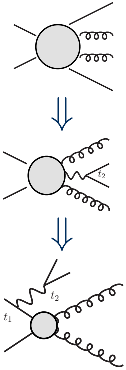
  $\rightarrow$ two options to translate ME events into shower language:

Example:



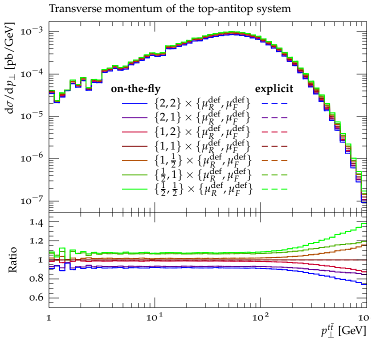
“Inclusive” merging

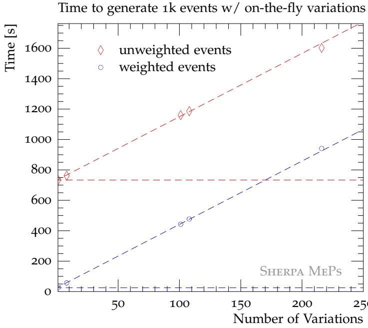
(EXCLUSIVE_CLUSTER_MODE=0)

- Allow EW clusterings in emission history
  $\Rightarrow$ can end up with different core process
- This core process is then also used to define the core scales (e.g. factorisation scale)

On-the-fly perturbative variations

- Dedicated scale/PDF variation runs expensive, unfeasible for PDF4LHC prescription
- Instead: simultaneously keep track of variations in ME by multiple event weights
- Available since Sherpa 2.2.0 for fixed-order, S-Mc@Nlo and ME+PS@LO simulations
- Upcoming in next release for ME+PS@NLO as well





- Closure compared to variation in dedicated runs for $pp \to ttW$ with S-Mc@Nlo
- Mainly useful for expensive MEs and unweighted events

Functional form $Q_{ij}(z,t)$

ME+PS separation determined by “jet criterion” $Q_{ij}(z,t) > Q_{\text{cut}}$

- Has to identify soft/collinear divergences in MEs, like jet algorithm
- Otherwise arbitrary functional form

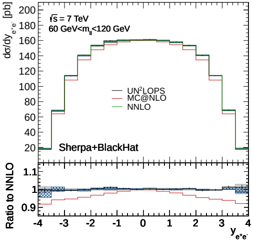
Cut value Q_{cut}

- If the merging prescription works well: ME region is supplemented consistently with resummation
  $\Rightarrow$ merging cut can be chosen arbitrarily low
- Disadvantages of very low merging cuts:
  - higher proportion of multi-parton MEs $\Rightarrow$ CPU time increases
  - MEs less stable, integration converges more slowly

  $\Rightarrow$ Typically compromise between physics and costs: merging cut softer than typical jet criterion in analysis (e.g. $p_\perp > 20\,\text{GeV}$)
- Careful with extreme phase space regions (e.g. very forward jets)!
- Dynamical definition of merging cuts for special circumstances, e.g. in photon production to capture fragmentation component

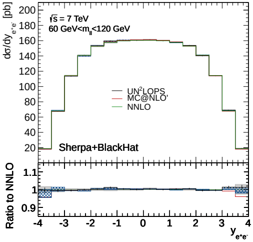
Consistent PDF and α_S usage

- Sherpa uses the same PDF and corresponding α_S parametrisation everywhere:
  MEs, parton shower, MPI, ...
- This implies that varying the PDF also changes the parton shower and MPI behaviour
- Since recently using NNLO PDF as default
  - PDF fits sensitive to shapes,
    ME+PS merging captures N(N(...))LO shapes
  - Some inclusive processes benefit significantly from usage of more reliable NNLO PDF



Tuning

- Tuning is done with a given PDF, e.g. default in Sherpa 2.2 is NNPDF 3.0 NNLO
- Should one change the full tune when using different PDFs (double counting of systematic uncertainties)?
  (irrelevant for on-the-fly PDF variation, since that is only available for MEs)



Negative weights

- NLO-matched simulations $\Rightarrow$ negative weight events from subtraction terms and $N_C = 3$ shower
- Fraction of negative weights can vary
  - $r =$ few % for simple processes
  - $r = 20 - 30\%$ for complex ones

$\Rightarrow$ effective statistical uncertainty increased by factor $\frac{1}{1-2r}$

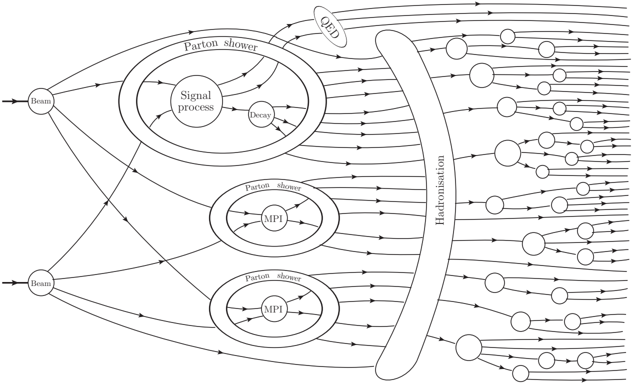
Weight distributions

- Unweighted events would ideally have weights reduced to ± 1
- There are a few additional weights which can not be removed by unweighting
  - "Overweight" events: phase space point yields ME value larger than the maximum found during integration
  - $N_C = 3$ shower weights
  - "local K-factor" for LO multiplicities on top of NLO

$\Rightarrow$ (steeply falling) weight distribution around ± 1

Experimentalists worries: Event record

- Experiment software prefers tree-like event records with straightened mother-daughter relations
- This is not necessarily the case in Sherpa:



- Dipole-like parton showers imply there is no distinction between ISR and FSR
  $\Rightarrow$ Parton shower "blob" can lead to particle "loops"
- (New option in Sherpa 2.2 removes the inside of shower blobs to give straight event record)

Conclusions

NLO+PS matching

- Parton shower on top of NLO prediction (e.g. inclusive W production)
- Objectives: ✓
  - avoid double counting in real emission
  - preserve inclusive NLO accuracy

ME+PS@LO merging

- Multiple LO+PS simulations for processes of different jet multi (e.g. W, Wj, Wjj, ...)
- Objectives: ✓
  - combine into one inclusive sample by making them exclusive
  - preserve resummation accuracy

$\Downarrow$ $\Downarrow$

Combination: ME+PS@NLO

- Multiple NLO+PS simulations for processes of different jet multiplicity e.g. W, Wj, Wjj, ...
- Objectives: ✓ ✓
  - combine into one inclusive sample
  - preserve NLO accuracy for jet observables

Outlook

- Skipped today: NNLO+PS matching in Sherpa Höche, Li, Prestel (2014)

$\Rightarrow$ Perturbative accuracy covered with new approaches in recent years

- Big effort on bringing the improvements into full production within experiments
  - Experimental validation
  - Feasibility for (unweighted) event generation with highest accuracies
  - User support for new practical issues
- Future focus on improvement of resummation accuracy in parton showers

Backup

Original POWHEG

- Choose additional subtraction terms as

$$\mathcal{D}_{ij}^{(\mathrm{A})} \to \rho_{ij}\,\mathcal{R} \qquad \text{where} \qquad \rho_{ij} = \frac{\mathcal{D}_{ij}^{(\mathrm{S})}}{\sum_{mn} \mathcal{D}_{mn}^{(\mathrm{S})}}$$

- $\mathcal{H}$-term vanishes $\Rightarrow$ No negative weighted events
- Similar to PS with ME-correction for 1st emission (e.g. Herwig, Pythia)

Mixed scheme

- Subtract arbitrary regular piece from $\mathcal{R}$ and generate separately as $\mathbb{H}$-events

$$\mathcal{D}_{ij}^{(\mathrm{A})}(\Phi_R) \to \rho_{ij}(\Phi_R)\ \left[\mathcal{R}(\Phi_R) - \mathcal{R}^r(\Phi_R)\right] \qquad \text{where} \qquad \rho_{ij} \text{ as above}$$

- Tuning of $\mathcal{R}^r$ to reduce exponentiation of arbitrary terms
- Allows to generate the non-singular cases of $\mathcal{R}$ without underlying $\mathcal{B}$