Hadronic final states in DIS with SHERPA

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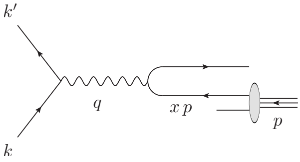
Leading order $e^{\pm}p$ - scattering in collinear factorisation Breit frame

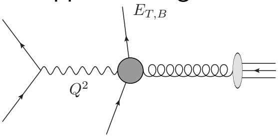
- **There are no jets !**
- Kinematic variables

$$Q^2 = q^2 = (k' - k)^2 \text{ and } x = \frac{Q^2}{2\,q \cdot p}$$

- Hadronic cm energy $W = Q\sqrt{(1-x)/x}$



What happens at higher orders ?



- **Multiple kinematical scales**
  e.g. Q^2 and $E^2_{T,B}$
- $e^{\pm}q \to e^{\pm}q$ if $E^2_{T,B} \lesssim Q^2$
  $\gamma^* g \to jets$ if $Q^2 \lesssim E^2_{T,B}$

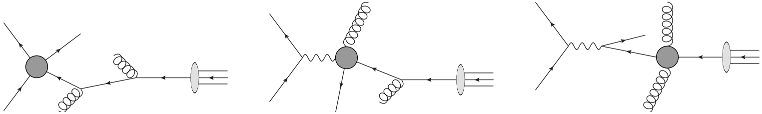
What makes DIS any different from $e^+e^- \to jets$ and $pp \to e^+e^-$?

The virtuality of the exchanged photon tends to be close to zero !

N.B. This is also the case in the Drell-Yan process $pp \to e^+e^-$,
but recent experimental studies usually focus on $m_{l\bar{l}} \approx m_Z$

Hadronic final states in DIS: A problem ?

More jets, more scales, more ambiguities ...

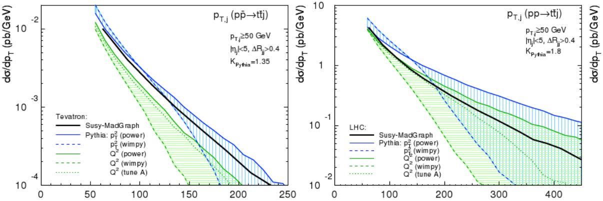


Problems with DIS event simulation in parton-shower Monte Carlos

- Leading-order process does not define sensible scale for jets, but
- Factorisation dictates "inclusive" scale Q^2 to maintain total cross section
- Higer-order corrections usually large due to large phase space ($\propto W^2$)

Well-known problem in the context of Drell-Yan lepton-pair and heavy resonances production at hadron colliders

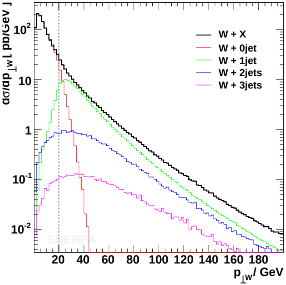
e.g. $t\bar{t} + jets$ hep-ph/0511306



Basic idea: **Separate phasespace into "hard" and "soft" region**

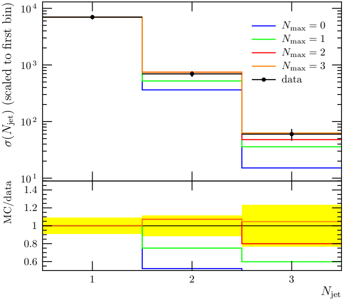
- Matrix elements populate hard domain
- Parton shower populates soft domain

$\longleftrightarrow$



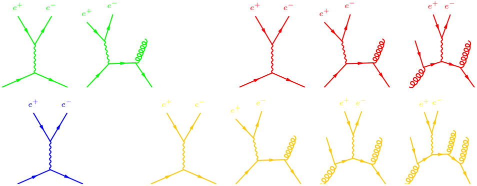
need criterion to define "hard" & "soft" as above and below a certain cut value

$\longrightarrow$ **Jet criterion** Q e.g. k_T-jet measure



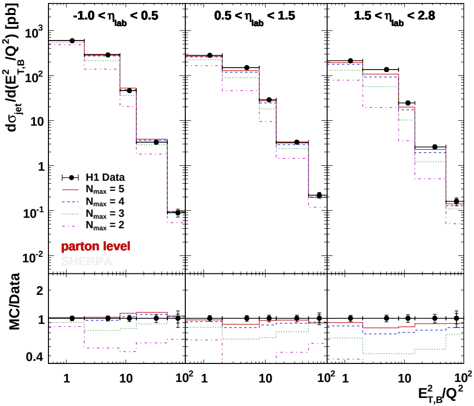
Example: $pp \longrightarrow e^+e^- + jets$ JHEP05(2009)053

Jet rates and -spectra improve over pure PS sim



ME & PS results: Inclusive jets in DIS PLB542(2002)193

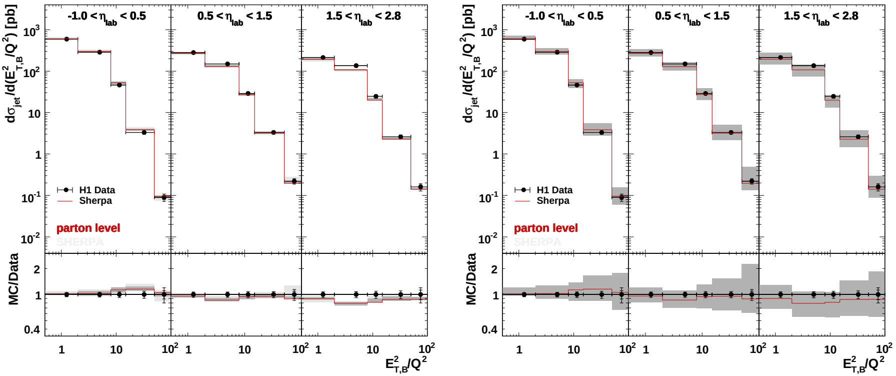
Variation of maximum matrix-element multiplicity, $N_{\max}$ [2]



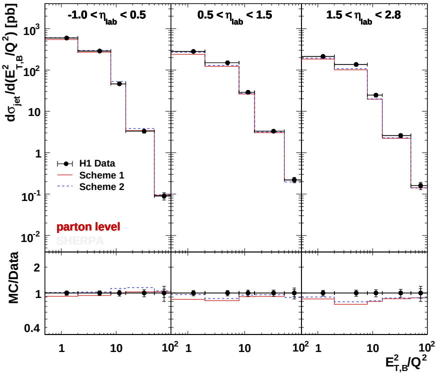
[2] SHERPA ⊕ HZTool from arXiv:0912.3715 [hep-ph]

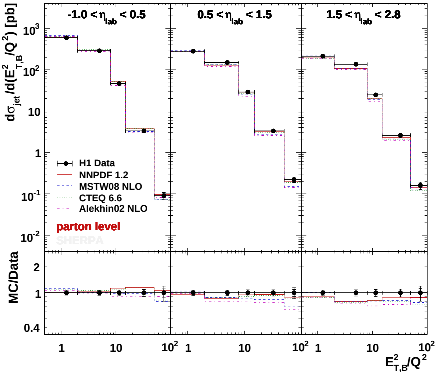
ME & PS results: Inclusive jets in DIS PLB542(2002)193

Variation of merging parameters and factorisation/renormalisation scales



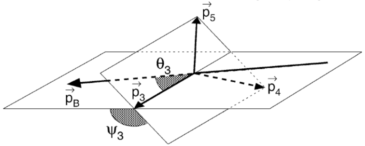
Variation of parton shower recoil kinematics [3] and PDF set



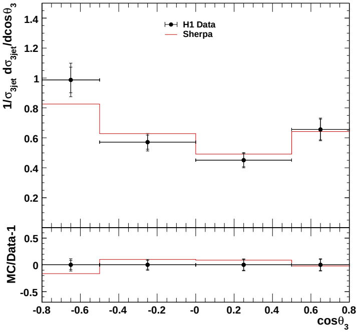


[3] see PRD81(2010)034026

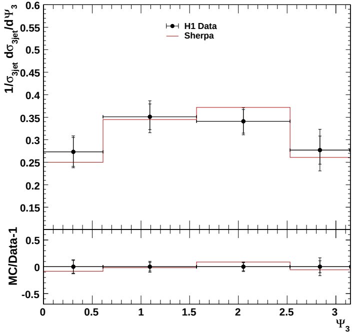
ME & PS results: Inclusive trijets in DIS PLB515(2001)17

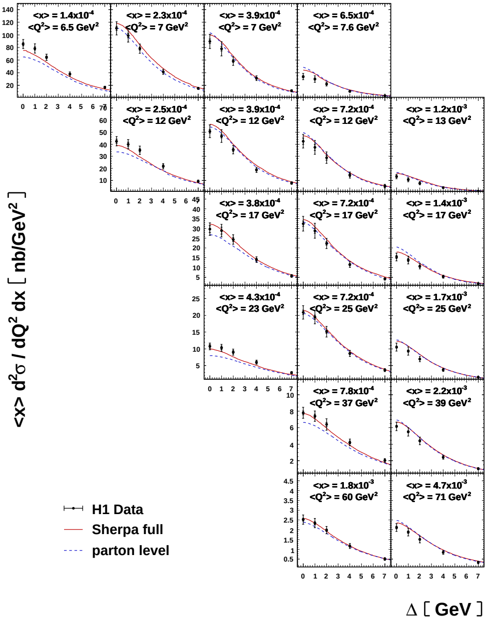


$\cos\theta_3$ $Q^2 > 150$ GeV^2



Ψ_3 $Q^2 > 150$ GeV^2



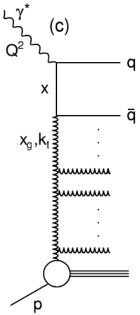


Δ in bins of $\langle x \rangle$ and $\langle Q^2 \rangle$

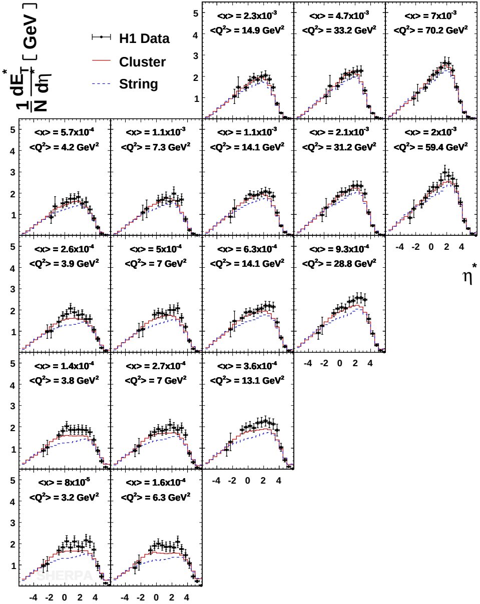
Δ defined as $E^*_{T,\mathrm{max}} > E^*_{T\,\mathrm{cut}} + \Delta$

$E^*_{T\,\mathrm{cut}} \rightarrow$ minimum jet transverse energy

$E^*_{T\,\mathrm{max}} \rightarrow$ transverse energy of hardest jet

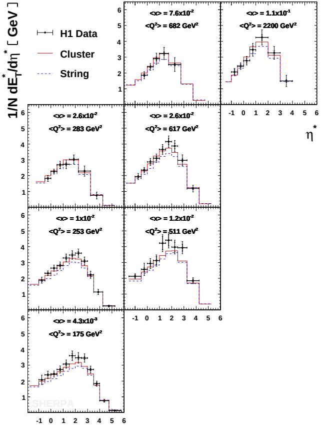


Hadron level results: Energy flow analysis EPJC12(2000)595



Transverse energy flow

SHERPA cluster fragmentation
vs. Lund string fragmentation



Summary

Things already done ...

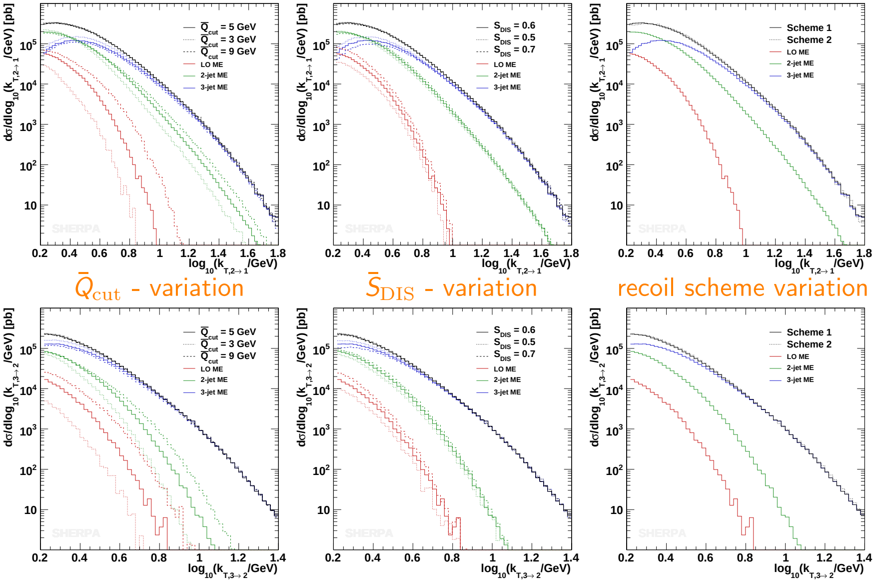
- SHERPA including ME$\otimes$PS set up for DIS
  framework stable, promising first results
- HZTool steering included in SHERPA
  $\rightarrow$ "any" existing HZTool analysis can be run

Things to be done ...

- More tests and validations
  forward jets, 4-jets, ...
- Resolved photons
- Multiparton events

Looking forward to meet the challenge !

Merging ME & PS: Stability tests



Combining ME and PS

We know ...

- Methods to compute full ME's given order in coupling
  ME generators implement these to simulate hard processes
- Schemes to compute resummation effects given logarithmic accuracy
  PS generators implement these to simulate parton cascades

To sensibly simulate *full events* we must combine the two !

Strategy: Get the best of both !

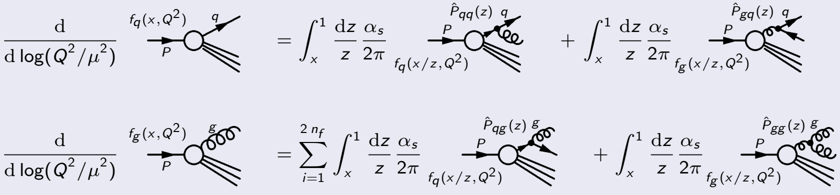
- Employ best possible ME for given analysis
  i.e. one that describes all investigated final states
  e.g. 3jet ME's in 3jet analyses ...
- Properly implement resummation using PS's
  i.e. fill remaining phasespace with softer emissions
  hardest, i.e. most important emissions should always be described by ME

Introduction: Parton Showers

The basis of Parton Showers: QCD evolution equations DGLAP

$$\frac{\partial f_a(z,Q^2)}{\partial \log(Q^2/\mu^2)} = \int_x^1 \frac{\mathrm{d}z}{z}\,\frac{\alpha_s}{2\pi} \sum_{b=q,g} \hat{P}_{ba}(z)\, f_b\left(\frac{x}{z}, Q^2\right)$$

Pictorially:



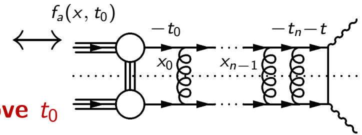
Can iterate these equations

$\longrightarrow$ ladder-like structure of amplitude squared

with strong ordering in scales $t_0 < \ldots < t$

Factorization now occurs at any stage above t_0

can split emissions off ME one by one



Introduction: Parton Showers

In MC event generators, we employ *exclusive* evolution think of DGLAP again

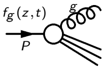
$$\frac{\partial g_a(z,t)}{\partial \log(t/\mu^2)} = \int_z^{\zeta_{max}} \frac{d\zeta}{\zeta} \sum_{b=q,g} \mathcal{K}_{ba}(\zeta,t)\, g_b\!\left(\frac{z}{\zeta},t\right) - g_a(z,t) \int_{\xi_{min}}^{\xi_{max}} d\xi \sum_{b=q,g} \xi\, \mathcal{K}_{ab}(\xi,t)$$

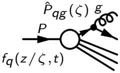
$\mathcal{K}_{ab}(\zeta,t)$ - evolution kernels of the scheme e.g. DGLAP kernels $\alpha_s/2\pi\ P_{ab}(z)$

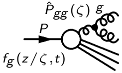
ξ_{min}, ξ_{max}/ζ_{max} - resolution criteria separate resolved from unresolved emissions

Example: DGLAP gluon-PDF evolution

inclusive form, i.e. $\xi_{min} \to 0$, $\xi/\zeta_{max} \to 1$ (no loss term) recover example from intro

$$\frac{d}{d\log(t/\mu^2)}$$ 

$$= \int_z^1 \frac{d\zeta}{\zeta} \frac{\alpha_s}{2\pi} \sum_{i=1}^{2\,n_f}$$ 

$$+ \int_z^1 \frac{d\zeta}{\zeta} \frac{\alpha_s}{2\pi}$$ 

Employ Sudakov form factors $\Delta_a(\mu^2,t)$ to rewrite want to absorb loss term

Interpretation: unconditional probability that parton a does not branch between scales μ^2 and t

$$\Delta_a(\mu^2,t) = \exp\left\{ -\int_{\mu^2}^{t} \frac{d\bar{t}}{\bar{t}} \int_{\xi_{\rm min}}^{\xi_{\rm max}} d\xi \sum_{b=q,g} \frac{1}{2} \mathcal{K}_{ab}(\xi,\bar{t}) \right\}$$

Using Sudakovs, QCD evolution reads loss term absorbed into derivative of Sudakov

$$\frac{\partial}{\partial \log(t/\mu^2)} \frac{g_a(z,t)}{\Delta_a(\mu^2,t)} = \frac{1}{\Delta_a(\mu^2,t)} \int_z^{\zeta_{\max}} \frac{\mathrm{d}\zeta}{\zeta} \sum_{b=q,g} \mathcal{K}_{ba}(\zeta,t)\, g_b(\frac{z}{\zeta},t)$$

Integrate this equation ...

$$\frac{\Delta_a(\mu^2,t')\, g_a(z,t)}{\Delta_a(\mu^2,t)\, g_a(z,t')} = \exp\left\{-\int_t^{t'} \frac{\mathrm{d}\bar{t}}{\bar{t}}\, \mathcal{I}(z,\bar{t})\right\}\,, \quad \mathcal{I}(z,\bar{t}) = \int_z^{\zeta_{\max}} \frac{\mathrm{d}\zeta}{\zeta} \sum_{b=q,g} \mathcal{K}_{ba}(\zeta,\bar{t})\, \frac{g_b(z/\zeta,\bar{t})}{g_a(z,\bar{t})}$$

Compare to radioactive decay: $\frac{\mathcal{N}(\tau)}{\mathcal{N}(\tau_0)} = \exp\left\{ -\int_{\tau_0}^{\tau} \mathrm{d}\tau'\, f(\tau') \right\}$

Integral of evolution equations is conditional no-branching probability !

probability not to radiate anything resolveable from parton a of energy fraction z between t and t'

$$\mathcal{P}^{(B)}_{\mathrm{no},\,a}(z,t,t') = \frac{\Delta_a(\mu^2,t')\, g_a(z,t)}{\Delta_a(\mu^2,t)\, g_a(z,t')}$$

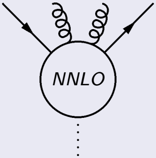
This is the basic equation of any Parton Shower !

Used to generate emission at t from parton at t' by

solving $1-\mathcal{P}^{(B)}_{\mathrm{no},a}(z,t,t') \stackrel{!}{=} R$ for t with R - random number

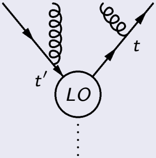
Combining ME & PS: The Problem

Problem: Matrix elements and parton showers deal with the same physics !



- Coherent sum of real NLO corrections
- No resummation

$\longleftrightarrow$



- Incoherent sum
- Proper resummation in parts of phase space

How do we run a parton shower on a N^xLO tree-level matrix element ?

1. Find suitable starting conditions for the parton shower
   i.e. find a tree-structure corresponding to the full ME
   which can be used by the parton shower as a branching history
2. Make sure not to double-count or miss out emissions
   i.e. eventually populate the whole available real emission
   phase space with *either* matrix elements *or* the parton shower

Solution part 1: Defining PS histories

Basic idea: **Interpret ME as if PS had produced it**

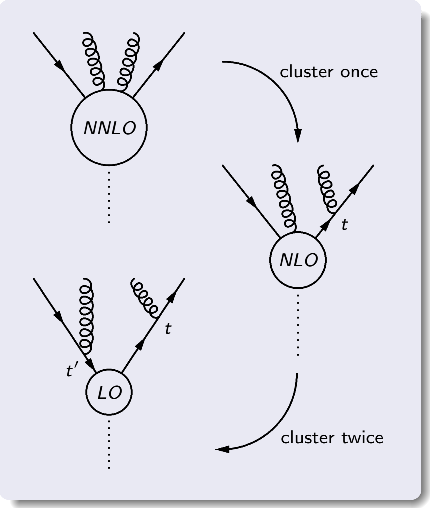
- Identify most likely splitting acc. to PS branching probability
- Combine partons into mother parton acc. to inverse PS kinematics
- Continue until 2 → 2 core process

→ Cluster algorithm similar to k_T algo

PS starts at core process and possibly radiates additional partons on intermediate lines i.e. “between” ME partons

ME branchings must be respected
evolution-, splitting- & angular variable preserved

→ Truncated shower see later
universal concept for ME-PS merging



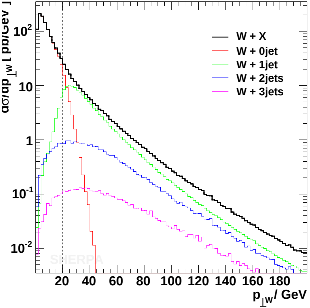
Solution part 2: Slicing the phasespace

Basic idea: **Separate phasespace into "hard" and "soft" region**

- Matrix elements populate hard domain
- Parton shower populates soft domain

need criterion to define "hard" & "soft" as above and below a certain cut value
$\rightarrow$ **Jet criterion** Q e.g. k_T-jet measure

$\longleftrightarrow$



First replace kernels in QCD evolution equations with note that $\mathcal{K}_{ab} = \mathcal{K}_{ab}^{\mathrm{ME}} + \mathcal{K}_{ab}^{\mathrm{PS}}$

$$\mathcal{K}_{ab}^{\mathrm{ME}}(\xi,\bar{t}) = \mathcal{K}_{ab}(\xi,\bar{t})\,\Theta\left[Q_{ab}(\xi,\bar{t}) - Q_{\mathrm{cut}}\right] \qquad \mathcal{K}_{ab}^{\mathrm{PS}}(\xi,\bar{t}) = \mathcal{K}_{ab}(\xi,\bar{t})\,\Theta\left[Q_{\mathrm{cut}} - Q_{ab}(\xi,\bar{t})\right]$$

Then replace PS evolution kernel in ME domain with full ME

$$\mathcal{K}_{ab}^{\mathrm{ME}}(z,t) \rightarrow \frac{1}{\sigma_a^{(N)}(\Phi_N)}\,\frac{\mathrm{d}^2\sigma_b^{(N+1)}(z,t;\Phi_N)}{\mathrm{d}\log(t/\mu^2)\,\mathrm{d}z}$$

ME & PS: Theory in a nutshell

Recall: Sudakov form factor $\Delta_a(\mu^2,t) \;=\; \exp\left\{\;-\int_{\mu^2}^{t}\frac{\mathrm{d}\bar{t}}{\bar{t}}\int_{\xi_{\min}}^{\xi_{\max}}\mathrm{d}\xi\sum_{b=q,g}\frac{1}{2}\,\mathcal{K}_{ab}(\xi,\bar{t})\;\right\}$

Evolution kernels $\mathcal{K}_{ab}(\xi,\bar{t}) = \mathcal{K}^{\rm ME}_{ab}(\xi,\bar{t}) + \mathcal{K}^{\rm PS}_{ab}(\xi,\bar{t})$

$\longrightarrow$ Factorization of Sudakovs follows trivially !

$$\Delta_a(\mu^2,t) = \Delta^{\rm ME}_a(\mu^2,t)\,\Delta^{\rm PS}_a(\mu^2,t)$$

Conditional no-branching probabilities factorize almost identically

$$\mathcal{P}^{(B)}_{\text{no},\,a}(z,t,t') \;=\; \frac{\Delta^{\rm ME}(\mu^2,t')}{\Delta^{\rm ME}(\mu^2,t)}\,\frac{\Delta^{\rm PS}_a(\mu^2,t')\,g_a(z,t)}{\Delta^{\rm PS}_a(\mu^2,t)\,g_a(z,t')} \;=:\; \mathcal{P}^{\rm ME}_{\text{no},\,a}(t,t')\,\mathcal{P}^{(B)\,\rm PS}_{\text{no},\,a}(z,t,t')$$

Remaining task: **Interpret this equation !**

Note the scheme independence: decomposition of $\mathcal{P}^{(B)}_{\text{no},\,a}(z,t,t')$ works independent of the definition of $\mathcal{K}_{ab}$

$\longrightarrow$ can be implemented for any parton shower and any jet measure Q

ME & PS: The need for truncated showers

How to interpret $\mathcal{P}^{(B)\,\mathrm{PS}}_{\mathrm{no},\,a}(z,t,t')$?

Assume predefined branchings at t and $t' > t$

$$\mathcal{K}_{ab}(\xi,\bar{t})\;\Theta\left[Q_{\mathrm{cut}} - Q_{ab}(\xi,\bar{t})\right]$$

means running a vetoed shower

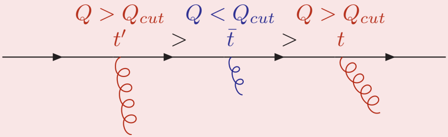
emission phase space is limited from above by Q_{cut}

$$\mathcal{P}^{(B)\,\mathrm{PS}}_{\mathrm{no},\,a}(z,t,t')$$

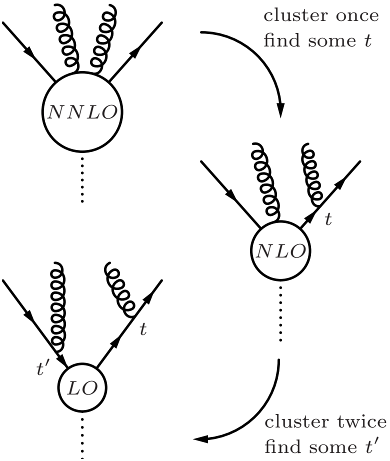
means running a truncated shower

t is larger than global shower cutoff t_0

What is the catch of it ?



Example branching history



ME & PS: Sudakov suppression and cross sections

How to interpret $\mathcal{P}^{\rm ME}_{{\rm no},\,a}(t,t')$?

Assume predefined branchings at t and $t' > t$

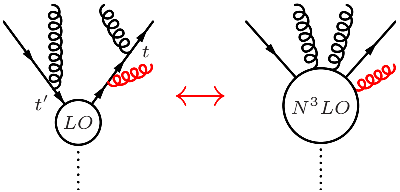
$$\mathcal{K}_{ab}(\xi,\bar{t})\,\Theta\left[Q_{ab}(\xi,\bar{t})-Q_{\rm cut}\right]$$

means running a vetoed shower
emission phase space is limited from below by $Q_{\rm cut}$

$$\mathcal{P}^{\rm ME}_{{\rm no},\,a}(t,t')$$

means running a truncated shower
t is larger than global shower cutoff t_0

Example emission



What happens if we emit something ?

Emission must be implemented to preserve full QCD evolution, i.e. $\mathcal{P}^{(B)}_{{\rm no},\,a}(z,t,t')$

But we want matrix elements to take care of such emissions !
To avoid double-counting, the complete event must be rejected

Event is lost $\Rightarrow$ rejection reduces initial cross section σ to $\sigma\cdot\mathcal{P}^{\rm ME}_{{\rm no},\,a}(t,t')$
"Gap" is filled by higher order ME$\otimes$PS $\Rightarrow$ σ preserved at LO