New developments in Sherpa

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From Parton Showers to NNLO

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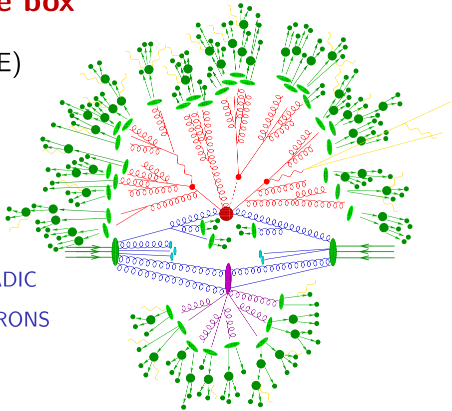
[1] For Sherpa: J. Archibald, T. Gleisberg, S.H., F. Krauss, M. Schönherr, S. Schumann, F. Siegert, J.-C. Winter

Sherpa's event generation framework

Things that are currently in the box

- A multi-purpose Matrix Element (ME) generator AMEGIC++ JHEP02(2002)044
- A Parton Shower (PS) generator APACIC++ CPC174(2006)876
- A multiple interaction simulation à la Pythia AMISIC++ hep-ph/0601012
- A cluster fragmentation module AHADIC
- A hadron and τ decay package HADRONS
- A photon radiation generator à la YFS PHOTONS JHEP12(2008)018



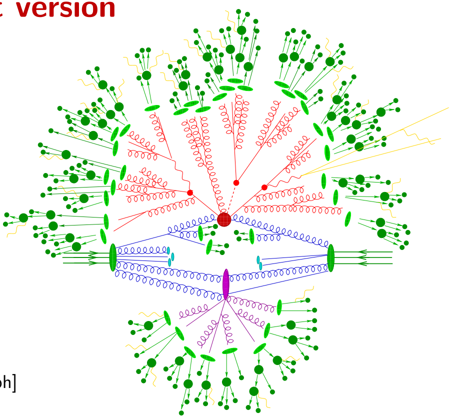
Sherpa's traditional strength is the perturbative part of the event

NLO real ME's consistently combined with PS using CKKW JHEP11(2001)063

Sherpa's event generation framework

Things to be added in the next version

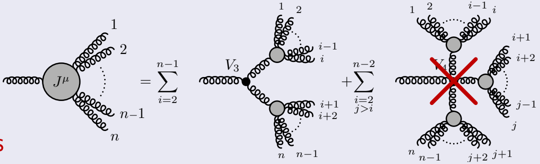
- The multi-purpose high-multiplicity ME generator Comix JHEP12(2008)039
- Automated Catani-Seymour dipole subtraction for MEs EPJ C53(2008)501
- A Parton Shower based on Catani-Seymour subtraction terms CSS JHEP03(2008)038
- A new method for merging tree-level multi-leg MEs and PSs, based on truncated showering arXiv:0903.1219 [hep-ph]



Comix

Construction principle

- Generalised Berends-Giele type recursive relations
- Vertex decomposition of all four-particle vertices



Growth in computational complexity solely determined by number of external legs at model's vertices

Full standard model implemented, extension to MSSM under way
Particularly suited for large multiplicity MEs (e.g. SM background processes)

Performance in QCD benchmark

gg → ng	Cross section [pb]				
n $\sqrt{s}$ [GeV]	8 1500	9 2000	10 2500	11 3500	12 5000
Comix	0.755(3)	0.305(2)	0.101(7)	0.057(5)	0.026(1)
PRD67(2003)014026	0.70(4)	0.30(2)	0.097(6)		
NPB539(1999)215	0.719(19)				

Comix

Phase-space generation à la NPB9(1969)568

Phase space factorises over timelike "propagators" (s-integrals)

Remaining building blocks interpreted as "decay vertices"

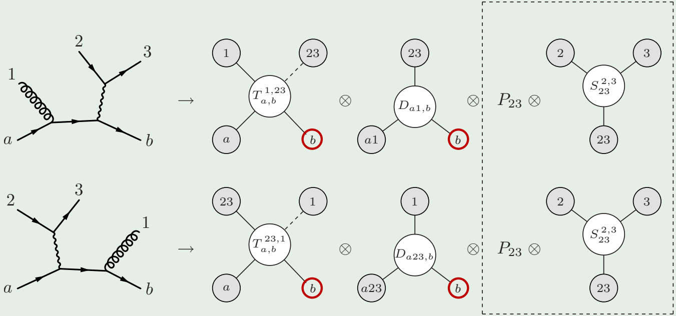
$\longrightarrow$ Phase space exhibits structure analogous to ME

$\Rightarrow$ Recursive phase-space generation possible (guided by ME)

Example: $\mathrm{q}\bar{\mathrm{q}} \to \mathrm{e}^+\mathrm{e}^-\mathrm{g}$

Note that
b is fixed
$\Downarrow$
t-channel weights
can be labeled
by final states !

Obviously $P_{23} \otimes S_{23}^{2,3}$
must be computed
only once !



Comix

Example: Drell-Yan + b-pair + jets

σ [pb]	Number of jets					
$e^-e^+ + b\bar{b}$ + jets	0	1	2	3	4	5
Comix	18.90(3)	6.81(2)	3.07(3)	1.536(9)	0.763(6)	0.37(1)
ALPGEN	18.95(8)	6.80(3)	2.97(2)	1.501(9)	0.78(1)	
AMEGIC	18.90(2)	6.82(2)	3.06(4)			

Example: b-pair + jets

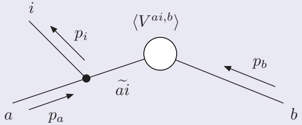
σ [μb]	Number of jets						
$b\bar{b}$ + jets	0	1	2	3	4	5	6
Comix	471.2(5)	8.83(2)	1.813(8)	0.459(2)	0.150(1)	0.0531(5)	0.0205(4)
ALPGEN	470.6(6)	8.83(1)	1.822(9)	0.459(2)	0.150(2)	0.053(1)	0.0215(8)
AMEGIC	470.3(4)	8.84(2)	1.817(6)				

The CSS

Construction of the parton shower

Evolution kernels given by Catani-Seymour dipole terms

- Spin averaged
- Leading $1/N_C$



e.g. initial-initial dipoles $\longrightarrow \langle V^{ai,b}(x_{i,ab})\rangle = P_{a\to\widetilde{ai}\,i}(x_{i,ab})$

Ordering parameter $k_\perp^2$ given by

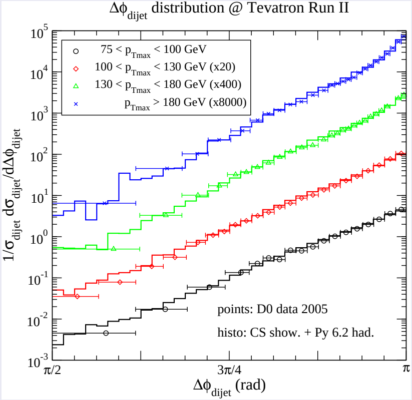
- Transverse momentum in cms of splitting dipole for final state splitters
- $2\tilde{p}_{ai}p_b\,\tilde{v}_i\,\frac{1-x_{i,ab}}{x_{i,ab}}$ for initial-initial dipoles ($\tilde{v}_i = \frac{p_ip_a}{p_ap_b}$, $x_{i,ab} = 1 - \frac{p_i(p_a+p_b)}{p_ap_b}$)
  Similar for inital-final dipoles ($\tilde{v}_i \leftrightarrow u_i$, $p_b \leftrightarrow p_k$)

Advantages over conventional schemes

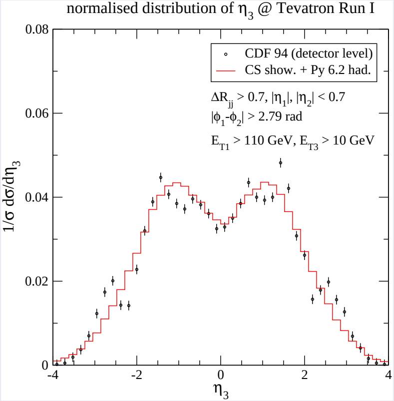
- Catani-Seymour dipoles give excellent approximation of real NLO ME
- Recoil is carried solely by the spectator parton !
  $\Rightarrow$ PS can be inverted into a clustering algorithm arXiv:0903.1219 [hep-ph]

The CSS

$p\bar{p} \longrightarrow$ jets PRL94(2005)221801



$p\bar{p} \longrightarrow$ jets PRD50(1994)5562



Combining ME & PS

Why should I combine matrix elements and parton showers ... ?

Because accelerated QCD charges radiate !

Well-defined schemes to account for the bulk of radiation effects
in certain regions of phase space exist (DGLAP, BFKL, ...)
Shower generators implement these schemes to simulate QCD events

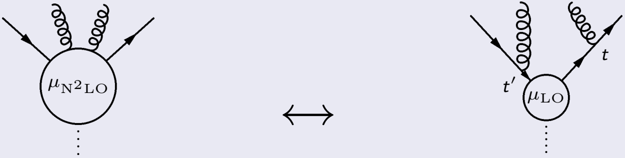
But this is not the end of the story !

All resummation calculations are, in the end, approximate
If we are interested in a particular QCD final state, however,

We should correct this approximation with a matrix element without spoiling the inclusive picture of the event

Combining ME & PS

Tree-level matrix elements and parton showers deal with the same physics !



- Coherent sum of real NLO corrections
- No resummation

- Incoherent sum
- Proper resummation in parts of phase space

Now how do you run a parton shower on a $\mathrm{N^xLO}$ tree-level matrix element ?

The actual problems in combining ME & PS

- 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
- 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

Combining ME & PS

The starting point for all parton showers: QCD evolution equations

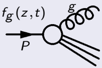
$$\frac{\partial g_a(z,t)}{\partial \log(t/\mu^2)} = \int_z^{\zeta_{\max}} \frac{d\zeta}{\zeta} \sum_{b=q,g} \mathcal{K}_{ba}(\zeta,t)\, g_b(z/\zeta,t) - g_a(z,t) \int_{\xi_{\min}}^{\xi_{\max}} d\xi \sum_{b=q,g} \xi\, \mathcal{K}_{ab}(\xi,t)$$

$\mathcal{K}_{ab}(\zeta,t) \longrightarrow$ evolution kernels of the scheme, $\xi_{\min}$, $\xi/\zeta_{\max} \longrightarrow$ resolution criteria

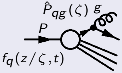
For example: DGLAP gluon-PDF evolution

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

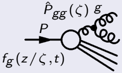
$$\frac{d}{d\log(t/\mu^2)}$$



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



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



What do parton showers do with this ?

Generate *exclusive* radiation patterns, i.e. $\xi_{\min} > 0$, $\xi/\zeta_{\max} < 1$

Basic quantities are the Sudakov form factors

no-emission probabilities in unconstrained (i.e. forward) evolution

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

Combining ME & PS

Rephrasing the evolution equations

In terms of Sudakov form factors, QCD evolution reads

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

This defines the conditional no-branching probability for parton showers
probability not to radiate anything resolveable at μ between t and t', basic eqn. of any parton shower

$$\mathcal{P}^{(B)}_{\text{no},\,a}(z,t,t') = \frac{\Delta_a(\mu^2,t')\, g_a(z,t)}{\Delta_a(\mu^2,t)\, g_a(z,t')} = \exp\left\{ -\int_t^{t'} \frac{\mathrm{d}\bar{t}}{\bar{t}} \int_z^{\zeta_{\max}} \frac{\mathrm{d}\zeta}{\zeta} \sum_{b=q,g} \mathcal{K}_{ba}(\zeta,\bar{t})\, \frac{g_b(z/\zeta,\bar{t})}{g_a(z,\bar{t})} \right\}$$

Basic requirements for ME-PS merging

- Preserve the above probability for conditional shower evolution
- Describe hardest emissions by matrix elements through

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

ME & PS with truncated showers

Separating the phase space into ME & PS domain

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

What happens to the conditional no-branching probability ?

Factorization of Sudakovs follows trivially !

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

Conditional no-branching probabilities factorize almost identically

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

Remaining task: interpret this equation !

Note

- $\mathcal{P}^{(B)}_{{\rm no},\,a}(z,t,t')$ is preserved, independent of the definition of Q !
- $\mathcal{P}^{\rm ME}_{{\rm no},\,a}(t,t')$ is independent of z !

ME & PS with 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

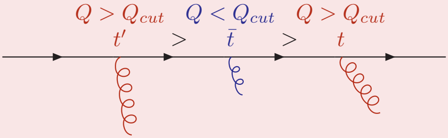
emission phase space is limited from above by Q_{cut}

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

means running a truncated shower

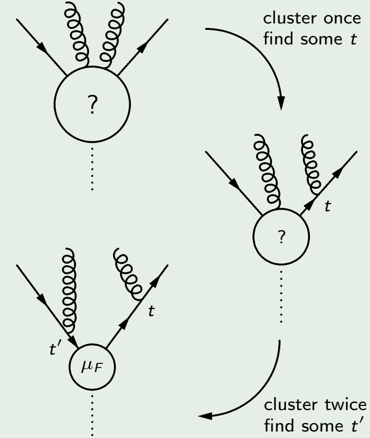
t is larger than global shower cutoff t_0

What is the catch of it ?



Example branching history

obtained by "running PS backwards" on ME



ME & PS with truncated showers

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

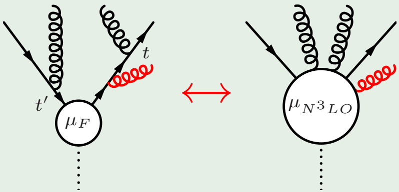
emission phase space is limited from below by $Q_{\rm cut}$

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

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

ME & PS with truncated showers

Now we need a definition of the jet criterion Q

$$Q_{ij}^2 = 2\,p_i p_j \min_{k\neq i,j} \frac{2}{C_{i,j}^k + C_{j,i}^k} \;;\quad C_{i,j}^k = \begin{cases} \dfrac{p_i p_k}{(p_i + p_k) p_j} - \dfrac{m_i^2}{2\,p_i p_j} & \text{if } j = g \\ 1 & \text{else} \end{cases}$$

Initial state splittings: $C_{a,\,j}^k \to C_{(aj),\,j}^k$

Make sure this is sensible

Requirement: Q must identify the soft and collinear divergences of QCD MEs

Separate phase space by cutting in Q $\Leftrightarrow$ regularise tree-level MEs by cutting in Q

- Soft limit

$$\frac{1}{Q_{ij}^2} \to \frac{1}{2\,\lambda^2}\,\frac{1}{2\,p_i\,q} \max_{k\neq i,j} \left[\frac{p_i p_k}{(p_i + p_k)\,q} - \frac{m_i^2}{2\,p_i q} \right]$$

- (Quasi-)Collinear limit

$$\frac{1}{Q_{ij}^2} \to \frac{1}{2\,\lambda^2}\,\frac{1}{\left|p_{ij}^2 - m_i^2 - m_j^2\right|} \left(\tilde{C}_{i,j} + \tilde{C}_{j,i} \right) \;;\quad \tilde{C}_{i,j} = \begin{cases} \dfrac{z}{1-z} - \dfrac{m_i^2}{2\,p_i p_j} & \text{if } j = g \\ 1 & \text{else} \end{cases}$$

ME & TS: Theoretical uncertainties

Merging-related

- Choice of the jet criterion (fixed by now)
- Value of the phase-space separation cut, $Q_{\rm cut}$
- Maximum number of jets from hard MEs, $N_{\rm max}$

pQCD-related

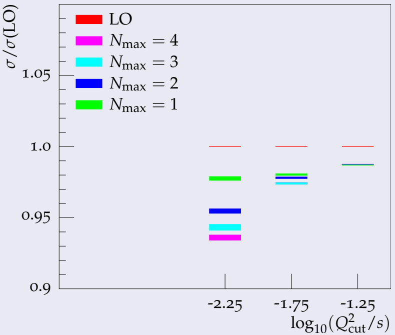
- Scale uncertainties from MEs
- Scale uncertainties from PSs
- PDF uncertainties

Others

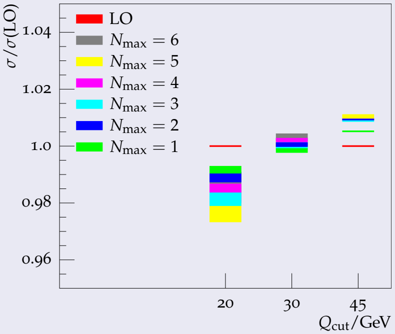
Choice of the LO process see arXiv:0903.1219 [hep-ph]

ME & TS Results: total cross sections

$e^+e^- \to$ hadrons @ LEP I

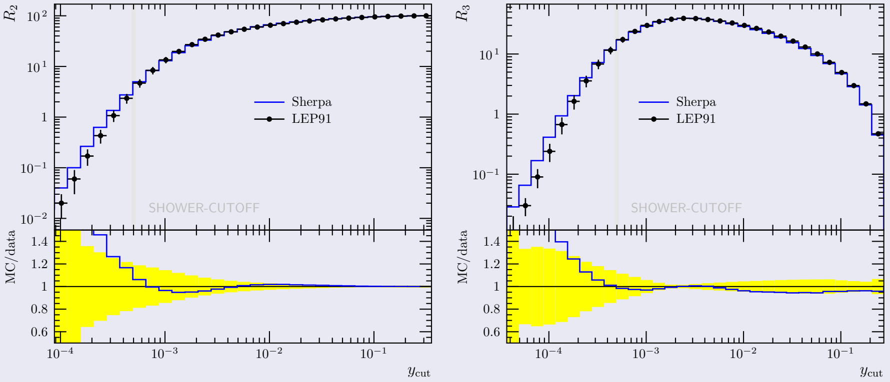


Drell-Yan @ Tevatron Run II



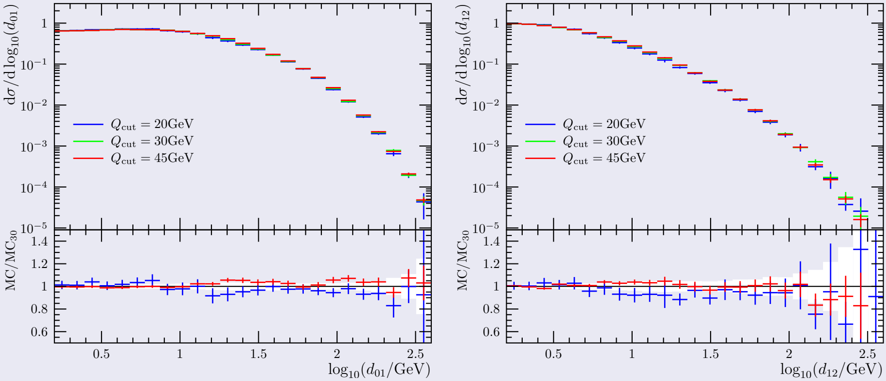
ME & TS Results: $e^+e^- \longrightarrow$ hadrons @ LEP I

Durham jet fractions (hadron level, untuned) Data: EPJC17(2000)19



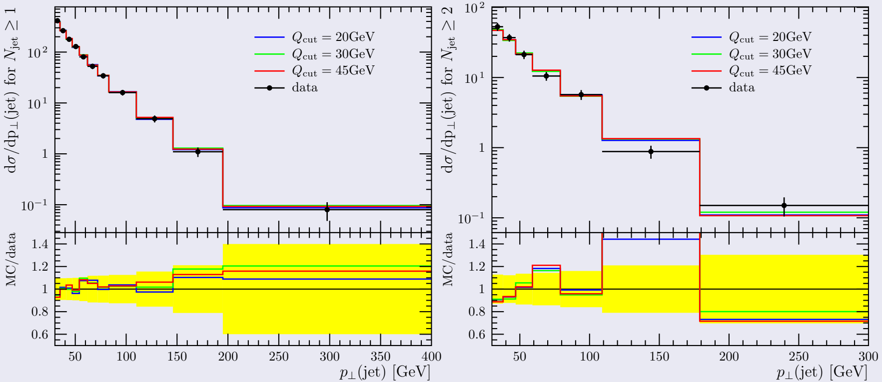
ME & TS Results: Drell-Yan @ Tevatron Run II

Differential jet rates in Q_{cut} variation (hadron level)



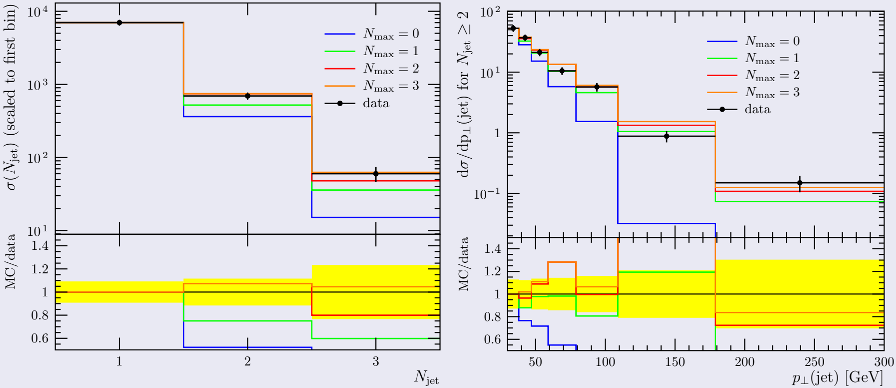
ME & TS Results: Drell-Yan @ Tevatron Run II

Jet observables in Q_{cut} variation (hadron level) Data: PRL100(2008)102001



ME & TS Results: Drell-Yan @ Tevatron Run II

Jet observables in N_{max} variation (hadron level) Data: PRL100(2008)102001



Summary

ME & TS: What has been improved w.r.t. CKKW ?

- Proof of correctness in initial-state evolution
- Freedom to define μ_F and μ_R at leading order
- Largely reduced merging systematics
- Improved phase-space separation

Uncertainties can be assessed separately

What comes next ?

- Cross-checks and applications
- Multi - leading-order prescription
- Release of the code with SHERPA v1.2

Summary

What else has been improved ?

- Parton shower generation through the CSS
- Large multiplicity ME generation through Comix
- Implementation of user-defined models into AMEGIC++
- Automated CS-subtraction in AMEGIC++
- Interfaces, e.g. to NLO loop codes

What comes next ?

- Extension of the framework for POWHEG with the CSS
- Tuning and validation of fragmentation
- Release of the code with SHERPA v1.2

Updates on Sherpa are (mostly) found on

http://www.sherpa-mc.de

E-Mail us on

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