ME+PS merging - theory

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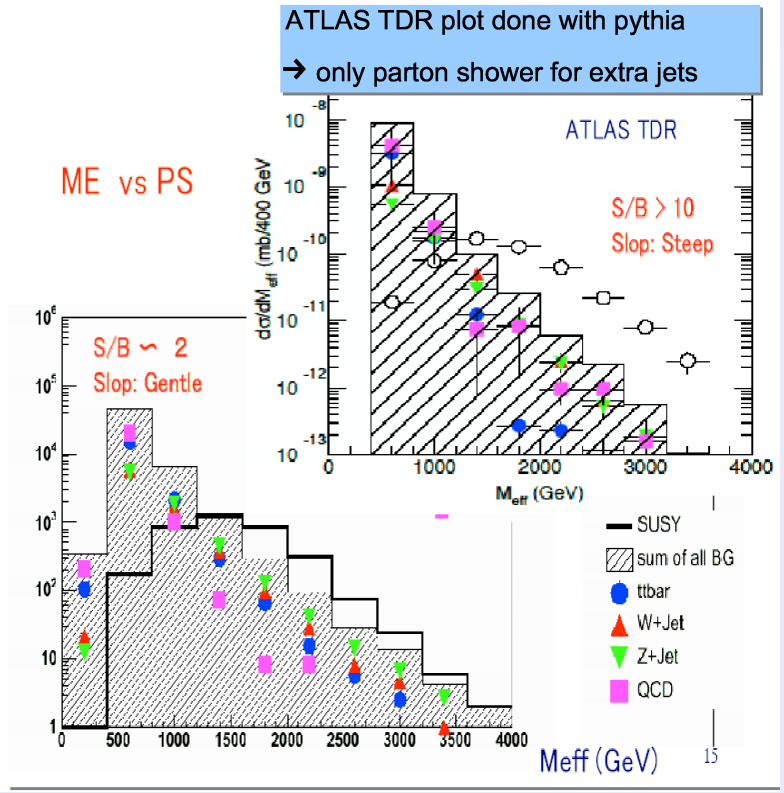
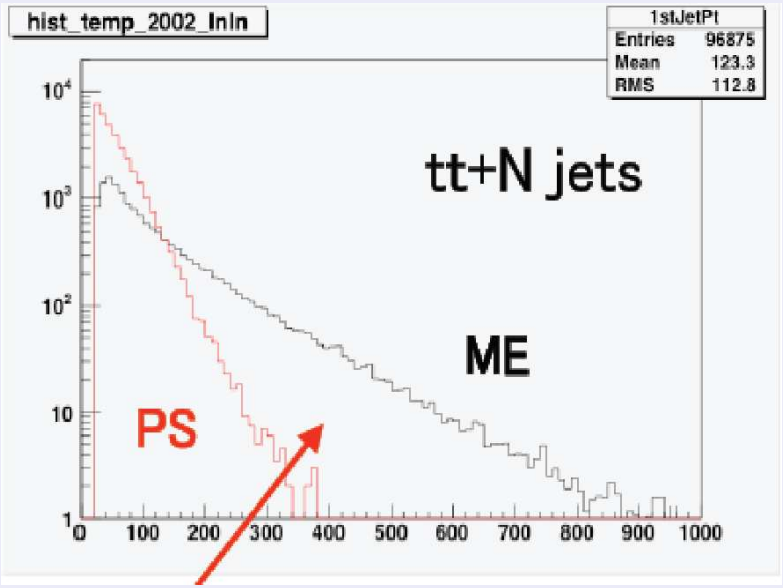
Split, 30.9.2008

Outline

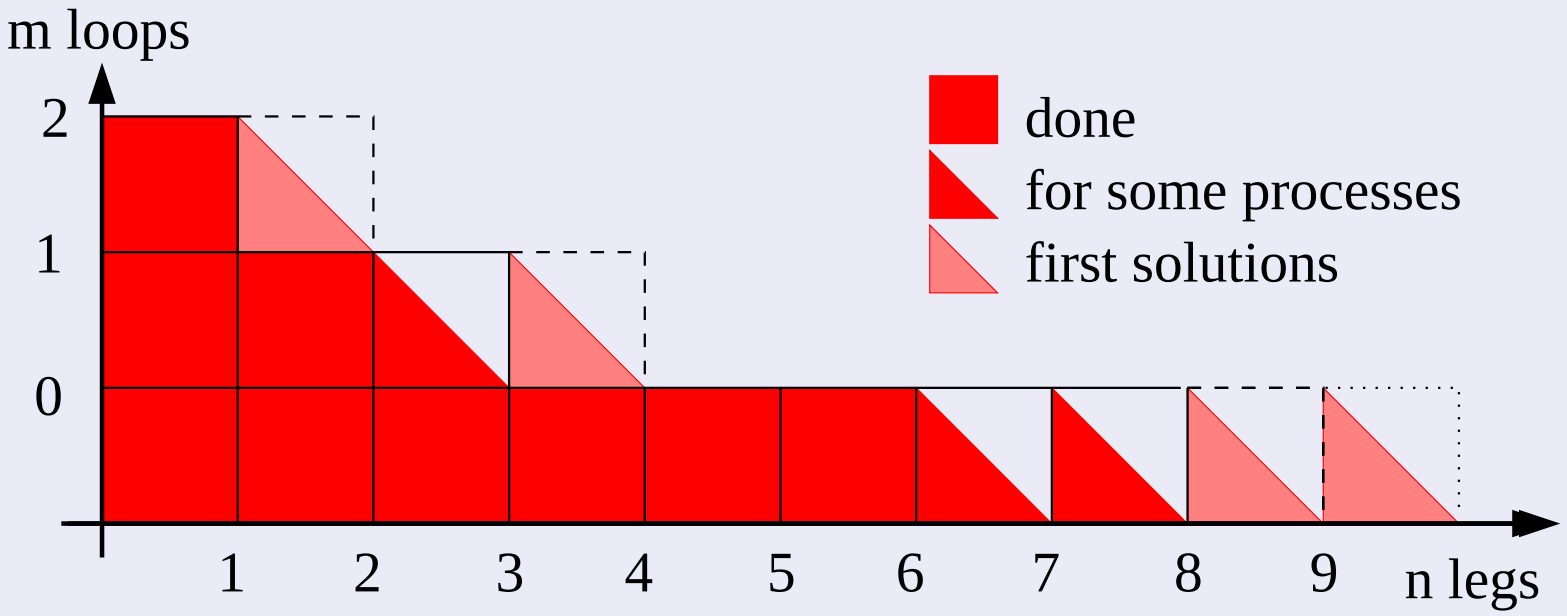
The impact of HO QCD

Example: SUSY searches (4 jets + $\not{E}_T$), observable: $M_{\rm eff}$





Availability of exact calculations



Parton showers

- Universal pattern of soft & collinear radiation:

$$\mathrm{d}\sigma_{N+1} \sim \mathrm{d}\sigma_N \sum_{a\in N} \frac{\mathrm{d}t_a}{t_a}\,\alpha_s\,\mathrm{d}z\,P_{a\to bc}(z)\,.$$

- Introduce "resolution of partons" (e.g. $p_\perp^{\min}$)
  $\Longrightarrow$ Large logarithms at each emission.
- Resummation of soft & collinear logs in Sudakov form factor:

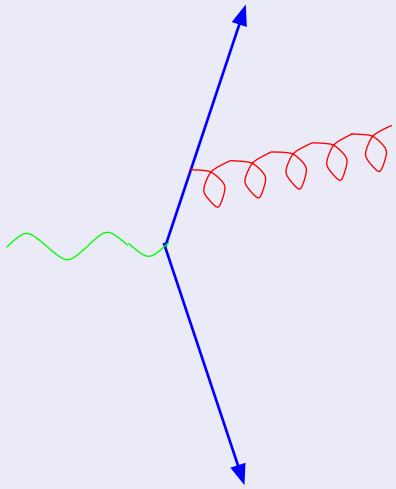
$$\Delta_a(t,\,t_0) = \exp\left[-\int_{t_0}^{t}\frac{\mathrm{d}t'}{t'}\int_{z_-}^{z_+}\mathrm{d}z\,\alpha_s\,P_{a\to bc}(z)\right]\,.$$

- Interpretation: No-emission probability ($\to$ simulation).

n-jet rates @ NLL

S.Catani *et al.* Phys. Lett. **B269** (1991) 432

Example: NLL-jet rates in $\gamma^* \longrightarrow$ jets



$$\mathcal{R}_2(Q_{\rm jet}) = \left[\Delta_q(E_{\rm c.m.}, Q_{\rm jet})\right]^2$$

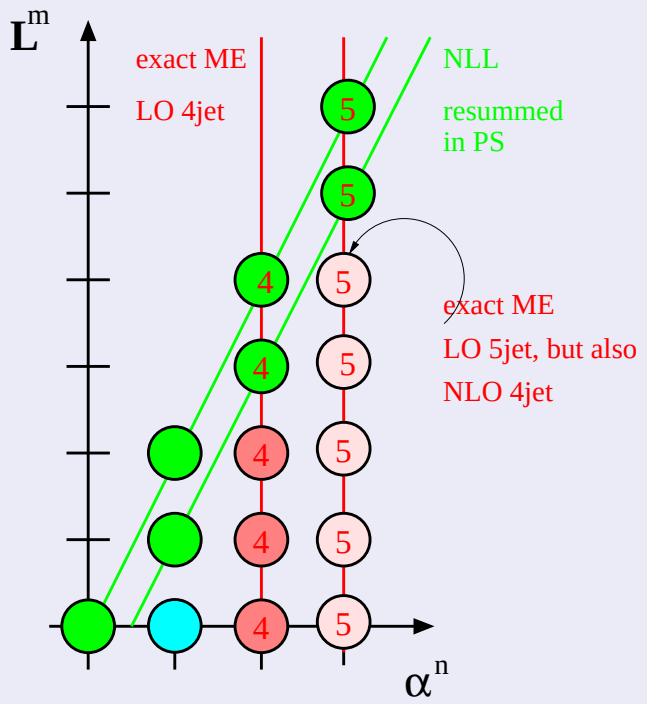
$$\mathcal{R}_3(Q_{\rm jet}) = \Delta_q(E_{\rm c.m.}, Q_{\rm jet}) \cdot \int {\rm d}q \left[2\alpha_s(q)\Gamma_q(E_{\rm c.m.}, q) \frac{\Delta_q(E_{\rm c.m.}, Q_{\rm jet})}{\Delta_q(q, Q_{\rm jet})} \Delta_q(q, Q_{\rm jet})\Delta_g(q, Q_{\rm jet}) \right]$$

($\Gamma_q(E_{\rm c.m.}, q)$ = z-integrated splitting function, acts as matrix element approximation)

ME vs. PS

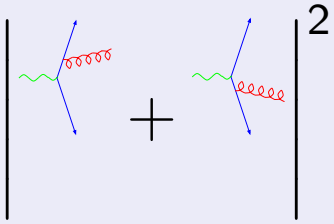
- Matrix elements good for: hard, large-angle emissions; take care of interferences.
- Parton shower good for: soft, collinear emissions; resums large logarithms.
- Want to combine both! Avoid double-counting.

Orders in ME & PS

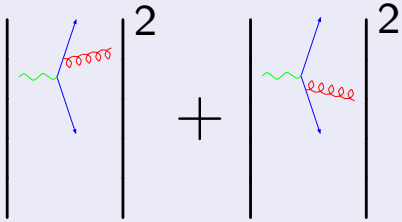


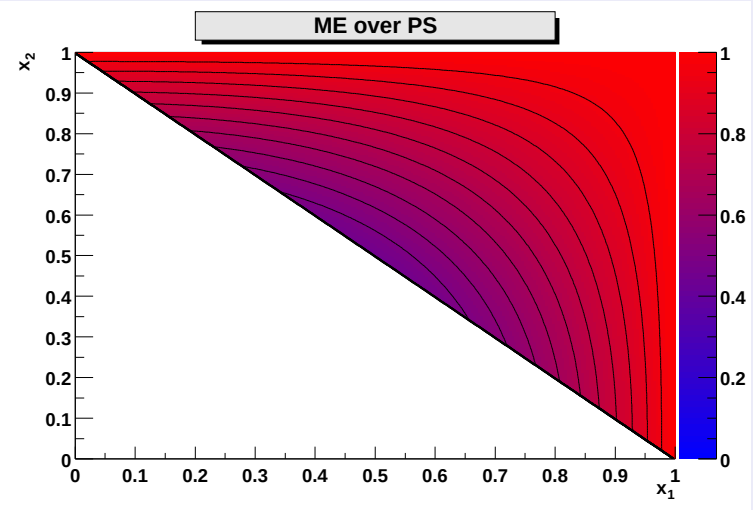
Correcting the parton shower: $e^+e^- \to 3$ jets

ME :



PS :





Generate jet with PS, accept or reject with ME/PS.

Practicalities of ME-corrections

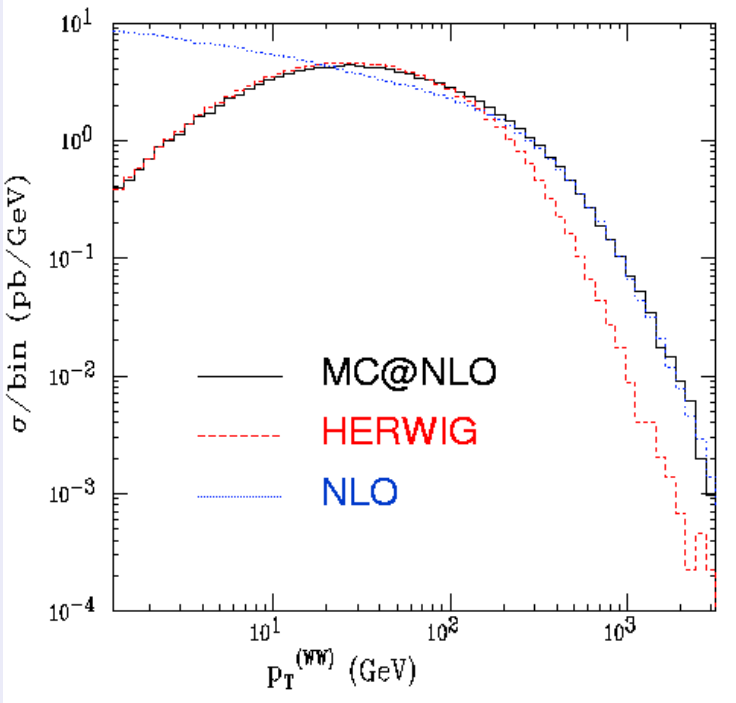
- Obviously, $ME < PS$ is not always fulfilled.
- Could enhance PS expression by a (large) factor.
  Question: Efficiency of the approach?
- Therefore: realized in few processes only:
  Best-known: $ee \to q\bar{q}$, $q\bar{q} \to V$, $t \to bW$

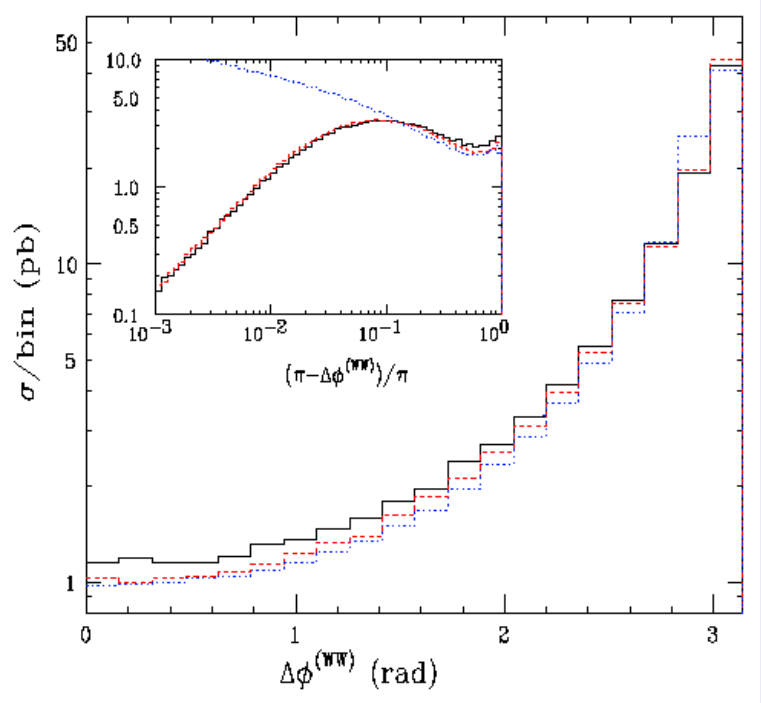
MC@NLO

S.Frixione, B.R.Webber, JHEP **0206** (2002) 029
S.Frixione, P.Nason, B.R.Webber, JHEP **0308** (2003) 007

- Want:
  - NLO-Normalisation and first (hard) emission correct,
  - Soft emissions correctly resummed in PS.
- Method:
  - Modify subtraction terms for real infrared divergences,
  - use first order parton shower-expression,
  - this is process-dependent!
- In practise much more complicated.
- Implemented for DY, W-pairs, $gg \to H$, Q-pairs.

MC@NLO example results: W-pairs @ Tevatron





PowHEG

S.Frixione, P.Nason, C.Oleari, JHEP **0711** (2007) 070

- Occurrence of negative weights in MC@NLO.
- Improved matching scheme avoiding negative weights:
  - Generate process with LO kinematics and NLO weight
  - Generate hardest emission according to real-emission ME: $\sim \exp\left[-\int \mathrm{d}\Phi_1 \sigma_{n+1}(\Phi_{n+1})/\sigma_n(\Phi_n)\right]$
  - Effect: Replacing the approximation (splitting function) with exact result
- Reproduces rate and first emission at NLO accuracy.
- Shower-independent: The method of choice.

Combining MEs & PS: LO-Merging

S.Catani, F.K., R.Kuhn and B.R.Webber, JHEP **0111** (2001) 063
F.K., JHEP **0208** (2002) 015

- Want:
  - All jet emissions correct at tree level + LL,
  - Soft emissions correctly resummed in PS
- Method:
  - Separate Jet-production/evolution by $Q_{\rm jet}$ ($k_\perp$ algorithm).
  - Produce jets according to LO matrix elements
  - re-weight with Sudakov form factor + running α_s weights,
  - veto jet production in parton shower.
- Process-independent implementation.

n-jet rates @ NLL, again

S.Catani *et al.* Phys. Lett. **B269** (1991) 432

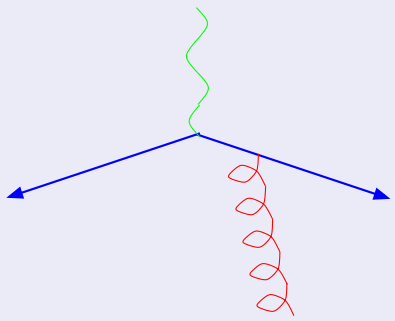
At NLL-Accuracy

$$\mathcal{R}_2(Q_{\rm jet}) = \left[\Delta_q(E_{\rm c.m.}, Q_{\rm jet})\right]^2$$

$$\mathcal{R}_3(Q_{\rm jet}) = \Delta_q(E_{\rm c.m.}, Q_{\rm jet}) \cdot \int {\rm d}q \left[2\alpha_s(q)\Gamma_q(E_{\rm c.m.}, q) \frac{\Delta_q(E_{\rm c.m.}, Q_{\rm jet})}{\Delta_q(q, Q_{\rm jet})} \Delta_q(q, Q_{\rm jet})\Delta_g(q, Q_{\rm jet}) \right]$$

Sudakov weights

Example: $\gamma^* \to q\bar{q}g$

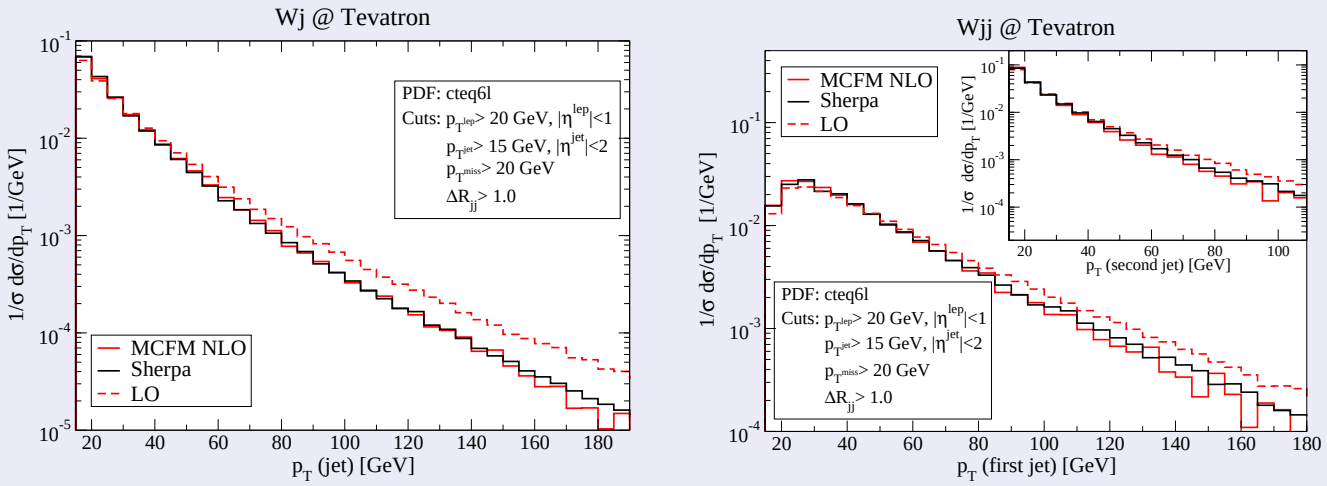


$$\mathcal{W}_{\rm Sud} = \frac{\alpha_s(q)}{\alpha_s(Q_{\rm jet})} \cdot \Delta_q(E_{\rm c.m.}, Q_{\rm jet}) \frac{\Delta_q(E_{\rm c.m.}, Q_{\rm jet})}{\Delta_q(q, Q_{\rm jet})} \Delta_q(q, Q_{\rm jet})\Delta_g(q, Q_{\rm jet})$$

Algorithm as scale-setting prescription

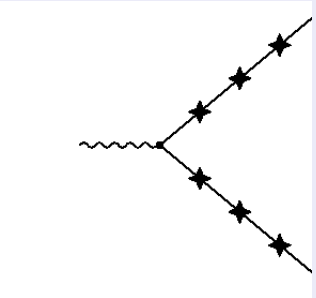
- Example: $p_\perp$ distribution of jets @ Tevatron
- Consider exclusive $W+1$- and $W+2$-jet production

Comparison with MCFM; J.Campbell and R.K.Ellis, Phys. Rev. D **65** (2002) 113007
in : F.K., A.Schälicke, S.Schumann and G.Soff, Phys. Rev. D **70** (2004) 114009



Sherpa = tree-level matrix elements with α_s scales and Sudakov form factors.

Vetoing the shower



$$\mathcal{W}_{\rm Veto} = \left\{1 + \int_{Q_{\rm jet}}^{E_{\rm c.m.}} {\rm d}q\, \Gamma_q(E_{\rm c.m.}, q) + \int_{Q_{\rm jet}}^{E_{\rm c.m.}} {\rm d}q\, \Gamma_q(E_{\rm c.m.}, q) \int_{Q_{\rm jet}}^{q} {\rm d}q'\, \Gamma_q(E_{\rm c.m.} q') + \cdots \right\}^2$$

$$= \left\{\exp\left(\int_{Q_{\rm jet}}^{E_{\rm c.m.}} {\rm d}q\, \Gamma_q(E_{\rm c.m.}, q)\right)\right\}^2 = \Delta_q^{-2}(E_{\rm c.m.}, Q_{\rm jet})$$

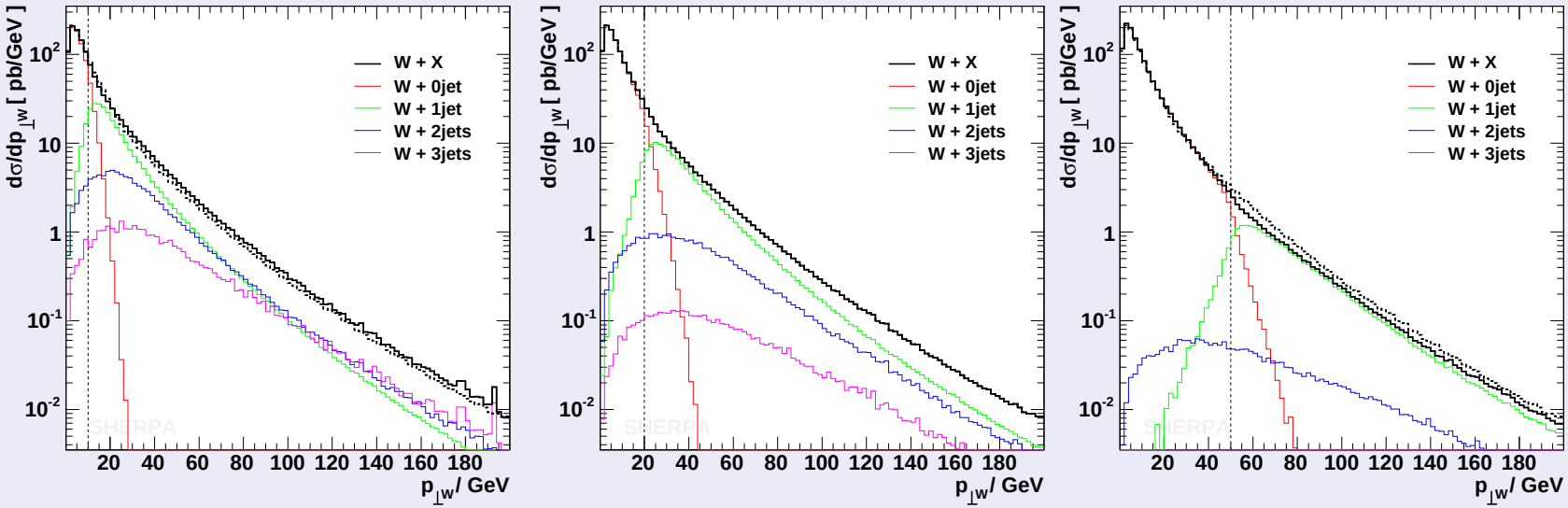
$\Longrightarrow$ Cancels dependence on $Q_{\rm jet}$.

Combining MEs & PS: Independence on $Q_{\rm jet}$

Example: $p_\perp$ of W in $p\bar{p} \to W + X$ @ Tevatron

F.K., A.Schälicke, S.Schumann and G.Soff, Phys. Rev. D **70** (2004) 114009

$Q_{\rm jet} = 10\,{\rm GeV}$ $Q_{\rm jet} = 30\,{\rm GeV}$ $Q_{\rm jet} = 50\,{\rm GeV}$



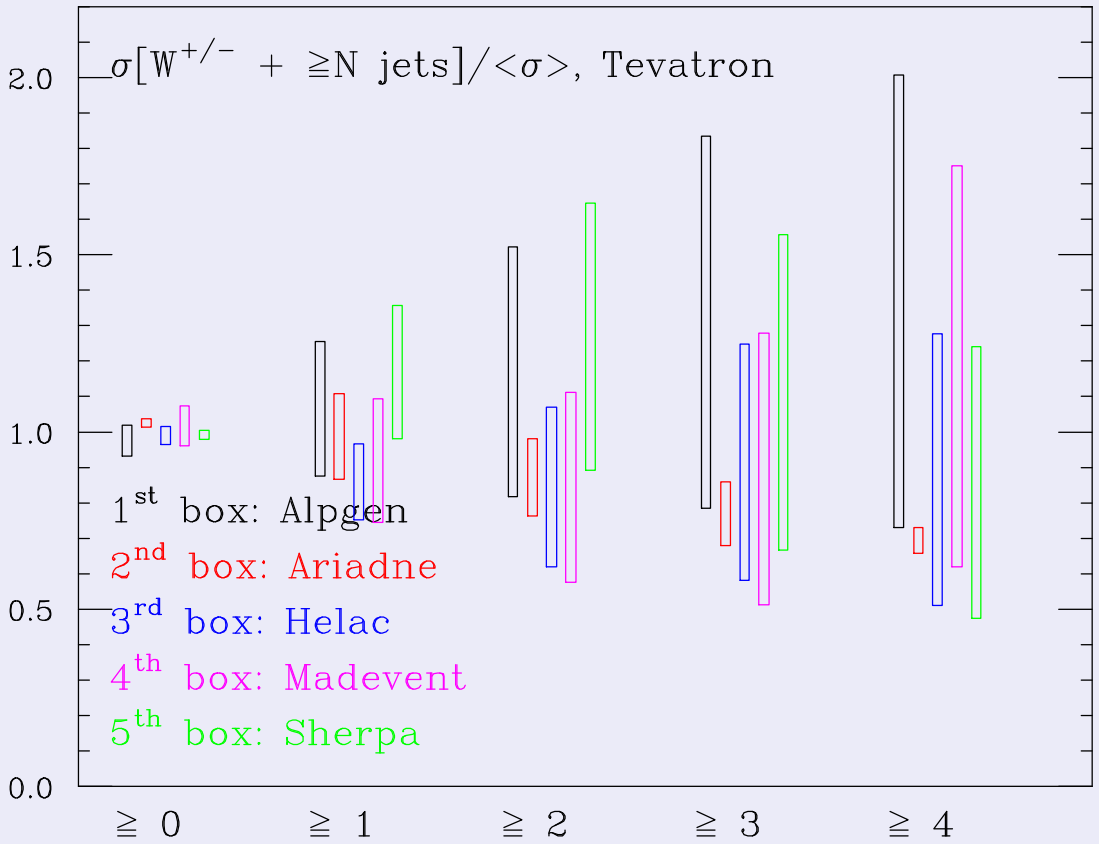
Other prescriptions

- CKKW-L L.Lönnblad, JHEP **0205** (2002) 046
  - Start with ME, jets defined with $k_\perp$ algorithm,
  - Cluster backwards with shower-specific $k_\perp$,
  - Use "PS-history" to fix starting conditions for shower,
  - Use first trial emission to reject/accept event
  - Run shower below jet scale.
- MLM M.Mangano *et al.*, Nucl. Phys. **B632** (2002) 343
  - Start with ME, jets defined with cones,
  - Feed configuration into shower, through LHA interface,
  - Match cone jets before hadronisation with partons, reject event in case of mismatch.

Comparison with other merging algorithms: MLM

J.Alwall *et al.* Eur. Phys. J. **C53** (2008) 473

Jet rates in inclusive W+jets at Tevatron



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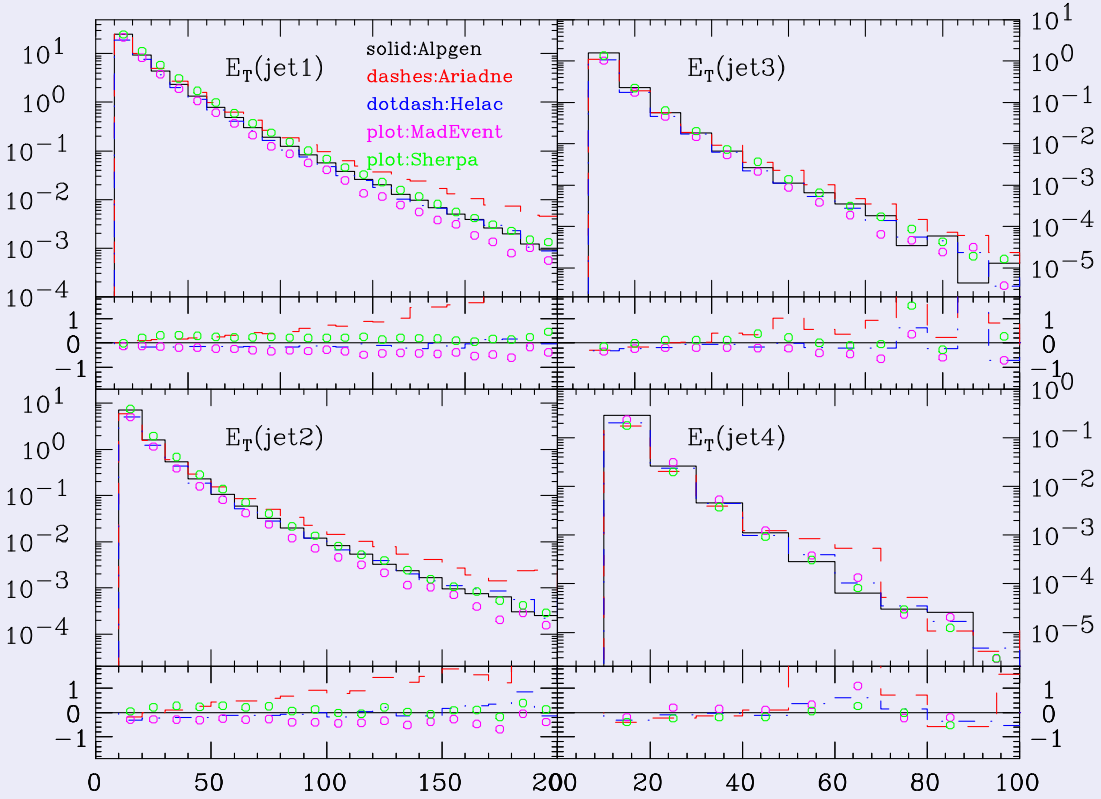
J.Alwall *et al.* Eur. Phys. J. **C53** (2008) 473

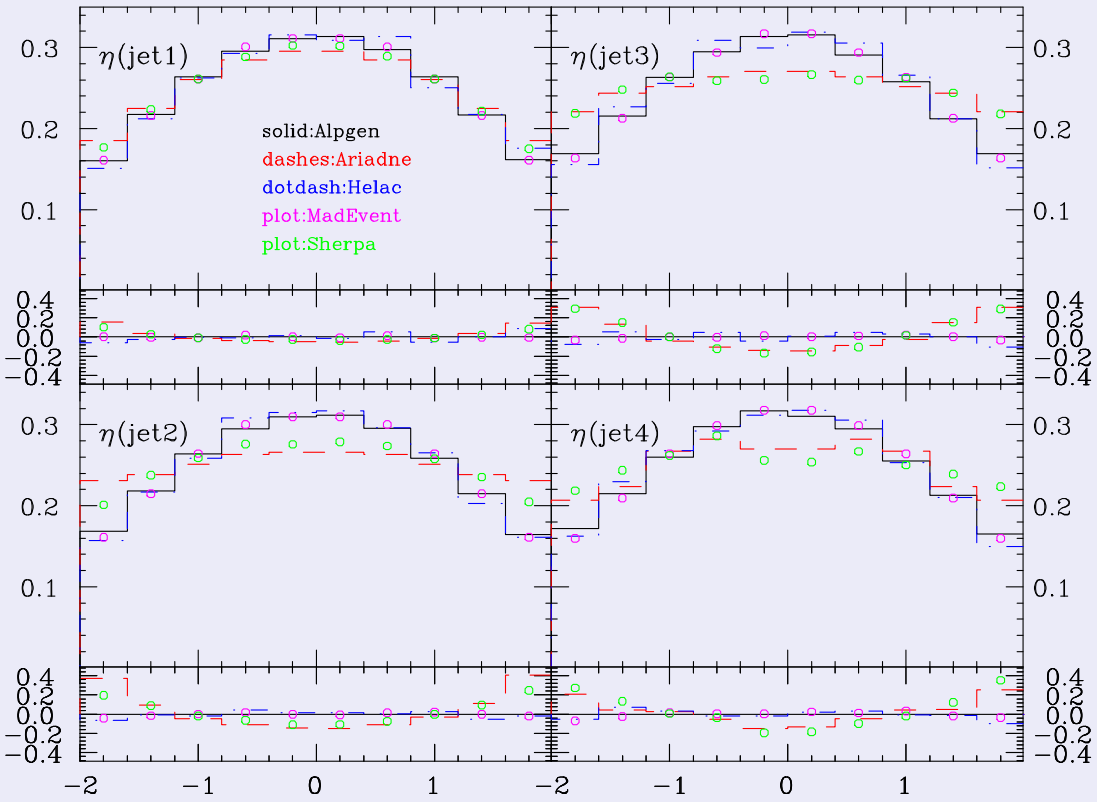
$p_\perp$ of jets in inclusive W+jets at Tevatron



Comparison with other merging algorithms: MLM

J.Alwall *et al.* Eur. Phys. J. **C53** (2008) 473

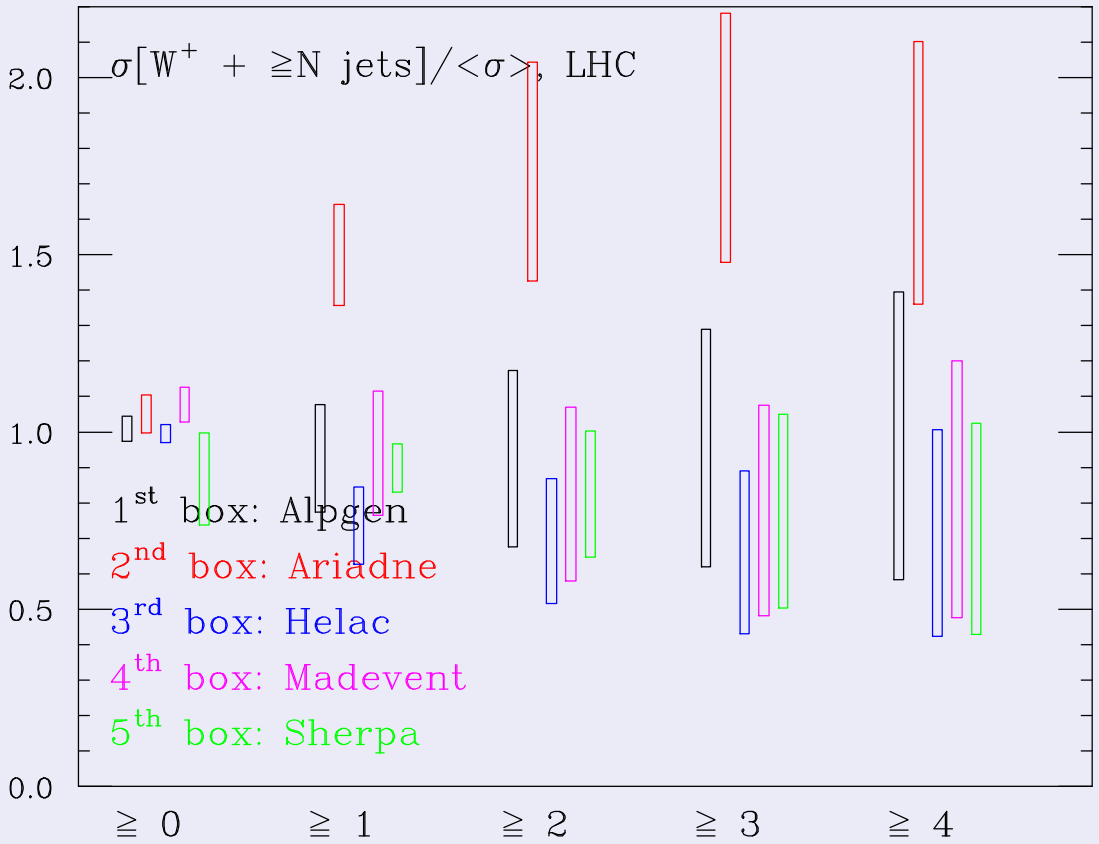
η of jets in inclusive W+jets at Tevatron



Comparison with other merging algorithms: MLM

J.Alwall *et al.* Eur. Phys. J. **C53** (2008) 473

Jet rates in inclusive W+jets at LHC



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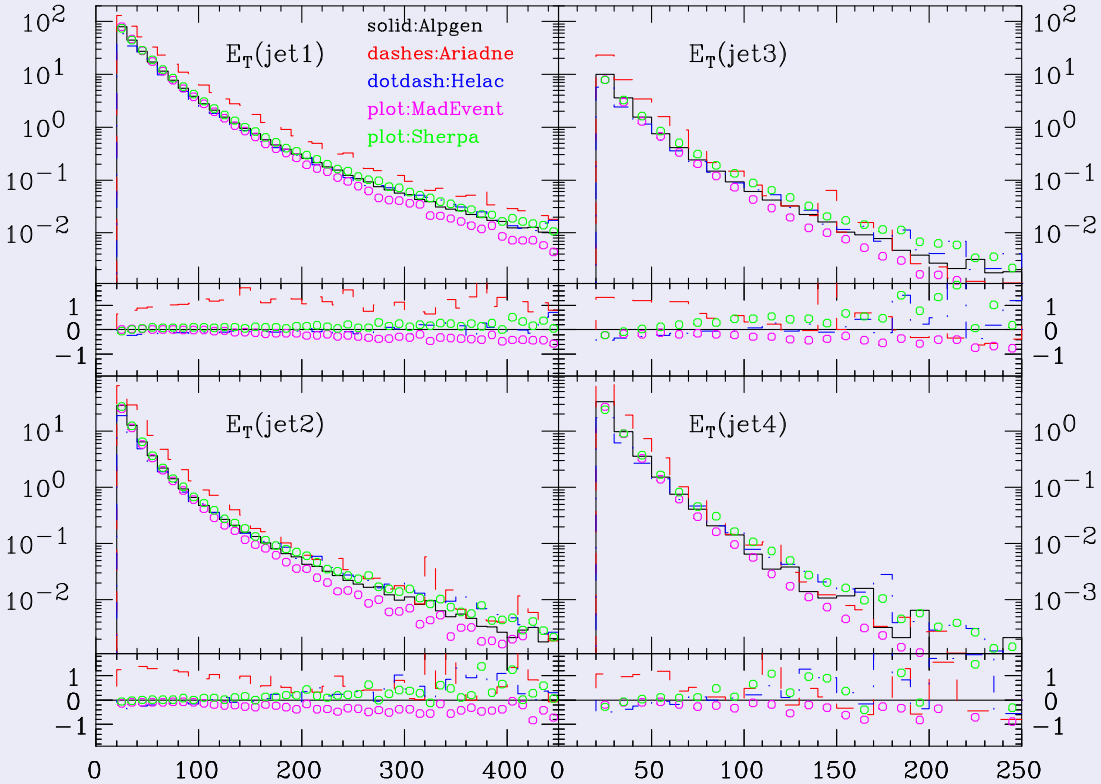
J.Alwall *et al.* Eur. Phys. J. **C53** (2008) 473

$p_\perp$ of jets in inclusive W+jets at LHC



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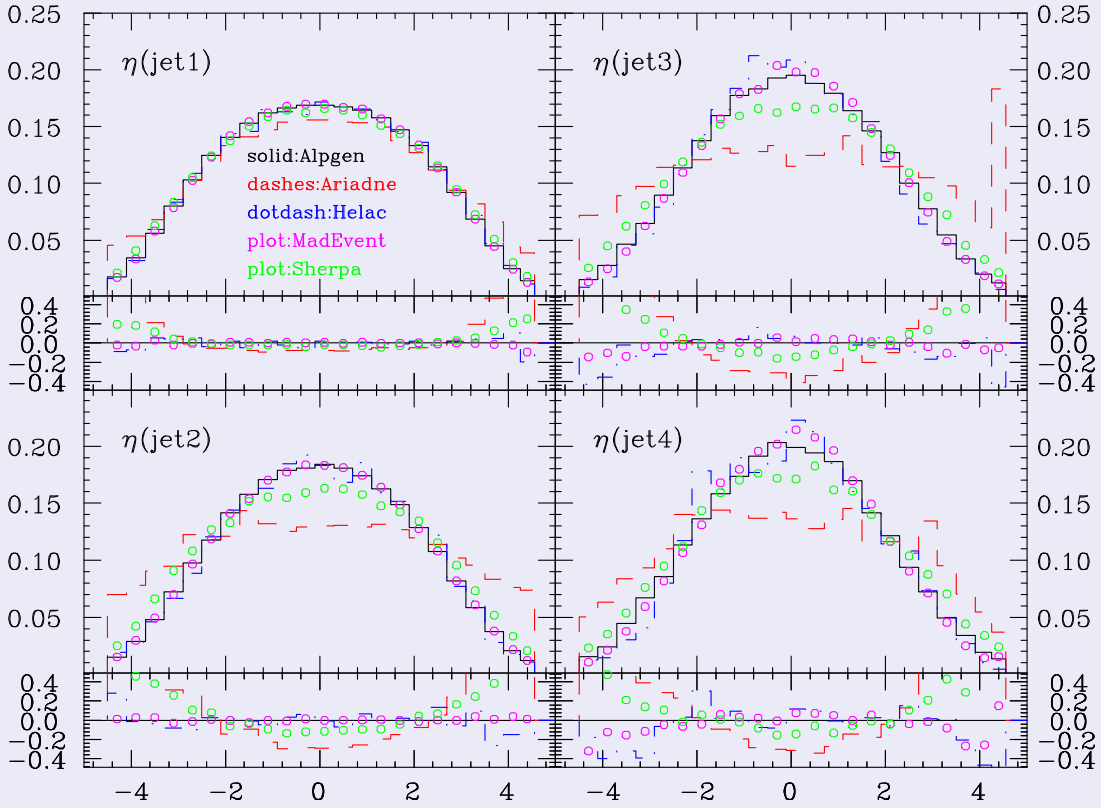


Conclusion

- Astonishing change of paradigm in MC generators: Pushing towards precision (matching and merging)
- Sociological: Field is becoming playground of QCD-theorists
  $\Longrightarrow$ new ideas, new technology (NLO)
- Practical: Development of better tools.
- Extremely powerful if used together!
- But: Validation needed (see next talk)

Outlook

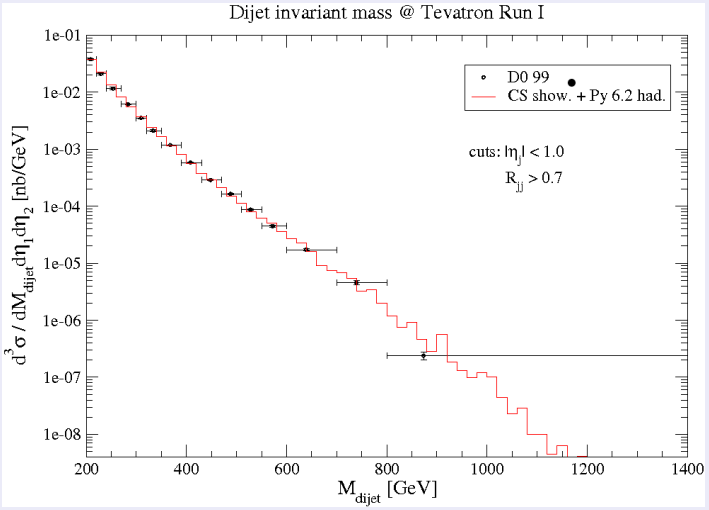
- Work started to push for NLO merging:
  - Calculate exclusive NLO for exactly n jets
  - Select configuration according to this rate and NLO-ME.
  - Reject with modified Sudakov form factor (expand to first order in α, and subtract)
  - Generate hardest emission with ME (like PowHEG).
  - Also: better control due to better showers.
- Time scale for e^+e^-: first half of 2009.
- Similar effort in CKKW-L (Ariadne) under way.

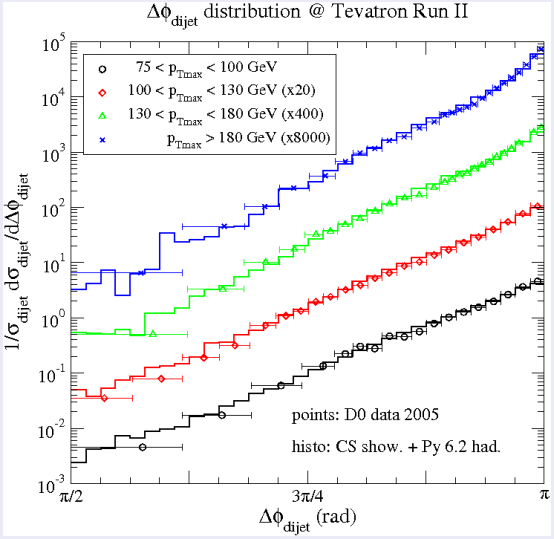
Using Catani-Seymour splitting kernels for showers

First discussed in: Z.Nagy and D.E.Soper, JHEP **0510** (2005) 024;

Implemented by M.Dinsdale, M.Ternick, S.Weinzierl Phys.Rev.**D76** (2007) 094003,

and S.Schumann& F.K., JHEP **0803** (2008) 038.





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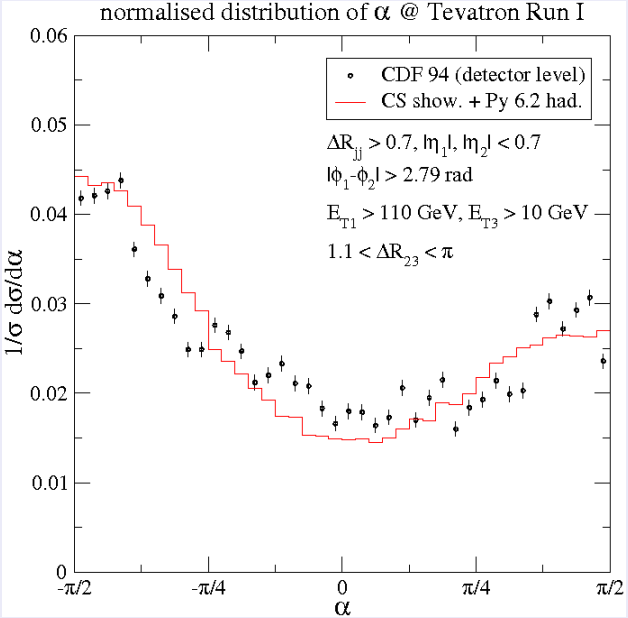

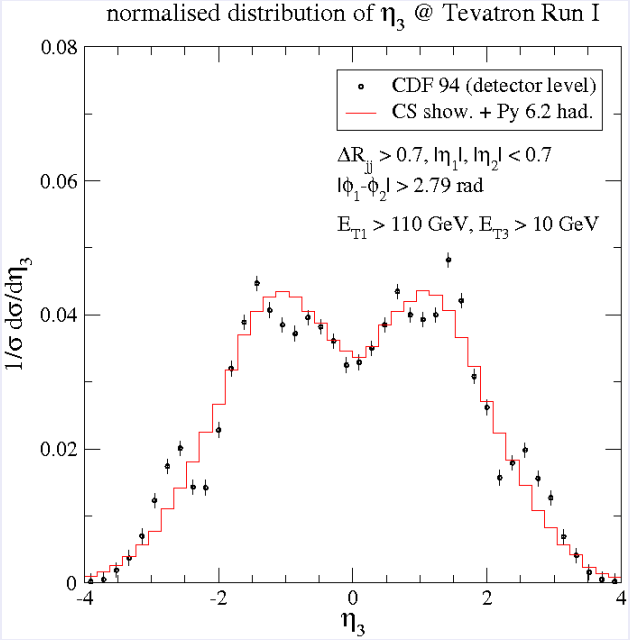

Implementing CSW recursion relations: A snaphot

F.Cachazo, P.Svrcek and E.Witten, JHEP **0409** (2004) 006

- Obtained summing over colours and helicities, sampling much better

Jet cross sections @ LHC, $k_\perp^{\min} = 20\text{GeV}$

Process	helicity	MHV where possible	MHV only ($\leq$ 2 quark lines)
$jj \to jj$	745.85 μb$\pm$0.10% 57 s	745.85 μb$\pm$0.10% 44 s	
$jj \to jjj$	81.274 μb$\pm$0.20% 826 s	81.274 μb$\pm$0.20% 166 s	
$gg \to gggg$	10.112 μb$\pm$0.23% 1.5 ks	10.145 μb$\pm$0.23% 0.6 ks	
$jj \to jjjj$	23.23 μb$\pm$0.27% 35 ks	23.245 μb$\pm$0.26% 7.6 ks	23.208 μb$\pm$0.26% 5.8 ks
$gg \to ggggg$	2.6592 μb$\pm$0.16% 131 ks	2.6915 μb$\pm$0.15% 41 ks	
$jj \to jjjjj$	not possible	7.3829 μb$\pm$0.25% 970 ks	7.3294 μb$\pm$0.17% 295 ks

COMIX - a new matrix element generator for Sherpa

- Colour-dressed Berends-Giele amplitudes in the SM
- Fully recursive phase space generation
- Example results (cross sections):

$gg \to ng$	Cross section [pb]				
n	8	9	10	11	12
$\sqrt{s}$ [GeV]	1500	2000	2500	3500	5000
Comix	0.755(3)	0.305(2)	0.101(7)	0.057(5)	0.019(2)
Maltoni (2002)	0.70(4)	0.30(2)	0.097(6)		
Alpgen	0.719(19)				

σ [μb]	Number of jets						
$b\bar{b}$ + QCD jets	0	1	2	3	4	5	6
Comix	4.80(5)	8.83(2)	1.826(8)	0.459(2)	0.1500(8)	0.0544(6)	0.023(2)
ALPGEN	4.76(6)	8.83(1)	1.822(9)	0.459(2)	0.150(2)	0.053(1)	0.0215(8)
AMEGIC++	4.73(4)	8.84(2)	1.817(6)				

COMIX - a new matrix element generator for Sherpa

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- Fully recursive phase space generation
- Example results (phase space performance):