Higher orders in simulation

Frank Krauss

IPPP Durham

Heidelberg, 25.2.2009

Outline

What Monte Carlo's are good for . . .

. . . and what not . . .

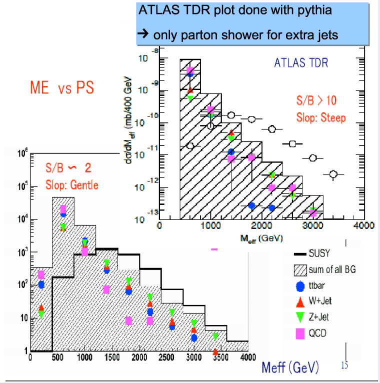
- To my understanding, Monte Carlo's are indispensible to

  extrapolate from a control region
  to the signal region of a background process.

- Any discovery, that is **solely** based on Monte Carlo's, or maybe worse, its fine details, will most likely not be trusted.

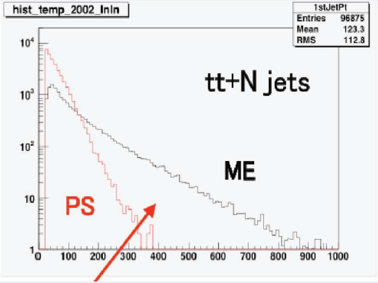
The impact of HO QCD

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

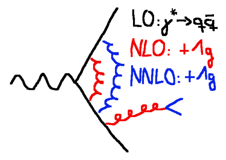


ATLAS TDR plot done with pythia

→ only parton shower for extra jets



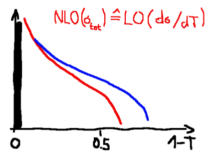
Specifying higher-order corrections: $\gamma^* \to$ hadrons



- In general: $\text{N}^n\text{LO} \leftrightarrow \mathcal{O}(\alpha_s^n)$
- But: only for inclusive quantities

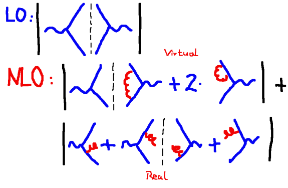
(e.g.: total xsecs like $\gamma^* \to$hadrons).

Counter-example: thrust distribution



- In general, distributions are HO.
- Distinguish real & virtual emissions: Real emissions → mainly distributions, virtual emissions → mainly normalization.

Anatomy of HO calculations: Virtual and real corrections



NLO corrections: $\mathcal{O}(\alpha_s)$

Virtual corrections = extra loops
Real corrections = extra legs

- UV-divergences in virtual graphs → renormalization
- But also: IR-divergences in real & virtual contributions
  Must cancel each other, non-trivial to see:
  N vs. $N+1$ particle FS, divergence in PS vs. loop

Cancelling the IR divergences: Subtraction method

- Total NLO xsec:
  $\sigma_{\rm NLO} = \sigma_{\rm Born} + \int {\rm d}^D k |\mathcal{M}|^2_V + \int {\rm d}^4 k |\mathcal{M}|^2_R$
- IR div. in real piece → regularize:
  $\int {\rm d}^4 k |\mathcal{M}|^2_R \longrightarrow \int {\rm d}^D k |\mathcal{M}|^2_R$
- Construct subtraction term with same IR structure:

  $\int {\rm d}^D k \left(|\mathcal{M}|^2_R - |\mathcal{M}|^2_S\right) = \int {\rm d}^4 k |\mathcal{M}|^2_{RS} = \text{finite}.$

  Possible: $\int {\rm d}^D k |\mathcal{M}|^2_S = \sigma_{\rm Born} \int {\rm d}^D k |\tilde{\mathcal{S}}|^2$, universal $|\tilde{\mathcal{S}}|^2$.
- $\int {\rm d}^D k |\mathcal{M}|^2_V + \sigma_{\rm Born} \int {\rm d}^D k |\tilde{\mathcal{S}}|^2 = \text{finite}$ (analytical)

State-of-the-art NLO calculations: General strategy

- Construct Born + 1st order terms
- Subtraction term: Born term × (analytical) divergences

  Evaluate loop term analytically - perform cancellation
- Monte Carlo separately over subtracted real emission and virtual+subtraction term

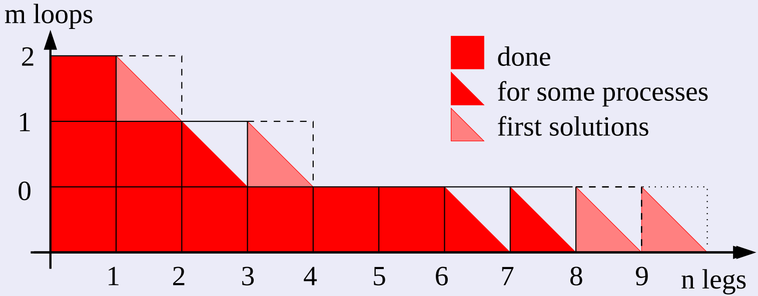
Limitations

- So far only loops with ≤ 5 propagators under full control

  $\Longrightarrow$ in general, only $2 \to 3$ processes at NLO

  But exiting new methods start hitting the market!
- Soft/collinear corners maybe still badly described

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:

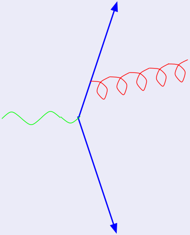
$$\Delta_a(t,\, t_0) = \exp\left[-\int\limits_{t_0}^{t} \frac{\mathrm{d}t'}{t'} \int\limits_{z_-}^{z_+} \mathrm{d}z\, \alpha_s\, P_{a\to bc}(z)\right]\,.$$

- Interpretation: No-emission probability (→ simulation).

n-jet rates @ NLL

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

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



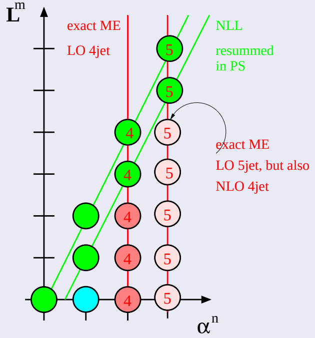
$$\begin{aligned}
\mathcal{R}_2(Q_\mathrm{jet}) &= \left[\Delta_q(E_\mathrm{c.m.}, Q_\mathrm{jet})\right]^2\\
\mathcal{R}_3(Q_\mathrm{jet}) &= \Delta_q(E_\mathrm{c.m.}, Q_\mathrm{jet})\\
&\quad \cdot \int \mathrm{d}q \left[2\alpha_s(q)\Gamma_q(E_\mathrm{c.m.}, q)\,\frac{\Delta_q(E_\mathrm{c.m.}, Q_\mathrm{jet})}{\Delta_q(q, Q_\mathrm{jet})}\right.\\
&\qquad\qquad \left.\Delta_q(q, Q_\mathrm{jet})\Delta_g(q, Q_\mathrm{jet})\right]
\end{aligned}$$

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

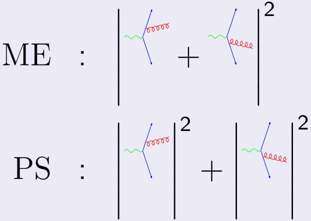
ME vs. PS

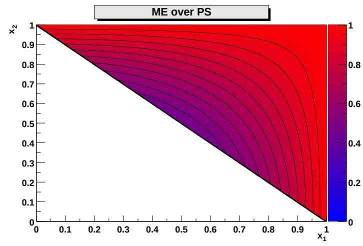
- Matrix elements good for: hard, large-angle emissions; take care of interferences.
- Parton shower good for: soft, collinear emissions; resums large logarithms.
- Want to combine both! Avoid double-counting.

Orders in ME & PS



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





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

Practicalities of ME-corrections

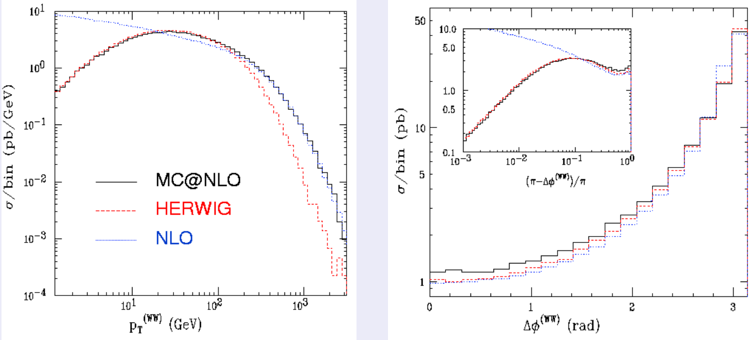
- Obviously, $ME < PS$ is not always fulfilled.
- Could enhance PS expression by a (large) factor.
  Question: Efficiency of the approach?
- Therefore: realized in few processes only:
  Best-known: $ee \to q\bar{q}$, $q\bar{q} \to V$, $t \to bW$
- Beware of “power-showers”.

MC@NLO

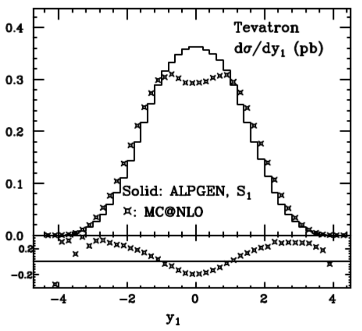
S.Frixione, B.R.Webber, JHEP **0206** (2002) 029
S.Frixione, P.Nason, B.R.Webber, JHEP **0308** (2003) 007

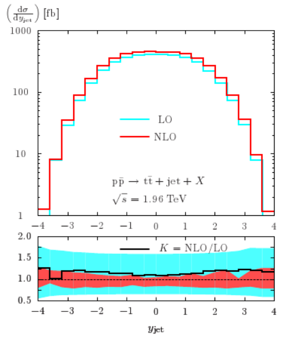
- Want:
  - NLO-Normalisation and first (hard) emission correct,
  - Soft emissions correctly resummed in PS.
- Method:
  - Modify subtraction terms for real infrared divergences,
  - use first order parton shower-expression,
  - this is process-dependent!
- In practise much more complicated.
- Implemented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

MC@NLO example results: W-pairs @ Tevatron



A little MC@NLO problem: $t\bar{t}$ at Tevatron



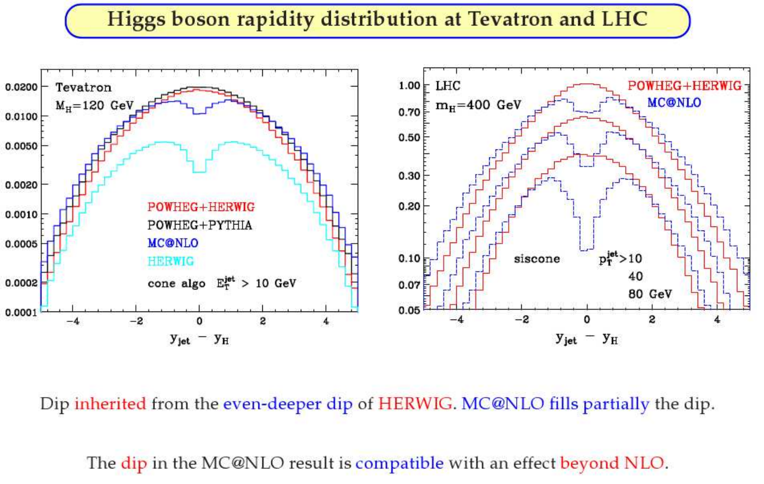


PowHEG

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.

PowHEG vs. MC@NLO (stolen from C.Oleari)

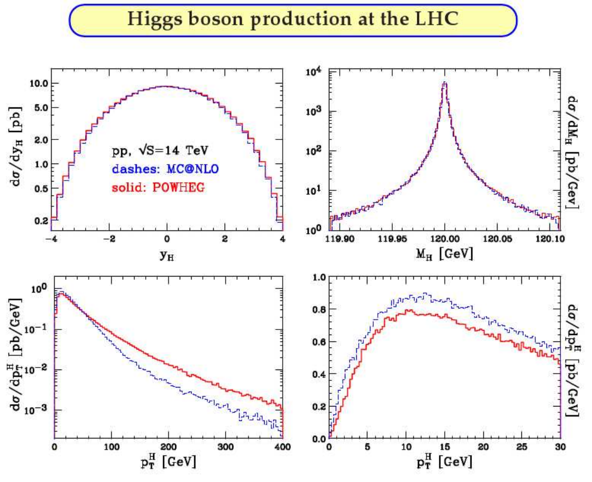


Higgs boson rapidity distribution at Tevatron and LHC

Dip inherited from the even-deeper dip of HERWIG. MC@NLO fills partially the dip.

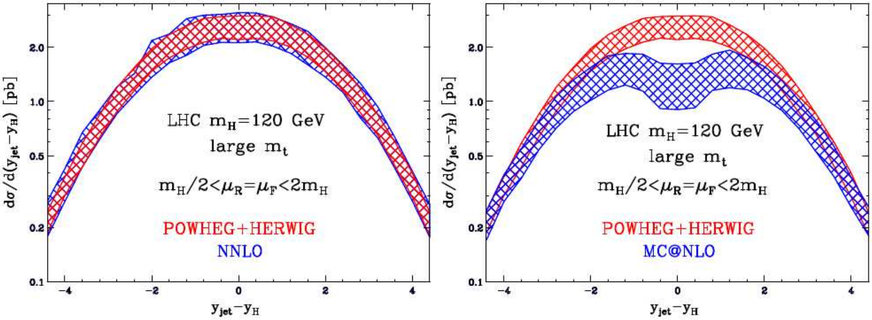
The dip in the MC@NLO result is compatible with an effect beyond NLO.

PowHEG vs. MC@NLO (stolen from C.Oleari)



PowHEG vs. MC@NLO (stolen from C.Oleari)

Higgs boson production at the LHC



NNLO result obtained with `HNNLO` by Catani & Grazzini

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

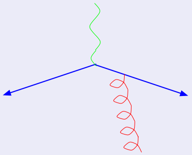
At NLL-Accuracy

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

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

Sudakov weights

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

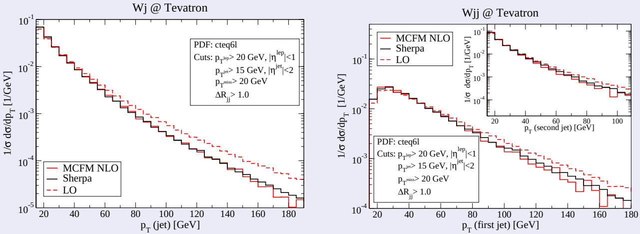


$$\mathcal{W}_{\rm Sud} = \frac{\alpha_s(q)}{\alpha_s(Q_{\rm jet})} \cdot \Delta_q(E_{\rm c.m.}, Q_{\rm jet}) \frac{\Delta_q(E_{\rm c.m.}, Q_{\rm jet})}{\Delta_q(q, Q_{\rm jet})}\Delta_q(q, Q_{\rm jet})\Delta_g(q, Q_{\rm jet})$$

Algorithm as scale-setting prescription

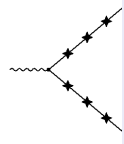
- Example: $p_\perp$ distribution of jets @ Tevatron
- Consider exclusive $W + 1$- and $W + 2$-jet production

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



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

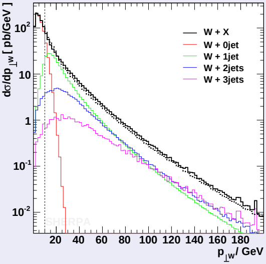
$\Longrightarrow$ Cancels dependence on $Q_{\rm jet}$.

Combining MEs & PS: Independence on Q_jet

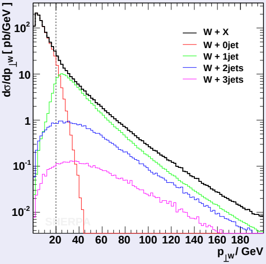
Example: $p_\perp$ of W in $p\bar{p} \to W + X$ @ Tevatron

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

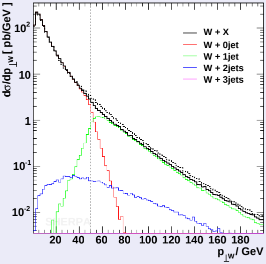
$Q_\mathrm{jet} = 10\,\mathrm{GeV}$



$Q_\mathrm{jet} = 30\,\mathrm{GeV}$

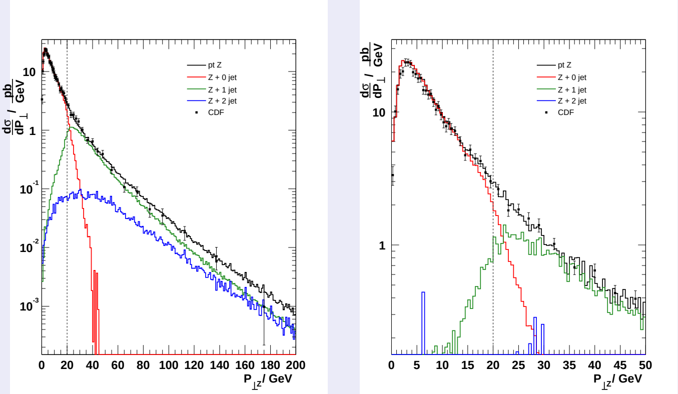


$Q_\mathrm{jet} = 50\,\mathrm{GeV}$



Comparison with data from Tevatron

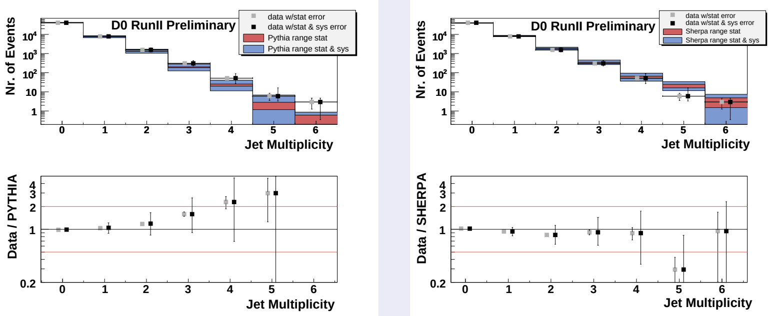
$p_\perp$ of Z-bosons



Combining MEs & PS

Comparison with data from Tevatron

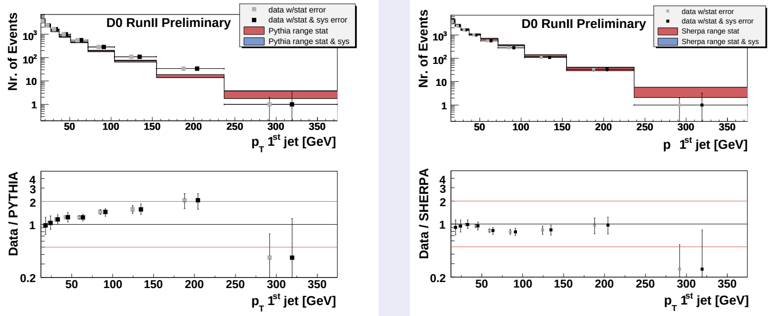
Jet multiplicities in $p\bar{p} \to Z + X$ (D0-Note 5066)



Combining MEs & PS

Comparison with data from Tevatron

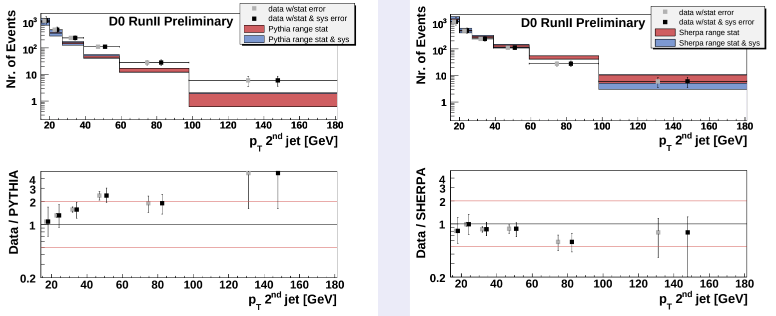
Jet spectra (1st jet) in $p\bar{p} \longrightarrow Z + X$ (D0-Note 5066)



Combining MEs & PS

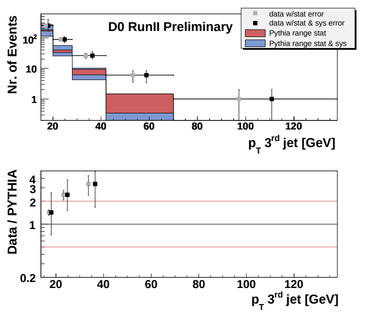
Comparison with data from Tevatron

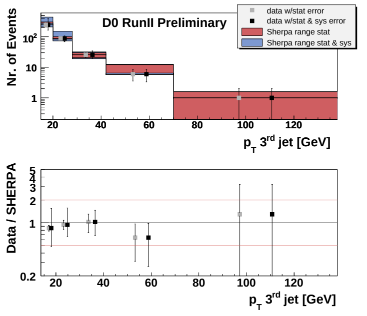
Jet spectra (2nd jet) in $p\bar{p} \longrightarrow Z + X$ (D0-Note 5066)



Comparison with RunII $Z + X$ data: $p_\perp^{j_3}$

(D0-Note 5066)

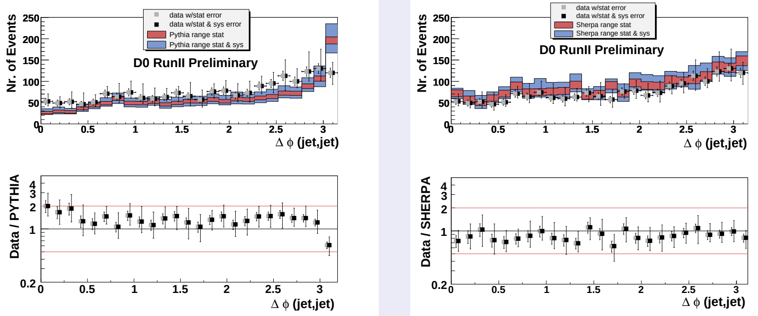




Combining MEs & PS

Comparison with data from Tevatron

Azimuthal correlation ($\angle_{1.\mathrm{jet},2.\mathrm{jet}}$) in $p\bar{p} \to Z + X$ (D0-Note 5066)



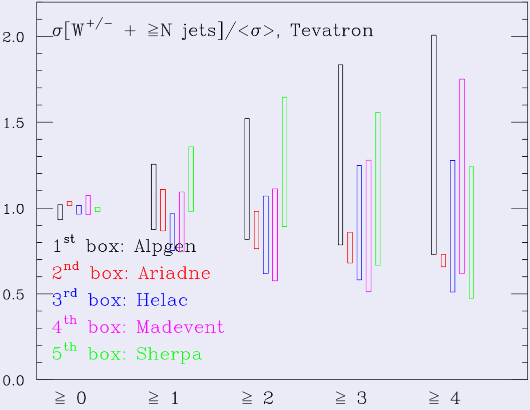
Other prescriptions

- 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.
- Theory: CKKW and CKKW-L equivalent, MLM not.

Comparison with other merging algorithms: MLM

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

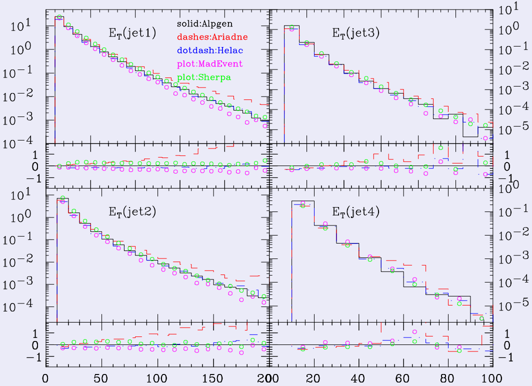
Jet rates in inclusive W+jets at Tevatron



Comparison with other merging algorithms: MLM

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

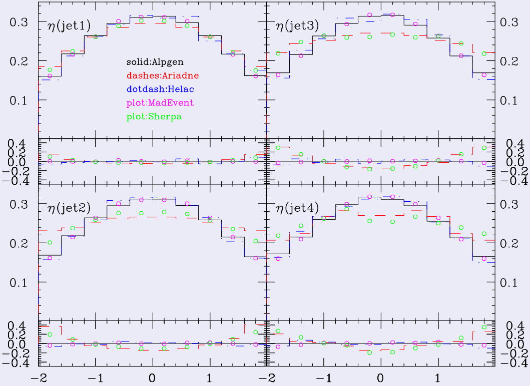
$p_\perp$ of jets in inclusive W+jets at Tevatron



Comparison with other merging algorithms: MLM

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

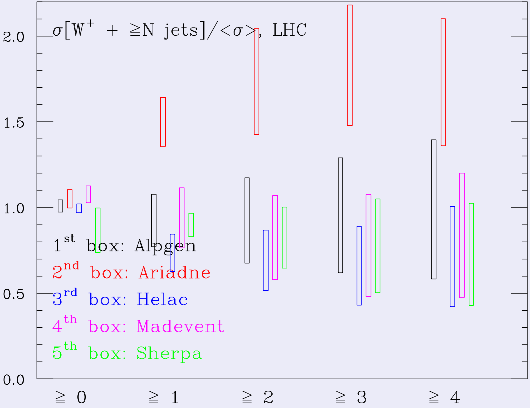
η of jets in inclusive W+jets at Tevatron



Comparison with other merging algorithms: MLM

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

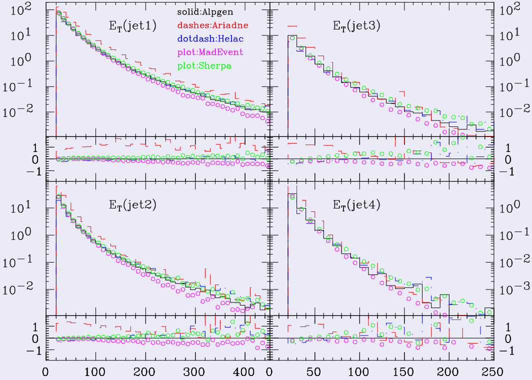
Jet rates in inclusive W+jets at LHC



Comparison with other merging algorithms: MLM

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

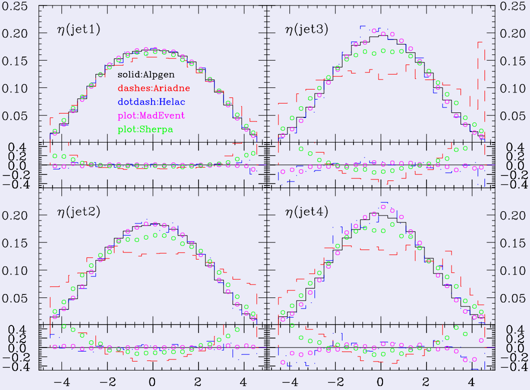
$p_\perp$ of jets in inclusive W+jets at LHC



Comparison with other merging algorithms: MLM

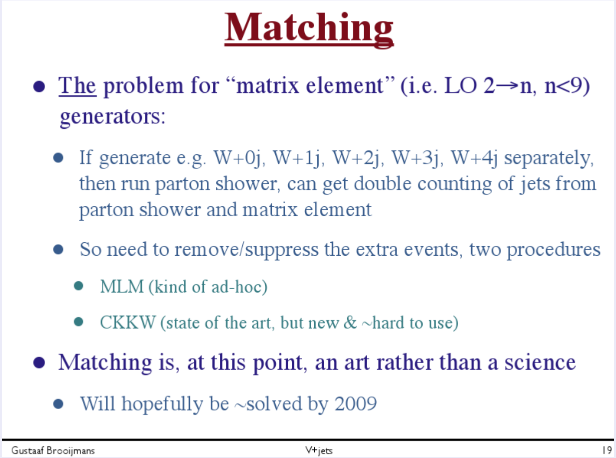
J.Alwall *et al.* Eur. Phys. J. **C53** (2008) 473

η of jets in inclusive W+jets at LHC



$V+$ jets at Tevatron: Experimental

Matching (stolen from G.Brooijmans)

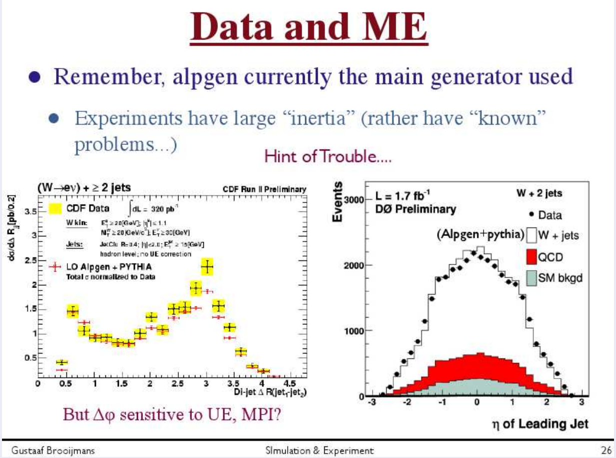


Matching

- The problem for "matrix element" (i.e. LO 2→n, n<9) generators:
  - If generate e.g. W+0j, W+1j, W+2j, W+3j, W+4j separately, then run parton shower, can get double counting of jets from parton shower and matrix element
  - So need to remove/suppress the extra events, two procedures
    - MLM (kind of ad-hoc)
    - CKKW (state of the art, but new & ~hard to use)
- Matching is, at this point, an art rather than a science
  - Will hopefully be ~solved by 2009

Gustaaf Brooijmans V+jets 19

Problems in matching (stolen from G.Brooijmans)



Data and ME

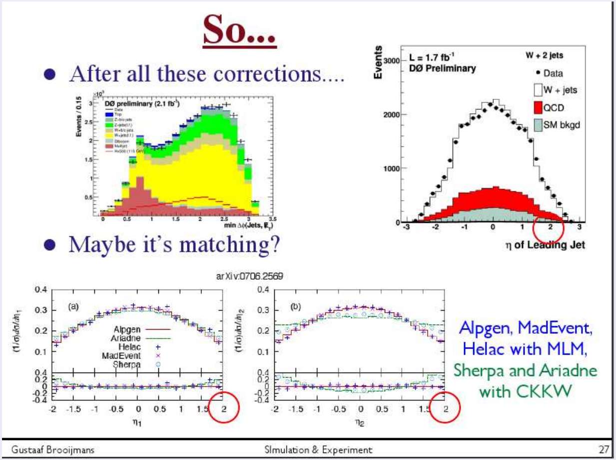
- Remember, alpgen currently the main generator used
  - Experiments have large "inertia" (rather have "known" problems…)

Hint of Trouble....

But Δφ sensitive to UE, MPI?

Gustaaf Brooijmans Simulation & Experiment 26

Problems in matching (stolen from G.Brooijmans)



So...

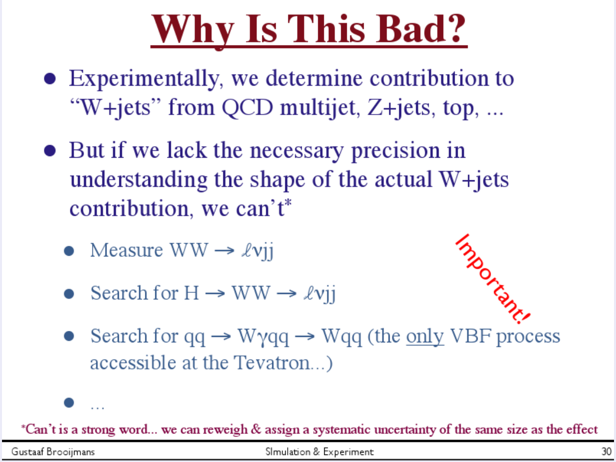
- After all these corrections....
- Maybe it's matching?

Alpgen, MadEvent, Helac with MLM, Sherpa and Ariadne with CKKW

arXiv:0706.2569

Gustaaf Brooijmans Simulation & Experiment 27

Problems in matching (stolen from G.Brooijmans)



Why Is This Bad?

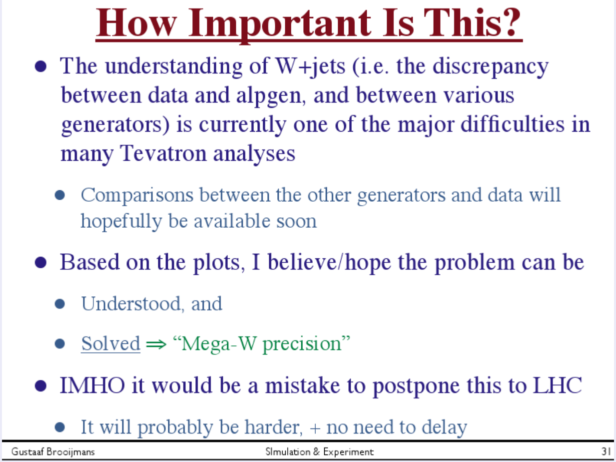
- Experimentally, we determine contribution to "W+jets" from QCD multijet, Z+jets, top, ...
- But if we lack the necessary precision in understanding the shape of the actual W+jets contribution, we can't*
  - Measure WW → $\ell\nu jj$
  - Search for H → WW → $\ell\nu jj$
  - Search for qq → Wγqq → Wqq (the <u>only</u> VBF process accessible at the Tevatron...)
  - ...

Important!

*Can't is a strong word... we can reweigh & assign a systematic uncertainty of the same size as the effect

Gustaaf Brooijmans Simulation & Experiment 30

Problems in matching (stolen from G.Brooijmans)

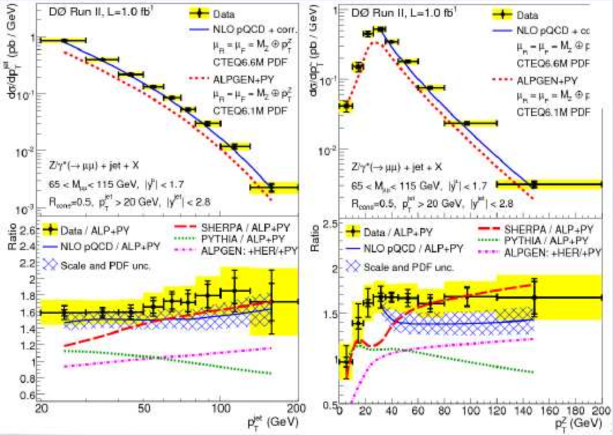


How Important Is This?

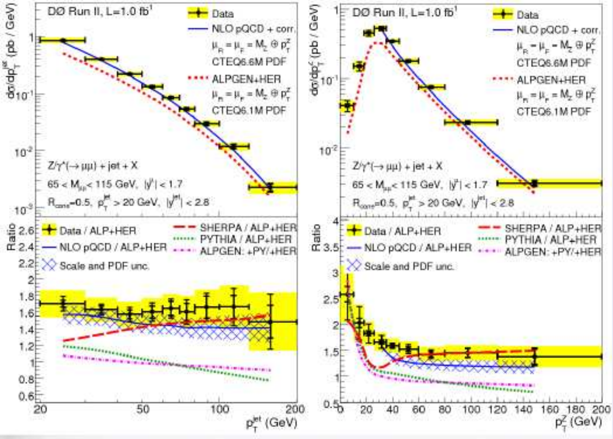
- The understanding of W+jets (i.e. the discrepancy between data and alpgen, and between various generators) is currently one of the major difficulties in many Tevatron analyses
    - Comparisons between the other generators and data will hopefully be available soon
- Based on the plots, I believe/hope the problem can be
    - Understood, and
    - Solved ⇒ "Mega-W precision"
- IMHO it would be a mistake to postpone this to LHC
    - It will probably be harder, + no need to delay

Gustaaf Brooijmans Simulation & Experiment 31

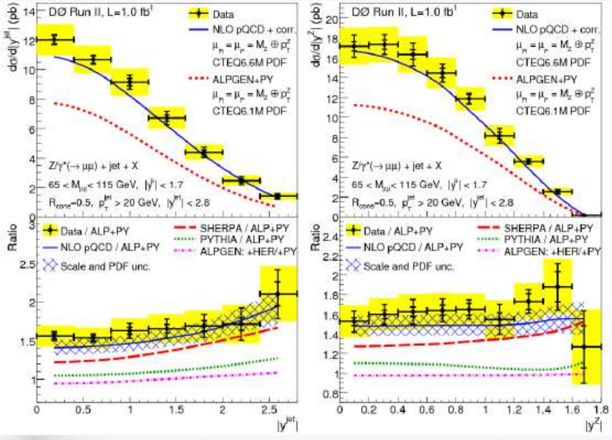
Sherpa & Alpgen vs. data



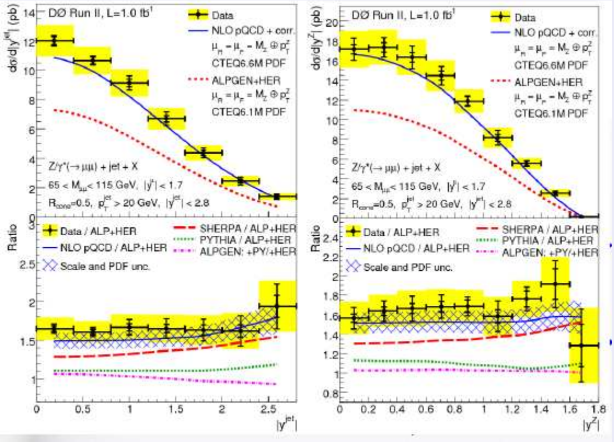
Sherpa & Alpgen vs. data



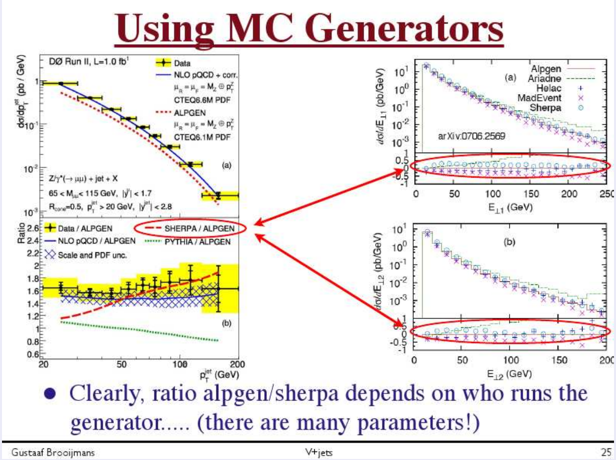
Sherpa & Alpgen vs. data



Sherpa & Alpgen vs. data



Interesting features: summary (stolen from G.Brooijmans)



Using MC Generators

- Clearly, ratio alpgen/sherpa depends on who runs the generator..... (there are many parameters!)

Gustaaf Brooijmans V+jets 25

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 and training needed

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), published recently.

Implementing CSW recursion relations: A snaphot

F.Cachazo, P.Svrcek and E.Witten, JHEP **0409** (2004) 006
R.Britto, F.Cachazo, B.Feng PRL**94** (2005) 181602

- Obtained summing over colours and helicities, sampling much better
- But: old-fashioned Berends-Giele methods superior

F.A.Berends, W.T.Giele NP**B306** (1988) 759

C.Duhr, S.Hoeche, F.Maltoni, JHEP **0608** (2006) 062

- $2 \to n$ gluons, 10^4 phase space points

n	BG, CO	BG, CD	CSW, CO	CSW, CD	BCF, CO	BCF, CD
2	0.24	0.28	0.31	0.26	0.28	0.33
4	1.2	1.04	1.63	1.75	0.84	1.32
6	14.2	7.19	27.8	30.6	11.9	59.1
8	276	82.1	919	1890	597	8690
10	7960	864	48900	-	64000	

COMIX - a new matrix element generator for Sherpa

T.Gleisberg & S.Hoeche, JHEP **0812** (2008) 039

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

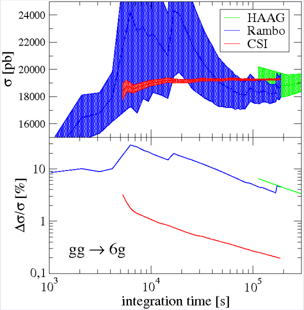
$gg \longrightarrow ng$	Cross section [pb]				
n $\sqrt{s}$ [GeV]	8 1500	9 2000	10 2500	11 3500	12 5000
Comix	0.755(3)	0.305(2)	0.101(7)	0.057(5)	0.019(2)
Maltoni (2002)	0.70(4)	0.30(2)	0.097(6)		
Alpgen	0.719(19)				

σ [μb]	Number of jets						
$b\bar{b}$ + QCD jets	0	1	2	3	4	5	6
Comix	470.8(5)	8.83(2)	1.826(8)	0.459(2)	0.1500(8)	0.0544(6)	0.023(2)
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)				

COMIX - a new matrix element generator for Sherpa

T.Gleisberg & S.Hoeche, JHEP **0812** (2008) 039

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



Further performance tests

T.Gleisberg, S.Hoche and F.K., arXiv:0808.3672 [hep-ph]

- All numbers on 2.53 GHz Intel Core Duo T9400 CPU
- List time for reaching the stat. error.

$pp \longrightarrow n$ jets gluons only	$n = 2$	$n = 3$	$n = 4$	$n = 5$	$n = 6$
$\delta\sigma$	0.1%	0.1%	0.2%	0.5%	1%
$\sigma_{MC}[pb]$	$8.915 \cdot 10^7$	$5.454 \cdot 10^6$	$1.150 \cdot 10^6$	$2.757 \cdot 10^5$	$7.95 \cdot 10^4$
CSW (HAAG)	4	165	1681	12800	$2 \cdot 10^6$
CSW (CSI)	-	480	6500	11900	197000
AMEGIC (HAAG)	6	492	41400	-	-
COMIX (RPG)	159	5050	33000	38000	74000
COMIX (CSI)	-	780	6930	6800	12400

Further performance tests

T.Gleisberg, S.Hoche and F.K., arXiv:0808.3672 [hep-ph]

- All numbers on 2.53 GHz Intel Core Duo T9400 CPU
- List time for reaching the stat. error.

$pp \longrightarrow n$ jets $le1$ quark line	$n = 2$	$n = 3$	$n = 4$	$n = 5$	$n = 6$
$\delta\sigma$	0.1%	0.1%	0.2%	0.5%	1%
σ_{MC} [pb]	$1.456 \cdot 10^8$	$1.051 \cdot 10^7$	$2.490 \cdot 10^6$	$6.75 \cdot 10^5$	$2.14 \cdot 10^5$
CSW (HAAG)	10	354	6980	60000	$9 \cdot 10^6$
AMEGIC (HAAG)	13	930	73000	-	-
COMIX (RPG)	254	5370	15900	36800	64100

$\leq$ 2 quark lines	$n = 2$	$n = 3$	$n = 4$	$n = 5$	$n = 6$
σ_{MC} [pb]	$1.5129 \cdot 10^8$	$1.1198 \cdot 10^7$	$2.831 \cdot 10^6$	$8.12 \cdot 10^5$	$2.71 \cdot 10^5$
CSW (HAAG)	16	730	12300	120000	$2 \cdot 10^7$
AMEGIC (HAAG)	19	1530	78000	-	-
COMIX (RPG)	525	10800	25600	59000	113000

Further performance tests

T.Gleisberg, S.Hoche and F.K., arXiv:0808.3672 [hep-ph]

- All numbers on 2.53 GHz Intel Core Duo T9400 CPU
- List time for reaching the stat. error.
- Note: With Comix can easily go up to ≤ 6 jets.

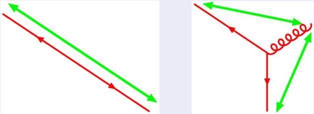
$pp \to Z + n$ jets gluons only	$n = 0$	$n = 1$	$n = 2$	$n = 3$	$n = 4$
$\sigma_{MC}[pb]$	1080.8	121.67	54.67	23.59	11.22
$\delta\sigma$	0.1%	0.1%	0.1%	0.2%	0.5%
CSW (MC)	12	210	4100	57000	1500000
AMEGIC (MC)	7	98	1060	10400	310000
COMIX (RPG)	15	364	6400	16400	54000

Dipole showers

Implemented in Ariadne (L.Lonnblad, Comput. Phys. Commun. **71**, 15 (1992)).

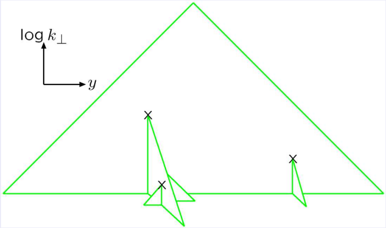
Upshot

- Expansion around soft logs, particles always on-shell
$$\mathrm{d}\sigma = \sigma_0 \frac{C_F\alpha_s(k_\perp^2)}{2\pi}\frac{\mathrm{d}k_\perp^2}{k_\perp^2}\mathrm{d}y.$$
- Always color-connected partners (recoil of emission)
$\Longrightarrow$ emission: 1 dipole → 2 dipoles.



- Quantum coherence on similar grounds for angular and k_T-ordering.

Radiation pattern

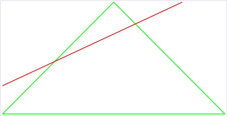


IS Radiation

- There is none! (in Ariadne)

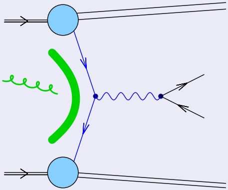
  Treat radiation in DIS as FS radiation between remnant & quark

  Thus, no real Dipole Shower for *pp* collisions.
- Cut FS phase space of remnants:



Initial state dipole showers

J.Winter & F.K., JHEP **0807**, 040 (2008)

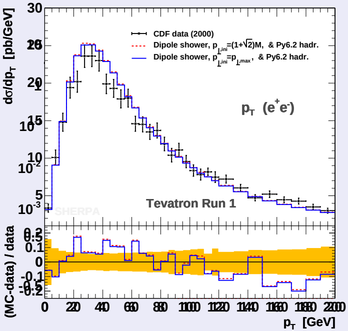


- Complete perturbative formulation.
- Dipoles and their radiation associated to **IS-IS**, **IS-FS** and **FS-FS** colour lines.
- Beam remnants kept outside evolution.
- Onshell kinematics, evolution in $k_\perp$.

Results for the new dipole shower

J.Winter & F.K., JHEP **0807**, 040 (2008)

- Testbed: DY production.
- P_T spectrum of Z^0 boson.
- Mainly recoils vs. 1st emission:
  by construction: ME-corrected.



A new parton shower approach

Using Catani-Seymour splitting kernels

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.

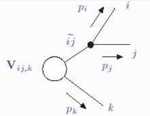
- Catani-Seymour dipole subtraction terms as universal framework for QCD NLO calculations.
- Factorization formulae for real emission process:
- Full phase space coverage & good approx. to ME.

Example: final-state final-state dipoles

splitting: $\tilde{p}_{ij} + \tilde{p}_k \longrightarrow p_i + p_j + p_k$

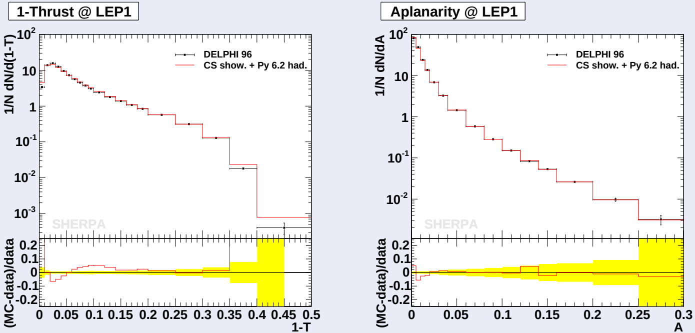
variables: $y_{ij,k} = \frac{p_i p_j}{p_i p_j + p_i p_k + p_j p_k}\,, \quad z_i = \frac{p_i p_k}{p_i p_k + p_j p_k}$

consider $\mathrm{q}_{ij} \longrightarrow \mathrm{q}_i \mathrm{g}_j$: $\langle V_{\mathrm{q}_i \mathrm{g}_j,k}(\tilde{z}_i, y_{ij,k})\rangle = C_F \left\{ \frac{2}{1-\tilde{z}_i+\tilde{z}_i y_{ij,k}} - (1+\tilde{z}_i) \right\}$



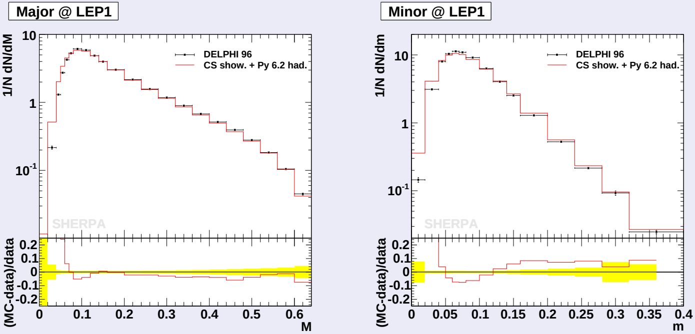
Results in e^+e^- collisions at LEP1

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



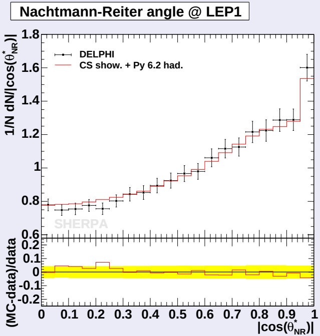
Results in e^+e^- collisions at LEP1

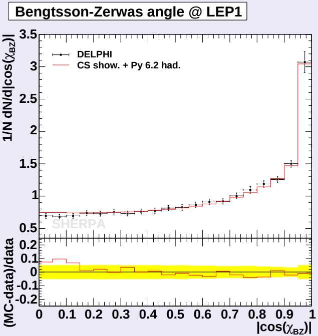
S.Schumann& F.K., JHEP **0803** (2008) 038.



Results in e^+e^- collisions at LEP1

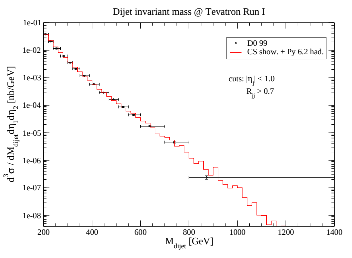
S.Schumann& F.K., JHEP **0803** (2008) 038.



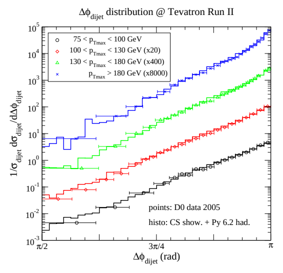


CS-Shower: Results in $p\bar{p}$ collisions

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



Dijet invariant mass @ Tevatron Run I



$\Delta\phi_{dijet}$ distribution @ Tevatron Run II

CS-Shower: Results in $p\bar{p}$ collisions

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