Simulation of jet physics at hadron colliders

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Outline

improving QCD jet modelling through multi-leg tree-level calculations

- **The physics: multi-particle final states at the LHC**
- **The tools: Monte Carlo event generators**
  - the parton shower approach
  - (multi-leg tree-level calculations)
- **The method: combining matrix elements and parton showers**
  - merging prescriptions: anatomy and systematics
  - sample applications: DY+jets, $t\bar{t}+$jets

Setting the scene: physics at the LHC

main objectives for the LHC era

- reveal the mechanism of EWSB [discovery of the Higgs?, alternatives?]
- search for physics beyond the SM: weak scale SUSY, ED, W’ & Z’, ...

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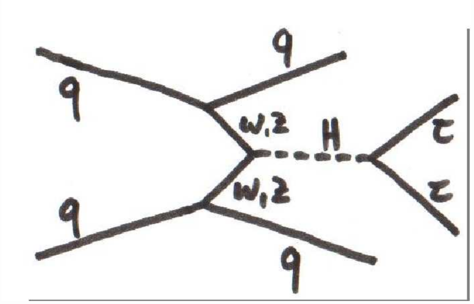
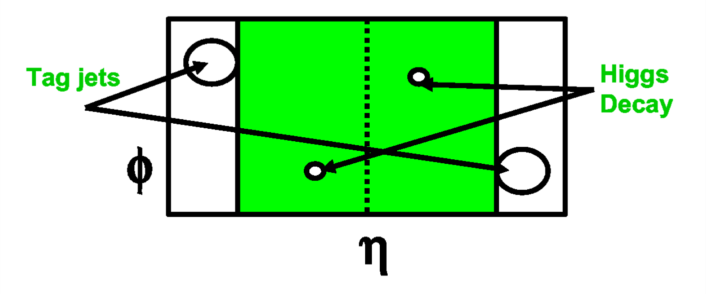
example: Higgs production in weak boson fusion



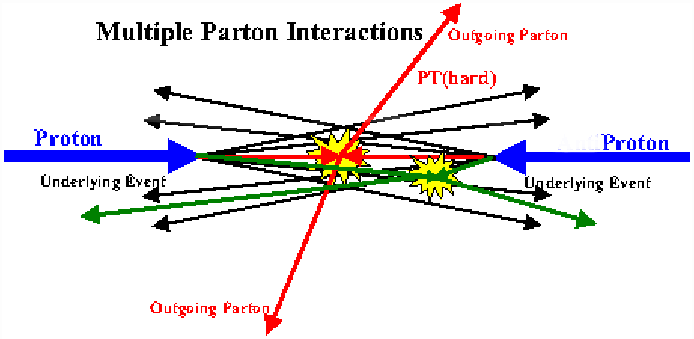


- rapidity gap between two forward tagged jets
- signal/background ratio depends on central jet veto

What happens at higher orders?

How well can we model the backgrounds?

Does the underlying event spoil the signal?



Setting the scene: physics at the LHC

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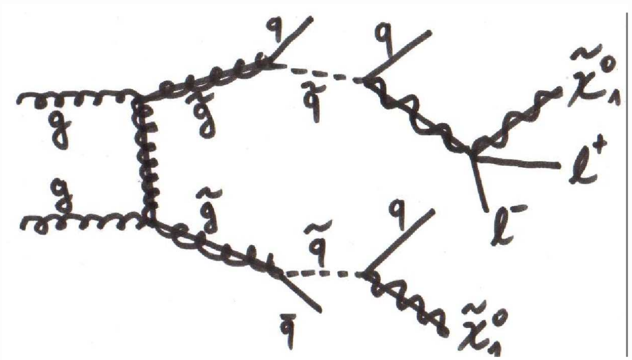
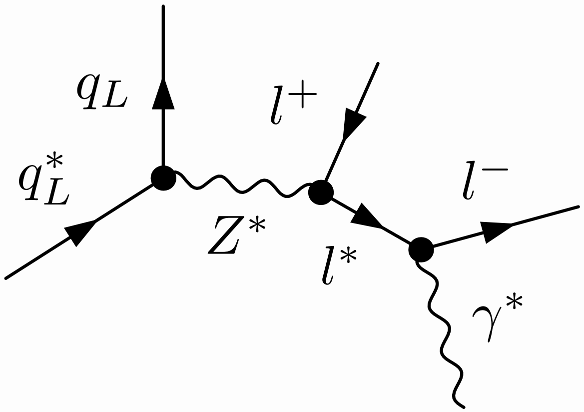
example: cascade decays of new heavy states





➔ signals: leptons + n-jets + $\not{E}_T$

➔ backgrounds: QCD jets, V+jets, VV+jets, $t\bar{t}$+jets

➔ jet properties depend on nature of new physics [energies, flavours, edges]

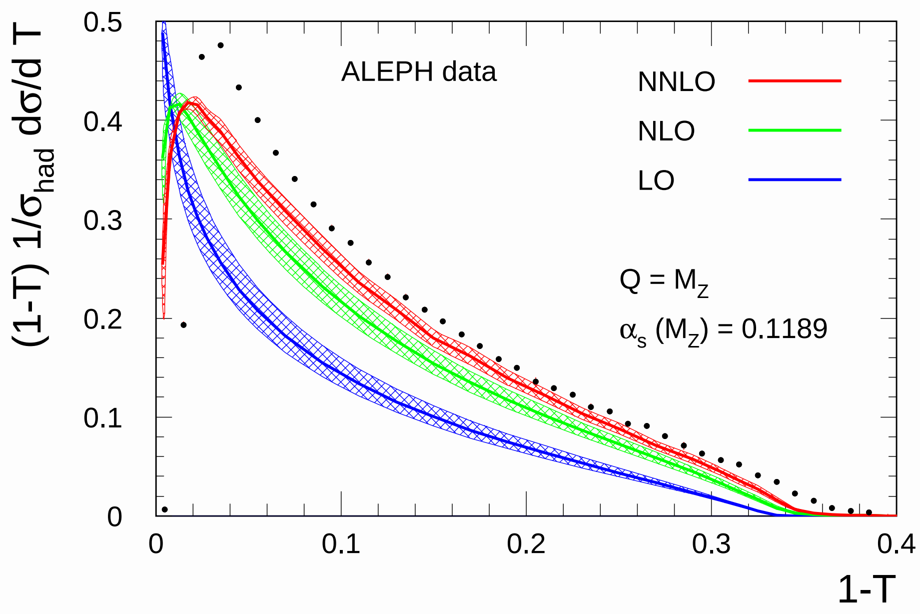
How well can we describe the multi-jet backgrounds?

Setting the scene: perturbative aspects

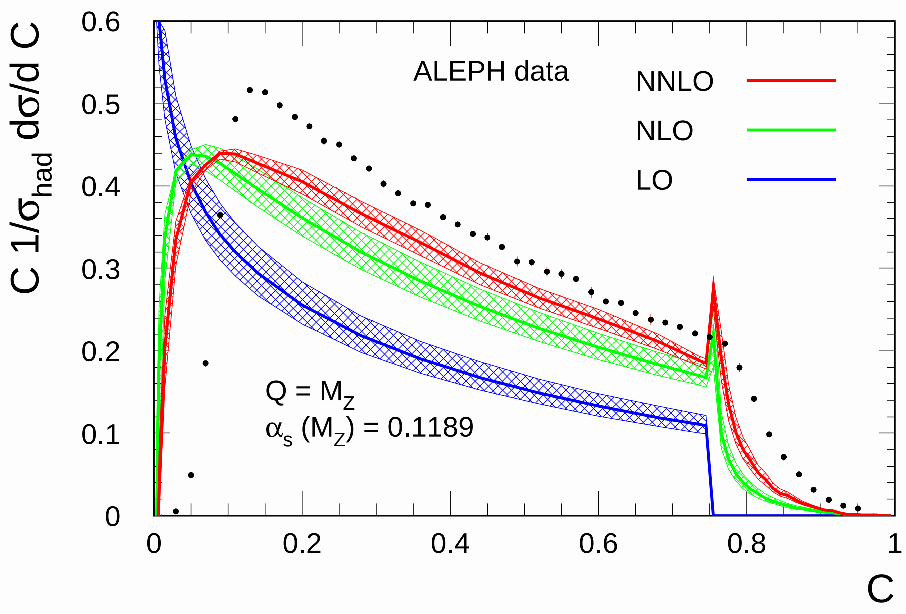
NNLO corrections to event shapes in e^+e^- annihilation

[A. Gehrmann-De Ridder, T. Gehrmann, E. W. N. Glover and G. Heinrich, arXiv:0711.4711]

1-T



C-parameter

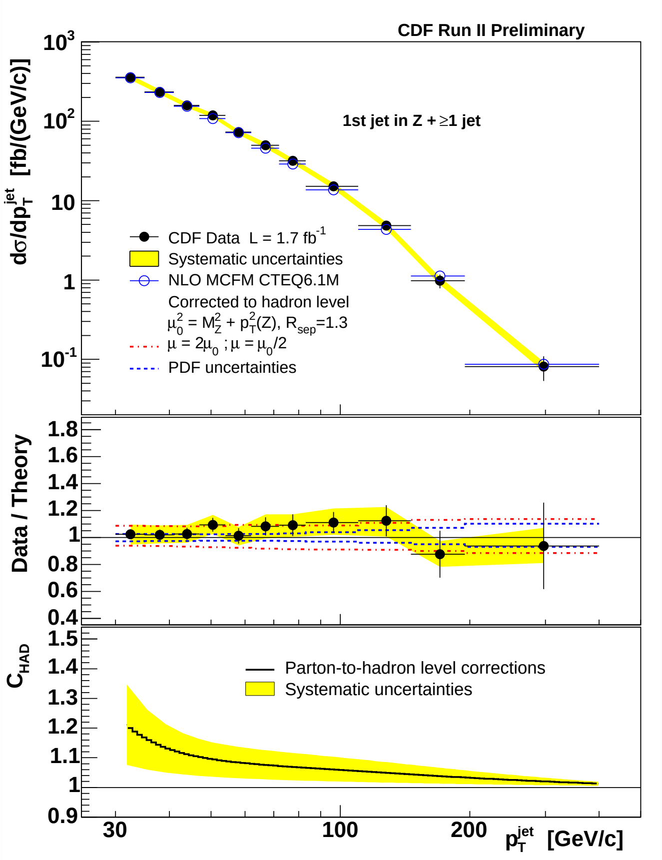


- strong need for higher order QCD calculations (multiple emissions)
  - accurate rate prediction
  - reduced scale uncertainties
- but, have to consider all-orders resummation of large logarithms as well

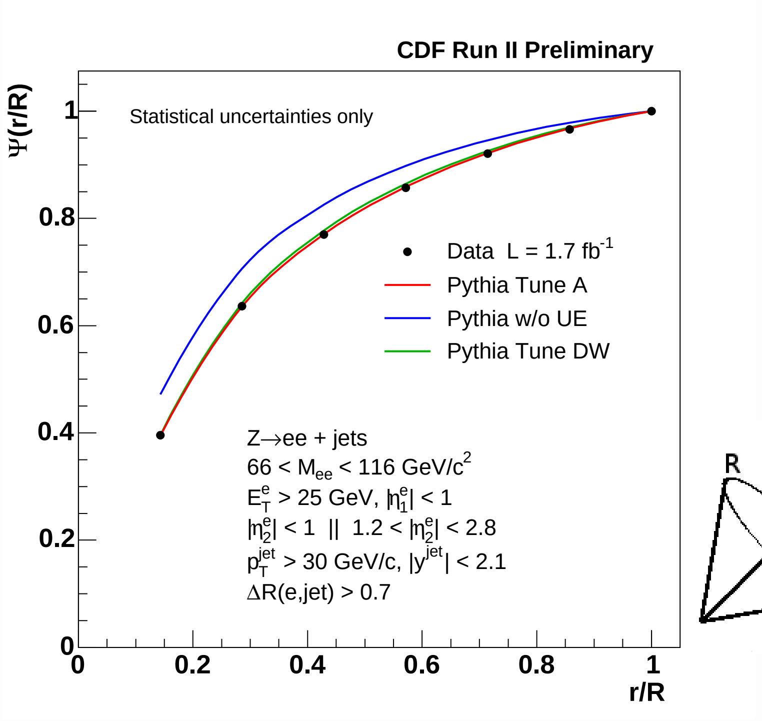
Setting the scene: non-perturbative aspects

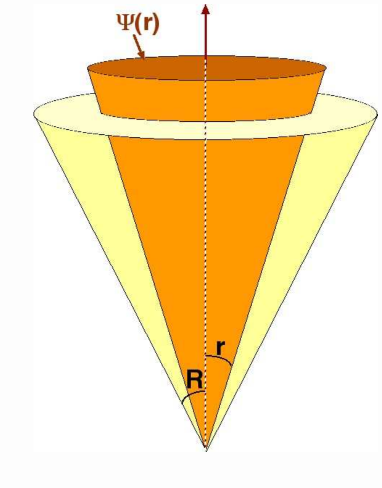
jet observables in $p\bar{p} \to Z(\to e^+e^-) + X$ @ CDF [CDF note 8827]

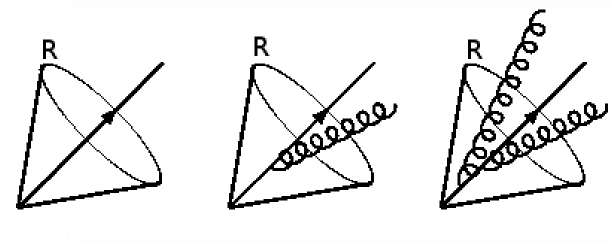
p_T-1st jet



jet shape $\Psi(r)$





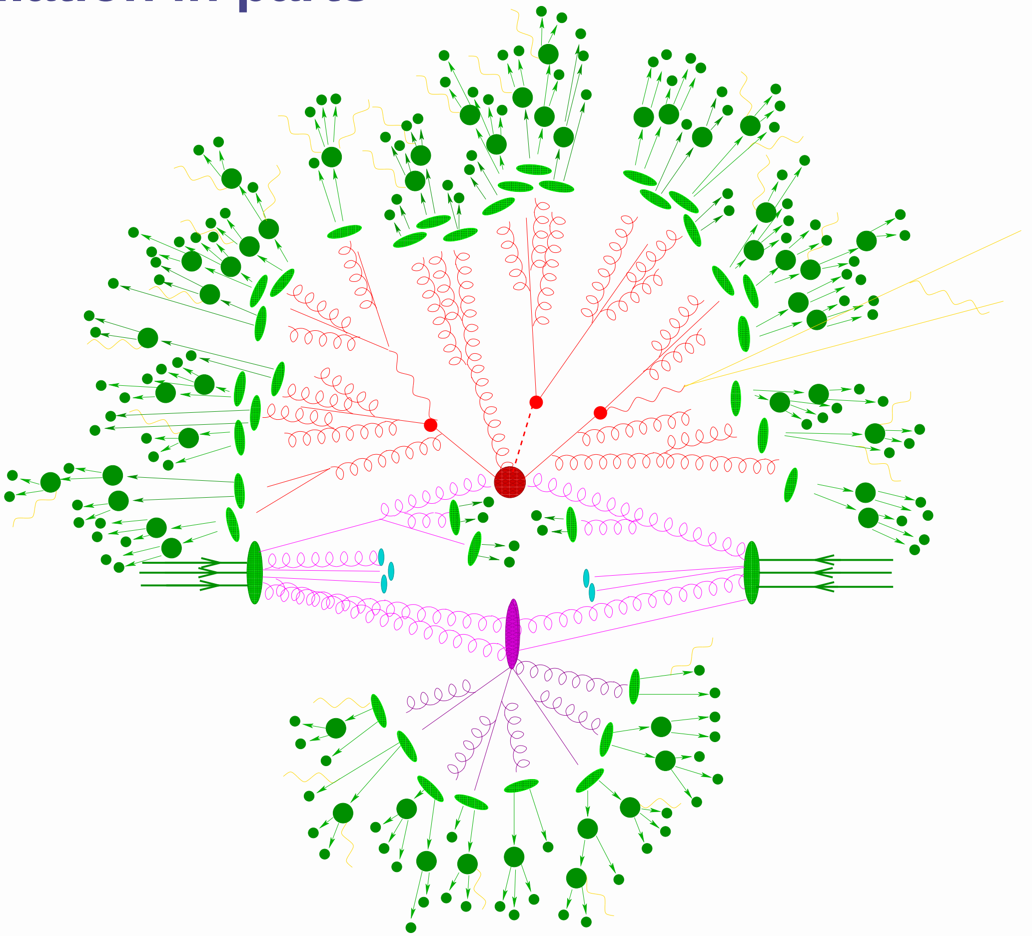


- corrections needed to compare fixed order with data [Monte Carlo studies]
- account for non-perturbative aspects like hadronisation & underlying event

Monte Carlo Event Generators

Monte Carlo paradigm: split the simulation in parts

- **Signal/Background process**
  exact matrix elements
- **QCD bremsstrahlung**
  parton showers in the initial and final state
- **Multiple Interactions**
  beyond factorisation: modelling
- **Hadronisation**
  non perturbative QCD: modelling
- **Hadron Decays**
  phase space or effective theories



➔ **fully exclusive hadronic final states**

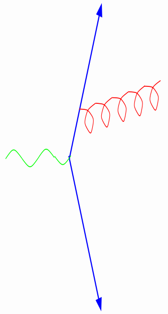
➔ **can directly be compared with experimental data**

Herwig, Pythia,Sherpa

Parton showers in a nutshell

QCD emissions are enhanced near the collinear and/or soft limit

- propagator factor for $\mathrm{q} \to \mathrm{qg}$ splitting (or $\mathrm{g} \to \mathrm{gg}$)



$$\frac{1}{(p_q + p_g)^2} \simeq \frac{1}{2E_q E_g (1 - \cos\theta_{qg})}$$

[soft- and collinear divergences dominate the matrix element]

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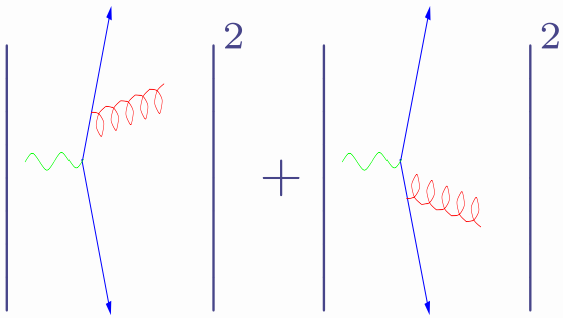

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- cross section factorises in the collinear limit

$$|\mathcal{M}_{\mathrm{q\bar{q}g}}|^2 \mathrm{d}\Phi_{\mathrm{q\bar{q}g}} \approx |\mathcal{M}_{\mathrm{q\bar{q}}}|^2 \mathrm{d}\Phi_{\mathrm{q\bar{q}}} \left\{ \frac{\mathrm{d}t_{\mathrm{qg}}}{t_{\mathrm{qg}}} \frac{\alpha_S}{2\pi} P_{\mathrm{q,qg}}(z_{\mathrm{q}}) \mathrm{d}z_{\mathrm{q}} + \frac{\mathrm{d}t_{\mathrm{\bar{q}g}}}{t_{\mathrm{\bar{q}g}}} \frac{\alpha_S}{2\pi} P_{\mathrm{\bar{q},\bar{q}g}}(z_{\bar{q}}) \mathrm{d}z_{\bar{q}} \right\}$$

with $z_{\mathrm{q}} = p^0_{\mathrm{q}}/(p^0_{\mathrm{q}} + p^0_{\mathrm{g}})$ and $P_{\mathrm{q,qg}}(z_{\mathrm{q}}) = C_{\mathrm{F}} \frac{1+z_{\mathrm{q}}^2}{1-z_{\mathrm{q}}}$ (spin averaged Altarelli-Parisi kernels)

$$\int\limits_{t_o}^{t} \frac{\mathrm{d}\tilde{t}}{\tilde{t}} \int\limits_{\sqrt{t_o/\tilde{t}}}^{1-\sqrt{t_o/\tilde{t}}} \frac{\mathrm{d}z}{1-z} \sim \ln^2 \frac{t}{t_o}$$

$\Rightarrow$ **double leading logarithms**

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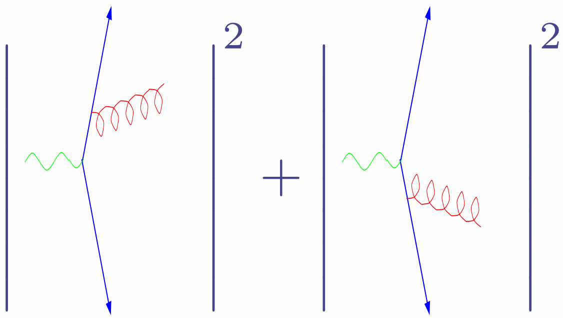

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- probability for no emission off a quark line from t to t_o ($> \Lambda_{\mathrm{QCD}}$)

$$\Delta_{\mathrm{q}}(t_o, t) \equiv \exp\left(-\int_{t_o}^{t} \frac{\mathrm{d}\tilde{t}}{\tilde{t}} \int_{\sqrt{t_o/\tilde{t}}}^{1-\sqrt{t_o/\tilde{t}}} \mathrm{d}z \frac{\alpha_S(\tilde{t}, z)}{2\pi} P_{\mathrm{q,qg}}(z) \right)$$

$\Rightarrow$ **Sudakov form factor**

Parton showers in a nutshell

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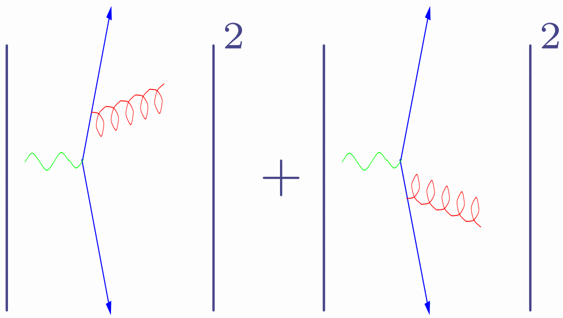

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$\Rightarrow$ **Sudakov form factor**

- probability for $\mathrm{q} \to \mathrm{qg}$ splitting at $t' < t$

$$\mathrm{d}\mathcal{P} = \Delta_{\mathrm{q}}(t', t) \frac{\alpha_S(t', z)}{2\pi} \frac{1}{t'} P_{\mathrm{q,qg}}(z) \mathrm{d}t' \mathrm{d}z$$

$\Rightarrow$ **emissions ordered in t**

Parton showers in a nutshell

main features of parton shower approach

- emissions of soft/collinear partons from initial & final state [resum LL]
- evolve partons from high scales to low scales [ordered in t: virtuality, angle, p_T]
- allow for incorporation of universal hadronisation models [scales $\mathcal{O}(1\ \mathrm{GeV})$]

limitations

- shower seeds are leading-order QCD processes only [Herwig,Pythia]
- lack of high-energetic large-angle emissions
- interferences and correlations only approximate

} needs exact $|\mathcal{M}|^2$

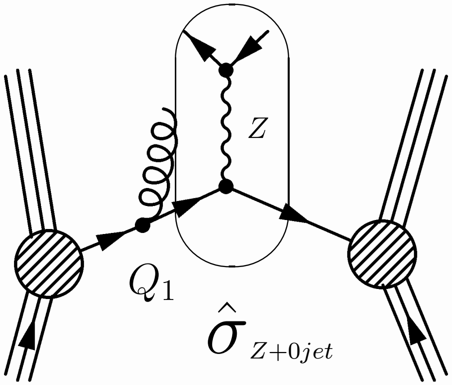
passing lanes

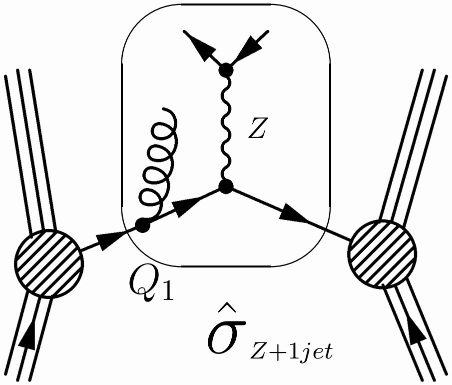
- first few hardest emissions according to exact tree-level matrix elements [called ME+PS merging – CKKW, MLM]
- take NLO QCD core processes instead [called MC at NLO]
- go beyond the present shower approximations [subleading colour,...]

Combining ME and PS

objectives

- provide good description for soft and hard emissions [PS pros + ME pros]
- incorporate quantum interferences and correlations
- avoid double counting of phase space configurations in PS & ME





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solution

- divide multi-jet phase space in two regimes [measure $Q_{\rm cut}$ or $\Delta R_{\rm min}\&E_{T,{\rm min}}$]
  - jet seeds produced through tree-level ME's [hard partons]
  - jets evolved down to fragmentation scale by PS
- reweight MEs to get exclusive samples at resolution scale

  $\Rightarrow$ allows to add samples of different ME jet multiplicities
- reject PS configurations taken into account by higher order ME

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features

- inclusive samples with up to $n_{\rm max}$-jets described by MEs
- process independent implementation feasible
- rates leading order only, but real corrections included

Combining ME and PS – CKKW

The CKKW method [Catani,Krauss,Kuhn,Webber 2001; Krauss 2002]

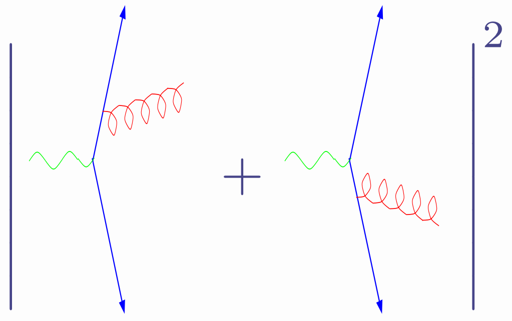
[as implemented in Sherpa, using built-in ME generator Amegic++]

- evaluate MEs $X + 0, 1, .., n_{\max}$–jets at k_T-resolution $Q_{\rm cut}$ [regulator,μ_F,μ_R]
- select a jet multiplicity with probability

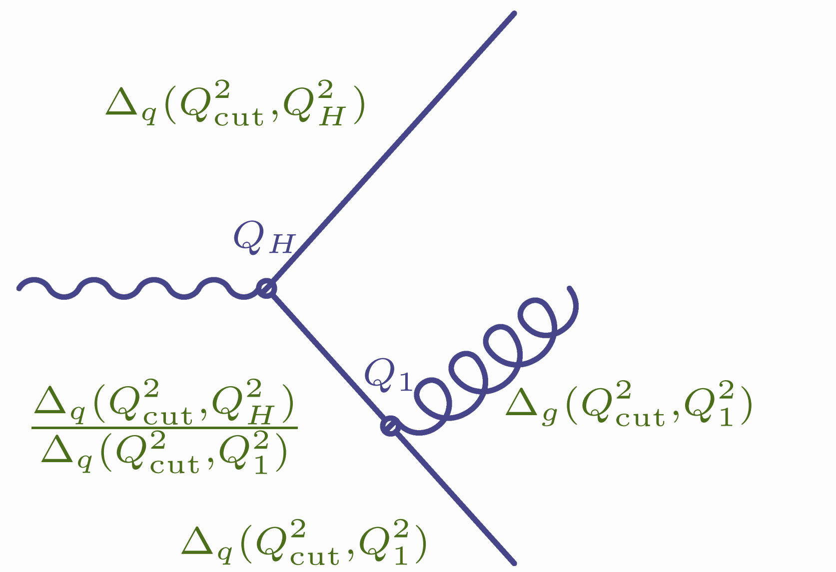
$$P_n = \frac{\sigma_n}{\sum_{i=0}^{n_{\max}} \sigma_i}$$

- generate final-state momenta p_i according to the ME
- reweight ME according to a reconstructed pseudo shower history
  - determine jet emission scales $Q_{\rm n}$,...,Q_1 with a k_T cluster algorithm
  - calculate corresponding Sudakov weights
    - $\Delta_{q,g}(Q^2_{\rm cut}, Q^2_{\rm prod})$ for outgoing partons
    - $\Delta_{q,g}(Q^2_{\rm cut}, Q^2_{\rm prod})/\Delta_{q,g}(Q^2_{\rm cut}, Q^2_{\rm dec})$ for lines between $Q_{\rm prod} > Q_{\rm dec}$
  - recalculate α_S at each vertex in the tree at the corresponding k_T scale
- start initial- or final-state parton shower for all partons of the events
  - at scale where it was produced
  - veto on shower emissions above the scale $Q_{\rm cut}$

Combining ME and PS – CKKW



shower history $\Longrightarrow$ exclusive event



$$W=\Delta_g(Q^2_{\rm cut},Q^2_1)[\Delta_q(Q^2_{\rm cut},Q^2_H)]^2\,\frac{\alpha_s(Q^2_1)}{\alpha_s(Q^2_{\rm cut})}$$

$\hookrightarrow$ inclusive events for $n_{\rm max}$

replace $Q_{\rm cut}$ by $Q_{n_{\rm max}}$

- general implementation for e^+e^- and hadron colliders in Sherpa
- $Q_{\rm cut}$ dependence cancels to (N)LL accuracy
- a variant, the Lönnblad scheme, implemented for Ariadne

Combining ME and PS – MLM

The MLM method [Mangano 2002]

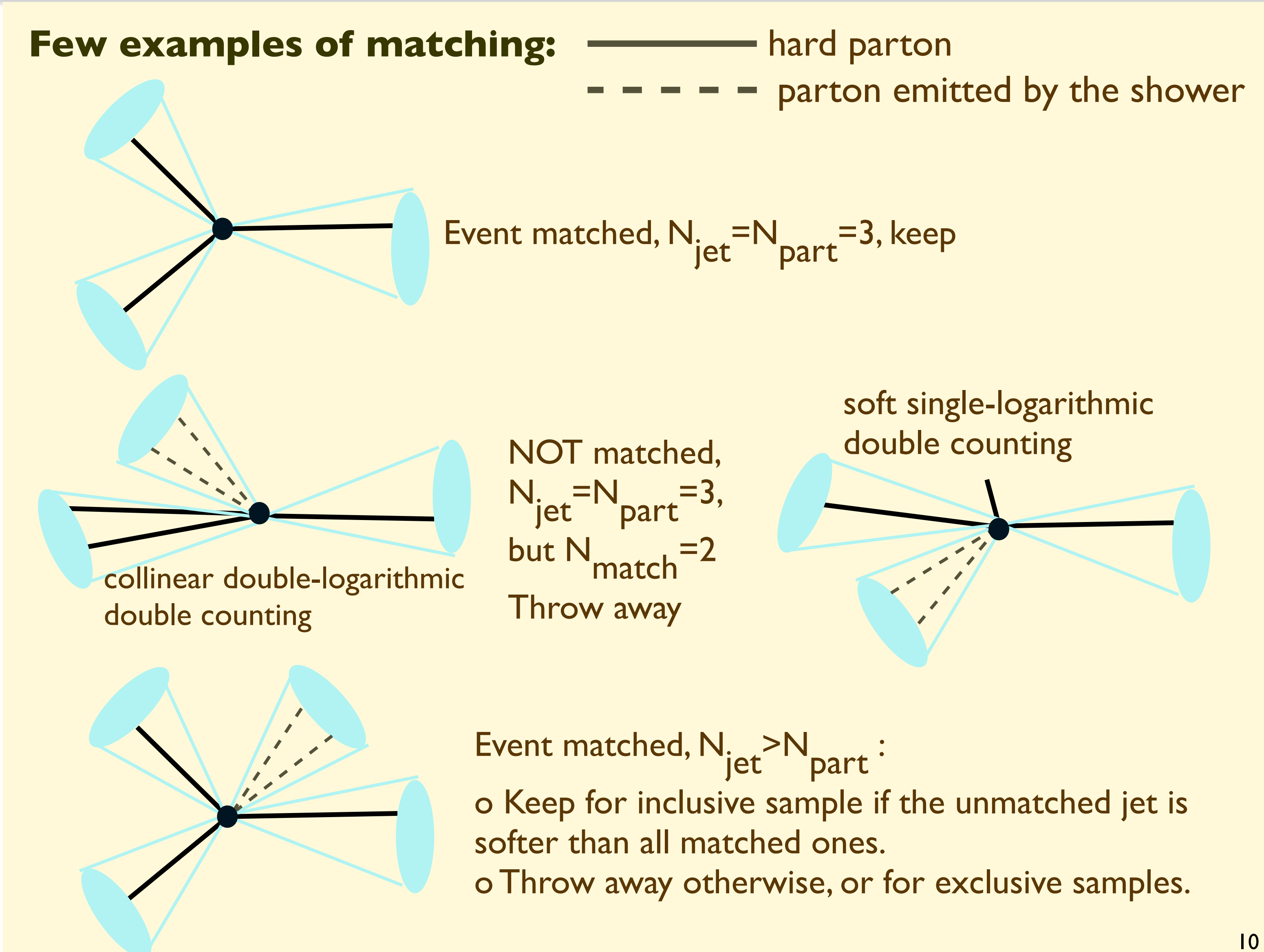
[as implemented for Alpgen, combined with Herwig or Pythia showers]

- evaluate the $n = 0, .., n_{\rm max}$-parton MEs with cone measure $R_{\rm min}$ & $E_{T,\rm min}$
- α_S at k_T scales
- generate unweighted events for each multiplicity
- perform showering by Herwig or Pythia [LHA interface]
- after showers (before hadronisation) run cone finder with $R_{\rm clus}$ and $E_{T,\rm clus}$
- try to geometrically match ME partons with jets after showering
  - for each ME parton select the jet with minimal $\Delta R_{\rm j,parton}$
  - if $\Delta R_{\rm j,parton} < R_{\rm match}$ the parton is "matched" [default $R_{\rm match}$ =1.5$R_{\rm clus}$]
  - a jet can be matched to a single parton only
  - if all partons are matched, keep the event, else reject it

  $\Rightarrow$ this defines an inclusive sample, $n_{\rm jet} \geq n_{\rm max}$

  $\Rightarrow$ for exclusive sample require in addition $n_{\rm jet} = n$
- after matching combine exclusive and inclusive samples

Combining ME and PS – MLM

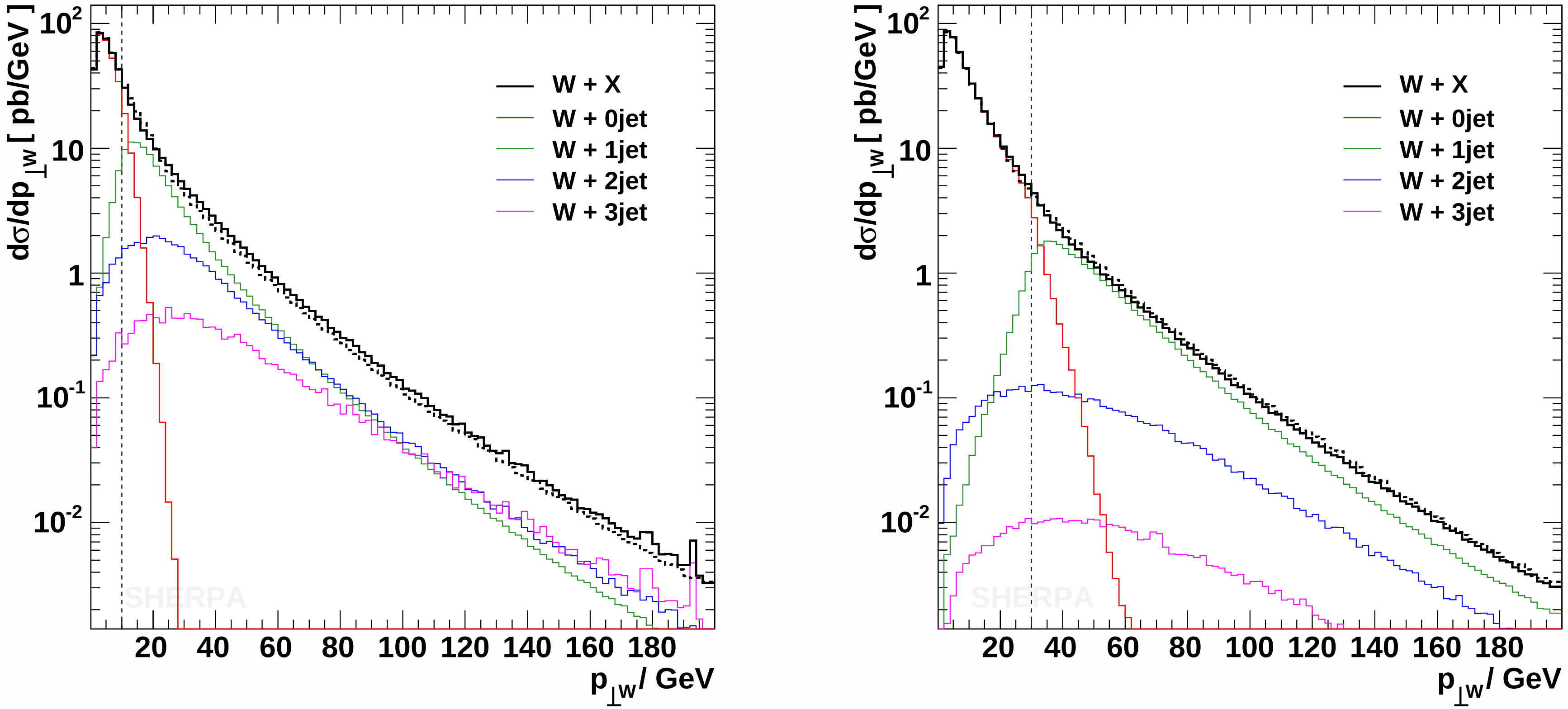


➔ variants implemented for MadGraph & Helac/Phegas

Sherpa consistency checks: variation of Q_{cut}

$p_\perp$ distribution of the W^- in $p\bar{p} \to e^- \, \bar{\nu}_e + X$ @ $\sqrt{s} = 1.96$ TeV

[Krauss, Schälicke, S., Soff, 2004]



Q_{cut}=10 GeV Q_{cut}=30 GeV

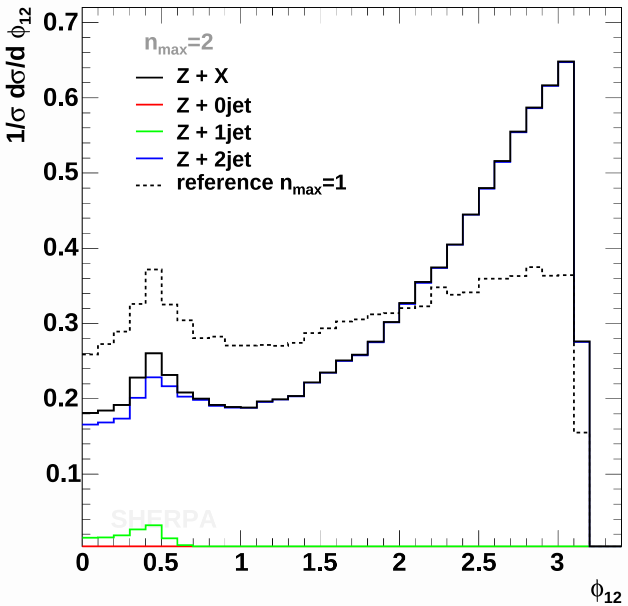
[dashed reference Q_{cut}=20 GeV]

➔ combines different multiplicity final states into fully inclusive sample

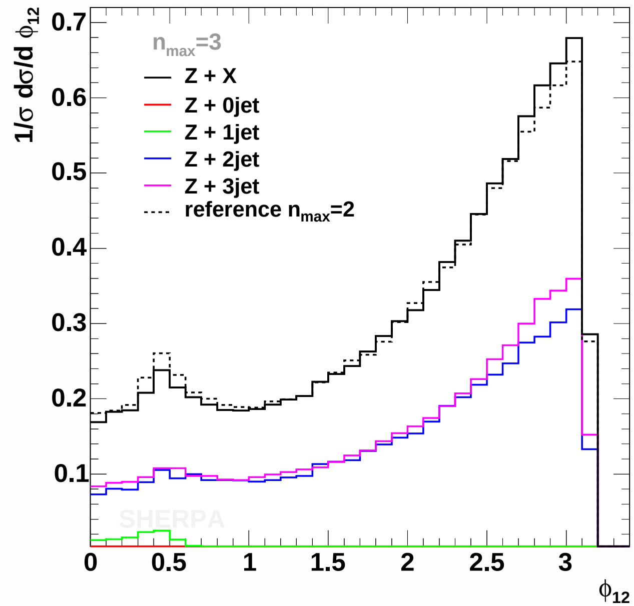
Sherpa consistency checks: variation of n_{max}

The $\Delta\phi$ separation of the two hardest k_T-jets in $pp \to e^+e^- + X$ @ LHC

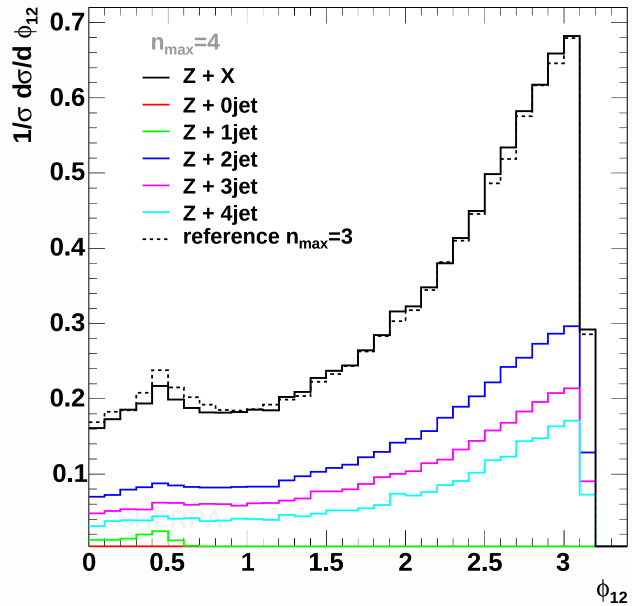
[Krauss, Schälicke, S., Soff, 2005]



$n_{\rm max}$=2



$n_{\rm max}$=3



$n_{\rm max}$=4

two-jet observable in DY

[dashed reference $\tilde{n}_{\rm max} = n_{\rm max} - 1$]

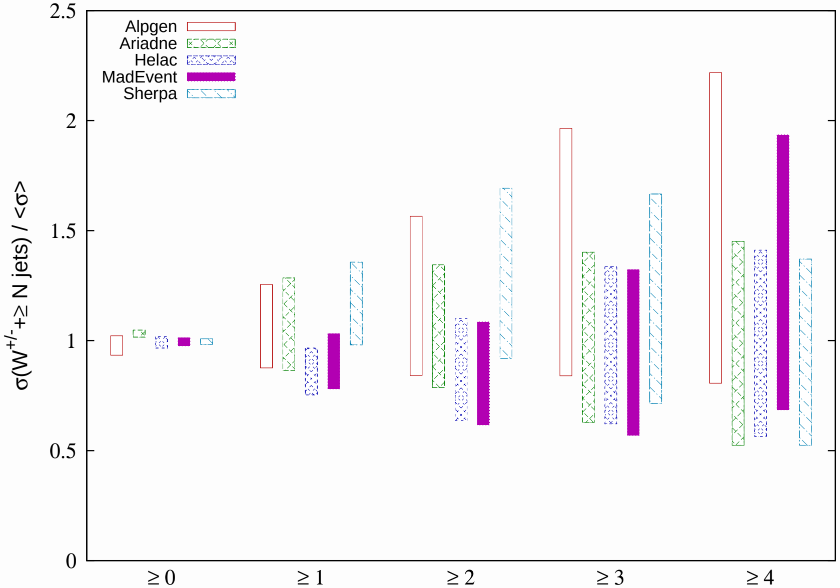
- standard shower accurracy $\sum_{n=2}^{\infty} \alpha_S^n \ln^{2n} Q^2/Q_0^2$, uncorrelated emissions
- merging approach yields $\alpha_S^2 \sum_{n=0}^{\infty} \alpha_S^n \ln^{2n} Q^2/Q_0^2$, full ME correlations

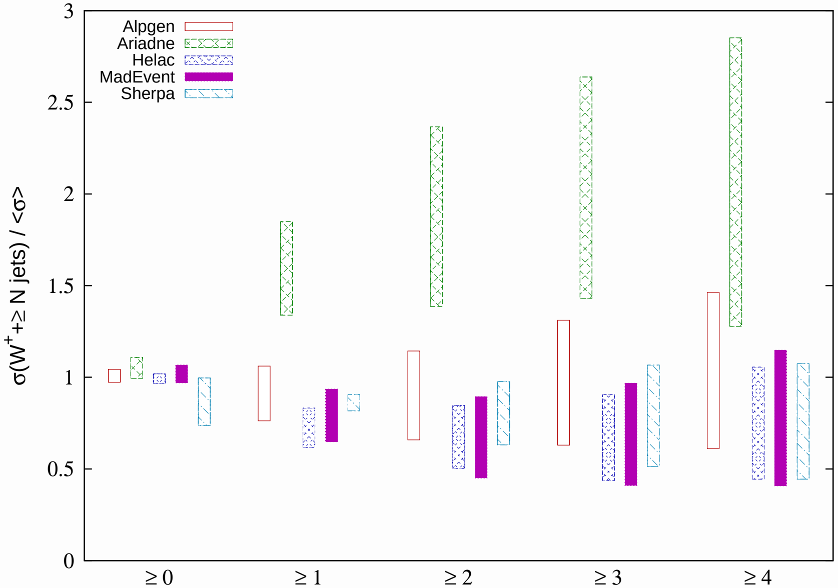
Comparative study of merging algorithms for W+jets

comparing implementations for ME+PS merging [Alwall et al. 2007]

- up-to 4 matrix element jets taken into account [hadron level, UE off]
- analysed for cone jets with $\Delta R = 0.7(0.4)$, $E_T = 10(20)$ GeV at TEV(LHC)
- attempt to estimate the systematics for each generator
  - residual dependence on merging params, $Q_{\rm cut}$, $E_{T,\rm clus}$, ($\Delta R_{\rm clus}$, $n_{\rm max}$)
  - scale dependencies: $\alpha_S(k_\perp$ vs. 0.5$k_\perp$ vs. 2$k_\perp$), Sherpa also μ_F

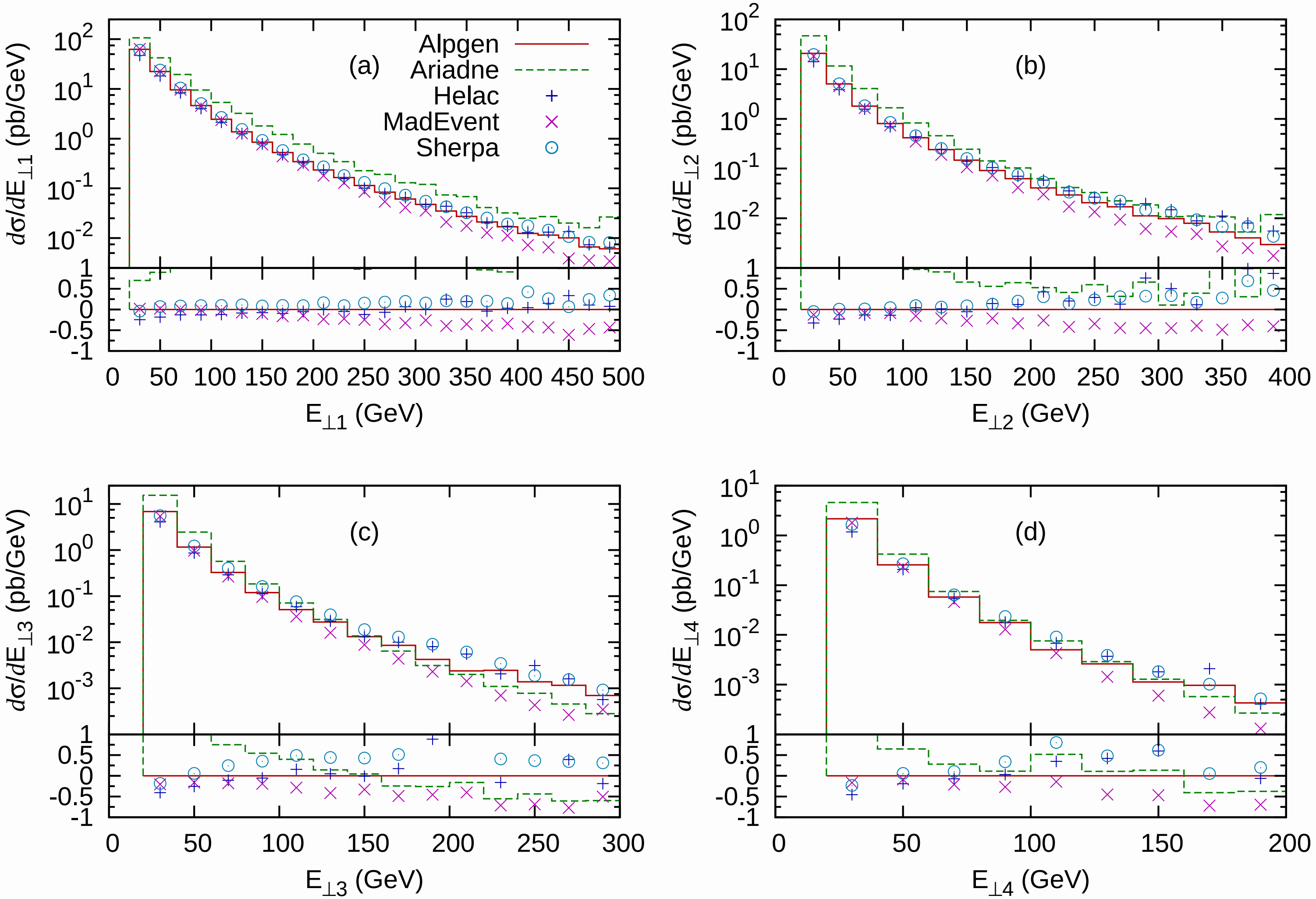
multi-jet rate variations @ Tevatron & LHC





Comparative study of merging algorithms for W+jets

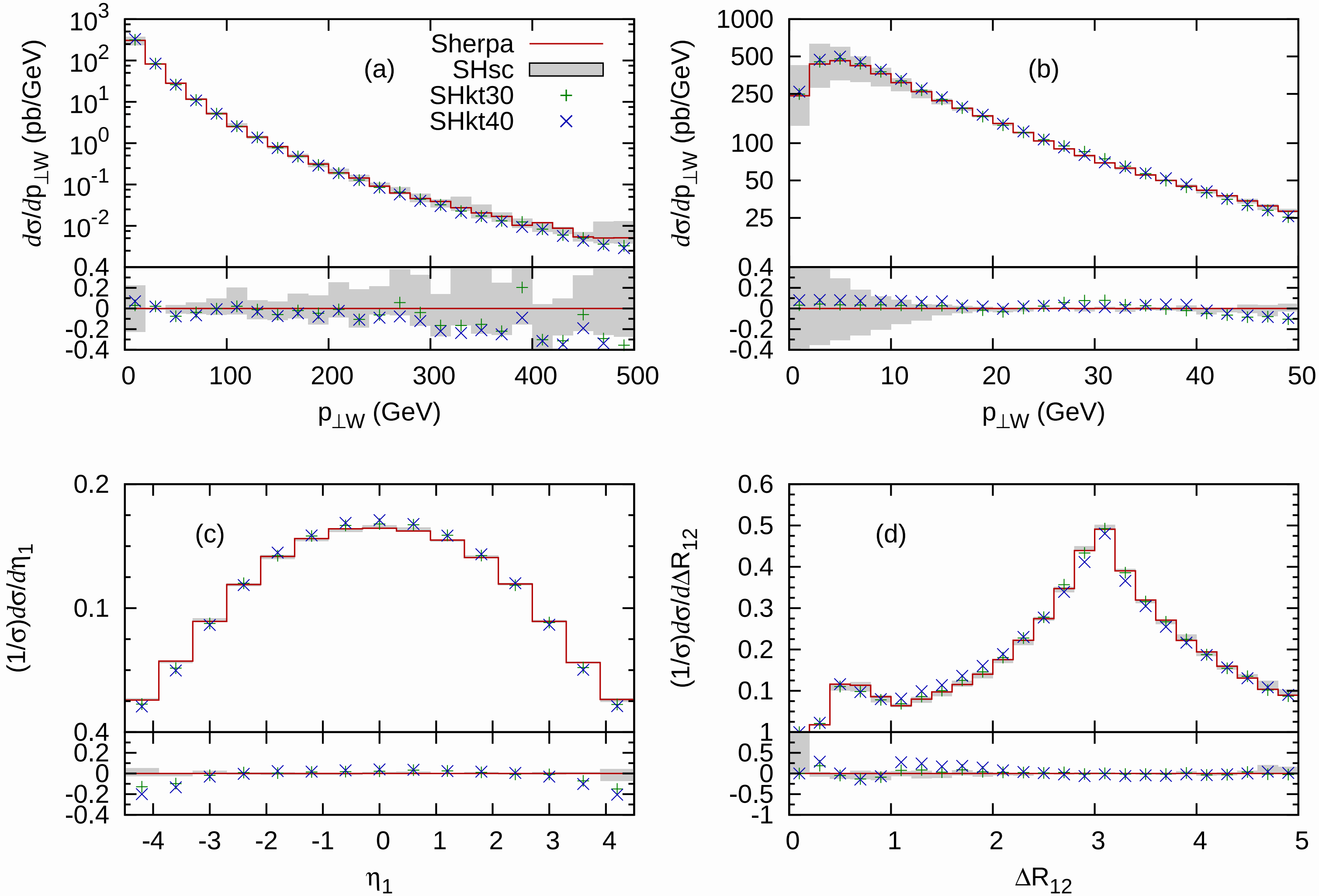
jet transverse energies @ LHC [Alpgen as reference in lower panels]



➔ similar pattern for Tevatron & LHC energies: Tevatron studies desirable

Comparative study of merging algorithms for W+jets

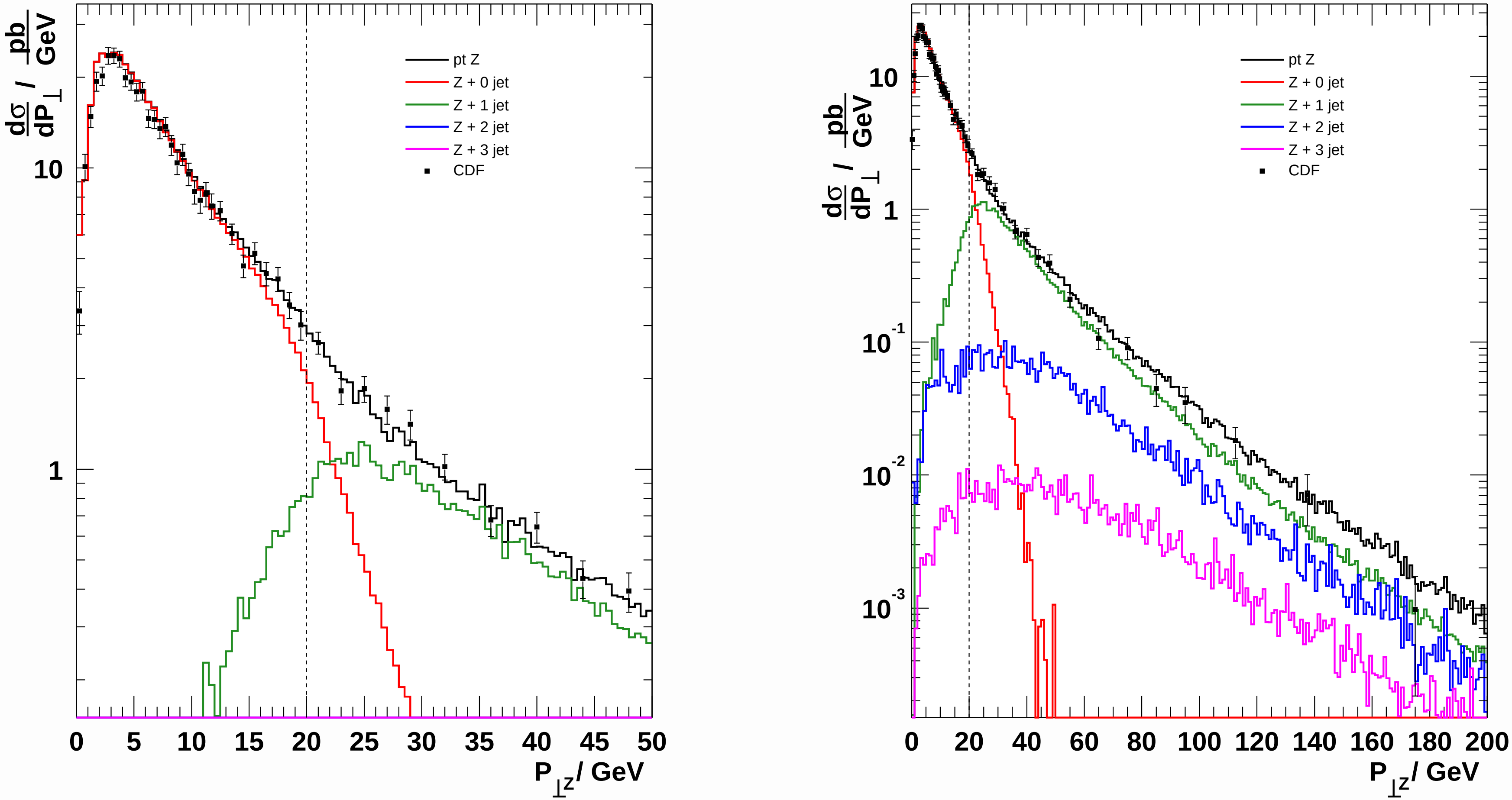
Sherpa's uncertainty band @ LHC



➔ again similar pattern for Tevatron

Sherpa comparison with data: DY

$p_\perp$ distribution of the Z measured by CDF

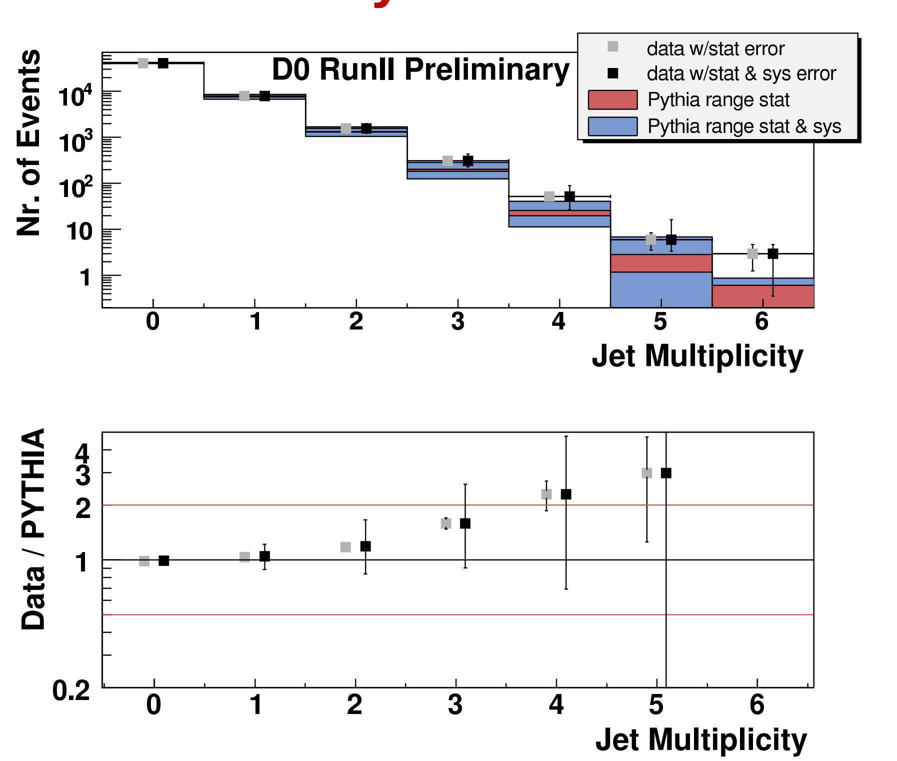


- distribution multiplied by appropriate K-factor!
- good description of soft and hard region

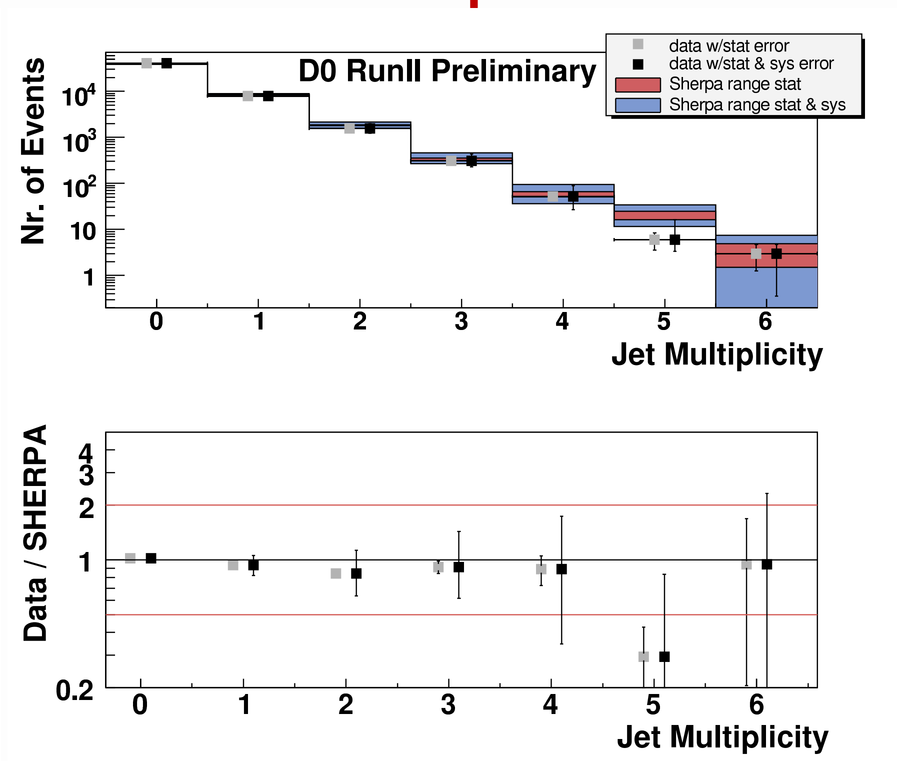
Sherpa comparison with data: DY

e^+e^-+jets @ Tevatron RunII: jet-multiplicities [DØ Note 5066]

Pythia



Sherpa

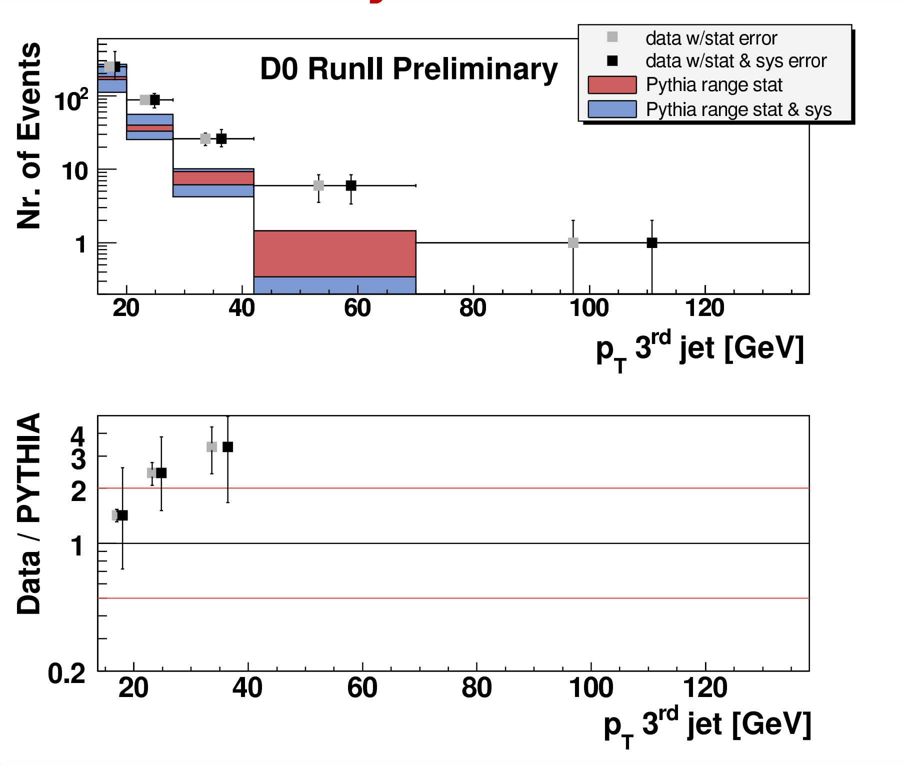


- inclusive samples normalised to total number of measured events
- pure shower approach underestimates multi-jet contributions

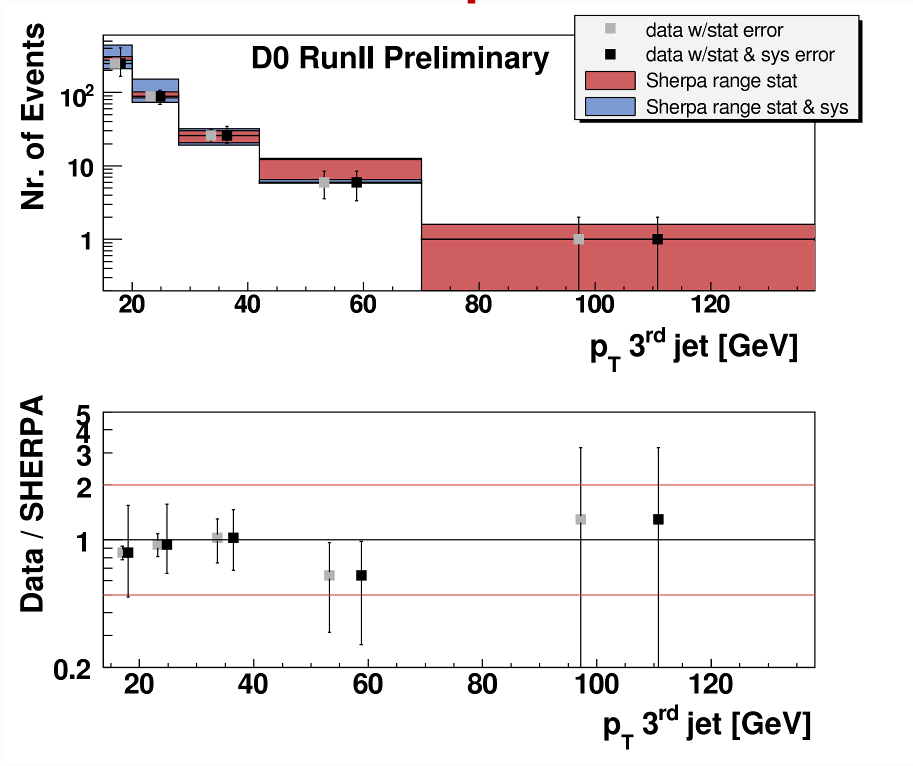
Sherpa comparison with data: DY

e^+e^-+jets @ Tevatron RunII: $p_\perp$ of the third jet [DØ Note 5066]

Pythia



Sherpa



- the more hard jets you require the worse gets the leading log approximation
- similar analyses done for Alpgen within CDF

Alpgen + Herwig for $t\bar{t}$+X: consistency checks

inclusive $t\bar{t}$ production @ Tevatron & LHC [Mangano et al. 2006]

- ME generation Tevatron(LHC): $E_{T,min} = 20(30)$ GeV, $R_{\min} = 0.7(0.7)$
- matching parameters: $E_{T,\text{clus}} = 25(36)$ GeV, $R_{\text{match}} = 1.5 \times 0.7$
- inclusive xsecs: merged $t\bar{t} + 0, 1$ (S_1) vs. $t\bar{t} + 0, 1, 2, 3$ (S_3) hard partons

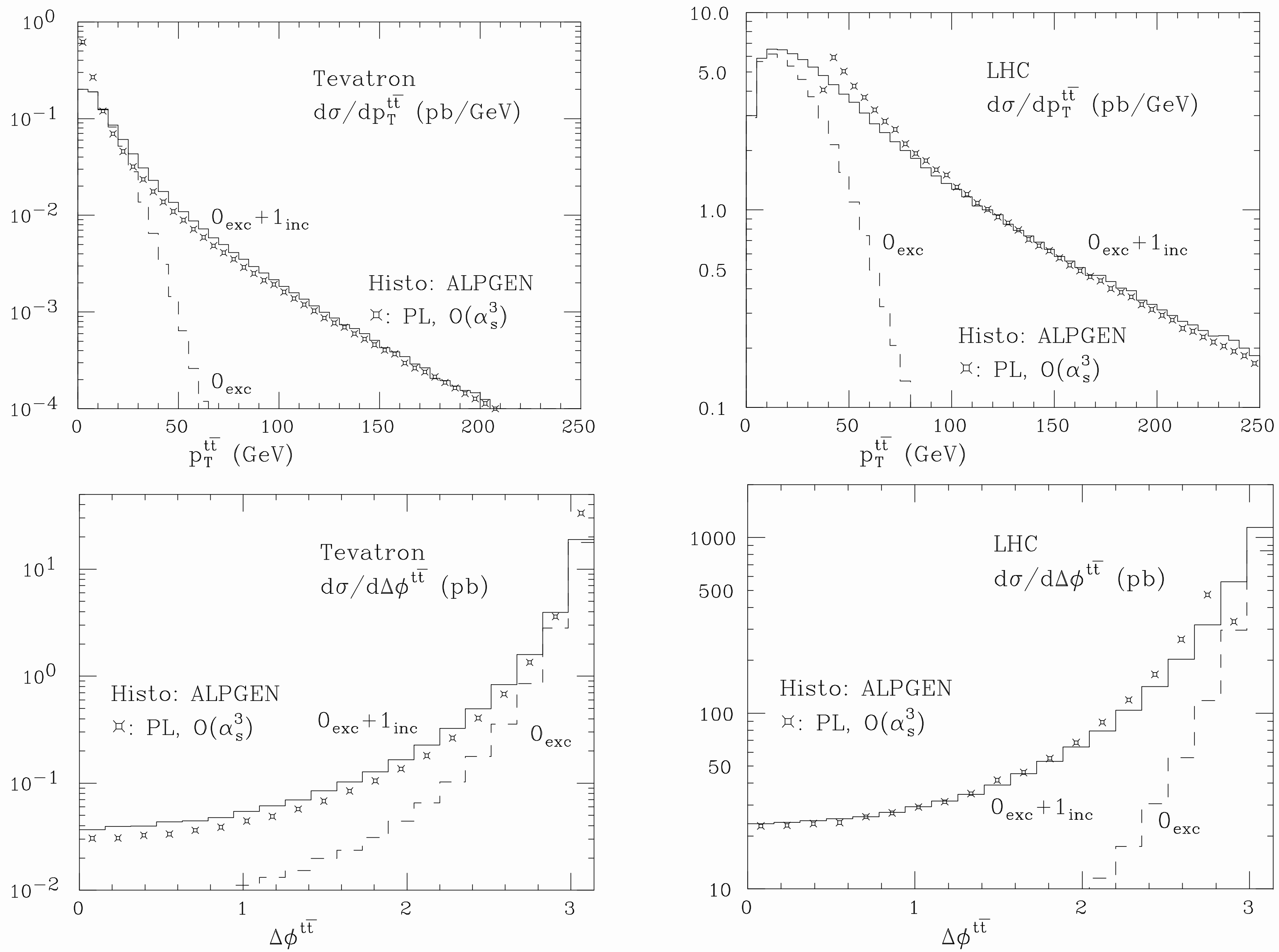
	Tevatron	LHC
0_{exc}	3.42	217
1_{inc}	0.78	252
total	**4.20**	**469**

	Tevatron	LHC
0_{exc}	3.42	216.6
1_{exc}	0.66	149.9
2_{exc}	0.09	65.8
3_{inc}	0.010	29.9
total	**4.18**	**462.2**

➔ naive leading order results for $t\bar{t}$+X Tevatron(LHC): **4.37(471) pb**

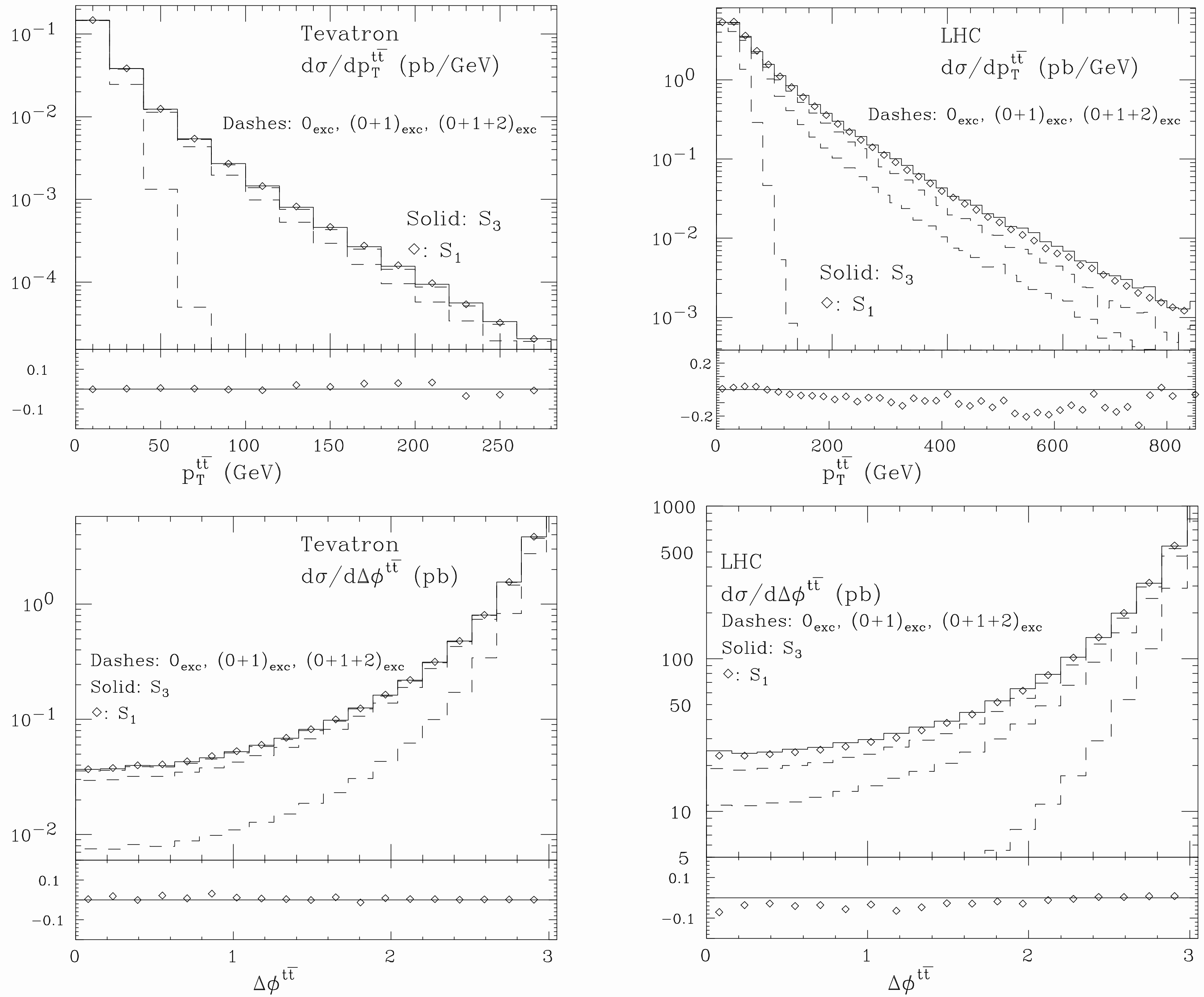
Alpgen + Herwig for $t\bar{t}$+X: consistency checks

$p_T^{t\bar{t}}$ and $\Delta\phi^{t\bar{t}}$ distributions @ Tevatron & LHC (S_1)



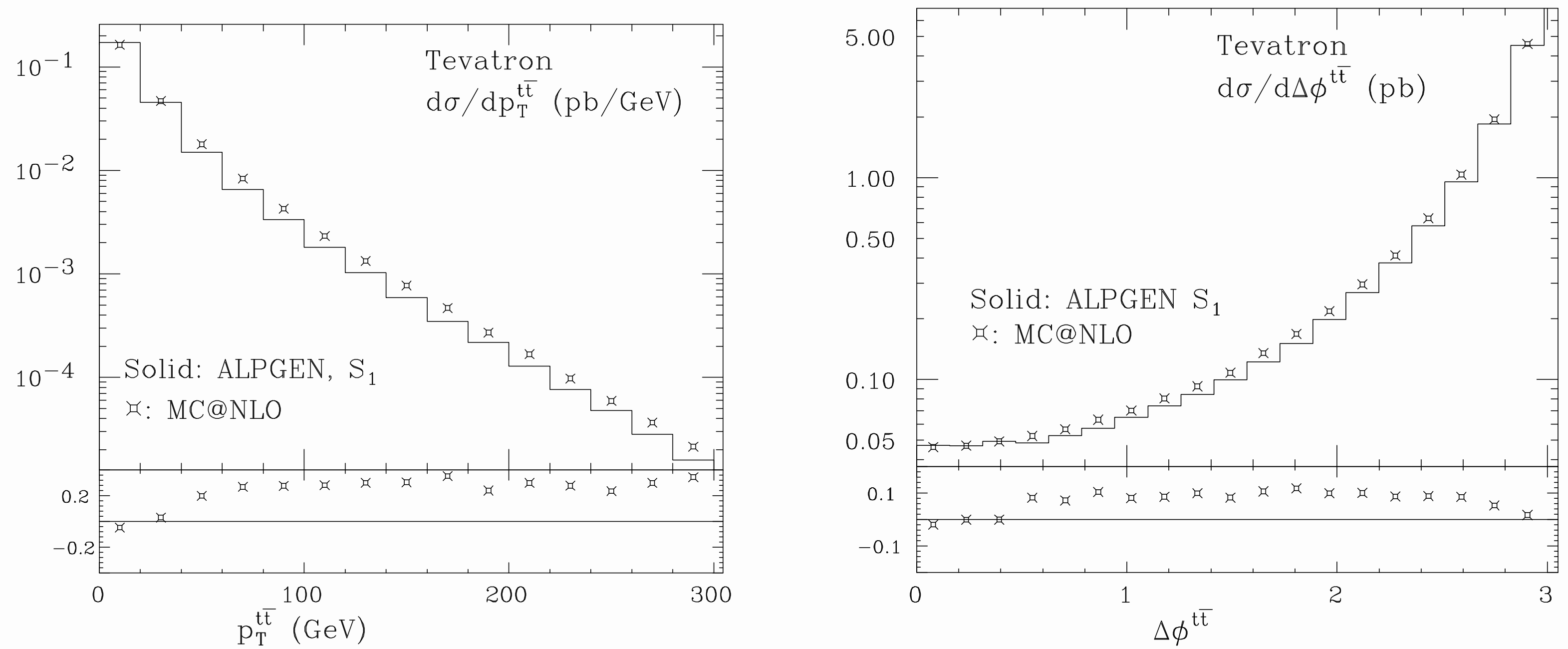
Alpgen + Herwig for $t\bar{t}$+X: consistency checks

$p_T^{t\bar{t}}$ and $\Delta\phi^{t\bar{t}}$ distributions @ Tevatron & LHC (S_1 vs. S_3)



Alpgen + Herwig for $t\bar{t}$+X: comparison with MC@NLO

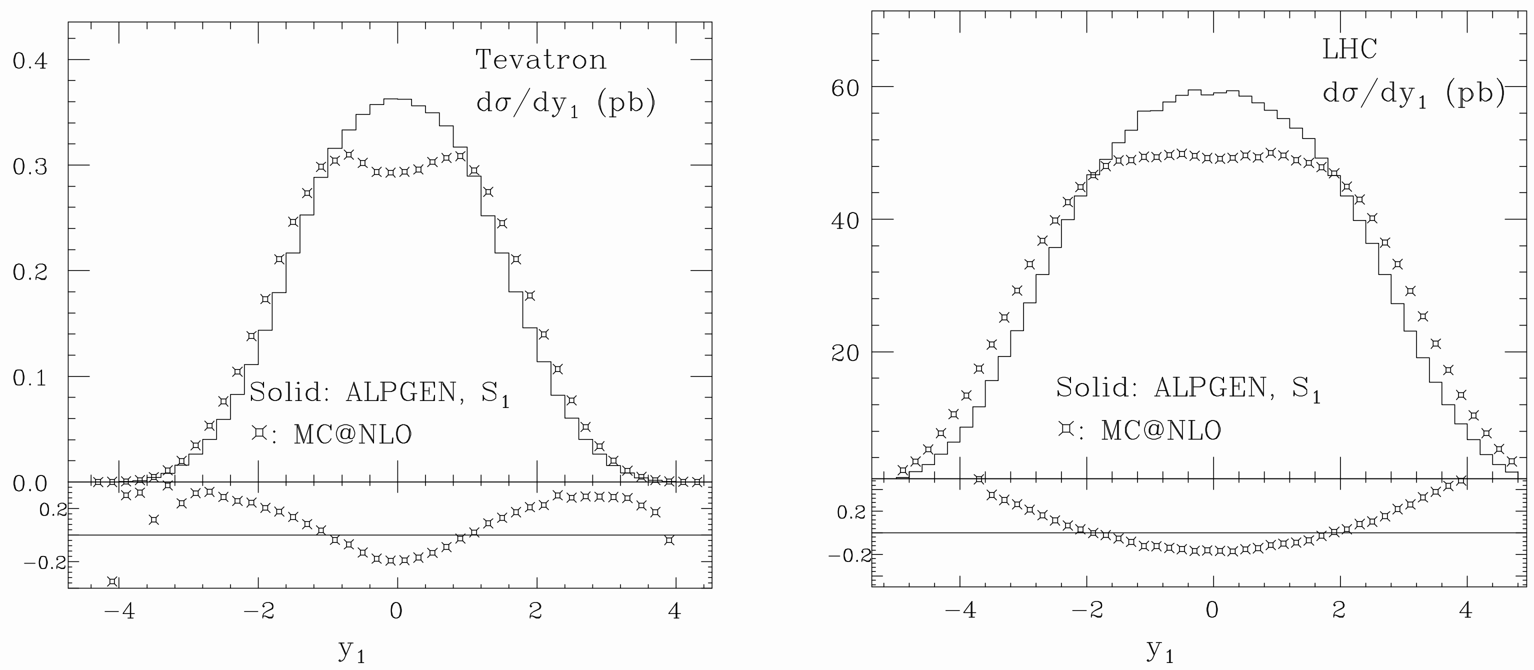
$p_T^{t\bar{t}}$ and $\Delta\phi^{t\bar{t}}$ distributions @ Tevatron (S_1)



- K-factor of 1.36 applied for Alpgen
- good agreement for inclusive quantities (both at Tevatron & LHC)
- but, ...

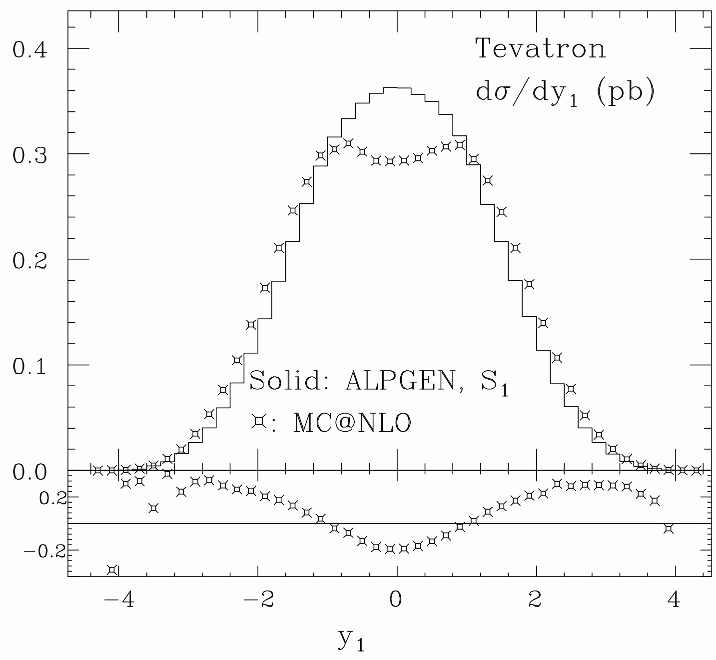
Alpgen + Herwig for $t\bar{t}$+X: comparison with MC@NLO

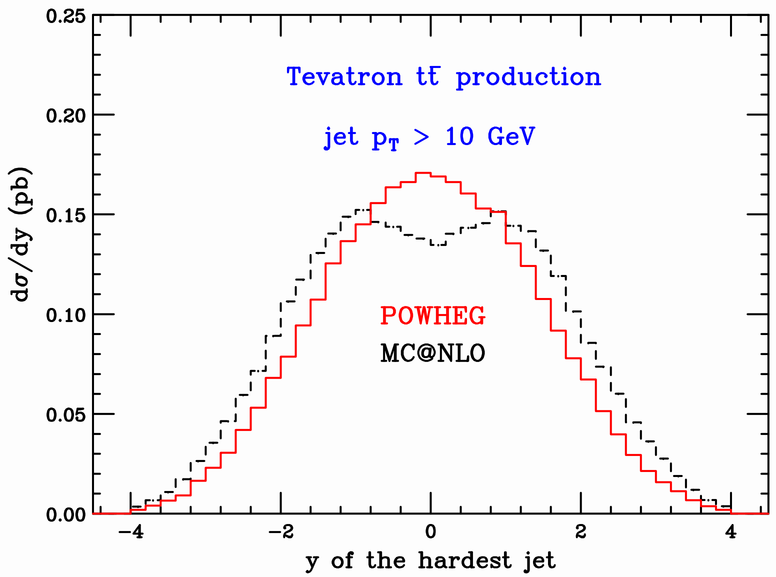
rapidity distribution of hardest jet @ Tevatron & LHC



- significant difference in shape around $y_1 \approx 0$

rapidity distribution of hardest jet @ Tevatron & LHC





- significant difference in shape around $y_1 \approx 0$
- fixed order result looks like Alpgen [confirmed by POWHEG, $t\bar{t}$+jet @ NLO]
- effect of shower dead-cone in MC@NLO [new mass treatment in Herwig++]

Summary/Outlook

The LHC physics programme requires a detailed understanding of QCD

improved theoretical modelling of QCD jets in Monte Carlos

- merging higher-order matrix elements and parton showers
  - matrix elements for final states with many hard partons
  - parton showers, hadronisation, UE for realistic events
  - inclusive samples independent on parton level generation
- improved predictions for multi-jet events [SM backgrounds, Higgs signals]

other directions

- MC at NLO: MC@NLO, POWHEG
- new parton shower formalism(s) [Krauss, S. 2007, Weinzierl et al. 2007]

future steps

- apply merging techniques to BSM processes [Alwall, Maltoni, Wacker]
- towards automatisation of NLO + shower
- MC at NLO + tree-level merging