Theoretical issues in Monte Carlo modelling for W/Z production

[Physics of W and Z bosons – workshop @ RIKEN BNL research center]

Jan Winter [a]

– Fermilab –

- *Monte Carlo event generation*
- *Vector boson production and parton showers*
- *V + n jets using (Sherpa's) tree-level ME+PS merging*
- *V + n jets @ next-to-leading order*

[a] Sherpa authors: J. Archibald, T. Gleisberg, S. Höche, H. Hoeth, F. Krauss, M. Schönherr, F. Siegert, S. Schumann, J. Winter and K. Zapp

http://www.sherpa-mc.de/

Monte Carlo modelling of a (high-p_T) event

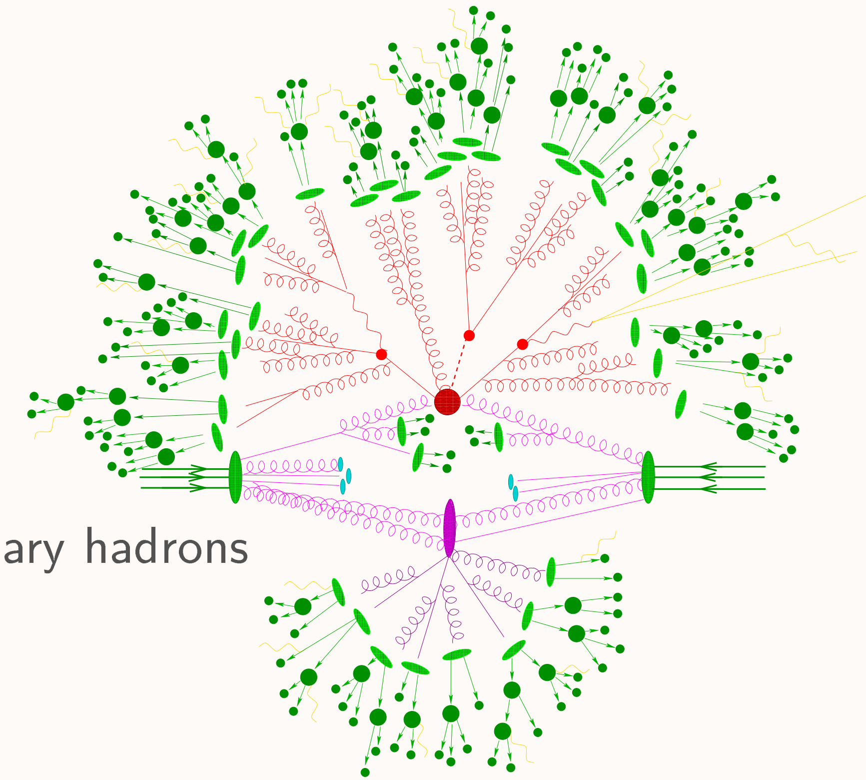
Factorization approach: divide jet simulation into different phases

Perturbative Phases: *[parton jets]*

- ***Hard process/interaction (hard jet production)***
  exact matrix elements $|\mathcal{M}|^2$
- ***QCD bremsstrahlung (soft/coll multiple emissions)***
  initial- and final-state parton showering
- ***Multiple/Secondary interactions***
  modelling the underlying event

Non-perturbative Phases: *[jet confinement – particle jets]*

- ***Hadronization***
  phenomenological models to convert partons into primary hadrons
- ***Hadron decays***
  phase-space or effective models to decay unstable into stable hadrons as observed in detectors



predictions at hadron level – comparable to experimental data if corrected for detector effects

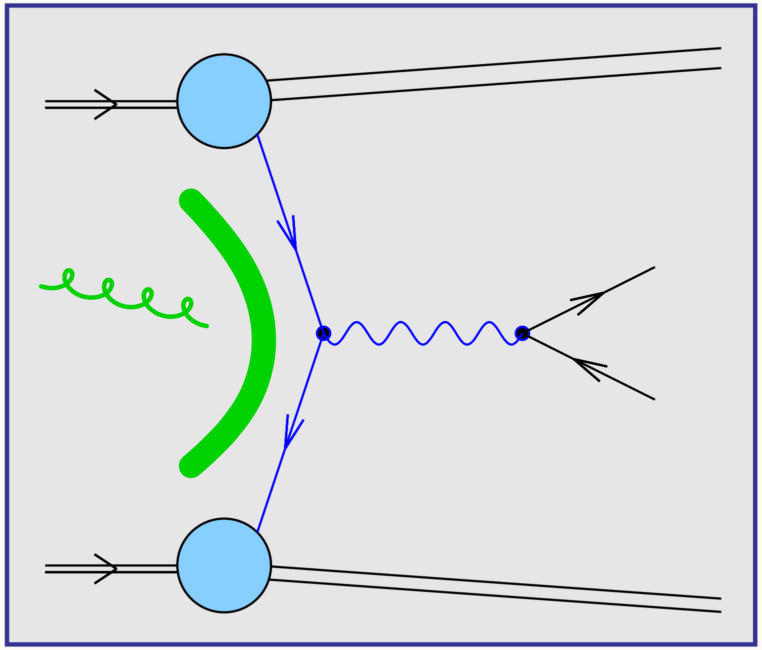
Vector boson production

- calculation of the hadronic cross section relying on factorization theorem
  … … expected to hold for $A + B \to V + X$ [Collins, Soper, Sterman, 2004 review]

$$\sigma_{\rm hadr} \;=\; \sum_{ij} \int dx_1 dx_2 \; f_i(x_1, \mu_{\rm F}) \; f_j(x_2, \mu_{\rm F}) \; \sigma_{\rm part}(ij \to V \to \ldots)$$

  $\sigma_{\rm part}$ … calculable in pQCD; $f_{i,j}$ … extracted from data;
  separation of perturbative and non-perturbative regimes; pQCD used to predict cross sections in complicated hadron collider environment

- V production @ LO: two initial-state partons fuse to make either $W^\pm \to \ell\nu$ or $Z/\gamma^* \to \ell^+\ell^-$
  vector boson has no transverse momentum



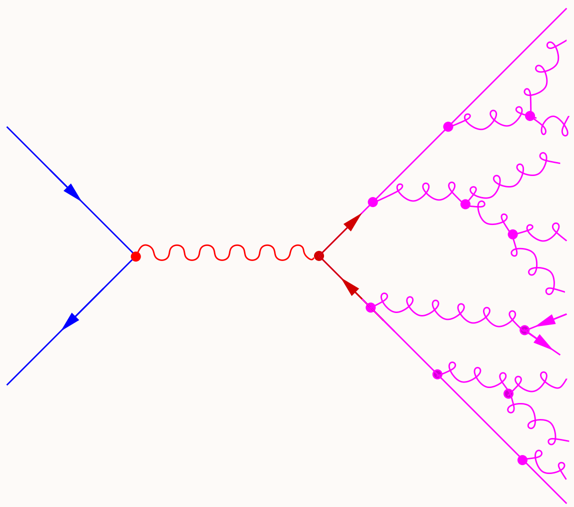
- V + n jet production @ LO: vector boson recoils against one or more jets (parton-level jets)
  - ← highly automated ME generators @ tree level
  - Alpgen, MadGraph, Helac, Amegic, Comix, Whizard, LO MCFM

Parton shower concept

Traditional approach: describe additional jet activity by parton showers.

→ ***QCD emissions preferably populate collinear and soft phase-space regions.***

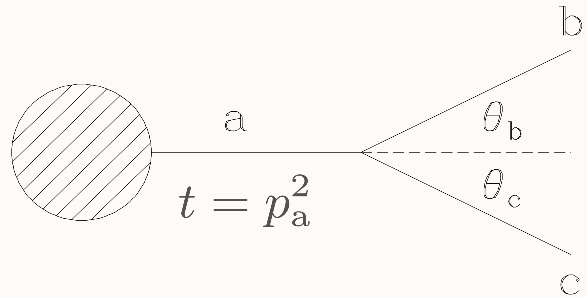
[Pythia, Herwig, Ariadne]



- QCD amplitudes factorize in the coll/soft limit.

→ Recursive definition of multiple emissions:

$$d\sigma_{n+1} = d\sigma_n \frac{\alpha_s(t)}{2\pi} \frac{dt}{t} dz\, P_{a\to bc}(z) \qquad \text{(e.g. coll limit)}$$

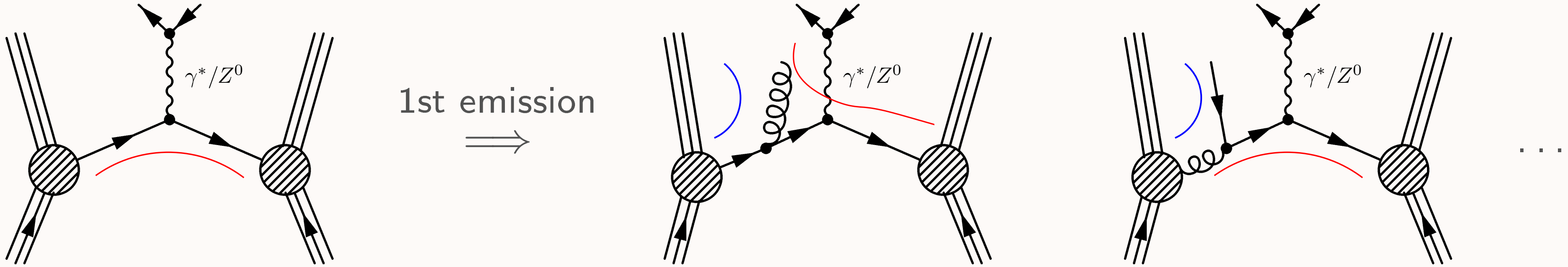


- coll/soft parton emissions iteratively added to the initial/final states *[LL resummation]*
- good description of bulk of radiation and particle multiplicity growth
- partonic ensemble evolved down to hadronization scale *[ordering variable Q, ϑ, p_T]*
  → provides suitable input for universal hadronization models *[$\mathcal{O}(1$ GeV$)$]*

→ <u>vector boson production:</u> inclusive V + n jets prediction @ LO+LL

Sherpa's Catani–Seymour shower: DY production

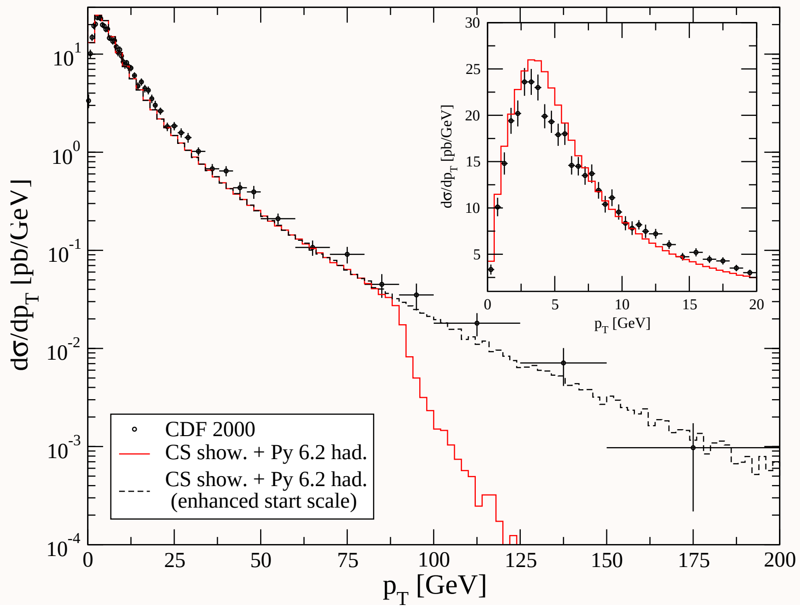
- universal dipole terms used to describe $1 \to 2$ parton splittings
- exponentiation in a Sudakov form factor (large-N_C limit, spin averaging)
- correct soft & collinear limits, local momentum conservation (spectator for $2 \to 3$ kinematics)



- hard scale fixed by $M_{ee}^2 \Rightarrow \mathbf{k}_{\perp,\max}^2$

CS Shower [SCHUMANN, KRAUSS, JHEP 03 (2008),038]

- transverse momentum of lepton-pair determined by multiple QCD emissions



- comparison with Tevatron CDF data
  - rate normalised to data
  - dominant contribution for p_T^{ee}
  - Sudakov damping for $p_T^{ee} \to 0$
  - hardest emission below $\mathbf{k}_{\perp,\max}$

    $\hookrightarrow p_T^{ee} > \mathbf{k}_{\perp,\max}$ matrix-element regime
- ME corrections can be implemement to improve 1st emission

V + n jet predictions @ LO+LL ?

Limitations

- shower seeds are LO QCD processes only
- lack of high-energetic large-angle emissions
- semi-classical picture; quantum interferences and correlations only approximate
- shower evolution proceeds in the limit of large N_{C}

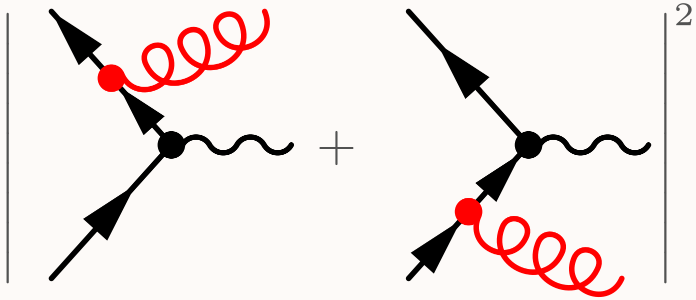
Improvements

- first few hardest emissions given by tree-level MEs

  [called (tree-level/LO) ME+PS merging – CKKW, L-CKKW, MLM, ME&TS]
- use NLO QCD core processes and match to parton shower

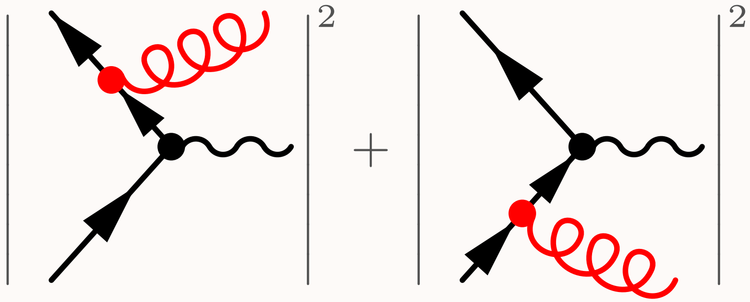
  [called NLO+PS matching – MC@NLO, POWHEG]

matrix element:



$|A_R|^2 + |B_R|^2 + 2\,\mathrm{Re}(\mathrm{A_R B_R^*})$

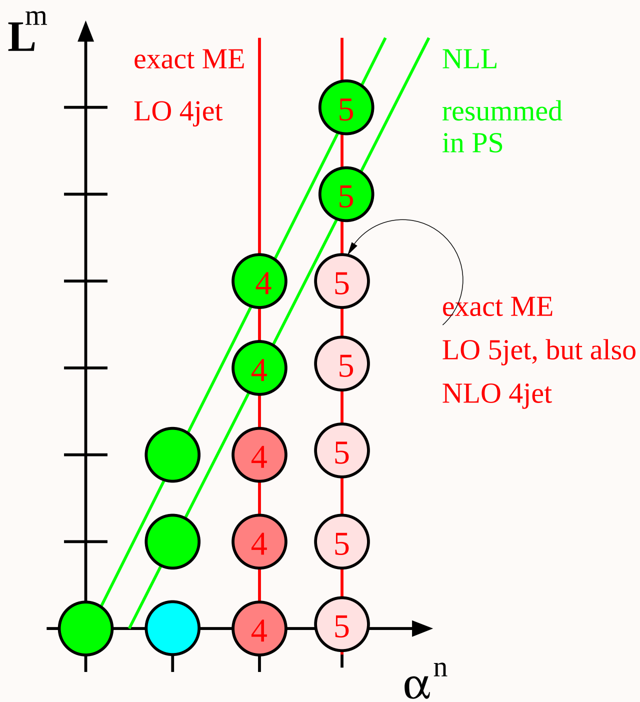
parton shower:



$|A_R|^2 + |B_R|^2$

Combine advantages, remove weaknesses.

Beware of double counting, preserve universality of hadronization.



α_S vs. Log

ME+PS merging – CKKW method

[Catani, Krauss, Kuhn, Webber, JHEP 11 (2001) 063]
[Krauss, JHEP 08 (2002) 015]

- *combine parton-shower pros (soft emissions)* +

  ME pros (hard emissions, quantum interferences, correlations)
- *avoid double counting and missing phase space regions*

Divide multijet phase space into two regimes by k_T jet measure at $Q_{\rm jet}$.

- tree-level MEs: jet seed (hard parton) production above $Q_{\rm jet}$
- parton showers: (intra-)jet evolution $Q_{\rm jet} > Q > Q_{\rm cut-off}$
- MEs regularized by $Q^2_{ij} \; = \; 2 \min \left\{ p_T^{(i)}, \, p_T^{(j)} \right\}^2 \frac{\left[\cosh(\eta^{(i)} - \eta^{(j)}) - \cos(\phi^{(i)} - \phi^{(j)})\right]}{D^2} > Q^2_{\rm jet}$

Eliminate/sizeably reduce $Q_{\rm jet}$ dependence.

- identify a possible shower history of MEs via backward clustering
- accordingly reweight MEs by combined α_s and Sudakov weight
- add showers to ME partons and veto emissions above $Q_{\rm jet}$

ME+PS merging – CKKW method

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[KRAUSS, JHEP 08 (2002) 015]

➡ *combine parton-show*

ME pros (hard emissi

➡ *avoid double counting*

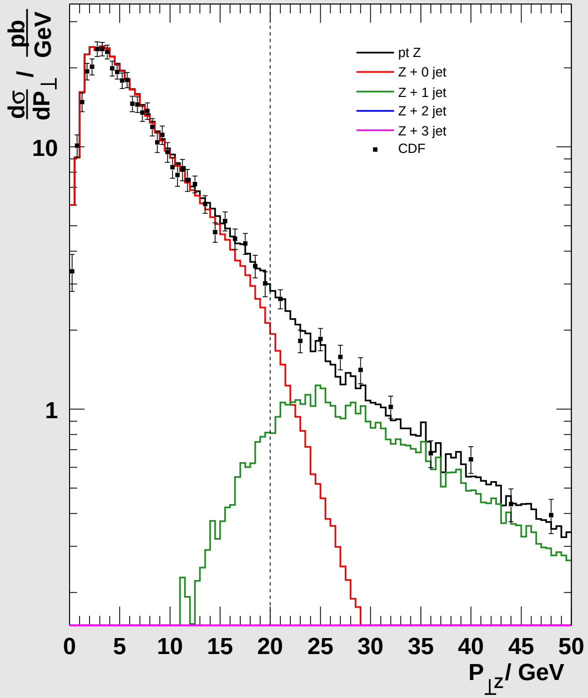
Divide multi

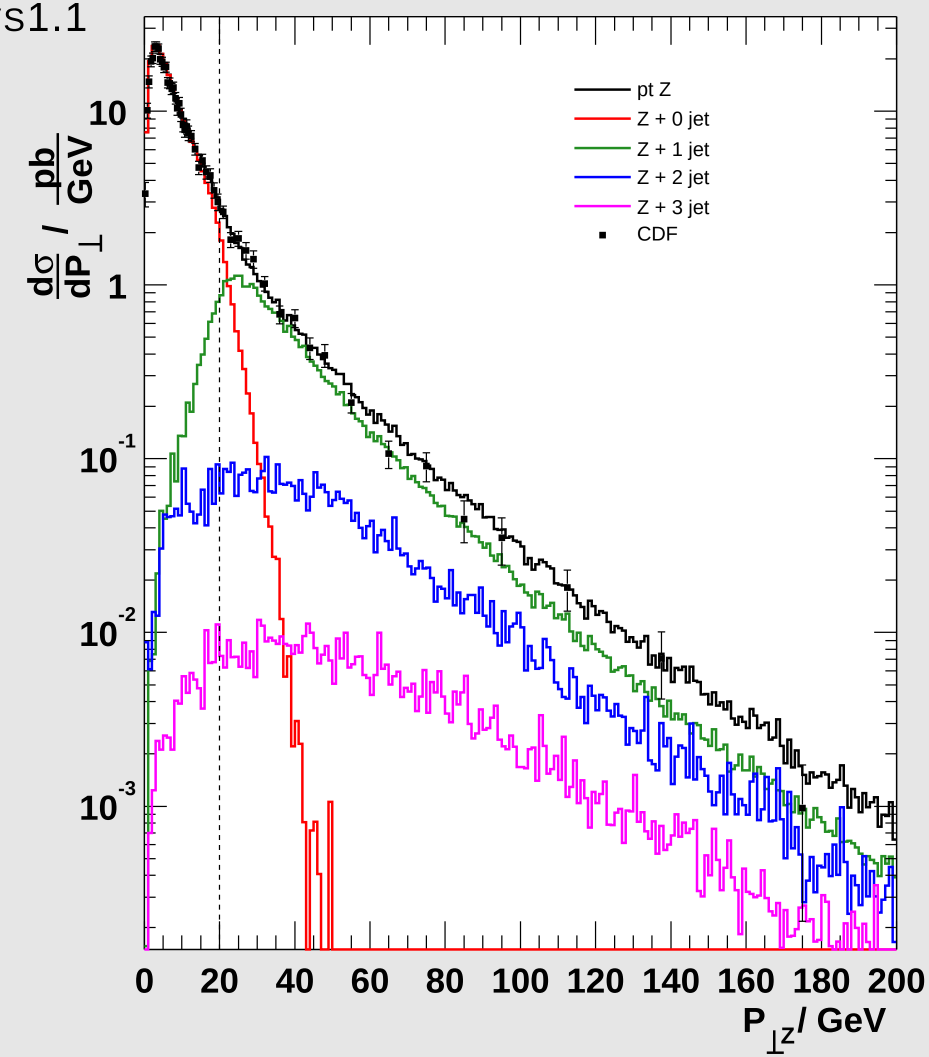
- tree-level MEs: jet
- parton showers: (i
- MEs regularized by
  - ider
  - acc
  - add

CKKW IN SHERPA VS1.0 AND VS1.1

E.G. Z + JETS @ 1.8 TEV

- AMEGIC + APACIC
- constant K-factor
- intrinsic k_T-smearing of order 1 GeV





KRAUSS ET AL. PRD 70 (2004) 114009

Vary maximal number of tree-level MEs included ...

➡ *Inclusive jet cross sections at the LHC for Z+jets normalized to the total inclusive cross section:*

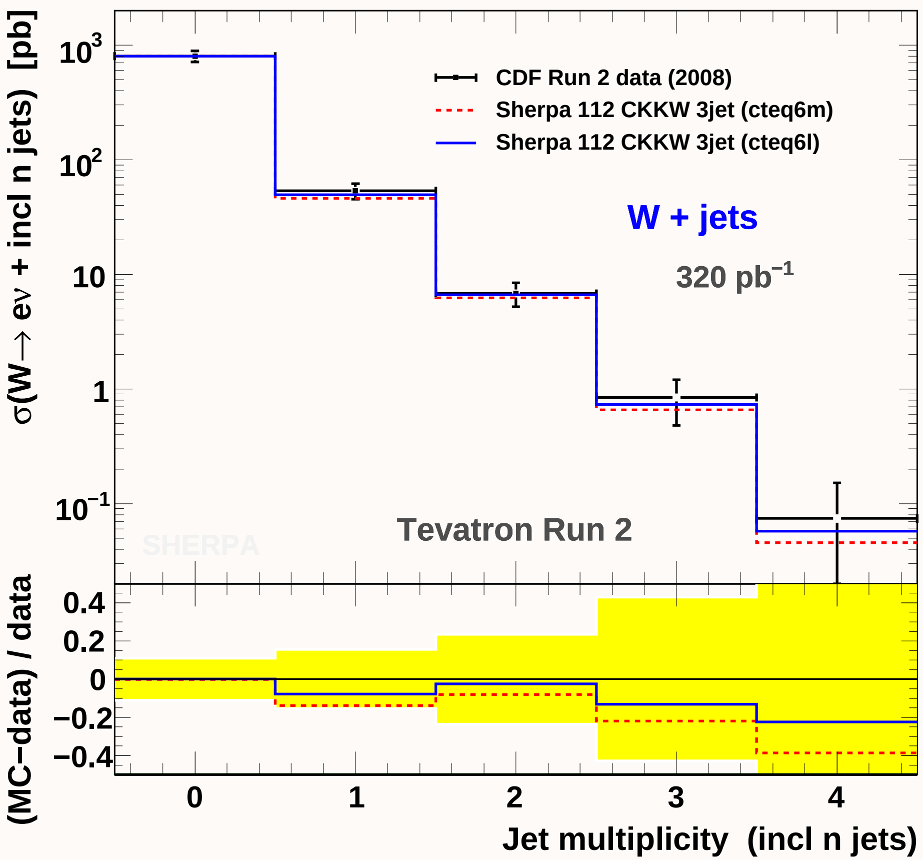
Monte Carlo	$\sigma_{\geq 1\text{jet}}/\sigma_0$	$\sigma_{\geq 2\text{jet}}/\sigma_0$	$\sigma_{\geq 3\text{jet}}/\sigma_0$	$\sigma_{=1\text{jet}}/\sigma_0$	$\sigma\|_{y_1 y_2 < -2}/\sigma_0$
CKKW $n_{\text{ME}} = 1$	0.304	0.082	0.017	0.222	0.016
CKKW $n_{\text{ME}} = 2$	0.340	0.108	0.025	0.231	0.017
CKKW $n_{\text{ME}} = 3$	0.348	0.119	0.034	0.229	0.018
Apacic	0.232	0.048	0.007	0.157	0.010

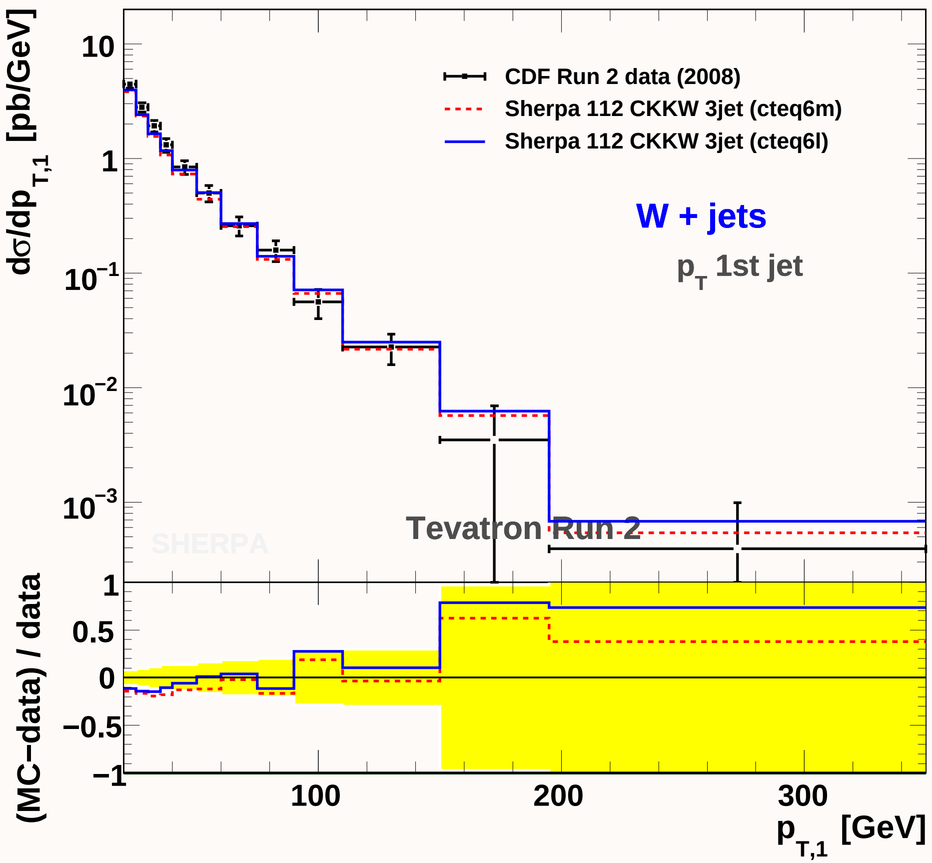
- Various Sherpa 1.0.10 predictions are shown;
  Apacic is Sherpa's pure shower prediction.
- Jets are defined according to the Run II k_T algorithm and required to have $p_{T,\text{jet}} > 20$ GeV.

Comparison with CDF data: W+jets production

[T. AALTONEN ET AL., PRD **77** (2008) 011108]

- Monte Carlos need to be validated and tuned against most recent Tevatron data.
- Sherpa vs1.1.3 predictions normalized to total inclusive cross section. Two choices of PDFs.
- Tree-level ME+PS can reproduce W+>=n jet xsecs to 20% after applying overall K factor.





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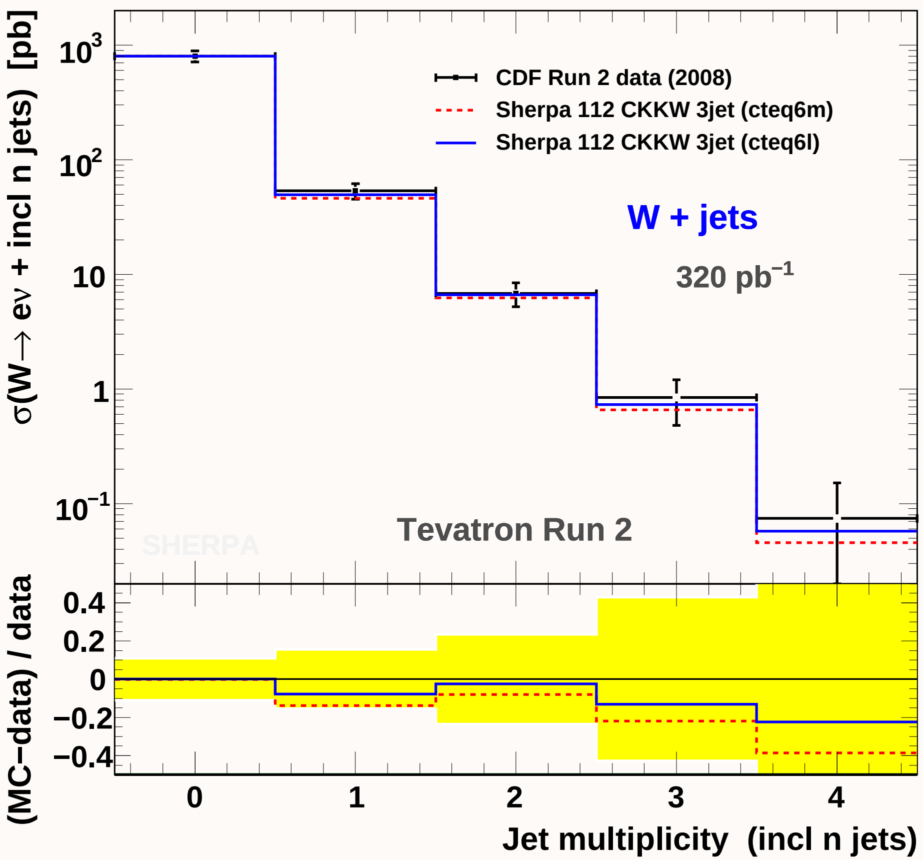

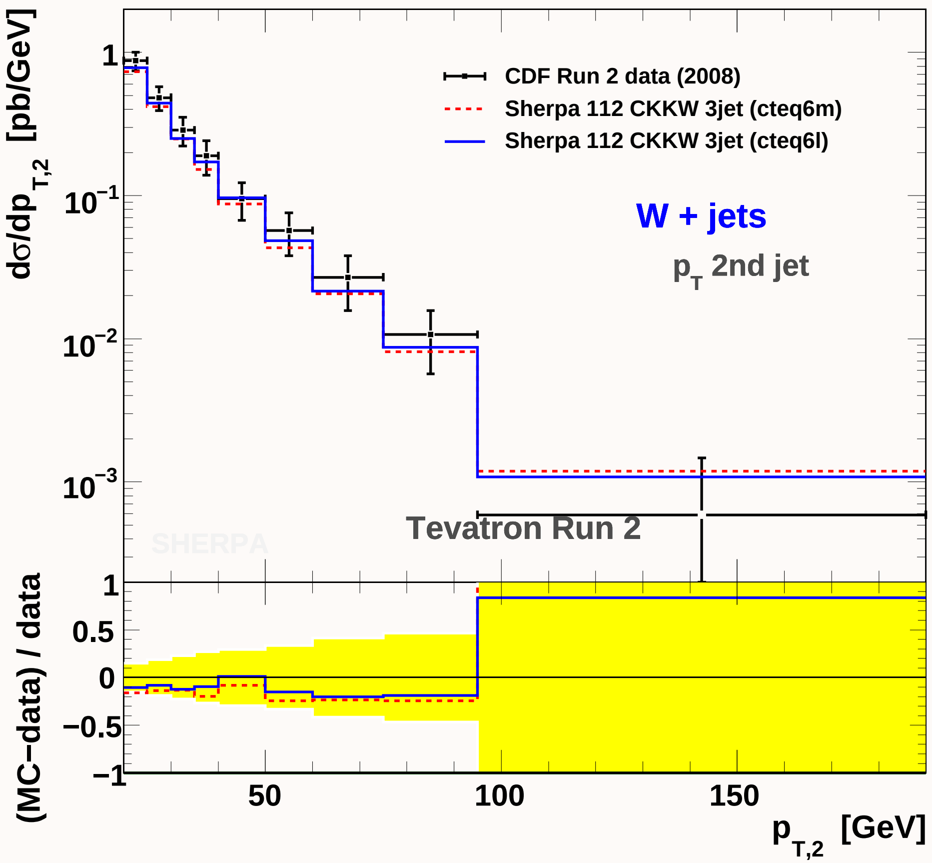

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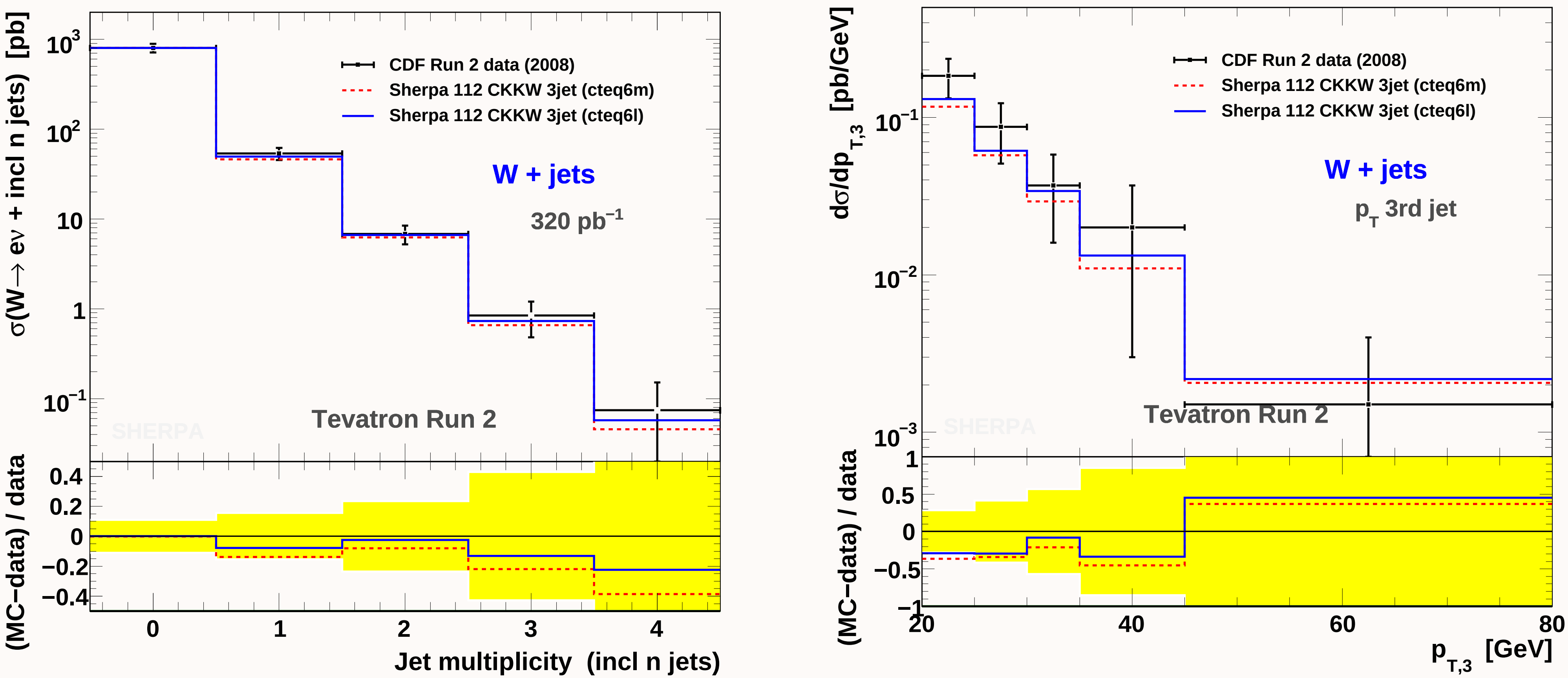
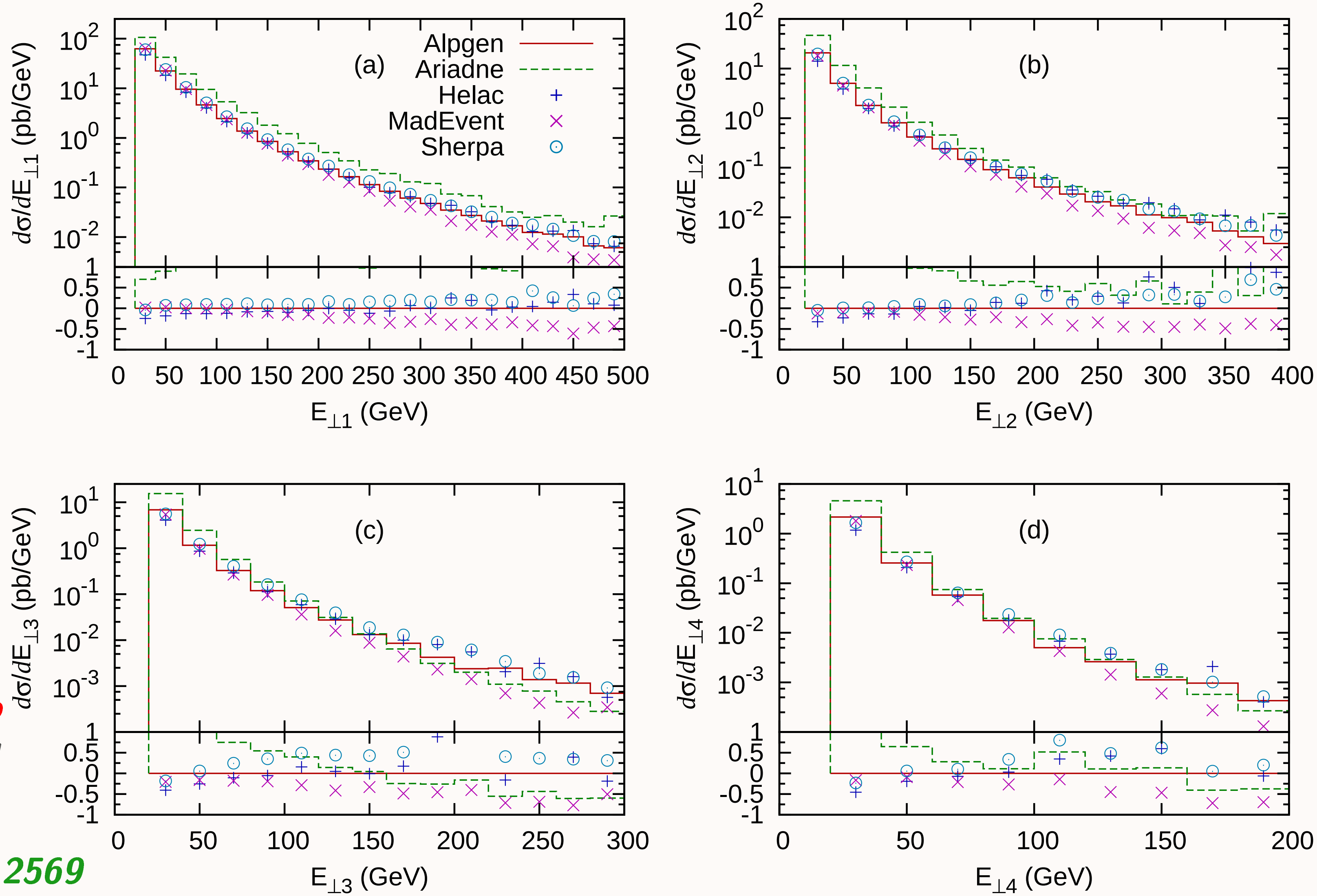


Comparison between merging approaches, ...

- *Alpgen, Ariadne, Helac, MadEvent and Sherpa ME+PS merging, has been accomplished.*

$W^+ + X$

- *jet E_T spectra at the LHC*



- *similar pattern wrt Tevatron*
- *once tuned to Tevatron data, same **extrapolation to LHC** can be expected*
- *Results in arXiv:0706.2569 (EPJC 53 (2008) 473)*

Comparison between merging approaches, ...

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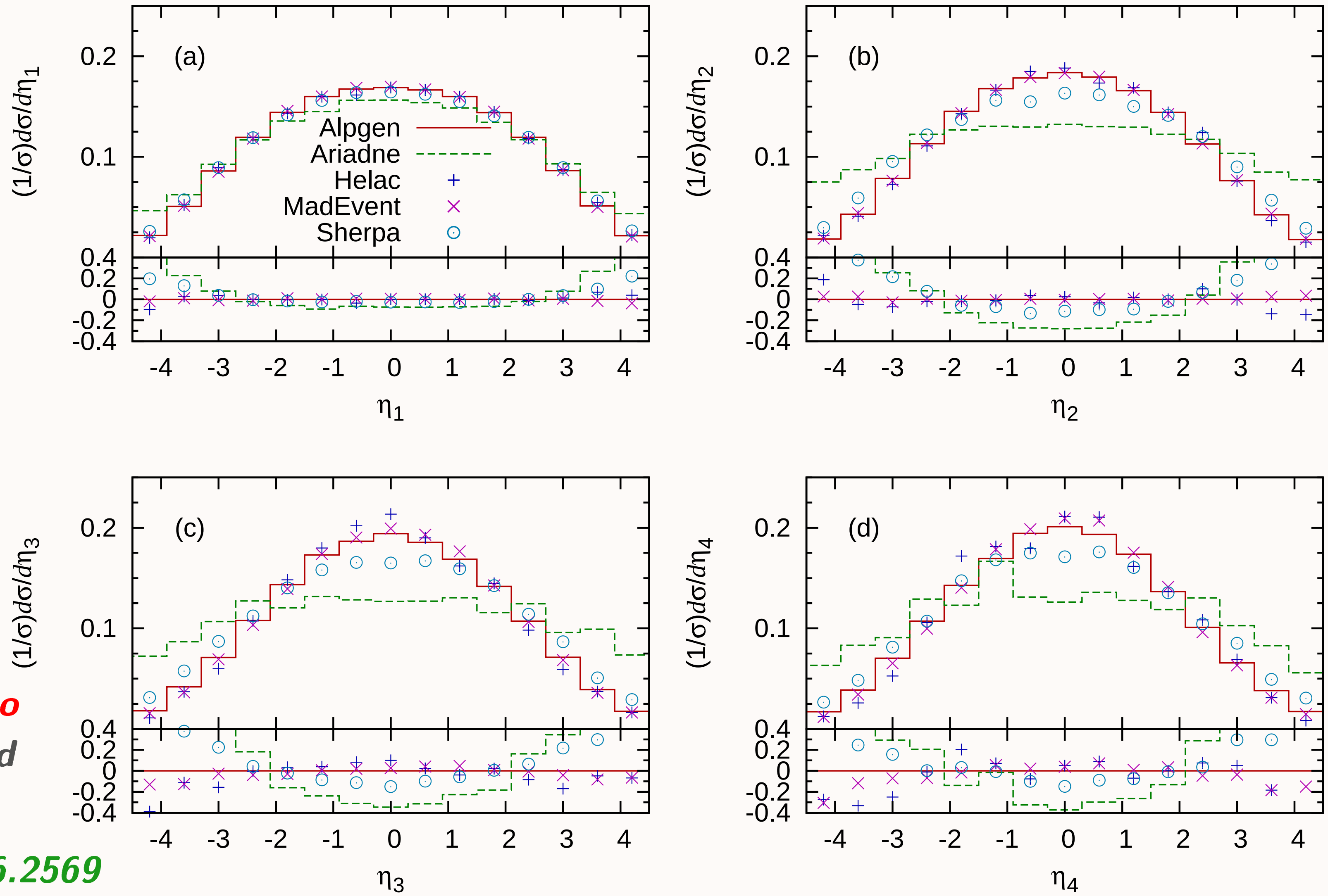
- *jet η spectra at the LHC*



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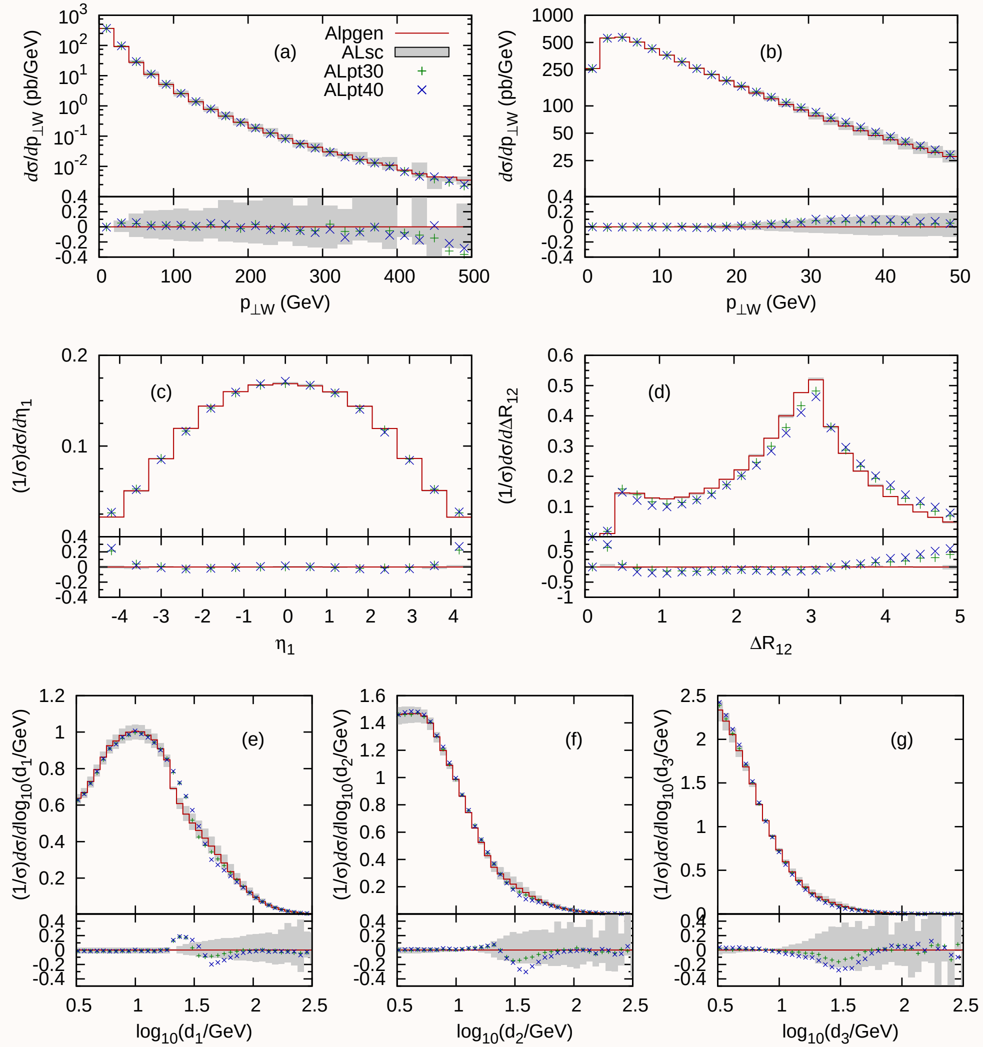
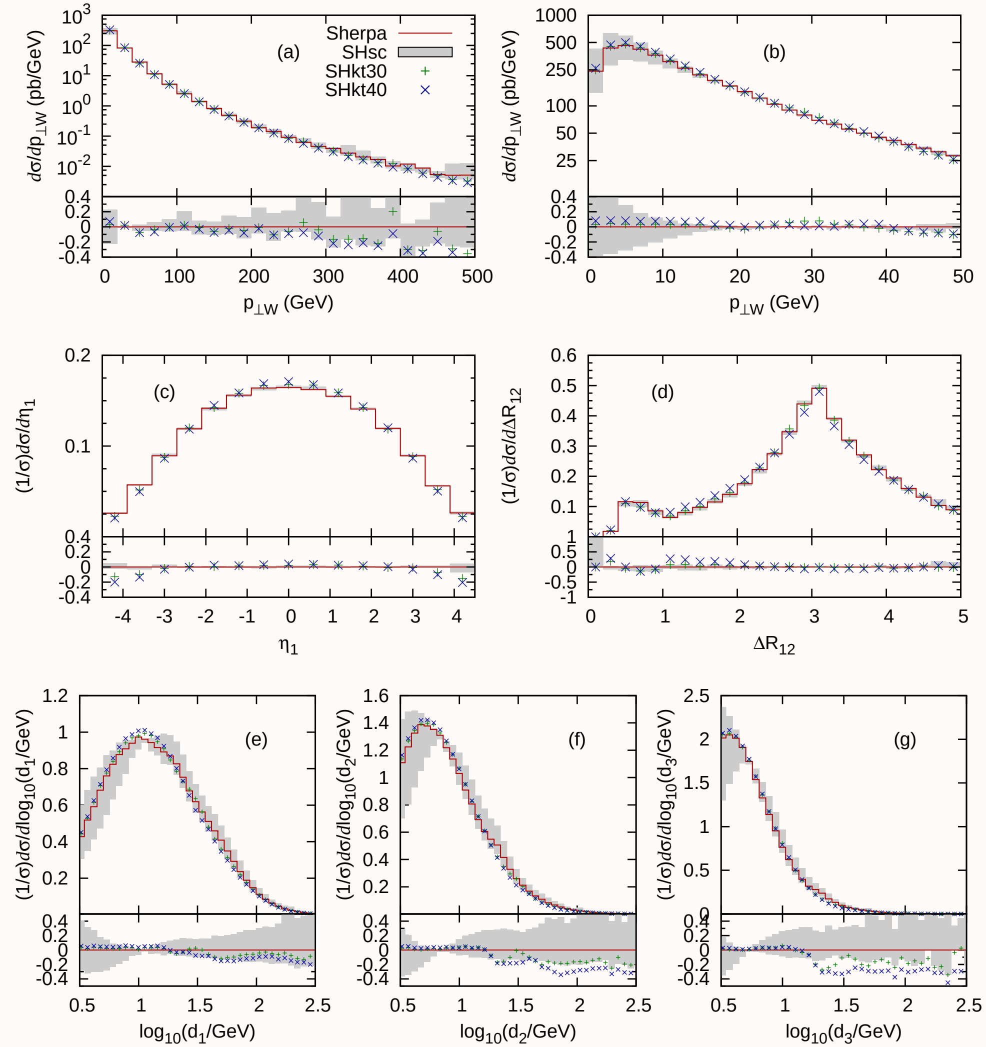
Systematics of merging approaches

[EPJC 53 (2008) 473]

W+jets @ Tevatron: ***Alpgen*** (+PS by Herwig) (left) *vs.* ***Sherpa*** (right)

Example distributions: p_T of W, η of 1st jet, ΔR_{12}, differential jet rates





➡ Monte Carlos need to be validated and tuned against most recent Tevatron data.

➡ Discriminating power increases with more data coming in. Use to refine algorithms!

Systematics of merging approaches [EPJC 53 (2008) 473]

W+jets @ Tevatron: ***Alpgen*** (+PS by Herwig) (left) *vs.* ***Sherpa*** (right)

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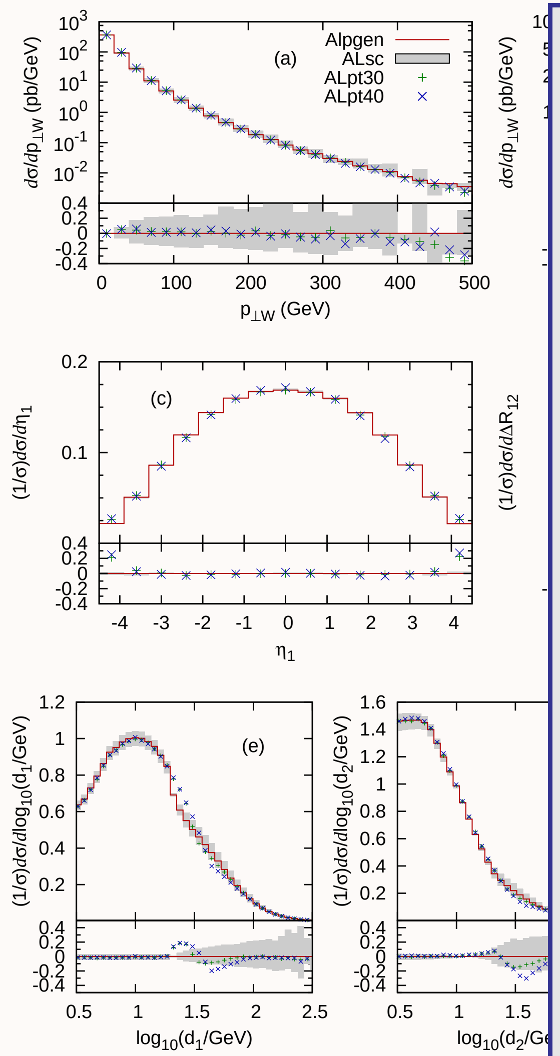


DØ data comparison with MCs for Z+jets (1/fb Run2) [Lammers et al.]

ALPGEN/MLM – Z+JET ANGLES ✗ – Z+JET PTS ✓

SHERPA/CKKW – Z+JET ANGLES ✓ – Z+JET PTS ✗

What's wrong with CKKW? → Nothing. → Tune parameters.

SHERPA VS1.1.2 $\Rightarrow$ VS1.1.3

Can we do better? Refine the method? – What are the weak points?

- no proof of correctness in IS evolution
- no beam info for k_T-type measures, but pQCD is crossing invariant
- mismatch between k_T and angular ordering
  $\Rightarrow$ spoiles colour-coherent evolution
- mismatch between cluster and parton-shower scales
- mismatch between analytic NLL Sudakovs and actual PS Sudakovs
- no complete freedom in defining μ_F and μ_R

Yes, we can improve on these issues.

→ Monte Carlos need to

→ Discriminating

Matrix elements and truncated showers: ME&TS

[HÖCHE, KRAUSS, SCHUMANN, SIEGERT, JHEP 05 (2009) 053] [SLIDE FROM STEFFEN SCHUMANN]

Describe few hardest emissions through ME

- emission phase space sliced IR sensible measure Q
  - Soft/collinear emissions from shower $Q < Q_{\rm cut}$
  - Hard emissions from matrix element $Q > Q_{\rm cut}$

⇝ Sudakov form factor factorises

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

⇝ $$\mathcal{K}_{ba}^{\rm ME}(z, k_\perp^2) \to \frac{1}{d\hat{\sigma}_a^{(N)}(\Phi_N)} \frac{d\hat{\sigma}_b^{(N+1)}(z, k_\perp^2; \Phi_N)}{d\log(k_\perp^2/\mu^2)\, dz}$$

A new merging algorithm [Höche, Krauss, S., Siegert JHEP **0905** (2009) 053]

→ **pseudo shower history for MEs**

cluster algorithm inverse to the shower

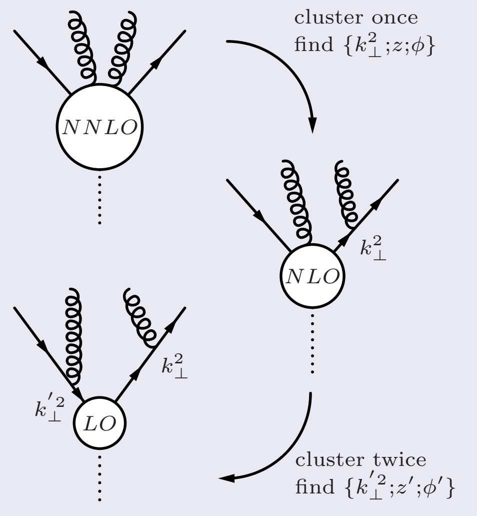
→ **Truncated Shower**

PS starts at 2 → 2 core and can radiate partons off intermediate lines i.e. "between" ME partons

ME branchings must be respected

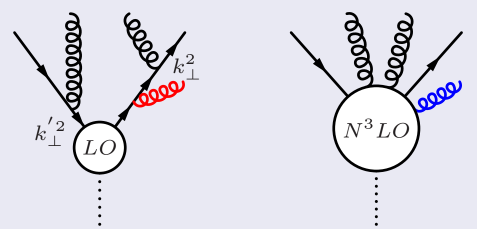
evolution-, splitting- & angular variables $\{k_\perp^2, z, \phi\}$ preserved

Pseudo shower history



Truncated shower

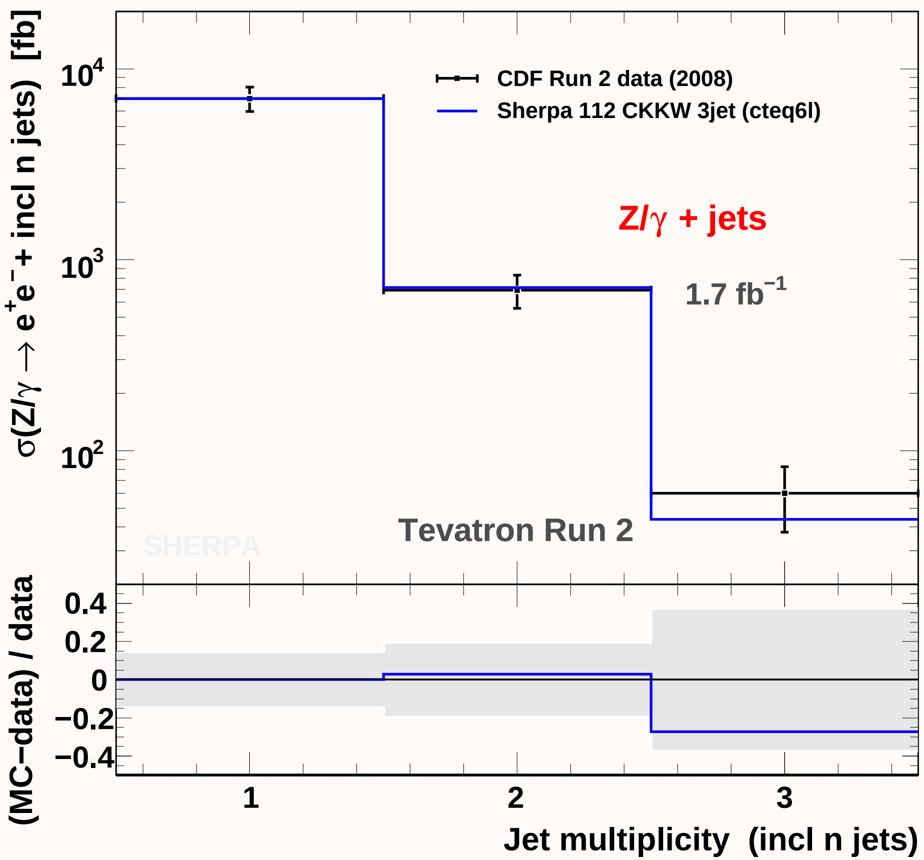
$Q < Q_{\rm cut}$ $Q > Q_{\rm cut}$

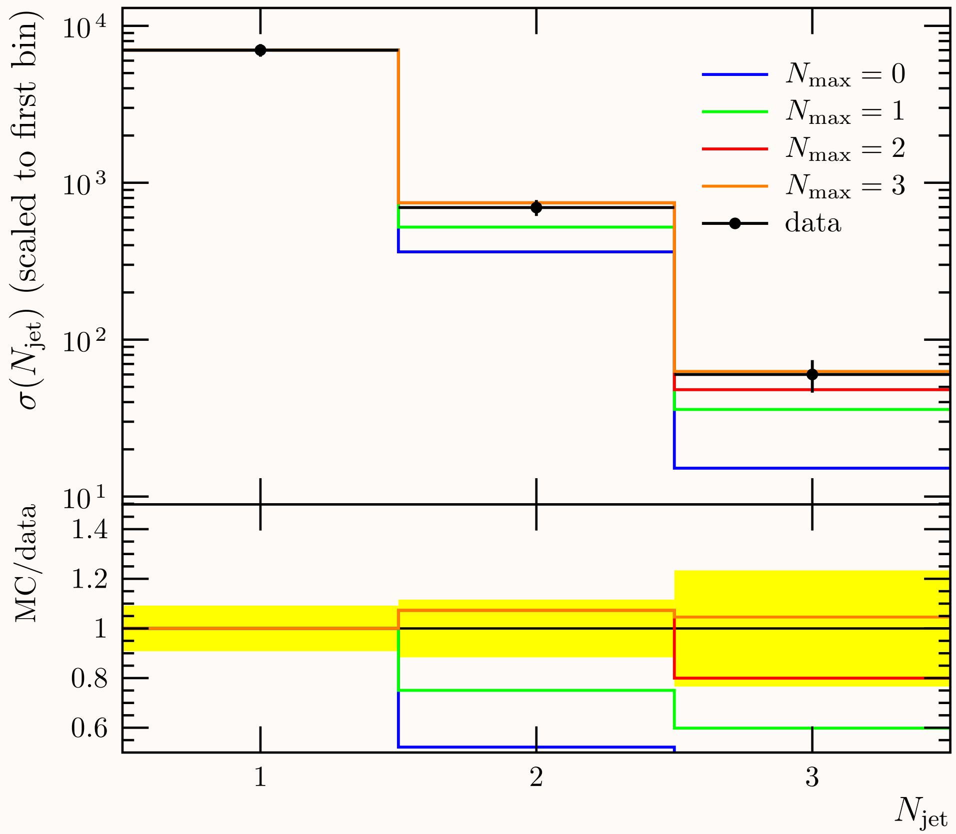


Comparison with CDF data: Z+jets production

ME&TS :: COMIX + CSS [T. Aaltonen et al., PRL **100** (2008) 102001]

- Sherpa vs1.1 [CKKW] (left) compared with Sherpa vs1.2 [ME&TS] (right).
- Examples of jet observables: new approach better describes the data.
- Sherpa predictions multiplied by constant K factor, normalized to first-jet bin xsec.





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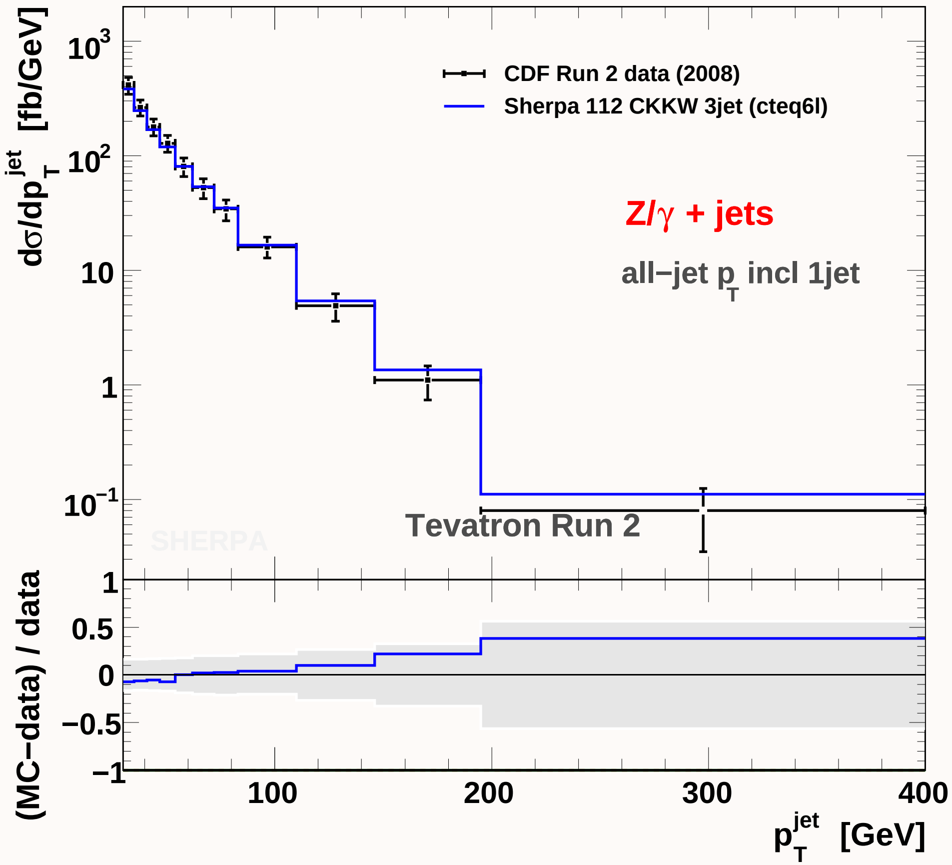

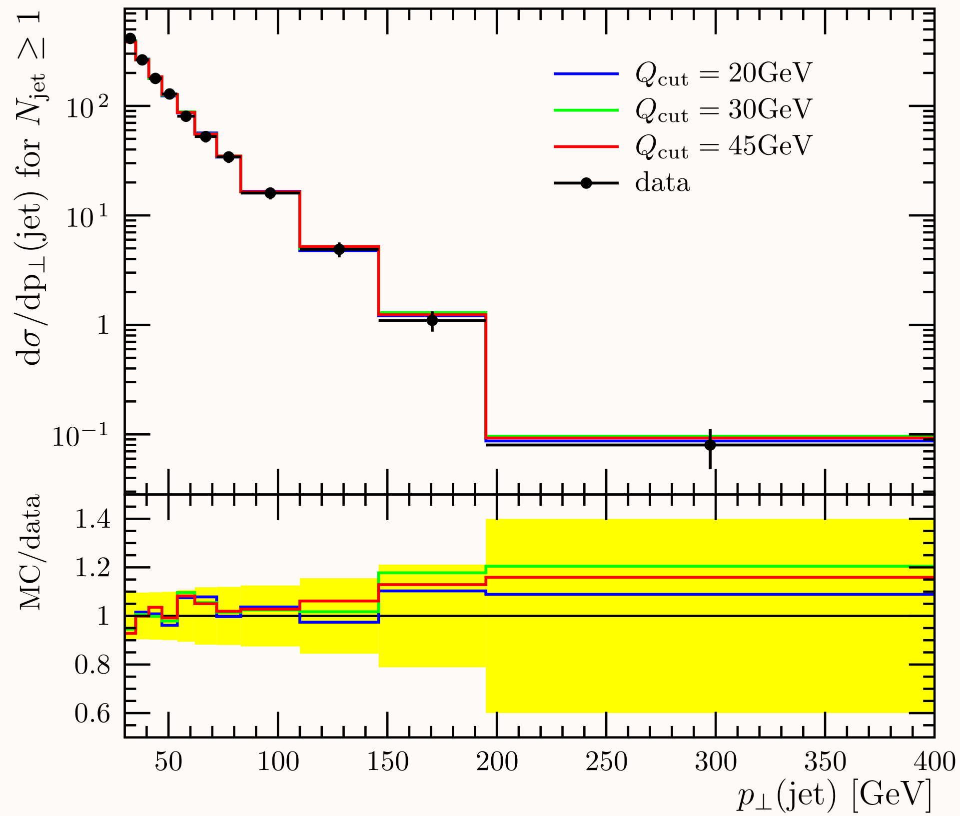

Z+jets production @ Tevatron Run2 energies

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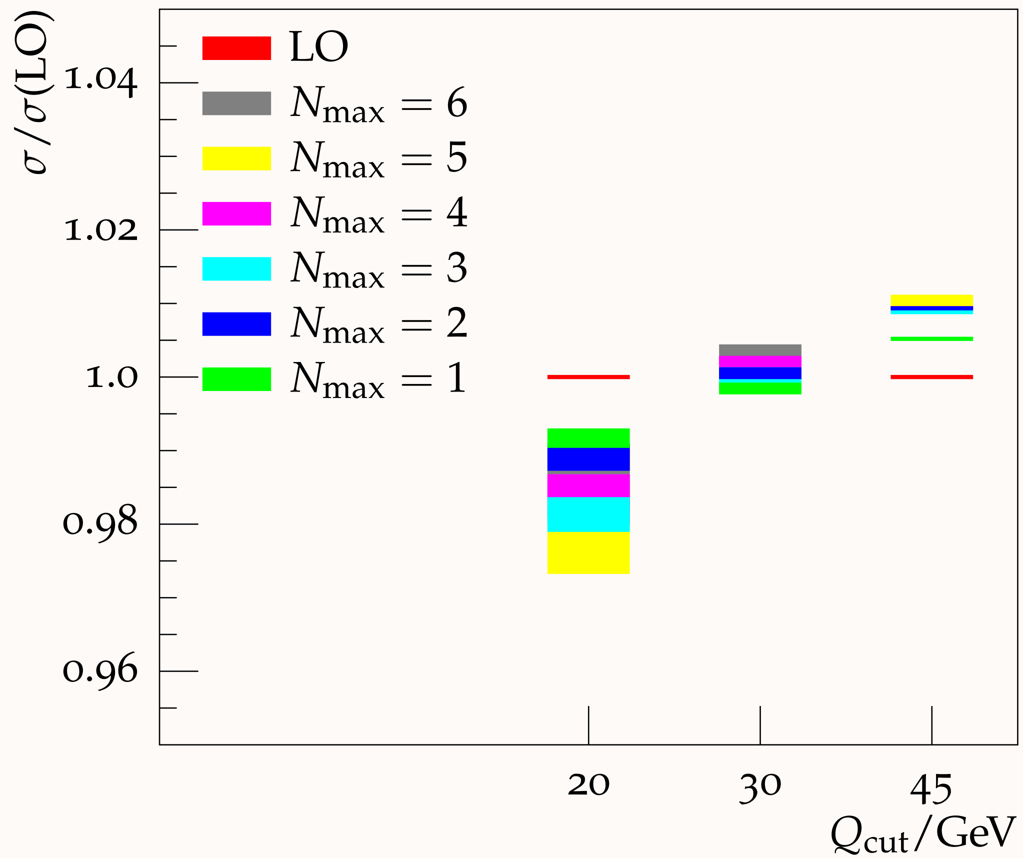
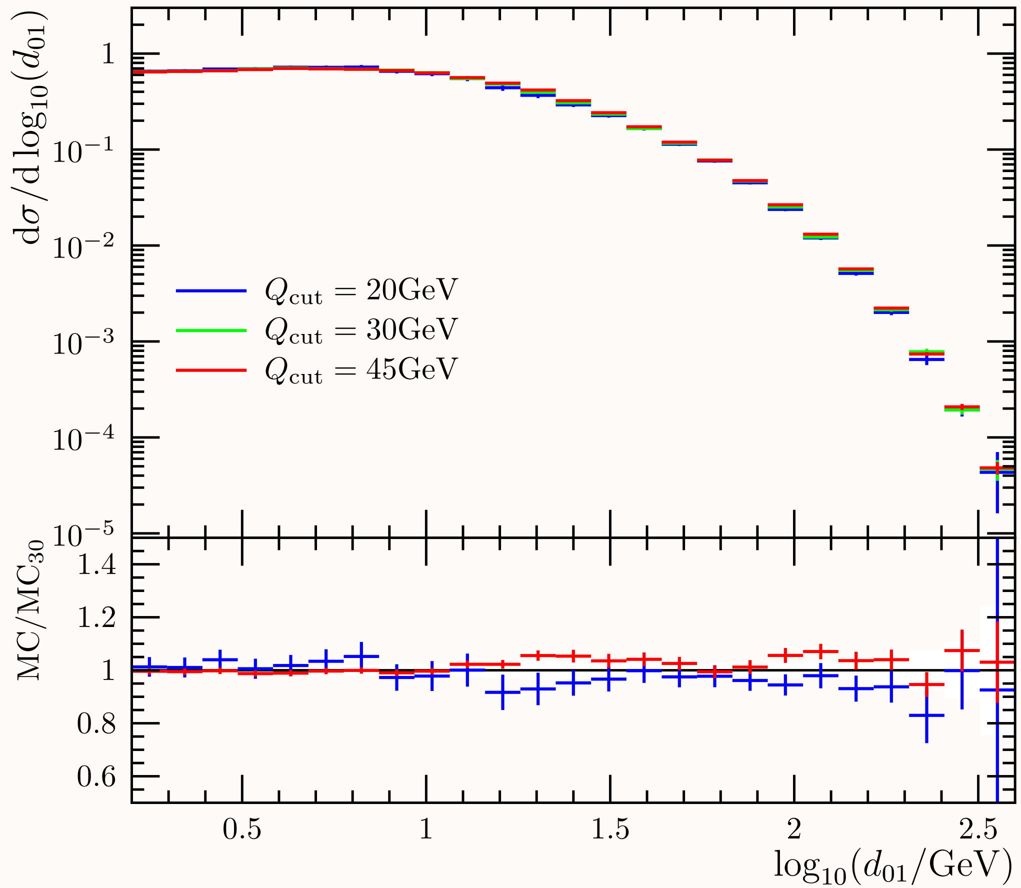
- Merging systematics of total cross section (LO) has improved: $\Delta\sigma_{\rm tot}/\sigma_{\rm tot} < \pm 3\%$
- Differential k_T jet rates in $Q_{\rm cut} = Q_{\rm jet}$ variation @ hadron level. Note $N_{\max} = 5$.
- $Q_{\rm cut}$ variation now within $\pm 10\%$. Note $\mu_F^2 = M_{ee}^2$ and 66 GeV $< M_{ee} <$ 116 GeV.





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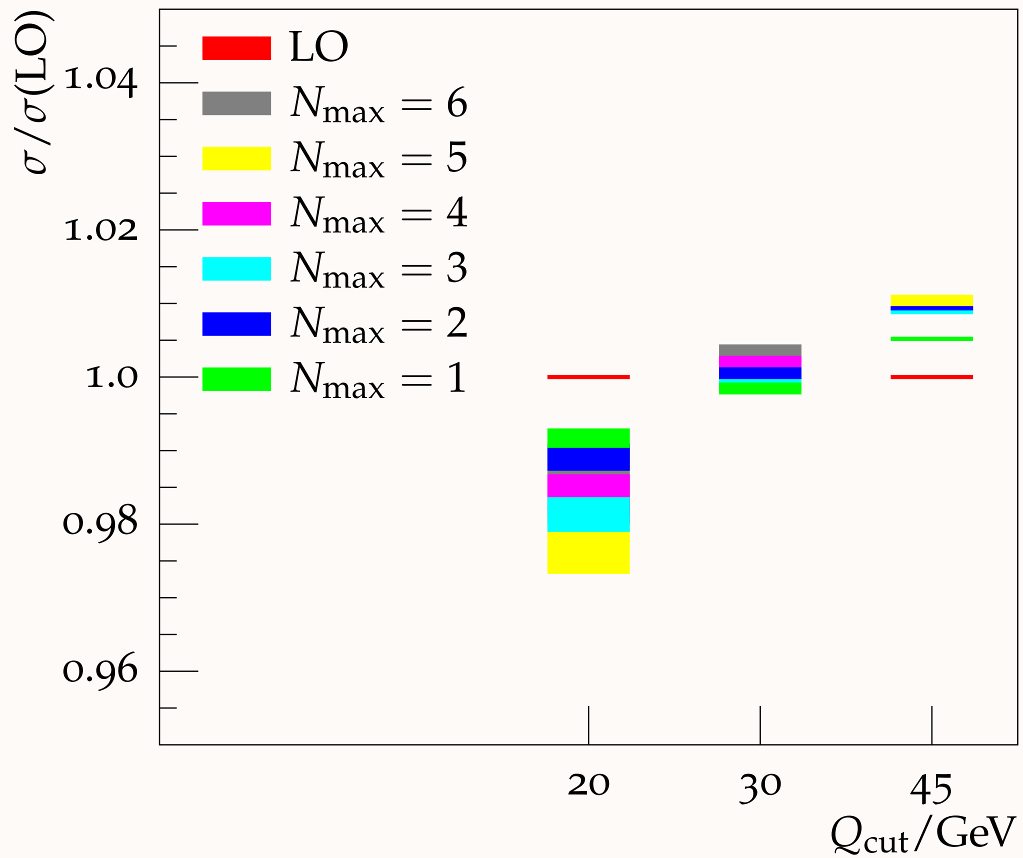

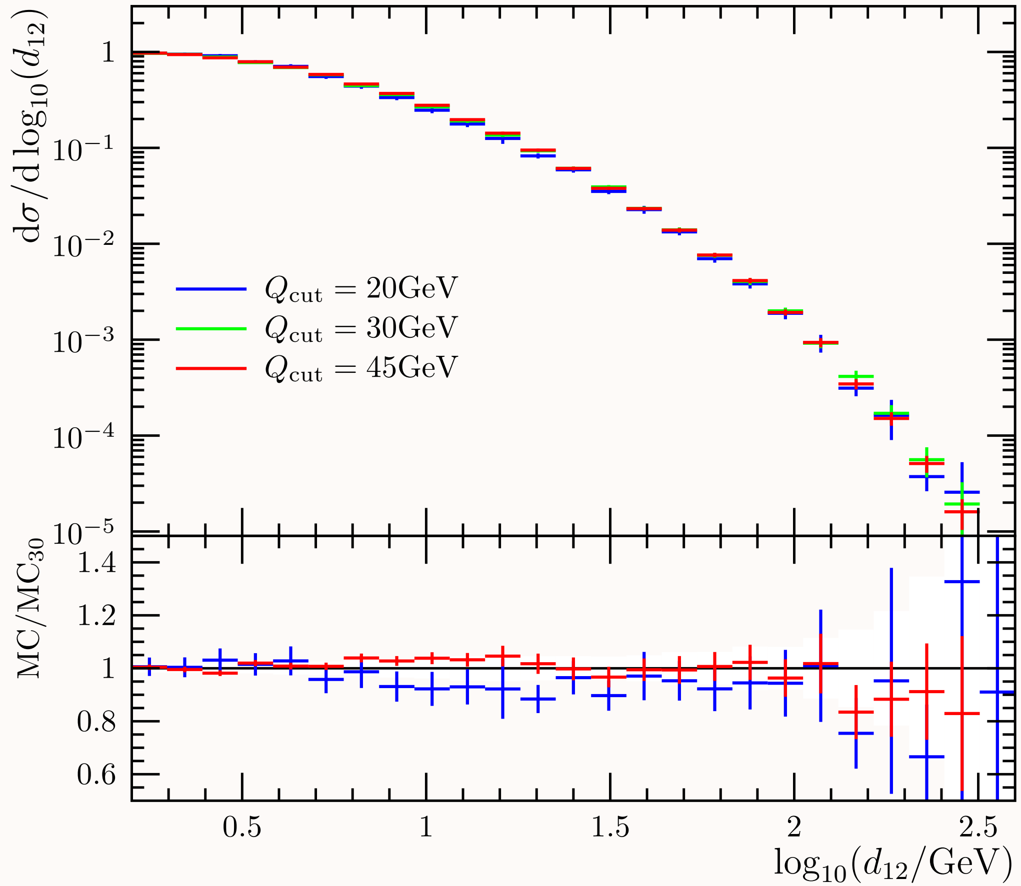

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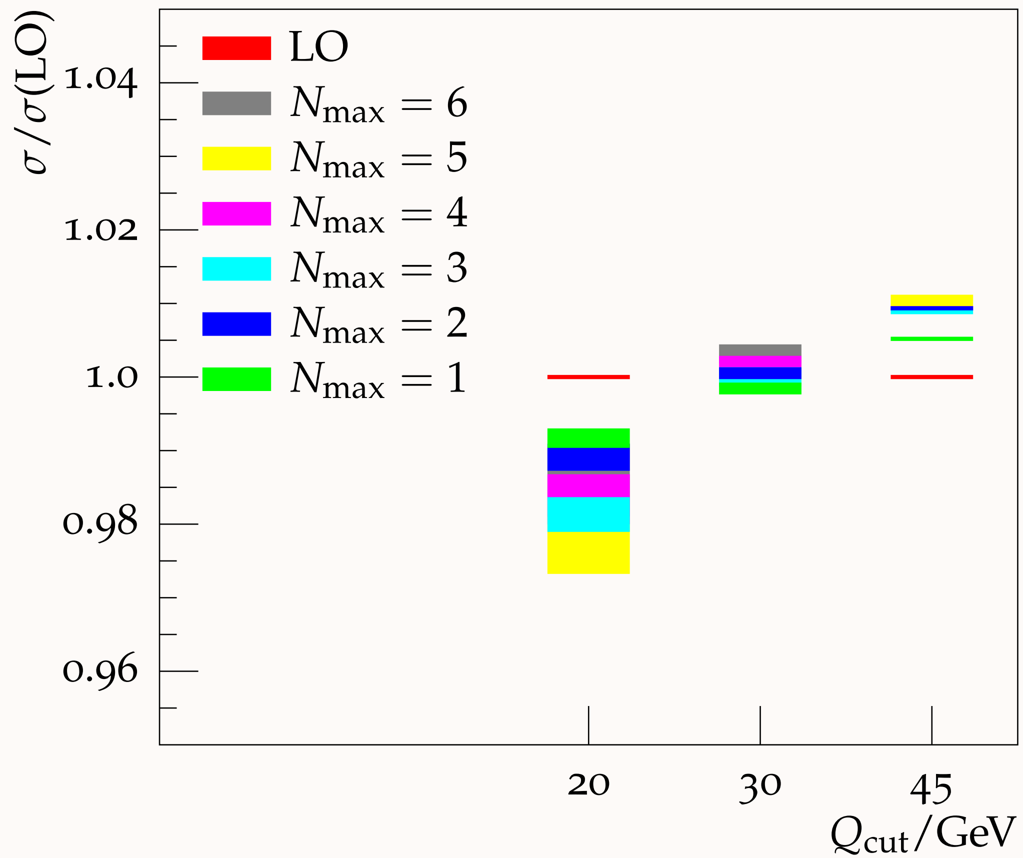
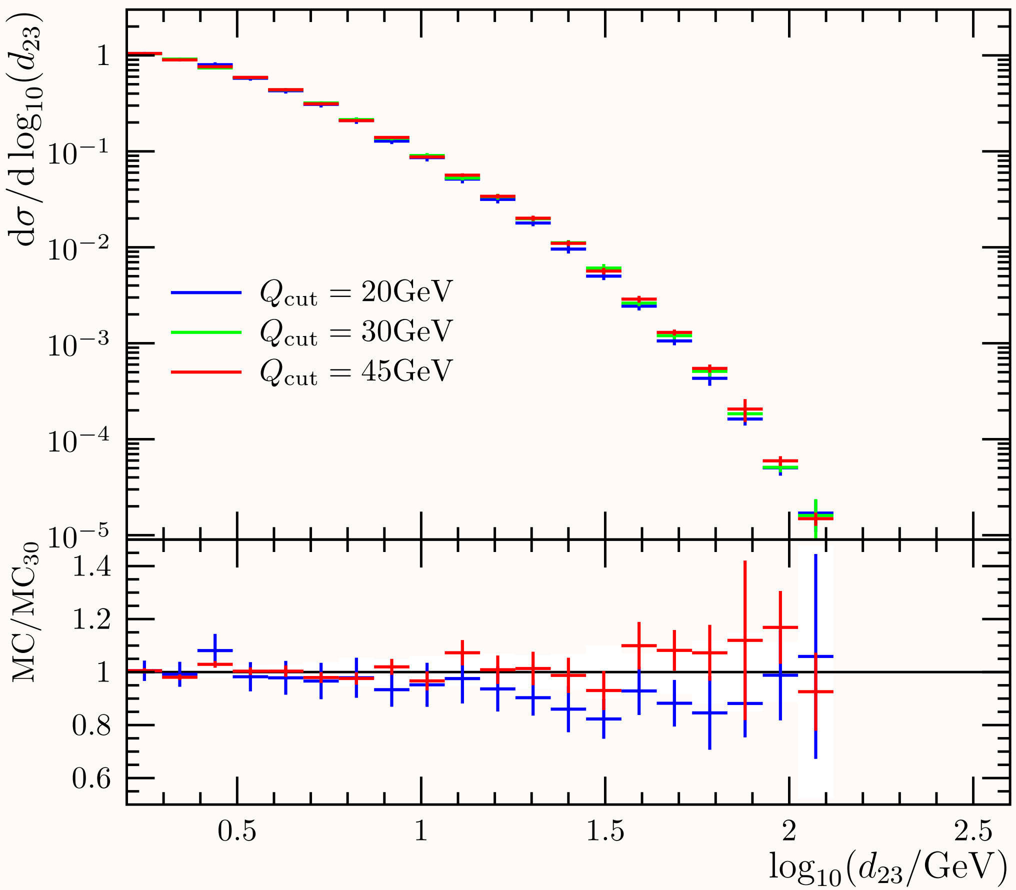




Systematic uncertainties of Sherpa predictions

➡ ***related to ME&TS merging*** [... have been reduced over the past few years.]

- $Q_{\rm cut}$ – magnitude of phase-space separation cut [cancels to log accuracy of shower]
- $N_{\rm ME}^{\rm max}$ – maximum number of jets from hard tree-level MEs
- [choice of internal jet separation measure]

➡ ***related to pQCD :: dynamical and local scale choices***

- scale uncertainties from MEs [renormalization and factorization scale settings]
- scale uncertainties from PSs [coupling and PDF scale settings]

➡ ***related to pQCD–npQCD transition***

- parton-shower IR cut-off / intrinsic transverse momentum [tuned @ LEP & low-p_T DY pair production]
- PDFs plus $\alpha_s(M_Z)$ taken from the fit [enter globally, affect ME and PS]

➡ ***related to npQCD*** [phenomenological universal(?) models need be tuned to data]

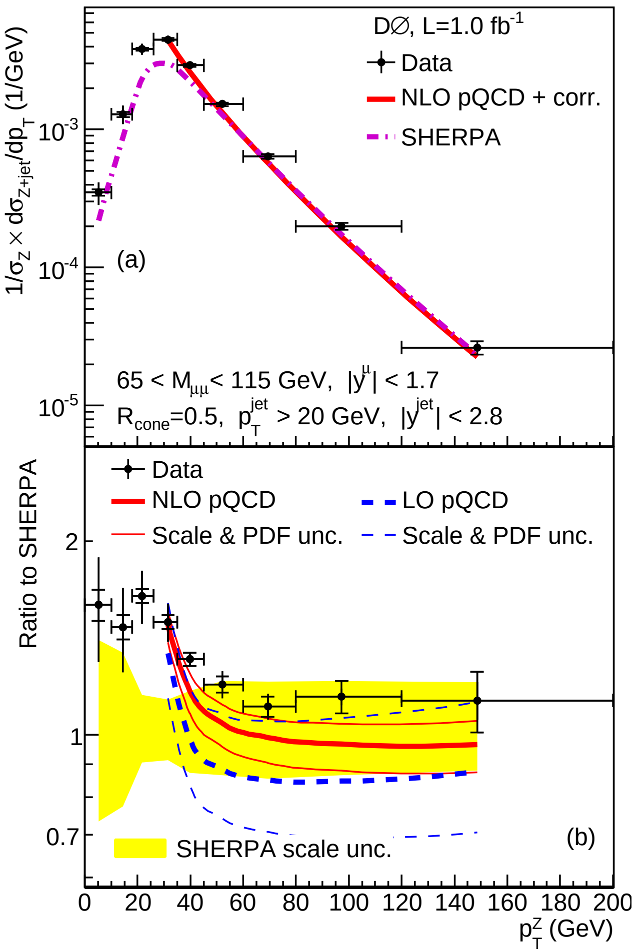
- hadronization parameters [PROFESSOR tune against LEP data]
- underlying event parameters [tuned mainly by hand, partly by PROFESSOR]

Z+jets as measured by DØ

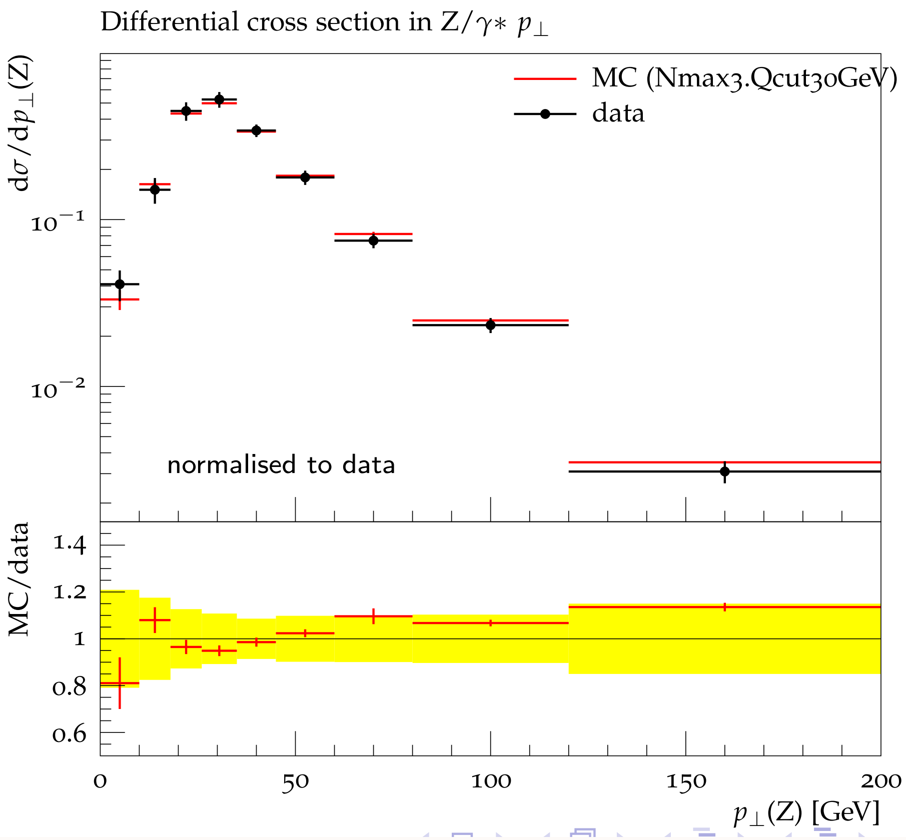
Comparison to Sherpa's CKKW implementation in v1.1.3

Example: DY-p_T in Z/γ^*+jet events DØ Data: Phys. Lett. B **669** (2008) 278

Sherpa v1.1.3



Sherpa v1.2

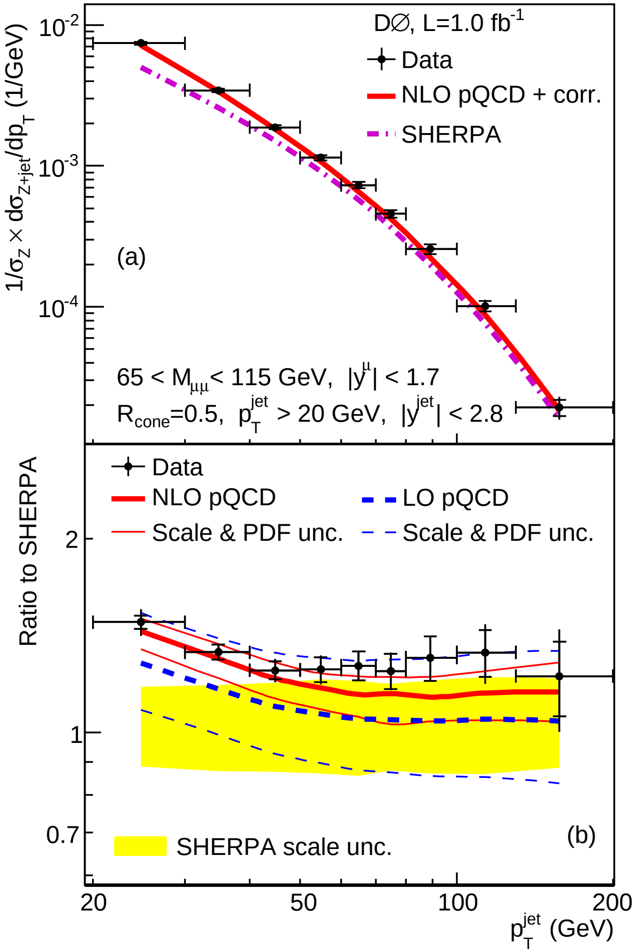


Z+jets as measured by DØ

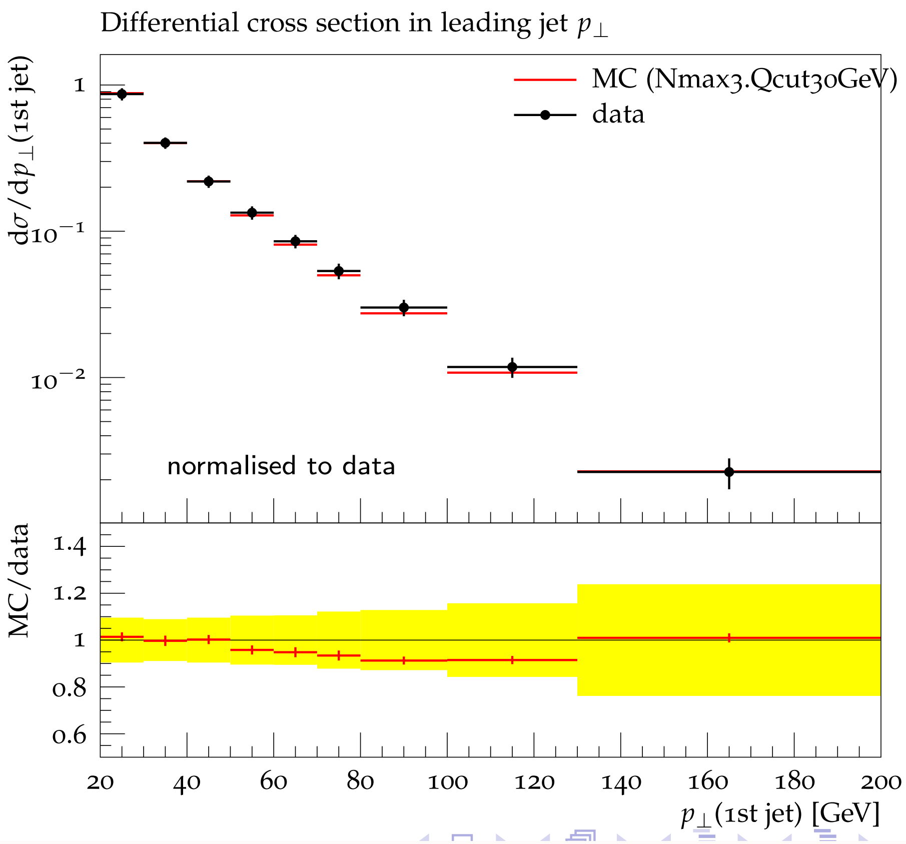
Comparison to Sherpa's CKKW implementation in v1.1.3

Example: 1st jet-p_T in Z/γ^*+jet events DØ Data: Phys. Lett. B **669** (2008) 278

Sherpa v1.1.3



Sherpa v1.2



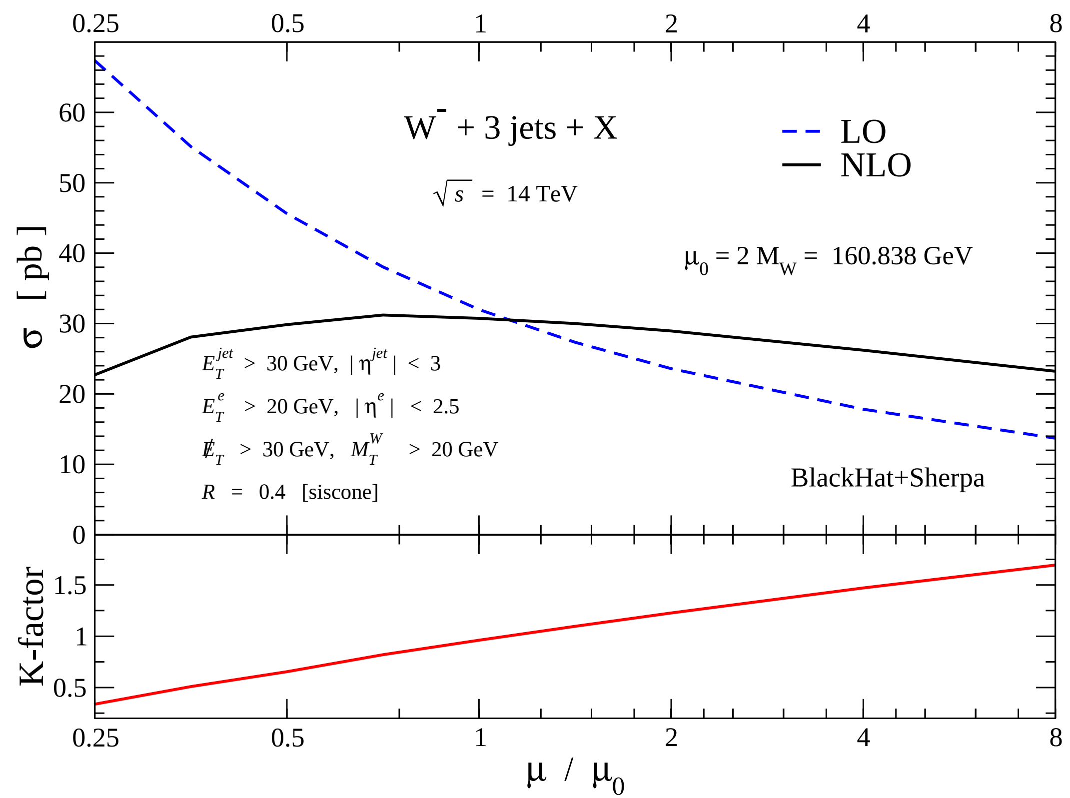
V + n jets ....

at & beyond NLO ... ..

Need for NLO calculations

➡ ***Lessons learned from LEP, HERA, Tevatron:***
LO predictions are fine, yet often only give rough estimates

@ NLO: 1st real prediction of normalization of many observables
less sensitivity to unphysical input scales (μ_{F} & μ_{R})
more physics (parton merging, jet substructure, ISR, more IS parton species)



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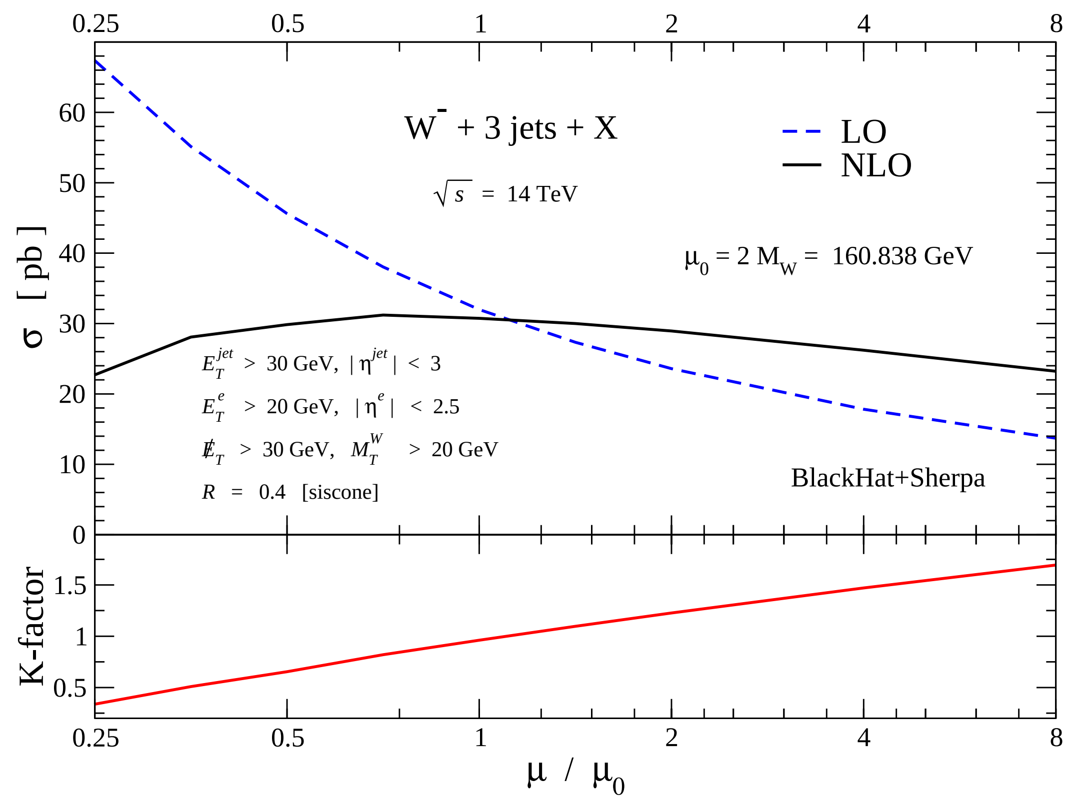
➡ ***Components of NLO calculations***

- tree-level amplitudes (LO & real radiation)
- + one-loop correction to Born level
- + subtraction terms to handle and combine singularities
- + phase-space generator



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- ***Componen***

- tree-level a
  (LO & real
- \+ one-loop c
- \+ subtraction
  combine si
- \+ phase-spac

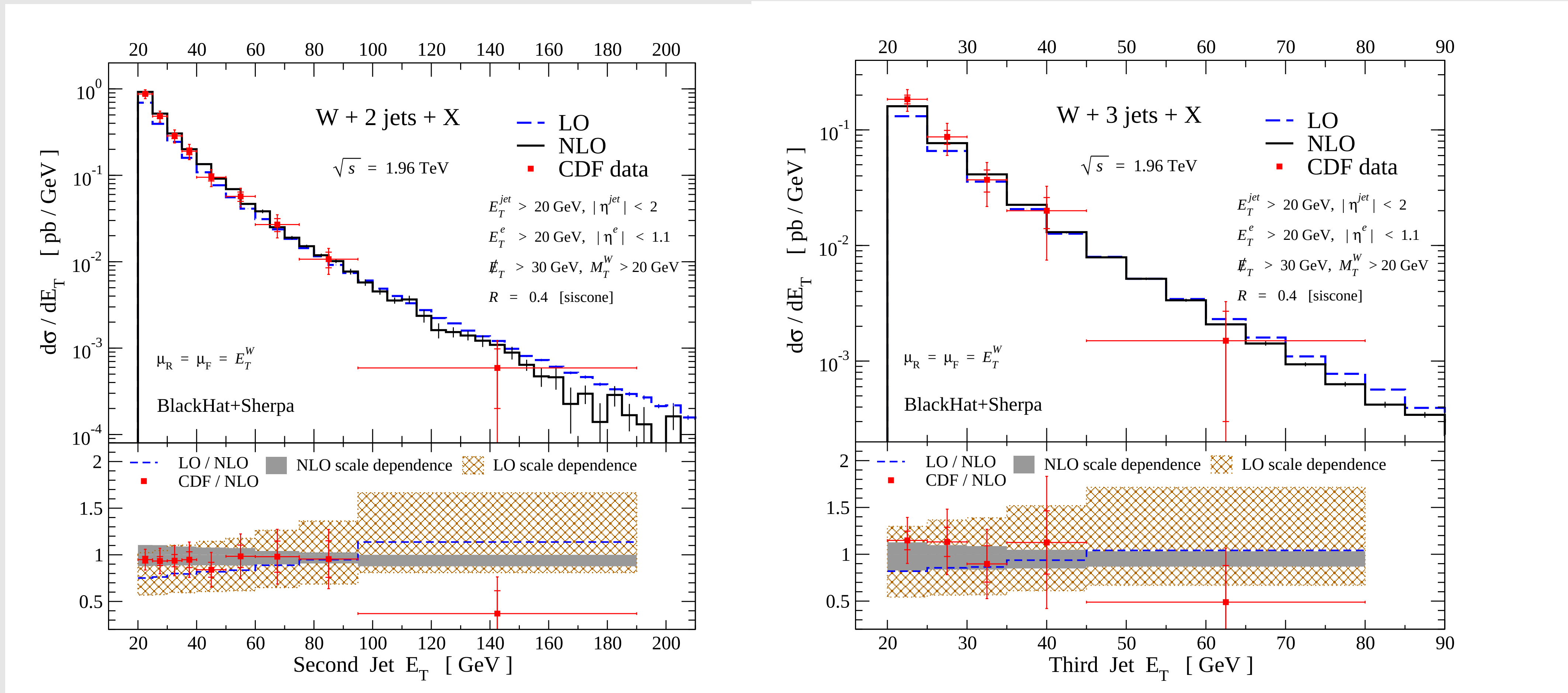
→ for example, BLACKHAT+SHERPA

$$\sigma = \int_m d\sigma^B + \int_{m+1}(d\sigma^R - d\sigma^A) + \int_m (d\sigma^V + \int_1 d\sigma^A)$$

BlackHat+Sherpa interfacing in two steps

[Gleisberg, Krauss, EPJC53 (2008) 501] [Berger et al., Phys Rev D80 (2009) 074036]

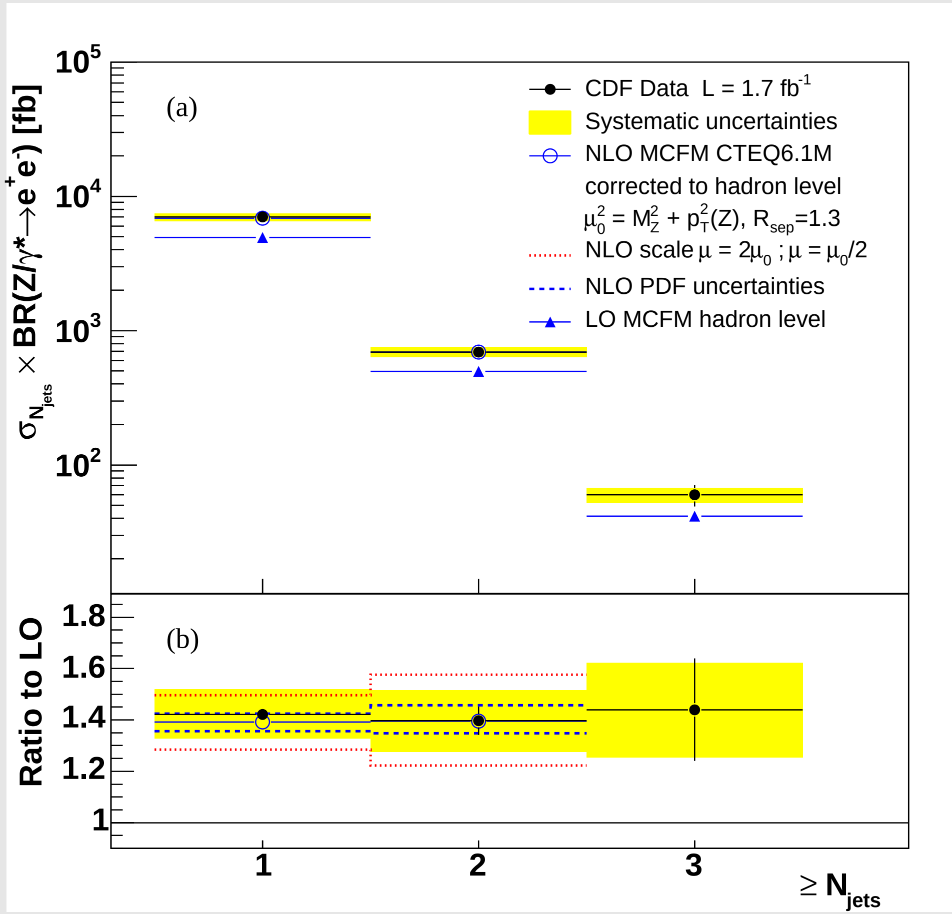
- Initialization: Process and parameter (model, μ_R scheme, sampling) agreement
- Run time: Sherpa provides phase-space point, gets back $|\mathcal{M}^{(1)}|^2$
- Interface details: Les Houches 2009 accord

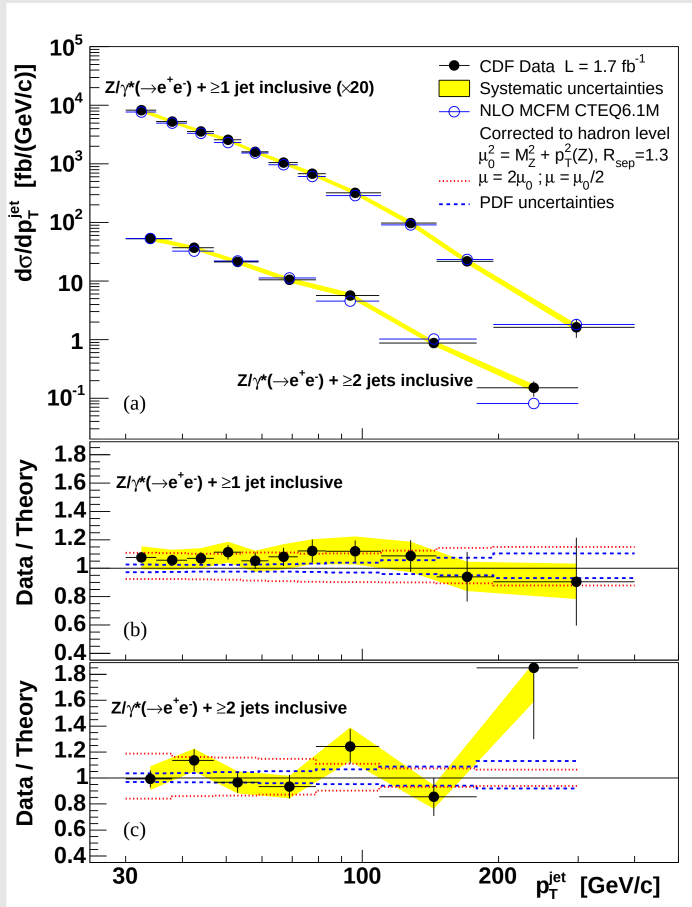


MCFM

[Campbell, Ellis, http://mcfm.fnal.gov/] [T. Aaltonen et al., PRL **100** (2008) 102001]

- NLO parton-level event generator for a range of processes at hadron colliders.
- Anybody can study V + 0,1,2 jets @ NLO (and LO) by running MCFM themselves.
- Spin correlations maintained in decays. Helicity amplitudes. Slightly modified CS subtraction.





Z+jets
CDF data
2007
1.7/fb

Sherpa 1.2 results compared to

predictions at NLO ...

➡ *Study at Les Houches 2009 workshop:*

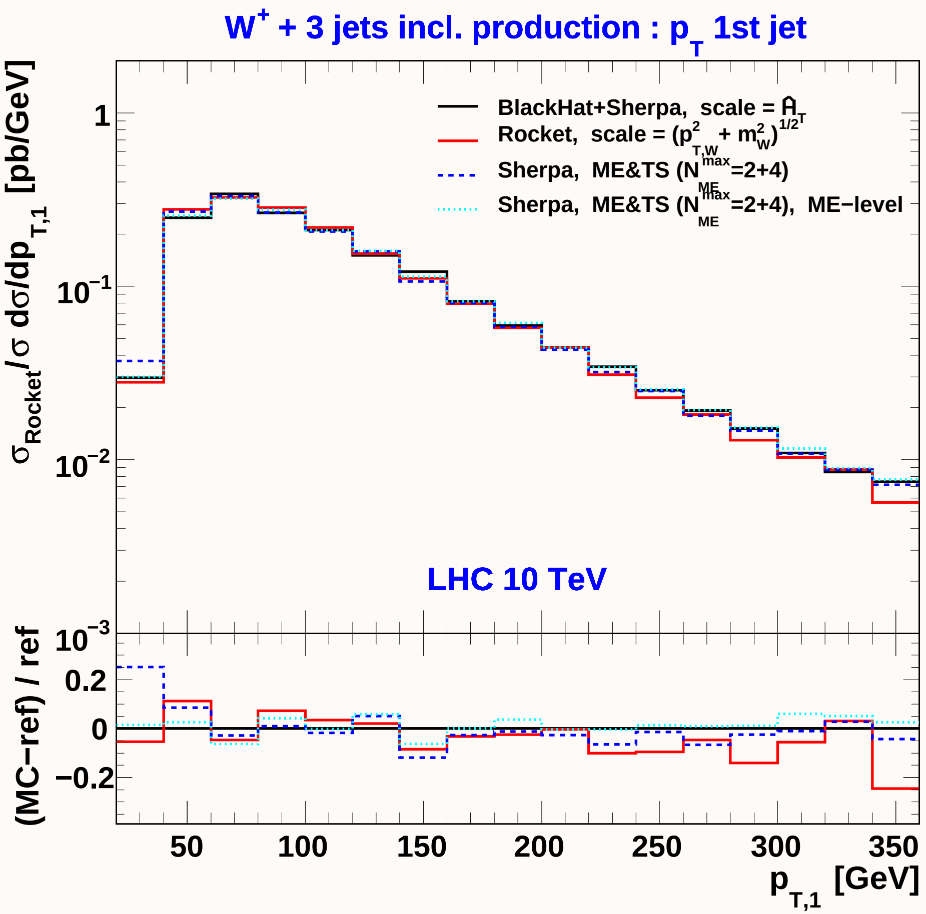
Inclusive $W + 3$ jets @ 10 TeV LHC.

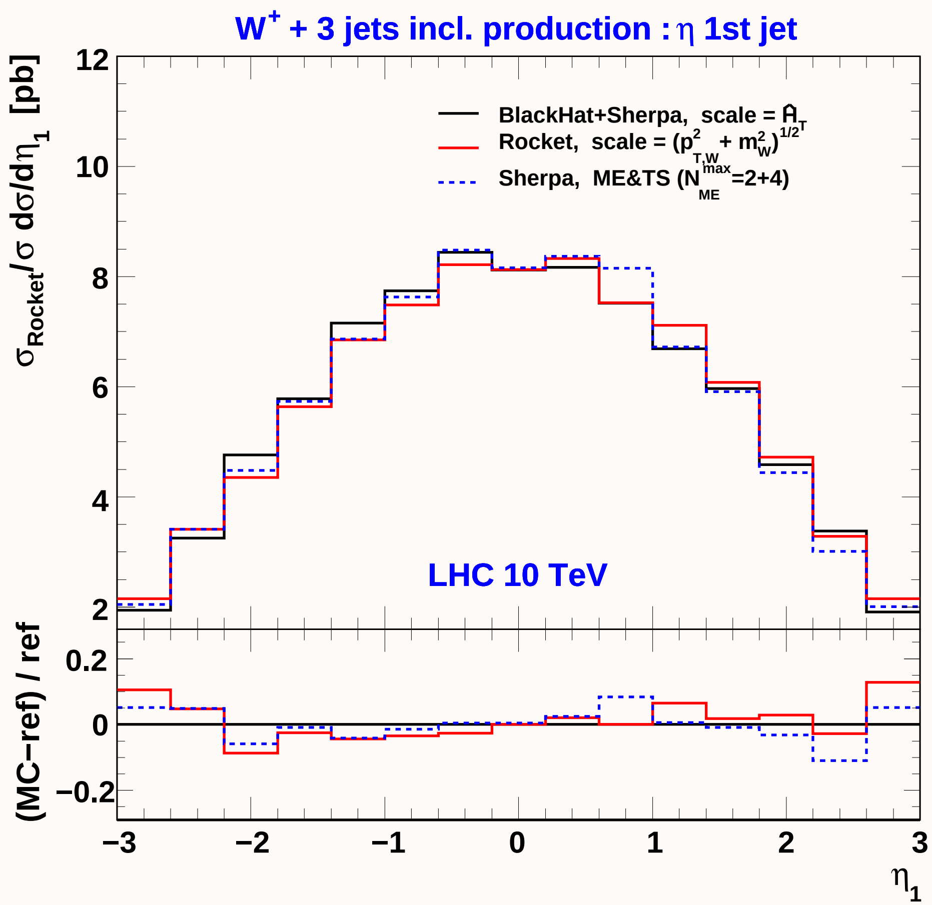
[ARXIV:1003.1241] – *also H+dijets+X via gluon fusion*
[ARXIV:1003.1643] – *also H+jets via gluon fusion*

Recent comparison of LHC predictions for W+3jets

[HÖCHE, HUSTON, MAITRE, WINTER, ZANDERIGHI; LH09 PROCEED.: ARXIV:1003.1241]

- between BLACKHAT [BERGER ET AL.], ROCKET [ELLIS, MELNIKOV, ZANDERIGHI] and SHERPA [GLEISBERG ET AL.]
- rather different scale choices at NLO yield $>$ 20% deviations … impact on BSM searches !
- SHERPA's ME&TS merging in good agreement with NLO once rescaled to NLO xsec





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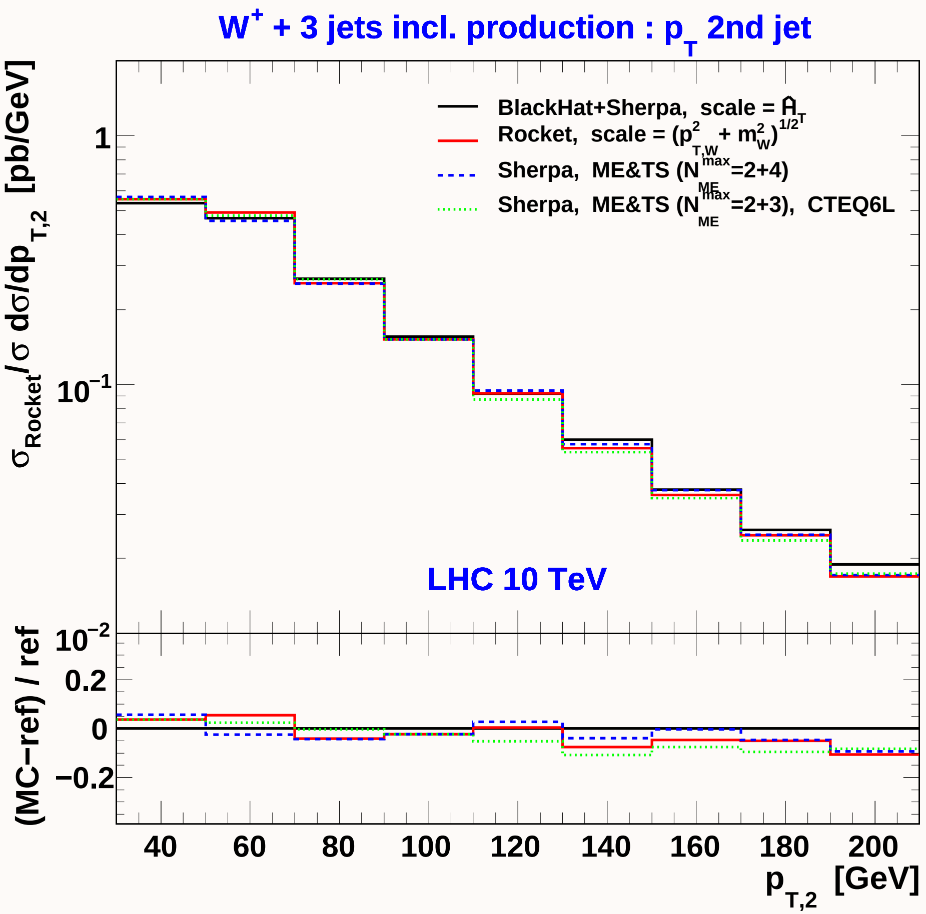

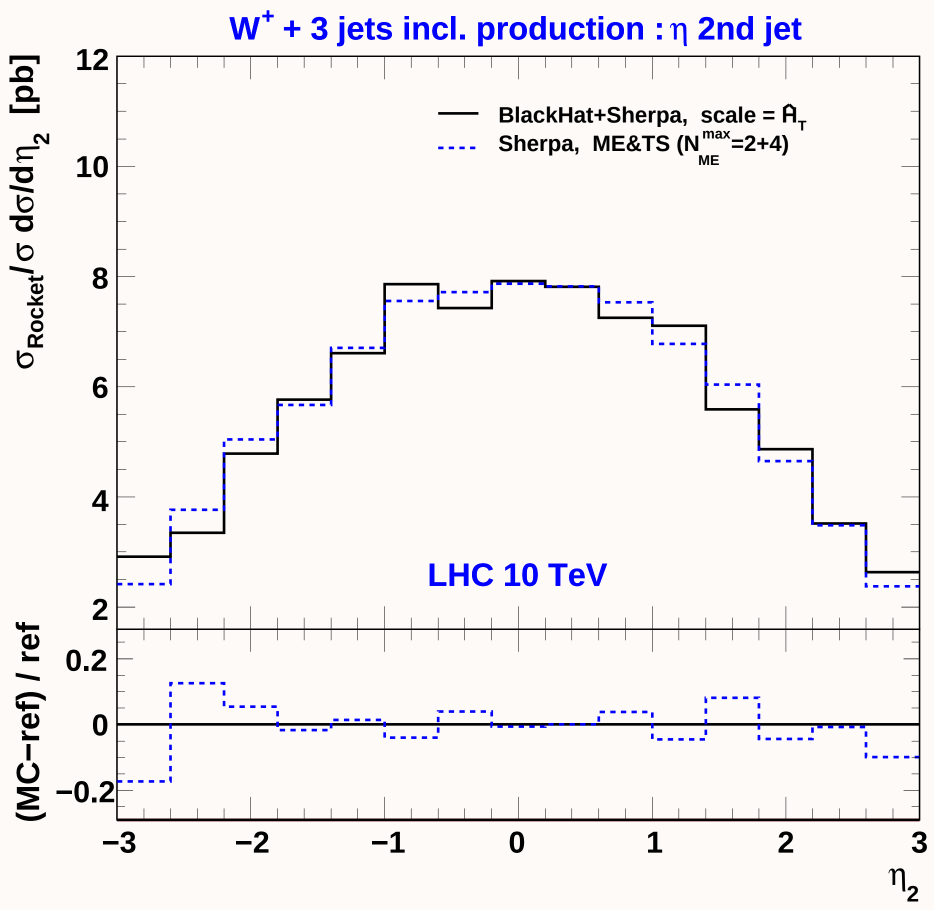

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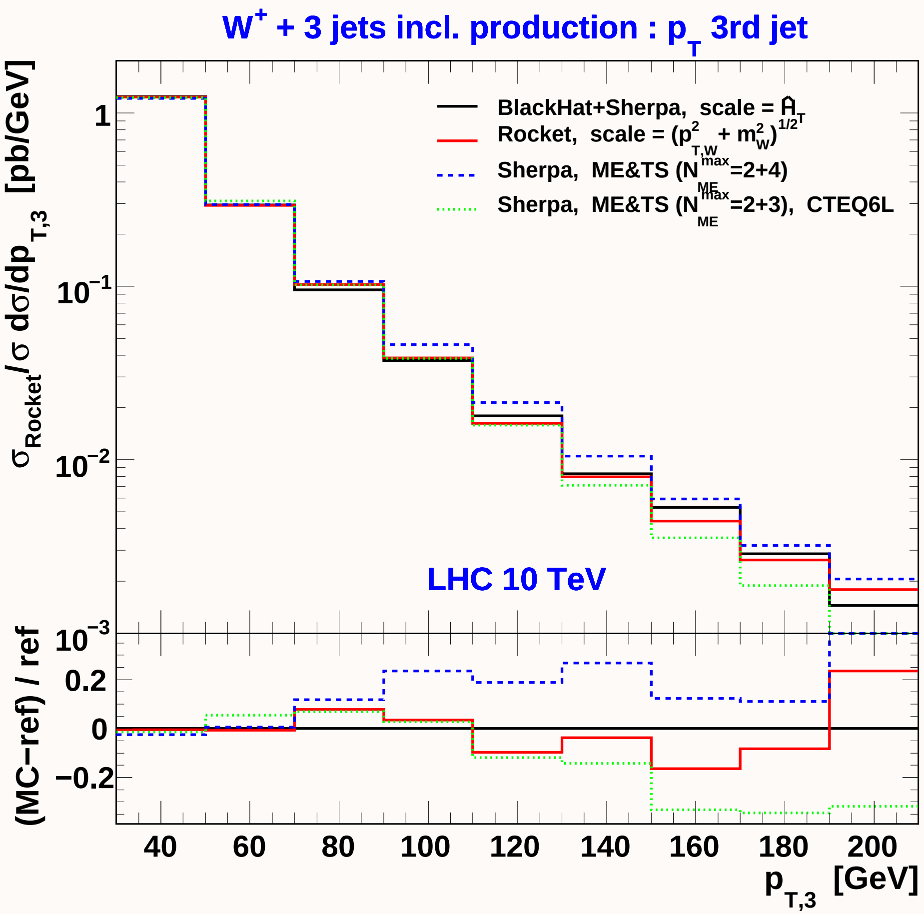

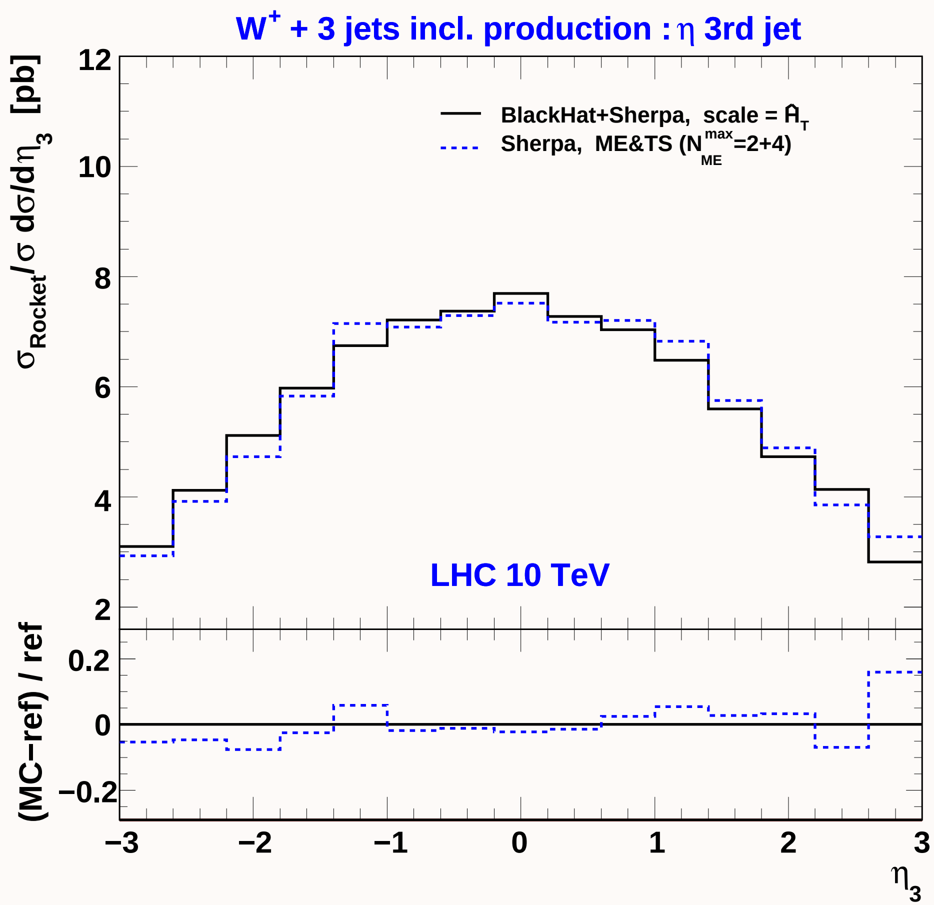

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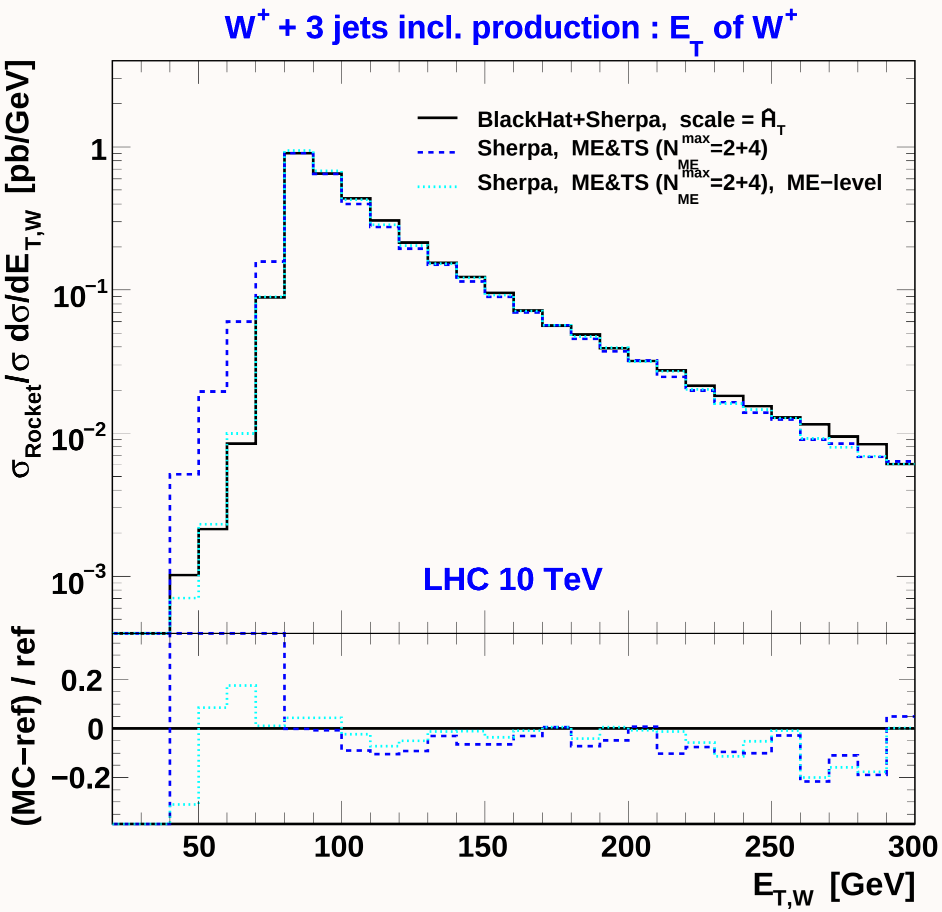

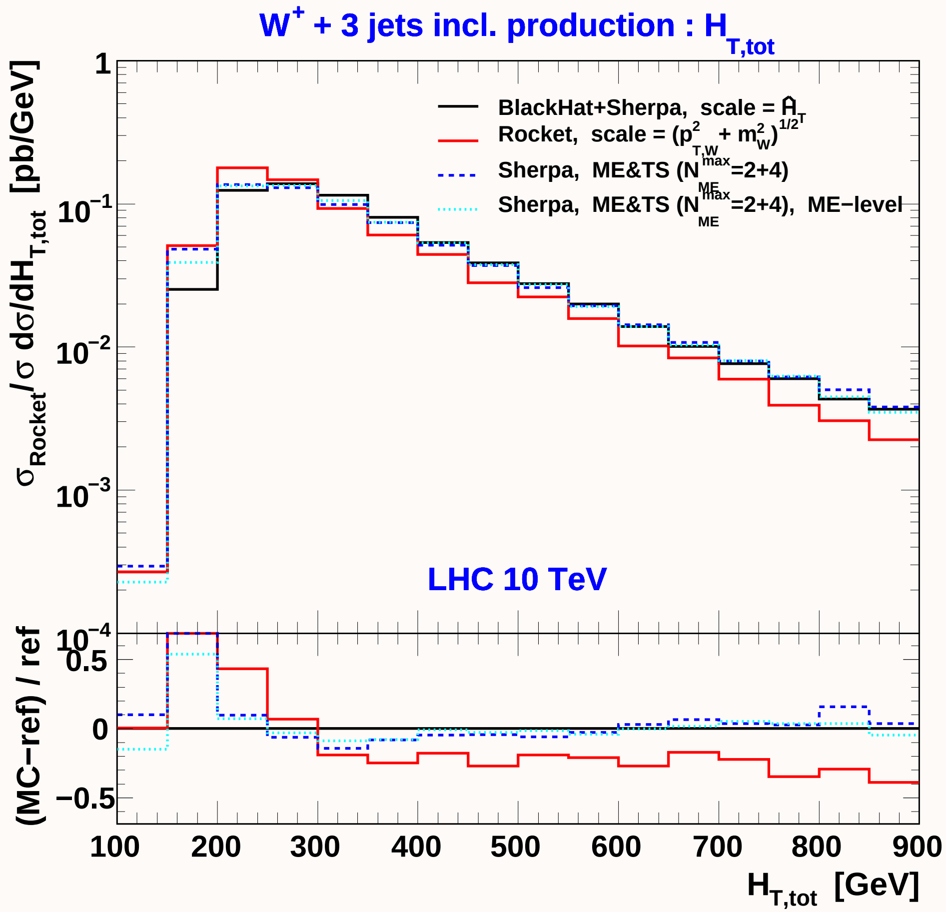

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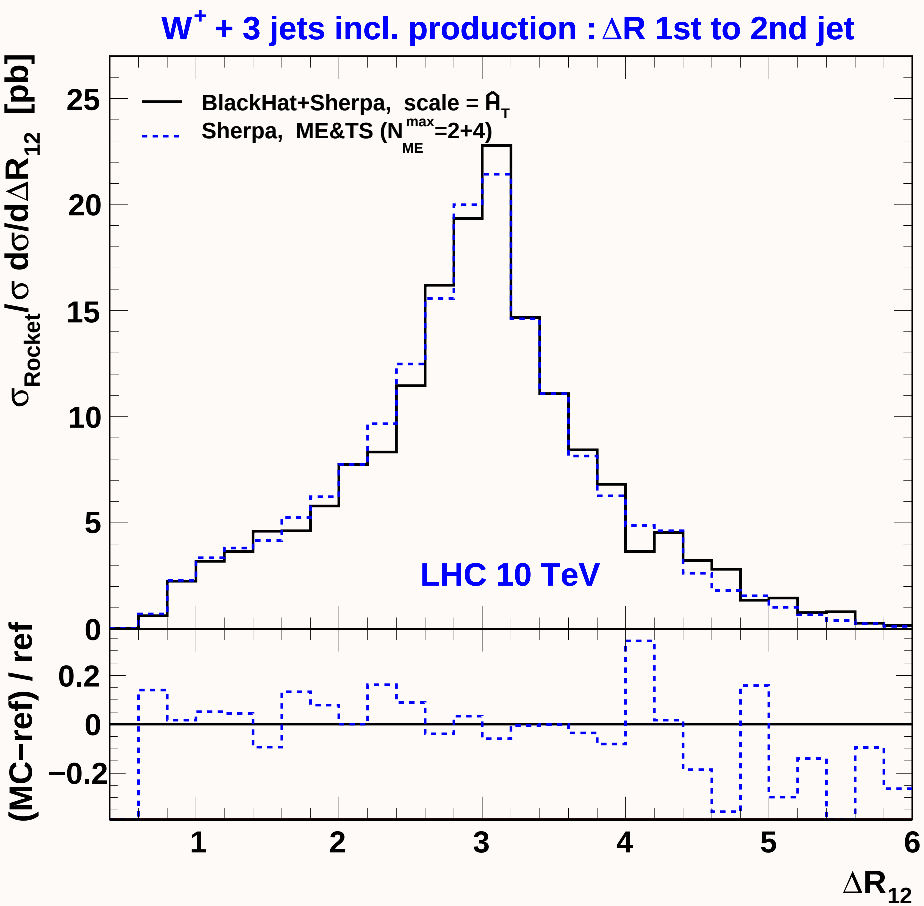

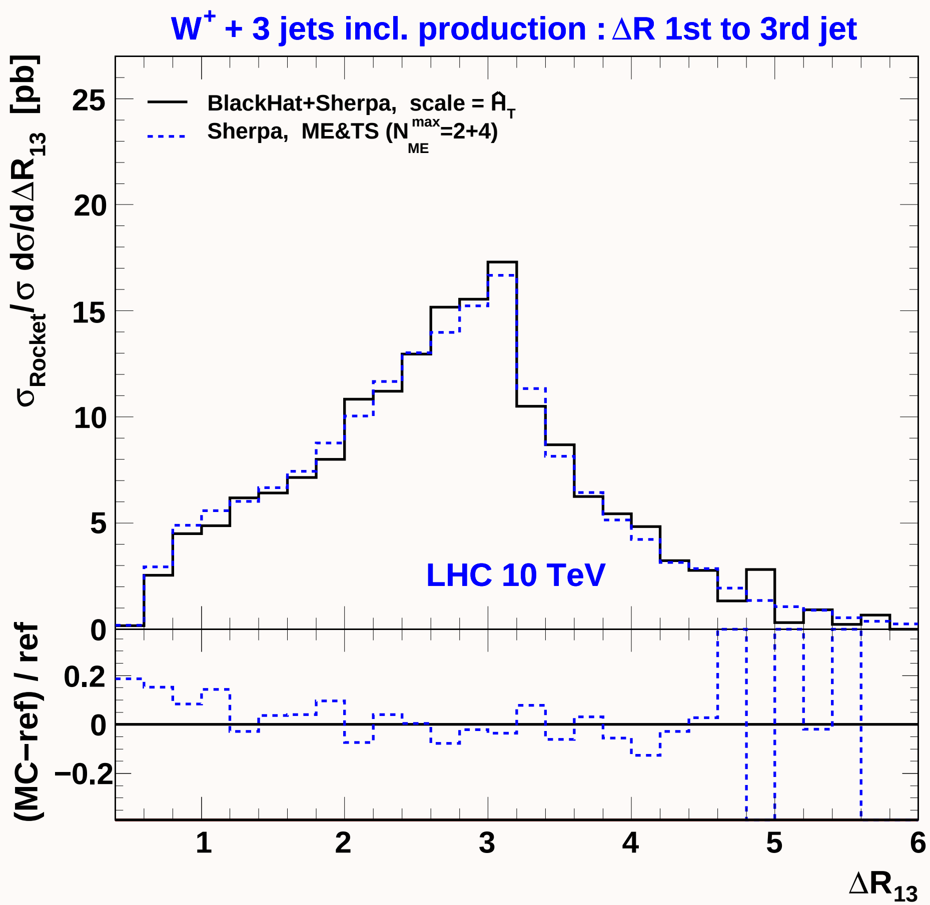

Remark: ratios

- cross section ratios are more robust, since many uncertainties cancel or partially cancel in the ratio, … … hence, one may define

$$C_n^V \equiv \frac{\sigma(V+n\text{ jets})}{\sigma(V+(n+1)\text{ jets})} \sim \frac{C}{\alpha_s(\mu)}$$

- observed @ Tevatron experiments: C is approximately independent of n ➔ Berends scaling

  it costs you one power of α_s to make the last jet
  the value of C depends on the actual jet definiton

- limitations

  multijet events have multiple scales, so α_s has different values at different hard "vertices"

  if jets are too soft one expects large logs to dominate over α_s counting

  for fixed jet parameters, with too many jets one expects to run out of phase space

Beyond NLO

NLO+PS matching

- match PS to NLO preserving good features of PS (Sudakov suppression at small p_T, multiple soft/coll emissions) and NLO (rate, high-p_T shape, reduced scale dependence)
- among other processes, V production + decays fully correlated
- MC@NLO: http://www.hep.phy.cam.ac.uk/theory/webber/MCatNLO/
  [Frixione, Webber; ...]
- POWHEG: http://moby.mib.infn.it/ nason/POWHEG/
  [Nason; Oleari, ...] work on Z+1jet under way

NNLO

- see Frank Petriello's talk on Friday

q_T resummation + matching to higher orders

- calculations taylored to describe specific observable very accurately, e.g. p_T of V
- for example ResBos, see C.-P. Yuan's talk

Summary

- Overview of how vector boson production is processed in Monte Carlo event generators.
- In a high-energy hadron collider environment the production of W/Z bosons is always affected by QCD radiation.
  - ⇒ recoiling against "QCD" generates the vector boson's p_T distribution.
- Parton showers can capture the leading effects of soft and collinear emissions.
  - ⇒ for certain observables, analytic resummations go beyond these limits
  - ⇒ for example, CSS resummation for $d^2\sigma/dp_T dy$.
- Vector bosons often come with additional hard jets.
  - ⇒ V + n jets is a major background to all new physics searches.
- Parton showers can be improved by merging them with real-emission MEs for hard radiation.
  - ⇒ CKKW, MLM, ...; Sherpa's new scheme is ME&TS improving over CKKW.
- Comparison with data: differences are on 20-40% level if an overall K factor is used to correct for the total inclusive cross section as measured in the experiment.
- V + n jets @ NLO: not only predicts shapes but also total rate @ NLO. Hadronization corrections need be applied to compare to data.
- As long as no data, validate ME+PS merging against NLO predictions: Application of overall K factor sufficient to account for missing virtual pieces? What is effect of local scales in ME+PS vs. global dynamic scales in NLO?