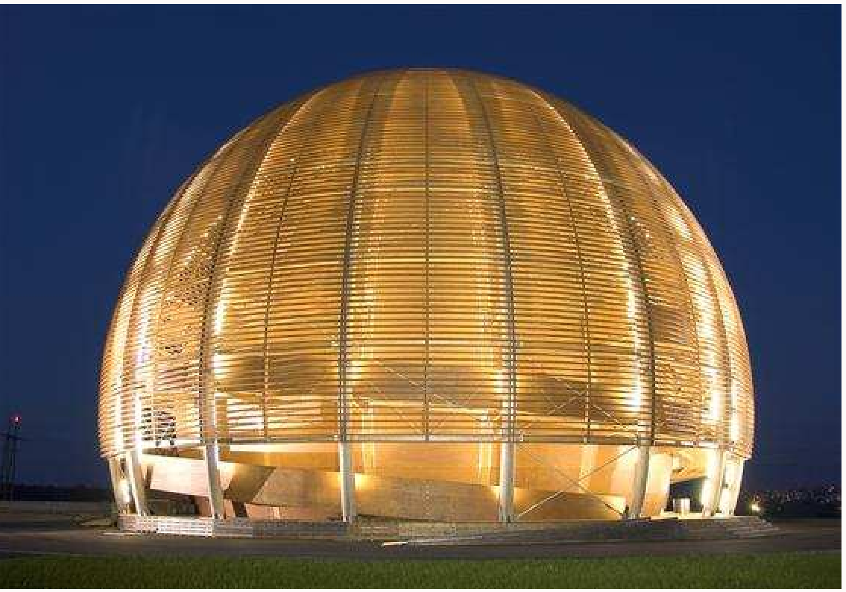
Developments in ME+PS merging

[Fermilab Theory Seminar – Curia II]

Jan Winter [a]

– CERN –



➡ ***Will mainly talk about ...***

- *how to combine MEs and PSs, and*
- *various sophisticated ways to get V+jets predictions.*
- *Plus recent puzzles related to it.*

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

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

- We probably do not need higher-order corrections for discoveries.
  - → If we get smoking-gun signals, we can use data-driven background subtractions.

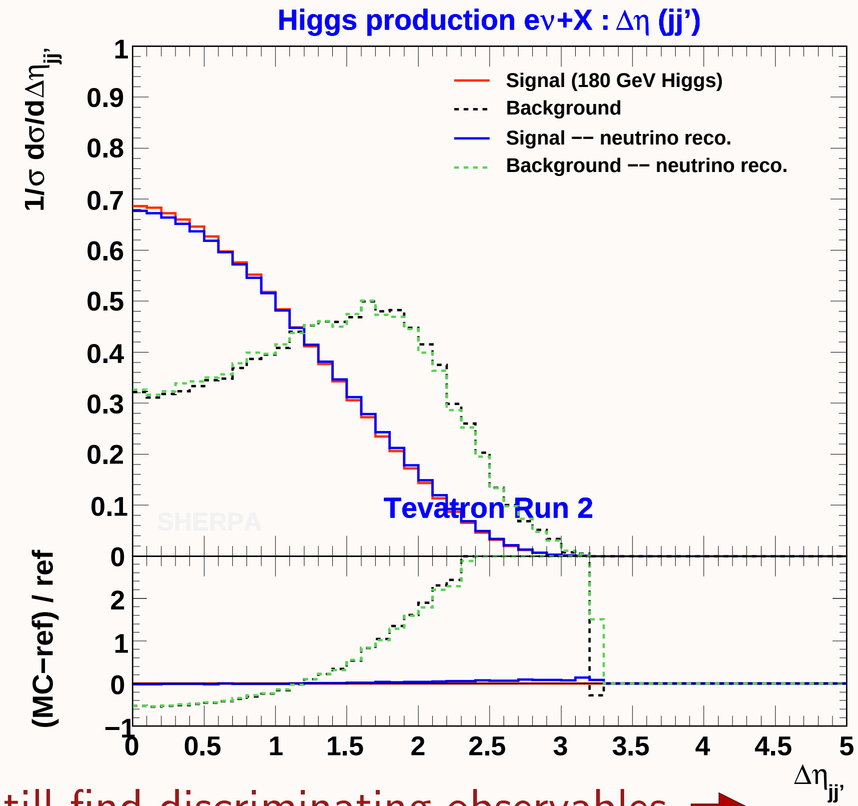
- Likely, end up in tricky situations requiring us to know multi-jet backgrounds [& signals] precisely.
  - → Many new-physics signatures have leptons, MET and several jets.
  - → E.g. sparticle masses <3TeV @ 14TeV LHC: reduced SM systematics (50% → 20%) ⇒ increases # discovered models (68% → 81%) in pMSSM study by [Conley, Gainer, Hewett, Phuong Le, Rizzo].

⇒ SM Higgs situation is good example of such a scenario.
  - → We run exclusion analyses @ Tevatron + LHC and hope for some excess to build up with more data.

- Largely unexploited @ Run2: $gg \to h \to WW \to \ell\nu jj$.

our approach [Lykken, Martin, Winter, in preparation]

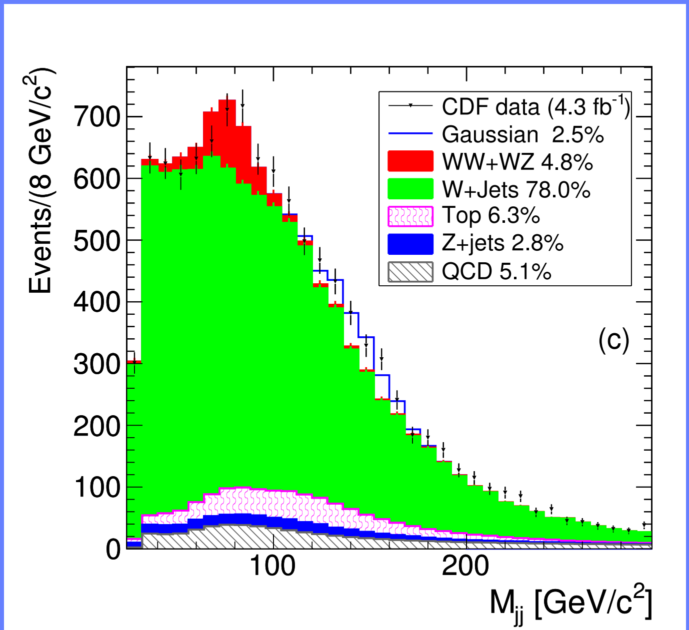
- signal and (dominant) W+2jets background with Sherpa
  ⇒ QCD corrections (shapes) well included
- correct rates with K-factors (latest NNLO for signal, MCFM NLO for W+2jets)
- after basic cuts plus combinatorial h selection using mass windows for h and jj ⇒ $S/\sqrt{B} \sim 1.9(1.2)$ @ hadron level for $M_h = 165(180)$GeV.

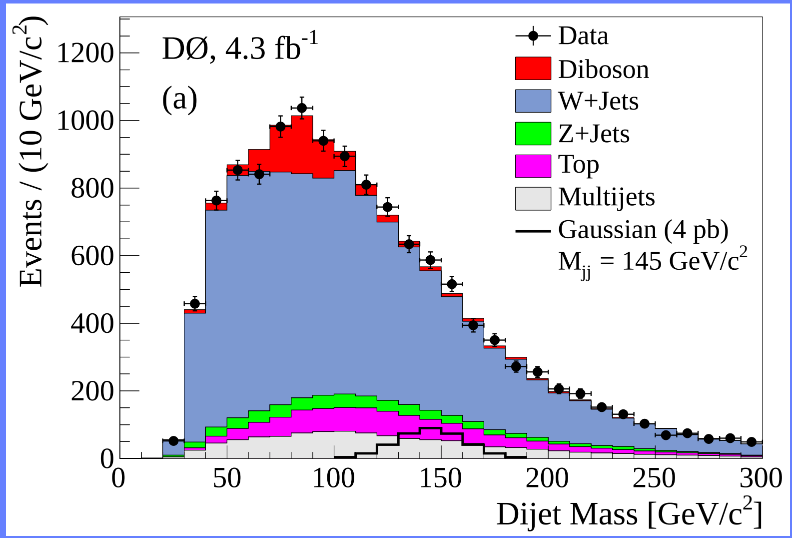


Still find discriminating observables →

Recent measurements tell us ... .

➡ *... a different story.* *And it's exactly this final state: lepton + MET + (excl.) 2 jets.*





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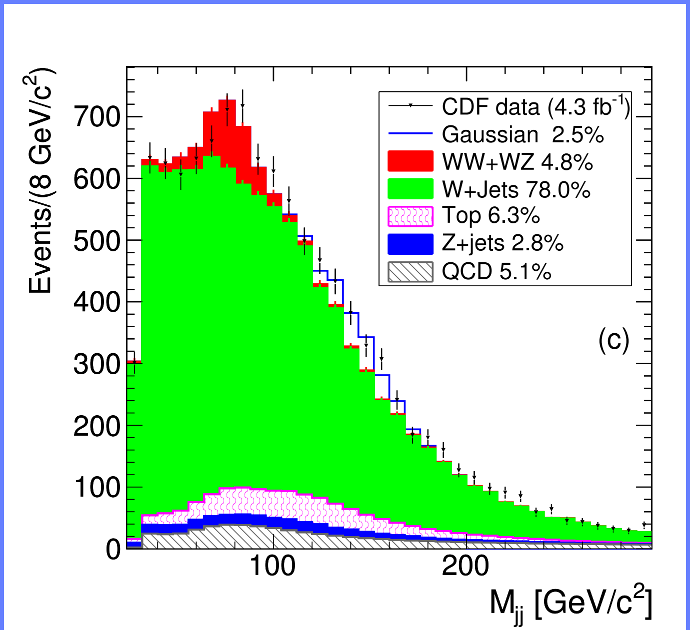
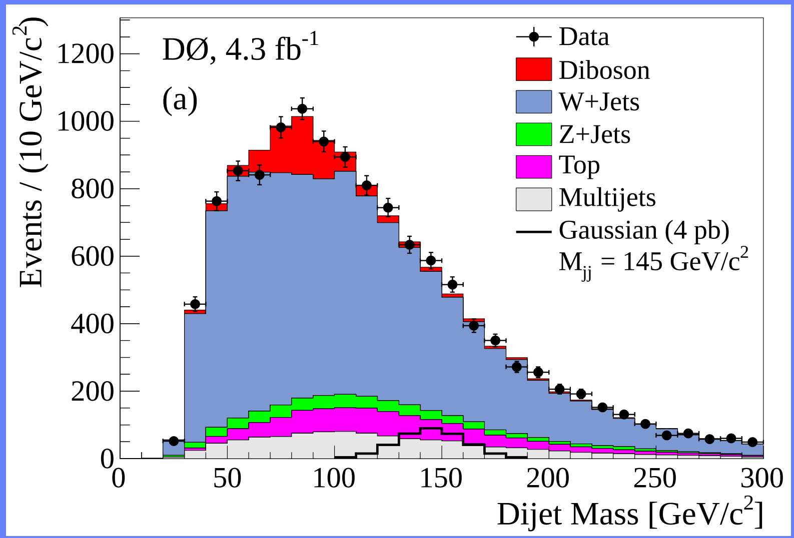


CDF [arXiv:1104.0699]

Are the results compatible?

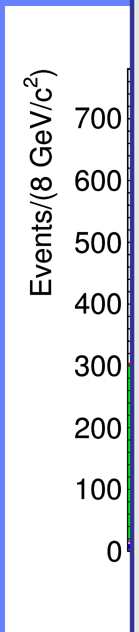
DØ [arXiv:1106.1921]

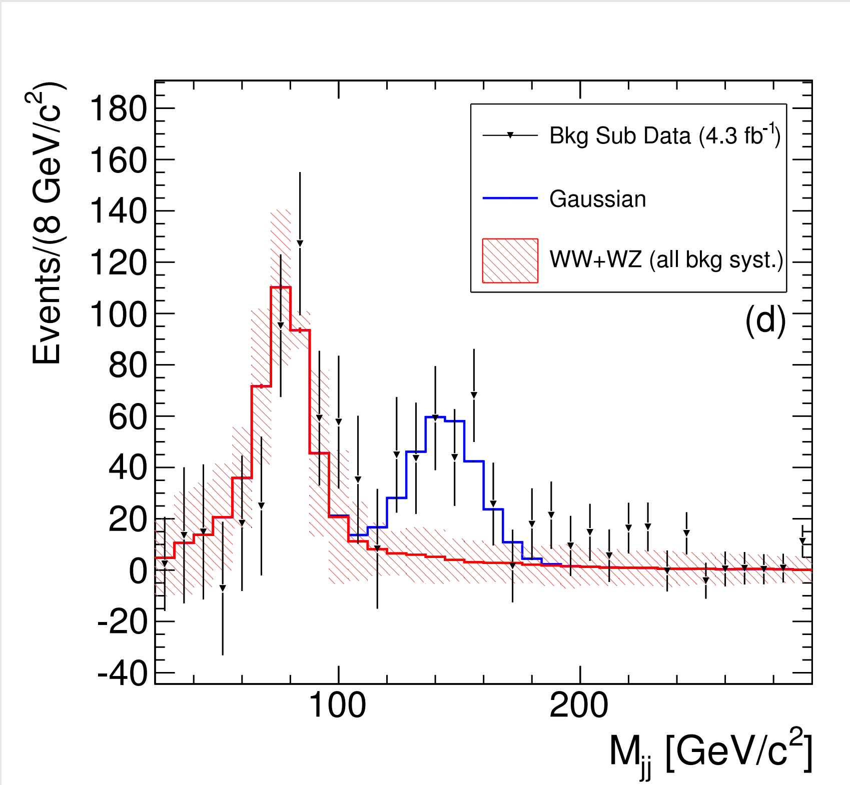


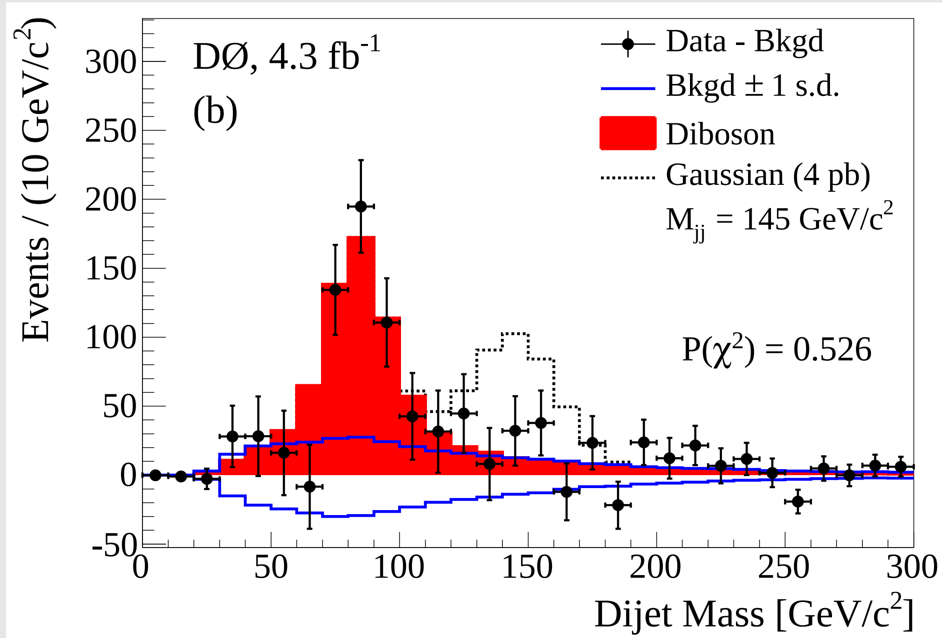
Recent measurements tell us ... .

➡ *... a different story.* *And it's exactly this final state: lepton + MET + (excl.) 2 jets.*

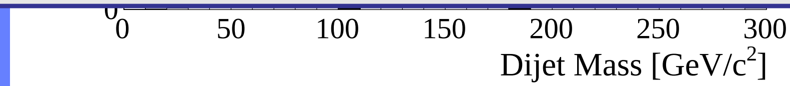
➡ subtracting all backgrounds but WW/WZ



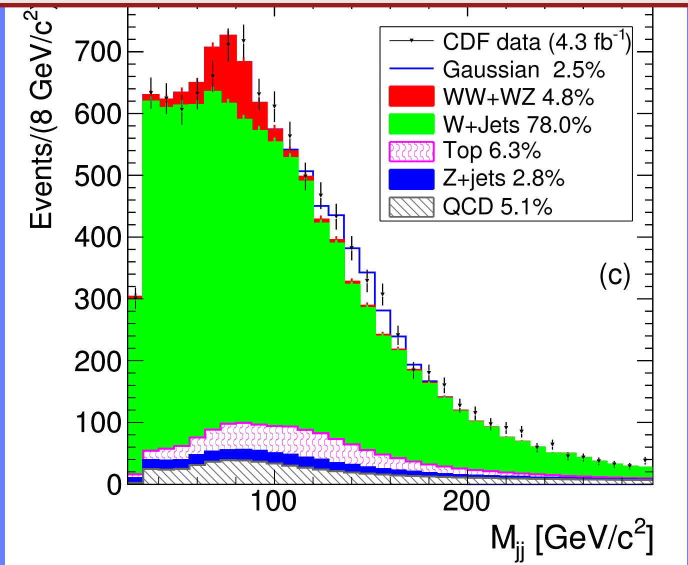




CD



- What are the differences in the two analyses. How large of an effect can they make?
- Why do the diboson (or W+jets) contributions look pretty different?
  (... just jet algorithms, cone sizes and binning?) (Size of diboson prod. xsec extracted by DØ?)
- Why is the QCD background in DØ roughly twice as large? (... just looser electron criteria?)
- How well do we understand all the backgrounds and their systematics ...
  with the major contribution coming from ***W+2jets*** ?



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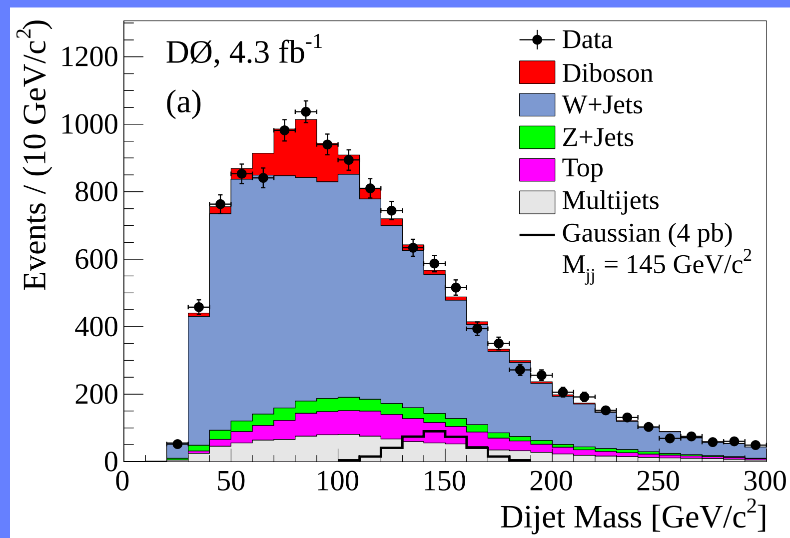


Hadronic cross sections for weak-boson production

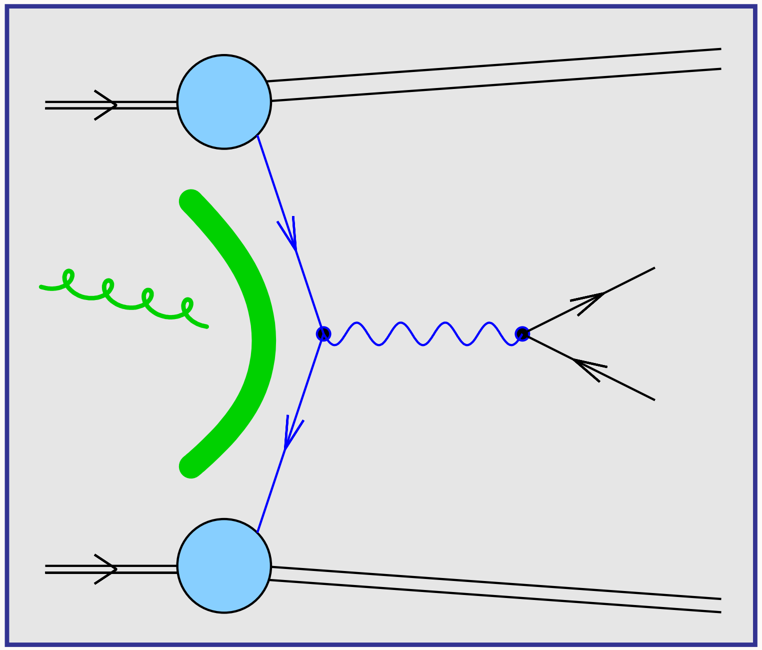
- calculation of the hadronic cross section relying on factorization theorem

  … … 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 = parton density functions (PDFs) … extracted from data;

separation of perturbative and non-perturbative regimes ➡ pQCD used to predict cross sections in complicated hadron collider environment



- E.g. 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

- E.g. V + n-jet production @ LO: vector boson recoils against one or more jets (parton-level jets)

  ⬅ highly automated ME generators @ tree level

  - Alpgen, MadGraph/Event, Helac, LO MCFM, Amegic, Comix, Whizard

Beyond LO

- E.g. V production @ NNLO: fully differential codes:
  - FEWZ [Melnikov, Petriello]
  - DYNNLO [Catani, Cieri, Ferrera, de Florian, Grazzini]
- E.g. V + n-jet production @ NLO:

  based on generalized unitarity and OPP methods
  - BlackHat+Sherpa [Bern, Dixon, Maitre, ...]
  - Rocket

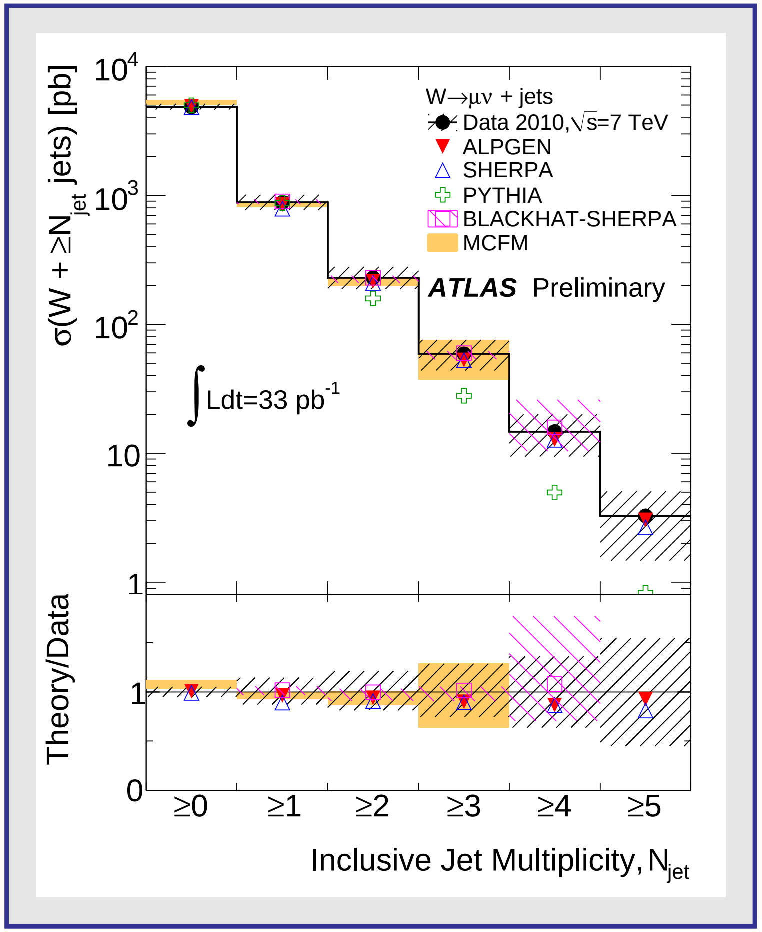
    [Melnikov, Zanderighi, ...]

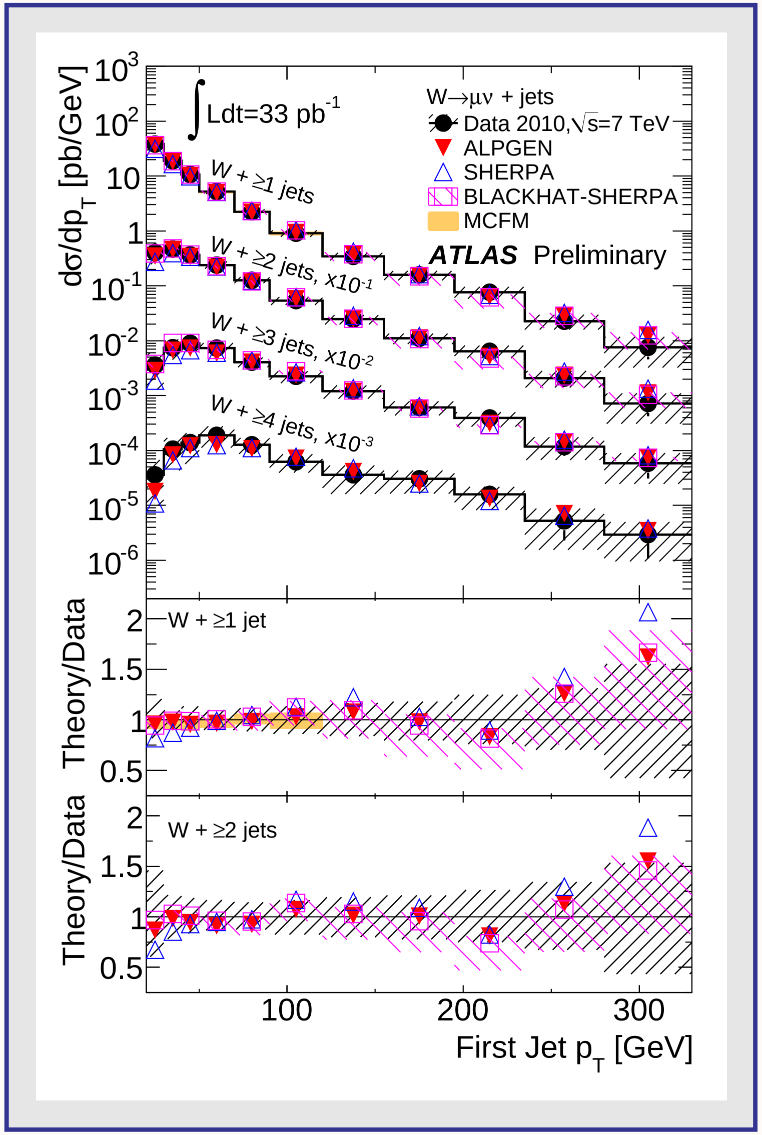
  established
  - MCFM

    [Campbell, Ellis, ...]

  automated
  - MadFKS+ MadLoop

    [Hirschi, Frederix, Frixione, Garzelli, Maltoni, Pittau]



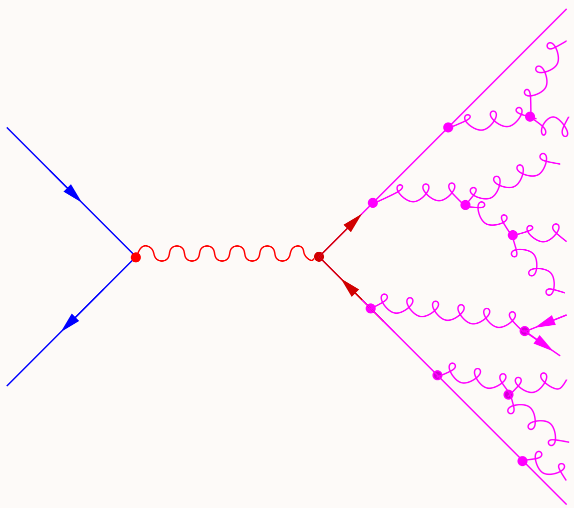


Jet production from parton showers

Inclusive multi-jet predictions @ LO + LL accuracy (underlying core process given @ LO).

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

[Pythia, Herwig, Ariadne, CSshower]

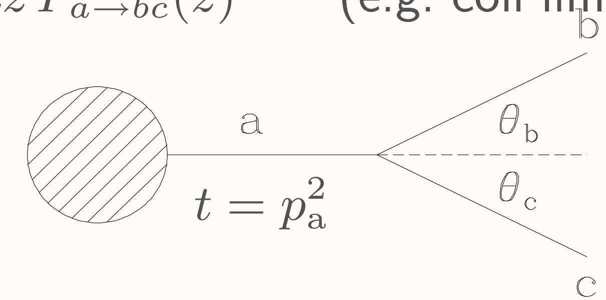


- QCD amplitudes factorize in the coll/soft limit.

➡ Recursive definition of multiple emissions:

$$d\sigma_{n+1} \;=\; d\sigma_n \,\frac{\alpha_s(t)}{2\,\pi}\,\frac{dt}{t}\; dz\, P_{a\to bc}(z)$$

(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 *[$\mathcal{O}(1\mathrm{GeV})$]*

Multi-jet predictions @ LO+LL and beyond

Traditional approach: parton showers describe additional jet activity. There are 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 (number of colours)

Possible improvements:

- first few hardest emissions given by tree-level MEs ➡ improved LO+LL predictions

  [called (tree-level/LO) ME+PS merging – CKKW, L-CKKW, MLM, ME&TS – No NLO xsecs!]

- use NLO QCD core processes and match to parton showers ➡ NLO+LL predictions

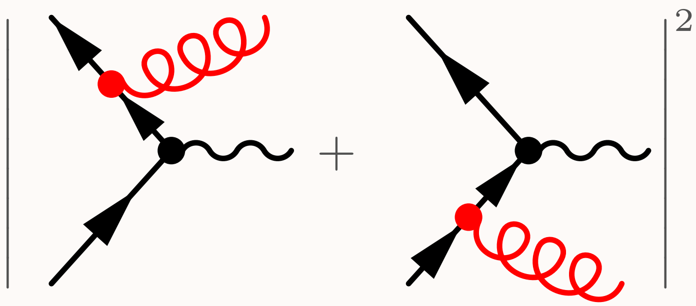
  [called NLO+PS matching – MC@NLO, POWHEG – Full NLO xsecs!]

- MENLOPS ➡ combination of POWHEG and ME+PS

Systematic embedding of higher-order QCD corrections in multi-purpose Monte Carlos like Herwig, Pythia or Sherpa. (enormous progress in last 10 years with two effects)

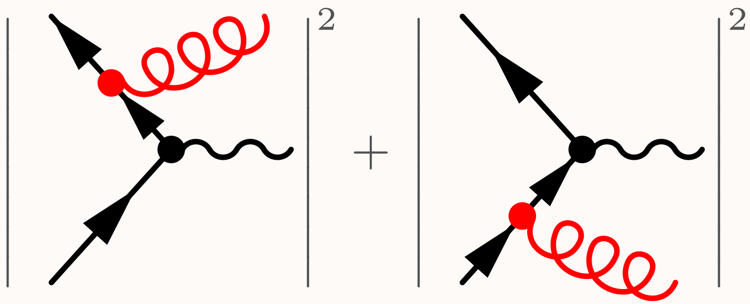
$\Rightarrow$ qualitatively better description of QCD jet data at all colliders (LEP, Hera, Tevatron)

$\Rightarrow$ improved handling and understanding of systematic uncertainties matrix element: exact to given order



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

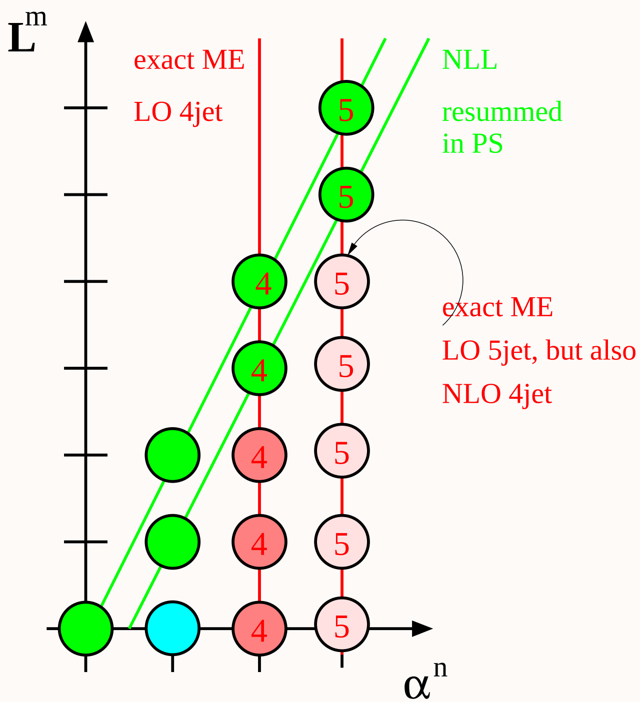
parton shower: approximates ME in singular region



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

Combine advantages of MEs and PSs, remove weaknesses of MEs and PSs.

Avoid double counting and dead regions, preserve accuracy of PS evolution and universality of hadronization.



α_S vs. Log

in $ee \longrightarrow$ jets

Tree-level ME+PS merging

Merging procedures have main steps in <u>common</u>:

(1) calculate n-jet cross sections: use jet criteria to define/regularize the MEs,

(2) generate hard-parton samples with ME kinematics and $P \propto n$-jet/total xsecs,

(3) accept/reject jet configurations based on their (further) PS evolution,

(4) find suitable starting conditions for the parton showering and veto unwanted jets.

<u>Different</u> methods use <u>different</u> techniques in dealing with (1), (3) and (4):

- CKKW, for example: (1) employ k_T-jet measure; (3) reweight MEs through α_s and analytical Sudakov form factors; (4) evolve each ME parton using k_T cluster scales & veto emissions above $Q_{\rm cut}$

Examples for ME+PS merging Monte Carlos:

- Alpgen – MLM; interfaced to Pythia or Herwig [Mangano et al.]
- MadGraph/Event – MLM, cone or k_T jets; interfaced to Pythia [Maltoni et al.]
- Sherpa – CKKW, ME&TS from vs1.2; truly interconnected with PSs [Krauss et al.]
- Herwig++ – modified CKKW, i.e. truncated showers [Richardson et al.]

Tree-level ME+PS merging

Merg

(1) calculate n-jet cro

(2) generate hard-part

(3) accept/reject jet c

(4) find suitable starti

Different* methods use *diffe

- CKKW, for example: through α_s and analytica using k_T cluster scales &
  - Alpgen – ML
  - MadGraph/E
  - Sherpa – CK
  - Herwig++ –

CKKW

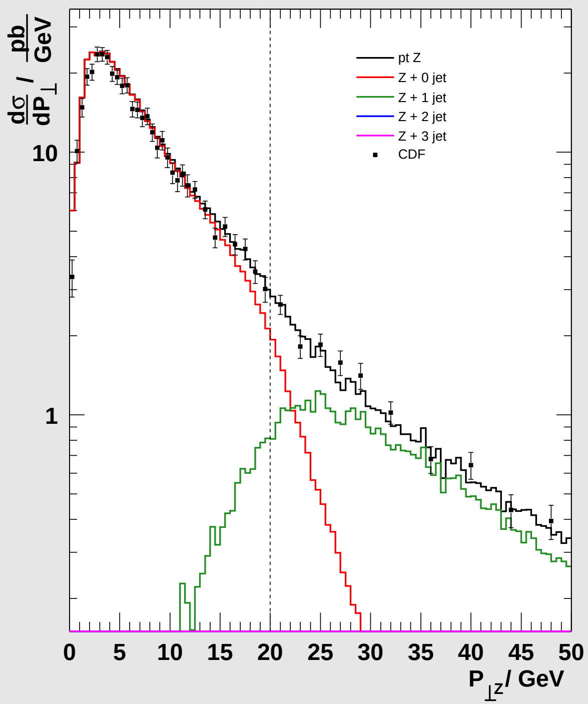
[Catani, Krauss, Kuhn, Webber, JHEP 11 (2001) 063]

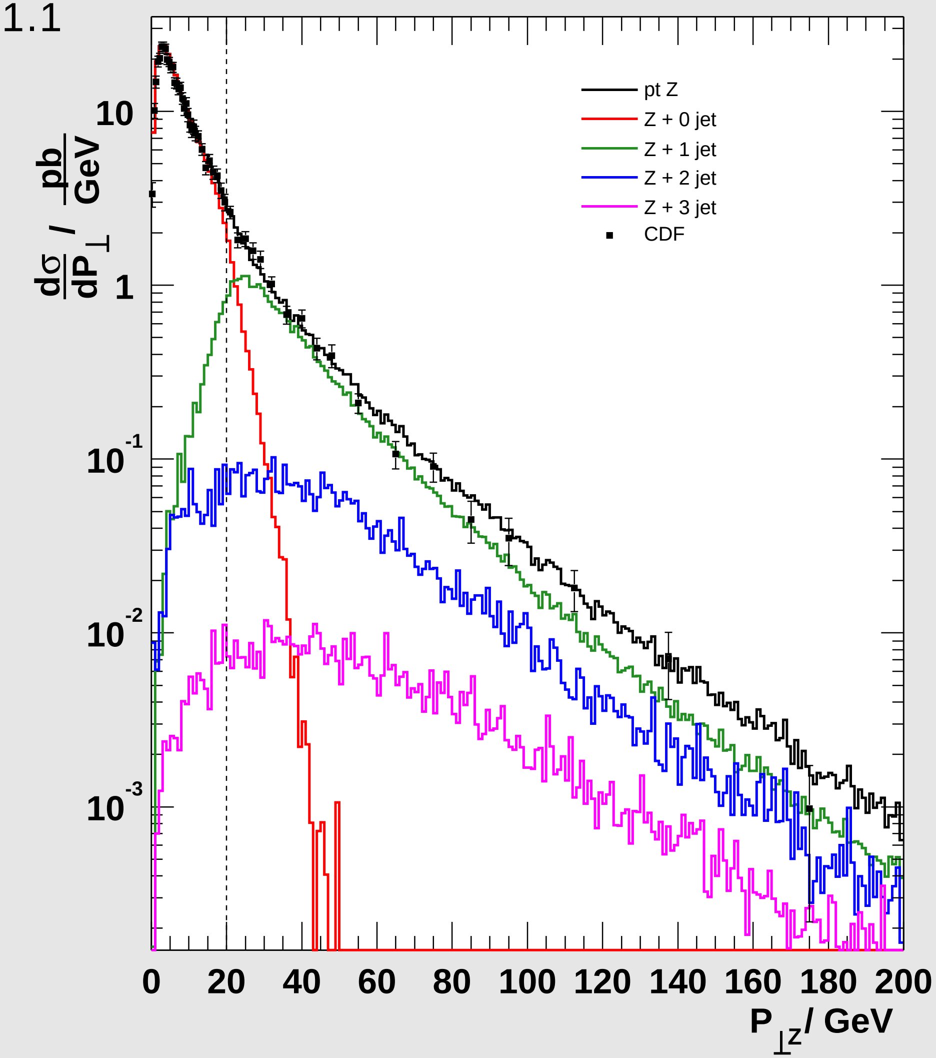
[Krauss, JHEP 08 (2002) 015]

⇒ 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





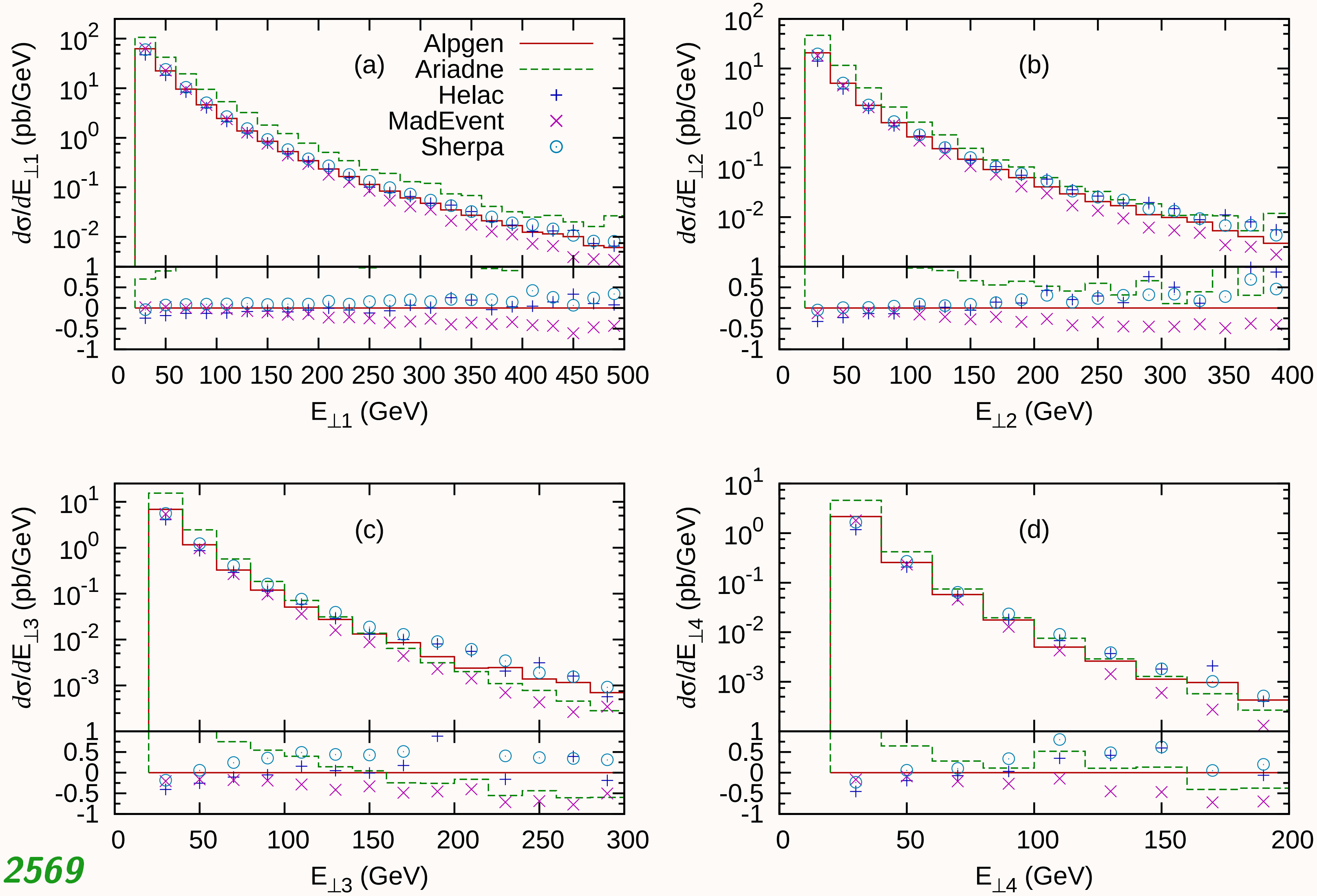
Krauss et al. PRD 70 (2004) 114009

Comparison between merging approaches

➡ *Tree-level ME+PS merging predictions of Alpgen, Ariadne, Helac, MadEvent and Sherpa.*

$$W^+ + X$$

- *jet E_T spectra at the LHC*
- *similar pattern wrt. Tevatron*
- *extrapolation to LHC energies makes differences more pronounced*
- *Results in arXiv:0706.2569 (EPJC 53 (2008) 473)*

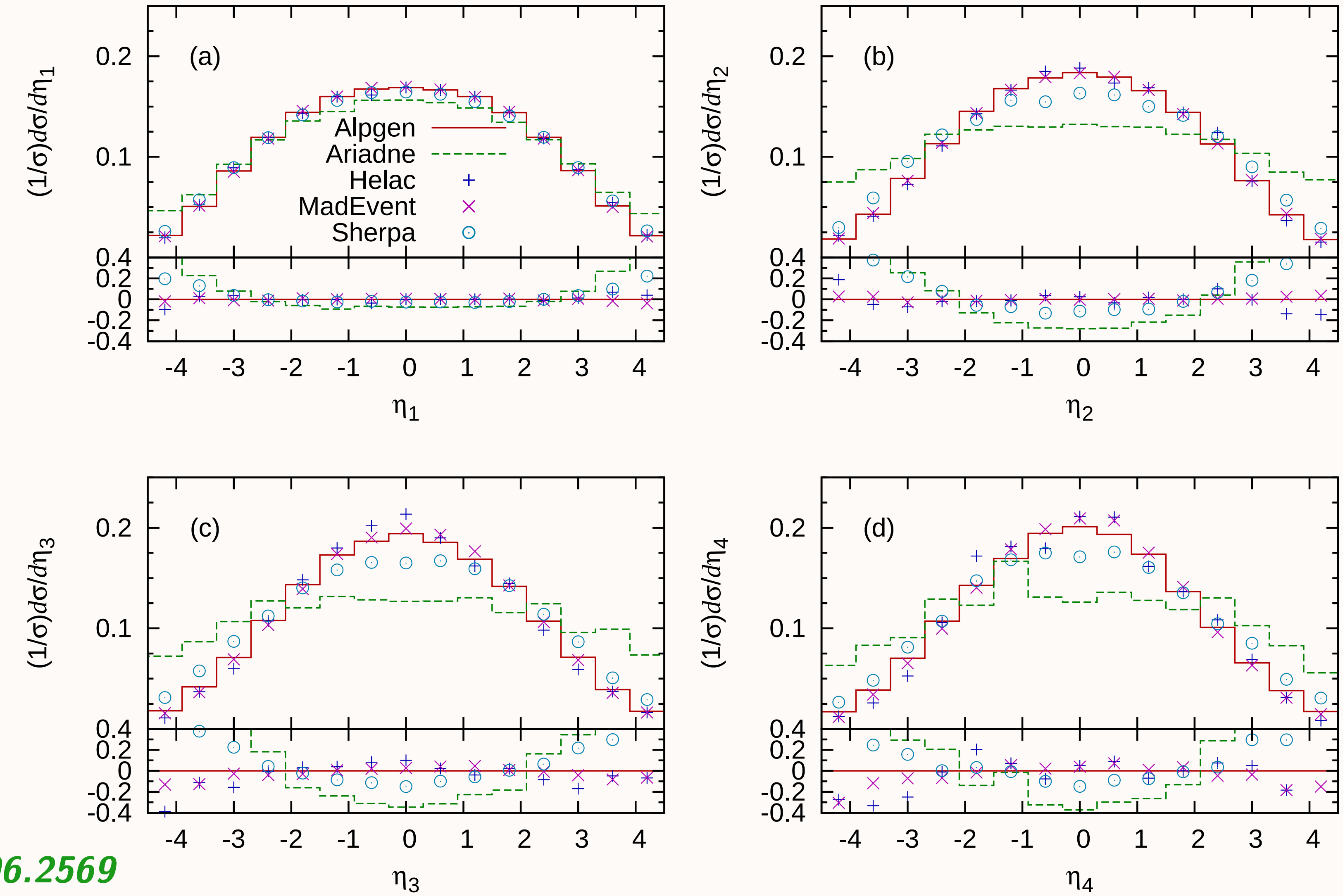


Comparison between merging approaches

➡ *Tree-level ME+PS merging predictions of Alpgen, Ariadne, Helac, MadEvent and Sherpa.*

$W^+ + X$

- *jet η spectra at the LHC*



- *similar pattern wrt. Tevatron*
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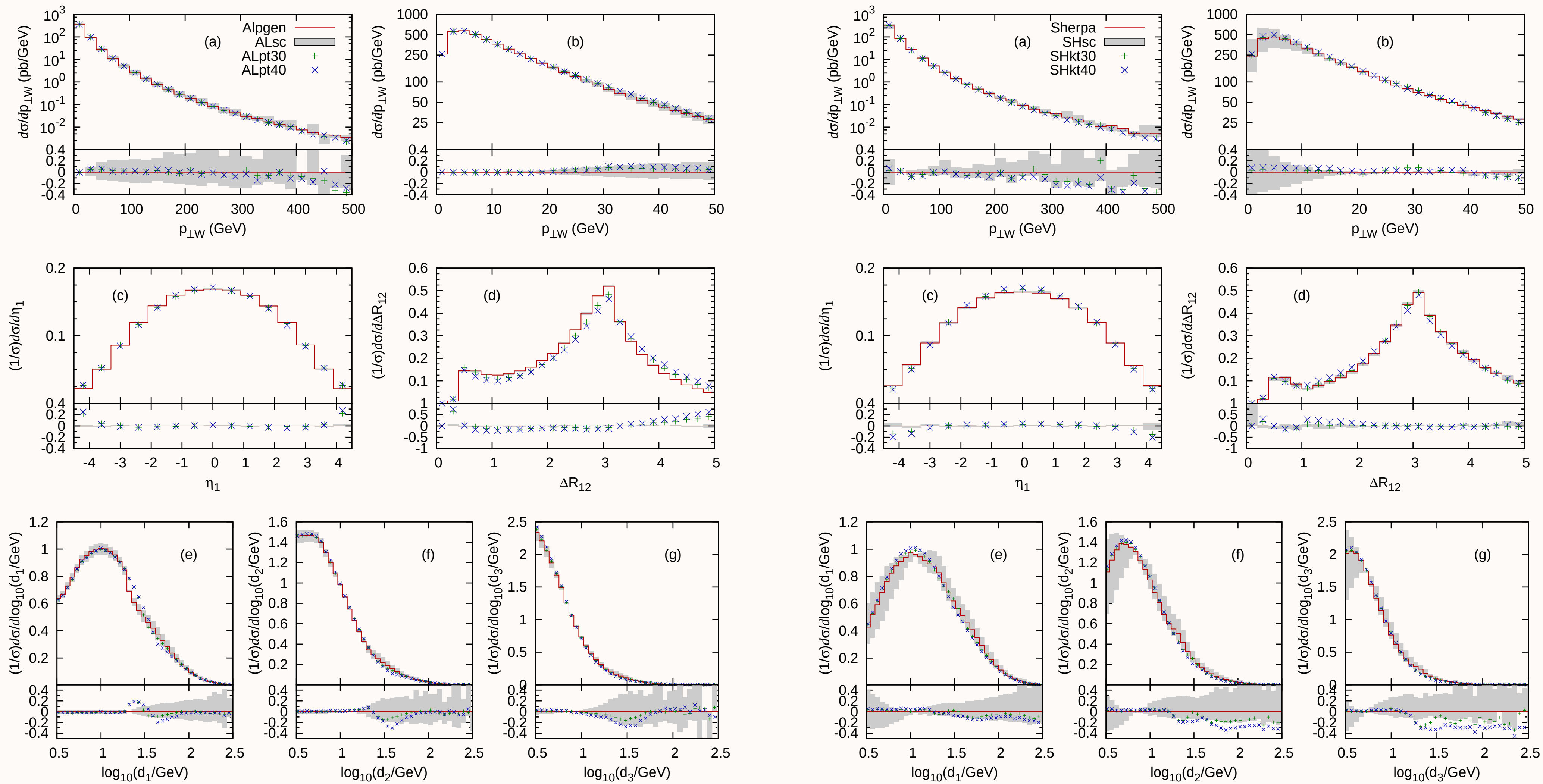
Systematics of merging approaches

[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



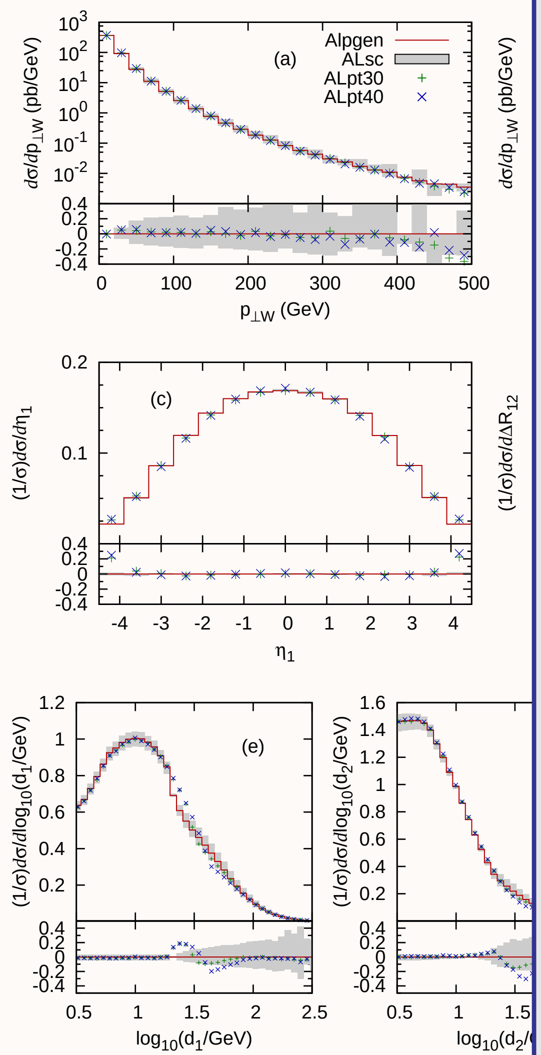
➡ Monte Carlos need to be validated and tuned against most recent LHC and Tevatron data.

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

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

W+jets @ Te

Example distribu



➡ Monte Carlos need to

➡ Discriminating

A little bit of history:

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 ✗

First answer (short time scale) ➡ Re-tune parameters.

SHERPA VS1.1.2 ⇒ VS1.1.3 [2008]

Second answer (longer time scale) ➡ Improve CKKW.

SHERPA VS1.1.3 ⇒ VS1.2.X [2009/10] – What were 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
  ⇒ spoils 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

We improved on these issues by relying on truncated showers.

Matrix elements and truncated showers – ME&TS

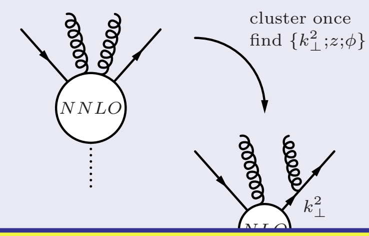
Key feature of Sherpa is tree-level ME+PS merging. Steadily improved over recent years.
State-of-the-art: ME&TS [Höche, Krauss, Schumann, Siegert, JHEP 05 (2009) 053]

➡ combine PS pros (resumming soft emissions) + ME pros (hard emissions, quantum interferences, correlations)

⇒ Fully populate emission's phase space with either ME or PS – avoid dead regions.

⇒ ME and PS describe the same final state – remove double counting.

Pseudo shower history



Slice multi-jet phase space into two domains: via IR-safe jet criterion Q

➡ tree-level MEs: jet seed (hard parton) production $Q > Q_{\rm cut}$

➡ parton showers: (intra-)jet evolution $Q_{\rm cut} > Q > Q_{\rm hadr}$

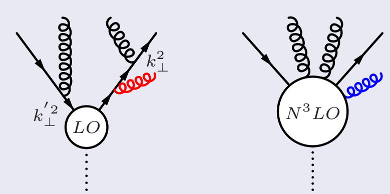
$$\mathcal{K}^{\rm ME}_{ab}(\xi,\bar{t}) = \mathcal{K}_{ab}(\xi,\bar{t})\,\Theta\left[Q_{ab}(\xi,\bar{t}) - Q_{\rm cut}\right] \qquad \mathcal{K}^{\rm PS}_{ab}(\xi,\bar{t}) = \mathcal{K}_{ab}(\xi,\bar{t})\,\Theta\left[Q_{\rm cut} - Q_{ab}(\xi,\bar{t})\right]$$

Ps

- cluster ME final states according to inverse shower formalism
- PS starts at $2 \to 2$ core and may emit partons off intermediate lines
- ME branchings as resolved must be respected
  - ○ preserve evolution, splitting and angular variables.

Truncated shower

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



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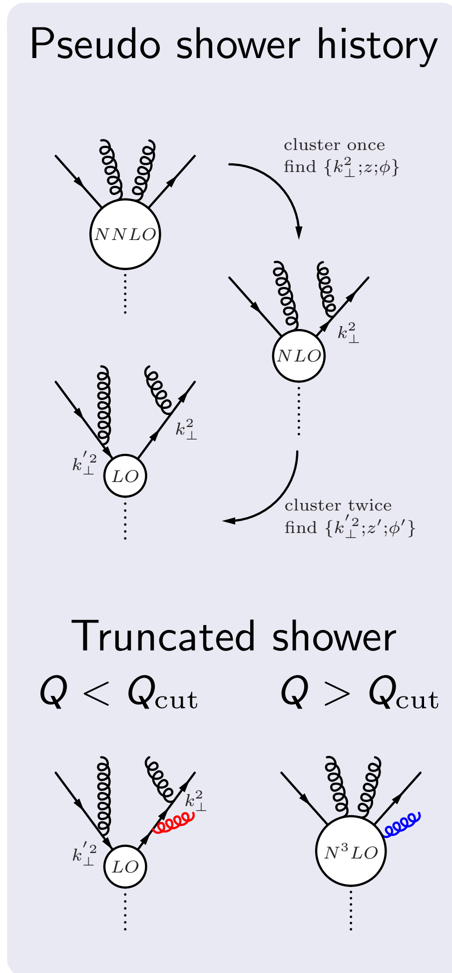
- Sudakov form factor factorizes into ME and PS part.
- Replace kernel in ME domain by correct ME expression.

Pseudo-shower history for MEs and truncated showering:

- cluster ME final states according to inverse shower formalism
- PS starts at $2 \to 2$ core and may emit partons off intermediate lines
- ME branchings as resolved must be respected
  - preserve evolution, splitting and angular variables.



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- parton showers: (intra-)jet evolution $Q_{\rm cut} > Q > Q_{\rm hadr}$

  ∘ Sudakov form factor factorizes into ME and PS part.

  ∘ Repl

Pseudo-sho

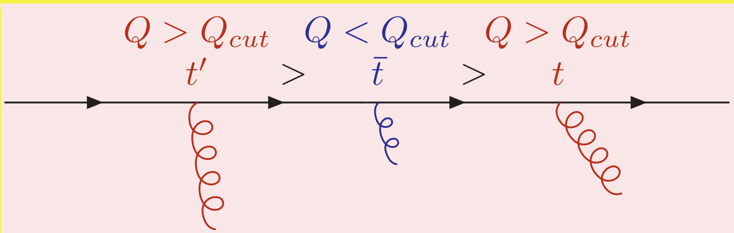
- cluste
- PS st
- ME b

  ∘ pres

Emission above $Q_{\rm cut}$: event rejected.

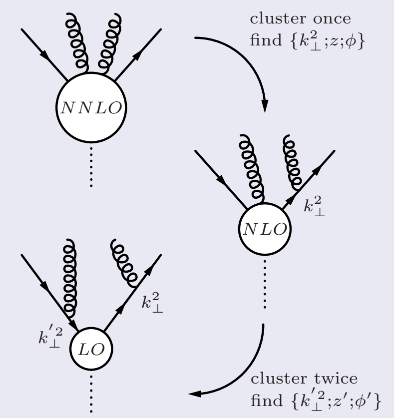
to be described by ME / preserves total xsec / Sudakov suppression

Emission below $Q_{\rm cut}$: emission accepted.



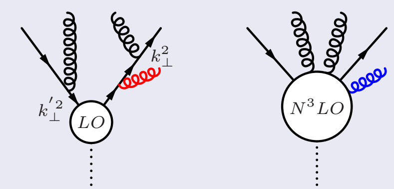
large-angle soft emissions
soft colour coherence
in CKKW only approximately

Pseudo shower history



Truncated shower

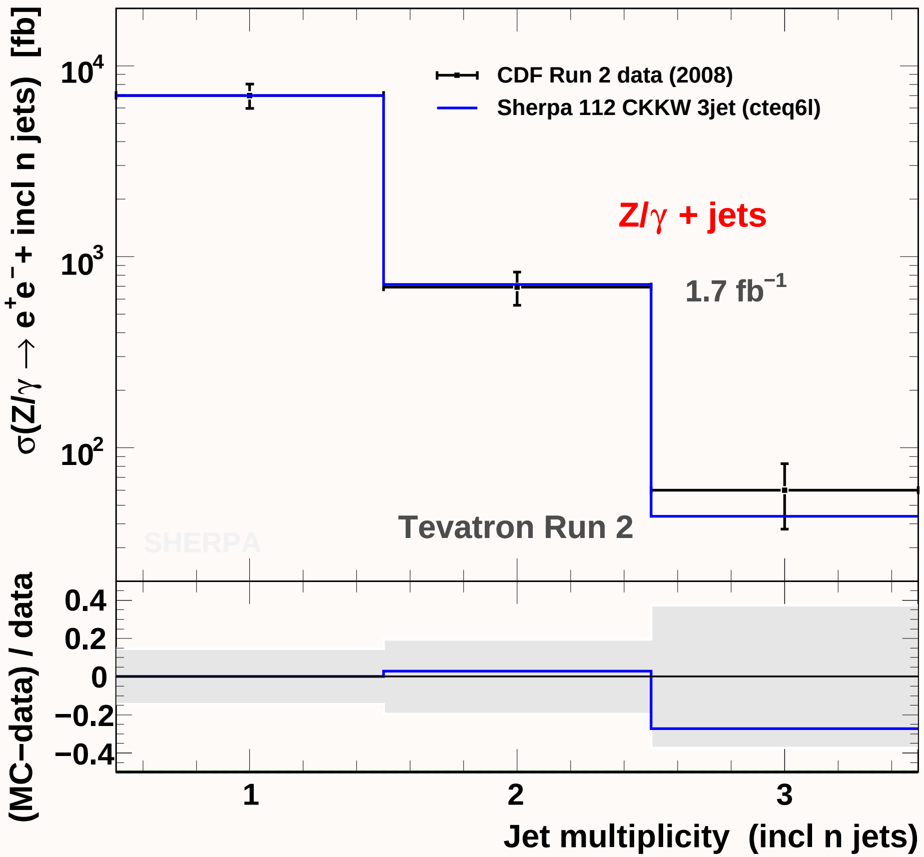
$Q < Q_{\rm cut}$ $Q > Q_{\rm cut}$

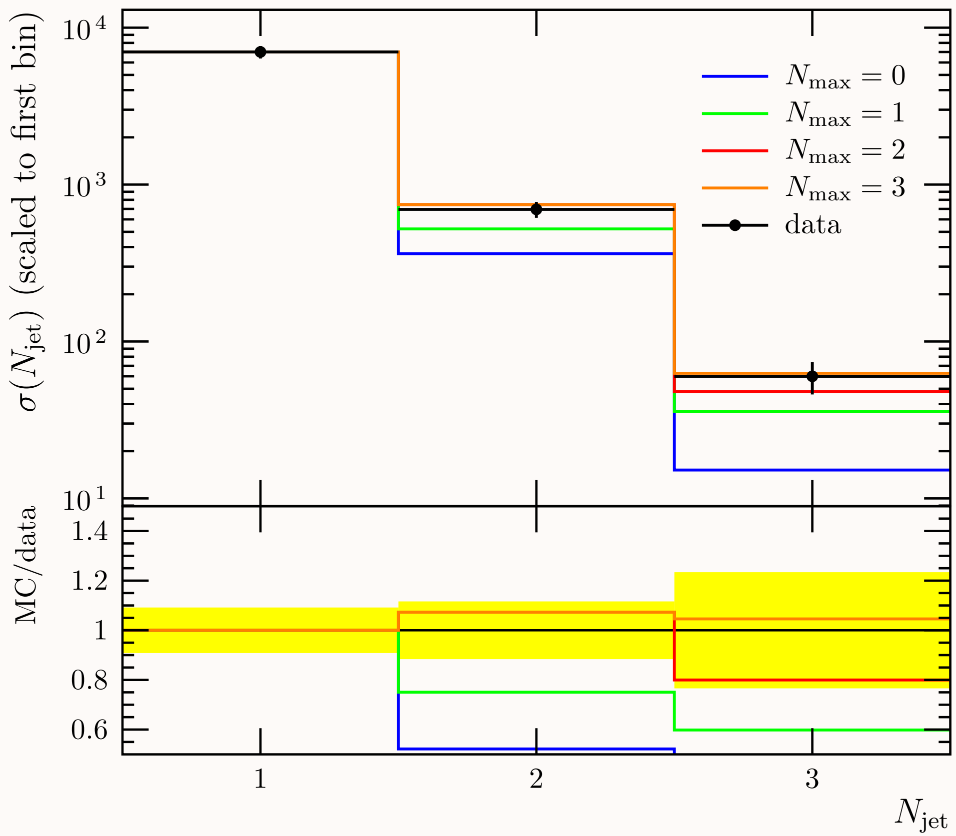


Comparison with CDF data – Z+jets production

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.
- Similar plots avail. for Herwig++'s mod. CKKW. [Hamilton, Richardson, Tully, JHEP **11** (2009) 038]



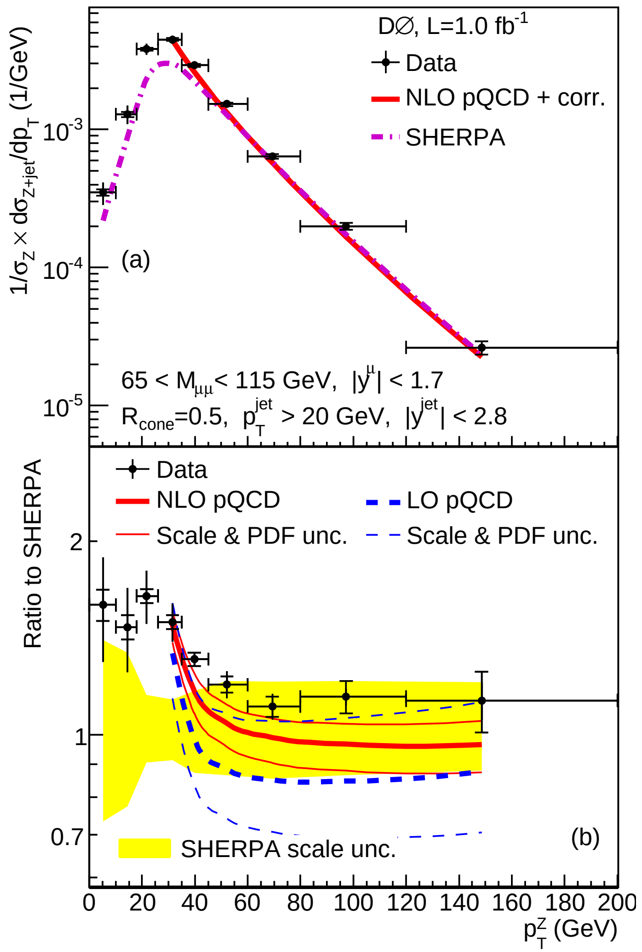


Z+jets as measured by DØ

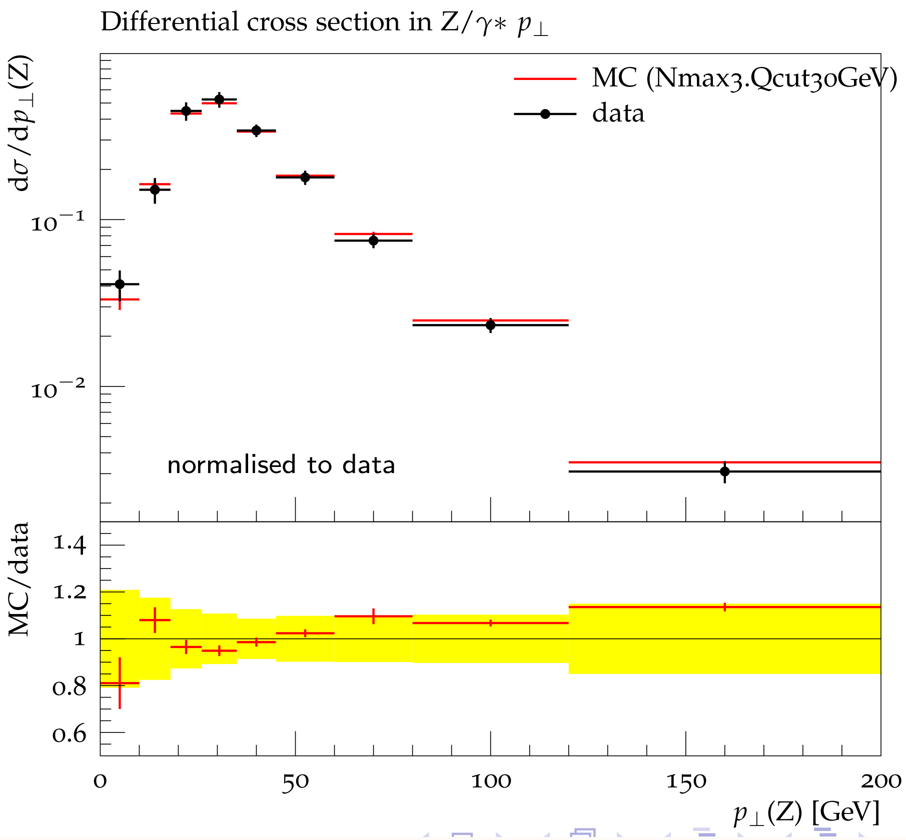
Comparison to Sherpa's CKKW implementation in v1.1.3

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

Sherpa v1.1.3



Sherpa v1.2

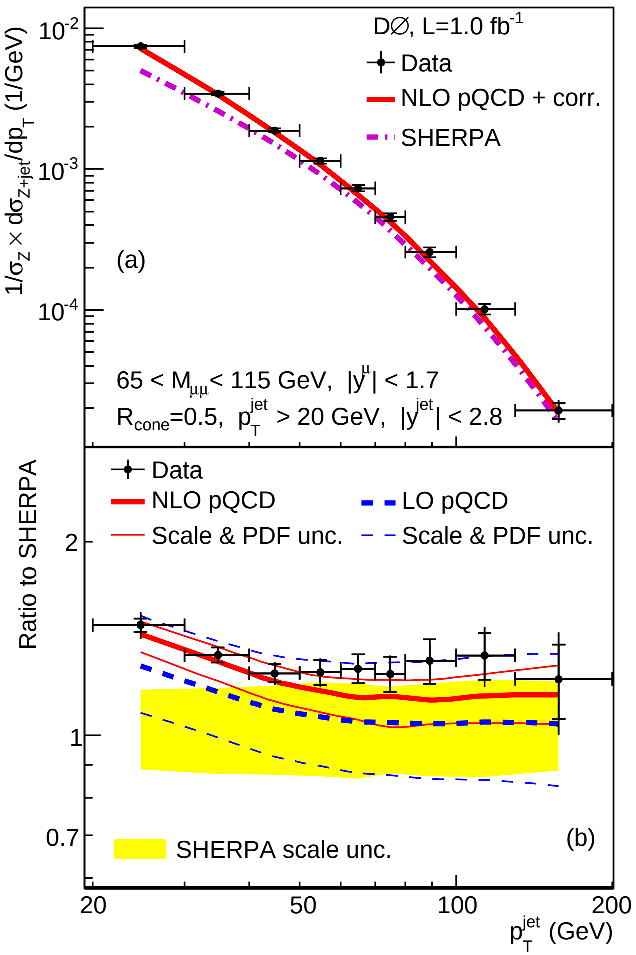


Z+jets as measured by DØ

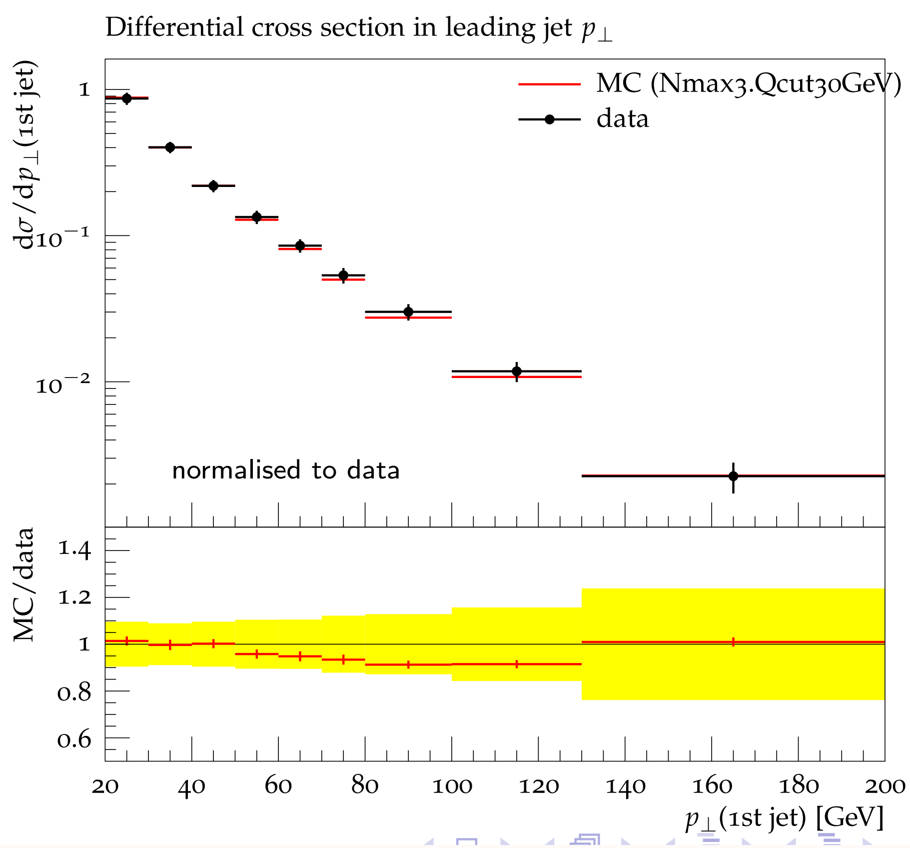
Comparison to Sherpa's CKKW implementation in v1.1.3

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

Sherpa v1.1.3



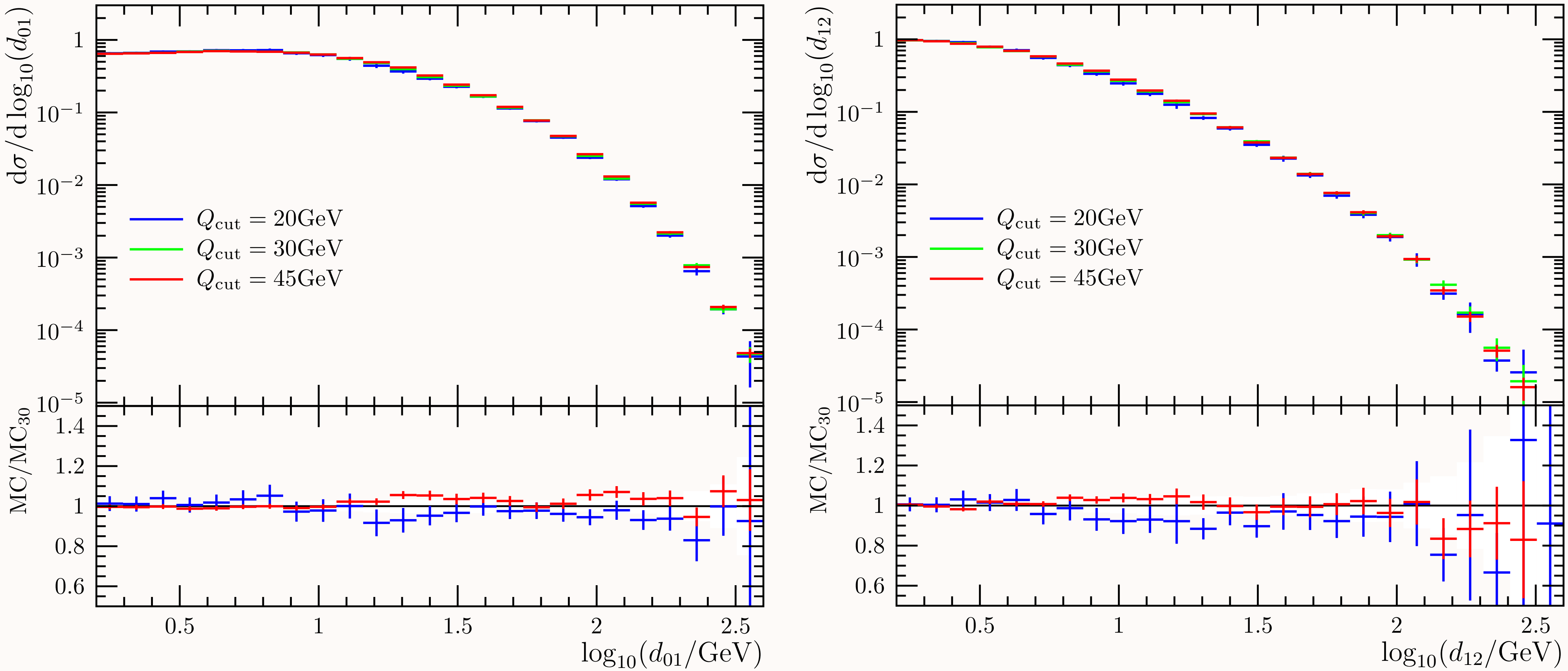
Sherpa v1.2



Z+jets production @ Tevatron Run2 energies

ME&TS :: COMIX + CSS [HÖCHE, KRAUSS, SCHUMANN, SIEGERT, JHEP 05 (2009) 053]

- Merging systematics has improved: Q_{cut} variation now within $\pm 10\%$.
- Differential k_T jet rates in $Q_{\text{cut}} = Q_{\text{jet}}$ variation @ hadron level. Note $N_{\max} = 5$.
- Note $\mu_F^2 = M_{ee}^2$ and 66 GeV $< M_{ee} < 116$ GeV.



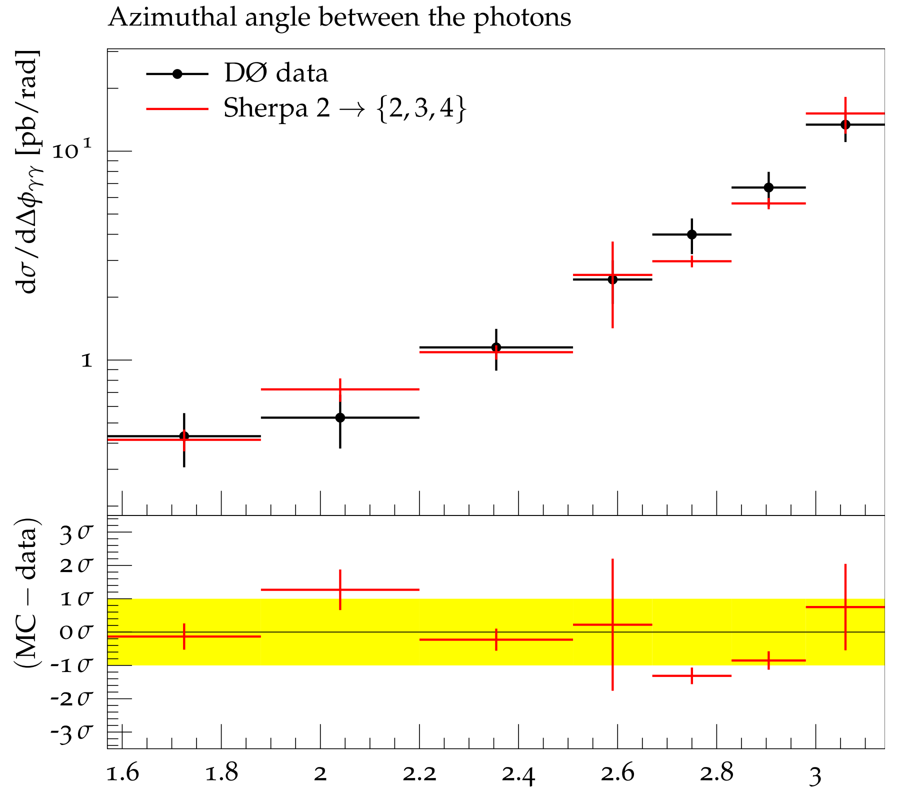
Diphoton production @ Run2

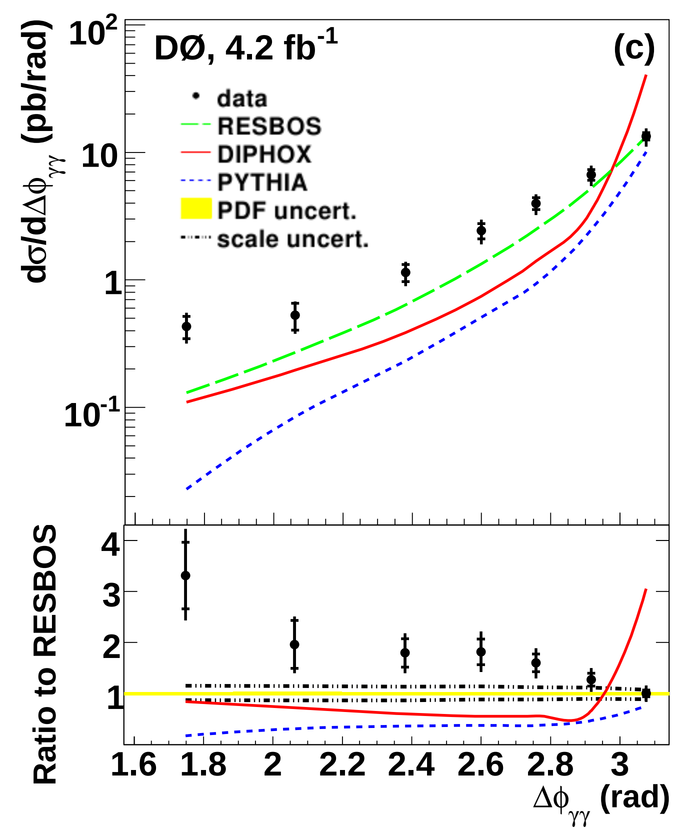
- photons & QCD partons treated democratically
- combine ME of different parton/photon mult. with QCD+QED evolution and hadronization
- add splitting functions $q \to q\gamma$, QCD and QED Sudakovs factorize
- unlike large-N_C of QCD, spectators are all particles of opposite charge
- neglect (negative) interference with same-sign charges
- Sherpa prediction: merged $2 \to \{2,3,4\}$-jet/γ plus $gg \to \gamma\gamma$ box

Diphoton production at Tevatron

- Recently published by DØ Phys.Lett.B690:108-117,2010
- Isolated hard photons with:
  - $E_\perp^{\gamma^1} > 21$ GeV
  - $E_\perp^{\gamma^2} > 20$ GeV
  - $|\eta_\gamma| < 0.9$
  - Isolation: $E_\perp(R = 0.4) - E_\perp^\gamma < 2.5$ GeV
- Here: Azimuthal angle between the diphoton pair

ME⊗PS simulation using SHERPA 1.2.2 with QCD+QED interleaved shower and merging as in Phys.Rev.D81:034026,2010



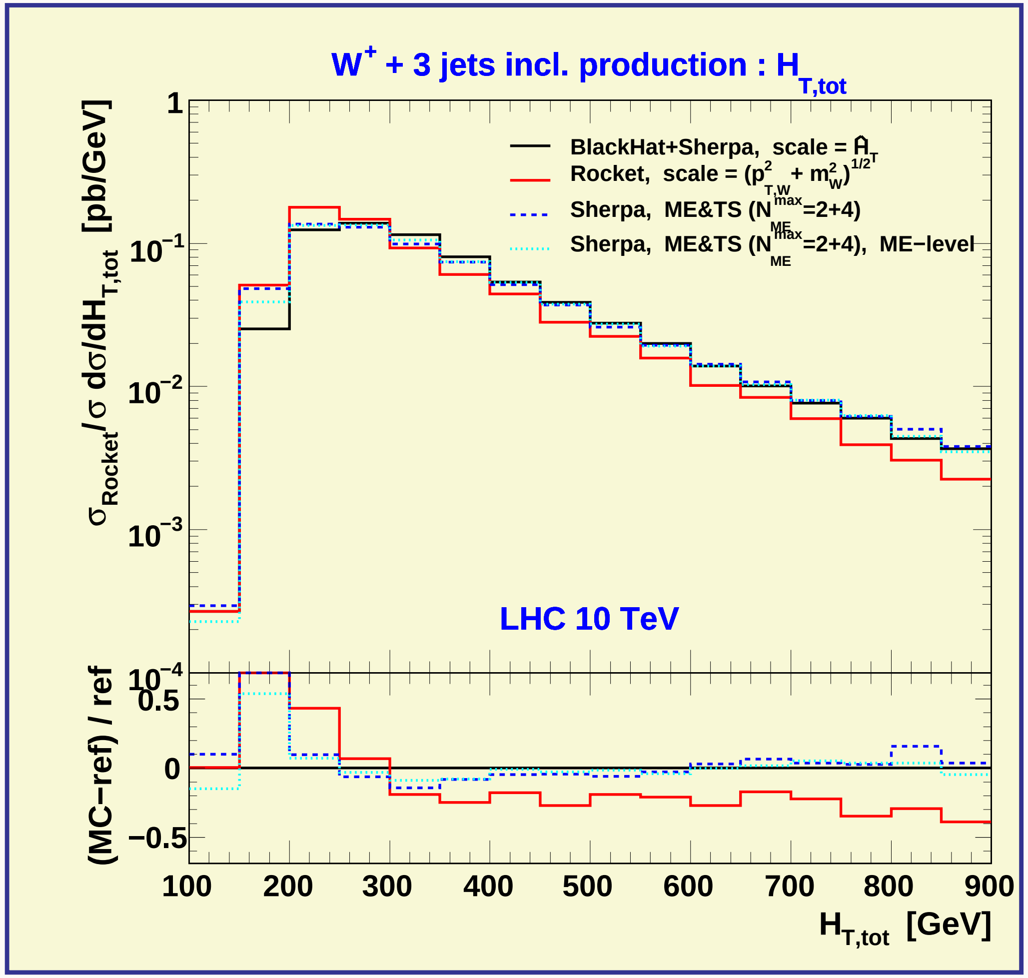


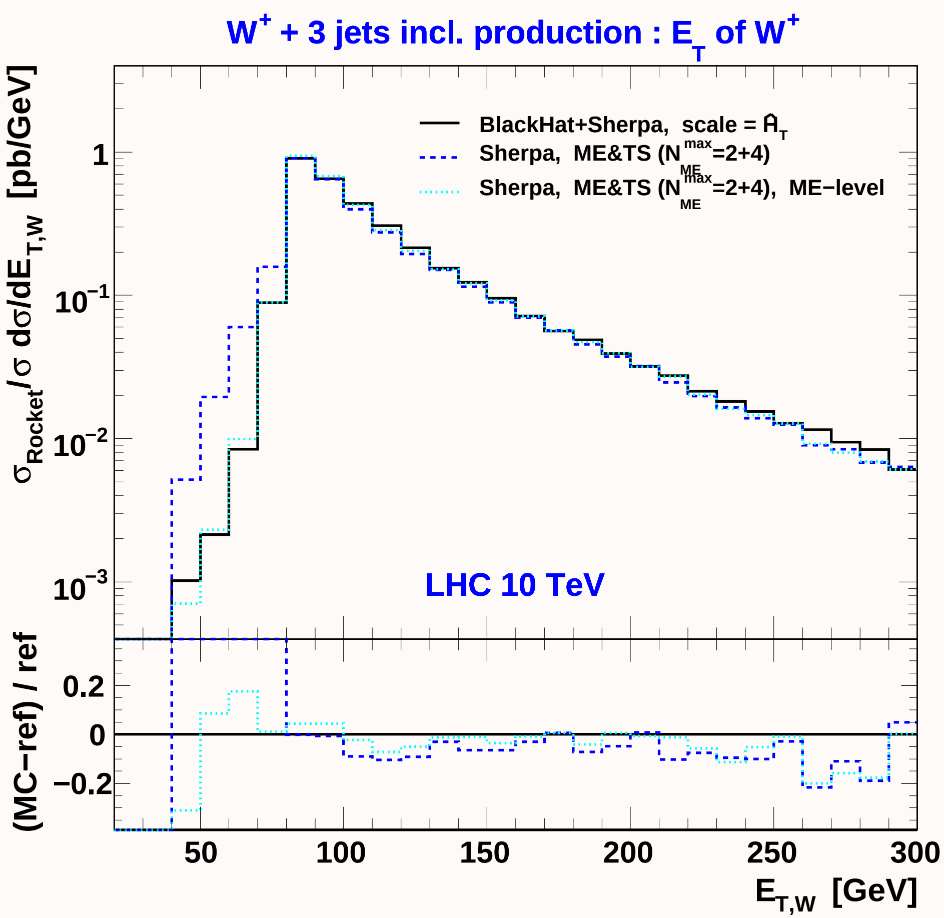
[HÖCHE, SCHUMANN, SIEGERT] similarly in PRD81(2010)034026

NLO vs. ME&TS – LHC predictions for W+3jets

[Höche, Huston, Maitre, Winter, Zanderighi; LesHouches09 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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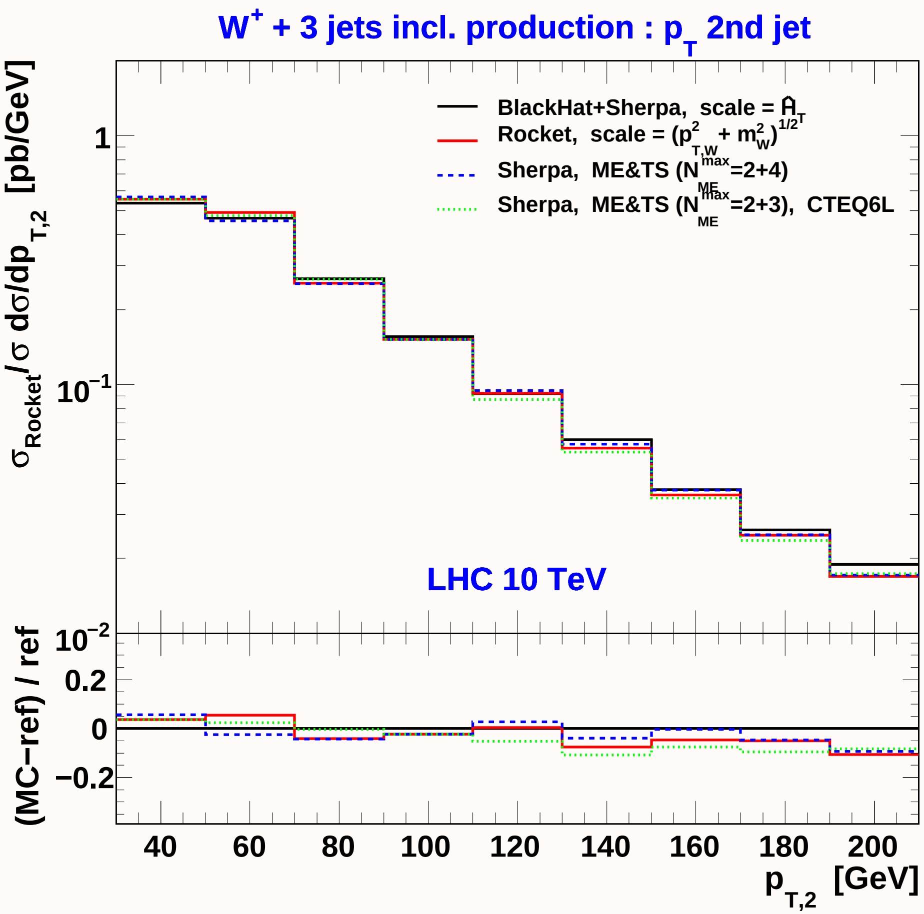

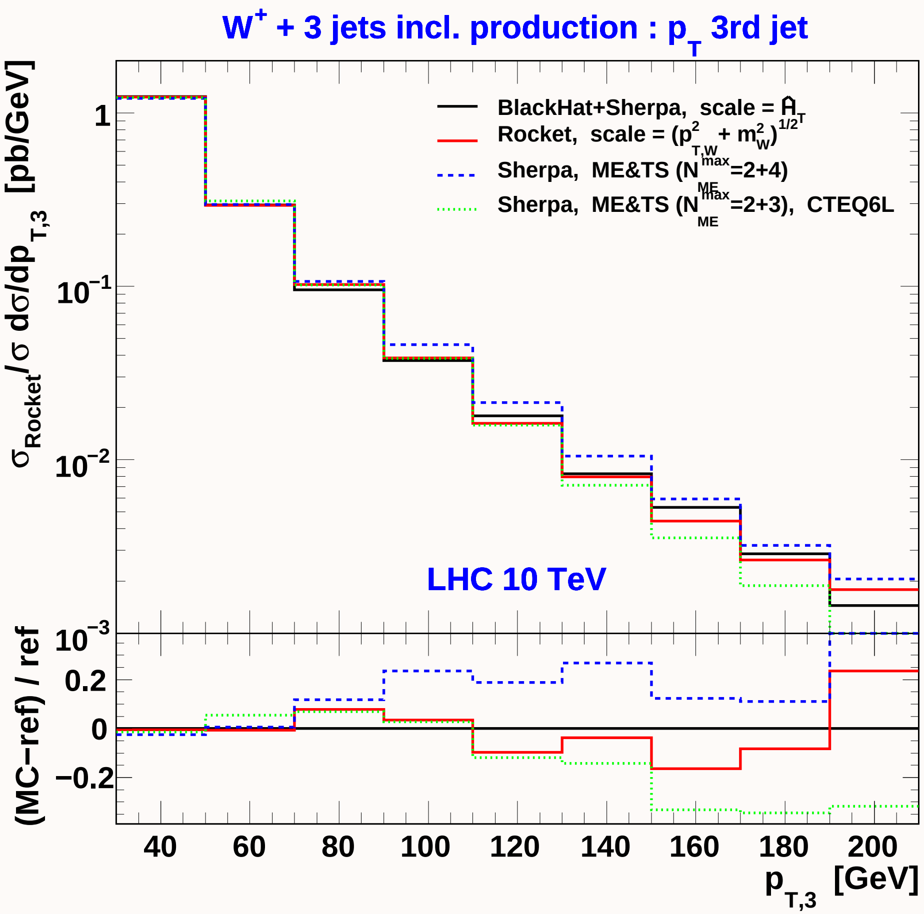

NLO vs. ME&TS – LHC predictions for W+3jets

[HÖCHE, HUSTON, MAITRE, WINTER, ZANDERIGHI; LESHOUCHES09 PROCEED.: ARXIV:1003.1241]

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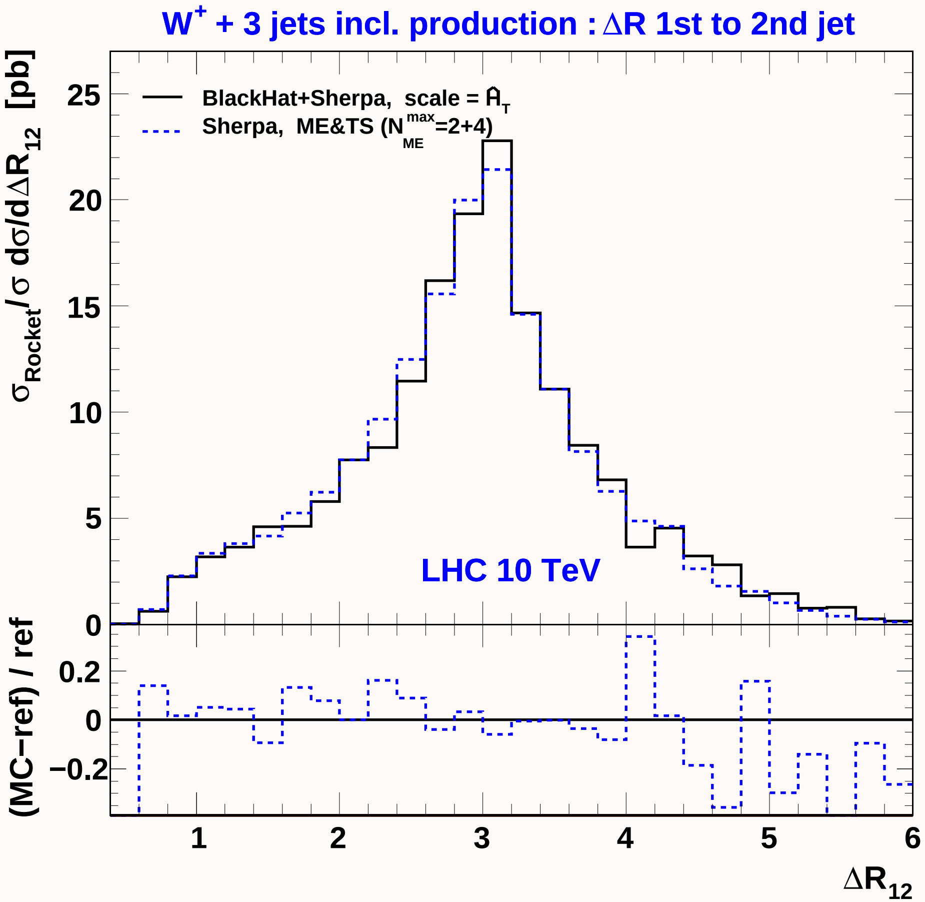
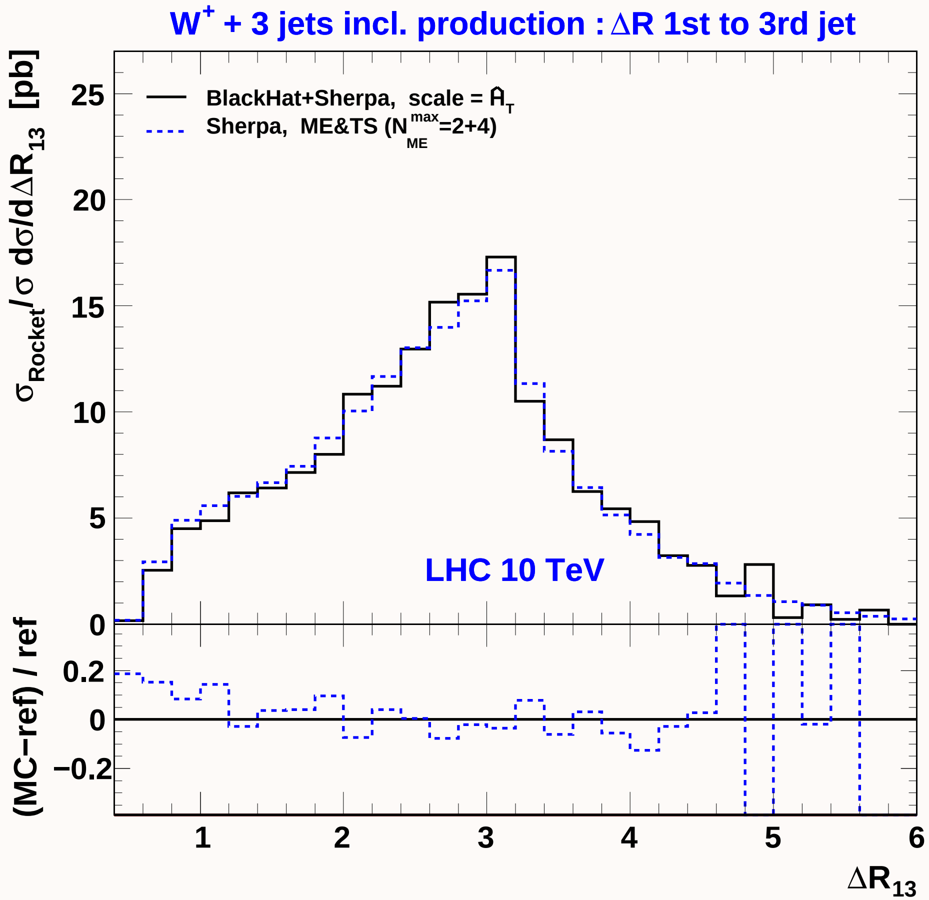




Aside – scale uncertainty of multi-leg procs @ NLO

- Common agreement: scale dependence defined by varying $\mu_0/2 < \mu < 2\mu_0$.

- Works relatively well for one-scale processes where typical NLO scale uncertainties are $\mathcal{O}(10\%)$. But multi-leg processes are different for at least 2 reasons:

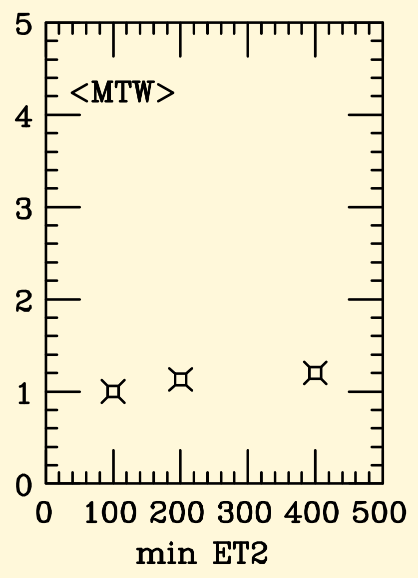
  → Higher powers of the strong coupling.
  → Many – possibly very disparate – kinematical scales.

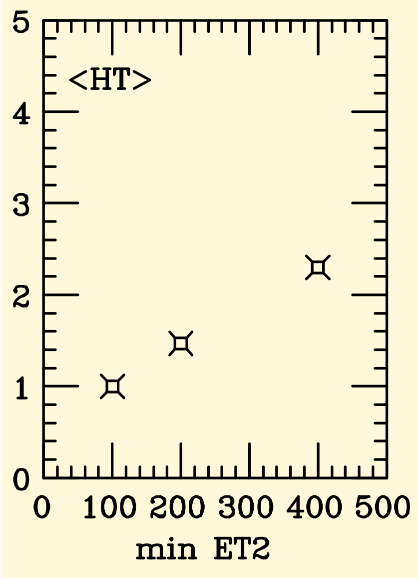
- New insight from the W+3jets calculations: "scales leading to good perturbative behaviour".

  → @ large H_T, properties of W are not important, hence $E_{T,W}$ is not a good scale anymore
  → Alpgen W+3jets (plots from MLM): $\langle O\rangle = \langle O\rangle(E_{T,2} > \min E_{T,2})/\langle O\rangle(E_{T,2} > 100\text{GeV})$

Questions:

→ What sets the natural value of μ_0?
→ Do we have to modify the simple approach?
→ Should we think about local scale setting methods as in CKKW based on relative p_T identification between partons?





Systematic uncertainties of ME+PS predictions

➡ *related to ME+PS merging*

- Q_{cut} – magnitude of phase-space separation cut [cancels to log accuracy of shower]
- $N_{\text{ME}}^{\max}$ – 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]

> Les Houches 2011:
>
> Step-by-step systematics study.
>
> Estimate and understand uncertainties related to each source.

NLO+PS matching

- match PS to NLO preserving good features of both approaches
  (Sudakov suppression at small p_T, multiple soft/coll emissions)
  (NLO rate, high-p_T shape, reduced scale dependence)

- matching is smooth, no phase-space separation cut, final states are ready to be hadronized

- ***MC@NLO:*** http://www.hep.phy.cam.ac.uk/theory/webber/MCatNLO/
  [Frixione, Webber; ...]

- ***aMC@NLO:*** automation of MC@NLO $\equiv$ MadFKS + MadLoop [arXiv:1103.0621] + automation of MC subtraction terms
  [Frederix, Frixione, Torielli (+ Hirschi, Garzelli, Maltoni, Pittau)] ($W/Zb\bar{b}$ [arXiv:1106.6019])

- ***POWHEG:*** http://powhegbox.mib.infn.it
  [Alioli, Hamilton, Nason, Oleari, Re] (recent achievements: V+1jet, $Wb\bar{b}$ [arXiv:1105.4488])
  (POWHEG in Herwig/++ [Richardson et al.] to be automated in Matchbox [Plätzer et al.])

- MEnloPS: combine POWHEG and ME+PS via phase-space slicing
  [Hamilton, Nason, JHEP 06 (2010) 039]
  (ME+PS rescaled to correct inclusive norm by global cut-dependent K-factor.)
  (Non-unitarity of ME+PS is no problem as long as is smaller than NLO effects.)

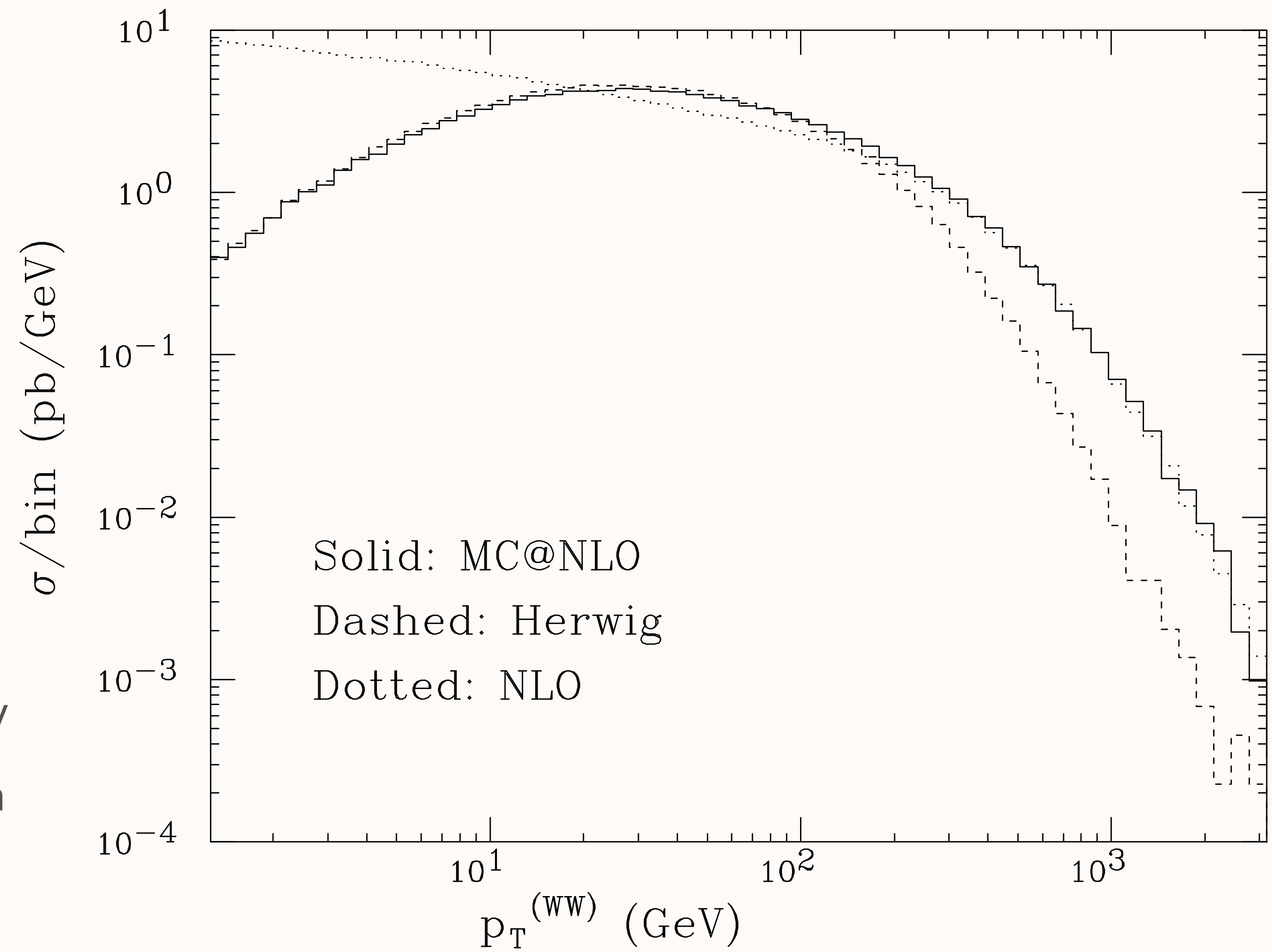
Example – MC@NLO

[S. Frixione and B.R. Webber, JHEP 0206 (2002) 029]

➡ $pp \to W^+W^- + X$ @ 14 TeV LHC: • p_T of the WW system

➡ rate & shape comparison
MC@NLO *vs.* Herwig PS
and NLO prediction

- naive NLO+PS leads to double counting
- PS has real-emission contribution due to final-state branching
- PS has virtual contribution due to no-branching probability
- solution: subtract PS evolution terms from $2 \to n+1$ and add back to $2 \to n$



- NLO results recovered upon expansion of NLO+PS in α_s, matching is smooth, no phase-space separation cut, final states can be hadronized

POWHEG in Sherpa

[Höche, Krauss, Schönherr, Siegert, JHEP 04 (2011) 024, arXiv:1009.1127] [slide from Marek Schönherr]

$$\langle O \rangle = \int \mathrm{d}\Phi_B \, \bar{B}(\Phi_B) \left[\Delta^{(\text{ME})}(t_0) \, O(\Phi_B) + \sum \int_{t_0} \mathrm{d}\Phi_{R|B} \, \frac{R(\Phi_R)}{B(\Phi_B)} \, \Delta^{(\text{ME})}(t) \, O(\Phi_R) \right]$$

- method for matching NLO calculation to PS resummation
  JHEP11(2004)040, JHEP11(2007)070
- ME reweighted PS with local K-factor
- NLO event weight $\bar{B} = B + V + I + \int \mathrm{d}\Phi_{R|B} \, [R - S]$
  - **B**orn, **R**eal from automated tree-level generators
  - **V**irtual e.g. via Binoth Les Houches Accord CPC181(2010)1612
    $\rightarrow$ for results here BlackHat & Mcfm libraries interfaced
  - **I**ntegrated/**S**ubtraction terms from automated implementation of Catani-Seymour subtraction terms EPJC53(2008)501
- correct PS to ME via weight $w(\Phi_R) = R(\Phi_R)/R^{(\text{PS})}(\Phi_R)$
  $\rightarrow$ alleviated by good approximation of CSShower++ JHEP03(2008)038
- Powheg Sudakov $\Delta^{(\text{ME})}(t) = \exp \left[- \sum \int_t \mathrm{d}\Phi_{R|B} \, \frac{R(\Phi_R)}{B(\Phi_B)} \right]$

$\Rightarrow$ **preserves both NLO and LL accuracy**

POWHEG and ME+PS – MENLOPS in Sherpa

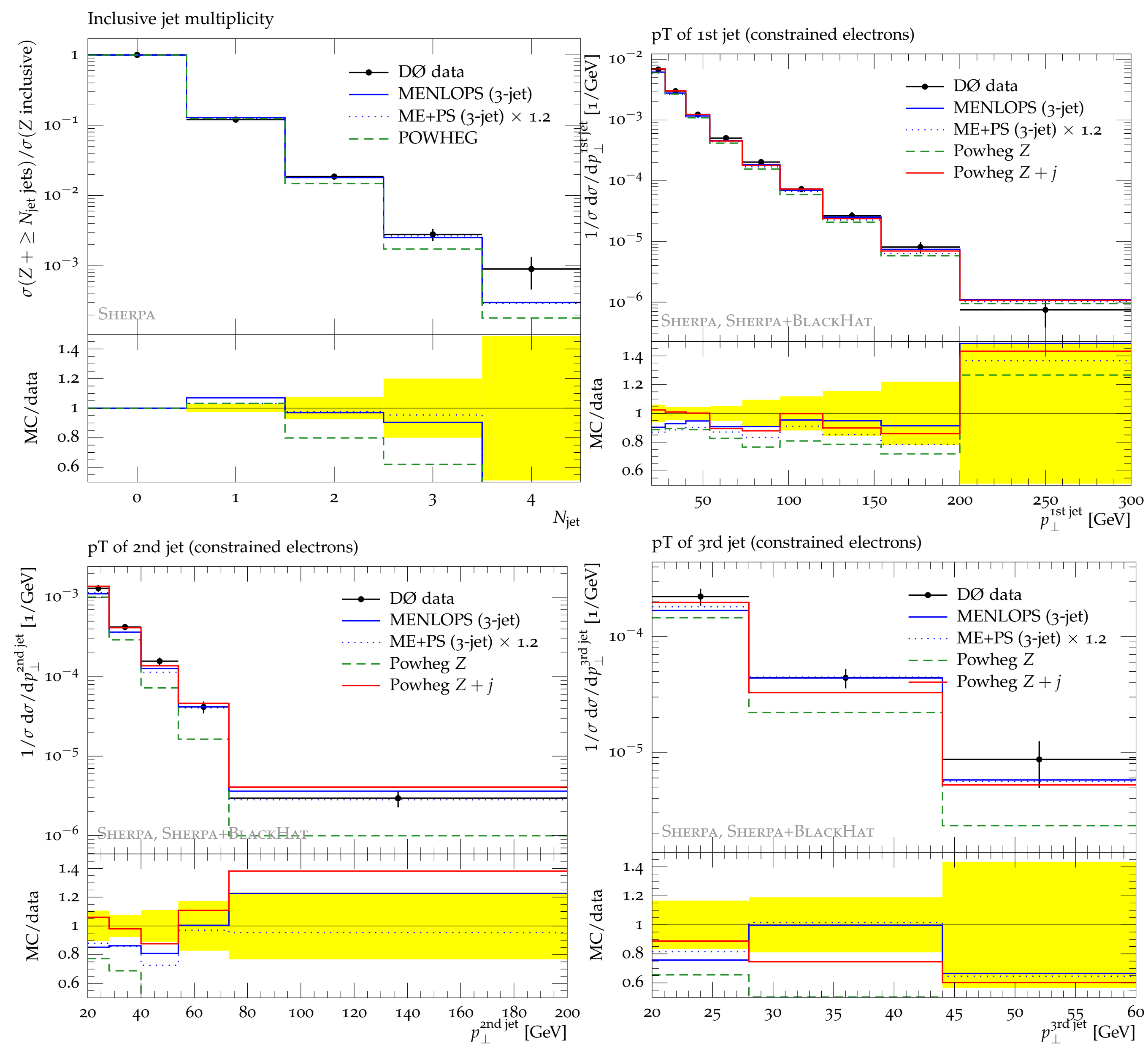
[HÖCHE, KRAUSS, SCHÖNHERR, SIEGERT, JHEP 04 (2011) 024, ARXIV:1009.1127] [SLIDE FROM MAREK SCHÖNHERR]

$$\langle O \rangle = \int \mathrm{d}\Phi_B\, \bar{B}(\Phi_B) \Big[\Delta^{(\mathrm{ME})}(t_0)\, O(\Phi_B) + \overbrace{\int \mathrm{d}\Phi_{R|B} \frac{R(\Phi_R)}{B(\Phi_B)} \Delta^{(\mathrm{ME})}(t)\, \Theta(Q_{\mathrm{cut}} - Q)\, O(\Phi_R)}^{\text{POWHEG domain}} + \underbrace{\int \mathrm{d}\Phi_{R|B} \frac{R(\Phi_R)}{B(\Phi_B)} \Delta^{(\mathrm{PS})}(t)\, \Theta(Q - Q_{\mathrm{cut}})\, O(\Phi_R)}_{\text{ME domain}} \Big]$$

- POWHEG domain restricted to soft emissions $Q < Q_{\mathrm{cut}}$
  ⇒ **NLO accuracy preserved for inclusive observables**
- ME⊗PS used for hard emission & higher order emissions
  ⇒ **preserves LO accuracy of every ME emission & LL accuracy of PS**
- higher order emissions receive local K-factor $\frac{\bar{B}(\Phi_B)}{B(\Phi_B)}$
- developed in parallel by JHEP06(2010)039, but using global K-factor

MENLOPS in Sherpa – Results

[HÖCHE, KRAUSS, SCHÖNHERR, SIEGERT, JHEP 04 (2011) 024, ARXIV:1009.1127] [SLIDE FROM MAREK SCHÖNHERR]



$p\bar{p} \to \ell^+\ell^- + X$

Data from DØ :

Phys.Lett.B658(2008)112-119

Phys.Lett.B678(2009)45-54

POWHEG and MENLOPS agree well on $p_\perp$ of hardest jet

MENLOPS superior for 2nd and 3rd jet

Application of ME+PS – revisiting CDF's Wjj excess

Mismodelled backgrounds ?

- single top [Sullivan, Menon, arXiv:1104.3790], top pairs [Plehn, Takeuchi, arXiv:1104.4087]
- carefully investigated by CDF → no issues

NLO effects ?

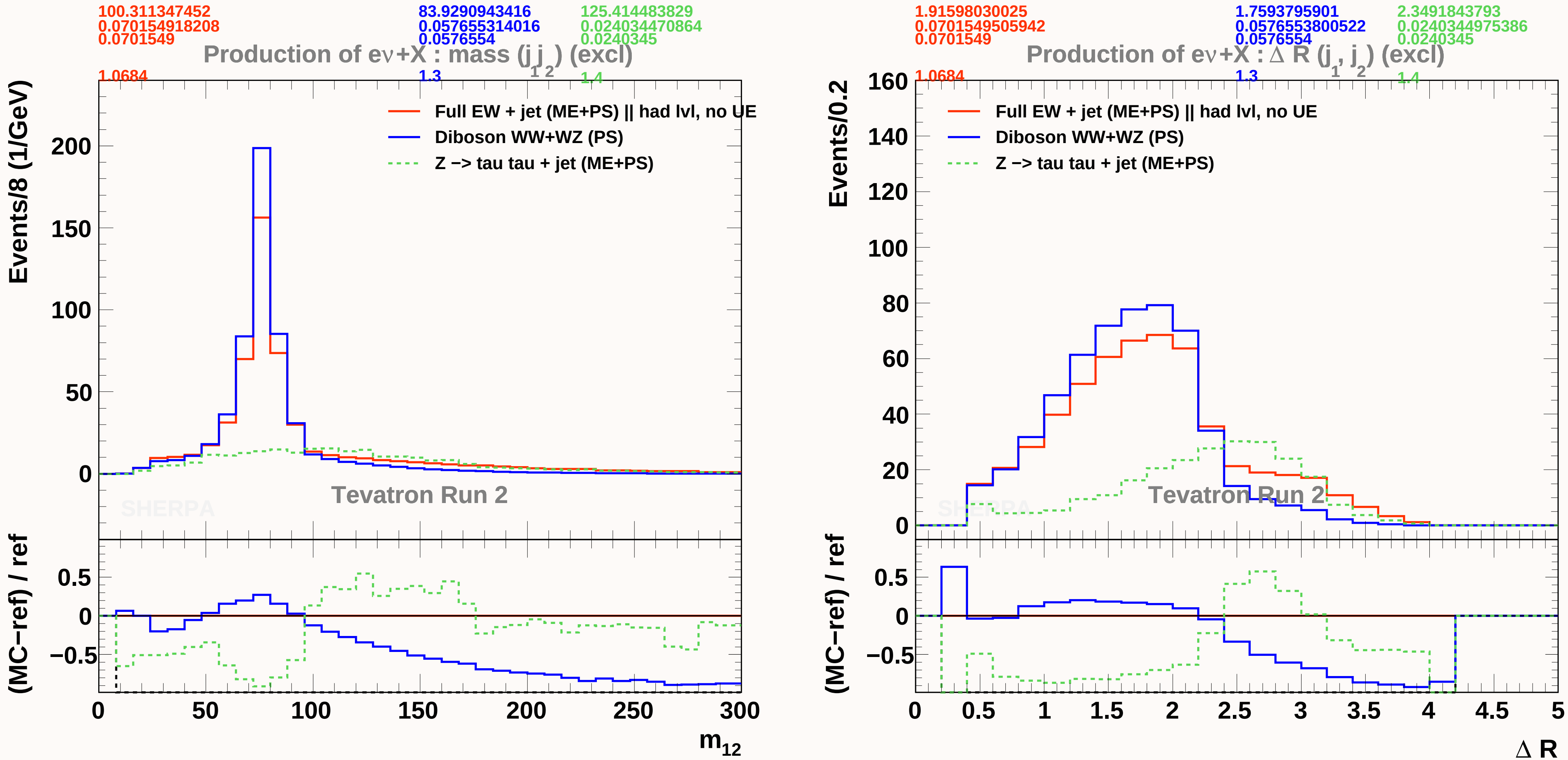
- [Campbell, Martin, Williams, arXiv:1105.4594] checked excl. and incl. W+2jet cross sections
- no inconsistencies / no surprises in K-factors

⇨ Only 3 publications deal with the backgrounds while >20 supply us with BSM explanations.

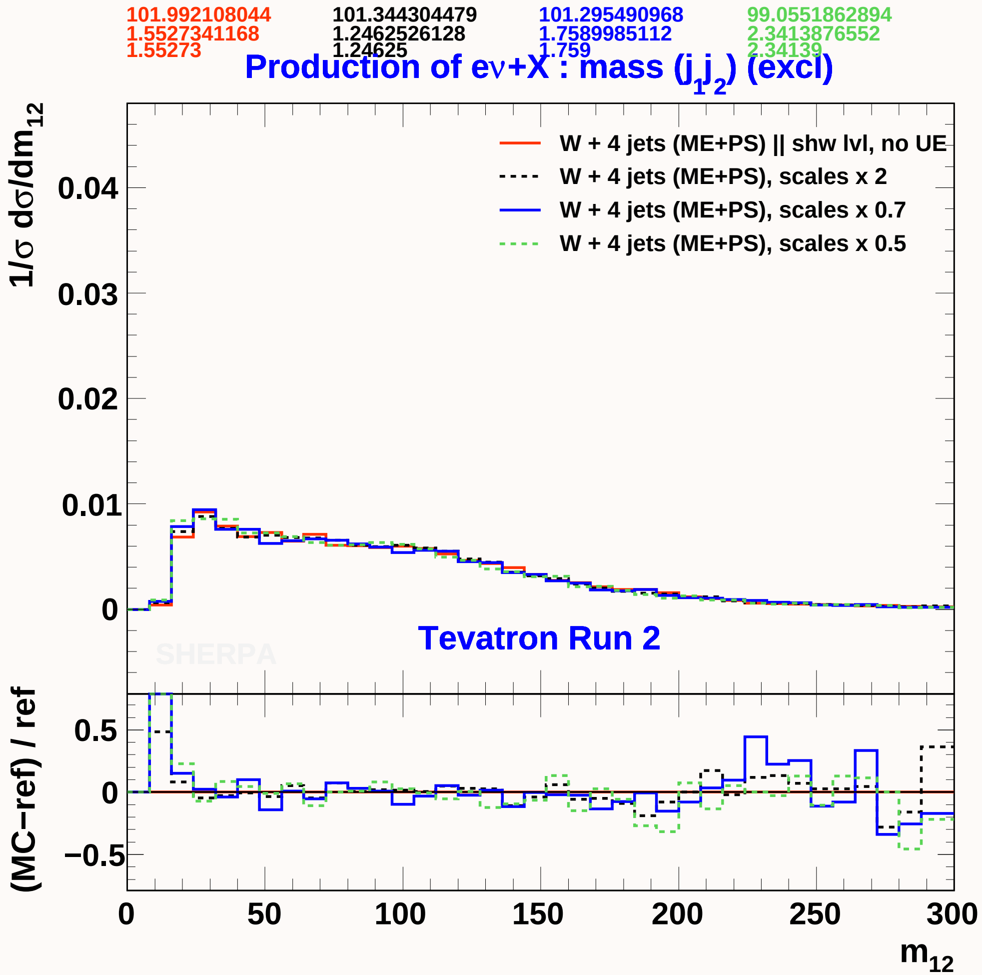
But we have a "Multitude of tools".

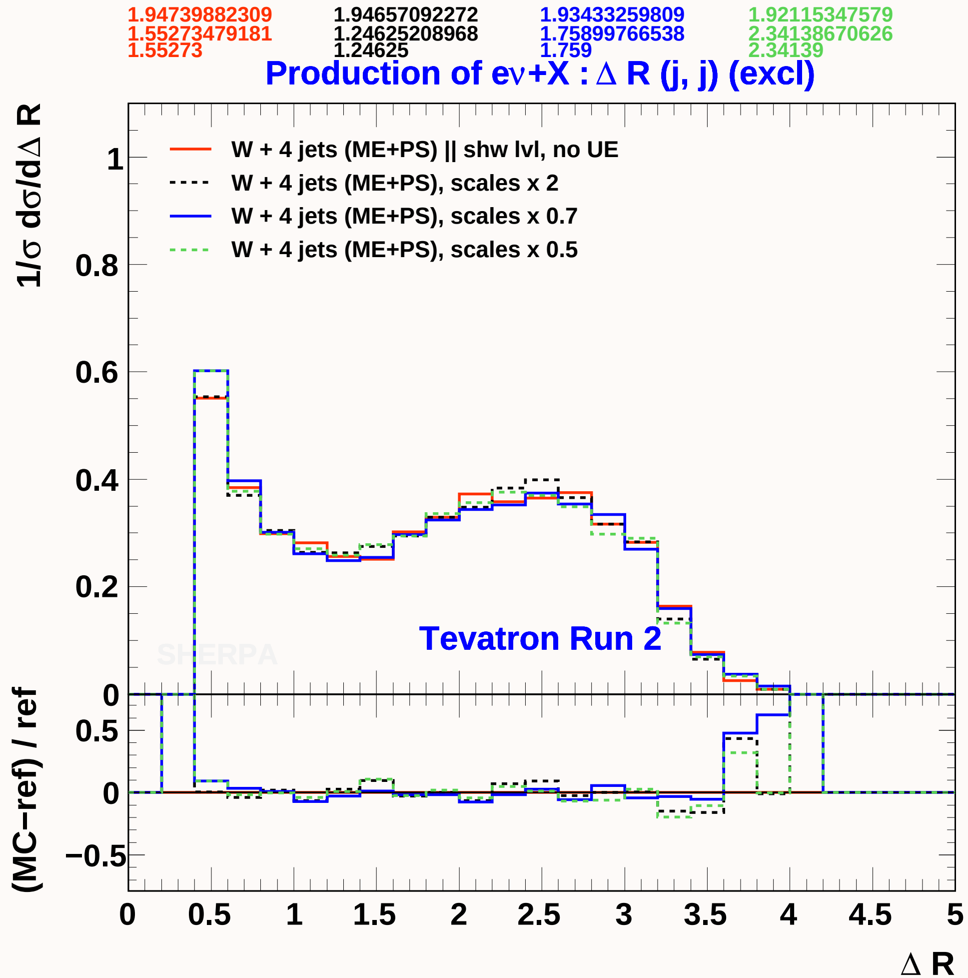
- How well do they compare? How well do we know their systematics?
- Can a cocktail of SM effects resolve the issue?
- ***Les Houches 2011 study*** [Krauss, Winter]
  - Effect of different ways to compute diboson production.
  - Contribution of $Z \to \tau\tau +$jet to the CDF analysis' final state.
  - Effect of scale variations on W+2jet shapes of ME+PS Sherpa samples.

preliminary



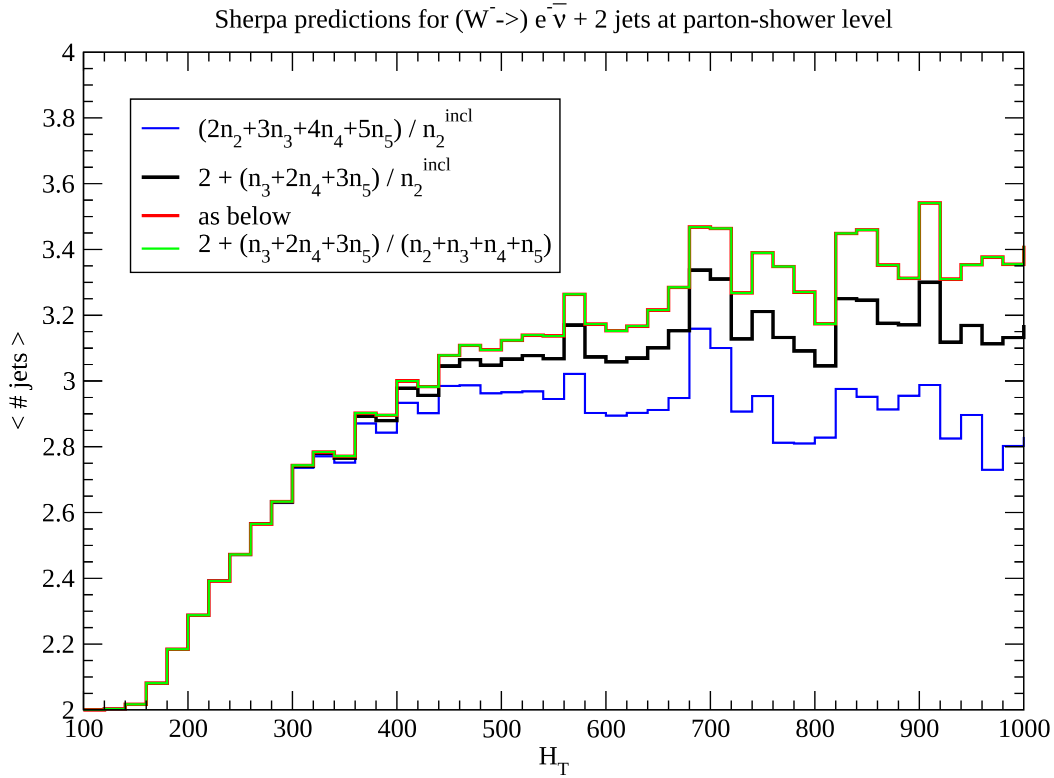
preliminary





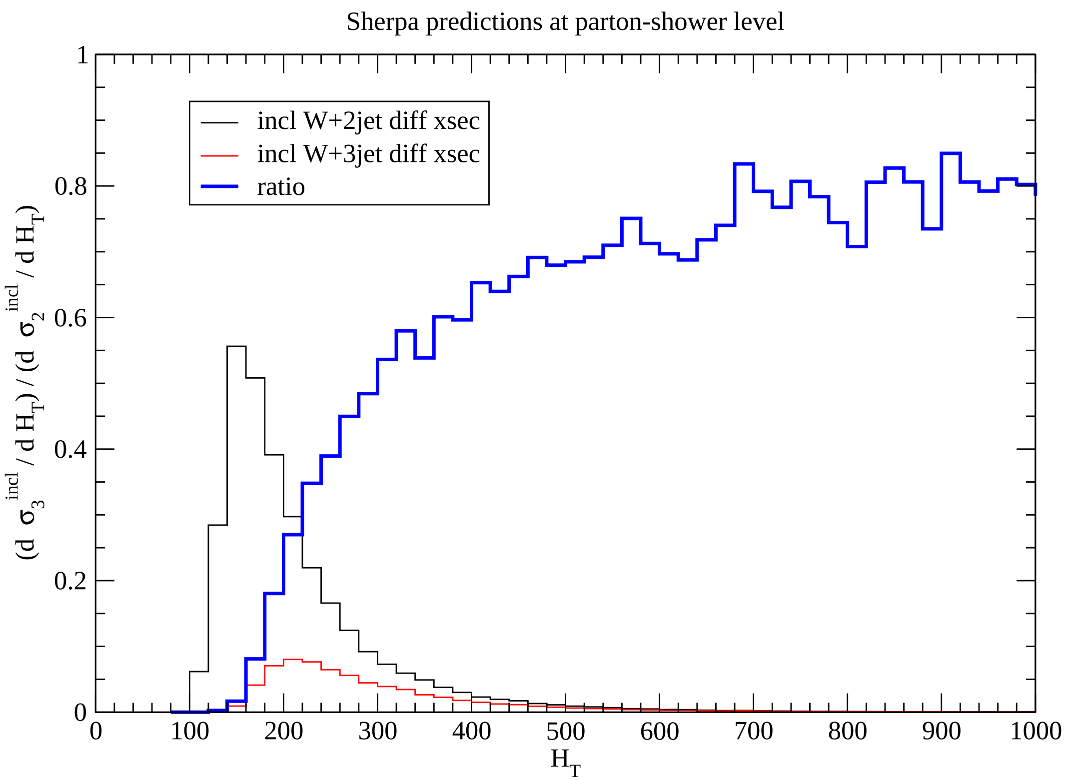
Application of ME+PS – W+jets @ LHC 7 TeV

Sherpa preliminary



average number of jets versus H_T

ratio of differential 3- to 2-jet incl. xsec versus H_T



[ANDERSEN, DIXON, MAITRE, SMILLIE, WINTER]

Summary

- Higher-order calculations are needed to meet the requirements on the precision of theoretical predictions in the LHC era.
  - Or is it the era of puzzles to be solved.

- Parton showers are improved by merging them with real-emission MEs for hard radiation.

  $\Rightarrow$ ME+PS: CKKW(L), MLM, ...

  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.

  $\Rightarrow$ Sherpa's new scheme is ME&TS. (Also in Herwig++.) Reduced systematic uncertainties.

- Beyond ME+PS/ME&TS: combine NLO+PS consistently $\Rightarrow$ MC@NLO and POWHEG with a number of processes available. New automated approach aMC@NLO. Moreover, MENLOPS is a first successful attempt to combine NLO with tree-level higher-order MEs.

  $\Rightarrow$ Very active field of research.

- Need for good understanding of how NLO, NLO+PS, ME+PS and shower models compare to each other and data. What are reliable estimates for their theoretical uncertainties?
  - This is crucial for assessing the reported anomalies.