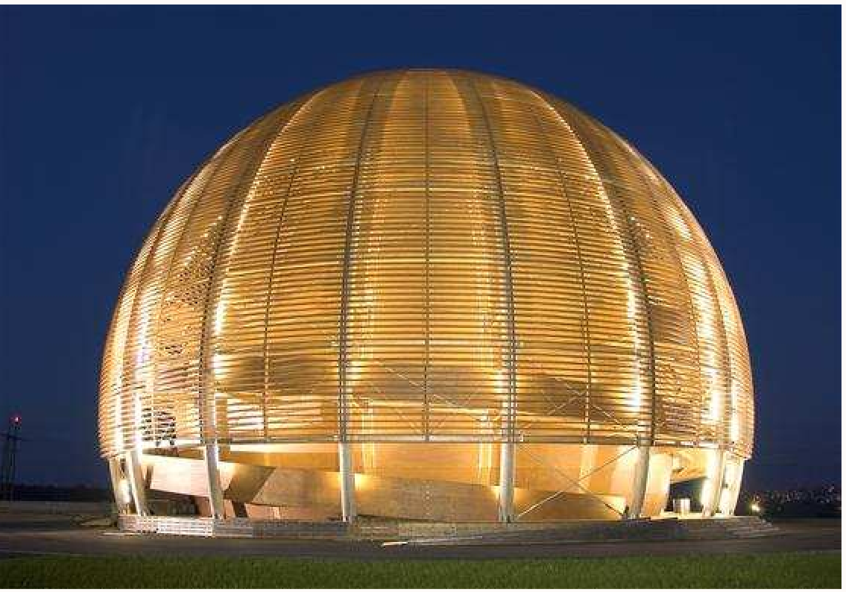
W and Z boson production at hadron colliders in different channels

[SM Benchmarks at High-Energy Hadron Colliders – DESY Zeuthen]

Jan Winter [a]

– CERN –



➡ ***Will mainly talk about ...***

- *V + jets and,*
- *the various sophisticated ways to get 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.

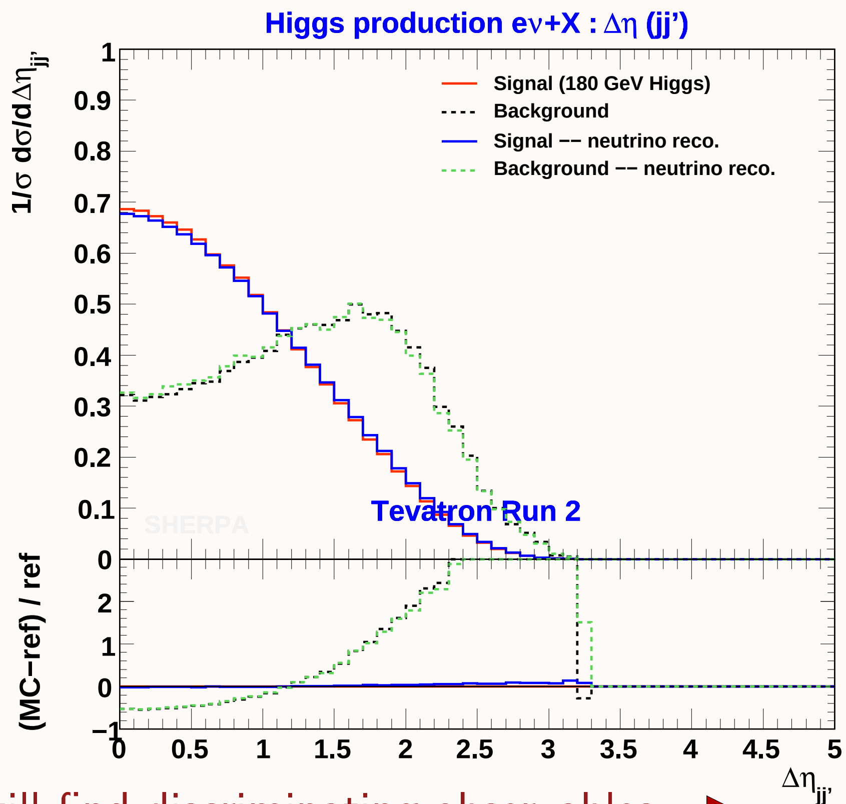
- Largely unexploited @ Run2: $gg \to h \to WW \to \ell\nu jj$.

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

- signal and (dominant) W+2jets background with Sherpa

⇒ QCD corrections (shapes) well included

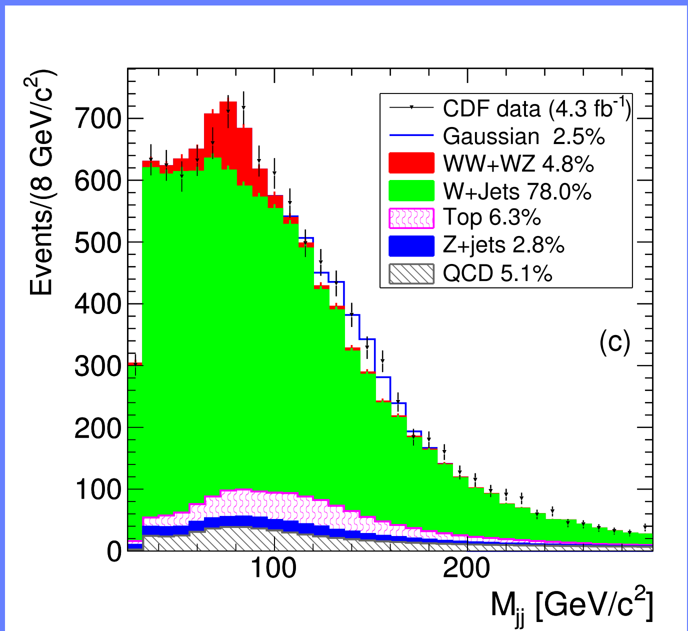
- correct rates with K-factors (latest NNLO for signal, MCFM NLO for W+2jets)
- after basic cuts plus combinatorial h selection using mass windows for h and jj ⇒ $S/\sqrt{B} \sim 1.9(1.2)$ @ hadron level for $M_h = 165(180)$GeV.

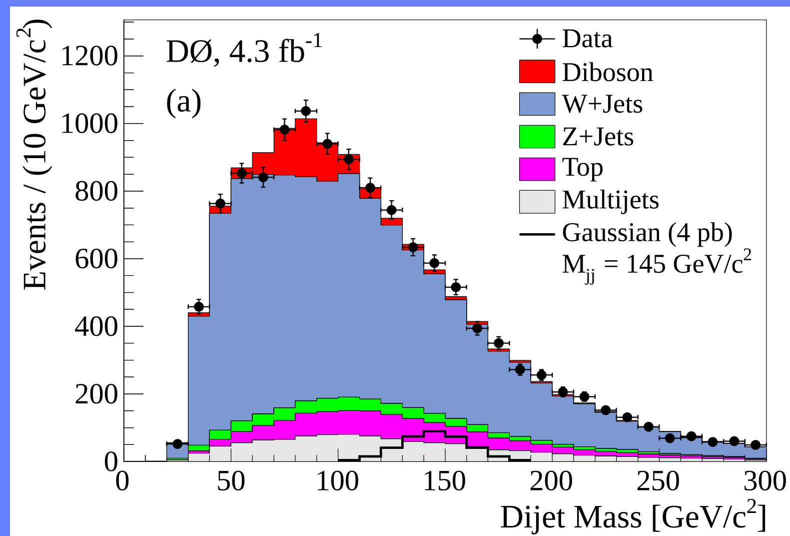


Still find discriminating observables →

Recent measurements tell us ... .

➡ *... a different story.* *And it is exactly this final state: lepton + MET + 2 jets.*





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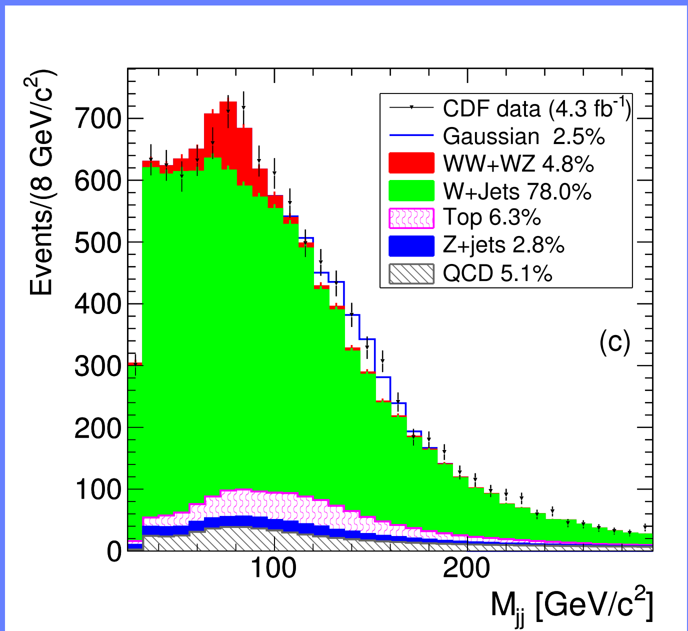
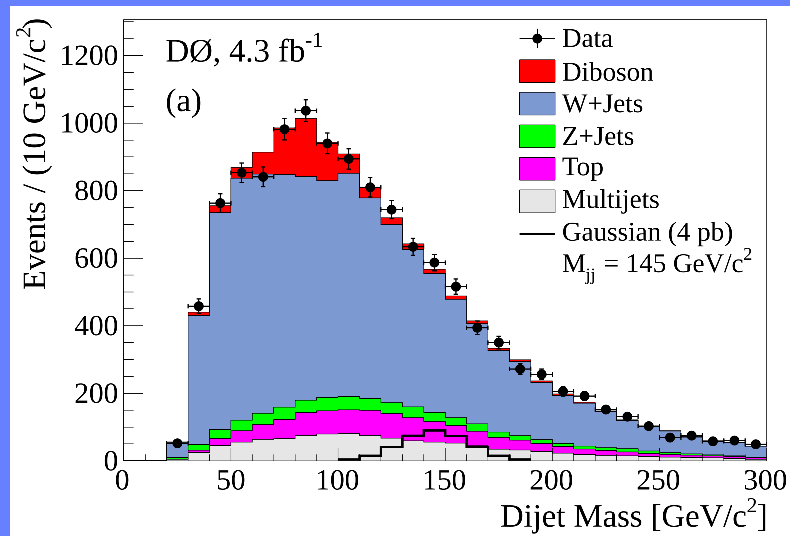


CDF [ARXIV:1104.0699]

Are the results compatible?

DØ [ARXIV:1106.XXXX]



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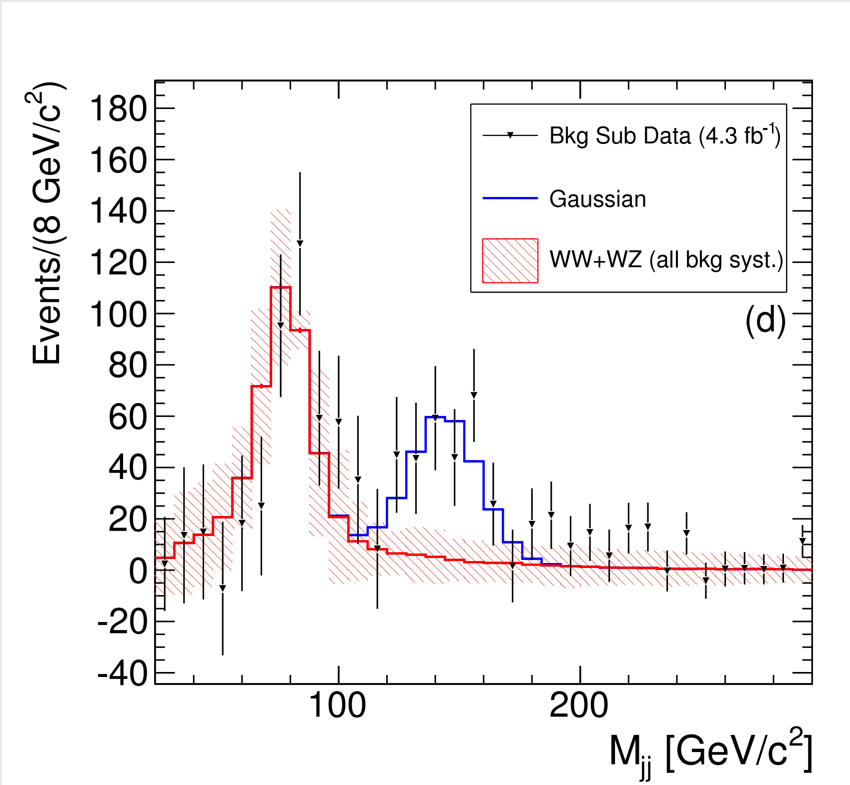
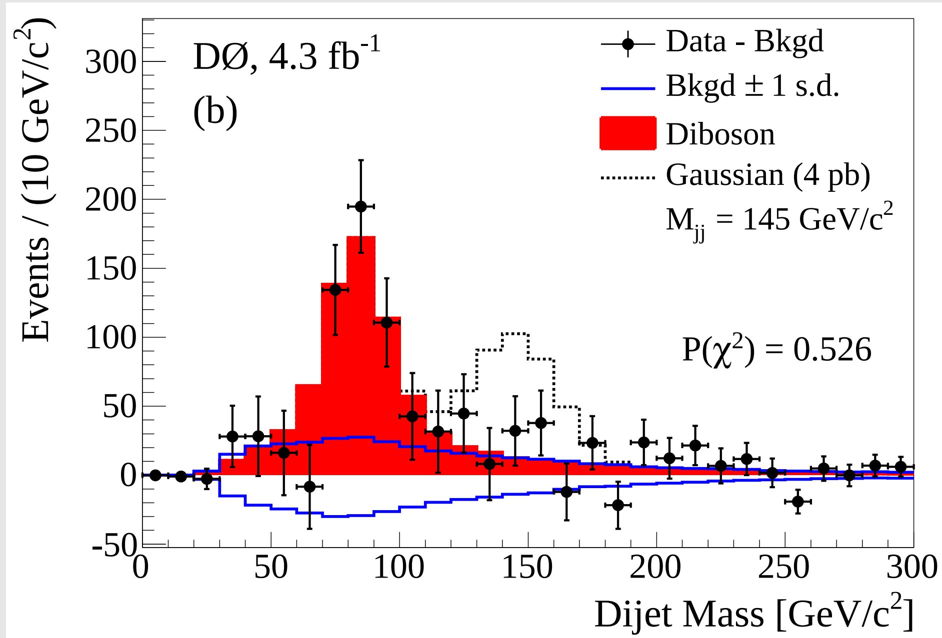
➡ subtracting all backgrounds but WW/WZ





CD

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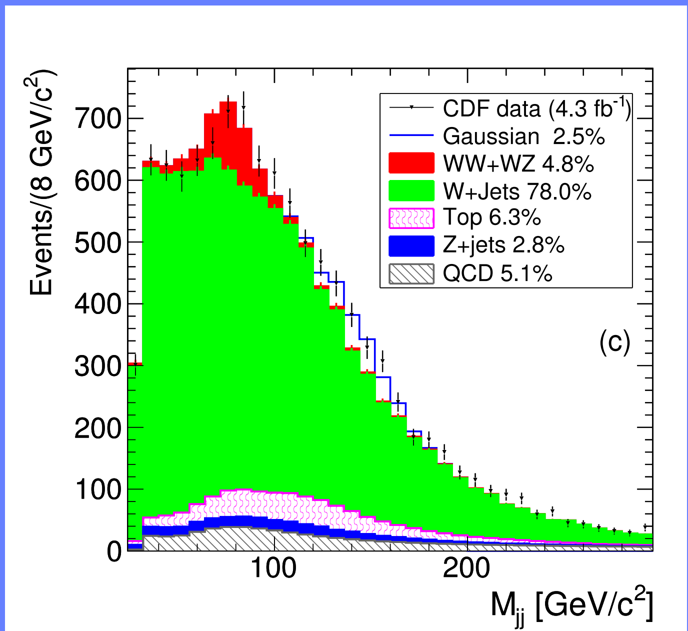

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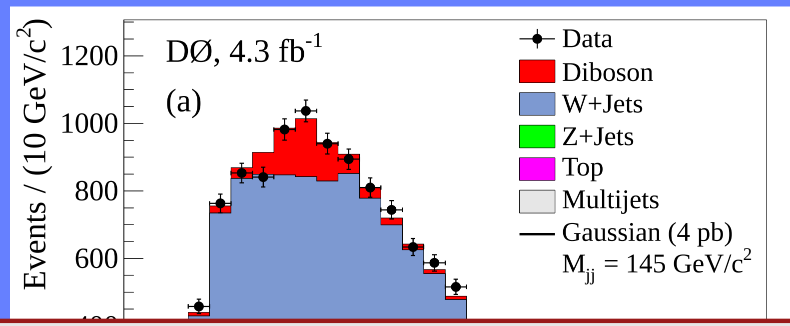


- What are the differences in the two analyses. How large of an effect can they make?
- Why do the diboson contributions look pretty different (just binning)?
- Why is the QCD background in DØ roughly twice as large (just looser electron criteria)?
- How well do we understand all the backgrounds ...

  with the major contribution coming from ***W+2jets*** ?

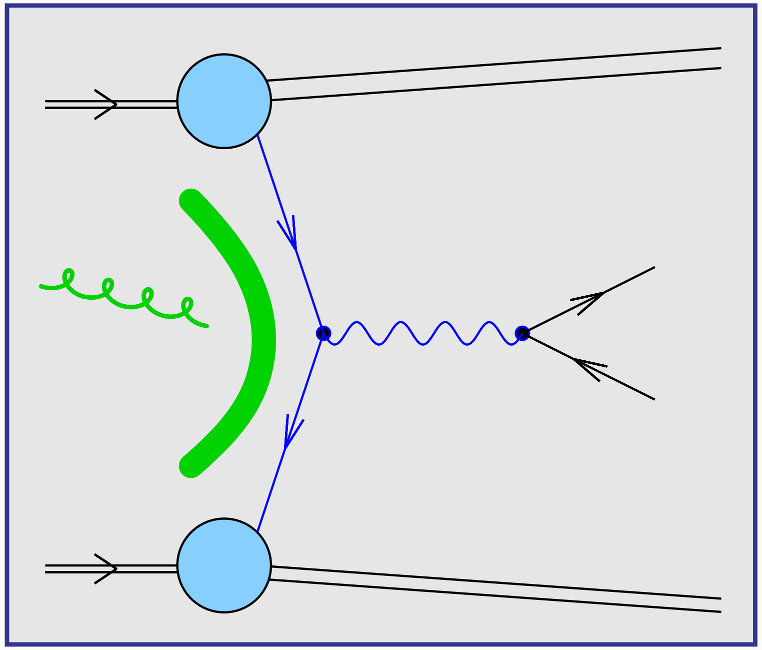
Hadronic cross sections for V production

- 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, Helac, Amegic, Comix, Whizard, LO MCFM

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

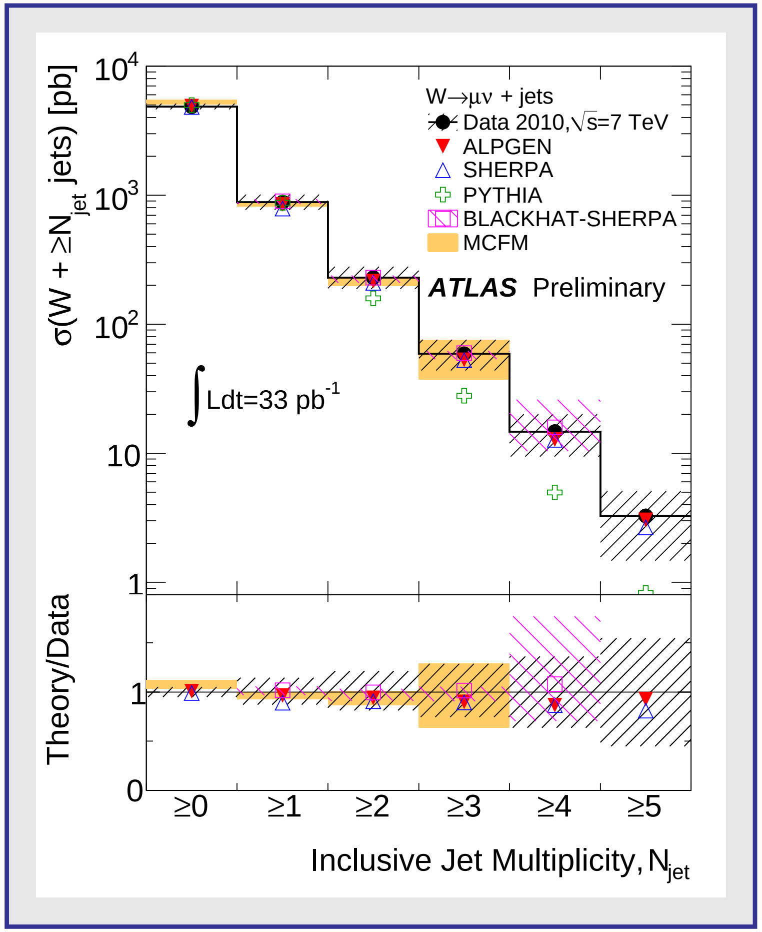
  [Melnikov, Zanderighi, ...]

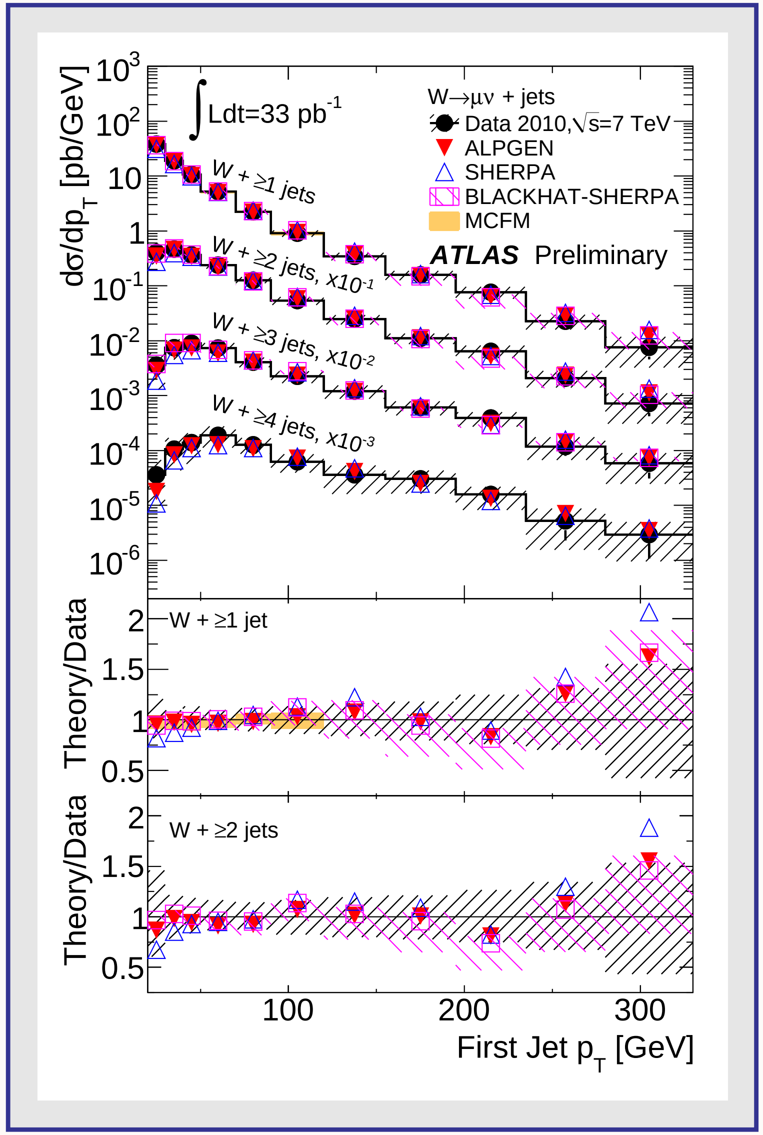
  established
  - MCFM

  [Campbell, Ellis, ...]

  automated
  - MadFKS+ MadLoop

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





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

Tree-level ME+PS merging

Merging procedures have main steps in common:

(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.

Different methods use different 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 $Q_{\rm jet}$

Examples for ME+PS merging Monte Carlos:

- Alpgen – MLM; interfaced to Pythia or Herwig [MANGANO ET AL.]
- MadGraph – 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

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  - Alpgen – ML
  - MadGraph –
  - Sherpa – CK
  - Herwig++ –

CKKW

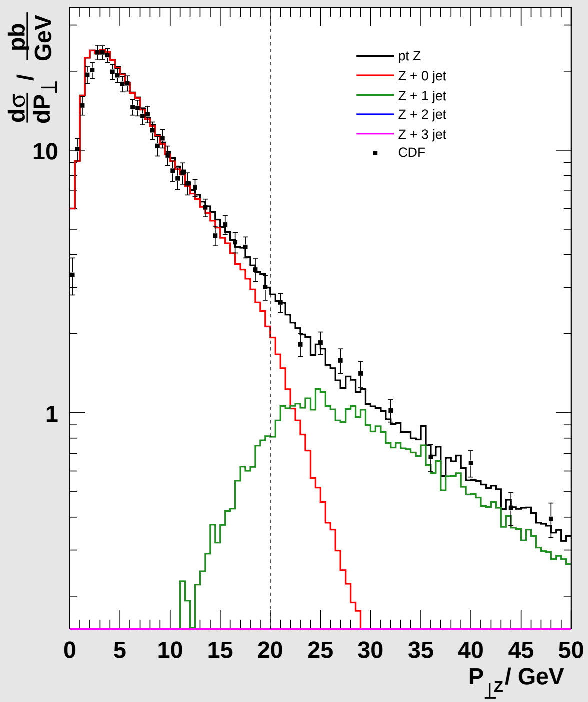
[Catani, Krauss, Kuhn, Webber, JHEP 11 (2001) 063]

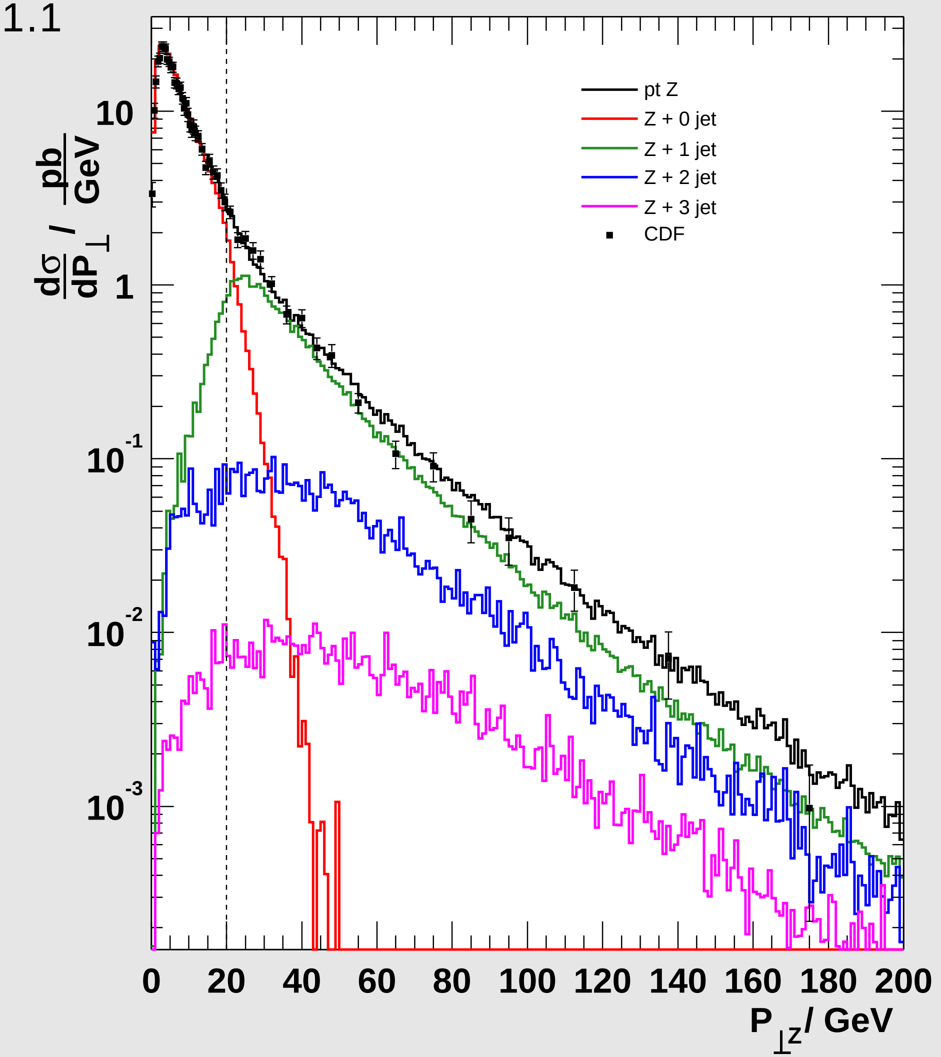
[Krauss, JHEP 08 (2002) 015]

⇒ 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





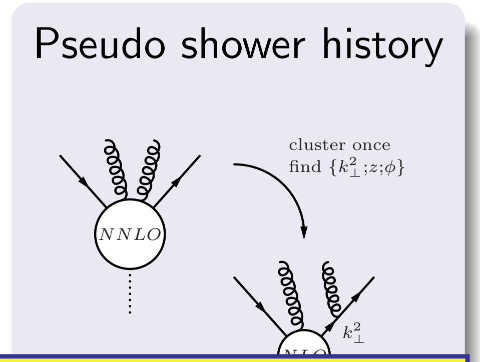
Krauss et al. PRD 70 (2004) 114009

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)

$\Rightarrow$ Fully populate emission's phase space with either ME or PS – avoid dead regions.
$\Rightarrow$ ME and PS describe the same final state – remove double counting.



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

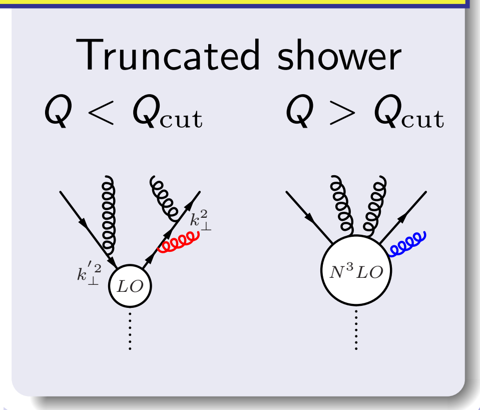
➡ tree-level MEs: jet seed (hard parton) production $Q > Q_{\rm cut}$

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

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

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.



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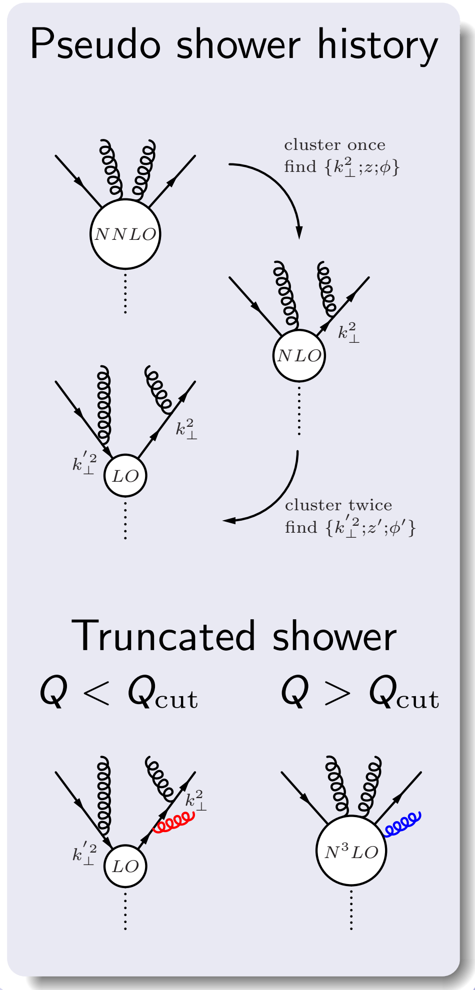
- parton showers: (intra-)jet evolution $Q_{\rm cut} > Q > Q_{\rm hadr}$
  - ∘ Sudakov form factor factorizes into ME and PS part.
  - ∘ Replace kernel in ME domain by correct ME expression.

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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○ Sudakov form factor factorizes into ME and PS part.

○ Repl

Pseudo-sho

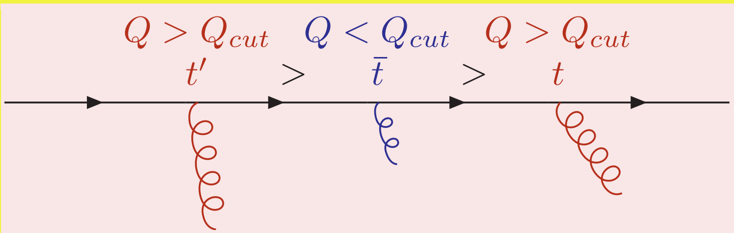
- cluste
- PS st
- ME b

○ pres

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

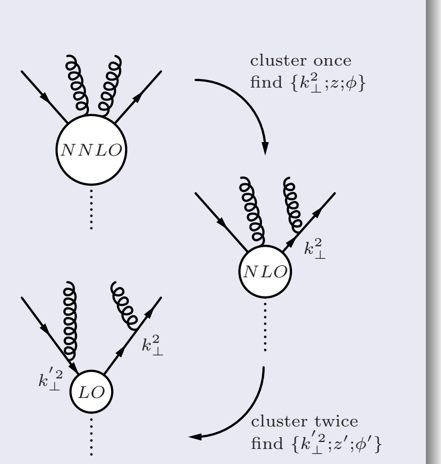
to be described by ME / preserves total xsec / Sudakov suppression

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



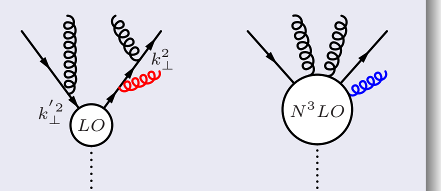
large-angle soft emissions
soft colour coherence
in CKKW only approximately

Pseudo shower history



Truncated shower

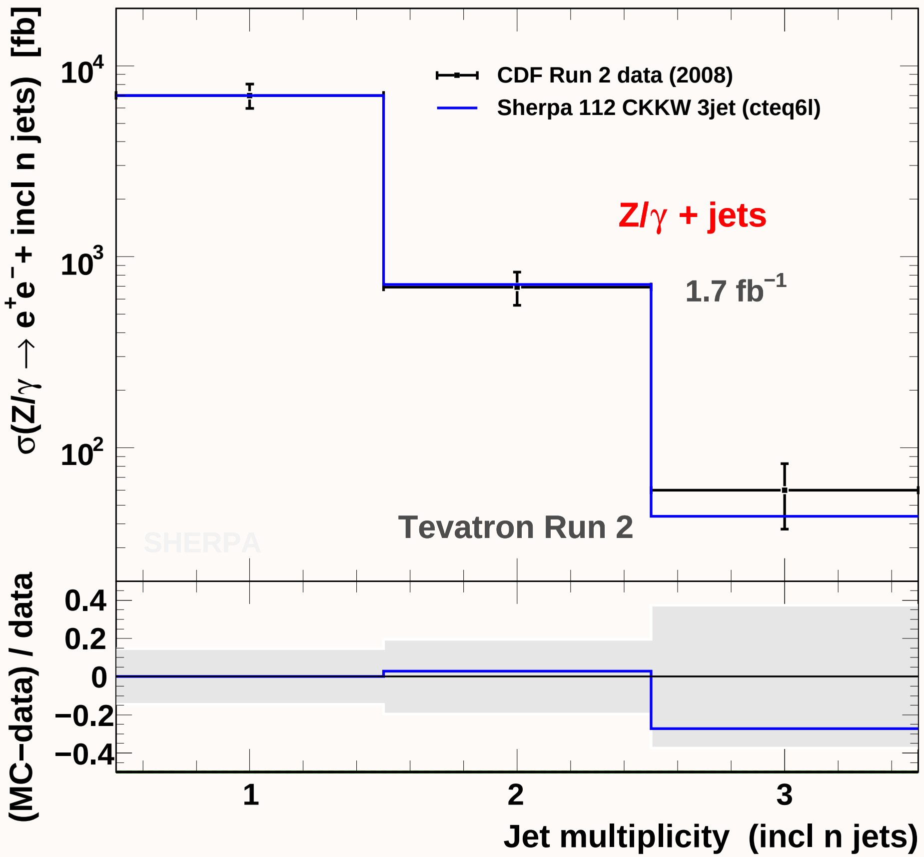
$Q < Q_{\rm cut}$ $Q > Q_{\rm cut}$

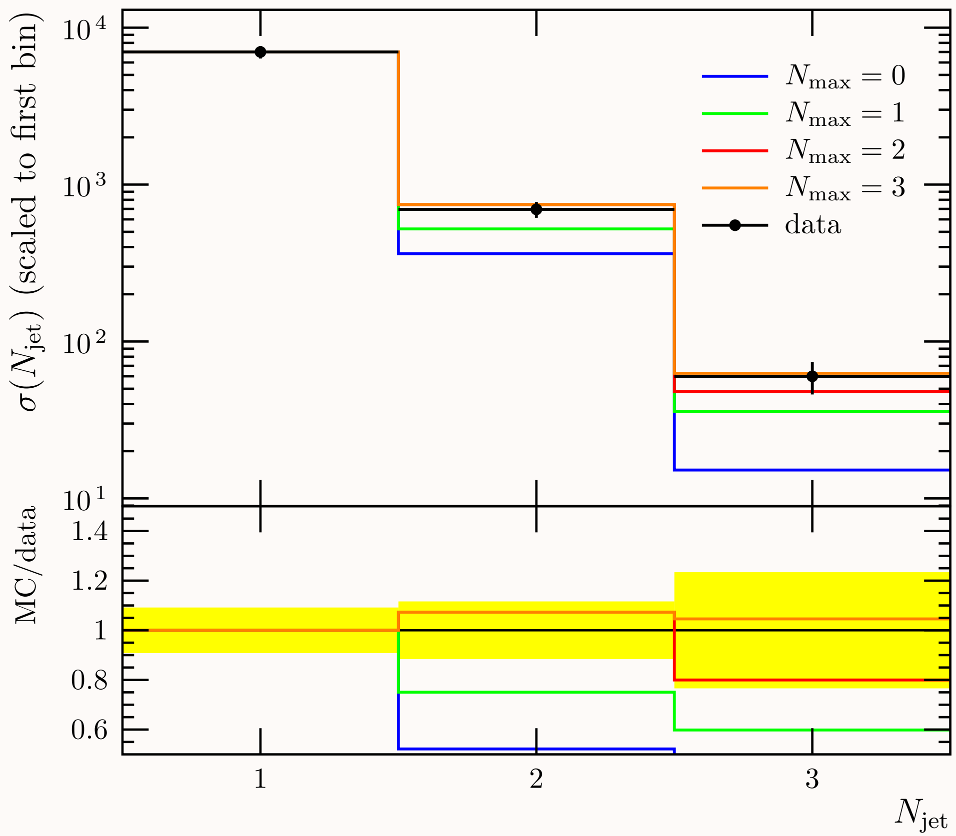


Comparison with CDF data: Z+jets production

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]



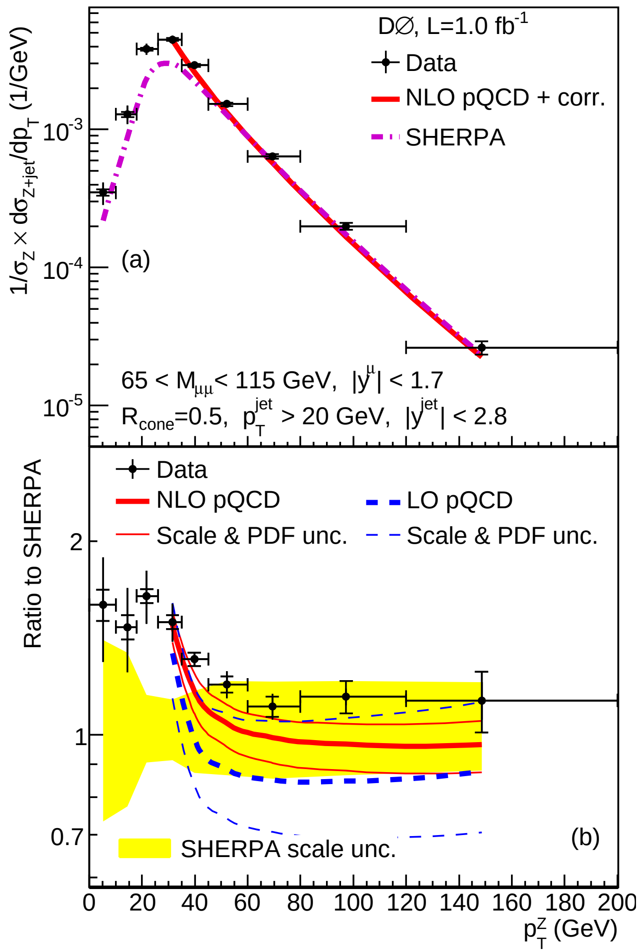


Z+jets as measured by DØ

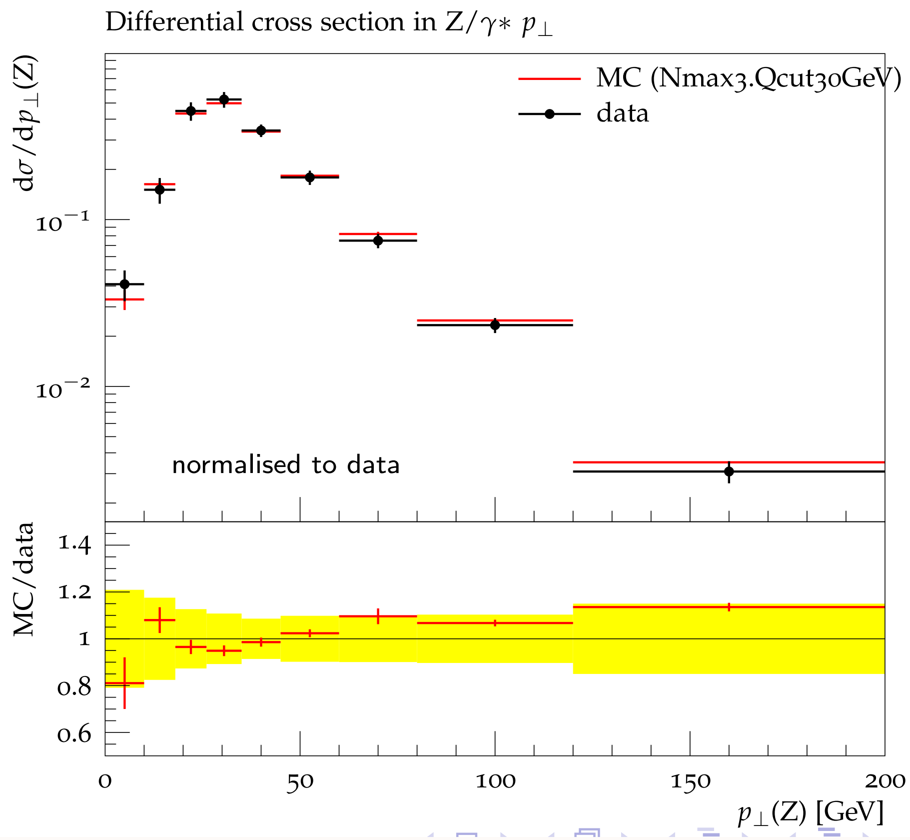
Comparison to Sherpa's CKKW implementation in v1.1.3

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

Sherpa v1.1.3



Sherpa v1.2

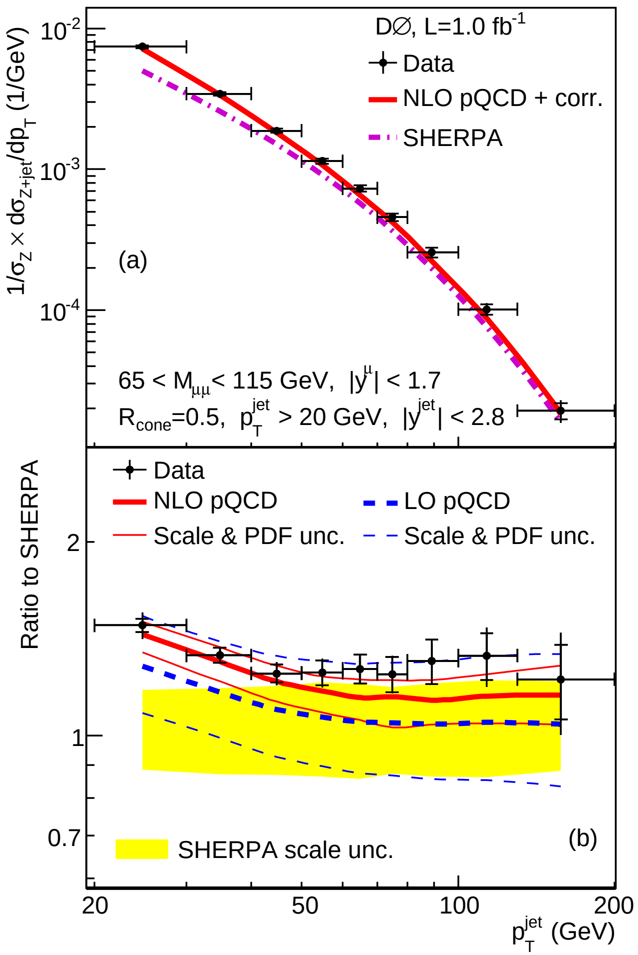


Z+jets as measured by DØ

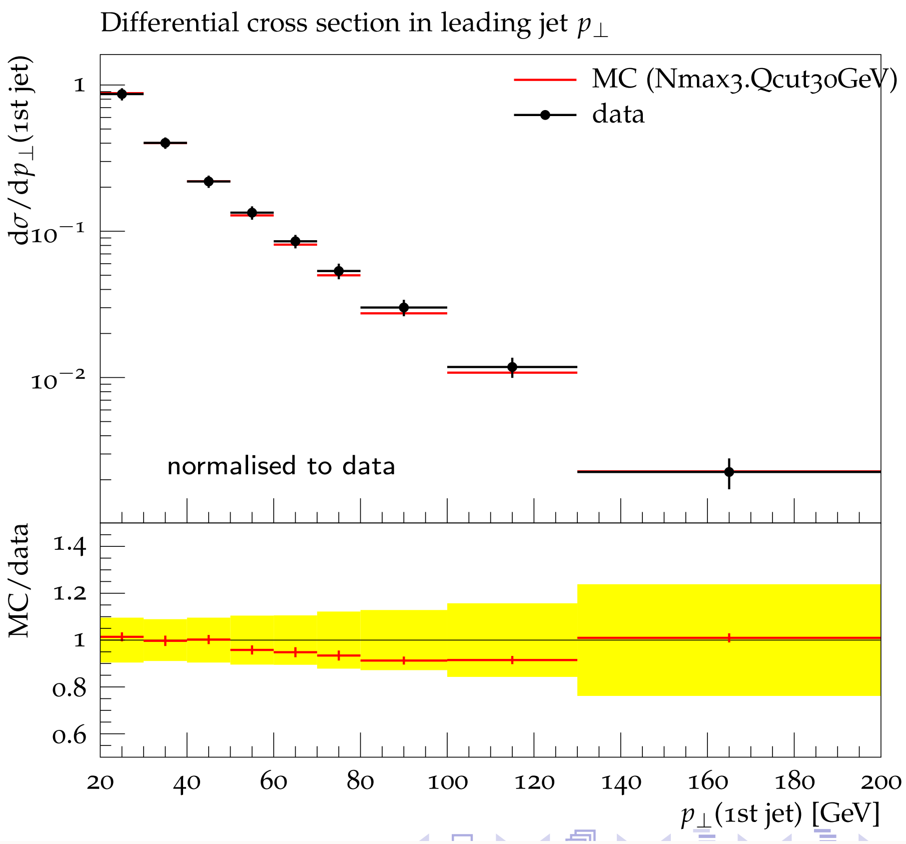
Comparison to Sherpa's CKKW implementation in v1.1.3

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

Sherpa v1.1.3



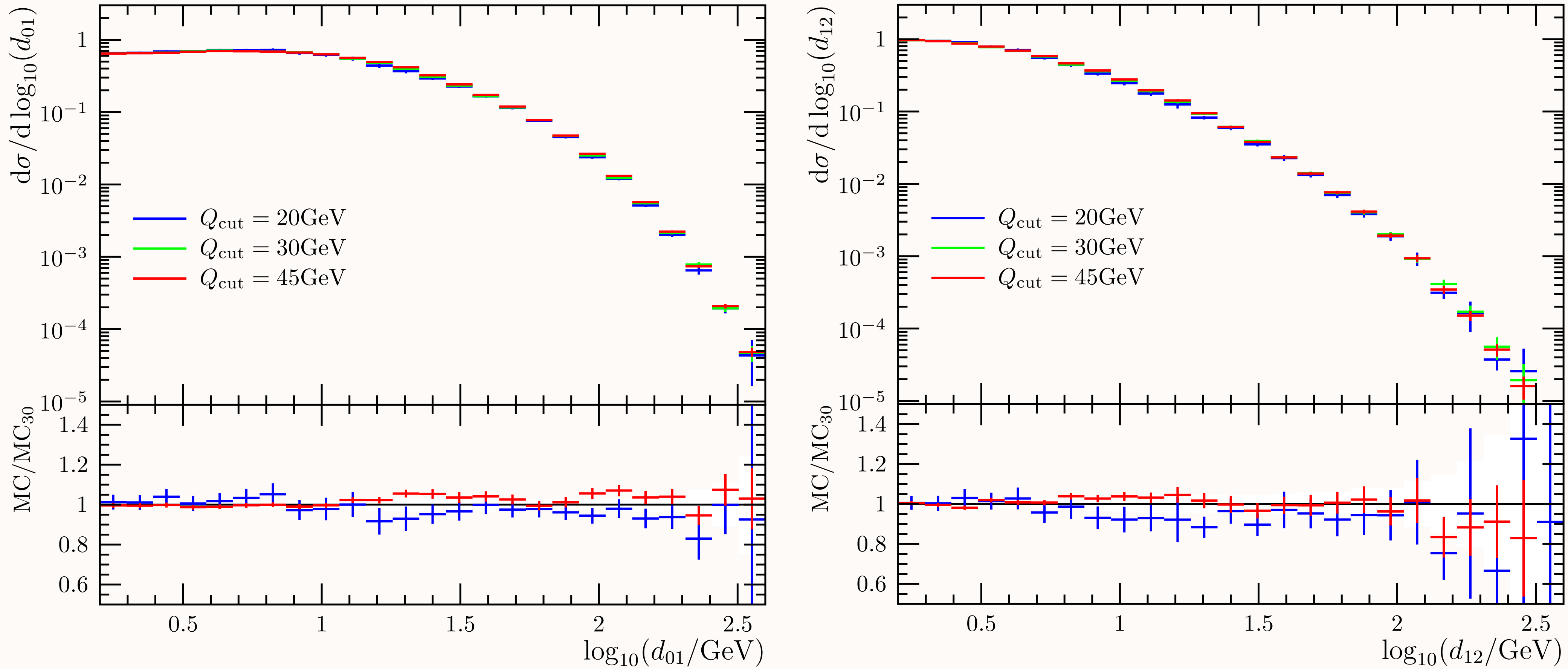
Sherpa v1.2



Z+jets production @ Tevatron Run2 energies

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

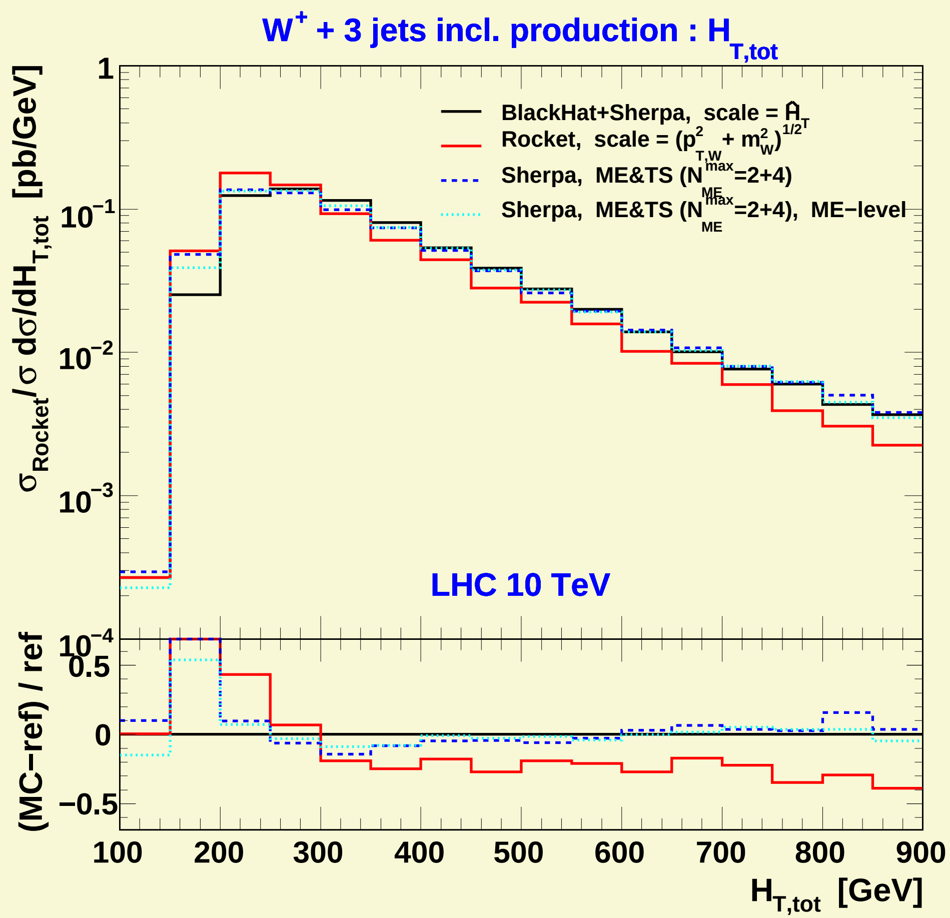
- Merging systematics has improved: $Q_{\rm cut}$ variation now within $\pm 10\%$.
- Differential k_T jet rates in $Q_{\rm cut} = Q_{\rm jet}$ variation @ hadron level. Note $N_{\rm max} = 5$.
- Note $\mu_{\rm F}^2 = M_{ee}^2$ and 66 GeV $< M_{ee} <$ 116 GeV.

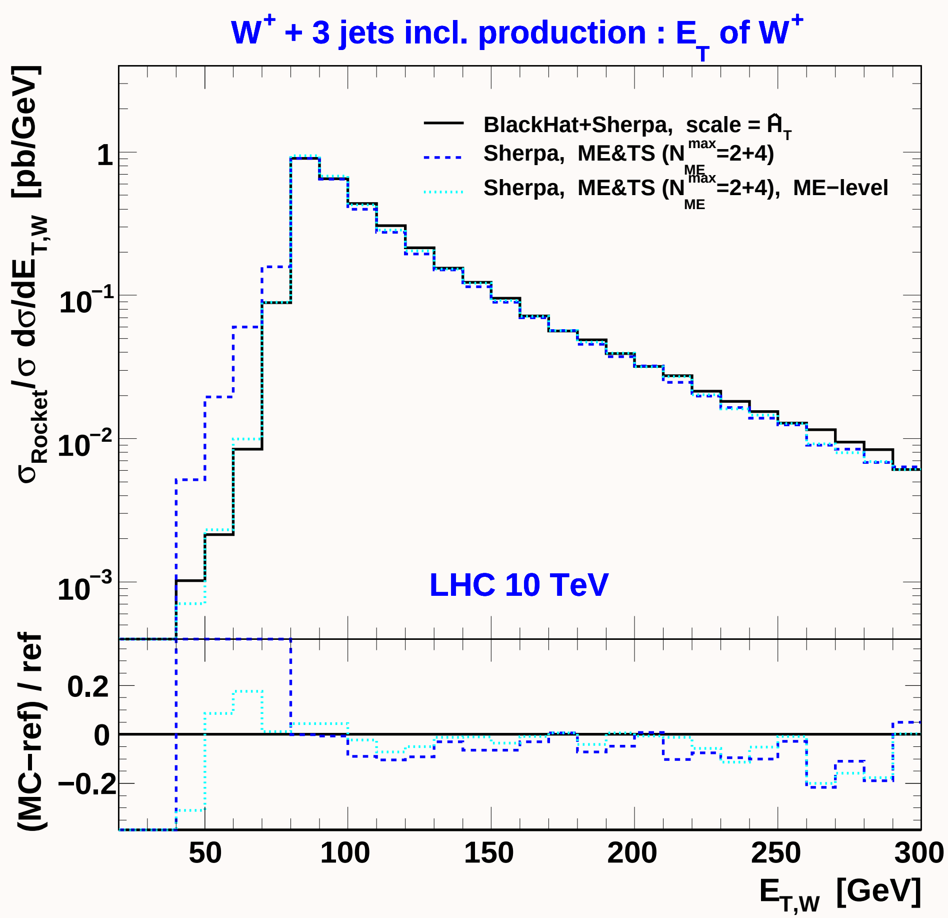


NLO vs. ME&TS: LHC predictions for W+3jets

[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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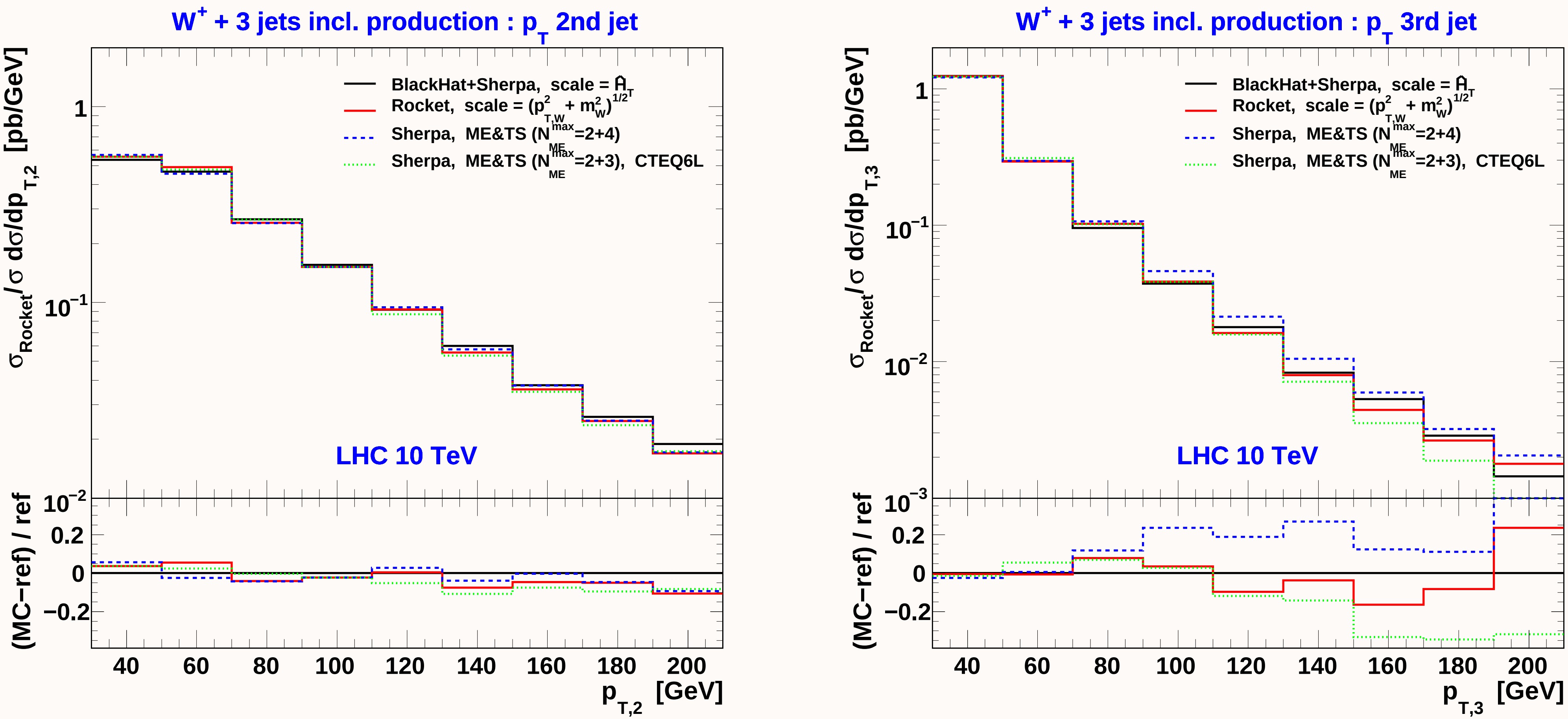

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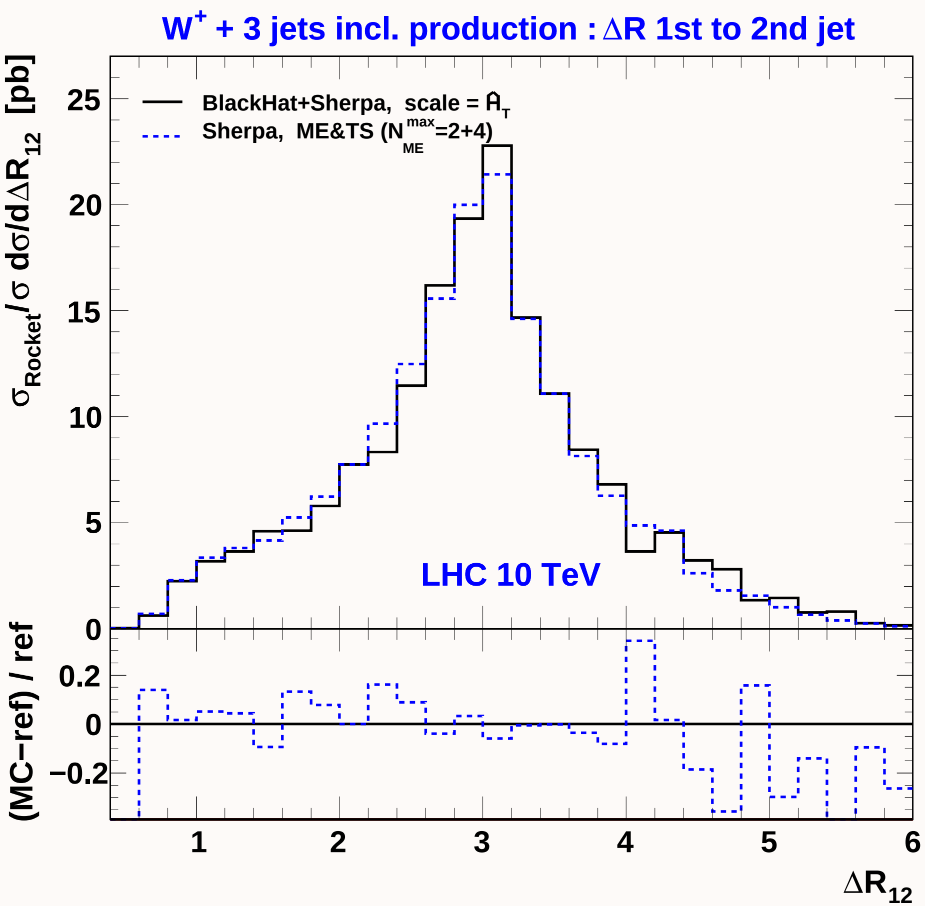
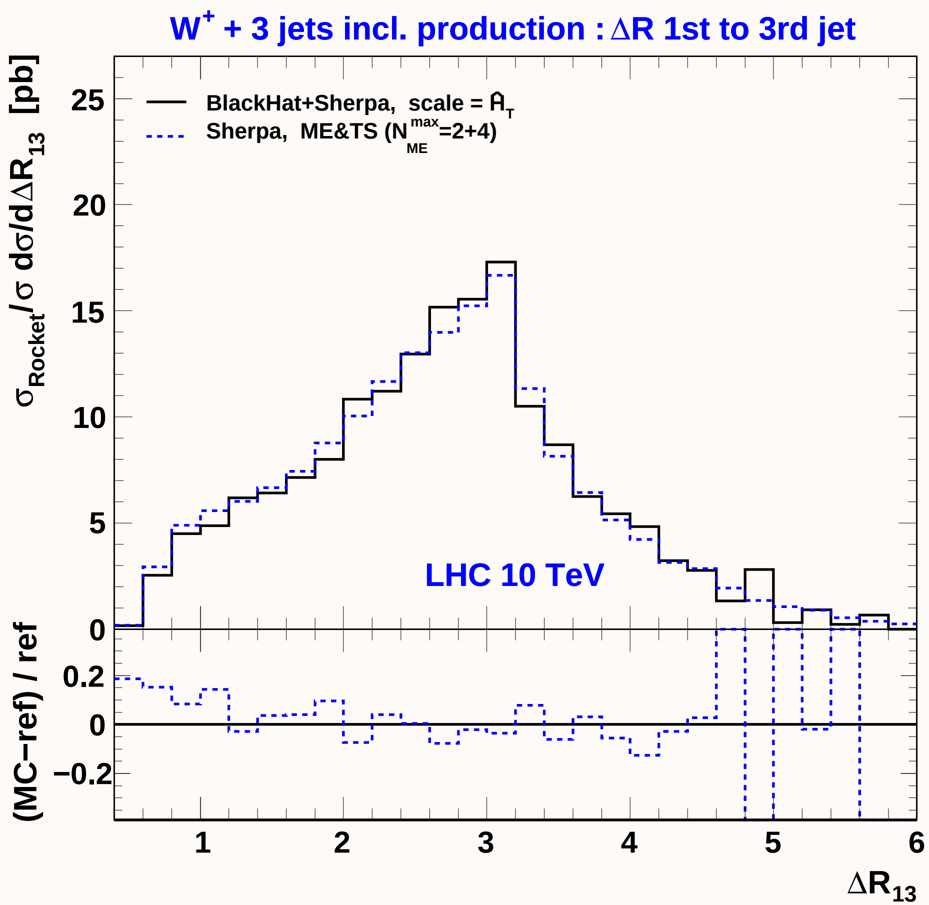




Scale uncertainty for multi-leg processes at NLO

- 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:

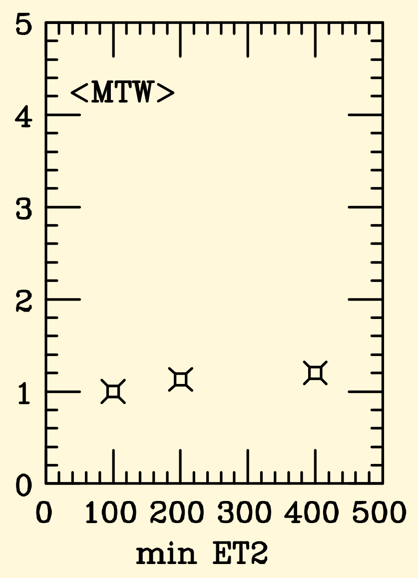
  → Higher powers of the strong coupling.
  → Many – possibly very disparate – kinematical scales.

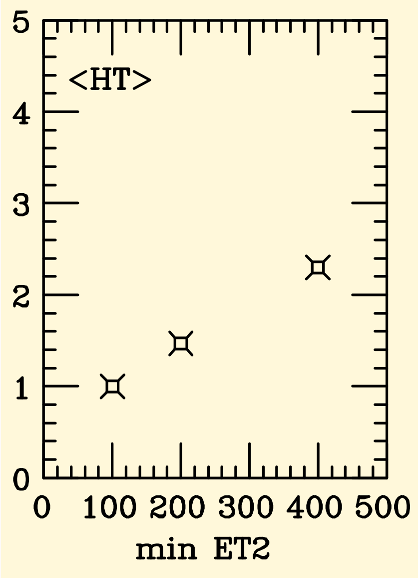
- New insight from recent W+3jets calculations: scales leading to good perturbative behaviour.

  → @ 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*

- $Q_{\rm cut}$ – 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]

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)] ($Wb\bar{b}$, work on V+1jet under way)

- ***POWHEG:*** http://powhegbox.mib.infn.it
  [ALIOLI, HAMILTON, NASON, OLEARI, RE] (recent achievements: V+1jet, $Wb\bar{b}$ [ARXIV:1105.4488])

- 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.)

POWHEG and ME+PS: MENLOPS in Sherpa

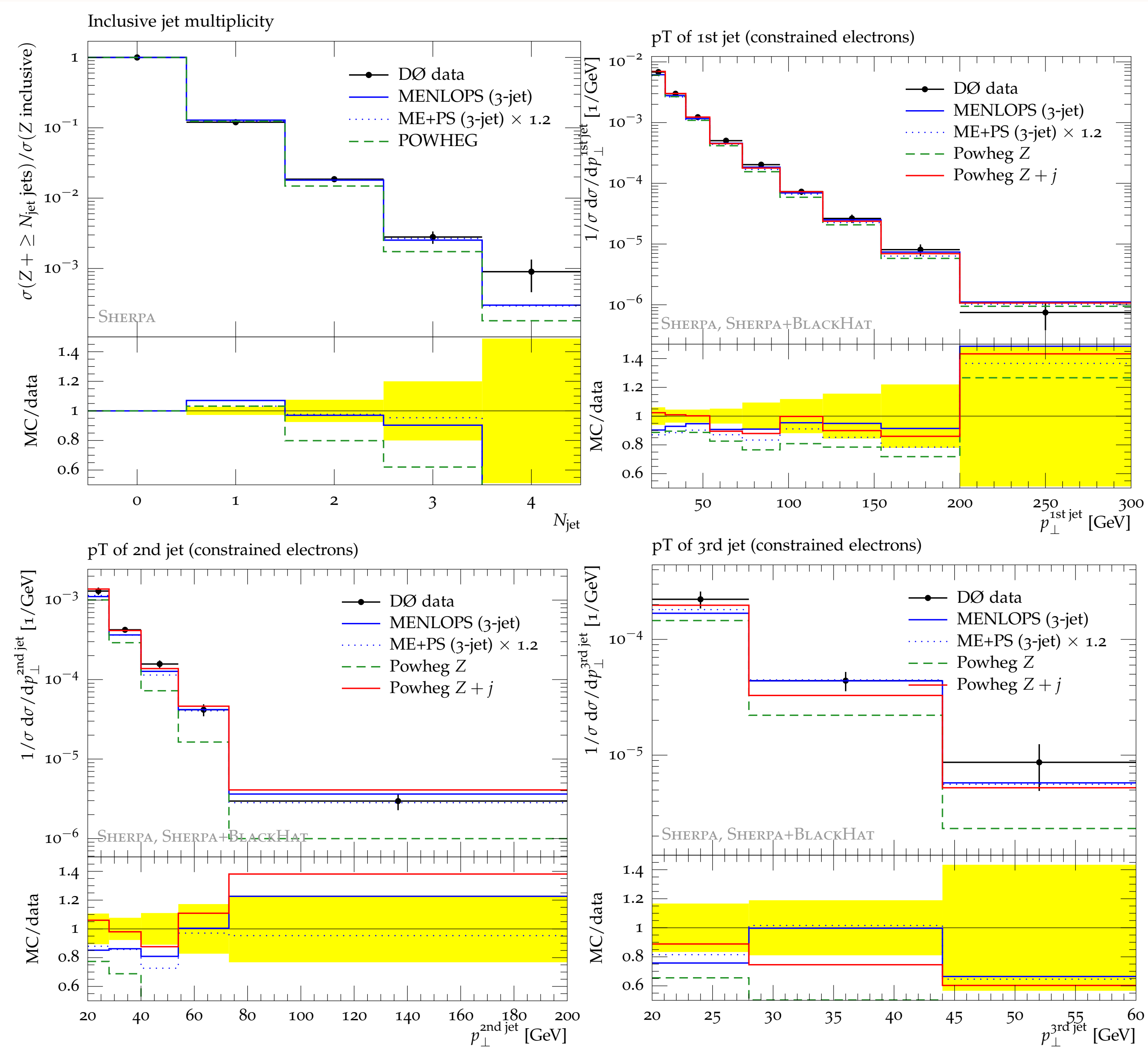
[Höche, Krauss, Schönherr, Siegert, JHEP 04 (2011) 024, arXiv:1009.1127] [slide from Marek Schönherr]

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

- POWHEG domain restricted to soft emissions $Q < Q_{\mathrm{cut}}$
  $\Rightarrow$ **NLO accuracy preserved for inclusive observables**
- ME$\otimes$PS used for hard emission & higher order emissions
  $\Rightarrow$ **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

Other channels: W+b-jet example

- Wbb is important background for Tevatron low-mass Higgs search: $W + h(\to b\bar{b})$
  [sanity check for low-mass Higgs search: $W + Z(\to b\bar{b})$]
- first calculation of Wbb with massive b-quarks including correlations in W decay
  [Badger, Campbell, Ellis, arXiv:1011.6647]
  included in current version of MCFM (v6.0, May 2011, http://mcfm.fnal.gov)

# of jets	1 jet		2 jets		
jet identities	b	(bb)	bj	(bb)j	bb
LO	0.430	0.105	-	-	0.162
NLO	0.582	0.130	0.090	0.030	0.150

- sum of NLO line: $\sigma_{evt}(Wb) =$ 0.982 pb; include bb twice, per CDF: $\sigma_{b\text{-}jet}(Wb) =$ 1.132 pb;
- estimate uncertainties: $0.913 < \sigma_{b\text{-}jet}(Wb) < 1.389$ pb;
- Alpgen: 0.78 pb; Pythia: 1.10 pb;
- CDF [arXiv:0909.1505]: 2.74 ± 0.27(stat) $\pm$ 0.42(syst) pb. ***Puzzle not solved!***

Other channels: back to the Wjj bump

Mismodelled backgrounds ?

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

NLO effects ?

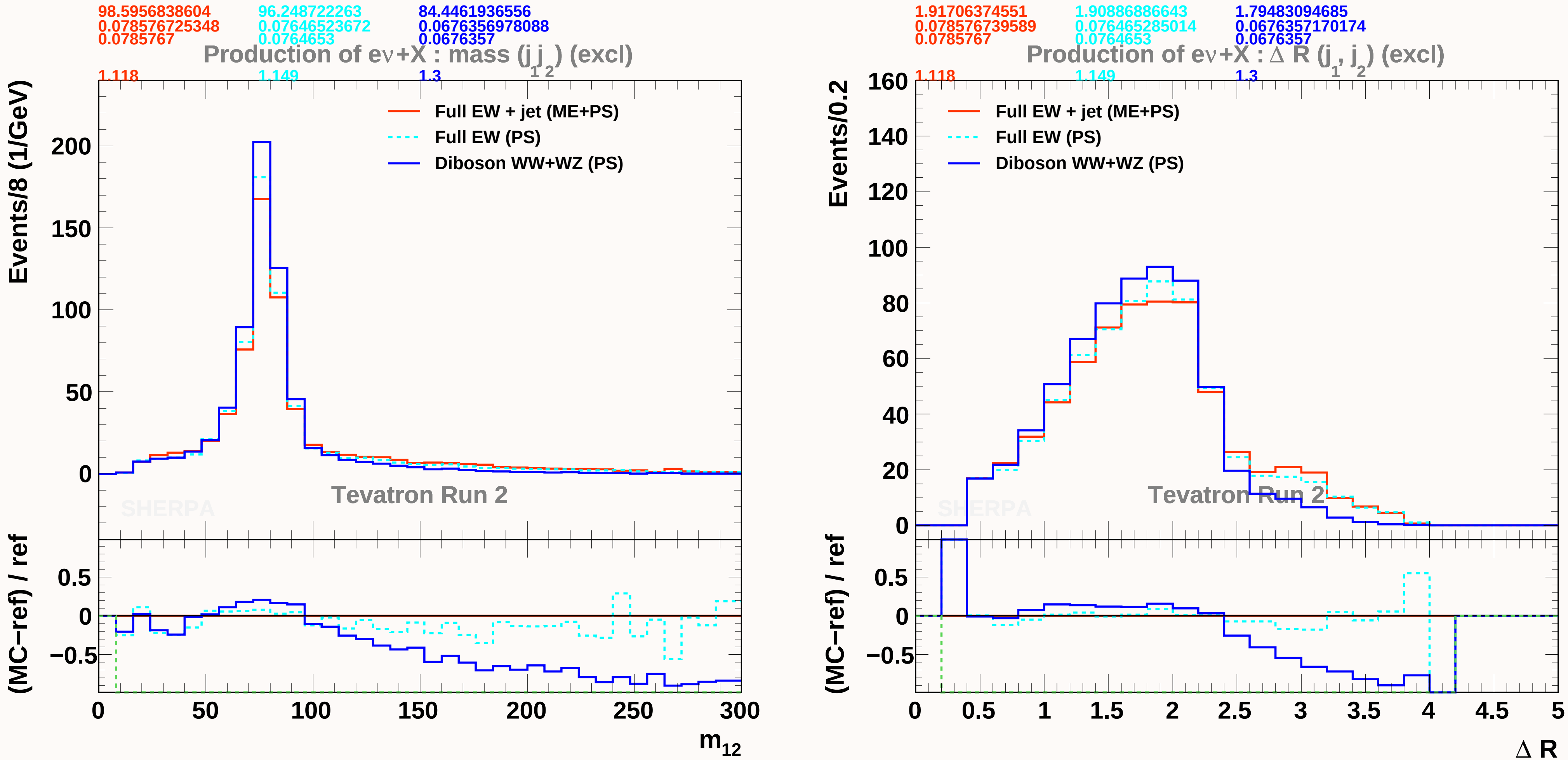
- [Campbell, Martin, Williams, arXiv:1105.4594] checked excl. and incl. W+2jet cross sections
- no inconsistencies / surprises in K-factors

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

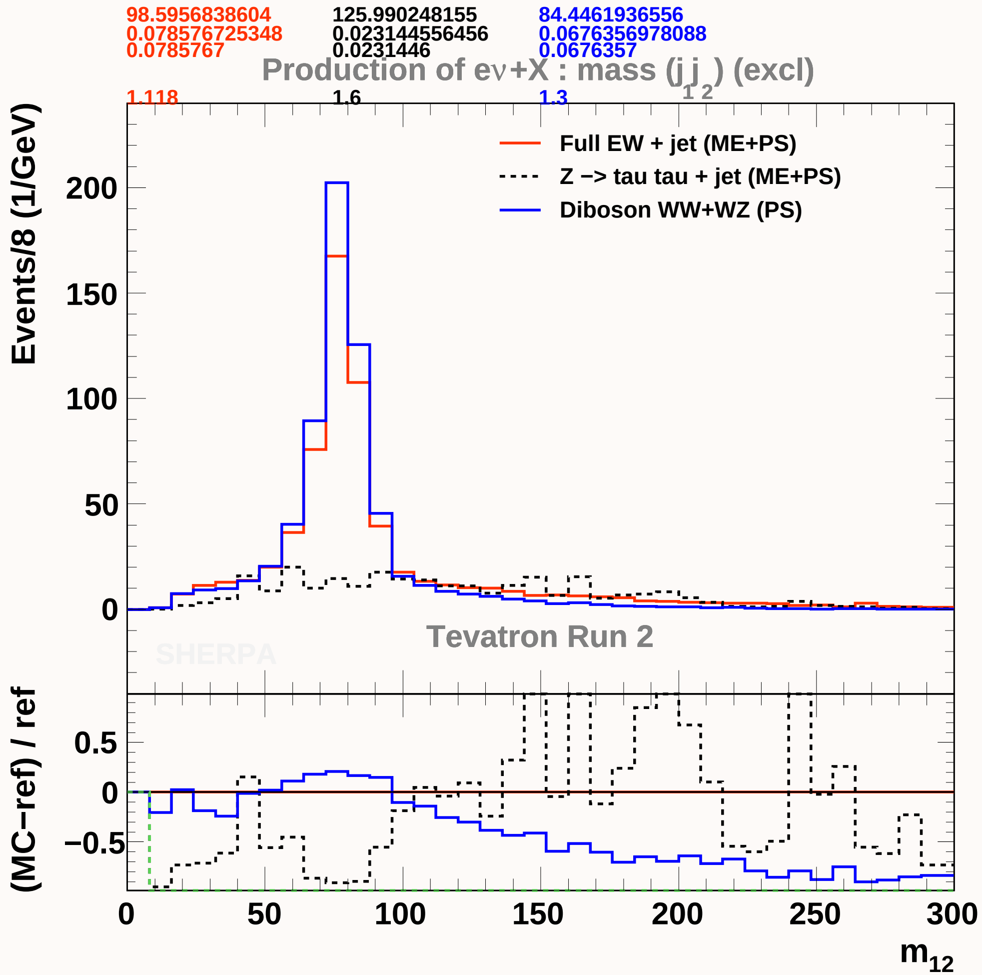
But we have a ...

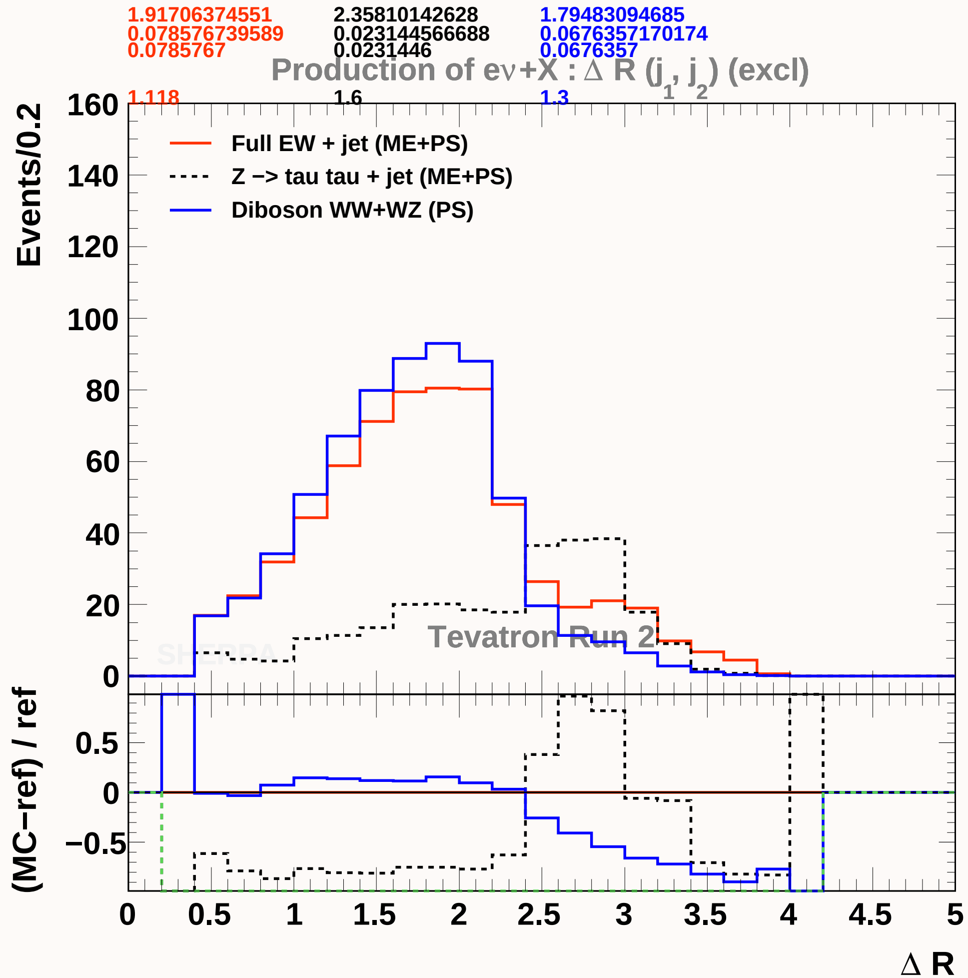
Multitude of tools.

- 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.


98.5956838604
0.078576725348
0.0785767
96.248722263
0.07646523672
0.0764653
84.4461936556
0.0676356978088
0.0676357
Production of eν+X : mass (j1 j2) (excl)
1.118
1.149
1.3
Full EW + jet (ME+PS)
Full EW (PS)
Diboson WW+WZ (PS)
Events/8 (1/GeV)
Tevatron Run 2
SHERPA
(MC−ref) / ref
m12
1.91706374551
0.078576739589
0.0785767
1.90886886643
0.076465285014
0.0764653
1.79483094685
0.0676357170174
0.0676357
Production of eν+X : Δ R (j1, j2) (excl)
Events/0.2
Δ R

preliminary





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 systematics.
- 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.
- Apologies for being selective, could have well mentioned your tool.
  - MatchBox to automate POWHEG in Herwig++, or VBF@NLO for multi-V final states.