Developments in ME+PS merging

[Fermilab Theory Seminar – Curia II]

Jan Winter
– 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: $gg \rightarrow h \rightarrow WW \rightarrow \ell\nu jj$.

our approach [LYKKEN, MARTIN, WINTER, IN PREPARATION]
• signal and (dominant) $W+2$jets background with Sherpa
⇒ QCD corrections (shapes) well included
• correct rates with $K$-factors (latest NNLO for signal,
  MCFM NLO for $W+2$jets)
• 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.

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Recent measurements tell us ...

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

Are the results compatible?

CDF [ARXIV:1104.0699]

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

![Graph showing Dijet Mass distribution with data, background, and Gaussian fit.](image)

**DØ, 4.3 fb⁻¹**

- **Data - Bkgd**
- **Bkgd ± 1 s.d.**
- **Diboson**
- **Gaussian (4 pb)**

\[ M_{jj} = 145 \text{ GeV}/c^2 \]

\[ P(\chi^2) = 0.526 \]
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 \( W+2\text{jets} \)?
Hadronic cross sections for weak-boson production

calculation of the hadronic cross section relying on factorization theorem
... ... expected to hold for \( A + B \rightarrow V + X \) \([\text{Collins, Soper, Sterman, 2004 Review}]\)

\[
\sigma_{\text{hadr}} = \sum_{ij} \int dx_1 dx_2 \ f_i(x_1, \mu_F) \ f_j(x_2, \mu_F) \ \sigma_{\text{part}}(ij \rightarrow V \rightarrow \ldots)
\]

\( \sigma_{\text{part}} \ldots \) calculable in pQCD; \( f_i \) = parton density functions (PDFs) ... extracted from data;

separation of perturbative and non-perturbative regimes \( \rightarrow \) pQCD used to predict cross sections in complicated hadron collider environment

E.g. \( V \) production \( @ \) LO: \( \) two initial-state partons fuse to make either \( W^\pm \rightarrow \ell \nu \) or \( Z/\gamma^* \rightarrow \ell^+ \ell^- \)

vector boson has no transverse momentum

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

\( \rightarrow \) highly automated ME generators \( @ \) tree level

\( \rightarrow \) Alpgen, MadGraph/Event, Helac, LO MCFM, Amegic, Comix, Whizard

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Beyond LO

E.g. V production @ NNLO: fully differential codes:
- **FEWZ** [**Melnikov, Petriello**]
- **DYNLO** [**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:

\[
d\sigma_{n+1} = d\sigma_n \frac{\alpha_s(t)}{2\pi} \frac{dt}{t} dz P_{a\rightarrow bc}(z) \quad \text{(e.g. coll limit)}
\]

- 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 $Q, \vartheta, p_T$]

- Provides suitable input for universal hadronization models [$O(1\text{GeV})$]
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  $\rightarrow$ **improved** LO+LL predictions
  
  [ called (tree-level/LO) ME+PS merging  \quad – \quad CKKW, L-CKKW, MLM, ME&TS  \quad – \quad No NLO xsecs! ]

- use NLO QCD core processes and match to parton showers  $\rightarrow$ NLO+LL predictions
  
  [ called NLO+PS matching  \quad – \quad MC@NLO, POWHEG  \quad – \quad Full NLO xsecs! ]

- MELOPS  $\rightarrow$ 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

\[ |A_R|^2 + |B_R|^2 + 2 \text{Re}(A_R B_R^*) \]

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.

\[ \alpha_S \text{ vs. } \log \, \text{in } e e \rightarrow \text{jets} \]
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 $\alpha_s$ and analytical Sudakov form factors; (4) evolve each ME parton using $k_T$ cluster scales & veto emissions above $Q_{cut}$

Examples for ME+PS merging Monte Carlos:

- Alpgen – MLM; interfaced to Pythia or Herwig  [Manganò 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

Merging:
1. calculate $n$-jet cross-section
2. generate hard-parton showers
3. accept/reject jet configuration
4. find suitable starting point

Different methods use different algorithms:
- CKKW, for example:
  - through $\alpha_s$ and analytical series
  - using $k_T$ cluster scales &
- Alpgen – MLM
- MadGraph/EVTGEN
- Sherpa – CKKW
- Herwig++ –

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

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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

Comparison between merging approaches

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

\[ W^+ + X \]

- Jet $\eta$ spectra at the LHC
- Similar pattern wrt. Tevatron
- Extrapolation to LHC energies makes differences more pronounced

Example distributions: $p_T$ of $W$, $\eta$ of 1st jet, $\Delta R_{12}$, 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**

**W+jets @ Tevatron**

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Example distributions:

- **W**\(\rightarrow l\nu\)\(-Z+\) jets (1/fb Run2) [Lammers et al.]
  - **ALPGEN/MLM** – **Z+JET ANGLES** \(\times\) – **Z+JET PTS** \(\checkmark\)
  - **SHERPA/CKKW** – **Z+JET ANGLES** \(\checkmark\) – **Z+JET PTS** \(\times\)

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

**SHERPA vs1.1.2 \(\Rightarrow\) vs1.1.3 [2008]**

Second answer (longer time scale) \(\Rightarrow\) Improve CKKW.

**SHERPA vs1.1.3 \(\Rightarrow\) 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
  \(\Rightarrow\) 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 \(\mu_F\) and \(\mu_R\)

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**We improved on these issues by relying on truncated showers.**

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**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.

**Slice multi-jet phase space into two domains:** via IR-safe jet criterion \( Q \)

- tree-level MEs: jet seed (hard parton) production \( Q > Q_{\text{cut}} \)
- parton showers: (intra-)jet evolution \( Q_{\text{cut}} > Q > Q_{\text{hadr}} \)

\[
\mathcal{K}_{ab}^{\text{ME}}(\xi, \vec{t}) = \mathcal{K}_{ab}(\xi, \vec{t}) \Theta [Q_{ab}(\xi, \vec{t}) - Q_{\text{cut}}] \\
\mathcal{K}_{ab}^{\text{PS}}(\xi, \vec{t}) = \mathcal{K}_{ab}(\xi, \vec{t}) \Theta [Q_{\text{cut}} - Q_{ab}(\xi, \vec{t})]
\]

- cluster ME final states according to inverse shower formalism
- PS starts at 2 → 2 core and may emit partons off intermediate lines
- ME branchings as resolved must be respected
  - preserve evolution, splitting and angular variables.
Matrix elements and truncated showers – ME&TS

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- tree-level MEs: jet seed (hard parton) production $Q > Q_{\text{cut}}$
- parton showers: (intra-)jet evolution $Q_{\text{cut}} > Q > Q_{\text{hadr}}$
  - 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
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→ tree-level MEs: jet seed (hard parton) production $Q > Q_{\text{cut}}$

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

- Sudakov form factor factorizes into ME and PS part.
- Reproduces previous ME results with PS corrections.

Pseudo-shower history

cluster once find $\{k_1^2, z, \phi\}$

cluster twice find $\{k_2^2, z', \phi'\}$

Truncated shower

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

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

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

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

large-angle soft emissions soft colour coherence in CKKW only approximately
Comparison with CDF data – Z+jets production

**ME & TS :: COMIX + CSS**

- 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


Sherpa v1.1.3

Sherpa v1.2

Differential cross section in $Z/\gamma^* p_{\perp}$

MC (Nmax3,Qcut30GeV) normalised to data
Z+jets as measured by DØ

Comparison to Sherpa’s CKKW implementation in v1.1.3

Example: 1st jet-$p_T$ in $Z/\gamma^*+\text{jet}$ events


**Sherpa v1.1.3**

![Graph showing comparison to Sherpa's CKKW implementation in v1.1.3](image)

**Sherpa v1.2**

Differential cross section in leading jet $p_T$

![Graph showing differential cross section in leading jet $p_T$](image)

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Merging systematics has improved: \( Q_{\text{cut}} \) variation now within \( \pm 10\% \).

Differential \( k_T \) jet rates in \( Q_{\text{cut}} = Q_{\text{jet}} \) variation @ hadron level. Note \( N_{\text{max}} = 5 \).

Note \( \mu_F^2 = M_{ee}^2 \) and \( 66 \text{ GeV} < M_{ee} < 116 \text{ GeV} \).
Diphoton production @ Run2

- Photons & QCD partons treated democratically
- Combine ME of different parton/photon mult.
  with QCD+QED evolution and hadronization
- Add splitting functions $q \rightarrow q\gamma$,
  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
  \( 2 \rightarrow \{2,3,4\}\text{-jet}/\gamma \)
  plus $gg \rightarrow \gamma\gamma$ box


Isolated hard photons with:

- $E_{\gamma 1}^\perp > 21$ GeV
- $E_{\gamma 2}^\perp > 20$ GeV
- $|\eta_{\gamma}| < 0.9$
- Isolation: $E_\perp (R = 0.4) - E_{\gamma}^\perp < 2.5$ 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)

Azimuthal angle between the diphotons

Similarly in PRD81(2010)034026

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HÖCHE, SCHUMANN, SIEGERT

DØ, 4.2 fb$^{-1}$

Ratio to RESBOS

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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

**W^+ + 3 jets incl. production : \(H_{T,\text{tot}}\)**

**W^+ + 3 jets incl. production : \(E_T\) of W^+**

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between BLACKHAT [BERGER ET AL.], ROCKET [ELLIS, MELNIKOV, ZANDERIGHI] and SHERPA [GLEISBERG ET AL.]

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SHERPA’s ME&TS merging in good agreement with NLO once rescaled to NLO xsec
between BLACKHAT [BERGER ET AL.], ROCKET [ELLIS, MELNIKOV, ZANDERIGHI] and SHERPA [GLEISBERG ET AL.]

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SHERPA's ME&TS merging in good agreement with NLO once rescaled to NLO xsec
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 $\mu_0$?
  - 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**

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

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

- scale uncertainties from MEs  \[\text{[renormalization and factorization scale settings]}\]
- scale uncertainties from PSs  \[\text{[coupling and PDF scale settings]}\]

→ **related to pQCD–npQCD transition**

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

→ **related to npQCD**  \[\text{[phenomenological universal(?) models need be tuned to data]}\]

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

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:**  [Frixione, Webber; ...]

**aMC@NLO:**  automation of MC@NLO ≡ 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:**  [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

$pp \rightarrow W^+ W^- + X \ @ 14 \ TeV \ LHC$:

- $p_T$ 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 $2 \rightarrow n + 1$ and add back to $2 \rightarrow n$

NLO results recovered upon expansion of NLO+PS in $\alpha_s$, 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]

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

- method for matching NLO calculation to PS resummation
- ME reweighted PS with local $K$-factor
- NLO event weight $\bar{B} = B + V + I + \int d\Phi_R |_B [R - S]$
  - Born, Real from automated tree-level generators
  - Virtual e.g. via Binoth Les Houches Accord CPC181(2010)1612
  → for results here BLACKHAT & MCFM libraries interfaced
- Integrated/Subtraction terms from automated implementation of Catani-Seymour subtraction terms EPJC53(2008)501
- correct PS to ME via weight $w(\Phi_R) = R(\Phi_R)/R^{(\text{PS})}(\Phi_R)$
  → alleviated by good approximation of CSSHOWER++ JHEP03(2008)038
- POWHEG Sudakov $\Delta^{(\text{ME})}(t) = \exp \left[ - \sum \int_t^\infty d\Phi_R |_B \frac{R(\Phi_R)}{B(\Phi_B)} \right]$
  ⇒ preserves both NLO and LL accuracy
\[ \langle O \rangle = \int d\Phi_B \bar{B}(\Phi_B) \left[ \Delta^{(\text{ME})}(t_0) O(\Phi_B) \right. \\
\left. + \int d\Phi_R|_B \frac{R(\Phi_R)}{B(\Phi_B)} \Delta^{(\text{ME})}(t) \Theta(Q_{\text{cut}} - Q) O(\Phi_R) \right. \\
\left. + \int d\Phi_R|_B \frac{R(\Phi_R)}{B(\Phi_B)} \Delta^{(\text{PS})}(t) \Theta(Q - Q_{\text{cut}}) O(\Phi_R) \right] \\
\]

- **POWHEG domain** restricted to soft emissions \( Q < Q_{\text{cut}} \) \\
  \( \Rightarrow \) **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


[SLIDE FROM MAREK SCHÖNHERR]

\[ p\bar{p} \rightarrow \ell^+\ell^- + X \]


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?
- carefully investigated by CDF ➔ no issues

NLO effects?
- 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 $Z \rightarrow \tau \tau +$ jet to the CDF analysis’ final state.
  - Effect of scale variations on W+2jet shapes of ME+PS Sherpa samples.
### Production of $e^+X$ : mass $(j_1 j_2)$ (excl)

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|-------------|</p>
<table>
<thead>
<tr>
<th>Events/8 (1/GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full EW + jet (ME+PS)</td>
</tr>
<tr>
<td>Diboson WW+WZ (PS)</td>
</tr>
<tr>
<td>$Z \to \text{tau tau} + \text{jet}$ (ME+PS)</td>
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</tbody>
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### Production of $e^+X : \Delta R (j_1, j_2)$ (excl)

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<table>
<thead>
<tr>
<th>Events/0.2</th>
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<tbody>
<tr>
<td>Full EW + jet (ME+PS)</td>
</tr>
<tr>
<td>Diboson WW+WZ (PS)</td>
</tr>
<tr>
<td>$Z \to \text{tau tau} + \text{jet}$ (ME+PS)</td>
</tr>
</tbody>
</table>

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**Tevatron Run 2**

**SHERPA**

**preliminary**
Production of $e^+X$ : mass ($j_1j_2$) (excl)
Application of ME+PS – W+jets @ LHC 7 TeV

Sherpa predictions for $(W\rightarrow)e\bar{\nu}$ + 2 jets at parton-shower level

**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.

⇒ 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.

⇒ Sherpa’s new scheme is ME&TS. (Also in Herwig++. ) Reduced systematic uncertainties.

Beyond ME+PS/ME&TS: combine NLO+PS consistently ⇒ 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.

⇒ 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.