Merging MEs and the parton shower with SHERPA

[ILC Workshop Valencia 2006]

Jan Winter [a]

CERN PH TH *and* Institute for Theoretical Physics, TU Dresden

- **Challenge: appropriate treatment of multijets**
- **CKKW method overview**
- **Survey of application examples**
- **Current developments**

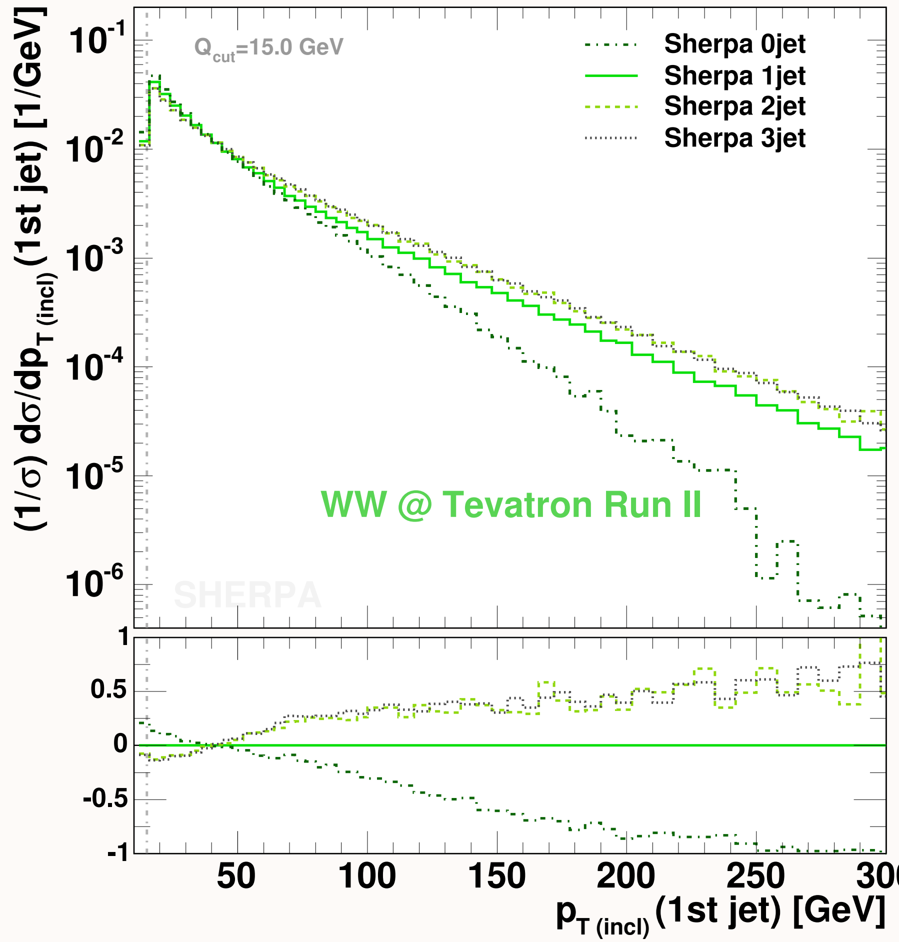
[a] SHERPA authors: T. Gleisberg, S. Höche, F. Krauss, F. Siegert, S. Schumann, J. W.

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

Challenge – multijet production

... at future hadron *and* **linear collider experiments.**

- LHC: tremendously large phase space for QCD radiation
- is a QCD machine ⇒ **Multijets**
- ILC: goes for high precision
- of course not free of strong interactions
- hadronic decay channels of weak bosons
- top pairs, SUSY particles and decay chains



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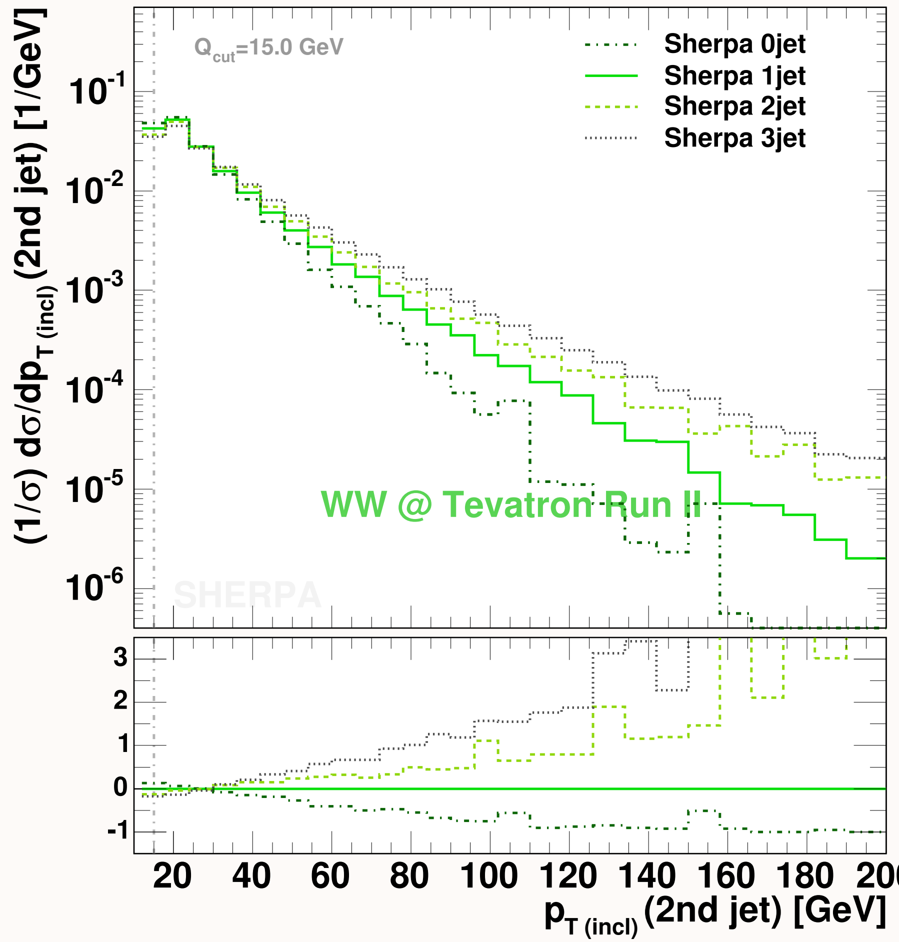

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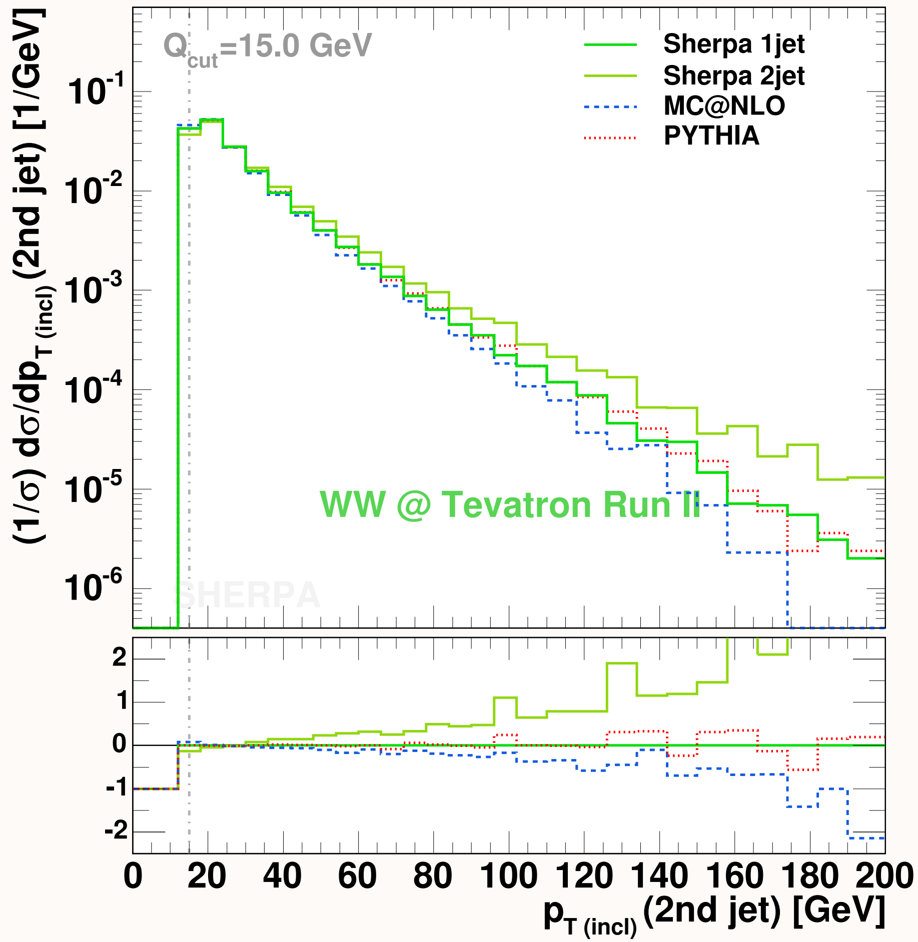

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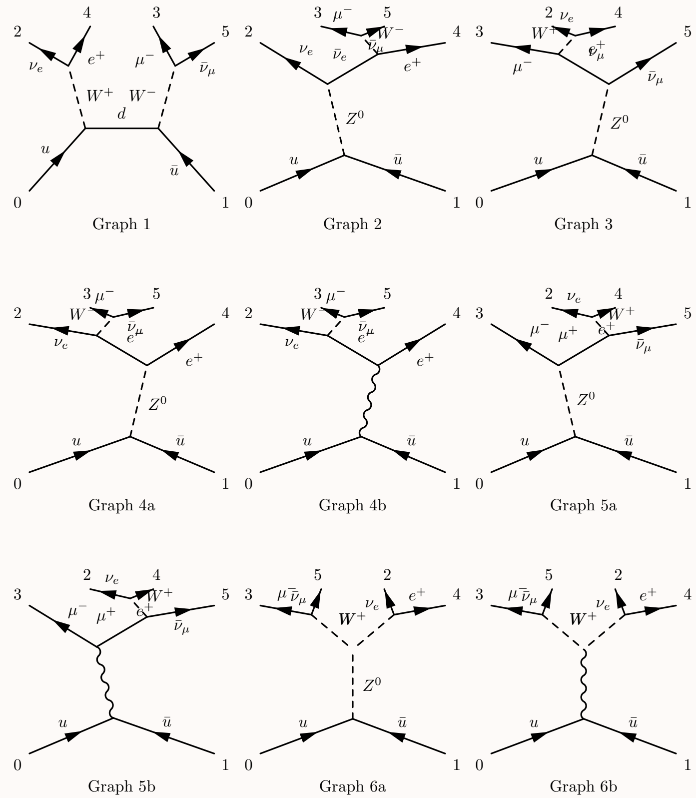
Model...!!! **Jet production** ⇨ **Jet evolution** ⇨ **Hadronization**

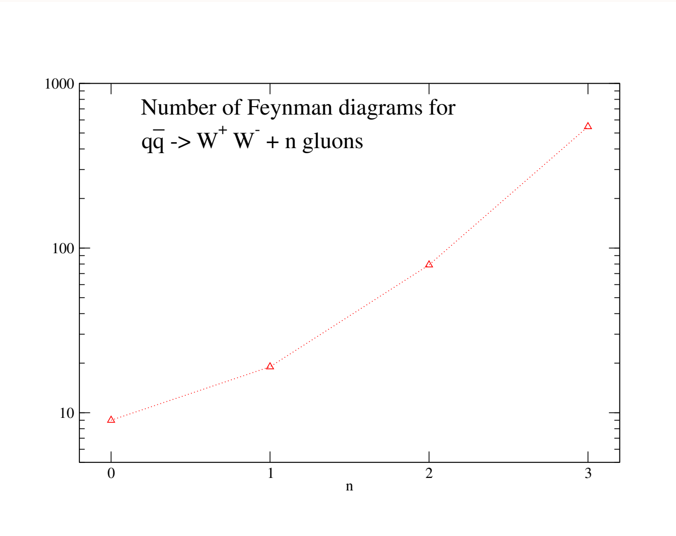
SHERPA: AMEGIC++'s MEs ⇦ **CKKW** ⇨ **APACIC++ Shower** ⇨

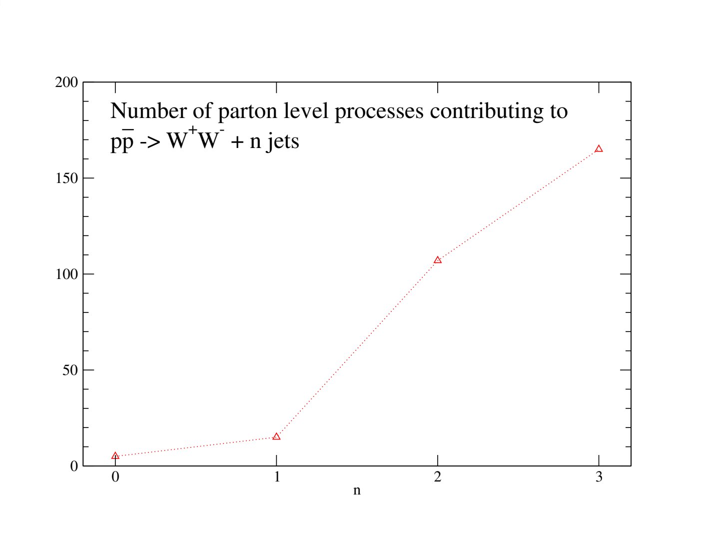
SHERPA: ⇨ **PYTHIA (phenomenological) Models**

Multiparton MEs

- ✓ exact at some fixed order (FO) in the coupling
- ✓ quantum interferences & spin correlations & mass/offshell effects
- ✓ exact phase space filling: correct high energetic/wide angle configurations
- ✗ factorial growth of calculational work
  complicated phase-space structures
  lack of bulk of radiation: multiple soft/coll emissions







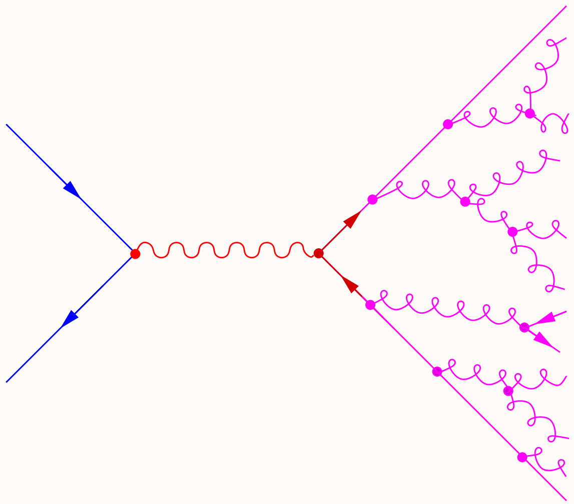
Parton showers (PSs)

- annihilation vs. hadronization time: $t_{ann} \approx 1/Q \quad : \quad t_{had} \approx QR^2$
  - typical hadron size: $R \approx 0.01\ \mathrm{MeV}^{-1}$
  - $50\ \mathrm{GeV}$ quark: $t_{ann} \approx 0.02\ \mathrm{GeV}^{-1} \ll t_{had} \approx 5 \cdot 10^3\ \mathrm{GeV}^{-1}$

✓ free colour particle radiates partons perturbatively

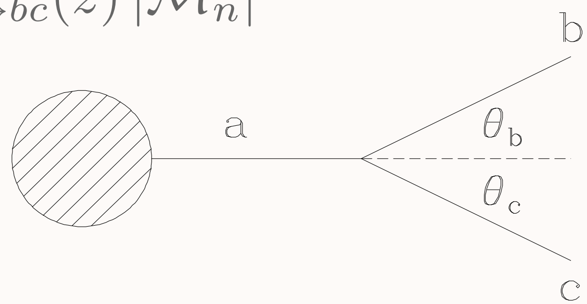
✓ mainly in the coll/soft limit: AO resummation/LL exponentiation ⇒ tower of logs

$$\mathcal{O} = \sum r_n \alpha_S^n \quad \Rightarrow \quad \mathcal{O} = \sum c_n \alpha_S^n \log^{2n}(q/q_0) + \mathrm{NLL} + \ldots$$



- factorization – recursive definition in collinear limit

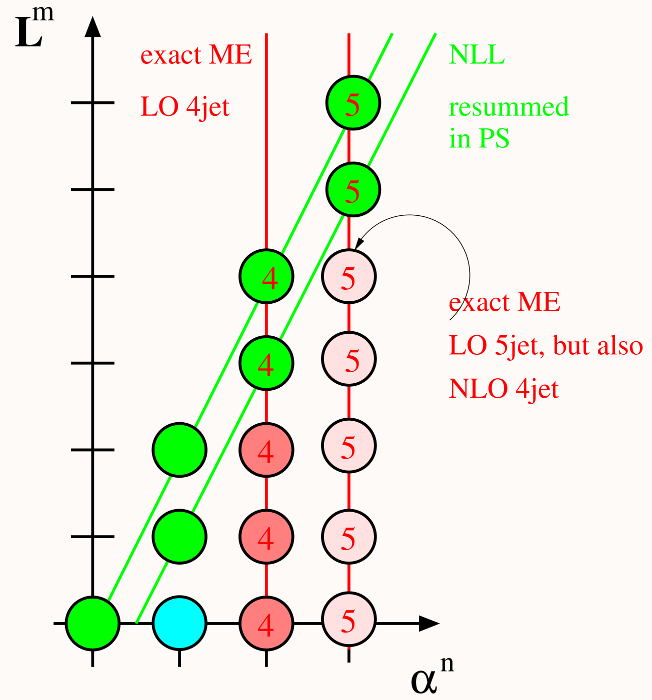
$$|\mathcal{M}_{n+1}|^2 \sim \frac{g^2}{t} C_a^{bc} P_{a\to bc}(z) |\mathcal{M}_n|^2$$



Combine advantages, remove weaknesses.

Beware of double counting, preserve universality of hadronization.

α_S **vs. Log**



Un tour de CKKW: ansatz

Divide multijet phase space into two regimes.

- tree level MEs: jet production above Q_{jet}
- PS: (intra-)jet evolution $Q_{jet} < Q < Q_{\text{cut-off}}$
- regularize MEs through Q_{jet}
- large, unphysical Q_{jet} dependence for fixed multiplicity n, ambiguous phase space

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Use (hadr.) $k_\perp$-measure (IRsafe) to define jets.

$$Q_{ij} = \min(k_{\perp i}^2, k_{\perp j}^2) \cdot R_{ij}^2 \quad \text{and} \quad Q_{iB} = k_{\perp i}^2$$

$$R_{ij}^2 = 2\,[\cosh(\eta_i - \eta_j) - \cos(\phi_i - \phi_j)]$$

- Backward clustering.
- Initial conditions for shower.

Un tour de CKKW: reweighting

Eliminate/sizeably reduce Q_{jet} dependence.

- reweight MEs by combined coupling and Sudakov weight
- Veto PS configurations already included through higher order MEs

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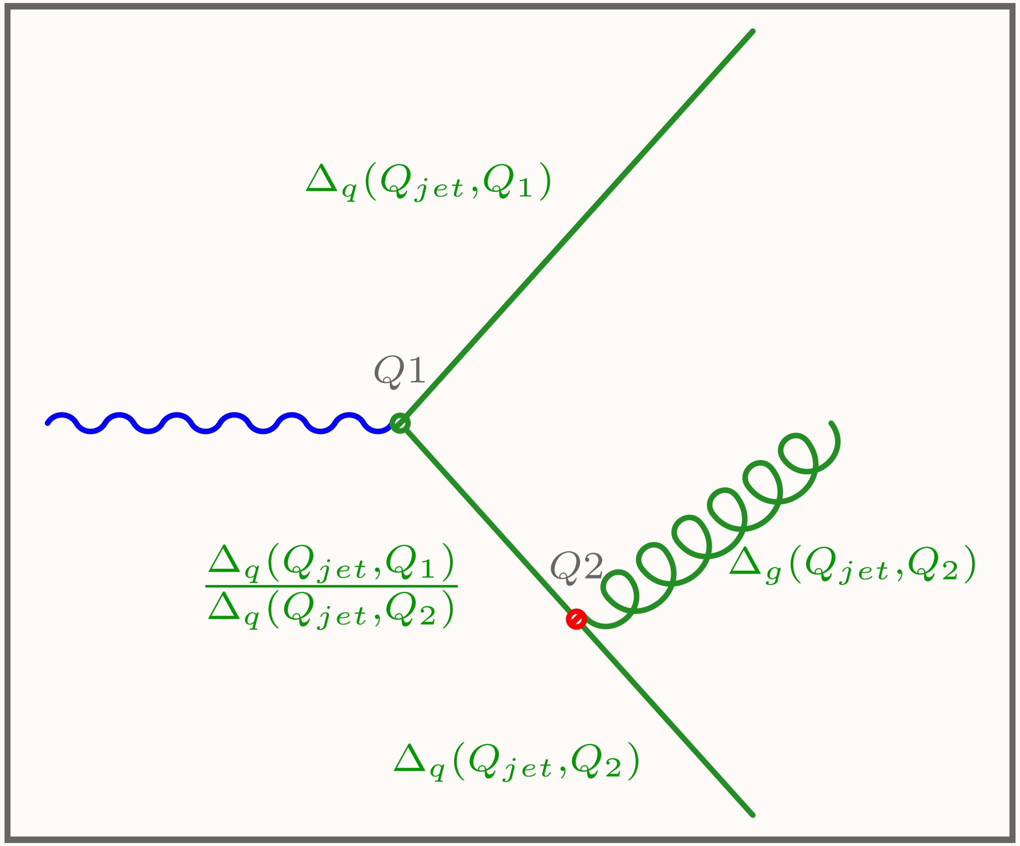


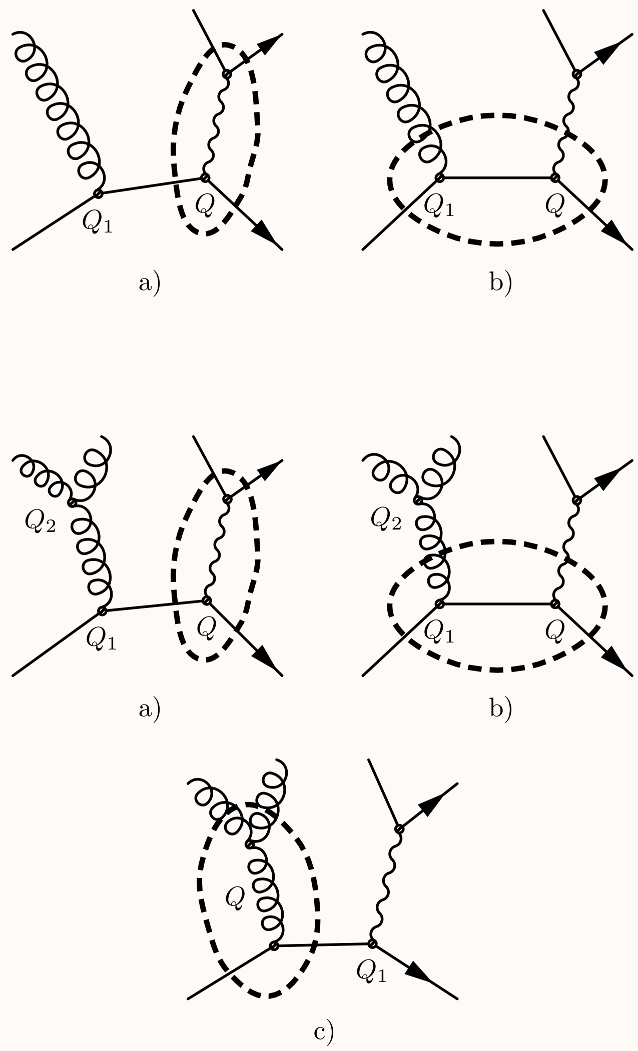
$$W = \Delta_g(Q_{jet},Q_2)[\Delta_q(Q_{jet},Q_1)]^2 \frac{\alpha_s(Q_2)}{\alpha_s(Q_{jet})}$$

- recall: Sudakov form factor

$$\Delta_a(t,t_0) = \exp\left\{-\int_{t_0}^{t}\frac{dt'}{t'}\int_{z_-}^{z_+} dz \frac{\alpha_s}{2\pi} P_{a\to bc}(z)\right\}$$

→ no-emission probability

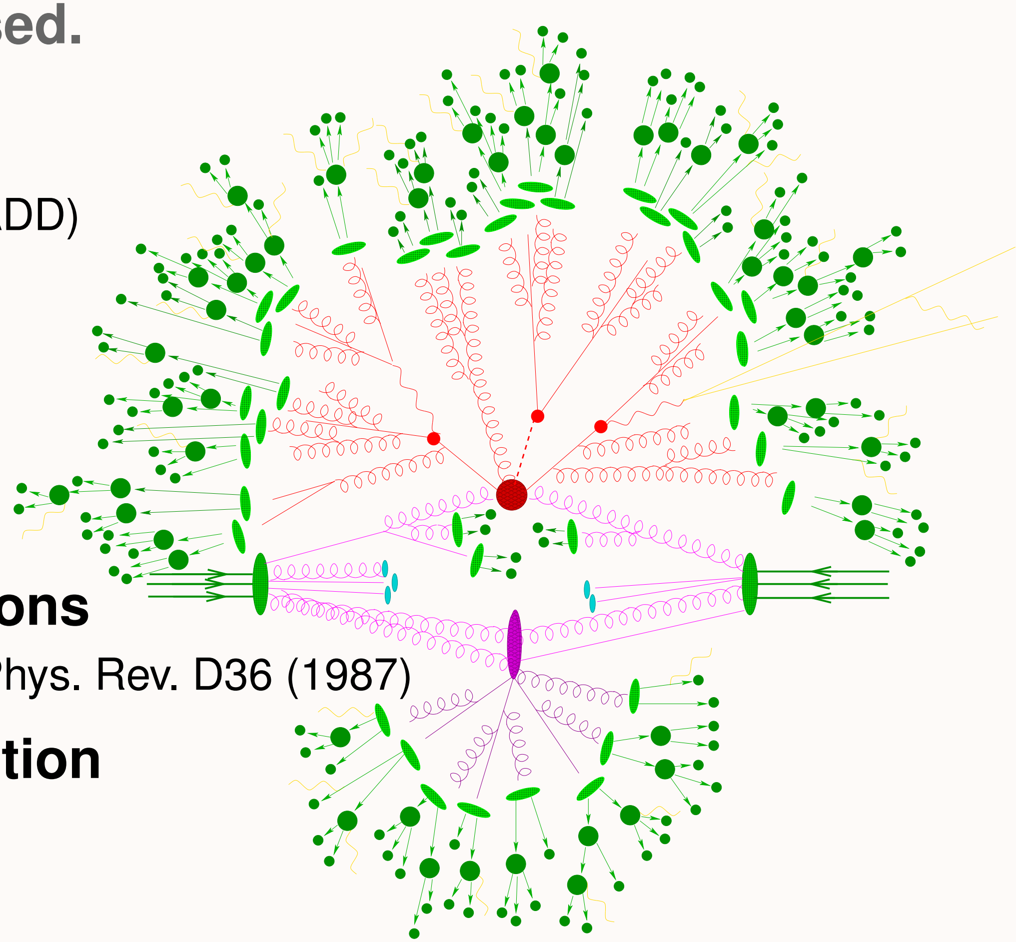
Un tour de CKKW: create inclusive sample



- exclusive samples at given resolution scale Q_{jet}
- inclusive sample by adding them up + highest multiplicity treatment for $n_{\max}$ ME

What is SHERPA

T. Gleisberg, S. Höche, F. Krauss, A. Schälicke, S. Schumann and J. W., JHEP **0402** 056 (2004).



- **SHERPA version 1.0.8 has been released.**

- **ME generator AMEGIC++**
  (at tree level, provides HP and HD in SM, MSSM, ADD)
- **IS and FS shower module APACIC++**
  (virtuality ordered, PYTHIA-like showers)
- **Combination of ME and PS according to CKKW**
- **Simulation of multiple parton interactions**
  main ideas based on T. Sjöstrand and M. van Zijl, Phys. Rev. D36 (1987)
- **Interface to PYTHIA's string hadronization**
- **Interface to PYTHIA's hadron decays**

Sherpa is the event generation framework:

- initialization of the different phases - interplay of the various stages -
- steering the event generation -

CKKW – key feature of SHERPA

- **Method has been implemented within SHERPA in full generality.**

  S. Catani, F. Krauss, R. Kuhn and B. Webber, JHEP **0111** (2001) 063

  F. Krauss, JHEP **0208** (2002) 015

- **Process-independent implementation.**

! **Validation**

- **W/Z+jets @ Tevatron/LHC**

  F. Krauss, A. Schälicke, S. Schumann,

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- **WW production @ Tevatron**

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- **ongoing: detailed comparison to ARIADNE & MLM merging**

  1st results in "HERA and the LHC" proceedings

- **ongoing: pure jets, $Zb\bar{b}+X$, $gg \to H+X$, VBF**

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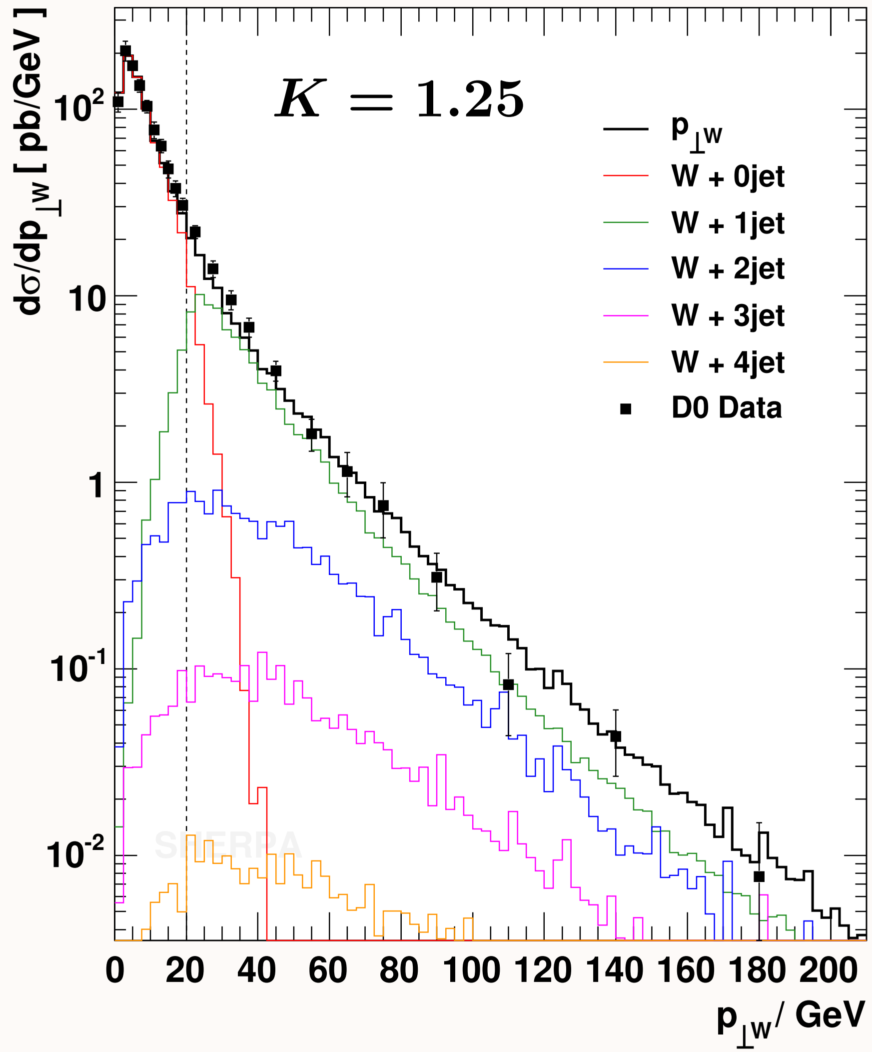

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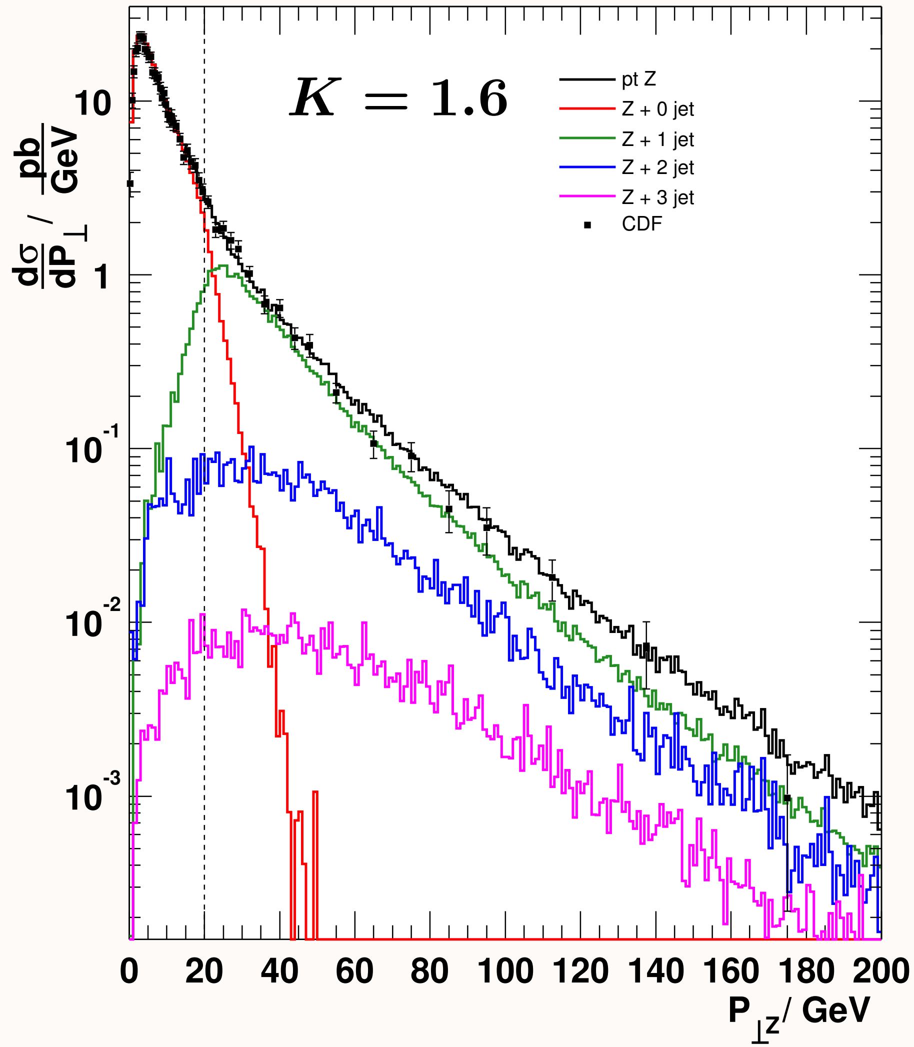

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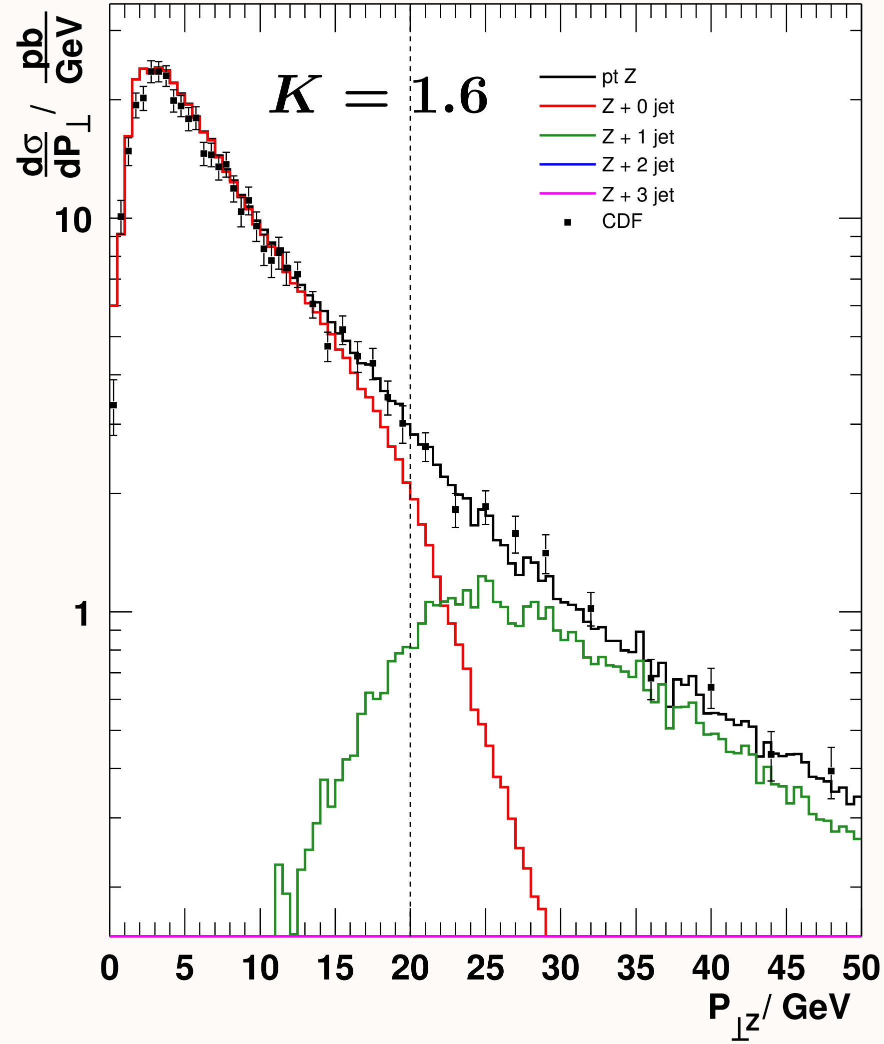

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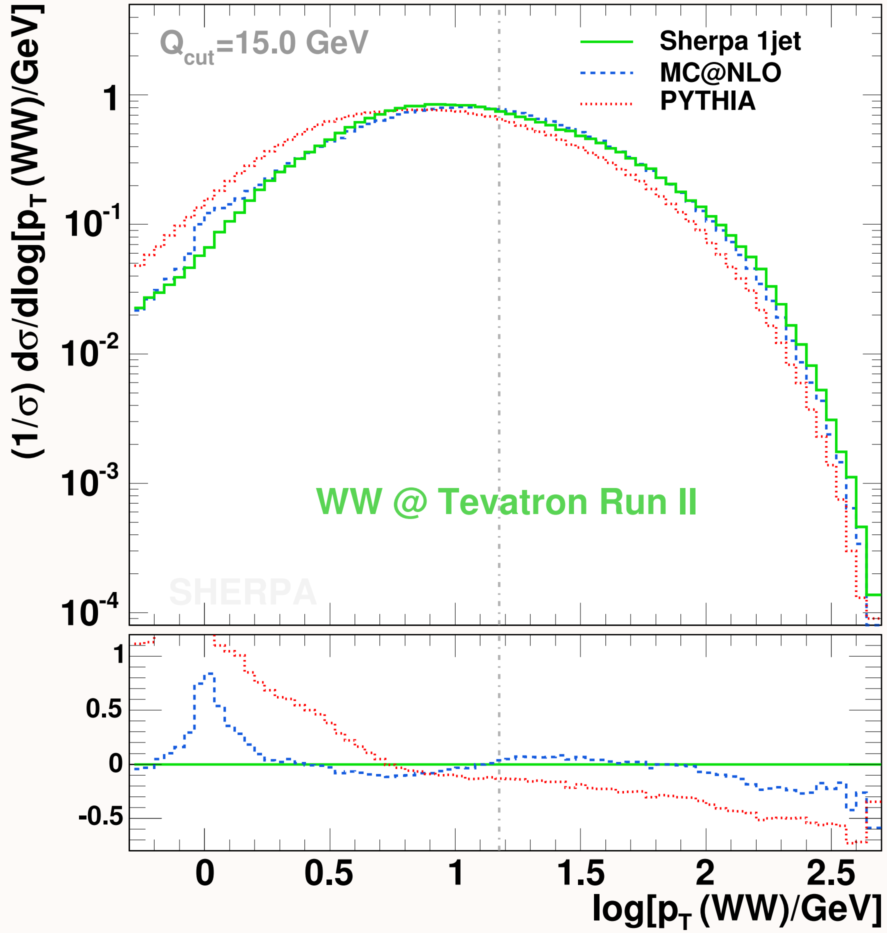
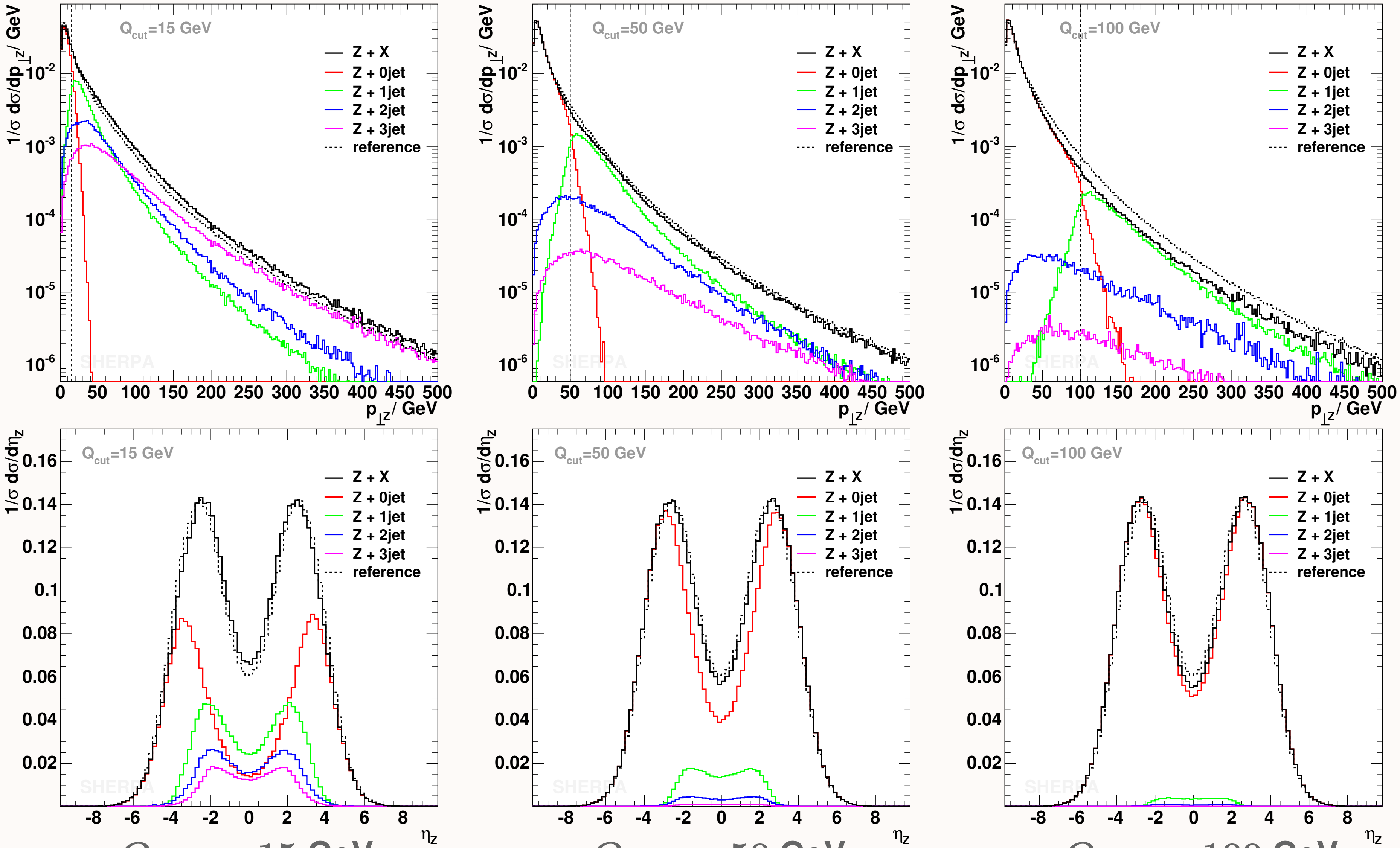


Vary jet separation cut ... $pp \longrightarrow e^+e^- + X$ @ LHC

$p_{\perp,Z}$

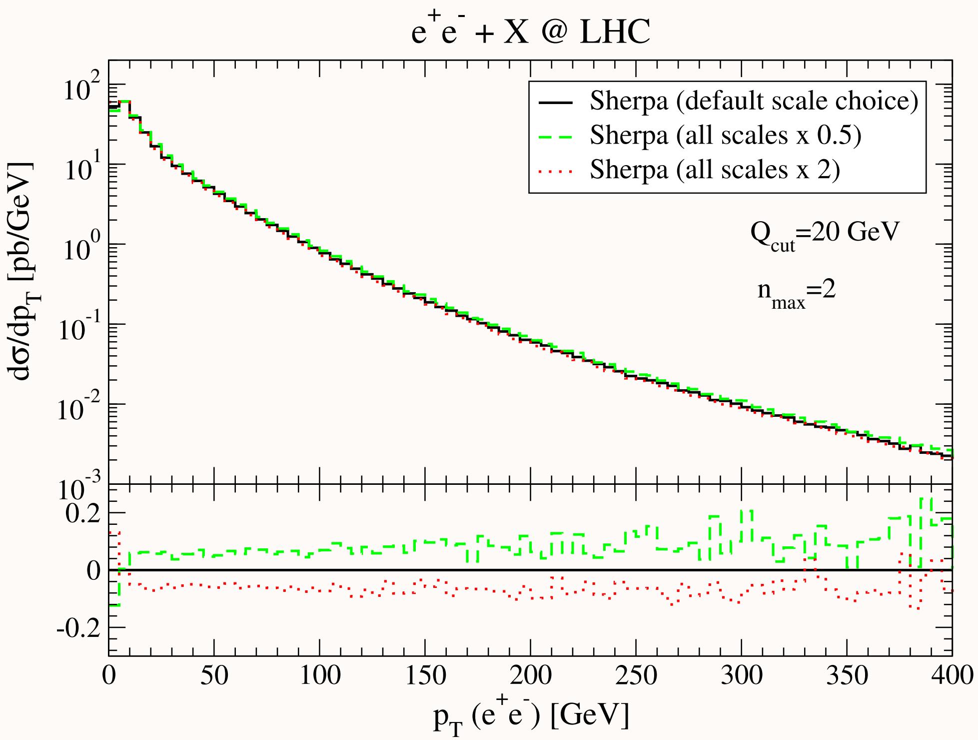
η_Z

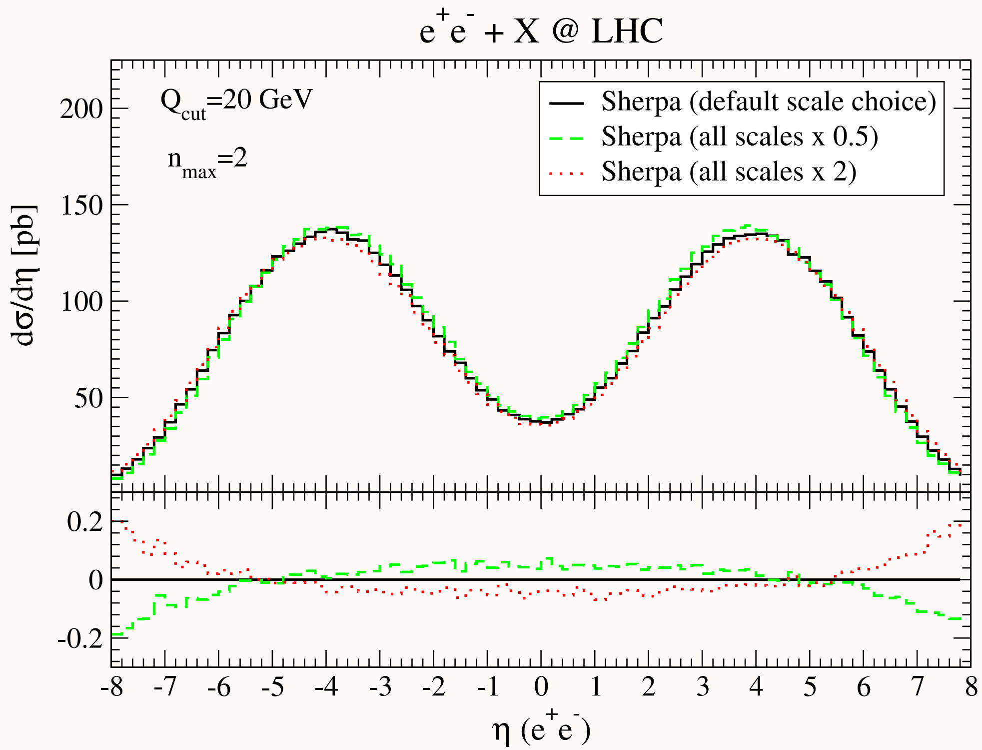


Q_{cut} = 15 GeV Q_{cut} = 50 GeV Q_{cut} = 100 GeV

- Strongly Q_{cut}-dep. subprocesses cooperate so that total result is decently stable.
- Residual dependence can be used to tune to a candle process.

Vary scales ... μ_R and μ_F



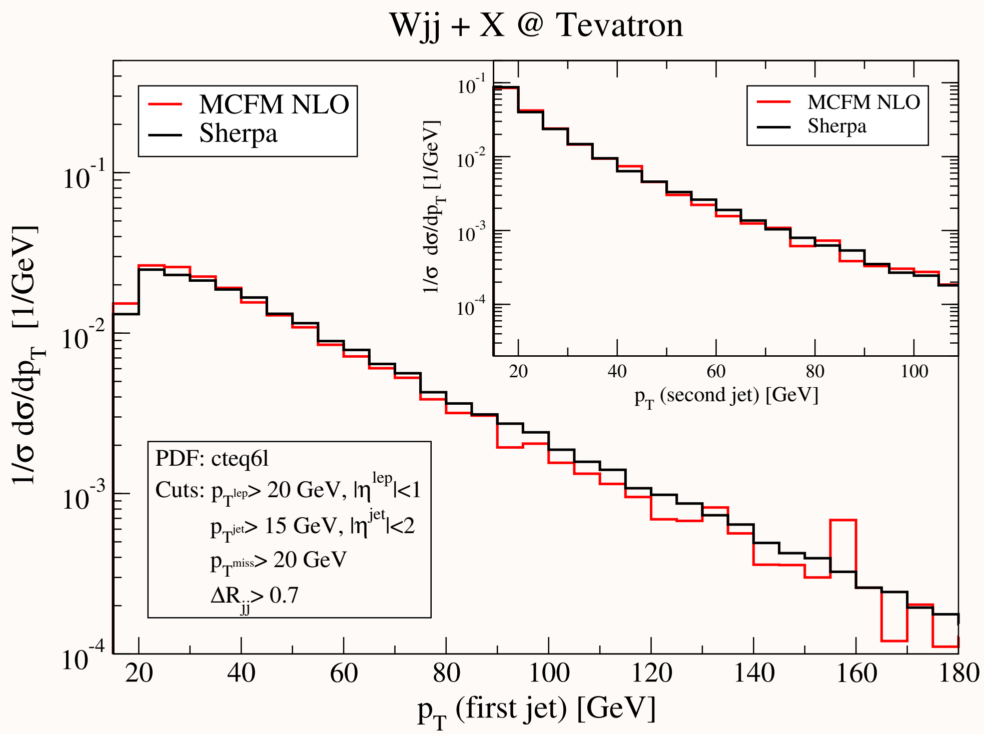


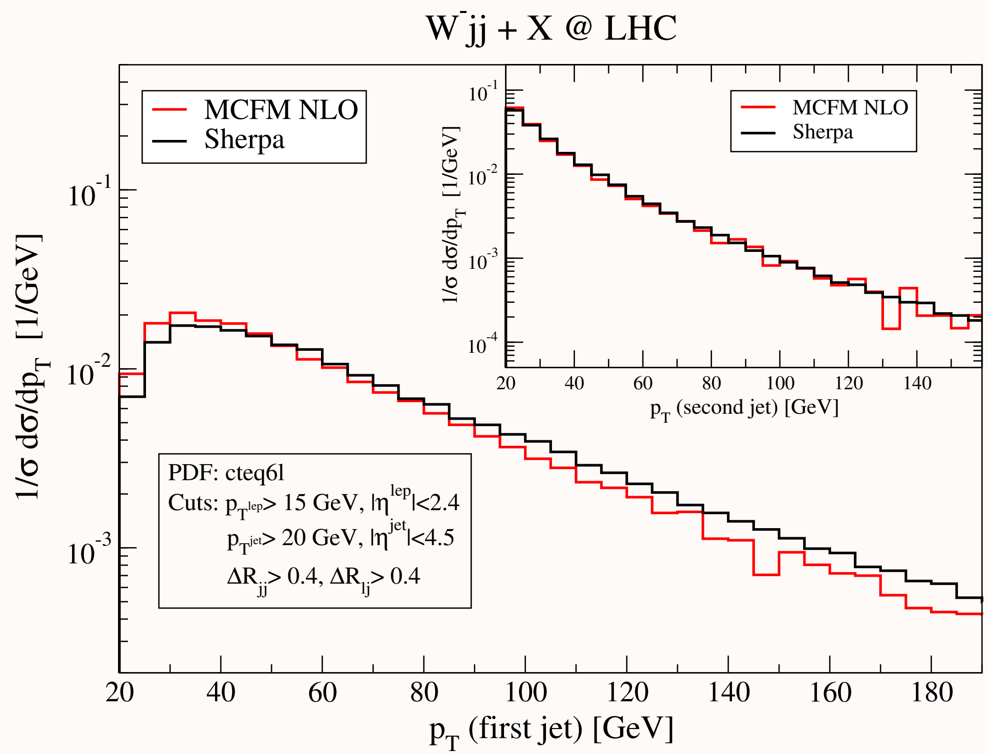
➡ On the $\pm 20\%$ level only. Much better than pure LO.

What about shapes: inclusive Wjj @ Tevatron/LHC

J. Campbell, R.K. Ellis, D.L. Rainwater, Phys. Rev. D **68** (2003) 094021

- MCFM @ parton level *vs.* SHERPA @ shower level.



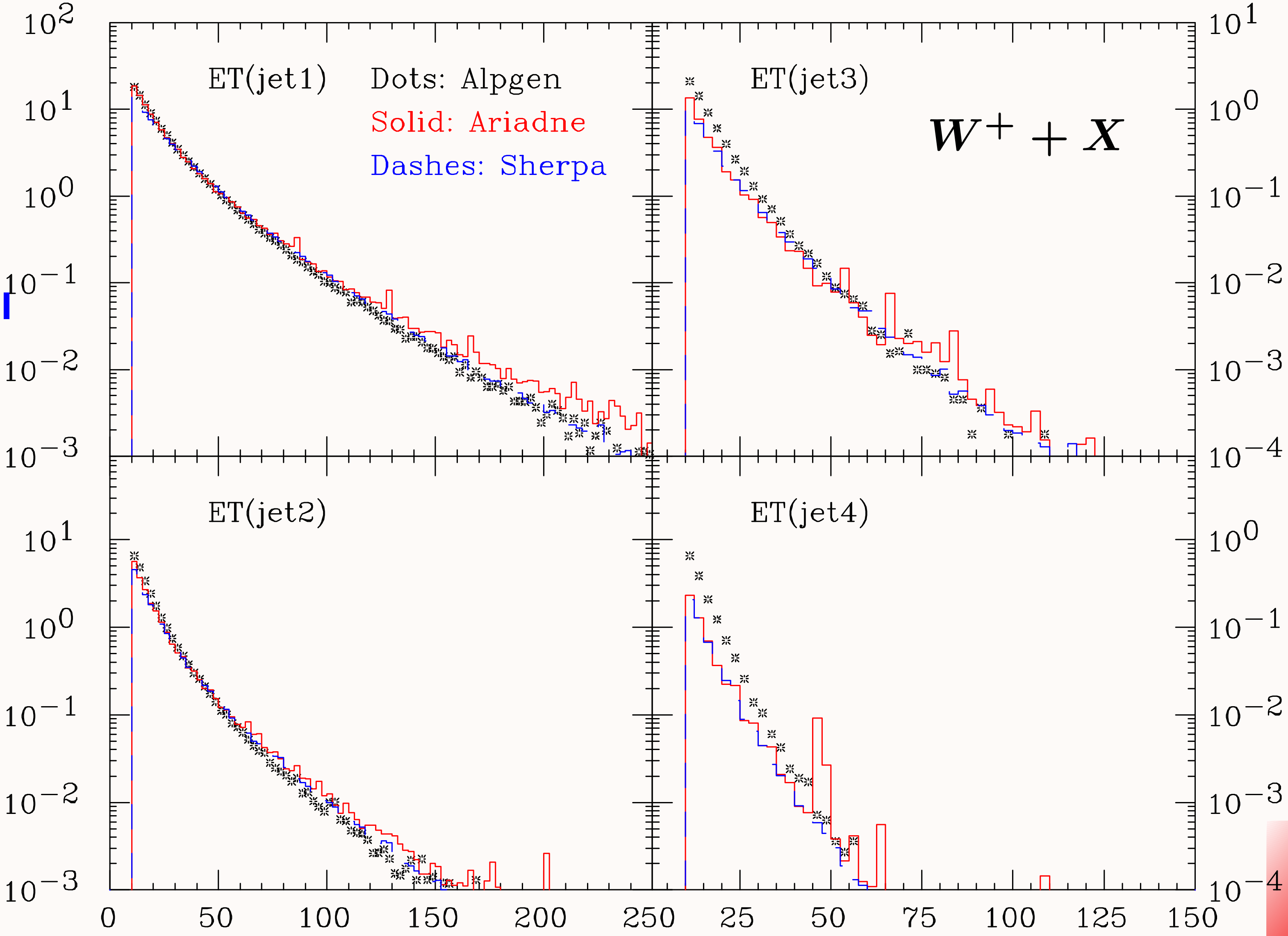


- Shapes in fairly good agreement. **!**Rates not NLO. Improved LO+LL prediction.
- Solid support that constant K-factors may be sufficient.

Comparison between merging approaches, ...

- the MLM, LL and SHERPA ME-PS-merging, has started: **hep-ph/0602031.**

- E_T jet spectra at Run II
  Alpgen $\mu_R \times 0.5$



Comparison between merging approaches, ...

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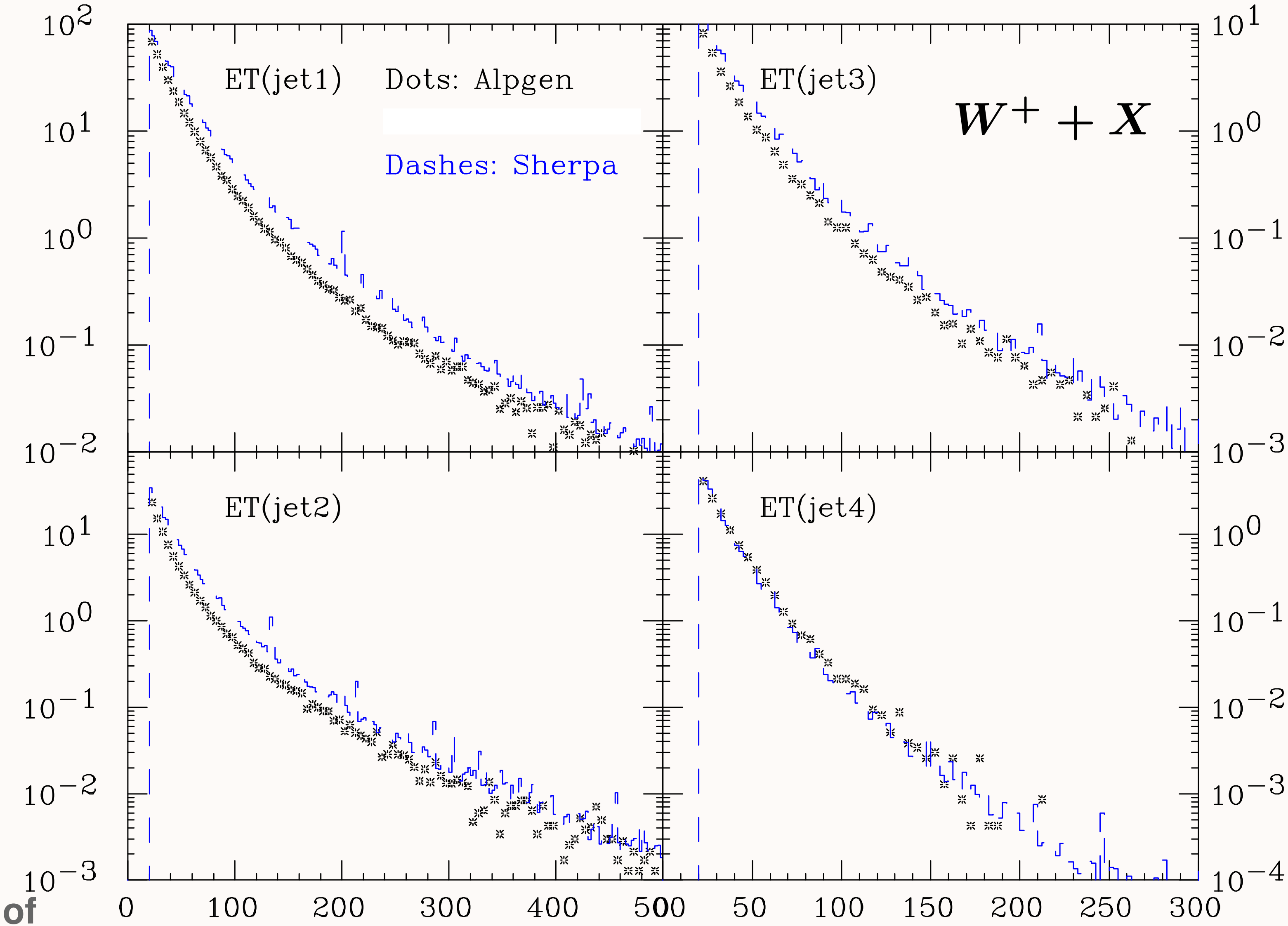
- E_T jet spectra at the LHC

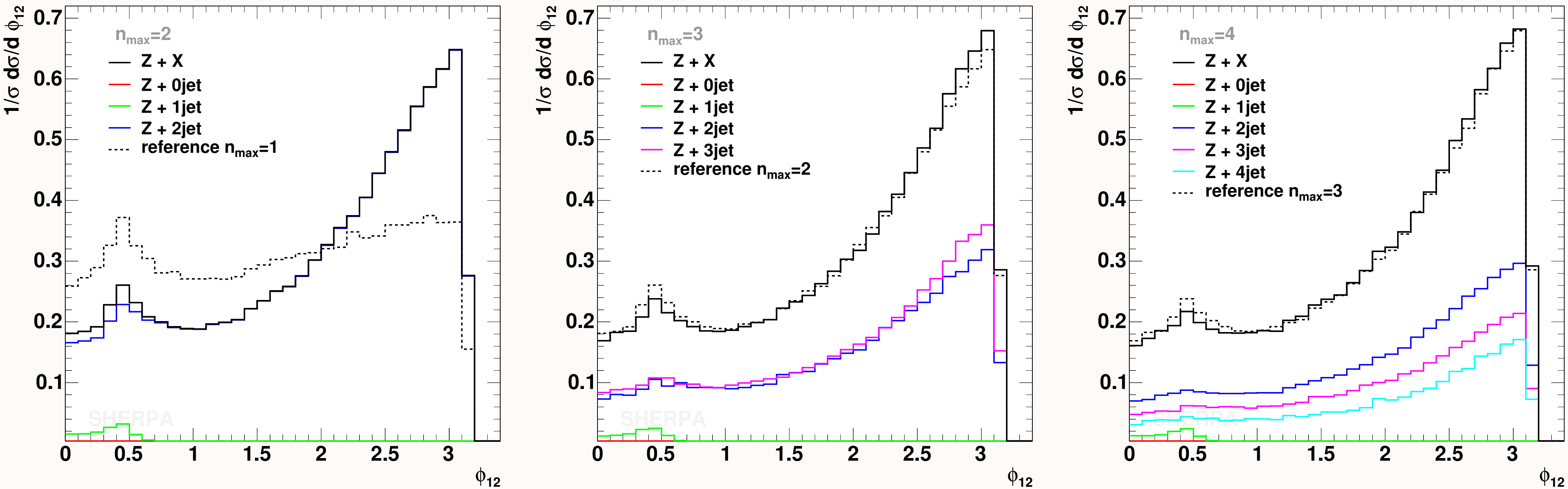


- similar pattern wrt Tevatron
- once tuned to Tevatron data, same extrapolation to LHC can be expected
- exploring differences of merging approaches is essential to assess systematic uncertainties of multijet calculations

Correlations ... $Z/\gamma^* + X$ @ LHC

F. Krauss, A. Schälicke, S. Schumann, Phys. Rev. D **72** (2005) 054017

- $\Delta\Phi$ (azimuthal) separation of the two leading jets.



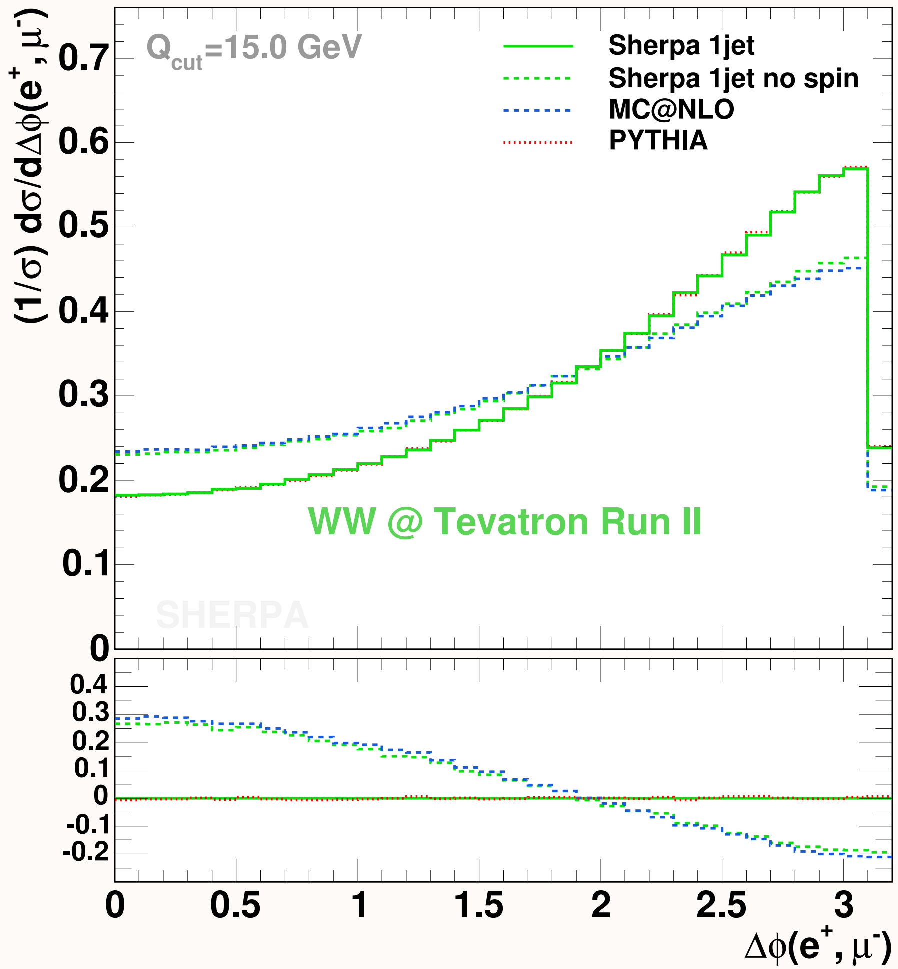
$n_{\max} = 2$ $n_{\max} = 3$ $n_{\max} = 4$

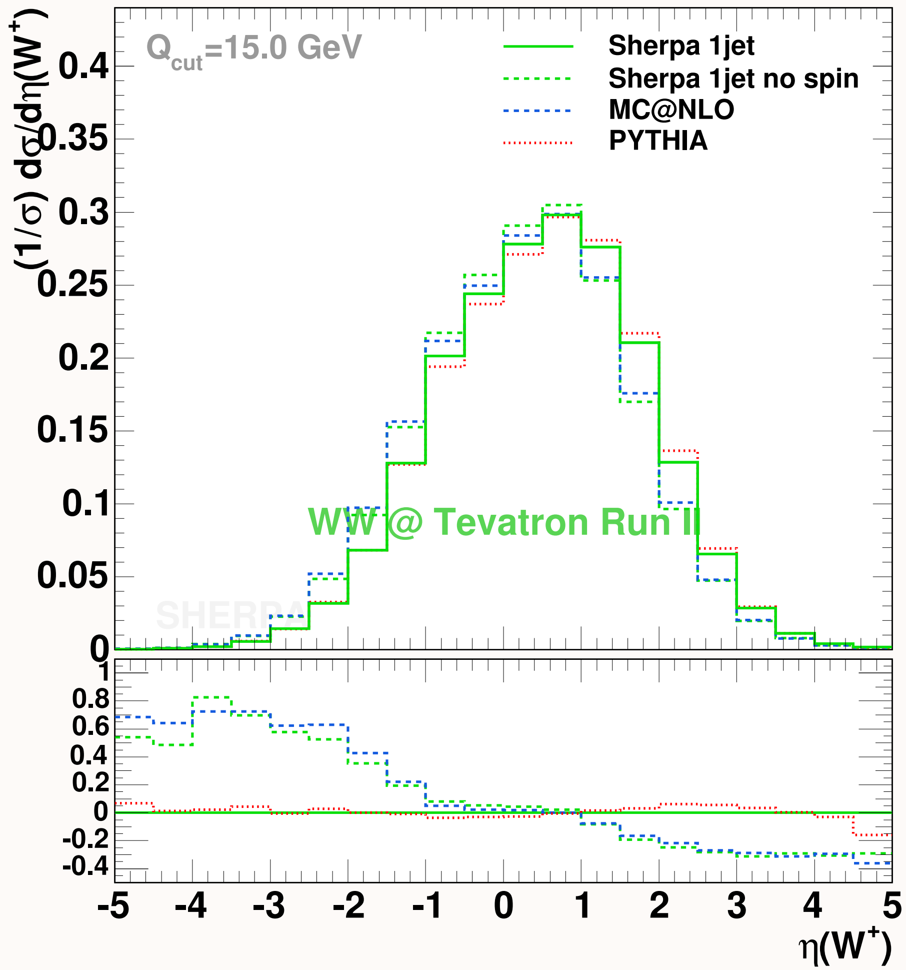
- Dependence on maximal number of MEs included.
- Reference is $n'_{\max} = n_{\max} - 1$ (dashed curve).

Spin correlations ... WW production

T. Gleisberg et al., Phys. Rev. D **72** (2005) 034028

- Exact treatment of spin correlations is an issue.



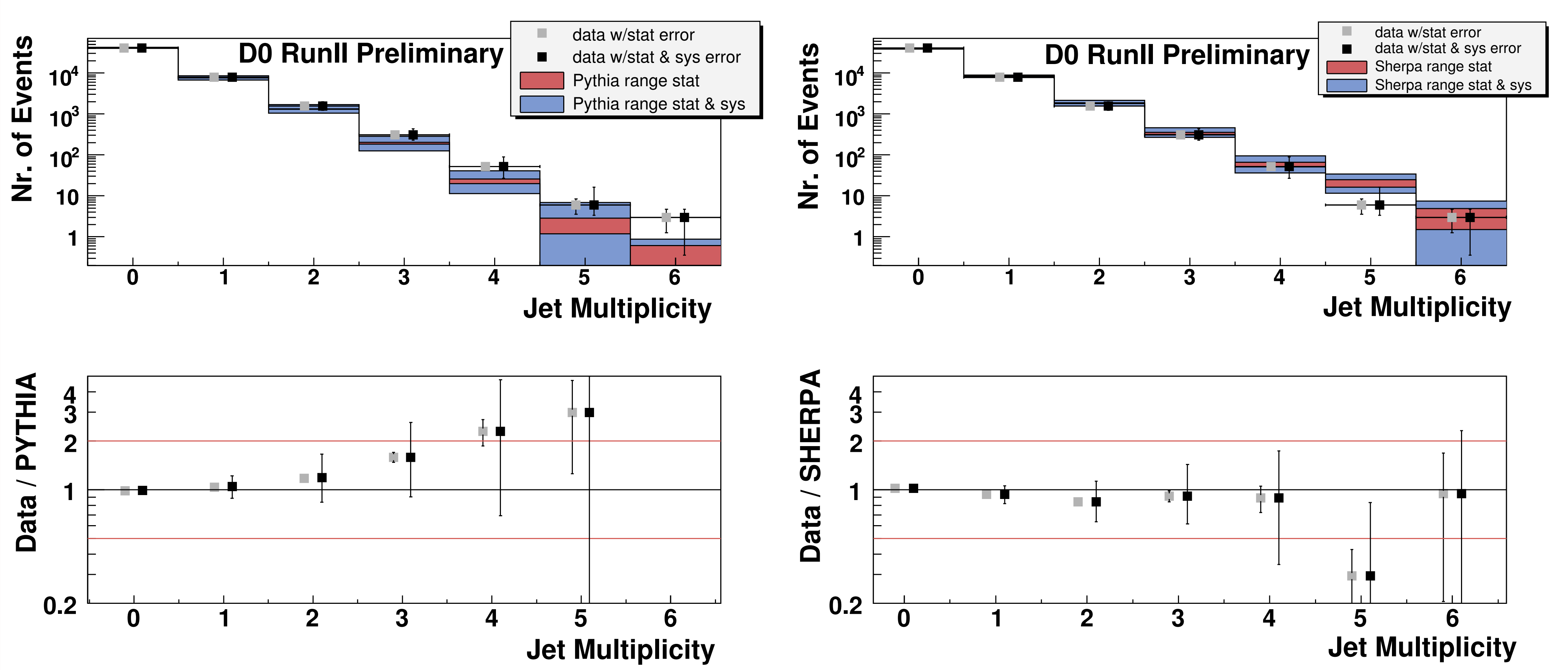


- Cuts on lepton observables can influence secondary observables.

Preliminary DØ results in Z+jet-production

H. Nilsen, DØ collaboration, DØ note 5066-CONF

➡ Jet multiplicity, data vs. PYTHIA (left) and SHERPA (right).



- MC predictions are normalized to total number of events observed in data.
- large systematic uncertainties arise from low p_T jets $\Rightarrow$ both predictions are in agreement with data.

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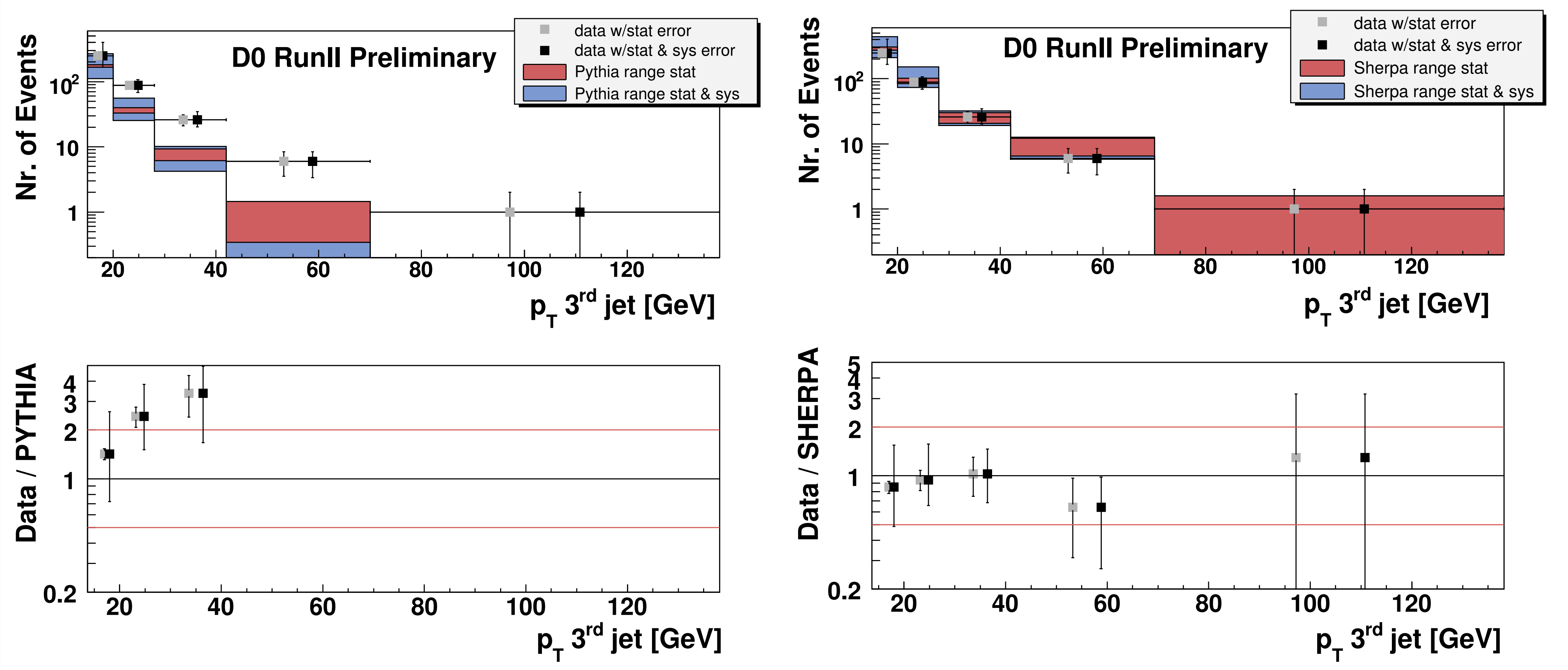
The DØ collaboration, DØ note 5066-CONF

➡ Jet spectra: 3rd jet, data vs. PYTHIA (left) and SHERPA (right).



- PYTHIA: clear, positive slope in the ratio; lack of hard jets.

Current developments

- **Ongoing CKKW projects (validations):**
  - pure jets, $Zb\bar{b}+X$, $gg\to H+X$, VBF
  - more detailed comparison with the MLM and ARIADNE merging approaches
- **Extending the CKKW implementation: production & decay of heavy particles**
  - first key scenario to accomplish: $t\bar{t}$ production and their subsequent decays
  - use narrow width, factorize production and decay
  - provide production and decay showers based on massive splitting functions
  - reweighting and vetoing respecting the factorization
  - idea, e.g.: $e^-e^+\to t\,[\to W^+bg\{1\}]\,\bar{t}\,[\to W^-\bar{b}g\{1\}]\,g\{1\}$
- **Alternative parton shower implementations:**
  - construction of a PS based on Catani–Seymour splitting functions
  - construction of a shower evolution based on QCD colour dipoles
  - intention is to provide variants of CKKW merging with these showers
  - expect to gain a much better understanding of underlying systematic uncertainties

Summary

- **CKKW implementation is the key feature of SHERPA.**
  - A powerful tool for jet physics.
  - Improved (leading-order) description of hard multijet configurations together with jet fragmentation in SM processes.
  - Way of consistently incorporating QCD corrections provided by real-emission MEs.
  - Thanks to the built-in tree-level ME generator AMEGIC++.
  - Fairly process independent implementation.
  - Valuable tool for experimentalists owing to the ability to fully simulate hadron-level events.
- **New developments are on the way.**
  - CKKW for hard decaying massive coloured particles.
  - New shower formulations.