The Sherpa approach of calculating multijet backgrounds.

[Theory seminar @ FNAL]

Jan Winter [a]

- Aim: improved description of multijet final states
- Sherpa at a glance
- CKKW method ... merging tree-level MEs and PSs
- Survey of application examples
- ALPGEN vs. Sherpa studies (see EPJC53 (2008) 473)
- Current developments

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

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

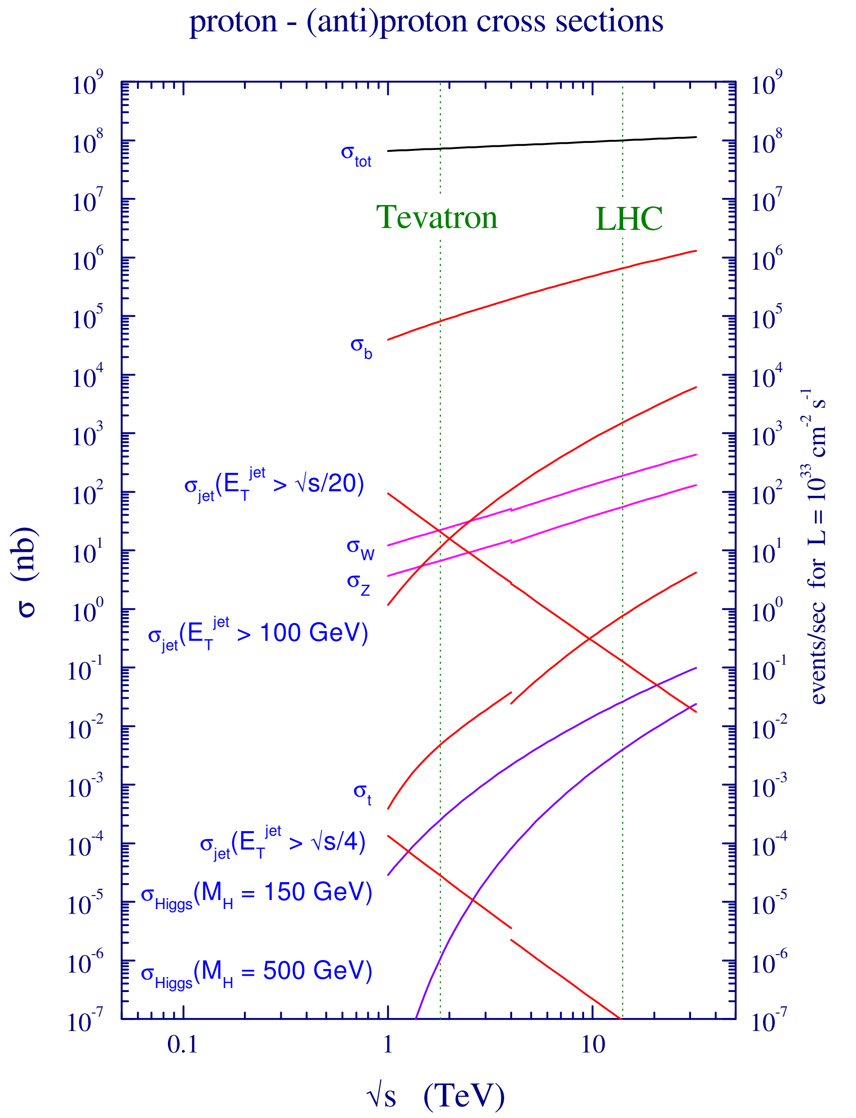
Challenge – Physics at ...

... future (and present) hadron *and* **linear collider experiments.**

- LHC physics: reveal EWSB mechanism, large rates of (B)SM final states
- LHC: is a QCD machine → **Multijets** huge production phase space
- Prior to new physics: need to understand SM physics/backgrounds
- V+jets, VV+jets, $Q\bar{Q}$+jets, single t's
- VBF and g–g fusion, Higgs production
- SUSY particles and decay chains

Today's signals will be tomorrow's backgrounds.

CAMPBELL, HUSTON, STIRLING



Challenge – Physics at ...

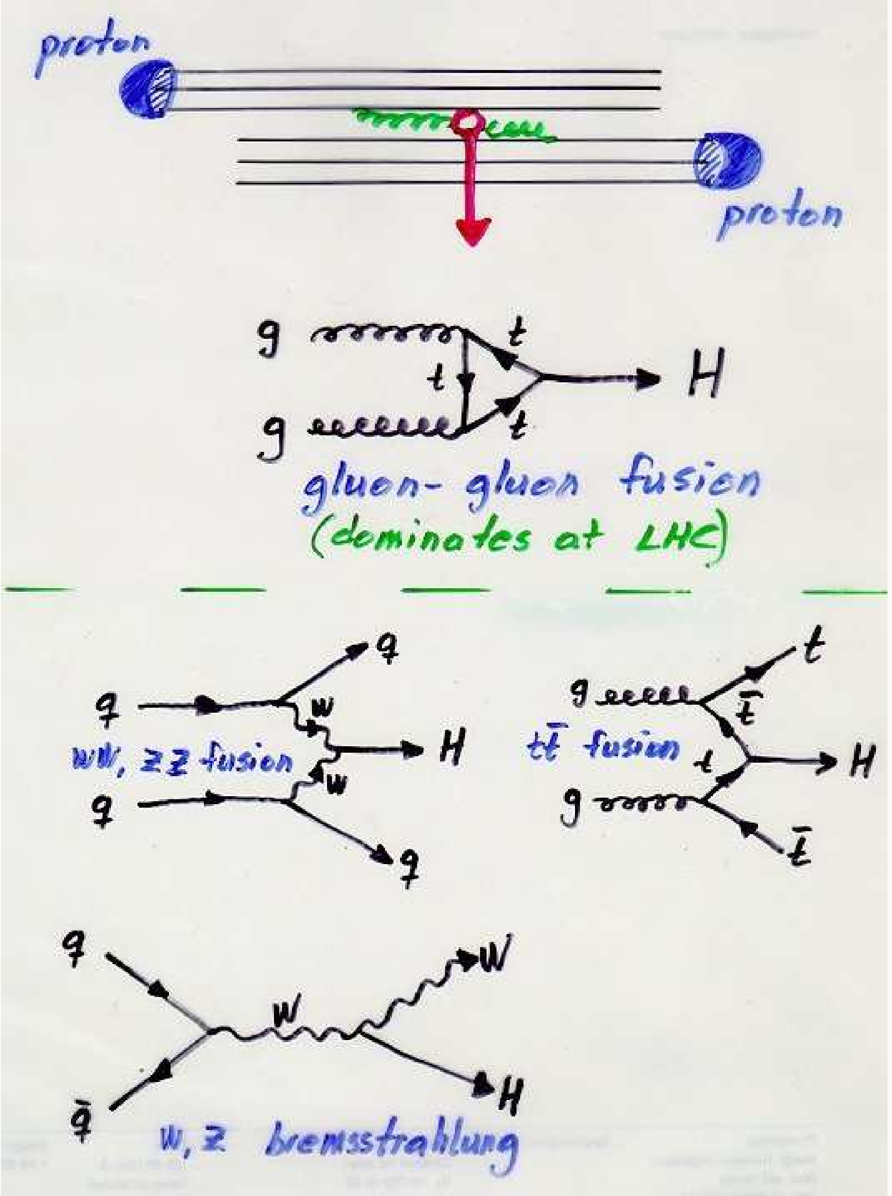
... future (and present) hadron *and* **linear collider experiments.**

- LHC physics: reveal EWSB mechanism, large rates of (B)SM final states
- LHC: is a QCD machine → **Multijets** huge production phase space
- Prior to new physics: need to understand SM physics/backgrounds
- V+jets, VV+jets, $Q\bar{Q}$+jets, single t's
- VBF and g–g fusion, Higgs production
- SUSY particles and decay chains

The signal-to-background puzzle.

E.g. Higgs in weak boson fusion: Nice rapidity gap.

- *Signal/background ratio depends on central jet veto.*
- *Loss of gap structure for higher orders in QCD?*
- *Central jet veto to be modified?*
- *Backgrounds well modelled? Signal spoiled by UE?*



Challenge – Physics at ...

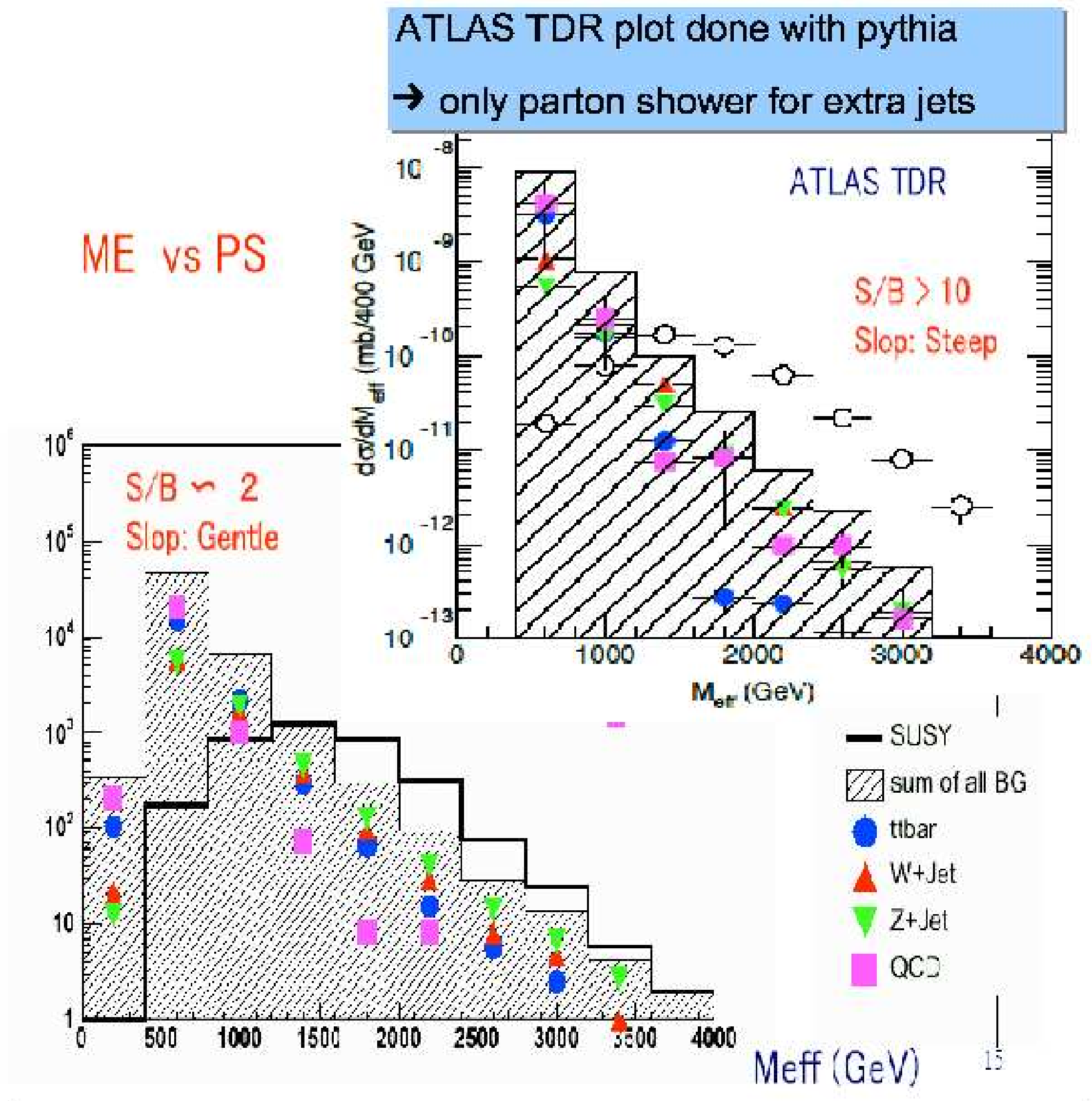
... future (and present) hadron *and* **linear collider experiments.**

- LHC physics: reveal EWSB mechanism.
  large rates of (B)SM final states
- LHC: is a QCD machine → **Multijets**
  huge production phase space
- Prior to new physics: need to understand SM physics/backgrounds
- V+jets, VV+jets, $Q\bar{Q}$+jets, single t's
- VBF and g–g fusion, Higgs production
- SUSY particles and decay chains

The signal-to-background puzzle →

New-physics discovery signalled by enhanced rate of hard events?

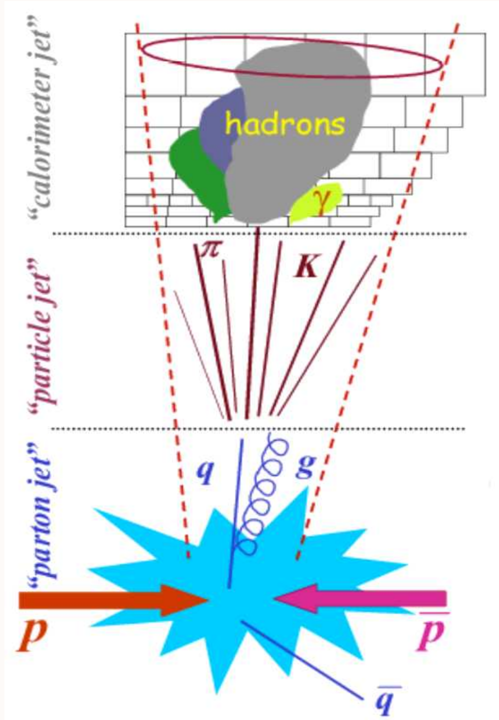
- *Signal: leptons + jets + $\not{E}_T$.*
- *Is SM backround precisely known?*
- *Is it sufficient using PSs only?*
- *Jet properties depend on nature of new physics.*



Challenge – Physics at ...

... future (and present) hadron *and* **linear collider experiments.**

- LHC physics: reveal EWSB mechanism, large rates of (B)SM final states
- LHC: is a QCD machine → **Multijets** huge production phase space
- Prior to new physics: need to understand SM physics/backgrounds
- V+jets, VV+jets, $Q\bar{Q}$+jets, single t's
- VBF and g–g fusion, Higgs production
- SUSY particles and decay chains



Need for tools that model...!!!

Jet production → Jet evolution → Hadronization

Example: jet mass

→ BAUR, ORR

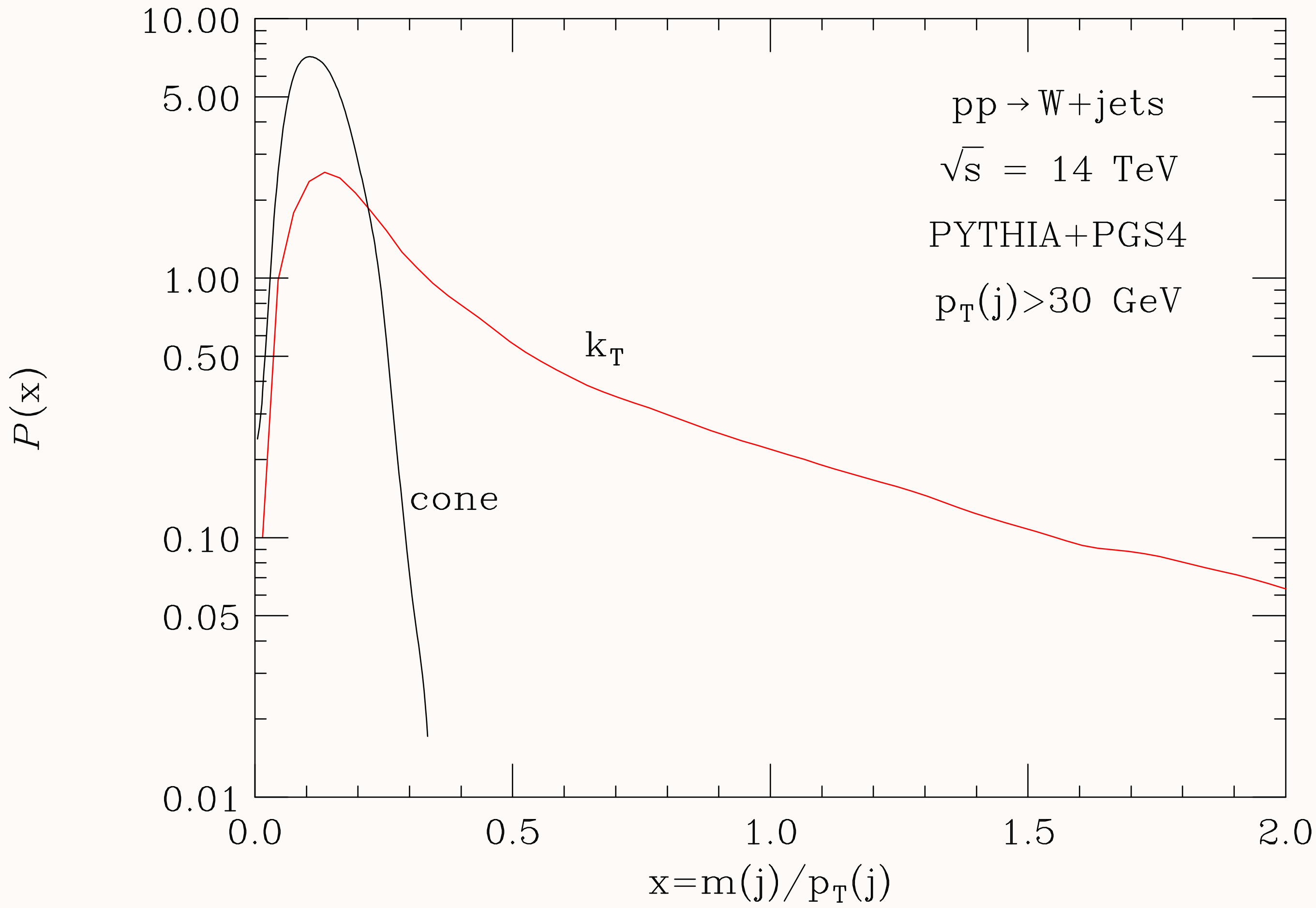
arXiv:0707.2066

- $\langle m^{\rm jet} \rangle \propto \sqrt{\alpha_s}\, p_T^{\rm jet}$, ...

At higher orders light quark and gluon jets acquire a mass which depends on jet algorithm and ΔR separation.

However, non-perturbative QCD effects may significantly contribute.

Before we search for new physics, we want to make sure that detector and reconstruction algorithms operate properly.

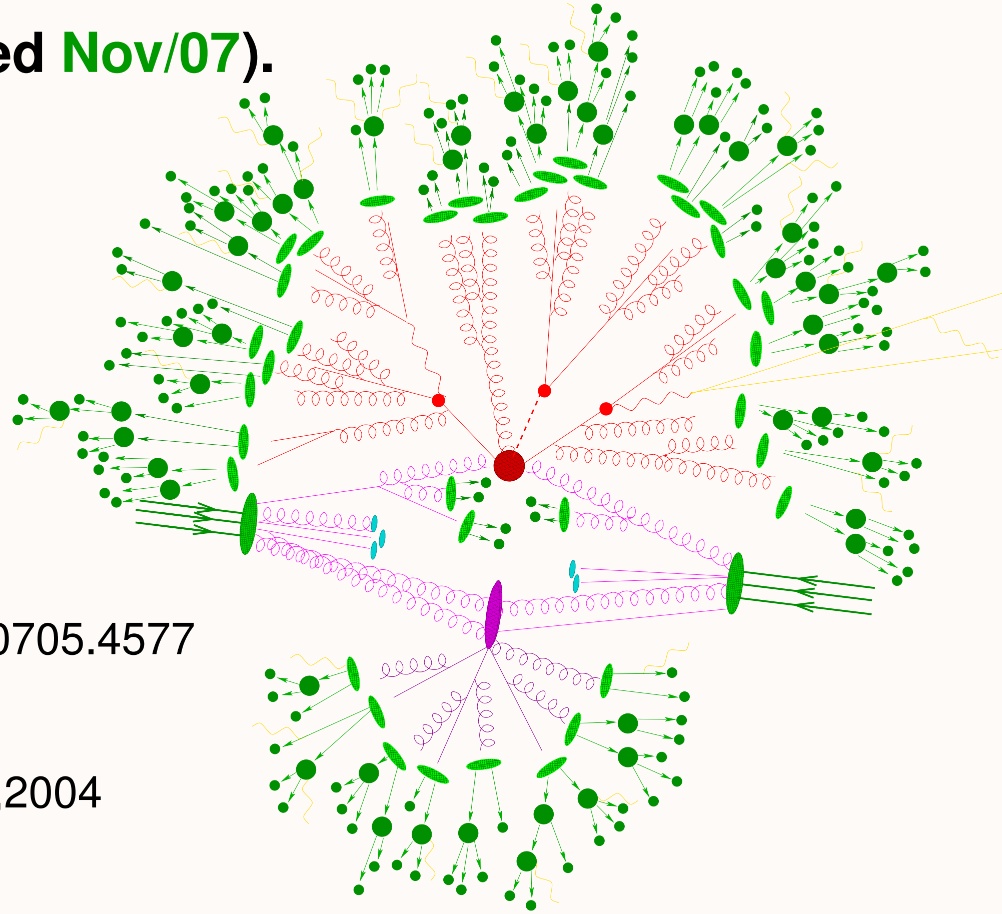


- *Jets are always defined according to some algorithm.*
- *And different algorithms will give different results.*

Monte Carlo event generator Sherpa

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

➡ **Current version: SHERPA 1.0.11 (released Nov/07).**



- **Signal process: AMEGIC++**
  tree-level ME generator for HP in SM, MSSM, ADD
- **IS and FS QCD shower: APACIC++**
  virtuality ordered, Pythia-like showers
- **ME-PS combination according to CKKW**
- **Multiple parton interactions: AMISIC++**
  à la PRD36:2019,1987; **own model** under way arXiv:0705.4577
- **Hadronization:** interface to Pythia's string model;
  own model under way according to EPJC36:381-395,2004
- **Hadron decays:** interface to Pythia's decay tool;
  own comprehensive packages **HADRONS++ PHOTONS++** under way

Sherpa is the event generation framework:

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

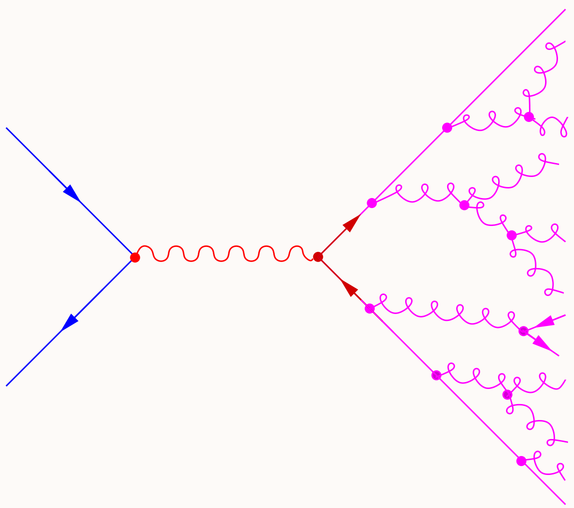
Parton showers (PSs)

✓ free colour particle radiates partons perturbatively

- 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: $t_{ann} \approx 0.02\ \mathrm{GeV}^{-1} \ll t_{had} \approx 5 \cdot 10^3\ \mathrm{GeV}^{-1}$

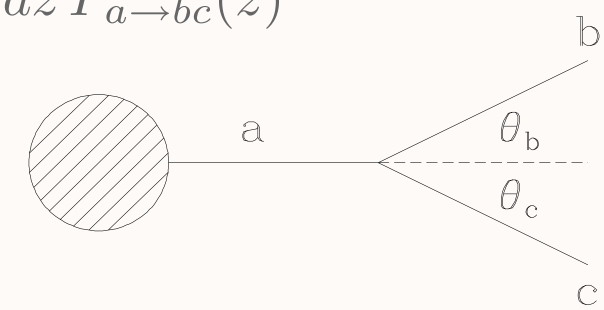
✓ coll/soft limits ⇒ large logs: AO resummation/LL exponentiation ⇒ tower of logs

$$\mathcal{O} = \sum r_n \alpha_S^n \quad \Rightarrow \quad \mathcal{O} = \sum c_n \alpha_S^n \log^{2n}(Q^2/Q_0^2) + \mathrm{NLL} + \ldots$$



- factorization – recursive definition in collinear limit

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



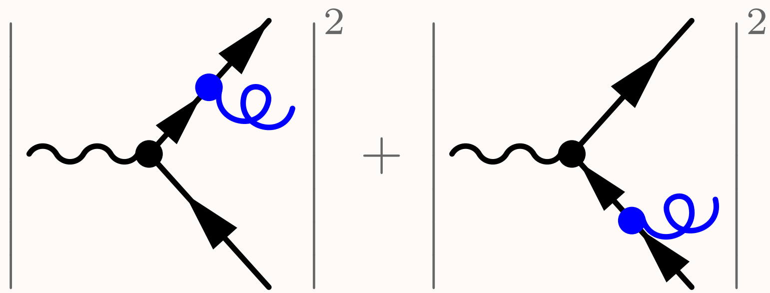
Parton showers (PSs)

QCD emissions preferably populate collinear and soft phase-space regions

- propagator factor for $q \to qg$ splitting

  $$[p_q + p_g]^{-2} \approx [2E_q E_g (1 - \cos\theta_{qg})]^{-2}$$

  soft and collinear singularities



- cross section factorizes in the collinear limit

$$|\mathcal{M}_{q\bar{q}g}|^2 d\Phi_{q\bar{q}g} \approx |\mathcal{M}_{q\bar{q}}|^2 d\Phi_{q\bar{q}} \frac{\alpha_s}{2\pi} \left(\frac{dt_{qg}}{t_{qg}} P_{q\to qg}(z_q) + \frac{dt_{\bar{q}g}}{t_{\bar{q}g}} P_{\bar{q}\to \bar{q}g}(z_{\bar{q}}) \right)$$

- probability for no resolvable emission off quark line between t and t_0:
  Sudakov form factor $\quad (P_{q\to qg}(z) = C_F \frac{1+z^2}{1-z}$ ... spin averaged AP kernel)

$$\Delta_q(t_0, t) = \exp\left\{ - \int_{t_0}^{t} \frac{dt'}{t'} \int_{z_-}^{z_+} dz \frac{\alpha_s}{2\pi} P_{q\to qg}(z) \right\}, \qquad z_+ = 1 - z_-\,, \quad z_- = \sqrt{t_0/t'}$$

- probability for splitting at $t_1 < t \quad \Rightarrow \quad dP = \Delta_q(t_1, t)\, \frac{\alpha_s}{2\pi} \frac{1}{t_1} P_{q\to qg}(z) dt_1 dz$

Parton showers (PSs)

main features of parton shower approach

- soft/collinear parton emissions added to initial & final state *[resum LLs]*
- partons are evolved down to hadronization scale *[ordering in virtuality, angle, p_T]*
- provides suitable input for universal hadronization models *[scales of $\mathcal{O}(1$ GeV$)$]*

limitations

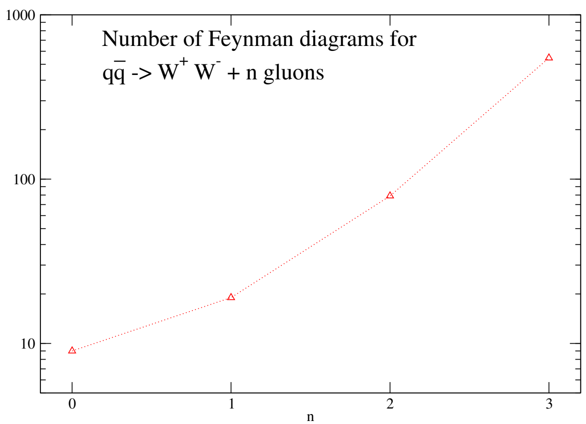
- shower seeds are LO QCD processes only
- lack of high-energetic large-angle emissions
- semi-classical picture, quantum interferences and correlations only approximate

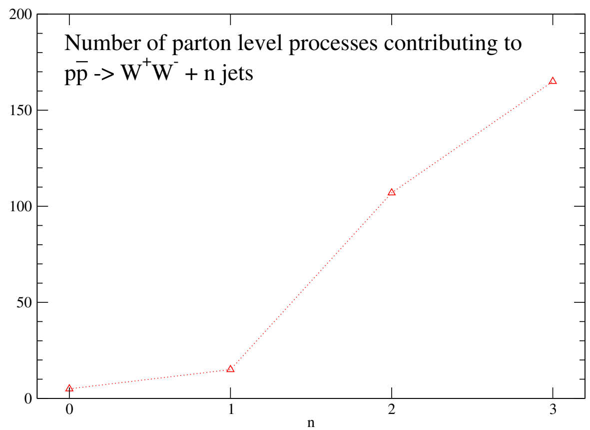
improvements

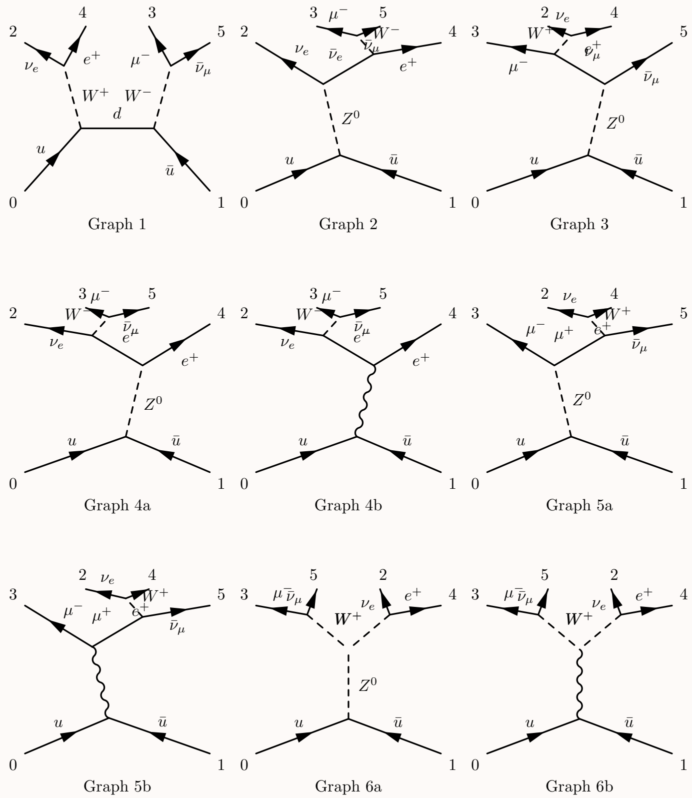
- first few hardest emissions according to tree-level MEs
  [called ME+PS merging – (L)CKKW, MLM]
- use NLO QCD core processes and match to PS *[called MC @ NLO]*
- Going beyond present shower approximations? *[beyond large N_{C}]*

Multiparton tree-level MEs

- ✓ exact at some fixed order (FO) in the coupling (number of legs)
- ✓ 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





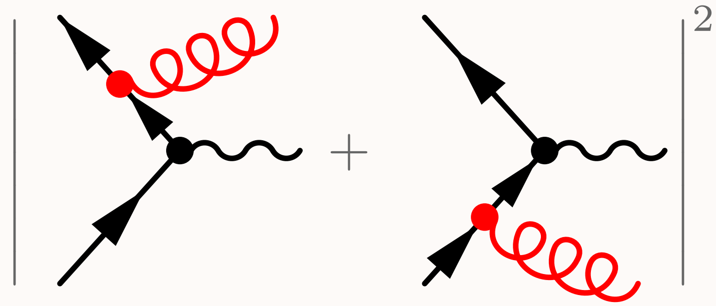


CKKW merging of tree-level MEs and parton showers.

Combine advantages, remove weaknesses.

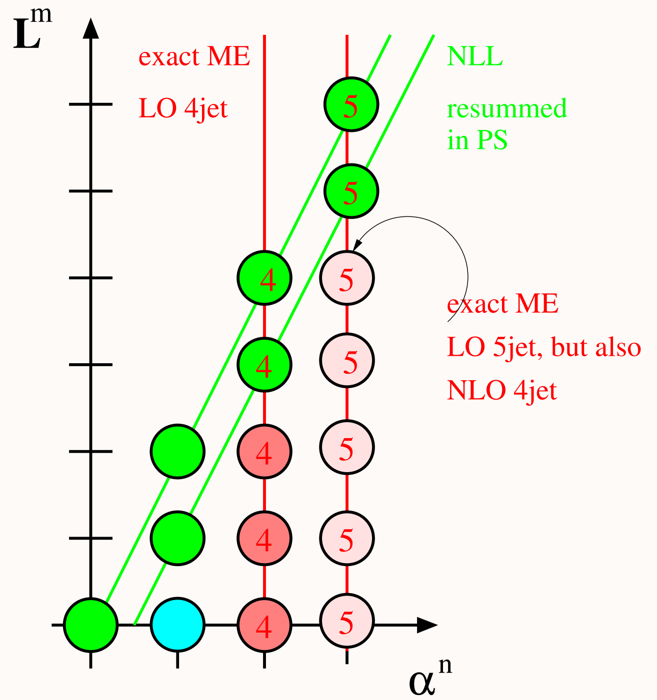
Beware of double counting, preserve universality of hadronization.

matrix element:

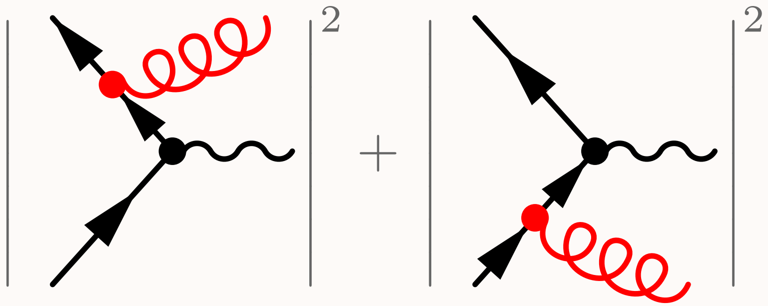


$|A_R|^2 + |B_R|^2 + 2\,\mathrm{Re}(\mathrm{A_R B_R^*})$

α_S vs. Log



parton shower:



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

NLL jet rates

Catani, Dokshitzer, Olsson, Turnock, Webber, Phys. Lett. **B269** (1991) 432

Catani, Krauss, Kuhn, Webber, JHEP **0111** (2001) 063

➡ **Exclusive e^+e^- n-jet fractions at cm energy Q and k_T resolution Q_1^2/Q^2**

$$R_2(Q_1,Q) = \left[\Delta_q(Q_1,Q)\right]^2 , \qquad R_3(Q_1,Q) = 2\left[\Delta_q(Q_1,Q)\right]^2 \int_{Q_1}^{Q} dq\, \Gamma_q(q,Q)\, \Delta_g(Q_1,q)$$

$$\Delta_q(Q_1,Q) = \exp\left(-\int_{Q_1}^{Q} dq\, \Gamma_q(q,Q)\right) , \quad \Gamma_q(q,Q) = \frac{2C_\mathrm{F}}{\pi}\frac{\alpha_s(q)}{q}\left(\ln\frac{Q}{q} - \frac{3}{4}\right) , \; \Gamma_f(q,Q) = \frac{N_\mathrm{F}}{3\pi}\frac{\alpha_s(q)}{q}$$

$$\Delta_g(Q_1,Q) = \exp\left(-\int_{Q_1}^{Q} dq\, \left[\Gamma_g(q,Q) + \Gamma_f(q)\right]\right) , \quad \Gamma_g(q,Q) = \frac{2C_\mathrm{A}}{\pi}\frac{\alpha_s(q)}{q}\left(\ln\frac{Q}{q} - \frac{11}{12}\right)$$

Sudakov form factors represent probs for q, g to evolve from Q to Q_1 with no Q_1-resolvable branching.

NLL jet rates

Catani, Dokshitzer, Olsson, Turnock, Webber, Phys. Lett. **B269** (1991) 432

Catani, Krauss, Kuhn, Webber, JHEP **0111** (2001) 063

- **Exclusive e^+e^- n-jet fractions at cm energy Q and k_T resolution Q_1^2/Q^2**

$$R_2(Q_1,Q) \;=\; [\Delta_q(Q_1,Q)]^2\,, \qquad R_3(Q_1,Q) \;=\; 2\,[\Delta_q(Q_1,Q)]^2 \int_{Q_1}^{Q} dq\, \Gamma_q(q,Q)\, \Delta_g(Q_1,q)$$

- **Improve n-jet distributions above Q_1 by replacing ...** $\Gamma_q(q,Q) \to |\mathcal{M}_{q\bar{q}g}|^2$

- **Generate distributions below $Q_1 = Q_{jet}$ by vetoed parton showering ...**

shower started at Q and any emission above Q_1 is rejected *[to ensure angular ordering]*

this will e.g. reproduce $R_2(Q_0,Q) = [\Delta_q(Q_0,Q)]^2$:

consider one quark line,

$$\Delta_q(Q_1,Q)\Delta_q(Q_0,Q)\left\{1+\int_{Q_1}^{Q} dq\Gamma_q + \int_{Q_1}^{Q} dq\Gamma_q \int_{Q_1}^{q} dq'\Gamma'_q + \ldots\right\} = \frac{\Delta_q(Q_1,Q)\Delta_q(Q_0,Q)}{\exp\left(-\int_{Q_1}^{Q} dq\Gamma_q\right)}\,,$$

naive showering from Q_1 will not reproduce R_2: $\Delta_q(Q_1,Q)\Delta_q(Q_0,Q_1) \neq \Delta_q(Q_0,Q)$.

CKKW method: phase-space separation

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

- tree-level MEs: jet seed (hard parton) production above Q_{jet}
- PS: (intra-)jet evolution $Q_{jet} < Q < Q_{\mathrm{cut-off}}$
- MEs regularized by k_T measure requirement Q_{jet}
- large, unphysical Q_{jet} dependence for fixed multiplicity n, ambiguous phase space

CKKW method: phase-space separation

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

- tree-level MEs: jet seed (hard parton) production above Q_{jet}
- PS: (intra-)jet evolution $Q_{jet} < Q < Q_{\text{cut-off}}$
- MEs regularized by k_T measure requirement Q_{jet}
- large, unphysical Q_{jet} dependence for fixed multiplicity n, ambiguous phase space

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

hadron–hadron collisions:

$$Q_{ij} = \min\{k_{\perp i}^2, k_{\perp j}^2\} \cdot R_{ij}^2 > Q_{jet} \quad \textit{and}$$

$$Q_{iB} = k_{\perp i}^2 > Q_{jet}$$

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

electron–positron collisions:

$$y_{ij} = 2\min\{E_i^2, E_j^2\}(1 - \cos\theta_{ij})/S > y_{\text{cut}}$$

CKKW method: reweighting & vetoing

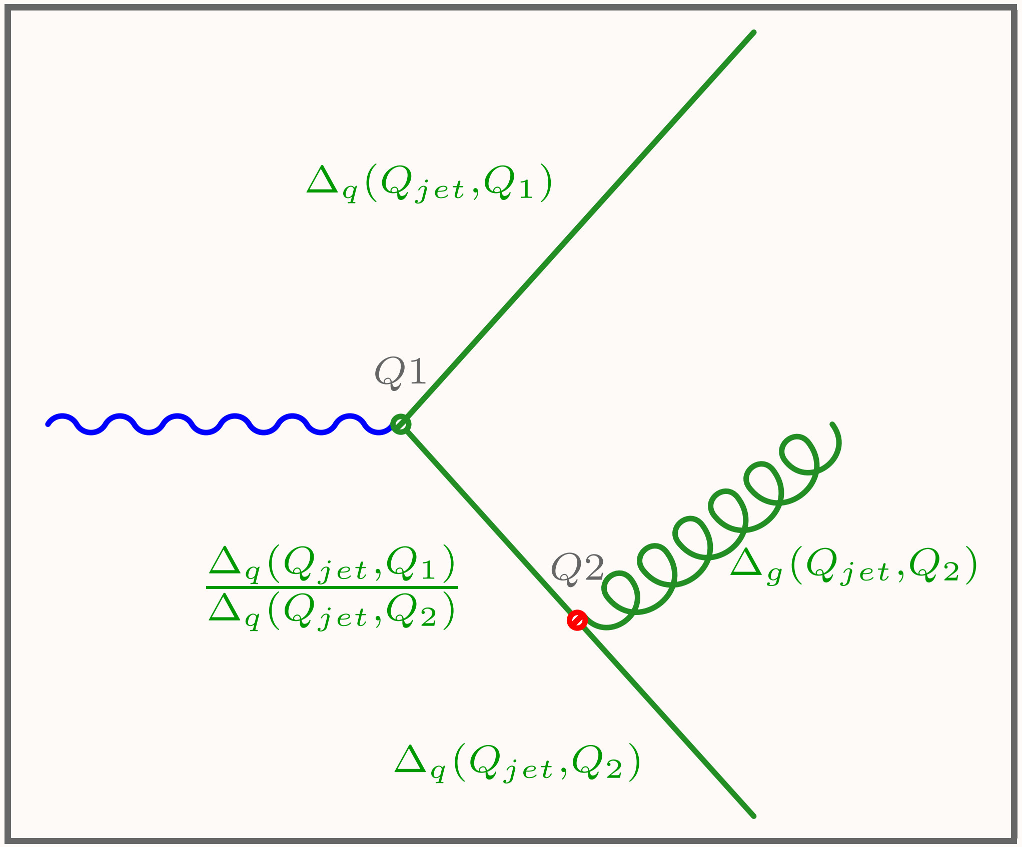
Eliminate/sizeably reduce Q_{jet} dependence at (N)LL.

- identify pseudo shower history of MEs via backward clustering
- accordingly reweight MEs by combined α_s and Sudakov weight
- veto PS configurations already included through higher order MEs

CKKW method: reweighting & vetoing

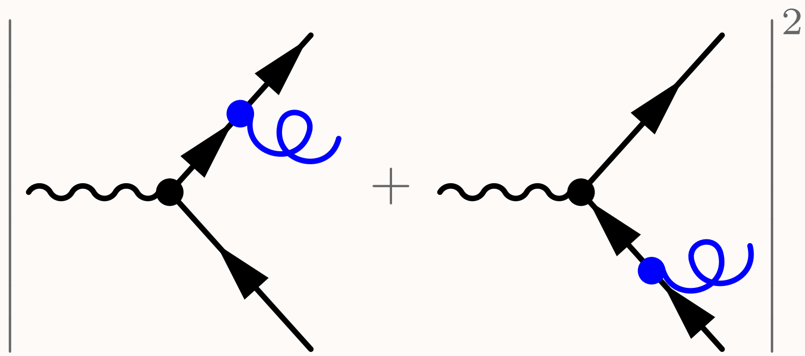
Eliminate/sizeably reduce Q_{jet} dependence at (N)LL.

- identify pseudo shower history of MEs via backward clustering
- accordingly reweight MEs by combined α_s and Sudakov weight
- veto PS configurations already included through higher order MEs



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

⇐ shower history of



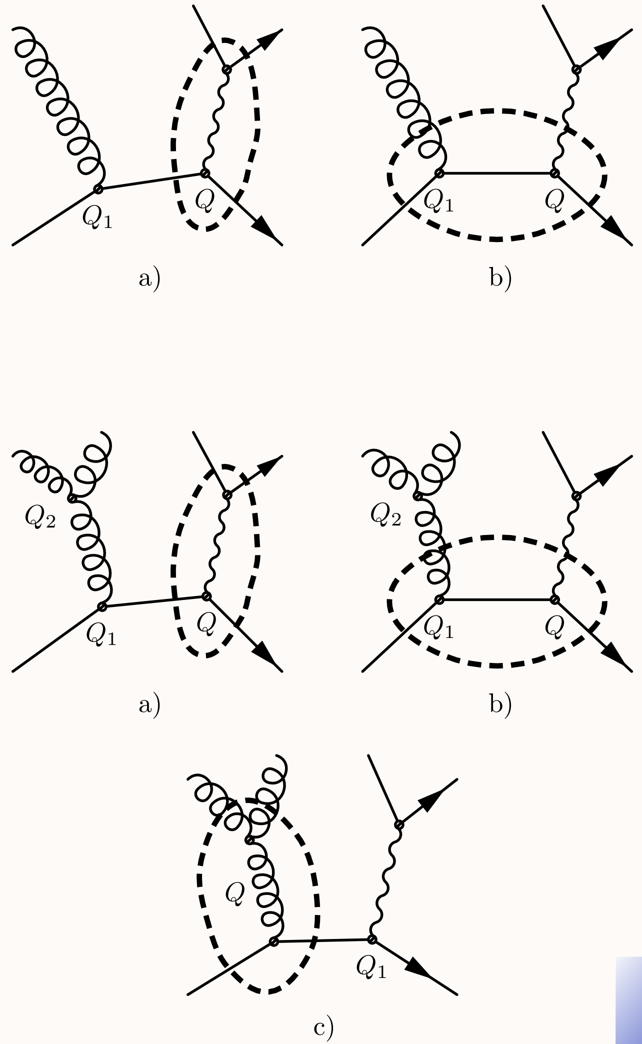
⇒ recall $\Delta_{q,g}$: no-emission probability

CKKW method at work

- *evaluate MEs for $0, 1, \ldots, n_{\max}$ extra partons passing jet criteria at Q_{jet} [regulator, $\mu_{F,R}$]*
- *select a parton multiplicity with probability $P_n = \sigma_n / \sum_{i=0}^{n_{\max}} \sigma_i$*
- *generate parton-level momenta according to the ME*
- *reweight ME according to reconstructed pseudo shower history*
  - *determine parton emission scales $Q_n, \ldots, Q_1$ using k_T cluster algorithm*
  - *calculate corresponding Sudakov weights*
    - *external partons: $\Delta_{q,g}(Q_{jet}, Q_{prod})$*
    - *internal partons: $\Delta_{q,g}(Q_{jet}, Q_{prod})/\Delta_{q,g}(Q_{jet}, Q_{dec})$*
  - *recalculate $\alpha_s = \alpha_s(Q_k)$ at each cluster tree vertex k*
- *start initial-/final-state parton shower for all ME partons*
  - *at scale where parton was produced*
  - *and veto shower emissions above Q_{jet}*

➜ *exclusive samples at given resolution scale Q_{jet}*

➜ *inclusive sample with up to $n_{\max}$ "ME" jets by adding them up + highest multiplicity treatment for the $n_{\max}$ MEs*

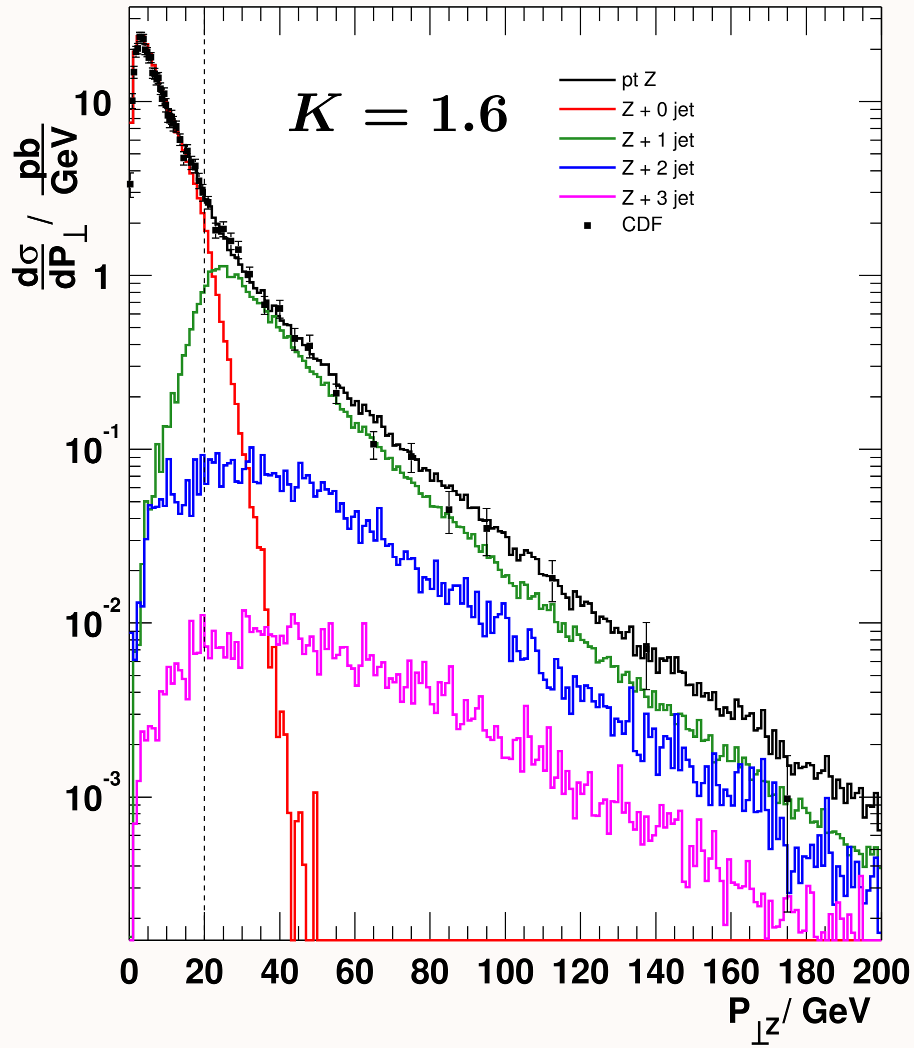


CKKW – key feature of Sherpa

- ➡ **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
- ➡ **Uses built-in ME generator AMEGIC++.**
- ➡ **Process-independent implementation.**

! Validation

- **W/Z+jets @ Tevatron/LHC** ➡
  F. Krauss, A. Schälicke, S. Schumann,
  Phys. Rev. D **70** (2004) 114009, D **72** (2005) 054017
- **WW production @ Tevatron Run II**
  T. Gleisberg et al., Phys. Rev. D **72** (2005) 034028
- **Detailed comparison to MLM merging & Lönnblad-CKKW**
  Results in EPJC53 (2008) 473
- **Applications: QCD jets, $Zb\bar{b}+X$, VBF, tops, $gg \to H+X$, b-associated Higgs**



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

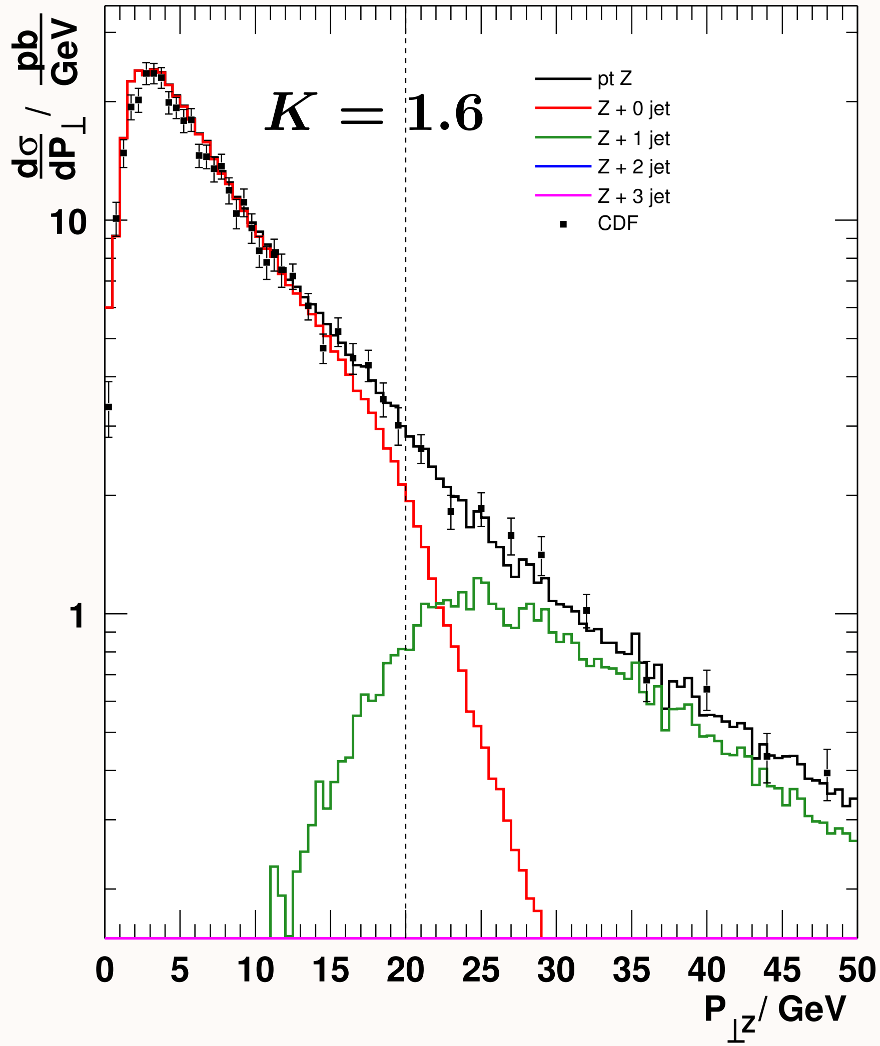
F. Krauss, JHEP **0208** (2002) 015

➔ **Uses built-in ME generator AMEGIC++.**

➔ **Process-independent implementation.**

! Validation

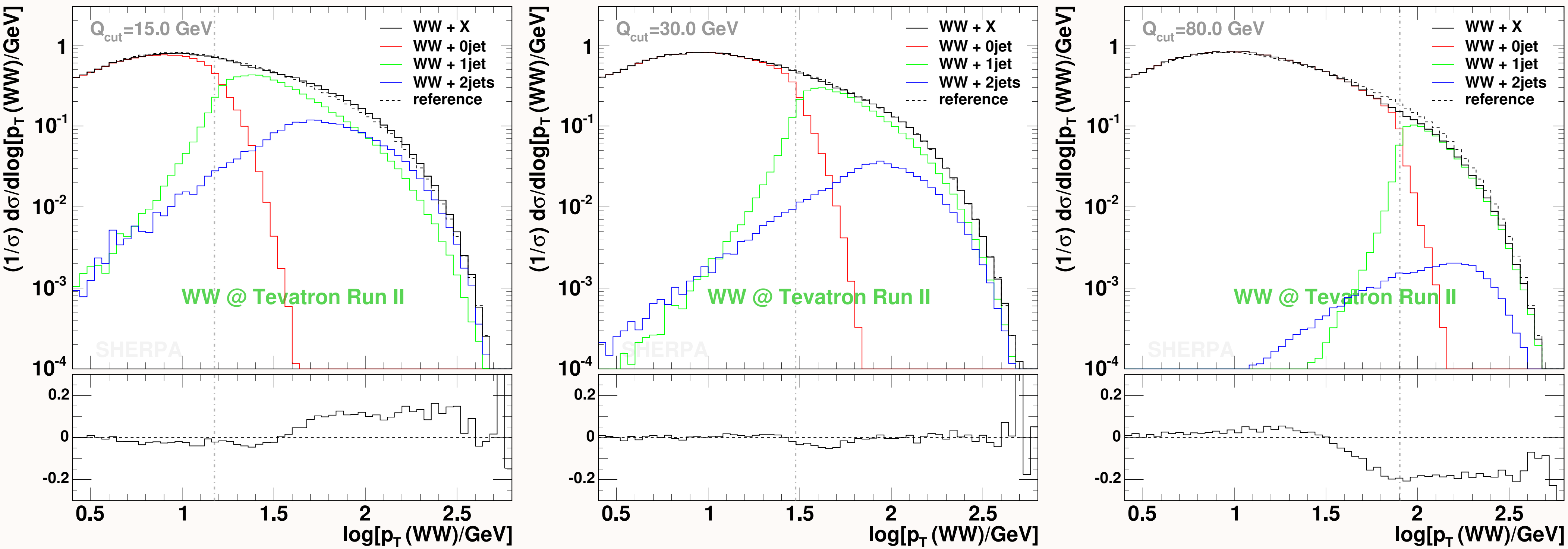
- **W/Z+jets @ Tevatron/LHC** ➔
  F. Krauss, A. Schälicke, S. Schumann,
  Phys. Rev. D **70** (2004) 114009, D **72** (2005) 054017
- **WW production @ Tevatron Run II**
  T. Gleisberg et al., Phys. Rev. D **72** (2005) 034028
- **Detailed comparison to MLM merging & Lönnblad-CKKW**
  Results in EPJC53 (2008) 473
- **Applications: QCD jets, $Zb\bar{b} + X$, VBF, tops, $gg \to H + X$, b-associated Higgs**



Vary jet separation cut in Sherpa ...

➡ $p\bar{p} \to W^+W^- + X$ @ Tevatron II: $p_\perp$ of the WW system

$Q_{\rm cut} \equiv Q_{jet}$



➡ Strongly $Q_{\rm cut}$-dep. subprocesses cooperate ➡ total result is decently stable.

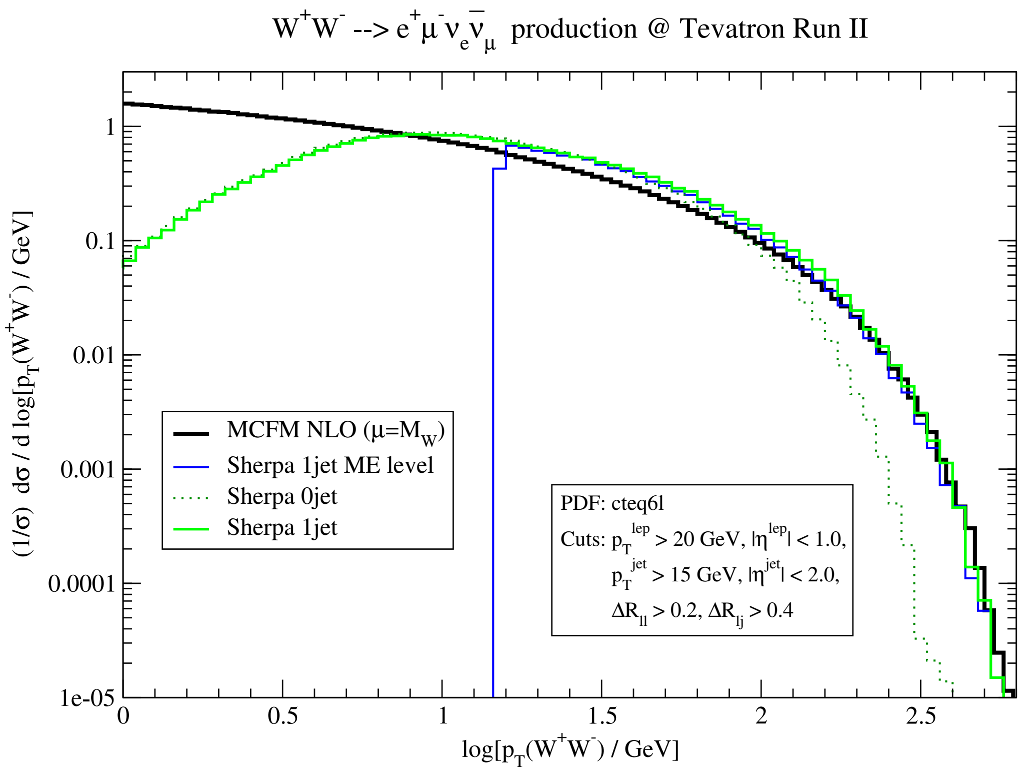
➡ Residual dependence can be used to tune to a candle process.

Comparison with MCFM's NLO QCD prediction

J.M. Campbell and R.K. Ellis, Phys. Rev. D **60** (1999) 113006

➡ $p\bar{p} \to W^+W^- + X$ @ Tevatron II:

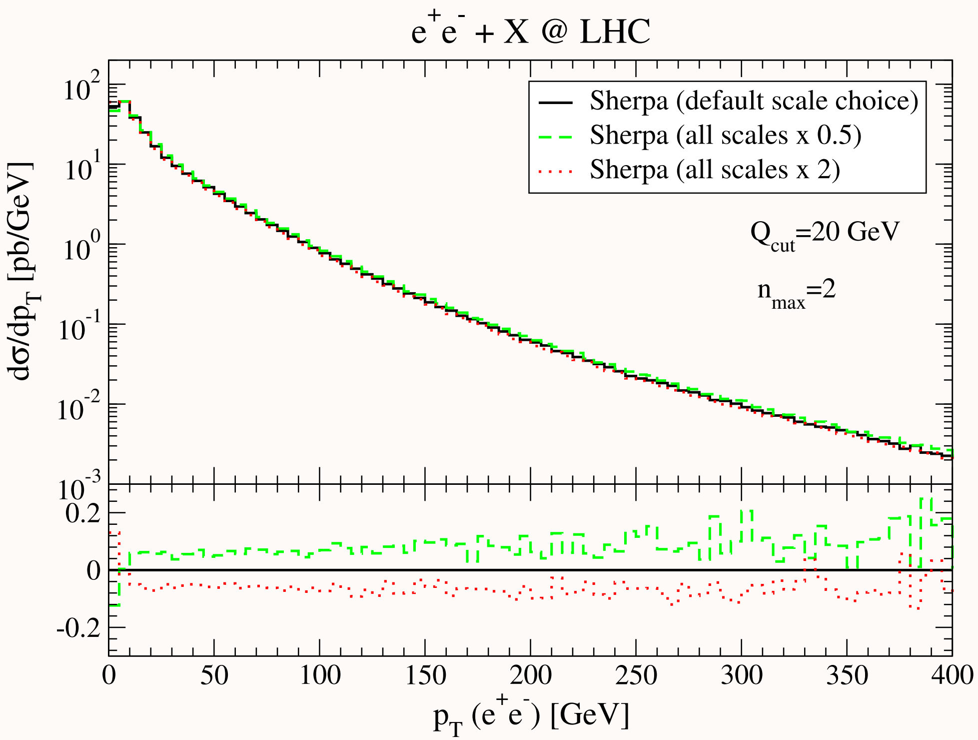
- $p_\perp$ of the WW system

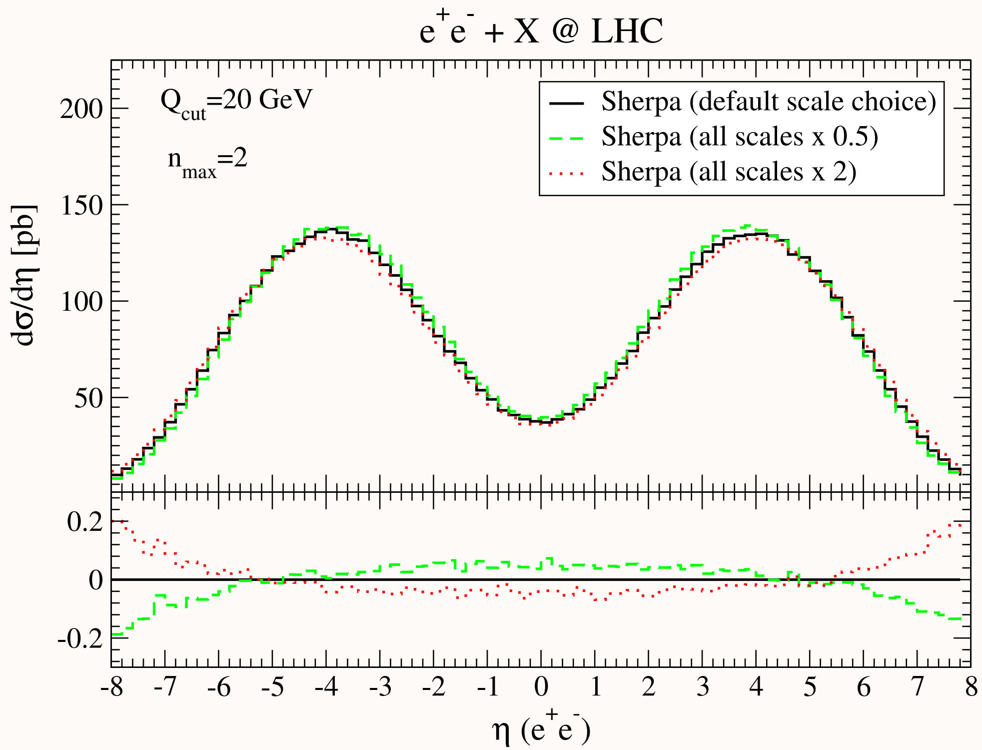


➡ MCFM @ parton level *vs.* Sherpa @ shower level:

- LO ME-level Distribution is described by a delta peak at 0.
- At NLO the $p_\perp$ of the WW system diverges for soft $p_\perp$s.

Vary scales in Sherpa ... μ_R and μ_F



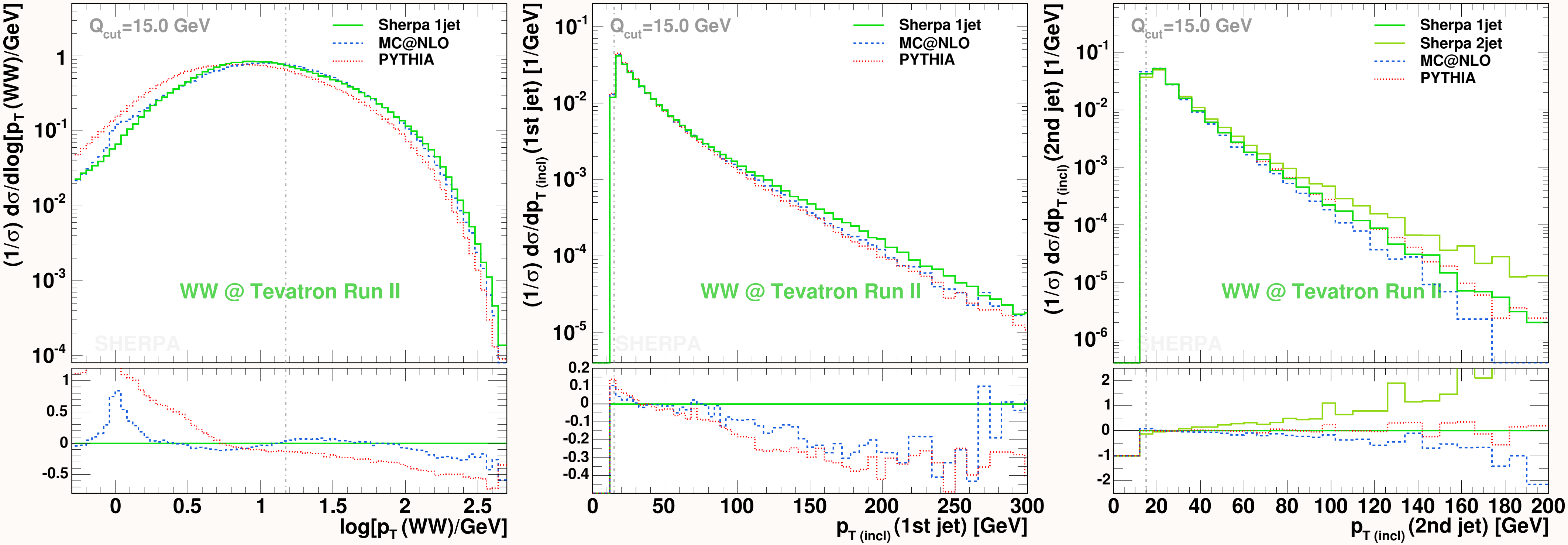


- On the $\pm$20% level only. Much better than pure LO.

Comparison of QCD activity for different MCs

S. Frixione et al., JHEP **0206** (2002) 029; JHEP **0308** (2003) 007
T. Sjöstrand et al., CPC **135** (2001) 238

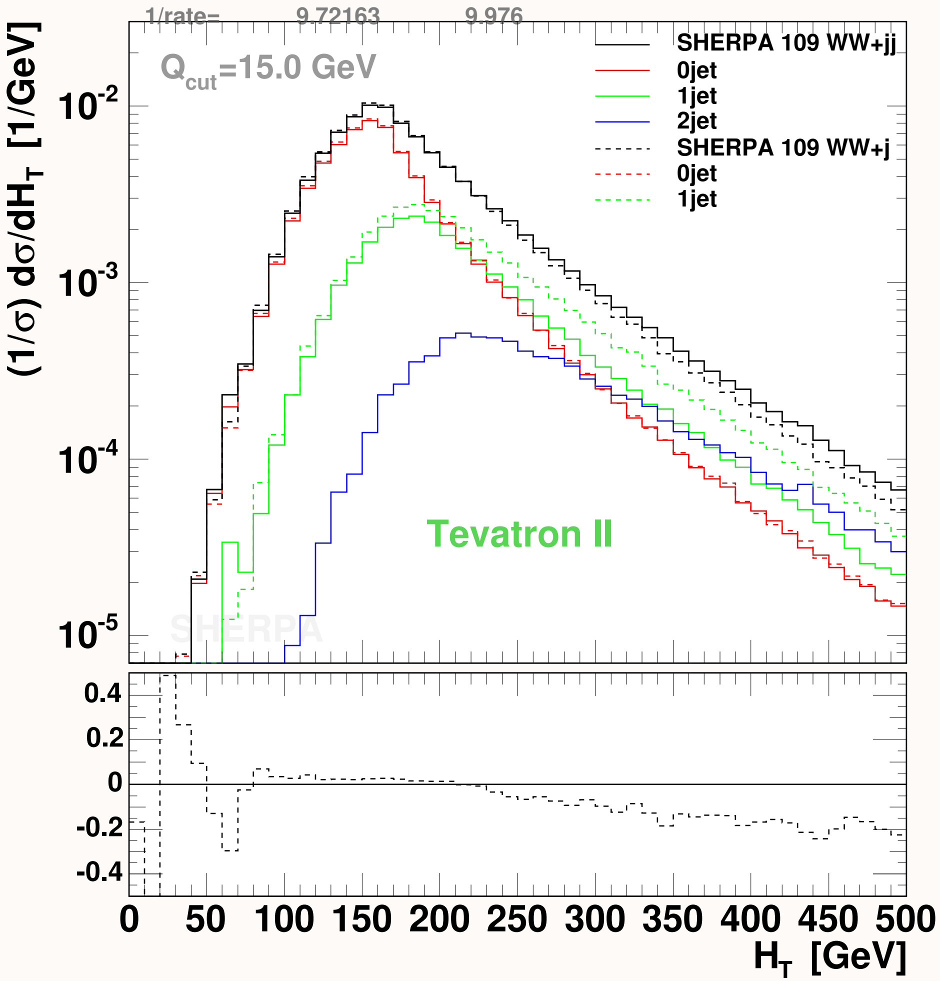
- $p\bar{p} \to W^+W^- + X$ @ Tevatron II:
  1: $p_\perp$ of the WW system
  2, 3: incl $p_\perp$ of the 1st and 2nd hardest jet

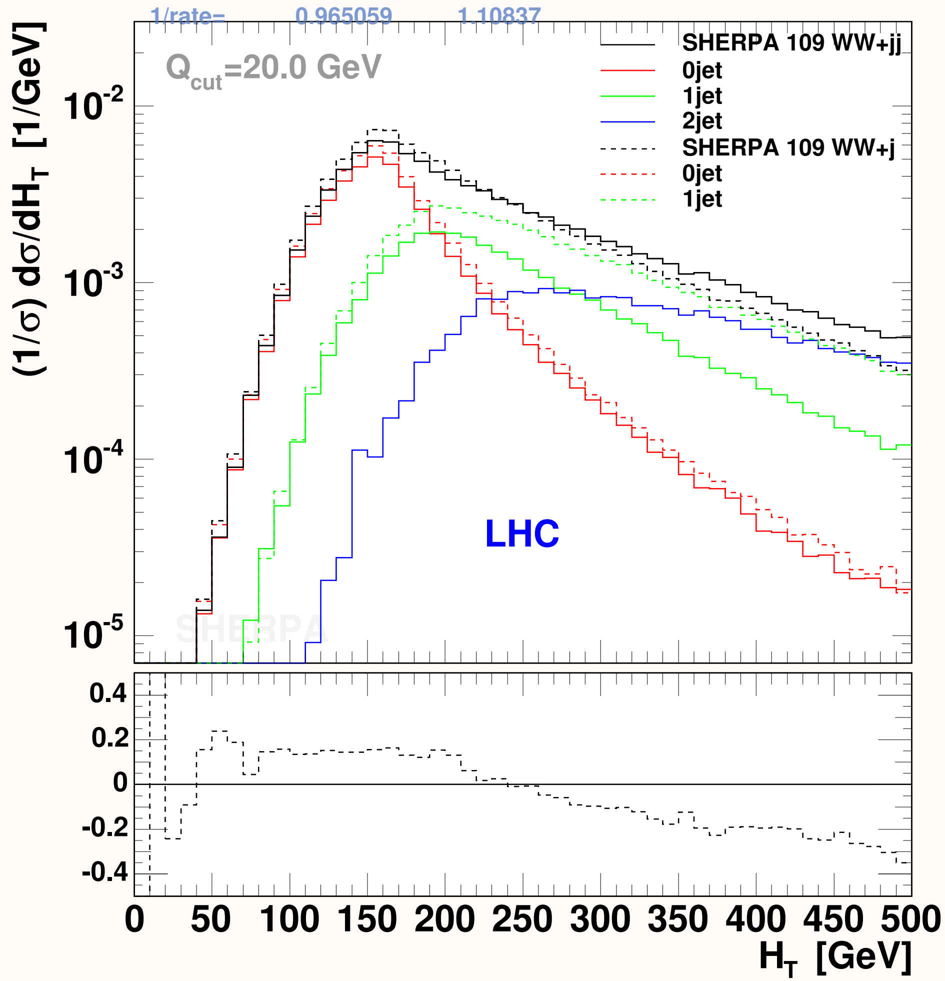


- Sherpa *vs.* MC@NLO and Pythia (shower scale S): comparison of different physics input!

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

- Sherpa: $p\bar{p}/p \to W^+W^- + X$: Scalar sum of lepton & jet transverse momenta.





- Example of extrapolation to LHC E's: enhanced QCD radiation phase space.
- $WW + jj$ vs. $WW + j$. Slightly different jet p_T thresholds for Tevatron/LHC.

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

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

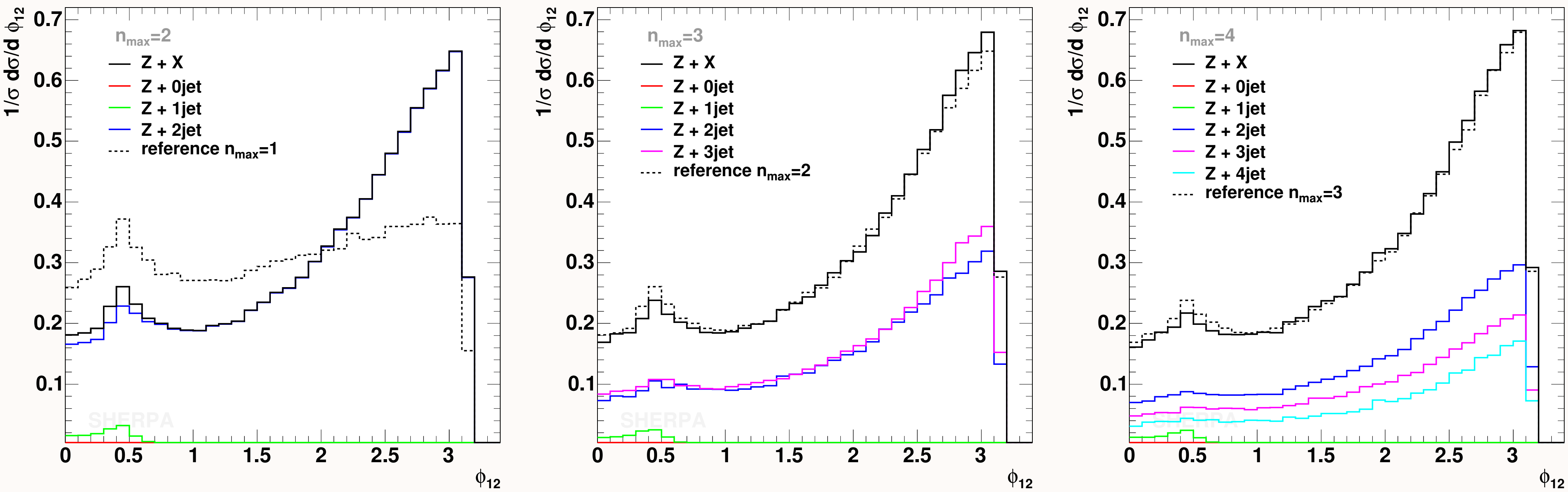
Monte Carlo	$\sigma_{\geq 1\text{jet}}/\sigma_0$	$\sigma_{\geq 2\text{jet}}/\sigma_0$	$\sigma_{\geq 3\text{jet}}/\sigma_0$	$\sigma_{=1\text{jet}}/\sigma_0$	$\sigma\|_{y_1 y_2 < -2}/\sigma_0$
CKKW $n_{\rm ME} = 1$	0.304	0.082	0.017	0.222	0.016
CKKW $n_{\rm ME} = 2$	0.340	0.108	0.025	0.231	0.017
CKKW $n_{\rm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

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

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

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

- $\Delta\Phi$ (azimuthal) separation of the two leading k_T jets in $Z/\gamma^* + X$ @ LHC.



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

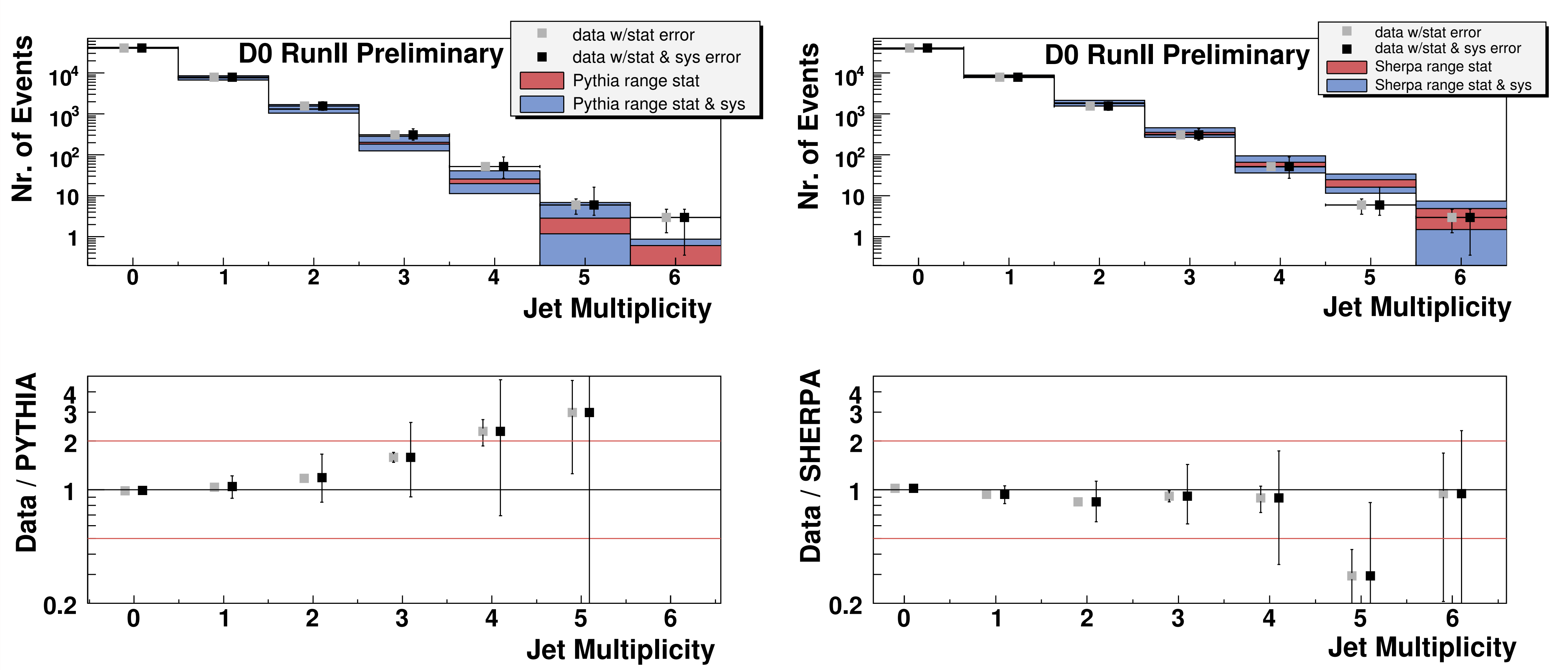
- Reference is $n'_{\max} = n_{\max} - 1$ (dashed curve).
- shower: uncorrelated emissions, accuracy $\sum_{n=2} \alpha_s^n \ln^{2n}(Q^2/Q_0^2)$
- merging: has full ME correlations, yields $\alpha_s^2 \sum_{n=0} \alpha_s^n \ln^{2n}(Q^2/Q_0^2)$

Sherpa validation against Tevatron data.

Comparison with data: DØ Z+jet production results

DØ collaboration, DØ note 5066-CONF

➡ Jet multiplicity, data *vs.* Pythia (left) and Sherpa (right).

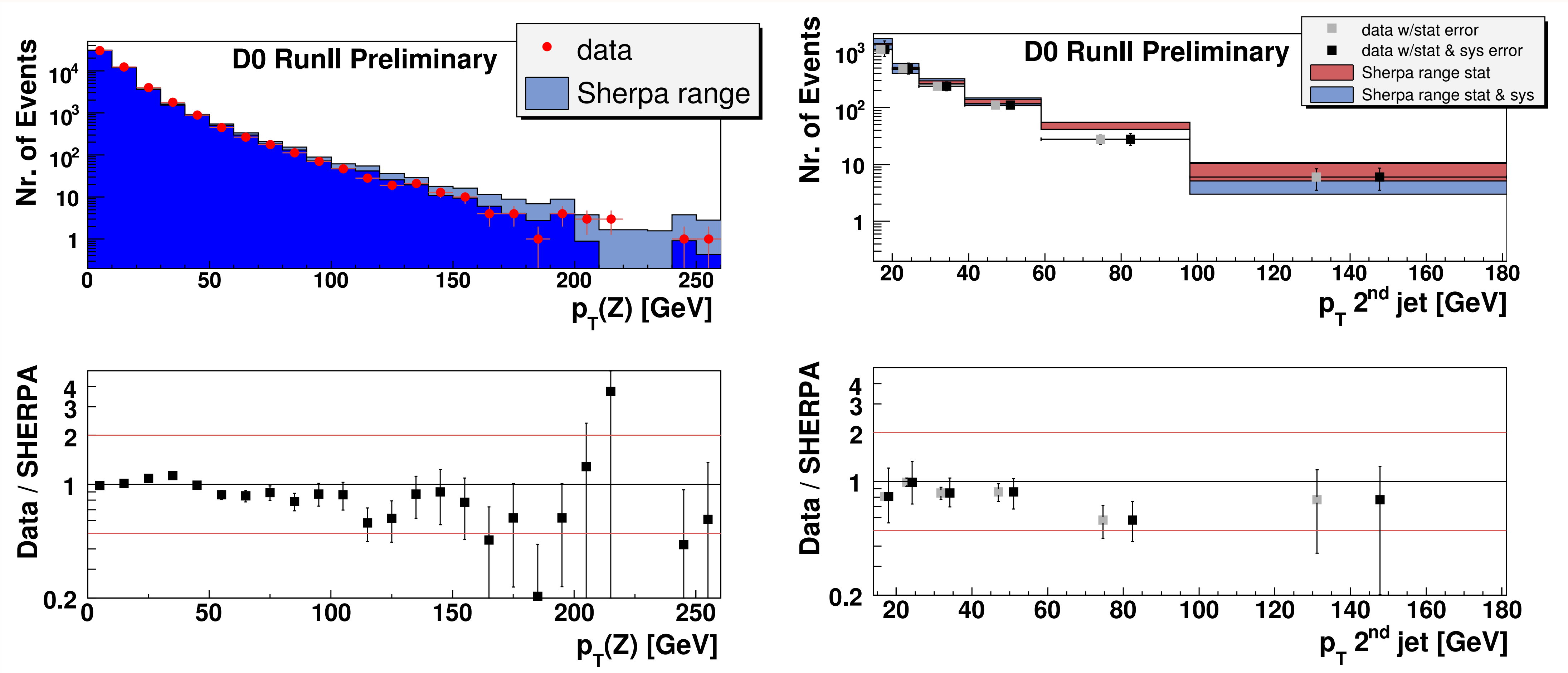


- MC predictions are normalized to total number of events observed in data.
- Large systematic uncertainties arise from low p_T jets $\Rightarrow$ both predictions are in agreement with data. Pythia tends to underestimate the data.

Comparison with data: DØ Z+jet production results

DØ collaboration, DØ note 5066-CONF

➡ Boson transverse momentum (left) and p_T of the 2nd jet, data *vs.* Sherpa.

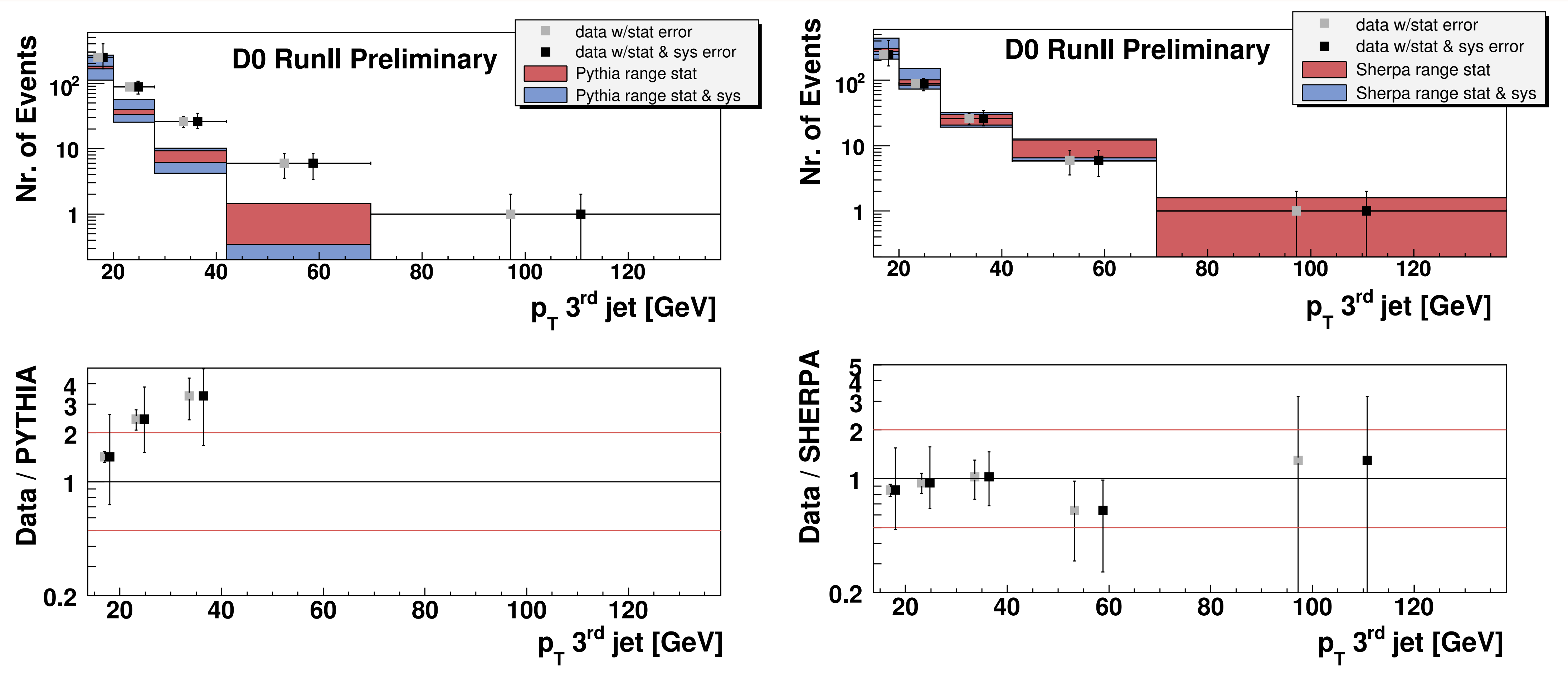


- MC predictions are normalized to total number of events observed in data.
- Di-electron system balances the p_T of the jet system.

Comparison with data: DØ Z+jet production results

DØ collaboration, DØ note 5066-CONF

➡ p_T of the 3rd jet, data *vs.* Pythia (left) and Sherpa (right).

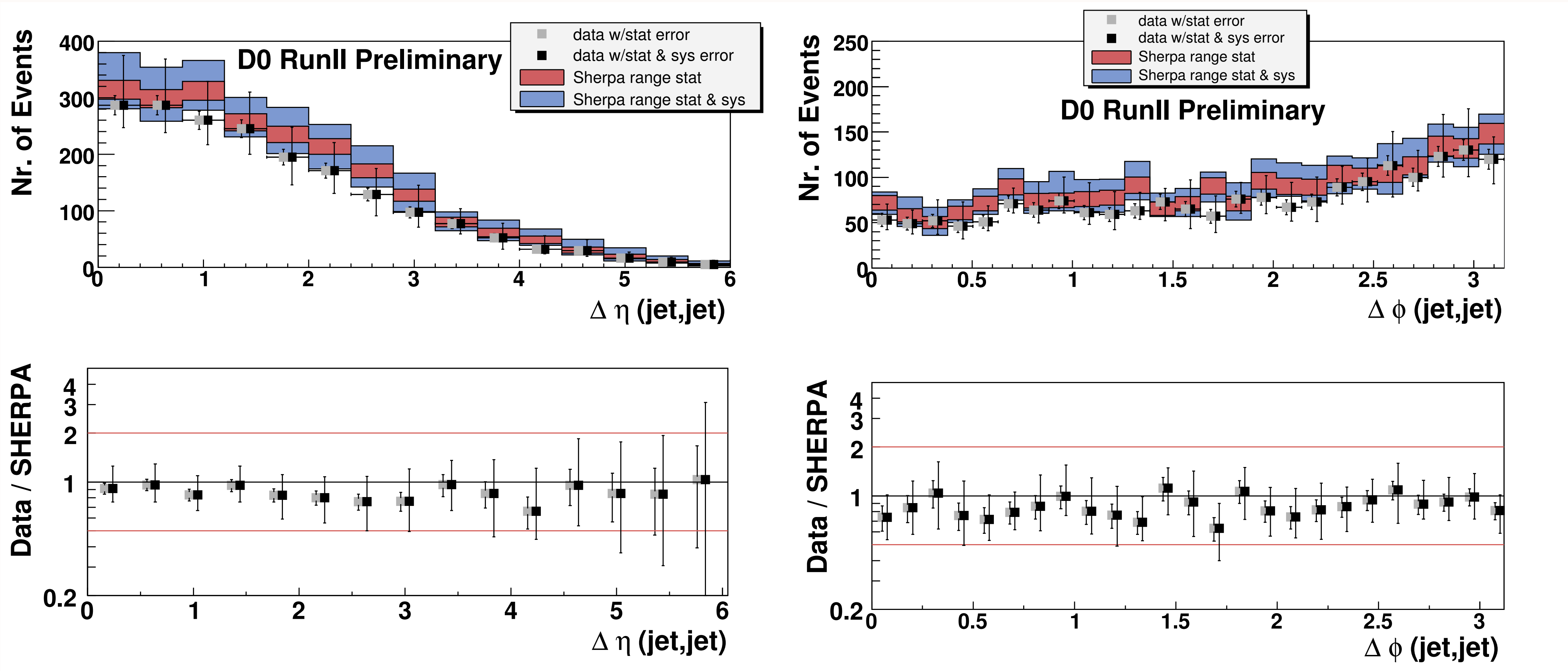


- MC predictions are normalized to total number of events observed in data.

Comparison with data: DØ Z+jet production results

DØ collaboration, DØ note 5066-CONF

➡ Eta and phi difference between the two hardest jets, data *vs.* Sherpa.

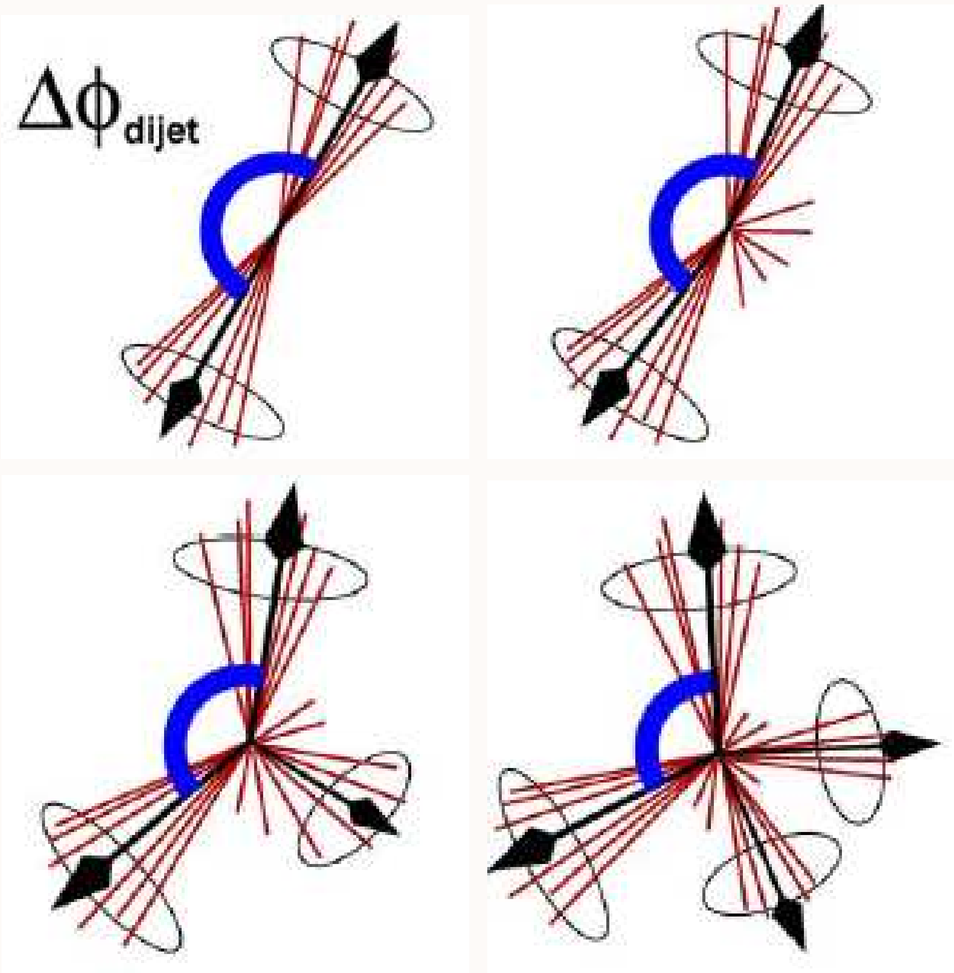


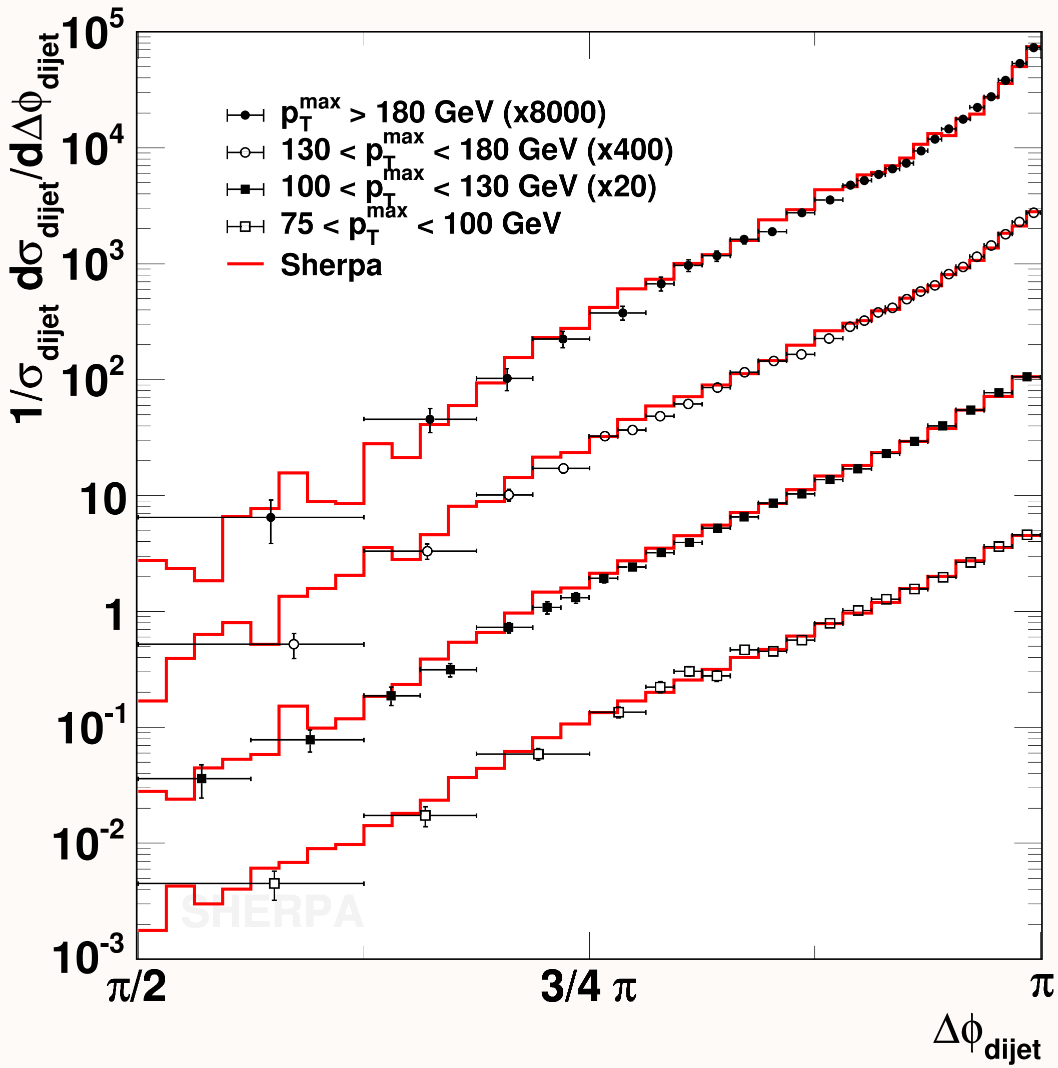
- MC predictions are normalized to total number of events observed in data.
- Description of angular correlations is ME dominated.

Comparison with data: inclusive dijets @ Tevatron

V.M. Abazov et al., Phys. Rev. Lett. **94** (2005) 221801

- Dijet azimuthal decorrelation measured by DØ in Run II.
- Idea: reconstruct only the 2 leading jets and test soft+hard QCD radiation pattern.





Alpgen

Ariadne

Helac

Madevent

Sherpa

CERN-PH-TH/2007-066
LU-TP 07-13
KA-TP-06-2007
DCPT/07/62
IPPP/07/31
SLAC-PUB-12604

EPJC53 (2008) 473

Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions *

J. Alwall[1], S. Höche[2], F. Krauss[2], N. Lavesson[3], L. Lönnblad[3], F. Maltoni[4], M.L. Mangano[5], M. Moretti[6], C.G. Papadopoulos[7], F. Piccinini[8], S. Schumann[9], M. Treccani[6], J. Winter[9], M. Worek[10,11]

[1] SLAC, USA;
[2] IPPP, Durham, UK;
[3] Department of Theoretical Physics, Lund University, Sweden;
[4] Centre for Particle Physics and Phenomenology (CP3) Université Catholique de Louvain, Belgium;
[5] CERN, Geneva, Switzerland;
[6] Dipartimento di Fisica and INFN, Ferrara, Italy;
[7] Institute of Nuclear Physics, NCSR Demokritos, Athens, Greece;
[8] INFN, Pavia, Italy;
[9] Institut für Theoretische Physik, TU Dresden, Germany;
[10] ITP, Karlsruhe University, Karlsruhe, Germany;
[11] Institute of Physics, University of Silesia, Katowice, Poland.

Comparison between merging approaches.

Abstract

We compare different procedures for combining fixed-order tree-level matrix-element generators with parton showers. We use the case of W-production at the Tevatron and the LHC to compare different implementations of the so-called CKKW and MLM schemes using different matrix-element generators and different parton cascades. We find that although similar results are obtained in all cases, there are important differences.

September 27, 2007

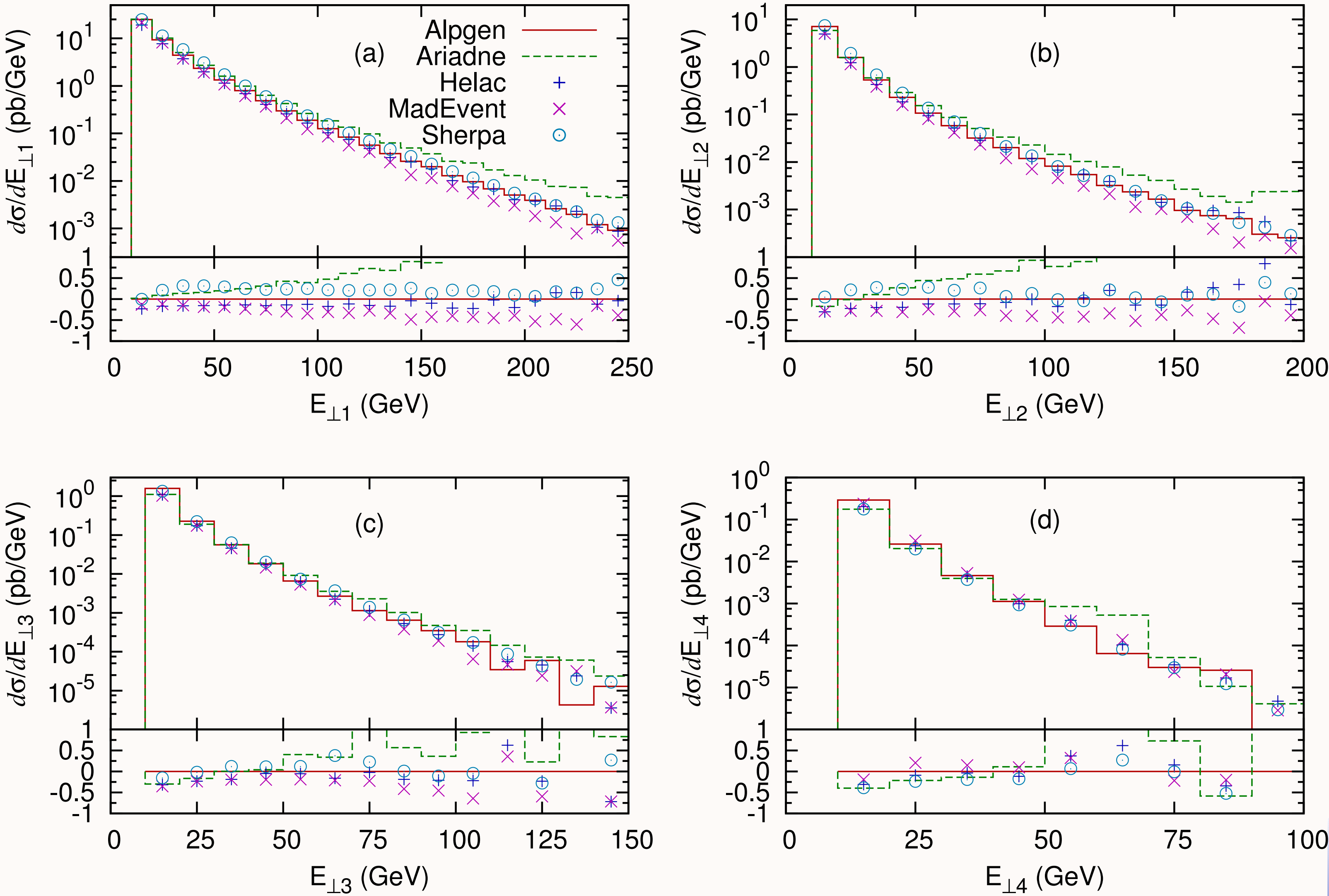
*Work supported in part by the Marie Curie RTN "MCnet" (contract number MRTN-CT-2006-035606) and "HEPTOOLS" (contract number MRTN-CT-2006-035505).

Comparison between merging approaches, ...

- namely MLM, LL and SHERPA ME-PS-merging, has been accomplished.

$W + X$

- jet E_T spectra at Tevatron Run II

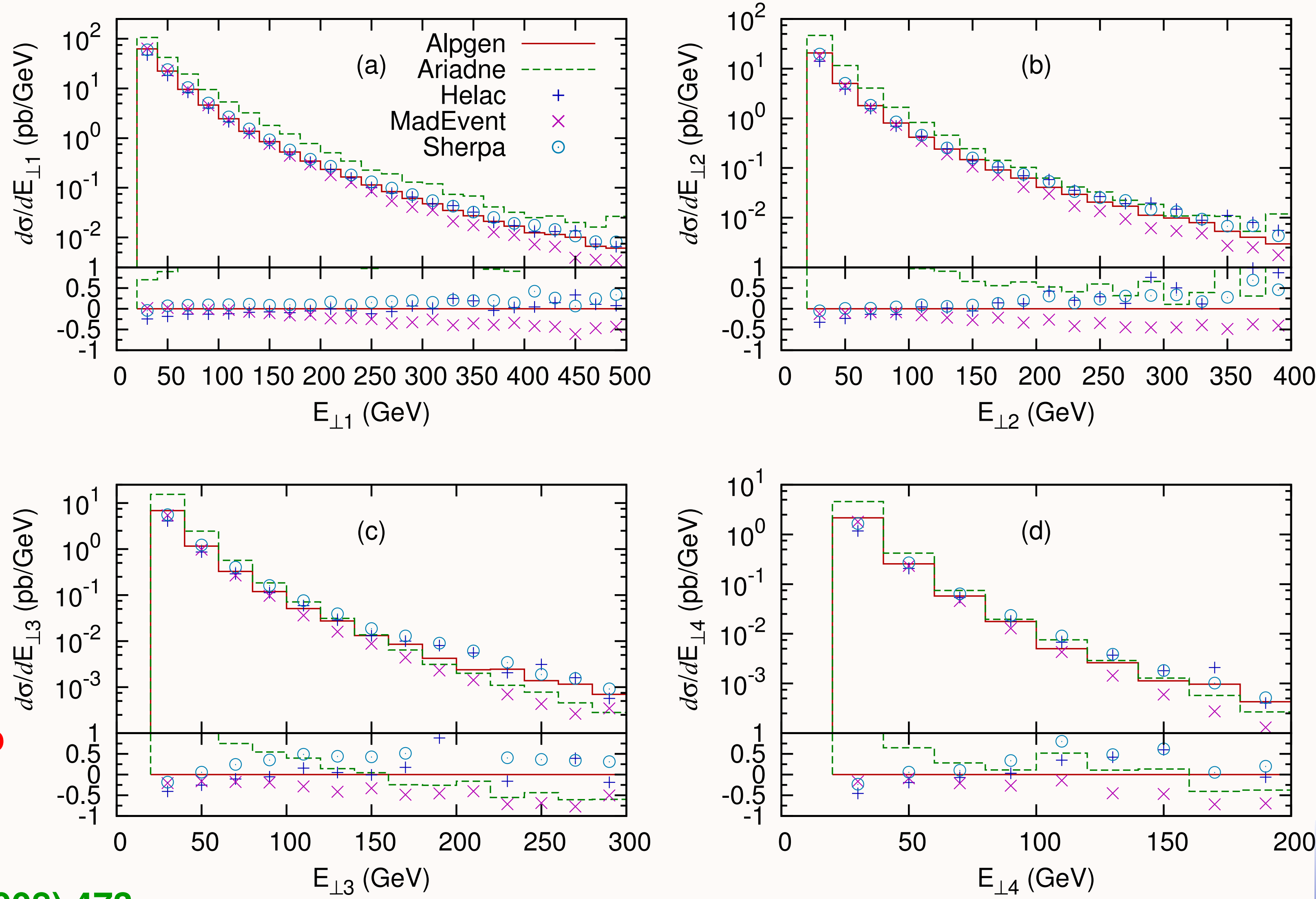


Comparison between merging approaches, ...

➡ namely MLM, LL and SHERPA ME-PS-merging, has been accomplished.

$W^+ + X$

- **jet E_T spectra at the LHC**



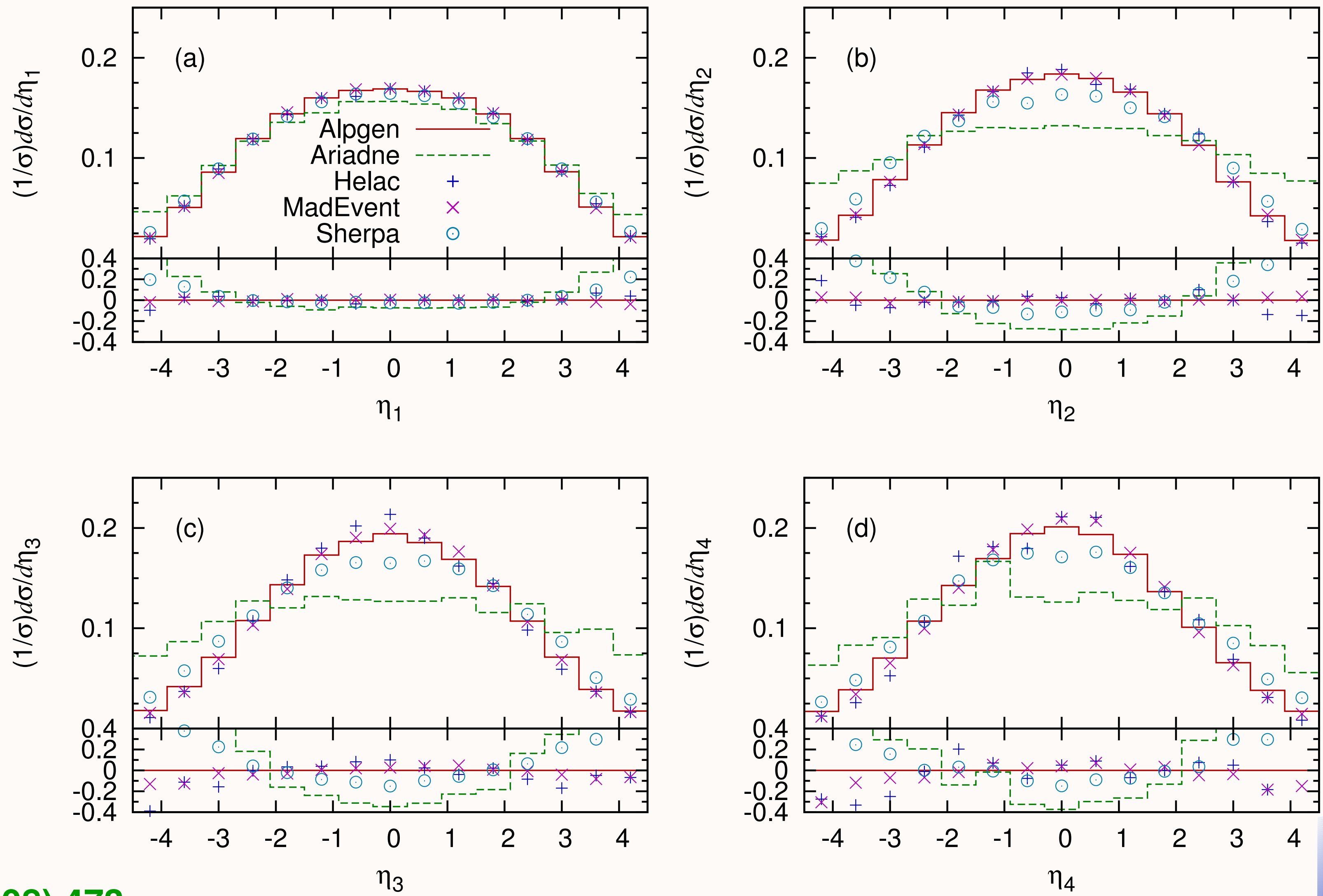
- similar pattern wrt Tevatron
- once tuned to Tevatron data, same **extrapolation to LHC** can be expected
- **Results in EPJC53 (2008) 473**

Comparison between merging approaches, ...

➡ namely MLM, LL and SHERPA ME-PS-merging, has been accomplished.

$W^+ + X$

- jet η spectra at the LHC



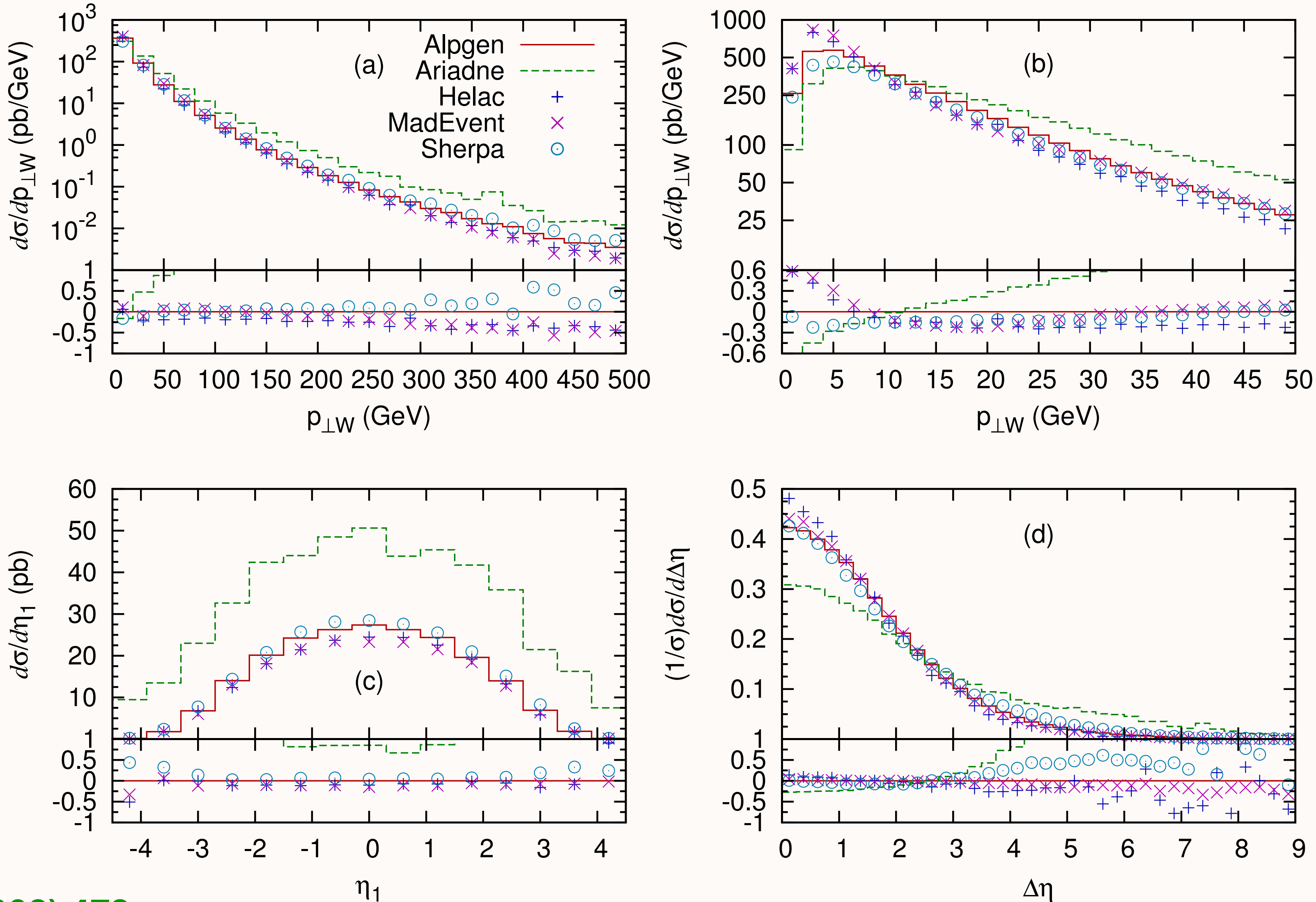
- similar pattern wrt Tevatron
- once tuned to Tevatron data, same **extrapolation to LHC** can be expected

- Results in EPJC53 (2008) 473

Comparison between merging approaches, ...

→ namely MLM, LL and SHERPA ME-PS-merging, has been accomplished.

$W^+ + X$



$\eta_1(p_{T,1} > 100\ \mathrm{GeV})$ $\quad |\eta_W - \eta_1|(p_{T,1} > 40\ \mathrm{GeV})$

- $p_T(W)$ spectra at the LHC
- similar pattern wrt Tevatron
- once tuned to Tevatron data, same extrapolation to LHC can be expected
- Results in EPJC53 (2008) 473

Merging tree-level MEs and PSs:

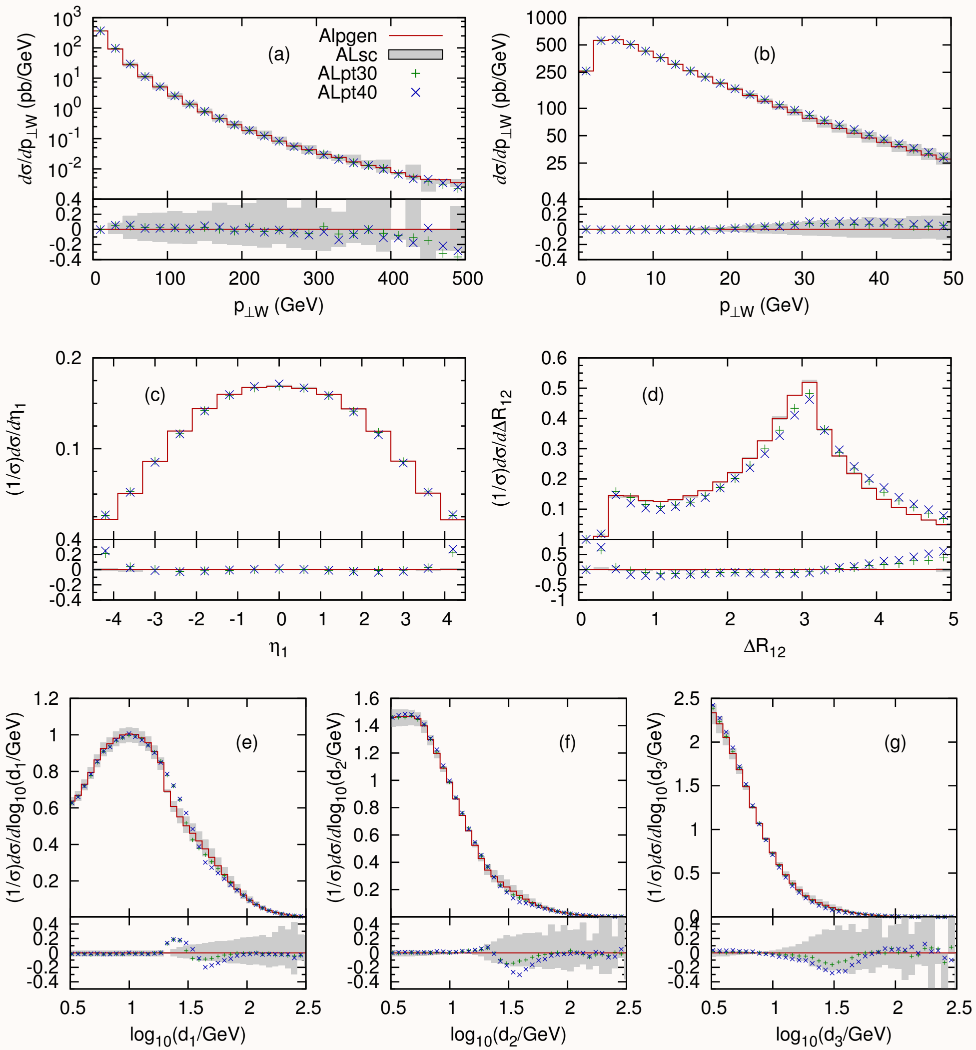
the MLM method differs from CKKW mainly in ...

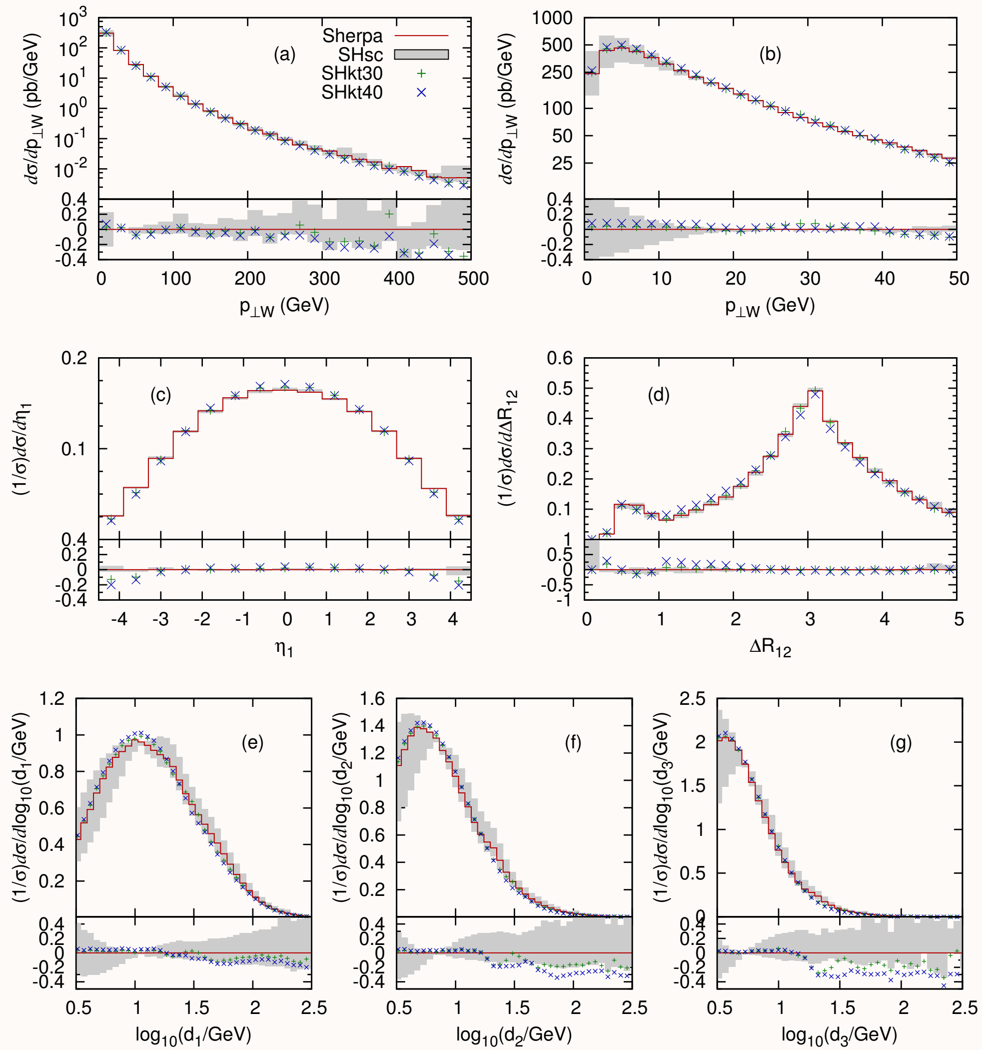
- the jet definition used in the MEs;
- the way of accepting/rejecting jet configurations stemming from the MEs;
- the details concerning the starting conditions and jet vetoing inside the parton showering.
- See also studies by Lönnblad, Lavesson (arXiv:0712.2966).

Study of systematics of the merging approaches

Alpgen (+PS by Herwig) (left) *vs.* **Sherpa** (right)

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





➡ Exploring the differences is essential to assess the systematic uncertainties of multijet calculations. ➡ Test, validate and tune new MC tools at Tevatron, now!

Inclusive jet cross sections at the LHC

ALpt *matching scale variations:*

ALsc *μ_R variations at vertices of clustering:*

SHkt *merging scale variations:*

SHsc *μ_R & μ_F variations: (applied in ME & PS phase)*

SHas *only μ_R variations:*

SHin *μ_F variations in initial ME integrations:*

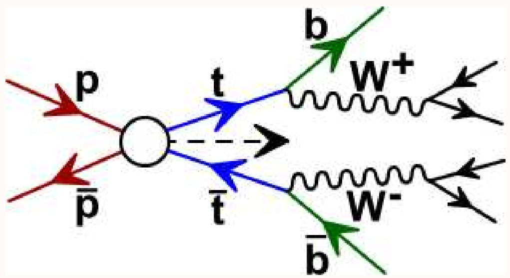
Code	σ[tot]	$\sigma[\geq 1$ jet]	$\sigma[\geq 2$ jet]	$\sigma[\geq 3$ jet]	$\sigma[\geq 4$ jet]
Alpgen, def	10170	2100	590	171	50
ALpt30	10290	2200	555	155	46
ALpt40	10280	2190	513	136	41
ALpt60	10140	2030	403	93	28
ALscL	10590	2520	790	252	79
ALscH	9870	1810	455	121	33
Sherpa, def	8803	2130	574	151	41
SHkt15	8840	2260	642	175	45
SHkt30	8970	2020	481	120	32
SHkt40	9200	1940	436	98.5	24
SHkt60	9650	1990	431	86.8	19
SHscL	7480	2150	675	205	58
SHscH	10110	2080	489	118	30
SHasL	9095	2366	677	190	53.2
SHasH	8597	1924	486	122	32.1
SHinL	7208	1918	552	156	43.1
SHinH	10347	2310	584	148	39.3

News on CKKW: heavy quark production + decays

Narrow width approximation ➡ **full ME factorizes into production & decay parts**

- AMEGIC++ ... use its decay-chain operation mode
  projection onto relevant Feynman diagrams, Breit-Wigner intermediate particle masses
- APACIC++ ... enable production + decay showers based on massive splittings
  e.g. $e^+e^- \to t\bar{t}$ FS shower for tops
  e.g. $t \to W^+b$ IS shower for top, FS shower for bottom
- CKKW ... separate and independent merging of MEs with extra jets & showers in production and any decay
- CKKW ... reweight and veto by respecting the factorization
- Schematically, e.g.: $\boldsymbol{p\bar{p} \to t\,[\to W^+bg\{1\}]\;\bar{t}\,[\to W^-\bar{b}g\{1\}]\;g\{1\}}$

$p\bar{p} \to t\;[\to W^+b]\;\bar{t}\;[\to W^-\bar{b}]$
$p\bar{p} \to t\;[\to W^+b]\;\bar{t}\;[\to W^-\bar{b}]\;g$
$p\bar{p} \to t\;[\to W^+b]\;\bar{t}\;[\to W^-\bar{b}\;g]$
$p\bar{p} \to t\;[\to W^+b]\;\bar{t}\;[\to W^-\bar{b}\;g]\;g$
$p\bar{p} \to t\;[\to W^+b\;g]\;\bar{t}\;[\to W^-\bar{b}\;g]\;g$
...



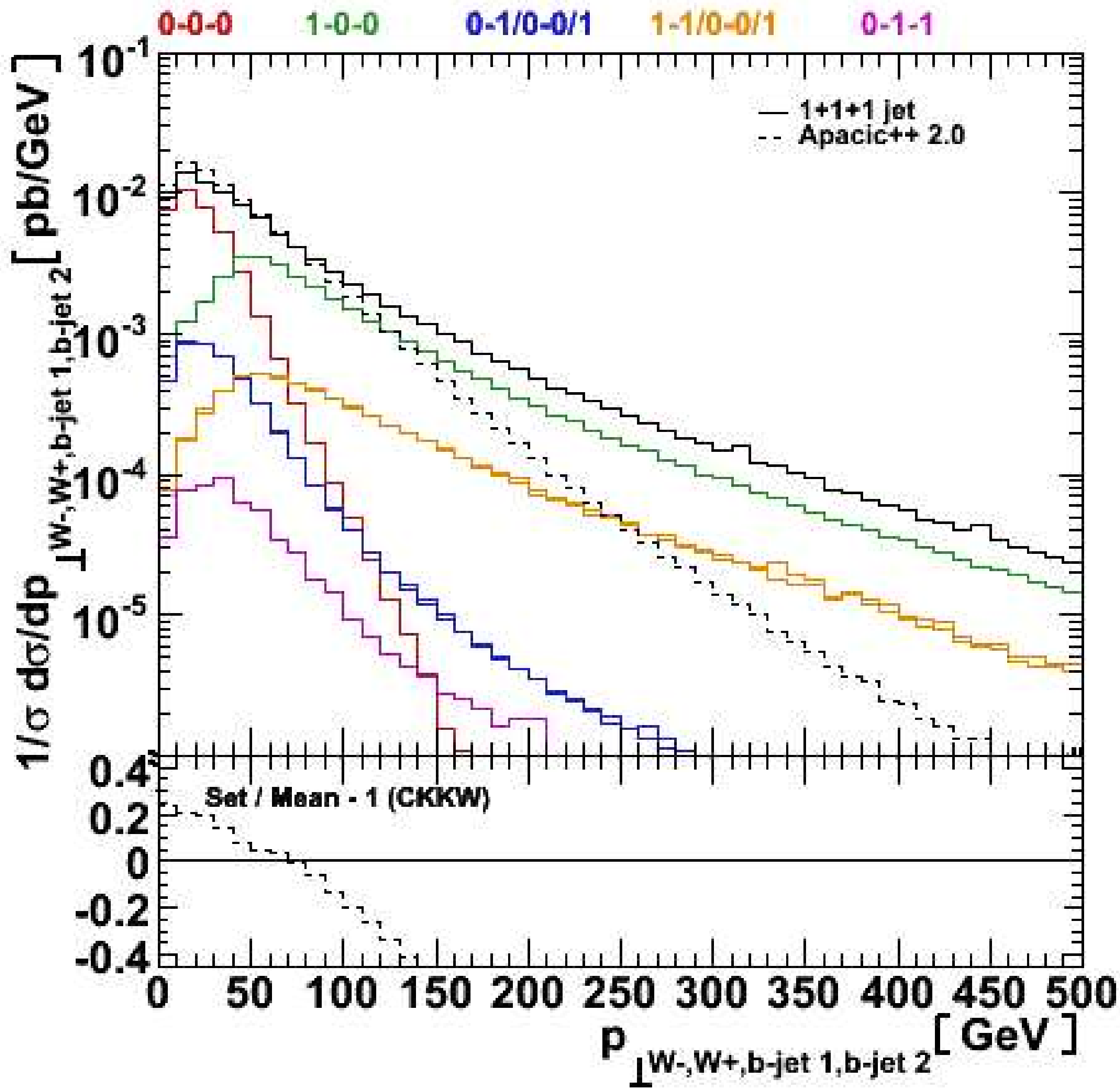
$\Rightarrow$ "CKKW 1-1-1"

News on CKKW: top pair production & decays

➡ **Some preliminary LHC results ...**

p_T of $t\bar{t}$-system

CKKW 1-1-1
compared to answer given by showering only.



- ## Signal studies

Experimentalists would like to better understand the impact of additional jets (ISR/FSR) and get an estimate on the uncertainty of available MC predictions.

- ## $t\bar{t}$+jets as background

Accurate treatment required to specify new-physics searches.

News on CKKW: top pair production & decays

➡ **Some preliminary Tevatron II results ...**

p_T of $t\bar{t}$-system

CKKW 1-1-1 compared to answer given by showering only.

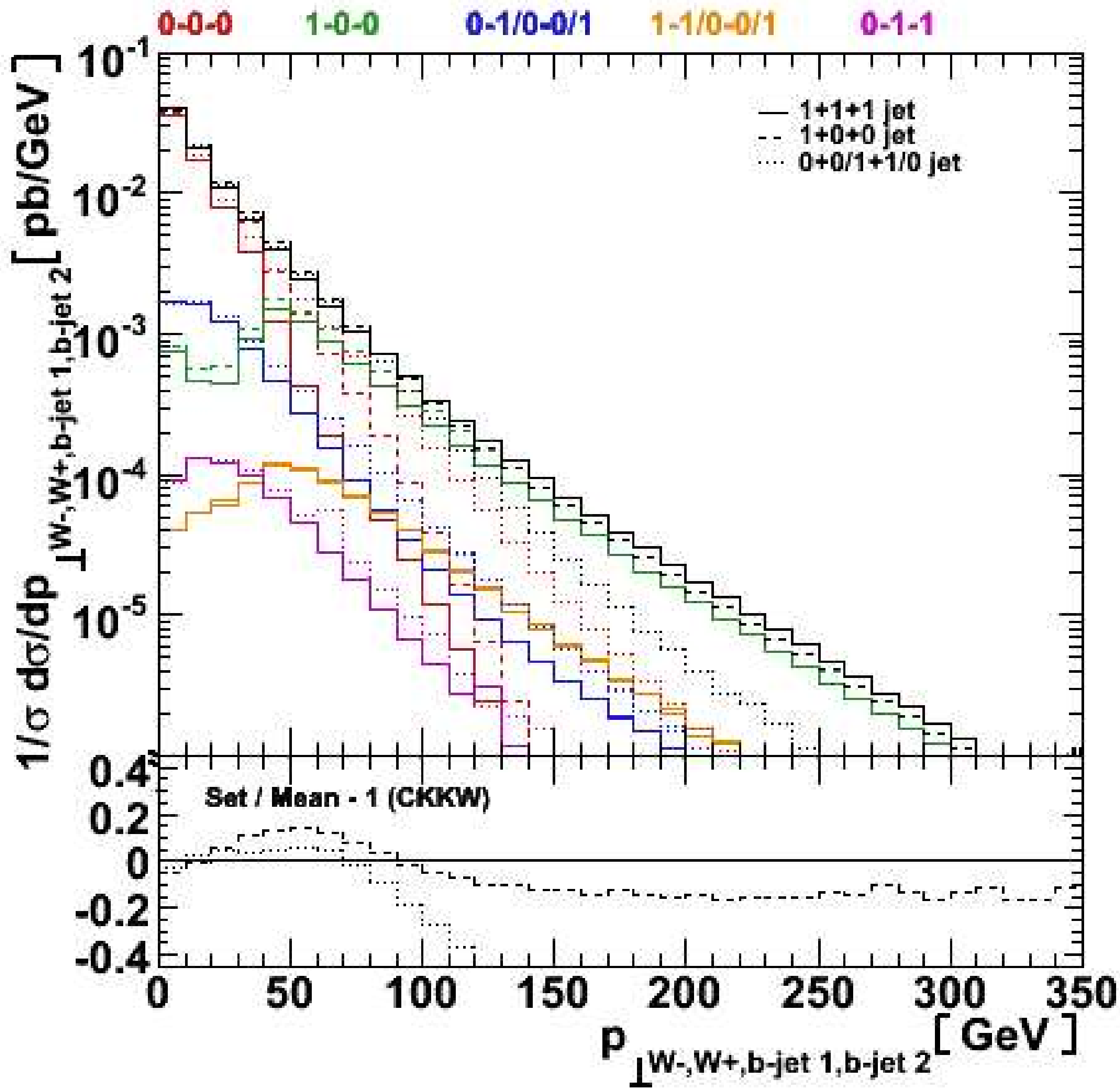
- **Signal studies**

Experimentalists would like to better understand the impact of additional jets (ISR/FSR) and get an estimate on the uncertainty of available MC predictions.

- **$t\bar{t}$+jets as background**

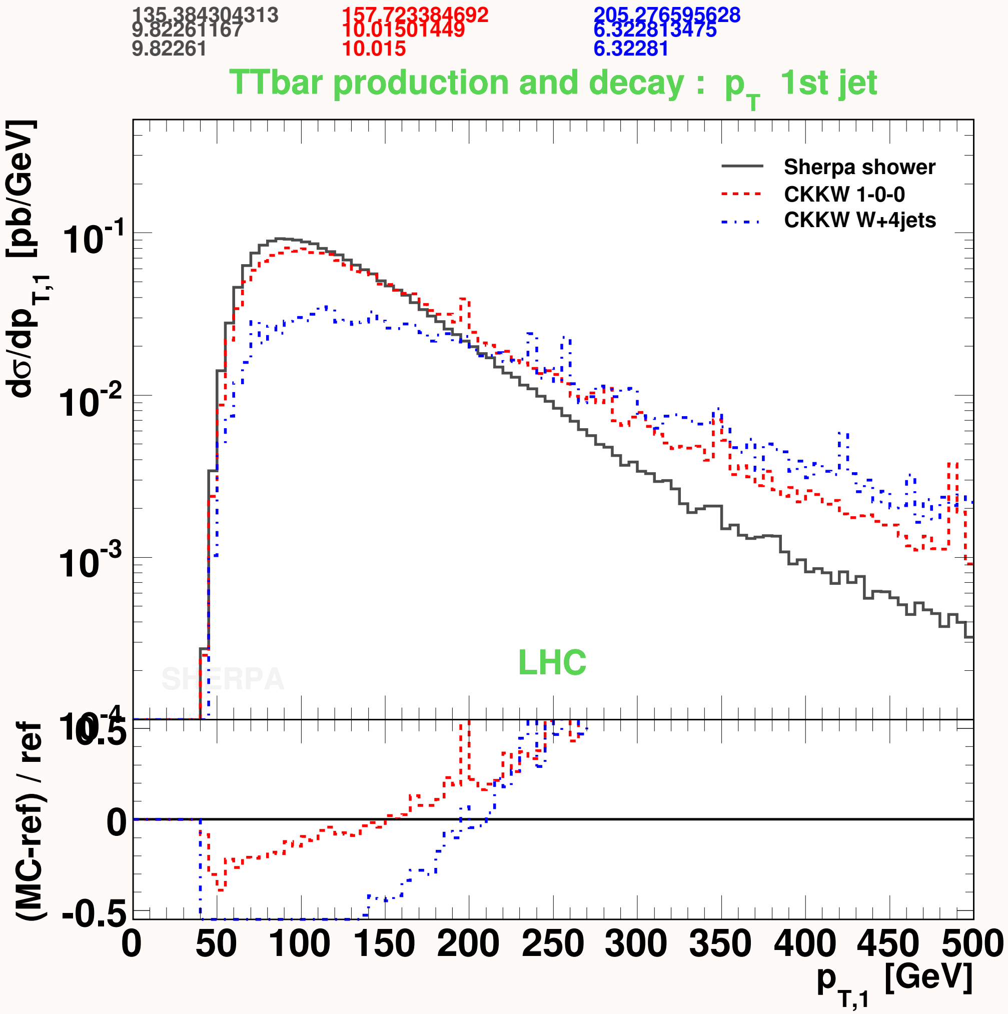
Accurate treatment required to specify new-physics searches.

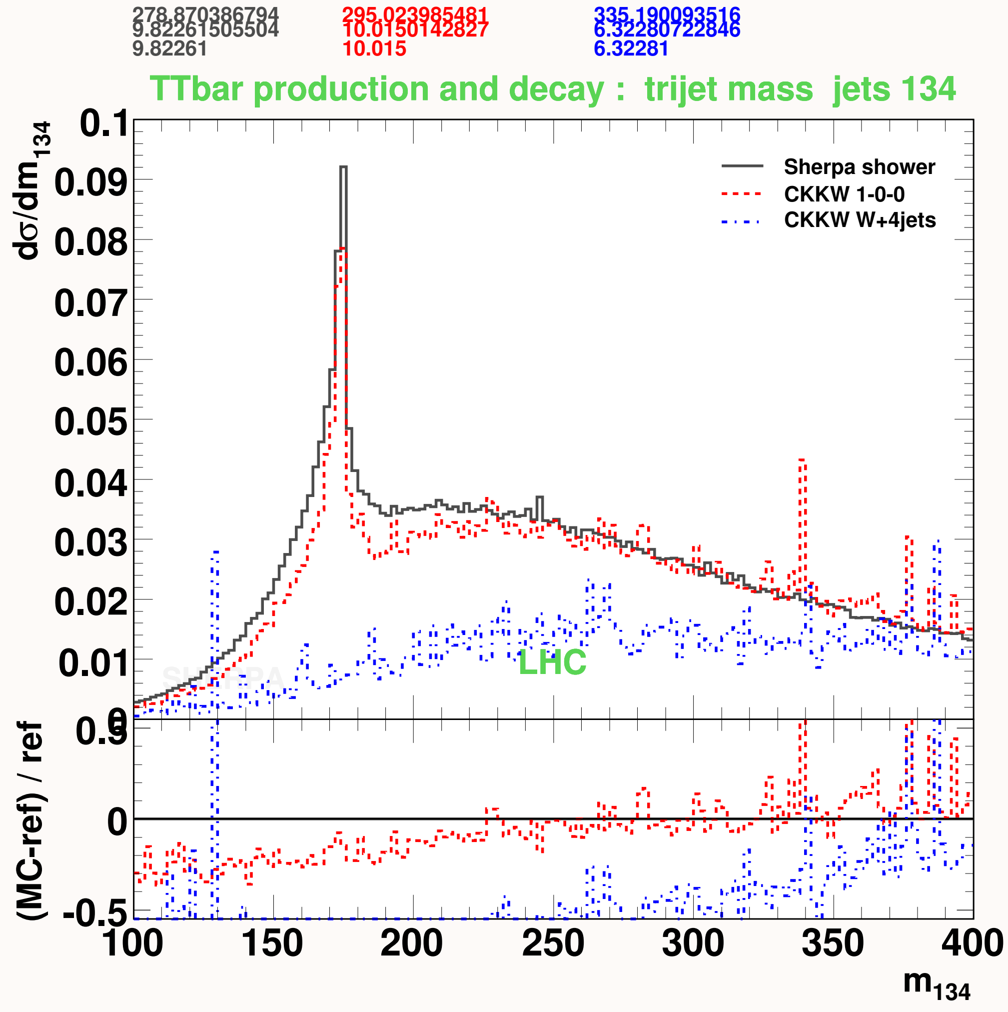
➡ **More CKKW studies.**



News on CKKW: top pair production & decays

- Sherpa: $pp \to t\bar{t} \to e^+\nu_e jjjj$: p_T of 1st jet & trijet mass of combination 134.





- require at least 4 jets ($p_T > 40$GeV, $|\eta| < 2.5$, $D = 0.4$); lepton cuts ($p_T > 20$GeV, $|\eta| < 2.5$); missing energy ($\not{E}_T > 20$GeV) ➡ PRELIMINARY RESULTS !!

CKKW at work – Summary

Improved (leading-order) description of hard multijet configurations together with jet fragmentation !

- Way of consistently incorporating QCD corrections provided by real-emission MEs.
- Avoids most serious problems of double counting and missing phase-space regions.
- CKKW is implemented for SM processes in Sherpa
  $\Rightarrow$ tool for jet physics.
- Thanks to the built-in tree-level ME generator AMEGIC++, real-emission MEs are easily provided.
- Shapes are in fairly good agreement with NLO predictions; rates, of course, are not NLO. Evidence that constant K-factors may be sufficient.
- Fairly process independent implementation.
- Full simulation of hadron-level events → valuable tool for experimentalists.