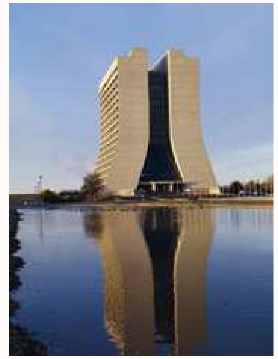
Sherpa Monte Carlo: status and new developments

[Brookhaven Forum 2008]

Jan Winter [a]

– Fermilab –



- *Monte Carlo event generator Sherpa*
- *New major release – Sherpa 1.1*
- *Sherpa projects – overview*

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

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

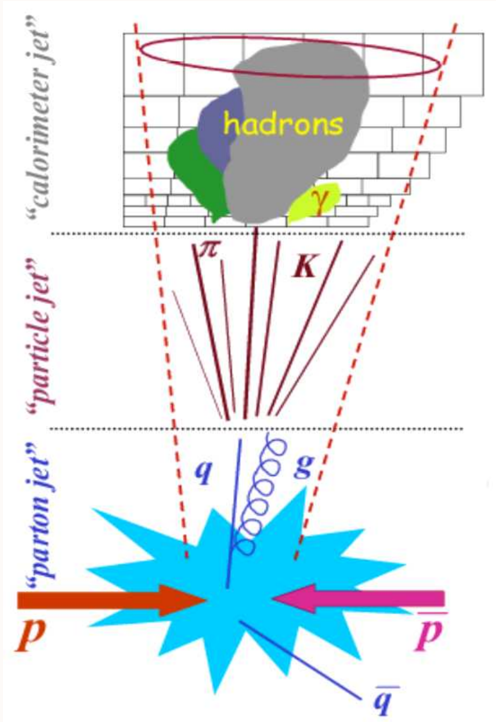
Physics at hadron colliders ...

... is largely influenced by jet physics.

- hadronic intial states: available phase space used to emit (additional) strong particles

➡ *Multijets*

- modify signals and backgrounds



Need for tools that model...!!!

Jet production ➡ *Jet evolution* ➡ *Hadronization*

Sherpa project:

➡ *provide a full-fledged, independent Monte Carlo event generator for collider physics – Sherpa 1.1* ✓

➡ *with focus on an improved modelling of QCD multijet final states*

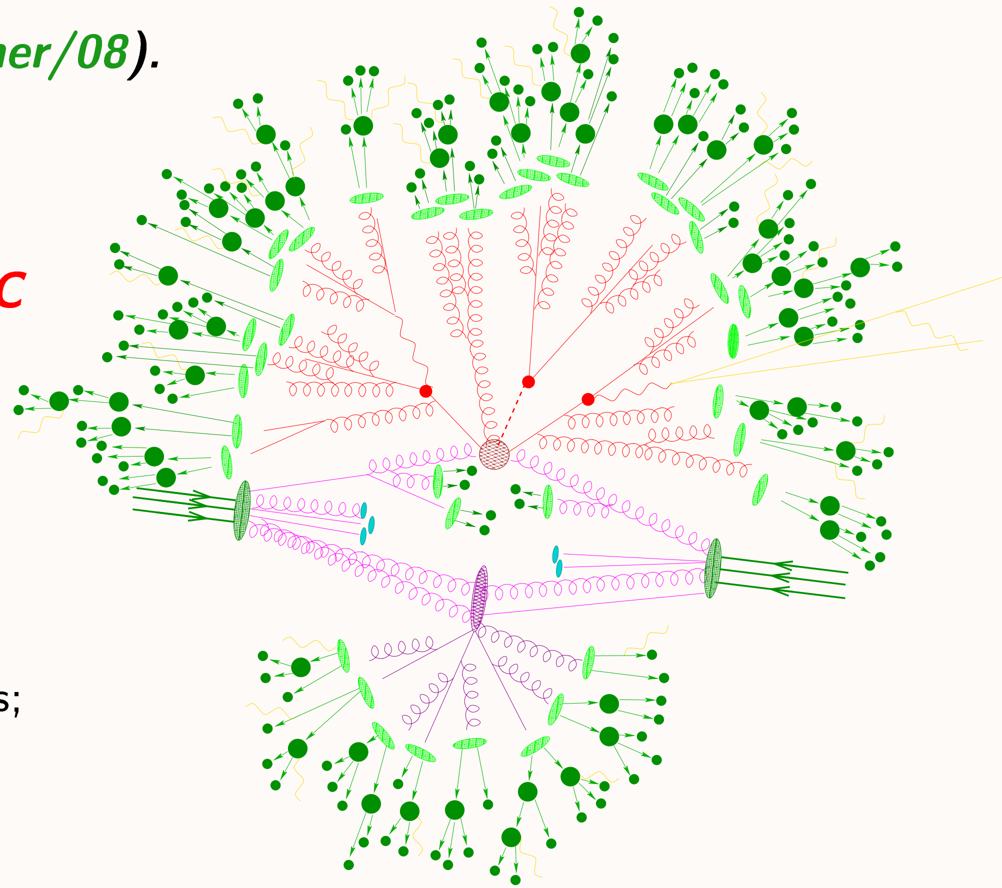
➡ *provide it as new (C++) code, which is modular, transparent, upgradeable and maintainable*

Monte Carlo event generator Sherpa

[Gleisberg, Höche, Krauss, Schälicke, Schumann, Winter, JHEP 02 (2004) 056]

➔ *Factorization approach: divide jet simulation into different phases*

➔ ***Current version: SHERPA 1.1.2 (released Summer/08).***



- ***Hard interactions: AMEGIC***
  tree-level ME generator (SM, MSSM, ADD, ...)
- ***QCD bremsstrahlung: IS + FS showers: APACIC***
  virtuality ordered, Pythia-like showers
- ***ME-PS merging according to CKKW***
- ***Multiple parton interactions: AMISIC***
  underlying event model à la Sjöstrand–Zijl model
- ***Hadronization: AHADIC***
  cluster model converting partons into primary hadrons;
  interface to Pythia's string model still available
- ***Hadron decays: HADRONS + PHOTONS***
  phase-space or effective models plus YFS treatment;
  interface to Pythia's hadron decays still available

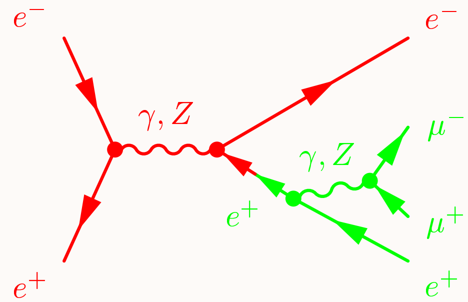
➔ predictions at the hadron-level – comparable to experimental data corrected for detector effects

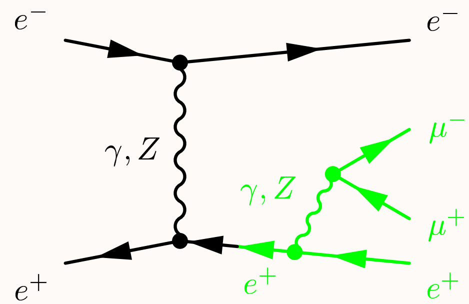
AMEGIC

[Krauss, Kuhn, Soff, JHEP 02 (2002) 044]

➯ ***Key feature: SHERPA has its own, built-in tree-level ME generator.***

- automatic generation of tree-level Feynman diagrams
- translation into helicity amplitudes
- factor out common parts
- multichanneling (singularities known!)
- VEGAS optimization of single channels
- well validated tool ***...!!!*** SM, MSSM, ADD





➯ ***Fully automated & efficient calculation of (polarized) cross sections & parton-level events.***

➯ ***AMEGIC generates SM and beyond SM events.*** ⇦

- SM+ggH+AGC+4th family; THDM; MSSM (fully general); ADD model of extra dimensions; Phantom-Higgs model; Axigluons; eff. model for hypercolour.
- ***Expandable:*** dynamic add-on model libs; 2 steps: (1) particles & model parameters
  (2) interaction vertices
- more general: ***FeynRules reader*** will be provided

➯ ***AMEGIC allows for specification of decay chains.***

$$\mathcal{A}^{(n)} = \mathcal{A}^{(n_{\rm prod})}_{\rm prod} \otimes \prod_{i\,\in\,\rm decays} \mathcal{P}_i \mathcal{A}^{(n_i)}_{{\rm dec}_i}$$

- take only resonant graphs into account, preserve correlations: off/on-shell mode available

ME+PS merging – CKKW method

[CATANI, KRAUSS, KUHN, WEBBER, JHEP 11 (2001) 063]

[KRAUSS, JHEP 08 (2002) 015]

- *combine parton-shower pros (soft emissions)* +

  ME pros (hard emissions, quantum interferences, correlations)
- *avoid double counting and missing phase space regions*

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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}
- parton showers: (intra-)jet evolution $Q_{jet} > Q > Q_{\text{cut-off}}$
- MEs regularized by $Q_{ij}^2 \;=\; 2\min\left\{p_T^{(i)},\, p_T^{(j)}\right\}^2 \frac{\left[\cosh(\eta^{(i)}-\eta^{(j)})-\cos(\phi^{(i)}-\phi^{(j)})\right]}{D^2} > Q_{jet}^2$

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Eliminate/sizeably reduce Q_{jet} dependence.

- identify a possible shower history of MEs via backward clustering
- accordingly reweight MEs by combined α_s and Sudakov weight
- add showers to ME partons and veto emissions above Q_{jet}

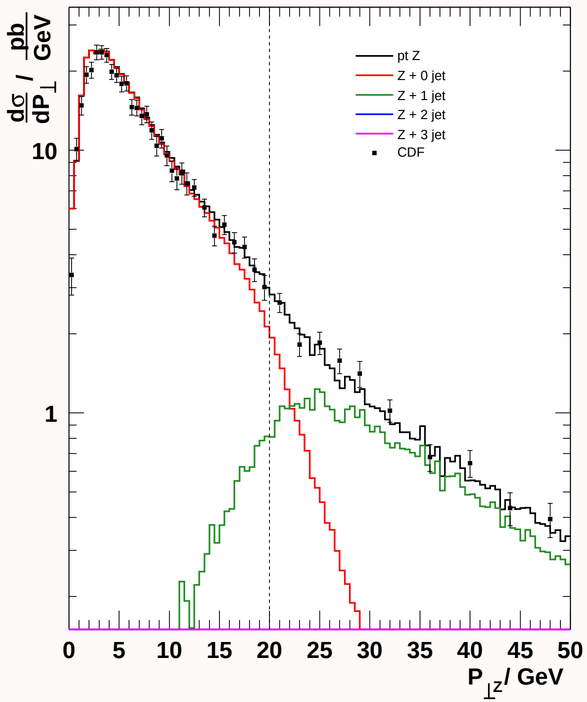
CKKW – key feature of Sherpa

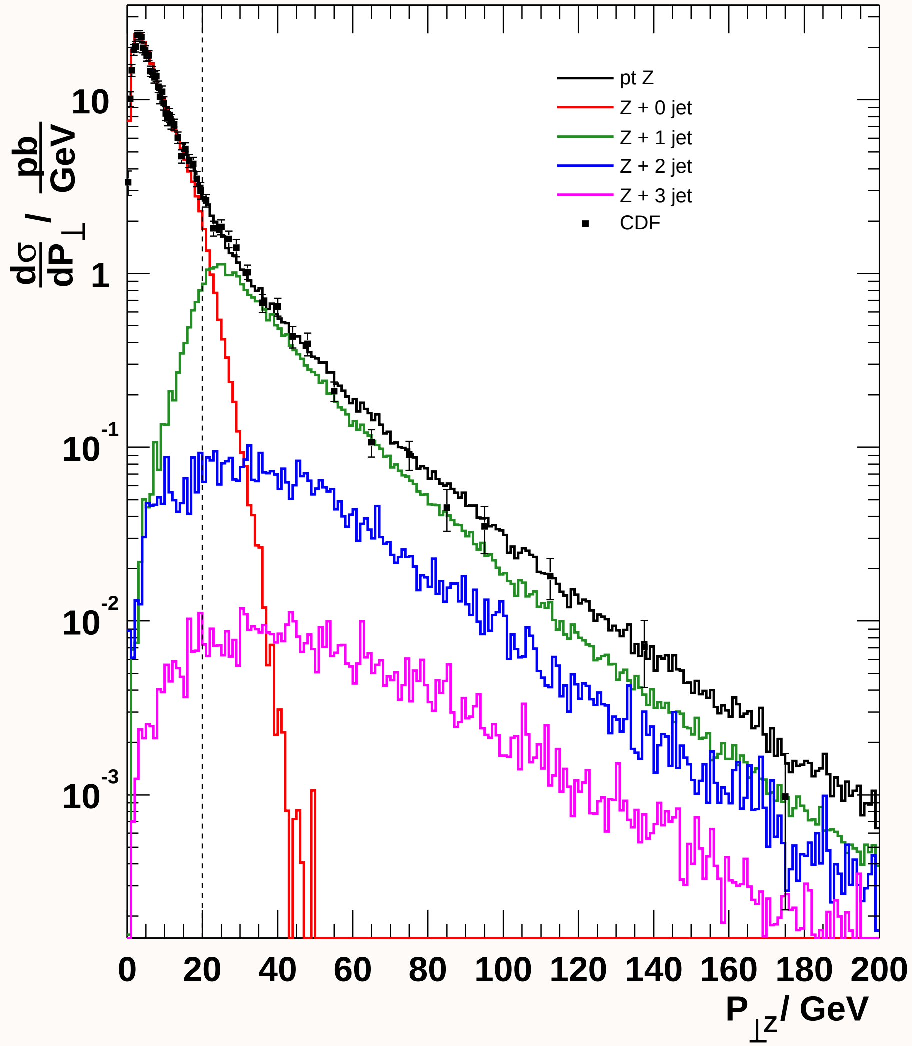
- *Method has been implemented within Sherpa in full generality.*
- *Uses built-in ME generator AMEGIC.*
- *Process-independent implementation.*

- ***Validation and applications***

  $W/Z/WW$+jets, QCD jets, $Zb\bar{b}+X$, VBF, tops, $gg \to H+X$, b-associated Higgs

- constant K-factor
- intrinsic k_T-smearing of order 1 GeV

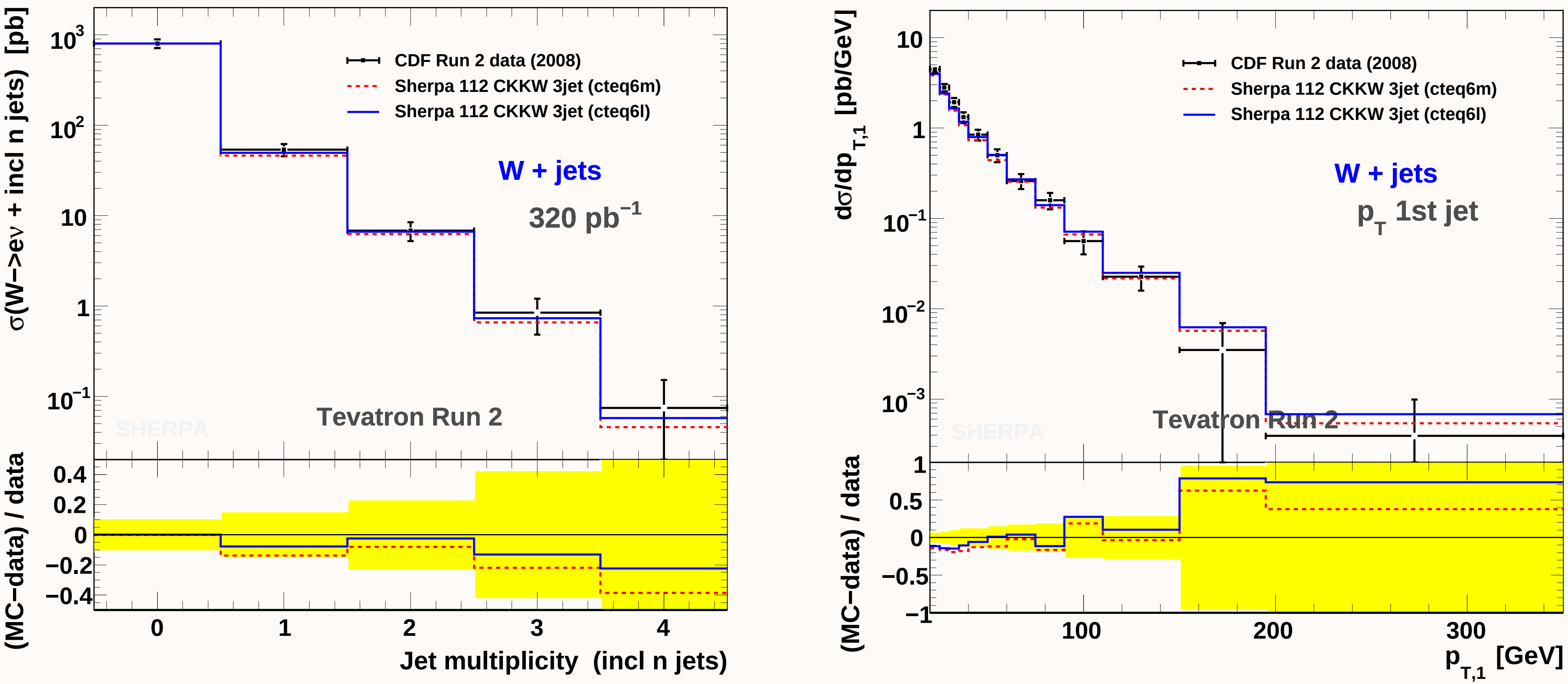




Comparison with recent CDF data: W+jets production

[T. Aaltonen et al., PRD **77** (2008) 011108]

- Monte Carlos need to be validated and tuned against most recent Tevatron data.
- Discriminating power increases as more and more data is coming in. Use to refine algorithms.
- Sherpa predictions normalized to total inclusive cross section. Two choices of PDFs.



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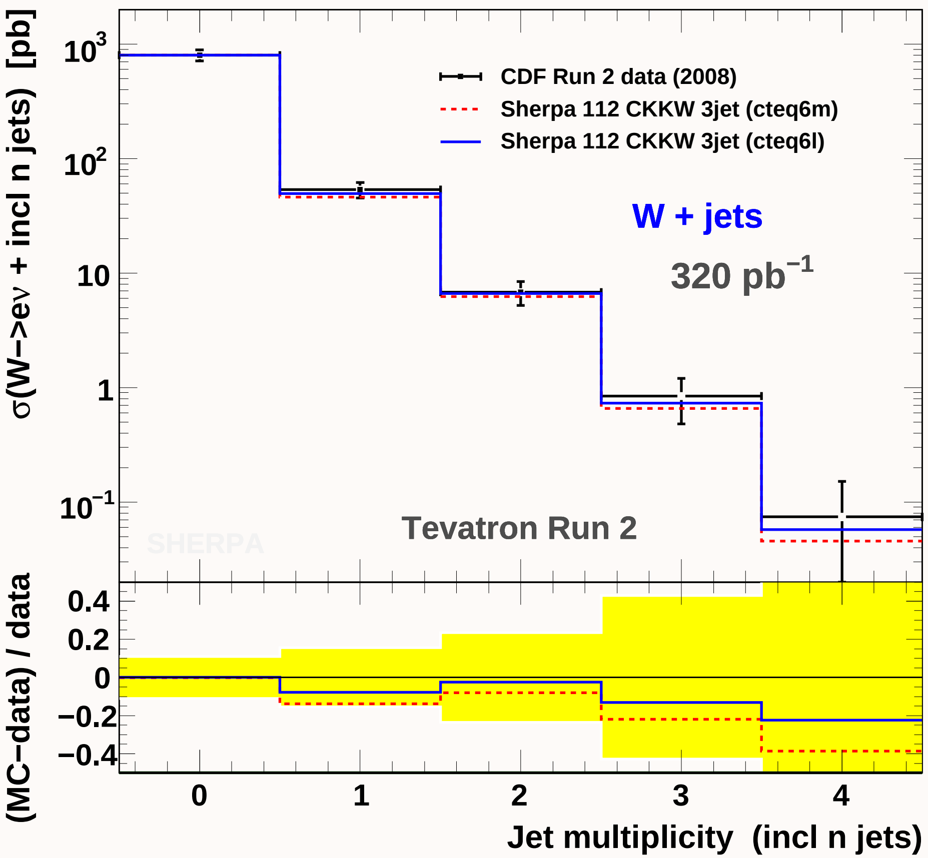

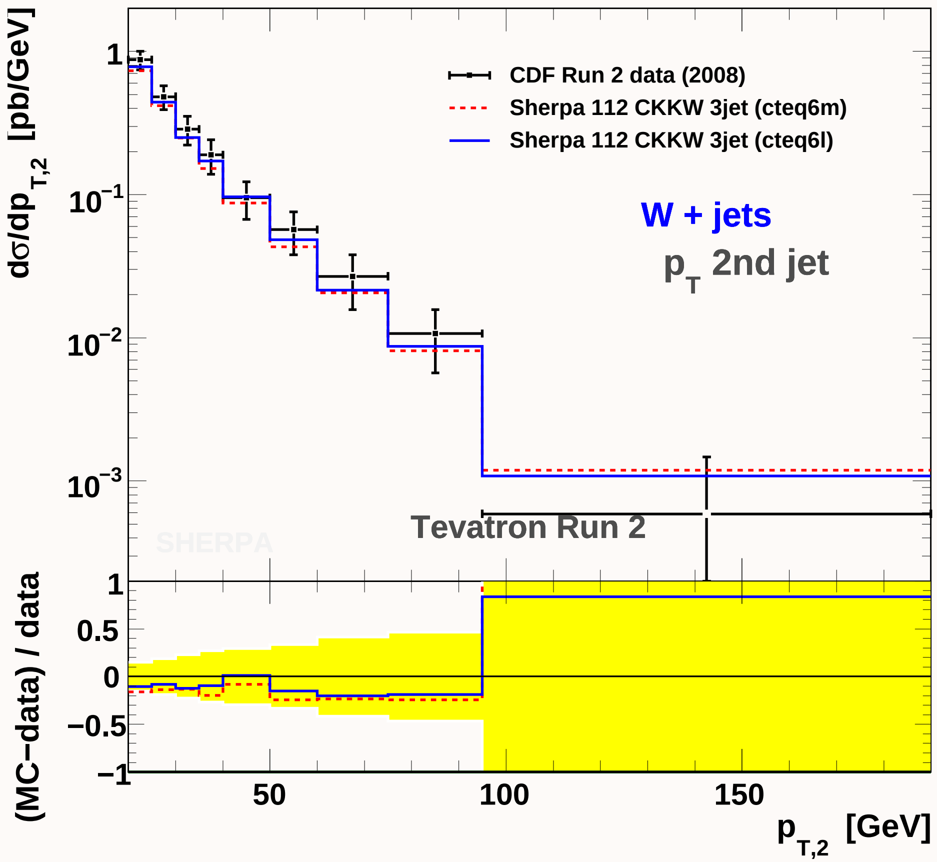

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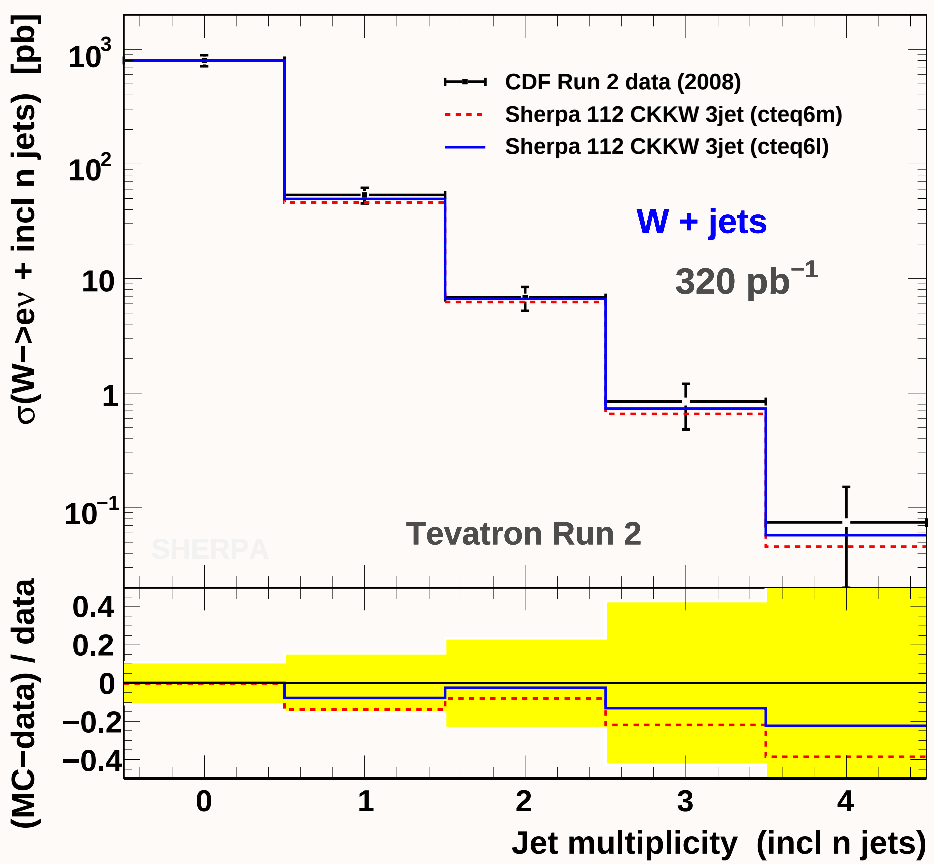

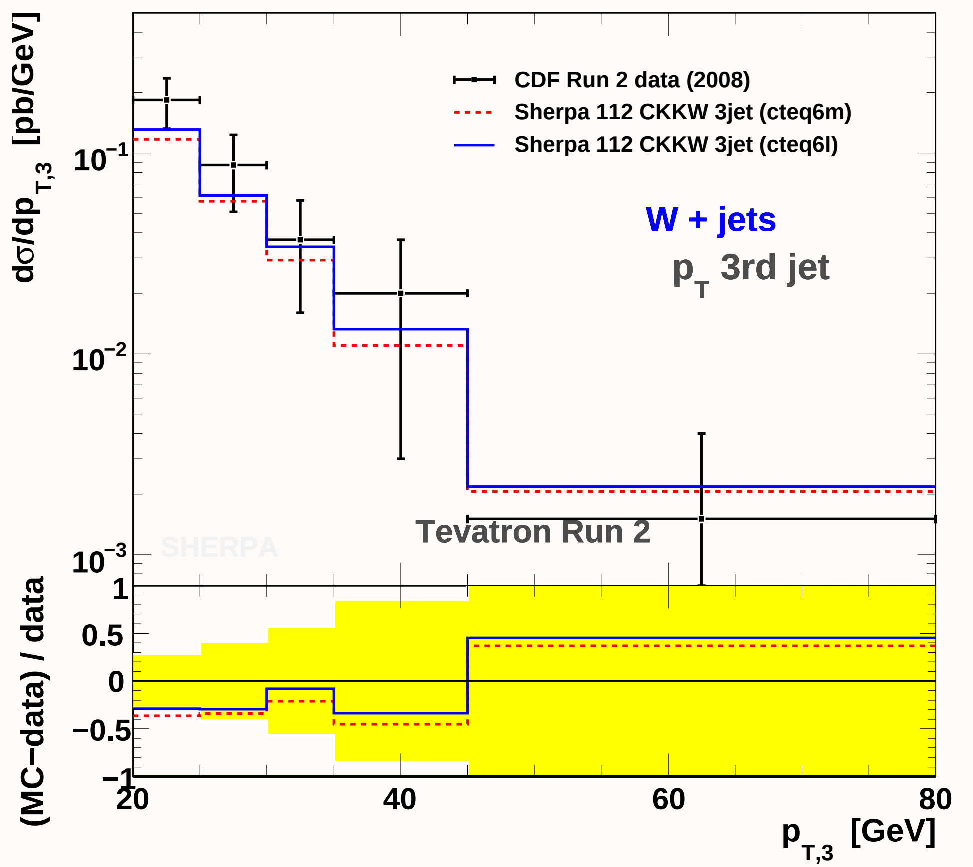

News on CKKW: heavy-quark production + decays

➡ ***Intermediate resonances*** ➡ ***full ME can be factorized into production & decays***

- AMEGIC ... make use of its decay-chain mode
- APACIC ... production + decay showers based on massive splittings
- CKKW ... separately merge MEs+showers in production and any decay (factorization)
- schematically, e.g.: $p\bar{p} \to t\,[\to W^+ b g\{1\}]\ \bar{t}\,[\to W^- \bar{b} g\{1\}]\ g\{1\}$ ⇒ "CKKW 1-1-1"

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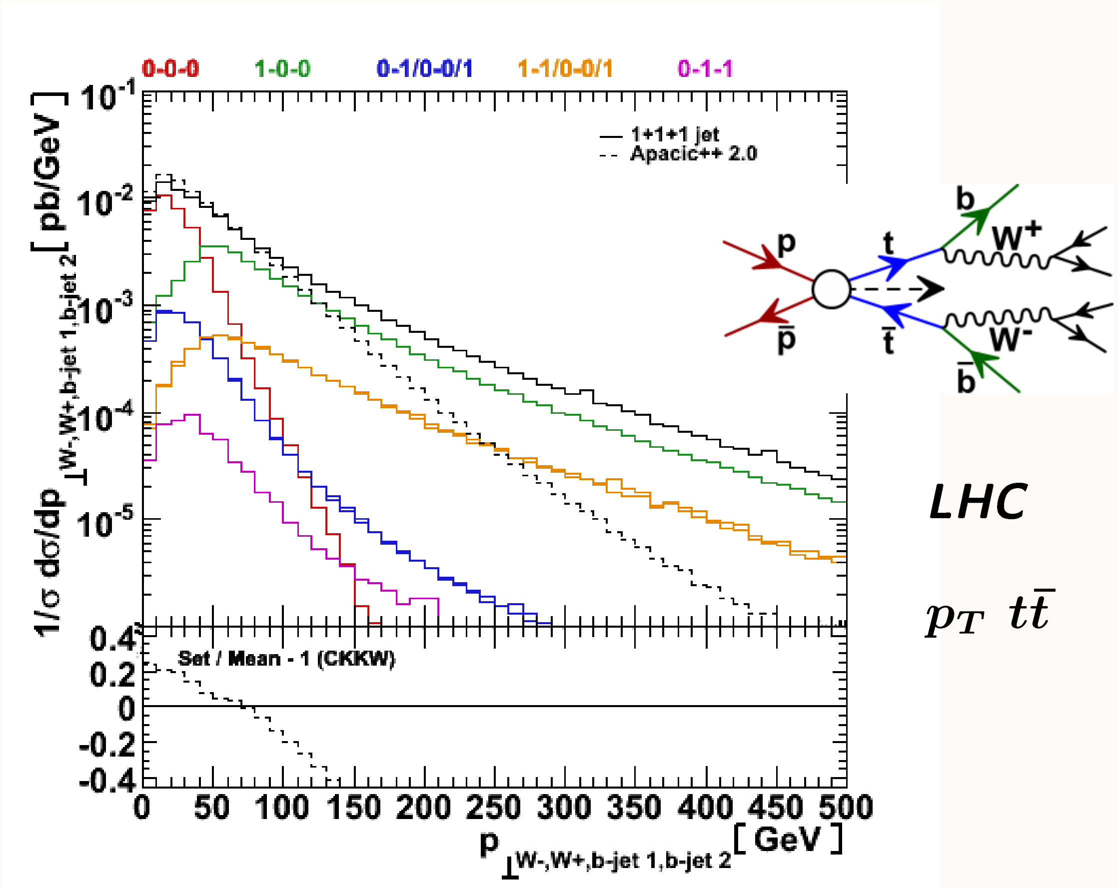
$$p\bar{p} \to t\,[\to W^+ b\ g]\ \bar{t}\,[\to W^- \bar{b}\ g]\ g$$
$$\ldots$$



LHC

$p_T\ t\bar{t}$

- $t\bar{t}$ as signal:

  Impact of additional jets (ISR/FSR) more important at LHC.

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

  Reliable uncertainty estimates needed to specify new-physics searches.

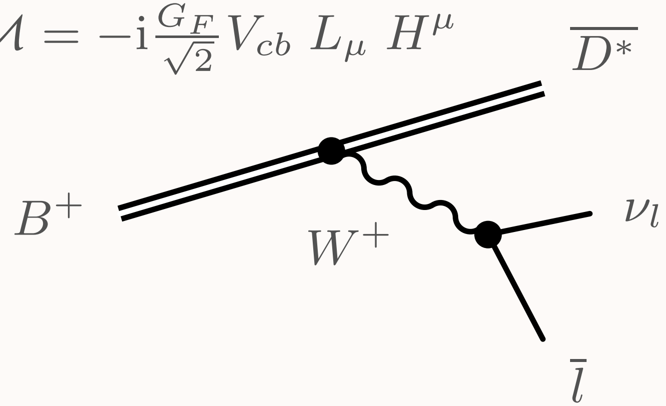
HADRONS: hadron decays for Sherpa

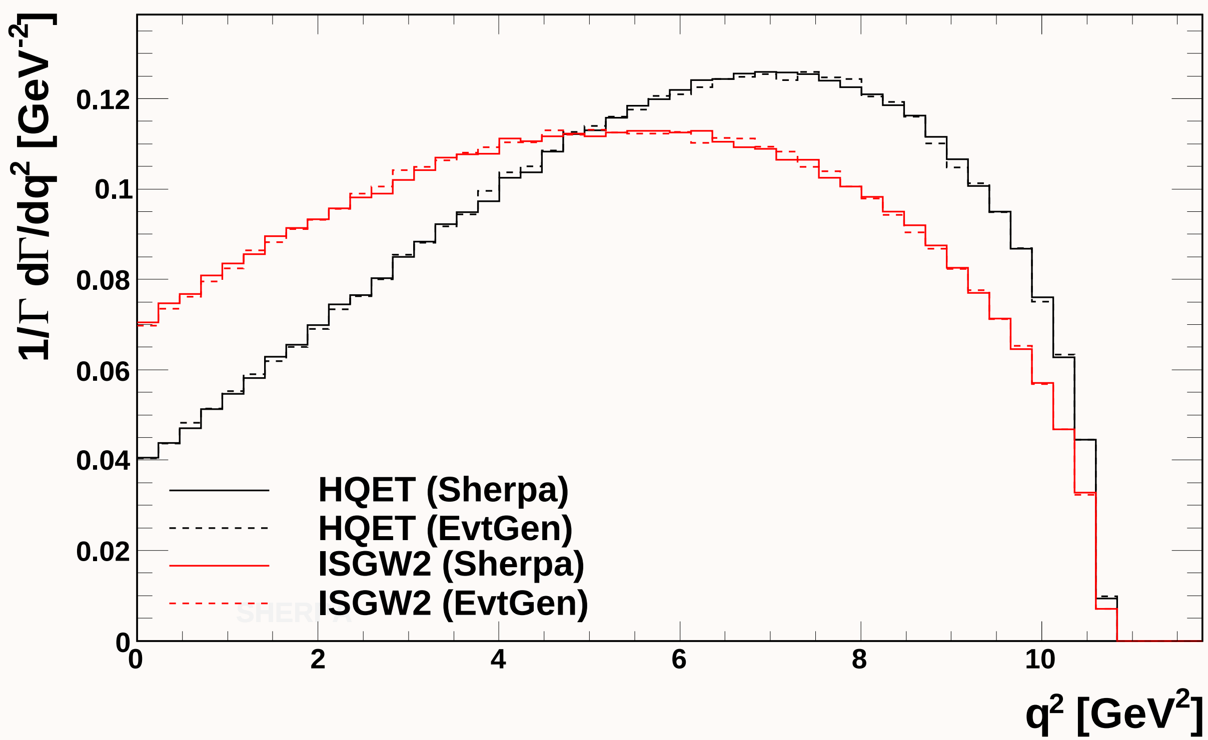
SHERPA's package to accomplish hadron and τ decays. [SIEGERT, KRAUSS, LAUBRICH]

- Branching ratios (e.g. from PDG) as input for decay tables.
- Decay kinematics à la $\mathrm{d}\Gamma(P \to p_1 \dots p_n) = \frac{1}{2M} \cdot |\mathcal{M}(P, p_1 \dots p_n)|^2 \cdot \mathrm{dLiPS}$
- Different form factor models for many decay channels (see plot).
- τ decay lib ... uses elaborated models (KS, RχPT).
- Hadron decay lib ... heavily extended during last 2 years: B, D, light mesons.
- 2-body decays according to spin.
  Other features:
  spin correlations,
  neutral meson mixing ($B\bar{B}$),
  CP violation, even rare decays.

Example: $B^+ \to \overline{D^*}(2007)^0 \nu_e e^+$

$$\mathcal{M} = -\mathrm{i}\frac{G_F}{\sqrt{2}} V_{cb}\, L_\mu\, H^\mu$$



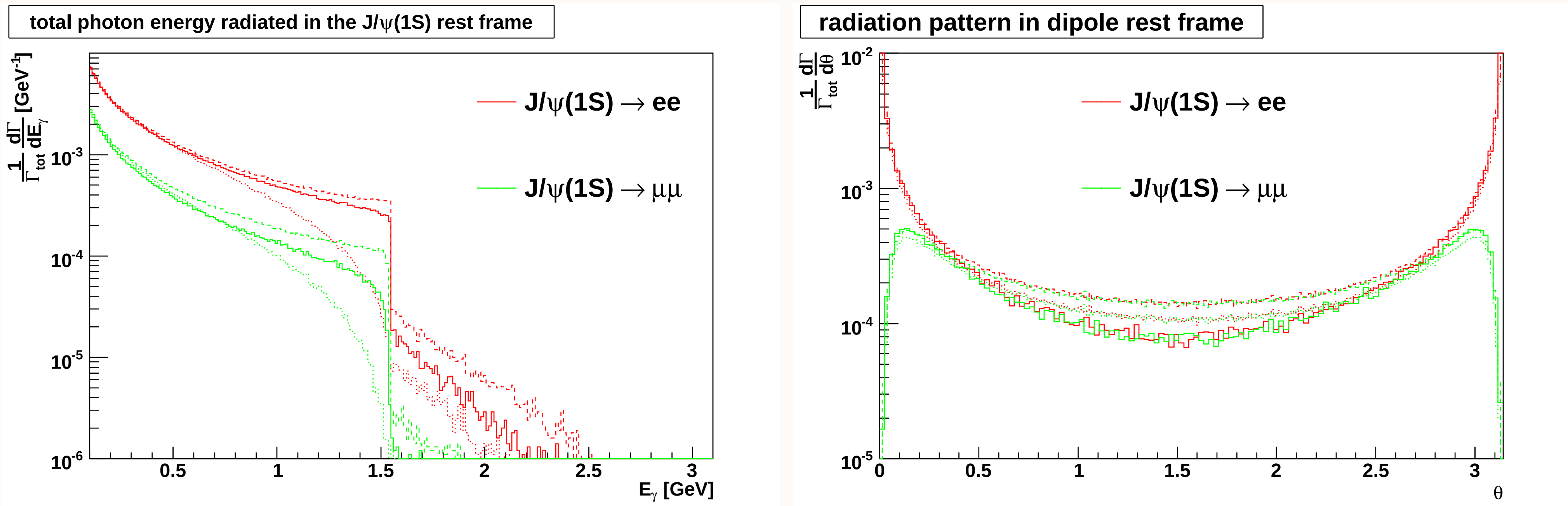


PHOTONS

➡ ***$U(1)_{\mathrm{em}}$ charged particles radiate off photons.***

- account for higher-order QED effects in hadron & τ decays: YFS approach.
  - exact for soft-photon radiation (real and virtual) ($k \to 0$)
  - perturbative series for hard-emission effects
  - hard emissions at $\mathcal{O}(\alpha)$ by approx matrix elements (quasi-coll limit)

    $\Rightarrow$ some cases by exact $\mathcal{O}(\alpha)$ real/virtual matrix elements



- Dotted: soft photons only.
- Dashed: coll approx ME. Solid: exact ME.

[Schönherr, Krauss, arXiv:0810.5071 [hep-ph]]

Sherpa projects:

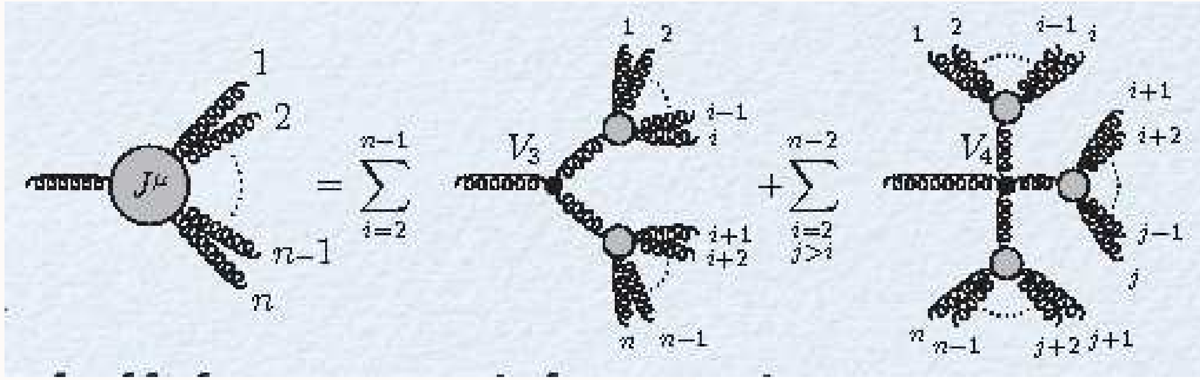
new developments ...

- *COMIX – tree-level SM ME generator based on colour-dressed Berends–Giele recursion relations.*
- *Automated Catani–Seymour dipole subtraction.*
- *Parton shower based on Catani–Seymour dipole factorization.*
- *Colour-dipole shower for hadronic collisions.*
- *Multiple-interactions model based on k_T-factorization (BFKL evolution):* [Höche, Krauss, Teubner, arXiv:0705.4577 [hep-ph]].

COMIX – ME generator for high multiplicities

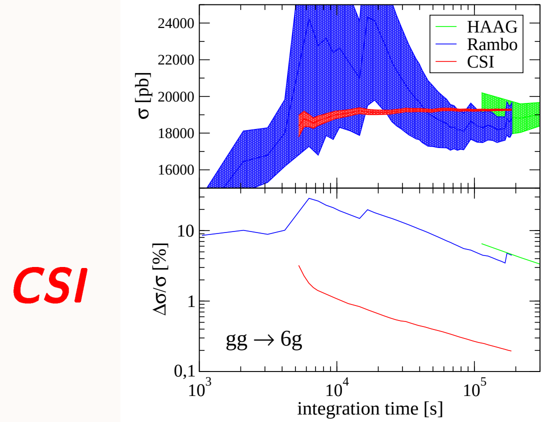
[GLEISBERG, HÖCHE, ARXIV:0808.3675 [HEP-PH]]

- based on colour-dressed Berends–Giele recursion relations [DUHR, HÖCHE, MALTONI, 2006]
- SM **fully** implemented



- Key point: vertex decomposition of all four-particle vertices (Growth in computational complexity determined by # of legs at vertices)

- Phase-space generation: can be accomplished recursively on the same footing as ME calculation
  ➡ sample colours, multichanneling of HAAGs on the flight



- Example: performance in QCD benchmark (2→n gluon)

World record ;-)

gg → ng	Cross section [pb]				
n $\sqrt{s}$ [GeV]	8 1500	9 2000	10 2500	11 3500	12 5000
Comix	0.755(3)	0.305(2)	0.101(7)	0.057(5)	0.026(1)
Phys. Rev. D67(2003)014026	0.70(4)	0.30(2)	0.097(6)		
Nucl. Phys. B539(1999)215	0.719(19)				

Automated Catani–Seymour dipole subtraction

Catani–Seymour dipole subtraction [Catani, Seymour, 1997; Catani et al., 2002]

- universal framework for jet cross sections @ NLO
- factorization formulae for real emission process (phase space & matrix element)
- construct subtraction terms $d\sigma^{\mathrm{A}}$ from Born process using universal dipole terms
- yields local approximation for the real-emission process, correct in soft & coll limits

$$\sigma = \sigma^{\mathrm{LO}} + \sigma^{\mathrm{NLO}} = \sigma^{\mathrm{LO}} + \int_{m+1} \left[d\sigma^{\mathrm{R}}_{\epsilon=0} - d\sigma^{\mathrm{A}}_{\epsilon=0} \right] + \int_{m} \left[d\sigma^{\mathrm{V}} + \int_{1} d\sigma^{\mathrm{A}} \right]_{\epsilon=0}$$

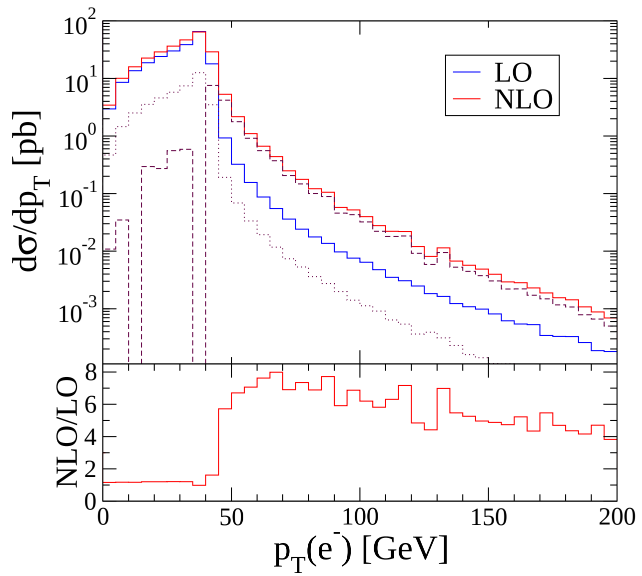
Fully automated generation of the real correction and all dipole subtraction terms

[Gleisberg, Krauss, EPJC53 (2008) 501]

- excellent numerical stability in all terms
- phase-space integration methods provided
- limits on particle multiplicities comparable to those of LO MEs
- interface one-loop MEs

→ NLO parton-level event generator

$p\bar{p} \to W^- \to e^- \bar{\nu}_e$



PS based on Catani–Seymour dipole factorization

Universal dipole terms describe parton splittings, momenta mappings are invertible

➡ basic ideas for a new parton shower *[Nagy,Soper / Dinsdale, Weinzierl / Schumann,Krauss]*

- dipole terms used to describe $1 \to 2$ splittings
- exponentiation in a Sudakov form factor (large-N_C limit, spin averaging)
- correct soft & collinear limits, local momentum conservation (spectator for $2 \to 3$ kinematics)
- subtraction formalism works for massive emitters too ➡ beneficial for shower formalism

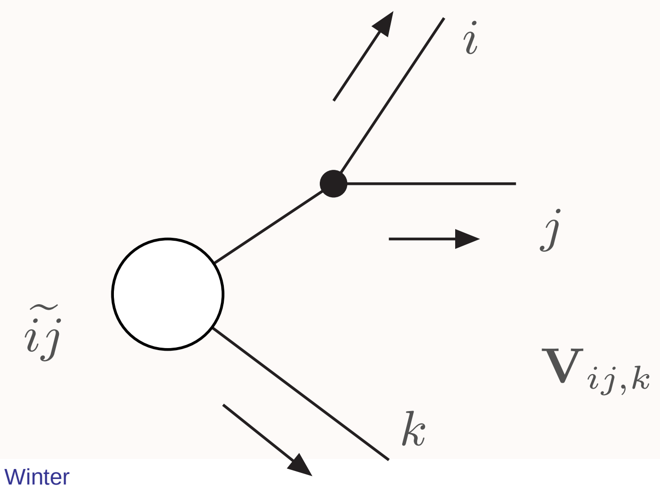
Example: final-state final-state dipoles

emitter+spectator: $\tilde{p}_{ij} + \tilde{p}_k \to p_i + p_j + p_k$

variables: $y_{ij,k} = \frac{p_i p_j}{p_i p_j + p_i p_k + p_j p_k}$, $z_i = \frac{p_i p_k}{p_i p_k + p_j p_k}$

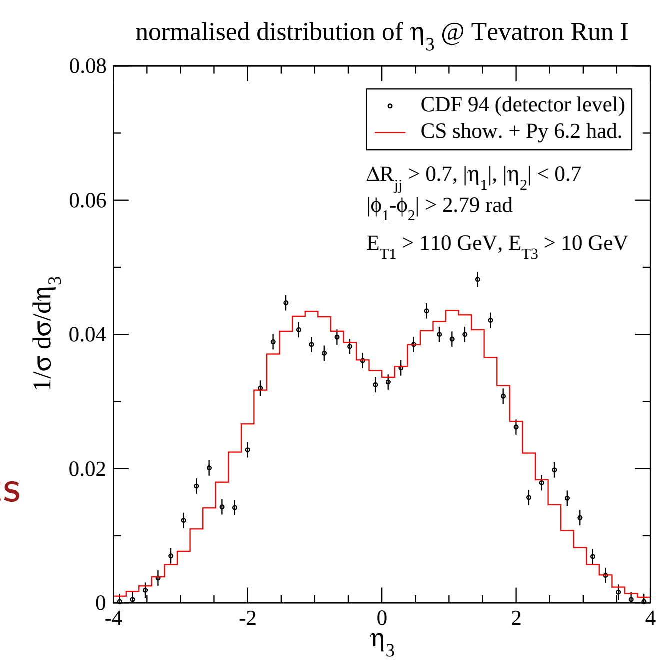
splitting function, e.g. $\mathrm{q}_{ij} \to \mathrm{q}_i \mathrm{g}_j$ ➡

$$\langle V_{\mathrm{q}_i \mathrm{g}_j, k}(z_i, y_{ij,k}) \rangle = C_F \left\{ \frac{2}{1 - z_i + z_i y_{ij,k}} - (1 + z_i) \right\}$$



CS-shower [Schumann, Krauss, JHEP 03 (2008),038]

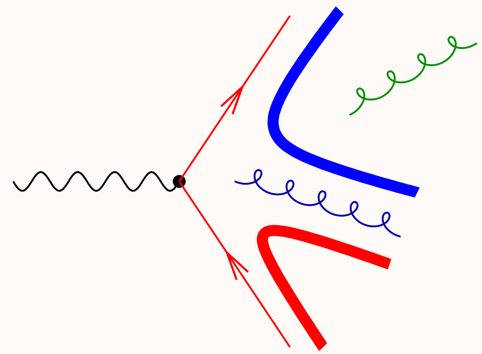
Colour coherence effects in QCD (three-)jet production ✓



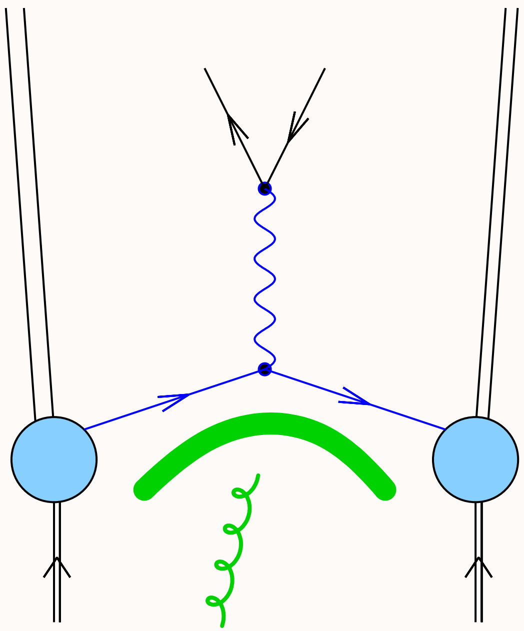
Colour dipole shower for hadronic collisions

[Winter, Krauss, JHEP 07 (2008),040]

- as alternative to conventional parton showers: exploit antenna structure of QCD to describe multiparton emission
- antennae formed by colour-connected partons: colour dipoles
- successful ***Lund CD Model*** at LEP & HERA
- beyond PT: dipoles including beam remnant(s)



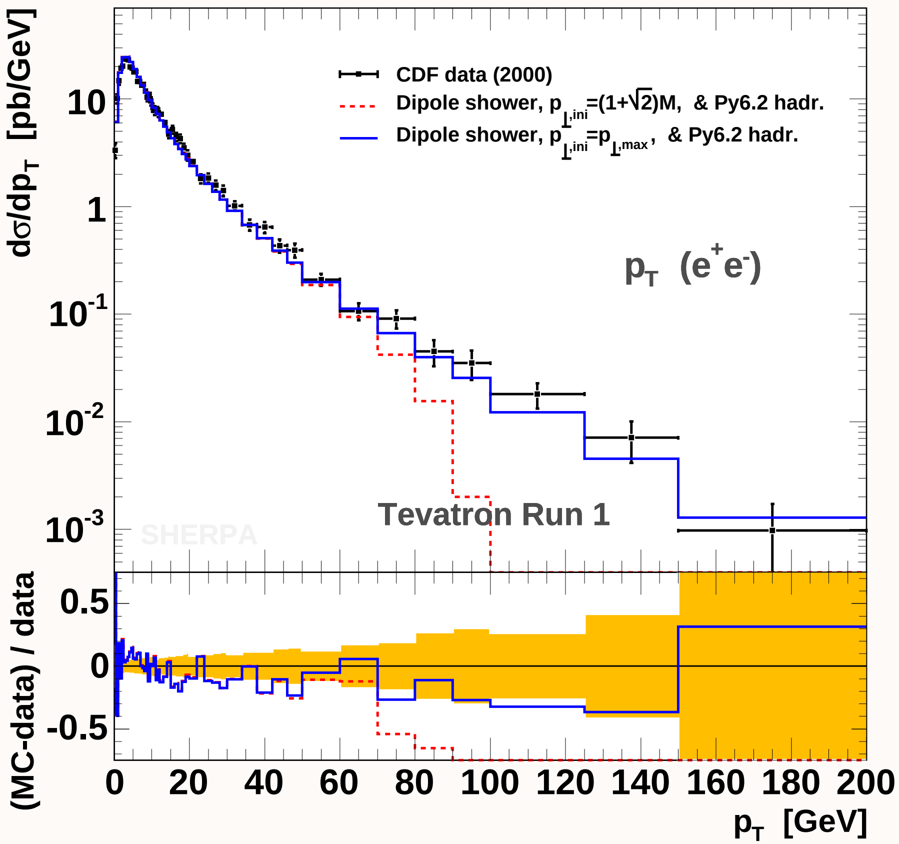
Our goal: develop fully perturbative CDM:



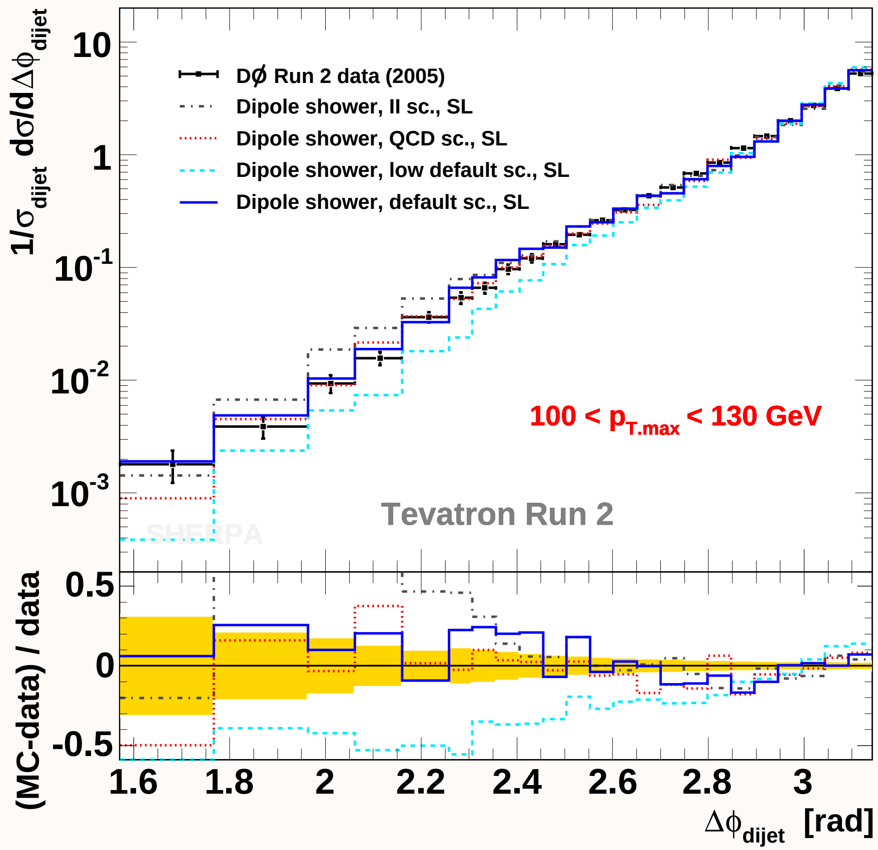
- incoming parton lines used to form dipoles, hence new types: $\bar{q}_i q_i,\ g_i q_i,\ g_i g_i$ and $q_f q_i,\ q_f g_i,\ g_f g_i$
- beam remnants excluded, will be treated during hadronization
- radiation pattern in terms of $2 \to 3$ splittings
  - *dipole ME factorization (re-calculate / crossing symmetry / antenna funcs)*
- generalized $2 \to 3$ onshell kinematics to include new cases
  - *dipole phase-space factorization and invariant evolution variables*
- probabilistic interpretation of Sudakov form factor here based on dipole splitting cross sections
- large N_C limit, all ISR in backward evolution

Results for hadronic collisions

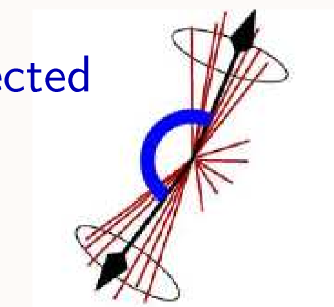
➡ *Testbed: inclusive Drell–Yan lepton pair production & inclusive jet production*



Jet production : Dijet azimuthal decorrelation



- boson transverse-momentum distribution (1st dipole-shower emission ME-corrected per construction) *[A.A. Affolder et. al. PRL* ***84*** *(2000) 845]*
- stringent test of QCD radiation pattern: dijet azimuthal decorrelation *[V.M. Abazov et al., PRL* ***94*** *(2005) 221801]*



Summary

- The LHC physics program requires a detailed understanding of QCD.
- New major release Sherpa 1.1 out ➡ fully independent MC event generator.
- Improved description of hard multijet configurations together with jet fragmentation **!**
- CKKW is implemented for SM processes in Sherpa.

  $\Rightarrow$ tool for jet physics.
- Real-emission MEs are provided by built-in tree-level ME generator AMEGIC.
- AMEGIC is ready for BSM as well.

  $\Rightarrow$ tool for new physics.
- Many new achievements for the simulation of soft physics.
  AHADIC, HADRONS, PHOTONS

  $\Rightarrow$ full simulation of hadron-level events.
- Many interesting ongoing projects beyond the physics already implemented in Sherpa 1.1.

  $\Rightarrow$ new merging strategy to combine AMEGIC/COMIX with APACIC/CSSHOWER

  $\Rightarrow$ inclusive decays