Sherpa: new developments

[LoopFestVII]

Jan Winter [a]

– Fermilab –

- *Monte Carlo event generator Sherpa*
- *New major release – Sherpa 1.1*
- *Sherpa projects – work in progress*

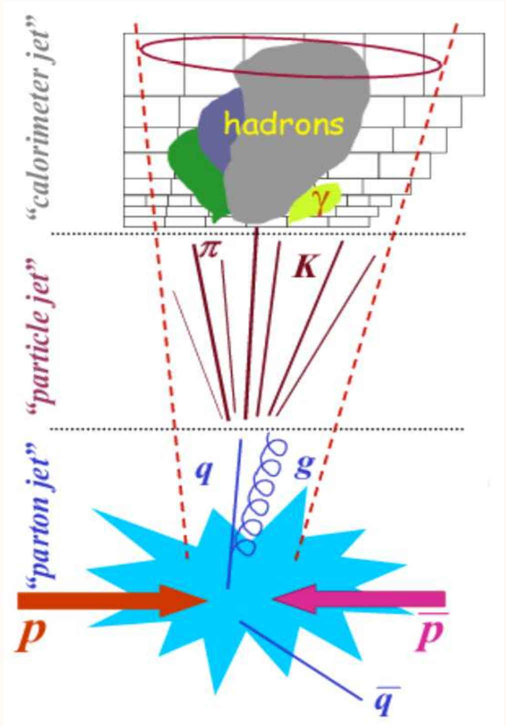
[a] Sherpa authors: T. Gleisberg, S. Höche, F. Krauss, M. Schönherr, F. Siegert, S. Schumann, J. Winter

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*
- Can lead to modifications of the signals.
- Can lead to additional and/or enhanced backgrounds.
- Can change signal-to-background ratios.
- V, VV, $Q\bar{Q}$, single t production, VBF and g–g fusion, Higgs, SUSY particle production and decay chains ...
  ... cannot be considered without jets.



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*

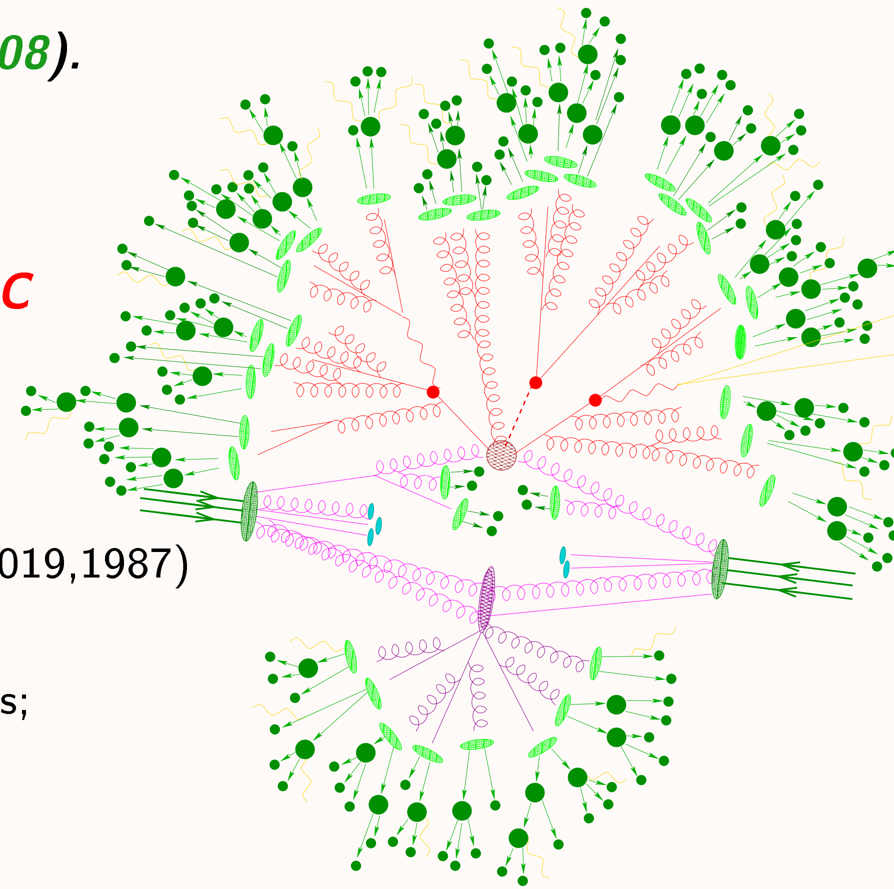
Monte Carlo event generator Sherpa

*[Gleisberg, Höche, Krauss, Schälicke, Schumann, Winter, JHEP **0402** (2004) 05*

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

➜ ***Current version: SHERPA 1.1.1 (released May/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 (PRD36:2019,1987)
- ***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



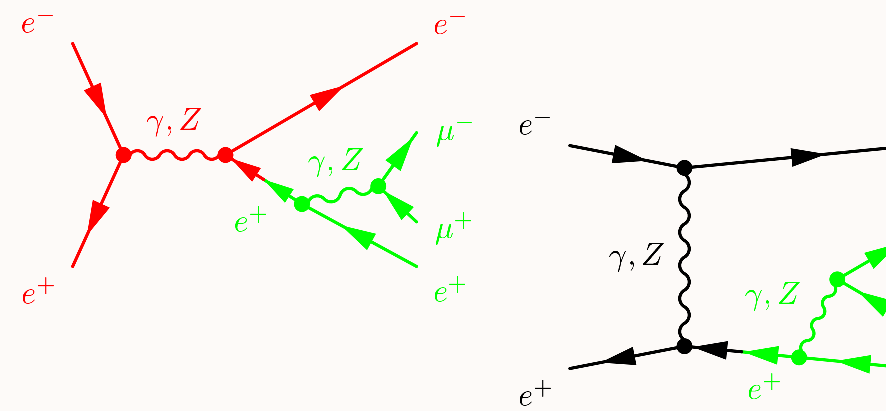
➜ predictions at the hadron-level – comparable to experimental data corrected for detector effec

AMEGIC

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

*[Krauss, Kuhn, Soff, JHEP **0202** (2002) 04*

- helicity-amplitude formalism
- 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.***

- Our new-physics tool is AMEGIC:
  - SM+ggH+AGC+4th family; THDM; MSSM (fully general); ADD model of extra dimensions; additional scalar singlet.
  - Expandable: dynamic add-on model libs, ***FeynRules reader*** (generic interface soon)

➡ ***CSW recursion – MHV techniques in AMEGIC.***

- twistor-inspired methods (CSW vertex rules) help speed up the calculation of pure QCD M for higher multiplicities *[Cachazo, Svrcek, Witten, JHEP **0409** (2004) 006]*
  - feasible $pp \to 5j$; $2g \to 4g$ time for 10^5 points reduced by factor of 100
  - LHC, $Q_{\rm cut} = 20$GeV, $pp \to 4j$, 23.245μb±0.27%, MHV-enabled 7.6ks vs no-MHV 35k

ME+PS merging ... à la CKKW

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

[Krauss, JHEP ***0208*** *(2002) 015*

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

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

ME+PS merging ... à la CKKW

*[Catani, Krauss, Kuhn, Webber, JHEP **0111** (2001) 063*
*[Krauss, JHEP **0208** (2002) 015*

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

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

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 $Q_{ij} = 2\min\{E_i, E_j\}(1 - \cos\theta_{ij}) > Q_{jet}$

ME+PS merging ... à la CKKW

*[Catani, Krauss, Kuhn, Webber, JHEP **0111** (2001) 063*
*[Krauss, JHEP **0208** (2002) 015*

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

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

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 $Q_{jet} > Q > Q_{\mathrm{cut-off}}$
- MEs regularized by $Q_{ij} = 2\min\{E_i, E_j\}(1 - \cos\theta_{ij}) > Q_{jet}$

Eliminate/sizeably reduce Q_{jet} dependence.

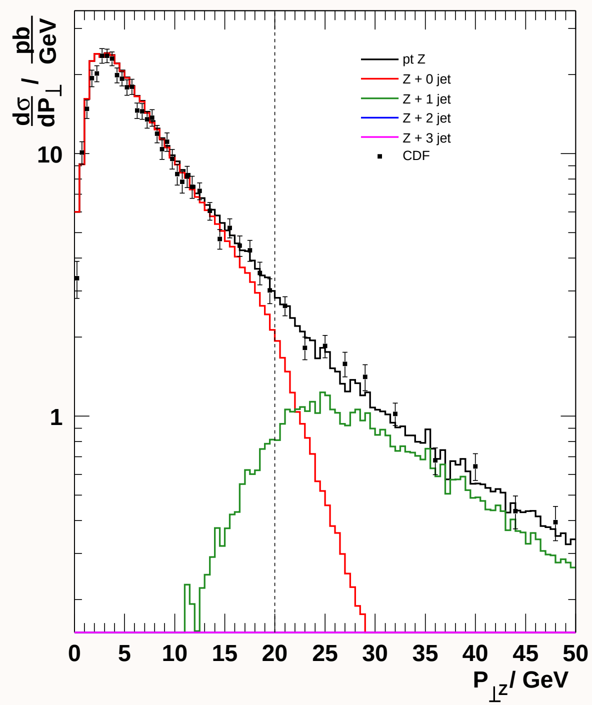
- identify a possible shower history of MEs via backward clustering
- accordingly reweight MEs by combined α_s and Sudakov weight
- add showers to ME partons and veto emissions above Q_{jet}

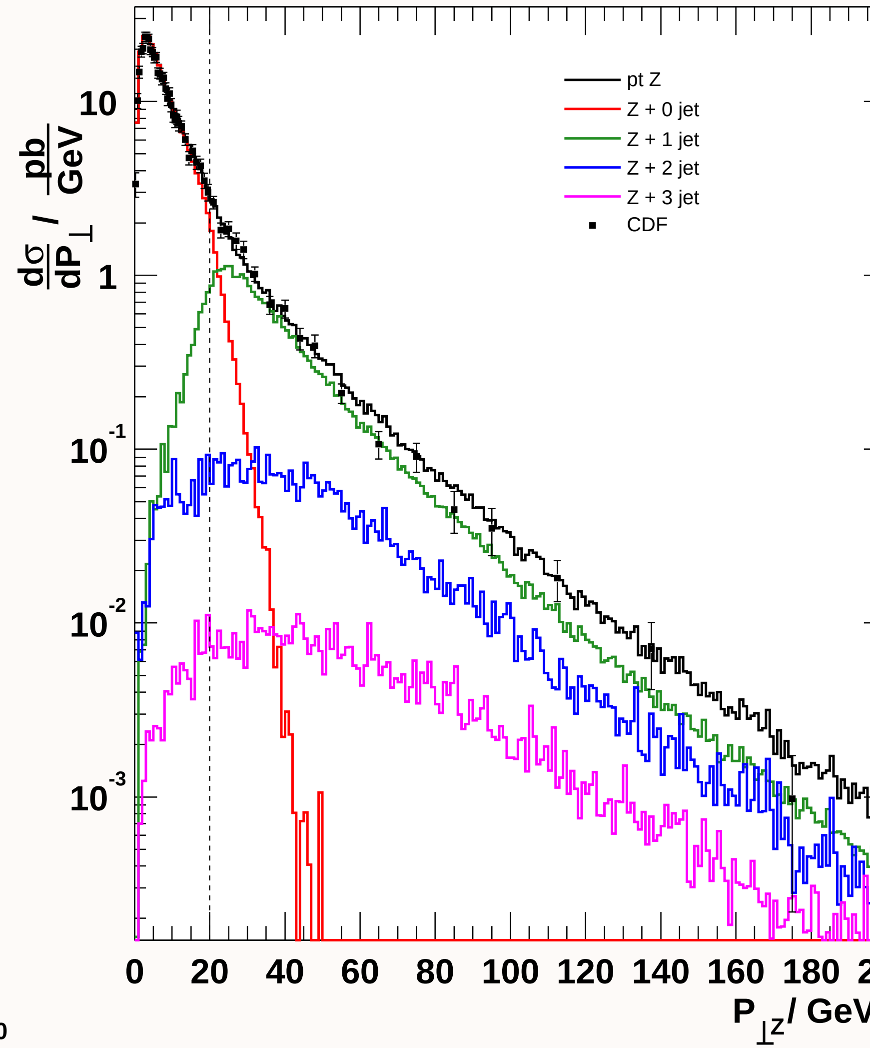
CKKW – key feature of Sherpa

- *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 and intrinsic k_T-smearing of order 0.8GeV

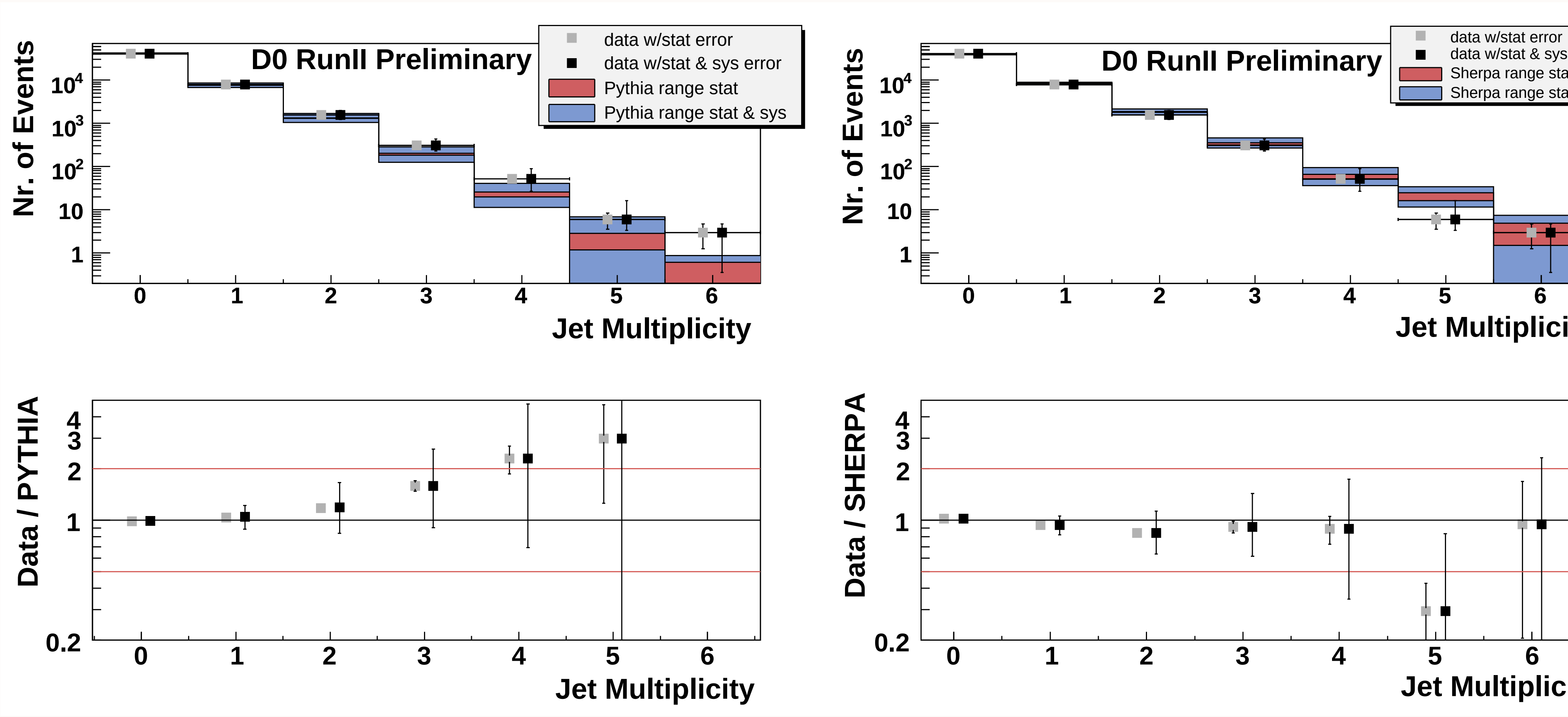




Comparison with DØ data: Z+jet production

DØ collaboration, DØ note 5066-CONF

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



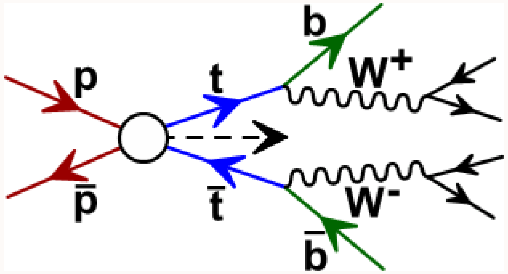
- MC predictions are normalized to total number of events observed in data.
- Large systematic uncertainties arise from low p_T jets $\Rightarrow$ both predictions are in agreement with data. Pythia tends to underestimate the data.

News on CKKW: heavy-quark production + decays

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

- AMEGIC ... use its decay-chain 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 multiparton MEs & showers in production and any decay
- CKKW ... reweight and veto by respecting the factorization
- Schematically, e.g.: $\boldsymbol{p\bar{p} \to t\,[\to W^+bg\{1\}]\;\bar{t}\,[\to W^-\bar{b}g\{1\}]\;g\{1\}}$

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



⇒ "CKKW 1-1-1

News on CKKW: top pair production & decays

➡ *Some preliminary LHC results ...*

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

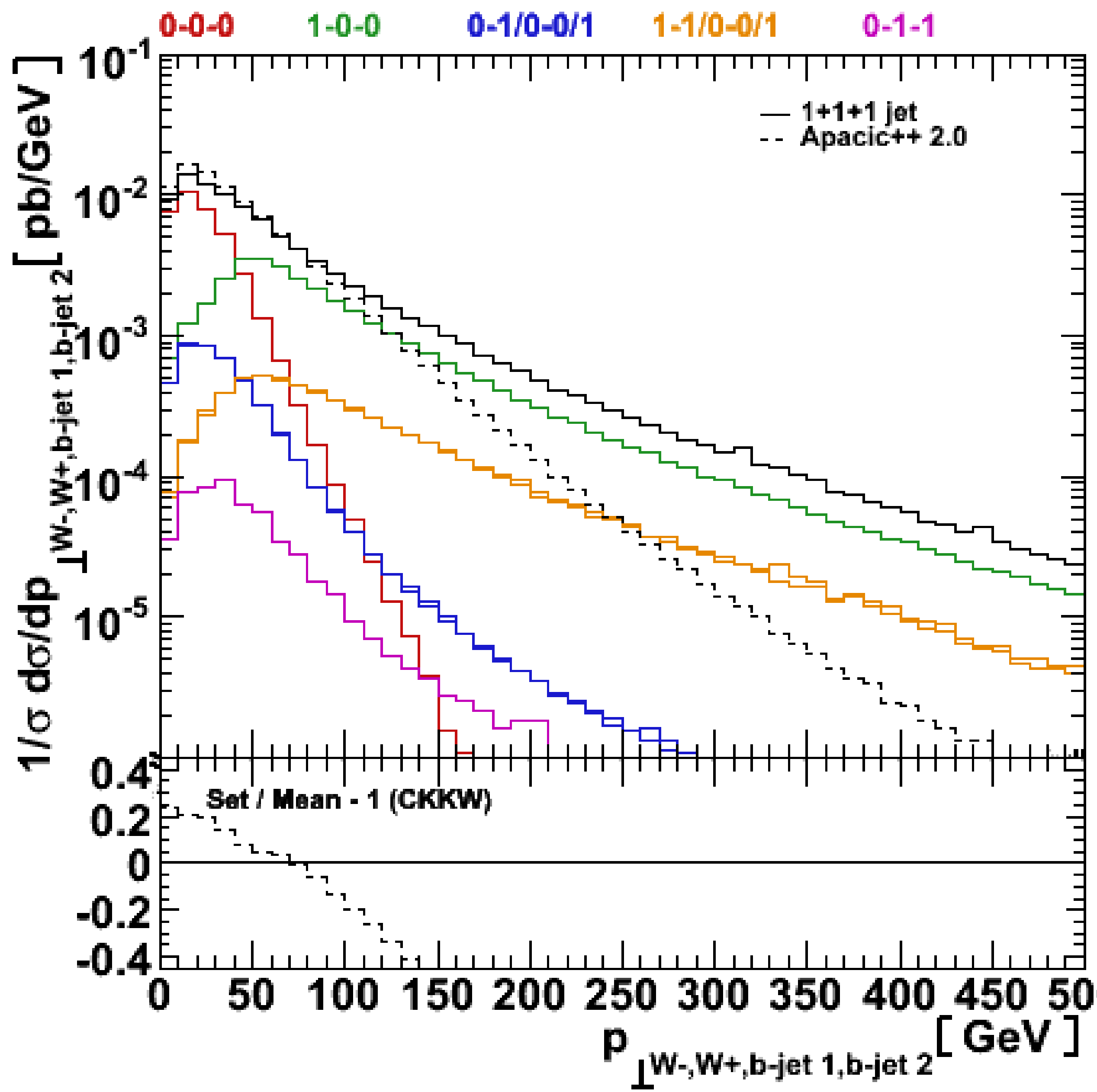
CKKW 1-1-1
compared to answer given by showering only.

- ***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.

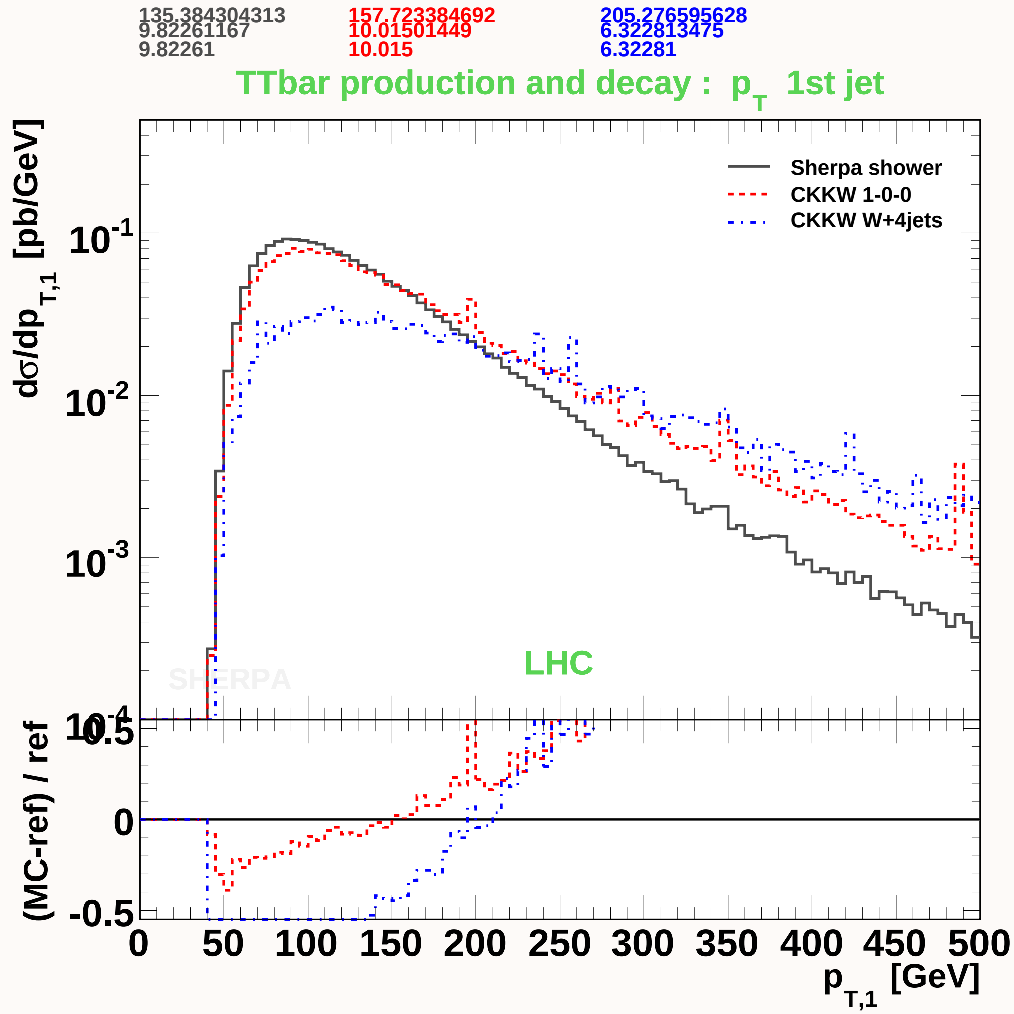
- ***$t\bar{t}$+jets as background***

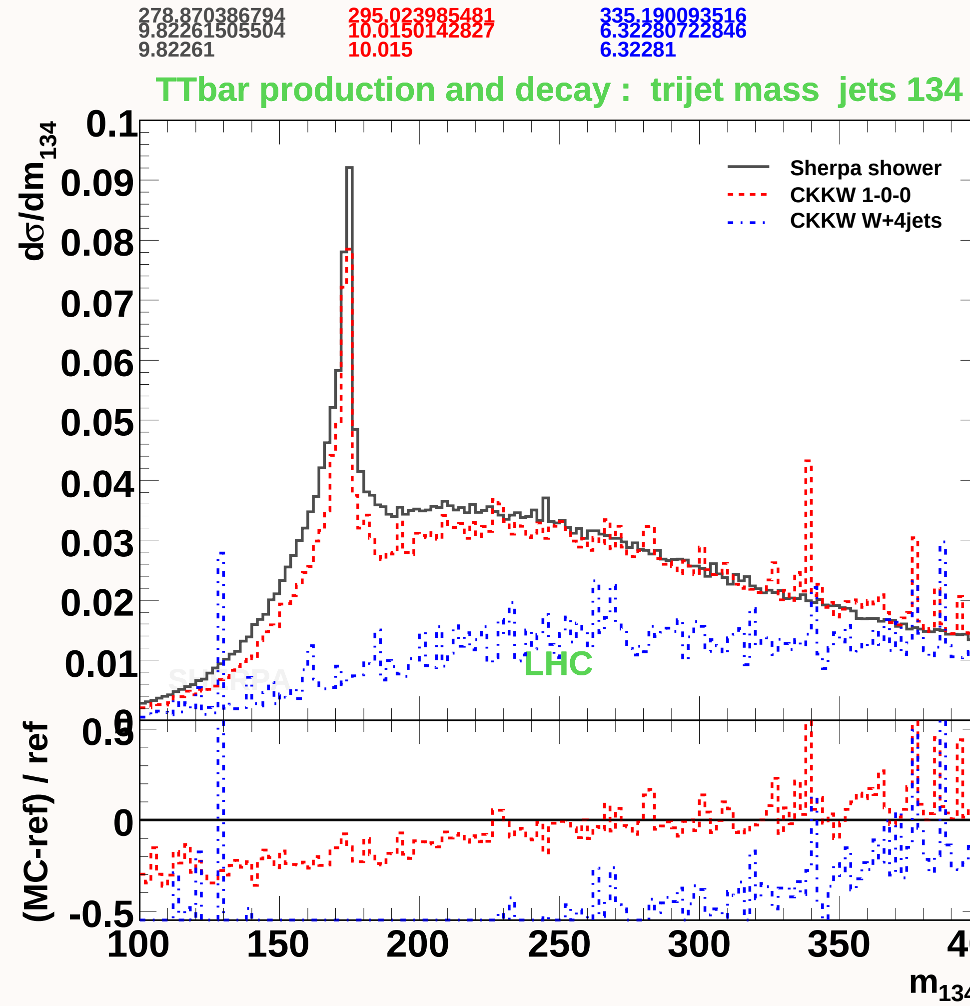
Accurate treatment required to specify new-physics searches.



News on CKKW: top pair production & decays

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





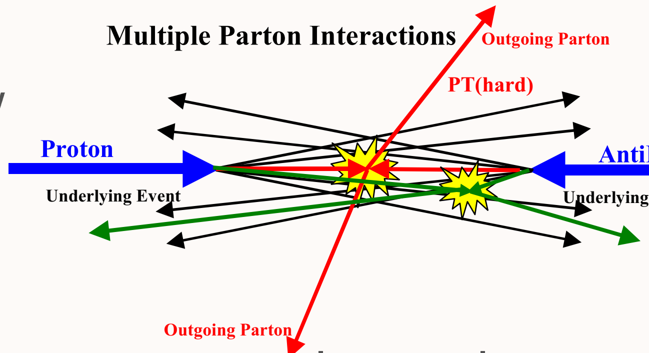
- require at least 4 jets ($p_T > 40$GeV, $|\eta| < 2.5$, $D = 0.4$); lepton cuts ($p_T > 20$GeV, $|\eta| < 2.5$); missing energy ($\not{E}_T > 20$GeV) ➡ PRELIMINARY RESULTS !!

Multiple interactions (Model for UE)

[Sjöstrand, Zijl, Phys. Rev. D36 (1987) 2019

Observed in had. collisions:

enhanced (ch) particle multiplicities and transverse-energy flow scale with hardness of interaction



Xsec of two-to-two QCD vs. total xsec $\sigma_{\rm ND}$:

supports $< N > = \sigma_{2\to 2}(p_{\perp 0})/\sigma_{\rm ND}$ ... additional incoherent parton-parton interactions
non-PT and confinement ... regularize $2 \to 2$ QCD processes

$$\frac{d\sigma_{2\to 2}}{dp_\perp^2} \propto \frac{\alpha_s(p_\perp^2)}{p_\perp^4} \to \frac{\alpha_s(p_\perp^2 + p_{\perp 0}^2)}{(p_\perp^2 + p_{\perp 0}^2)^2}$$

$p_{\perp 0}$ tuning parameter

Ordering in $p_\perp$: "Sudakov trick" $d\mathcal{P}/dp_{\perp i} = d\sigma/(\sigma_{\rm ND} dp_\perp)\Delta(p_{\perp i}, p_\perp)$

Colliding extended objects: impact parameter model (peripheral collisions)

simple/double Gaussian matter distribution

Energy extrapolation: $p_{\perp 0}(E_{\rm cms}) = p_{\perp 0}(E_{\rm ref}) \times (E_{\rm cms}/E_{\rm ref})^{0.16}$ (Landshoff-like)

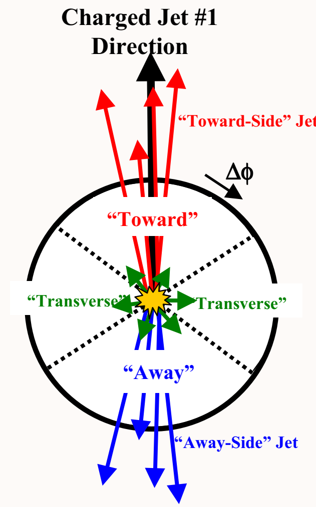
Simulation in Sherpa → AMISIC: based on this model + [Höche

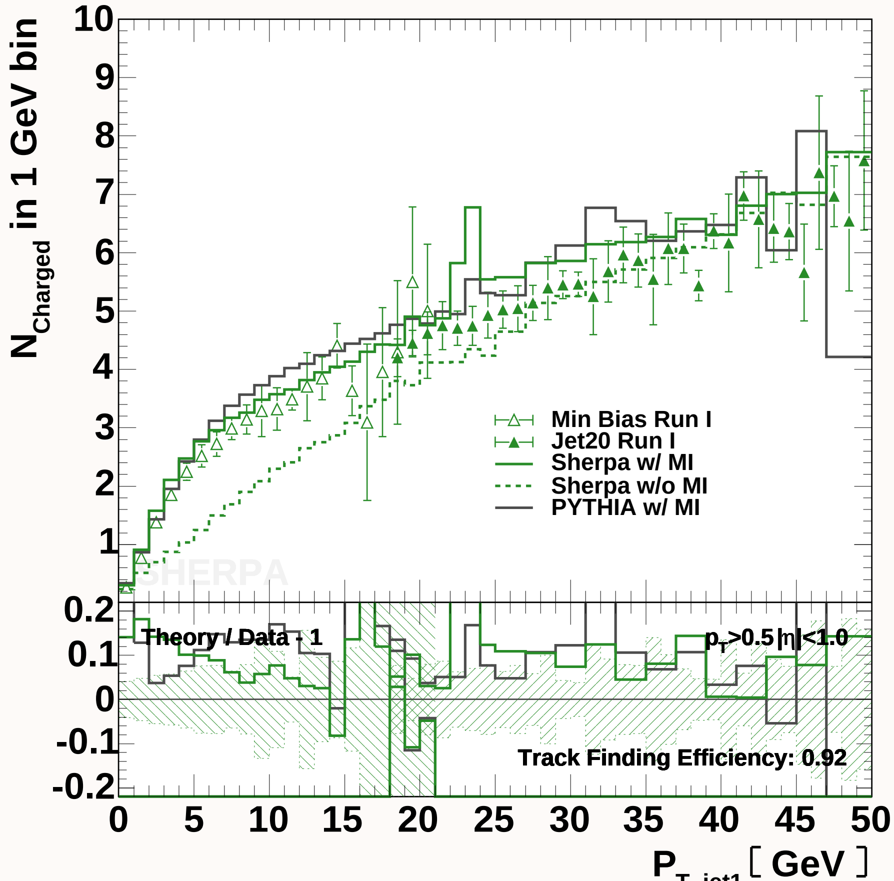
- showers attached to secondary interactions: moderate $< N > \approx 2.1$; $p_{\perp 0} \approx 2.4$GeV
- CKKW: k_T-algo to define core process, parton p_T sets MI scale & veto on shower emission

AMISIC

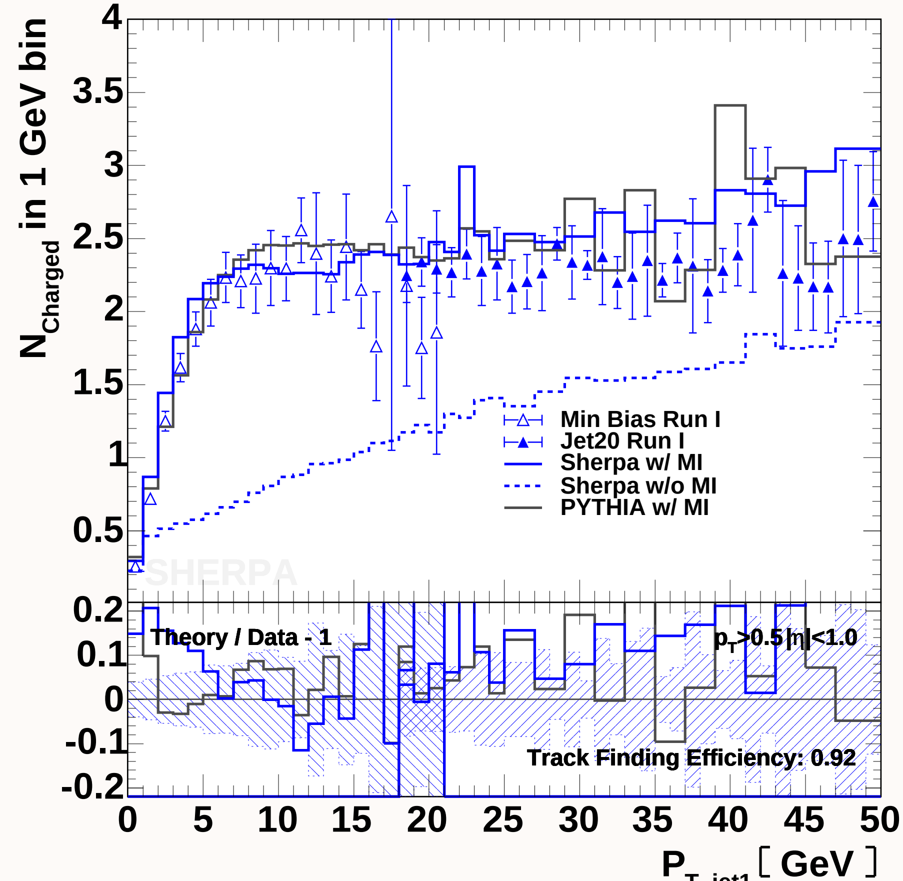
- CDF analysis by R. Field to investigate structure of UE.
- Charged multiplicity vs. P_T of leading ch. jet in $\Delta\Phi$ regions w.r.t. the leading ch. jet

[hep-ph/0601012]





Away



Transverse

AHADIC: cluster-hadronization model for Sherpa

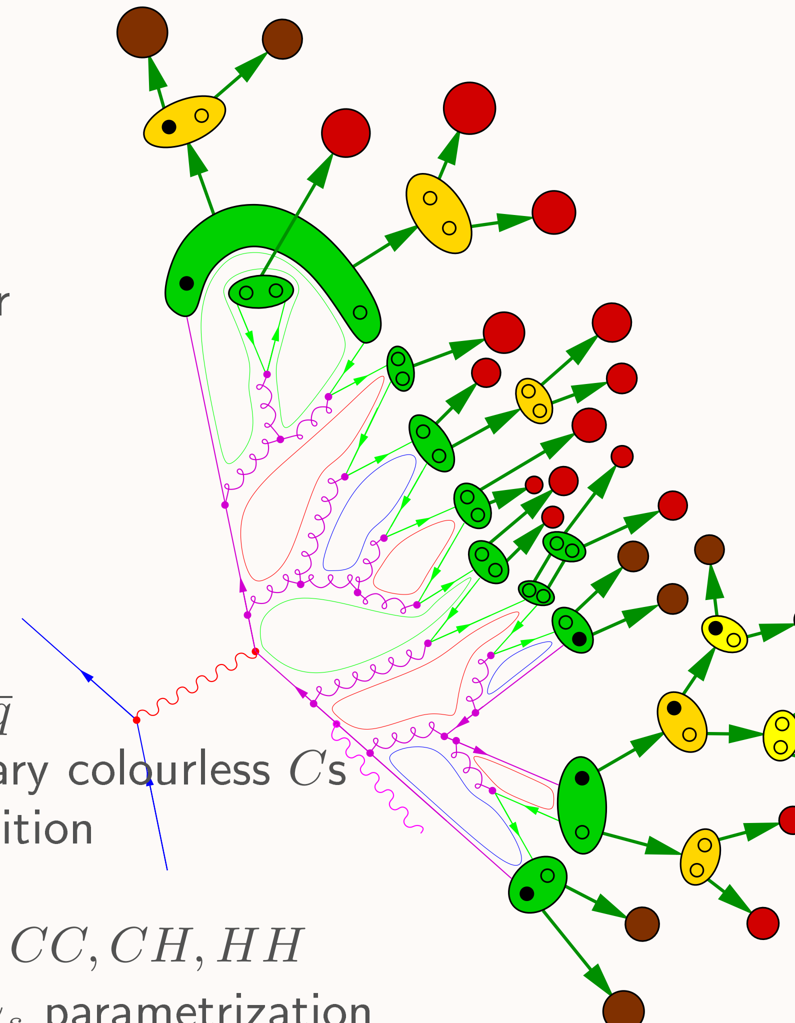
modelling the non-perturbative dynamics primary-hadron generation

- Cluster-formation model
- Cluster-decay model

Leading particle effects

Light-flavour pair production

- ***LPHD*** and ***preconfinement***
- ***Locality*** and ***universality*** $\Rightarrow$ modular structure
- Phenomenology: plateau in $N_{\rm had}$ vs rapidity,
  steep fall-off in $N_{\rm had}$ vs $p_\perp$
- Hadronization effects are soft: low momentum transfer



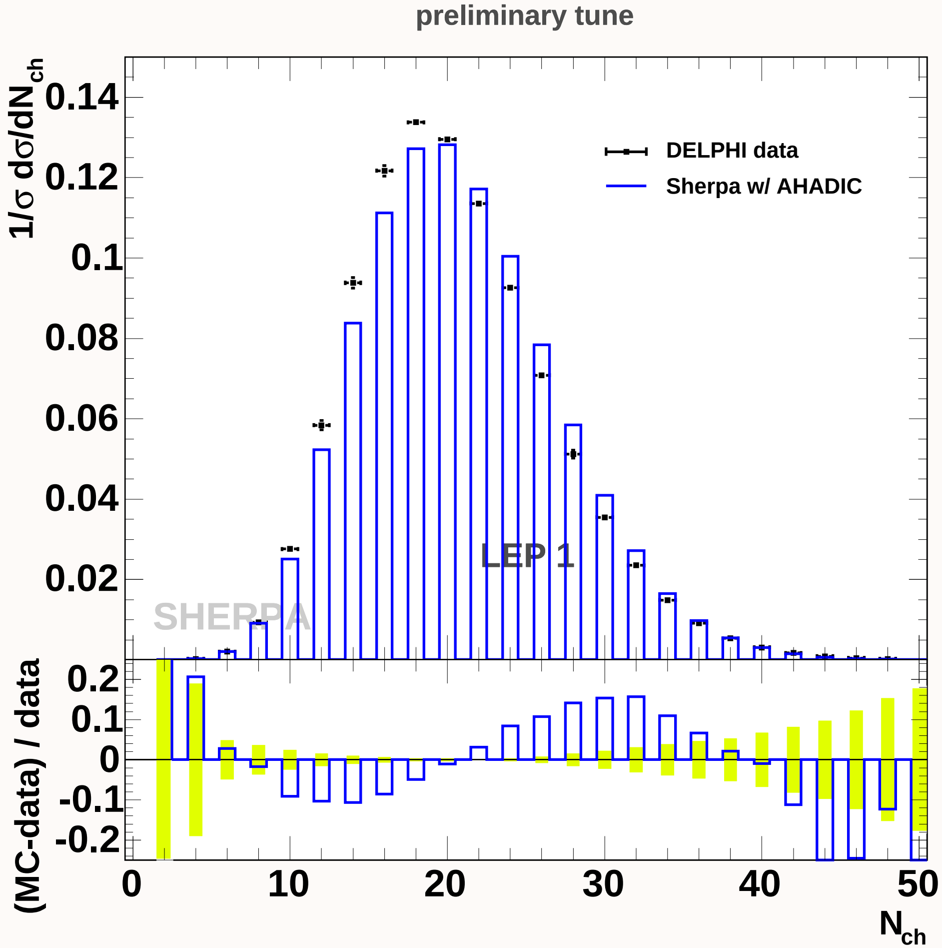
AHADIC:

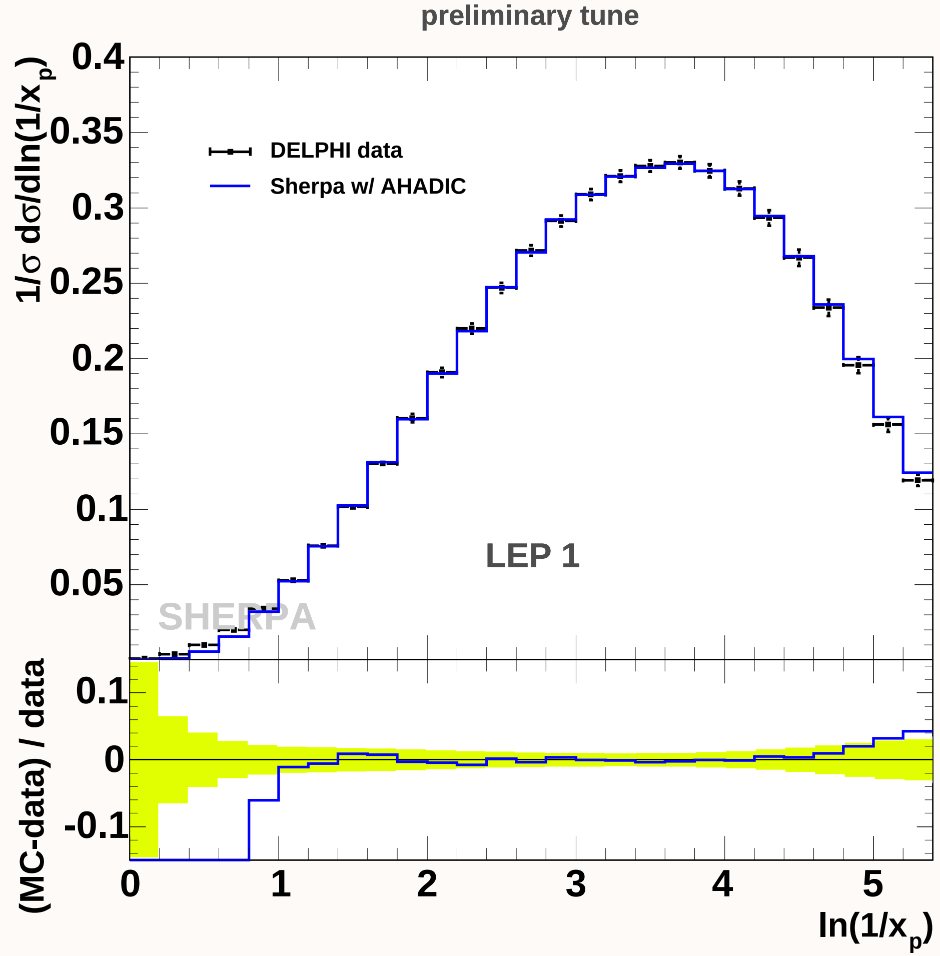
- based upon Field–Wolfram and Webber model
- modified cluster model, tested for light-quark sector
  [Winter,Krauss,Soff,2004]

- constituent masses only for quarks, gluons split into $q\bar{q}$
- shower colour ordering: adjacent parton pairs $\longrightarrow$ primary colourless Cs
- cluster mass in hadron regime: cluster-to-hadron transition
  according to overlap with hadron wave-functions
- else: cluster splits and daughters are categorized $C \to CC, CH, HH$
- all splittings dipole-like $\propto \alpha_s(p_\perp)/p_\perp^2$ with low-scale α_s parametrization

First AHADIC results

➡ *Testbed: hadron production in electron–positron annihilations @ Z pole*





- Example distributions: multiplicity (left panel) and scaled momentum of charged particles.
- Model parameters: so far just tuned by hand.
- Data: Abreu et al. Z. Phys. **C73** (1996) 11.

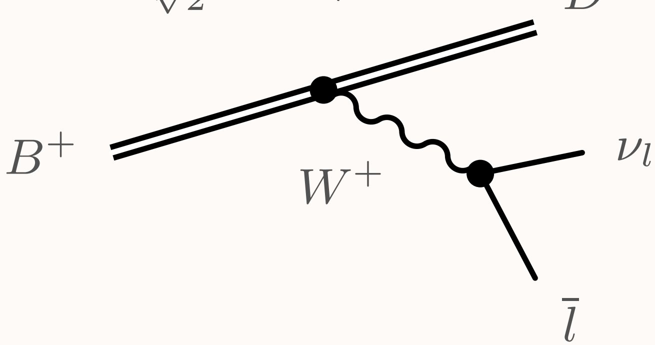
HADRONS: hadron decays for Sherpa

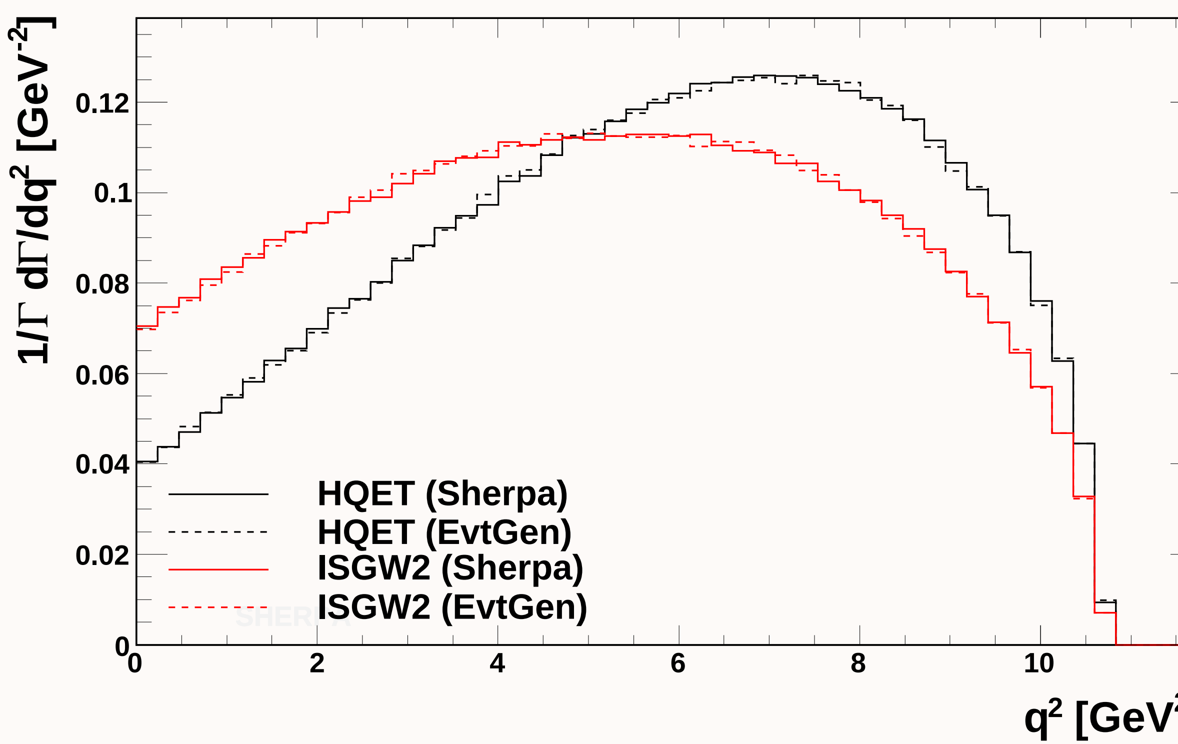
SHERPA's package to accomplish hadron and τ decays.

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

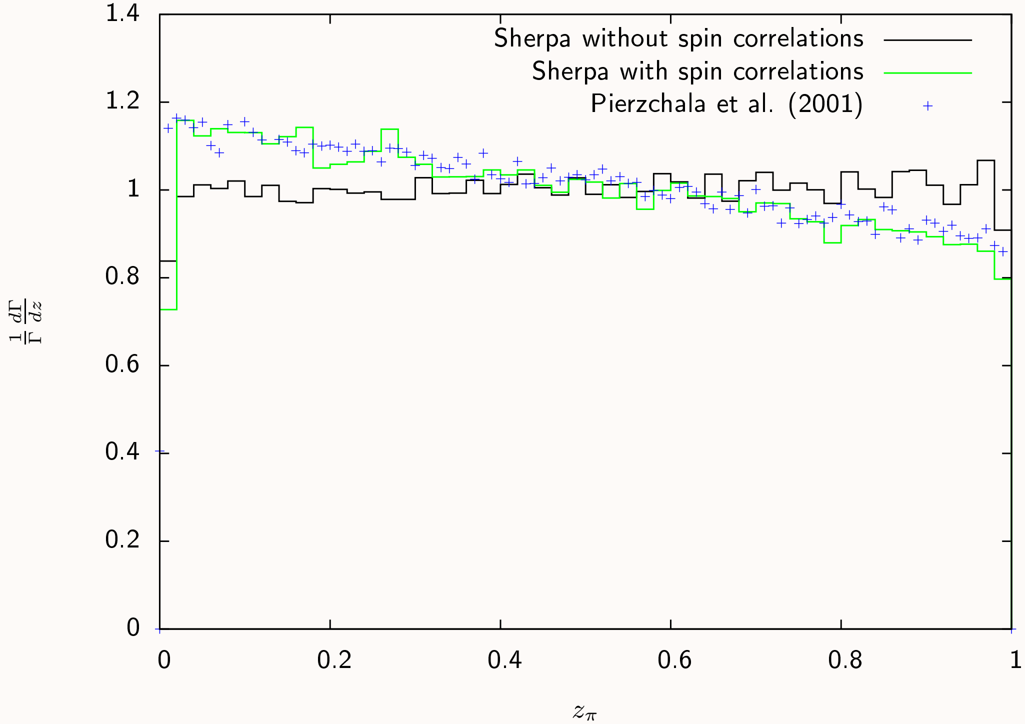
$$\mathcal{M} = -\mathrm{i}\frac{G_F}{\sqrt{2}} V_{cb}\, L_\mu\, H^\mu$$

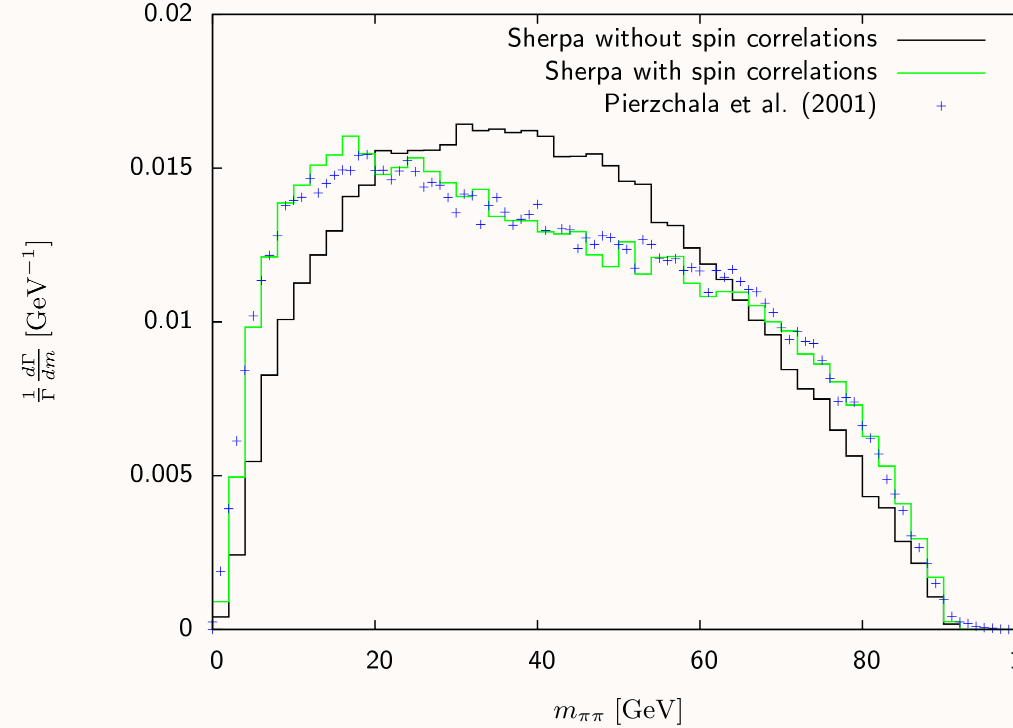




HADRONS results: comparison with Tauola

Spin correlations in $Z \rightarrow \tau^-\tau^+ \rightarrow \pi^-\nu_\tau\pi^+\bar{\nu_\tau}$





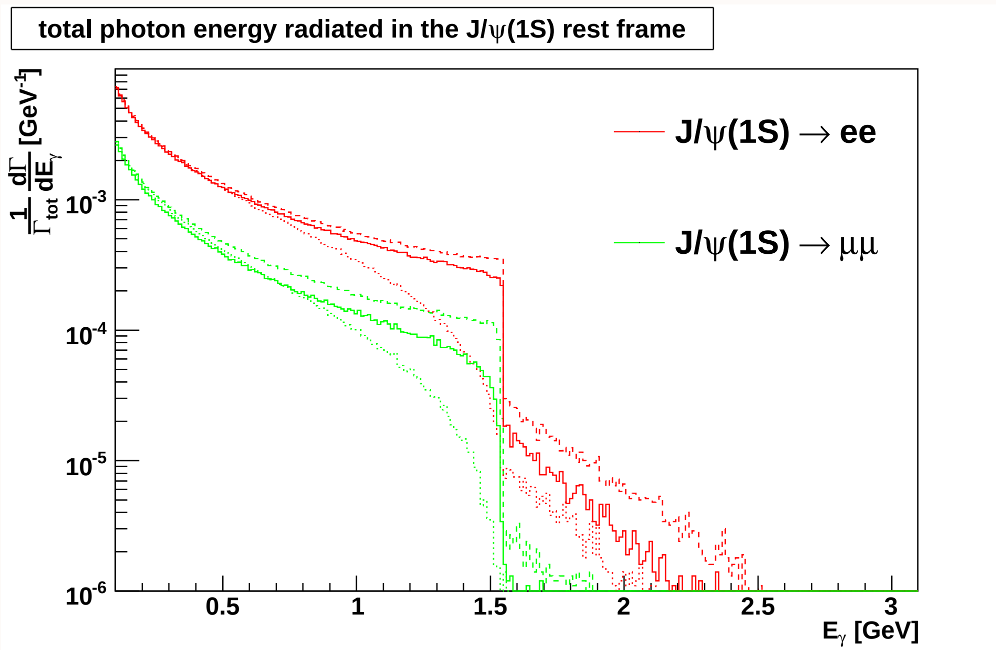
- Left: pion energy fraction in Z rest frame.
- Right: Invariant mass of outgoing pion pair.
- Tauola: Pierzchala et al. hep-ph/0101311.

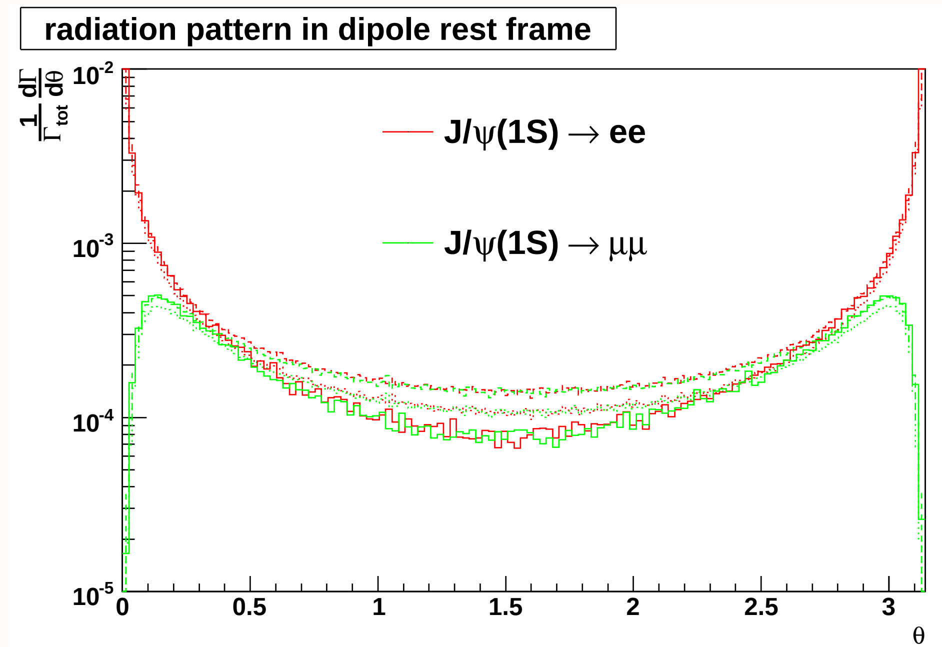
[Laubrich,Siegert,Krauss]

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]

Sherpa projects:

new developments ...

and work in progress.

- *COMIX – tree-level SM ME generator based on colour-dressed Berends–Giele recursion relations.*
- *Automated Catani–Seymour dipole subtraction* [Gleisberg,Krauss,2007] *: **see talk by Tanju Gleisberg.***
- *Parton shower based on Catani–Seymour dipole factorization.*
- *Colour-dipole shower for hadronic collisions.*
- *Multiple-interactions model based on k_T-factorization (BFKL evolution)* ***see*** [Höche,Krauss,Teubner,2007]

COMIX

- new tree-level ME generator based on recursive methods
- employs colour-dressed Berends–Giele recursion relations
  [Duhr,Höche,Maltoni,2006]
- general implementation of SM interactions

- Key point: vertex decomposition of all four-particle vertices
  (Growth in computational complexity for CDBG solely determined by
  number of external legs at vertices)

- Phase-space generation: can be accomplished recursively on the same footing as ME calculation

- publication in preparation by Höche & Gleisberg

COMIX: PERFORMANCE

T. Gleisberg, SH: in preparation

- Performance in QCD benchmarks

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)	0.019(2)
Phys. Rev. D67(2003)014026	0.70(4)	0.30(2)	0.097(6)		
Nucl. Phys. B539(1999)215	0.719(19)				

- "Real life" example: b-pair + jets
  comparison with other ME generators

σ [μb]	Number of jets						
$b\bar{b}$ + QCD jets	0	1	2	3	4	5	6
Comix	470.8(5)	8.83(2)	1.826(8)	0.459(2)	0.151(2)	0.0544(6)	0.023(2)
ALPGEN	470.6(6)	8.83(1)	1.822(9)	0.459(2)	0.150(2)	0.053(1)	0.0215(8)
AMEGIC++	470.3(4)	8.84(2)	1.817(6)				

Setup: http://mlm.home.cern.ch/mlm/mcwshop03/mcwshop.html

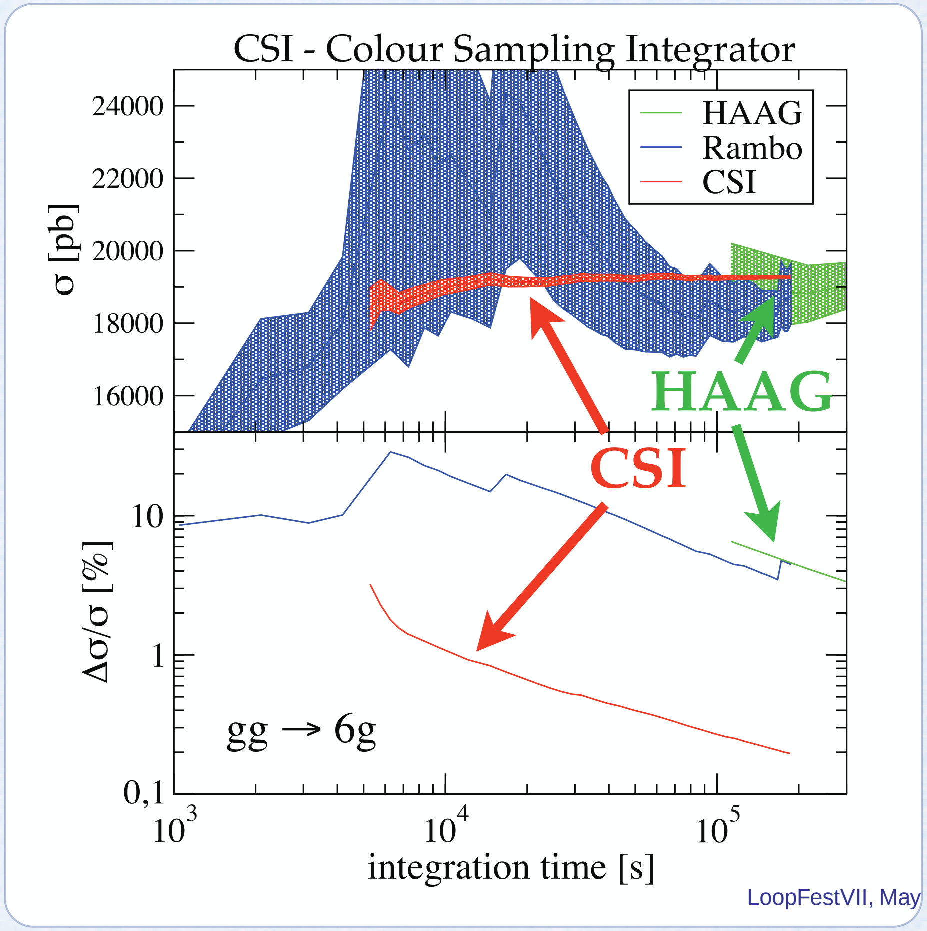
COMIX: PERFORMANCE

T. Gleisberg, SH: in preparation

- Efficiencies: LHC @ 14 TeV
  Cuts: $\mathbf{66\,GeV \leq m_{l\bar{l}} \leq 116\,GeV}$,
  CDF Run II K_T-algo @ 20GeV

Process	Efficiency
Z+0 jet	8.50%
Z+1 jet	1.05%
Z+2 jets	0.60%
Z+3 jets	0.15%
Process	**Efficiency**
W+0 jet	19.13%
W+1 jet	1.50%
W+2 jets	0.48%
W+3 jets	0.16%

- **Also new:** HAAG-based QCD integrator for colour sampling



PS based on Catani–Seymour dipole factorization

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 from Born process using universal dipole terms
- yields local approximation for the real-emission process, correct in soft & coll limits

Basic ideas for a new parton shower *[Nagy,Soper,2006; Dinsdale et al.,2007; Schumann,Krauss,2007]*

- dipole terms can be used to describe splittings
- exponentiation in a Sudakov form factor (large-N_{C} limit, spin averaging)
- correct soft & collinear limits, local four-momentum conservation
- formalism well worked out for massive emitters ➡ shower will profit

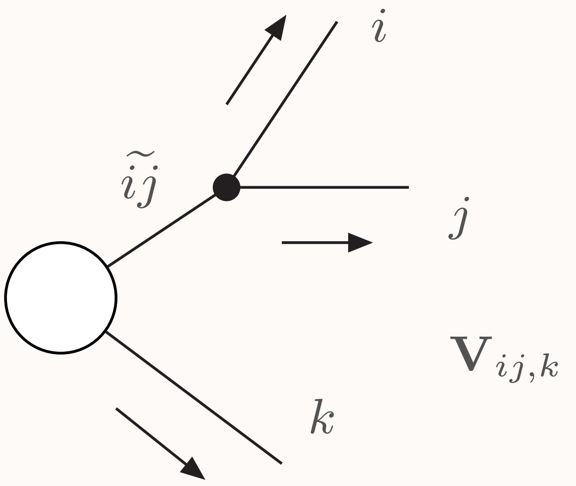
Example: final-state final-state dipoles

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

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

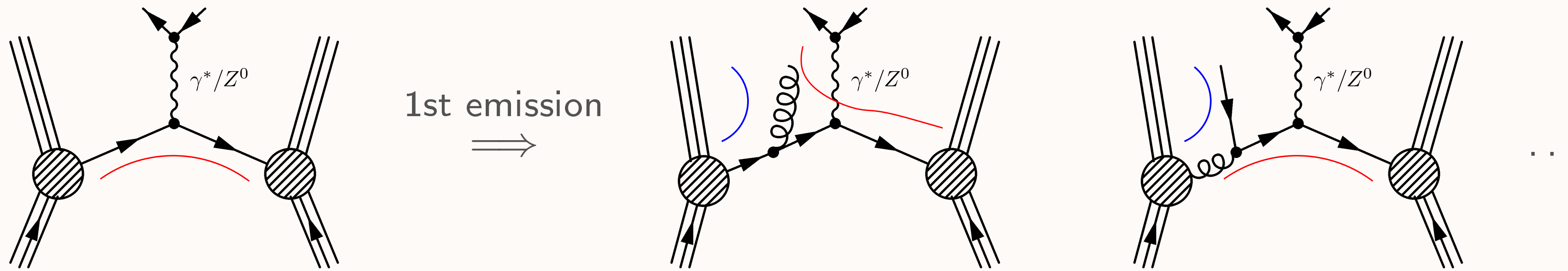
splitting function, e.g. $\mathrm{q}_{ij} \to \mathrm{q}_i \mathrm{g}_j$ ➡

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

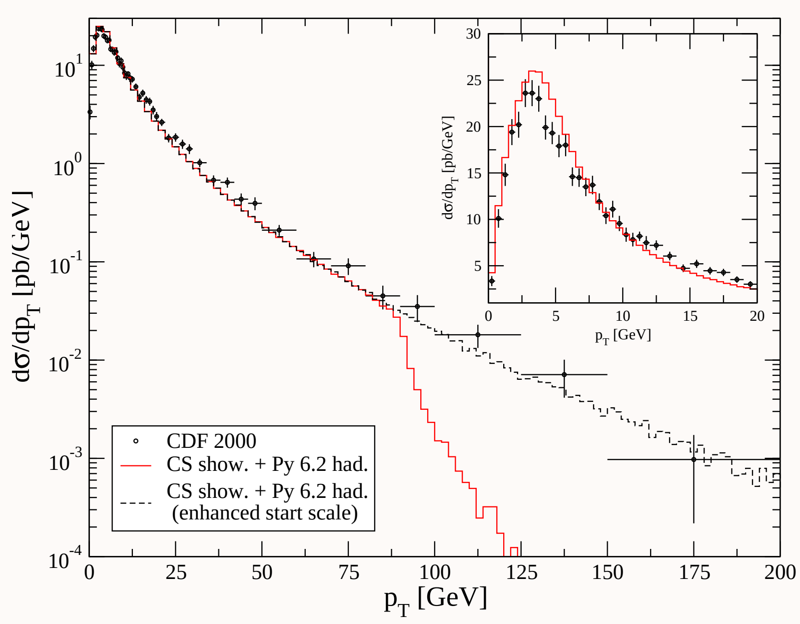


Drell–Yan production

Consider $p\bar{p} \to \gamma^*/Z^0 \to e^+e^-$



- hard scale fixed by $M^2_{e^+e^-} \Rightarrow \mathbf{k}^2_{\perp,\max}$
- transverse momentum of lepton-pair determined by QCD emissions



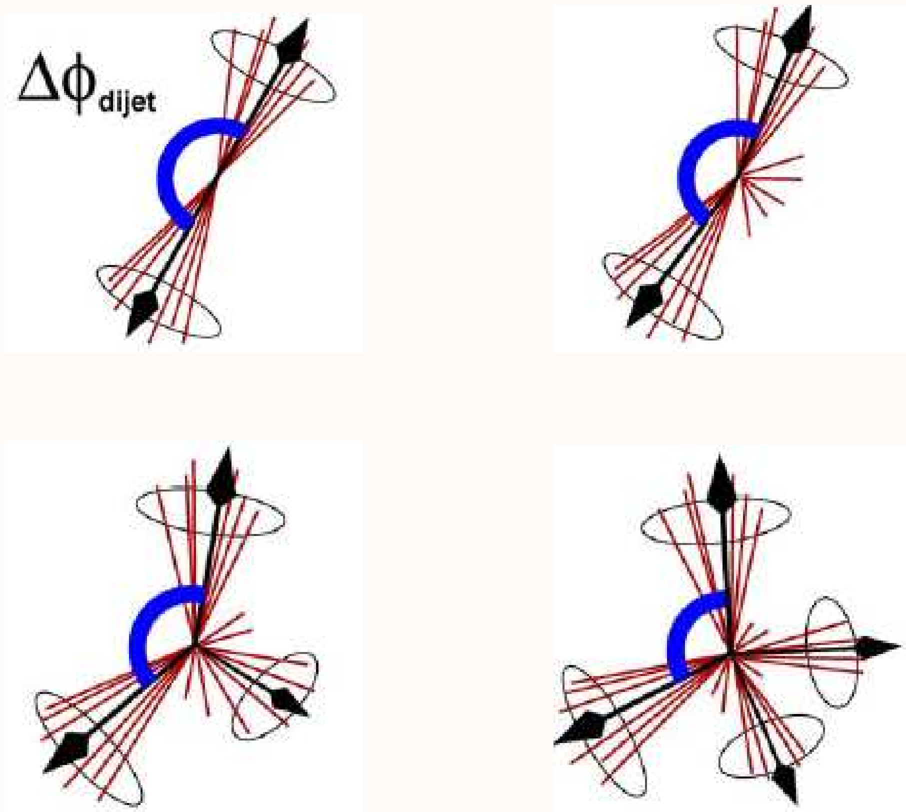
- Comparison with Tevatron CDF data
  - rate normalised to data
  - dominant contribution for $p_T^{e^+e^-}$
  - Sudakov damping for $p_T^{e^+e^-} \to 0$
  - hardest emission below $\mathbf{k}_{\perp,\max}$

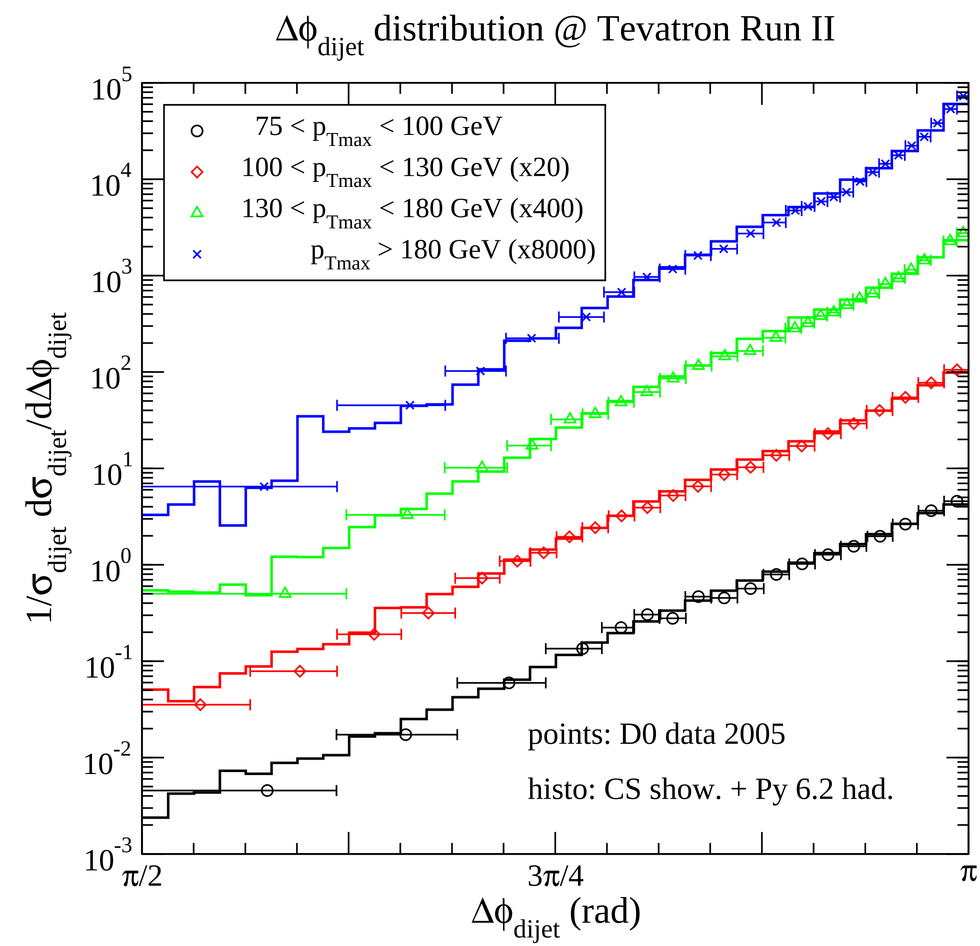
    $\hookrightarrow p_T^{e^+e^-} > \mathbf{k}_{\perp,\max}$ matrix element regime

[Schumann,Krauss,2007]

Inclusive jet production

Dijet azimuthal decorrelation [data DØ 2005]



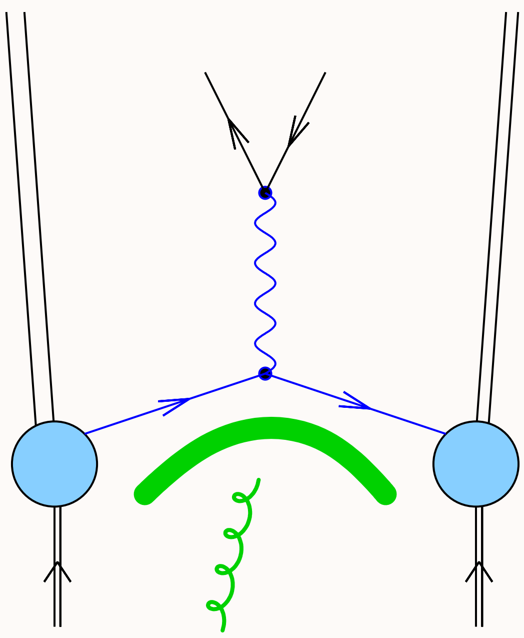


- only the two leading jets need to be reconstructed
- strong test of the initial- and final-state radiation pattern

Colour dipole shower for hadronic collissions

WINTER, KRAUSS, ARXIV:0712.391

- Formulate IS emission completely perturbatively through colour dipoles (partly) spanned by incoming parton lines.
- Radiation that is associated to ***initial***, ***initial-final*** and ***final*** colour lines.
- Keep beam remnants outside evolution as long as hadronization has not set in.

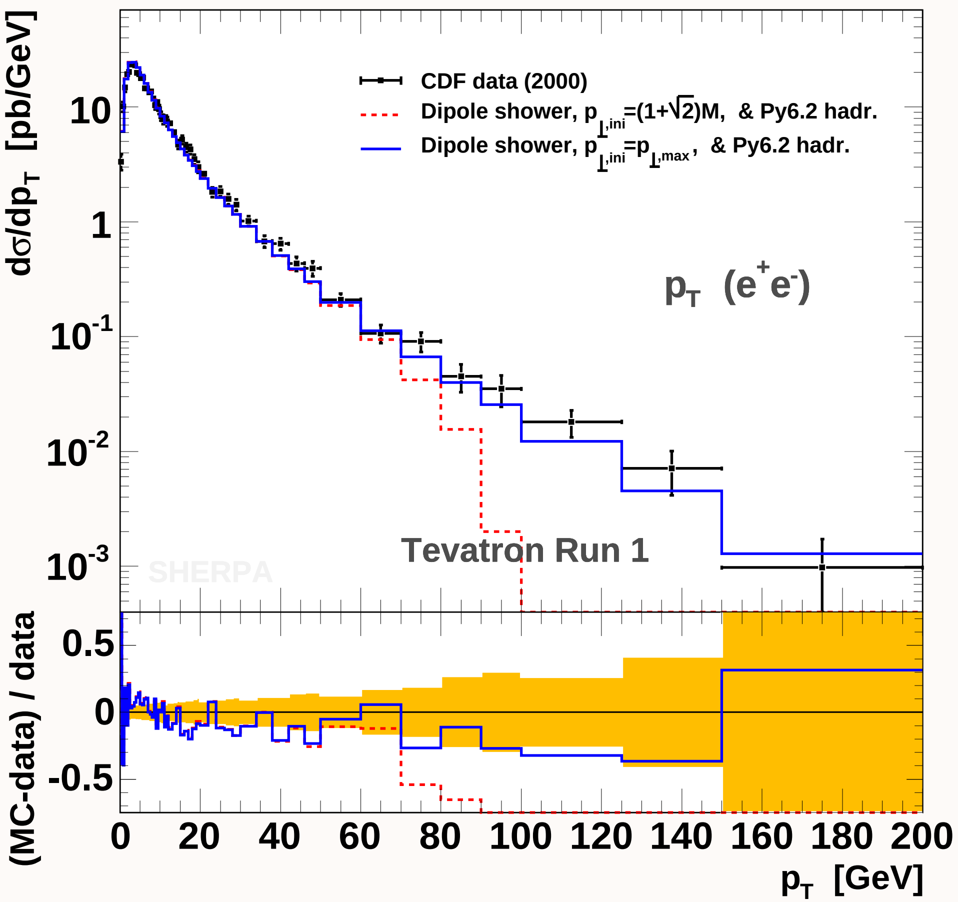


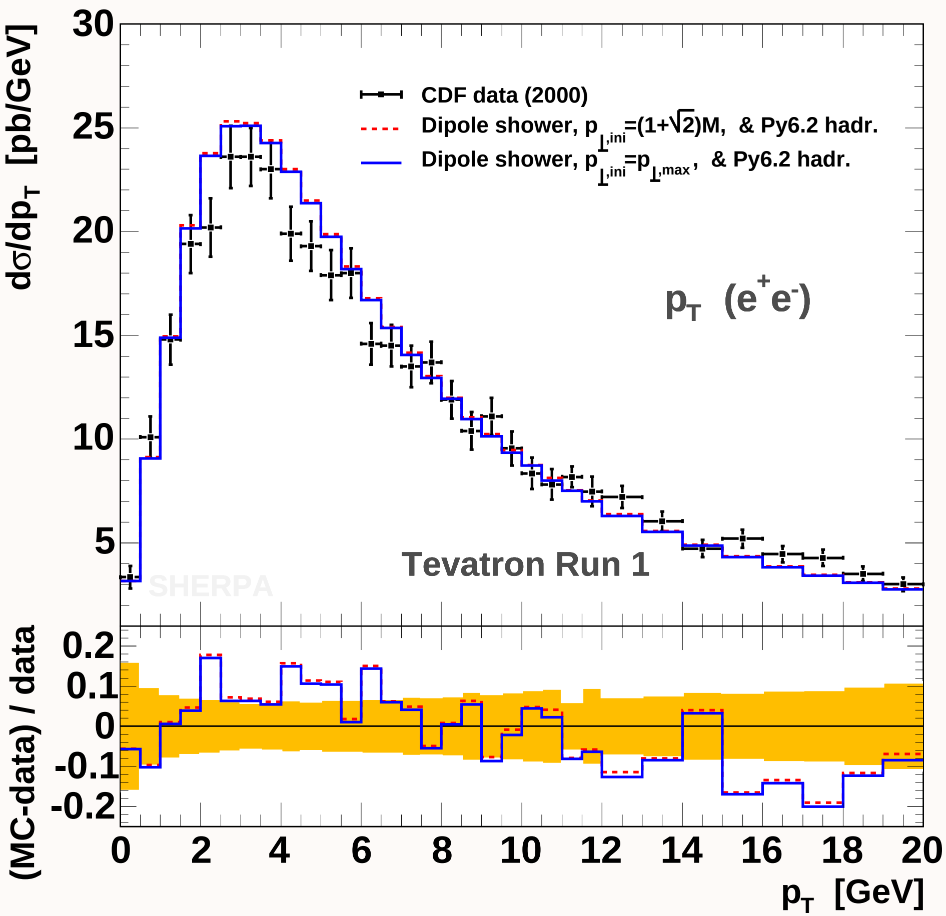
Construction principles of perturbative CDM:

- new dipole types: $\bar{q}_{\rm i} q_{\rm i},\ g_{\rm i} q_{\rm i},\ g_{\rm i} g_{\rm i}$ and $q_{\rm f} q_{\rm i},\ q_{\rm f} g_{\rm i},\ g_{\rm f} g_{\rm i}$.
- radiation pattern in terms of $2 \to 3$ splittings.
- generalization of the kinematics setup to the new cases
  - *dipole phase-space factorization and invariant evolution variables*.
- *dipole ME factorization* → re-calculate or use crossing symmetry of FF dipole MEs or use antenna functions.
- probabilistic interpretation of Sudakov form factor based on dipole splitting cross sections.
- large $N_{\rm C}$ limit, onshell kinematics, for all ISR apply backward evolution.

Results for hadronic collisions

➡ *Testbed: inclusive production of Drell–Yan lepton pairs @ Tevatron Run I*

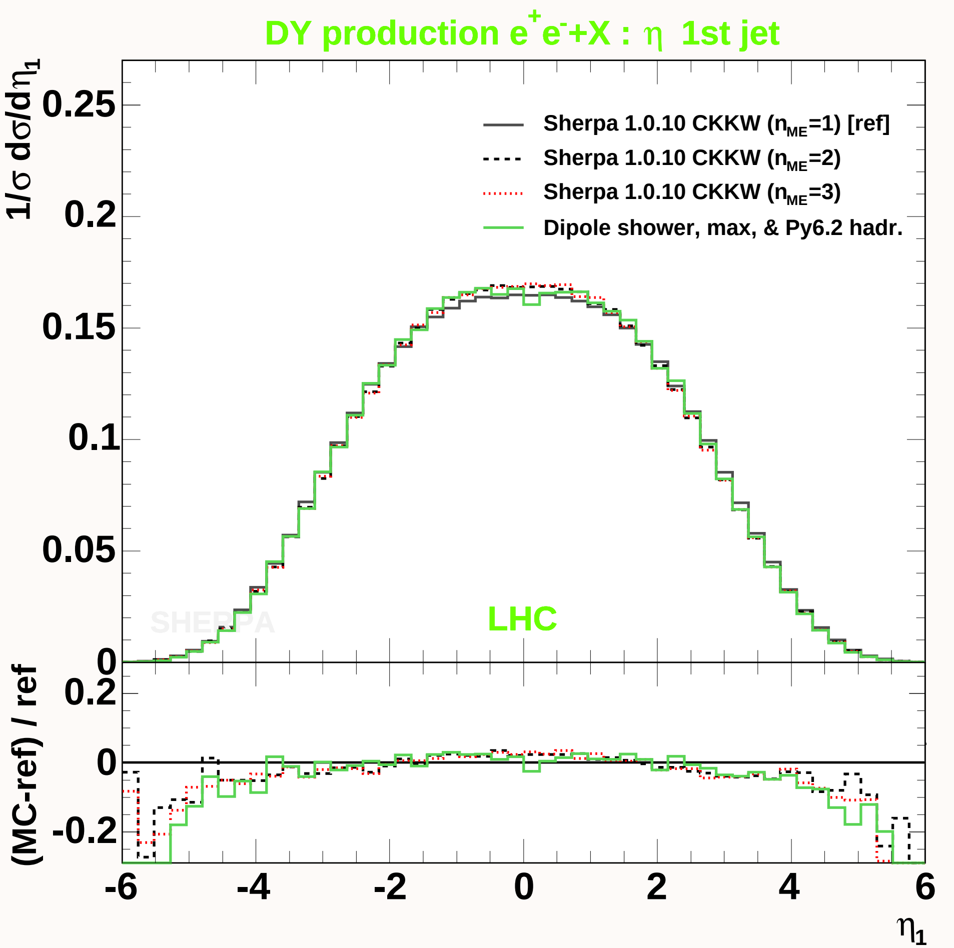


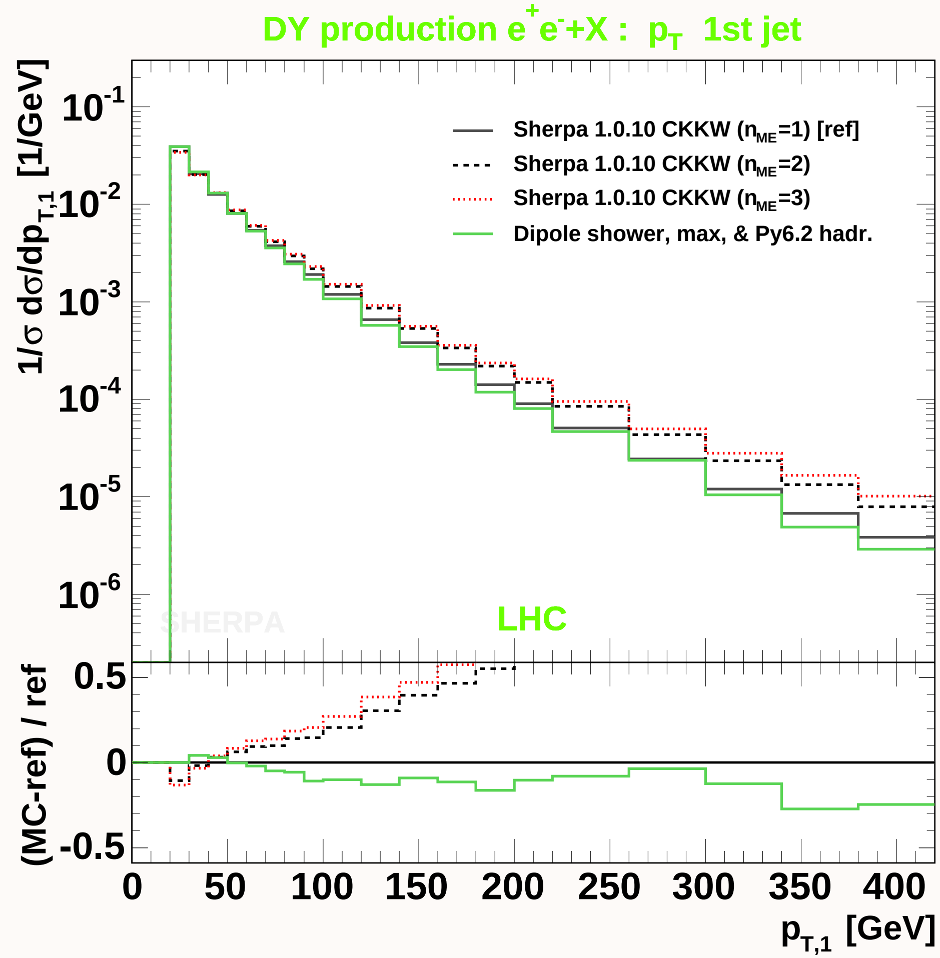


- Boson transverse-momentum distribution and its peak region in $e^+e^- + X$.
- The 1st emission in the dipole shower is ME corrected per construction.
- Data: A. A. Affolder et. al. Phys. Rev. Lett. **84** (2000) 845.

Results for hadronic collisions

➡ *Testbed: Drell–Yan pair production @ LHC, compared to SHERPA predictions*





- Pseudo-rapidity (left) and transverse-momentum (right) distribution of the first jet.
- The 1st emission in the dipole shower is ME corrected per construction.

Summary/Outlook

- The LHC physics programme requires a detailed understanding of QCD

- New major release Sherpa 1.1 out ➡ fully independent MC event generator
- hopefully well prepared for the LHC challenge

- 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.
- Many new achievements for the simulation of soft physics
  AHADIC, HADRONS, PHOTONS
- Full simulation of hadron-level events

- Many interesting ongoing projects beyond what is implemented in Sherpa 1.1