# SHERPA
# Status and prospects

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RHUL - Theory Experiment Interplay at the LHC - 8.4.2010

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[1] for the Sherpas: J. Archibald, T. Gleisberg, S. Höche, H. Hoeth, F. Krauss, M. Schönherr, S. Schumann, F. Siegert, J. Winter, and K. Zapp

# Outline

1. A brief introduction
2. Matrix elements
3. Parton showering
4. Multijet merging
5. Soft physics
6. Forthcoming attractions

# A brief introduction

- SHERPA has been under development since the late 1990's
  - In the beginning, borrowed and re-implemented physics from others: virtuality-ordered parton shower - APACIC++, underlying event like PYTHIA 6.2
  - Helicity amplitudes for matrix elements - AMEGIC++
  - Fragmentation/hadron decays through link to PYTHIA routines
- Constructed from scratch, in C++
  - Mainly done by diploma and PhD students

    up to now: 6 finished PhD theses
- Replaced physics modules one-by-one.
- Status in SHERPA 1.2: by now independent of other code
  - Virtuality-ordered shower replaced by dipole shower,
  - Berends-Giele matrix elements,
  - Own version of cluster fragmentation AHADIC++,
  - Huge own library of hadron and $\tau$-decays,
  - QED radiation through YFS formalism,
  - Only UE modelling still along the line of Sjostyrand-van der Zijl, PYTHIA 6.2.
- A full-fledged independent event generator

# High multiplicity matrix elements

## Matrix element generation in SHERPA 1.2

- Provides three kinds of matrix elements:
    - Since 1.2.0: COMIX- mainly SM, can handle up to 8-10 final state particles

      (implementations for BSM-relevant methods have low priority in COMIX.)
    - AMEGIC++- SM & BSM generator, up to 6 final state particles

      (development stalled, will eventually move to COMIX.)
    - specific, hard-coded ME's
- Using COMIX makes SHERPA even easier to handle:
  no more libraries written out to be compiled in intermediate step.
- SHERPA/AMEGIC++ support FEYNRULES

  (a tool to generate Feynman rules directly from Lagrangians - a new standard to propagate BSM models?)
- No support for LHA - considered pointless by SHERPA.

## SM matrix element generator COMIX

T.Gleisberg & S.Hoeche, JHEP **0812** (2008) 039

- Colour-dressed Berends-Giele amplitudes in the SM
- Fully recursive phase space generation
- Example results (cross sections):

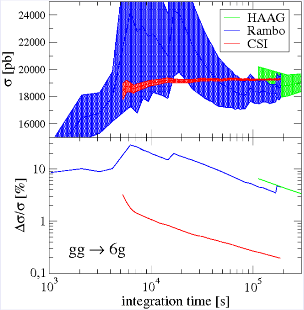
| gg $\longrightarrow$ ng | Cross section [pb] | | | | |
|---|---|---|---|---|---|
| n<br>$\sqrt{s}$ [GeV] | 8<br>1500 | 9<br>2000 | 10<br>2500 | 11<br>3500 | 12<br>5000 |
| Comix | 0.755(3) | 0.305(2) | 0.101(7) | 0.057(5) | 0.019(2) |
| Maltoni (2002) | 0.70(4) | 0.30(2) | 0.097(6) | | |
| Alpgen | 0.719(19) | | | | |

| $\sigma$ [$\mu$b] | Number of jets | | | | | | |
|---|---|---|---|---|---|---|---|
| $b\bar{b}$ + QCD jets | 0 | 1 | 2 | 3 | 4 | 5 | 6 |
| Comix | 4780(5) | 8.83(2) | 1.826(8) | 0.459(2) | 0.1500(8) | 0.0544(6) | 0.023(2) |
| ALPGEN | 4760(6) | 8.83(1) | 1.822(9) | 0.459(2) | 0.150(2) | 0.053(1) | 0.0215(8) |
| AMEGIC++ | 4730(4) | 8.84(2) | 1.817(6) | | | | |

## SM matrix element generator COMIX

T.Gleisberg & S.Hoeche, JHEP **0812** (2008) 039

- Colour-dressed Berends-Giele amplitudes in the SM
- Fully recursive phase space generation
- Example results (phase space performance):



# BSM matrix element generator AMEGIC++

F.K., R.Kuhn, G.Soff, JHEP **0202** (2002) 044.

- Uses helicity/recursion methods;
- Helicity method supplemented with “factoring out” (taming the factorial growth)
- Phase space integration through multi-channeling (i.e. one phasespace mapping/Feynman diagram)
- Implemented & tested models: SM, SM+AGC, THDM, MSSM, ADD.
- Tested in $> 1000$ SM & $> 500$ MSSM channels.
- Recently: Automated dipole subtraction for NLO calculations (Fully supports the NLO-LHA)

# Aside: Automated dipole subtraction

## Implementation in SHERPA

T.Gleisberg & F.K., Eur.Phys.J.**C53** (2008) 501

- Implemented in AMEGIC++, including the $\alpha_{\rm cut}$ prescription
- First example for a generic interface, with BLACKHAT

(W+3jets, C.F.Berger et al., PRL **102** (2009) 222001, PRD **80** (2009) 074036)

(Z+3jets, C.F.Berger et al., arXiv:0912.4927)

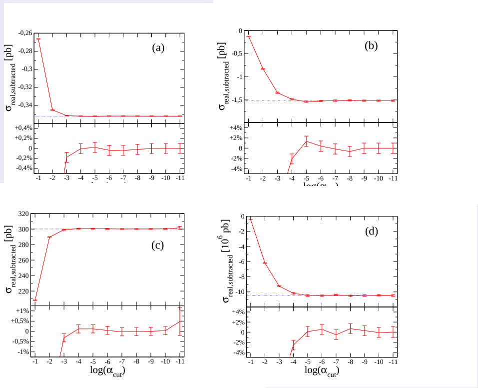
- Also interfaced to other calculations/codes

(ZZ+jet, T.Binoth et al., PLB **683** (2010) 154.)

- Conformal with the LH accord. Basic idea:
  - LO codes provide Born-level ME for given process;
  - LO code constructs and provides real corrections, their subtraction terms and the integrated subtracition terms;
  - LO code implements the phase space integration;
  - NLO code provides the loop MEs (i.e. virtual corrections only)

# Example checks & results: Independence of $\alpha_{\mathrm{cut}}$

T.Gleisberg & F.K., Eur.Phys.J.**C53** (2008) 501



(a) $e^+e^- \longrightarrow$ 2jets

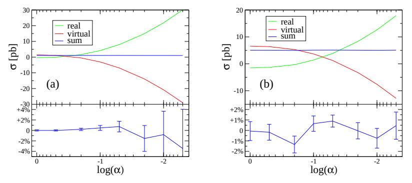
(b) $e^+e^- \longrightarrow$ 3jets

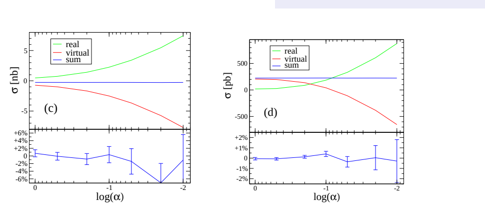
(c) $ep \longrightarrow e +$ 1jet

(d) $pp \longrightarrow$ 2jets

# Example checks & results: Stability of total cross sections

T.Gleisberg & F.K., Eur.Phys.J.**C53** (2008) 501





(a) $e^+e^- \longrightarrow$ 2jets

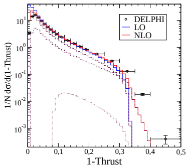
(b) $e^+e^- \longrightarrow$ 3jets

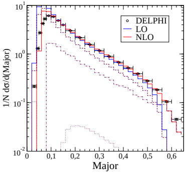
(c) $ep \longrightarrow e +$ 1jet

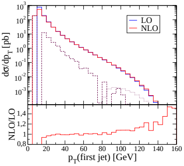
(d) $pp \longrightarrow W$

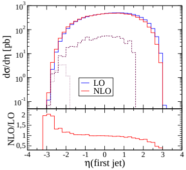
# Example checks & results: Various cross sections

T.Gleisberg & F.K., Eur.Phys.J.**C53** (2008) 501









# Parton showering

## Motivation

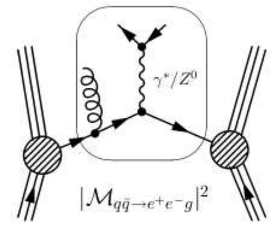
Matrix element calculations (collinear factorisation):

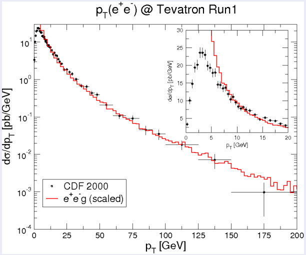
$$\sigma_{pp\to N}(Q^2) = \sum_{a,b} \int \mathrm{d}x_a \mathrm{d}x_b \; g_a(x_a, Q^2) g_b(x_b, Q^2) \; |\mathcal{M}_{ab\to N}|^2 \; \mathrm{d}\Phi_N$$

+ $|\mathcal{M}_{ab\to N}|^2$ encodes fundamental physics, interferences, off-shell effects
+ accounts for high-$p_T$, well separated partons
+ well-defined procedure to improve accuracy (perturbative expansion)
− poor for log-enhanced phase-space regions, few-parton final states only.
− link to hadronisation troublesome

# Motivation (cont'd)

Example: $p_\perp^{(Z)}$ due to additional radiation in $pp \to e^+e^- + X$





- $|\mathcal{M}_{q\bar{q}\to e^+e^-g}|^2 \sim |\mathcal{M}_{q\bar{q}\to e^+e^-}|^2 \frac{\alpha_S(\mu_R^2)}{p_T^2} \rightsquigarrow \sigma_{pp\to e^+e^-g} \sim \sigma_{pp\to e^+e^-}\,\alpha_S(\mu_R^2) \log \frac{p_T^{\max}}{p_T^{\min}}$
- large logs need to be resummed
- $|\mathcal{M}|^2$ factorise in IR limit (universal) $\rightsquigarrow$ parton shower approach

## Generating emissions from QCD evolution equations

(Also a warm-up exercise for new formalism for multijet merging in Sherpa 1.2)

Starting from d$\sigma$, generate radiation through QCD evolution

$$\frac{\partial g_a(z,t)}{\partial \log(t/\mu^2)} = \int_z^{\zeta_{\max}} \frac{\mathrm{d}\zeta}{\zeta} \sum_{b=q,g} \mathcal{K}_{ba}(\zeta,t)\, g_b(\frac{z}{\zeta},t) - g_a(z,t) \int_{\xi_{\min}}^{\xi_{\max}} \mathrm{d}\xi \sum_{b=q,g} \xi\, \mathcal{K}_{ab}(\xi,t)$$

- $\zeta$, $t$ - splitting, evolution variable

separate resolved from unresolved emissions

- $\mathcal{K}_{ba}(\zeta,t)$ - evolution kernels of the scheme:

$$\mathcal{K}_{ba}(\zeta,t) \overset{\mathrm{IR}}{\longleftrightarrow} \frac{1}{\sigma_a^{(N)}(\Phi_N)} \frac{\mathrm{d}\sigma_b^{(N+1)}(\zeta,t;\Phi_N)}{\mathrm{d}\log(t/\mu^2)\,\mathrm{d}\zeta}$$

e.g. collinear factorization scheme $\alpha_s/2\pi\ P_{ba}(\zeta)$

## The Sudakov form factor: No-emission probability

(Also a warm-up exercise for new formalism for multijet merging in Sherpa 1.2)

- Define Sudakov form factor:

$$\Delta_a(\mu^2,\,t) = \exp\left[-\int\limits_{\mu^2}^{t}\frac{\mathrm{d}t'}{t'}\int\limits_{z}^{\xi_{\max}}\mathrm{d}\xi\,\frac{1}{2}\sum_{b=q,g}\mathcal{K}_{ba}(\xi\,,t')\right]$$

- Rewrite equation above:

$$\frac{1}{\partial\log(t/\mu^2)}\,\frac{\partial g_a(z,t)}{\Delta_a(\mu^2,\,t)} = \frac{1}{\Delta_a(\mu^2,\,t)}\int\limits_{z}^{\zeta_{\max}}\frac{\mathrm{d}\zeta}{\zeta}\sum_{b=q,g}\mathcal{K}_{ba}(\zeta,t)\,g_b(\frac{z}{\zeta},t)$$

- Corresponding no-emission probability (from $\bar{t}$ to $t$):

$$\begin{aligned}\mathcal{P}^{\rm no}_a(z,\,t,\,\bar{t}) &= \frac{\Delta_a(\mu^2,\,\bar{t})}{\Delta_a(\mu^2,\,t)}\,\frac{g_a(z,\,t)}{g_a(z,\,\bar{t})}\\ &= \exp\left[-\int\limits_{t}^{\bar{t}}\frac{\mathrm{d}t'}{t'}\int\limits_{z}^{\zeta_{\max}}\frac{\mathrm{d}\zeta}{\zeta}\sum_{b=q,g}\mathcal{K}_{ba}(\xi\,,t')\,\frac{g_b(z/\zeta,\,t)}{g_a(z,\,\bar{t})}\right]\end{aligned}$$

# Parton showering in Sherpa 1.2

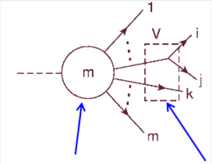
## Parton shower based on Catani-Seymour splitting kernels

First discussed in: Z.Nagy and D.E.Soper, JHEP **0510** (2005) 024

Implemented by M.Dinsdale, M.Ternick, S.Weinzierl Phys.Rev.**D76** (2007) 094003

and S.Schumann& F.K., JHEP **0803** (2008) 038.

- Explicit use of factorization formulae for real emission process ⟷ NLO dipole subtraction
- Full phase space coverage (invertible).
- Typically good approximation to ME.
- Project onto leading $1/N_c$ & employ spin-averaged dipole kernels.
- four types of splittings: FF, IF, FI, II.
- Recently: improved kinematics mappings to account for exponentiation properties



m-parton state splitting operator

(Work in progress.)

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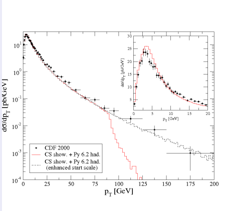
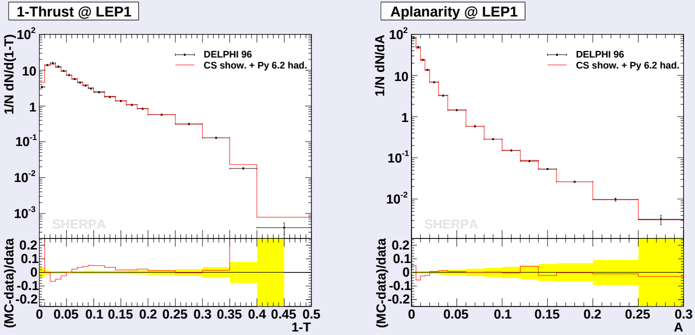


(Work in progress.)

# Results in $e^+e^-$ collisions at LEP1

S.Schumann& F.K., JHEP **0803** (2008) 038.



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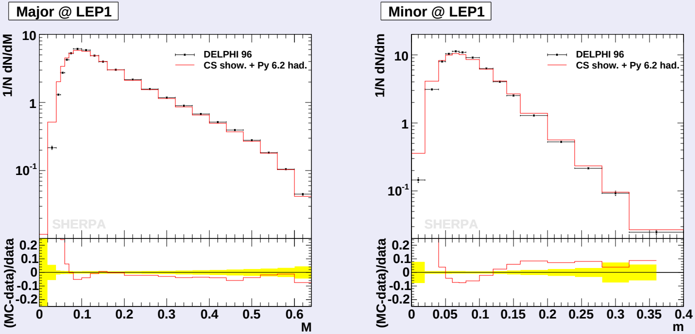

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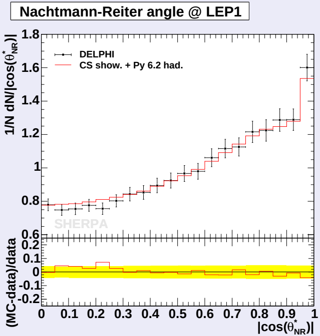
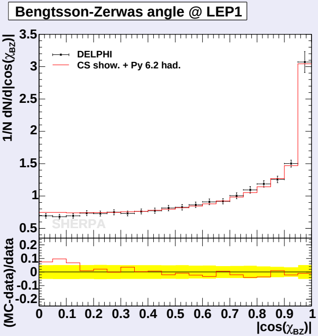


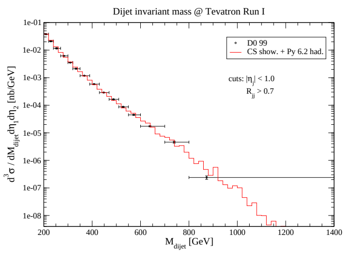
Nachtmann-Reiter angle @ LEP1

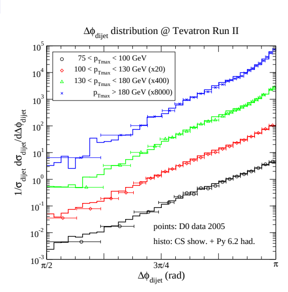


Bengtsson-Zerwas angle @ LEP1

## CS-Shower: Results in $p\bar{p}$ collisions

S.Schumann& F.K., JHEP **0803** (2008) 038.





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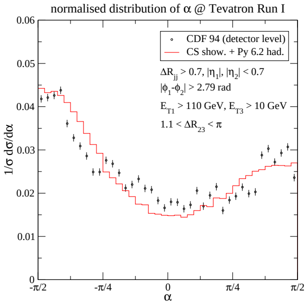
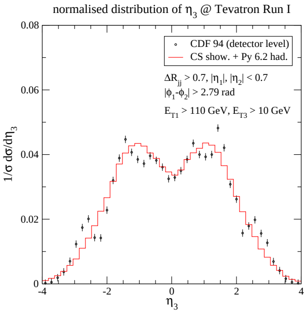
S.Schumann& F.K., JHEP **0803** (2008) 038.





# Multijet merging

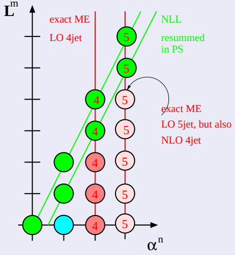
## From partons to hadrons

- Experimental definition of jets based on hadrons.
- But: Hadronization through phenomenological models (need to be tuned to data).

## ME vs. PS

- MEs: hard, large-angle emissions; interferences.
- PS: soft, collinear emissions; resumation of large logarithms.
- Combine both, avoid double-counting.

## $\alpha_s$ vs. Log



## Constructing the algorithm

- Want the best of both - what else?
  - Proper description of soft/collinear and hard emissions
  - Combine QCD matrix elements of different parton multiplicity with showers
- General outline of algorithm:
  - Use LO (tree-level) matrix elements for jet production
    - Could use parton shower kernel $K_{ba}^{ME} \propto |\mathcal{M}_{n+1}|^2/|\mathcal{M}_n|^2$
    - Idea effectively used in traditional reweighting
    - Also in generation of hardest emission in POWHEG
  - Preserve original parton shower evolution equation

    (N.B.: this guarantees preservation of log accuracy provided by shower)
  - Avoid double-counting (positive or negative)

    Must slice the phase space: Jet production vs. jet evolution

    $\Longrightarrow$ adds a parameter - the jet resolution criterion $Q_{\rm cut}$

    (but results should better not depend too strongly on this parameter)

## Slicing the phase space

- Write
  $K_{ba}(z,\,t) = K_{ba}(z,\,t)\Theta[Q_{\rm cut} - Q_{ba}(z,\,t)] + K_{ba}(z,\,t)\Theta[Q_{ba}(z,\,t) - Q_{\rm cut}]$.
- In hard region, call $K_{ba}\Theta[Q_{ba}(z,\,t) - Q_{\rm cut}] \to K_{ba}^{ME}$,
- Call $K_{ba}\Theta[Q_{\rm cut} - Q_{ba}(z,\,t)] \to K_{ba}^{PS}$ in soft region.
- Sudakov form factor factorises (exponential):

  $$\Delta_a(\mu^2,\,t) = \Delta_a^{PS}(\mu^2,\,t)\Delta_a^{ME}(\mu^2,\,t)$$

  Also, no emission probability can be rewritten:

  $$\mathcal{P}_a^{\rm no}(z,\,t,\,\bar{t}) = \frac{\Delta_a^{PS}(\mu^2,\,\bar{t})}{\Delta_a^{PS}(\mu^2,\,t)}\,\frac{\Delta_a^{ME}(\mu^2,\,\bar{t})}{\Delta_a^{ME}(\mu^2,\,t)}\,\frac{g_a(z,\,t)}{g_a(z,\,\bar{t})}$$
- In shower, need to veto emissions with $Q_{ba} > Q_{\rm cut}$.
  But possibly at $Q$ larger than those in ME
  "mismatch" of shower and jet measure $\longrightarrow$ truncated showers

## Phase space measure

- Motivated by parton shower/dipole kinematics:

$$Q_{ij}^2 = 2\,p_i p_j \min_{k\neq i,j} \frac{2}{C_{i,j}^k + C_{j,i}^k}\,;\, C_{i,j}^k = \begin{cases} \dfrac{p_i p_k}{(p_i+p_k)p_j} - \dfrac{m_i^2}{2\,p_i p_j} & \text{if } j = g \\ 1 & \text{else} \end{cases}$$

- IR limits:
  - soft limit: $p_j = \lambda q,\ \lambda \to 0$

$$\frac{1}{Q_{ij}^2} \to \frac{1}{2\,\lambda^2}\,\frac{1}{2\,p_i\,q}\,\max_{k\neq i,j}\left[\frac{p_i p_k}{(p_i+p_k)\,q} - \frac{m_i^2}{2\,p_i q}\right]$$

  - quasi-collinear limit: $k_\perp \to \lambda k_\perp,\ m \to \lambda m$

$$\frac{1}{Q_{ij}^2} \to \frac{1}{2\,\lambda^2}\,\frac{\widetilde{C}_{i,j} + \widetilde{C}_{j,i}}{p_{ij}^2 - m_i^2 - m_j^2}\ \widetilde{C}_{i,j} = \begin{cases} \dfrac{z}{1-z} - \dfrac{m_i^2}{2\,p_i p_j} & \text{if } j = g \\ 1 & \text{else} \end{cases}$$

- measure correctly identifies enhanced phase-space regions

## Defining PS histories

- Identify most likely splitting
  acc. to PS branching probability
- Combine partons into mother parton
  acc. to inverse PS kinematics
- Continue until $2 \longrightarrow 2$ core process

$\rightsquigarrow$ shower specific cluster algorithm

$\rightsquigarrow$ predetermined shower emissions

PS starts at core process

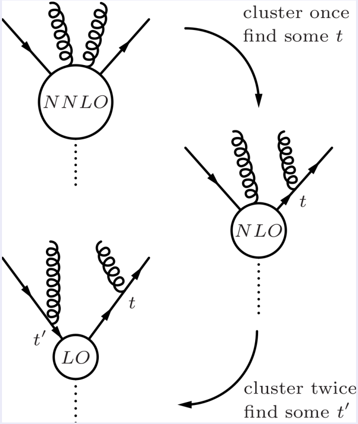
can radiate "between" ME emissions

ME branchings must be respected

evolution-, splitting- & angular variable preserved

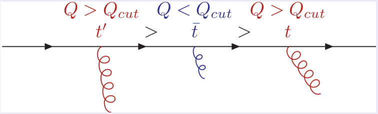
$\rightsquigarrow$ truncated shower

## Example branching history



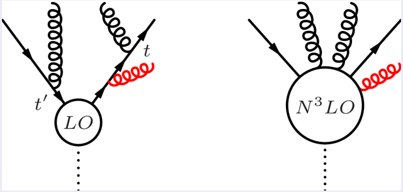
## Truncated shower

Shower emission below $Q_{\text{cut}}$:



- ⇝ emission accepted
- ⇝ large-angle soft emissions
- ⇝ soft color coherence
- ⇝ approx. in CKKW only

Shower emission above $Q_{\text{cut}}$:

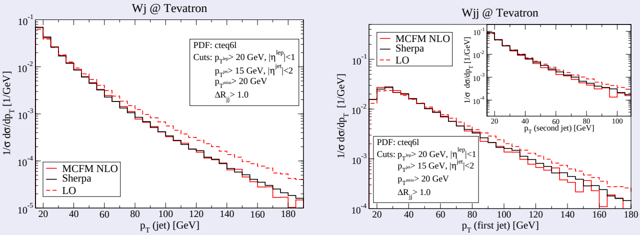


- ⇝ entire event is rejected
- ⇝ Sudakov suppression $\mathcal{P}^{\text{ME}}_{\text{no},\,a}(t,t')$
- ⇝ to be described by ME instead
- ⇝ $\sigma_{\text{tot}}$ preserved at LO

## Why it works: Algorithm as scale-setting prescription

- Example: $p_\perp$ distribution of jets @ Tevatron
- Consider exclusive $W+1$- and $W+2$-jet production

F.K., A.Schälicke, S.Schumann and G.Soff, Phys. Rev. D **70** (2004) 114009:
comparison with MCFM; J.Campbell and R.K.Ellis, Phys. Rev. D **65** (2002) 113007



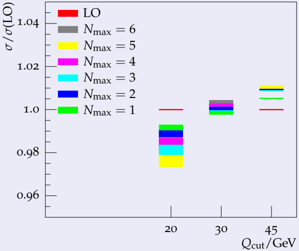
Sherpa = tree-level matrix elements with $\alpha_S$ scales and Sudakov form factors.

# $Z^0$+jets at Tevatron: Total cross sections

$Q_{cut}$ and/or $N_{max}$ variation should affect $\sigma_{tot}$ only beyond (N)LL

- Example: DY-pair production $\sigma_{\rm tot}$ @ Tevatron

| | | $N_{\rm max}$ | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 0 | 1 | 2 | 3 | 4 | 5 | 6 |
| $Q_{\rm cut}$ | 20 GeV | 192.6(1) | 191.0(3) | 190.5(4) | 189.0(5) | 189.4(7) | 188.2(8) | 189.9(10) |
| | 30 GeV | | 192.3(2) | 192.7(2) | 192.6(3) | 192.9(3) | 192.7(3) | 193.2(3) |
| | 45 GeV | | 193.6(1) | 194.4(1) | 194.3(1) | 194.4(1) | 194.6(2) | 194.4(1) |



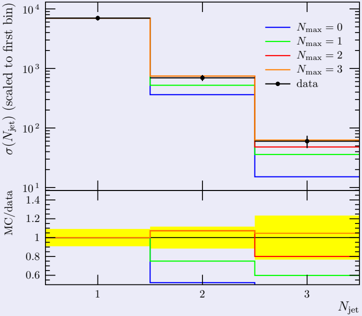
- improved “merging systematics” of $\boldsymbol{\sigma}_{\mathbf{tot}} < \pm$**3%**

# $Z^0$+jets at Tevatron: jet multiplicities

Jet rates and -spectra improved compared to pure PS simulation

- Example: DY-pair production $\sigma_{\mathrm{e^+e^-+N_{jet}}}$

CDF Data: PRL **100** (2008) 102001



$Q_{\rm cut} = 30$ GeV

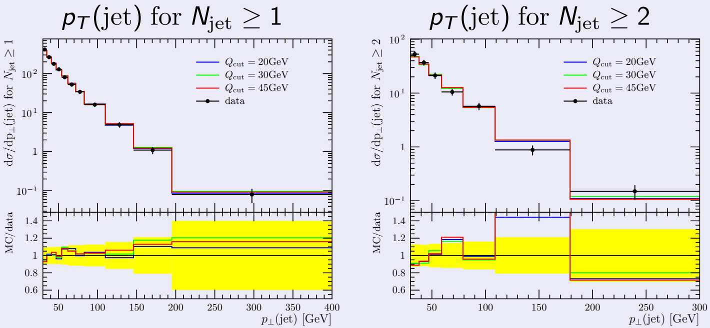
# $Z^0$+jets at Tevatron: jet spectra

Variation of $Q_{cut}$ should affect distributions only beyond (N)LL

But $Q_{cut}$ must be in range where PS approximation is valid!

- Example: All-jets $p_T$'s in DY-pair production

CDF Data: PRL **100** (2008) 102001


$p_T$(jet) for $N_{\text{jet}} \geq 1$

$p_T$(jet) for $N_{\text{jet}} \geq 2$

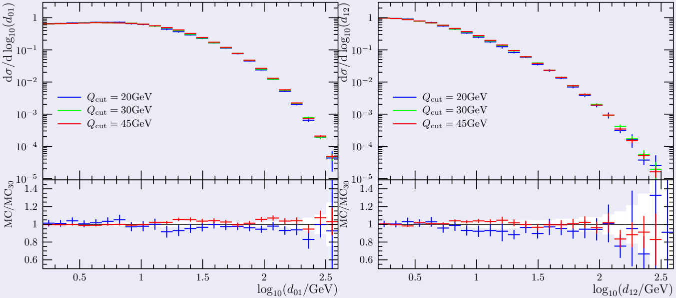
# $Z^0$+jets at Tevatron: jet spectra

Variation of $Q_{cut}$ should affect distributions only beyond (N)LL

But $Q_{cut}$ must be in range where PS approximation is valid!

- Example: Differential $\mathbf{k_T}$ jet rates

$1 \longrightarrow 0$ $2 \longrightarrow 1$



- $\mathbf{Q_{cut}}$ variations within $\pm$**10%**

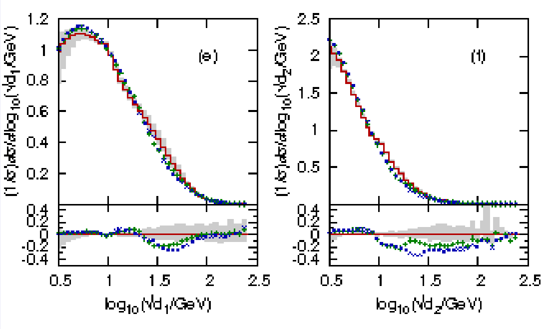
# $Z^0$+jets at Tevatron: jet spectra

Variation of $Q_{cut}$ should affect distributions only beyond (N)LL

But $Q_{cut}$ must be in range where PS approximation is valid!

- Example: Differential $\mathbf{k_T}$ jet rates
  Compare: standard CKKW for W+jets (Sherpa 1.1)

Alwall et. al Eur. Phys. J. C **53** (2008) 473

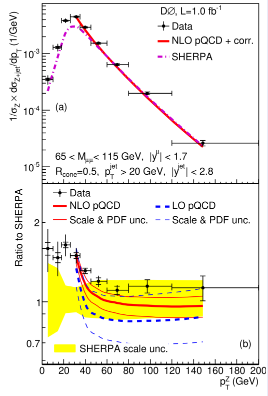


# $Z^0$+jets at Tevatron: $Z/\gamma^*$ transverse momentum

DØ data: Phys. Lett. B **669** (2008) 278

## Comparison with Sherpa's CKKW implementation in v1.1.3

### SHERPA v1.1.3



# $Z^0$+jets at Tevatron: $Z/\gamma^*$ transverse momentum

DØ data: Phys. Lett. B **669** (2008) 278

## Comparison with Sherpa's CKKW implementation in v1.1.3

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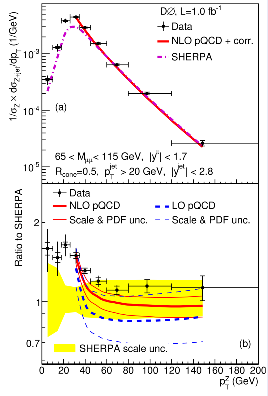
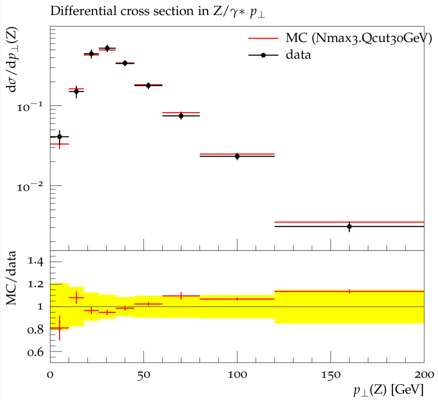


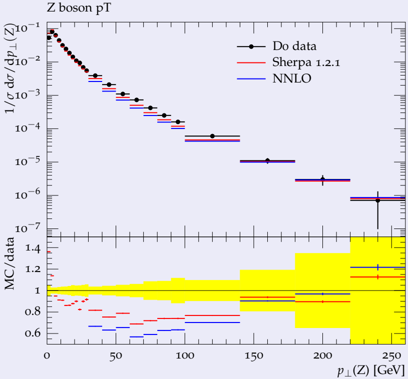
### SHERPA v1.2



# $Z^0$+jets at Tevatron: $Z/\gamma^*$ transverse momentum

DØ data: Phys. Lett. B **669** (2008) 278

## Comparison between SHERPA 1.2.1 and NNLO Z production

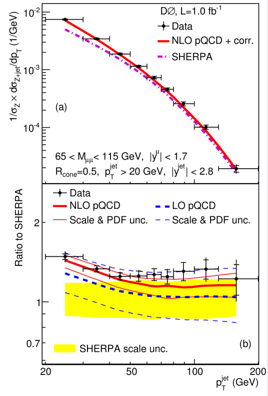


# $Z^0$+jets at Tevatron: jet spectra

DØ data: Phys. Lett. B **669** (2008) 278

## Comparison with Sherpa's CKKW implementation in v1.1.3

SHERPA v1.1.3

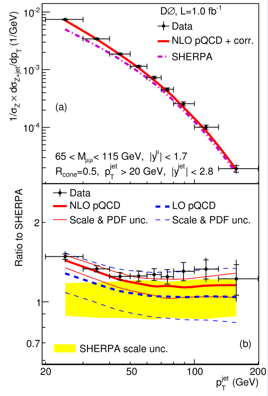


# $Z^0$+jets at Tevatron: jet spectra

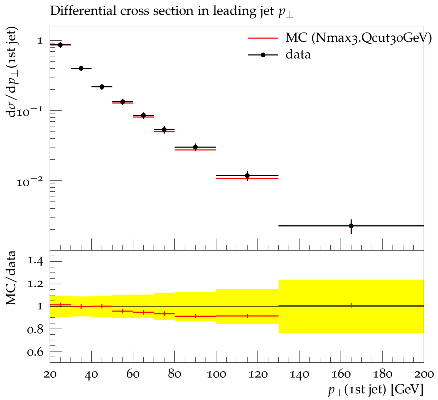
DØ data: Phys. Lett. B **669** (2008) 278

Comparison with Sherpa's CKKW implementation in v1.1.3

SHERPA v1.1.3



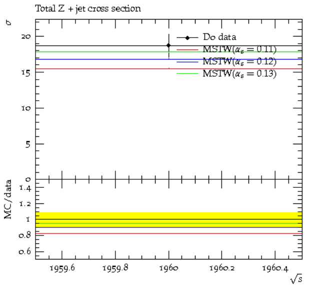
SHERPA v1.2

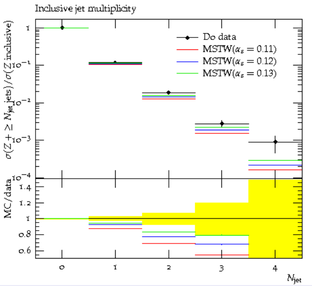


# $Z^0$+jets at Tevatron: cross sections

CDF data from PRL 100 (2008) 102001 and D0/, arXiv:0808:1296

## Impact of $\alpha_S$ - global in SHERPA

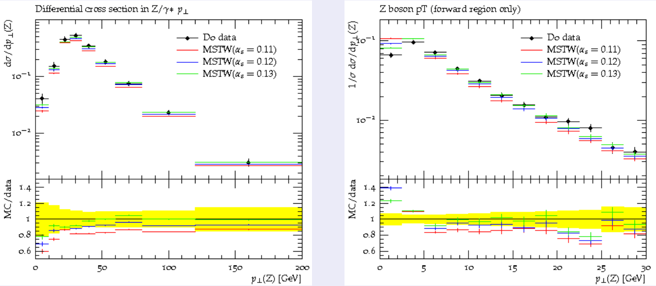




## $Z^0$+jets at Tevatron: $Z/\gamma^*$ transverse momentum

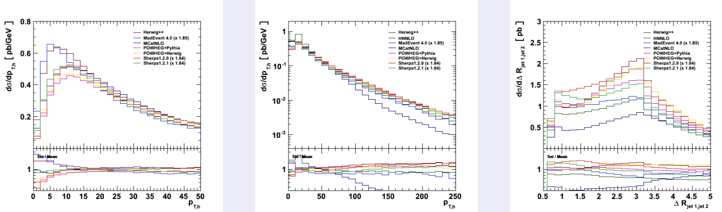
DØ data: PRL 100 (2008) 102002

### Impact of $\alpha_S$ - global in SHERPA



## Aside: Higgs boson $p_\perp$ in $gg \to H$

### Big LH comparison

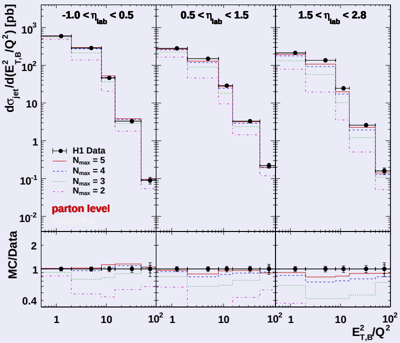


# Generalisation of merging algorithm to DIS

## ME & PS results: Inclusive jets in DIS

S.Hoeche et al., arXiv:0912.3715, data from PL **B542** (2002) 193

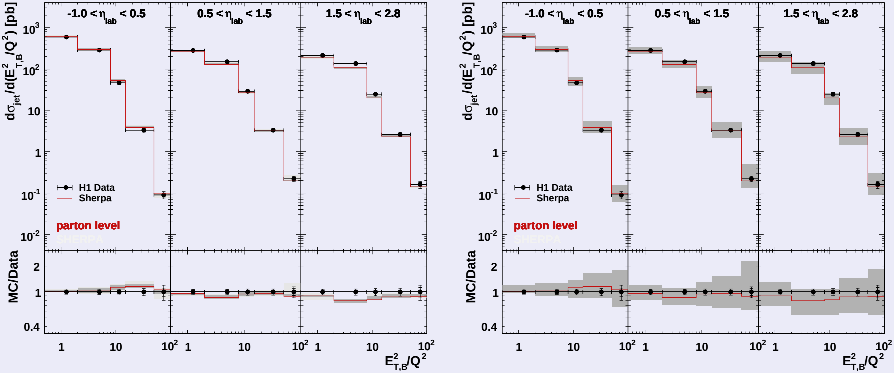
Variation of maximum matrix-element multiplicity, $N_{\max}$



# ME & PS results: Inclusive jets in DIS

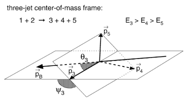
S.Hoeche et al., arXiv:0912.3715, data from PLB**542** (2002) 193

Variation of merging parameters and factorisation/renormalisation scales

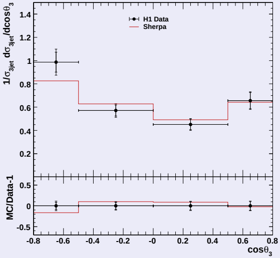


# ME & PS results: Inclusive trijets in DIS

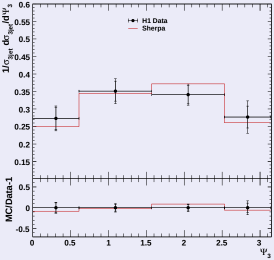
S.Hoeche et al., arXiv:0912.3715, data from PL **B515** (2001) 17



$\cos\theta_3$ $Q^2 > 150$ GeV$^2$

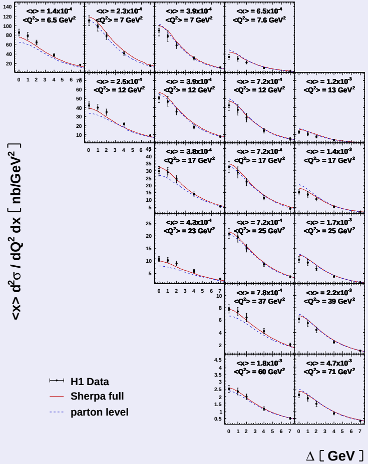


$\Psi_3$ $Q^2 > 150$ GeV$^2$



# ME & PS results: Low-$x$ dijets in DIS

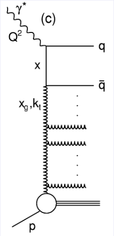
S.Hoeche et al., arXiv:0912.3715, data from EPJ **C33** (2004) 477



$\Delta$ in bins of $\langle x\rangle$ and $\langle Q^2\rangle$

$\Delta$ defined as $E^*_{T,\max} > E^*_{T\,\mathrm{cut}} + \Delta$

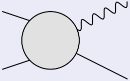
$E^*_{T\,\mathrm{cut}}$ $\longrightarrow$ minimum jet transverse energy
$E^*_{T\,\max}$ $\longrightarrow$ transverse energy of hardest jet



# Merging for Prompt-Photon Production

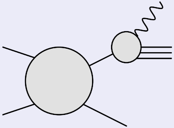
## The perturbative QCD approach

### Direct production



- fixed-order calculations
  - $\gamma$+jet @ NLO (JetPhox) [Catani et. al]
  - $\gamma\gamma$ @ NLO (DiPhox) [Binoth et. al]
  - $\gamma\gamma$+jet @ NLO [Del Duca et. al]
  - $gg \to \gamma\gamma g$ [de Florian et. al]

### Fragmentation component



- QED $\gamma - q$ collinear singularity
- resummation to all orders $\alpha_s$
- fragmentation function $D^{\gamma}_{q,g}$

- Apporach bases on IR safe xsec definition (photon isolation)

  [cone, smooth isolation, democratic approach]
- Assumption: non-prompt component, e.g. $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$, experimentally separable

## A new Monte Carlo approach for Prompt-Photon Production

(S.Höche, S.Schumann, F.Siegert PRD **81** (2010) 034026)

- treat photons and QCD partons fully democratically

(Glover, Morgan Z. Phys. C **62** (1994) 311)

- combine matrix elements of different parton/photon multiplicity with
- QCD⊕QED evolution and hadronization ⇝ models $D^{\gamma}_{q,g}(z, Q^2)$

## Generalized merging formalism

- Emission probabilities factorise trivially as before

$$\Delta_a(Q_0^2, Q^2) = \Delta_a^{\mathrm{(QCD)}}(Q_0^2, Q^2)\Delta_a^{\mathrm{(QED)}}(Q_0^2, Q^2)$$

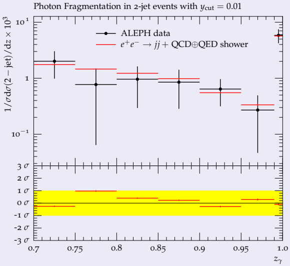
- Implemented by adding splitting functions $q \to q\gamma$
- Different then large-$N_C$ QCD: spectators *all* particles with opposite charge
- Neglect (negative) interference with same-sign charges

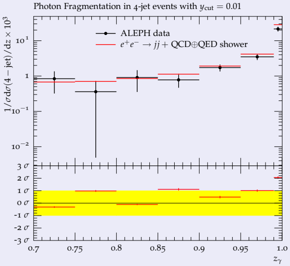
(S.Dittmaier, Nucl. Phys. B **565** (2000) 69)

# Results: photon fragmentation function in $e^+e^- \rightarrow$ Hadrons

(Aleph data from Z. Phys. C **69** (1996) 365)

- Validation of the shower/hadronization component
- Perform jet finding including final-state photons
- Study photon-energy fraction wrt its containing jet: $z_\gamma \equiv E_\gamma/E_{\rm jet}$





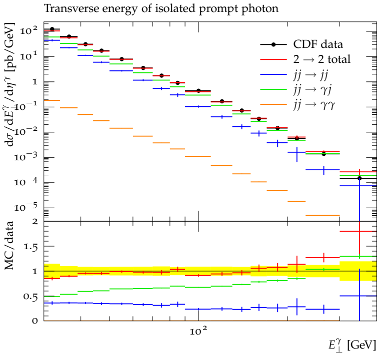
# Isolated prompt-photon production at Tevatron

(Data from CDF, Phys. Rev. D **80** (2009) 111106)

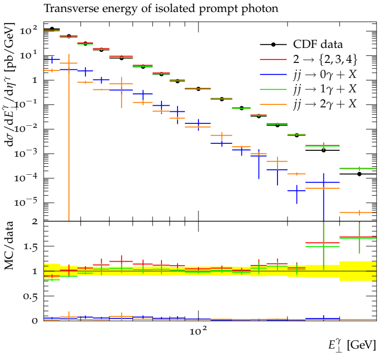
cuts: $30 < E_T^\gamma < 400$ GeV, $|\eta^\gamma| < 1$, isolation: $E_T^{R=0.4} - E_T^\gamma < 2$ GeV

- Sherpa: pure shower vs. ME$\oplus$TS

## $E_T^\gamma$ – pure shower



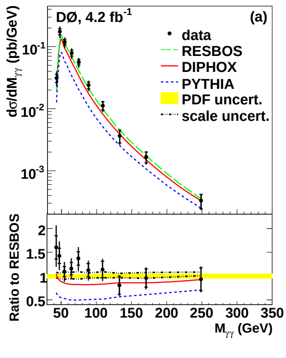
## $E_T^\gamma$ – ME$\oplus$TS

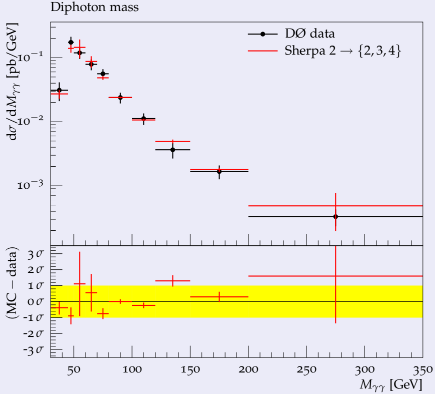


# Di-Photon production at Tevatron: Invariant mass

(D0/ data, arXiv:1002.4917)

- Compare with other codes: DiPhox, ResBos, Pythia
- Sherpa: merged $2 \to \{2,3,4\}$ plus $gg \to \gamma\gamma$ box

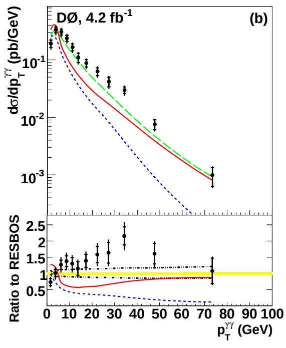


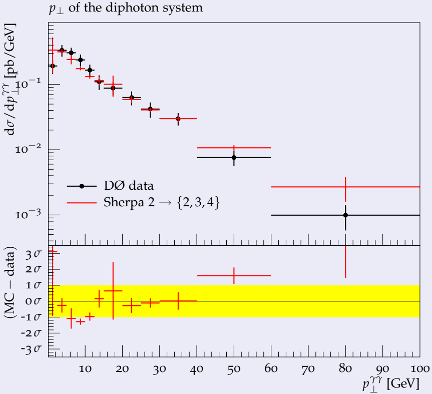


# Di-Photon production at Tevatron: Transverse momentum of pair

(D0/ data, arXiv:1002.4917)

- Compare with other codes: DiPhox, ResBos, Pythia
- Sherpa: merged $2 \to \{2, 3, 4\}$ plus $gg \to \gamma\gamma$ box

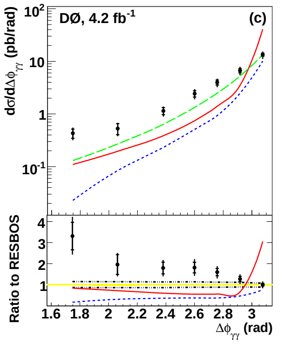


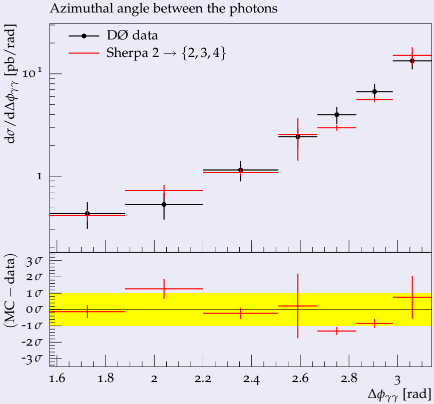


# Di-Photon production at Tevatron: Azimuthal decorrelation

(D0/ data, arXiv:1002.4917)

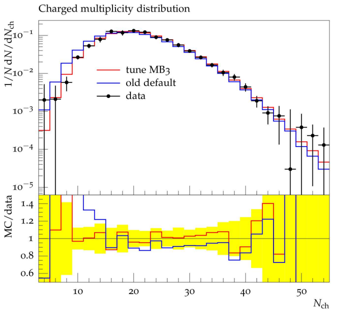
- Compare with other codes: DiPhox, ResBos, Pythia
- Sherpa: merged $2 \to \{2, 3, 4\}$ plus $gg \to \gamma\gamma$ box

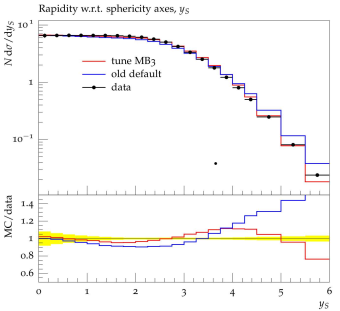




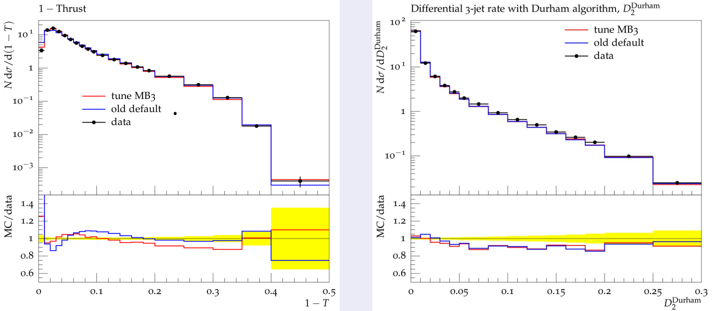
# Sherpa's hadronisation

## Recent results in $e^+e^- \longrightarrow$ hadrons

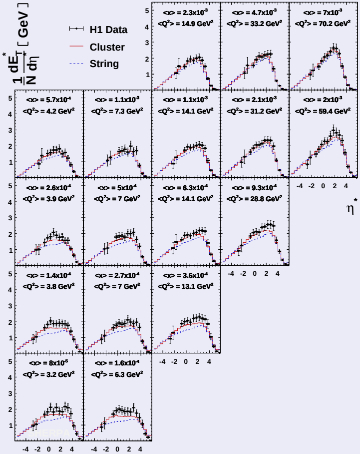




# Recent results in $e^+e^- \longrightarrow$ hadrons



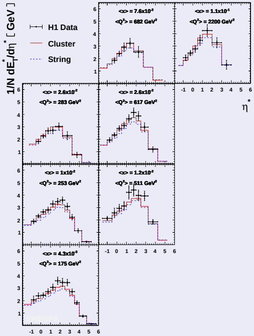
# Hadronisation in DIS: Energy flow analysis



EPJ **C12** (2000) 595

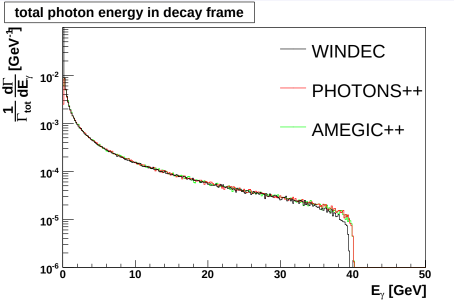
Transverse energy flow

SHERPA cluster fragmentation
vs. Lund string fragmentation

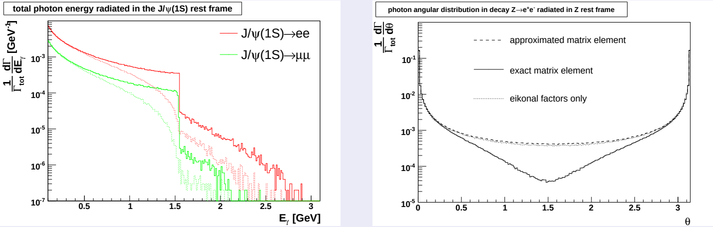


# QED radiation in Sherpa

## Example: Photon radiation in $W \longrightarrow \ell\nu$

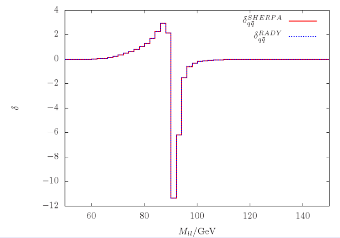


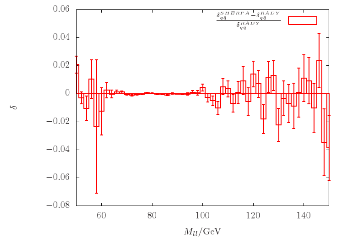
# Example: Photon radiation in $J/\psi \to \ell\bar{\ell}$



# Dipole subtraction for EW corrections

- LH accord for EW corrections more involved:
  defintions of schemes, complex masses for unstable particles, etc..
- Implemented and tested in QED corrections to DY.



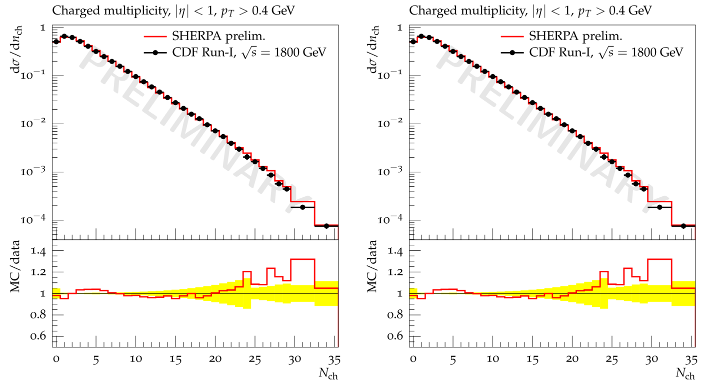


# A new model for Minimum Bias (and the underlying event)

## Underlying ideas

- Multi-channel eikonal approach
  allows for natural description of low-mass diffraction
- Rooted in unitarisation by exponentiating eikonals
- BFKL-inspired interpretation: exchange of "ladders" (cut pomerons) between hadrons
- Naturally incorporates diffraction/diffractive parts in ladder dynamics

# Some appetisers



# Conclusions

## SHERPA v1.2 and beyond

- SHERPA v1.2 added enhanced physics and usability:
  higher multis, no more libraries, merging completely automatic
- New merging algorithm with improved features:
  - less merging scale uncertainty (below 10% in most cases), smooth transitions
  - has been extended to DIS (→ VBF) and prompt photon production
- Added dipole subtraction for NLO calculations (LH accord)
- Will include new Minimum Bias model by summer
- First steps towards NLO precision under way.