# Event generators for the LHC

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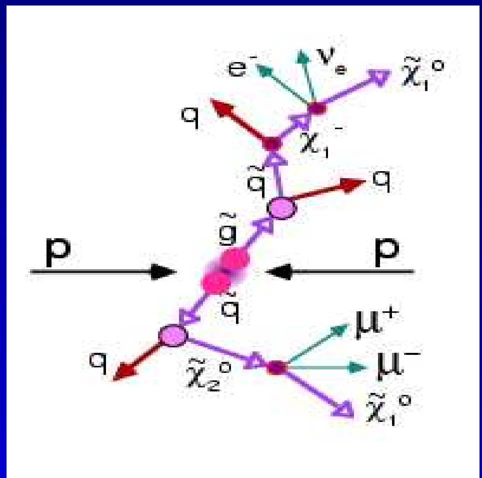
# Outline

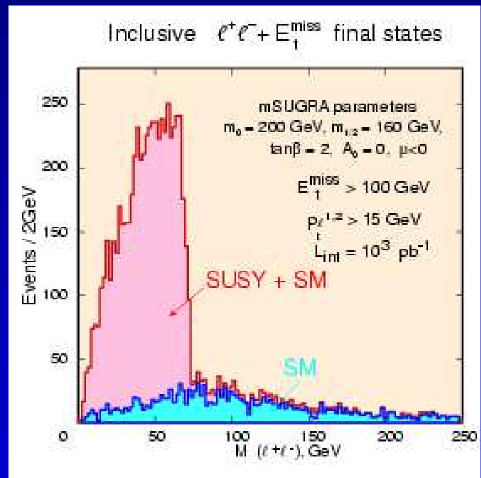
- Why event generators
- SHERPA in brief
- ME's in SHERPA
- Merging ME's + PS
- Results of SHERPA vs. others + data
  - W/Z+jets @ Tevatron
  - Jets only @ Tevatron
- Conclusion

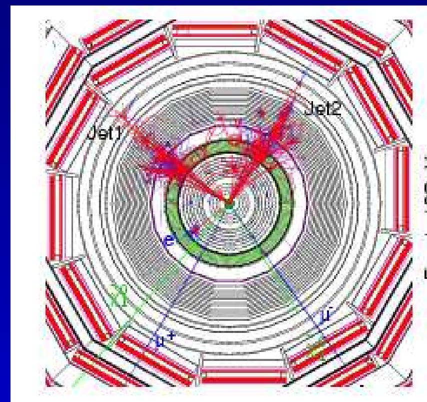
# The need for event generators

Physics issues:
simulation of signals & backgrounds in new domains

$\Longrightarrow$ new challenges: higher precision
$\Longrightarrow$ new challenges: more processes
$\Longrightarrow$ new challenges: more complexity



SUSY event with
3 leptons + 2 Jets signature

# The need for event generators

Physics demands:

1. Signals for new physics: (n)MSSM, extra dimensions . . .
2. Good treatment of backgrounds: SM physics
3. Different ME's, PDF's etc.
4. Model the underlying event
5. Different fragmentation schemes
6. Hadron decays a la PDG

# The need for event generators

Computing demands:

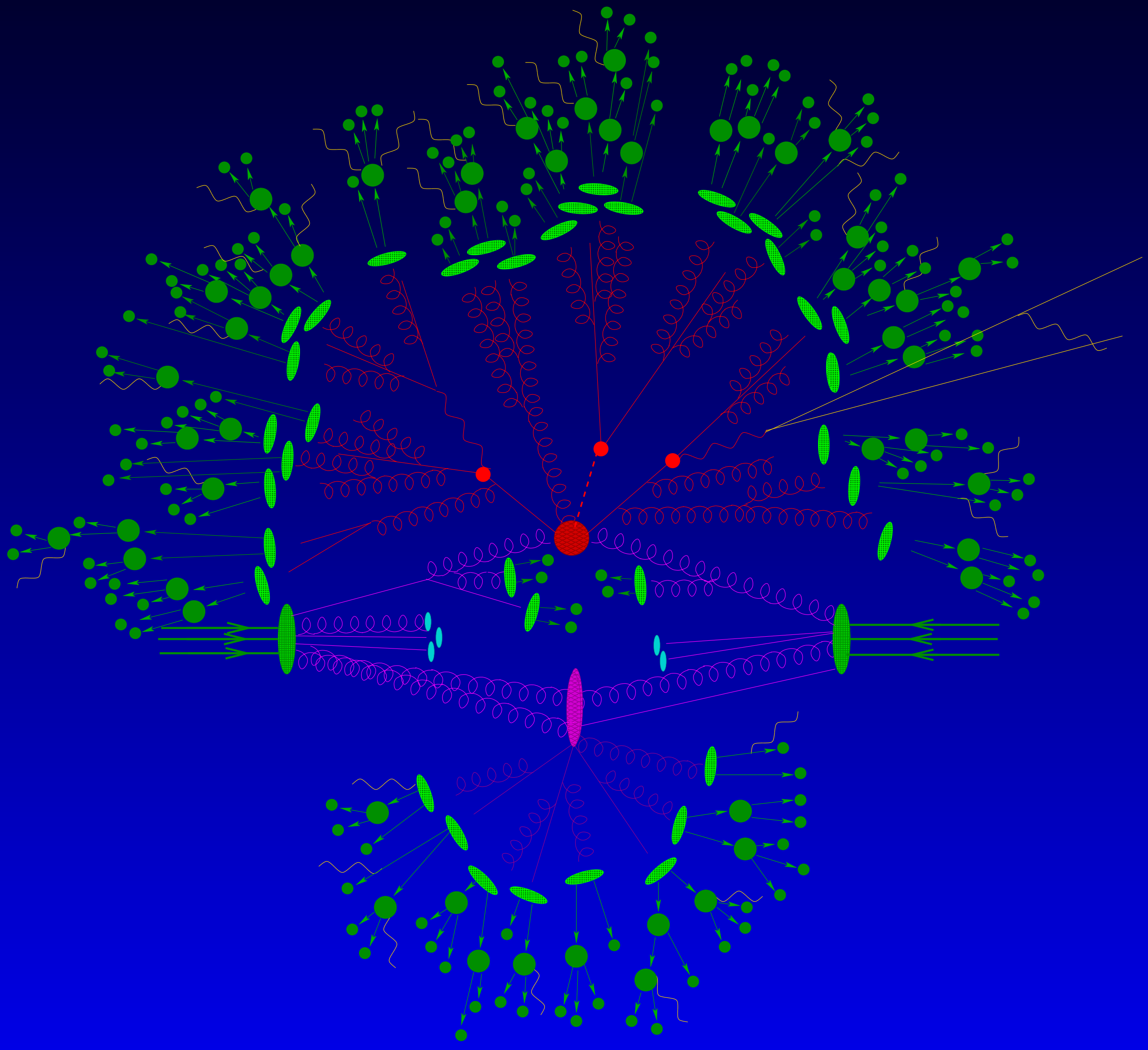
1. Transparency - maintenance becomes an issue!
2. Modularity for checks & simple replacements
3. Extensibility for new models etc.
4. Fast - for quick checks
5. Object–oriented language (the new paradigm)

# The need for event generators

MC paradigm: Split the simulation in parts:

1. Initialisation of incoming beams: PDF's
2. Hard event (and, eventually, decays): ME's
3. Secondary QCD radiation: PS
4. Multiple (parton) interactions
5. Hadronisation
6. Hadron decays

# The need for event generators



# New event generators

New codes emerging:
ThePEG/HERWIG++/PYTHIA7

("Top-Down" approach $\Longrightarrow$ next talk)

1. ThePEG = event generation framework organisation, event record, necessary tools (vectors etc.).
2. Construction of physics modules in ThePEG
3. `HERWIG++` (S.Gieseke et al., hep-ph/0311208):
   - $e^+e^-$ events: $e^+e^- \longrightarrow q\bar{q}$ + radiation
   - new parton shower
   - cluster fragmentation

# New event generators

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1. ThePEG = event generation framework organisation, event record, necessary tools (vectors etc.).
2. Construction of physics modules in ThePEG
3. `PYTHIA7` (L.Lonnblad, CPC.134, 365)
   - $e^+e^-$ and $pp$ events: $2 \rightarrow 2$ + radiation
   - string fragmentation

# New event generators

New codes emerging: `PYTHIA 8`

T.Sjöstrand (+, maybe later, others)

Project started recently (roughly a year ago).

Plan: provide a new event generator in three years.

# New event generators

New codes emerging: SHERPA

(T. Gleisberg, S. Höche, F. Krauss, A. Schälicke, S. S. and J. Winter, JHEP 0402:056,2004)

("Bottom-Up" approach)

Tested & interfaced modules:

1. Tree-level matrix elements (`AMEGIC++`) +
2. Parton shower (`APACIC++`) ...
3. ... and merging thereof
4. First underlying event simulations
5. Interfaces to string fragmentation, etc..

Allows to simulate $e^+e^-$, $\gamma\gamma$, $pp$ collisions.

# SHERPA status

(T.Gleisberg et al., JHEP 0402 (2004) 056)

- Initialisation of the incoming beams
  $\Rightarrow$ PDFs: LHAPDF, mrst99 (C++), cteq6

# SHERPA status

(T.Gleisberg et al., JHEP 0402 (2004) 056)

- Initialisation of the incoming beams
- Hard event and decays (through matrix elements)
  $\Rightarrow$ Interface to own ME generator AMEGIC++

(F.Krauss et al., JHEP 0202 (2002) 044)

# SHERPA status

(T.Gleisberg et al., JHEP 0402 (2004) 056)

- Initialisation of the incoming beams
- Hard event and decays (through matrix elements)
- Initial and final state parton shower
  $\Rightarrow$ Interface to own PS APACIC++

(R.Kuhn et al., CPC 134 (2001) 223,

and F.Krauss et al., hep-ph/0503087)

# SHERPA status

(T.Gleisberg et al., JHEP 0402 (2004) 056)

- Initialisation of the incoming beams
- Hard event and decays (through matrix elements)
- Initial and final state parton shower
- Multiple parton interactions (UE)

seems to work . . .

# SHERPA status

(T.Gleisberg et al., JHEP 0402 (2004) 056)

- Initialisation of the incoming beams
- Hard event and decays (through matrix elements)
- Initial and final state parton shower
- Multiple parton interactions (UE)
- Hadronisation and hadron decays
  $\Rightarrow$ Interface to Pythia's string fragmentation
  A modified cluster model in preparation

(J.Winter et al., Eur.Phys.J.C36 (2004) 381)

# SHERPA status

(T.Gleisberg et al., JHEP 0402 (2004) 056)

- Initialisation of the incoming beams
- Hard event and decays (through matrix elements)
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SHERPA is the framework responsible for

initialising different phases and
steering the event generation

# Matrix elements in SHERPA

## Presenting AMEGIC++:

- Calculates (nearly) arbitrary processes at tree level
  - Standard Model very well tested
  - MSSM being tested (spectra from SLHA)
  - ADD model (KK-graviton resonances)
- Mass effects fully taken into account
- Multi-channel MC integration with adaptive optimisation
- Completely automatic approach (a generator-generator)

Side note: AMEGIC++ is/will be implemented in HERWIG++

# Matrix elements in SHERPA

## Testing AMEGIC++:

- $e^+e^- \longrightarrow 4/6$ massive or massless jets/fermions
- $\gamma\gamma \longrightarrow 4f(+\gamma)$
- SUSY $2 \longrightarrow 2$ processes (cont'd)

## Validation for LHC (MC4LHC, CERN 2003):

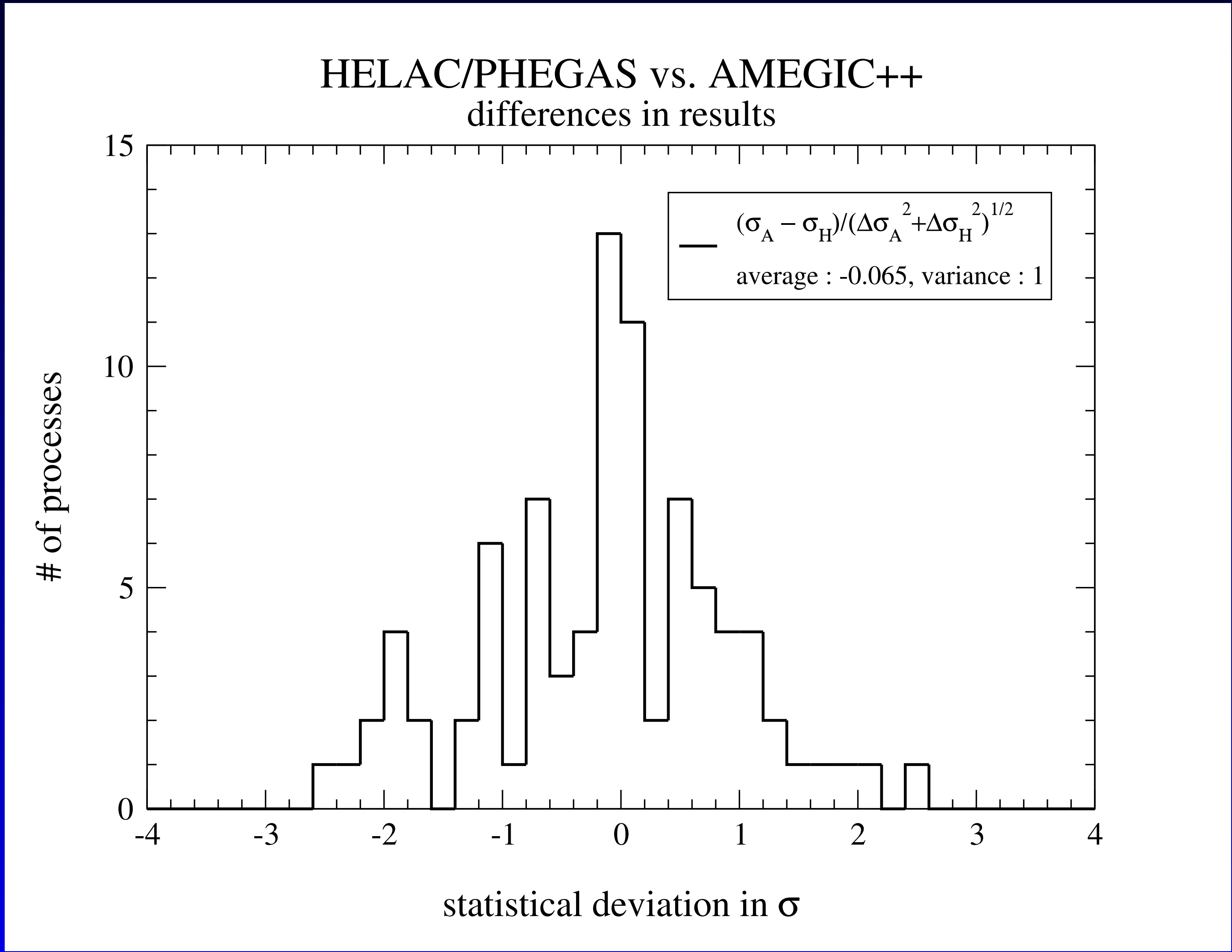
- $e^-\bar{\nu}_e$, $e^+\nu_e$, $e^-e^+$, $\nu_e\bar{\nu}_e$, + up to 4jets
- $e^-\bar{\nu}_e b\bar{b}$ , $e^-e^+b\bar{b}$, + up to 2jets
- $\gamma$, $\gamma\gamma$, + up to 3jets
- $t\bar{t}$, $b\bar{b}$, + up to 2jets
- 2-, 3-, 4-jet production

# Matrix elements in SHERPA

| X-sects (pb) | Number of jets | | | | | | |
|---|---|---|---|---|---|---|---|
| $e^- \bar{\nu}_e + n$ QCD jets | 0 | 1 | 2 | 3 | 4 | 5 | 6 |
| Alpgen | 3904(6) | 1013(2) | 364(2) | 136(1) | 53.6(6) | 21.6(2) | 8.7(1) |
| CompHEP | 3947.4(3) | 1022.4(5) | 364.4(4) | | | | |
| MadEvent | 3902(5) | 1012(2) | 361(1) | 135.5(3) | 53.6(2) | | |
| Amegic++/Sherpa | 3908(3) | 1011(2) | 362(1) | 137.5(5) | 54(1) | | |

| X-sects (pb) | Number of jets | | | | |
|---|---|---|---|---|---|
| $e^- \bar{\nu}_e + b\bar{b}$ | 0 | 1 | 2 | 3 | 4 |
| Alpgen | 9.34(4) | 9.85(6) | 6.82(6) | 4.18(7) | 2.39(5) |
| CompHEP | 9.415(5) | 9.91(2) | | | |
| MadEvent | 9.32(3) | 9.74(1) | 6.80(2) | | |
| Amegic++/Sherpa | 9.37(1) | 9.86(2) | 6.87(5) | | |

# Matrix elements in SHERPA



# Matrix elements in SHERPA

AMEGIC++ proved to work for up to six particle final states

$\Longrightarrow$ Acceleration of the ME and phase space evaluation is ongoing:

Gained a huge factor in performance since 2003

(But: Improvement remains a tedious and time-consuming job)

$\Longrightarrow$ One or two more jet(s) per process listed above maybe possible

$\Longrightarrow$ for even higher jet multiplicities it might be better to rely on PS

$\Longrightarrow$ SHERPA includes a state-of-the-art C++ ME generator,

one of the key ingredients of a modern event generator

# Combining ME and PS

S.Catani et al., JHEP 0111 (2001) 063,

and F.Krauss, JHEP 0208 (2002) 015

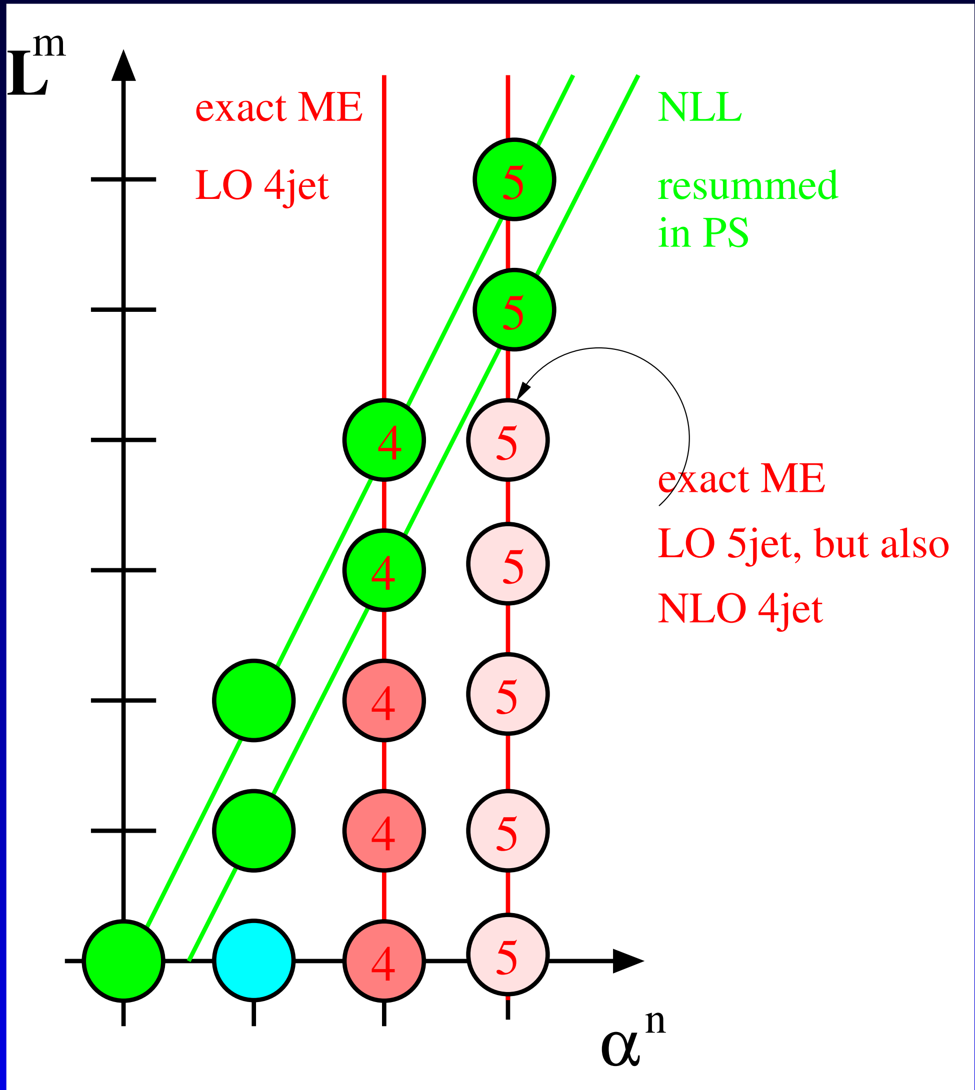
**Aim:**

- Good description of soft and hard region
- Universality of fragmentation (energy independent)

**Solution:**

- Divide multi-jet phase space into two regimes
  - Jet production by ME (if available)
  - Jet evolution down to fragmentation scale by the PS
- Reweight ME's for exclusive samples at a resolution scale
- Veto on PS configurations included in higher order ME

# Combining ME and PS



# Combining ME and PS

**The method has been implemented in SHERPA in full generality**

- Proofed to be successful in $e^+e^-$ collisions

  (comparable in event shapes etc., but better description for four-jet correlations etc.)
- Study of systematics of method is still ongoing
  - Vary choice of scales (functional form)
  - Different jet measures
  - Different treatment of highest multiplicity ME
- Extensions to study systematic errors in event generation (e.g. global scale factors, etc.)
  after all, it's only LO !

# $W/Z$+jets at the Tevatron

F.Krauss et al., Phys.Rev.D70 (2004) 114009

- $W/Z$+jets at Tevatron, Run II
- Jets according to Run II $k_\perp$-clustering algorithm:

$$p_\perp^{\rm jet} > 15\ {\rm GeV}, \quad |\eta^{\rm jet}| < 2, \quad D = 0.7$$

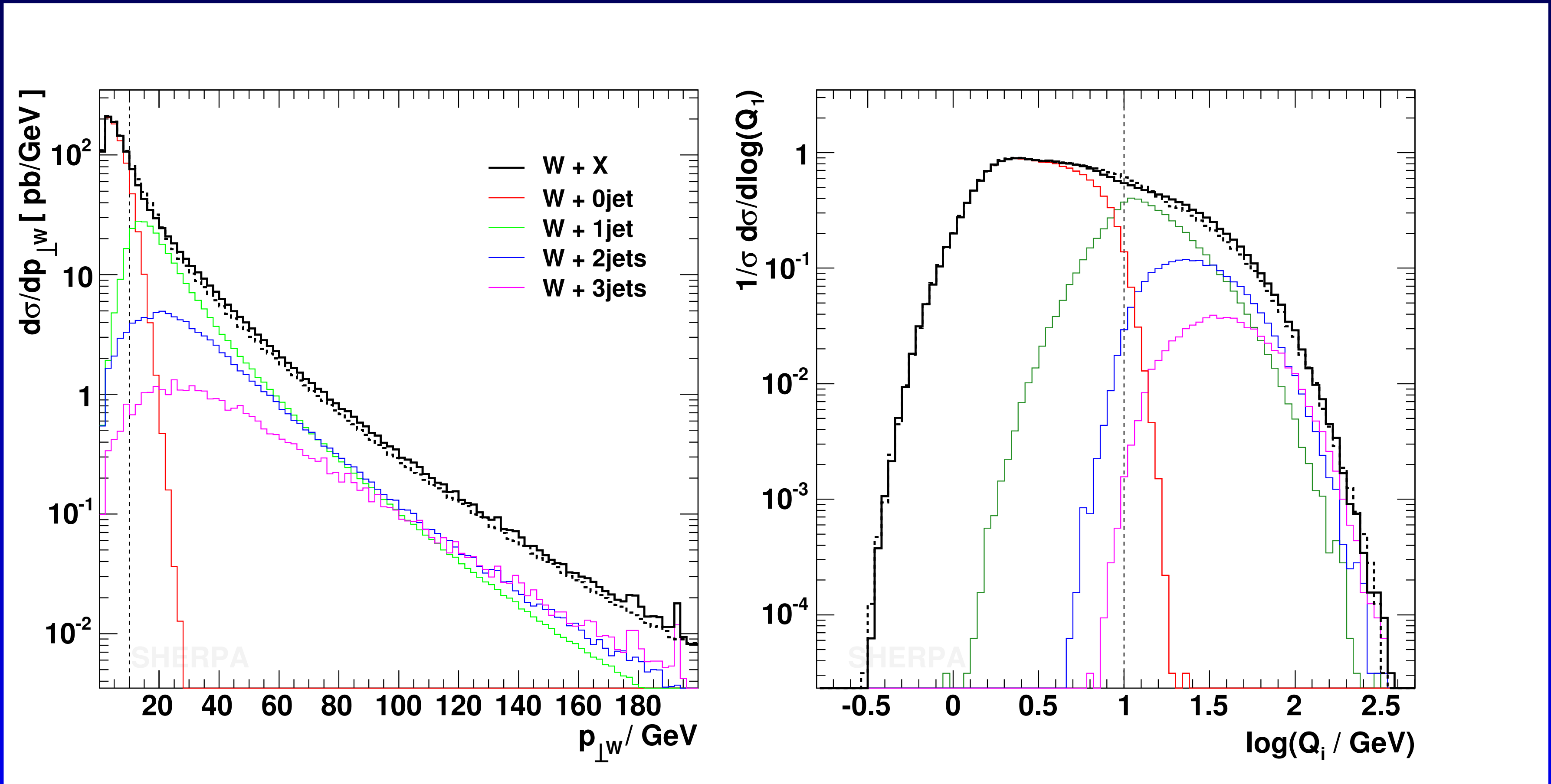
- Further cuts:

$$p_\perp^{\rm lepton} > 20\ {\rm GeV}, \quad |\eta^{\rm lepton}| < 1,$$

$m^{ll} > 15$ GeV, for $W$, also $p_\perp^{\rm miss} > 20$ GeV.

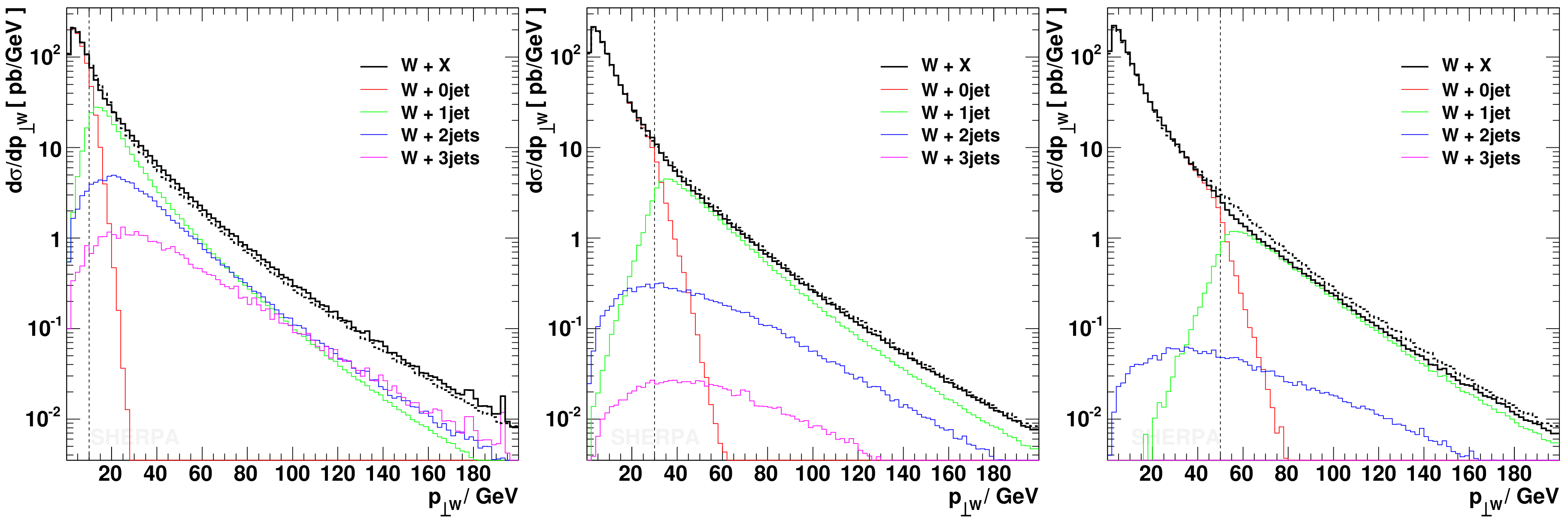
# $W/Z$+jets at the Tevatron

Two example plots (for consistency checks):



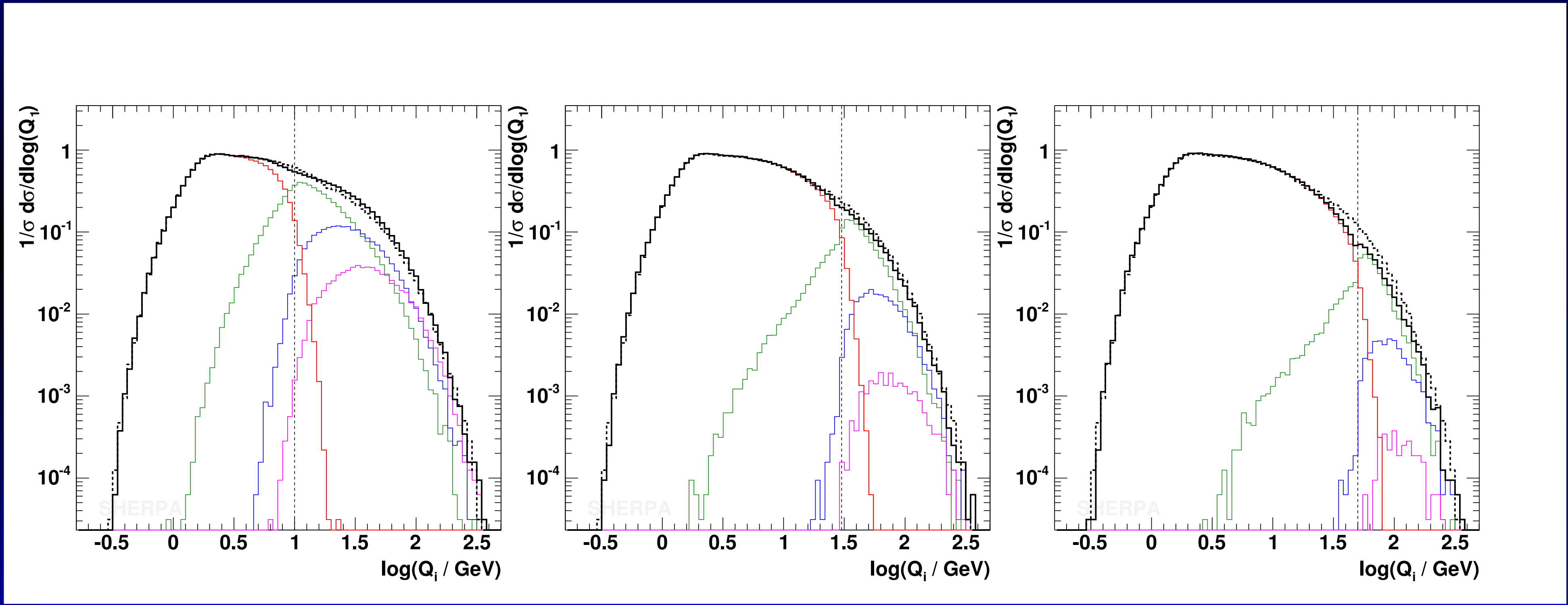
# $W/Z$+jets at the Tevatron

Effect of varying jet separation: $p_\perp$ of $W$



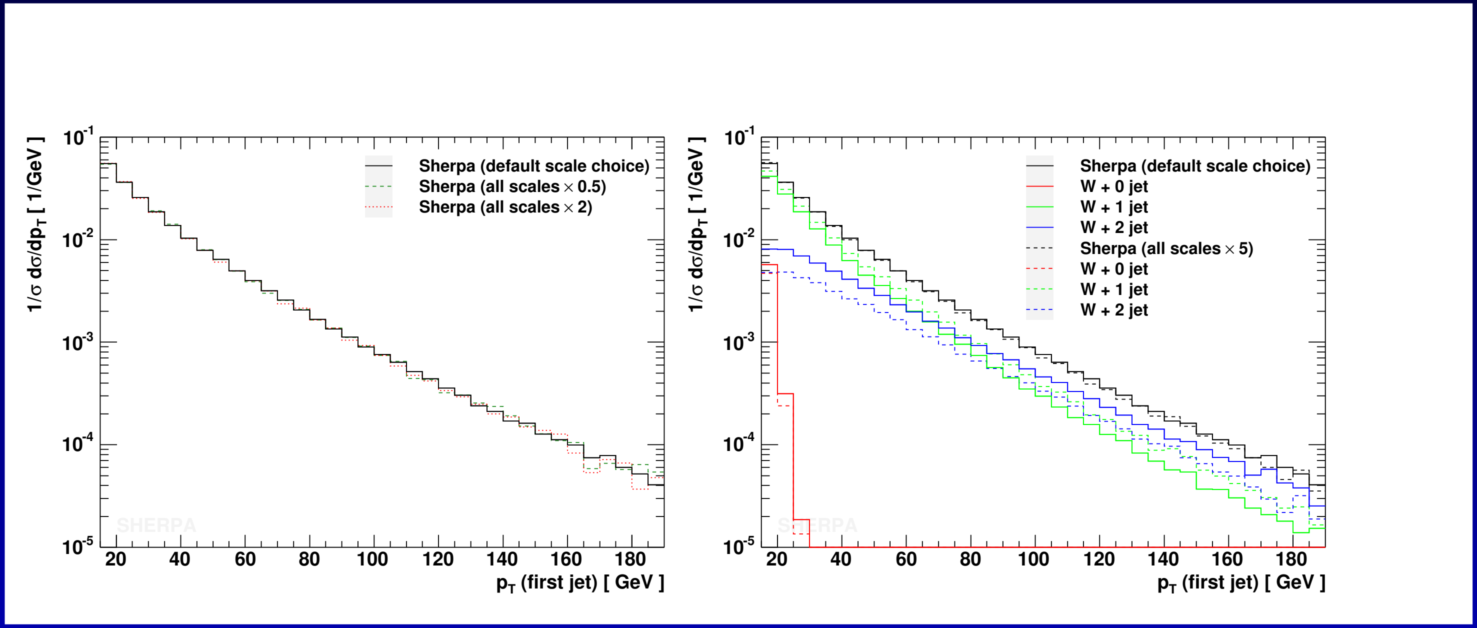
# $W/Z$+jets at the Tevatron

Effect of varying jet separation : Diff jetrates $1 \rightarrow 0$



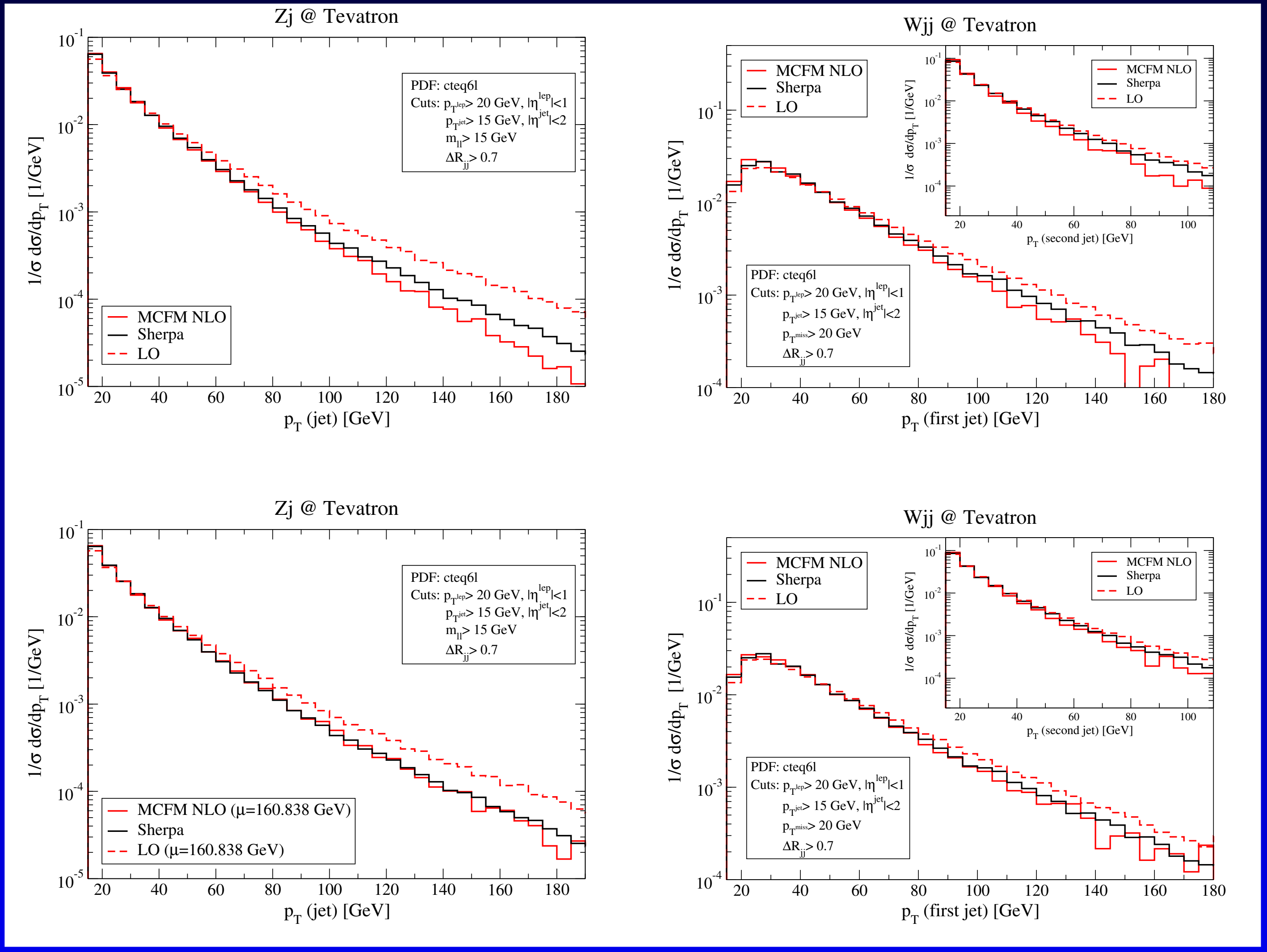
# $W/Z$+jets at the Tevatron

Effect of varying renormalisation & factorisation scale



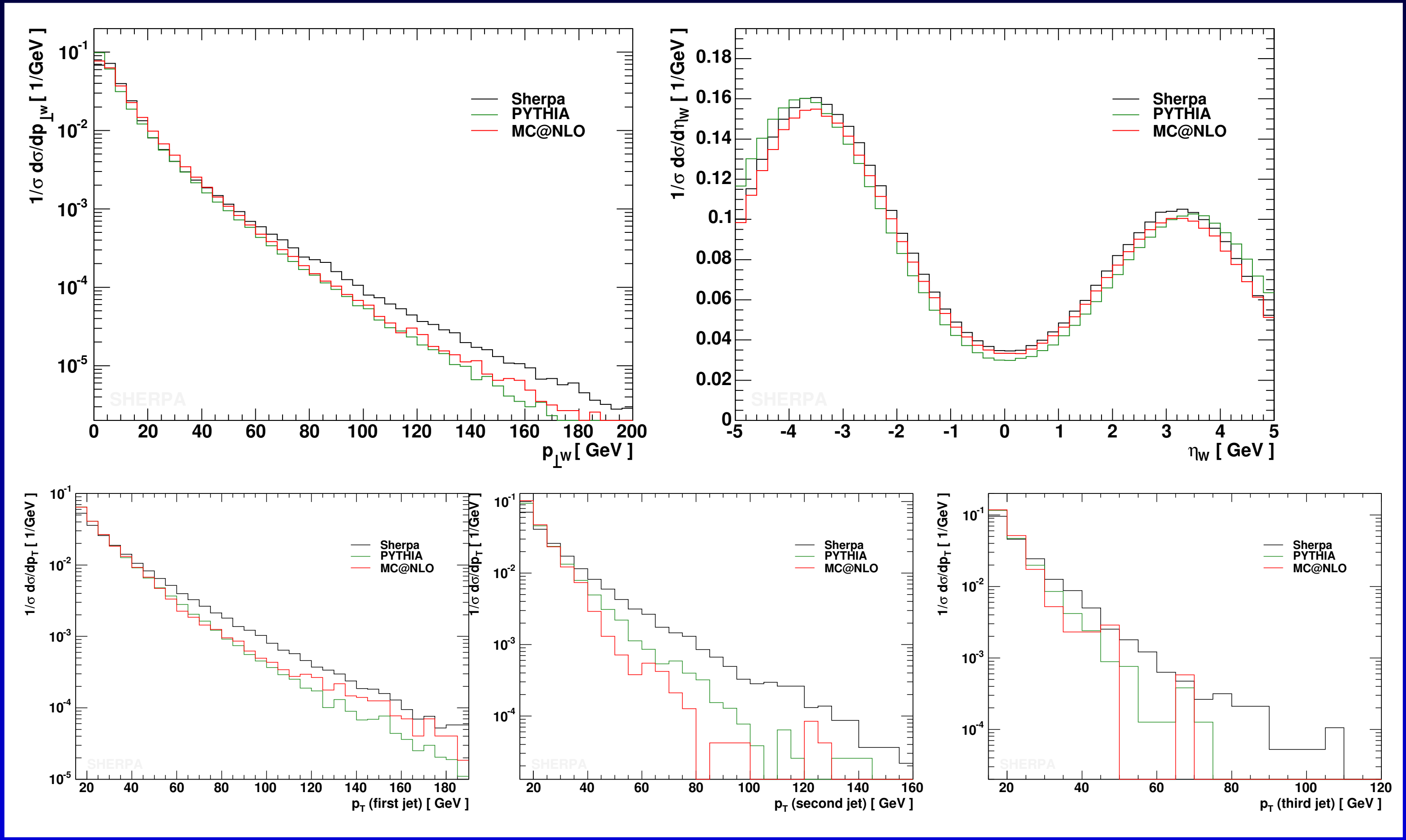
# $W/Z$+jets at the Tevatron

## Comparison with NLO calculation (MCFM, exclusive)



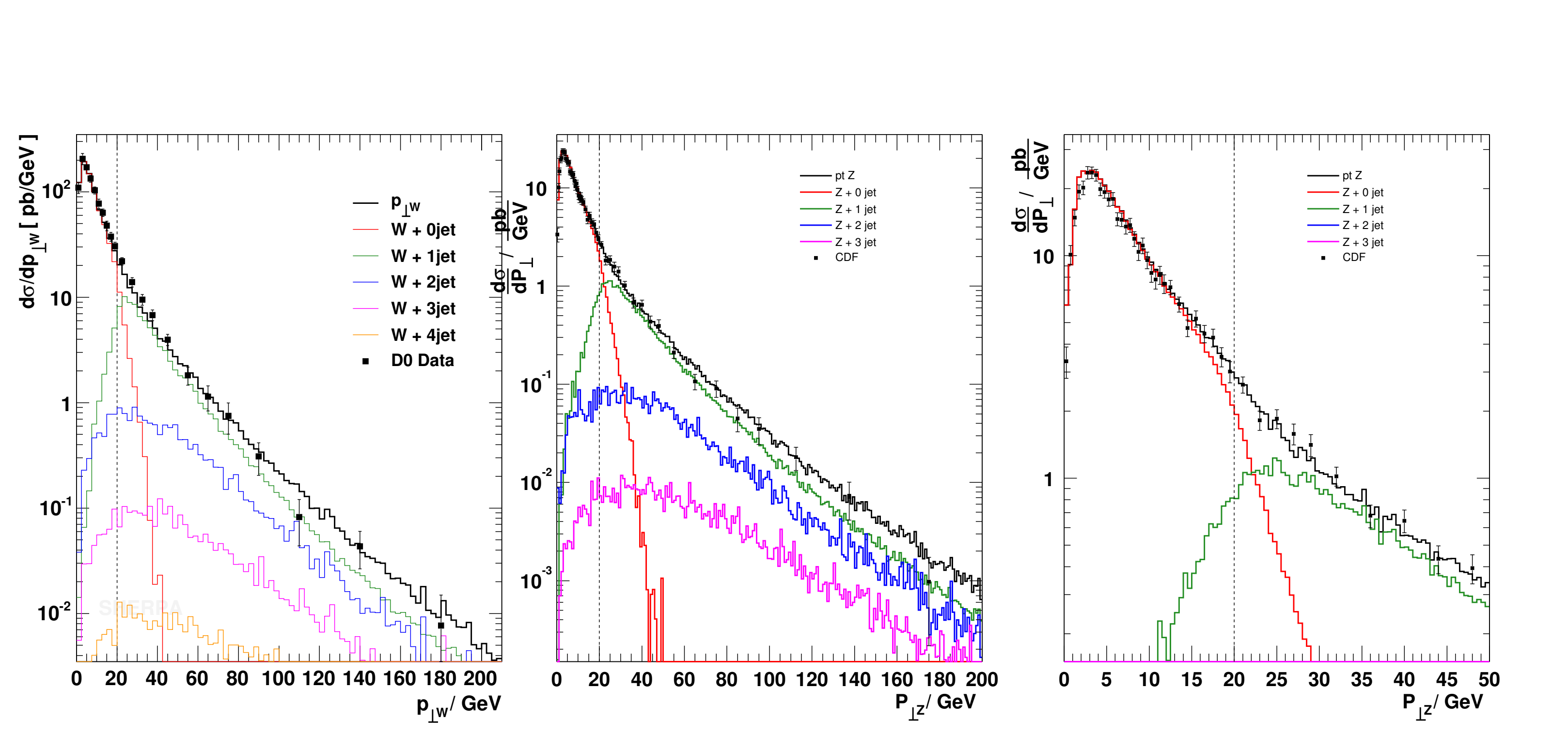
# $W/Z$+jets at the Tevatron

## Comparison with Pythia & MC@NLO



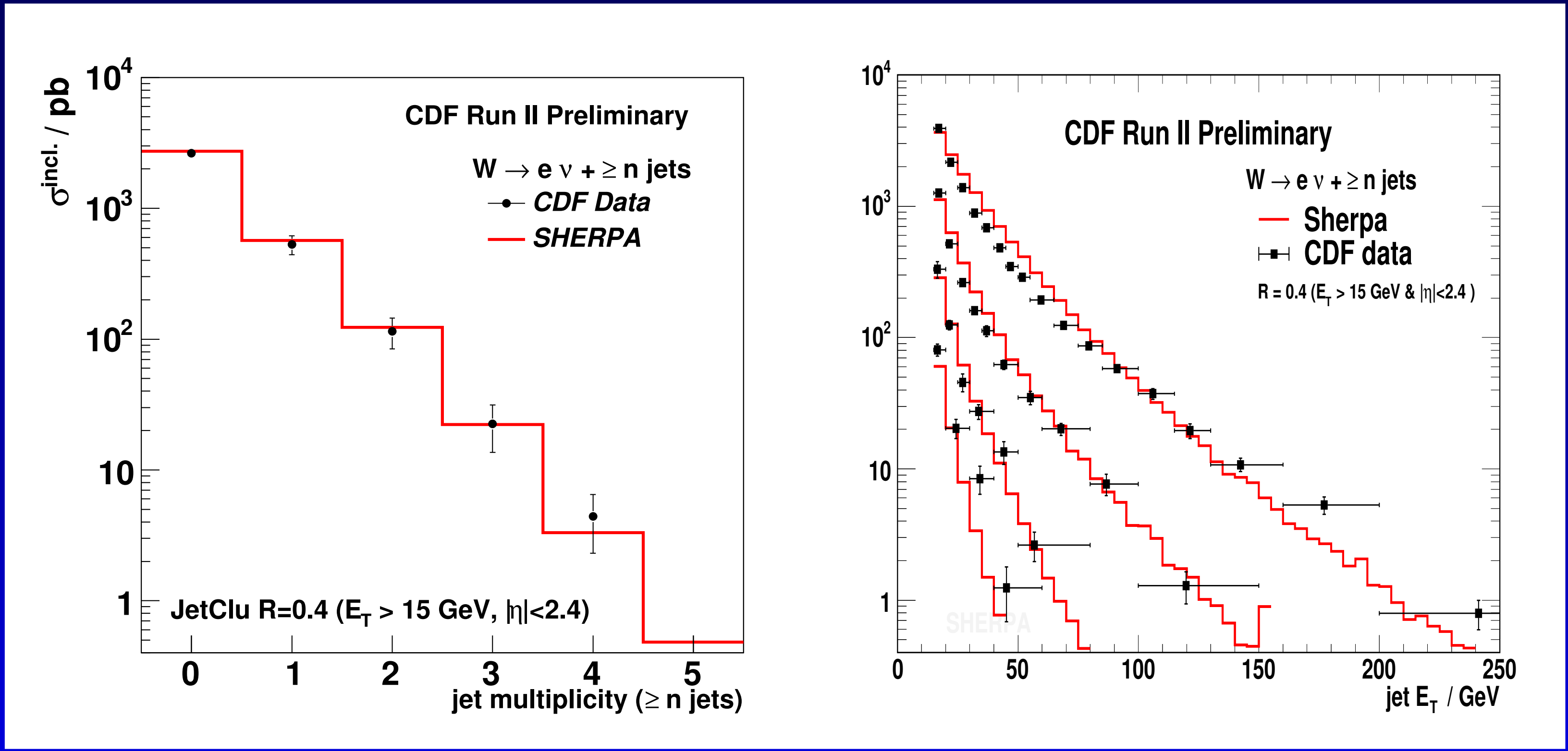
# $W/Z$+jets at the Tevatron

Comparison with data: $p_\perp$ of boson
(Run I, $W$ from D0, $Z$ from CDF)



# $W/Z$+jets at the Tevatron

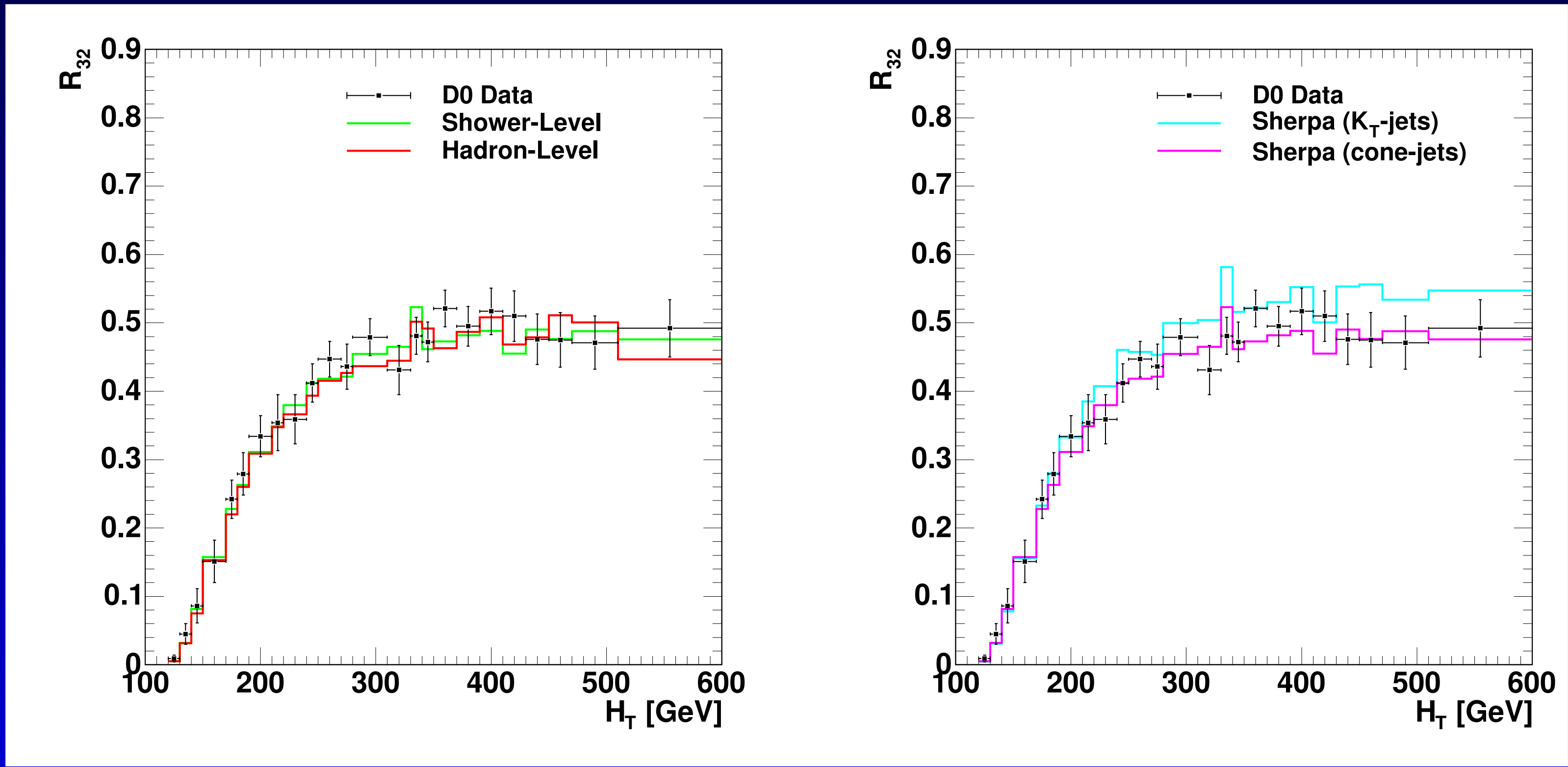
Comparison with data: jets
(Run II, preliminary from CDF, SHERPA: $K = 1.44$)



# Jets only at Tevatron, Run I

$R_{32}$ measurement at Run I (D0, PRL 86 (2001) 1955),

$E_T^{\mathrm{jet}} \geq 40 GeV$, $|\eta^{\mathrm{jet}}| \leq 3$, Midpoint with $R = 0.7$



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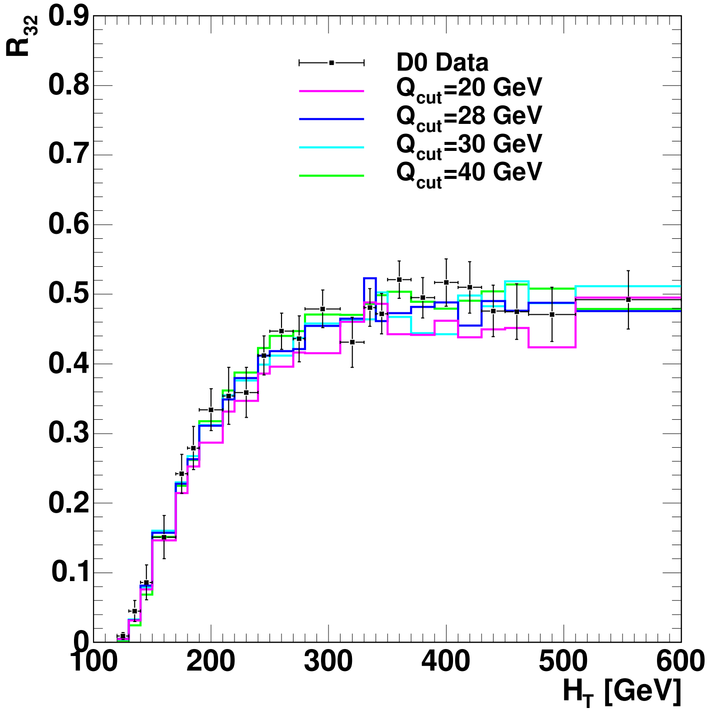


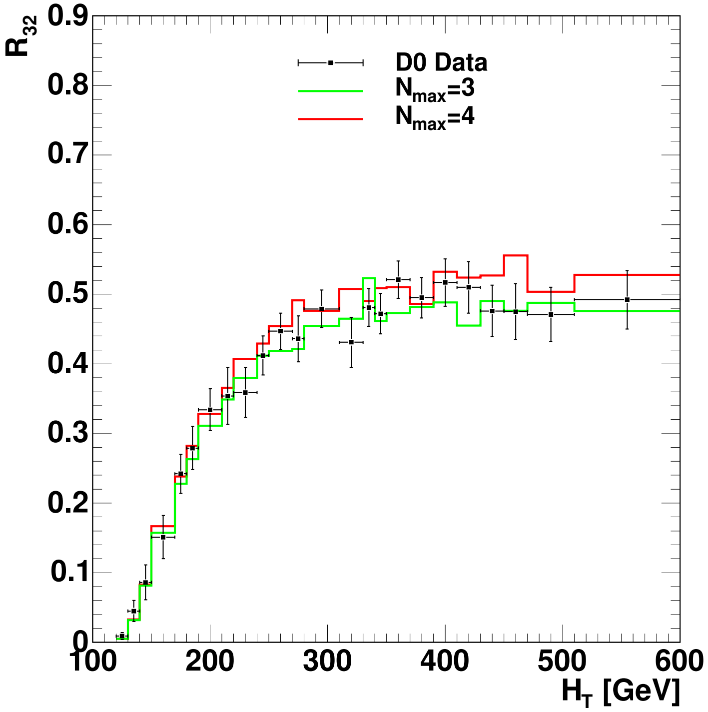

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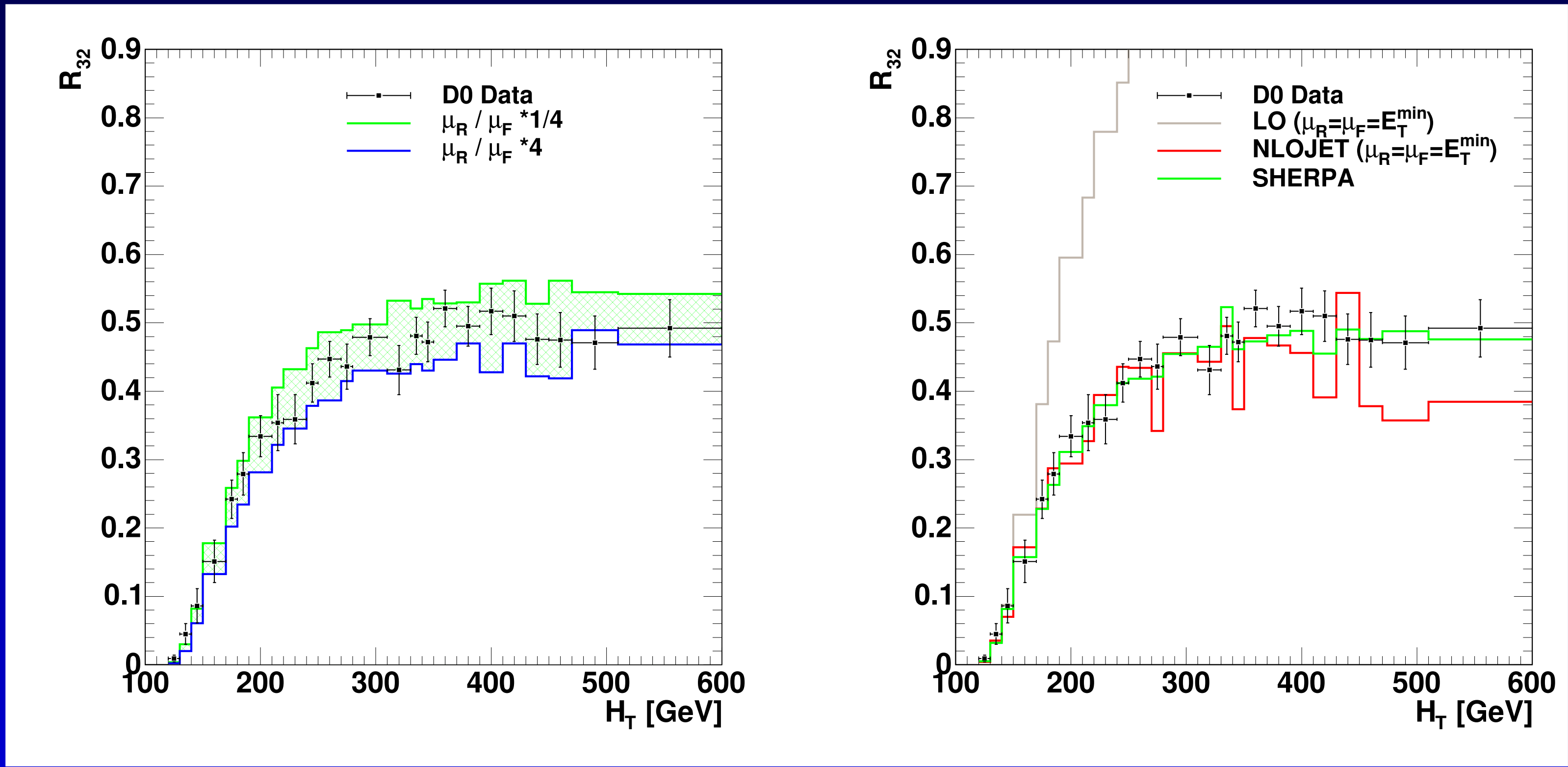
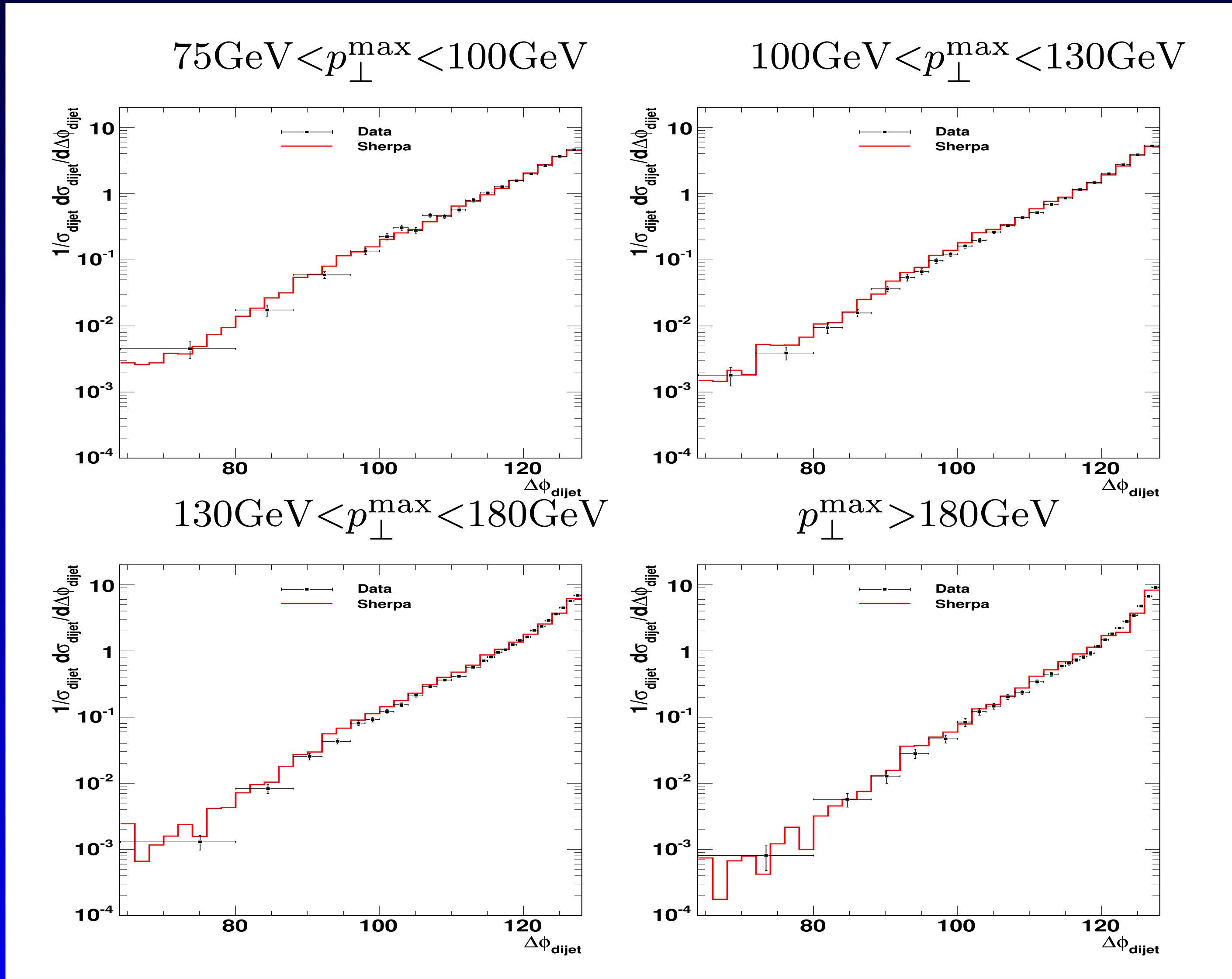


# Jets only at Tevatron, Run I

Di-Jet azimuthal angular decorrelation (D0, hep-ex/0409040), $p_T^{\rm jet} \geq 40GeV$, $|y^{\rm jet}| \leq 3$



# Conclusion/Outlook

- SHERPA well under way.
- ME's and PS work,
  construction of further modules started
- Implementation of merging prescription
  an unique & powerful tool.
  Shapes look NLO-ish, rates are LO!
- First UE model in working condition,
  seems softer than Pythia due to ME+PS.
- Aim at:Complete MC in 2005
  including cluster model, a new underlying event model, ...

# Conclusion/Outlook

**Thanks**

go to my fearless collaborators at Dresden:
Timo Fischer, Stefan Höche, Tanju Gleisberg,
Thomas Laubrich, Andreas Schälicke,
Steffen Schumann, Caro Semmling,
and Jan Winter.