MC tools for the LHC

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Outline

1. Introduction:The need for event generators
2. Signals & backgrounds at the parton level
3. From parton level to exclusive studies at hadron level
4. Results with SHERPA
5. Conclusions

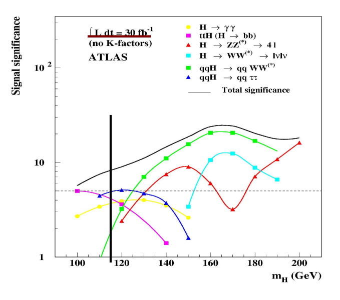
Why simulate events?

Reminder: Physics @ LHC

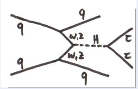
- Many interesting signals:
  Higgs (or alternative EWSB), SUSY, ED's, ...
- But: Severe backgrounds in nearly all channels,
  (almost always with large influence of QCD)
  $\Longrightarrow$ depend on detailed understanding of QCD.
- Examples:
  - Central jet-veto in VBF (Higgs)
  - Multi-jet backgrounds for SUSY (e.g. Z+jets)
- Todays signals = tomorrows backgrounds.

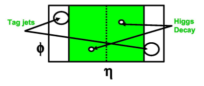
Why simulate events?

Higgs searches



Central jet veto in VBF

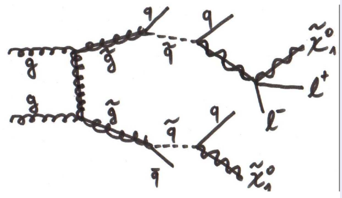




- Signal/background ratio depends on central jet veto.
  (rapidity gap between two "tagging jets",
  $\Longrightarrow$ beautiful signal at leading order)
- But: How many jets come at higher orders?
  $\Longrightarrow$ currently studied.

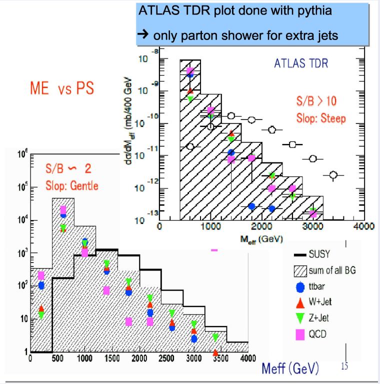
Why simulate events?

SUSY searches



- Large $\sigma_{\rm prod}$
- Many hard jets.
- $M_{\rm eff} = \sum p_\perp^{\rm hard}$.

Quick Discovery?



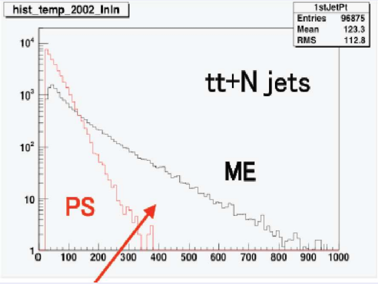
Why simulate events?

Event rates @ LHC

Final State	Evts/sec
$W \to l\nu_l$	20
$WW \to l\nu_l l\nu_l$	0.006
$t\bar{t}$	1
$b\bar{b}$	$5{\cdot}10^5$
Jet, $E_\perp \geq 100$ GeV	10^3
Jet, $E_\perp \geq 1$ TeV	0.015

(Rates @ pessimistic $\mathcal{L} = 10^{33}/\text{cm}^2$ s.)

Shape of tt-events



Again: $M_{\rm eff}$ significantly different!

Simulation's paradigm

Basic strategy

Divide event into stages, separated by different scales.

- Signal/background:

  Exact matrix elements.

- QCD-Bremsstrahlung:

  Parton showers (also in initial state).

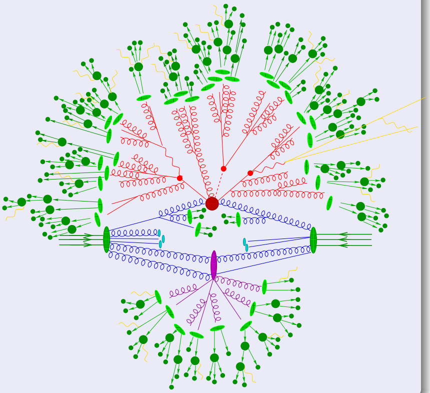
- Multiple interactions:

  Beyond factorization: Modeling.

- Hadronization:

  Non-perturbative QCD: Modeling.

Sketch of an event



New tools needed

Why does anyone write a new event generator?

- Increased needs (precision, new physics, etc.):
  $\longrightarrow$ getting rid of old errors (having new ones)
  $\longrightarrow$ incorporate new, better methods!
- Enhanced flexibility, modularity, capability:
  $\longrightarrow$ improved maintenance
- Object-orientation, the new paradigm
  $\longrightarrow$ "industrial" relevance of education
- New tools on the market:
  Pythia8 (Pythia7 died), Herwig++, Sherpa

Automatic cross section calculators

Calculating cross sections @ LO

- Multi-particle final states for signals & backgrounds.
- Need to evaluate $\mathrm{d}\sigma_N$:

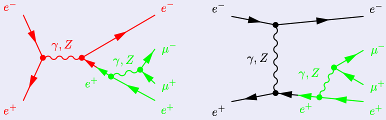
$$\int_{\text{cuts}} \left[\prod_{i=1}^{N} \frac{\mathrm{d}^3 q_i}{(2\pi)^3 2E_i}\right] \delta^4\left(p_1 + p_2 - \sum_i q_i\right) \left|\mathcal{M}_{p_1 p_2 \to N}\right|^2 .$$

- Problem 1: Factorial growth of number of amplitudes.
- Problem 2: Complicated phase-space structure.
- Solutions: Numerical methods.

Automatic cross section calculators

Helicity method

- Tame factorial growth by factoring out common parts:



- Fully automated tools:
  - MadGraph
    F.Maltoni and T.Stelzer, JHEP **0302** (2003) 027
  - Amegic
    F.K., R.Kuhn and G.Soff, JHEP **0202** (2002) 044

Recursion methods

- No Feynman diagrams
- Tame factorial growth by recursion:
  - One-particle off-shell Green's functions
  - MHV amplitudes (on-shell building blocks)
- Fully automated tools:
  - HELAC
    A.Kanaki and C.Papadopoulos, CPC **132** (2000) 306
  - AlpGen
    M.L.Mangano *et al.*, JHEP **0307** (2003) 001

Automatic cross section calculators

Monte Carlo integration

- Basic problem: Large fluctuations in integrand f

  (mostly due to near-by poles in the propagators)

  $\Longrightarrow$ Error estimate remains large.

- Solution: Analytically smooth out fluctuations.
- Method of choice: Multi-channeling.
  Idea: "Know your singularities".
  - Each Feynman diagram $\leftrightarrow$ one integration channel.
  - Interplay of channels used to minimize error estimate: Channels with large fluctuations get more impact.
  - "Best channels" further improved by VEGAS (or similar).

From partons to hadrons

Why is this important?

- Experimental definition of jets based on hadrons.
- But: Hadronization through phenomenological models
  (need to be tuned to data).
- Wanted: Universality of hadronization parameters
  (independence of hard process important).
- Link to fragmentation needed: Model softer radiation
  (inner jet evolution).

From partons to hadrons

Parton showers

- Universal pattern of soft & collinear radiation:

$$\mathrm{d}\sigma_{N+1} \sim \mathrm{d}\sigma_N \sum_{a\in N} \frac{\mathrm{d}t_a}{t_a}\,\alpha_s\,\mathrm{d}z\,P_{a\to bc}(z)\,.$$

- Introduce "resolution of partons" (e.g. $p_\perp^{\mathrm{min}}$)
  $\Longrightarrow$ Large logarithms at each emission.
- Resummation of soft & collinear logs in Sudakov form factor:

$$\Delta_a(t,\,t_0) = \exp\left[-\int\limits_{t_0}^{t}\frac{\mathrm{d}t'}{t'}\int\limits_{z_-}^{z_+}\mathrm{d}z\,\alpha_s\,P_{a\to bc}(z)\right]\,.$$

- Interpretation: No-emission probability ($\to$ simulation).

Dealing with the large logs

Different ways to express collinear variable

- Same form for any $t \propto \theta^2$:
  - Transverse momentum $k_\perp^2 \approx z^2(1-z)^2E^2\theta^2$
  - Invariant mass $q^2 \approx z(1-z)E^2\theta^2$

$$\frac{\mathrm{d}\theta^2}{\theta^2} \approx \frac{\mathrm{d}k_\perp^2}{k_\perp^2} \approx \frac{\mathrm{d}q^2}{q^2}$$

- Integration over $\mathrm{d}\theta^2$, $\mathrm{d}z$ with lower cuts $\longrightarrow$ logarithms: Leading logarithms of same form, but important subleading differences!

Different parton shower codes use different ways of expressing θ^2

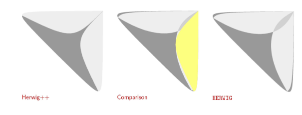
New shower formulations (based on $k_\perp$)

S.Gieseke, P.Stephens, and B.Webber JHEP **0312** (2003) 045

T.Sjostrand and P.Skands Eur.Phys.J. **C39** (2005) 129

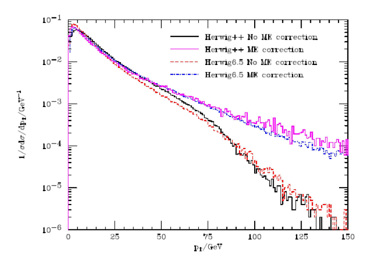
Example: Herwig++

- Improved soft region
- No overlap
- Treatment of heavy quarks (No dead "dead-cone")



Herwig++: 1st results

$p_\perp$ of Z at Tevatron

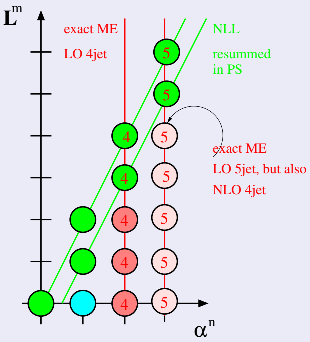


From partons to hadrons

ME vs. PS

- Matrix elements good for: hard, large-angle emissions; take care of interferences.
- Parton shower good for: soft, collinear emissions; resums large logarithms.
- Want to combine both! Avoid double-counting.

α_s vs. Log



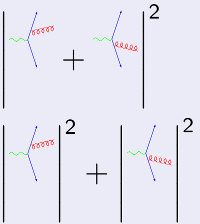
Correcting the parton shower

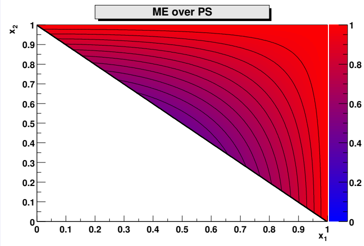
e.g. G.Corcella and M.Seymour Nucl.Phys.**B565** (1999) 227

Example: $e^+e^- \longrightarrow q\bar{q}g$

ME :

PS :





Practicalities of ME-corrections

Limitations

- Obviously, $ME < PS$ not always fulfilled.
- Could enhance PS expression by a (large) factor
- Therefore: realised in few processes only:
  Best-known: $ee \longrightarrow q\bar{q}$, $q\bar{q} \longrightarrow V$, $t \longrightarrow bW$

Power shower

Can use ME corrections for "power shower":

- In $q\bar{q} \longrightarrow V$, start parton shower @ $s_{\rm pp}$.
- Effect: More hard radiation through showering.
- Not very well controlled.

Matching MEs & PS: MC@NLO

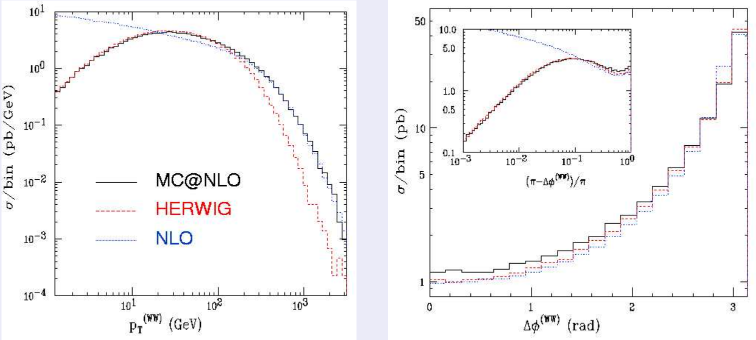
S.Frixione, B.R.Webber, JHEP **0206** (2002) 029
S.Frixione, P.Nason, B.R.Webber, JHEP **0308** (2003) 007

Basic principles

- Want:
  - NLO-Normalization and first (hard) emission correct,
  - Soft emissions correctly resummed in PS.
- Method:
  - Modify subtraction terms for real infrared divergences,
  - use first order parton shower-expression,
  - this is process-dependent!
- In practise much more complicated.
- Implemented for DY, W-pairs, $gg \longrightarrow H$, Q-pairs.

Matching MEs & PS: MC@NLO

Example results: W-pairs @ Tevatron



Combining MEs & PS: LO-Merging

S.Catani, F.K., R.Kuhn and B.R.Webber, JHEP **0111** (2001) 063
F.K., JHEP **0208** (2002) 015

Basic principles

- Want:
  - All jet emissions correct at tree level + LL,
  - Soft emissions correctly resummed in PS
- Method:
  - Separate Jet-production/evolution by $Q_{\rm jet}$ ($k_\perp$ algorithm).
  - Produce jets according to LO matrix elements
  - re-weight with Sudakov form factor + running α_s weights,
  - veto jet production in parton shower.
- Process-independent implementation.

Simple MEs & PS: MLM merging

How it works

"Intuitive" approach

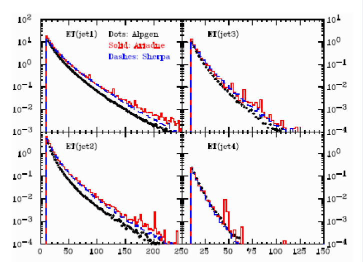
(not as systematic)

Idea:

- Produce parton configuration with ME
- Reweight with α_s
- Run shower - veto full events if wrong jets.
- No "second chance".

Example results

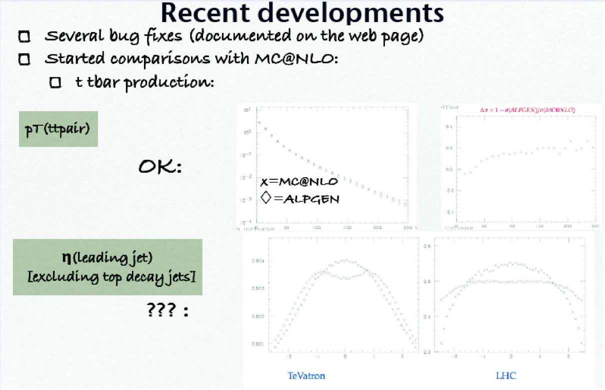
E_T of jets in $W+$ jets at Tevatron



Alpgen default

MC@NLO vs. MLM merging

$t\bar{t}$ production

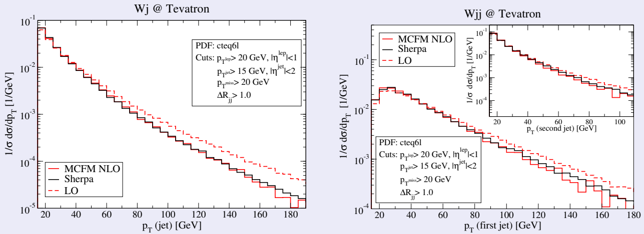


Combining MEs & PS: LO+LL

Algorithm as scale-setting prescription

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

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



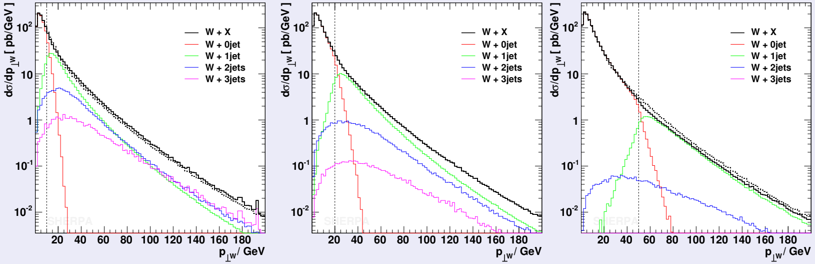
Sherpa = tree-level matrix elements with α_s scales and Sudakov form factors.

Combining MEs & PS: Independence on $Q_{\rm jet}$

F.K., A.Schälicke, S.Schumann and G.Soff, Phys. Rev. D **70** (2004) 114009

Example: $p_\perp$ of W in $p\bar{p} \to W + X$ @ Tevatron

$Q_{\rm jet} = 10\,{\rm GeV}$ $Q_{\rm jet} = 30\,{\rm GeV}$ $Q_{\rm jet} = 50\,{\rm GeV}$



Example results

Introducing SHERPA

T.Gleisberg, S.Höche, F.K., A.Schälicke, S.Schumann and J.C.Winter, JHEP **0402** (2004) 056

- New event generator, written from scratch in C++.
- Matrix elements from AMEGIC,
  combined with own parton shower implementation

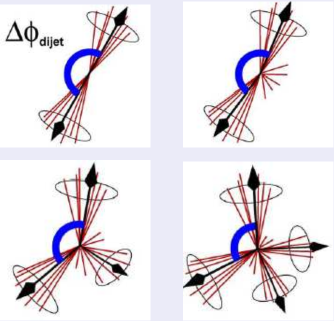
  (F.K., A.Schälicke and G.Soff, arXiv:hep-ph/0503087; similar to shower in PYTHIA)
- Hadronization of Pythia interfaced,
  will be replaced by own cluster model

  (J.Winter, F.K. and G.Soff, Eur. Phys. J. C**36** (2004) 381)
- Underlying event according to old Pythia model,
  write-up for new model in preparation.

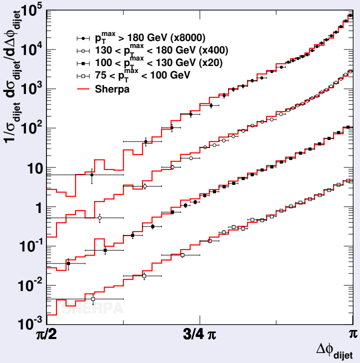
Azimuthal decorrelations of jets at the Tevatron

Idea

- Check QCD radiation pattern



Distributions @ Run II

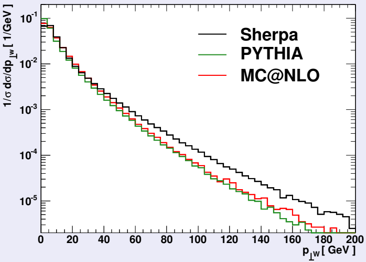


Comparison with other codes

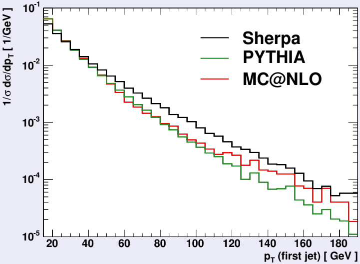
F.K., A.Schälicke, S.Schumann and G.Soff, Phys. Rev. D **70** (2004) 114009

$p_\perp$ of W-bosons & jets in $p\bar{p} \to W + X$ @ Tevatron

$p_\perp^W$



$p_\perp^{\rm 1st\,jet}$



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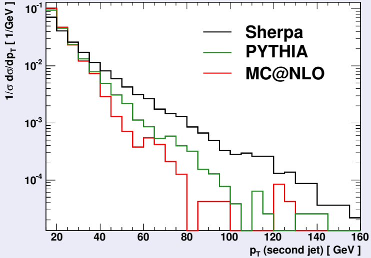
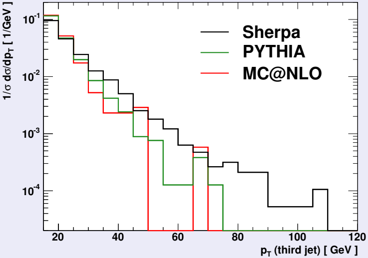
F.K., A.Schälicke, S.Schumann and G.Soff, Phys. Rev. D **70** (2004) 114009

$p_\perp$ of W-bosons & jets in $p\bar{p} \to W + X$ @ Tevatron

$p_\perp^{\text{2nd jet}}$



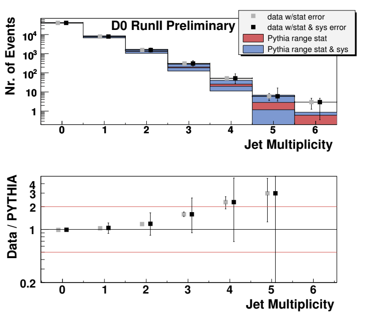
$p_\perp^{\text{3rd jet}}$

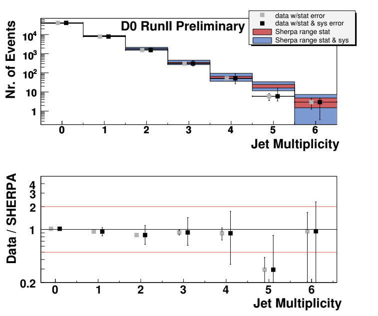


Comparison with data from Tevatron

Jet rates in $p\bar{p} \longrightarrow Z + X$

(D0-Note 5066)

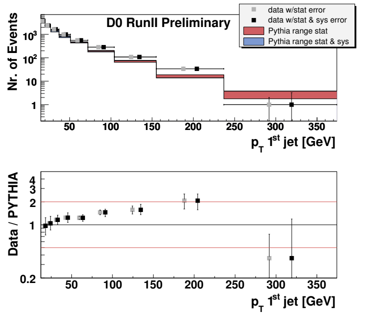


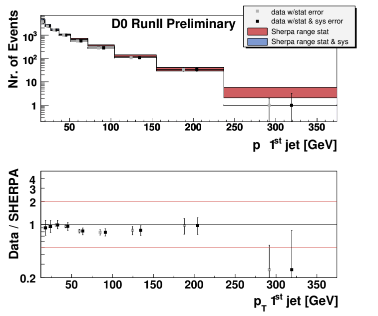


Comparison with data from Tevatron

Jet spectra (1st jet) in $p\bar{p} \to Z + X$

(D0-Note 5066)

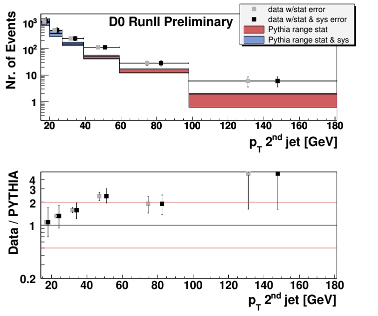


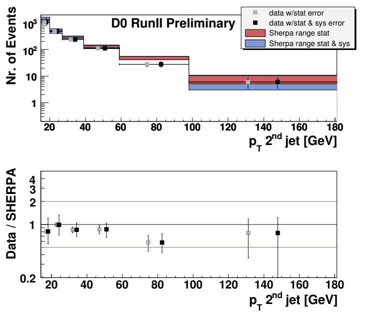


Comparison with data from Tevatron

Jet spectra (2nd jet) in $p\bar{p} \to Z + X$

(D0-Note 5066)

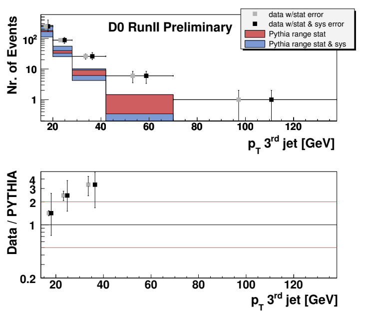


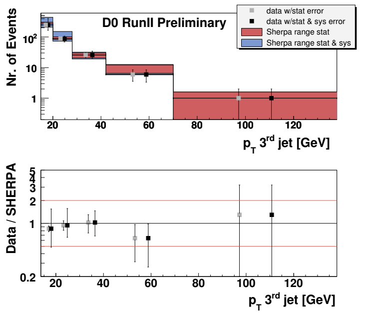


Comparison with data from Tevatron

Jet spectra (3rd jet) in $p\bar{p} \to Z + X$

(D0-Note 5066)

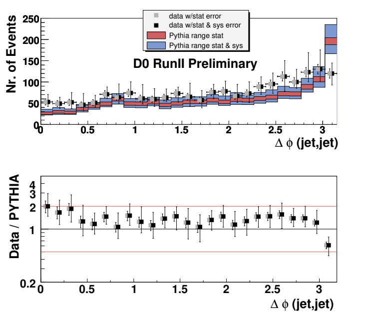


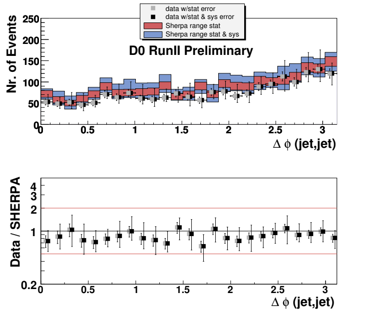


Comparison with data from Tevatron

Azimuthal correlation ($\angle_{1.\mathrm{jet},2.\mathrm{jet}}$) in $p\bar{p} \to Z + X$

(D0-Note 5066)

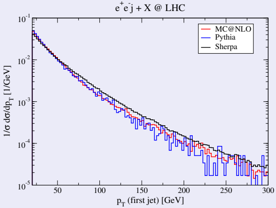


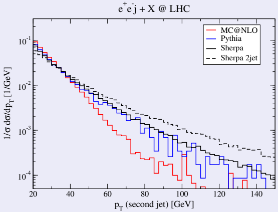


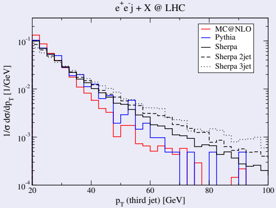
Extrapolation to LHC

$p_\perp$ of jets in inclusive Z+jets

- Influence of more jets.
- Displayed here: x-sections.
- Difference in shape & x-sec.







Summary & outlook

Summary: QCD & simulation tools

- Many interesting signals at LHC "spoiled" by QCD.
- Simulation tools mandatory for success of LHC
- Time to validate essential tools is now!
- Various new OO-projects in C++.
- New methods of merging of ME& PS extremely powerful.

Advertisement

- EU network on Monte Carlo tools to be launched.
- Many short-term positions for PhD students.