MC Theory Overview

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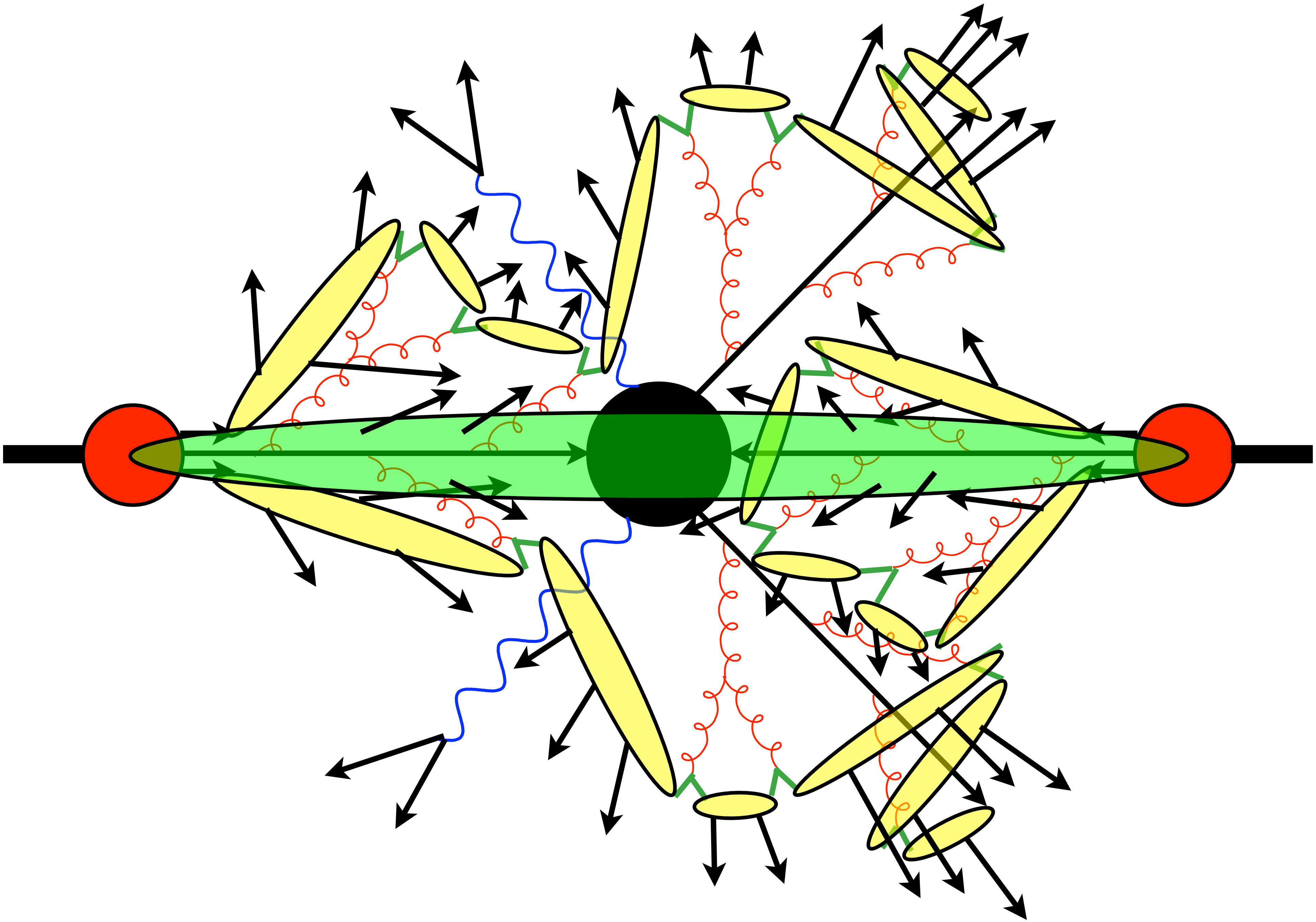
MC4BSM-3, CERN 10-11 March 2008

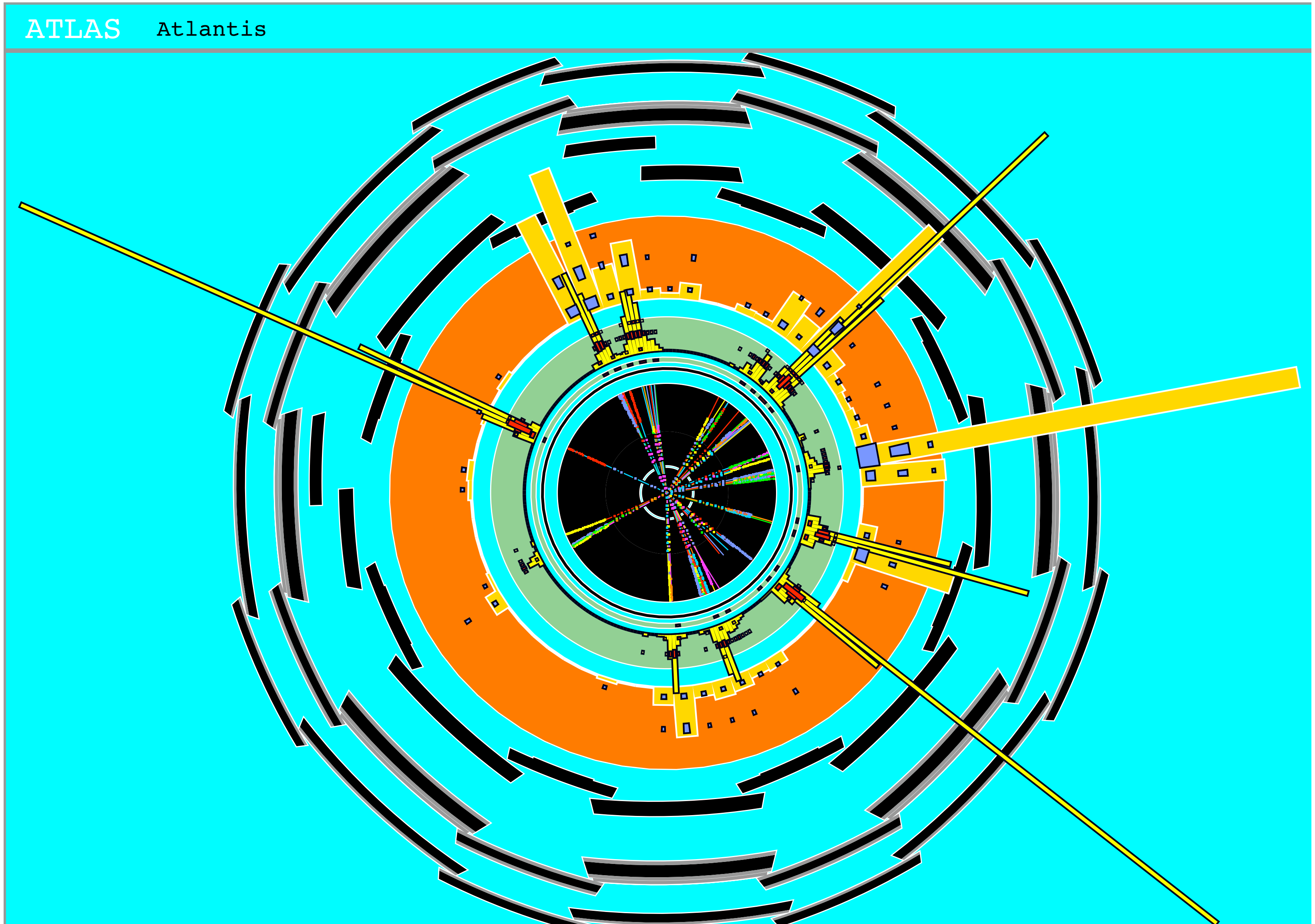
- General-purpose event generators
  - Issues
  - Survey
- Improving precision & modelling
  - Matching ME & PS
  - UE & intrinsic p_t
  - PDFs for MC
- Conclusions?

LHC Event Simulation



Black Hole Event at LHC

TOTDIM = 10 MPLNCK = 1 TeV M_{BH} = 8 TeV



Issues for Event Generators

- Interfacing to BSM models
  - LH Accords, PDG codes, ..., but ...
  - Spin, showering, widths, off-shell effects
- Precision & modelling
  - Mass effects, $1/N_c$
  - Matching to NLO, LO n-jets, ...
  - NP: hadronization, underlying event, intrinsic p_t, ...
  - Parton distributions for MC

General-Purpose Event Generators

- HERWIG
  - Angular-ordered shower, cluster hadronization
  - v6 Fortran, now Herwig++
- PYTHIA
  - Virtuality/k_T-ordered shower, string hadronization
  - v6 Fortran, v8 C++
- SHERPA
  - Virtuality-ordered shower, string/cluster hadronization
  - C++

http://www.hepforge.org/projects

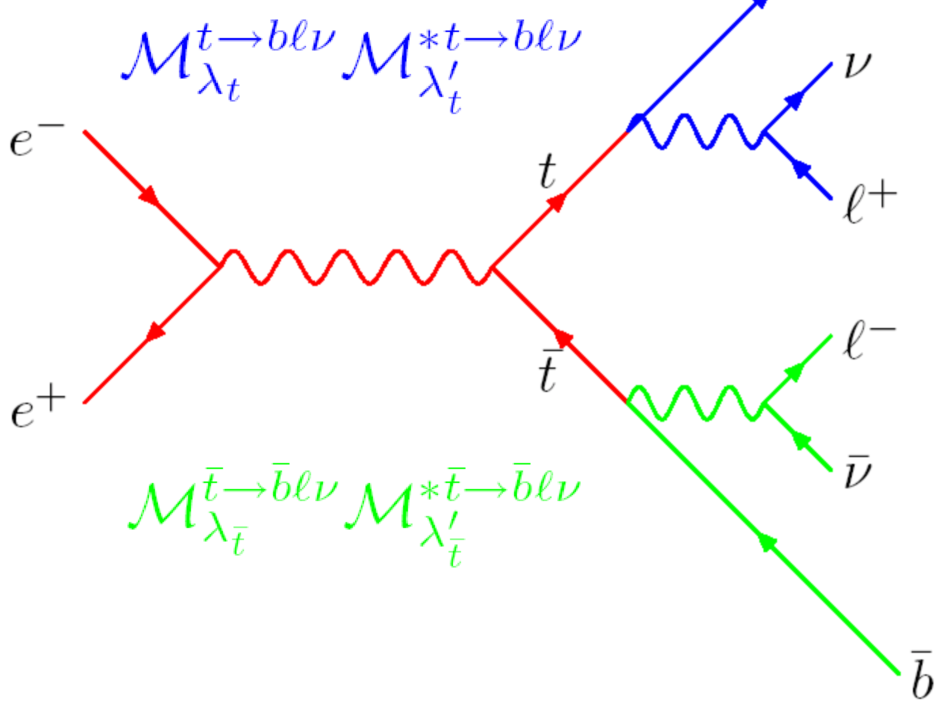
HERWIG 6

- Current status:
- Version 6.510 released on October 31st 2005
  - http://projects.hepforge.org/fherwig/
  - ~ 64,000 lines of FORTRAN, 11 authors (5 currently active)
- 6.51* will be the last FORTRAN version
- Some features:
  - Many built-in SM and MSSM processes
  - Les Houches Accord interface for arbitrary hard processes
  - Spin correlation algorithm
  - Interface to MC@NLO program (Frixione & Webber)
  - Interface to JIMMY multiple interaction underlying event model
  - Angular cutoff $\theta > m/E \Rightarrow$ "dead cone" for heavy quarks

Production/Decay Spin Correlations

- Example: top quark pairs in e+e- annihilation:

Full spin correlations included, by factorized, step-by-step algorithm



$$\rho_{\rm prod}^{\lambda_c\lambda'_c\lambda_d\lambda'_d} = \mathcal{M}_{ab\to cd}^{\lambda_c\lambda_d}\mathcal{M}_{ab\to cd}^{*\lambda'_c\lambda'_d},$$

$$D_c^{\lambda_c\lambda'_c} = \mathcal{M}_{c\ {\rm decay}}^{\lambda_c}\mathcal{M}_{c\ {\rm decay}}^{*\lambda'_c},$$

$$|\mathcal{M}|^2 = \rho_{\rm prod}^{\lambda_c\lambda'_c\lambda_d\lambda'_d} D_c^{\lambda_c\lambda'_c} D_d^{\lambda_d\lambda'_d}$$

$$= \rho_{\rm prod}^{\lambda_c\lambda_c\lambda_d\lambda_d}\left(\frac{\rho_{\rm prod}^{\lambda_c\lambda'_c\lambda_d\lambda_d} D_c^{\lambda_c\lambda'_c}}{\rho_{\rm prod}^{\lambda_c\lambda_c\lambda_d\lambda_d}}\right)$$

$$\times\left(\frac{\rho_{\rm prod}^{\lambda_c\lambda'_c\lambda_d\lambda'_d} D_c^{\lambda_c\lambda'_c} D_d^{\lambda_d\lambda'_d}}{\rho_{\rm prod}^{\lambda_c\lambda'_c\lambda_d\lambda_d} D_c^{\lambda_c\lambda'_c}}\right)$$

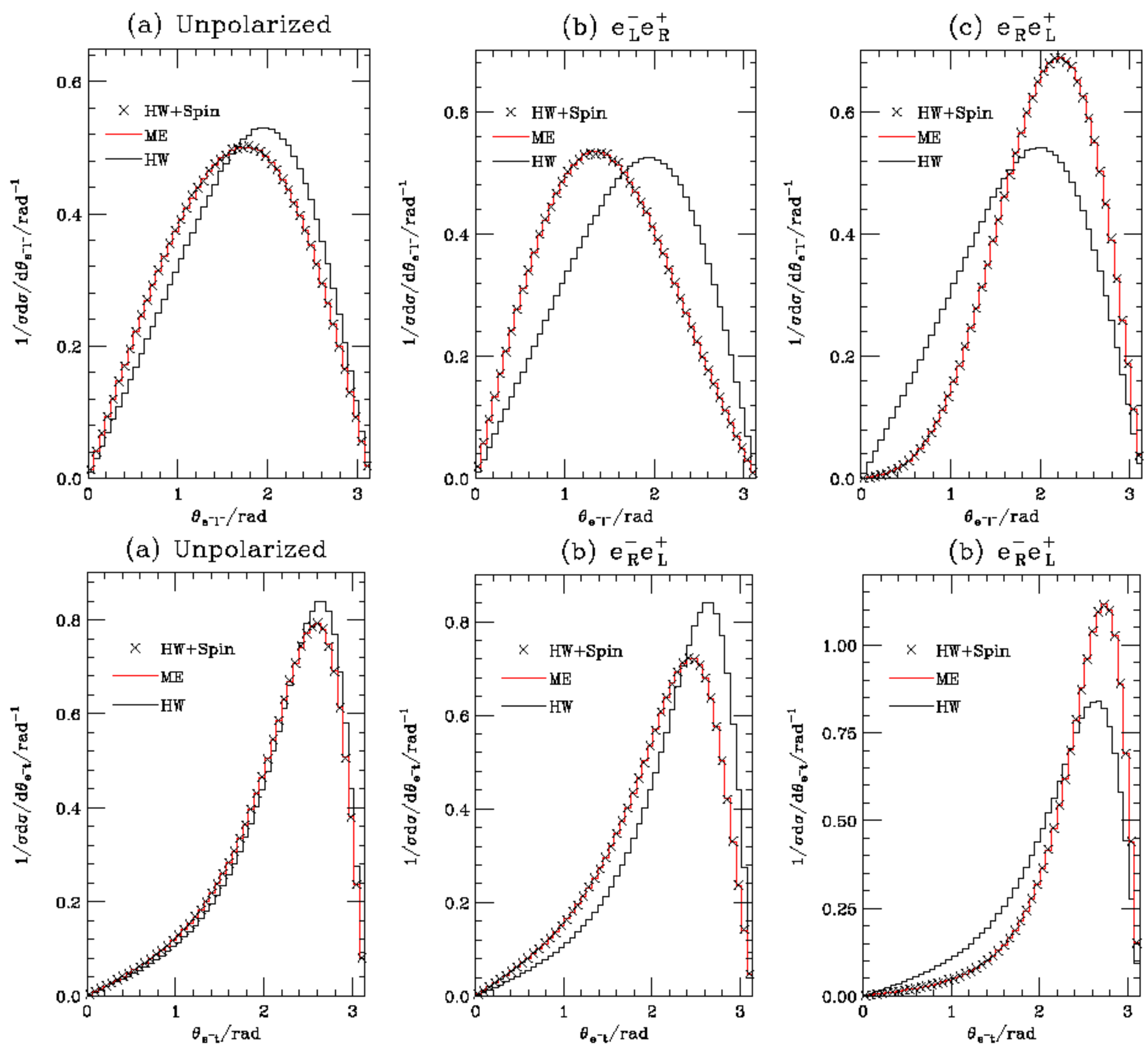
P Richardson, JHEP11(01)029 [hep-ph/0110108]

Production/Decay Spin Correlations

- Top quark pairs in e+e- annihilation:

Correlation between lepton and beam

Correlation between lepton and top



PYTHIA 6 status

PYTHIA has its roots in JETSET, begun in 1978 $\rightarrow$ almost 30 years.

PYTHIA 6 still being (slightly) developed and (fully) maintained:

- multiple interactions and underlying event, with
- transverse-momentum-ordered showers
- SUSY interfaces (SLHA) and simulation
- regular bug fixes and minor improvements
- moved to CEDAR HepForge (code management, bugtracking)

Currently PYTHIA 6.413:

- 75,000 lines of code (including comments/blanks)
- 580 page PYTHIA 6.4 Physics and Manual
  T. Sjöstrand, S. Mrenna and P. Skands,
  JHEP**05** (2006) 026 [hep-ph/0603175]
- + update notes, sample main programs, etc.

. . . but

- only add, never subtract

$\Rightarrow$ has become bloated and unmanageable

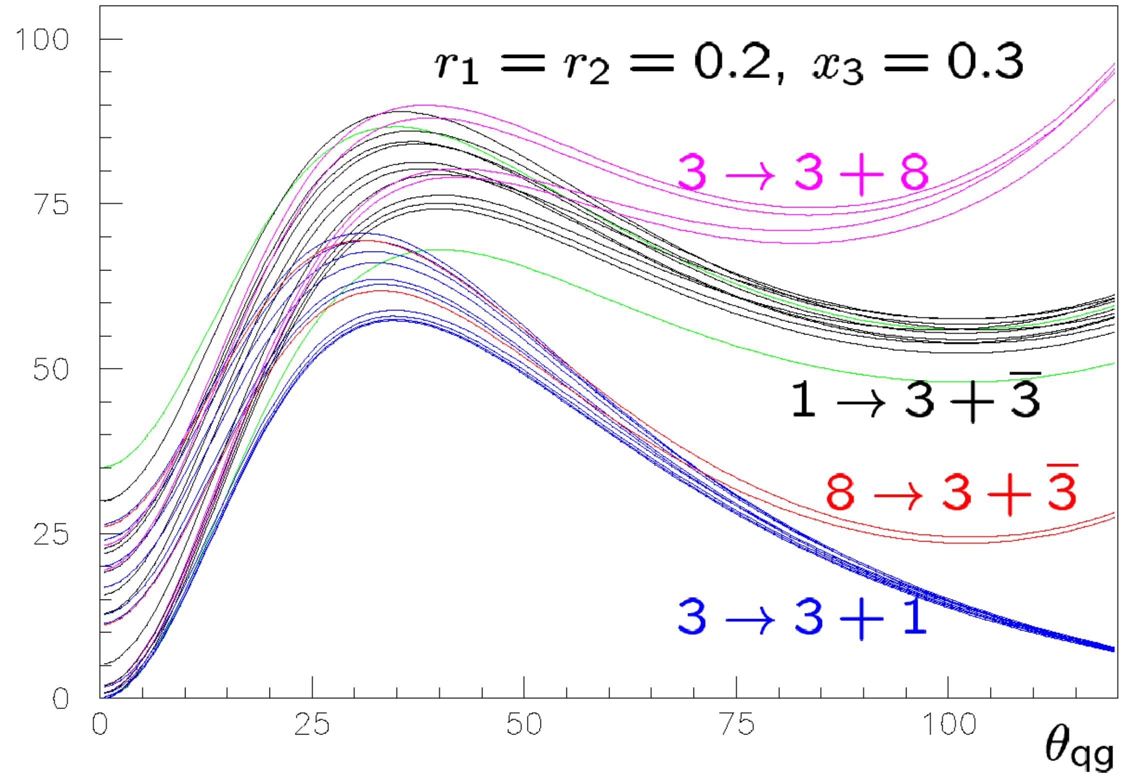
- is in Fortran 77, so not understood by young people

Mass Effects in PYTHIA

- Dead cone only exact for
  - emission from spin-0 particle, or
  - infinitely soft emitted gluon

colour	spin	γ_5	example
$1 \to 3 + \overline{3}$	—	—	(eikonal)
$1 \to 3 + \overline{3}$	$1 \to \frac{1}{2} + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$Z^0 \to q\overline{q}$
$3 \to 3 + 1$	$\frac{1}{2} \to \frac{1}{2} + 1$	$1, \gamma_5, 1 \pm \gamma_5$	$t \to bW^+$
$1 \to 3 + \overline{3}$	$0 \to \frac{1}{2} + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$H^0 \to q\overline{q}$
$3 \to 3 + 1$	$\frac{1}{2} \to \frac{1}{2} + 0$	$1, \gamma_5, 1 \pm \gamma_5$	$t \to bH^+$
$1 \to 3 + \overline{3}$	$1 \to 0 + 0$	1	$Z^0 \to \tilde{q}\overline{\tilde{q}}$
$3 \to 3 + 1$	$0 \to 0 + 1$	1	$\tilde{q} \to \tilde{q}'W^+$
$1 \to 3 + \overline{3}$	$0 \to 0 + 0$	1	$H^0 \to \tilde{q}\overline{\tilde{q}}$
$3 \to 3 + 1$	$0 \to 0 + 0$	1	$\tilde{q} \to \tilde{q}'H^+$
$1 \to 3 + \overline{3}$	$\frac{1}{2} \to \frac{1}{2} + 0$	$1, \gamma_5, 1 \pm \gamma_5$	$\chi \to q\overline{\tilde{q}}$
$3 \to 3 + 1$	$0 \to \frac{1}{2} + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$\tilde{q} \to q\chi$
$3 \to 3 + 1$	$\frac{1}{2} \to 0 + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$t \to \tilde{t}\chi$
$8 \to 3 + \overline{3}$	$\frac{1}{2} \to \frac{1}{2} + 0$	$1, \gamma_5, 1 \pm \gamma_5$	$\tilde{g} \to q\overline{\tilde{q}}$
$3 \to 3 + 8$	$0 \to \frac{1}{2} + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$\tilde{q} \to q\tilde{g}$
$3 \to 3 + 8$	$\frac{1}{2} \to 0 + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$t \to \tilde{t}\tilde{g}$

- In general, depends on
  - energy of gluon
  - colour and spin of emitting particle & partner
  - ➔ process-dependent mass corrections



PYTHIA Underlying Event Models

Parameter	**Value**	**Description**
MSTP(81)	0,10,20	Multiple-Parton Scattering off, for old, intermediate & new models
	1,11,21	Multiple-Parton Scattering on, for old, intermediate & new models
MSTP(82)	1 2	Multiple interactions with fixed probability & abrupt cut-off PTmin=PARP(81) or smooth turn-off at PARP(82)
MSTP(82)	3	Multiple interactions with varying impact parameter & hadronic matter overlap with single Gaussian matter distribution, with smooth turn-off at PARP(82)
MSTP(82)	4 5	Multiple interactions with varying impact parameter and a hadronic matter overlap with double Gaussian matter distribution (governed by PARP(83) and PARP(84)), or distribution PARP(83), both with smooth turn-off at PARP(82)

Object Oriented Event Generators

- ThePEG: Toolkit for High Energy Physics Event Generation, used by Herwig++ (and ARIADNE++?)
- Herwig++: Physics improvements from HERWIG 6
- PYTHIA 8: Implementation of physics of PYTHIA 6 plus some improvements: see http://www.thep.lu.se/~torbjorn
- SHERPA: Completely new event generator

http://www.hepforge.org/projects

Hard Processes in Herwig++

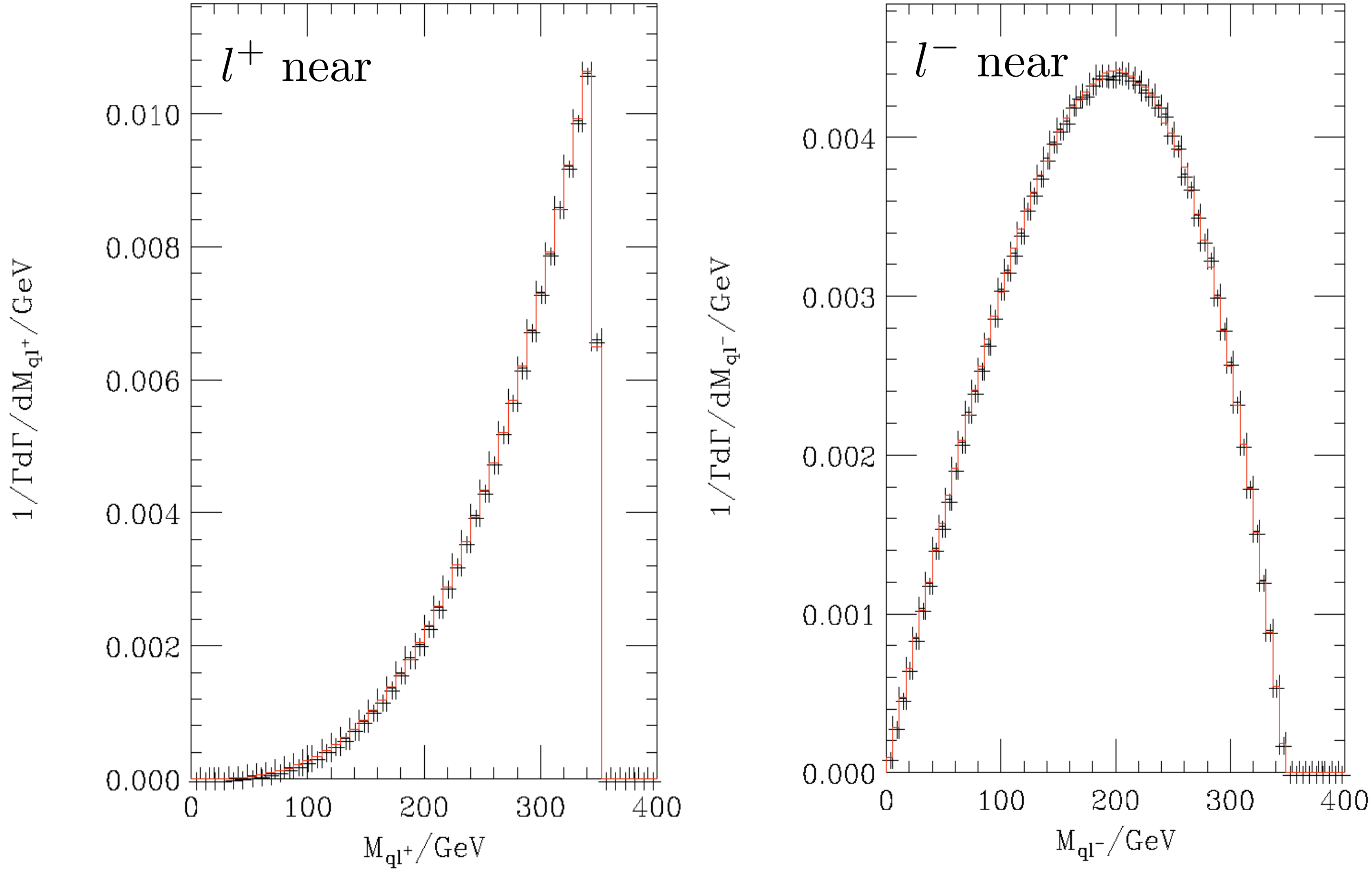
- In FORTRAN HERWIG each hard process and decay matrix element was typed in by hand.
  - Isn't a good use of time.
  - Meant that models of new physics were very hard to include.
- Herwig++ uses an entirely different philosophy.
  - A C++ helicity library based on the HELAS formalism is used for all matrix element and decay calculations.
  - Code the hard 2→2 matrix elements based on the spin structures.
  - Code the 1→2 decays in the same way and use phase space for the 1→3 decays to start with.
  - Easy to include spin correlations as we have access to the spin unaveraged matrix elements.

Herwig++ Physics and Manual, M Bähr et al. arXiv:0803:0883

M Gigg and P Richardson EPJ C51(07)989 [hep-ph/0703199]

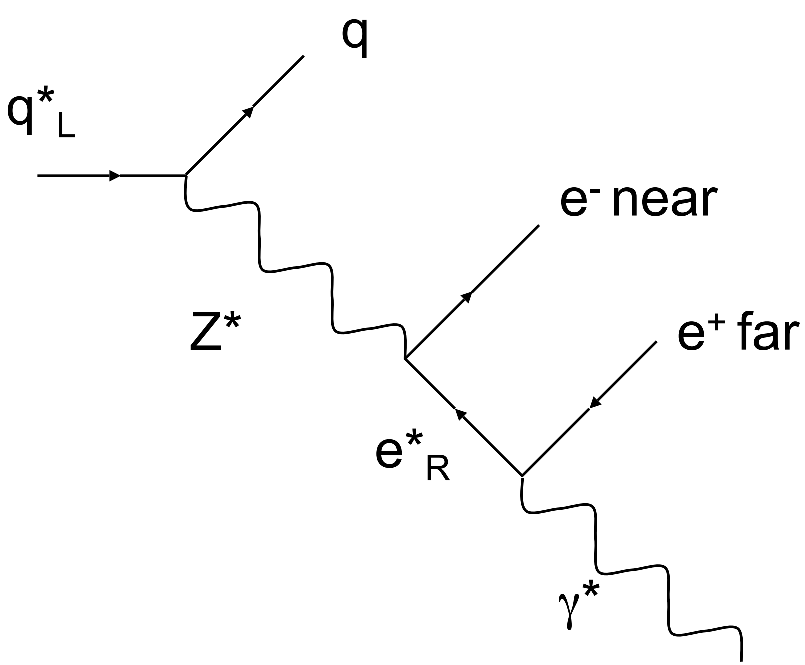
Herwig++ New Physics: MSSM

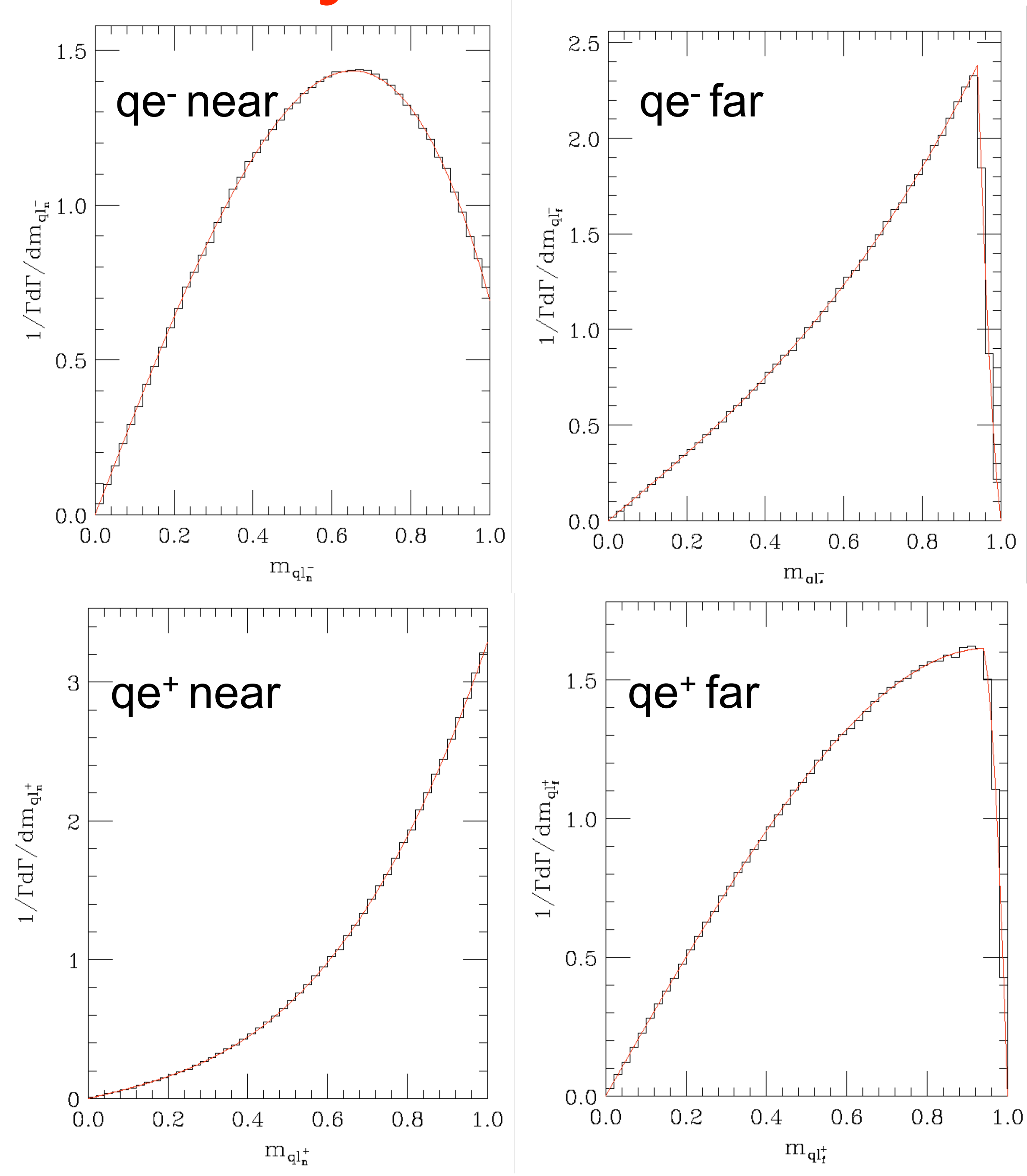
$$\tilde{q}_L \to q\tilde{\chi}_2^0 \to ql^{\pm}\tilde{l}^{\mp} \to ql^{\pm}l^{\mp}\tilde{\chi}_1^0$$



Herwig++ New Physics: UED

Analogous decay:





Curves: J Smillie, BW
JHEP 10(05)069
[hep-ph/0507170]

PYTHIA 8 status

task	status
administative structure	operational; extensions planned
hard processes, internal	much of PYTHIA 6; SUSY & TC & more to do
resonance decays	much of PYTHIA 6; SUSY & TC & more to do
hard processes, external	interfaces to LHA F77, LHEF, PYTHIA 6
SUSY(+more) parameters	primitive SLHA2; more needed
initial-state showers	operational
final-state showers	operational
matching ME's to showers	some exists; much more needed
multiple interactions	operational; extensions planned
beam remnants & colour flow	operational; alternatives to come
parton densities	only 2 internal, but interface to LHAPDF
string fragmentation	operational; improvements planned
decays & particle data	operational; may need updates
Bose-Einstein	operational; off by default (tuning)
analysis	some simple tools; may be enough
graphical user interface	operational; could be extended
tuning	major task for MCnet postdocs!
testing	major task for experimentalists!

Key differences between PYTHIA 6.4 and 8.1

Old features definitely removed include, among others:
- independent fragmentation
- mass-ordered showers

Features omitted so far include, among others:
- ep, γp and $\gamma\gamma$ beam configurations
- several processes, especially SUSY & Technicolor

New features, not found in 6.4:
- interleaved $p_\perp$-ordered MI + ISR + FSR evolution
- richer mix of underlying-event processes (γ, J/ψ, DY, ...)
- possibility for two selected hard interactions in same event
- possibility to use one PDF set for hard process and another for rest
- elastic scattering with Coulomb term (optional)
- updated decay data

Preliminary plans for the future:
- rescattering in multiple interactions
- NLO and L-CKKW matching

Introducing SHERPA

Physics of 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)
- Tested in a number of processes (highlights see below).
- A few other implementations exist for specific channels.

Automatic cross section calculators

Example: AMEGIC++

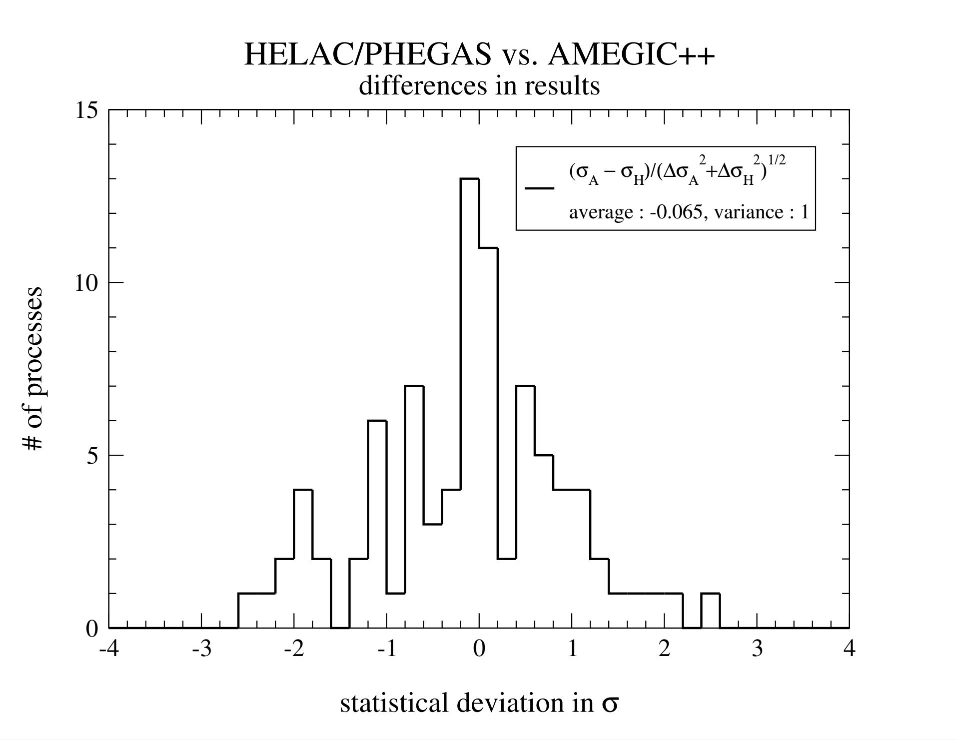
F.K., R.Kuhn, G.Soff, JHEP **0202** (2002) 044.

- Uses helicity method + multi-channeling.
  Operational mode: 2 runs.
  - Generation run:
    - Generate Feynman diagrams,
    - construct and simplify helicity amplitudes,
    - produce integration channels,
    - write out library files.
  - Compile & link libraries.
  - Production run:
    - cross section calculations,
    - parton level events.
- Implemented & tested models: SM, MSSM, ADD.

Standard Model @ Linear Collider

Consistency of HELAC/PHEGAS & AMEGIC++

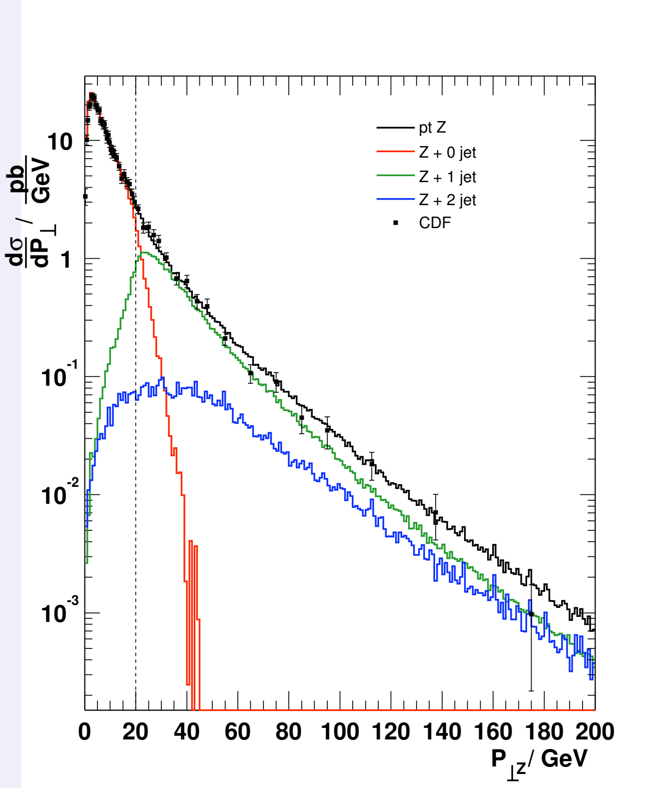
T.Gleisberg, F.K., C.Papadopoulos, A.Schälicke and S.Schumann, Eur. Phys. J. C **34** (2004) 173

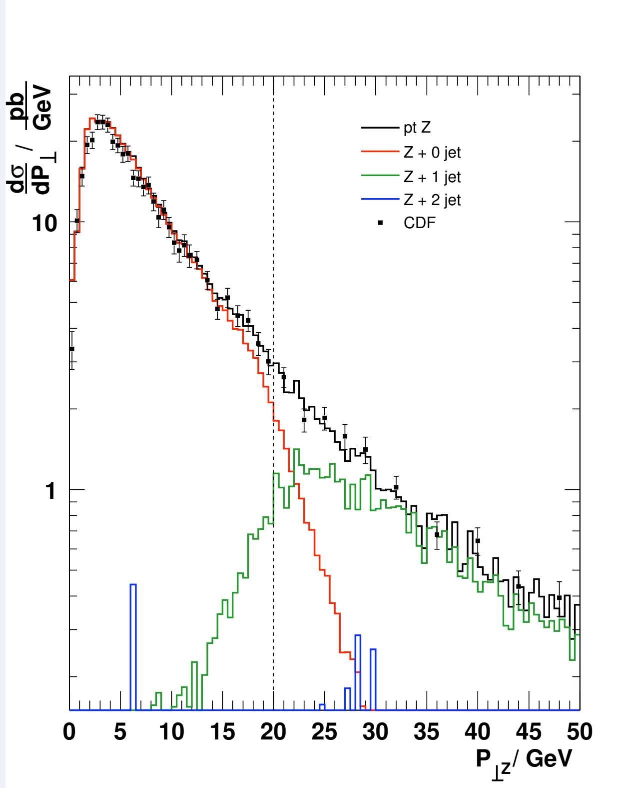


Comparison with data from Tevatron

$p_\perp$ of Z-bosons in $p\bar{p} \to Z + X$

Data from CDF, Phys. Rev. Lett. 84 (2000) 845





ME-PS Matching

- Two rather different objectives:
- Matching parton showers to NLO matrix elements, without double counting
  - MC@NLO
  - POWHEG
- Matching parton showers to LO n-jet matrix elements, minimizing jet resolution dependence
  - CKKW
  - Dipole
  - MLM Matching
  - Comparisons

MC@NLO

Illustrate with simple one-dim. example:

$$|\mathcal{M}_{m+1}|^2 \equiv \frac{1}{x}\mathcal{M}(x)$$

x = gluon energy or two-parton invariant mass.

Divergences regularized by $d = 4 - 2\epsilon$ dimensions.

$$|\mathcal{M}_m^{\text{one-loop}}|^2 \equiv \frac{1}{\epsilon}\mathcal{V}$$

Cross section in d dimensions is:

$$\sigma = \int_0^1 \frac{dx}{x^{1+\epsilon}}\,\mathcal{M}(x)\;F_1^J(x) + \frac{1}{\epsilon}\mathcal{V}\;F_0^J$$

Infrared safety: $F_1^J(0) = F_0^J$

KLN cancellation theorem: $\mathcal{M}(0) = \mathcal{V}$

Subtraction Method

Exact identity:

$$\sigma^J = \int_0^1 \frac{dx}{x^{1+\epsilon}}\,\mathcal{M}(x)\;F_1^J(x) - \int_0^1 \frac{dx}{x^{1+\epsilon}}\,\mathcal{V}\;F_0^J + \int_0^1 \frac{dx}{x^{1+\epsilon}}\,\mathcal{V}\;F_0^J + \frac{1}{\epsilon}\mathcal{V}\;F_0^J$$

$$= \int_0^1 \frac{dx}{x}\left(\mathcal{M}(x)\;F_1^J(x) - \mathcal{V}\;F_0^J\right) + \mathcal{O}(1)\;\mathcal{V}\;F_0^J.$$

➡ Two separate finite integrals.

Modified Subtraction

$$\sigma^J = \int_0^1 \frac{dx}{x} \left(\mathcal{M}(x)\, F_1^J(x) - \mathcal{V}\, F_0^J \right) + \mathcal{O}(1)\, \mathcal{V}\, F_0^J$$

Now add parton shower:

$F_{0,1}^J \Rightarrow$ result from showering after 0,1 emissions.

But shower adds $\mathcal{M}_{\rm MC}/x$ to 1 emission. Must subtract this, and add to 0 emission (so that $F_{0,1}^{\rm tot} = 1 \Rightarrow \sigma^{\rm tot}$ fixed)

$$\begin{aligned} \sigma^J &= \int_0^1 \frac{dx}{x} \Big(\{\mathcal{M}(x) - \mathcal{M}_{\rm MC}(x)\}\, F_1^J(x) \\ &\quad - \{\mathcal{V} - \mathcal{M}_{\rm MC}(x)\}\, F_0^J \Big) + \mathcal{O}(1)\, \mathcal{V}\, F_0^J \end{aligned}$$

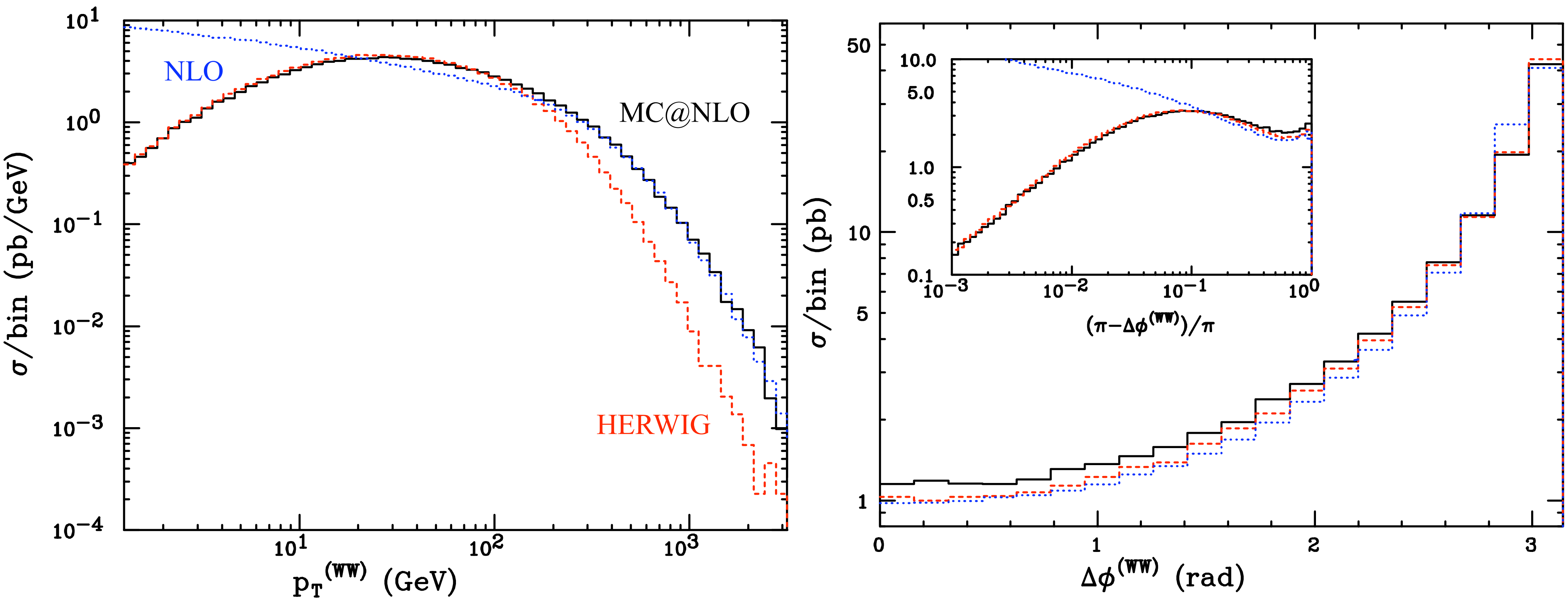
MC good for soft and/or collinear $\Rightarrow \mathcal{M}_{\rm MC}(0) = \mathcal{M}(0)$

➡ 0 & 1 emission contributions separately finite now!

(But some can be negative “counter-events”)

MC@NLO Results

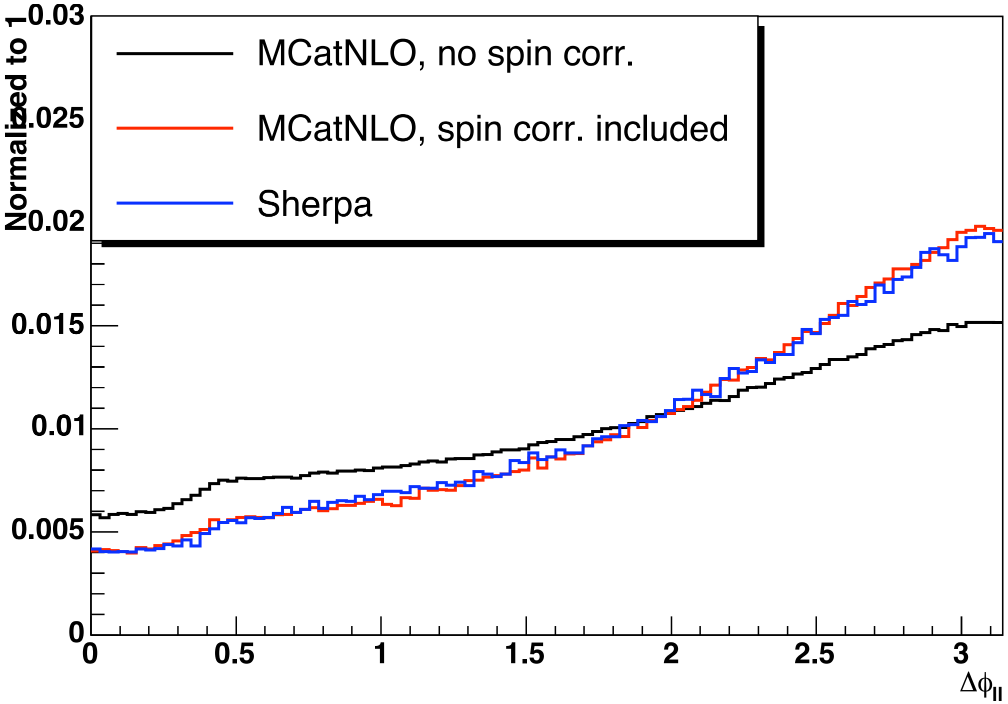
- WW production at LHC

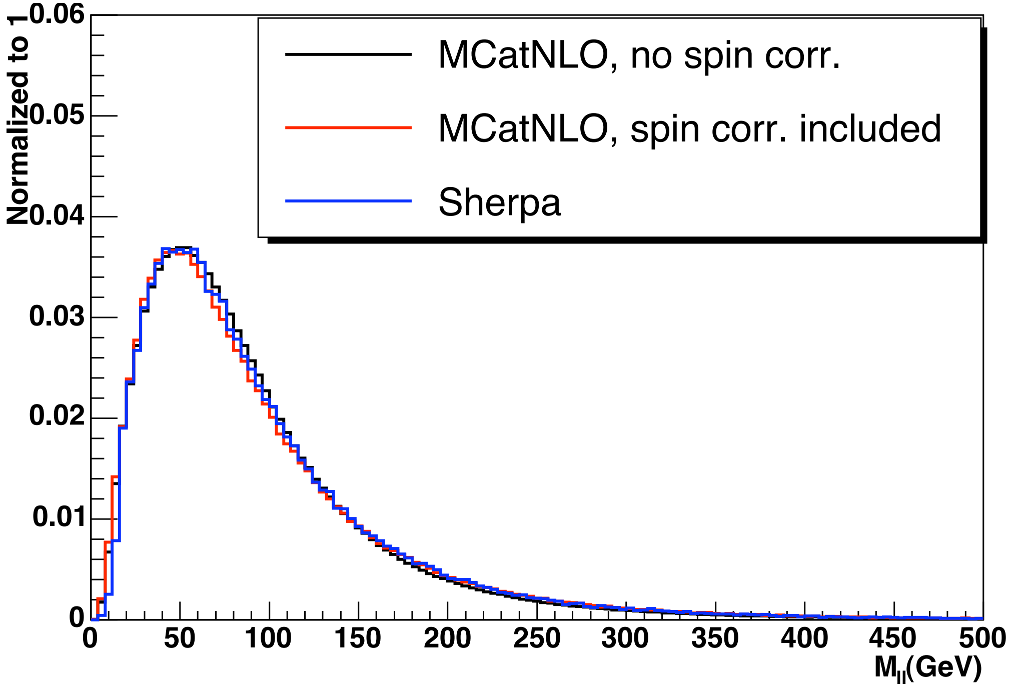


- Interpolates between MC & NLO in $p_T^{(WW)}$
- Above both at $\Delta\phi^{(WW)} \simeq 0$

S Frixione & BW, JHEP 06(2002)029

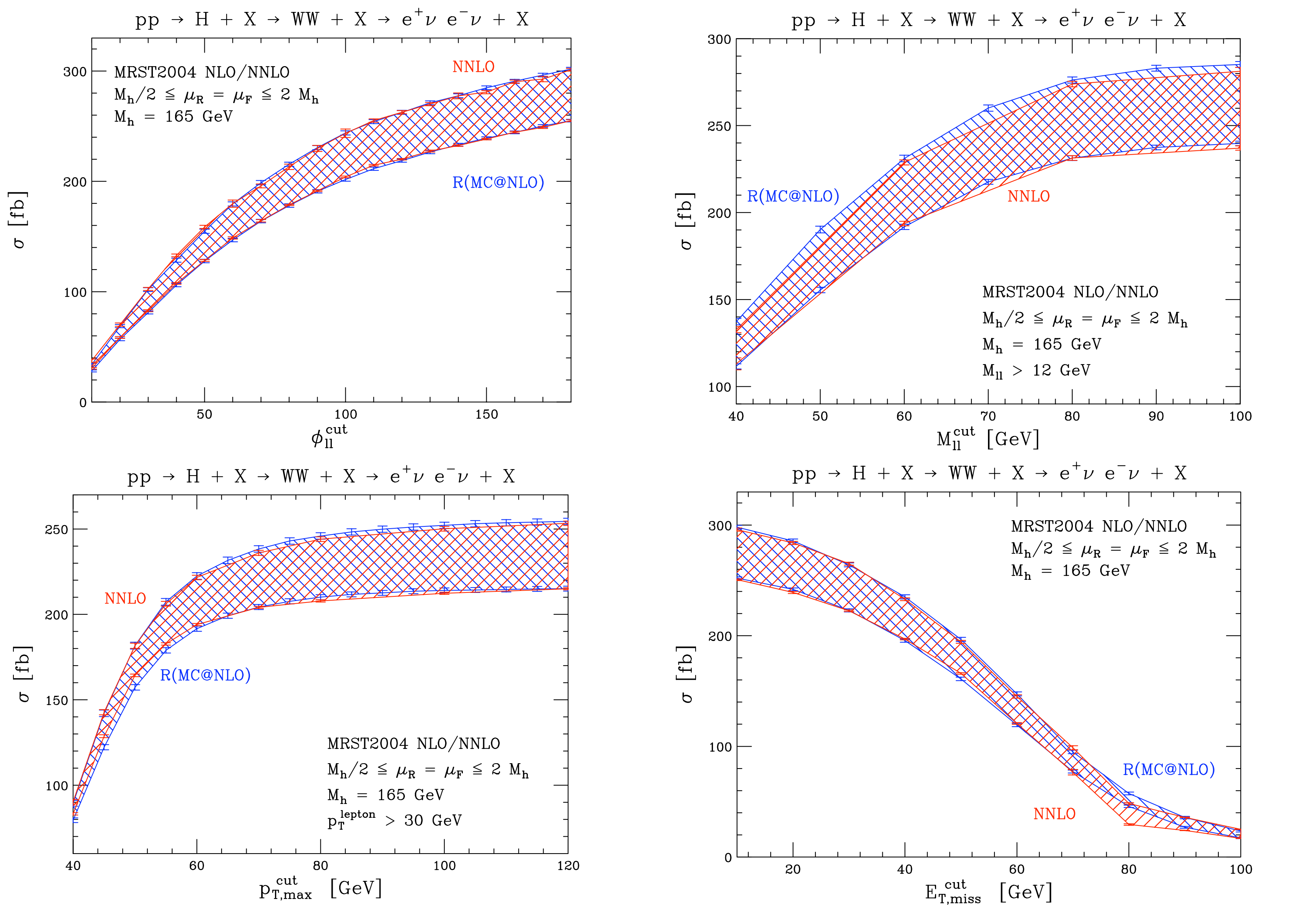
W^+W^- Spin Correlations



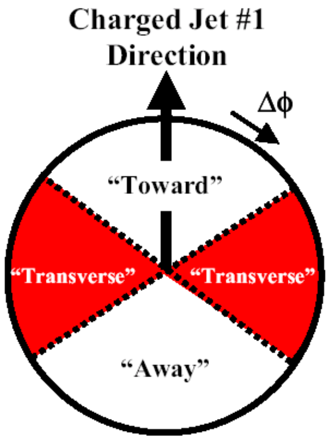


Plots from W. Quayle (preliminary)

H→WW: MC@NLO vs NNLO



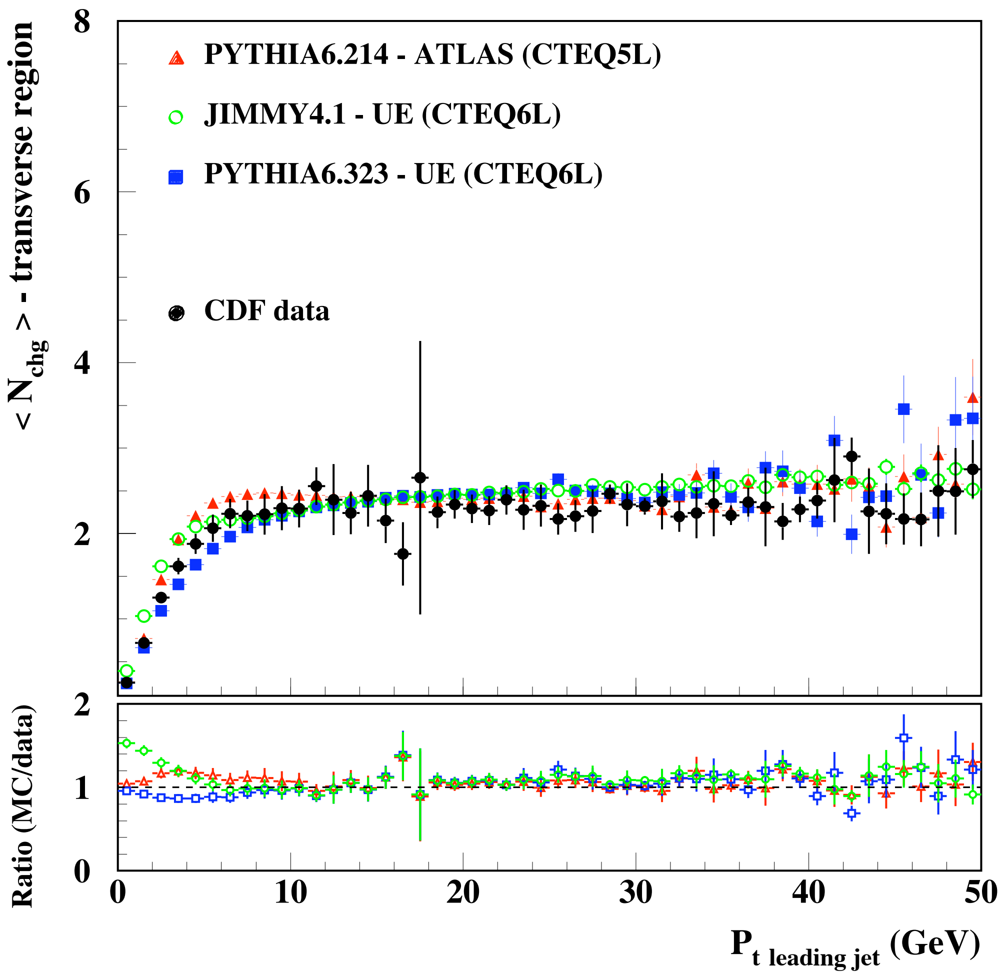
C Anastasiou, G Dissertori, F Stöckli & BW, JHEP03(2008)017 [arXiv:0801.2682]

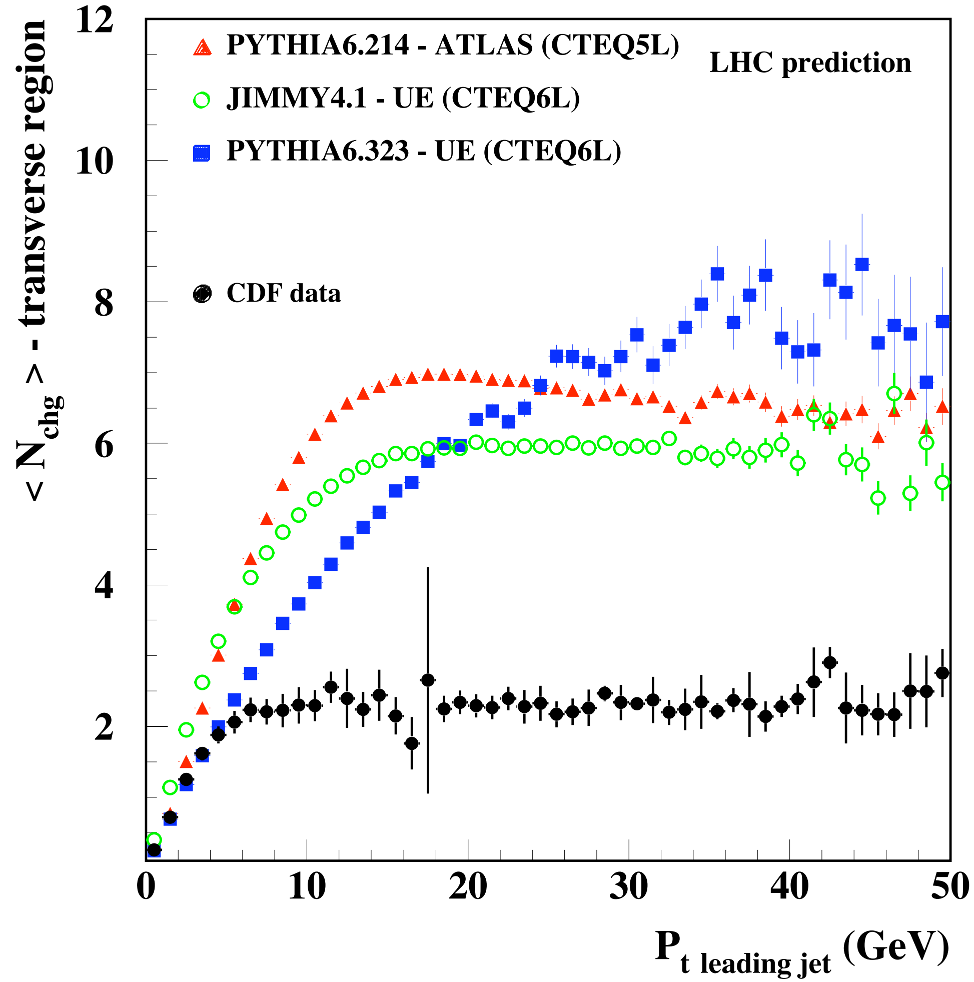


Underlying Event

- Affects jet observables
- Extrapolation to LHC uncertain

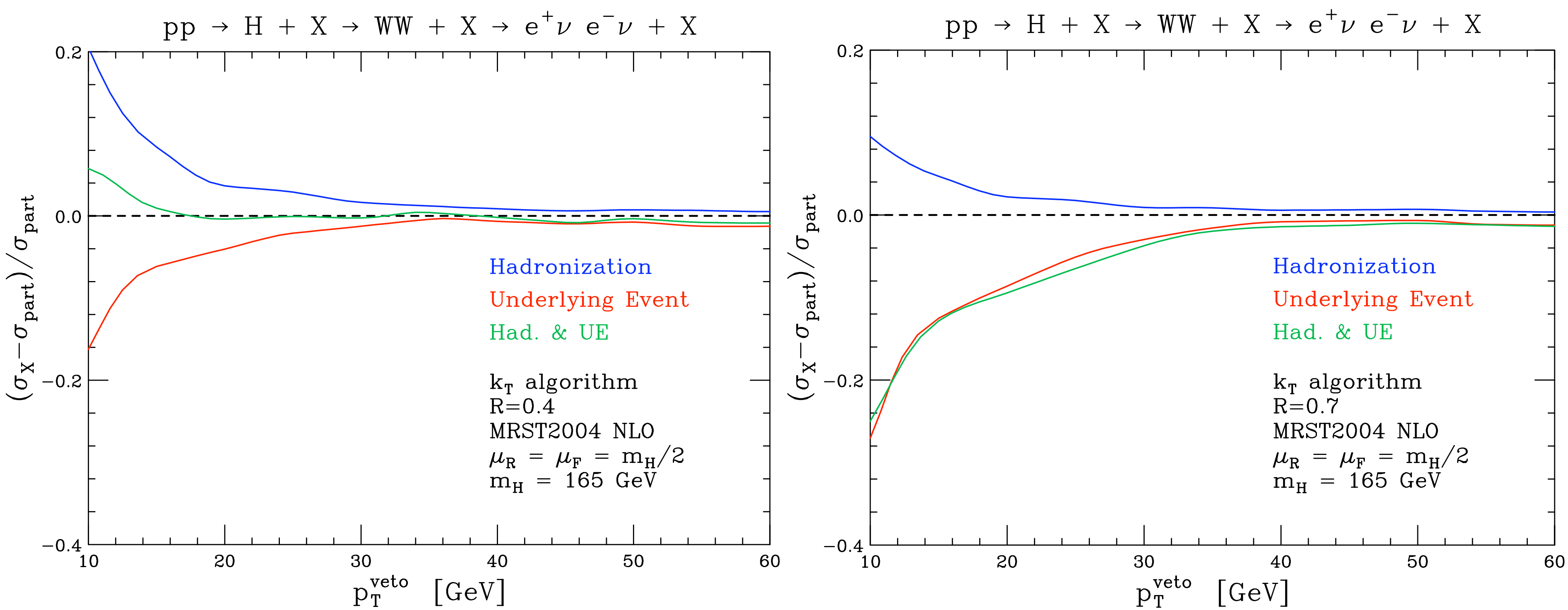
http://projects.hepforge.org/jimmy



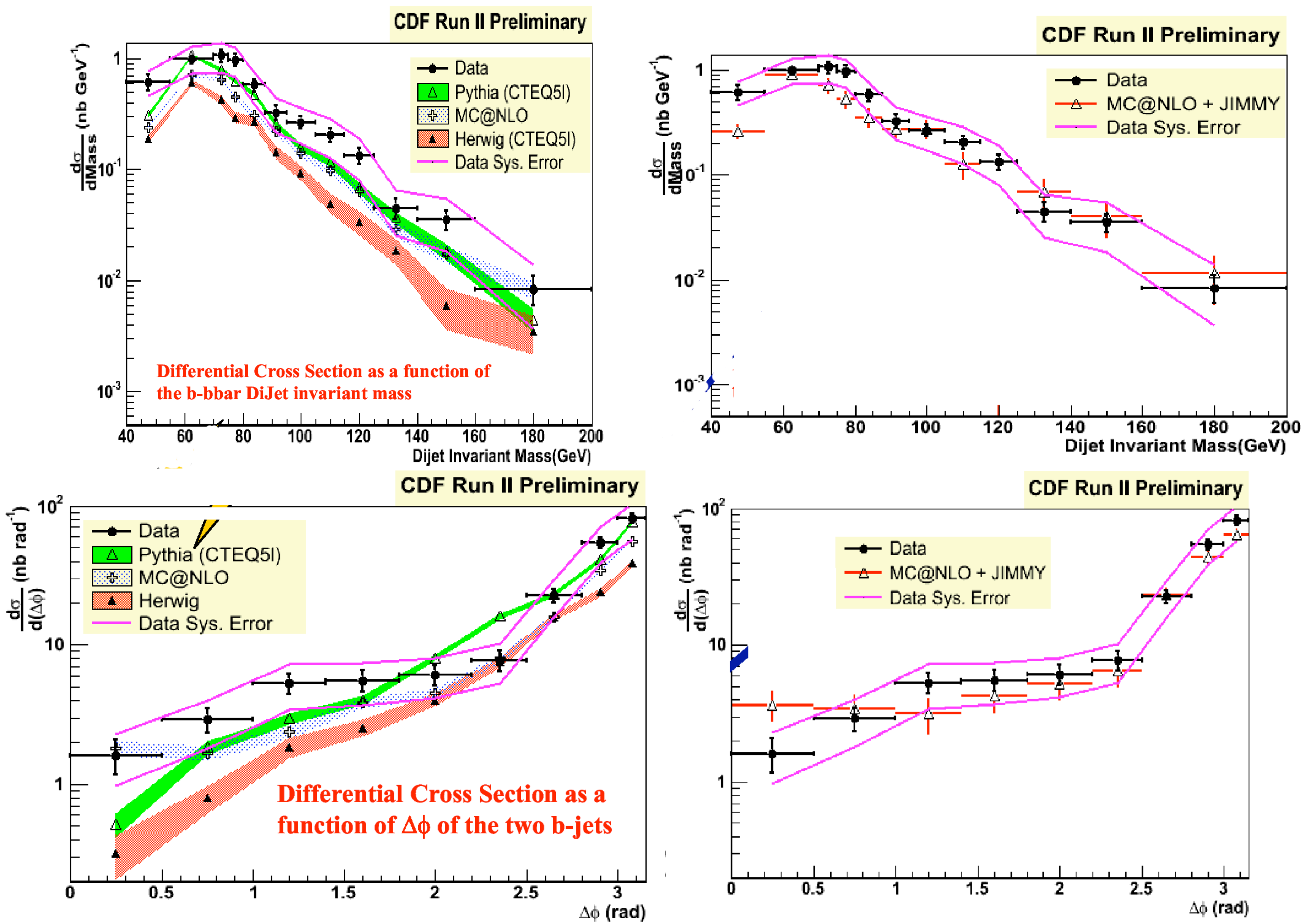


UE in H→WW

- Effect of UE increases with jet size
- Effect of hadronization decreases
- May cancel in jet veto

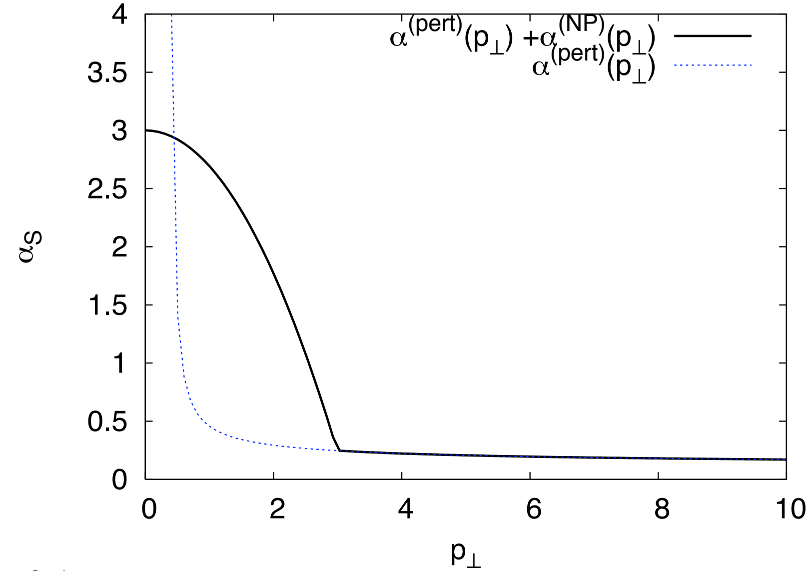


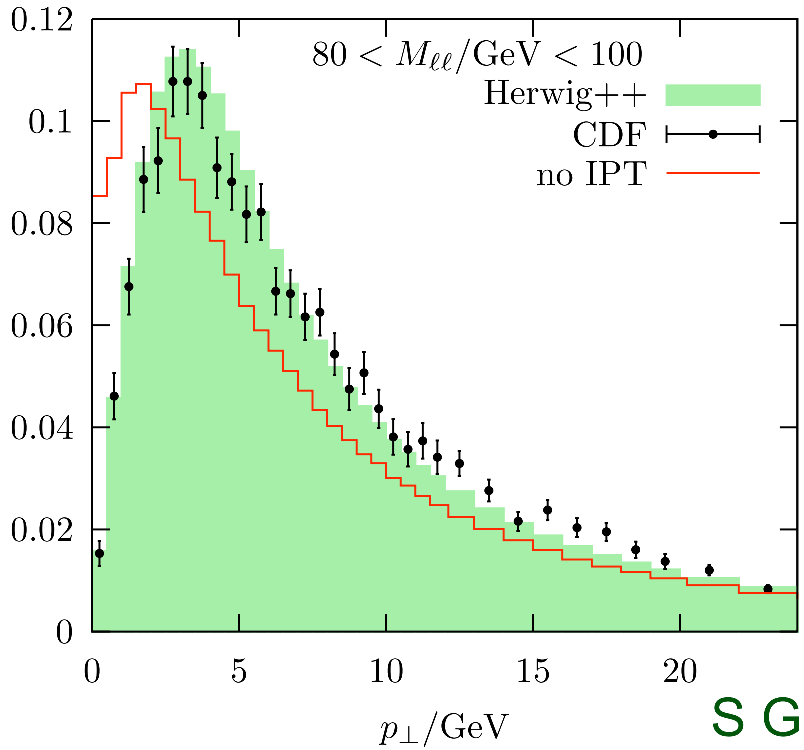
MC@NLO & UE: $b\bar{b}$-dijets

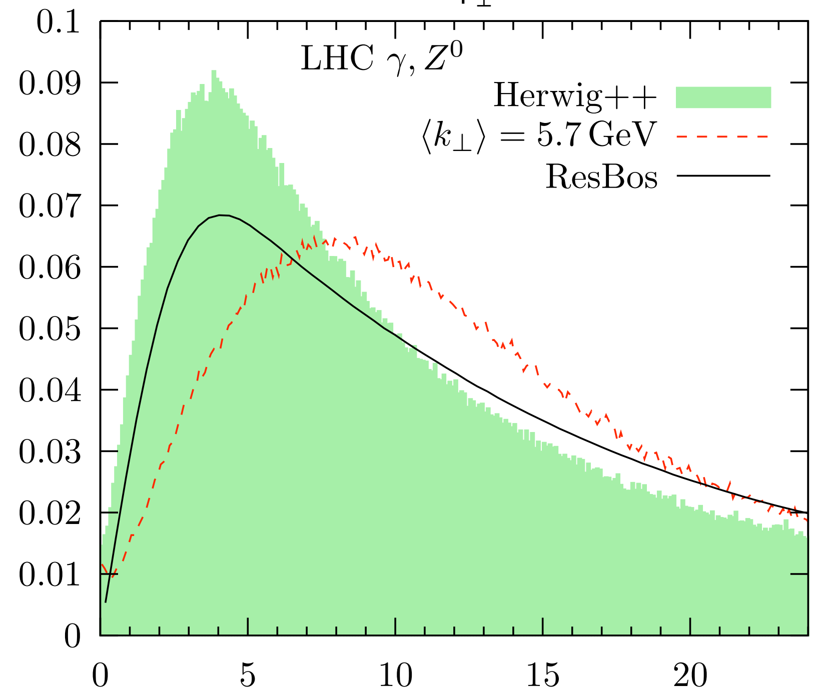


Intrinsic p_t

- Low-scale effective α_S in showers: predicts energy dependence
- Similar to ResBos (CSS resummation)







S Gieseke, M Seymour & A Siódmok, arXiv:0712.1199

CKKW Matching

- Use Matrix Elements down to scale Q_1
- Use Parton Showers below Q_1
- Correct ME by reweighting
- Correct PS by vetoing
- Ensure that Q_1 cancels (to NLL)

S Catani, F Krauss, R Kuhn & BW, JHEP11 (2001) 063

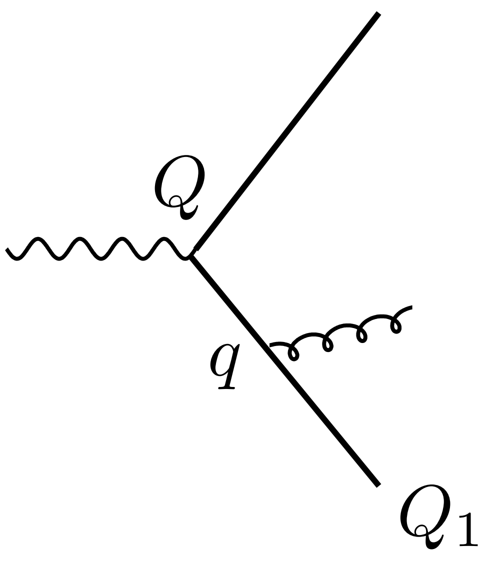
Example: $e^+e^- \to$ hadrons

- 2- & 3-jet rates at scale Q_1:

$$R_2(Q,Q_1) = [\Delta_q(Q,Q_1)]^2 \;,$$

$$R_3(Q,Q_1) = 2\Delta_q(Q,Q_1)\int_{Q_1}^{Q} dq\,\frac{\Delta_q(Q,Q_1)}{\Delta_q(q,Q_1)}\Gamma_q(Q,q) \times\Delta_q(q,Q_1)\Delta_g(q,Q_1)$$

$$= 2\,[\Delta_q(Q,Q_1)]^2\int_{Q_1}^{Q} dq\,\Gamma_q(Q,q)\Delta_g(q,Q_1)$$



$$\Gamma_q(Q,q) = \frac{2C_F}{\pi}\frac{\alpha_S(q)}{q}\left(\ln\frac{Q}{q} - \frac{3}{4}\right)$$

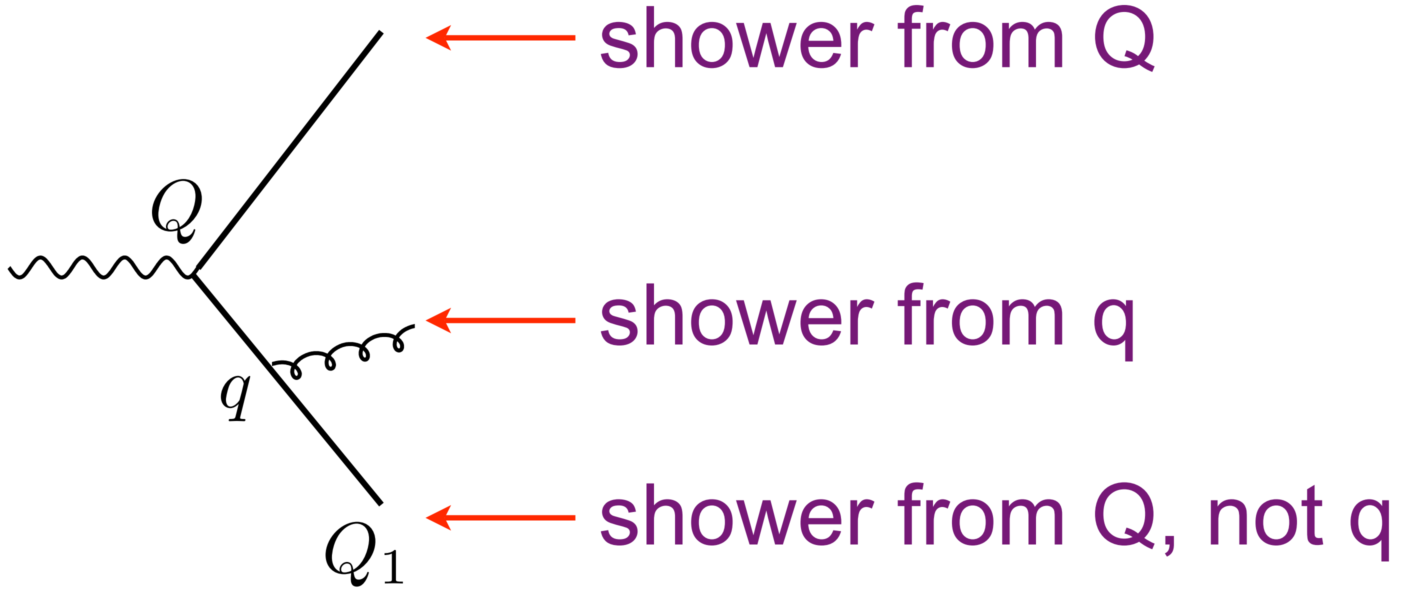
CKKW reweighting

- Choose n according to $R_n(Q, Q_1)$ (LO)
  - use $[\alpha_S(Q_1)]^n$
- Use exact LO ME to generate n partons
- Construct "equivalent shower history"
  - preferably using k_T-type algorithm
- Weight vertex at scale q by $\alpha_S(q)/\alpha_S(Q_1) < 1$
- Weight parton of type i from Q_j to Q_k by

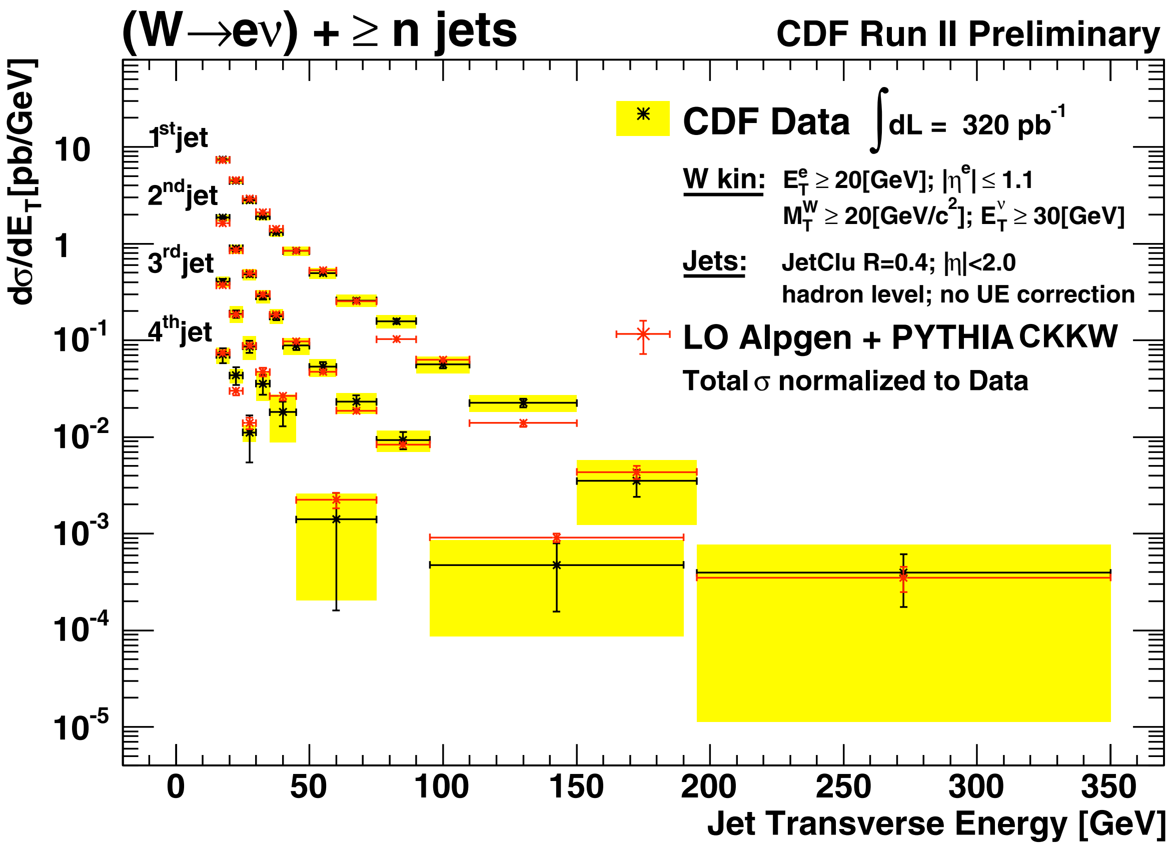
$$\Delta_i(Q_j, Q_1)/\Delta_i(Q_k, Q_1)$$

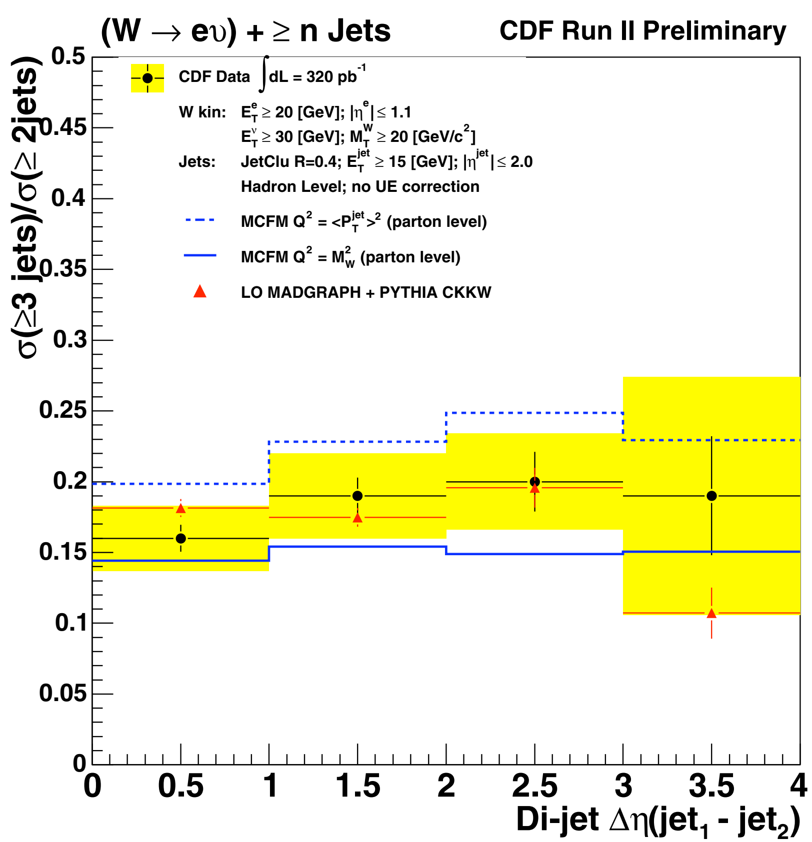
CKKW shower veto

- Shower n partons from "creation scales"
  - includes coherent soft emission
- Veto emissions at scales above Q_1
  - cancels leading (LL&NLL) Q_1 dependence



Comparisons with Tevatron data





from JM Campbell, JW Huston & WJ Stirling, Rept.Prog.Phys.70(2007)89

➡ M.E. + PYTHIA CKKW looks good

Dipole Matching

- Implemented in ARIADNE dipole MC
- Dipole cascade replaces parton shower
- Construct equivalent dipole history $\{p_{Ti}\}$
- Rejection replaces Sudakov weights
  - cascade from p_{Ti}, reject if $p_T > p_{Ti+1}$

L Lönnblad, JHEP05(2002)046

MLM Matching

- Use cone algorithm for jet definition:

$$R_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$$

$$E_{Ti} > E_{Tmin}, \ R_{ij} > R_{min}$$

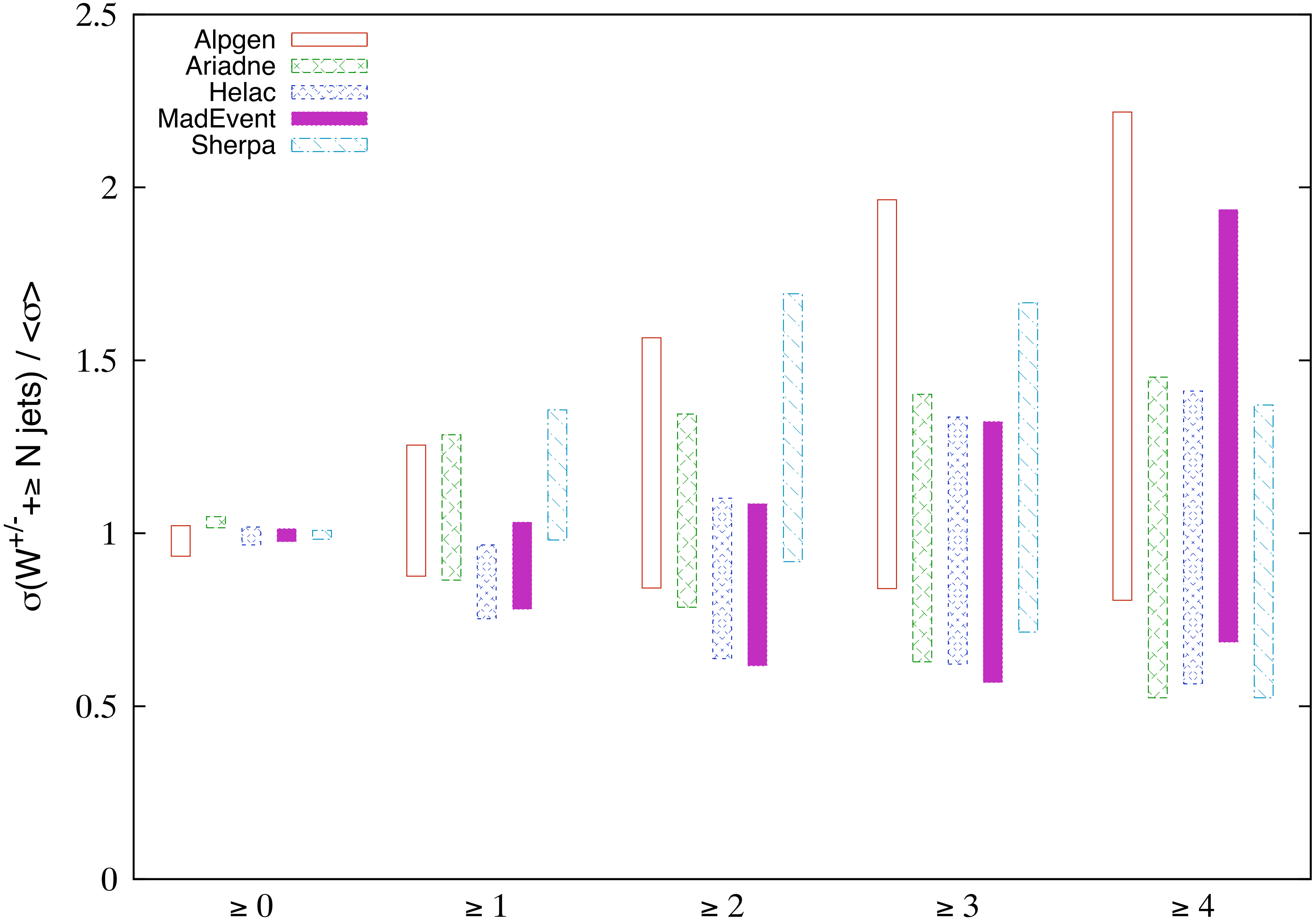
- Generate n-parton configurations with $E_{Ti} > E_{Tmin}, \ R_{ij} > R_{min}$ (no Sudakov weights)
- Generate showers (no vetos)
- Form jets using same jet definition
- Reject event if njets $\neq$ npartons

Comparisons

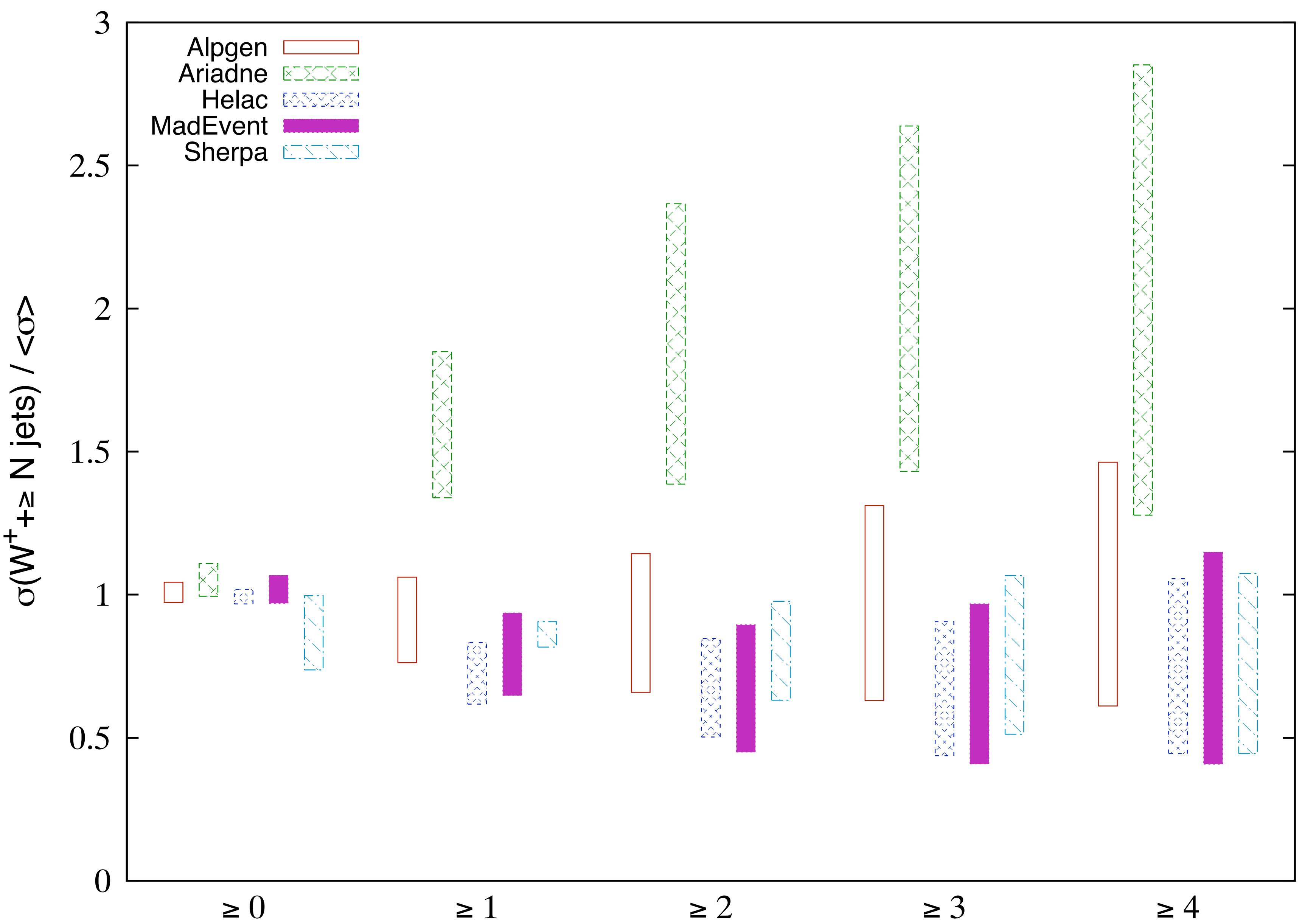
- ALPGEN: MLM matching
- ARIADNE: Dipole matching
- HELAC: MLM matching
- MadEvent: hybrid MLM/CKKW
- SHERPA: CKKW matching

J. Alwall el al., EPJ C53(08)473 [arXiv:0706.2569]

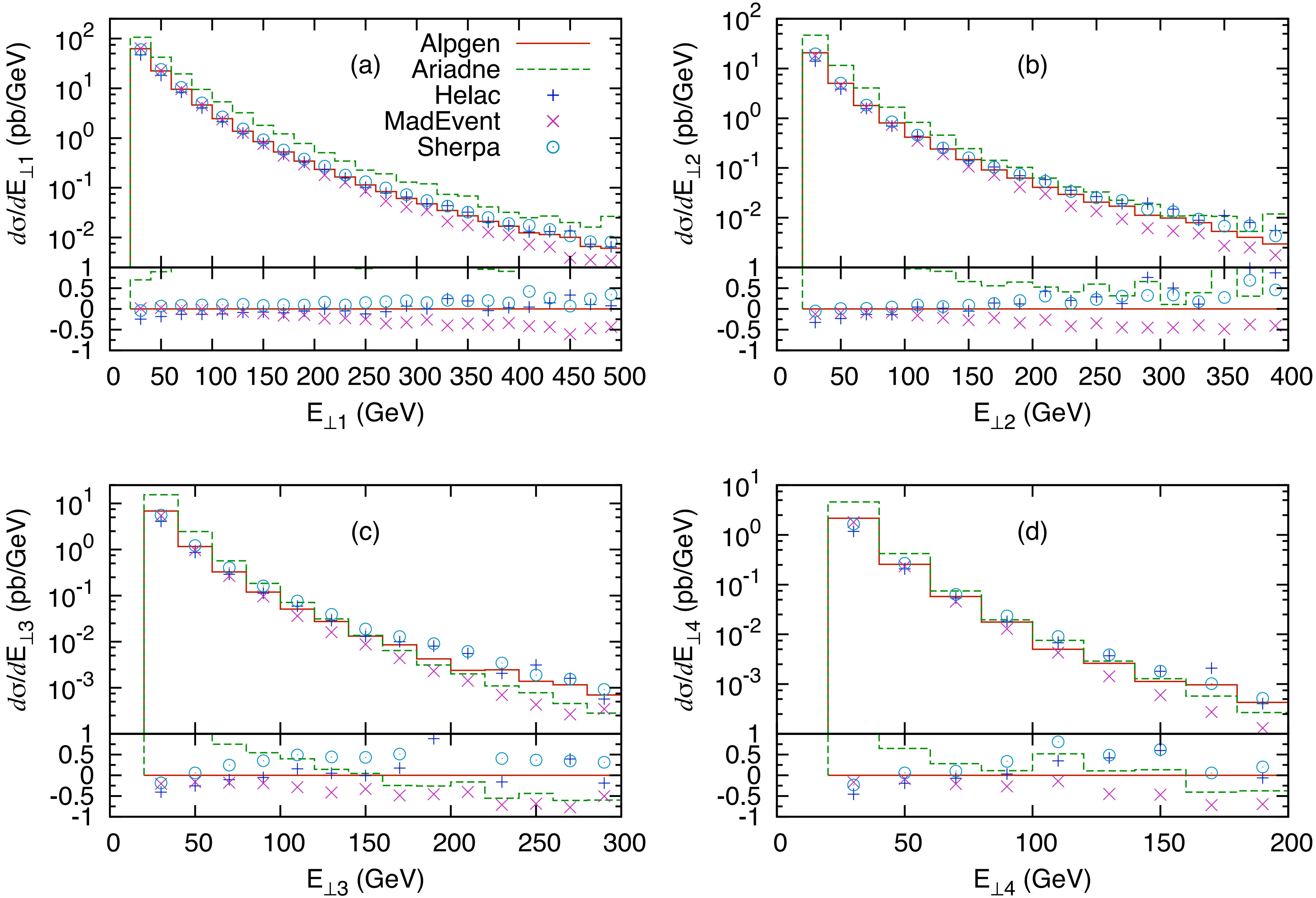
W + Multijets (Tevatron)



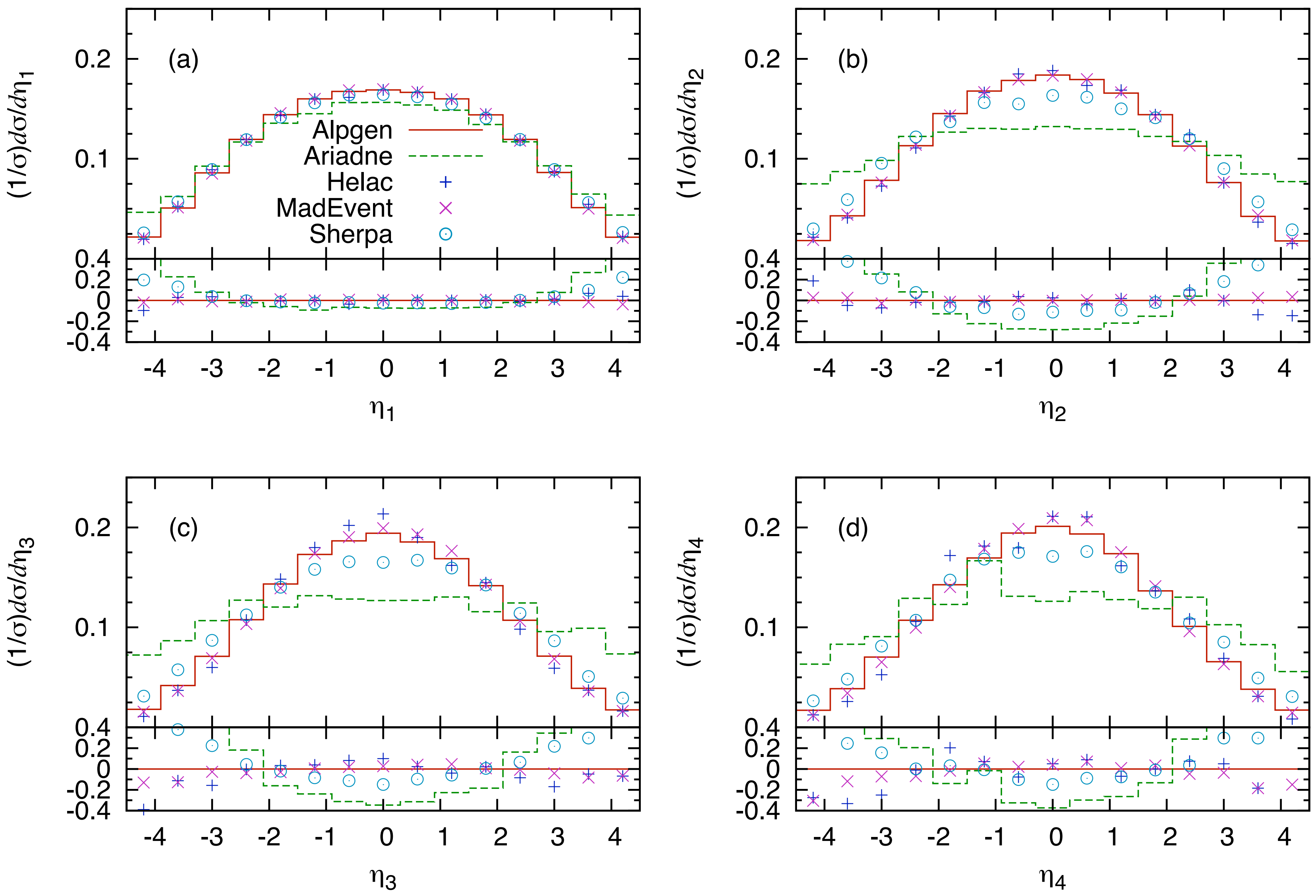
W + Multijets (LHC)



W + Multijets (LHC)

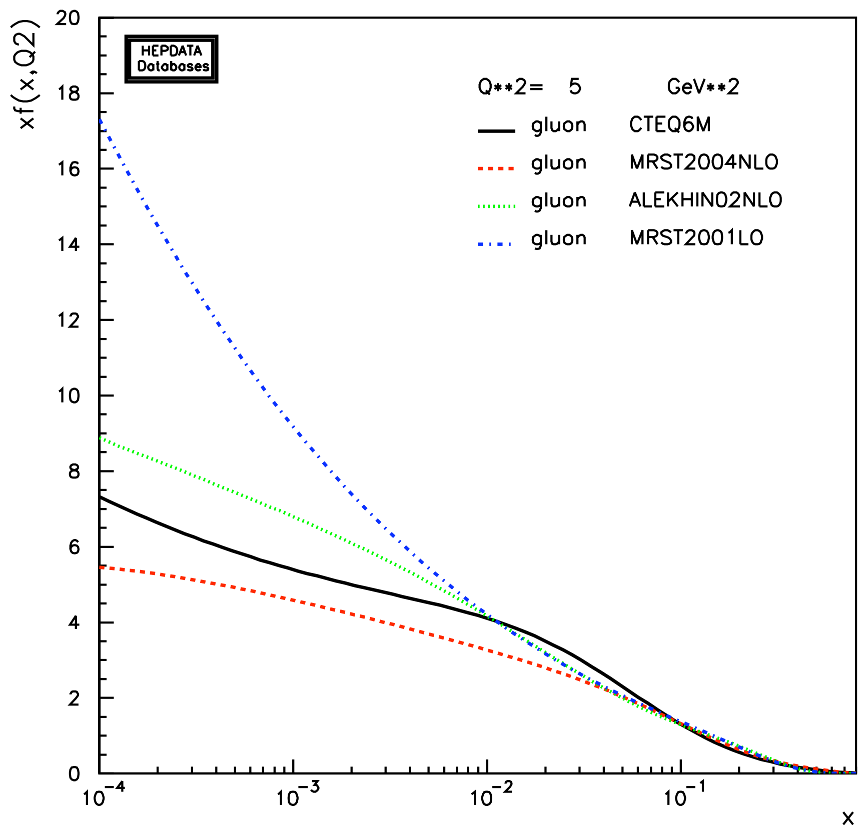


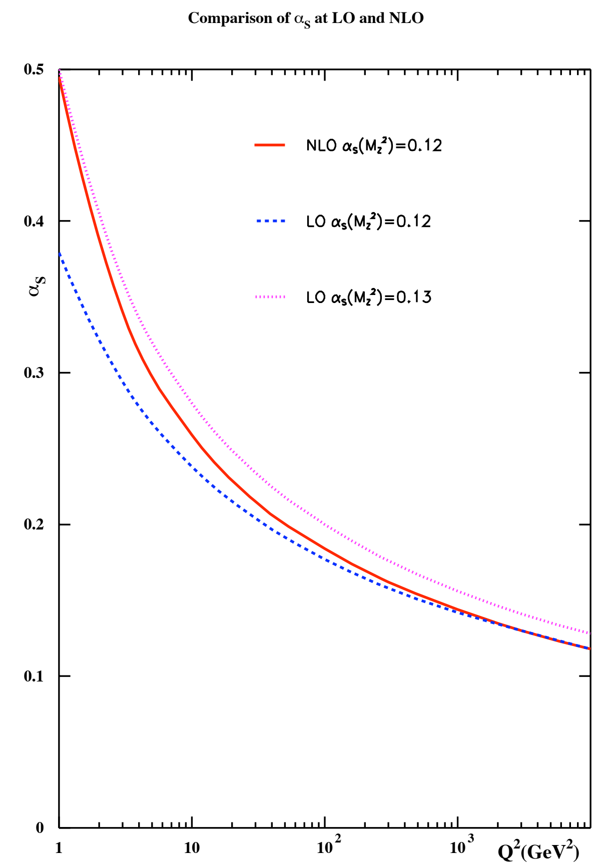
W + Multijets (LHC)



PDFs for LO MCs

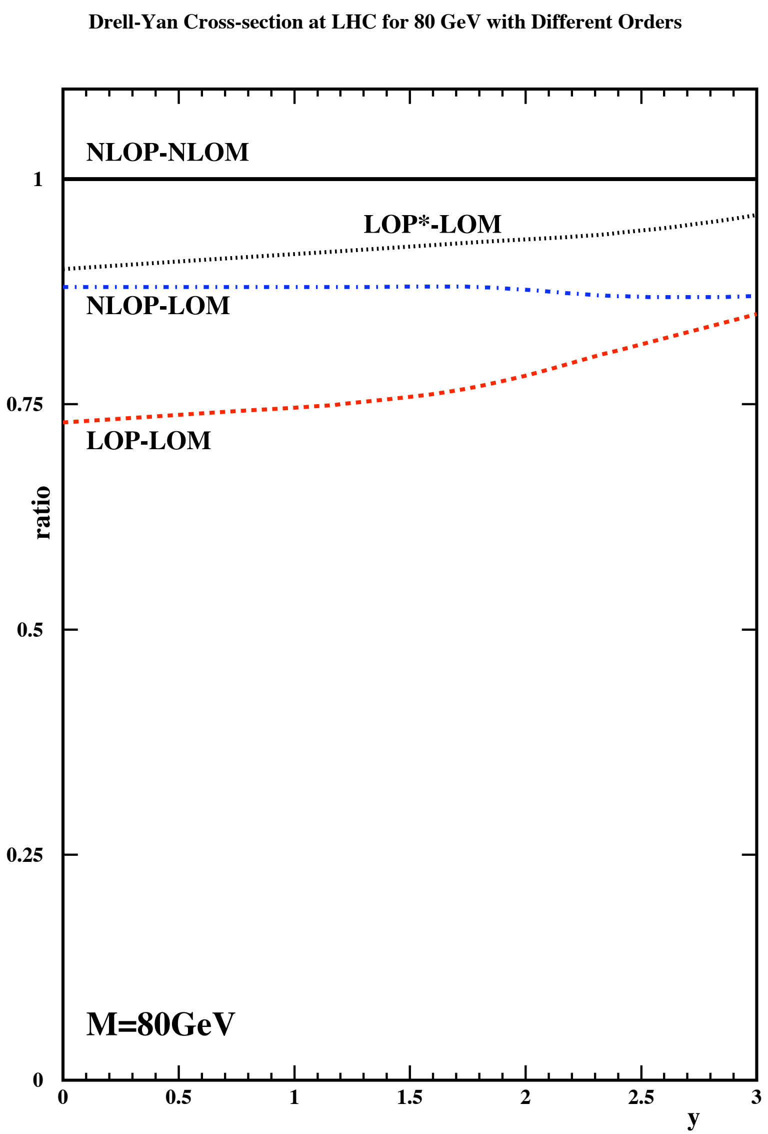
- Lack of NLO ⇒ large LO gluon
- Fast evolution at low Q^2 ⇒ large α_s
- Proposal: use NLO α_s , no mom. cons'n
  ⇒ Good fits, close to NLO





A Sherstnev & RS Thorne arXiv:0711.2473

LO* PDFs



$$pp \longrightarrow jj$$

pdf type	matrix element	σ (μb)	K-factor
NLO	NLO	183.2	
LO	LO	149.8	1.22
NLO	LO	115.7	1.58
LO*	LO	177.5	1.03

$$pp \longrightarrow H$$

pdf type	matrix element	σ (pb)	K-factor
NLO	NLO	38.0	
LO	LO	22.4	1.70
NLO	LO	20.3	1.87
LO*	LO	32.4	1.17

Conclusions?

- New generation of OO MCs
  - More adaptable for BSM
  - Need user feedback and tuning
- Continuous improvements
  - Precision: NLO & n-jet matching
  - Modelling: UE, PDFs, intrinsic p_t, ...