Monte Carlo Event Generators

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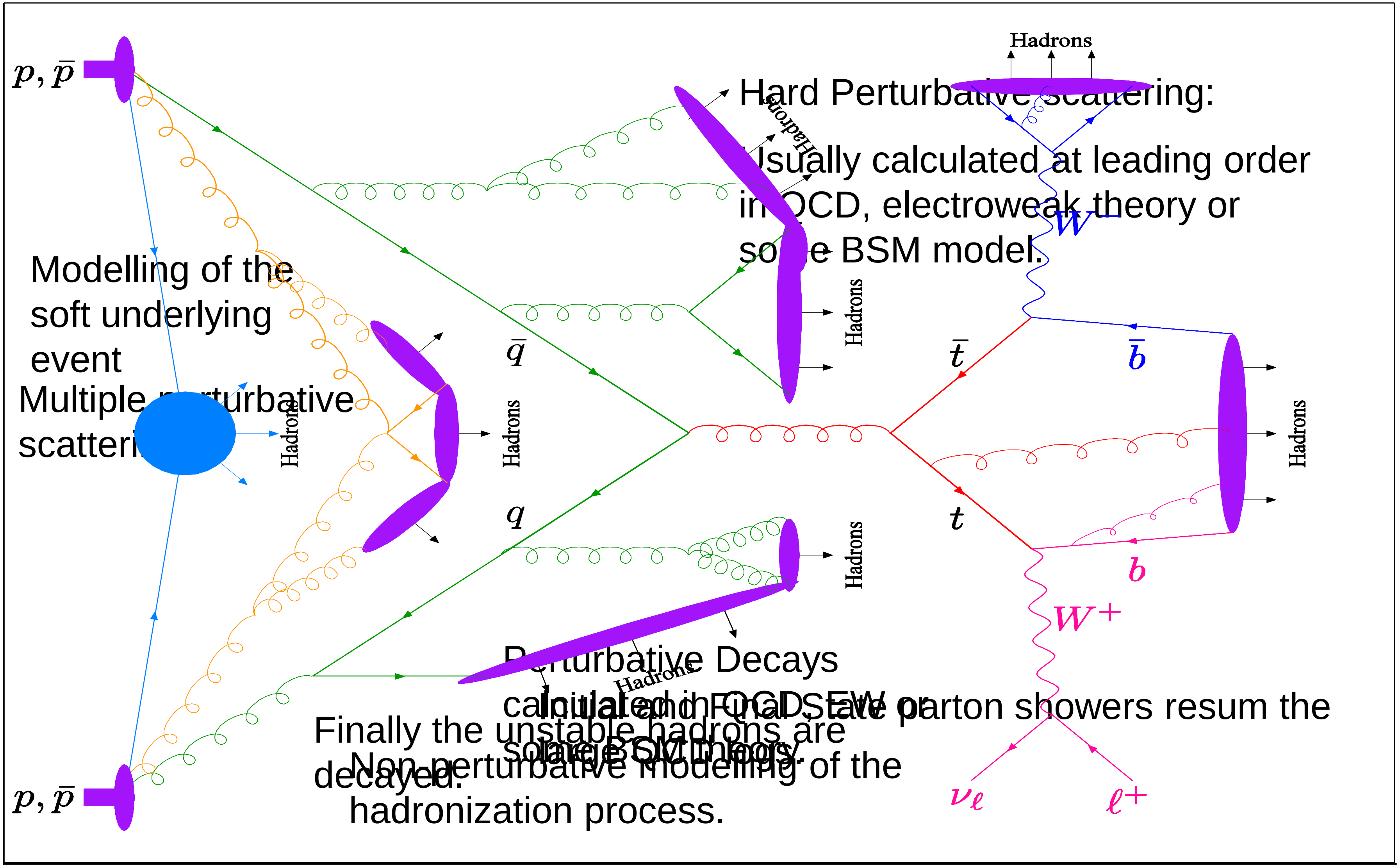
Summary

- Introduction
- Basics of Monte Carlo Simulations
- Parton Showers and Matching
- BSM Simulation
- Future
- Conclusions

Introduction

- Monte Carlo event generators are programs which starting with some fundamental process predict the stable particles which will interact with a detector.
- There are a number of Monte Carlo event generators in common use
  - PYTHIA6/8
  - HERWIG/Herwig++
  - SHERPA
- They all split the event generation up into the same pieces.
- The models and approximations they use for the different pieces are of course different.

A Monte Carlo Event



Hard Perturbative scattering:

Usually calculated at leading order in QCD, electroweak theory or some BSM model.

Modelling of the soft underlying event

Multiple perturbative scattering.

Perturbative Decays calculated in QCD, EW or some BSM theory.

Initial and Final State parton showers resum the large QCD logs.

Finally the unstable hadrons are decayed.

Non-perturbative modelling of the hadronization process.

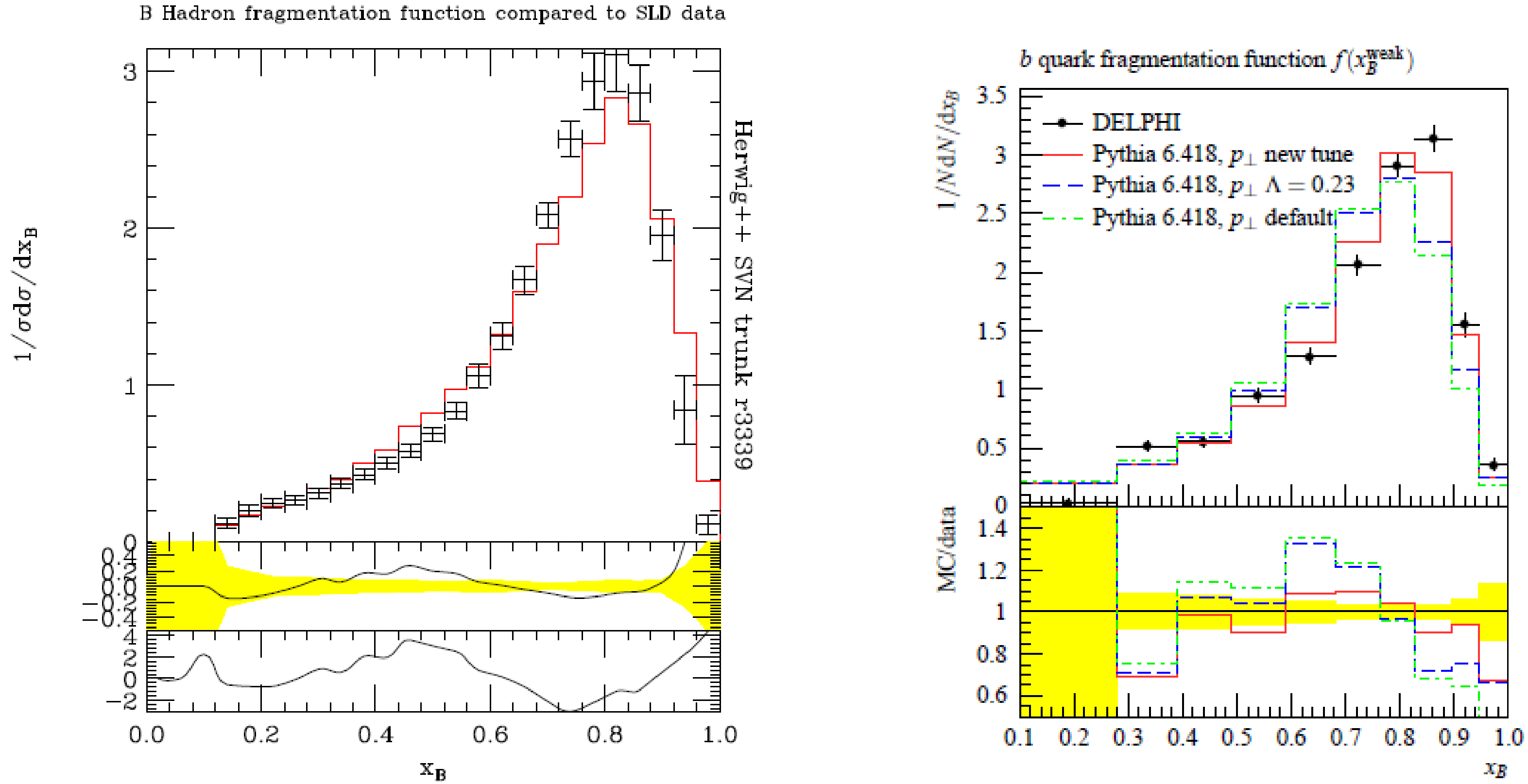
Parton Shower

- Most recent work has been improving the simulations by combining the parton shower with either:
    - NLO matrix elements;
    - High multiplicity leading-order matrix elements.
- This has been facilitated by improved parton shower algorithms.

Parton Shower Algorithms

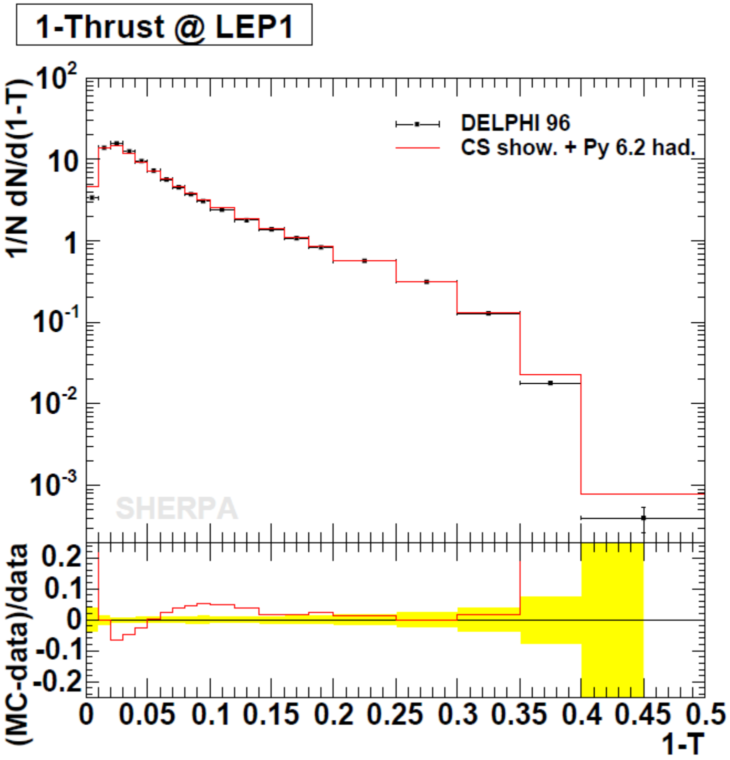
- In the recent years there have been a number of parton shower algorithms with improved theoretical properties:
  - Improved angular-ordered parton shower in Herwig++;
  - p_T ordered shower in PYTHIA;
  - Shower based on Catani-Seymour dipoles.
- All give good agreement with experimental results.
- Other ideas, but no concrete implements for hadron-hadron collisions.

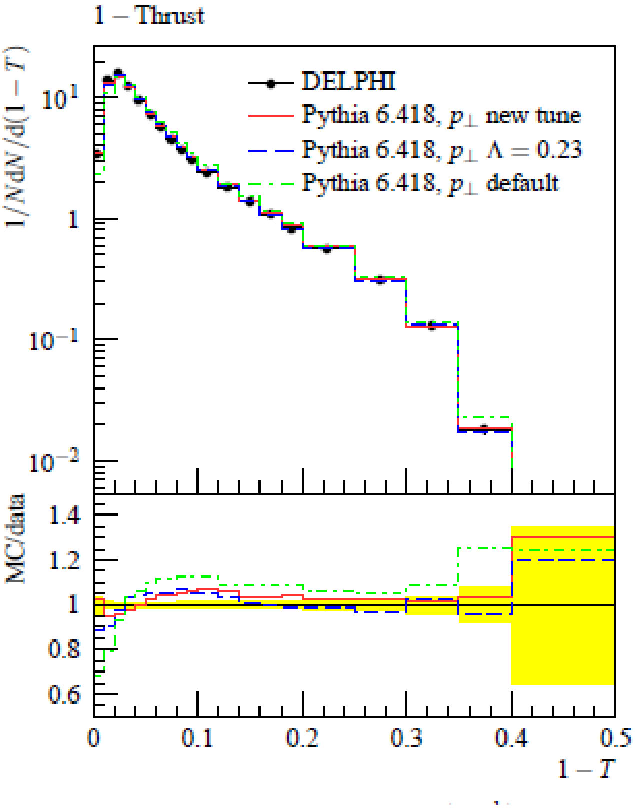
B Fragmentation Function



Herwig++ compared to SLD
Phys.Rev.D65:092006,2002

Thrust





SHERPA compared to DELPHI data from Schumann and Krauss JHEP 0803:038,2008

NLO Simulations

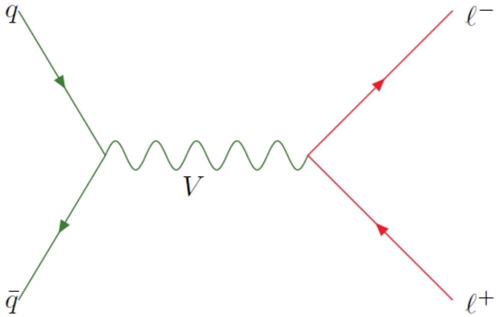
- NLO simulations rearrange the NLO cross section formula.

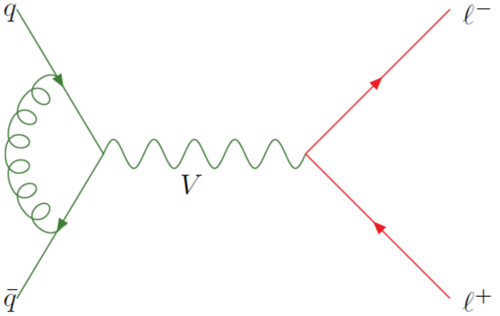
$$d\sigma = B(v)d\Phi_v + (V(v) + C(v,r)d\Phi_r)d\Phi_v$$
$$+ (R(v,r) - C(v,r))d\Phi_v d\Phi_r$$

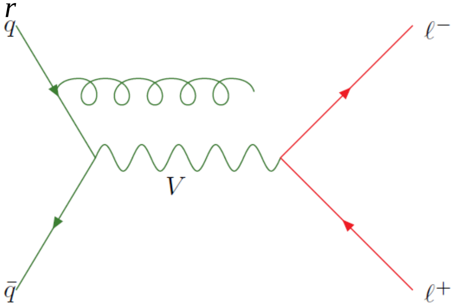
- Either choose C to be the shower approximation

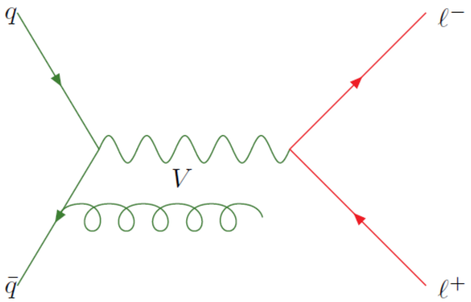
$$d\sigma = B(v)d\Phi_v + (V(v) + C_{\text{shower}}(v,r)d\Phi_r)d\Phi_v$$
$$+ (R(v,r) - C_{\text{shower}}(v,r))d\Phi_v d\Phi_r$$

MC@NLO (Frixione, Webber)









NLO Simulations

- Or a more complex arrangement POWHEG(Nason)

$$d\sigma = \bar{B}(v)\,d\Phi_v \left[\Delta_R^{NLO}(0) + \Delta_R^{NLO}(p_T)\,\frac{R(v,r)}{B(v)}\,d\Phi_r \right]$$

where

$$\bar{B}(v) = B(v) + V(v) + C(v,r)\ d\Phi_r + \int R(v,r) - C(v,r)\ d\Phi_r$$

$$\Delta_R^{NLO}(p_T) = \exp\left[-\int d\Phi_r \frac{R(v,r)}{B(v)}\,\theta\left(k_T(v,r) - p_T\right) \right]$$

Pros and Cons

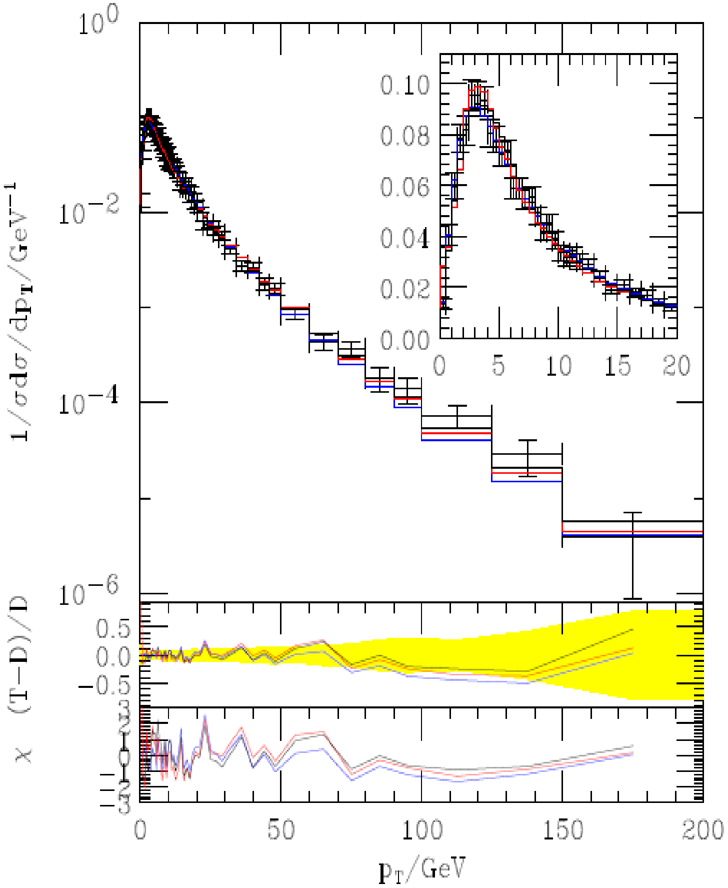
POWHEG

- Positive weights.
- Implementation doesn’t depend on the shower algorithm.
- Needs changes to shower algorithm for non-p_T ordered showers.
- Differs from shower and NLO results, but changes can be made to give NLO result at large $p_{T.}$

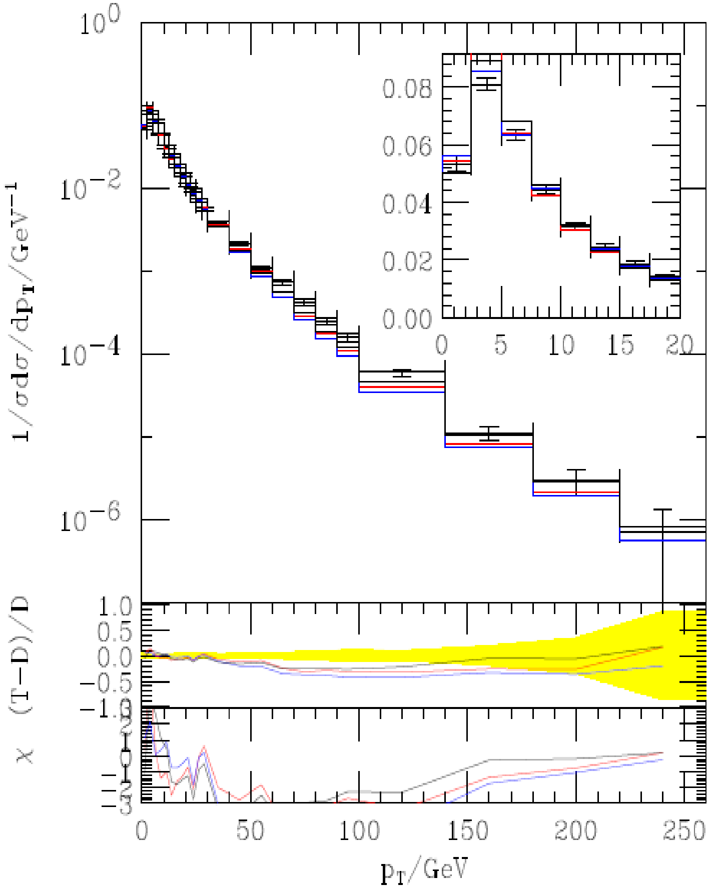
MC@NLO

- Negative weights
- Implementation depends on the specific shower algorithm used.
- No changes to parton shower.
- Reduces to the exact shower result at low p_T and NLO result at high p_T

Drell Yan



CDF Run I Z p_T



D0 Run II Z p_T

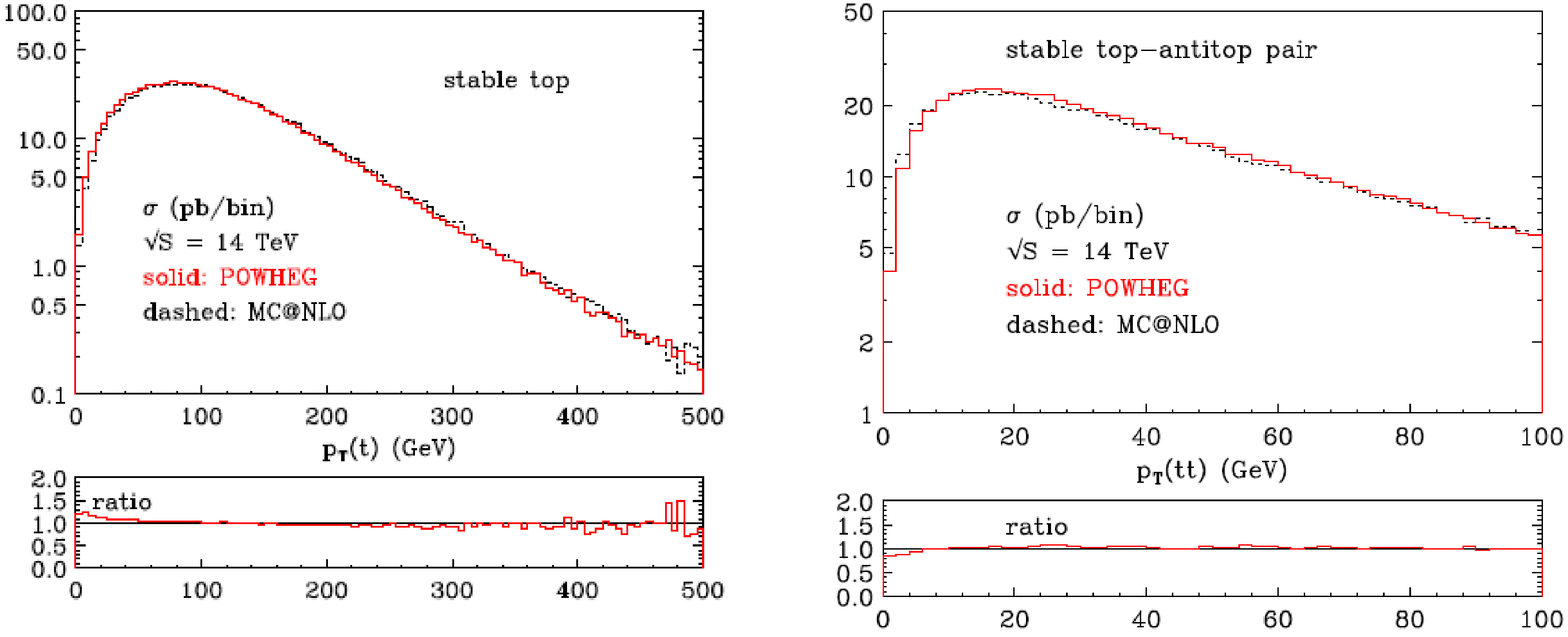
Herwig++

POWHEG

MC@NLO

JHEP 0810:015,2008 Hamilton, PR, Tully

Top Quark Production



Taken from Frixione, Nason, Ridolfi JHEP 0709:126,2007.

Different Approaches

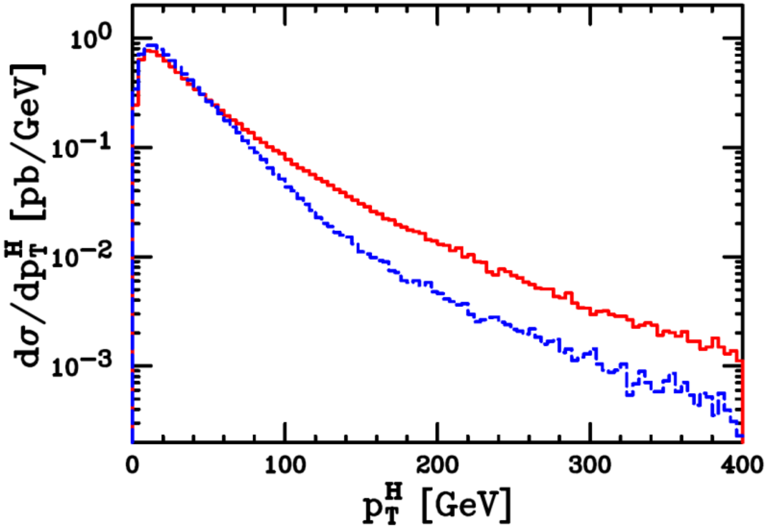
- The two approaches are the same to NLO.
- Differ in the subleading terms.
- In particular at large p_T

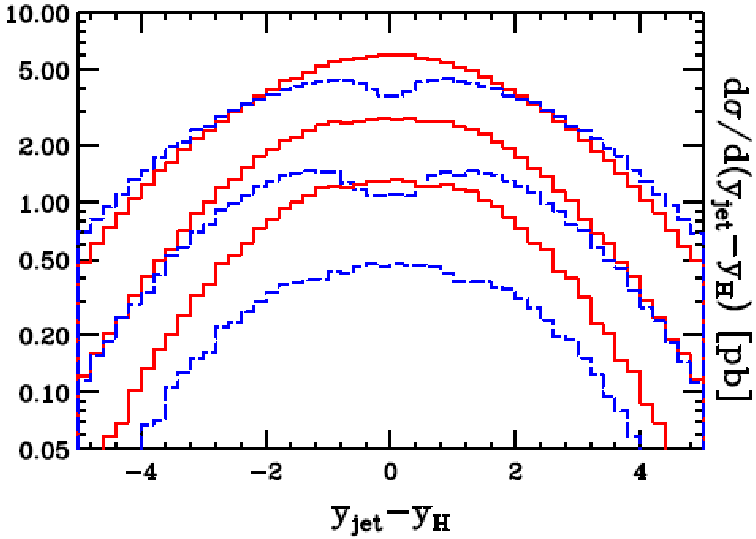
$$d\sigma \approx R(v,r)\,d\Phi_v\,d\Phi_r$$

MC@NLO

$$d\sigma \approx \frac{\bar{B}(v)}{B(v)} R(v,r)\,d\Phi_v\,d\Phi_r$$

POWHEG





JHEP 0904:002,2009 Alioli et. al.

NLO Status

- A large range of processes are available in the MC@NLO approach together with the FORTRAN HERWIG program (**Frixione, Webber, et.al.**).
- Work in progress for MC@NLO with PYTHIA (Torrielli, Frixione) and Herwig++(Frixione, Stoekli, Webber)
- Fewer processes in the POWHEG approach available either standalone (Alioli, Nason, Oleari, Re) together with recent work on automation.
- A range of colour singlet production processes in the POWHEG scheme in Herwig++(Hamilton, Richardson, Tully).

NLO Status

- Important processes for early physics
  - W/Z production
  - top/bottom production

  are available in both approaches.
- However other important processes
  - jets
  - photon+jet

  are available in neither.

Multi-Jet Leading Order

- While the NLO approach is good for one hard additional jet and the overall normalization it cannnot be used to give many jets.
- Therefore to simulate these processes use matching at leading order to get many hard emissions correct.
- The most sophisticated approaches are variants of the CKKW method (Catani, Krauss, Kuhn and Webber JHEP 0111:063,2001)
- Recent new approaches in SHERPA(Hoeche, Krauss, Schumann, Siegert, JHEP 0905:053,2009) and Herwig++(JHEP 0911:038,2009 Hamilton, PR, Tully)

CKKW Procedure

- Catani, Krauss, Kuhn and Webber JHEP 0111:063,2001.
- In order to match the ME and PS we need to separate the phase space:
  - one region contains the soft/collinear region and is filled by the PS;
  - the other is filled by the matrix element.
- In these approaches the phase space is separated using in k_T-type jet algorithm.

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CKKW Procedure

- Radiation above a cut-off value of the jet measure is simulated by the matrix element and radiation below the cut-off by the parton shower.

1) Select the jet multiplicity with probability

$$P_n = \frac{\sigma_n}{\sum_{k=0}^{N} \sigma_k}$$

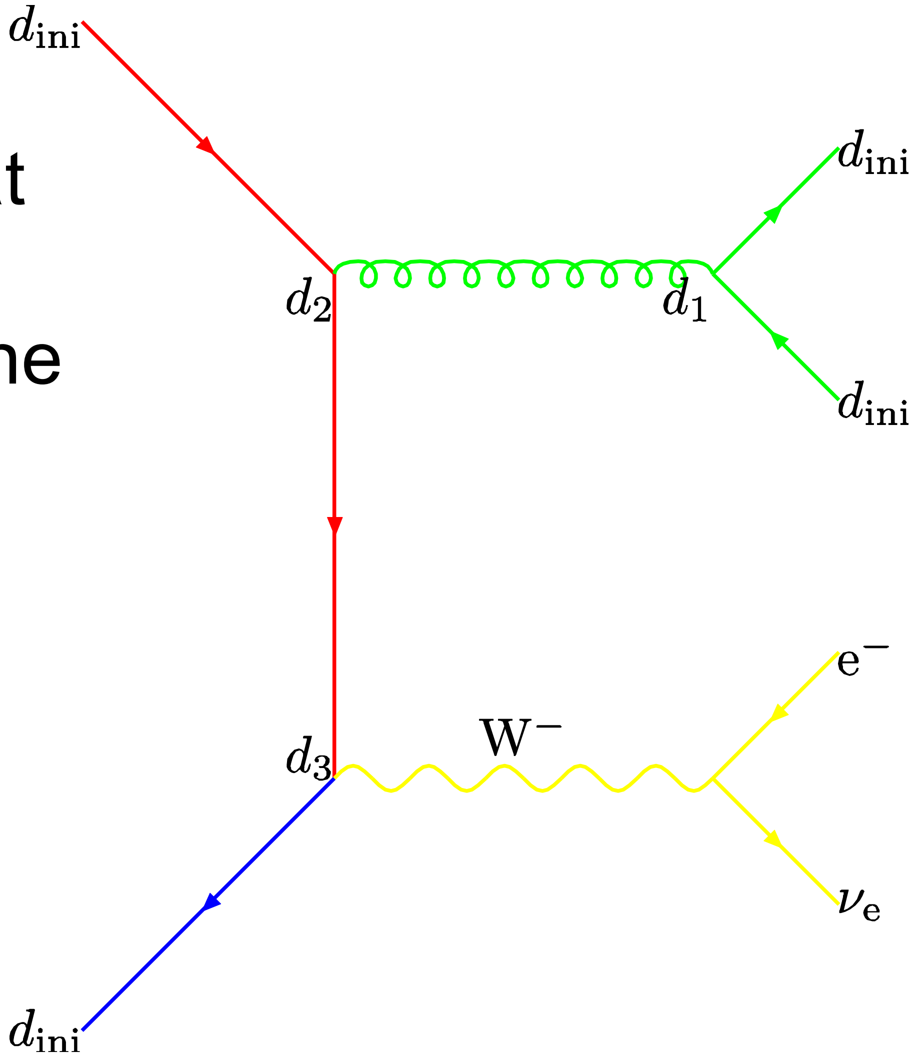
where σ_n is the *n*-jet matrix element evaluated at resolution d_{ini} using d_{ini} as the scale for the PDFs and α_S, *n* is the number of jets

2) Distribute the jet momenta according the ME.

CKKW Procedure

3) Cluster the partons to determine the values at which 1,2,..*n*-jets are resolved. These give the nodal scales for a tree diagram.
4) Apply a coupling constant reweighting.

$$\frac{\alpha_S(d_1)\alpha_S(d_2)\ldots\alpha_S(d_3)}{\alpha_S(d_{\text{ini}})^n} \leq 1$$

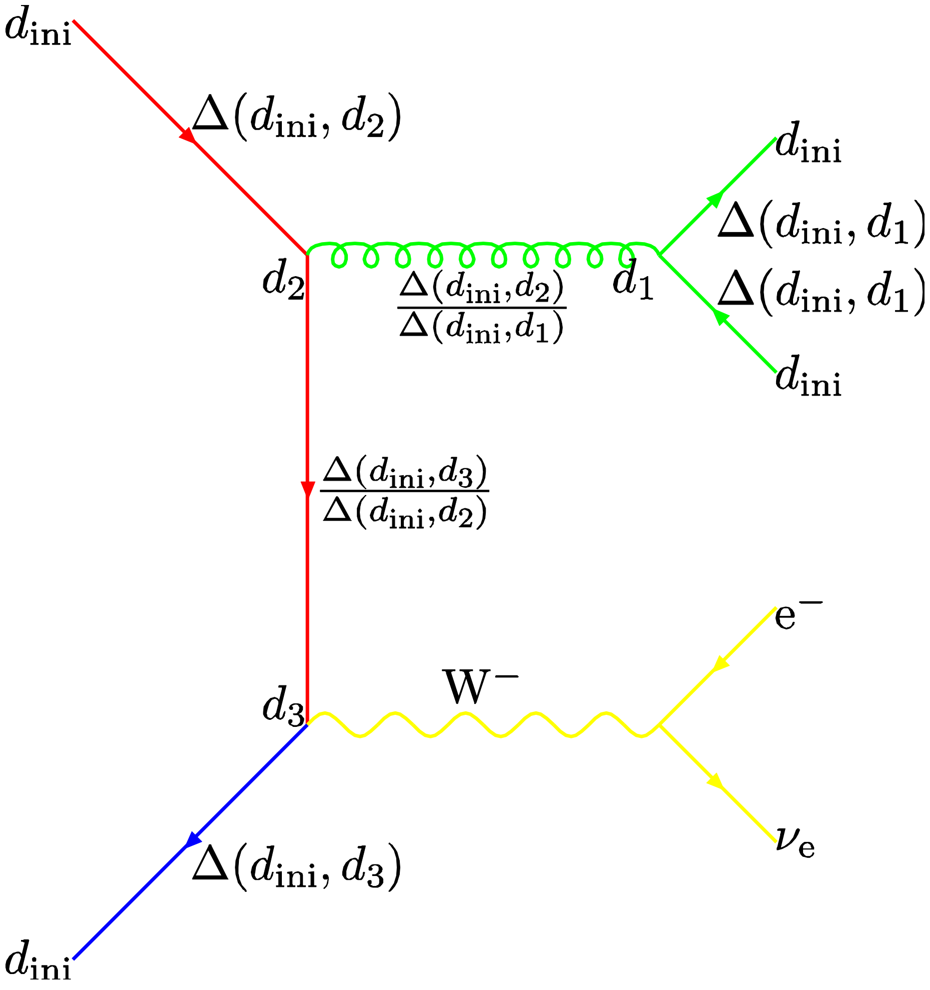


CKKW Procedure

5) Reweight the lines by a Sudakov factor

$$\frac{\Delta(d_{\text{ini}}, d_j)}{\Delta(d_{\text{ini}}, d_k)}$$

6) Accept the configuration if the product of the α_S and Sudakov weight is less than $R \in [0,1]$ otherwise return to step 1.



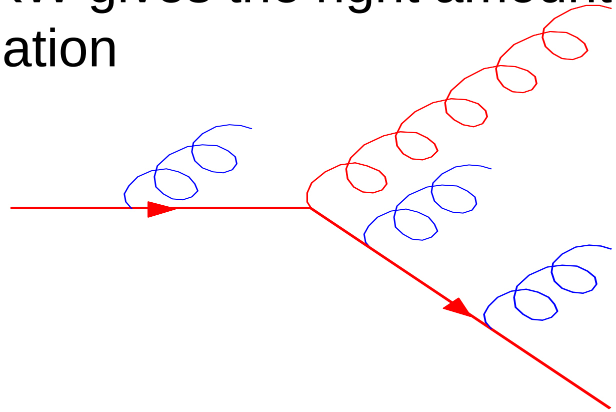
CKKW Procedure

7) Generate the parton shower from the event starting the evolution of each parton at the scale at which it was created and vetoing emission above the scale d_{ini}.

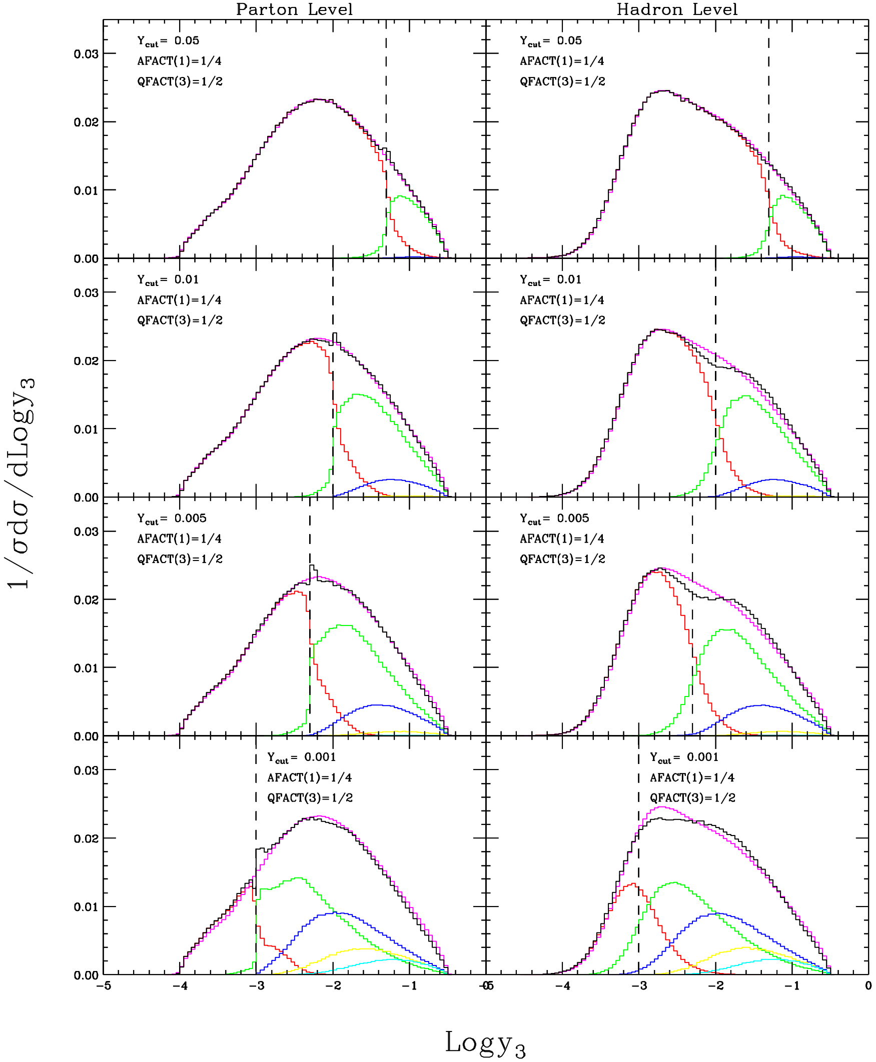
Recent improvements use an idea from POWHEG to simulate soft radiation from the internal lines giving improved results.

Problems with CKKW

- CKKW uses an enhanced starting scale for the evolution of the partons which is designed to simulate soft, wide angle emission from the internal lines.
- CKKW gives the right amount of radiation



- But puts some of it in the wrong place with the wrong colour flow.



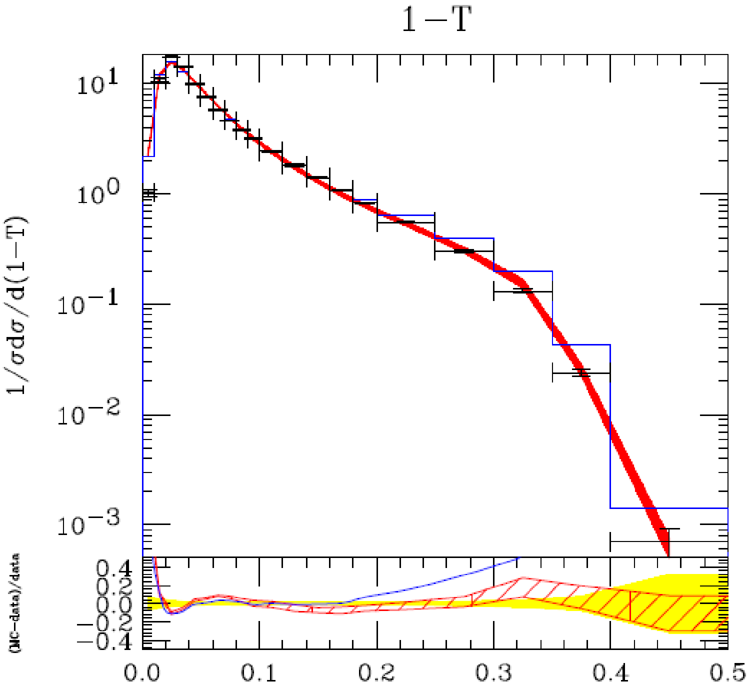
S. Mrenna and PR JHEP 0405: 04 (2004)

Solution

- The solution is that we should use a truncated shower to generate the soft wide angle emission.
- Use the truncated shower rather than enhanced emission scales to generate radiation from internal lines.
- Available in SHERPA and the next Herwig++ release.

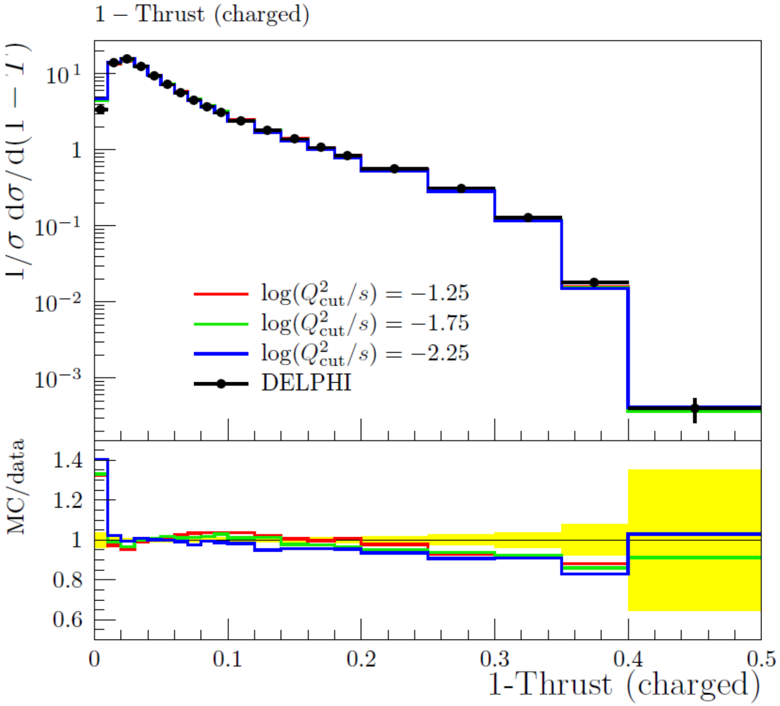
Leading Order $e^+e^-\rightarrow$jets

Herwig++



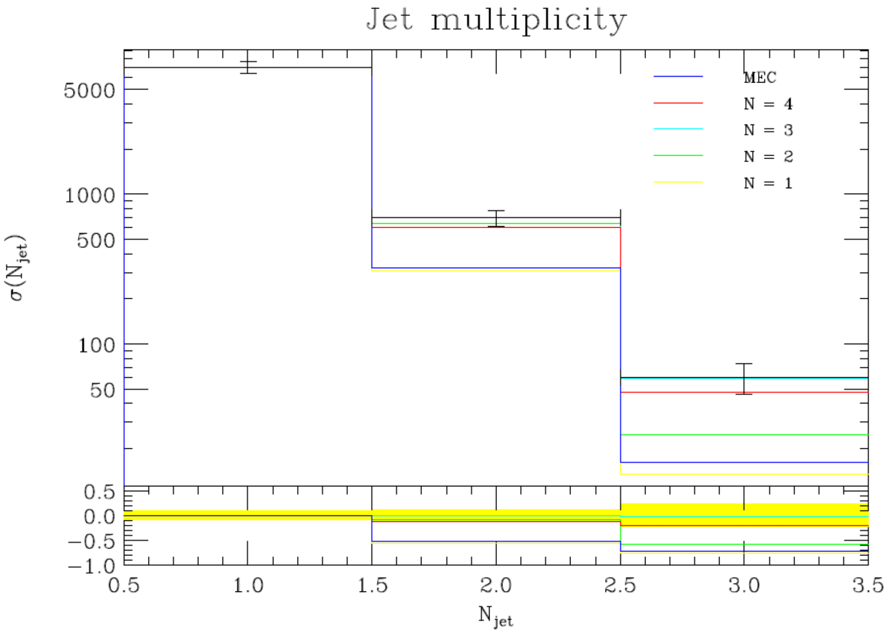
Hamilton, PR, Tully arXiv:0905.3072

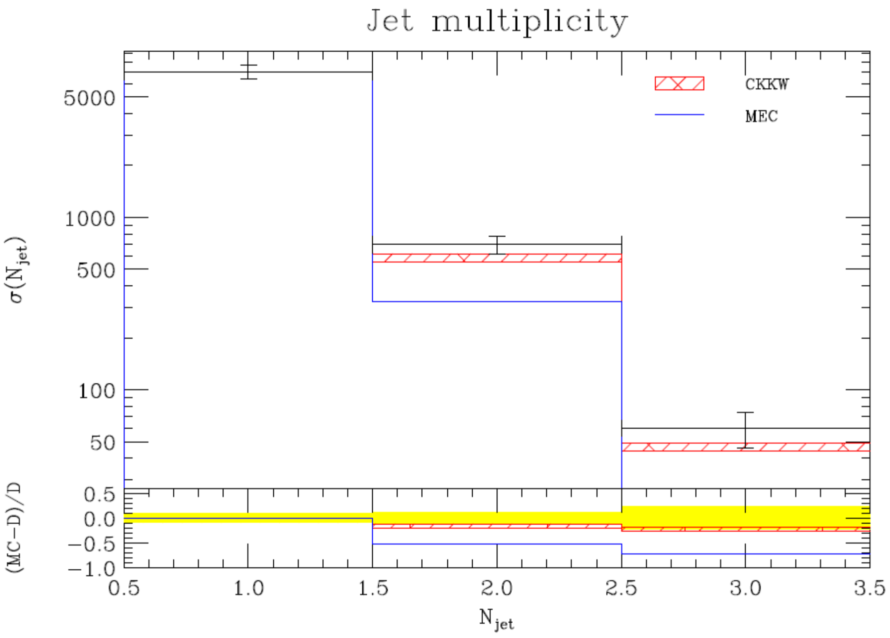
SHERPA



Hoeche, Krauss, Schumann, Siegert JHEP 0905:053,2009

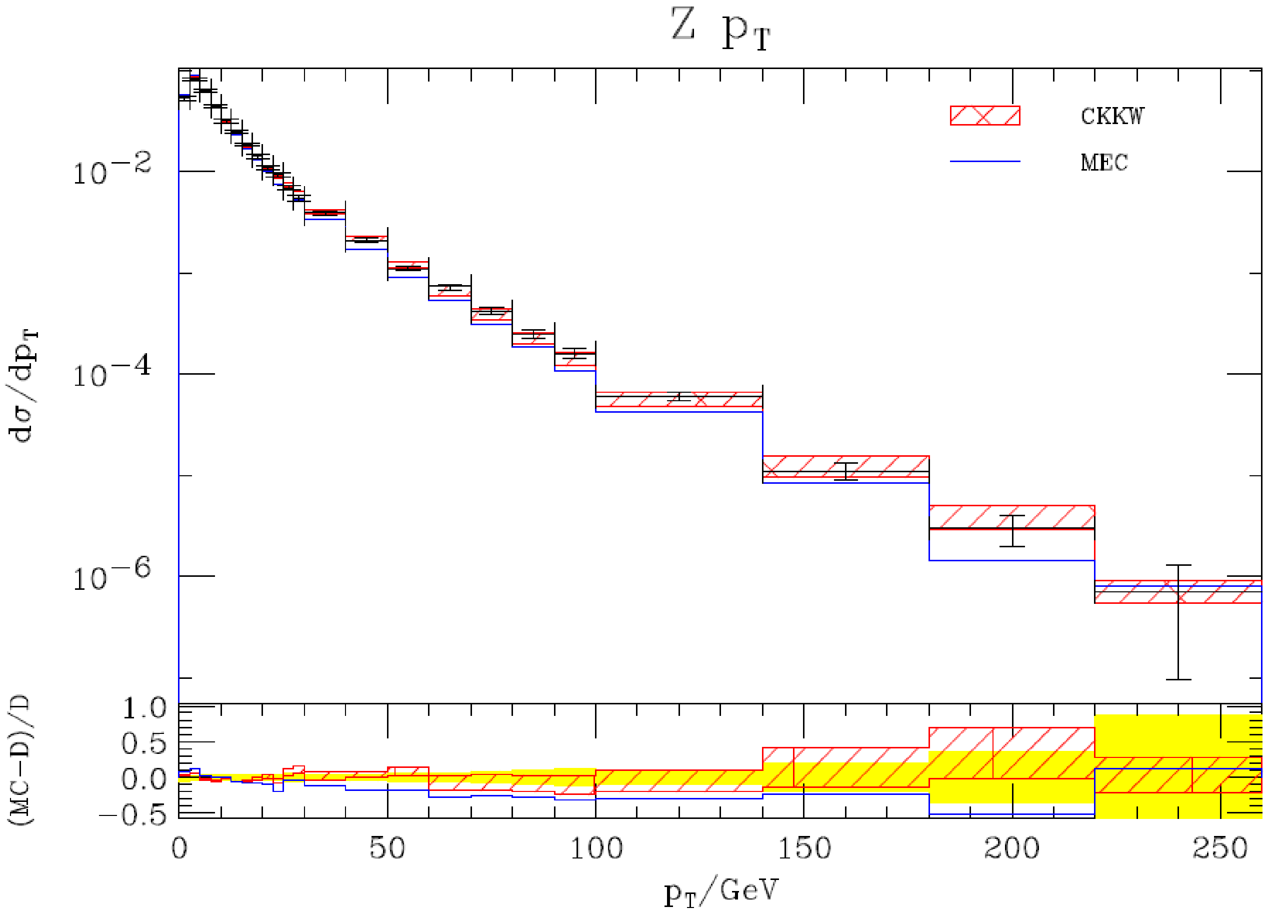
Jet Multiplicity in Z+jets at the Tevatron





Herwig++ compared to data from CDF
Phys.Rev.Lett.100:102001,2008

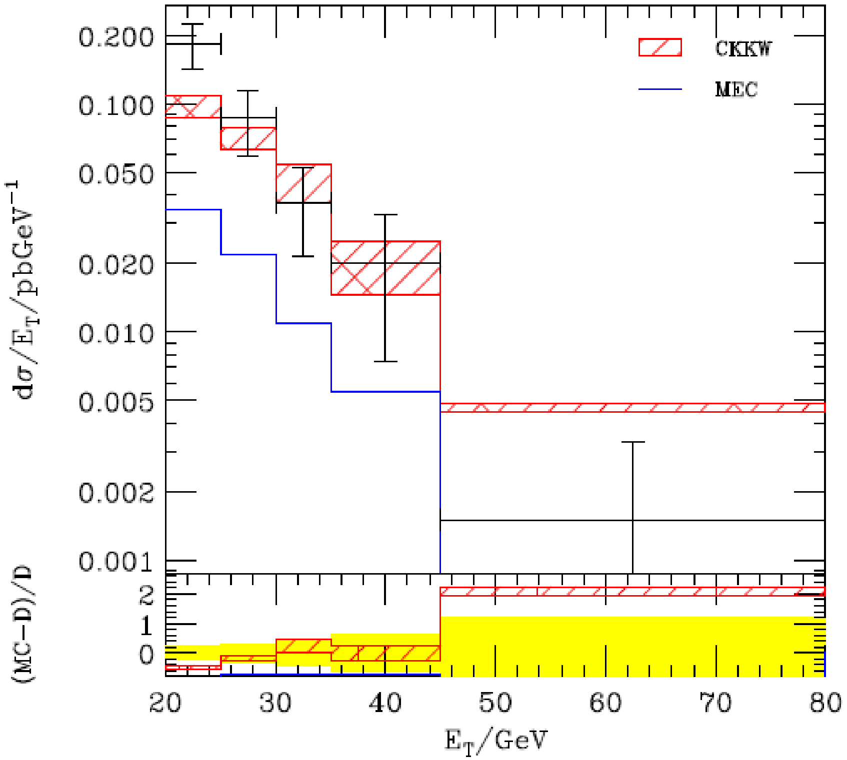
p_T of the Z in Z+jets at the Tevatron



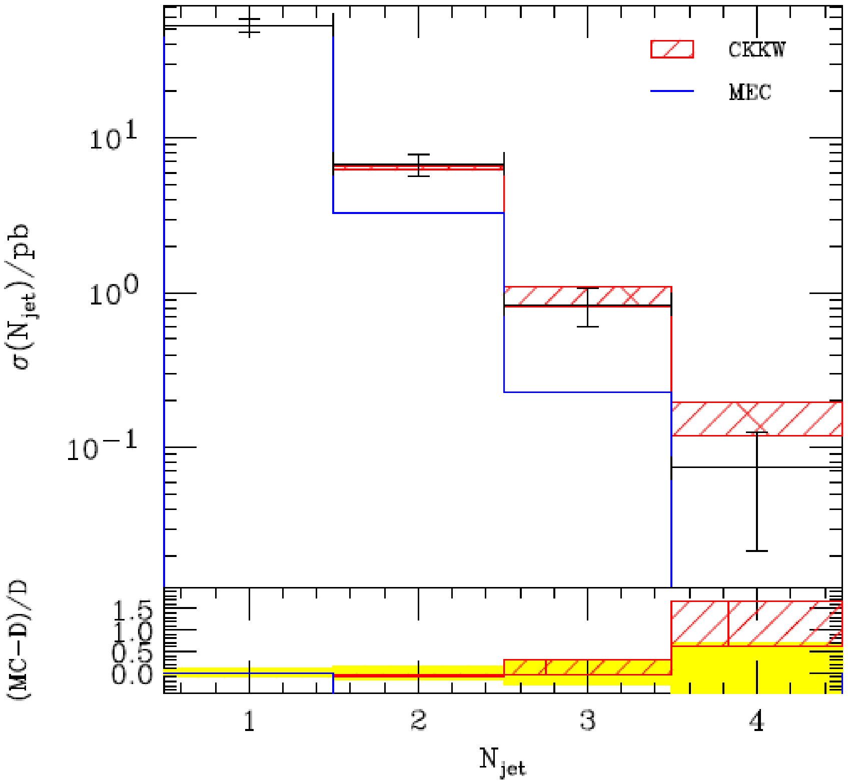
Herwig++ compared to data from D0
Phys.Rev.Lett.100:102002,2008

p_T of jets in W+jets at the Tevatron

3rd Hardest Jet



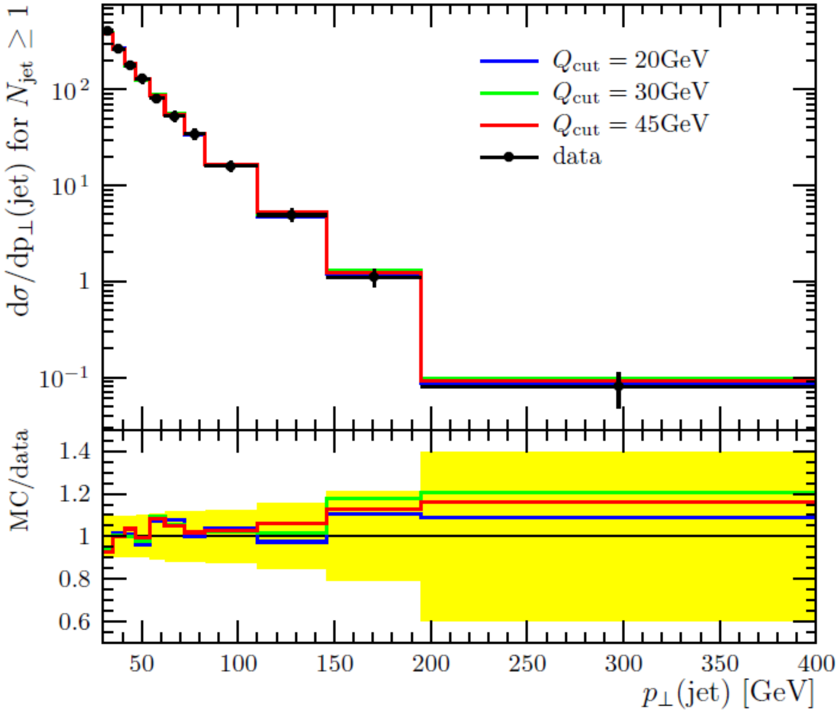
All Jets



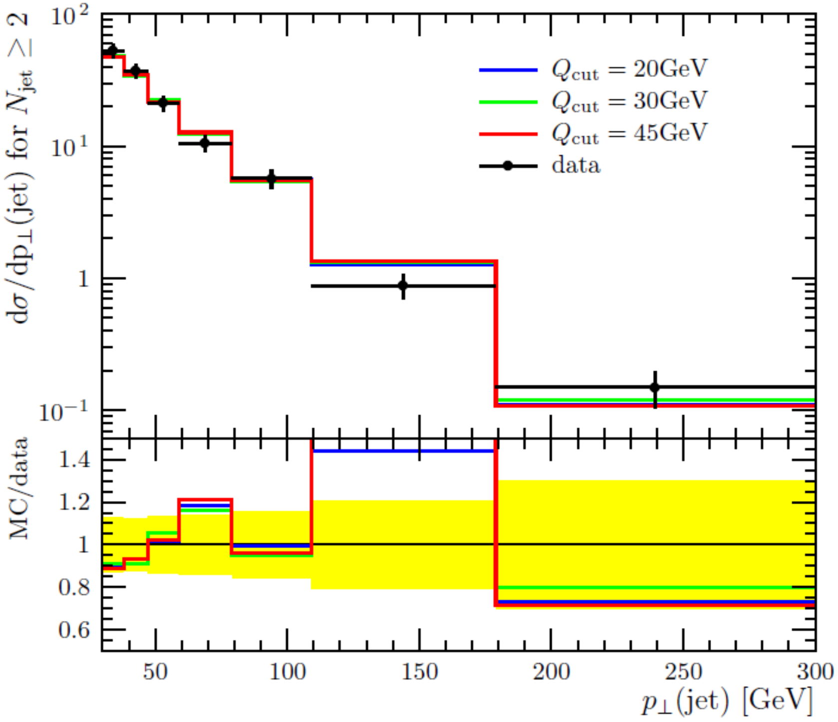
Herwig++ compared to data from CDF
Phys.Rev.D77:011108,2008

Leading Order $q\bar{q}$→Z+jets

SHERPA



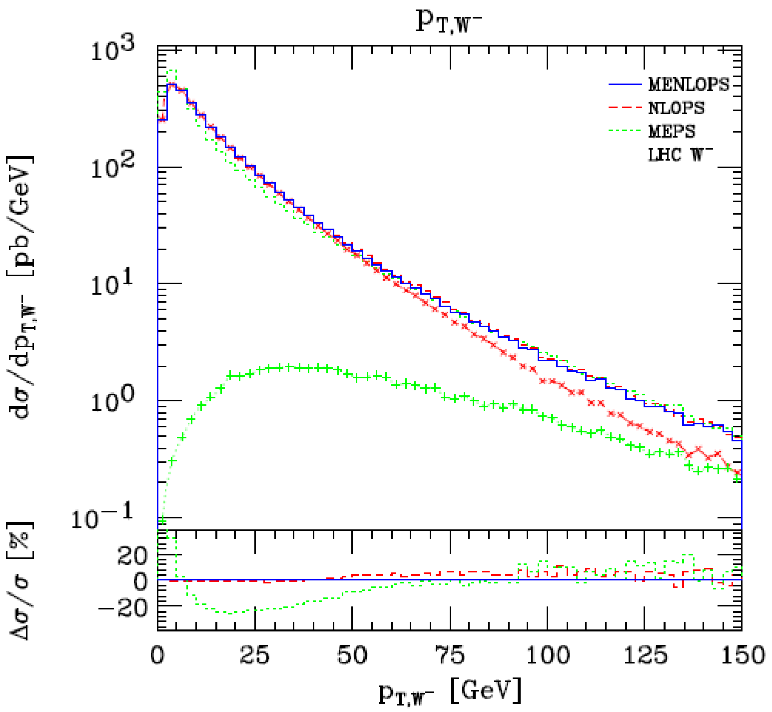
Highest p_T jet

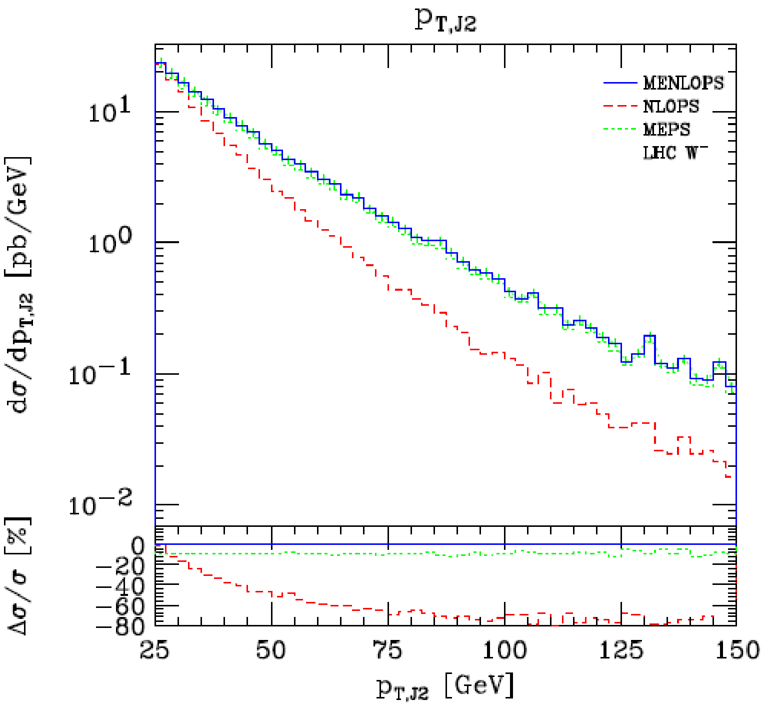


2nd Highest p_T jet

Hoeche, Krauss, Schumann, Siegert
JHEP 0905:053,2009

Combing the two approaches

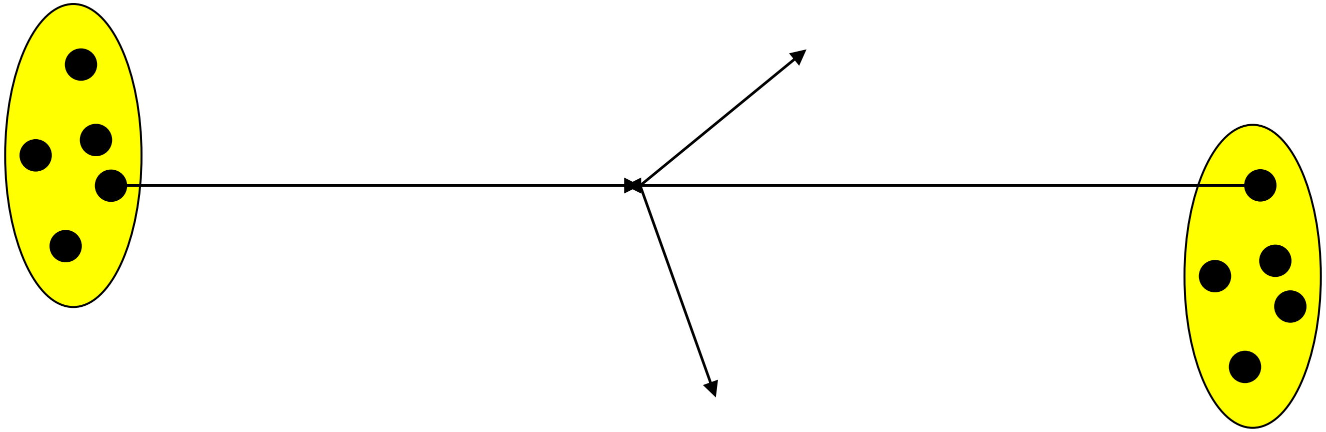




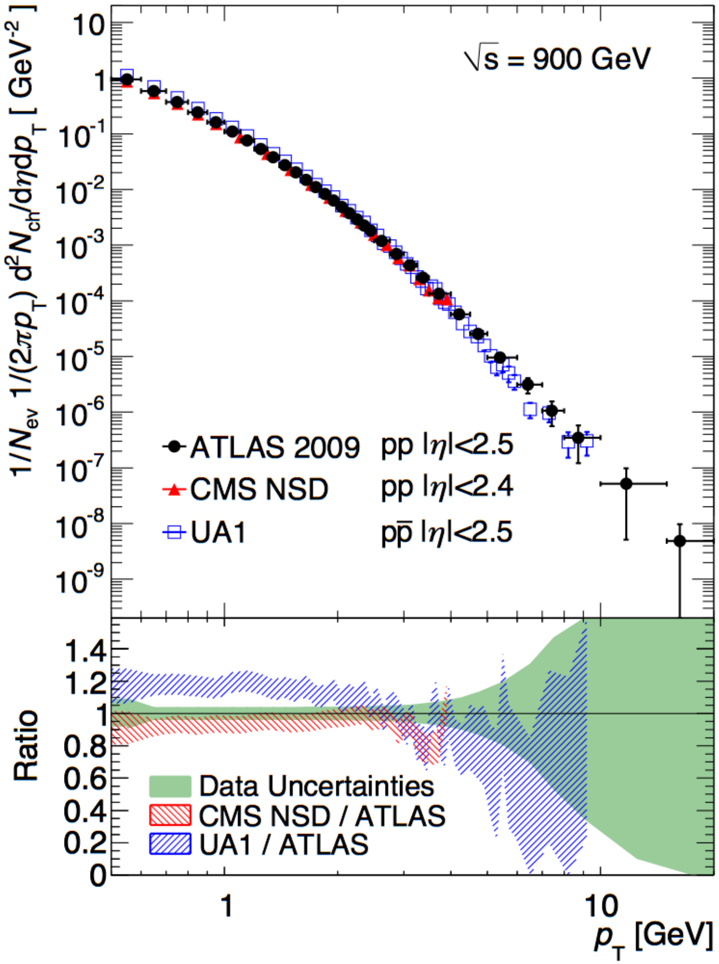
Recent work on combing the POWHEG approach and higher multiplicity matrix elements arXiv:1004.1764 Hamilton, Nason.

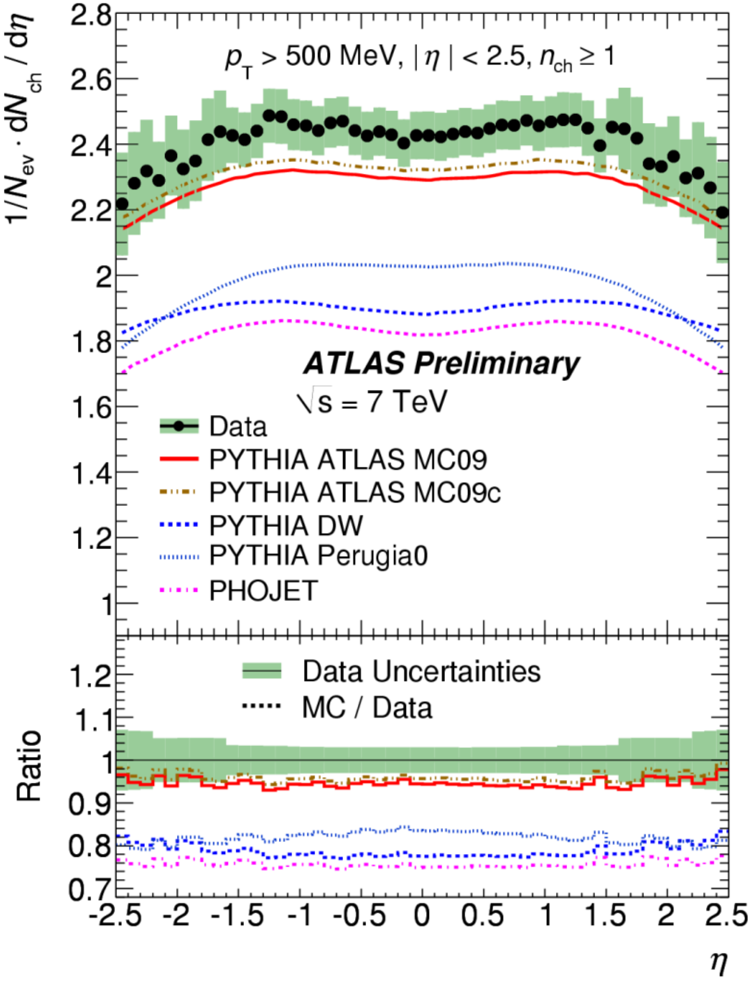
Multiple Parton Interactions

- Given that we finally have some LHC data I'll briefly say something about the min bias and underlying event.
- All modern simulations use a multiple parton scattering model.



Charged Particle Multiplicities at √s=0.9, 7 TeV



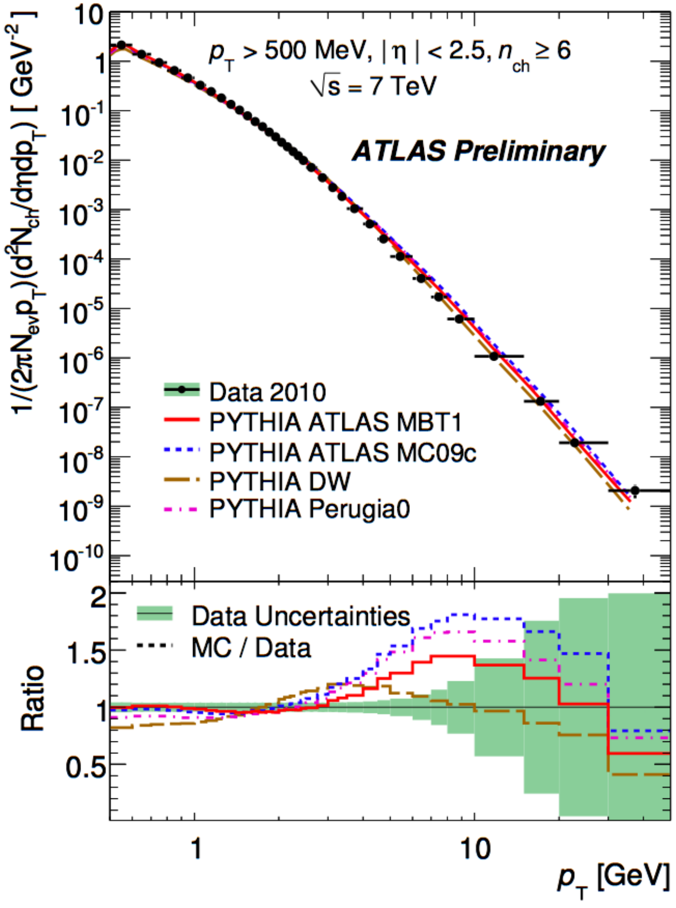


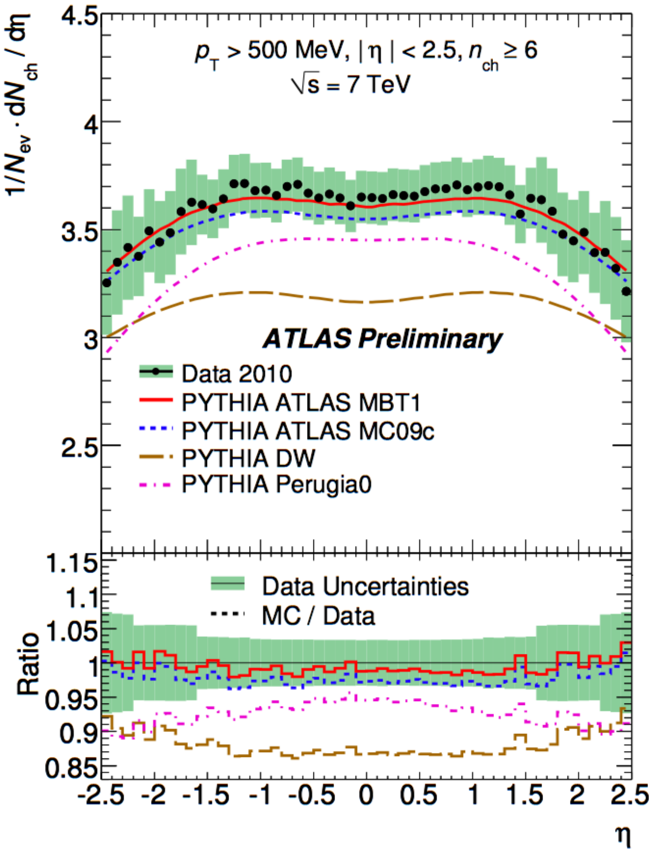
Monte Carlo underestimates the track multiplicity seen in ATLAS

Pythia Tune to ATLAS MinBias and Underlying Event

Used for the tune

ATLAS UE data at 0.9 and 7 TeV
ATLAS charged particle densities at 0.9 and 7 TeV
CDF Run I underlying event analysis (leading jet)
CDF Run I underlying event "Min-Max" analysis
D0 Run II dijet angular correlations
CDF Run II Min bias
CDF Run I Z pT





Result

This tune describes most of the MinBias and the UE data
Significant improvement compared to pre-LHC tunes
Biggest remaining deviation in → $\frac{1}{N_{\mathrm{ev}}} \cdot \frac{1}{2\pi p_{\mathrm{T}}} \cdot \frac{\mathrm{d}^2 N_{\mathrm{ch}}}{\mathrm{d}\eta \mathrm{d}p_{\mathrm{T}}}$
These deviations could not be removed
Needs further investigations

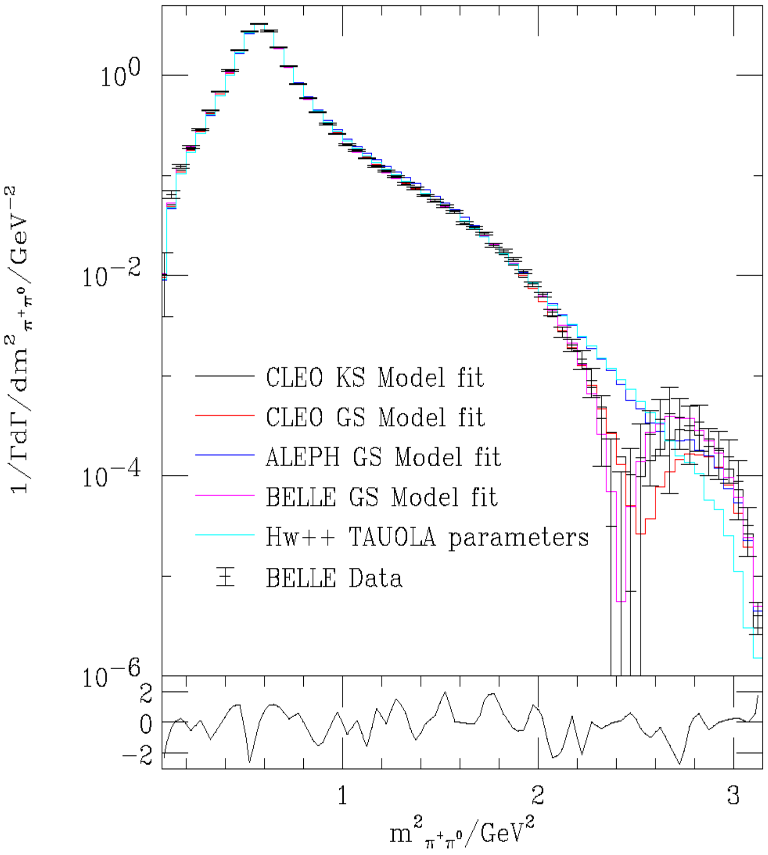
Multiple Parton Scattering

- Results are encouraging.
- The results of the tunes made before data taking don't exactly agree with the data but aren't orders of magnitude off.
- Including the new results in the tuning gives good agreement.
- The models seem reasonable, perhaps some theoretical tweaking needed, but not a major rethink of the whole approach.

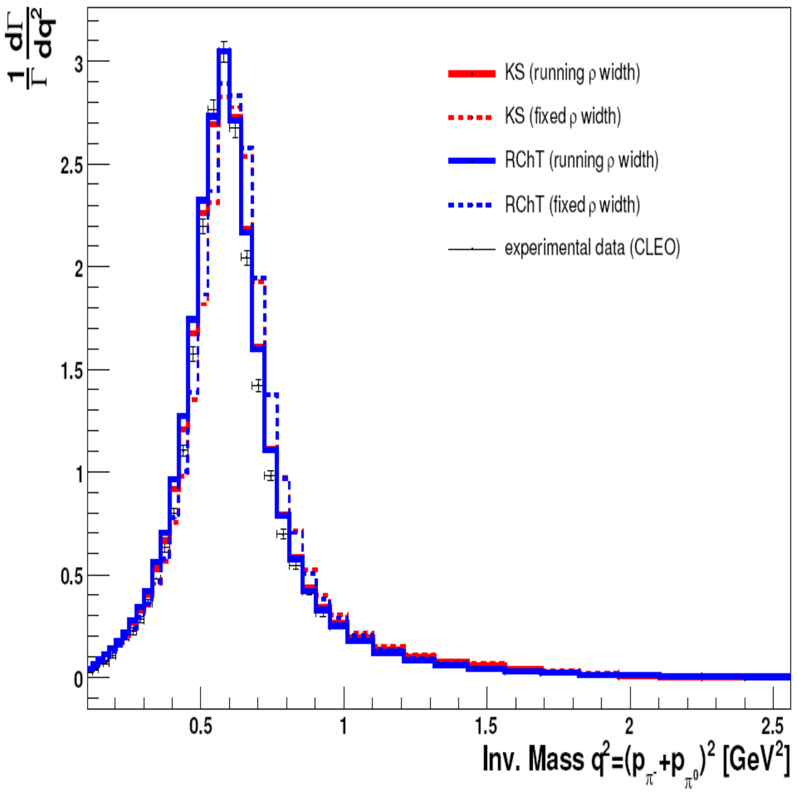
Hadron and Tau Decays

- Historically external packages were used for QED radiation, hadron and tau decays.
- In principle a good idea as it allows the experts to concentrate on what they are good at.
- In practice more bugs/problems in the interfaces to TAUOLA and PHOTOS than the rest of FORTRAN HERWIG.
- Herwig++ and SHERPA now include a sophisticated simulation of QED radiation, hadron and tau decays.

Tau Decays, $\tau \rightarrow \rho \nu_\tau$

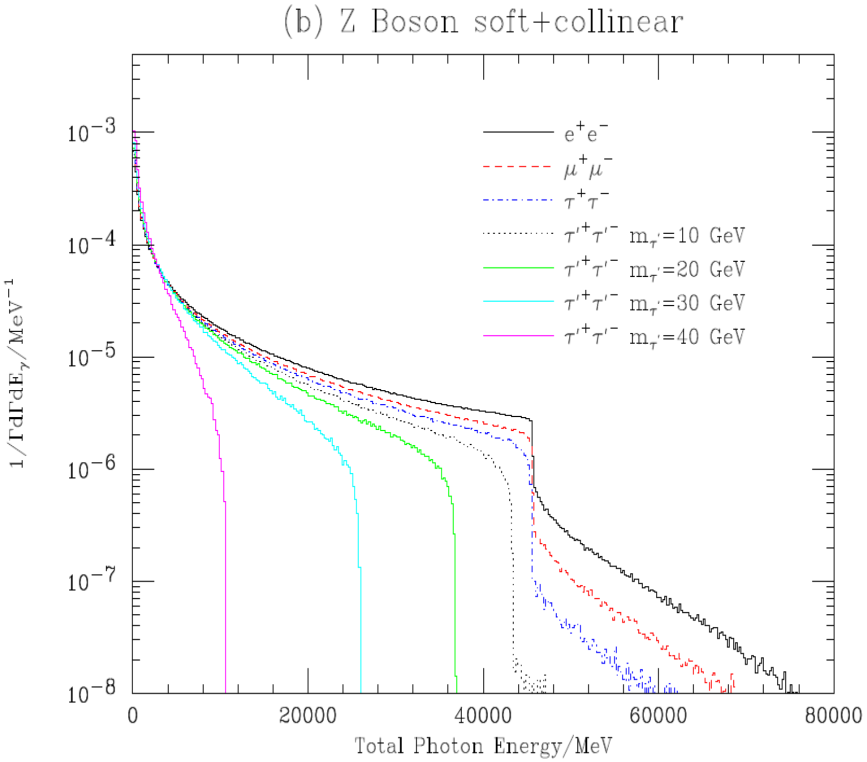


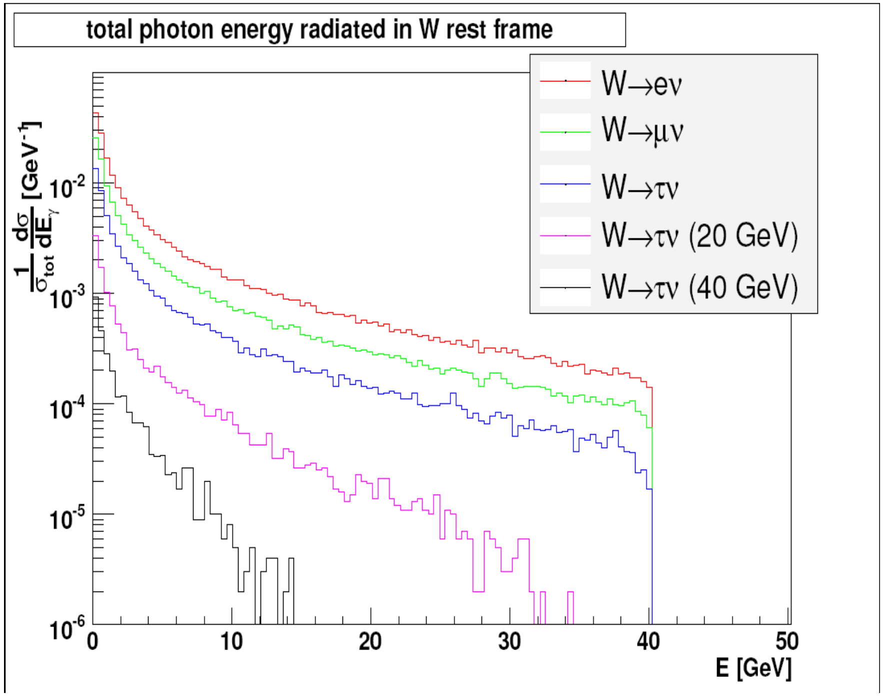
Herwig++



SHERPA

QED Radiation





Herwig++ K. Hamilton and P. Richardson JHEP 0607:010, 2006.

SHERPA M. Schoenherr

BSM Simulation

- For BSM physics the main pieces of the event generators are

1) Hard Process
    - New intermediate particles
    - New particles produced
    - Changes to SM distributions
2) Decays
    - Decays of new particles produced in the hard process or previous decays.

Built In Models

- Traditionally models of new physics are built into the event generator.
- This will often include hard processes and decays.
- Relatively few models have been implemented and the sophistication of the simulation varies.
- Each one was hard-coded by an author of the general purpose generator which was very time consuming.

Built In Models

	HERWIG	PYTHIA
SUSY	✓	✓
SUSY+RPV	✓	✓
RS Gravitons	✓	✓
Z’/W’	✓	✓
Technicolor	✗	✓
Left-Right Models	✗	✓
Compositeness	✗	✓
Excited fermions	✗	✓
Leptoquarks	✗	✓
Fourth generation	✗	✓

Progress

- In the last few years things have moved on.
- Less new models are being implemented inside the event generators.
- Relying more on both:
  - Matrix element generators for specific processes, interfaced via the Les Houches matrix element accord;
  - Matrix element generators which automatically calculate the processes from the Feynman rules and allow the Feynman rules for new models to be implemented.

Progress

- The four main matrix element generators for BSM physics are:
  - COMPHEP/CALCHEP;
  - MadGraph;
  - Omega/Whizard;
  - SHERPA.
- In addition Herwig++ can automatically generate 2→2 scatterings and 1→2,3 decays.
- All of these have the Feynman rules for a range of models included.
- Can also implement new models relatively easily from either the Feynman rules or Lagrangian.
- Recently progress with FeynRules to automated further automated this.

BSM Simulation

- In general there are two different classes of models to be simulated.
  1) Models which only have either new hard scattering processes, or modifications to the Standard Model ones.
  2) Models in which new heavy particles are produced and subsequently decay.
- The first type are relatively simple to simulate.
- The second class, e.g. SUSY, UED, Little Higgs with T-parity are more complicated.

Cascade Decays

- These models were implemented as follows:
  - implement the production of the new particles in 2→2 scatterings;
  - recursively decay the new particles using either phase space or matrix elements.
- This neglects both:
  - spin correlation effects, which will be important in determining what a signal is;
  - some off-shell effects, which may be important for specific models or values of parameters.

Cascade Decays

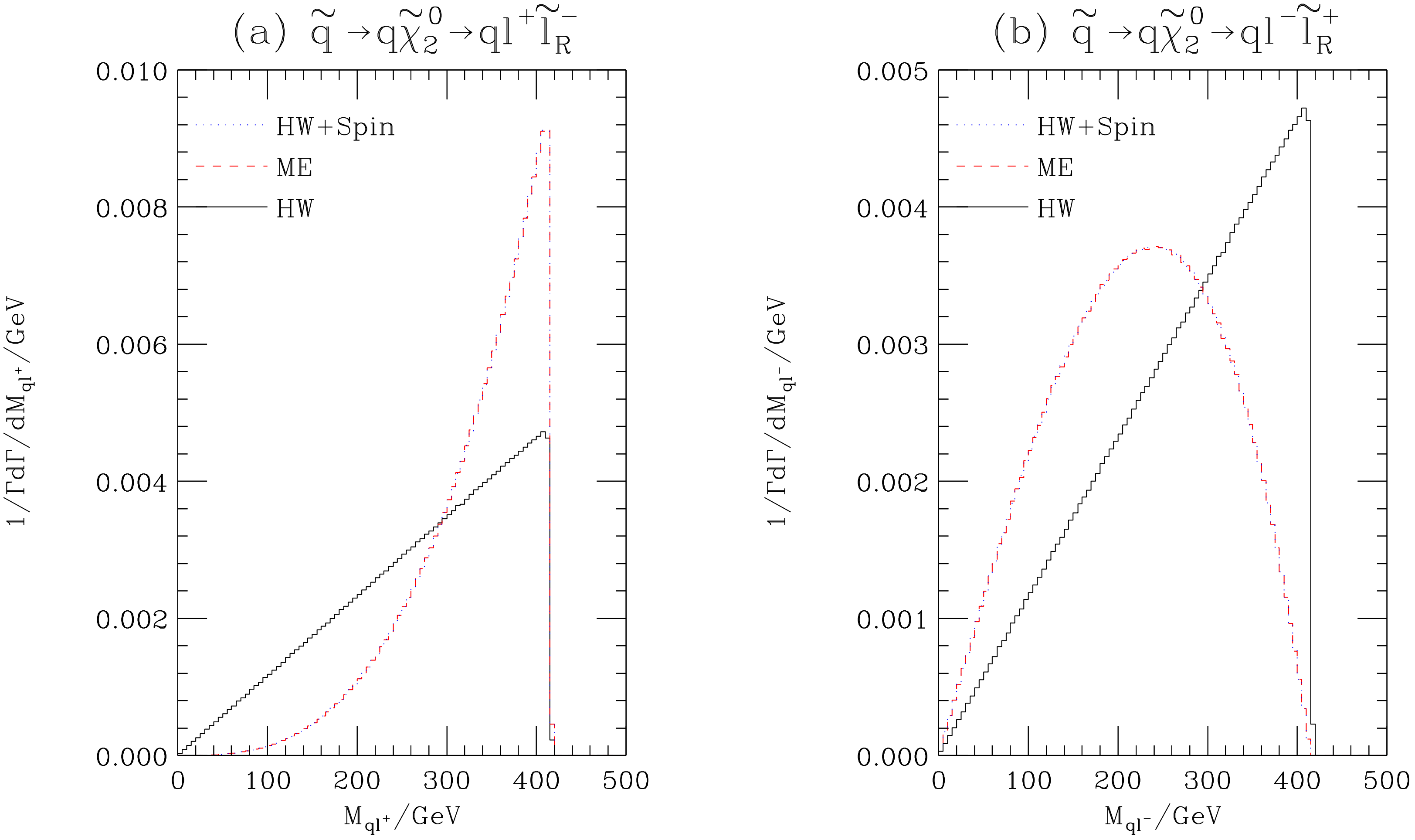
There are two ways round these limitations.

1) Calculate the matrix element for the hard scattering as a 2→n scattering process.
   - Ensures that both the spin correlations and off-shell effects are correctly treated.
   - Can be inefficient for long decay chains or many decay modes.
2) Still factorize the process into production and decay but include correlations.
   - Efficient for long decay chains and large numbers of decay modes.
   - Only gets the spin correlations right, although some off-shell effects can be included.

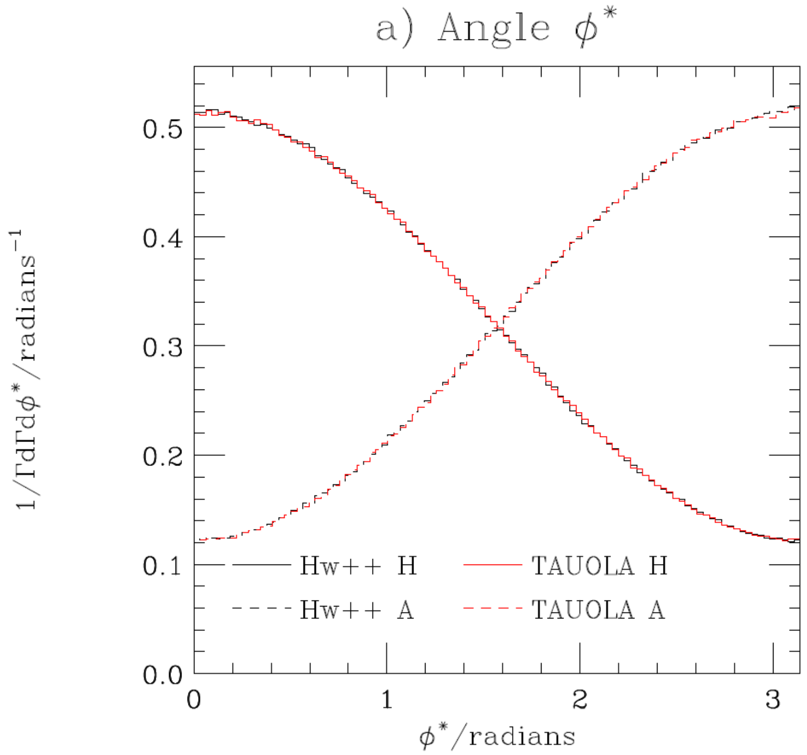
Spin Correlations

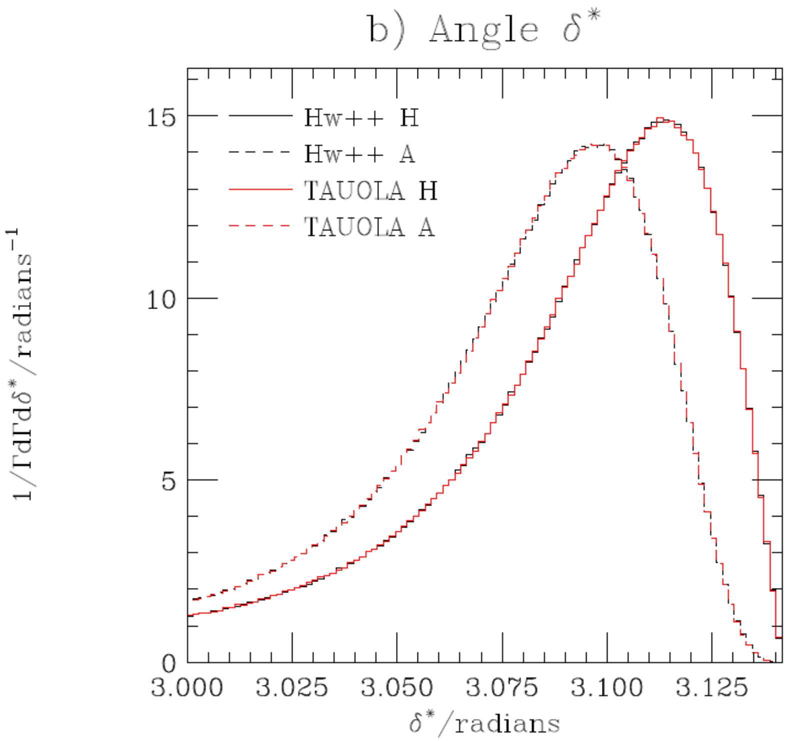
- In order to simulate long decay chains for the LHC we need to simulate the production and decay separately:
  - matrix elements for high multiplicity final-states are complicated to evaluate and integrate;
  - many different channels must be simulated.
- In HERWIG/Herwig++ we use an algorithm which reproduces the matrix element, in the narrow width limit, for these chains.
- However the algorithm still allows us to generate the production and decay of particles separately.
- Probably the best compromise for models like SUSY with long decay chains.

Spin Correlations



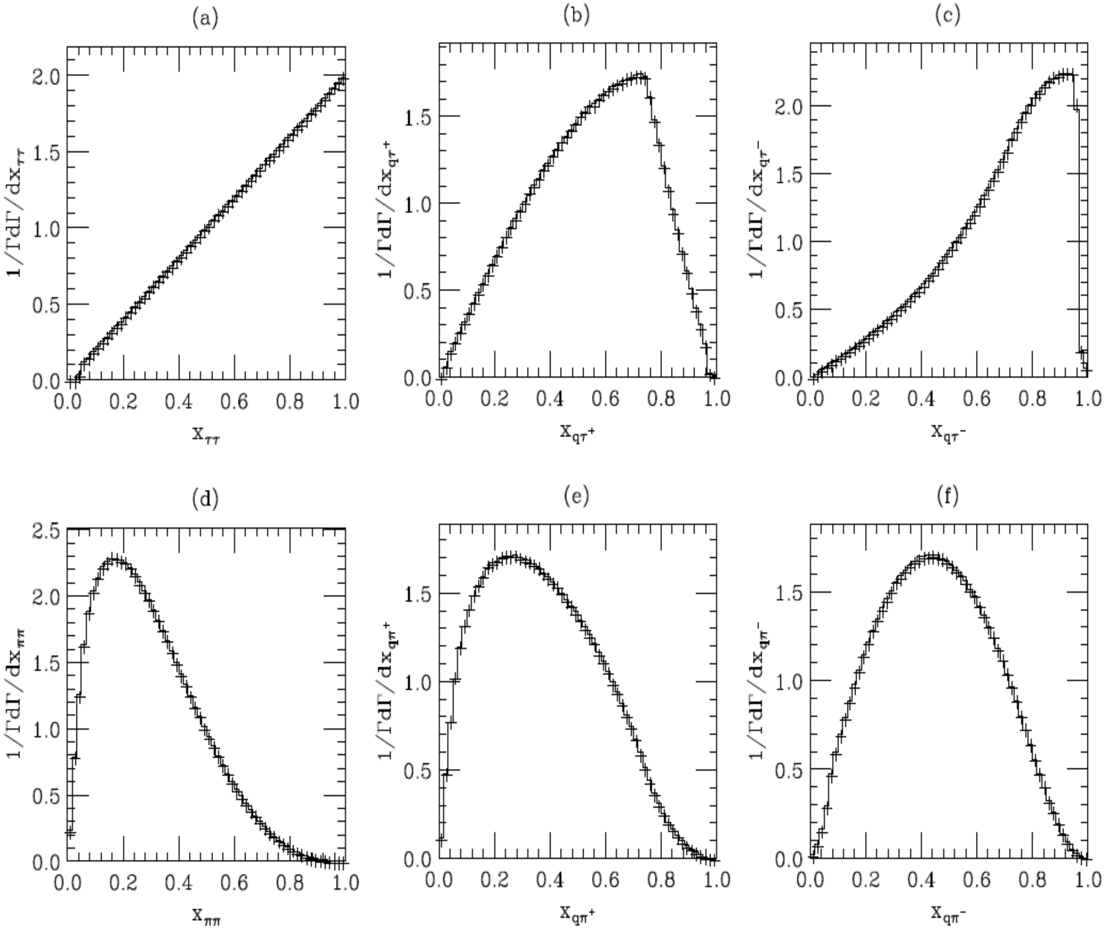
Higgs Decays





- Spin correlations are also included.
- In the decay $H \to \tau^+\tau^- \to \bar{\nu}_\tau \pi^+ \nu_\tau \pi^-$ the angle between the tau decay planes, ϕ^*, and between the pions, δ^*, depends on whether the parity of the Higgs boson.

Correlations in Tau Decays



$$\tilde{q}_\alpha \to q\chi_2^0 \to \tau^\pm_{near}\tilde{\tau}_1^\mp \to \tau^\mp_{far}\chi_1^0$$

- Based on hep-ph/0612237 Choi et al.

FeynRules

- The big change in the last few years is the FeynRules package.
- Automatically generates the Feynman rules from the Lagrangian.
- Can generate the required information for a range of tools:
  - COMPHEP/CalcHEP;
  - Madgraph/MadEvent;
  - SHERPA;
  - Whizzard;
  - Herwig++(in progress).
- Makes many more models available.

What is Available

- More effort has gone into the simulation of SUSY than everything else put together.
- The simulation of SUSY is very sophisticated including:
  - simulation of the hard process, matrix elements for the decays and spin correlations.
  - also available in all the matrix element generators.
- Some extra dimensional models, graviton resonances and now UED in HERWIG, PYTHIA and SHERPA.
- A range of model files for COMPHEP/CALCHEP and MadGraph.
- Now a lot more models available using FeynRules.

We Need a Range of Tools

American Cheese

French Cheese

Use the Best Tool for the Job

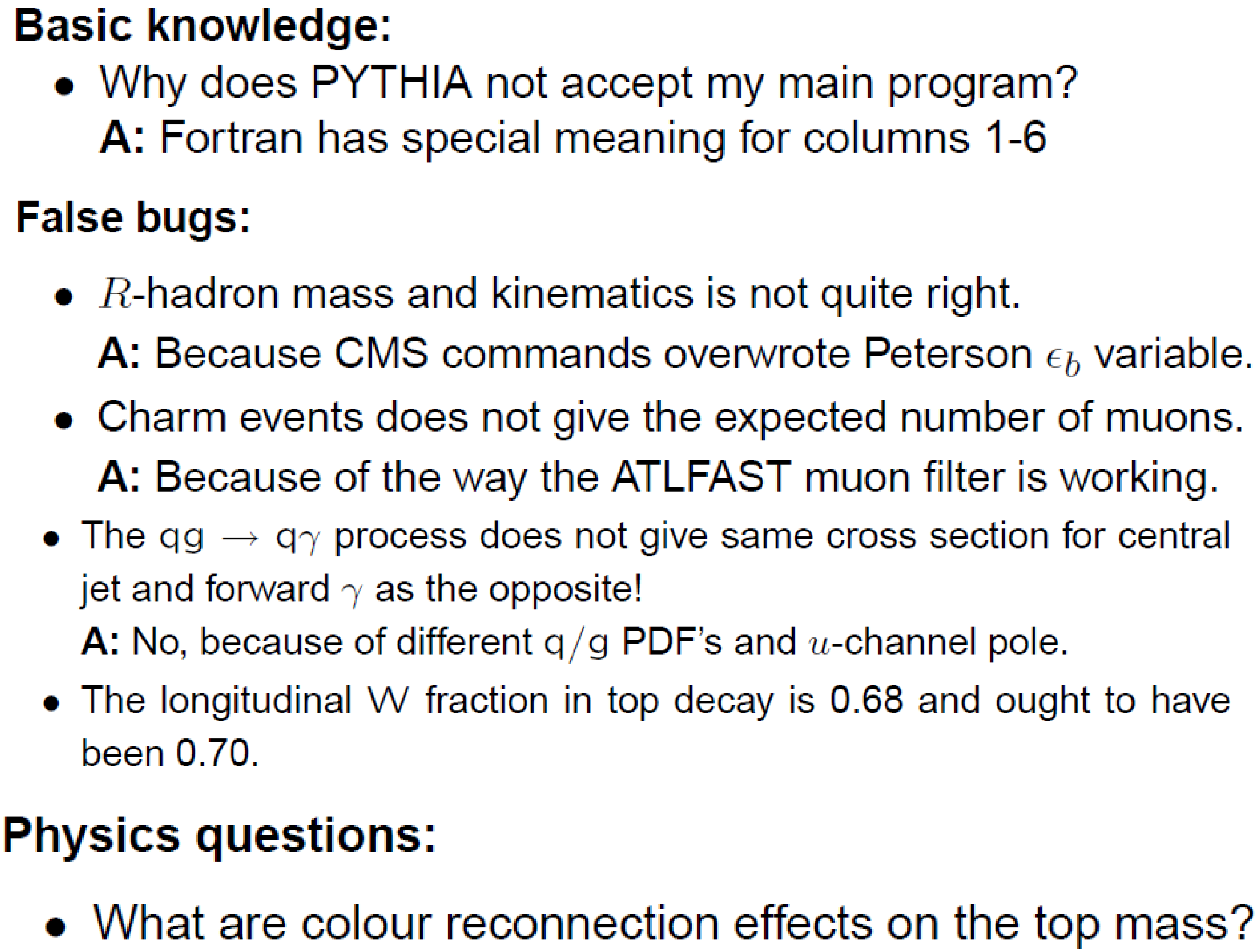
Swiss Army Knife

Stone Axe

Wide range of Tools

Experimental Questions Examples

- Taken from talk by Torbjorn Sjostrand at GENER meeting



Basic knowledge:

- Why does PYTHIA not accept my main program?
  A: Fortran has special meaning for columns 1-6

False bugs:

- R-hadron mass and kinematics is not quite right.
  A: Because CMS commands overwrote Peterson ϵ_b variable.
- Charm events does not give the expected number of muons.
  A: Because of the way the ATLFAST muon filter is working.
- The $\mathrm{qg} \to \mathrm{q}\gamma$ process does not give same cross section for central jet and forward γ as the opposite!
  A: No, because of different q/g PDF's and u-channel pole.
- The longitudinal W fraction in top decay is 0.68 and ought to have been 0.70.

Physics questions:

- What are colour reconnection effects on the top mass?

Experimental Questions

- SHERPA: A very powerful tool, however very complicated generation procedure. No LHE interface, which makes life difficult. We desire a SHERPA LHE interface which would make interface with e.g. MADGRAPH possible.

- SHERPA includes the best ME generator on the market, why would you want to do this!
  - Availability of automated procedures for making inclusive BSM+jets samples would allow experimentalists to exercise more realistic simulation studies.
- Until we've seen something why do you want this? This is extremely complicated, needs significant expertise and the shower should already do a good job.

What Next?

- In recent years the most important thing for the simulation of BSM models has been the simulation of Standard Model processes.
- We’ve seen a lot of improvements in this area:
  - Simulations at NLO using both MC@NLO and POWHEG for a range of processes;
  - Simulations at leading order for many jets using CKKW, MLM and improved variants;
  - Recent progress in combining CKKW and NLO.
- In BSM simulation main advance is FeynRules.

What Next?

- For a long time my view has been that the level of simulation of BSM models we now have is good enough before we see anything.
- However some recent things may need a better treatment of QCD radiation:
  - Effect of additional QCD radiation in decays for recent studies of boosted objects;
  - the effect of additional hard QCD radiation in SUSY events for mass reconstruction etc.

Conclusions

- There's been a lot of progress in the last ten years in simulations of both Standard Model and BSM processes.
- The experimental uptake of the new tools isn't perhaps what it should be.
- It's noticeable that there's been better uptake of the new matching approaches at the Tevatron where they've needed them to describe the data.

There are a lot of sophisticated simulations on the market, please use them.