MC Tools: Status and New Developments

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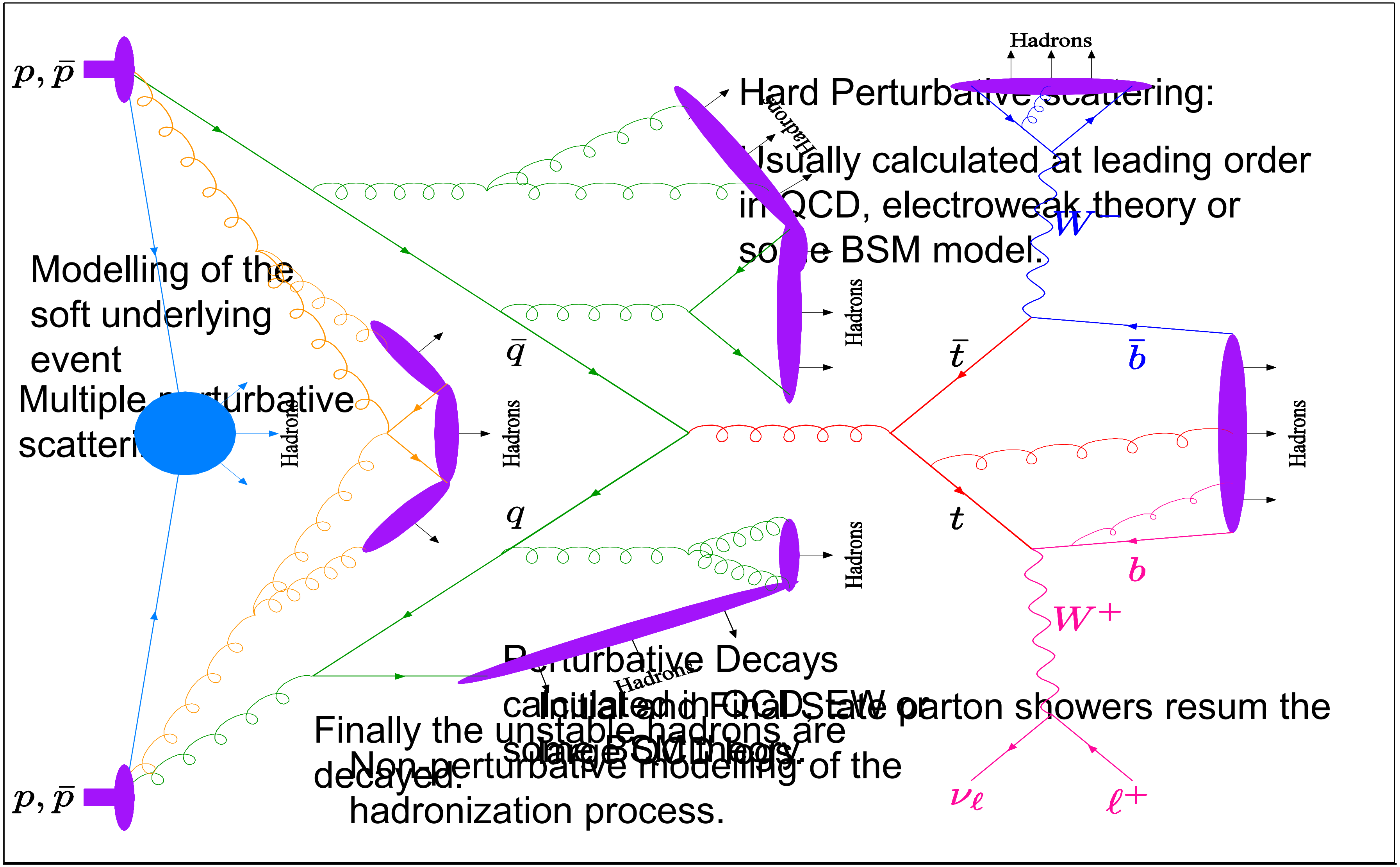
Summary

- Introduction
- Basics Of Event Generation
- Multiple Parton-Parton Scattering
- Higher Orders and Multiplicities
- Conclusions

Introduction

- Monte Carlo event generators are designed to simulate hadron collisions using a combination of:
  - Fixed order perturbative calculations;
  - Resummation of large QCD logarithms;
  - Phenomenological Models.
- It’s important to understand the different pieces of the simulation.
- Some are on firm theoretical ground and we’d be surprised if they didn’t work, others might break down in the new energy regime of the LHC.

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.

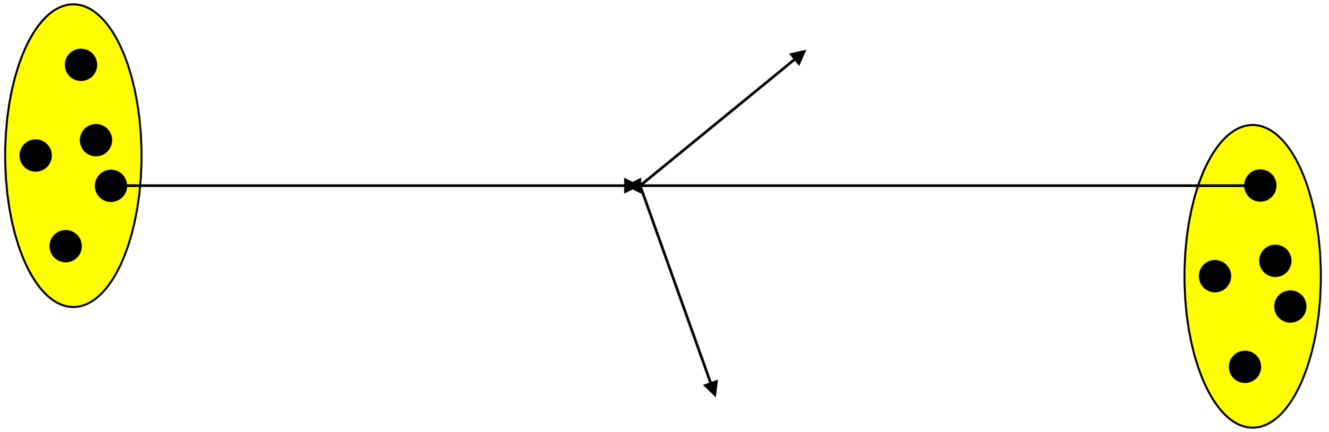
Non-perturbative modelling of the hadronization process.

Introduction

- The different models are generally tuned to different types of data:
  - parameters relating to the final-state parton shower and hadronization are tuned to LEP data;
  - parameters relating to initial-state parton showers and multiple parton-parton interactions are tuned to data from the Tevatron and UA5.
- We expected that the shower and hadronization models would work at LHC energies, less sure about the underlying event.

The Underlying Event

- Protons are extended objects.
- After a parton has been scattered out of each in the hard process what happens to the remnants?



Two Types of Model:

1) Non-Perturbative: Soft parton-parton cross section is so large that the remnants always undergo a soft collision.

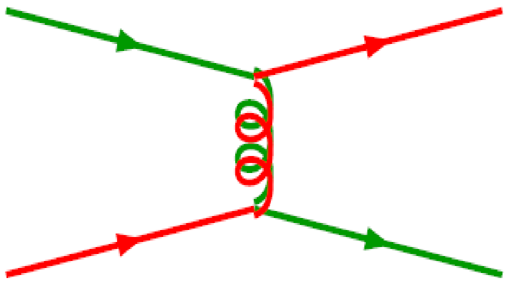
2) Perturbative: 'Hard' parton-parton cross section is huge at low p_T, dominates the inelastic cross section and is calculable.

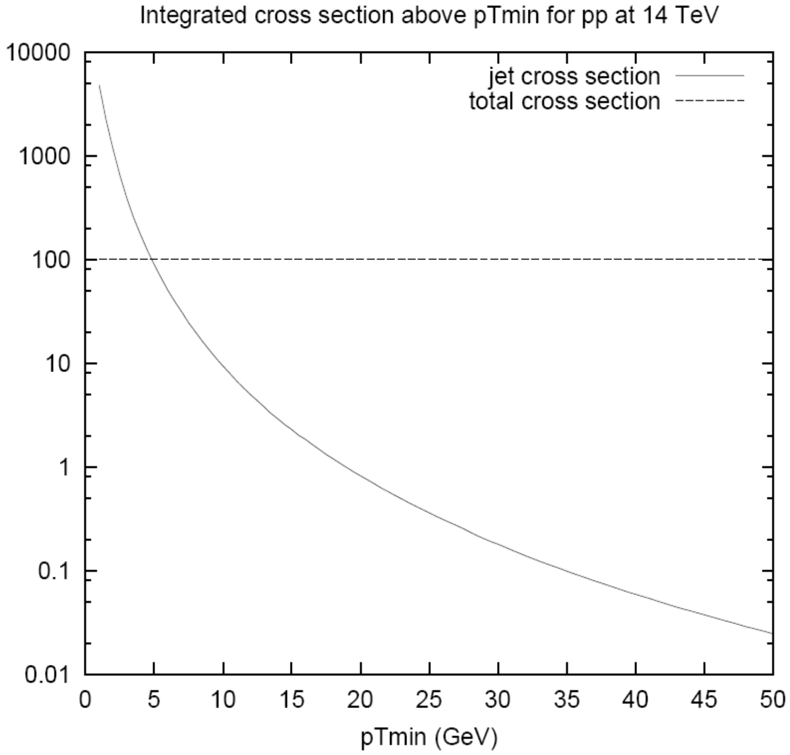
Multiparton Interaction Models

- The cross-section for 2→2 scattering is dominated by t-channel gluon exchange.
- It diverges like

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_\perp^2} \approx \frac{1}{p_\perp^4} \quad \text{for} \quad p_\perp \to 0$$

- This must be regulated used a cut of $p_{T\min}$.
- For small values of $p_{T\min}$ this is larger than the total hadron-hadron cross section.
- More than one parton-parton scattering per hadron collision



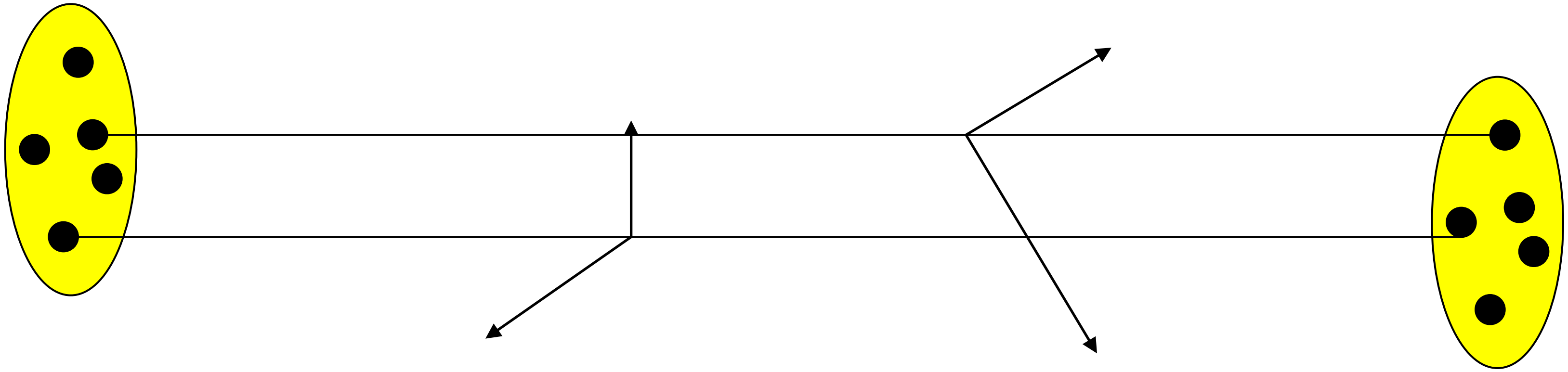


Multiparton Interaction Models

- If the interactions occur independently then follow Poissonian statistics

$$P_n = \frac{\langle n \rangle^n}{n!} e^{-\langle n \rangle}$$

- However energy-momentum conservation tends to suppressed large numbers of parton scatterings.



- Also need a model of the spatial distribution of partons within the proton.

Multiparton Interaction Models

- In general there are two options for regulating the cross section.

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_\perp^2} \propto \frac{\alpha_s^2\left(p_\perp^2\right)}{p_\perp^4} \to \frac{\alpha_s^2\left(p_\perp^2\right)}{p_\perp^4}\theta\left(p_\perp - p_{\perp\min}\right) \quad \text{simpler}$$

$$\text{or} \quad \to \frac{\alpha_s^2\left(p_\perp^2 + p_{\perp 0}^2\right)}{\left(p_\perp^2 + p_{\perp 0}^2\right)^2} \qquad \text{more complicate d}$$

  where $p_{\perp\min}$ or $p_{\perp 0}$ are free parameters of order 2 GeV.

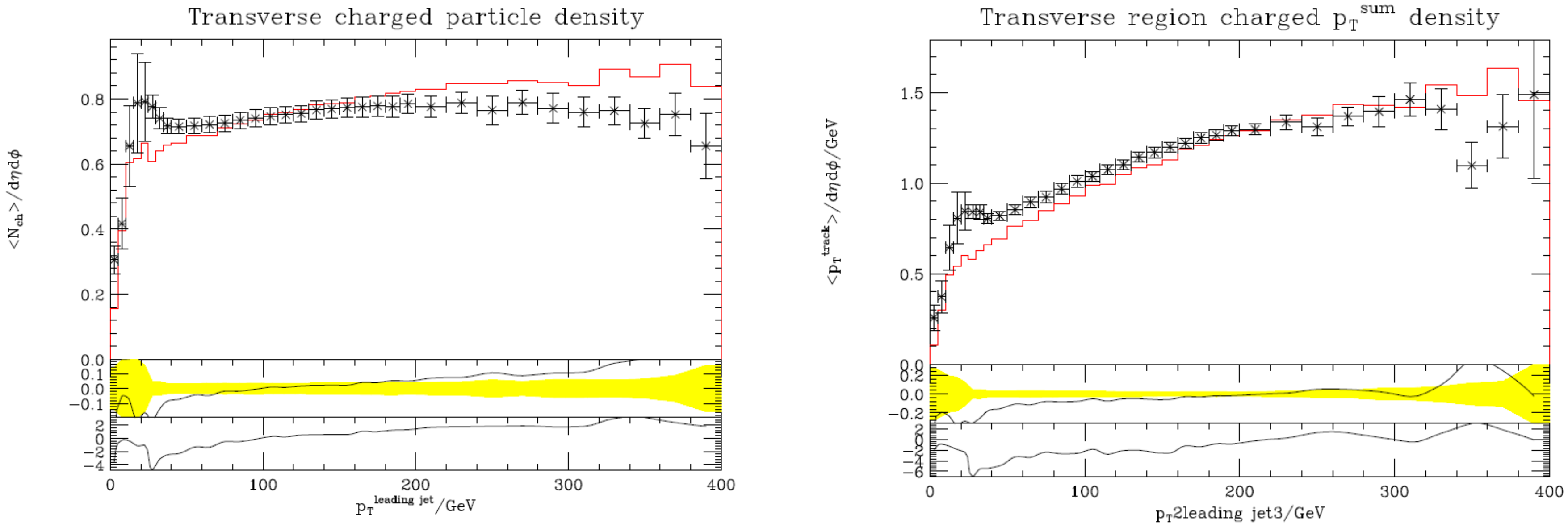
- Typically 2-3 interactions per event at the Tevatron and 4-5 at the LHC.
- However tends to be more in the events with interesting high p_T ones.

Prior to LHC

- Before the LHC data from:
  - UA5 experiment;
  - CDF at both 630, 1800 and 1960 GeV.

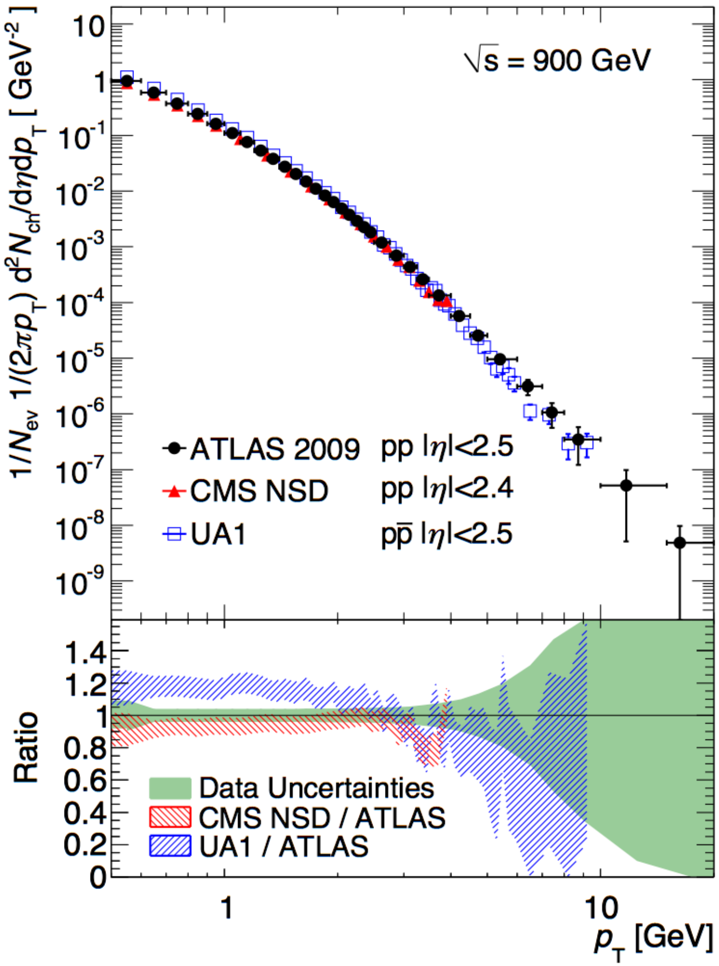
  were used to constrain the parameters of the underlying event model.
- The data at the higher Tevatron energies is the best for tuning the parameters at specific energy.
- Need the other points to extrapolate the parameters to LHC energies.

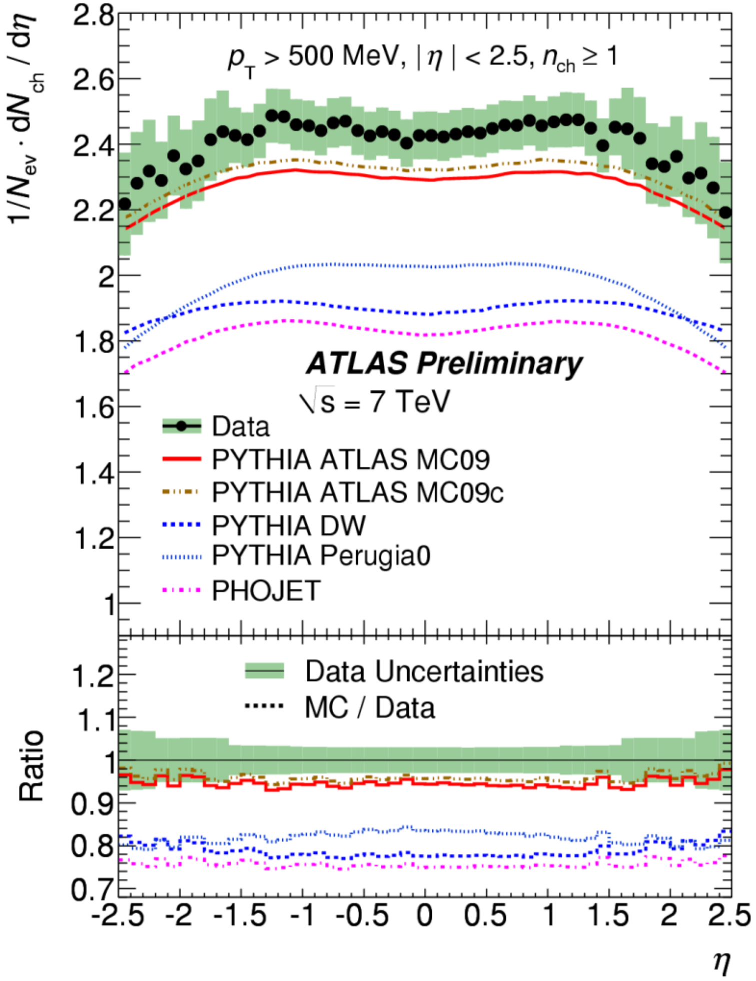
Underlying Event



Herwig++ compared to CDF data

Charged Particle Multiplicities at √s=0.9, 7 TeV



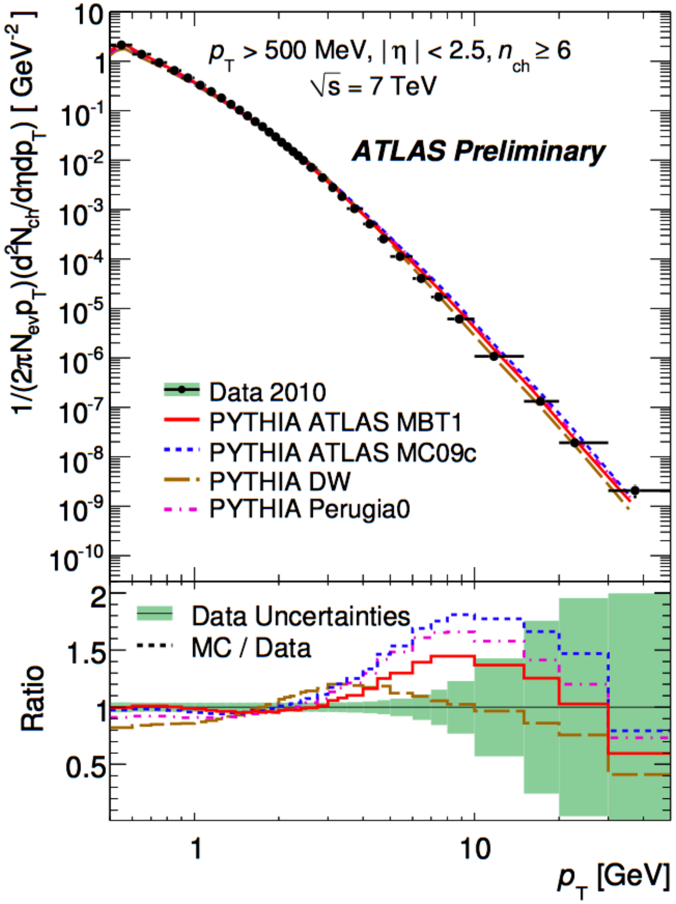


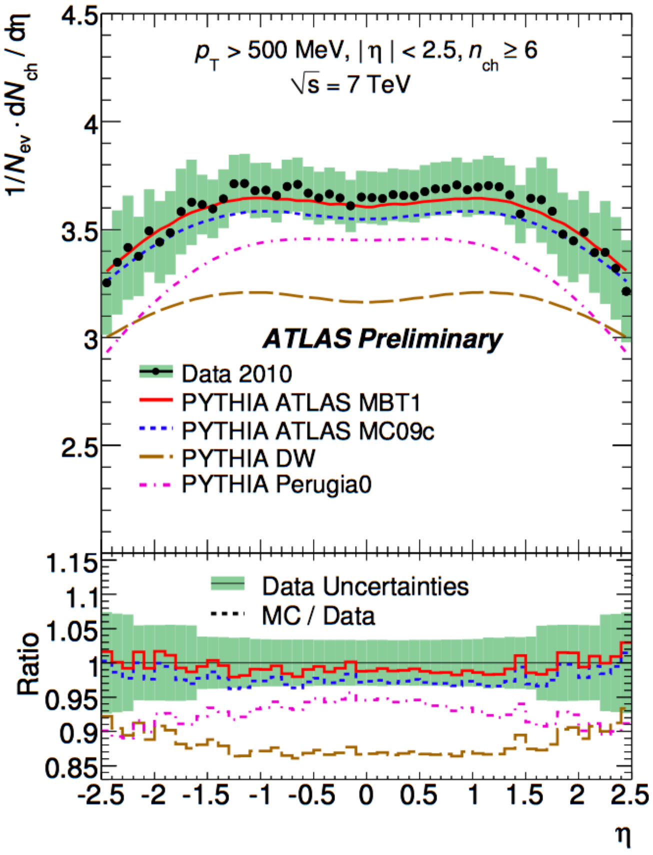
Monte Carlo underestimates the
track multiplicity seen in ATLAS

Pythia Tune to ATLAS MinBias and Underlying Event

Used for the tune

ATLAS UE data at 0.9 and 7 TeV
ATLAS charged particle densitites 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

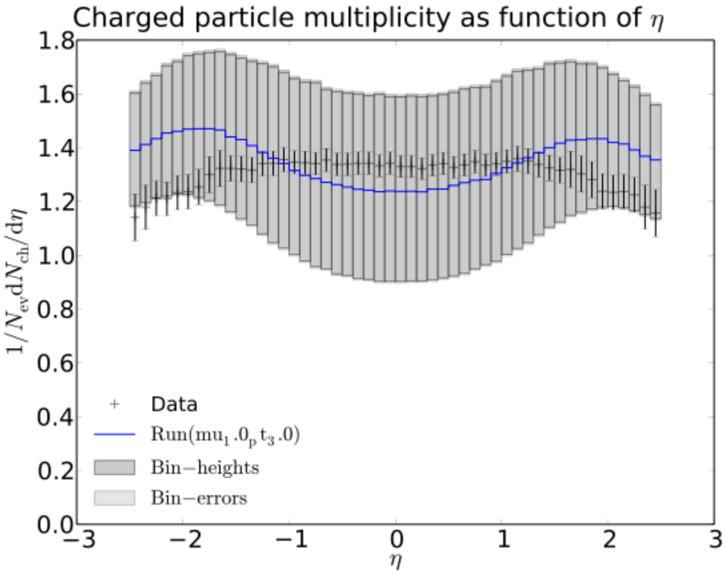
This tune describes most of the MinBias and the UE data
Significant improvement compared to pre-LHC tunes
Biggest remaining deviation in → $\frac{1}{N_{\mathrm{ev}}} \cdot \frac{1}{2\pi p_{\mathrm{T}}} \cdot \frac{\mathrm{d}^2 N_{\mathrm{ch}}}{\mathrm{d}\eta \mathrm{d}p_{\mathrm{T}}}$
These deviations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

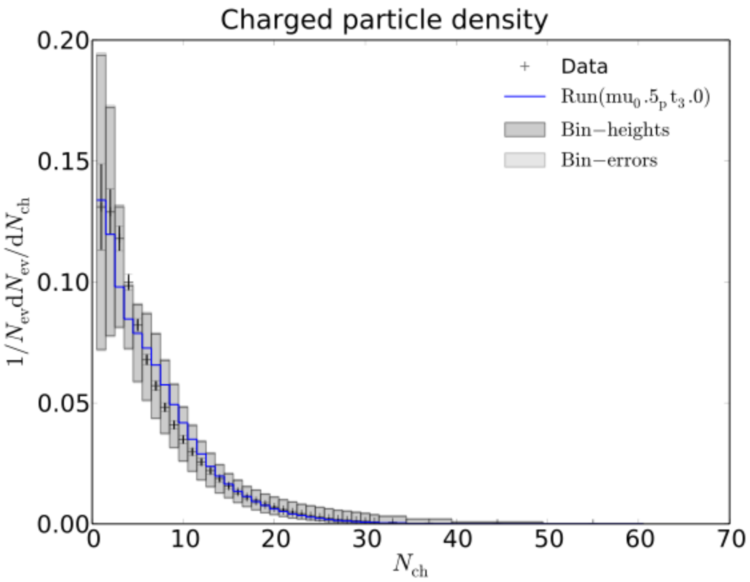
Minimum Bias

- Completely new in Herwig++

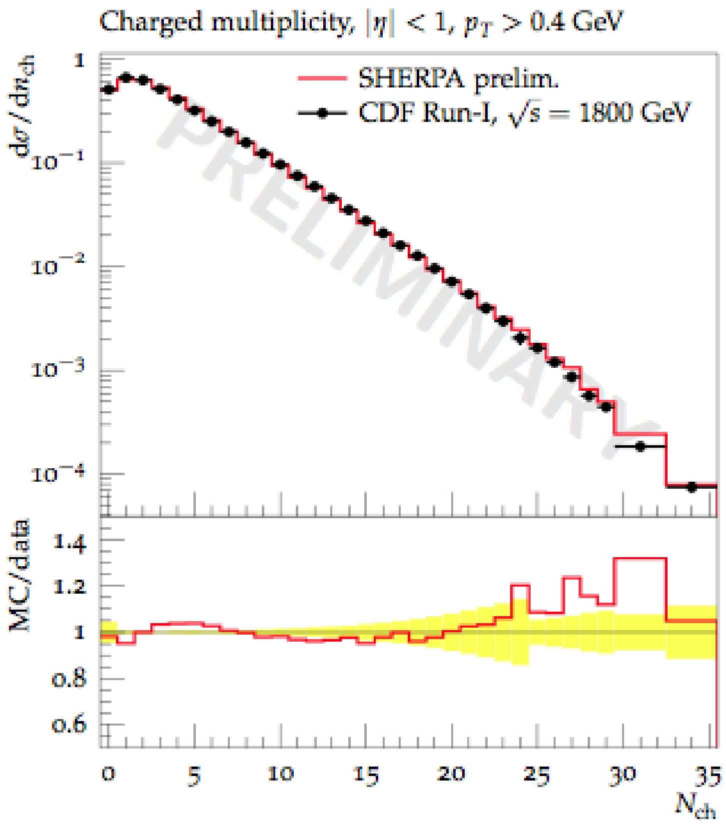
  hard + soft multi-parton interaction model

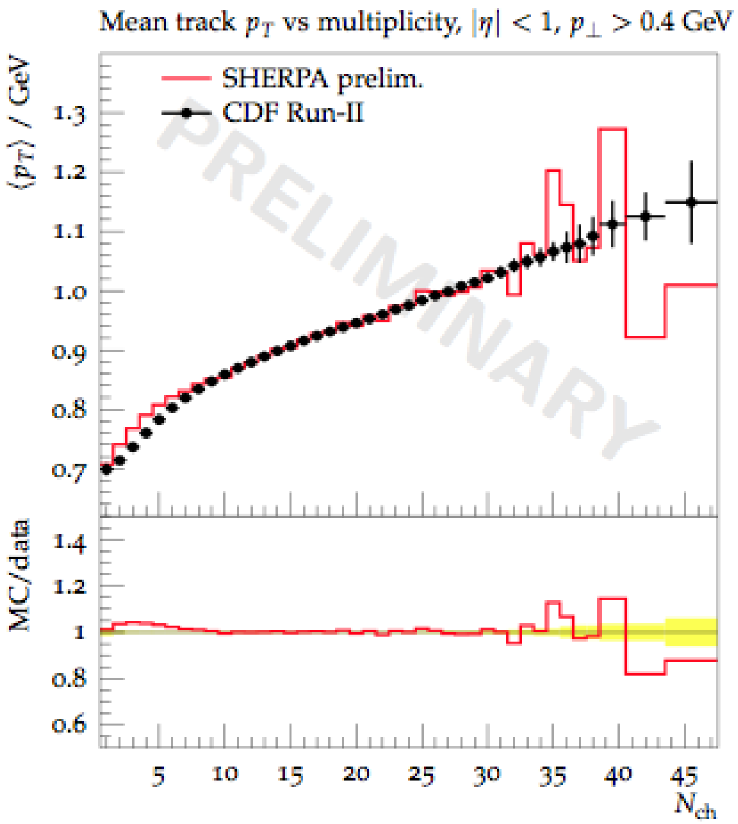
  First comparison with ATLAS data looks promising…





New MinBias model: First preliminary results

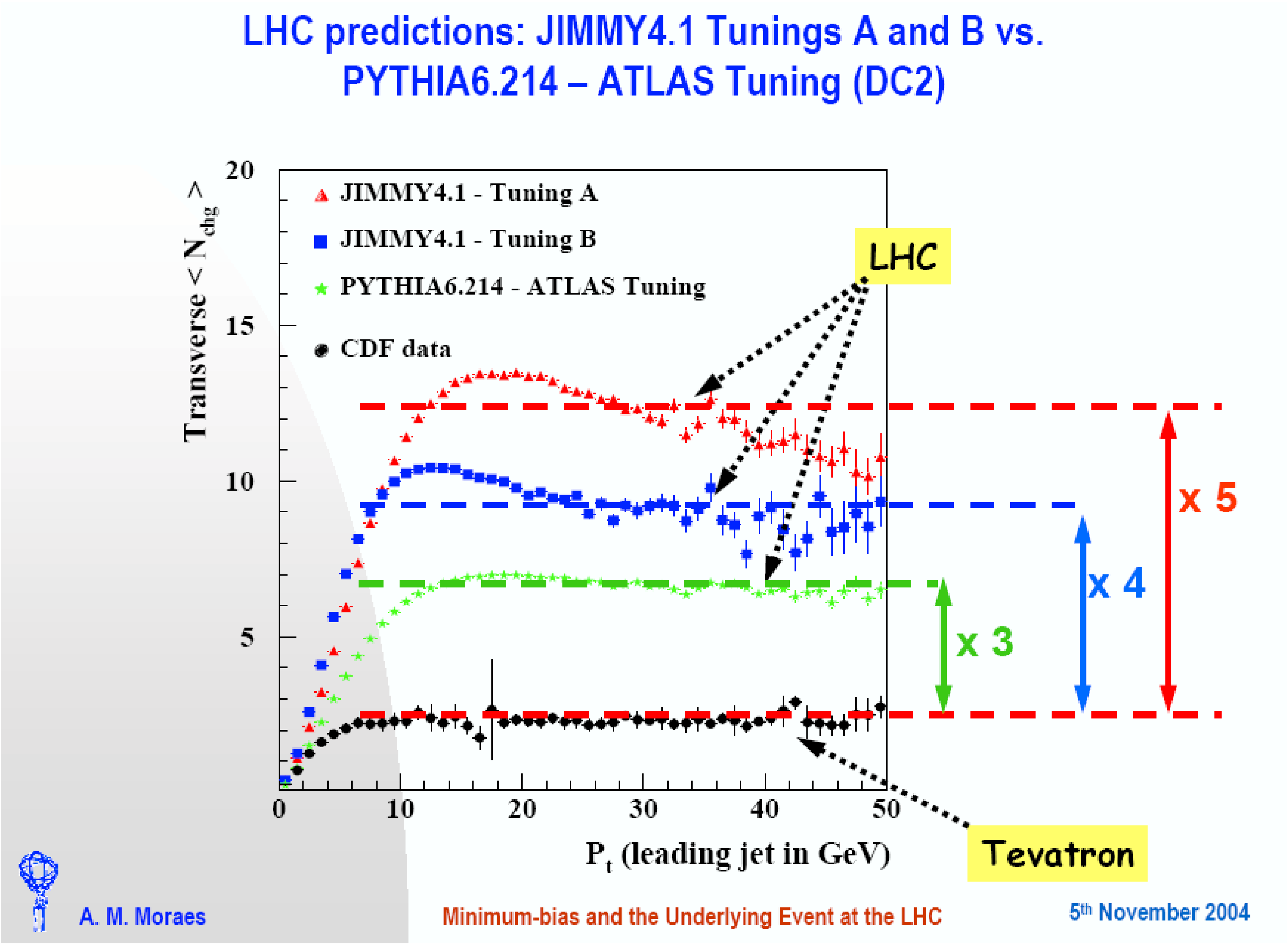

Charged multiplicity, $|\eta| < 1$, $p_T > 0.4$ GeV


Mean track p_T vs multiplicity, $|\eta| < 1$, $p_\perp > 0.4$ GeV

Phys.Rev.D65:072005,2002 Phys.Rev.D79:112005,2009

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 fitting gives good agreement.
- The models therefore seem reasonable, perhaps some theoretical tweaking needed, but not a major rethink of the whole approach.



LHC predictions: JIMMY4.1 Tunings A and B vs. PYTHIA6.214 – ATLAS Tuning (DC2)

A. M. Moraes

Minimum-bias and the Underlying Event at the LHC

5th November 2004

NLO Simulations

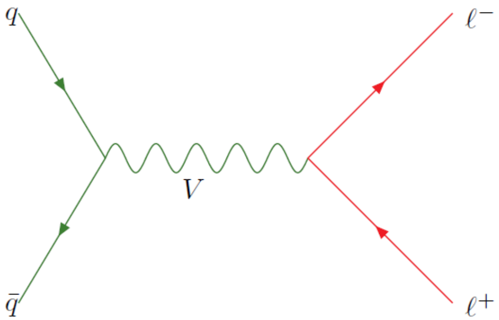
- NLO simulations rearrange the NLO cross section formula.

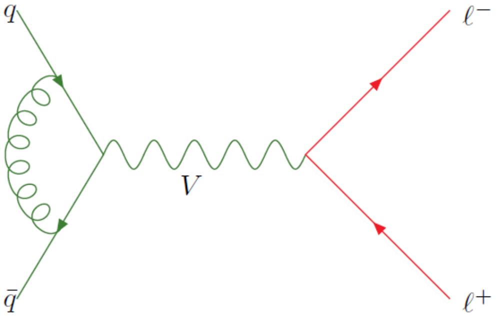
$$d\sigma = B(v)d\Phi_v + (V(v) + C(v,r)d\Phi_r)d\Phi_v$$
$$+ (R(v,r) - C(v,r))d\Phi_v d\Phi_r$$

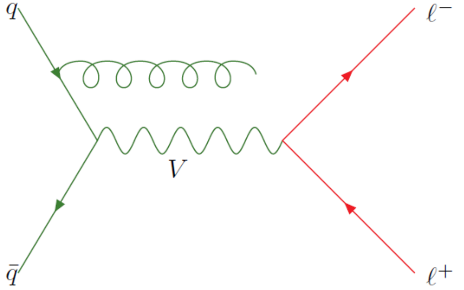
- Either choose C to be the shower approximation

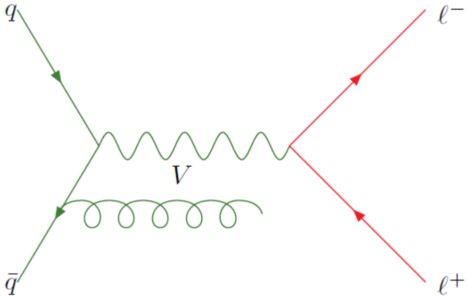
$$d\sigma = B(v)d\Phi_v + (V(v) + C_{\text{shower}}(v,r)d\Phi_r)d\Phi_v$$
$$+ (R(v,r) - C_{\text{shower}}(v,r))d\Phi_v d\Phi_r$$

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

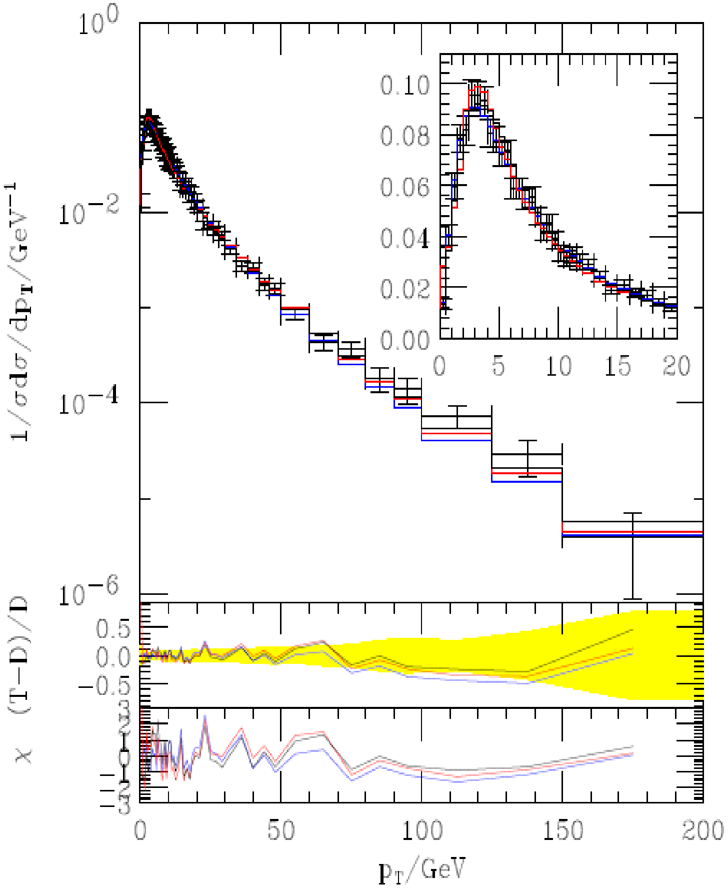
POWHEG

- 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 $p_{T.}$

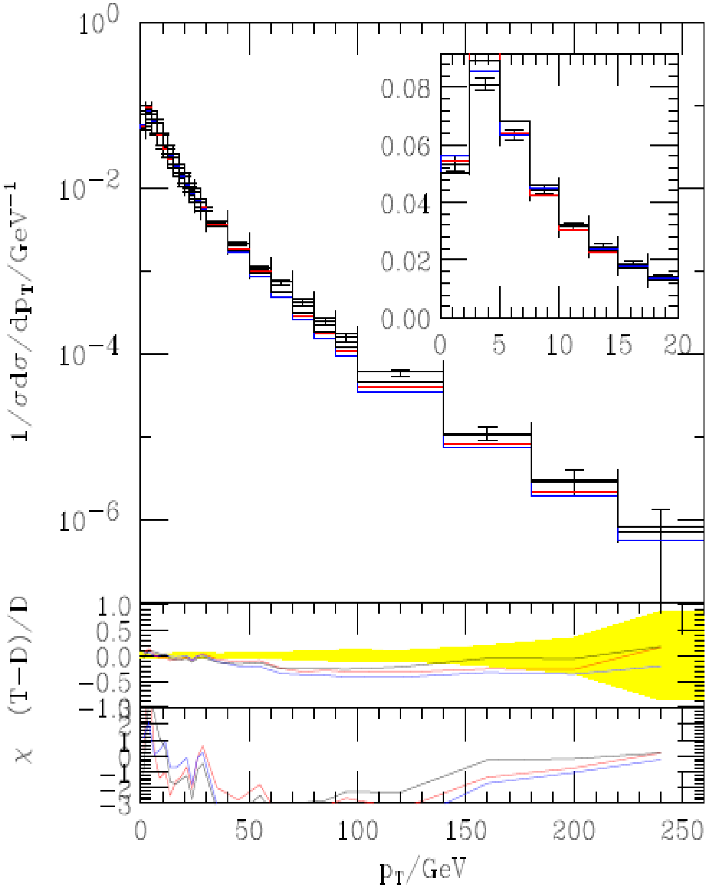
MC@NLO

- 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

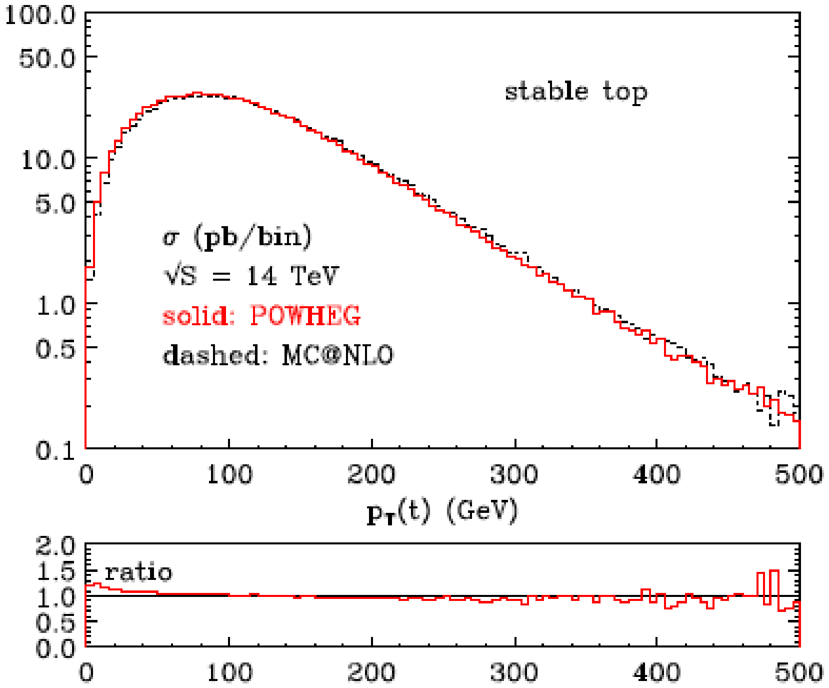
Herwig++

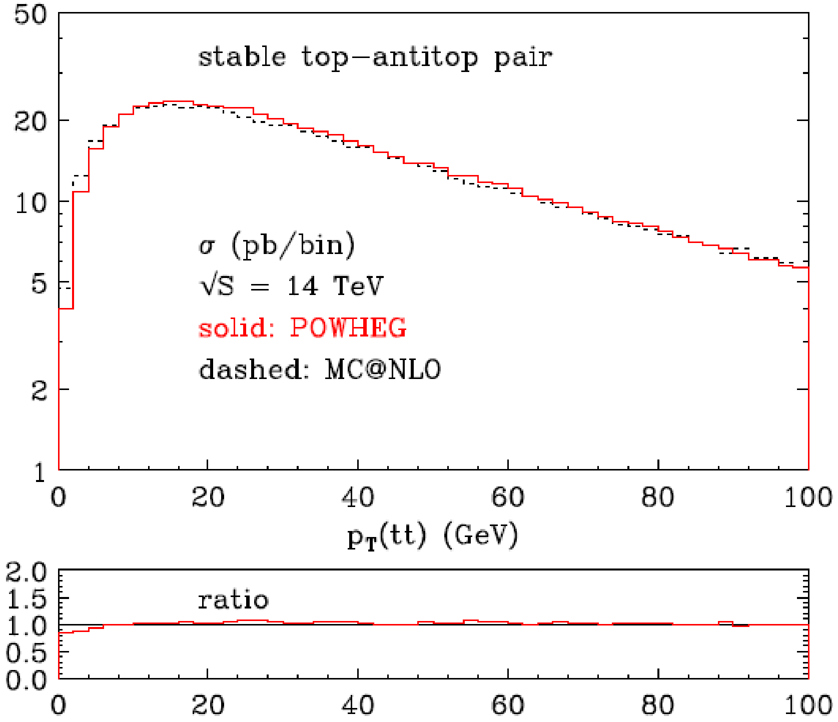
POWHEG

MC@NLO

JHEP 0810:015,2008 Hamilton, PR, Tully

Top Quark Production





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

Different Approaches

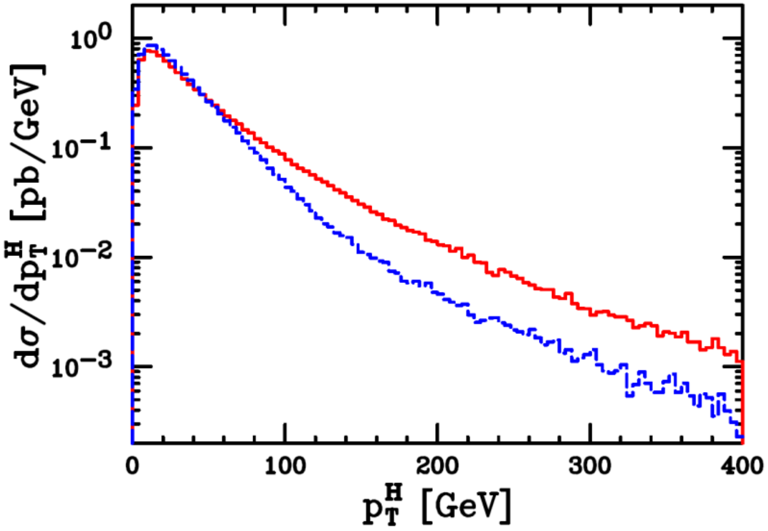
- The two approaches are the same to NLO.
- Differ in the subleading terms.
- In particular at large p_T

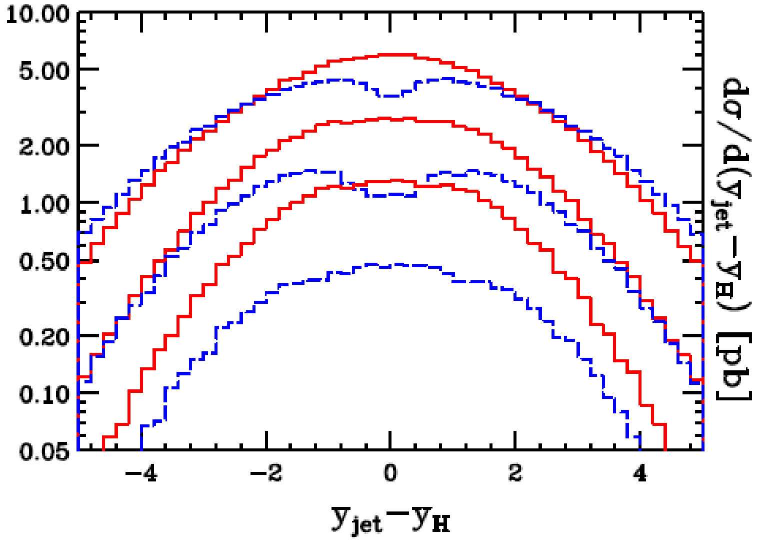
$$d\sigma \approx R(v,r)\,d\Phi_v\,d\Phi_r$$

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

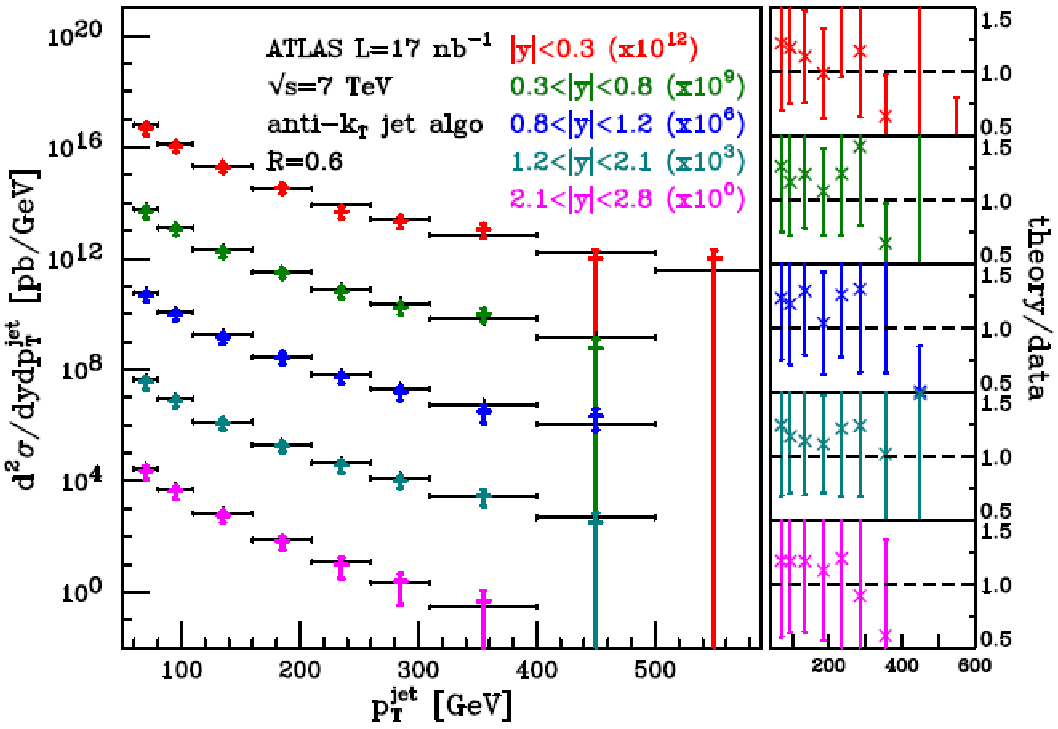
- A large range of processes are available in the MC@NLO approach together with the FORTRAN HERWIG and Herwig++ programs (Frixione, Webber, et.al.).
- Work in progress for MC@NLO with PYTHIA (Torrielli, Frixione).
- Fewer processes in the POWHEG approach available either standalone (Alioli, Nason, Oleari, Re) or in Herwig++(Hamilton, Richardson, Tully) or SHERPA (Hoeche, Krauss, Schonherr, Siegert).

NLO Status

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

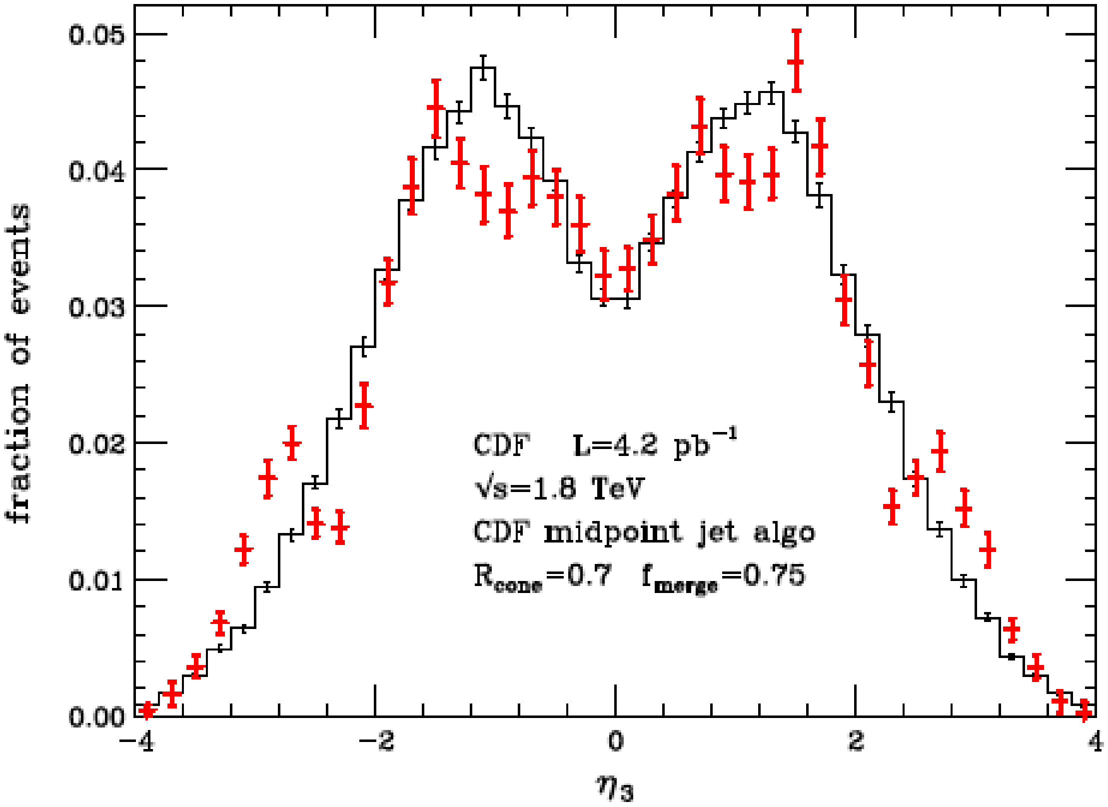
  are available in both approaches.
- Recent developments
  - Automation (POWHEG Box and SHERPA)
  - Jet production in POWHEG approach (Alioli, Hamilton, Nason, Oleari, Re).

NLO Jet Production



POWHEG compared to ATLAS data arXiv:1012.3380 Alioli et. al.

NLO Jet Production



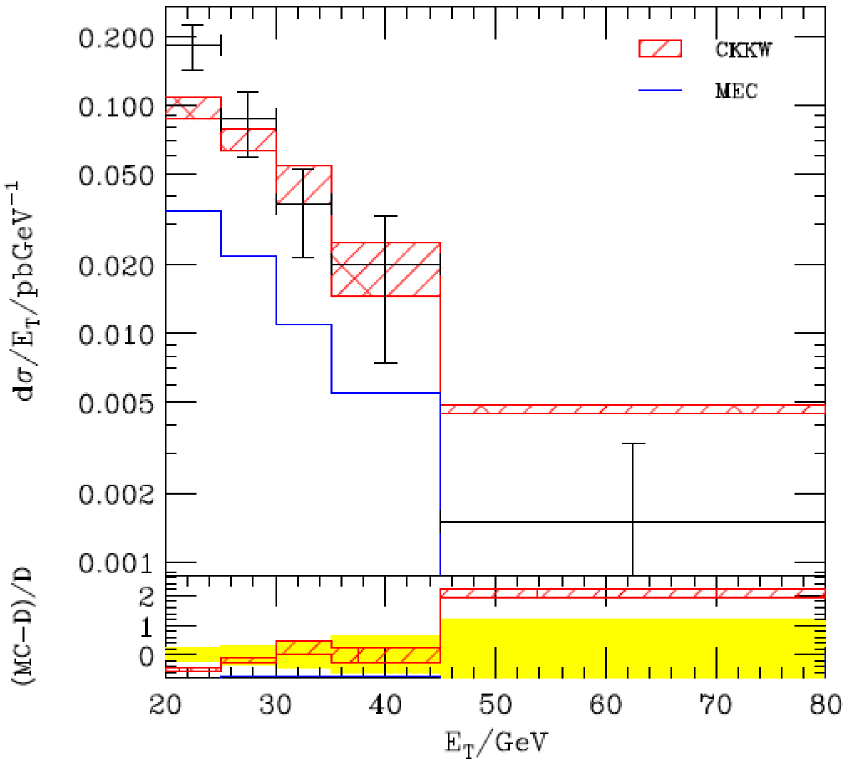
POWHEG compared to CDF data arXiv:1012.3380 Alioli et. al.

Multi-Jet Leading Order

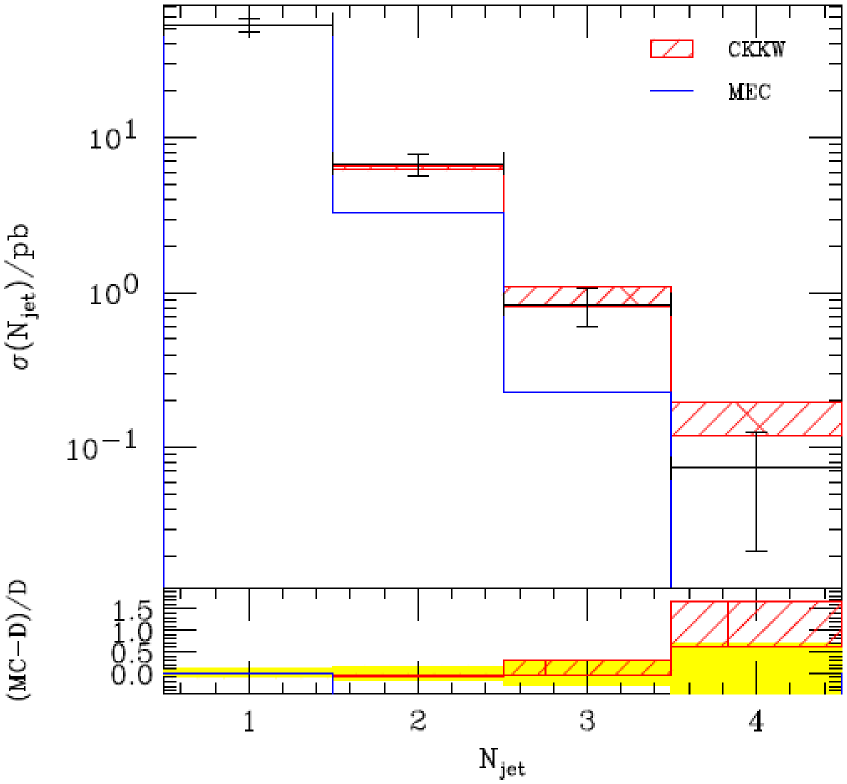
- While the NLO approach is good for one hard additional jet and the overall normalization it cannot be used to give many jets.
- Therefore to simulate these processes use matching at leading order to get many hard emissions correct.
- The most sophisticated approaches are variants of the CKKW method (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)

p_T of jets in W+jets at the Tevatron

3rd Hardest Jet



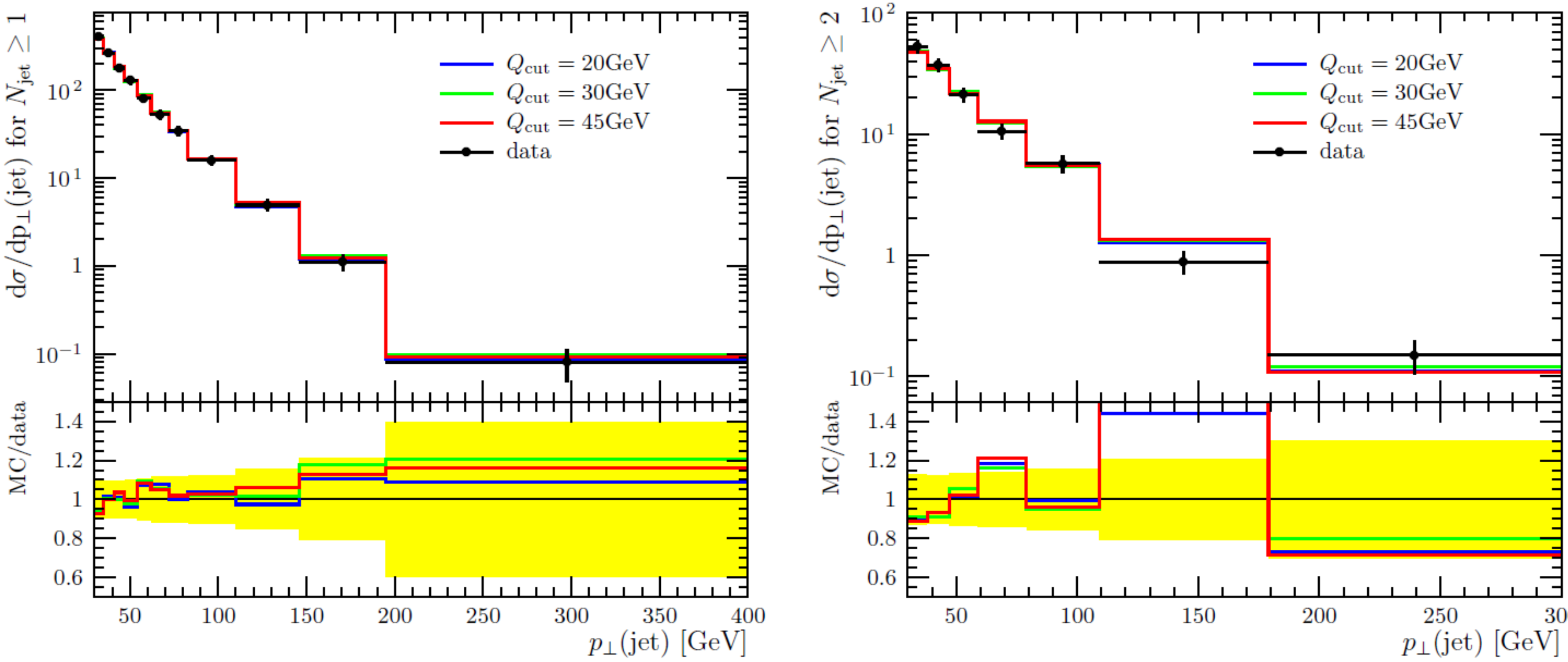
All Jets



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

Leading Order $q\bar{q}\rightarrow Z$+jets

SHERPA

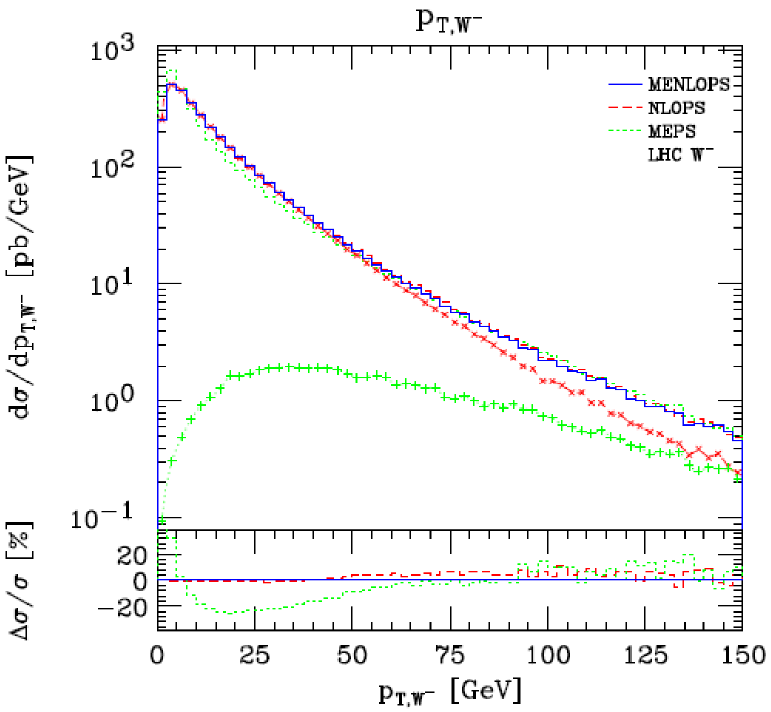


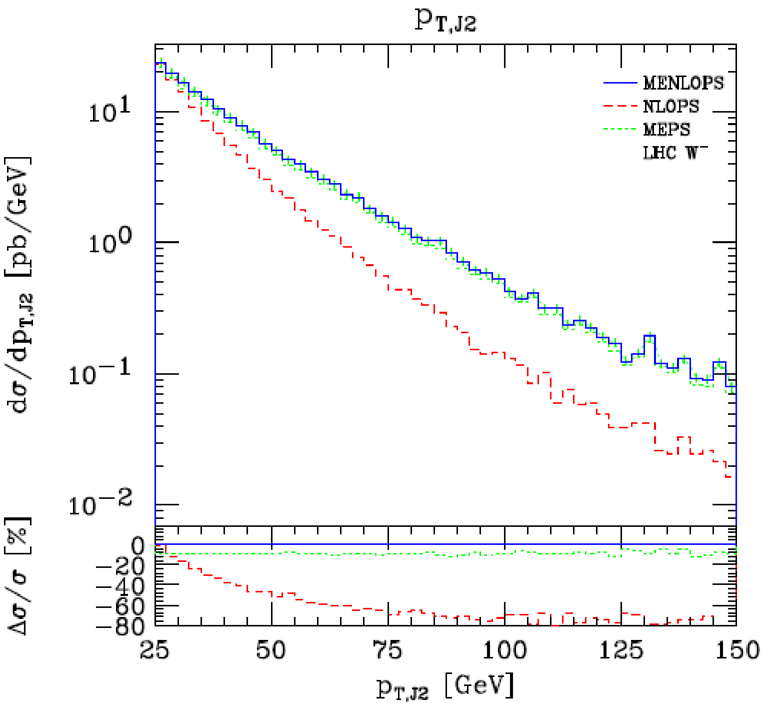
Highest p_T jet

2^{nd} 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.

Summary

- We’ve spent a long time developing a new generation of simulations for the LHC.
- We’ve done a lot to compare and tune the results to existing data.
- However as we enter the new energy regime of the LHC some things we will need to:
  - retune parameters;
  - improve the perturbative physics.
- So far things look O.K. but that may well change as statistics improve.