LUND UNIVERSITY

Monte Carlos and Tools

- Introduction
- Generators at LEP/HERA/LHC
- Forward activity
- Underlying events & Multiple scattering
- Matrix Elements & Parton Showers
- THEPEG & future Event Generators
- HZTOOL & JETWEB
- Conclusions

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I will not talk about

- Matrix Element generators
- NLO generators
- SUSY and BSM
- Resummations and power corrections
- Heavy Ions

Why do we need Monte Carlo Event Generators

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Blah blah blah blah blah. . .

Why do we need Monte Carlo Event Generators

Blah blah blah blah blah...

The first commandment of event generation:

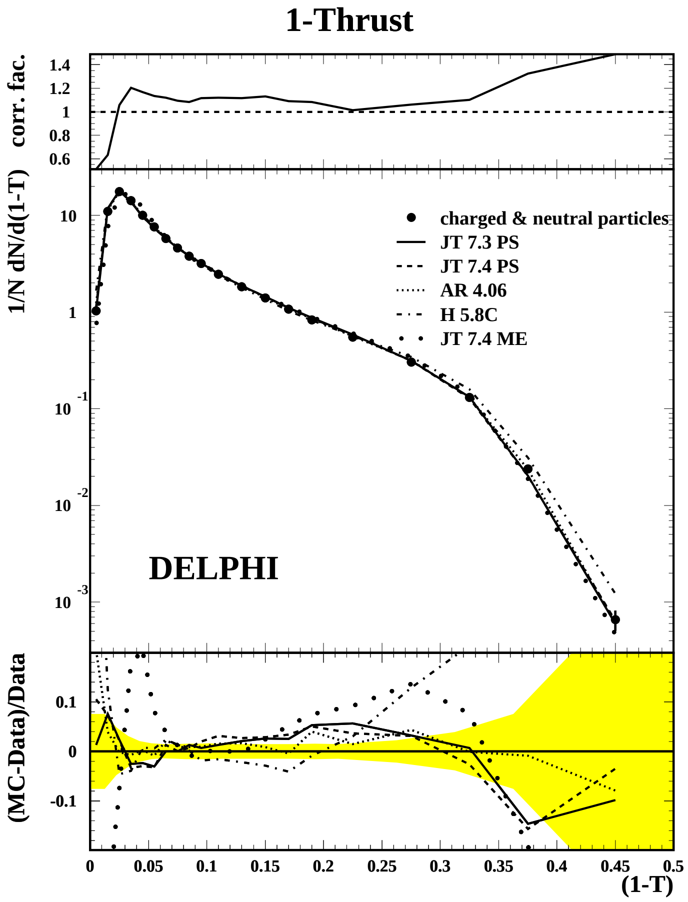
Why do we need Monte Carlo Event Generators

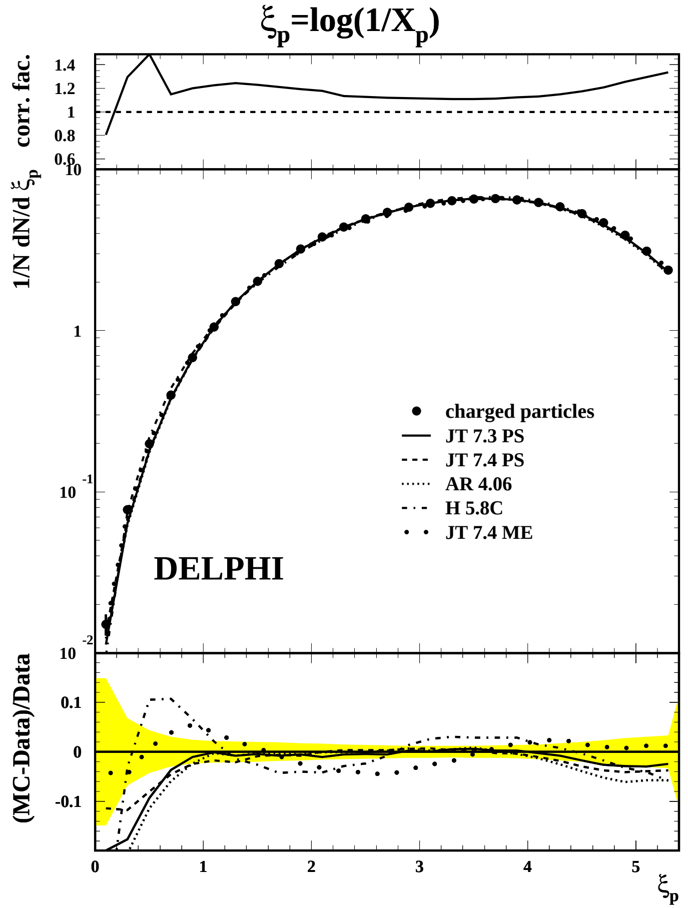
Blah blah blah blah blah. . .

The first commandment of event generation:

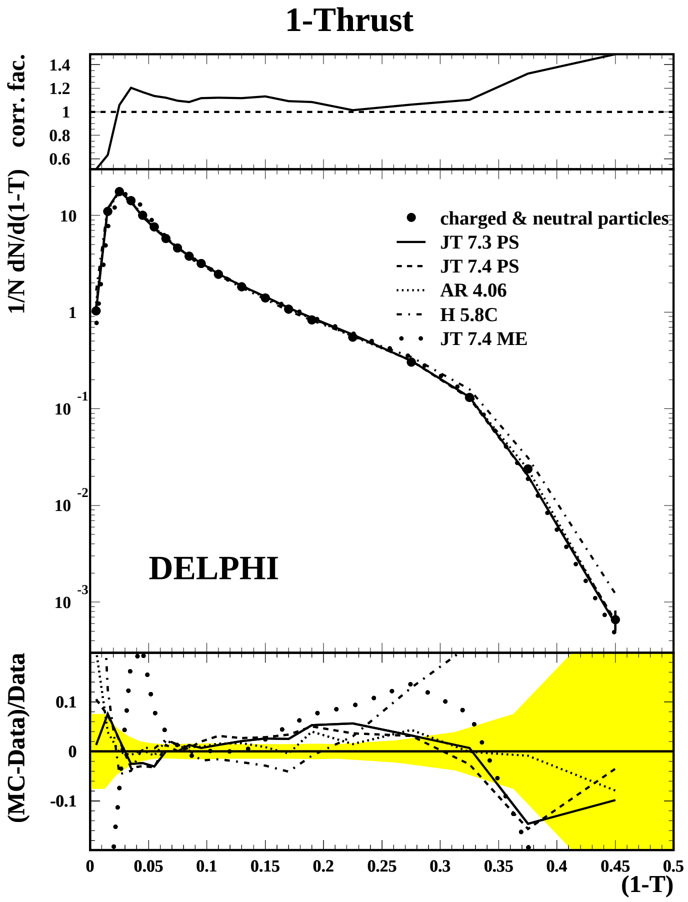
Thou shalt always conserve energy and momentum

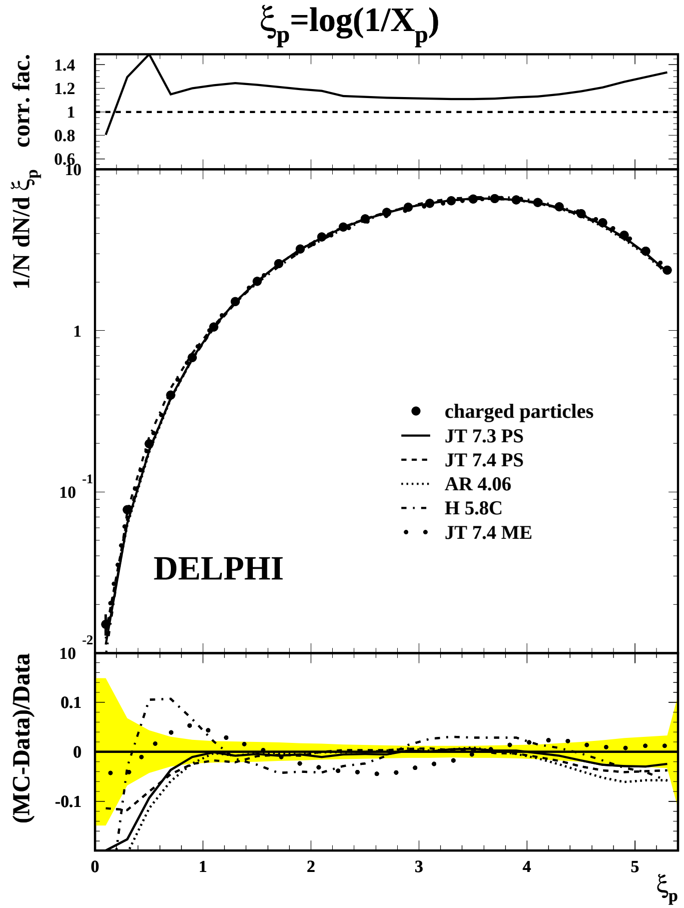
Event Generators at LEP



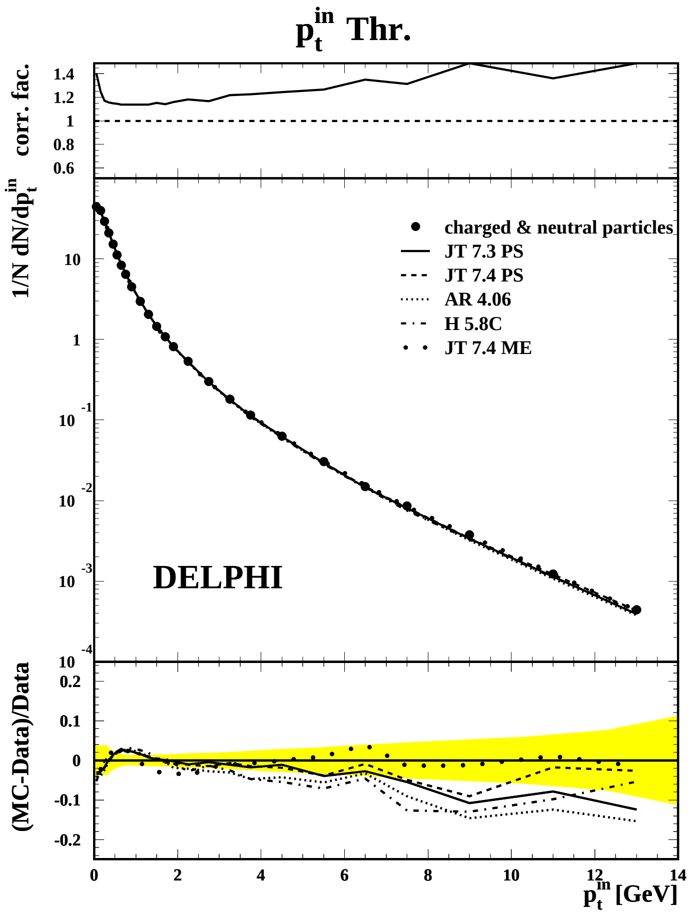


Event Generators at LEP

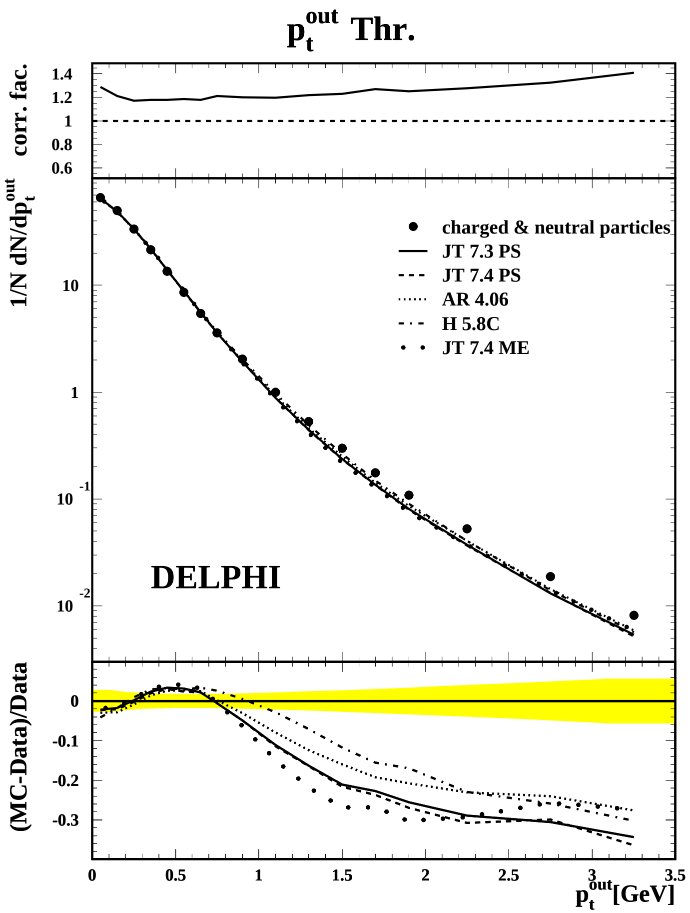




Who needs data when we have PYTHIA, HERWIG and ARIADNE?



p_t^{in} Thr.
corr. fac.
1/N dN/dp$_t^{in}$
charged & neutral particles
JT 7.3 PS
JT 7.4 PS
AR 4.06
H 5.8C
JT 7.4 ME
DELPHI
(MC-Data)/Data
p_t^{in} [GeV]



p_t^{out} Thr.
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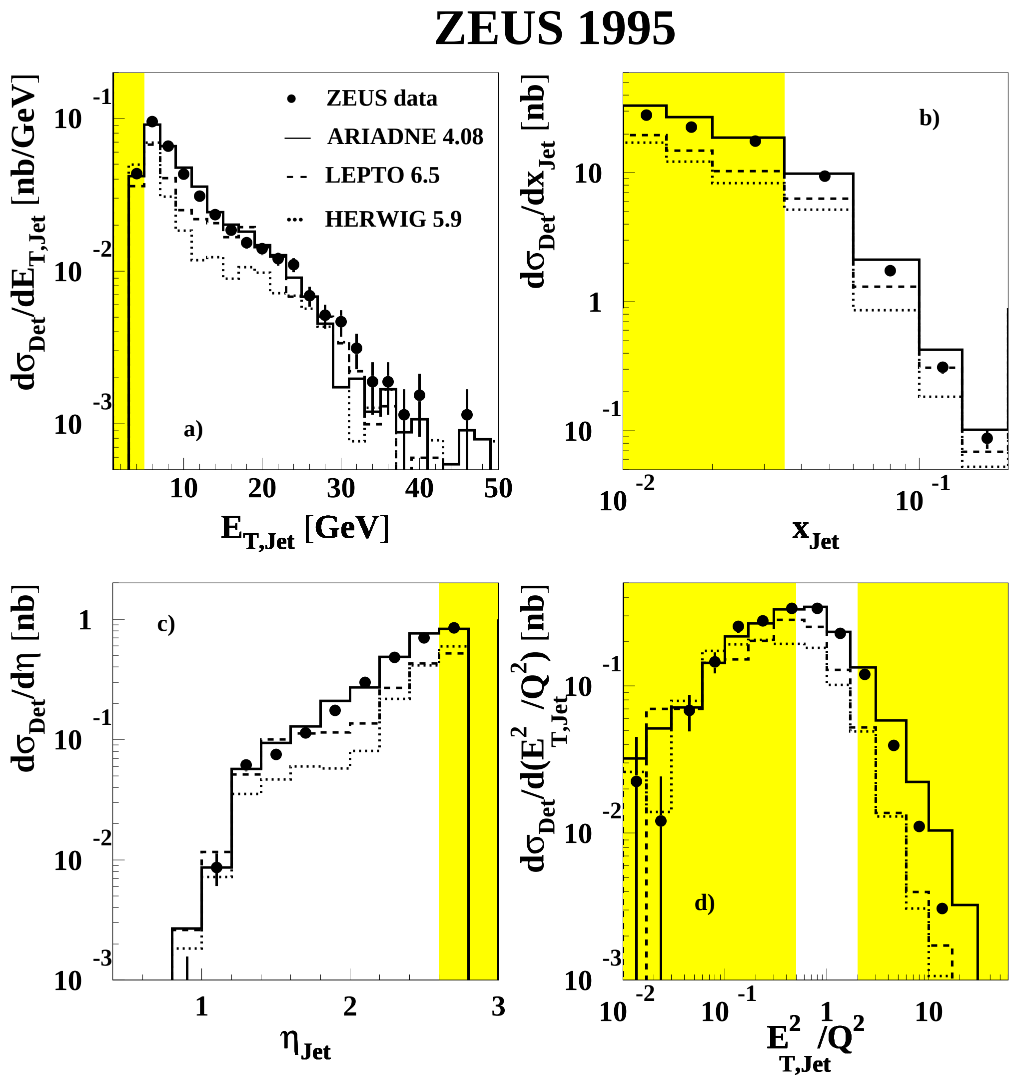
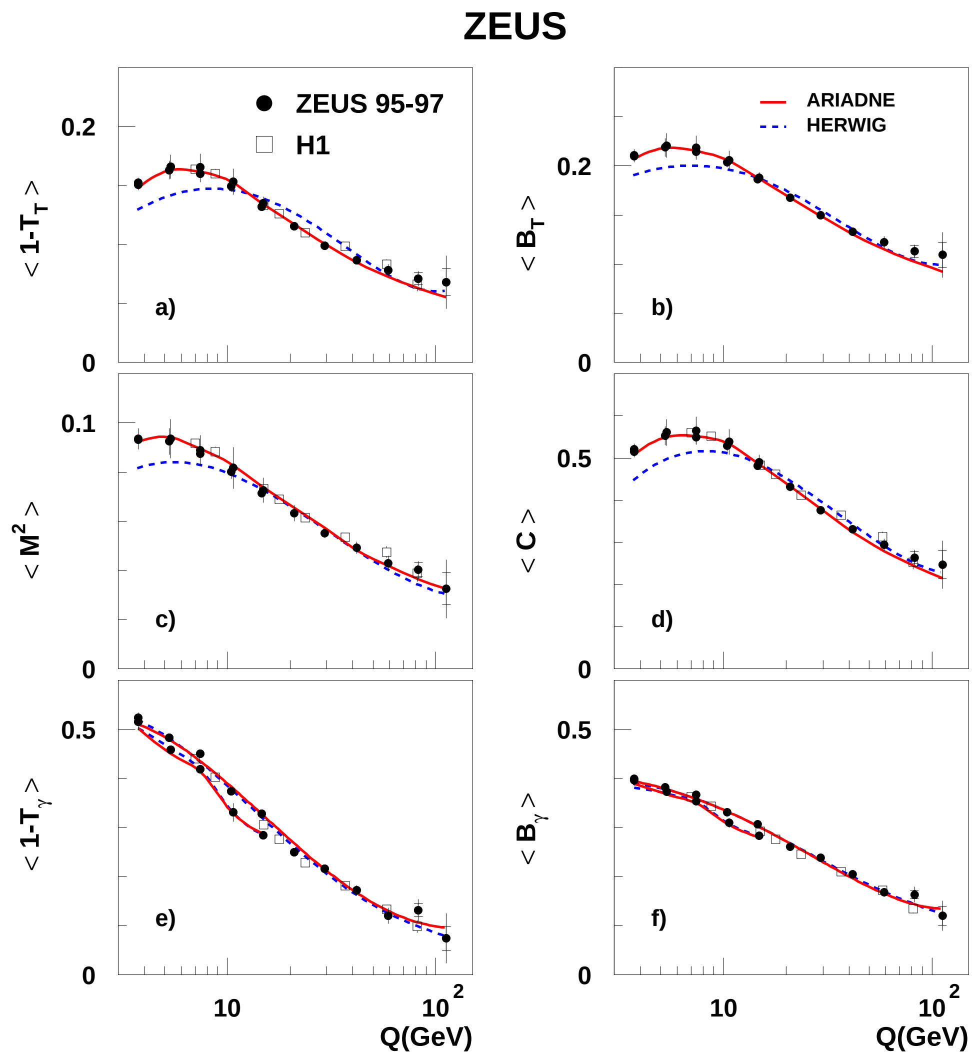
Event Generators at HERA





Not only in the forward region

At HERA we have a hadron in the initial state

There are initial-state parton showers, but they are not quite up to the task at small x

Not even in the current region of the Breit frame, where things should look like half an $\mathrm{e}^+\mathrm{e}^-$ event. At small x the target region is very much larger and hard emissions there affect the current region (energy-momentum conservation).

Event Generators: HERA→LHC

All small-x problems at HERA are there at the LHC

In addition we have multiple scatterings and underlying events (also in photoproduction at HERA)

HERA has a lot to tell us about where to trust the current event generators at LHC

	LEP	HERA	LHC	
HERWIG	•	•	•	with or without JIMMY
PYTHIA	•	•	•	

	LEP	HERA	LHC	
HERWIG	•	•	•	with or without JIMMY
PYTHIA	•	•	•	
ISAJET	(•)		•	
PHOJET		•	•	PYTHIA based
SHERPA	•	(•)	•	AMEGIC + APACIC
ARIADNE	•	•	(•)	PYTHIA based (LDCMC for DIS)
CASCADE		•	(•)	
RAPGAP		•	•	PYTHIA based
LEPTO		•		PYTHIA based

	LEP	HERA	LHC	
HERWIG	•	•	•	with or without JIMMY
PYTHIA	•	•	•	
ISAJET	(•)		•	
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ARIADNE	•	•	(•)	PYTHIA based (LDCMC for DIS)
CASCADE		•	(•)	
RAPGAP		•	•	PYTHIA based
LEPTO		•		PYTHIA based
and more	...			

	LEP	HERA	LHC		Gaps
HERWIG	•	•	•	with or without JIMMY	POMWIG
PYTHIA	•	•	•		soft (and POMPYT or SCI)
ISAJET	(•)		•		
PHOJET		•	•	PYTHIA based	always
SHERPA	•	(•)	•	AMEGIC + APACIC	
ARIADNE	•	•	(•)	PYTHIA based (LDCMC for DIS)	(pomeron)
CASCADE		•	(•)		
RAPGAP		•	•	PYTHIA based	pomeron
LEPTO		•		PYTHIA based	SCI
and more	...				

Forward activity

The second commandment of event generation:

Thou shalt never omit any part of phase space

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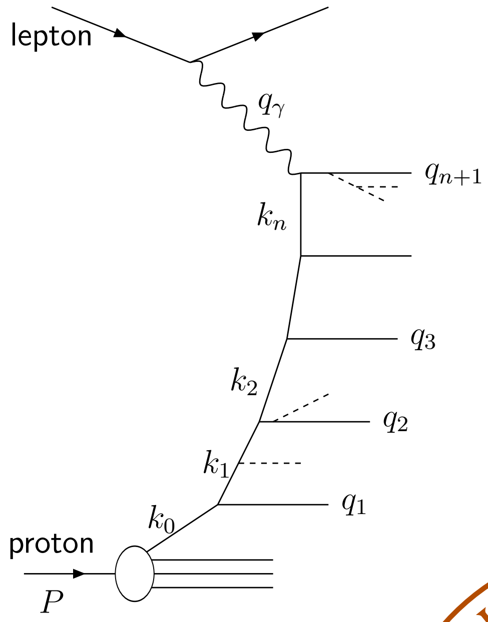
DGLAP based initial-state parton showers limits emissions to be at lower scales than the hard scattering. How severe is this restriction?

For forward jets at HERA it is clearly a severe restriction.

For small-x and moderate scales it is clearly a severe restriction.



ARIADNE is one of the most successful generators at HERA.

Treats all (gluon) radiation as final-state emissions from colour-dipoles formed in the hard scattering.

All phase space is allowed, but suppressed in the forward direction due to the extendedness of the hadron remnant.

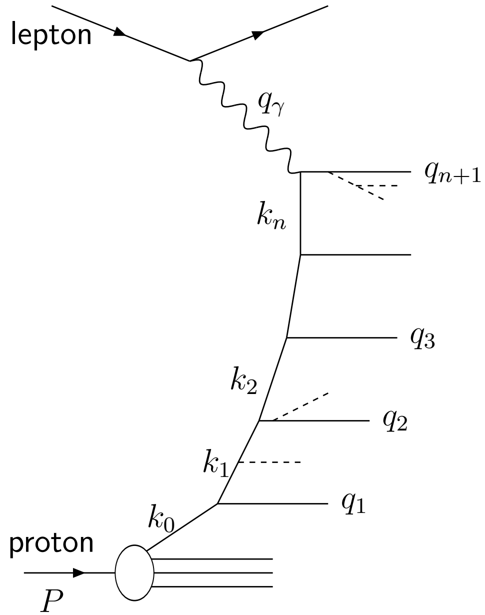
Semi-classical picture which is difficult to relate to conventional evolution schemes. But it seems to work.

RAPGAP (H. Jung) includes a resolved virtual photon and also works.

It is DGLAP based but the $eq \to eq$ is not necessarily the hardest scattering in the event.

Gives two initial-state parton showers

The evolution is allowed to go up and then down, but the whole phase space is not included.



$k_\perp$-factorized (BFKL/CCFM) generators

BFKL is the correct description of QCD in the high-energy limit

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Really?

$k_\perp$-factorized (BFKL/CCFM) generators

BFKL is the correct description of QCD in the high-energy limit

Really?

As soon as you have finite energies, the non-leading corrections are huge.

Some of these corrections are due to the assumption that energy is unlimited. Maybe the first commandment of event generation can help us.

Both CASCADE and LDCMC implements CCFM evolution (BFKL + coherence, close to DGLAP at large Q^2).

Both agree that non-leading corrections are large, even after energy-momentum conservation.

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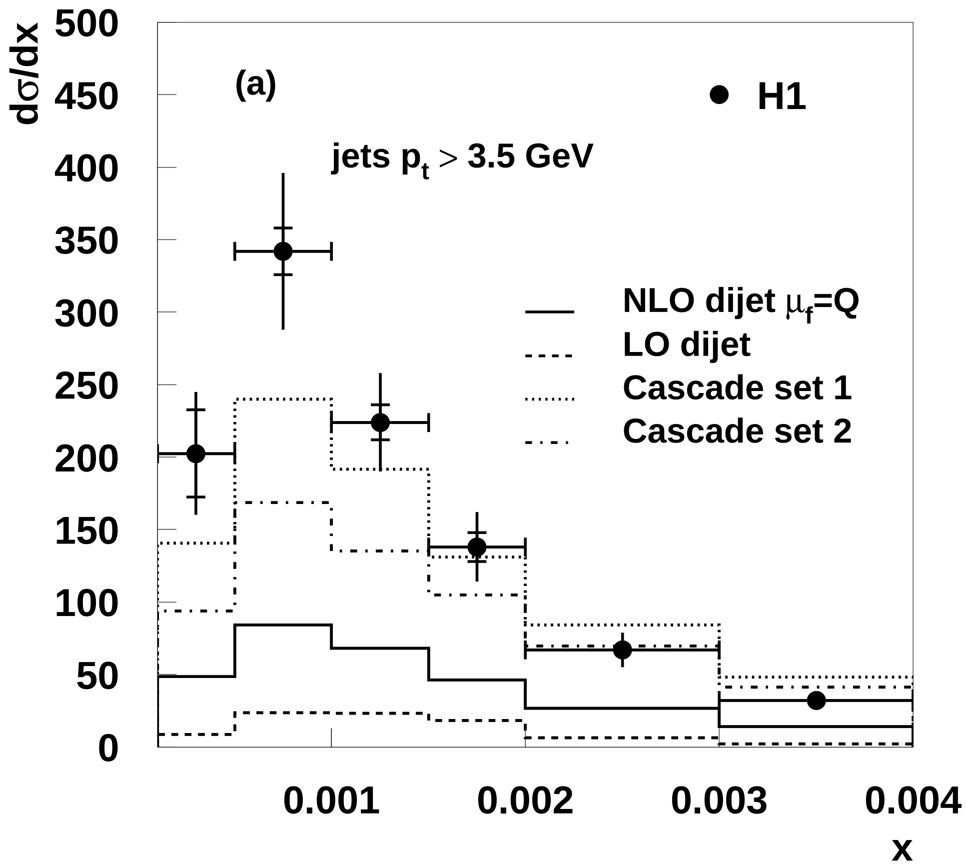
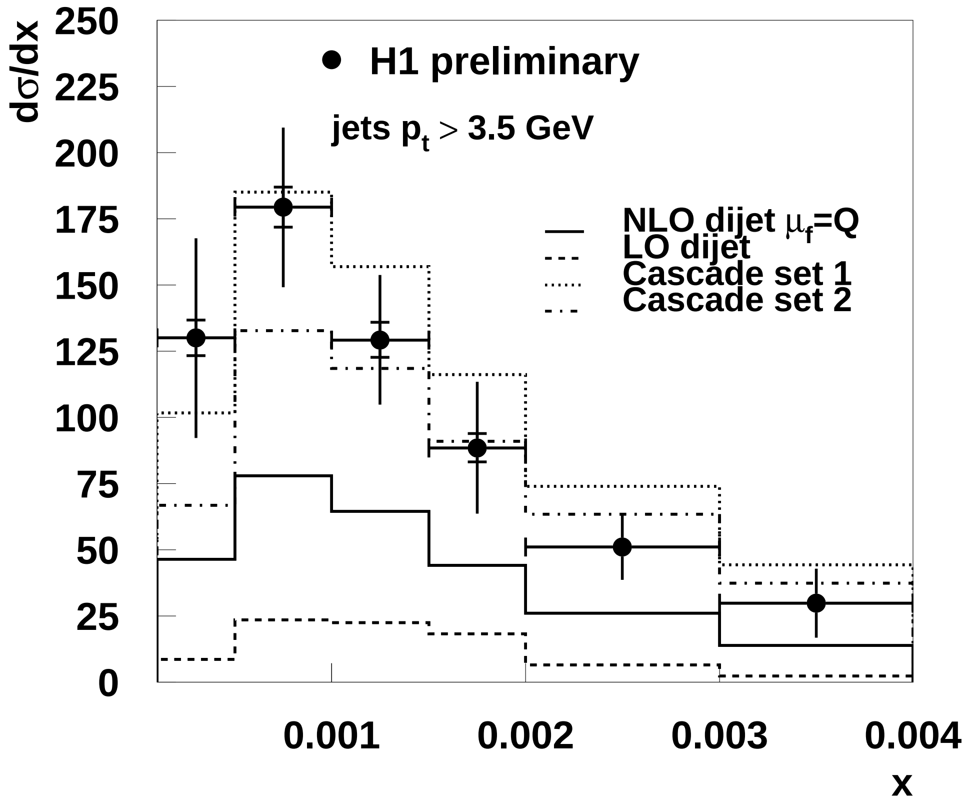
Both agree that non-leading corrections are large, even after energy-momentum conservation.

Both can describe forward jet rates if only gluon ladders are included and if only leading terms of the gluon splitting function is used.

With full splitting functions and quarks in the ladders it is difficult to reproduce data.



Cone algorithm



$k_\perp$-algorithm

Do we care about forward jets at the LHC?

At LHC we will be looking for high scale processes in the middle of the detector.

But consider W-production. Typical x values at the Tevatron is $m_{\mathrm{W}}/S \propto 0.01 - 0.1$, but at LHC they are an order of magnitude lower.

DGLAP-based generators cannot explore this extra phase space, but nature certainly will.

Are these "small-x" effects noticeable already at Tevatron?

Neither PYTHIA or HERWIG can describe the W $k_\perp$-spectrum at small $k_\perp$.

Adding a non-perturbative intrinsic transverse momentum $\langle k_{\perp i} \rangle \lesssim 1$ GeV due to Fermi motion does not help.

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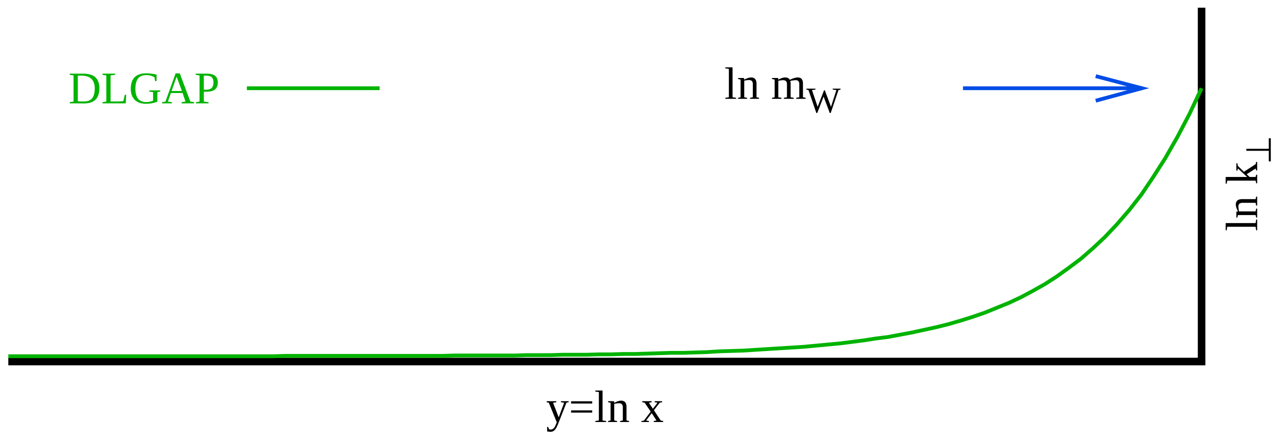
What is the typical evolution path?



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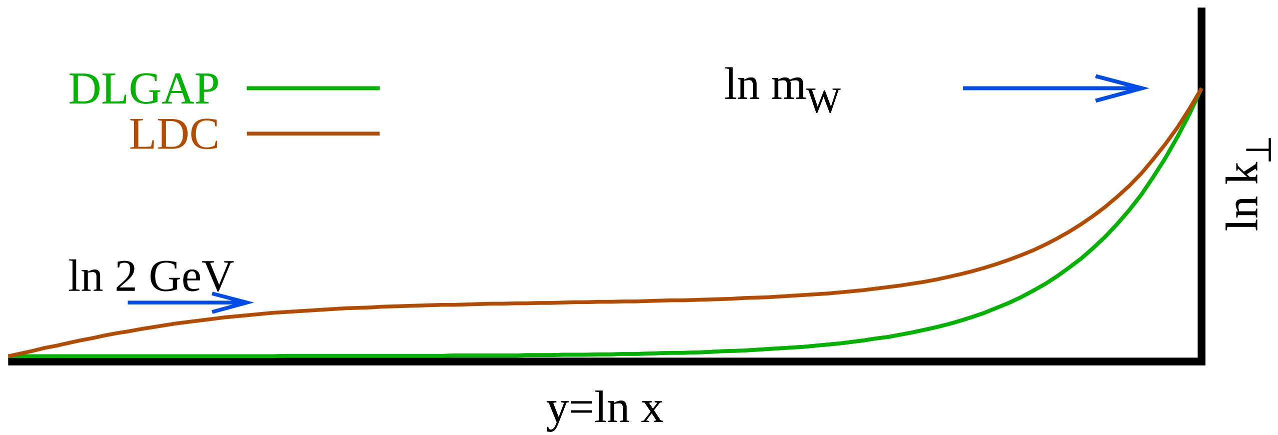

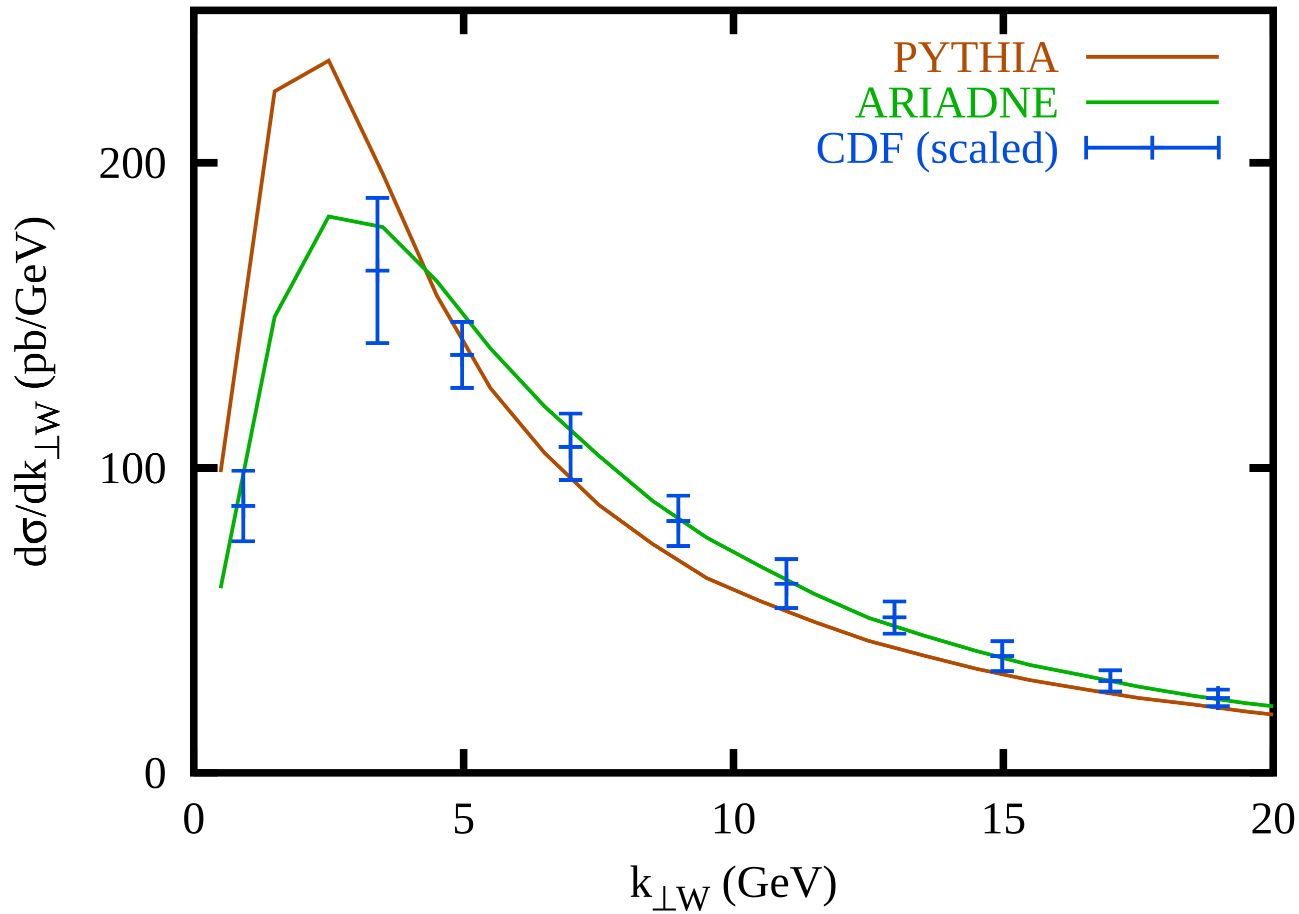
PYTHIA
ARIADNE
CDF (scaled)
0
100
200
0
5
10
15
20
dσ/dk⊥W (pb/GeV)
k⊥W (GeV)

Forward region: Too much or nothing at all

At HERA we have gaps basically once every ten events.

Lots of models can reproduce this:

Factorized pomerons

Dipole/Saturation models

Soft colour interactions

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GMARGETE

...

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Fourth commandment of event generation:

Thou shalt never be satisfied with reproducing inclusive cross sections

Forward region: Too much or nothing at all

At HERA we have gaps basically once every ten events.

Lots of models can reproduce this:

Factorized pomerons (POMPYT, POMWIG, RAPGAP)

Dipole/Saturation models (SATRAP, BJLW)

Soft colour interactions (LEPTO, PYTHIA)

GMARGETE

...

Fourth commandment of event generation:

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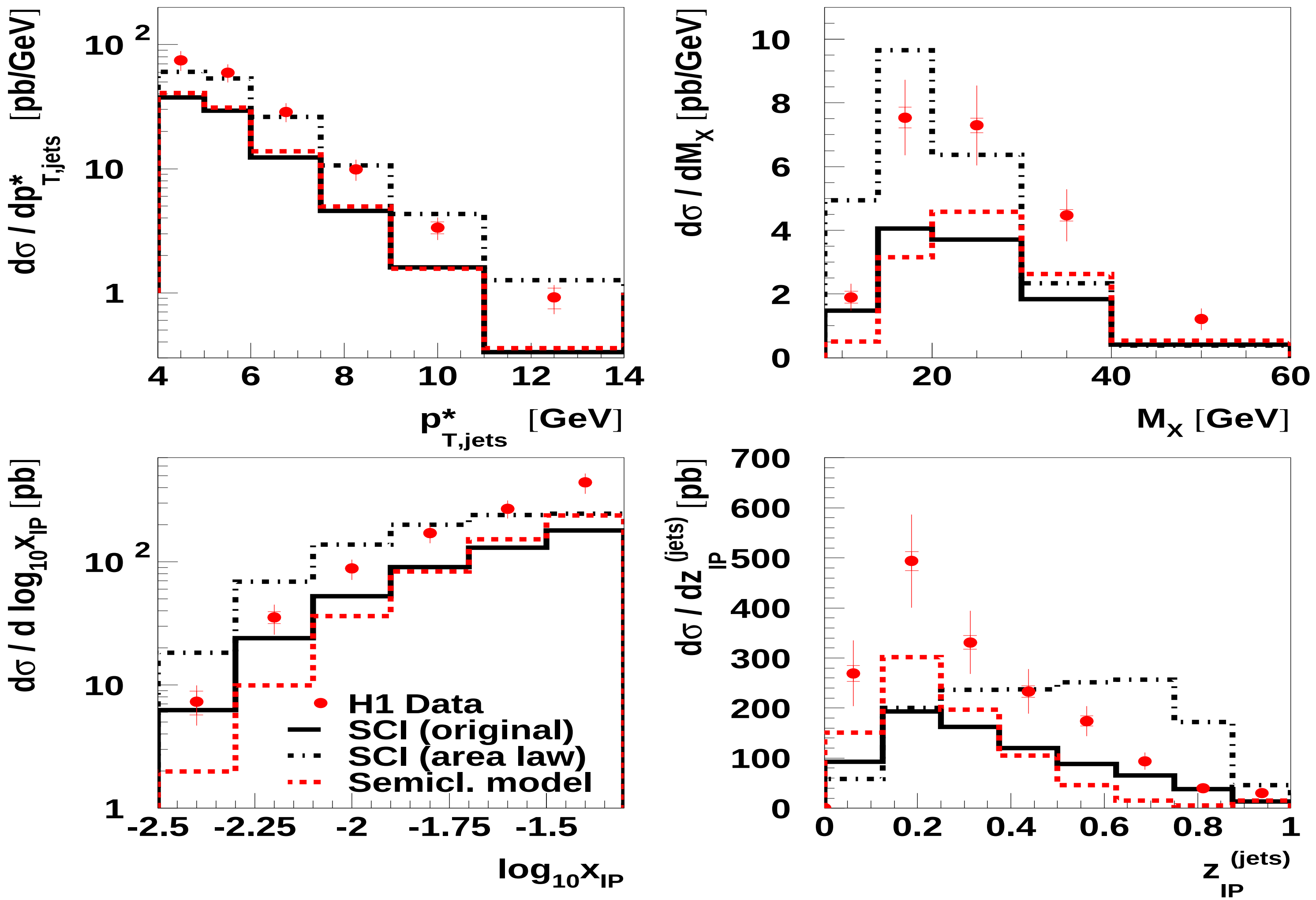
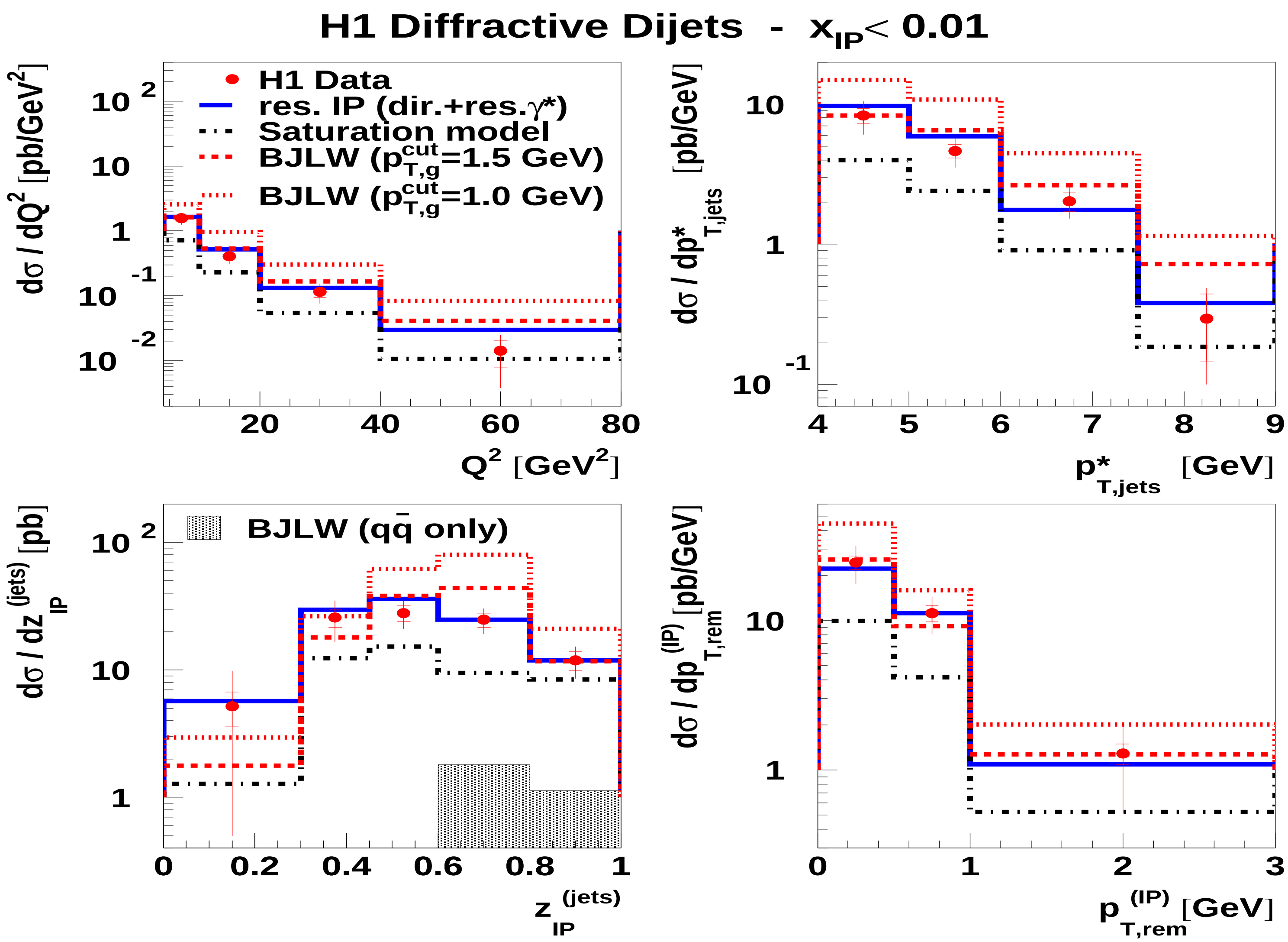
H1 Diffractive Dijets




H1 Diffractive Dijets - x_IP< 0.01
H1 Data
res. IP (dir.+res.γ*)
Saturation model
BJLW (p_T,g^cut=1.5 GeV)
BJLW (p_T,g^cut=1.0 GeV)
dσ / dQ² [pb/GeV²]
Q² [GeV²]
dσ / dp*_T,jets [pb/GeV]
p*_T,jets [GeV]
BJLW (qq̄ only)
dσ / dz_IP^(jets) [pb]
z_IP^(jets)
dσ / dp_T,rem^(IP) [pb/GeV]
p_T,rem^(IP) [GeV]

Only the factorized pomeron and SCI generators can be directly applied at the LHC.

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When you have rapidity gaps, you also have saturation, and you have multiple scatterings — It's the same triple-pomeron diagram cut in different ways.

Underlying events and Multiple scattering

Most UE/MI models (JIMMY, PYTHIA, ...) are based on the eikonalization of the jet cross section.

$$\sigma_{\mathrm{hard}}(p_{\perp\min}^2) = \int_{p_{\perp\min}^2} \frac{d\sigma_{\mathrm{hard}}(p_\perp^2)}{dp_\perp^2} dp_\perp^2$$

Diverges faster than $1/p_{\perp\min}^4$ as $p_{\perp\min}^2 \to 0$ and eventually exceeds the total inelastic (non-diffractive) cross section.

The average number of scatterings are given by

$$\langle n \rangle = \sigma_{\mathrm{hard}}(p_{\perp\min})/\sigma_{\mathrm{nd}}$$

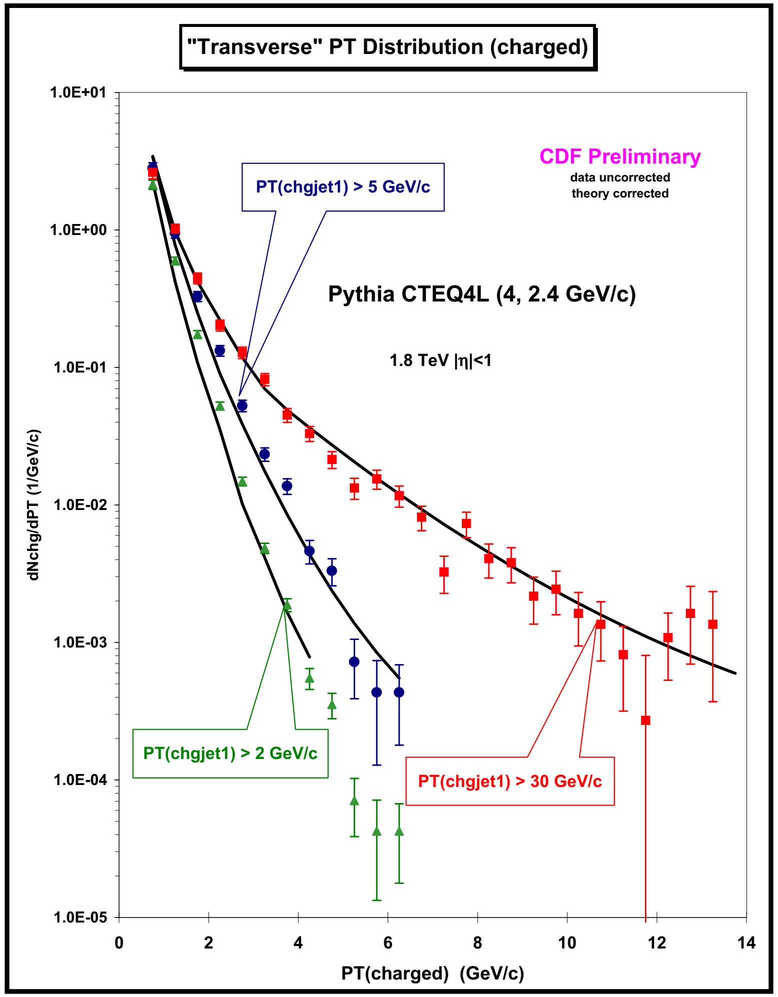
Secondary interactions are not very hard, but PYTHIA models also soft scatterings with partons. Instead of a cut, the partonic cross section is regularized with

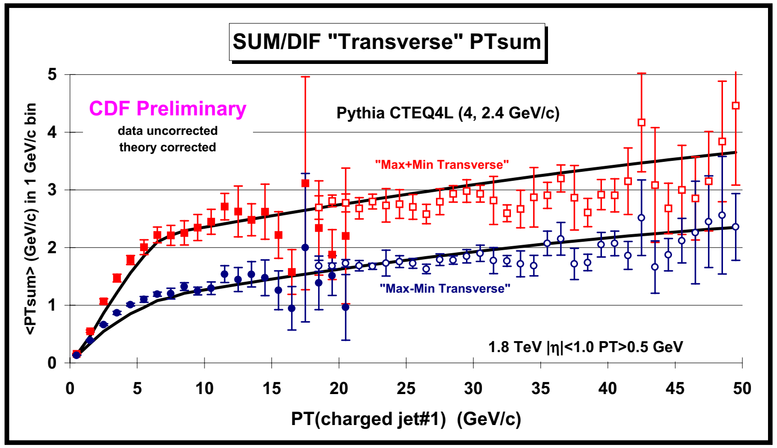
$$\frac{d\hat{\sigma}}{dp_\perp^2} \rightarrow \frac{d\hat{\sigma}}{dp_\perp^2} \times \frac{p_\perp^4}{(p_{\perp 0}^2 + p_\perp^2)^2}$$
$$\alpha_{\mathrm{s}}(p_\perp^2) \rightarrow \alpha_{\mathrm{s}}(p_{\perp 0}^2 + p_\perp^2)$$

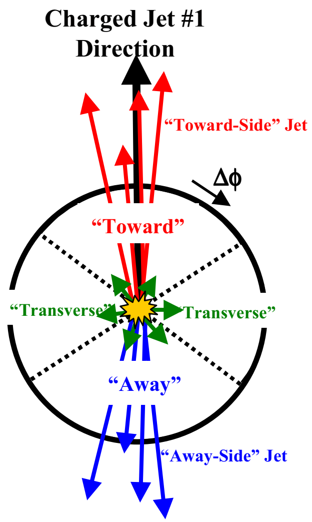
where $p_{\perp 0} \sim 1$ GeV and depends on the total energy.

The model also has an impact-parameter dependence where the partons in a hadron is assumed to be distributed according to a double Gaussian distribution. This introduces non-trivial correlations between scatterings.

It's only a model, but it works:







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But can we really treat these soft, very small-x, secondary scatterings with collinear factorization?

There is a very strong dependence on soft cutoff, $p^2_{\perp 0}$, which is a nasty parameter. It varies with energy and we can only make a guestimate of what it will be at LHC.

But can we really treat these soft, very small-x, secondary scatterings with collinear factorization?

Preliminary investigations using the LDC model gives results which are consistent with PYTHIA, but almost insensitive to the soft cutoff.

UE/MI at HERA

Photoproduction at HERA is a very good testbed for UE/MI models.

Using the x_γ observable we can continuously switch on and off the hadronic part in the photon and hence also the underlying event.

We can also vary the virtuality of the photon, from photoproduction to DIS, and see what happens to the UE.

Maybe there is a jet pedestal under the forward jets cranking up the cross section.

The PYTHIA MI not only predicts the average number of scatterings, it also predicts the distribution in number of scatterings.

If we have a pomeron-induced gap in hadron collisions, any additional scattering will destroy the gap.

The probability of only having one scattering is the Gap Survival Probability

PYTHIA predicts eg. for diffractive exclusive Higgs production a survival probability of 0.040 (Tevatron) and 0.026 (LHC)

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A factorized pomeron (plus reggeon) plus a gap survival probability describes all hard diffraction at HERA and the Tevatron.

Matrix Elements and Parton Showers

Parton shower generators are not good at describing more than one or two hard jets. If we want more we need to use Matrix Element generators. But we still need parton showers to be able to use hadronization models to get proper jets.

How do we combine ME and PS?

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How do we combine ME and PS?

The third commandment of event generation:

Thou shalt never double-count any part of phase space

(Cf. also the second commandment)

A general fixed (second) order calculation

$$\begin{aligned} O_{+0\text{jet}} &= C_{0,0} + C_{0,1}\alpha_\text{s} + C_{0,2}\alpha_\text{s}^2 \\ O_{+1\text{jet}} &= C_{1,1}\alpha_\text{s} + C_{1,2}\alpha_\text{s}^2 \\ O_{+2\text{jet}} &= C_{2,2}\alpha_\text{s}^2 \end{aligned}$$

But all the coefficients are divergent in the soft and collinear limit, so we need a cutoff.

When we add PS, we must not add radiation above this cutoff and also not leave out any phase space below it.

But if you add a PS below the cutoff to an N-jet state from an ME generator, the PS assumes there are no other emissions above.

Parton shower generators do things to all orders, summing up all virtual corrections to leading log into Sudakov form factors.

$$
\begin{aligned}
O_{+0\text{jet}} &= C^{\text{PS}}_{0,0}\Delta_{\text{S0}} \\
O_{+1\text{jet}} &= C^{\text{PS}}_{1,1}\alpha_{\text{s}}\Delta_{\text{S1}} \\
O_{+2\text{jet}} &= C^{\text{PS}}_{2,2}\alpha_{\text{s}}^2\Delta_{\text{S2}} \\
&\ldots
\end{aligned}
$$

$O_{+1\text{jet}} = C^{\text{PS}}_{1,1}\alpha_{\text{s}}\Delta_{\text{S1}}$ is the cross section for to producing one additional jet and nothing else. The Sudakov form factor is a no-emission probability.

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$$
\begin{aligned}
O_{+0\mathrm{jet}} &= C^{\mathrm{PS}}_{0,0}\Delta_{\mathrm{S}0} = C^{\mathrm{PS}}_{0,0} + C^{\mathrm{PS}}_{0,1}\alpha_{\mathrm{s}} + C^{\mathrm{PS}}_{0,2}\alpha_{\mathrm{s}}^2 + \ldots \\
O_{+1\mathrm{jet}} &= C^{\mathrm{PS}}_{1,1}\alpha_{\mathrm{s}}\Delta_{\mathrm{S}1} = C^{\mathrm{PS}}_{1,1}\alpha_{\mathrm{s}} + C^{\mathrm{PS}}_{1,2}\alpha_{\mathrm{s}}^2 + C^{\mathrm{PS}}_{1,3}\alpha_{\mathrm{s}}^3 + \ldots \\
O_{+2\mathrm{jet}} &= C^{\mathrm{PS}}_{2,2}\alpha_{\mathrm{s}}^2\Delta_{\mathrm{S}2} = C^{\mathrm{PS}}_{2,2}\alpha_{\mathrm{s}}^2 + C^{\mathrm{PS}}_{2,3}\alpha_{\mathrm{s}}^3 + C^{\mathrm{PS}}_{2,4}\alpha_{\mathrm{s}}^4 + \ldots \\
\ldots
\end{aligned}
$$

$O_{+1\mathrm{jet}} = C^{\mathrm{PS}}_{1,1}\alpha_{\mathrm{s}}\Delta_{\mathrm{S}1}$ is the cross section for to producing one additional jet and nothing else. The Sudakov form factor is a no-emission probability.

Also these coefficients are divergent. But when summed to all orders the result is finite.

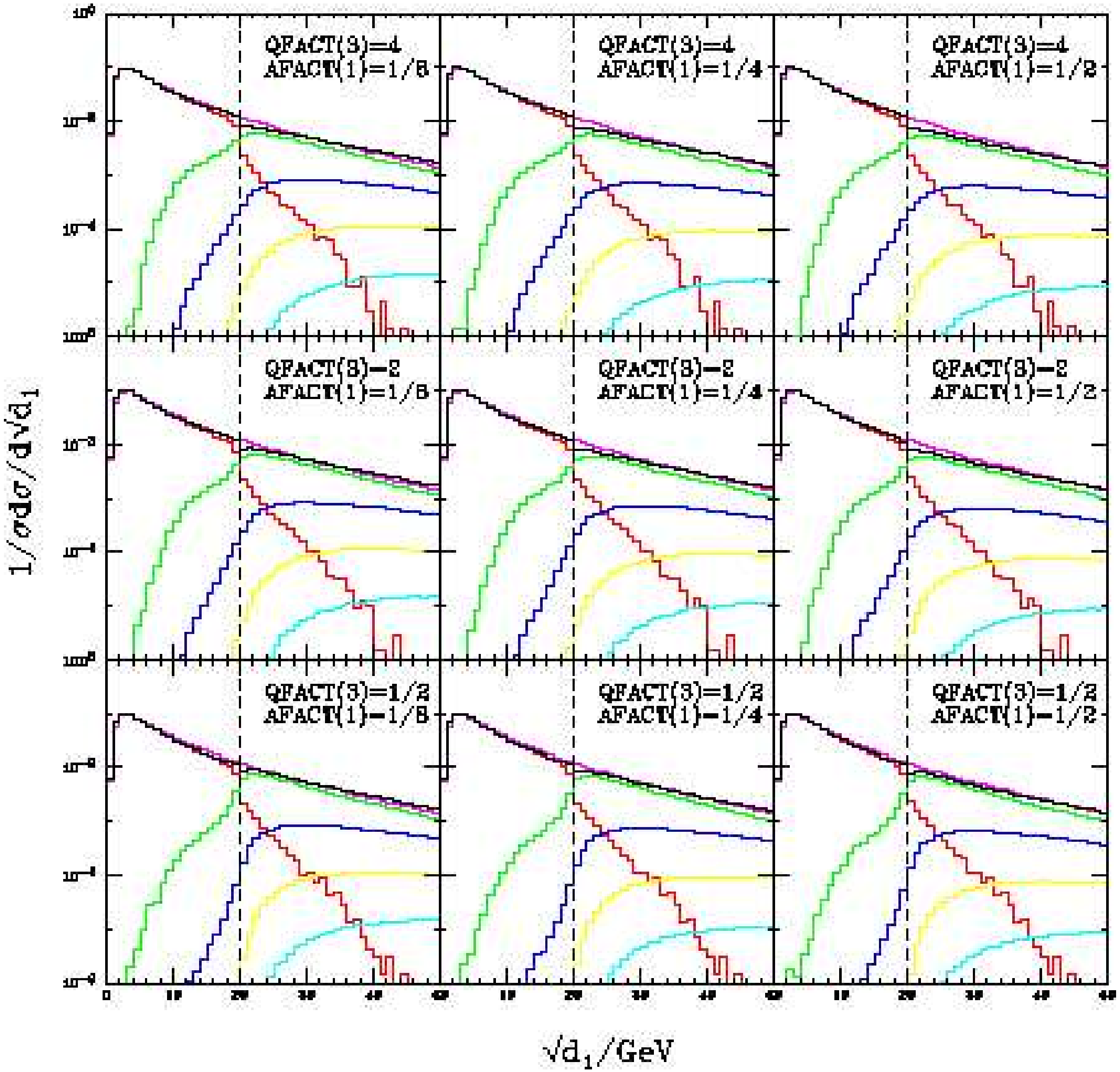
The CKKW strategy

$$
\begin{aligned}
O_{+0\text{jet}} &= C_{0,0}^{\text{ME}}\Delta_{\text{S}0} \\
O_{+1\text{jet}} &= C_{1,1}^{\text{ME}}\alpha_{\text{s}}\Delta_{\text{S}1} \\
O_{+2\text{jet}} &= C_{2,2}^{\text{ME}}\alpha_{\text{s}}^{2}\Delta_{\text{S}2} \\
&\dots
\end{aligned}
$$

Use tree-level ME generator with some cutoff. Make a jet reconstruction to find a sequence of ordered emissions. Reweight with the Sudakov form factors (and running α_{s}) and add a (vetoed) parton shower below the cutoff.

The dependence on the cutoff disappears to NNLL. But it is still visible and some tuning is needed.

S. Mrenna, P. Richardson



CKKW: The ARIADNE version

Use tree level generator with some cutoff.

Make an inverse PS to see how ARIADNE would have generated this state.

Use a Sudakov-veto algorithm to reweight with the exact Sudakovs ARIADNE would have used.

Add PS below the cut, but take special care when adding to the highest multiplicity state from the ME generator not to loose any phase space.

Formally the same as CKKW, but no visible cutoff dependence and no tuning needed.

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Formally the same as CKKW, but no visible cutoff dependence and no tuning needed.

Works for e^+e^-. Started implementing W production and DIS, but there are problems with way of treating initial-state radiation.

MC@NLO

(Frixione, Nason, Webber)

How can we improve also on the virtual corrections?

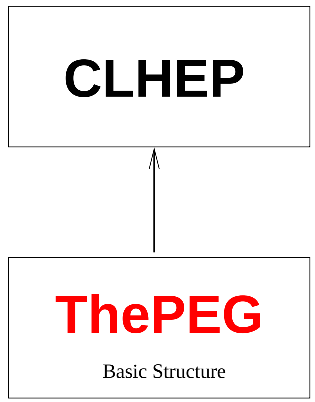
$$
\begin{aligned}
O_{+0\text{jet}} &= \{C_{0,0}^{\text{ME}} + (C_{0,1}^{\text{ME}} - C_{0,1}^{\text{PS}})\alpha_{\text{s}}\}\Delta_{\text{S0}} \\
O_{+1\text{jet}} &= \{C_{1,1}^{\text{ME}} - C_{1,1}^{\text{PS}}\}\alpha_{\text{s}} + C_{1,1}^{\text{PS}}\Delta_{\text{S1}} \\
O_{+2\text{jet}} &= C_{2,2}^{\text{PS}}\alpha_{\text{s}}^{2}\Delta_{\text{S2}} \\
&\dots
\end{aligned}
$$

The divergencies cancel analytically and we have no cutoff.

Only +1jet though . . .

ThePEG & future Event Generators

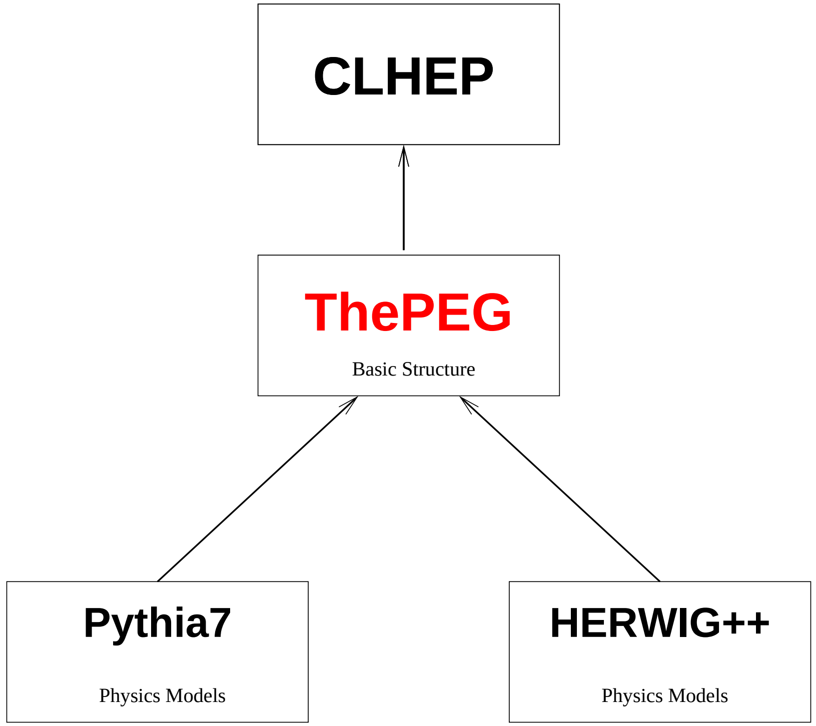
ThePEG consists of the parts of Pythia7 which were not specific to the Pythia physics models. It provides a general structure for implementing models for event generation.



ThePEG & future Event Generators

ThePEG consists of the parts of Pythia7 which were not specific to the Pythia physics models. It provides a general structure for implementing models for event generation.

Both Pythia7 and HERWIG++ are built on ThePEG.



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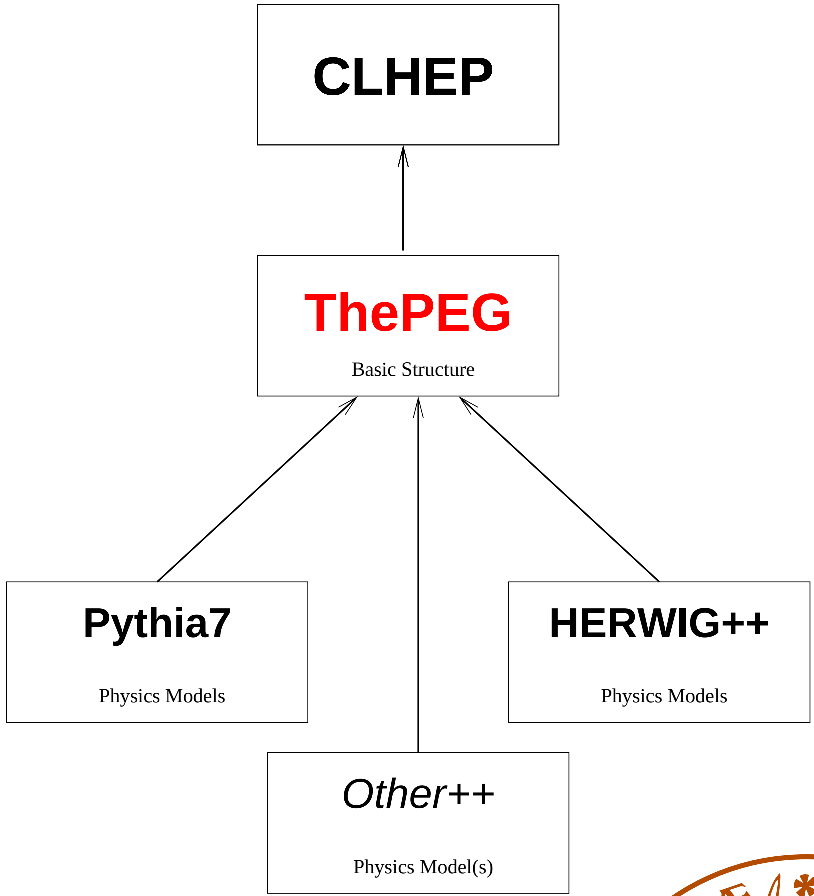
THEPEG consists of the parts of PYTHIA7 which were not specific to the PYTHIA physics models. It provides a general structure for implementing models for event generation.

Both PYTHIA7 and HERWIG++ are built on THEPEG.

But it is open for anyone...



The components of ThePEG

- Basic infrastructure: Smart pointers, extended type information, object persistency, Exceptions, Dynamic loading, . . .
- Kinematics: Extra utilities on top of CLHEP vectors, 5-vectors, flat n-body decay, . . .
- Repository: Manipulation of interfaced objects. Setting of parameters and switches and connecting objects together.
- Handler classes: to inherit from to implement a specific physics model.
- Event record: Used to communicate between handler classes.
- Particle data: particle properties, decay tables, decayers etc...

ThePEG defines a set of abstract Handler classes for hard partonic sub-processes, parton densities, QCD cascades, hadronization, etc...

These handler classes interacts with the underlying structure using a special Event Record and a pre-defined set of virtual function definitions.

The procedure to implement e.g. a new hadronization model, is to write a new (`C++`) class inheriting from the abstract `HadronizationHandler` base class, implementing the relevant virtual functions. Plug it in and run...

Status

THEPEG version 1.0α exists and is working. Snapshots of the current development code is available from http://www.thep.lu.se/ThePEG.

PYTHIA7 is now based on THEPEG. Version 1.0α exists and is working. Snapshots of the current development code is available from http://www.thep.lu.se/Pythia7.

HERWIG++ is also based on THEPEG. Version 1.0 exists and s working. Can be obtained from http://www.hep.phy.cam.ac.uk/theory/Herwig++/.

PYTHIA7/THEPEG (L.L., T. Sjöstrand) includes some basic $2 \to 2$ matrix elements, a couple of PDF parameterizations, remnant handling, initial- and final-state parton showers, Lund string fragmentation and particle decays.

HERWIG++ (S. Gieseke, A. Ribon, P. Richardson, M. Seymour, P. Stephens, B. Webber) includes a new parton shower algorithm, improved cluster fragmentation. Mainly $\mathrm{e}^+\mathrm{e}^-$, but initial-state PS is coming.

SHERPA

SHERPA is an alternative C++ framework for event generation developed by F. Krauss et al.

It is a simpler design than THEPEG, and may have a lower learning threshold.

HZTool

Instead of just publishing the results of an experimental analysis, H1 and ZEUS publish the actual analysis routines applied to standard event generator output (HEPEVT) and the data corrected to hadron level.

A wonderful tool if your are developing a new model or tuning an existing one. Just run your generator, inserting a couple of HZTool calls, and out comes a clean comparison with published data.

JetWeb takes it a bit further to automate the comparison between generators and data: http://jetweb.hep.ucl.ac.uk/

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LHC should copy this concept.

Conclusions

- Event generation is easy.
- We do not understand QCD at small x and in the forward region.
- We cannot get rid of the underlying event, we have to understand it.
- PS generators need to be improved with fixed order ME (or vice versa).

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- PS generators need to be improved with fixed order ME (or vice versa). We know how to do it in principle, but we're not quite there. HERA is the place to test it.
- The future has a $++$ appended to it.