Hadronization, Soft Modelling and Heavy Ions (1)

LUND UNIVERSITY

Leif Lönnblad

Department of Astronomy
and Theoretical Physics
Lund University

MCnet School
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Outline

- Hadronization
- The (semi-) inclusive pp cross section(s)
- Minimum bias and Regge theory
- Multiple interactions
- Underlying events
- Summary: General Purpose Event Generators

Hadronization

Now that we are able to generate partons, both hard, soft, collinear, we now need to convert them to hadrons.

This is a non-perturbative process, and all we can do is to construct models, and try to include as much as possible of what we know about non-perturbative QCD.

Local Parton–Hadron Duality

An analytic approach ignoring non-perturbative difficulties.

Run shower down to scales $\sim \Lambda_{\mathrm{QCD}}$.

Each parton corresponds to one (or 1.something) hadron.

Can describe eg. momentum spectra surprisingly well.

Can be used to calculate power corrections to NLO predictions for event shapes,

- $\langle 1 - T \rangle = c_1 \alpha_{\mathrm{s}}(E_{\mathrm{cm}}) + c_2 \alpha_{\mathrm{s}}^2(E_{\mathrm{cm}}) + c_p / E_{\mathrm{cm}}$

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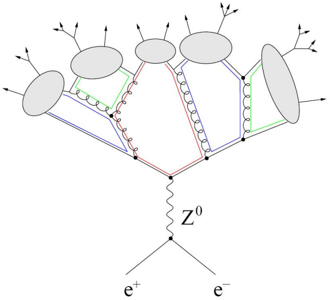
Cannot generate real events with this though.

Cluster Hadronization

Close to local parton–hadron duality in spirit. Based on the idea of Preconfinement:

The pattern of perturbative gluon radiation is such that gluons are emitted mainly between colour-connected partons. If we emit enough gluons the colour-dipoles will be small.



After the shower, force $g \to q\bar{q}$ splittings giving low-mass, colour-singlet clusters

Decay clusters isotropically into two hadrons according to phase space weight
$\sim (2s_1 + 1)(s_2 + 1)(2p/m)$

Cluster hadronization is very simple and clean.
Maybe too simple. . .

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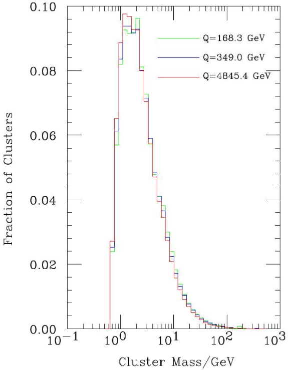
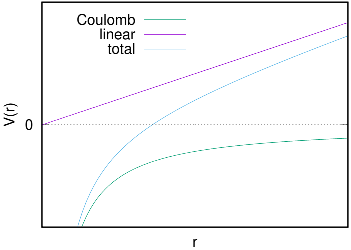
Maybe too simple…



- Cluster masses can be large (finite probability for no gluon emission): Introduce *string-like* decays of heavy clusters into lighter ones (with special treatment of proton remnant).
- In clusters including a heavy quark (or a di-quark) the heavy meson (or baryon) should go in this direction: introduce anisotropic cluster decays.
- …

String Hadronization

What do we know about non-perturbative QCD?



- At small distances we have a Coulomb-like asymptotically free theory
- At larger distances we have a linear confining potential

For large distances, the field lines are compressed to vortex lines like the magnetic field in a superconductor

1+1-dimensional object $\sim$ a massless relativistic string

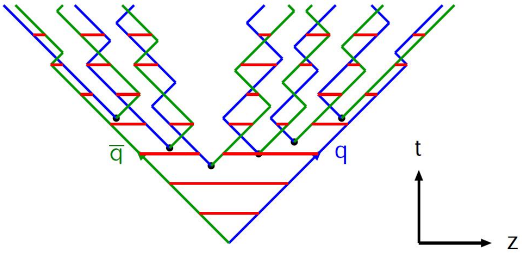
As a $\mathrm{q\bar{q}}$-pair moves apart, they are slowed down and more and more energy is stored in the string.

If the energy is small, the $\mathrm{q\bar{q}}$-pair will eventually stop and move together again. We get a “YoYo”-state which we interpret as a meson.

If high enough energy, the string will break as the energy in the string is large enough to create a new $\mathrm{q\bar{q}}$-pair.

The energy in the string is given by the string tension

$$\kappa = \left|\frac{dE}{dz}\right| = \left|\frac{dE}{dt}\right| = \left|\frac{dp_z}{dz}\right| = \left|\frac{dp_z}{dt}\right| \sim 1\mathrm{GeV/fm}$$



The quarks obtain a mass and a transverse momentum in the breakup through a tunneling mechanism

$$\mathcal{P} \propto e^{-\frac{\pi m_{q\perp}^2}{\kappa}} = e^{-\frac{\pi m_q^2}{\kappa}} e^{-\frac{\pi p_\perp^2}{\kappa}}$$

Gives a natural supression of heavy quarks
$\mathrm{d\bar{d}} : \mathrm{u\bar{u}} : \mathrm{s\bar{s}} : \mathrm{c\bar{c}} \approx 1 : 1 : 0.3 : 10^{-11}$

The break-ups starts in the middle and spreads outward, but they are causually disconnected. So we should be able to start anywhere.

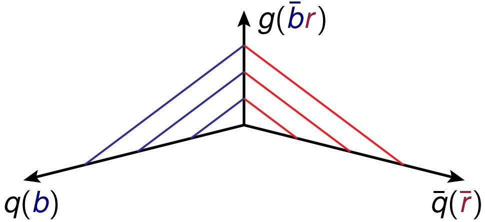
In particular we could start from either end and go inwards.

Requiring left-right symmetry we obtain a unique *fragmentation function* for a hadron taking a fraction z of the energy of a string end in a breakup

$$p(z) = \frac{(1-z)^a}{z} e^{-bm_\perp^2/z}$$

The Lund symmetric fragmentation function.

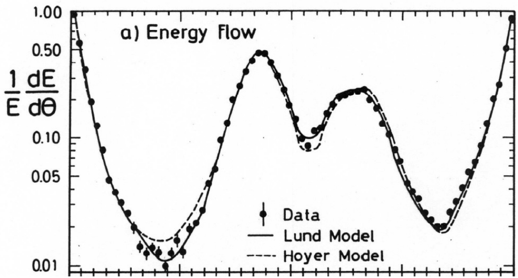
Gluons complicates the picture somewhat. They can be interpreted as a “kinks” on the string carrying energy and momentum



The gluon carries twice the charge ($N_C/C_F \to 2$ for $N_C \to \infty$)

A bit tricky to go around the gluon corners, but we get a consistent picture of the energy–momentum structure of an event with no extra parameters.

The Lund string model predicted the string effect measured by Jade.



In a three-jet event there are more energy between the $\mathrm{g} - \mathrm{q}$ and $\mathrm{g} - \bar{\mathrm{q}}$ jets than between $\mathrm{q} - \bar{\mathrm{q}}$.

For the flavour structure the picture becomes somewhat messy.

Baryons can be produced by having $\mathrm{qq}-\bar{\mathrm{q}}\bar{\mathrm{q}}$-breakups (diquarks behaves like an anti-colour), but more complicated mechanisms ("popcorn") needed to describe baryon correlations.

We also need special suppression of strange mesons, baryons. Parameters for different spin states, ...

There are *lots* of parameters i PYTHIA.

Strings vs. Clusters

Model	string (PYTHIA)	cluster (HERWIG)
energy–momentum picture	powerful, predictive few parameters	simple, unpredictive many parameters
flavour composition	messy, unpredictive many parameters	simple, reasonably predictive few parameters

There will always be parameters. . .

Most hadronization parameters have been severely constrained by LEP data. Does this mean we can use the models directly at LHC?

The PDG decay tables

The Particle Data Group has machine-readable tables of decay modes.

But they are not complete and cannot be used directly in an event generator.

- Branching ratios need to add up to unity.
- Some decays are listed as $B^{\star 0} \to \mu^+ \nu_\mu X$.
- ...

Most decays need to be coded by hand

Particle Decays

Not the most sexy part of the event generators,
but still essential.

$$
\begin{aligned}
&B^{\star 0} \to \gamma \;\; B^0 \\
&\qquad\qquad \hookrightarrow \overline{B}^0 \to e^- \bar{\nu}_e \;\; D^{\star +} \\
&\qquad\qquad\qquad\qquad\qquad \hookrightarrow \pi^+ \;\; D^0 \\
&\qquad\qquad\qquad\qquad\qquad\qquad\quad \hookrightarrow K^- \;\; \rho^+ \\
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EM decays

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Weak mixing

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$\hookrightarrow e^+ e^- \gamma$

Weak decay, displaced vertex, $|\mathcal{M}|^2 \propto (p_{\bar{B}} p_{\bar{\nu}})(p_e p_{D^\star})$

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Strong decay

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\end{array}
$$

Weak decay, displaced vertex, ρ mass smeared

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ρ polarized, $|\mathcal{M}|^2 \propto \cos^2\theta$ in ρ rest frame

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Dalitz decay, $m_{e^+e^-}$ peaked

What happens at LHC? (13 TeV)

Total	100 mb
Non-diffractive	56 mb
Elastic	22 mb
Diffractive	22 mb
Jets $p_\perp > 150\ GeV$	220 nb
W+Z	200 nb
Top	600 pb
Higgs	30 pb

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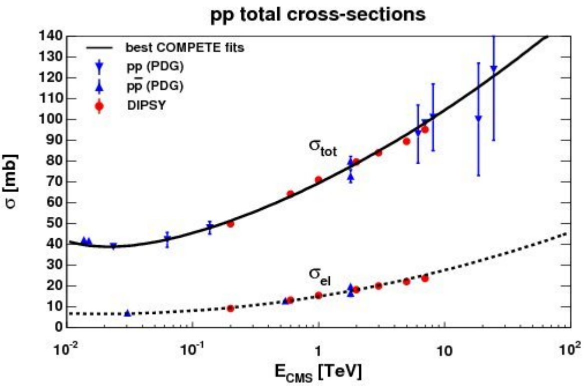
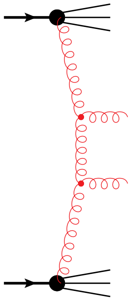
Almost everything at LHC is pure QCD

Inclusive cross sections.



Minimum Bias: The typical *pp* collision



soft $gg \to gg$

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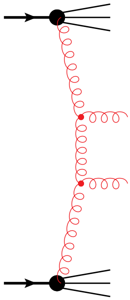

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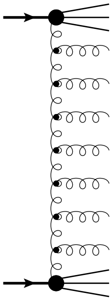

+ISR

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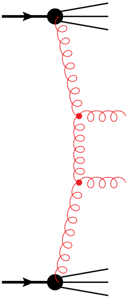

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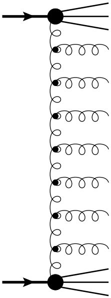

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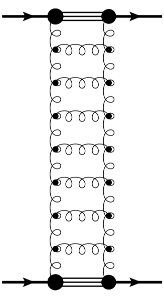

Related to elastic scattering
via optical theorem

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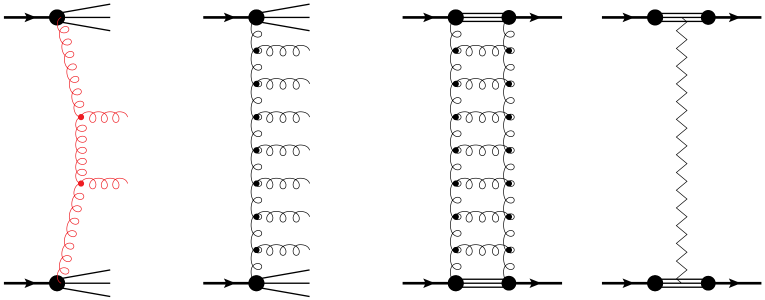

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Pomeron exchange

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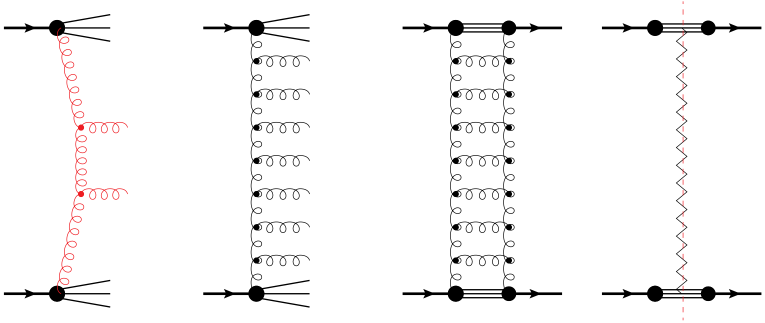


soft $gg \to gg$

+ISR

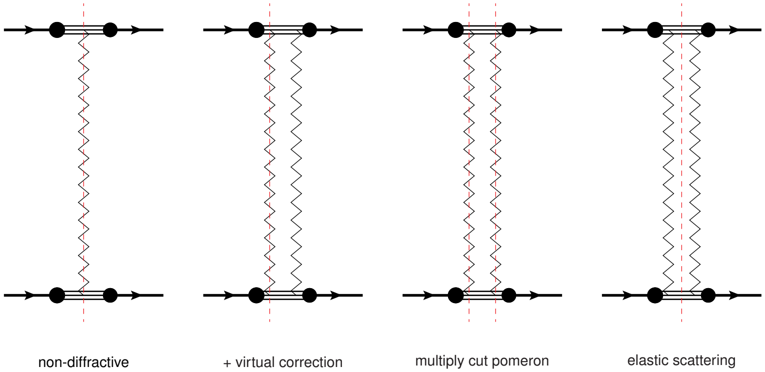
Related to elastic scattering via optical theorem

Pomeron exchange

A cut pomeron in an elastic amplitude gives the non-diffractive cross section.

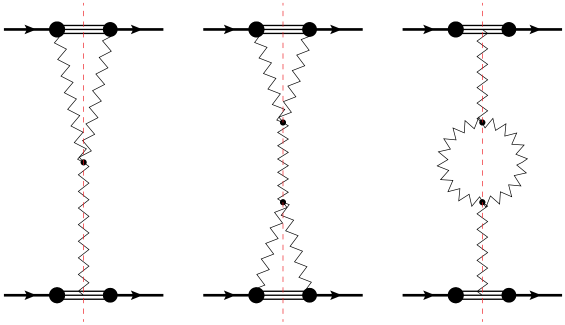
(From Regge theory [Regge. T, *Nuovo Cim.* **14** (1959) 951])

Multi-pomeron diagrams



Each cut pomeron contributes with evenly distributed particle production in the corresponding rapidity interval.
Like two flat strings.

Diffraction and triple-pomeron vertices

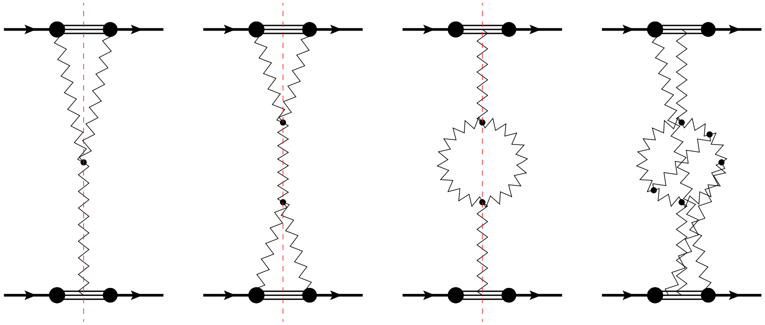


single diffractive excitation

central diffraction

double diffraction

Diffraction and triple-pomeron vertices



single diffractive excitation

central diffraction

double diffraction

?

Soft multiple interactions

- PHOJET [Engel et al.]
- Shrimps (SHERPA) [Zapp et al.]
- EPOS-LHC (also Heavy ions) [Werner et al.]

Where are the (mini-) jets?

(Semi-) Hard Multiple Interactions

Starting Point in PYTHIA:

$$\frac{d\sigma^H}{dk_\perp^2} = \sum_{ij} \int dx_1 dx_2 f_i(x_1, \mu_F^2) f_j(x_2, \mu_F^2) \frac{d\hat{\sigma}_{ij}^H}{dk_\perp^2}$$

The QCD $2 \to 2$ cross section is divergent $\propto \alpha_S^2(k_\perp^2)/k_\perp^4$

$\int_{k_{\perp c}^2} d\sigma^H$ will exceed the total (non-diffractive) *pp* cross section at the LHC for $k_{\perp c} \lesssim 5$ GeV.

There are more than one partonic interaction per *pp*-collision

$$\langle N_H \rangle (k_{\perp c}) = \frac{\int_{k_{\perp c}^2} d\sigma^H}{\sigma^{\mathrm{ND}}}$$

The trick in PYTHIA is to treat everything as if it is perturbative.

$$\frac{d\hat{\sigma}_{ij}^{H}}{dk_{\perp}^{2}} \rightarrow \frac{d\hat{\sigma}_{ij}^{H}}{dk_{\perp}^{2}} \times \left(\frac{\alpha_S(k_{\perp}^2 + k_{\perp 0}^2)}{\alpha_S(k_{\perp}^2)} \cdot \frac{k_{\perp}^2}{k_{\perp}^2 + k_{\perp 0}^2} \right)^2$$

Where $k_{\perp 0}^2$ is motivated by colour screening (saturation) and is dependent on collision energy.

$$k_{\perp 0}(E_{\mathrm{CM}}) = k_{\perp 0}(E_{\mathrm{CM}}^{\mathrm{ref}}) \times \left(\frac{E_{\mathrm{CM}}}{E_{\mathrm{CM}}^{\mathrm{ref}}} \right)^{\epsilon \sim 0.16}$$

(using handwaving about the the rise of the total cross section)

The total and non-diffractive cross section is put in by hand (or with a Donnachie—Landshoff parameterization).

- Pick a hardest scattering according to

$$\frac{1}{\sigma^{\mathrm{ND}}}\frac{d\sigma^H}{dk_\perp^2} \times \exp\left(-\int_{k_\perp^2} dq_\perp^2 \frac{1}{\sigma^{\mathrm{ND}}}\frac{d\sigma^H}{dq_\perp^2}\right)$$

- Pick an impact parameter, b, from the overlap function (high $k_\perp$ gives bias for small b).
- Generate additional scatterings with decreasing $k_\perp$ using $d\sigma^H(b)/\sigma^{\mathrm{ND}}$

Hadronic matter distributions

We assume that we have factorization

$$\mathcal{L}_{ij}(x_1, x_2, b, \mu_F^2) = \mathcal{O}(b) f_i(x_1, \mu_F^2) f_j(x_2, \mu_F^2)$$

$$\mathcal{O}(b) = \int dt \int dxdydz \rho(x, y, z) \rho(x + b, y, z + t)$$

Where ρ is the matter distribution in the proton
(note: general width determined by σ^{ND})

- A simple Gaussian (too flat)
- Double Gaussian (hot-spot)
- x-dependent Gaussian

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x-dependent overlap

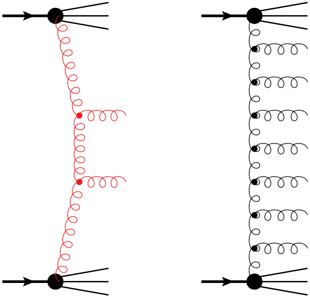
Small-x partons are more spread out

$$\rho(r, x) \propto \exp\left(-\frac{r^2}{a^2(x)}\right)$$

with $a(x) = a_0(1 + a_1 \log 1/x)$

Note that high $k_\perp$ generally means higher x and more narrow overlap distribution.

Is it reasonable to use collinear factorization even for very small $k_\perp$?
Soft interactions means very small x, should we not be using $k_\perp$-factorization and BFKL?



Energy–momentum conservation

Each scattering consumes momentum from the proton, and eventually we will run out of energy.

- Continue generating MI's with decreasing $k_\perp$, until we run out of energy.
- Or rescale the PDF's after each additional MI. (Taking into account flavour conservation).

Note that also initial-state showers take away momentum from the proton.

Interleaved showers

When do we shower?

- First generate all MI's, then shower each?
- Generate shower after each MI?

Is it reasonable that a low-$k_\perp$ MI prevents a high-$k_\perp$shower emission? Or vice versa?

- Include MI's in the shower evolution

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After the primary scattering we can have

- Initial-state shower splitting, $P_{\rm ISR}$
- Final-state shower splitting, $P_{\rm FSR}$
- Additional scattering, $P_{\rm MI}$
- Rescattering of final-state partons, $P_{\rm RS}$

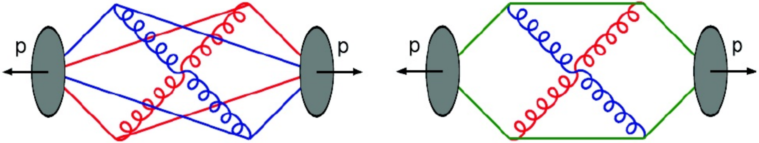
Let them compete

$$\frac{d\mathcal{P}_a}{dk_\perp^2} = \frac{dP_a}{dk_\perp^2} \times \exp - \left(\int_{k_\perp^2} (dP_{\rm ISR} + dP_{\rm FSR} + dP_{\rm MI} + dP_{\rm RS}) \right)$$

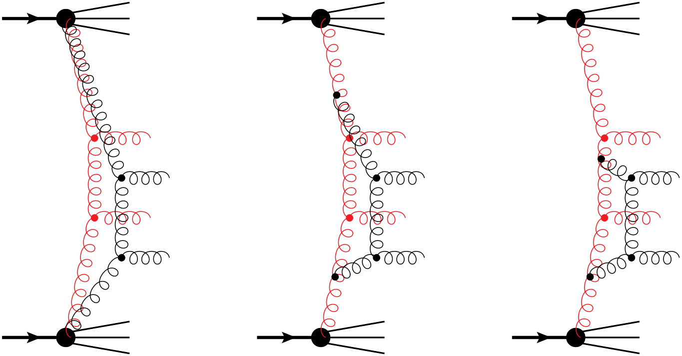
Colour Connections

Every MI will stretch out new colour-strings.

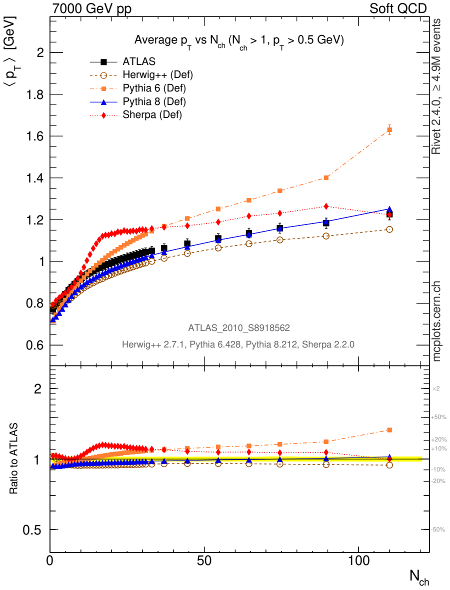
Evidently not all of them can stretch all the way back to the proton remnants.



To be able to describe observables such as $\langle p_\perp \rangle(n_{\mathrm{ch}})$ we need (a lot of) colour (re-)connections.



(a) (b) (c)


7000 GeV pp
Soft QCD
Average p_T vs N_{ch} (N_{ch} > 1, p_T > 0.5 GeV)
ATLAS
Herwig++ (Def)
Pythia 6 (Def)
Pythia 8 (Def)
Sherpa (Def)
ATLAS_2010_S8918562
Herwig++ 2.7.1, Pythia 6.428, Pythia 8.212, Sherpa 2.2.0
Rivet 2.4.0, ≥ 4.9M events
mcplots.cern.ch
$\langle p_T \rangle$ [GeV]
Ratio to ATLAS
N_{ch}

Beyond simple strings

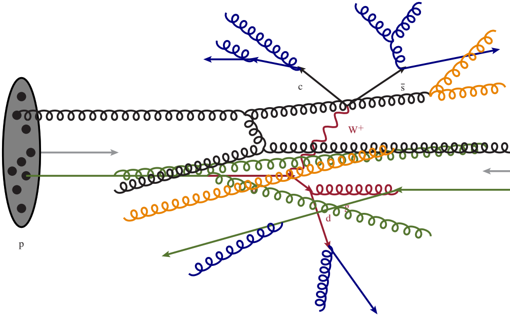
What if we kick out two valens quarks from the same proton?

Normally it is assumed that the proton remnant has a di-quark, giving rise to a leading baryon in the target fragmentation.

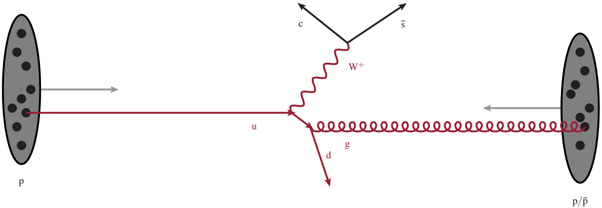
PYTHIA8 has can hadronize string junctions
(also used for baryon-number violating BSM models)

Non-trivial baryon number distribution in rapidity.

What is the Underlying Event?

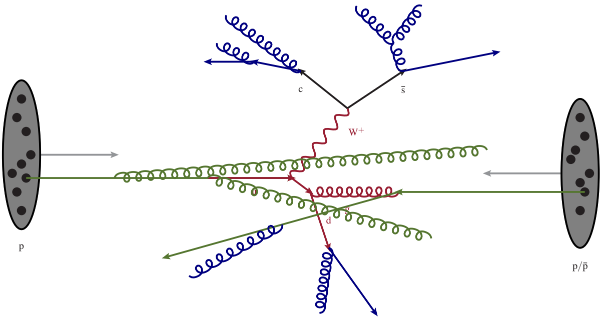


What is the Underlying Event?



Everything except the hard sub-process?

What is the Underlying Event?



Everything except the hard sub-process
and initial- and final-state showers?

Subtracting underlying events from jets.

- ISR adds energy
- FSR removes energy
- UE adds energy
- Hadronization removes energy

Some of these can be made to cancel eachother by adjusting the size of the jet cone.

But we still need to understand the underlying event.

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UE is not MB

- Harder processes gives a bias towards larger overlap (smaller *b*) giving more UE.
- The UE fluctuates — we can't just subtract a number
- Beware of jet cuts in a steeply falling spectrum

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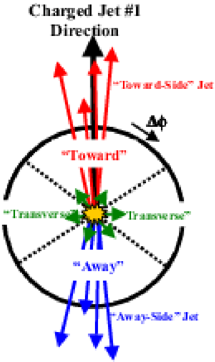
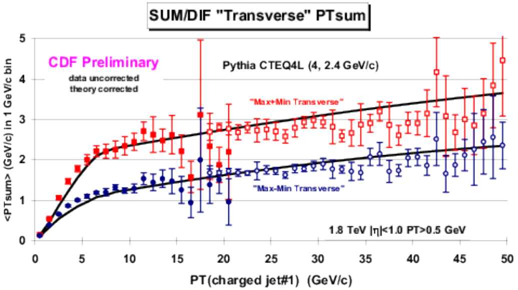
Also relevant for pile-up


Charged Jet #1 Direction
"Toward-Side" Jet
Δφ
"Toward"
"Transverse"
"Transverse"
"Away"
"Away-Side" Jet


SUM/DIF "Transverse" PTsum
CDF Preliminary
data uncorrected
theory corrected
Pythia CTEQ4L (4, 2.4 GeV/c)
"Max+Min Transverse"
"Max-Min Transverse"
1.8 TeV |η|<1.0 PT>0.5 GeV
<PTsum> (GeV/c) in 1 GeV/c bin
PT(charged jet#1) (GeV/c)

A note on Tuning

The Min-bias and UE machineries contains a fair number of parameters that need to be tuned to data. In PYTHIA we have:

- Soft regularisation parameters
- Overlap function parameters
- Cross section parameterisations
- Colour reconnection parameters
- Intrisic transverse momenta
- PDF choices
- …

Global Tuning

General purpose event generators should describe everything. They should not be tuned to a single observable.

- Hadronization parameters and final-state showers can be tuned to $\mathrm{e}^{+}\mathrm{e}^{-}$ data (LEP).
- Initial-state showers and UE/MPI can be tuned to MB data.
- Anythings else should be fixed by measured Standard Model parameters.
- . . . in principle

Global Tuning

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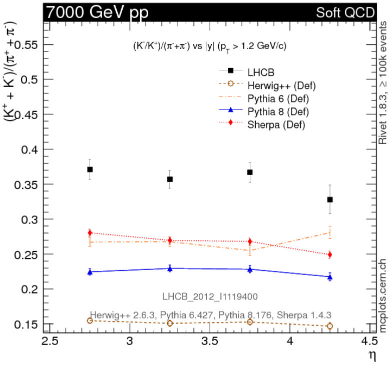
Jet universality

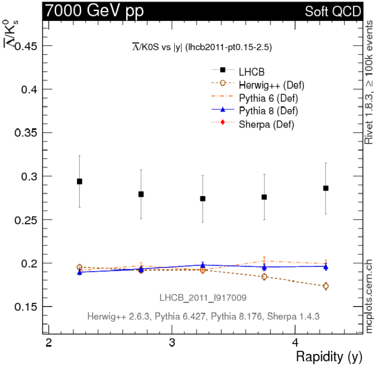
There may be problems with flavour and meson/baryon issues.

Also at LEP there were mainly quark jets, gluon jets are softer and not very well measured.

At LHC there will be very hard gluon jets.

We need to check that jet universality works.


7000 GeV pp
Soft QCD
(K⁻/K⁺)/(π⁻+π⁻) vs |y| (p_T > 1.2 GeV/c)
$(K^+ + K^-)/(\pi^+ + \pi^-)$
LHCB
Herwig++ (Def)
Pythia 6 (Def)
Pythia 8 (Def)
Sherpa (Def)
LHCB_2012_I1119400
Herwig++ 2.6.3, Pythia 6.427, Pythia 8.176, Sherpa 1.4.3
Rivet 1.8.3, ≥ 100k events
mcplots.cern.ch
η


7000 GeV pp
Soft QCD
$\bar{\Lambda}/K^0_s$
$\bar{\Lambda}$/K0S vs |y| (lhcb2011-pt0.15-2.5)
LHCB
Herwig++ (Def)
Pythia 6 (Def)
Pythia 8 (Def)
Sherpa (Def)
LHCB_2011_I917009
Herwig++ 2.6.3, Pythia 6.427, Pythia 8.176, Sherpa 1.4.3
Rivet 1.8.3, ≥ 100k events
mcplots.cern.ch
Rapidity (y)

General Purpose Event Generators

There are only a few programs which deals with the whole picture of the event generation

- Hard sub-processes
- Parton showers
- Multiple interactions
- Hadronization
- Decays

Many more programs deal with a specific part of the event generation

- Hard subprocess: AlpGen, MadEvent, . . . can be used with other generators using the Les Houches interface (but be sure to do proper merging)
- Parton Shower: ARIADNE, CASCADE, Vincia, DIRE, . . . need to be integrated with a specific general purpose generator
- Multiple interactions: JIMMY (HERWIG) Shrimps (SHERPA)
- Hadroniziation (?)
- Decays: Tauola, EvtGen, typically called from within other generators.

PYTHIA8

- A few simple MEs, the rest from Les Houches
- $k_\perp$-ordered initial-/final-state DGLAP-based shower
- (N)LO multi-leg matching (not automatic)
- Multiple interactions interleaved with shower
- Lund String Fragmentation
- Particle decays

https://pythia.org

HERWIG++

- Construction of arbitrary MEs using helicity amplitudes
- Angular ordered and dipole shower
- Different matching schemes via MatchBox
- Soft+hard multiple interactions
- Cluster hadronization
- Particle decays with correlations

http://projects.hepforge.org/herwig

SHERPA

- Built-in automated ME generator
- Dipole-based shower
- Semi-automatic (N)LO multi-leg matching
- Multiple interactions ($\sim$ old PYTHIA) with some CKKW features (also Shrimps)
- Cluster hadronization (string fragmentation via old PYTHIA).
- Standard particle decays.

`https://sherpa-team.gitlab.io`

Related Tools

Matrix Element Generators

- **MadGraph5(aMC@NLO)**
- POWHEG
- ALPGEN
- HELAC
- CompHEP
- ...

PDF parametrizations

- LHAPDF

Rivet.hepforge.org

(Buckley et al.)

Analyze Event Generator output and compare with published experimental data, using exactly the same cuts, triggers, etc.

400+ analyses are already in there.

If you want to make your analyses useful for others — Publish them in Rivet!

Connected to *Professor* for tuning of parameters

MCplots.cern.ch

(Skands et al.)