Introduction to Monte Carlo generators - II

(Fully exclusive modeling of high-energy collisions)

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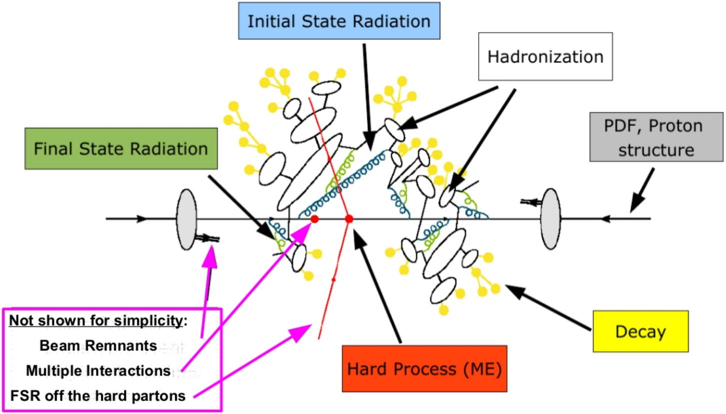
CTEQ School - University of Pittsburgh, USA 18 - 28 July 2017

Thanks to: S. Gieseke, S.Höche, F. Krauss,L. Lonnblad, W. Placzek, S. Prestel, M. H. Seymour, T. Sjöstrand, P. Skands, M. Schönherr, B. Webber

Reminder: Building blocks of Monte Carlo Generators



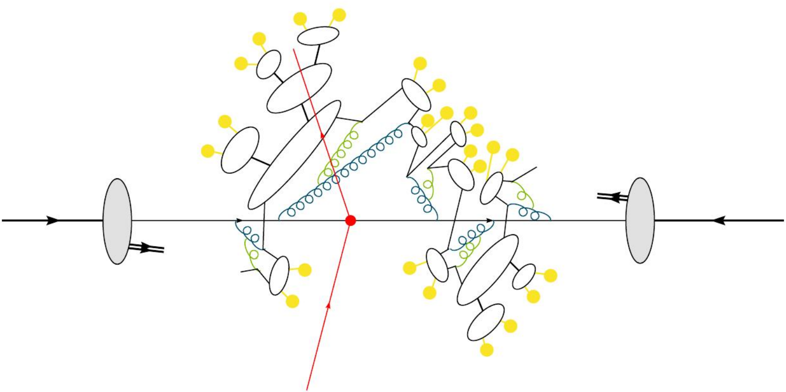
taken from Stefan Gieseke©

The general approach is the same in different programs but the models and approximations used are different.

Plan

- 1st lecture
  - Monte Carlo methods why and how?
  - Parton Shower
- 1st tutorial
  - Build your own Parton Shower (in Python)!
- 2nd lecture
  - Hadronization
  - Multiple Parton Interaction
  - Tuning
- 2nd tutorial
  - Shower uncertainties (in Python)
    or
  - MC@NLO/POWHEG (see Marek's lecture) matching in Python
- 3rd tutorial
  - Real life example - work with Herwig, Sherpa and Pythia!

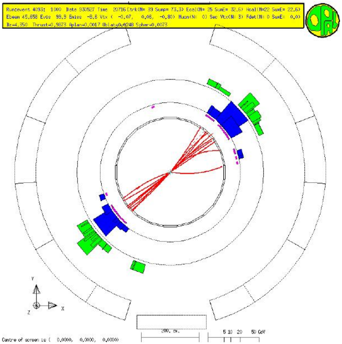
Hadronization (non-perturbative semi-empirical models)

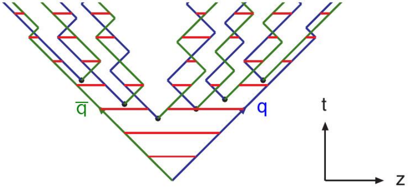


- Two main models: Lund string model and Cluster model
  also
  older: Flux tube model and Independent fragmentation (Feynman-Field fragmentation '78)
- Hadronization factorizes from hard process (process-independent)
- Both main models contain many parameters to be determined from data, preferably LEP.

[Andersson,Gustafson,Ingelman,Sjostrand] Phys.Rept.97(1983)31

Originally invented without parton showers in mind.

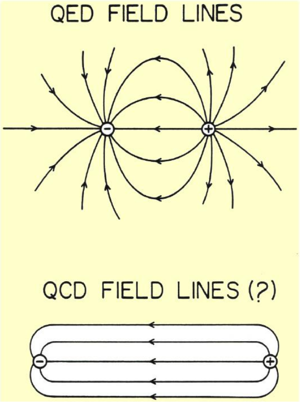




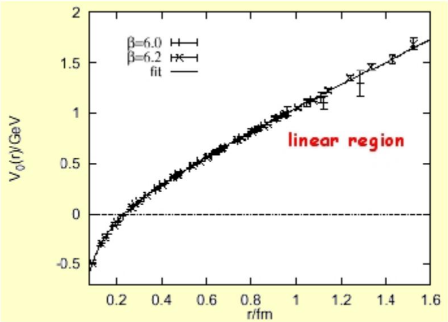
We start with 2-jet events in $e^+e^- \longrightarrow$ hadrons.
Lund string model: like rubber band that is pulled apart and breaks into pieces, or like a magnet broken into smaller pieces.

Lund model - Physical motivation

Self coupling of gluons
$\leftrightarrow$ "attractive field lines"



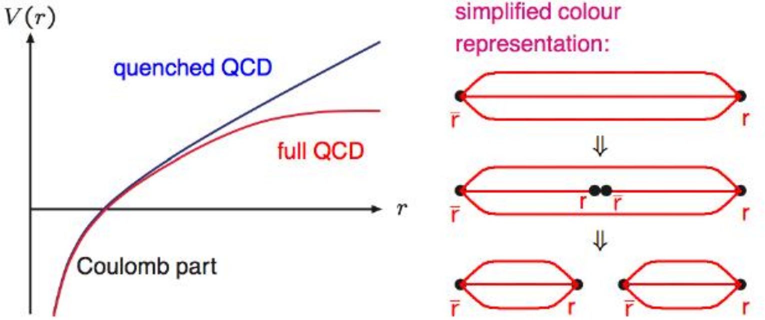
Linear static potential $V(r) \approx \kappa r$.



Supported by lattice QCD,
hadron spectroscopy.

$\kappa = 1$ GeV/fm $\sim$ potential energy gain lifting a 16 ton truck.
Flux tube uniform traversal shape (in the central region) $\rightarrow$ simple description as a 1+1 - dimensional object - a string

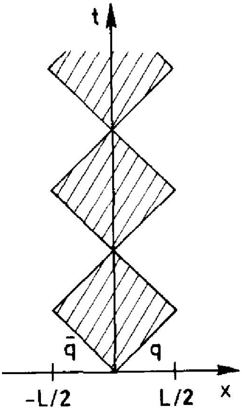
Lund string: like rubber band that is pulled apart and breaks into pieces



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

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

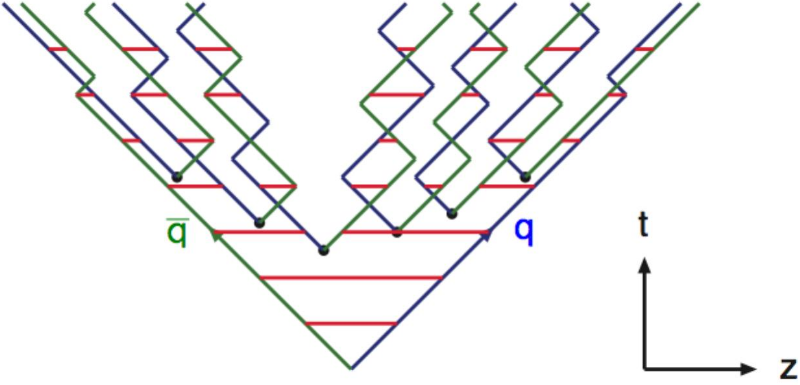
If high enough energy, the string will break as the energy in the string is large enough to create a new $q\bar{q}$ pair.



Assume negligibly small quark masses. Then linearity between space-time and energy-momentum gives:

$$\left|\frac{\mathrm{d}E}{\mathrm{d}z}\right| = \left|\frac{\mathrm{d}p_z}{\mathrm{d}z}\right| = \left|\frac{\mathrm{d}E}{\mathrm{d}t}\right| = \left|\frac{\mathrm{d}p_z}{\mathrm{d}t}\right| = \kappa$$

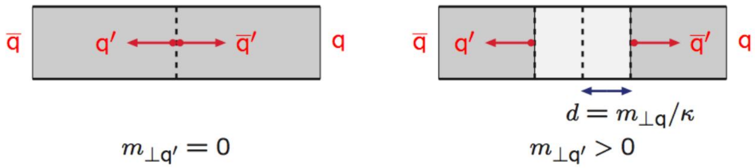
Combine yo-yo-style string motion with string breakings.
Motion of quarks and antiquarks with intermediate string pieces.



A quarks from one string break combines with a antiquarks from an adjacent one.

How does the string break?

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



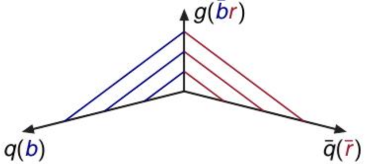
Probablity of tunneling:

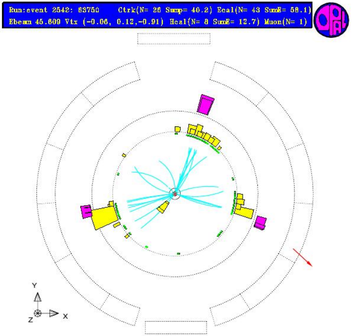
$$\mathcal{P} \propto \exp\left(-\frac{\pi m_{\perp q}^2}{\kappa}\right) = \exp\left(-\frac{\pi p_{\perp q}^2}{\kappa}\right) \exp\left(-\frac{\pi m_q^2}{\kappa}\right)$$

- Suppression of heavy quarks: $u\bar{u} : d\bar{d} : s\bar{s} : c\bar{c} \approx 1 : 1 : 0.3 : 10^{-11}$
- Diquark (qq - $\bar{q}\bar{q}$ breakups) $\sim$ antiquark $\Rightarrow$ simple model for baryon production.

String model has very good energy-momentum picture however it is unpredictive in understanding of hadron mass effects $\Rightarrow$ many parameters, 10-20 depending on how you count.

Gluon a kink in the string.



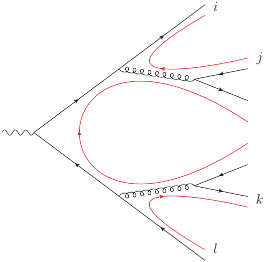


The Lund string model predicted the string effect measured by Jade. In a three-jet event there are more energy between the gq and $g\bar{q}$ jets than between $q\bar{q}$.

[Webber NPB238(1984)492]

What if we have PS (more perturbative input before hadronization).
Can we get a simpler model?

Cluster Model:



- QCD parton showers provide *pre-confinement* of colour:
- Planar approximation: gluon = colour-anticolour pair

[Webber NPB238(1984)492]

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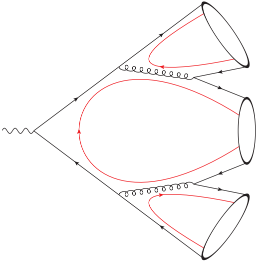
Cluster Model:

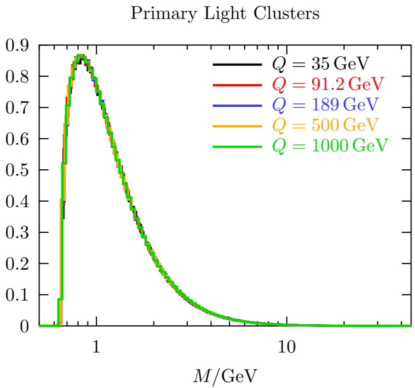


- QCD parton showers provide *pre-confinement* of colour:
- Planar approximation: gluon = colour-anticolour pair
- colour-singlet pairs end up close in phase space and form highly excited hadronic states, the *clusters*
- Clusters ($\sim$ excited hadrons) decay into hadrons

Mass spectrum of colour-singlet pairs asymptotically independent of energy, production mechanism

Cluster model - Mass spectrum

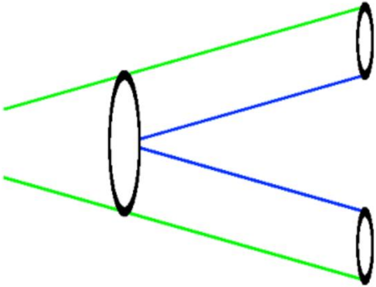
Mass spectrum of primordial clusters independent of cm energy.



Peaked at low mass (1-10 GeV) typically decay into 2 hadrons. Project colour singlets onto continuum of high-mass mesonic resonances (clusters). Decay to lighter well-known resonances and stable hadrons.

Heavy cluster

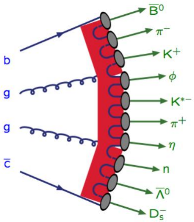
- Although cluster mass spectrum peaked at small m, broad tail at high m.
- Small fraction of clusters too heavy for isotropic two-body decay to be a good approximation
- heavy cluster decay first (Longitudinal cluster fission) into lighter cluster, or radiate a hadron $C \to CC$ $C \to HC$, it is rather

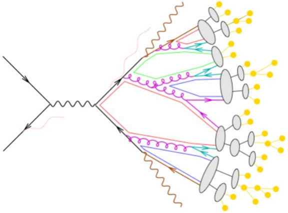


string-like.
- $\sim 15\%$ of primary clusters get split but $\sim 50\%$ of hadrons come from them!

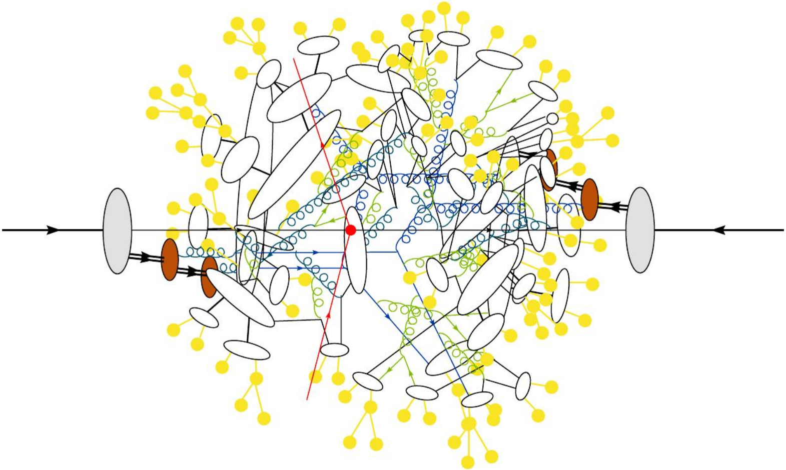
Hadronization - comparison of the model

Taken from T. Sjöstrand



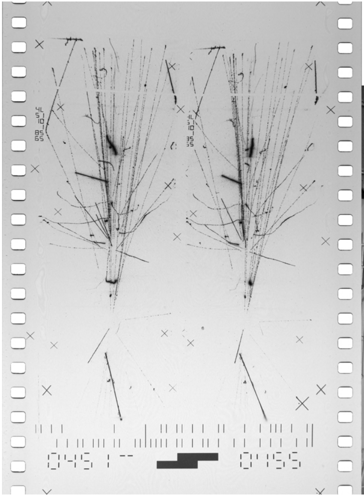


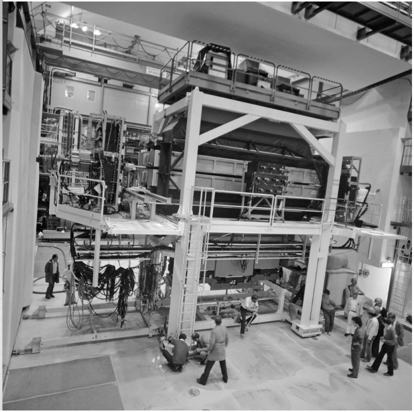
program	PYTHIA	Herwig
model	string	cluster
energy–momentum picture	powerful	simple
	predictive	unpredictive
parameters	few	many
flavour composition	messy	simple
	unpredictive	in-between
parameters	many	few



How do we know MPI exists? Data makes you smarter!

UA5 experiment at the SPS - proton-antiproton 540 GeV c.m.





Motivation - how do we know MPI exists?

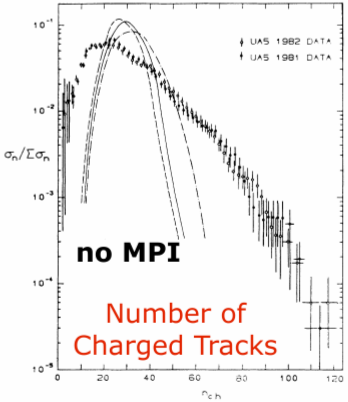


FIG. 3. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs simple models: dashed low p_T only, full including hard scatterings, dash-dotted also including initial- and final-state radiation.

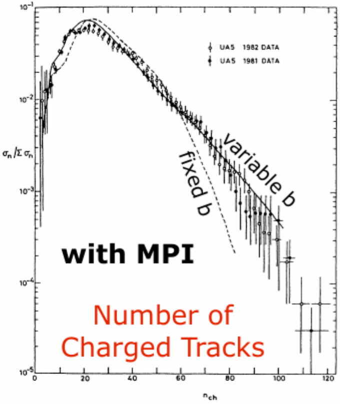


FIG. 12. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs multiple-interaction model with variable impact parameter: solid line, double-Gaussian matter distribution; dashed line, with fix impact parameter [i.e., $\tilde{O}_0(b)$].

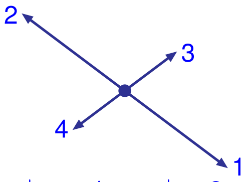
Sjöstrand & v. Zijl,
Phys.Rev.D36(1987)2019

Direct observation of multiple interactions

Five studies: AFS (1987), UA2 (1991), CDF (1993, 1997), D0 (2009)

Order 4 jets $\mathbf{p}_{\perp 1} > \mathbf{p}_{\perp 2} > \mathbf{p}_{\perp 3} > \mathbf{p}_{\perp 4}$ and define φ as angle between $\mathbf{p}_{\perp 1} \mp \mathbf{p}_{\perp 2}$ and $\mathbf{p}_{\perp 3} \mp \mathbf{p}_{\perp 4}$ for AFS/CDF

Double Parton Scattering

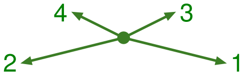


$|\mathbf{p}_{\perp 1} + \mathbf{p}_{\perp 2}| \approx 0$

$|\mathbf{p}_{\perp 3} + \mathbf{p}_{\perp 4}| \approx 0$

$\mathrm{d}\sigma/\mathrm{d}\varphi$ flat

Double BremsStrahlung

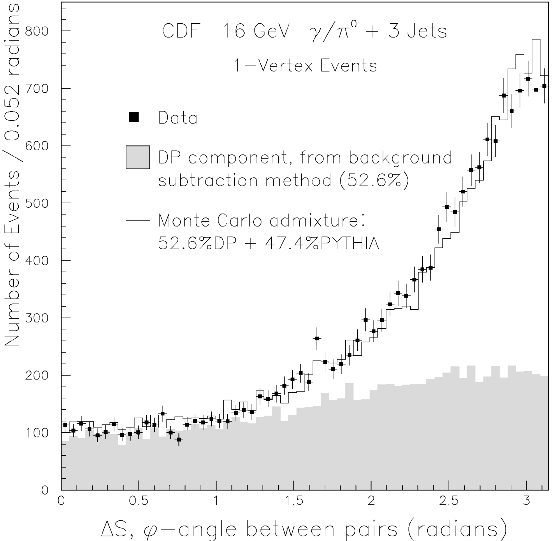


$|\mathbf{p}_{\perp 1} + \mathbf{p}_{\perp 2}| \gg 0$

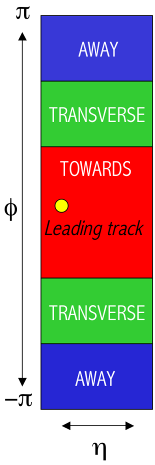
$|\mathbf{p}_{\perp 3} + \mathbf{p}_{\perp 4}| \gg 0$

$\mathrm{d}\sigma/\mathrm{d}\varphi$ peaked at $\varphi \approx 0/\pi$ for AFS/CDF

CDF: Double parton scattering in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$
[Phys. Rev. D 56, 3811-3832 (1997)]



CDF Run II



On event-by-event basis:

1) Identify the leading object in the event

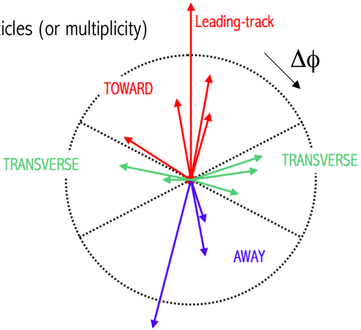
2) Build **TRANSVERSE REGIONS** w.r.t. it

3) Compute Σp_T of charged particles (or multiplicity) in the different regions

SETTINGS:

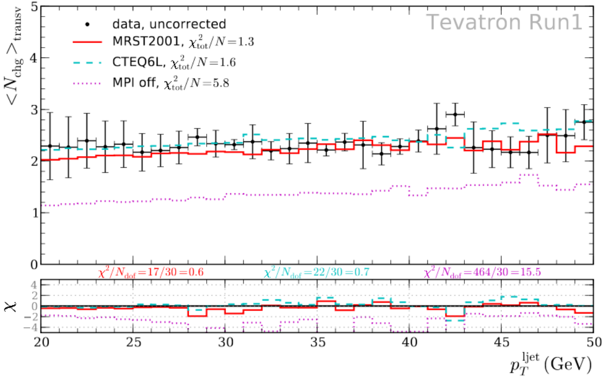
- pT > 0.5 GeV/c (tracks and leading-track)

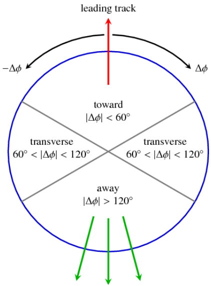
- leading-track not included in distributions



CDF Run II

Good description of Run I Underlying event data ($\chi^2 = 1.3$).





Only $p_T^{ljet} > 20\,\mathrm{GeV}$.

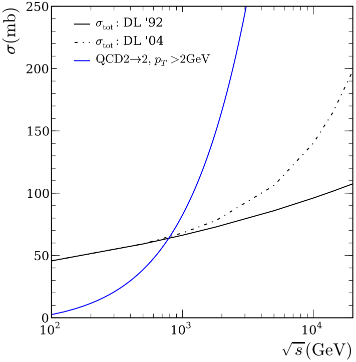
Motivation - is it really important?

Motivation:

- The minimum bias/underlying event is an unavoidable background to most collider observables and having good understand of it leads to more precise collider measurements!
- First LHC results are Minimum Bias and Underlying Event! Alice: [0911.5430], CMS [1002.0621], ATLAS [1003.3124] so it must be important ;)
- These will be particularly relevant for the LHC as, when it is operated at design luminosity, rare signal events will be embedded in a background of more than 20 near-simultaneous minimum-bias collisions.
- Any realistic experiment simulation event generator needs to be able to model these effects.
- “Don’t worry, we will measure and subtract it” But... fluctuations and correlations on an event-by-event basis are crucial.

Inclusive hard jet cross section in pQCD:

$$\sigma^{\text{inc}}(s, p_t^{\text{min}}) = \sum_{i,j} \int_{p_t^{\text{min}2}} \mathrm{d}p_t^2 \int \mathrm{d}x_1 \mathrm{d}x_2 \; f_i(x_1, Q^2) f_j(x_2, Q^2) \; \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2}$$



$\sigma^{\text{inc}} > \sigma_{\text{tot}}$ eventually

Interpretation:

- σ^{inc} counts all partonic scatters in a single *pp* collision
- more than a single interaction

$$\sigma^{\text{inc}} = \langle n_{\text{dijets}} \rangle \sigma_{\text{inel}}$$

Assumptions:

- the distribution of partons in hadrons factorizes with respect to the b and x dependence ⇒ average number of parton collisions:

$$\begin{aligned}
\bar{n}(\vec{b}, s) &= L_{\text{partons}}(x_1, x_2, \vec{b}) \otimes \sum_{ij} \int \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2} \\
&= \sum_{ij} \frac{1}{1+\delta_{ij}} \int \mathrm{d}x_1 \mathrm{d}x_2 \int \mathrm{d}^2\vec{b}' \int \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2} \\
&\quad \times D_{i/A}(x_1, p_t^2, |\vec{b}'|) D_{j/B}(x_2, p_t^2, |\vec{b} - \vec{b}'|) \\
&= \sum_{ij} \frac{1}{1+\delta_{ij}} \int \mathrm{d}x_1 \mathrm{d}x_2 \int \mathrm{d}^2\vec{b}' \int \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2} \\
&\quad \times f_{i/A}(x_1, p_t^2) G_A(|\vec{b}'|) f_{j/B}(x_2, p_t^2) G_B(|\vec{b} - \vec{b}'|) \\
&= A(\vec{b}) \sigma^{\text{inc}}(s; p_t^{\text{min}}) \, .
\end{aligned}$$

- at fixed impact parameter b, individual scatterings are independent (leads to the Poisson distribution)

From assumptions:

- at fixed impact parameter b, individual scatterings are independent,
- the distribution of partons in hadrons factorizes with respect to the b and x dependence.

we get the average number of partonic collisions at a given b value is

$$\bar{n}(b,s) = A(b)\sigma^{inc}(s; p_t^{\min}) = 2\chi(b,s)$$

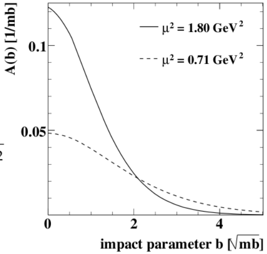
where $A(b)$ is the partonic overlap function of the colliding hadrons

$$A(b) = \int d^2\vec{b}' G_A(|\vec{b}'|) G_B(|\vec{b} - \vec{b}'|)$$

$G(\vec{b})$ from electromagnetic FF:

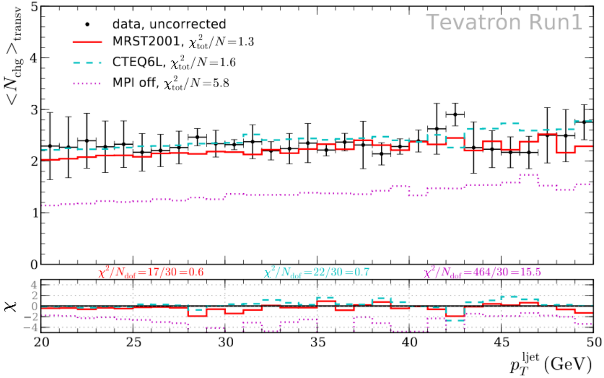
$$G_p(\vec{b}) = G_{\bar{p}}(\vec{b}) = \int \frac{d^2\vec{k}}{(2\pi)^2} \frac{e^{i\vec{k}\cdot\vec{b}}}{(1+\vec{k}^2/\mu^2)^2}$$

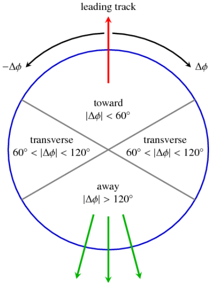
But μ^2 *not fixed* to the *electromagnetic* 0.71 GeV^2.
Free for colour charges.



⇒ Two main parameters: $\mu^2, p_t^{\min}$.

Good description of Run I Underlying event data ($\chi^2 = 1.3$).





Only $p_T^{\text{ljet}} > 20\,\text{GeV}$.

Extension to soft MPI, $p_t < p_t^{\mathrm{min}}$

Fix the two parameters μ_{soft} and $\sigma^{\mathrm{inc}}_{\mathrm{soft}}$ in

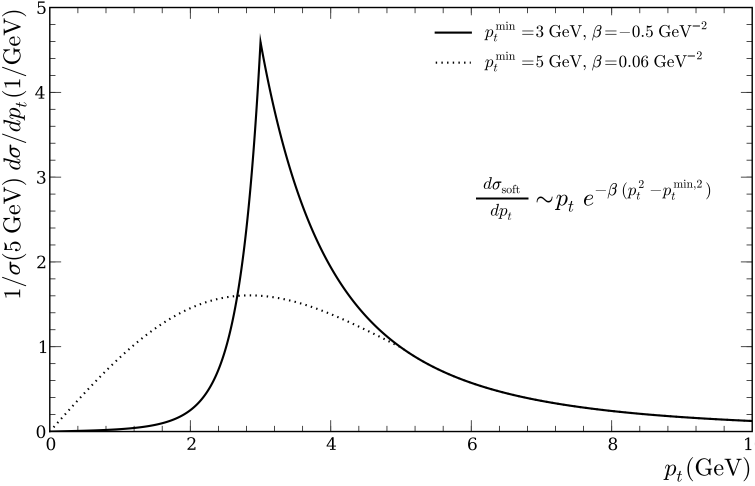
$$n_{\mathrm{tot}}(\vec{b}, s) = \left(A(\vec{b}; \mu) \sigma^{\mathrm{inc}} \mathrm{hard}(s; p_t^{\mathrm{min}}) + A(\vec{b}; \mu_{\mathrm{soft}}) \sigma^{\mathrm{inc}}_{\mathrm{soft}} \right)$$

from two constraints. Require simultaneous description of σ_{tot} and b_{el} (measured/well predicted),

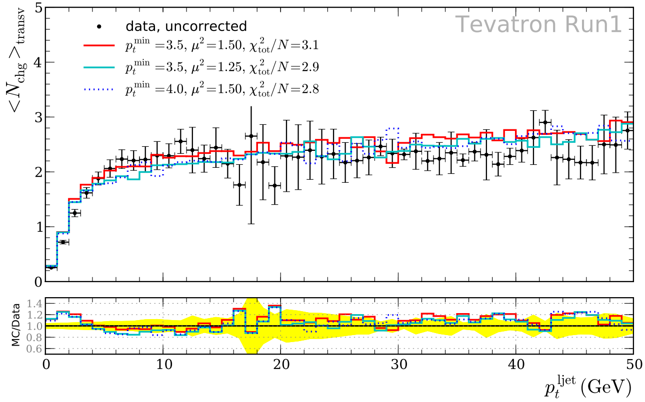
$$\sigma_{\mathrm{tot}}(s) \overset{!}{=} 2 \int \mathrm{d}^2\vec{b} \left(1 - \mathrm{e}^{-\chi_{\mathrm{tot}}(\vec{b},s)} \right) ,$$

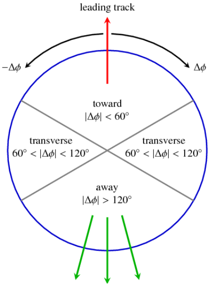
$$b_{\mathrm{el}}(s) \overset{!}{=} \int \mathrm{d}^2\vec{b} \frac{b^2}{\sigma_{\mathrm{tot}}} \left(1 - \mathrm{e}^{-\chi_{\mathrm{tot}}(\vec{b},s)} \right) .$$

Continuation of the differential cross section into the soft region
$p_t < p_t^{\min}$ (here: p_t integral kept fixed)



Detailed look at observables: Transverse Region

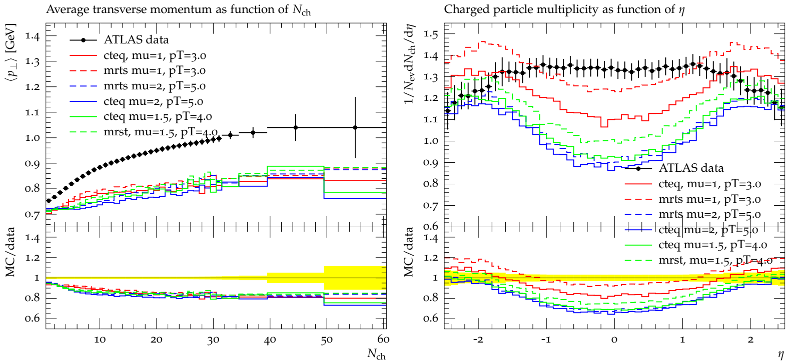




Notice Jet pedestal effect.

Look at LHC results (900 GeV)

- ATLAS charged particles in Min Bias ($N_{ch} \geq 1,\ p_T > 500MeV,\ |\eta| < 2.5$)



- oops, not so nice...
- despite very good agreement with Rick Field's CDF UE analysis.
- choice of PDF set (CTEQ6ll vs MSTW LO** (our default))
- Failure of a physically motivated model usually points to more, interesting physics ... colour structure?

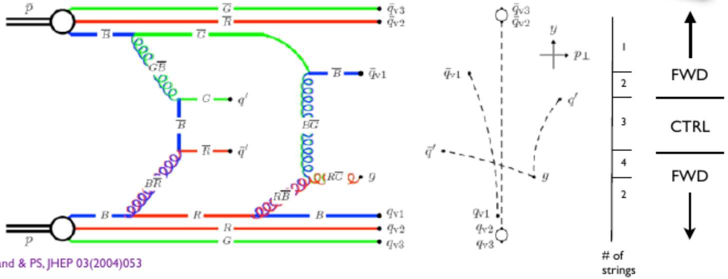
Colour Structure of the Underlying Event

Colour Structure of the Underlying Event multiple interactions, even when soft, can cause non-trivial changes to the colour topology of the colliding system as a whole, with potentially major consequences for the particle multiplicity in the final state

Each MPI (or cut Pomeron) exchanges color between the beams

- The colour flow determines the hadronizing string topology
  - Each MPI, even when soft, is a color spark
  - Final distributions crucially depend on color space

Different models make different ansätze



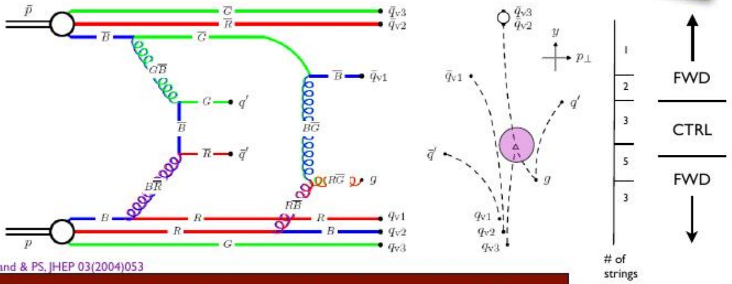
Sjöstrand & PS, JHEP 03(2004)053

Colour Structure of the Underlying Event multiple interactions, even when soft, can cause non-trivial changes to the colour topology of the colliding system as a whole, with potentially major consequences for the particle multiplicity in the final state

Each MPI (or cut Pomeron) exchanges color between the beams

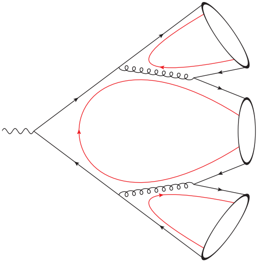
- The colour flow determines the hadronizing string topology
  - Each MPI, even when soft, is a color spark
  - Final distributions crucially depend on color space

Different models make different ansätze



Sjöstrand & PS, JHEP 03(2004)053

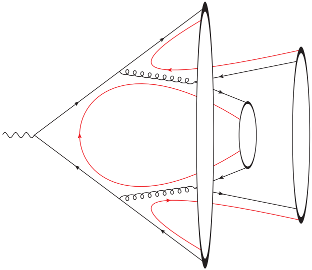
Forward region (and forward-backward + forward-central **correlations**)



Extending Herwig's hadronization model:

- QCD parton showers provide *pre-confinement* $\Rightarrow$ colour-anticolour pairs form highly excited hadronic states, the *clusters*

Colour reconnection (CR) in Herwig++



Extending Herwig's hadronization model:

- QCD parton showers provide *pre-confinement* $\Rightarrow$ colour-anticolour pairs form highly excited hadronic states, the *clusters*
- CR in the cluster hadronization model: allow *reformation* of clusters, *e.g.* $(il) + (jk)$
- Physical motivation: exchange of soft gluons during non-perturbative hadronization phase

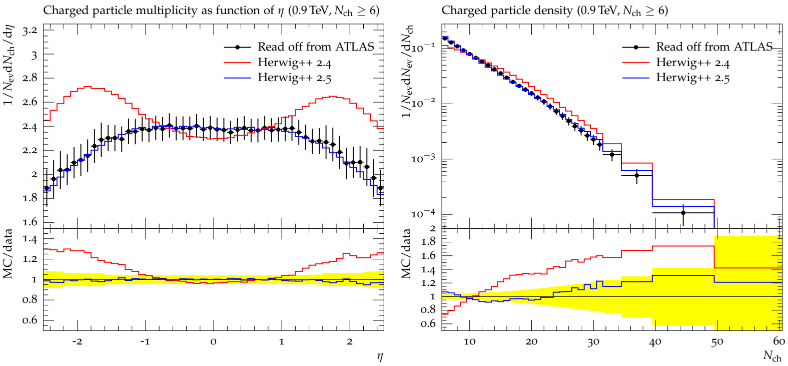
Implementation

- Allow CR if the cluster mass decreases,

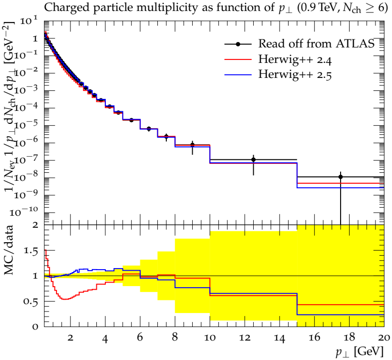
$$M_{il} + M_{kj} < M_{ij} + M_{kl},$$

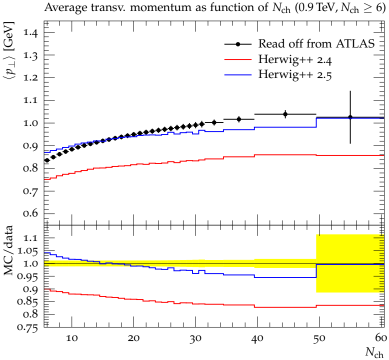
  where $M_{ab}^2 = (p_a + p_b)^2$ is the (squared) cluster mass
- Accept alternative clustering with probability p_{reco} (model parameter) $\Rightarrow$ this allows to switch on CR smoothly

MinBias ATLAS 900 GeV

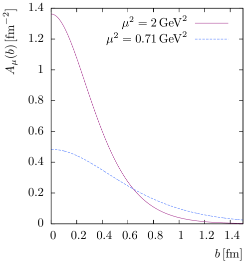


MinBias ATLAS 900 GeV





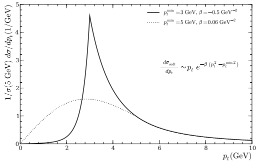
Matter distribution (μ^2)



Based on electromagnetic form factor

(radius of the proton free parameter)

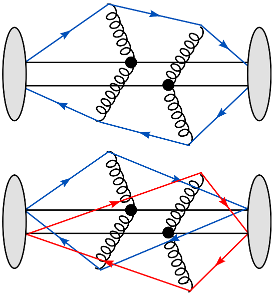
Extension to soft MPI ($p_t < p_t^{\min}$)



Gaussian extension below $p_t^{\min}$

Energy dependent $p_t^{\min}$

Colour structure (p_{reco}, p_{CD})



Possibility of change of color structure (color reconnection)

[Gieseke, Röhr, AS, EPJC 72 (2012)]

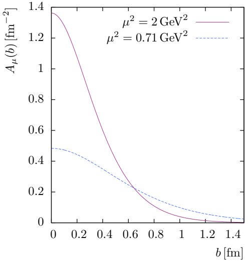
The least understood part of modeling

Main parameters:

- μ^2 - inverse hadron radius squared (parametrization of overlap function)
- $p_t^{\min}$ - transition scale between soft and hard components $\Rightarrow p_t^{\min} = p_{t,0}^{\min}\left(\frac{\sqrt{s}}{E_0}\right)^b$
- p_{reco} - colour reconnection

Underlying event in Herwig++ - key components

Matter distribution (μ^2)



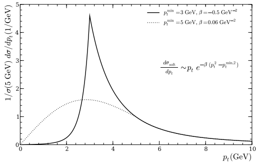
Based on electromagnetic form factor (radius of the proton free parameter)

Pythia:

- Many options including double Gaussian (similar shape to EE)

- x-depended overlap [Corke, Sjostrand, JHEP 1105:009]

Extension to soft MPI ($p_t < p_t^{\min}$)



Gaussian extension below $p_t^{\min}$

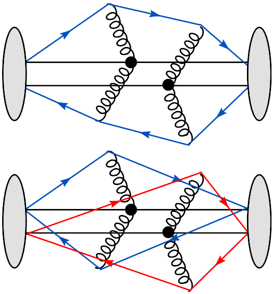
Energy dependent $p_t^{\min}$

Pythia:

Regularise cross section with $p_t^{\min}$ as free parameter:

$$\frac{d\sigma}{dp_T^2} \propto \frac{\alpha^2(p_T^2)}{p_T^4} \rightarrow \frac{\alpha^2(p_T^2+p_t^{\min 2})}{(p_T^2+p_t^{\min 2})^2}$$

Colour structure (p_{reco}, p_{CD})



Possibility of change of color structure (color reconnection) [Gieseke, Röhr, AS, EPJC 72 (2012)] The least understood part of modeling (very active area research)

Pythia:

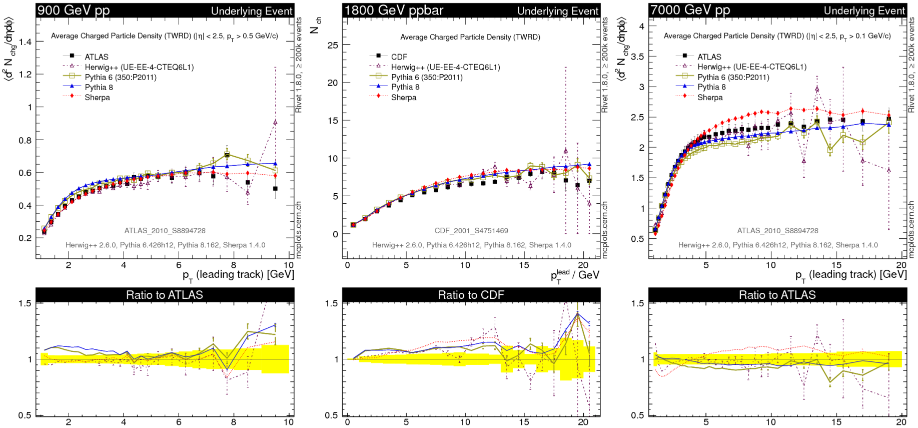
Recent development: String Formation Beyond Leading Colour J. Christiansen, P. Skands [arXiv:1505.01681]

Herwig++ MPI model with independent hard and soft processes, showered and with colour reconnection. Just few parameters. Min bias without integrated diffraction (work in progress).

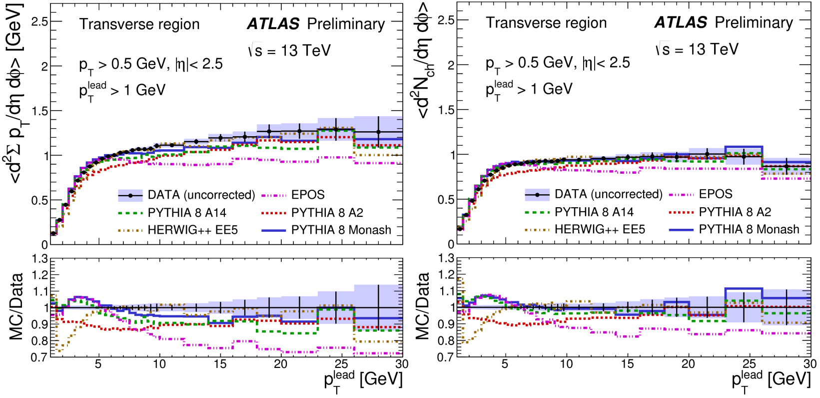
Pythia MPI interleaved with showering. MPI ordered in p_T. The most sophisticated model. Many options and parameters (Pythia has strong emphasis on NP physics) $\Rightarrow$ many tune families.

Sherpa New model - SHRiMPS with integrated diffraction based on KMR (Khoze-Martin-Ryskin model). Model in development - currently not suitable for UE studies (work in progress - this winter?). Currently for UE there is “cheap version of Pythia’s UE model” (F. Krauss)

UE measurements - Energy Overview

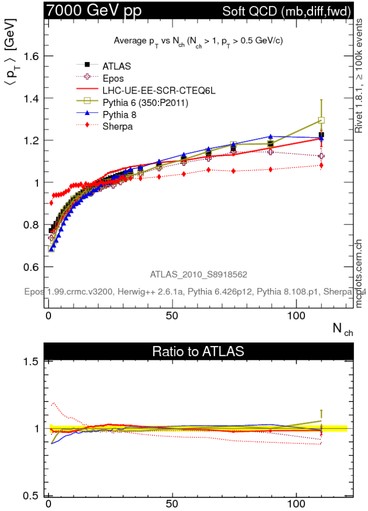


Run II results - UE [ATL-PHYS-PUB-2015-019]



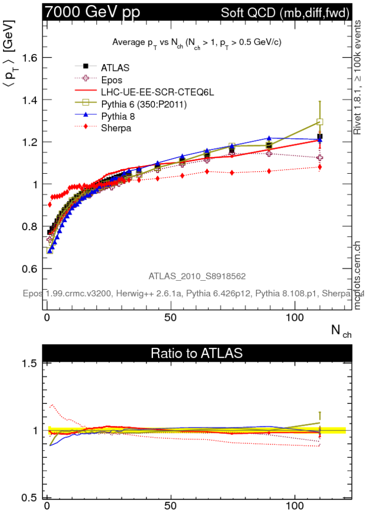
- Many LHC UE observables (not tuned since not available) and well described by most of the models!

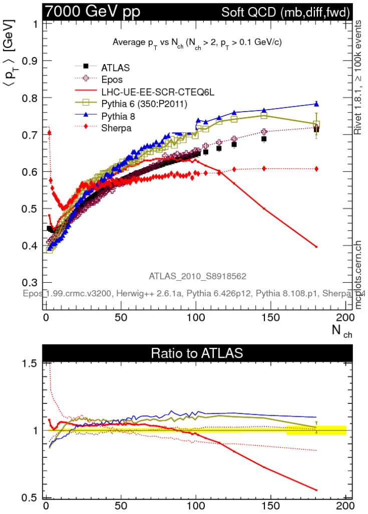
Problems - very soft MinBias ATLAS



Need of the colour reconnection.

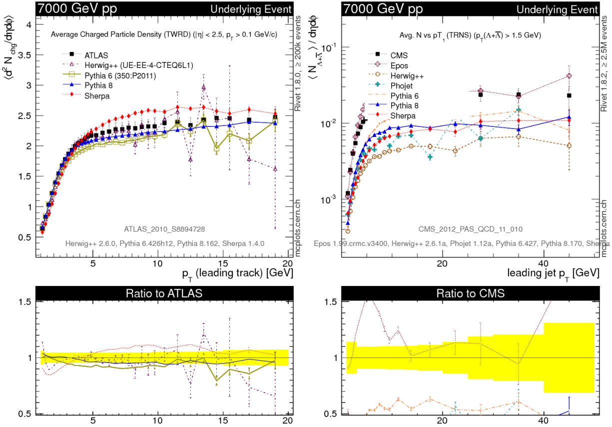
Problems - very soft MinBias ATLAS





Need of the colour reconnection.
MB 7000 TeV, problem at low p_T, high Nch (CMS ridge)

Problems - Identified particles

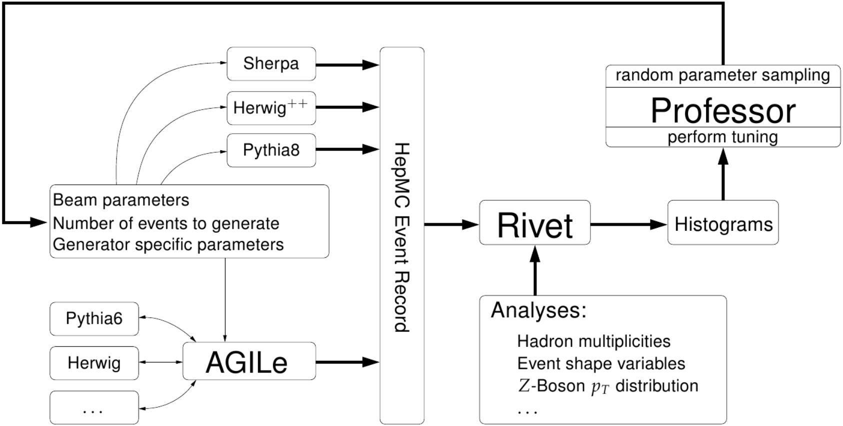


More plots: mcplots.cern.ch

Tuning

- MC models have parameters such as pT cutoff, energy evolution, colour-reconnection... + many parameters of hadronization models
- Tuning (fixing) of parameters required to constrain models
- No unique way of tuning: which data samples should be used? Divide and conquer (split parameters in subgroups which can be tune separately) ...
- “manual” tunning - hard and inefficient - lots of man and CPU power needed.
- new tools help to automatize this process -> however still you need to think it is not “Fire-and-forget”

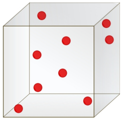
Rivet and Professor

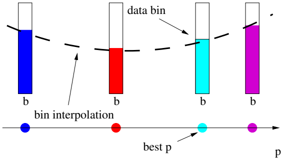


Rivet and Professor

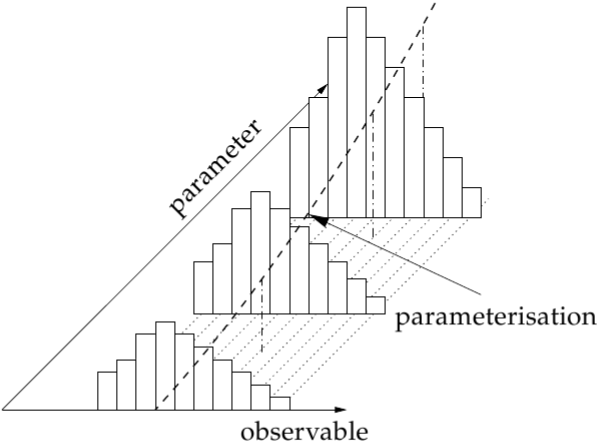
Tuning procedure in Professor (1D, 1Bin)

1. Random sampling: N parameter points in n-dimensional space
2. Run generator and fill histograms
3. For each bin: use N points to fit interpolation (2^{nd} or 3^{rd} order polynomial)
4. Construct overall (now trivial) $^2 \approx \sum_{bins} \frac{(interpolation - data)^2}{error^2}$
5. and Numerically *minimize* `pyMinuit, SciPy`





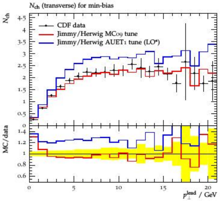
Rivet and Professor



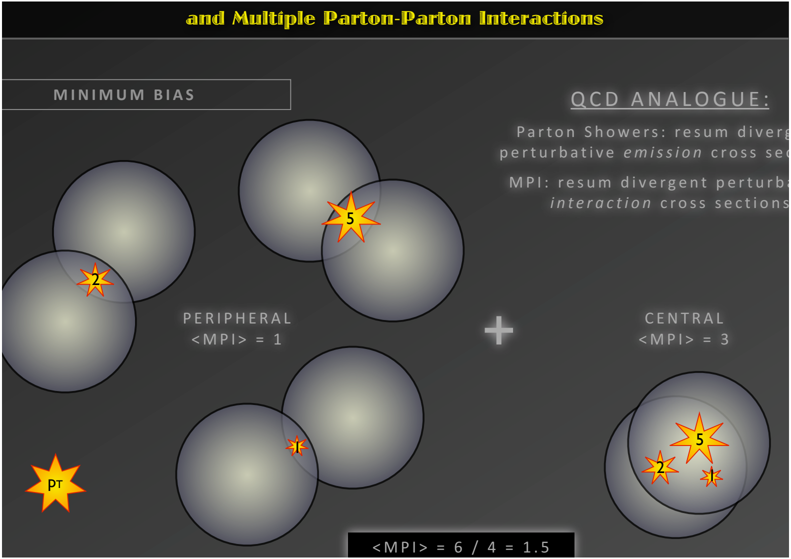
Rivet and Professor
Observables and Weights

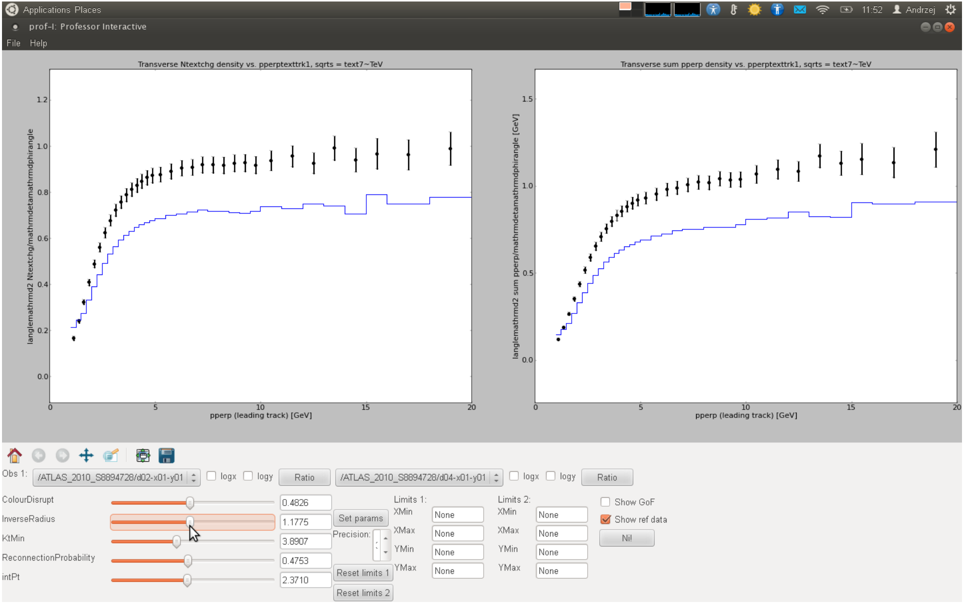
- This is what Professor minimises: $\chi^2(\vec{p}) = \sum_{\mathcal{O}} \sum_{b \in \mathcal{O}} w_b \frac{(f^{(b)}(\vec{p}) - \mathcal{R}_b)^2}{\Delta_b^2}$
- Slightly more art than science
- Garbage in, garbage out
- Use weights w_b to:
  - emphasize certain observables
  - emphasize certain bins of an observable
  - switch off single bins (e.g. MinBias region for Jimmy Herwig)

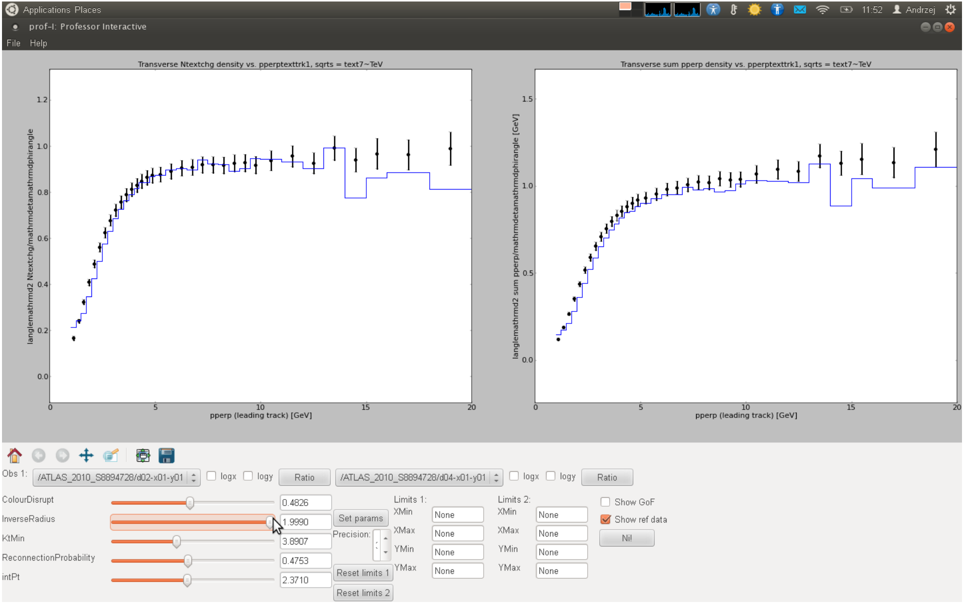
- No MinBias physics in Jimmy Herwig
- Cannot get first 3 bins or so right
- Transition from MinBias to UE type physics
- ⇒ Exclude these bins from Professor minimisation



Taken from Peter Skands:




Applications Places
11:52
Andrzej
prof-I: Professor Interactive
File Help
Transverse Ntextchg density vs. pperptexttrk1, sqrts = text7~TeV
langlemathrmd2 Ntextchg/mathrmdetamathrmdphirangle
pperp (leading track) [GeV]
Transverse sum pperp density vs. pperptexttrk1, sqrts = text7~TeV
langlemathrmd2 sum pperp/mathrmdetamathrmdphirangle [GeV]
pperp (leading track) [GeV]
Obs 1:
/ATLAS_2010_S8894728/d02-x01-y01
logx
logy
Ratio
/ATLAS_2010_S8894728/d04-x01-y01
logx
logy
Ratio
ColourDisrupt
0.4826
InverseRadius
1.1775
Set params
KtMin
3.8907
Precision:
ReconnectionProbability
0.4753
intPt
2.3710
Reset limits 1
Reset limits 2
Limits 1:
XMin
None
XMax
None
YMin
None
YMax
None
Limits 2:
XMin
None
XMax
None
YMin
None
YMax
None
Show GoF
Show ref data
Ni!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logx
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Ratio
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logx
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Ratio
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Precision:
Reset limits 1
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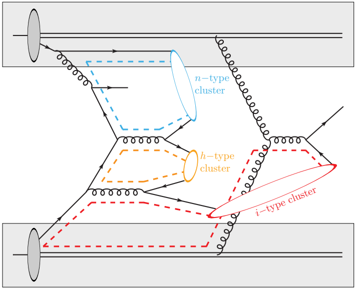
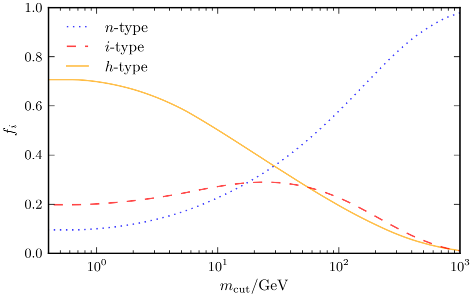
Limits 1:
XMin None
XMax None
YMin None
YMax None
Limits 2:
XMin None
XMax None
YMin None
YMax None
Show GoF
Show ref data
Ni!

Colour reconnections in Herwig++ [Gieseke, Röhr, AS, Eur.Phys.J. C72 (2012) 2225]

$$f_a(m_{cut}) \equiv N_a(m_{cut}) / \sum_{b=h,i,n} N_b(m_{cut}) = \frac{N_a(m_{cut})}{N_{cl}}\,, \qquad (1)$$





Since these n-clusters can lie at very different rapidities (the extreme case being the two opposite beam remnants), the strings or clusters spanned between them can have very large invariant masses (though normally low pT), and give rise to large amounts of (soft) particle production.

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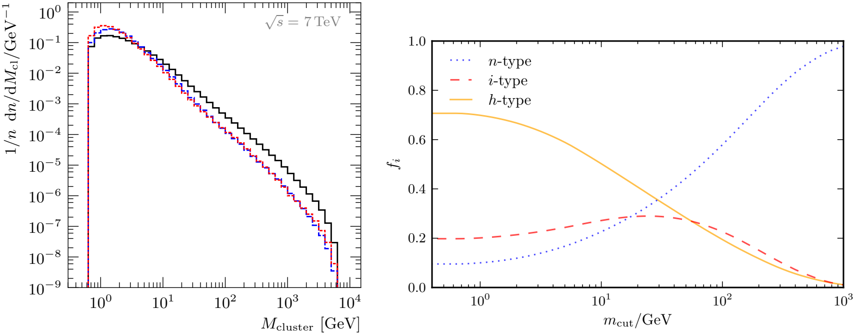

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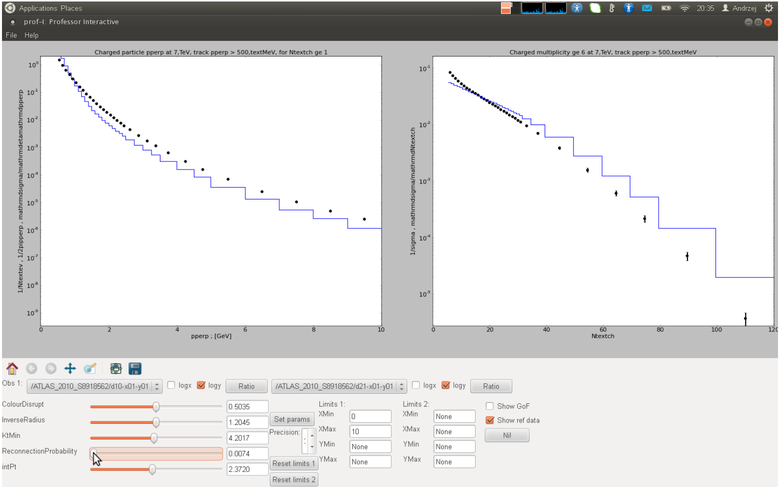
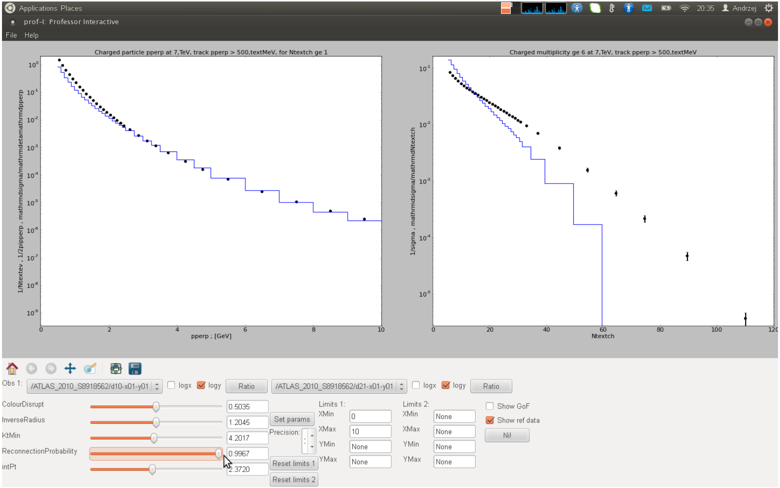


Applications Places
prof-I: Professor Interactive
File Help
Charged particle pperp at 7,TeV, track pperp > 500,textMeV, for Ntextch ge 1
1/Ntextev , 1/2pipperp , mathrmdsigma/mathrmdetamathrmdpperp
pperp ; [GeV]
Charged multiplicity ge 6 at 7,TeV, track pperp > 500,textMeV
1/sigma , mathrmdsigma/mathrmdNtextch
Ntextch
Obs 1:
/ATLAS_2010_S8918562/d10-x01-y01
logx
logy
Ratio
/ATLAS_2010_S8918562/d21-x01-y01
logx
logy
Ratio
ColourDisrupt
0.5035
InverseRadius
1.2045
KtMin
4.2017
ReconnectionProbability
0.0074
intPt
2.3720
Set params
Precision:
Reset limits 1
Reset limits 2
Limits 1:
XMin 0
XMax 10
YMin None
YMax None
Limits 2:
XMin None
XMax None
YMin None
YMax None
Show GoF
Show ref data
Nil


Applications Places
20:35 Andrzej
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File Help
Charged particle pperp at 7,TeV, track pperp > 500,textMeV, for Ntextch ge 1
1/Ntextev , 1/2pipperp , mathrmdsigma/mathrmdetamathrmdpperp
pperp ; [GeV]
Charged multiplicity ge 6 at 7,TeV, track pperp > 500,textMeV
1/sigma , mathrmdsigma/mathrmdNtextch
Ntextch
Obs 1: /ATLAS_2010_S8918562/d10-x01-y01 logx logy Ratio /ATLAS_2010_S8918562/d21-x01-y01 logx logy Ratio
ColourDisrupt 0.5035
InverseRadius 1.2045
KtMin 4.2017
ReconnectionProbability 0.9967
intPt 2.3720
Set params
Precision:
Reset limits 1
Reset limits 2
Limits 1: XMin 0 XMax 10 YMin None YMax None
Limits 2: XMin None XMax None YMin None YMax None
Show GoF
Show ref data
Nil

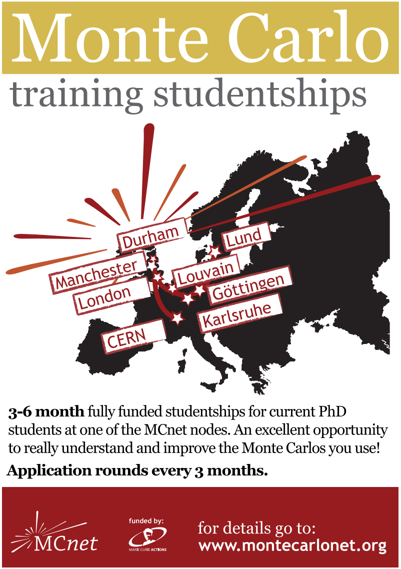
Summary:

- Tremendous amount of new developements in GPMCs.
- Parton showers well established.
- Hard matrix element - “NLO revolution” and more - see Marek’s lectures.
- Hadronization crucial to obtain fully exclusive simulation of the collisions. Two main models: string and cluster.
- MPI models under constant improvement (new MPI model Shrimps in Sherpa, improvements in Pythia and Herwig, for LHC)!
- Good first round of LHC data well described...
- ... but still a lot space for improvements.
- Not-too-soft not-too-high-multiplicity physics under good control (if you use modern models with modern tunes).

- Event generators crucial since the start of LHC studies.
- Qualitatively predictive already 25 years ago
- Quantitatively steady progress, continuing today:
  - continuous dialogue with experimental community,
  - more powerful computational techniques and computers,
  - new ideas.
- As LHC needs to study more rare phenomena and more subtle effects, generators must keep up by increased precision.

Thank you for the attention!

MCnet Short-term studentships



MC*net* projects

Pythia
Herwig
Sherpa
MadGraph
Ariadne
CEDAR

Enjoy the rest of the school!