Monte Carlo Methods in Particle Physics

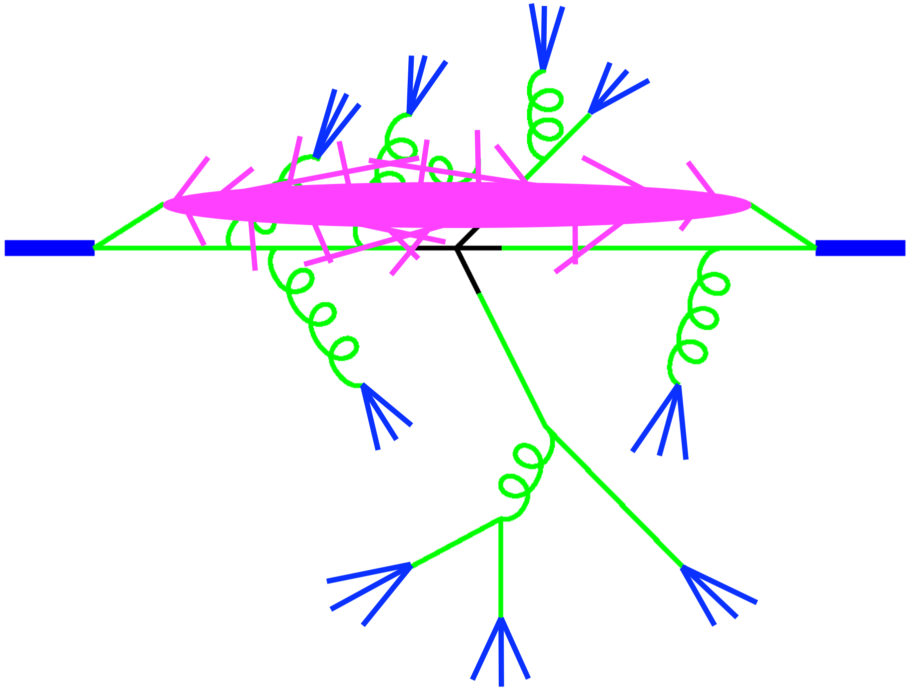
Bryan Webber
University of Cambridge

IMPRS, Munich

19-23 November 2007

Structure of LHC Events

1. Hard process
2. Parton shower
3. Hadronization
4. Underlying event



Lecture 3: Hadronization

Partons are not physical particles: they cannot freely propagate.

Hadrons are.

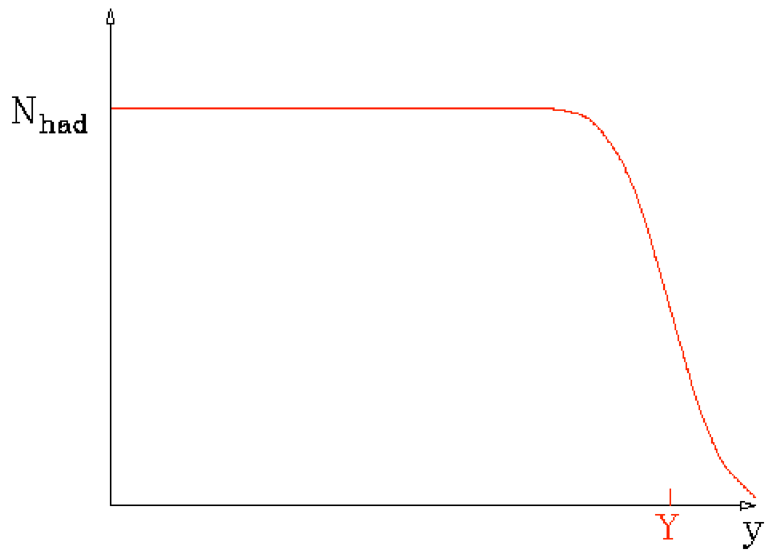
Need a model of partons' confinement into hadrons: hadronization.

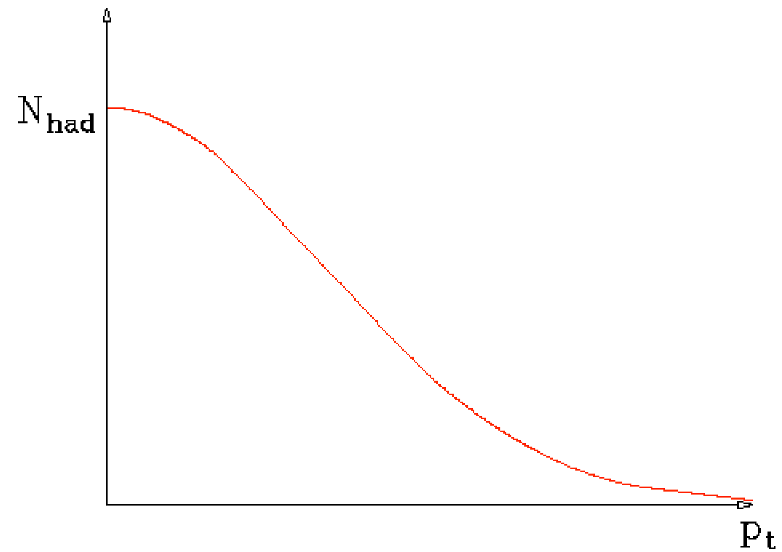
1. Phenomenological models.
2. Confinement.
3. The string model.
4. Preconfinement.
5. The cluster model.
6. Underlying event models.

Phenomenological Models

Experimentally, $e^+e^- \to$ two jets:

Flat rapidity plateau and limited p_t, $\rho(p_t^2) \sim e^{-p_t^2/2p_0^2}$





Estimate of Hadronization Effects

Using this model, can estimate hadronization correction to perturbative quantities.

Jet energy and momentum:

$$E = \int_0^Y dy\, d^2p_t\, \rho(p_t^2)\, p_t\, \cosh y = \lambda \sinh Y$$

$$P = \int_0^Y dy\, d^2p_t\, \rho(p_t^2)\, p_t\, \sinh y = \lambda(\cosh Y - 1) \sim E - \lambda,$$

with $\lambda = \int d^2p_t\, \rho(p_t^2)\, p_t$, mean transverse momentum.

Estimate from Fermi motion $\lambda \sim 1/R_{had} \sim m_{had}$.

Jet acquires non-perturbative mass: $M^2 = E^2 - P^2 \sim 2\lambda E$

Large: ~ 10 GeV for 100 GeV jets.

Independent Fragmentation Model ("Feynman—Field")

Direct implementation of the above.

Longitudinal momentum distribution = arbitrary fragmentation function: parameterization of data.

Transverse momentum distribution = Gaussian.

Recursively apply $q \to q' + \mathrm{had}.$

Hook up remaining soft q and $\bar{q}$.

Strongly frame dependent.

No obvious relation with perturbative emission.

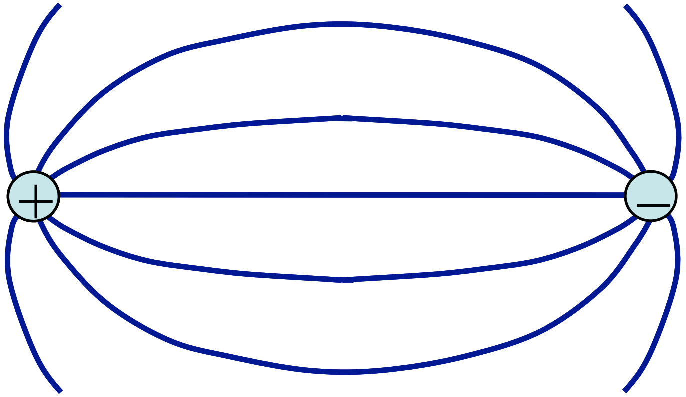
Not infrared safe.

Not a model of confinement.

Confinement

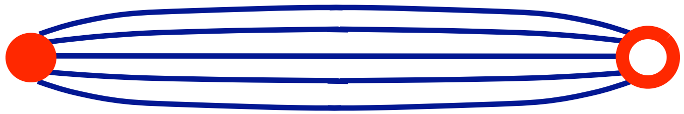
Asymptotic freedom: $Q\bar{Q}$ becomes increasingly QED-like at short distances.

QED:



but at long distances, gluon self-interaction makes field lines attract each other:

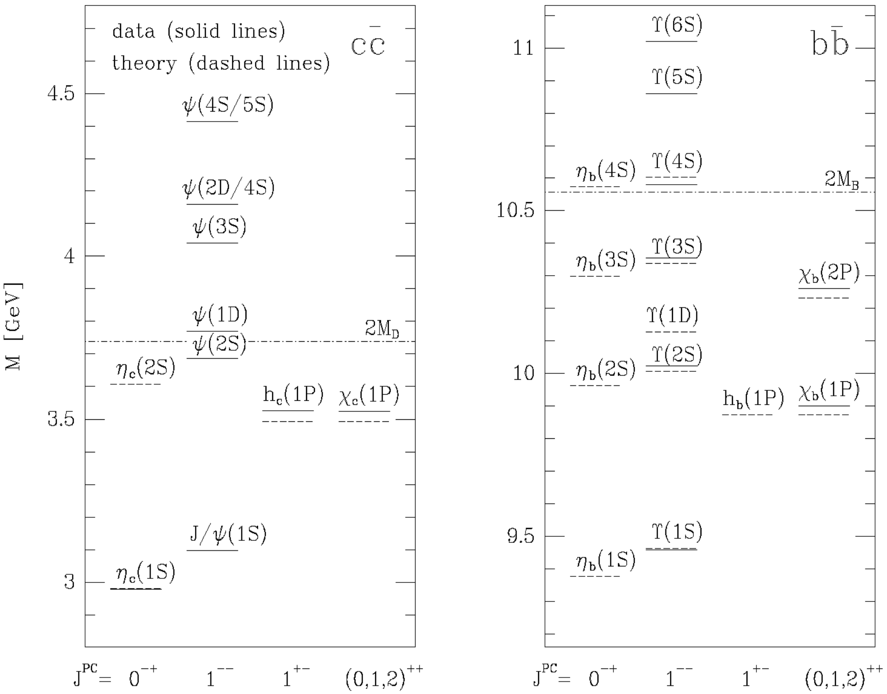
QCD:



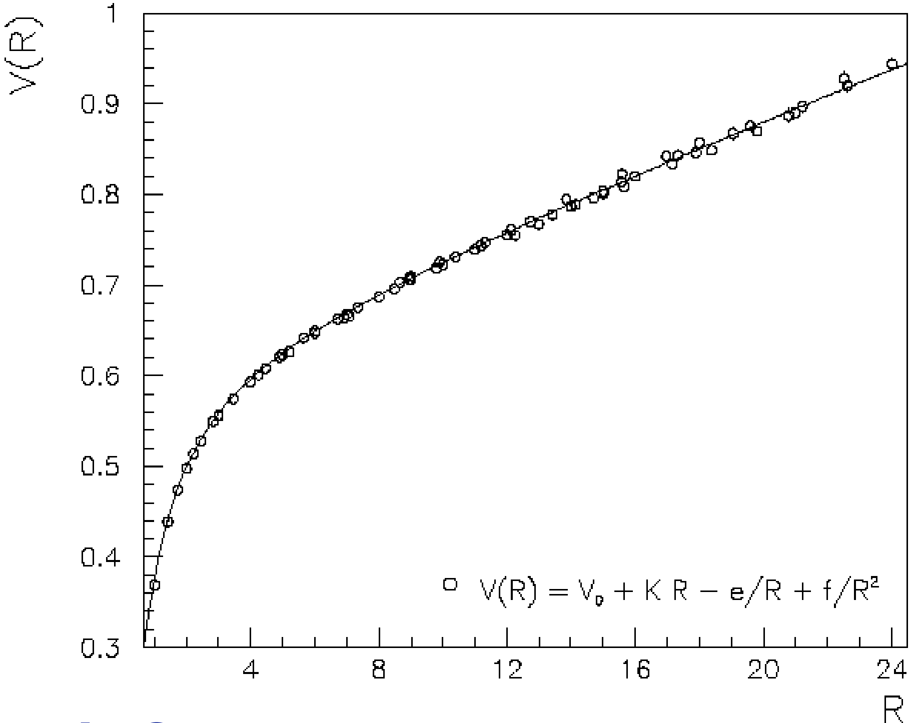
→linear potential → confinement

Interquark potential

Can measure from quarkonia spectra:



or from lattice QCD:



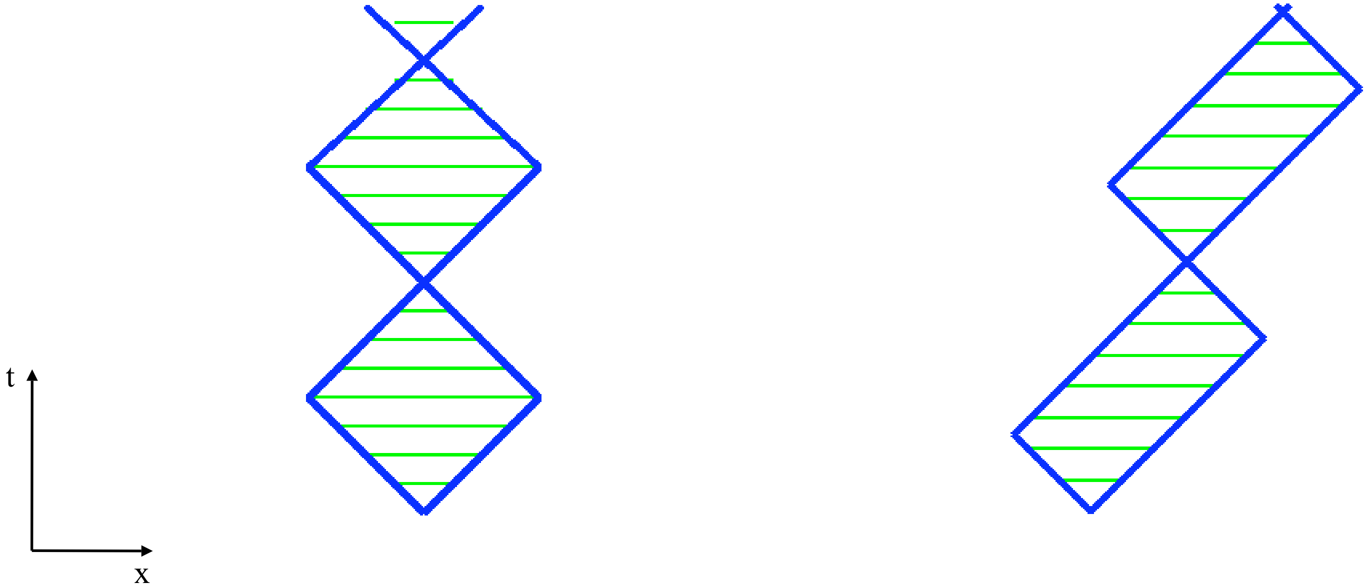
→ String tension

$$\kappa \approx 1 \text{ GeV/fm.}$$

String Model of Mesons

Light quarks connected by string.

L=0 mesons only have 'yo-yo' modes:



Obeys area law: $m^2 = 2\kappa^2 \text{ area}$

The Lund String Model

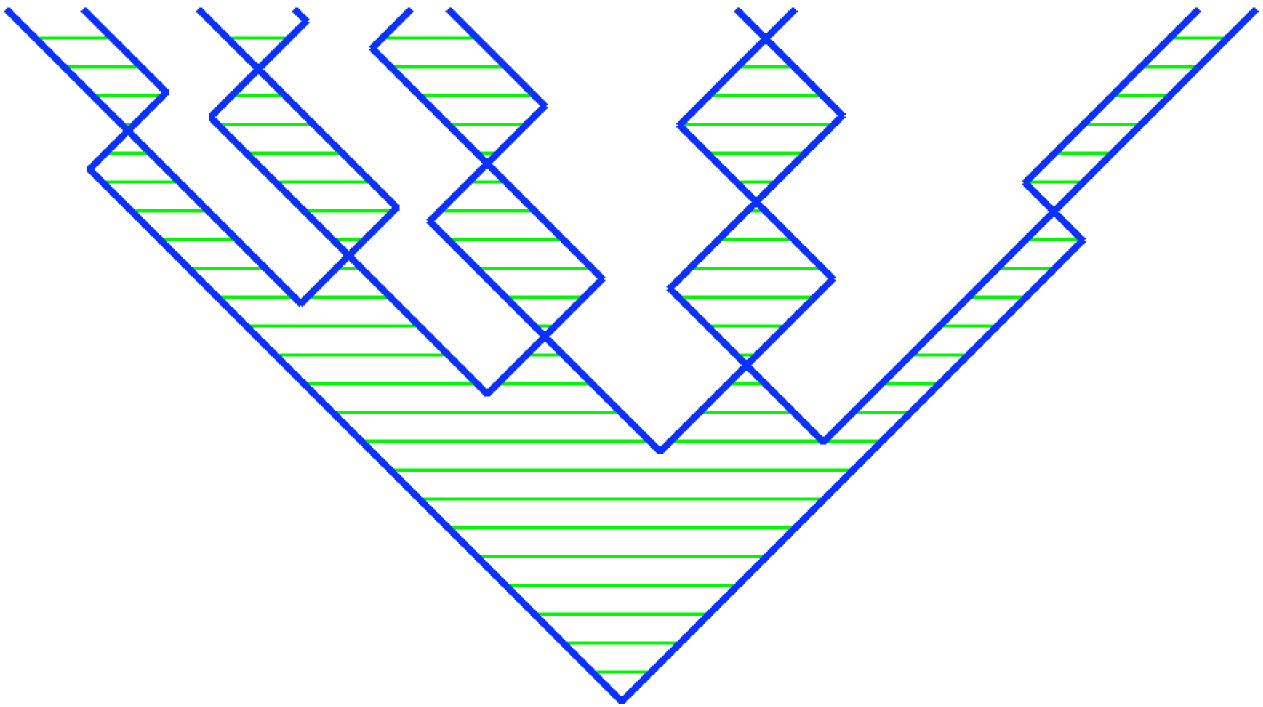
Start by ignoring gluon radiation:

e^+e^- annihilation = pointlike source of $q\bar{q}$ pairs

Intense chromomagnetic field within string → $q\bar{q}$ pairs created by tunnelling. Analogy with QED:

$$\frac{d(\text{Probability})}{dx\ dt} \propto \exp(-\pi m_q^2/\kappa)$$

Expanding string breaks into mesons long before yo-yo point.



Lund Symmetric Fragmentation Function

String picture → constraints on fragmentation function:

- Lorentz invariance
- Acausality
- Left—right symmetry

$$f(z) \propto z^{a_\alpha - a_\beta - 1}(1-z)^{a_\beta}$$

$a_{\alpha,\beta}$ adjustable parameters for quarks α and β.

Fermi motion → Gaussian transverse momentum.

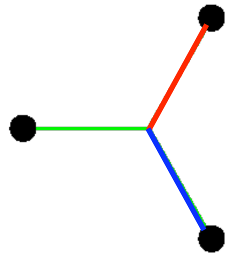
Tunnelling probability becomes

$$\exp\left[-b(m_q^2 + p_t^2)\right]$$

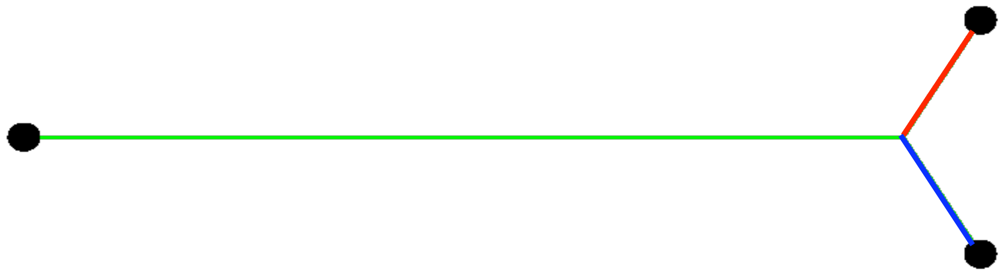
a, b and m_q^2 = main tuneable parameters of model

Baryon Production

Baryon pictured as three quarks attached to a common centre:



At large separation, can consider two quarks tightly bound: diquark



→ diquark treated like antiquark.

Two quarks can tunnel nearby in phase space: baryon—antibaryon pair

Extra adjustable parameter for each diquark!

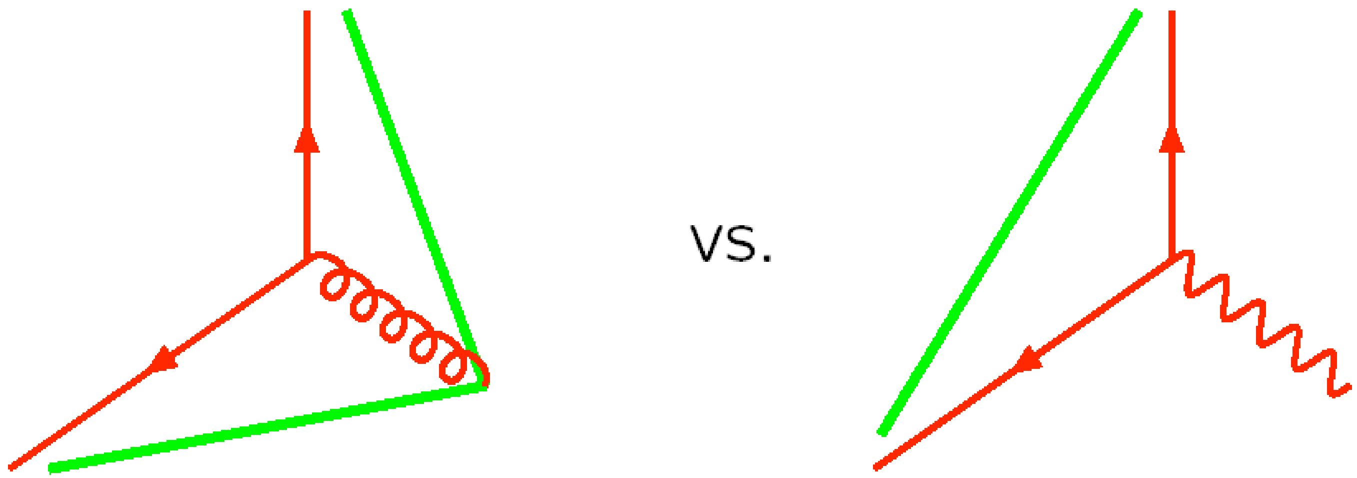
Alternative “popcorn” model:

Three-Jet Events

So far: string model = motivated, constrained independent fragmentation!

New feature: universal

Gluon = kink on string → the string effect



Infrared safe matching with parton shower: gluons with $k_\perp <$ inverse string width irrelevant.

String Model Summary

- String model strongly physically motivated.
- Very successful fit to data.
- Universal: fitted to e^+e^-, little freedom elsewhere.

- How does motivation translate to prediction?
  ~ one free parameter per hadron/effect!

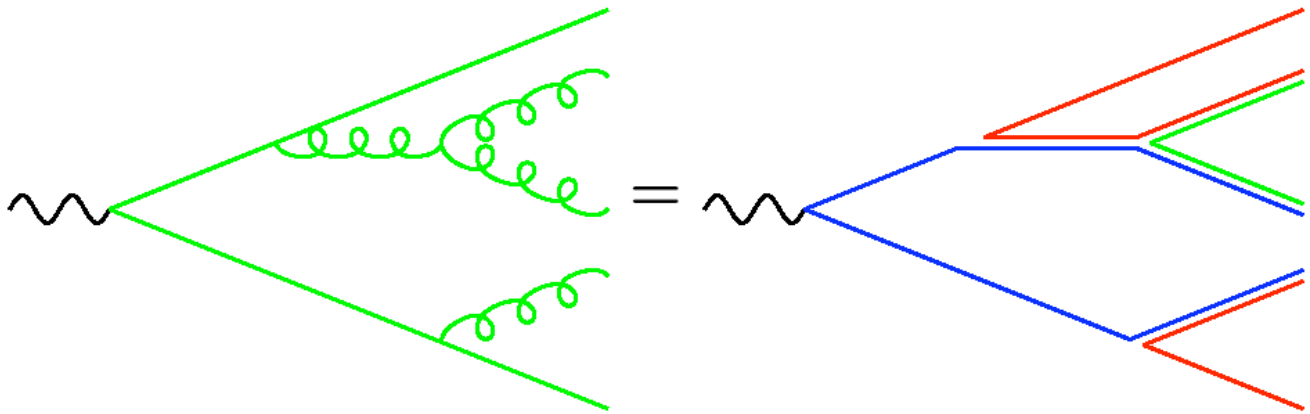
- Blankets too much perturbative information?

- Can we get by with a simpler model?

Preconfinement

Planar approximation: gluon = colour—anticolour pair.

Follow colour structure of parton shower: colour-singlet pairs end up close in phase space

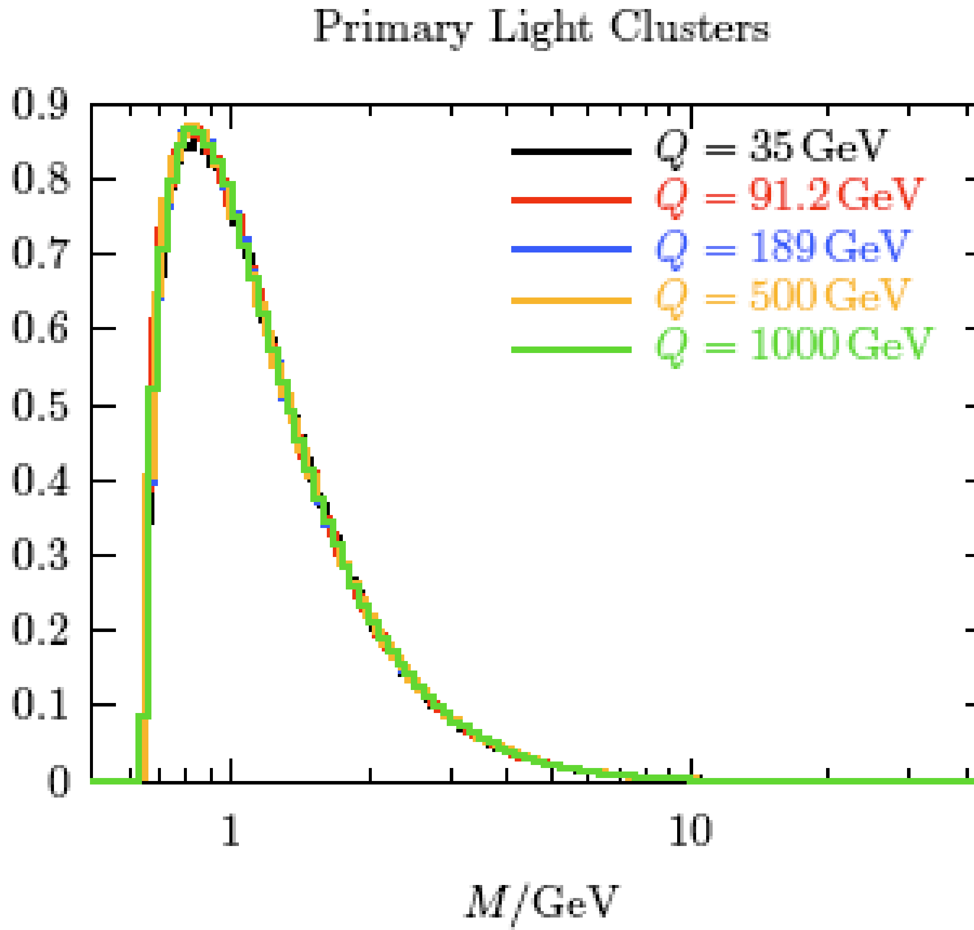


Mass spectrum of colour-singlet pairs asymptotically independent of energy, production mechanism, …

Peaked at low mass $\sim Q_0$.

Cluster mass distribution

- Independent of shower scale Q
  - depends on Q_0 and Λ



The Naïve Cluster Model

Project colour singlets onto continuum of high-mass mesonic resonances (=clusters). Decay to lighter well-known resonances and stable hadrons.

Assume spin information washed out:

decay = pure phase space.

→ heavier hadrons suppressed

→ baryon & strangeness suppression 'for free' (i.e. untuneable).

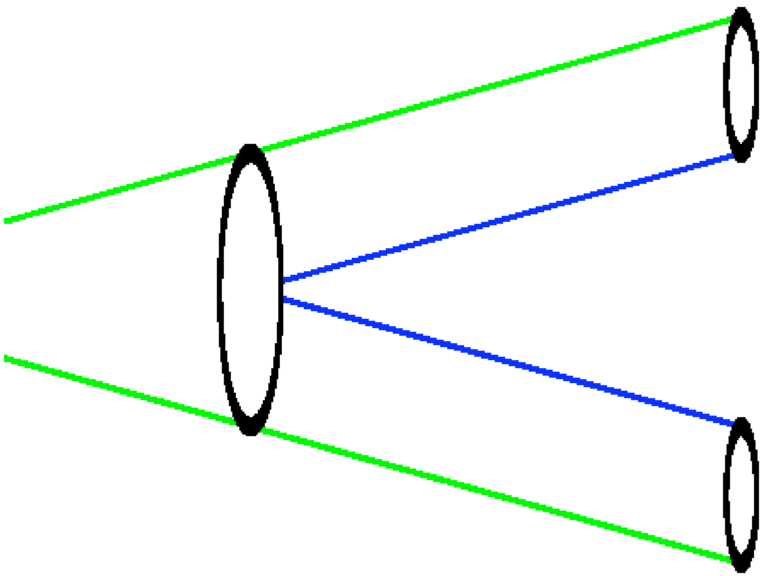
Hadron-level properties fully determined by cluster mass spectrum, i.e. by perturbative parameters.

Shower cutoff Q_0 becomes parameter of model.

The Cluster Model

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” → Longitudinal cluster fission:



Rather string-like.

Fission threshold becomes crucial parameter.

~15% of primary clusters get split but ~50% of hadrons come from them.

The Cluster Model

"Leading hadrons are too soft"

→ 'perturbative' quarks remember their direction somewhat

$$P(\theta^2) \sim \exp(-\theta^2/2\theta_0^2)$$

Rather string-like.

Extra adjustable parameter.

Strings

“Hadrons are produced by hadronization: you must get the non-perturbative dynamics right”

Improving data has meant successively refining perturbative phase of evolution…

Clusters

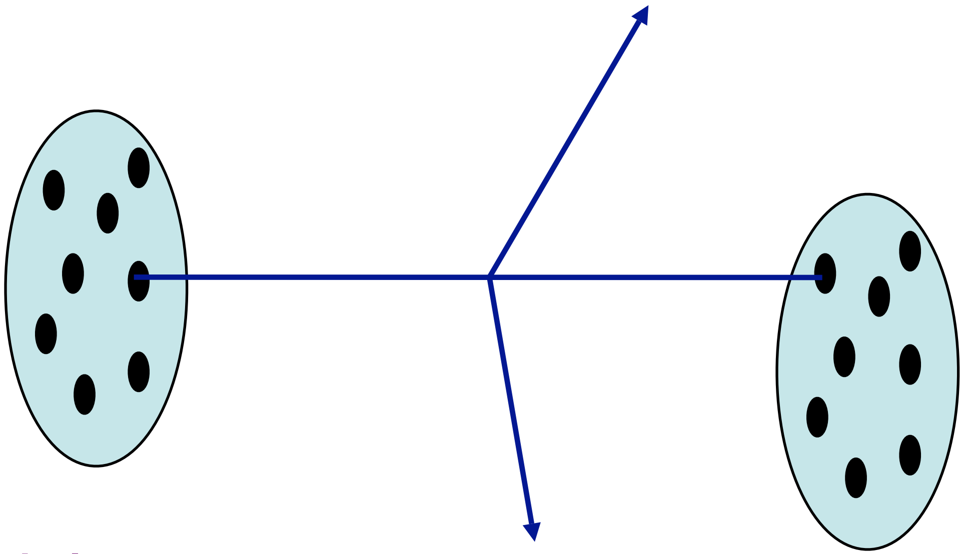
“Get the perturbative phase right and any old hadronization model will be good enough”

Improving data has meant successively making non-perturbative phase more string-like…

???

The Underlying Event

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



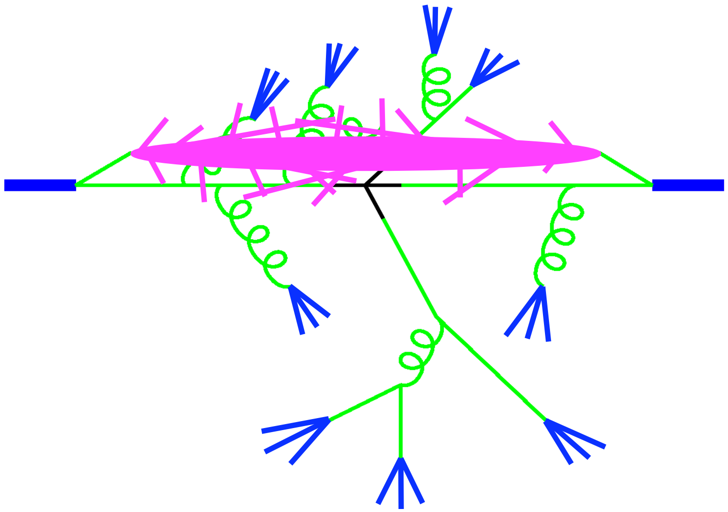
Two models:

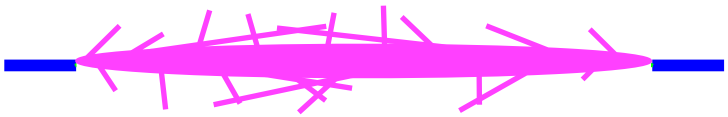
- Non-perturbative: Soft parton—parton cross section is so large that the remnants always undergo a soft collision.
- Perturbative: 'Hard' parton—parton cross section huge at low p_t, high energy, dominates inelastic cross section and is calculable.

Soft Underlying Event Model (HERWIG)

Compare underlying event with ‘minimum bias’ collision

(‘typical’ inelastic proton—proton collision)



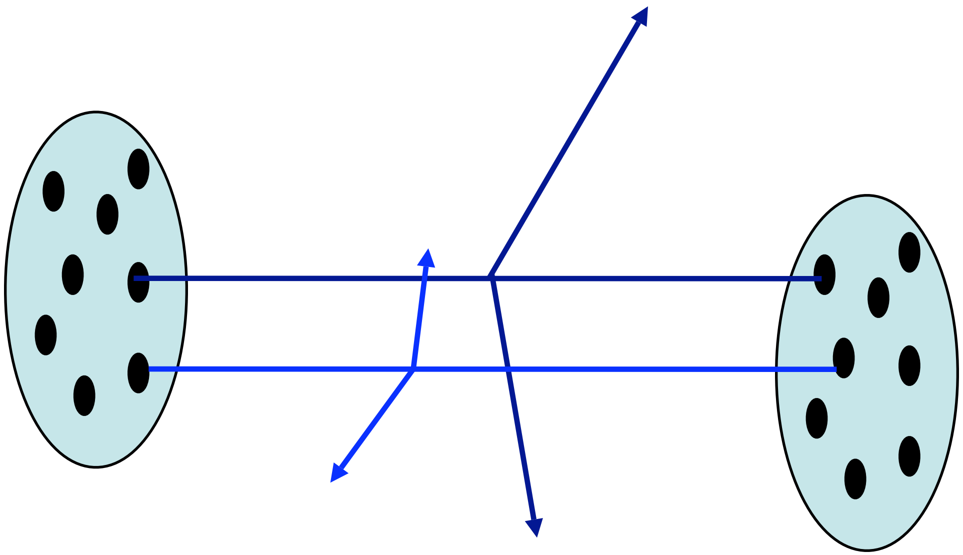


Parametrization of (UA5) data + model of energy dependence

Multiparton Interaction Model (PYTHIA/JIMMY)

For small $p_{t\,min}$ and high energy inclusive parton—parton cross section is larger than total proton—proton cross section.

→ More than one parton—parton scatter per proton—proton



Need a model of spatial distribution within proton

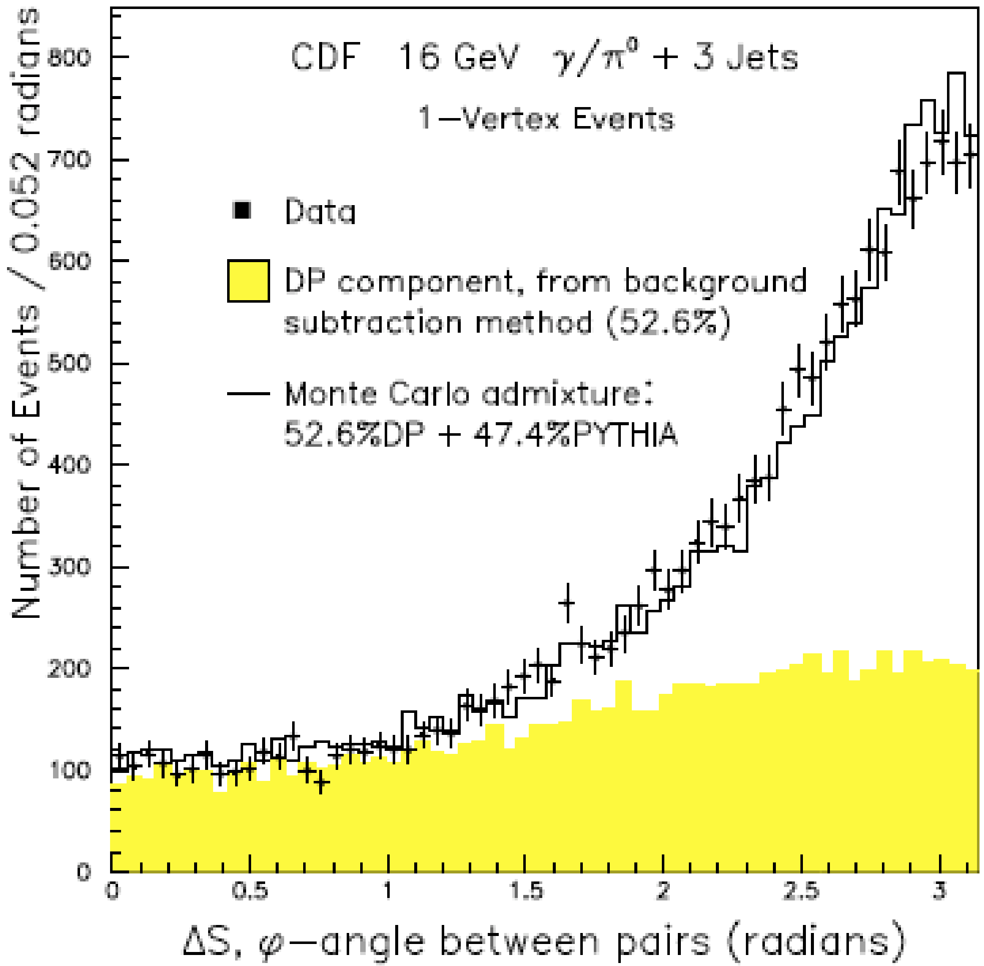
→ Perturbation theory gives you n-scatter distributions

Double Parton Scattering

- CDF Collaboration, PR D56 (1997) 3811

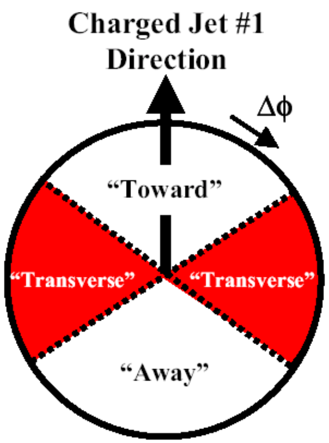
$$\sigma_{\rm DPS} = \frac{\sigma_{\gamma j}\sigma_{jj}}{\sigma_{\rm eff}}$$

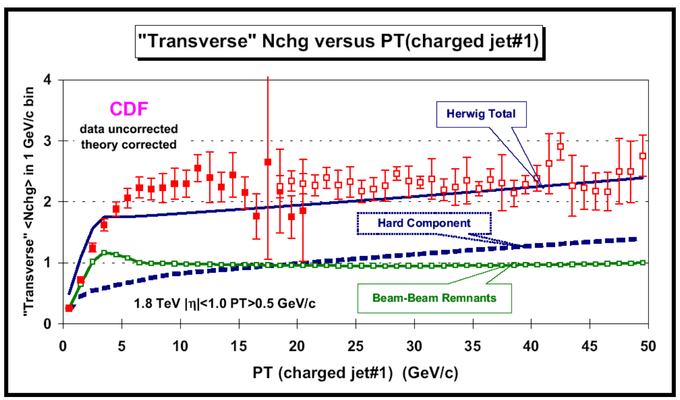
$$\sigma_{\rm eff} = 14 \pm 1.7^{+1.7}_{-2.3}\ {\rm mb}$$

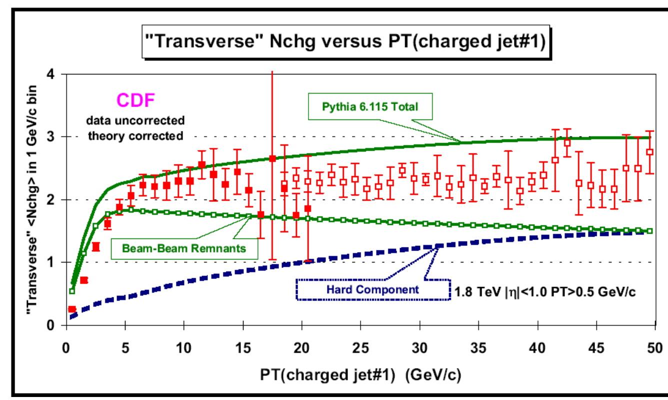


Some Warnings

- Not everyone means same thing by “underlying event”
  - Remnant—remnant interaction
  - Everything except hard process final state
- Separation into components is model dependent
  - Operational definition (R Field): “transverse” regions

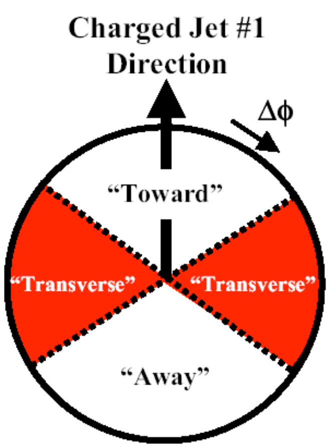


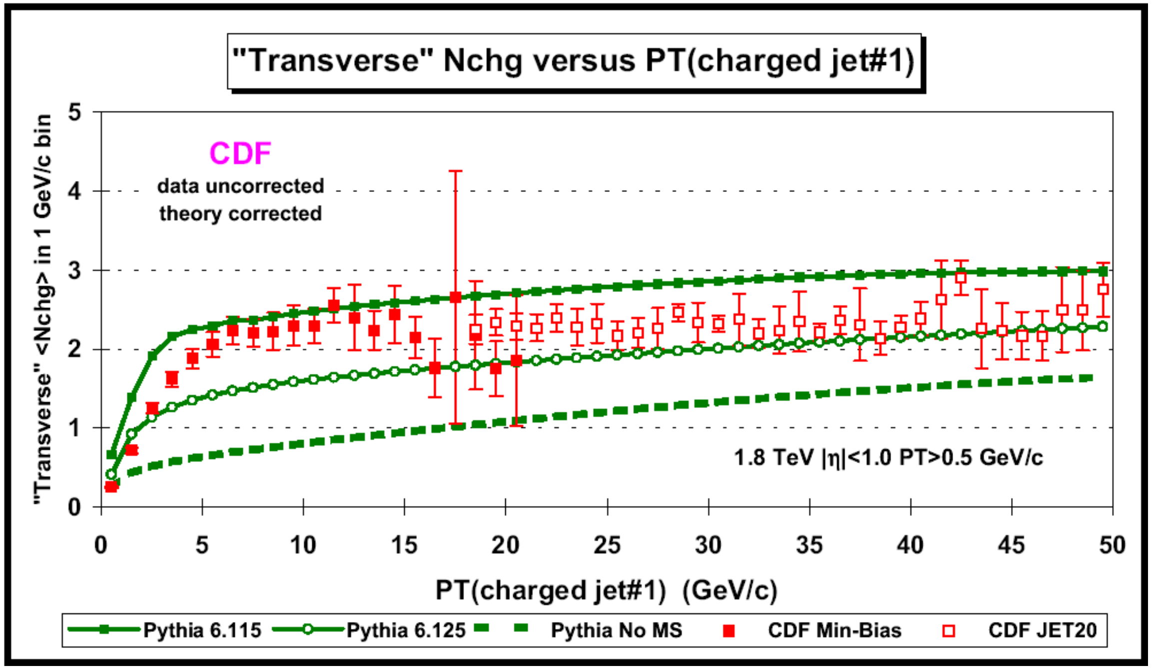




Tuning PYTHIA to the Underlying Event

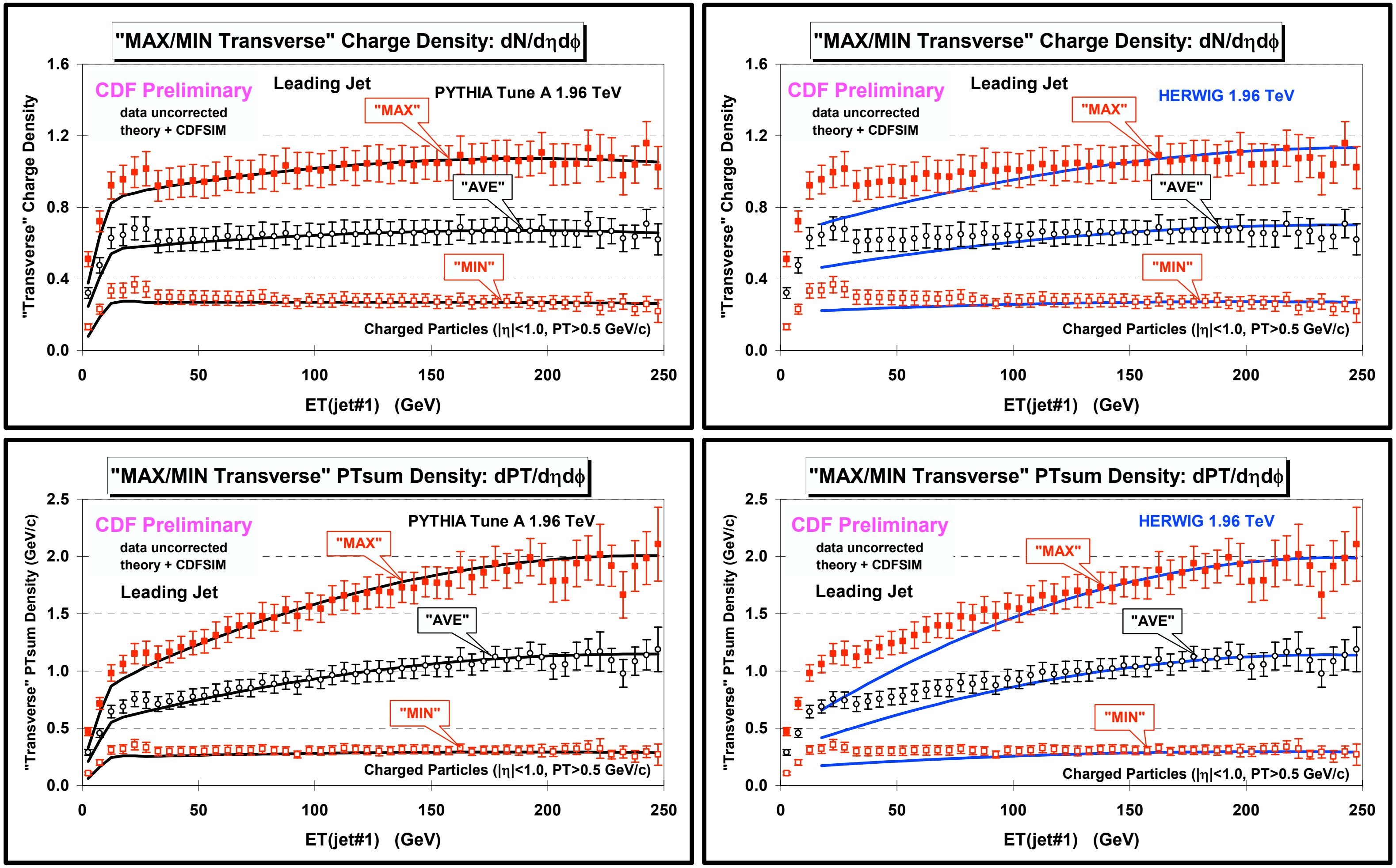
- Rick Field (CDF): keep all parameters that can be fixed by LEP or HERA at their default values. What's left?
- Underlying event. Big uncertainties at LHC...





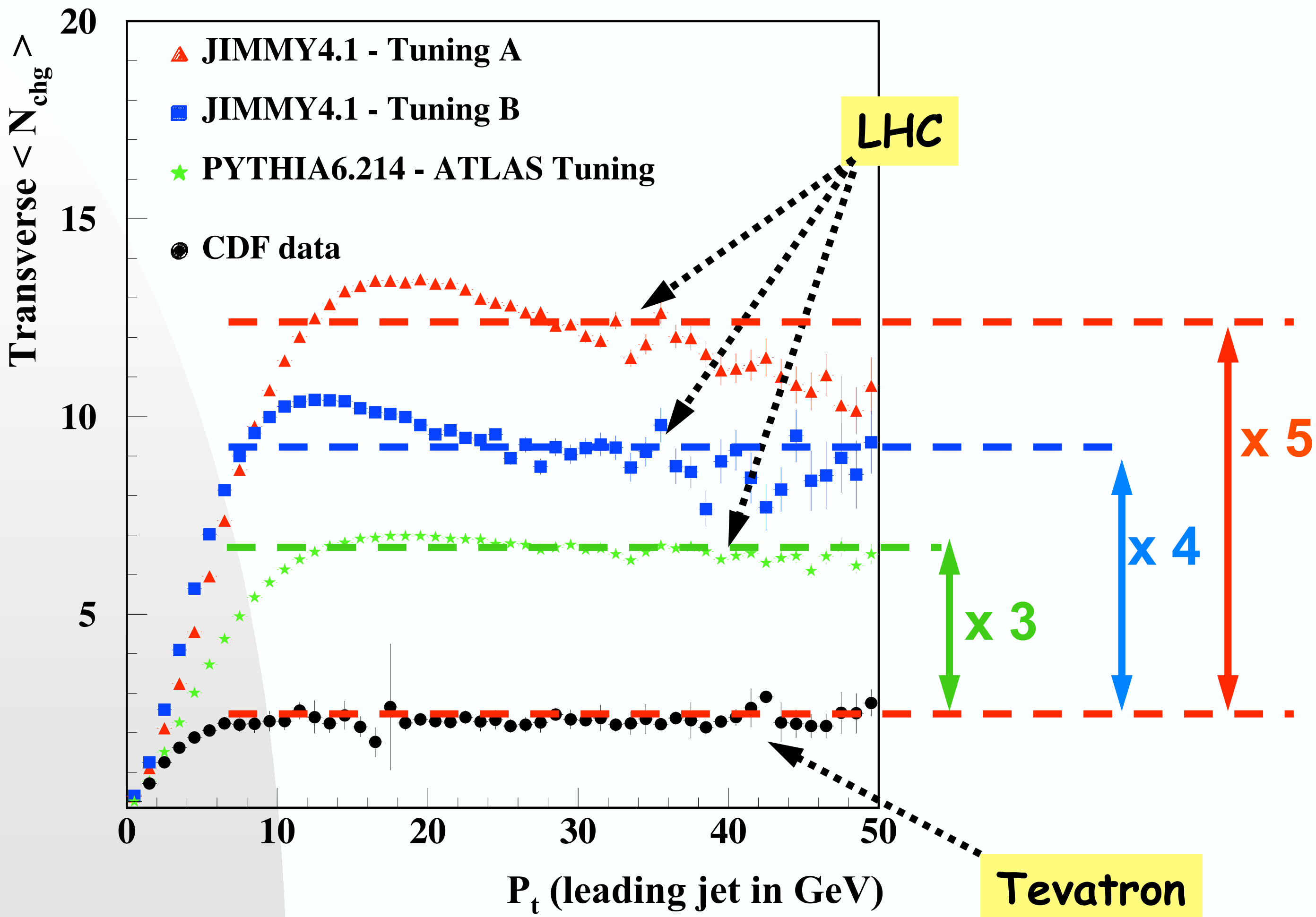
Leading Jet: "MAX & MIN Transverse" Densities

PYTHIA Tune A HERWIG



Charged particle density and PTsum density for "leading jet" events versus E_T(jet#1) for PYTHIA Tune A and HERWIG.

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

Summary

- Hard Process is very well understood: firm perturbative basis
- Parton Shower is fairly well understood: perturbative basis, with various approximations
- Hadronization is less well understood: modelled, but well constrained by data. Extrapolation to LHC fairly reliable.
- Underlying event least understood: modelled and only weakly constrained by existing data. Extrapolation?

- Always ask “What physics is dominating my effect?”