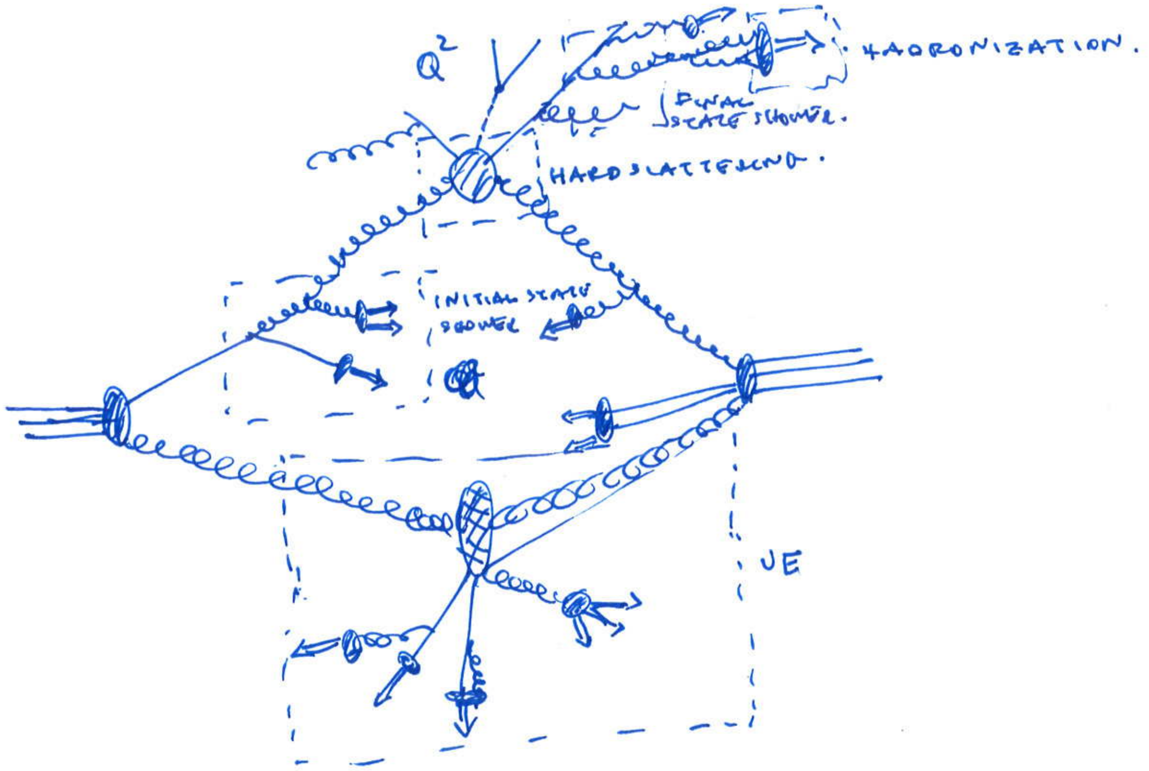
Lecture 13

Parton Showers - Hadronization - Underlying event

$Q_0^2 \sim 1\,GeV$



The need for parton showers:

- Accelerated charges radiate. The cascade of emission is a "parton shower"
- Jets are defined experimentally with respect to hadronic final states
- How to pass from few hardly emitted partons to a multitude of hadrons?
- Soft and collinear logs need to be factorized (modelled).

Probability in Radioactivity.

Survival probability after time t: $S(t) = P_{\text{no decay}}(t) = e^{-t/\tau} = e^{-t\Gamma}$

This is the cumulative probability. The decay probability distribution

is $$\frac{dP_{\text{decay}}}{dt} = -\frac{dP_{\text{no decay}}}{dt} = \Gamma e^{-\Gamma t}$$

Rewrite $\Gamma t \rightarrow \int_0^{t} dt' \, \Gamma(t')$

$$\rightarrow \frac{dP_{\text{decay}}}{dt} = \Gamma(t) \, \underbrace{e^{-\int_0^t dt' \, \Gamma(t')}}_{\text{Probability of no decay up to } t \text{ !}}$$

Remember: $$\frac{dq(x,Q^2)}{d(\log Q^2)} = \int_x^1 \frac{dy}{y} \, \alpha_s(Q^2) \, P_{qq}\left(\frac{x}{y}\right) q(y,Q^2).$$ DGLAP.

Remember: Collinear emission comes with a price!

$$d\sigma_{n+1} = d\sigma_n \, \frac{\alpha_s}{2\pi} \, \frac{dk_T^2}{k_T^2} \, P(z) \, dz.$$

You can write the collinear variable as
- k_T^2
- θ^2
- $q^2 = z(1-z) E^2 \theta^2$.

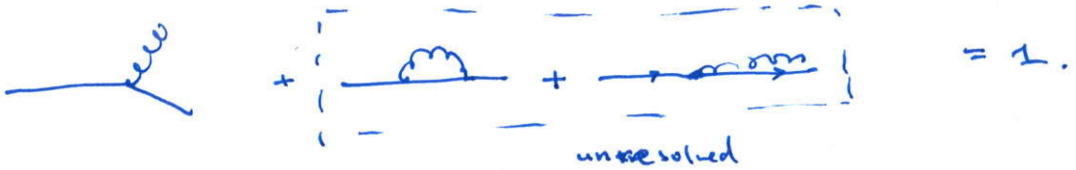
→ The k_T^2 integration diverges!

→ Introduce a cutoff t_0 ⟶ divergence becomes a $\log t_0$

→ $z \rightarrow 0$ divergence cured by cutoff.

→ Resolution criterion $k_T > Q_0$ (~ 1 GeV)

→ Combine virtual contributions with unresolved emissions would cancel divergences



→ The differential probability for emission between q^2 and $q^2 + dq^2$

$$dP = \frac{\alpha_s}{2\pi} \frac{dq^2}{q^2} \int_{z_{min}}^{z_{max}} dz\, P(z) \equiv dq^2 \underbrace{\frac{\alpha_s}{2\pi} \frac{1}{q^2} \int_{z_{min}}^{z_{max}} dz\, P(z)}_{\Gamma(q^2)}$$

→ No emission up to q^2 : Sudakov form factor $\Delta(Q^2, q^2) = e^{-\int_{q^2}^{Q^2} dk^2\, \Gamma(k^2)}$

Multiple emissions

Highest contribution comes from ordered emissions:

Cyeress picture.

$$t_1 > t_2 > t_3 \ldots > t_n$$

$$d\sigma \sim \sigma_0 \int_{Q_0^2}^{Q^2} \frac{dt_1}{t_1} \int_{Q_0^2}^{t_1} \frac{dt_2}{t_2} \cdots \int_{Q_0^2}^{t_{n-1}} \frac{dt_n}{t_n} \sim \log^n\left(\frac{Q^2}{Q_0^2}\right)$$

→ Ressummation of collinear logs!

→ Q^2 is process dependent!

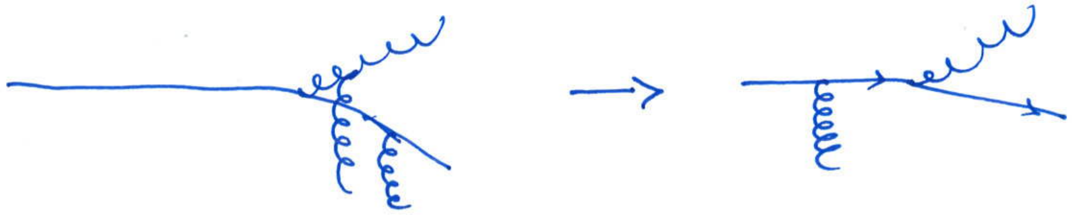
Improvement: instead of fixing α_s once and for all, one can introduce a k_T^2 dependent $\alpha_s(k_T^2)$, for every branching. This incorporates some virtual pieces!

→ Must avoid Landau pole $k_T^2 > Q_0^2 \gg \Lambda_{QCD}^2$

Soft logarithms

→ Problem: they come from all over!

→ But angular ordering takes care of soft limit! (Marchesini and Webber)



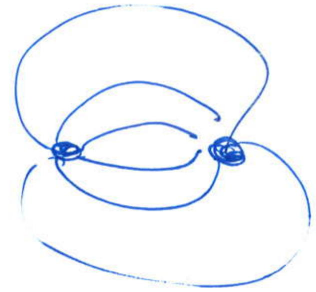
Coherence!

→ k_T^2 ordering doesn't automatically!

Existing Tools

	evolution	Coherence?
ARIADNE	k_T ordered	by const'
Herwig	angular	
Herwig++	improved angular	
Pythia 7	old: virtuality ordered new: k_T-ordered	
Sherpa	virtuality ordered new: k_T-ordered	
Vincia	k_T-ordered	

hadronization

→ Dipoles in QCD  in QED 

→ Assuming a linear QCD potential describes "well" Quarkonia spectrum

→ Feynman - Field fragmentation

- Recursively fragment $q \to q' + \text{hadron}$

  with p_T fitted Gaussian

  p_z arbitrary } from measurements

  Flavour from symmetry arguments

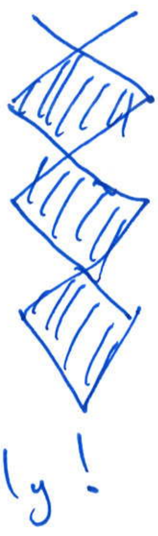
Problems: what to do with last quark?

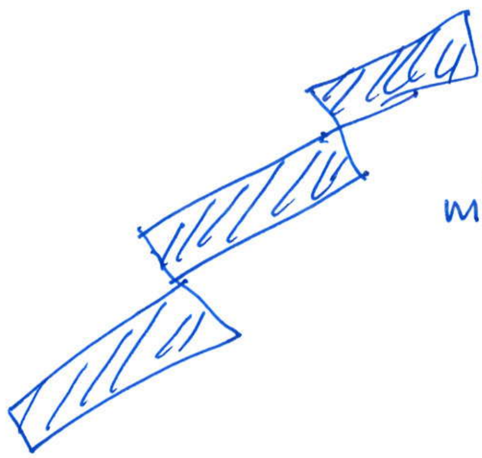
infrared unsafe

no direct link to pert. theory

no predictability!

→ Yo-yo strings

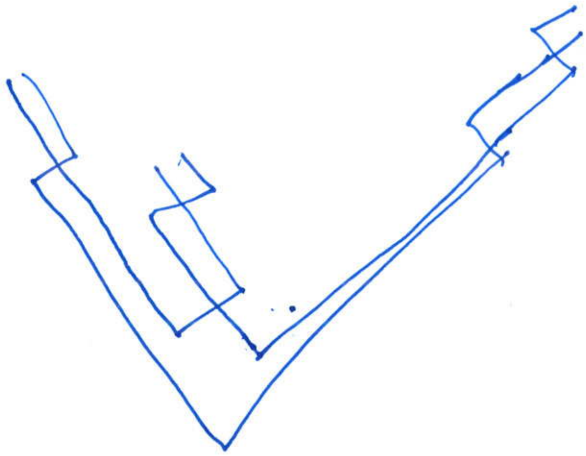




$m^2 \sim$ area.

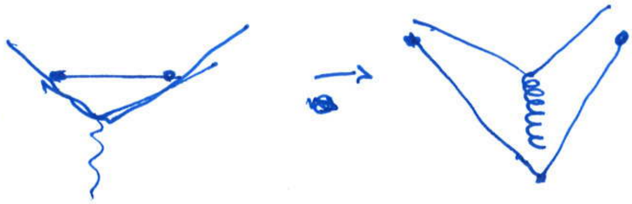
Mesons only! Should we treat ~~hadrons~~ baryons as $(\overline{qq}) - q$ bound states?

Ignoring gluon radiation ($q\bar{q}$ pairs pop out of vacuum)



string tension is a parameter!

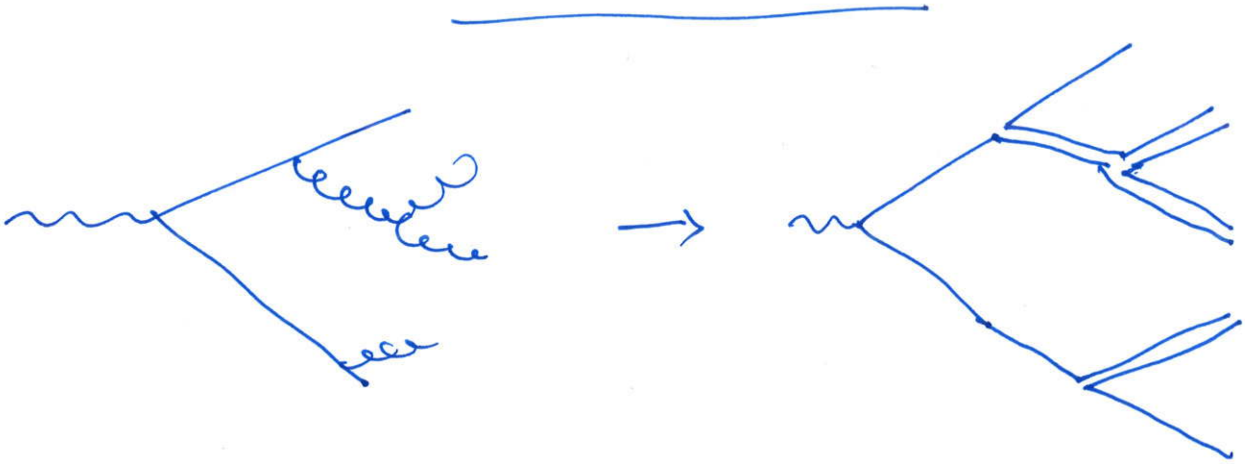
→ Gluons: kinks on strings!



Clustering – Preconfinement

Large N_c limit

ONLY PLANAR GRAPHS!



The mass of the singlets peaked at Q_0^2!

Preconfinement → gluons in $q\bar{q}$ → clusters (excited hadrons) → decay to hadrons

Underlying event (beyond factorization)!

- Protons are actually extended objects
- No guarantee for one scattering only
- Running of α_s : preference for soft scattering!

- Evidence for multiple scattering. in $\gamma + 3$ jets.
- Definition problem :
  - everything apart from hard + showers + hadronization
  - remnant-remnant interactions

- There is no first-principle approach yet.
- Models are usually based on collinear factorization x-sections, which makes them sensitive to p_T^{min}
- Tuning to data very aggresive!