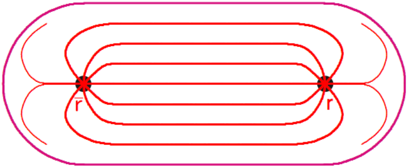
The Lund Model
and some extensions

Torbjörn Sjöstrand

Department of Astronomy and Theoretical Physics
Lund University
Sölvegatan 14A, SE-223 62 Lund, Sweden

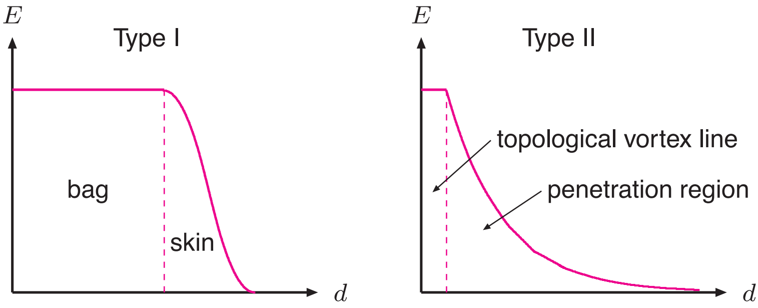
Workshop on Collective effects in small collisions systems,
CERN, 15 June 2017

The QCD string



QCD field lines compressed to tubelike region $\Rightarrow$ **string**.
Gives linear confinement $V(r) \approx \kappa r$, $\kappa \approx 1$ GeV/fm.
Confirmed e.g. on the lattice.

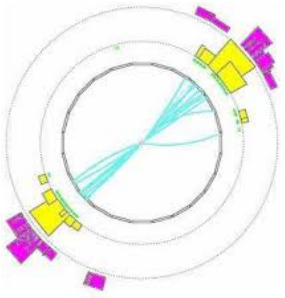
Nature of the string viewed in analogy with superconductors:



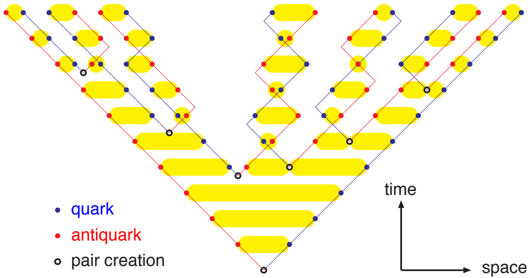
but QCD could be intermediate, or different.

The Lund string

PETRA two-jet event:



Lund model: repeated string breaks
for large system with pure $V(r) = \kappa r$:



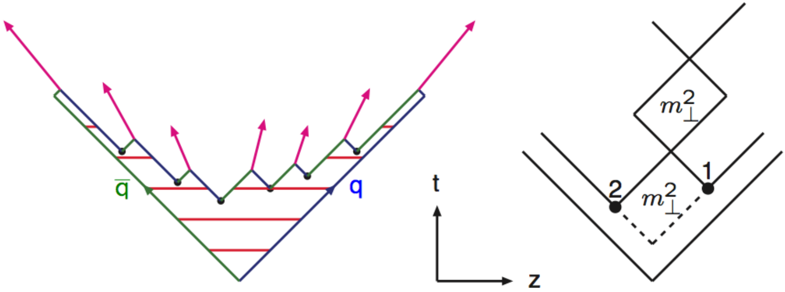
Linearity $\Rightarrow$ $$\left|\frac{\mathrm{d}E}{\mathrm{d}z}\right| = \left|\frac{\mathrm{d}p_z}{\mathrm{d}z}\right| = \left|\frac{\mathrm{d}E}{\mathrm{d}t}\right| = \left|\frac{\mathrm{d}p_z}{\mathrm{d}t}\right| = \kappa$$

$\Rightarrow$

energy–momentum quantities can be read off from space–time ones

Longitudinal fragmentation

Fragmentation starts in the middle and spreads outwards:



Breakup vertices causally disconnected $\Rightarrow$ *left–right symmetry*

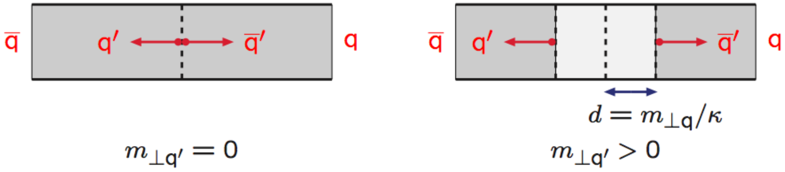
$$\mathcal{P}(1,2) = \mathcal{P}(1) \times \mathcal{P}(1 \to 2) = \mathcal{P}(2) \times \mathcal{P}(2 \to 1)$$

$\Rightarrow$ Lund symmetric fragmentation function:

$$f(z) \propto (1-z)^a \exp(-bm_\perp^2/z)/z$$

$a = 0 \Rightarrow$ exponential decay in string area spanned

The tunneling mechanism



String breaking modelled by tunneling:

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

1. common Gaussian $p_\perp$ spectrum
2. suppression of heavy quarks
   $\mathrm{u\overline{u}} : \mathrm{d\overline{d}} : \mathrm{s\overline{s}} : \mathrm{c\overline{c}} \approx 1 : 1 : 0.3 : 10^{-11}$
3. diquark $\sim$ antiquark $\Rightarrow$ simple model for baryon production

For tuning: replace $\kappa/\pi \to \sigma^2$ (broadened by soft g effects?).

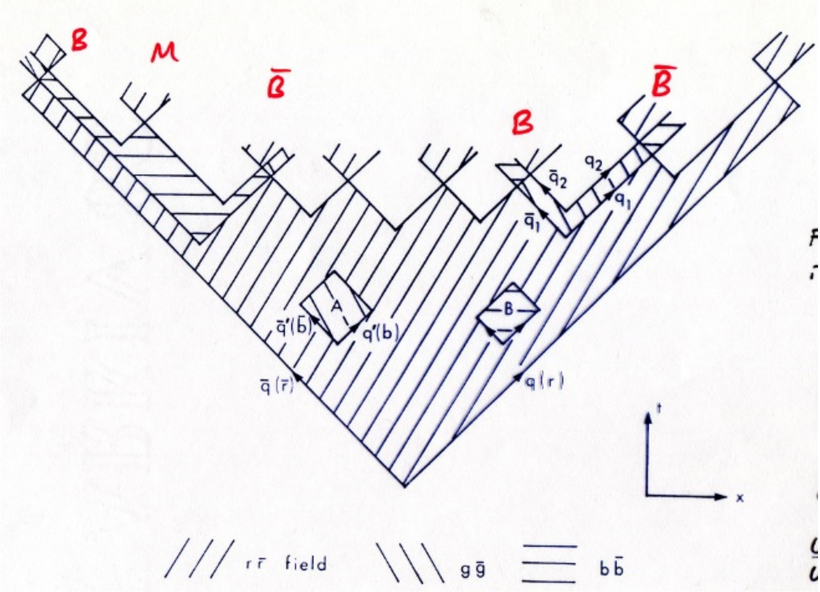
Flavour composition

Combination of q from one break and $\overline{\mathrm{q}}$ (qq) gives meson (baryon).
Many uncertainties in selection of hadron species, e.g.:

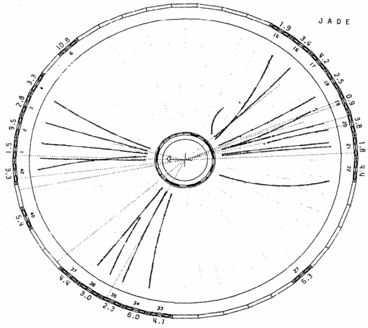
- Spin counting suggests vector:pseudoscalar $=$ 3:1, but $m_\rho \gg m_\pi$, so empirically $\sim$1:1.
- Also for same spin $m_{\eta'} \gg m_\eta \gg m_{\pi^0}$ gives mass suppression. String model unpredictive in understanding of hadron mass effects $\Rightarrow$ many "materials constants".
- There is one V and one PS for each $\mathrm{q}\overline{\mathrm{q}}$ flavour set, but baryons are more complicated, e.g. $\mathrm{uuu} \Rightarrow \Delta^{++}$ whereas $\mathrm{uds} \Rightarrow \Lambda^0$, Σ^0 or Σ^{*0}. SU(6) (flavour$\times$spin) Clebsch-Gordans needed; affects surrounding flavours.
- Simple diquark model too simpleminded; produces baryon–antibaryon pairs nearby in momentum space.

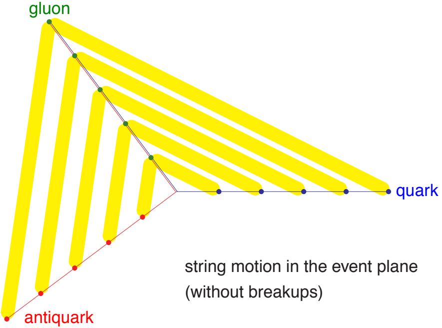
Many parameters, 10–20 depending on how you count, but no explicit dependence on hadron masses.

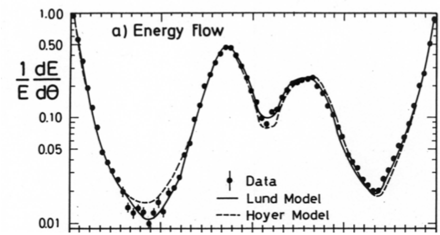
The popcorn model for baryon production



Extension to gluons

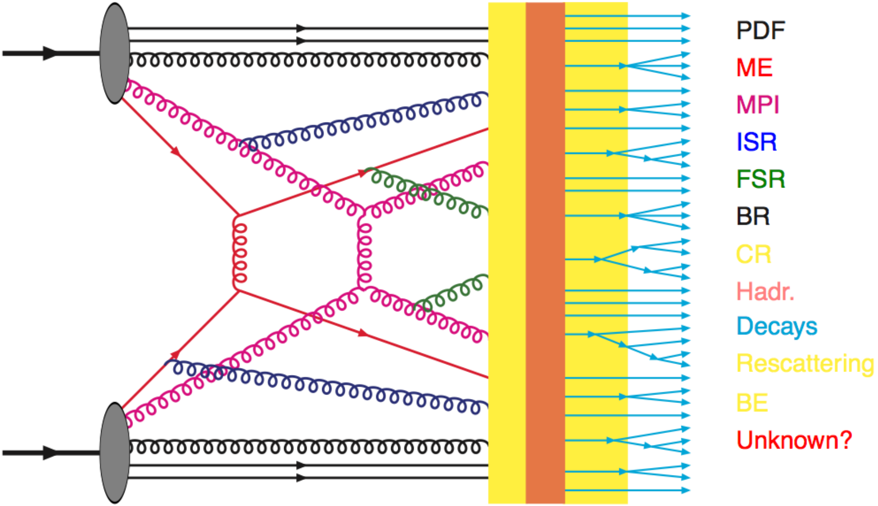






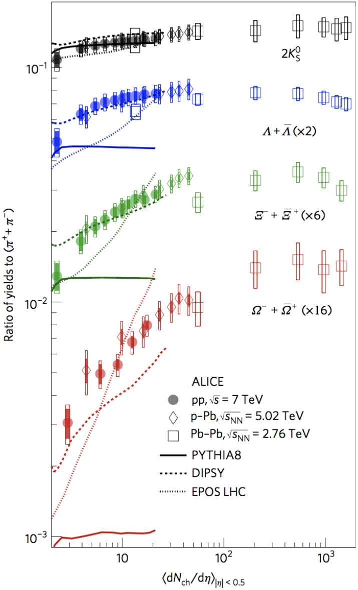
Lund model gives no-parameter extension to hadronization of multiparton system, given known colour flow (for $N_C \to \infty$).

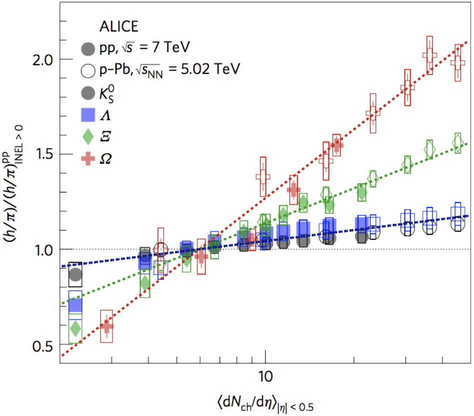
The assumption of jet universality



Jet universality: the string topology will depend on the collision process, but string fragmentation parameters are immutable.

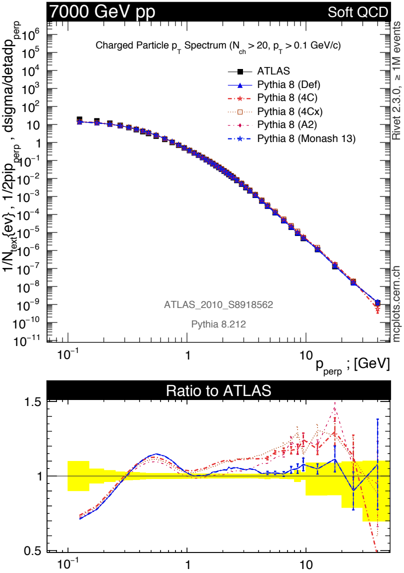
The ALICE revelation: goodbye jet universality!





Signs of QGP in high-multiplicity *pp* collisions? If not, what else? A whole new game!

Other issues



Problems brewing even earlier

- wrong shape for hadron spectra at low $p_\perp$
- undershoot rising trend of $\langle p_\perp \rangle$ with m_{hadron}
- (ridge effect, v_2)

$\Rightarrow$ work with Nadine Fischer, in JHEP 1701 (2017) 140.

Thermodynamical string model

Old lesson from fixed target and ISR (pp at $\sqrt{s} = 62$ GeV):

$$\frac{\mathrm{d}\sigma}{\mathrm{d}^2 p_\perp} = N \exp\left(-\frac{m_{\perp\mathrm{had}}}{T}\right) \quad , \quad m_{\perp\mathrm{had}} = \sqrt{m_{\mathrm{had}}^2 + p_\perp^2}$$

provides reasonable description, for $p_\perp$ not too large, with $\sim$ same N and T for all hadron species.

But inclusive description: no flavour, **p** or E conservation!

So construct local analogue with longitudinal string structure:

- $p_\perp$ spectrum at $\mathrm{q}\overline{\mathrm{q}}$ string breaks $\propto K_{1/4}(p_{\perp\mathrm{q}}/T)/(p_{\perp\mathrm{q}}/T)^{1/4}$ so that convolution gives exponential.
- Given $p_{\perp\mathrm{had}}$ and incoming q_1 pick among possible hadrons according to $P_{\mathrm{had}} \propto \exp(-m_{\perp\mathrm{had}}/T)$.
- Factors for diagonal meson mixing, baryon **SU(6)** symmetry.
- Free parameters for relative baryon production ($\sim$OK) and strangeness suppression (ugly).
- Some fine print (which multiplets, no popcorn, c quarks, ...).

Other model variations

Gaussian model: same as default PYTHIA, except allow larger Gaussian $p_\perp$ widths for strange quarks and diquarks.

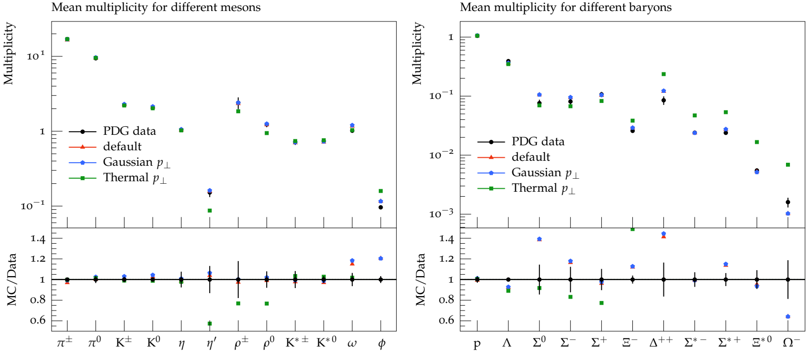
Changed string tension:
string close-packing $\Rightarrow$ smaller radius $\Rightarrow$ higher E $\Rightarrow$ larger κ

$$T \to \left(n_{\mathrm{string}}^{\mathrm{eff}} \right)^r T \quad ; \quad n_{\mathrm{string}}^{\mathrm{eff}} = 1 + \frac{n_{\mathrm{string}} - 1}{1 + p_{\perp\mathrm{had}}^2 / p_{\perp 0}^2}$$

with tuned $r \approx 0.13$;
similar to rope (Leif), but continuous effect.

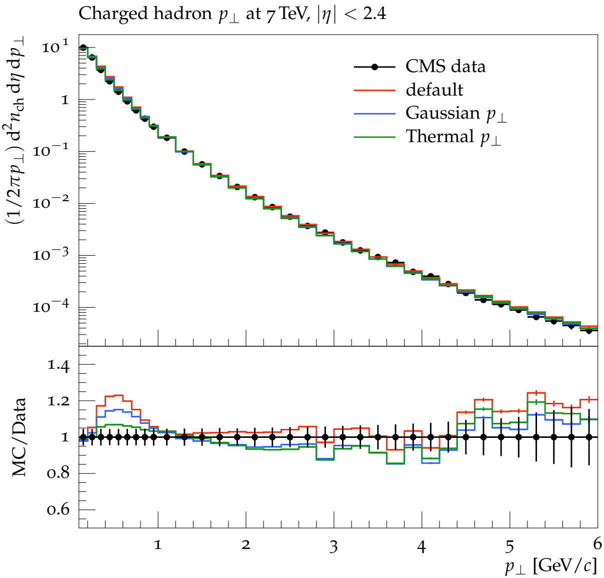
Hadronic rescattering: potential mechanism for collective flow.
Toy: isotropic scattering for hadron pairs with low mass or near in (y, φ), but not near neighbours inside same string.

Hadron composition



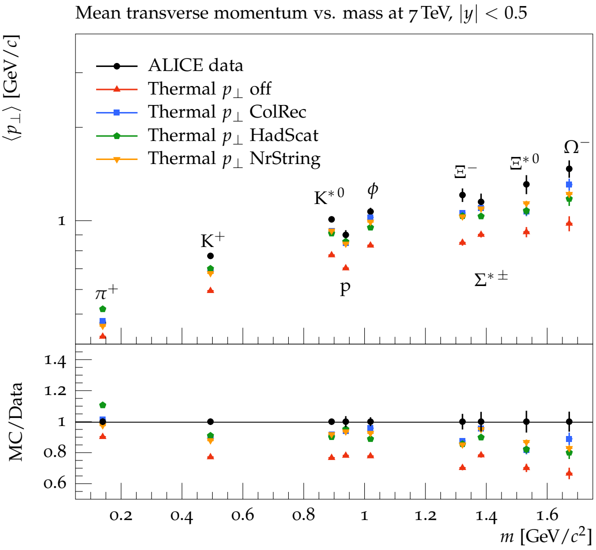
Exponential gives overall decent rates compared with LEP,
but with too many multistrange baryons.
Opposite to Gaussian, where too strong multistrange suppression
patched up by nonintuitive strange diquark parameters.
Significant reduction from ~ 20 parameters to 3:
$T \approx 0.20$ GeV, $\mathrm{s/u} \approx 0.5$, $\mathrm{qq/q} \approx 0.5$.

Hadronic transverse momenta



Effects strongly diluted by resonance decays (e.g. $\rho^0 \to \pi^+\pi^-$, $K^0_S \to K^+\pi^-$).

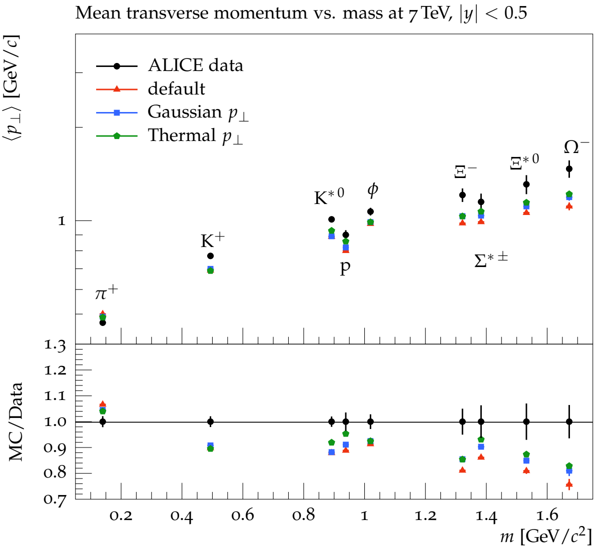
Hadron mean transverse momenta



Individual mechanisms improve $\langle p_\perp \rangle (m_{\mathrm{hadron}})$ ...

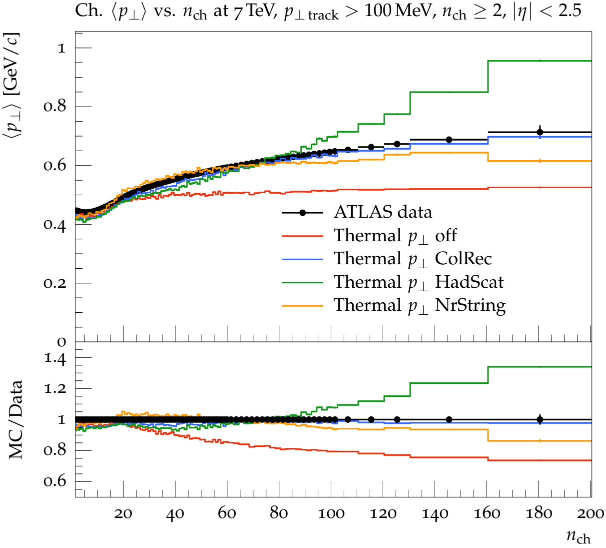
(off $\Rightarrow$ also no colour reconnection)

Hadron mean transverse momenta (2)



. . . but combined results, including other constraints, not as impressive.

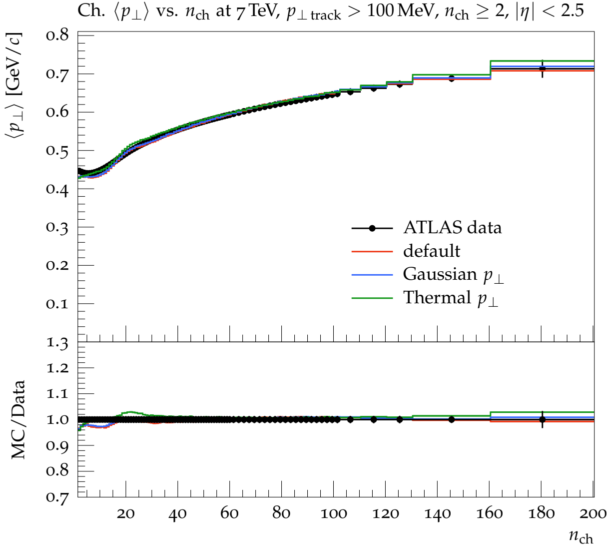
Multiplicity-dependence of transverse momenta



One key tuning distribution is $\langle p_\perp \rangle (n_{\mathrm{charged}})$, with each mechanism contributing to rise . . .

(off $\Rightarrow$ also no colour reconnection)

Multiplicity-dependence of transverse momenta (2)



... but tunes have to restrict net effect.

ALICE flavour composition as fn. of n_{charged}? Right trend, but no one-to-one comparison (RIVET, please)

What next?

- Look forward to ATLAS, CMS, LHCb studies of the change in flavour composition (K^0_S, Λ, Ξ, Ω have secondary vertices!).
- ϕ mesons to come: zero or two s quarks?
- Role of local vs. global multiplicity for enhancement.
- Flavour composition in jets vs. in UE:
  typically less overlap in jets, so expect less effect,
  but what about high-multiplicity jets?
  Data: Λ_b/B^0 and B_s/B^0 dropping with $p_\perp$.
- Flavour correlations, e.g. baryon-antibaryon.
- Correlation with ridges and flow v_n values?

Whole new field of study opening up!

Summary and outlook

- Lund string model historically successful, but now showing cracks.
- String close-packing likely to have effects before, during and after hadronization.
- Example models (to be) presented by Klaus, Leif and Peter.
- But currently no known unique solution, so free to explore; here thermal m and $p_{\perp}$ spectrum, changed string tension, and hadronic rescattering.
- Improvements nontrivial, e.g. resonance decays.
- Own plan for near future: detailed space–time mapping of hadronization process combined with hadronic rescattering.
- Further experimental input crucial!