Introduction to Event Generators

Part 3: Multiparton Interactions and Hadronization

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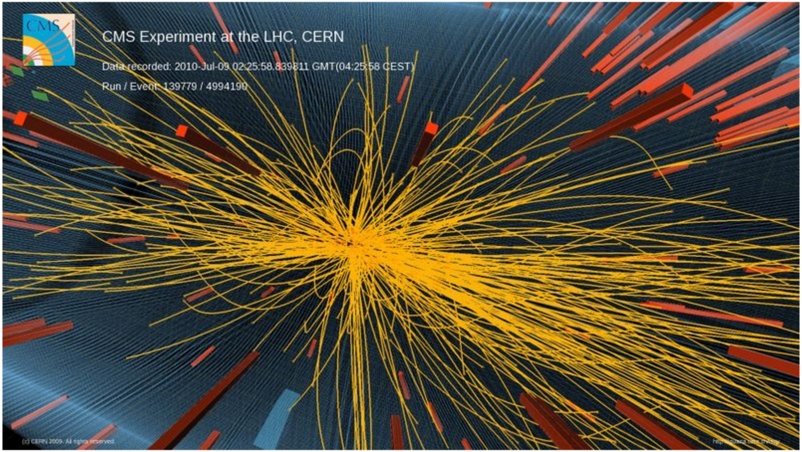
Event topologies



Expect and observe high multiplicities at the LHC.
What are production mechanisms behind this?

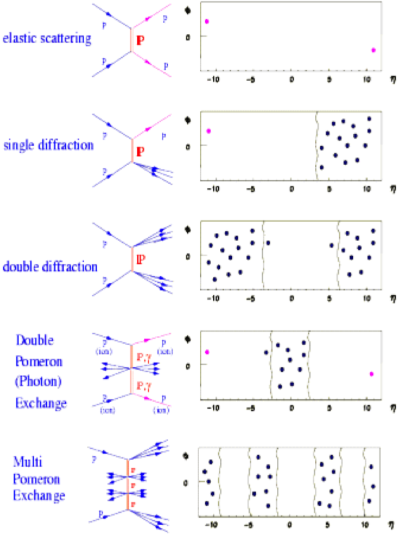
Event-type properties

Roughly 60% of $\sigma_{\rm tot} \approx 100$ mb consists of "ordinary" events, "inelastic nondiffractive", where the full rapidity range is populated by particle production.

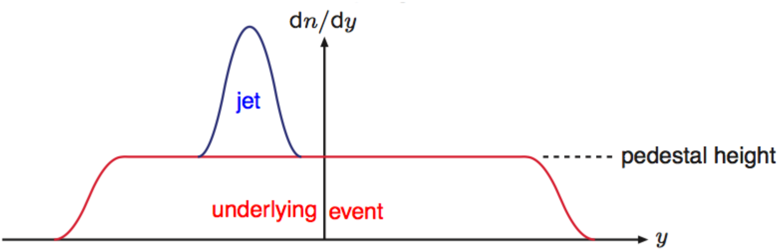
The remaining events have large or small rapidity gaps with no production.

Many of the latter events escape detection.

Minimum-bias events: all events that can be triggered/observed by a detector, without any further selection.



What is underlying event (UE)?

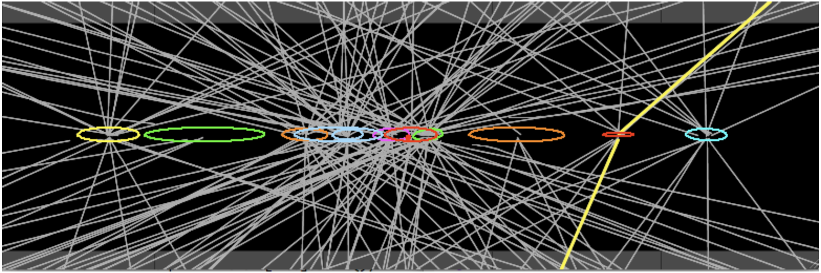


In an event containing a jet pair or another hard process, how much further activity is there, that does not have its origin in the hard process itself, but in other physics processes?

Pedestal effect: the UE contains more activity than a normal MB event does (even discarding diffractive events).

Trigger bias: a jet "trigger" criterion $E_{\perp \mathrm{jet}} > E_{\perp \mathrm{min}}$ is more easily fulfilled in events with upwards-fluctuating UE activity, since the UE $E_{\perp}$ in the jet cone counts towards the $E_{\perp \mathrm{jet}}$. *Not enough!*

What is pileup?



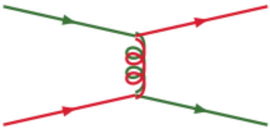
$\langle n \rangle = \overline{\mathcal{L}}\,\sigma$

where $\overline{\mathcal{L}}$ is machine luminosity per bunch crossing, $\overline{\mathcal{L}} \sim n_1 n_2 / A$ and $\sigma \sim \sigma_{\mathrm{tot}} \approx 100$ mb.
Current LHC machine conditions $\Rightarrow \langle n \rangle \sim 20 - 100$.

Pileup introduces no new physics, and is thus not further considered here, but can be a nuisance.
However, keep in mind concept of bunches of hadrons leading to multiple collisions.

The divergence of the QCD cross section

Cross section for $2 \to 2$ interactions is dominated by t-channel gluon exchange, so diverges like $\mathrm{d}\hat{\sigma}/\mathrm{d}p_\perp^2 \approx 1/p_\perp^4$ for $p_\perp \to 0$.



Integrate QCD $2 \to 2$

$\mathrm{qq}' \to \mathrm{qq}'$

$\mathrm{q\overline{q}} \to \mathrm{q}'\overline{\mathrm{q}}'$

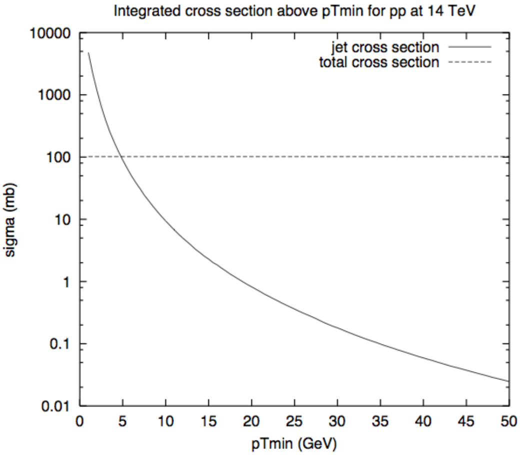
$\mathrm{q\overline{q}} \to \mathrm{gg}$

$\mathrm{qg} \to \mathrm{qg}$

$\mathrm{gg} \to \mathrm{gg}$

$\mathrm{gg} \to \mathrm{q\overline{q}}$

(with CTEQ 5L PDF's)



What is multiple partonic interactions (MPI)?

Note that $\sigma_{\mathrm{int}}(p_{\perp\mathrm{min}})$, the number of ($2 \to 2$ QCD) interactions above $p_{\perp\mathrm{min}}$, involves integral over PDFs,

$$\sigma_{\mathrm{int}}(p_{\perp\mathrm{min}}) = \iiint_{p_{\perp\mathrm{min}}} \mathrm{d}x_1 \, \mathrm{d}x_2 \, \mathrm{d}p_\perp^2 \, f_1(x_1, p_\perp^2) \, f_2(x_2, p_\perp^2) \, \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_\perp^2}$$

with $\int \mathrm{d}x \, f(x, p_\perp^2) = \infty$, i.e. infinitely many partons.

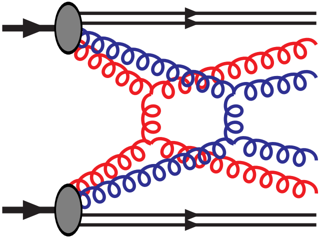
So half a solution to $\sigma_{\mathrm{int}}(p_{\perp\mathrm{min}}) > \sigma_{\mathrm{tot}}$ is

many interactions per event: MPI

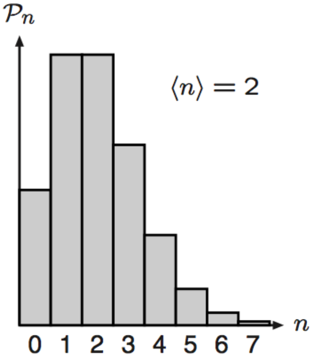
$$\sigma_{\mathrm{tot}} = \sum_{n=0}^{\infty} \sigma_n$$

$$\sigma_{\mathrm{int}} = \sum_{n=0}^{\infty} n \, \sigma_n$$

$$\sigma_{\mathrm{int}} > \sigma_{\mathrm{tot}} \iff \langle n \rangle > 1$$



Poissonian statistics



If interactions occur independently
then **Poissonian statistics**

$$\mathcal{P}_n = \frac{\langle n \rangle^n}{n!} \, e^{-\langle n \rangle}$$

but $n = 0 \Rightarrow$ no event (in many models)
and energy–momentum conservation
$\Rightarrow$ large n suppressed
so narrower than Poissonian

MPI is a logical consequence of the composite nature of protons,
$n_{\mathrm{parton}} \sim \sum_{\mathrm{q},\overline{\mathrm{q}},\mathrm{g}} \int f(x) \, \mathrm{d}x > 3$, which allows $\sigma_{\mathrm{int}}(p_{\perp\mathrm{min}}) > \sigma_{\mathrm{tot}}$,
but what about the limit $p_{\perp\mathrm{min}} \to 0$?

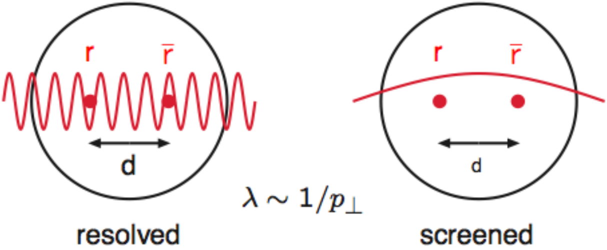
Colour screening

Other half of solution is that perturbative QCD is not valid at small $p_\perp$ since q, g are not asymptotic states (confinement!).

Naively breakdown at

$$p_{\perp\mathrm{min}} \simeq \frac{\hbar}{r_\mathrm{p}} \approx \frac{0.2\ \mathrm{GeV}\cdot\mathrm{fm}}{0.7\ \mathrm{fm}} \approx 0.3\ \mathrm{GeV} \simeq \Lambda_\mathrm{QCD}$$

. . . but better replace r_p by (unknown) colour screening length d in hadron:

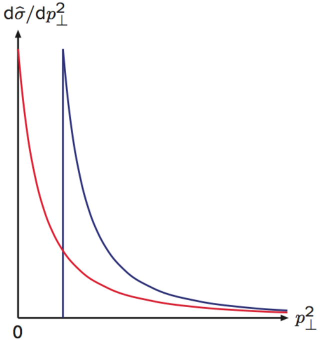


Regularization of low-$p_\perp$ divergence

so need **nonperturbative regularization for $p_\perp \to 0$**, e.g.

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_\perp^2} \propto \frac{\alpha_s^2(p_\perp^2)}{p_\perp^4} \quad \to \quad \frac{\alpha_s^2(p_\perp^2)}{p_\perp^4}\,\theta\,(p_\perp - p_{\perp\mathrm{min}}) \qquad \text{(simpler)}$$

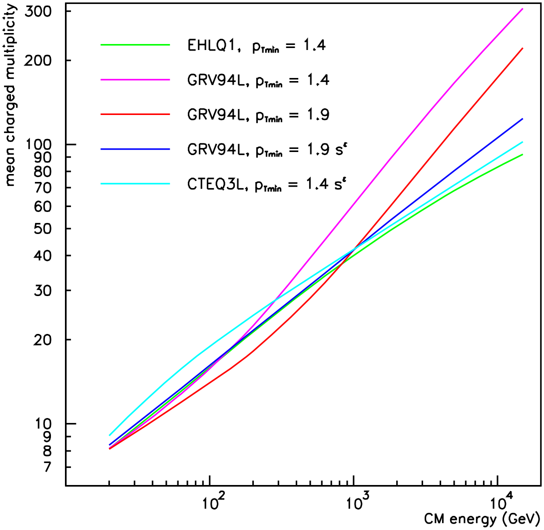
$$\text{or} \quad \to \quad \frac{\alpha_s^2(p_{\perp 0}^2 + p_\perp^2)}{(p_{\perp 0}^2 + p_\perp^2)^2} \qquad \text{(more physical)}$$



where $p_{\perp\mathrm{min}}$ or $p_{\perp 0}$ are free parameters, empirically of order **2–3 GeV**.

Typical number of interactions/event is 3 at 2 TeV, 4 – 5 at 13 TeV, but may be twice that in "interesting" high-$p_\perp$ ones.

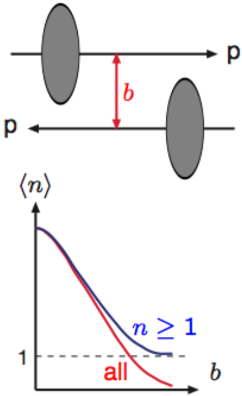
Energy dependence of $p_{\perp\mathrm{min}}$ and $p_{\perp 0}$



Larger collision energy
$\Rightarrow$ probe parton ($\approx$ gluon) density at smaller x
$\Rightarrow$ smaller colour screening length d
$\Rightarrow$ larger $p_{\perp\mathrm{min}}$ or $p_{\perp 0}$
$\Rightarrow$ dampened multiplicity rise

Impact parameter dependence

So far assumed that all collisions have equivalent initial conditions, but hadrons are extended, so dependence on impact parameter b.



Overlap of protons during encounter is

$$\mathcal{O}(b) = \int \mathrm{d}^3\mathbf{x}\,\mathrm{d}t\; \rho_1(\mathbf{x}, t)\,\rho_2(\mathbf{x}, t)$$

where ρ is (boosted) matter distribution in p, e.g. Gaussian or electromagnetic form factor.

Average activity at b proportional to $\mathcal{O}(b)$:

- ⋆ central collisions more active
  $\Rightarrow \mathcal{P}_n$ broader than Poissonian;
- ⋆ peripheral passages normally give
  no collisions $\Rightarrow$ finite σ_{tot}.

without MPI:

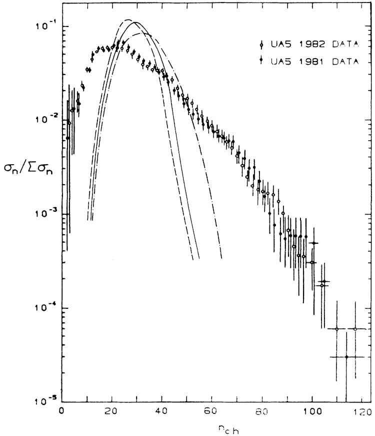


FIG. 3. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs simple models: dashed low p_T only, full including hard scatterings, dash-dotted also including initial- and final-state radiation.

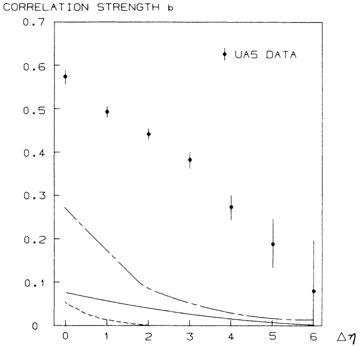


FIG. 4. Forward-backward multiplicity correlation at 540 GeV, UA5 results (Ref. 33) vs simple models; the latter models with notation as in Fig. 3.

Indirect evidence for multiparton interactions – 2

with MPI included:

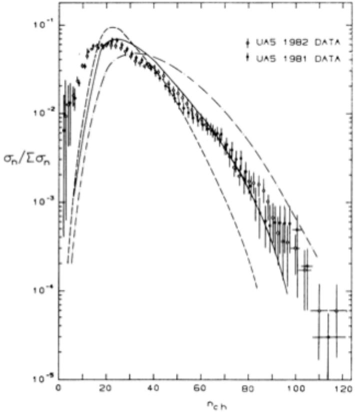


FIG. 5. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs impact-parameter-independent multiple-interaction model: dashed line, $p_{T\min} = 2.0$ GeV; solid line, $p_{T\min} = 1.6$ GeV; dashed-dotted line, $p_{T\min} = 1.2$ GeV.

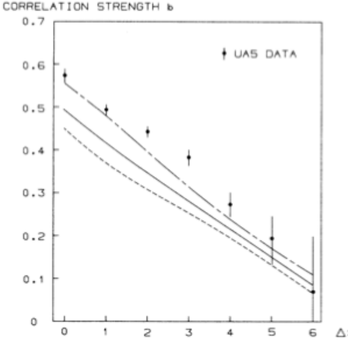
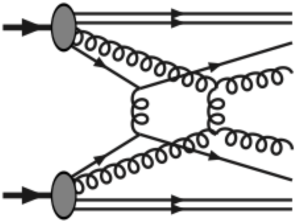


FIG. 6. Forward-backward multiplicity correlation at 540 GeV, UA5 results (Ref. 33) vs impact-parameter-independent multiple-interaction model; the latter with notation as in Fig. 5.

Double parton scattering

Double parton scattering (DPS): two hard processes in same event.



$$\sigma_{\mathrm{DPS}} = \begin{cases} \dfrac{\sigma_A \sigma_B}{\sigma_{\mathrm{eff}}} & \text{for } A \neq B \\ \dfrac{\sigma_A \sigma_B}{2\,\sigma_{\mathrm{eff}}} & \text{for } A = B \end{cases}$$

Poissonian statistics:

$$e^{A+B} = 1 + A + B + \frac{(A+B)^2}{2} + \cdots$$
$$= 1 + A + B + \frac{A^2}{2} + AB + \frac{B^2}{2} + \cdots$$

Studied by

- 4 jets
- $\gamma +$ 3 jets
- W/Z + 2 jets
- $\mathrm{W}^-\mathrm{W}^-$
- 4 jets, whereof two b- or c-tagged
- J/ψ or Υ + 2 jets (including $\upsilon \mathrm{c}\bar{\mathrm{c}}$)

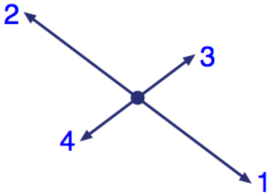
Note inverse relationship on σ_{eff}.
Natural scale is $\sigma_{\mathrm{ND}} \approx 50$ mb,
but "reduced" by b dependence.

Double parton scattering backgrounds

Always non-DPS backgrounds, so kinematics cuts required.

Example: 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

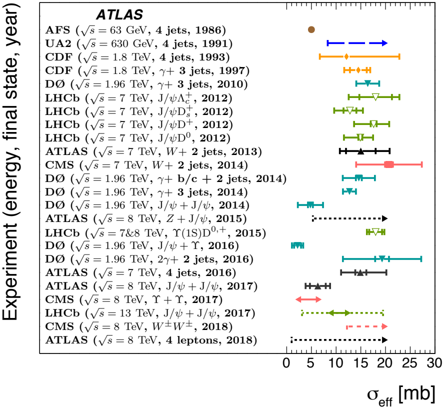
$|\mathbf{p}_{\perp 1} + \mathbf{p}_{\perp 2}| \gg 0$

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

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

Direct observation of double parton scattering

$$\sigma_{AB} = \frac{\sigma_A \sigma_B}{\sigma_{\mathrm{eff}}} \qquad \sigma_{AA} = \frac{\sigma_A^2}{2\sigma_{\mathrm{eff}}}$$



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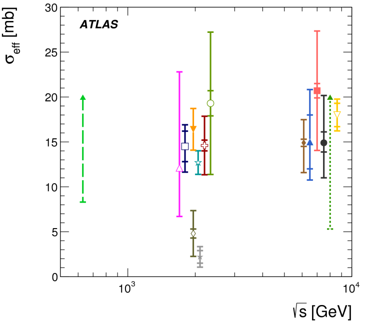
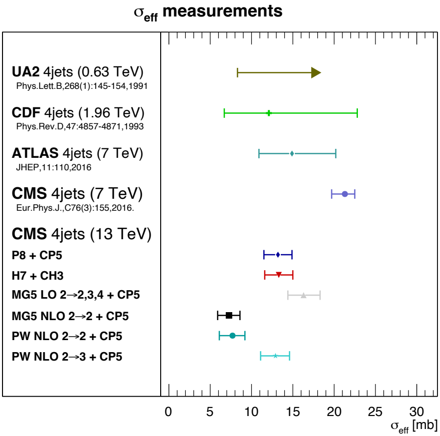


(D. Kar, MPI@LHC 2018)

Issues with DPS observations

Background modelling nontrivial,
especially when jets are involved.
Higher orders relevant for this.



Full model range even larger spread!

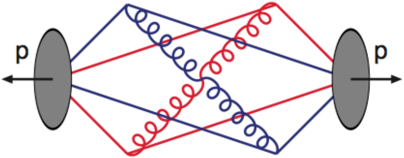
For Gaussian matter distribution expect

$$\sigma_{\mathrm{eff}} \approx 20 \text{ fm} .$$

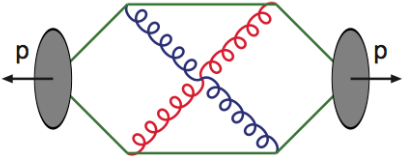
Lower $\sigma_{\mathrm{eff}} \Rightarrow$ "hot spots"?

Enhanced DPS rate should dampen at small $p_\perp$ scales.
Not seen in 3 J/ψ.
Probe with $\mathrm{c\bar{c}c\bar{c}}$ events?

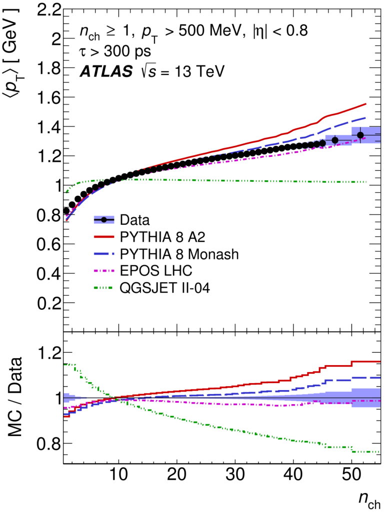
$\langle p_\perp \rangle(n_{\mathrm{ch}})$ is very sensitive to colour flow



long strings to remnants $\Rightarrow$ much n_{ch}/interaction $\Rightarrow \langle p_\perp \rangle(n_{\mathrm{ch}}) \sim$ flat

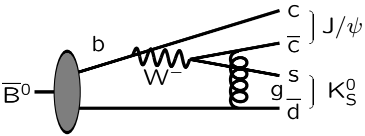


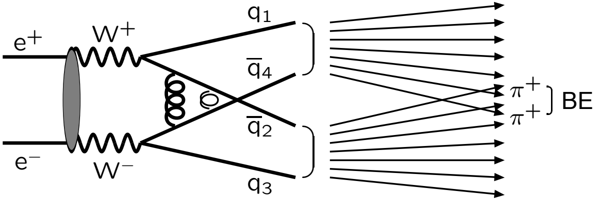
short strings (more central) $\Rightarrow$ less n_{ch}/interaction $\Rightarrow \langle p_\perp \rangle(n_{\mathrm{ch}})$ rising



Colour Reconnection Revisited

Colour rearrangement well established e.g. in B decay.





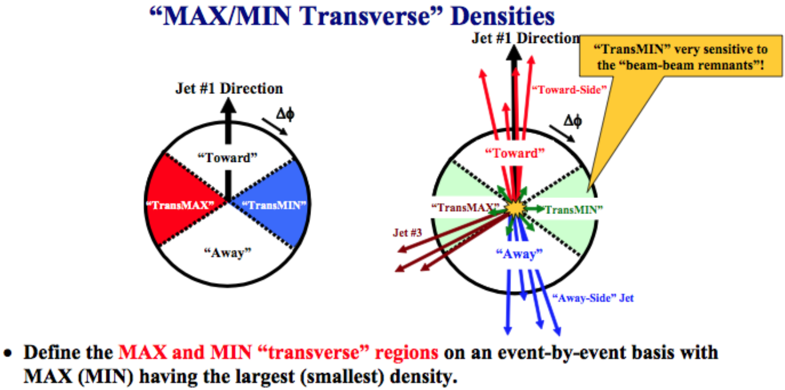
At LEP 2 search for effects in $e^+e^- \to W^+W^- \to q_1\overline{q}_2\, q_3\overline{q}_4$:

- perturbative $\langle \delta M_W \rangle \lesssim 5$ MeV : negligible!
- nonperturbative $\langle \delta M_W \rangle \sim 40$ MeV :
  favoured; no-effect option ruled out at 2.8σ.
- Bose-Einstein $\langle \delta M_W \rangle \lesssim 100$ MeV : full effect ruled out (while models with ~ 20 MeV barely acceptable).

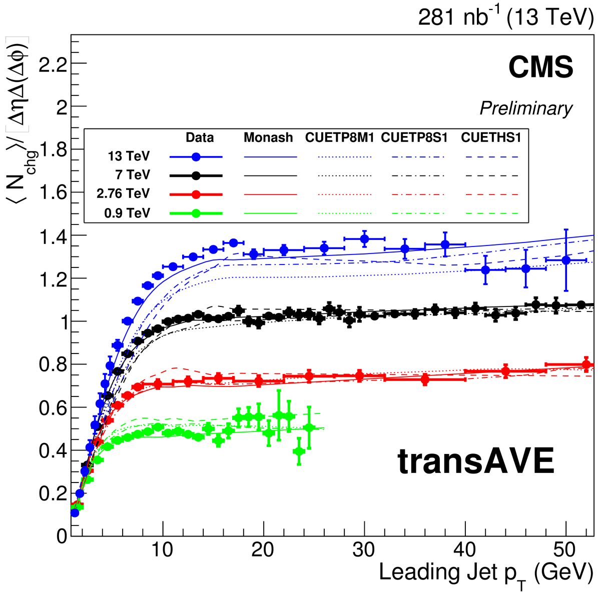
Events with hard scale (jet, $\mathrm{W/Z}$) have more underlying activity!

Events with *n* interactions have *n* chances that one of them is hard,
so "trigger bias": hard scale ⇒ central collision
⇒ more interactions ⇒ larger underlying activity.

Studied in particular by Rick Field, with CDF/CMS data:



Jet pedestal effect – 2



The Sudakov form factor applied to MPI

A Poissonian process is one where "events" (e.g. radioactive decays) can occur uncorrelated in "time" t (or other ordering variable).

If the probability for an "event" to occur at "time" t is $P(t)$ then the probability for an i'th event at t_i is

$$\mathcal{P}(t_i) = P(t_i) \exp\left(- \int_{t_{i-1}}^{t_i} P(t) \, \mathrm{d}t \right)$$

Example: Sudakov form factor for parton showers, where increasing $t \to$ decreasing evolution variable $p_\perp$ and "event" $\to$ parton branchings.

Can also apply to ordered sequence of MPIs at decreasing $p_\perp$ values, starting from $E_{\mathrm{cm}}/2$

$$\mathcal{P}(p_\perp = p_{\perp i}) = \frac{1}{\sigma_{\mathrm{nd}}} \frac{\mathrm{d}\sigma}{\mathrm{d}p_\perp} \exp\left[- \int_{p_\perp}^{p_{\perp(i-1)}} \frac{1}{\sigma_{\mathrm{nd}}} \frac{\mathrm{d}\sigma}{\mathrm{d}p'_\perp} \mathrm{d}p'_\perp \right]$$

MPI in PYTHIA

- MPIs are gererated in a falling sequence of $p_\perp$ values; recall Sudakov factor approach to parton showers.
- Energy, momentum and flavour conserved step by step: subtracted from proton by all "previous" collisions.
- Protons modelled as extended objects, allowing both central and peripheral collisions, with more or less activity.
- (Partons at small x more broadly spread than at large x.)
- Colour screening increases with energy, i.e. $p_{\perp 0} = p_{\perp 0}(E_{\mathrm{cm}})$, as more and more partons can interact.
- (Rescattering: one parton can scatter several times.)
- Colour connections: each interaction hooks up with colours from beam remnants, but also correlations inside remnants.
- Colour *re*connections: many interaction "on top of" each other ⇒ tightly packed partons ⇒ colour memory loss?

Interleaved evolution in PYTHIA

- Transverse-momentum-ordered parton showers for ISR and FSR
- MPI also ordered in $p_{\perp}$

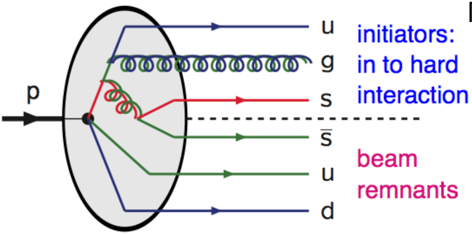
$\Rightarrow$ Allows interleaved evolution for ISR, FSR and MPI:

$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}p_{\perp}} = \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p_{\perp}} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p_{\perp}} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p_{\perp}} \right) \times \exp\left(- \int_{p_{\perp}}^{p_{\perp\mathrm{max}}} \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p'_{\perp}} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p'_{\perp}} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p'_{\perp}} \right) \mathrm{d}p'_{\perp} \right)$$

Ordered in decreasing $p_{\perp}$ using "Sudakov" trick.
Corresponds to increasing "resolution":
smaller $p_{\perp}$ fill in details of basic picture set at larger $p_{\perp}$.

- Start from fixed hard interaction $\Rightarrow$ underlying event
- No separate hard interaction $\Rightarrow$ minbias events
- Possible to choose two hard interactions, e.g. $\mathrm{W}^{-}\mathrm{W}^{-}$

Initiators and remnants



Need to assign:

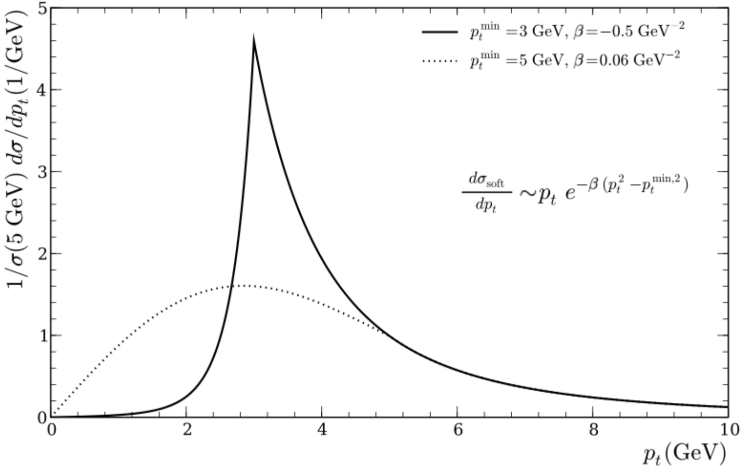
- correlated flavours
- correlated $x_i = p_{zi}/p_{z\mathrm{tot}}$
- correlated primordial $k_{\perp i}$
- correlated colours
- correlated showers

PDF after preceding MI/ISR activity:

1. Squeeze range $0 < x < 1$ into $0 < x < 1 - \sum x_i$ (ISR: $i \neq i_{\mathrm{current}}$)
2. Valence quarks: scale down by number already kicked out
3. Introduce companion quark $\mathrm{q}/\overline{\mathrm{q}}$ to each kicked-out sea quark $\overline{\mathrm{q}}/\mathrm{q}$, with x based on assumed $\mathrm{g} \to \mathrm{q}\overline{\mathrm{q}}$ splitting
4. Gluon and other sea: rescale for total momentum conservation

MPI in Herwig

Key point: two-component model

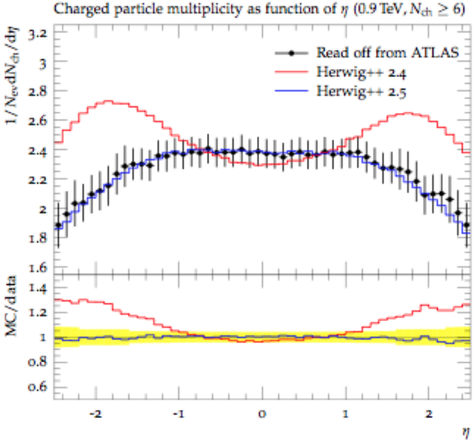


$p_\perp > p_{\perp\min}$: pure perturbation theory (no modification)

$p_\perp < p_{\perp\min}$: pure nonperturbative ansatz

MPI in Herwig – 2

- Number of MPIs first picked; then generated unordered in $p_\perp$.
- Interactions uncorrelated, up until energy used up.
- Force ISR to reconstruct back to gluon after first interaction.
- Impact parameter by em form factor shape, but tunable width.
- $p_{\perp\mathrm{min}}$ scale to be tuned energy-by-energy.
- Colour reconnection essential to get $\mathrm{d}n/\mathrm{d}\eta$ correct.

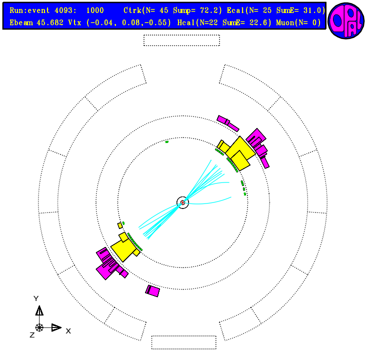


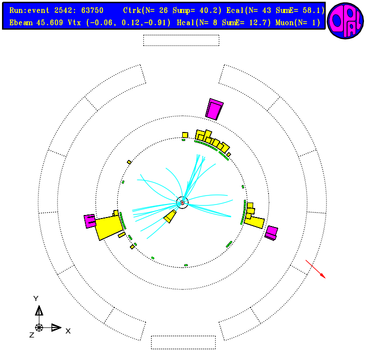
Hadronization

Hadronization/confinement is nonperturbative $\Rightarrow$ only models.

Main contenders: **string** and **cluster** fragmentation.

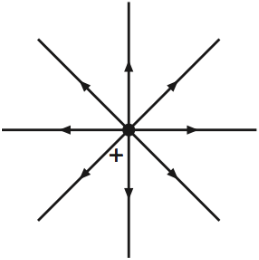
Begin with $\mathrm{e}^+\mathrm{e}^- \to \gamma^*/\mathrm{Z}^0 \to \mathrm{q}\overline{\mathrm{q}}$ and $\mathrm{e}^+\mathrm{e}^- \to \gamma^*/\mathrm{Z}^0 \to \mathrm{q}\overline{\mathrm{q}}\mathrm{g}$:

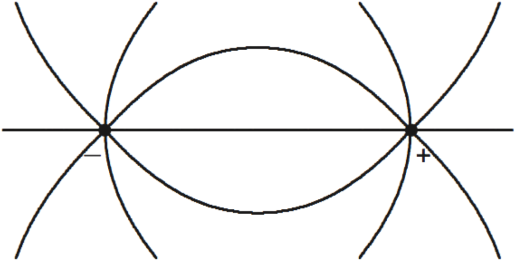




The QED potential

In QED, field lines go all the way to infinity





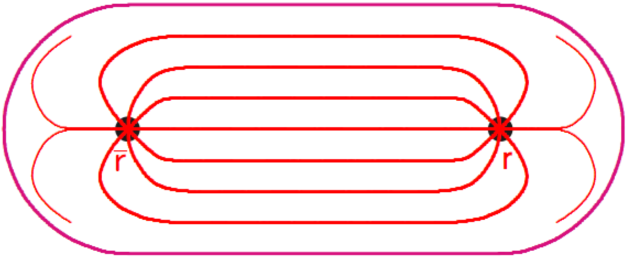
since photons cannot interact with each other.

Potential is simply additive:

$$V(\mathbf{x}) \propto \sum_i \frac{1}{|\mathbf{x} - \mathbf{x}_i|}$$

The QCD potential – 1

In QCD, for large charge separation, field lines are believed to be compressed to tubelike region(s) ⇒ **string(s)**



Gives force/potential between a q and a $\overline{\mathrm{q}}$:

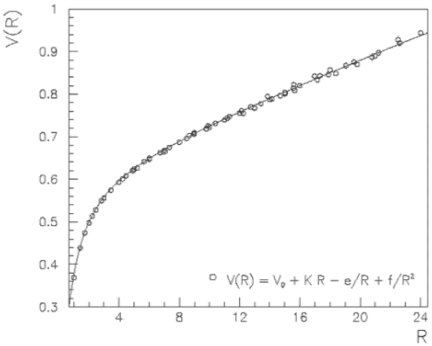
$F(r) \approx \mathrm{const} = \kappa \quad \Longleftrightarrow \quad V(r) \approx \kappa r$

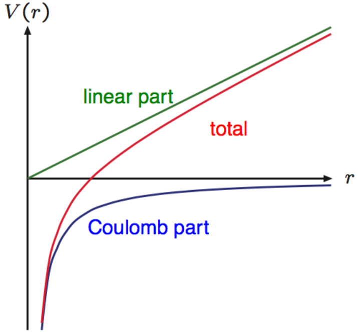
$\kappa \approx 1\ \mathrm{GeV/fm}$ ≈ potential energy gain lifting a 16 ton truck.

Flux tube parametrized by center location as a function of time ⇒ simple description as a 1+1-dimensional object – a string.

The QCD potential – 2

Linear confinement confirmed e.g. by lattice QCD calculation of gluon field between a static colour and anticolour charge pair:

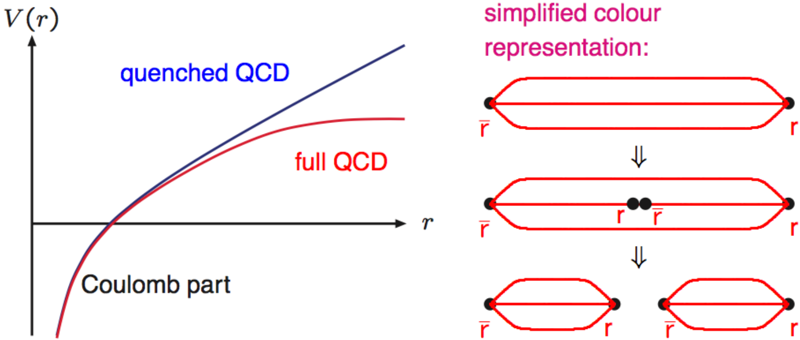




At short distances also Coulomb potential, important for internal structure of hadrons, but not for particle production (?).

The QCD potential – 3

Full QCD = gluonic field between charges ("quenched QCD")
plus virtual fluctuations $\mathrm{g} \to \mathrm{q}\overline{\mathrm{q}} \, (\to \mathrm{g})$
$\Longrightarrow$ nonperturbative string breakings $\mathrm{gg} \ldots \to \mathrm{q}\overline{\mathrm{q}}$



String motion

The Lund Model: starting point

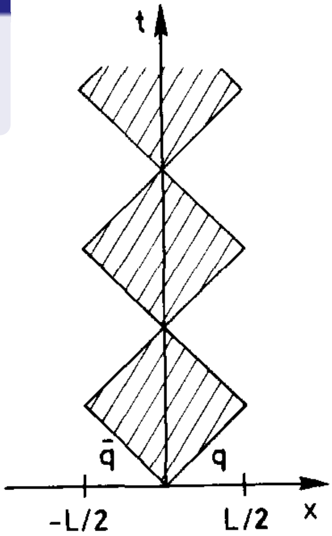
Use only linear potential $V(r) \approx \kappa r$ to trace string motion, and let string fragment by repeated $\mathrm{q\overline{q}}$ breaks.

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

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

$(c = 1)$ for a $\mathrm{q\overline{q}}$ pair flying apart along the $\pm z$ axis.

But signs relevant: the q moving in the $+z$ direction has $\mathrm{d}z/\mathrm{d}t = +1$ but $\mathrm{d}p_z/\mathrm{d}t = -\kappa$.

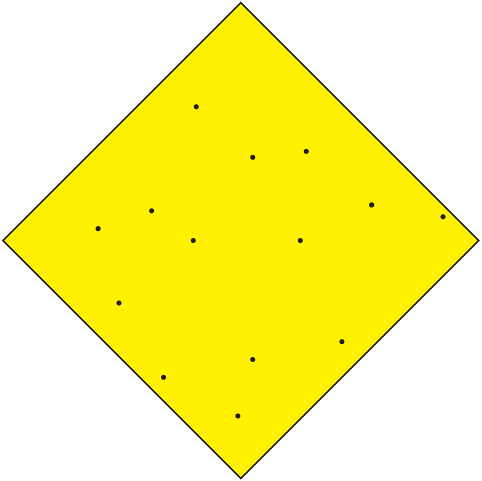


The Artru-Mennessier Model

1974: the first (semi-)realistic hadronization model

Assume fragmentation local, and string homogeneous.

Thus constant probability per unit string area of breaking.



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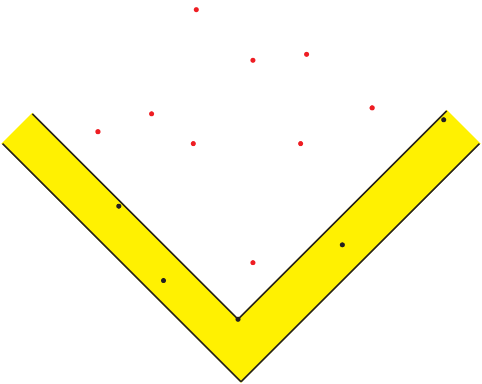

But a string cannot break where it has already broken

$\Rightarrow$ remove vertices in forward lightcone of another

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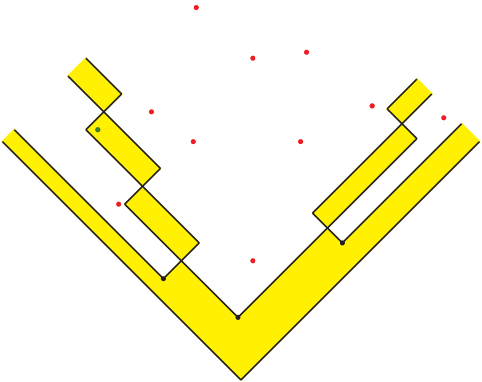


But a string cannot break where it has already broken
$\Rightarrow$ remove vertices in forward lightcone of another

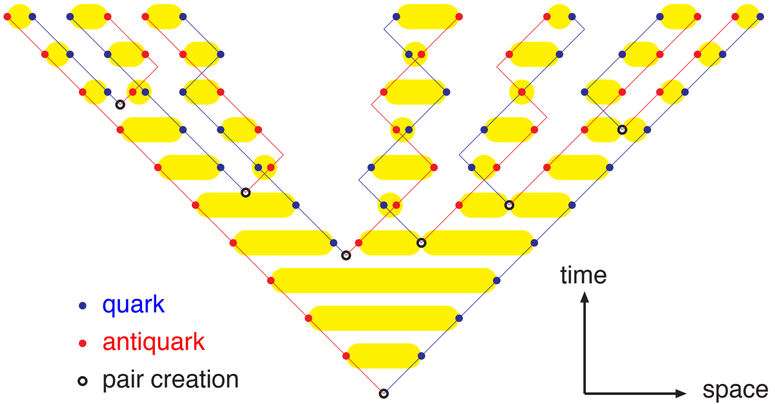
$\Rightarrow$ dampening factor $\exp(-\mathcal{P}\tilde{A})$, where $\tilde{A}$ is string area in the backwards lightcone

Drawback: continuous hadron mass spectrum

The Lund Model

Combine yo-yo-style string motion with string breakings!

Motion of quarks and antiquarks with intermediate string pieces:

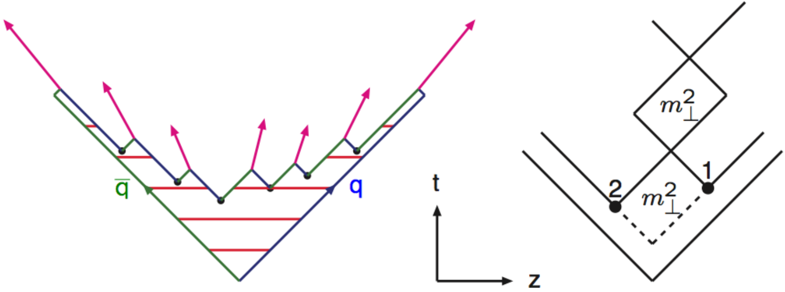


A q from one string break combines with a $\overline{q}$ from an adjacent one.

Gives simple but powerful picture of hadron production.

Where does the string break? – 1

Fragmentation starts in the middle and spreads outwards:



- Here $m_\perp^2$ fixed from hadron and $p_\perp$ selection (unlike AM).
- Lorentz covariant inside–out cascade.
- Breakup vertices causally disconnected
  $\Rightarrow$ iteration from ends inwards allowed!

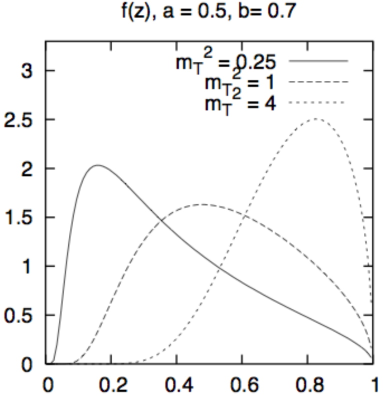
Where does the string break? – 2

Breakup vertices causally disconnected
$\Rightarrow$ can proceed in arbitrary order
$\Rightarrow$ *left–right symmetry*

$$\begin{aligned}\mathcal{P}(1,2) &= \mathcal{P}(1) \times \mathcal{P}(1 \to 2) \\ &= \mathcal{P}(2) \times \mathcal{P}(2 \to 1)\end{aligned}$$

$\Rightarrow$ Lund symmetric fragmentation function:

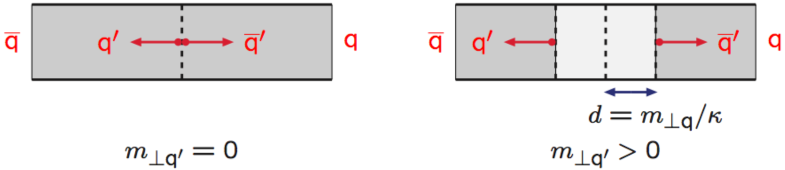
$f(z) \propto (1-z)^a \exp(-bm_\perp^2/z)/z$



Lund–Bowler modified shape for heavy quarks:

$$f(x) \propto \frac{1}{z^{1+bm_q^2}} \exp\left(-\frac{bm_\perp^2}{z}\right).$$

How does the string break?



String breaking modelled by tunneling:

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

- Common Gaussian $p_\perp$ spectrum, $\langle p_\perp \rangle \approx 0.4$ GeV.
- Suppression of heavy quarks,
  $u\overline{u} : d\overline{d} : s\overline{s} : c\overline{c} \approx 1 : 1 : 0.3 : 10^{-11}$.
- Diquark $\sim$ antiquark $\Rightarrow$ simple model for baryon production.

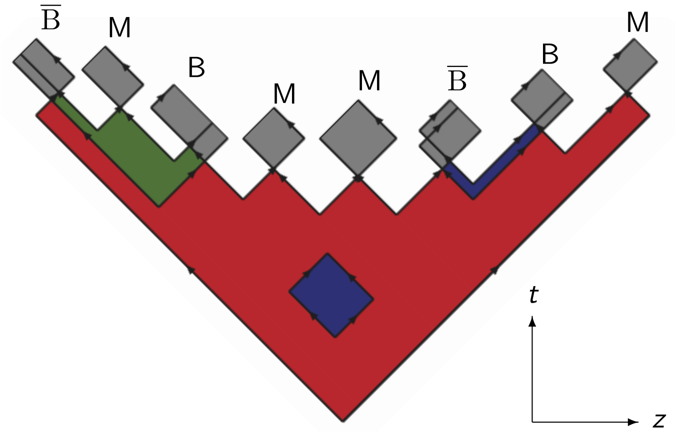
Flavour composition

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.

The popcorn model for baryon production



- SU(6) (flavour×spin) Clebsch-Gordans needed.
- Quadratic diquark mass dependence
  ⇒ strong suppression of multistrange and spin 3/2 baryons.
  ⇒ effective parameters with less strangeness suppression.

Heavy flavours: the dead cone

Consider eikonal expression for soft-gluon radiation

$$\frac{\mathrm{d}\sigma_{\mathrm{q\bar{q}g}}}{\sigma_{\mathrm{q\bar{q}}}} \propto (-1)\left(\frac{p_1}{p_1p_3}-\frac{p_2}{p_2p_3}\right)^2 \frac{\mathrm{d}^3p_3}{E_3}$$

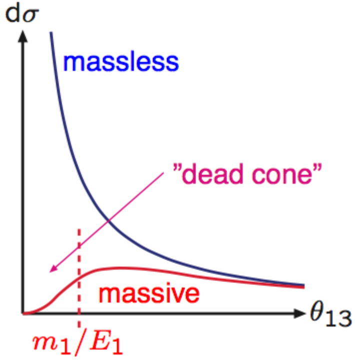
$$\propto \left(\frac{2p_1p_2}{(p_1p_3)(p_2p_3)}-\frac{m_1^2}{(p_1p_3)^2}-\frac{m_2^2}{(p_2p_3)^2}\right) E_3\,\mathrm{d}E_3\,d\cos\theta_{13}$$

For θ_{13} small

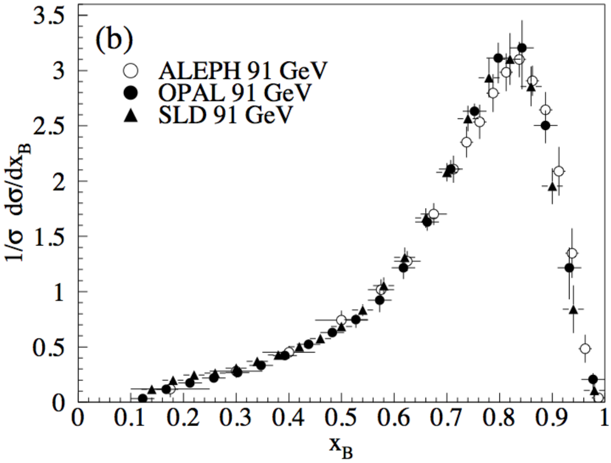
$$\frac{\mathrm{d}\sigma_{\mathrm{q\bar{q}g}}}{\sigma_{\mathrm{q\bar{q}}}} \propto \frac{\mathrm{d}\omega}{\omega}\frac{\mathrm{d}\theta_{13}^2}{\theta_{13}^2}\left(\frac{\theta_{13}^2}{\theta_{13}^2+m_1^2/E_1^2}\right)^2$$

$$= \frac{\mathrm{d}\omega}{\omega}\frac{\theta_{13}^2\,\mathrm{d}\theta_{13}^2}{(\theta_{13}^2+m_1^2/E_1^2)^2}$$

so “dead cone” for $\theta_{13} < m_1/E_1$



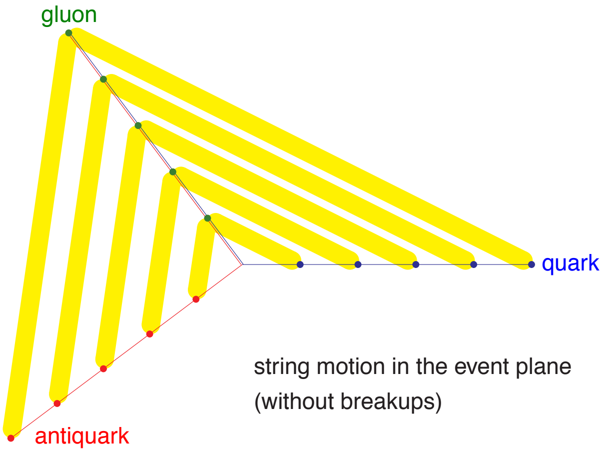
Heavy flavours: fragmentation data



But note that a heavy hadron decays to many secondaries,
filling up "dead cone" and
giving "normally-soft" light-hadron spectra.

The Lund gluon picture – 1

A gluon carries one colour and one anticolour. Thus it can be viewed as a kink on the string, carrying energy and momentum:



The most characteristic feature of the Lund model.

The Lund gluon picture – 2

Gluon = kink on string

Force ratio gluon/ quark = 2,
cf. QCD $N_C/C_F = 9/4$, $\to 2$ for $N_C \to \infty$
No new parameters introduced for gluon jets!

so

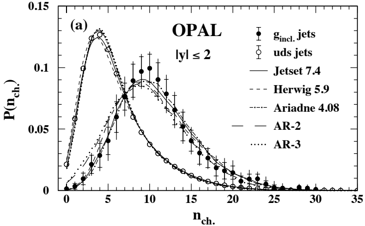
- Few parameters to describe energy-momentum structure!
- Many parameters to describe flavour composition!

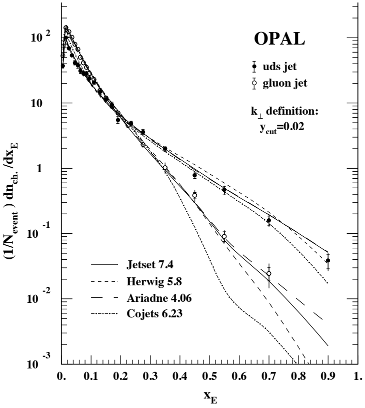
String piece ≈ dipole

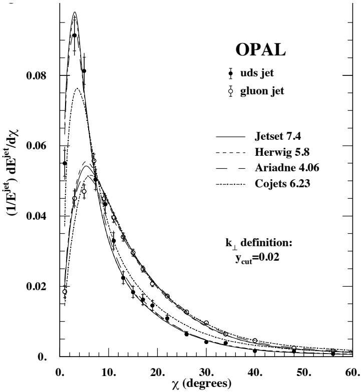
One-to-one correspondence between how strings and how colour dipoles are stretched between colour charges in $N_C \to \infty$ limit.
Dipole: emission in perturbative regime.
String: "emission" in nonperturbative regime.
String picture 5 years ahead. . .

Gluon vs. quark jets

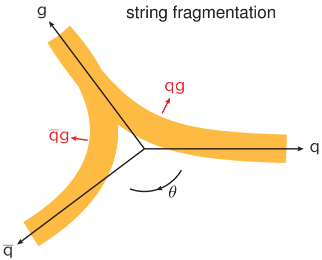
Energy sharing between two strings makes hadrons in gluon jets softer, more and broader in angle:

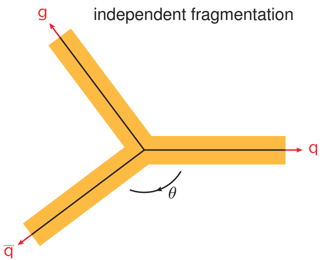


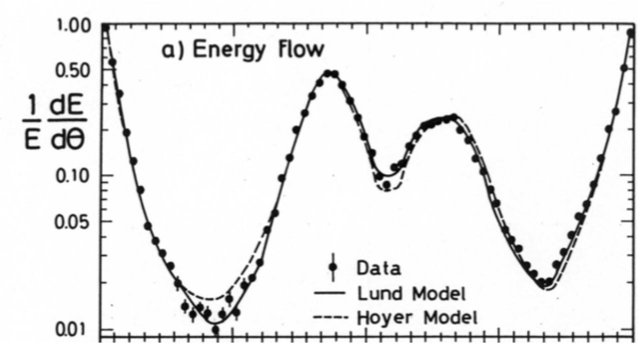




The string/JADE Effect (DESY 1980)







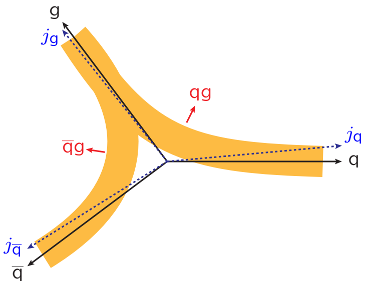
3 jets energy-ordered.

JADE (1980, 1983)

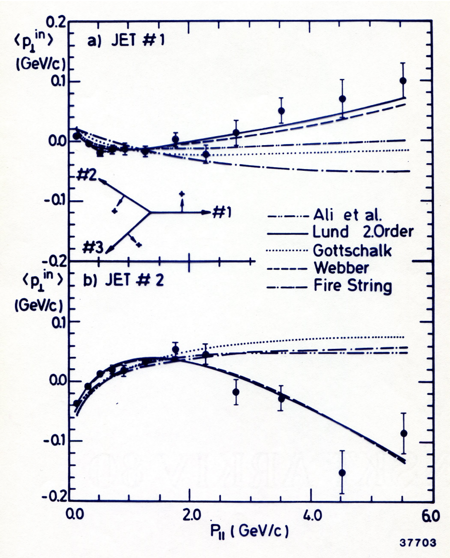
Jets are crooked

$(E, \mathbf{p})$ not preserved when massless partons become massive jets!

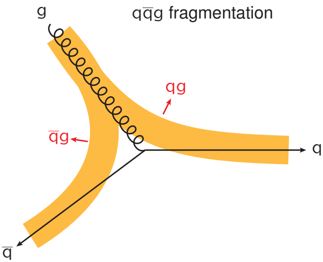
In the string model the reconstructed q and $\overline{\mathrm{q}}$ jet axes are shifted in the g direction:

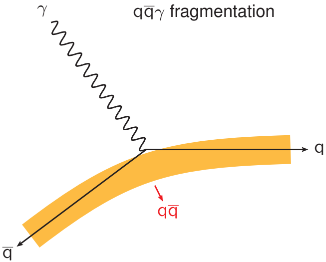


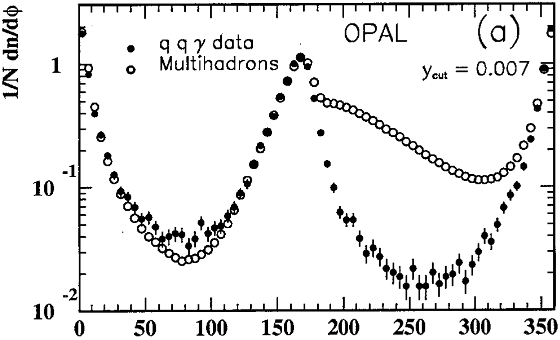
More two-jetlike events compensated by higher α_s in string than in independent fragmentation.



Photon vs. Gluon Emission



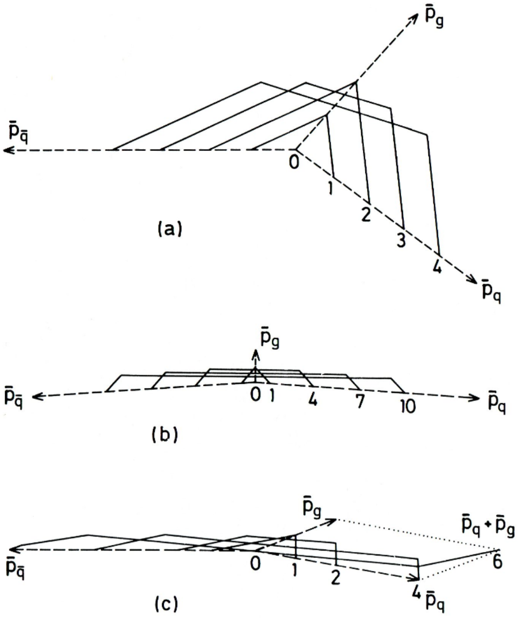




particle flow in the event plane; 3-jet selection, but third jet location not fixed

OPAL (1995)

Infrared and collinear safety of string fragmentation

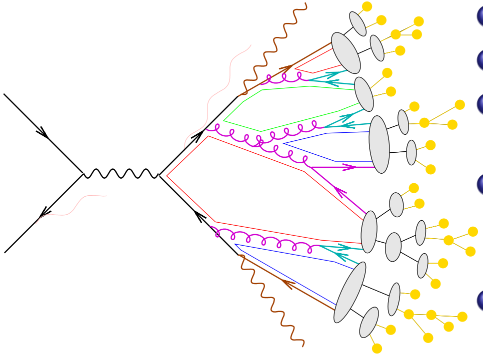


Emission of a soft or collinear gluon only negligibly perturbs string motion/evolution.

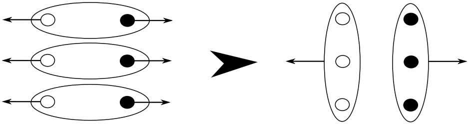
Therefore string fragmentation is soft and collinear safe.

Technically, tracing the string motion for many nearby gluons can become messy, prompting simplifications.

The Herwig Cluster Model

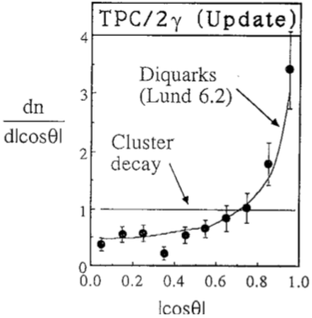


1. Force $g \to q\overline{q}$ branchings.
2. Form colour singlet clusters.
3. Decay high-mass clusters to smaller clusters.
4. Decay clusters to 2 hadrons according to phase space times spin weight.
5. New: allow three aligned $q\overline{q}$ clusters to reconnect to two clusters $q_1q_2q_3$ and $\overline{q}_1\overline{q}_2\overline{q}_3$.
6. New: allow nonperturbative $g \to s\overline{s}$ in addition to $g \to u\overline{u}$ and $g \to d\overline{d}$.

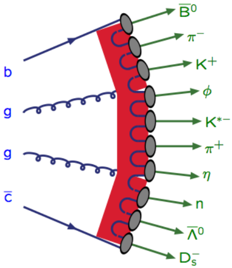


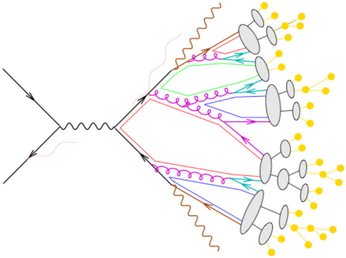
Cluster Model issues

1. Tail to very large-mass clusters (e.g. if no emission in shower); if large-mass cluster $\to$ 2 hadrons then incorrect hadron momentum spectrum, crazy four-jet events
   $\Longrightarrow$ split big cluster into 2 smaller along "string" direction; daughter-mass spectrum $\Rightarrow$ iterate if required;
   $\sim$ 15% of primary clusters are split,
   but give $\sim$ 50% of final hadrons
2. Isotropic baryon decay inside cluster
   $\Longrightarrow$ splittings $\mathrm{g} \to \mathrm{qq} + \overline{\mathrm{qq}}$
3. Too soft charm/bottom spectra
   $\Longrightarrow$ anisotropic leading-cluster decay
4. Charge correlations still problematic
   $\Longrightarrow$ all clusters anisotropic (?)
5. Sensitivity to particle content
   $\Longrightarrow$ only include complete multiplets



String vs. Cluster



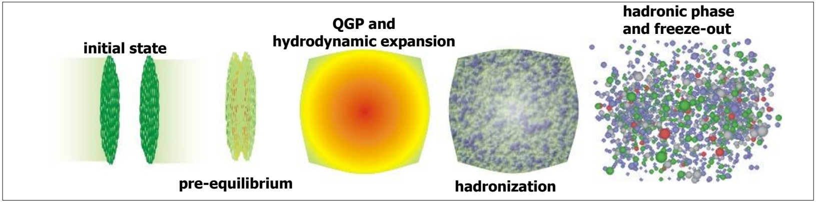


program	PYTHIA	Herwig
model	string	cluster
energy–momentum picture	powerful	simple
	predictive	unpredictive
parameters	few	many
flavour composition	messy	simple
	unpredictive	in-between
parameters	many	few

"There ain't no such thing as a parameter-free *good* description"

Heavy Ion Collisions

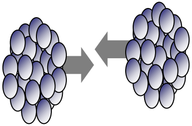
Conventional wisdom:

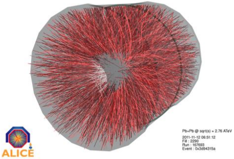


- The only way we can create the QGP in the laboratory!
- By colliding heavy ions it is possible to create a large (»1fm^3) zone of hot and dense QCD matter
- Goal is to create and study the properties of the Quark Gluon Plasma
- Experimentally mainly the final state particles are observed, so the conclusions have to be inferred via models

The three systems — understanding before 2012

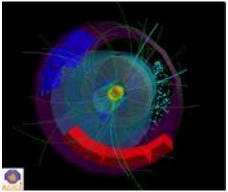
Pb-Pb





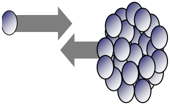
Hot QCD matter:
This is where we expect the QGP to be created in central collisions.

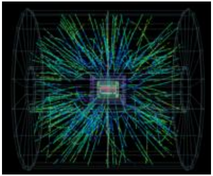
pp



QCD baseline:
This is the baseline for "standard" QCD phenomena.

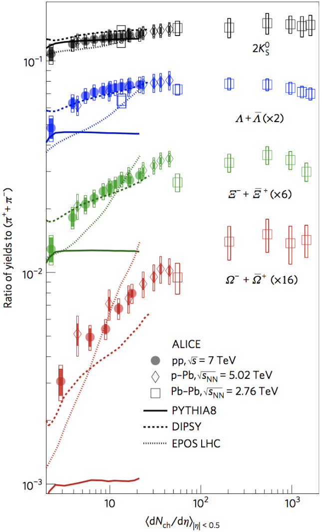
p-Pb

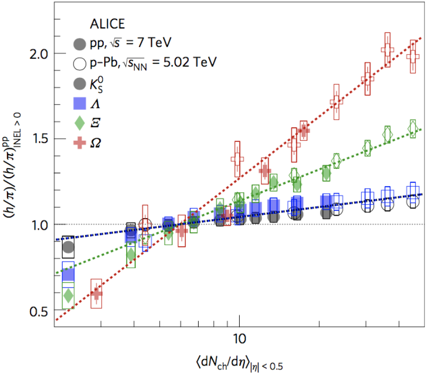




Cold QCD matter:
This is to isolate nuclear effects, e.g. nuclear pdfs.

Strangeness enhancement

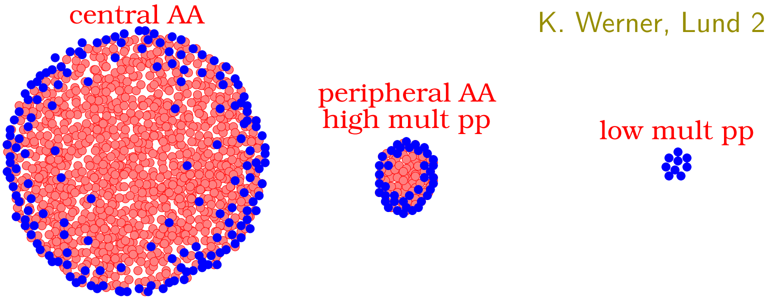




Signs of QGP in high-multiplicity pp collisions? If not, what else? A whole new game!

The Core–Corona solution

Currently most realistic "complete" approach



K. Werner, Lund 2017:

core => hydro => statistical decay ($\mu = 0$)
corona => string decay

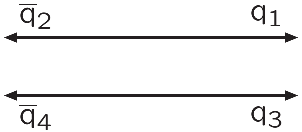
allows smooth transition. Implemented in **EPOS** MC
(Werner, Guiot, Pierog, Karpenko, Nucl.Phys.A931 (2014) 83)

Can conventional pp MCs be adjusted to cope?

Ropes (in Dipsy model)

Dense environment ⇒ several intertwined strings ⇒ **rope**.

Sextet example:



$3 \otimes 3 = 6 \oplus \overline{3}$

$C_2^{(6)} = \frac{5}{2} C_2^{(3)}$

At first string break $\kappa_{\mathrm{eff}} \propto C_2^{(6)} - C_2^{(3)} \Rightarrow \kappa_{\mathrm{eff}} = \frac{3}{2}\kappa$.

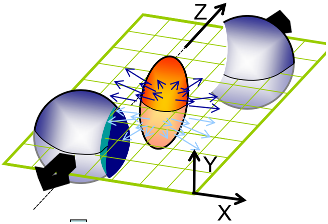
At second string break $\kappa_{\mathrm{eff}} \propto C_2^{(3)} \Rightarrow \kappa_{\mathrm{eff}} = \kappa$.

Multiple ∼parallel strings ⇒ random walk in colour space.

Larger κ_{eff} ⇒ larger $\exp\left(-\frac{\pi m_{\mathrm{q}}^2}{\kappa_{\mathrm{eff}}}\right)$

- more strangeness ($\tilde{\rho}$)
- more baryons ($\tilde{\xi}$)
- mainly agrees with ALICE (but p/π overestimated)

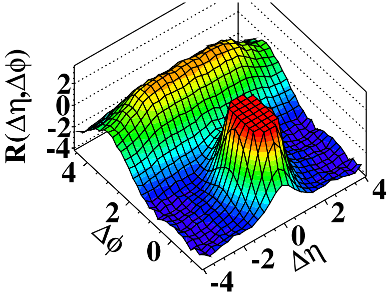
Bierlich, Gustafson, Lönnblad, Tarasov, JHEP 1503, 148;
from Biro, Nielsen, Knoll (1984), Białas, Czyz (1985), . . .



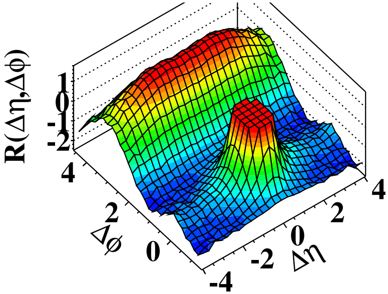
Elliptic flow in AA predicted from geometry + pressure.

Not so for pp, and yet ridge is observed at high multiplicities:

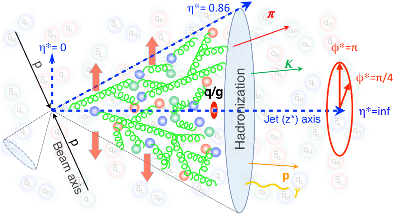
(c) CMS N ≥ 110, p_T>0.1GeV/c



(d) CMS N ≥ 110, 1.0GeV/c<p_T<3.0GeV/c



Ridge in jets? (2023)



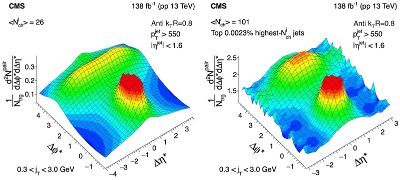


FIG. 2. Results for 2D two-particle angular correlation functions for particle $0.3 < j_T < 3.0$ GeV from inclusive (left) and the highest (right) $N^{\rm j}_{\rm ch}$ jets, for anti-k_T R $= 0.8$ algorithm with $p_T^{\rm jet} > 550$ GeV and $|\eta^{\rm jet}| < 1.6$.

2312.17103 [hep-ex]

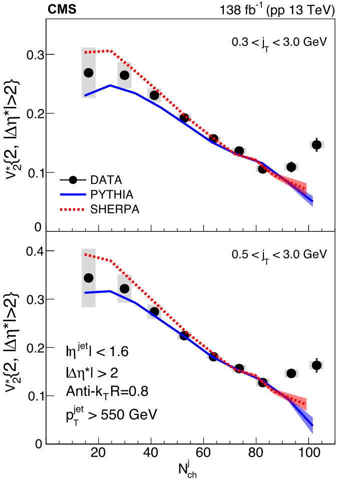
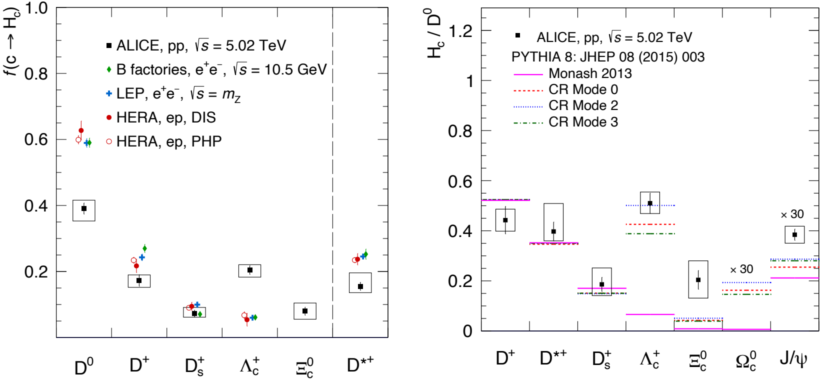


FIG. 4. The elliptic anisotropies v_2^*, obtained from two-particle correlations as a function of $N^{\rm j}_{\rm ch}$, for anti-k_T R $= 0.8$ jets with $p_T^{\rm jet} > 550$ GeV and $|\eta^{\rm jet}| < 1.6$ in pp collisions at 13 TeV from data, PYTHIA8, and SHERPA. Vertical bars on data points indicate statistical uncertainty, while shaded boxes represent systematic uncertainties. The shaded envelope around the MC curves shows

The charm baryon enhancement

In 2017/21 ALICE found/confirmed strong enhancement of charm baryon production, relative to LEP, HERA and default PYTHIA.



The QCDCR model does much better, with junctions ⇒ baryons.

Colour reconnection models

"Recent" PYTHIA option: QCD-inspired CR (QCDCR):

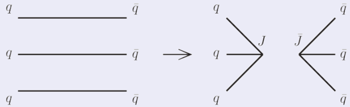
Ordinary string reconnection

($q\bar{q}$: 1/9, gg: 1/8, model: 1/9)

Double junction reconnection

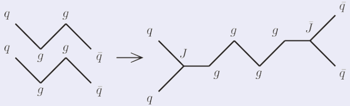
(qq: 1/3, gg: 10/64, model: 2/9)

Triple junction reconnection

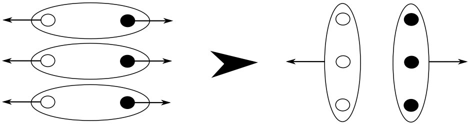


($q\bar{q}$: 1/27, gg: 5/256, model: 2/81)

Zipping reconnection

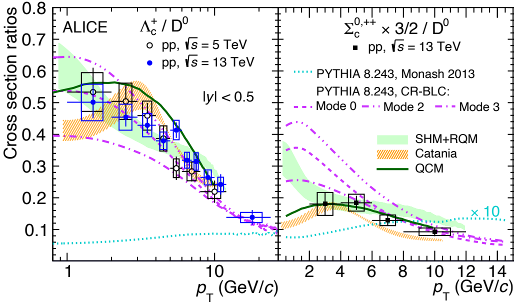


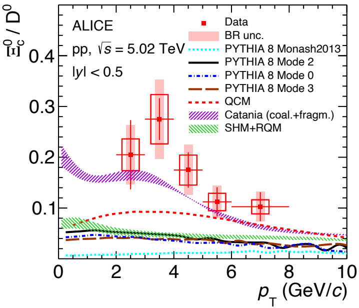
(Depends on number of gluons)

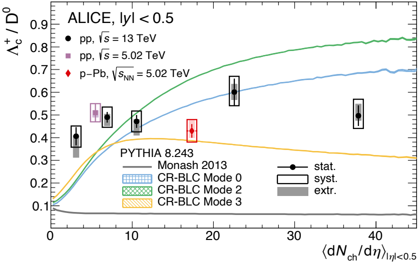


Triple-junction also in HERWIG cluster model.

Charm baryon differential distributions





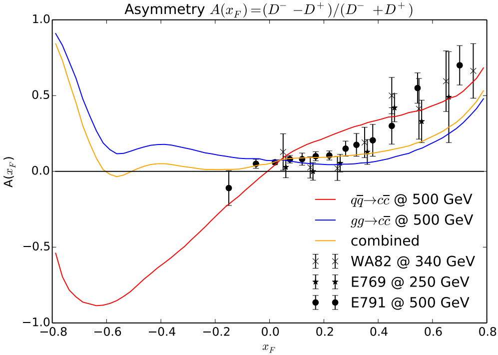


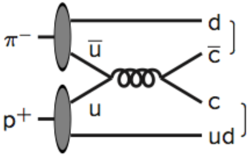
QCDCR does well
for some distributions,
less so for others.
Improvements needed,
but good starting point.

Beam drag effects

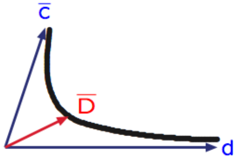
Colour flow connects hard scattering to beam remnants. Can have consequences, e.g. in $\pi^-\mathrm{p}$:

$$A(x_\mathrm{F}) = \frac{\sigma(\mathrm{D}^-) - \sigma(\mathrm{D}^+)}{\sigma(\mathrm{D}^-) + \sigma(\mathrm{D}^+)}$$



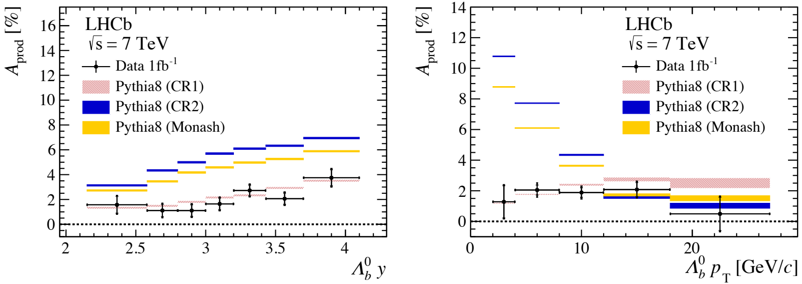


If low-mass string e.g.:
$\bar{\mathrm{c}}\mathrm{d} : \mathrm{D}^-, \mathrm{D}^{*-}$
$\mathrm{cud} : \Lambda_\mathrm{c}^+, \Sigma_\mathrm{c}^+, \Sigma_\mathrm{c}^{*+}$
$\Rightarrow$ flavour asymmetries



Can give D “drag” to larger x_F than c quark.

Bottom asymmetries



$$A(y), A(p_\perp) = \frac{\sigma(\Lambda_b^0) - \sigma(\overline{\Lambda}_b^0)}{\sigma(\Lambda_b^0) + \sigma(\overline{\Lambda}_b^0)}$$

CR1 = QCDCR, with no enhancement at low $p_\perp$.

Enhanced Λ_b production at low $p_\perp$, like for Λ_c, dilutes asymmetry?

Asymmetries observed also for other charm and bottom hadrons.

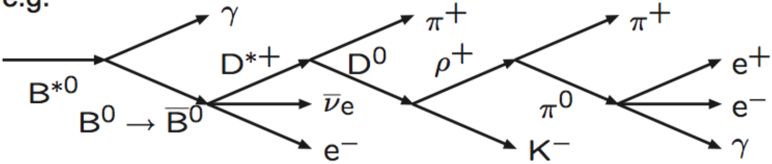
Warning: fragmentation function formalisms unreliable at low $p_\perp$.

May lead to incorrect conclusions about intrinsic charm.

Decays

Unspectacular/ungrateful but necessary:
this is where most of the final-state particles are produced!
Involves hundreds of particle kinds and thousands of decay modes.

e.g.



- $\mathrm{B}^{*0} \to \mathrm{B}^0\gamma$: electromagnetic decay
- $\mathrm{B}^0 \to \overline{\mathrm{B}}^0$ mixing (weak)
- $\overline{\mathrm{B}}^0 \to \mathrm{D}^{*+}\overline{\nu}_\mathrm{e}\mathrm{e}^-$: weak decay, displaced vertex,
  $|\mathcal{M}|^2 \propto (p_{\overline{\mathrm{B}}}p_{\overline{\nu}})(p_\mathrm{e}p_{\mathrm{D}^*})$
- $\mathrm{D}^{*+} \to \mathrm{D}^0\pi^+$: strong decay
- $\mathrm{D}^0 \to \rho^+\mathrm{K}^-$: weak decay, displaced vertex, ρ mass smeared
- $\rho^+ \to \pi^+\pi^0$: ρ polarized, $|\mathcal{M}|^2 \propto \cos^2\theta$ in ρ rest frame
- $\pi^0 \to \mathrm{e}^+\mathrm{e}^-\gamma$: Dalitz decay, $m(\mathrm{e}^+\mathrm{e}^-)$ peaked

Summary

- Perturbative jet cross section is divergent in $p_\perp \to 0$ limit $\Rightarrow$ colour screening invoked.
- MPI absolutely crucial to get right multiplicities, rapidity and $p_\perp$ spectra, and various correlations.
- String model most common approach to hadronization, with strong support in data and lattice QCD.
- String space–time picture well confirmed, e.g. in 3-jet, but flavour composition less well so.
- Cluster model valid alternative for most properties.
- LHC data has revolutionized the picture of soft physics: **Goodbye jet universality!**
- This has led to a renewed phenomenology interest: **Welcome new mechanisms!**