# Intro to Particle Physics and Event Generators

## Part 4: Hadronization; Beyond the SM

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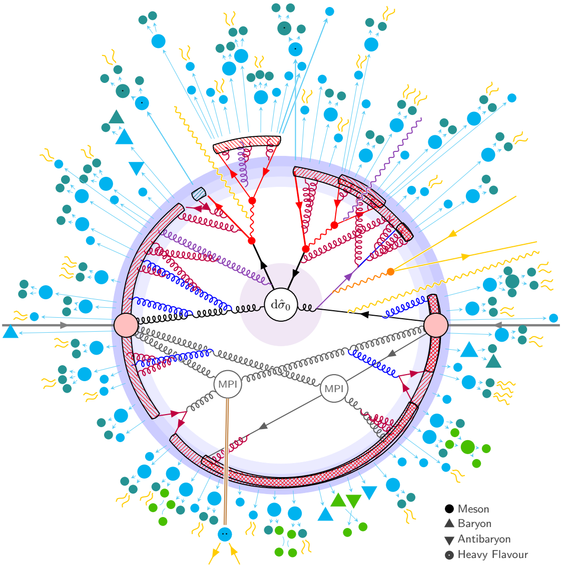
# Event component overview




- Hard Interaction
- Resonance Decays
- MECs, Matching & Merging
- FSR
- ISR*
- QED
- Weak Showers
- Hard Onium

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- Multiparton Interactions

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- Beam Remnants*
- Strings
- Ministrings / Clusters
- Colour Reconnections
- String Interactions
- Bose-Einstein & Fermi-Dirac
- Primary Hadrons
- Secondary Hadrons
- Hadronic Reinteractions

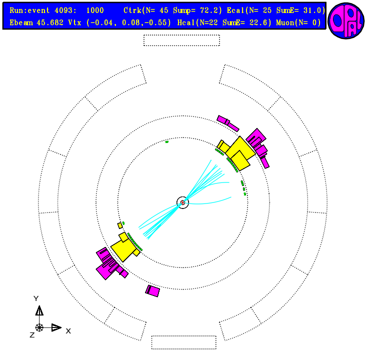
*(*: incoming lines are crossed)*

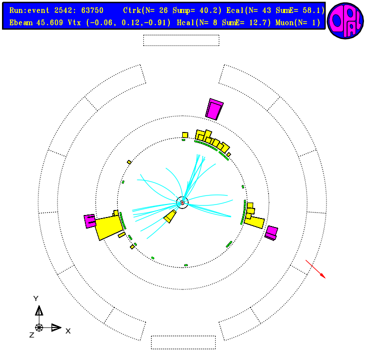
# Hadronization

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

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

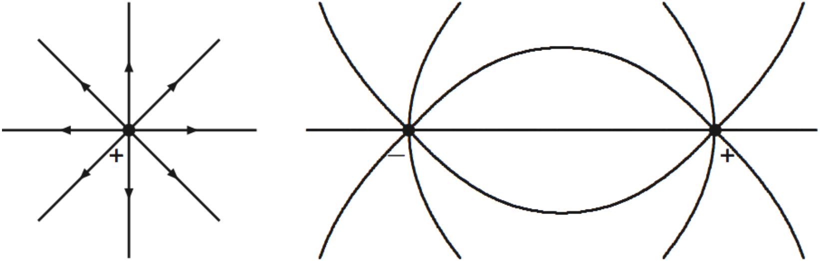
Begin with $\mathrm{e^+e^-} \to \gamma^*/\mathrm{Z}^0 \to \mathrm{q\overline{q}}$ and $\mathrm{e^+e^-} \to \gamma^*/\mathrm{Z}^0 \to \mathrm{q\overline{q}g}$:



# The QED potential

In QED, field lines go all the way to infinity



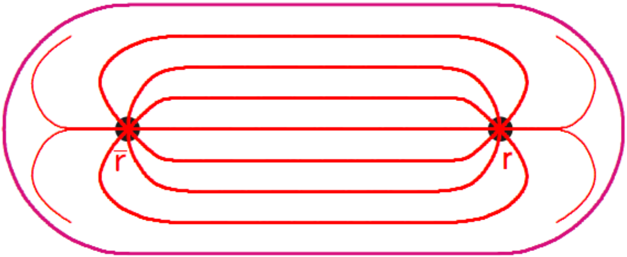

since photons cannot interact with each other.

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) $\Rightarrow$ **string(s)**




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

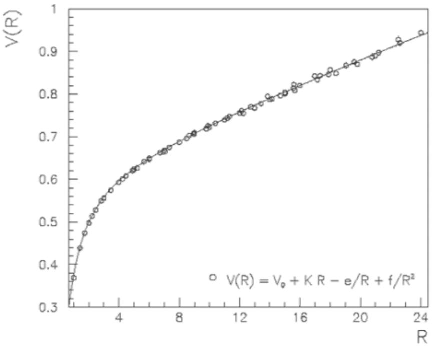
$$F(r) \approx \mathrm{const} = \kappa \quad \Longleftrightarrow \quad \boxed{V(r) \approx \kappa r}$$

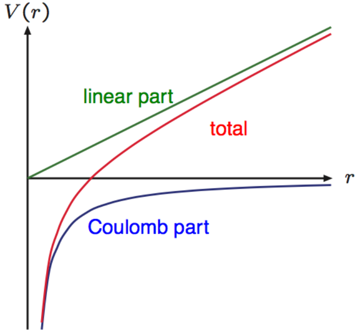
$\kappa \approx 1\ \mathrm{GeV/fm} \approx$ potential energy gain lifting a 16 ton truck.

Flux tube parametrized by center location as a function of time $\Rightarrow$ 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:

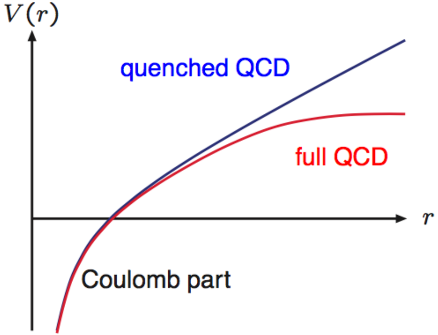


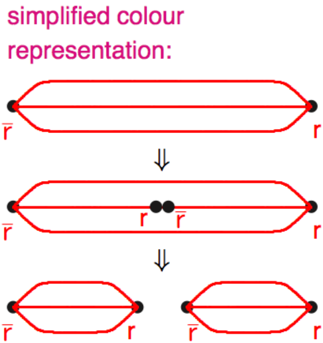




At short distances also Coulomb potential, important for internal structure of hadrons, but not for particle production (?).

# 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

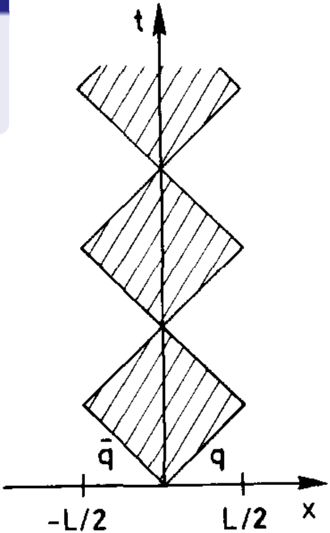
## The Lund Model: starting point

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

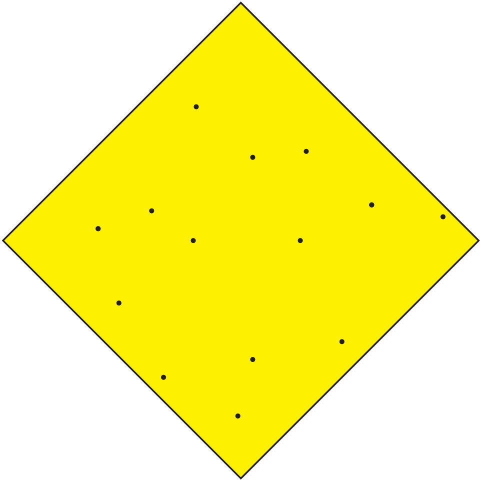


# The Artru-Mennessier Model

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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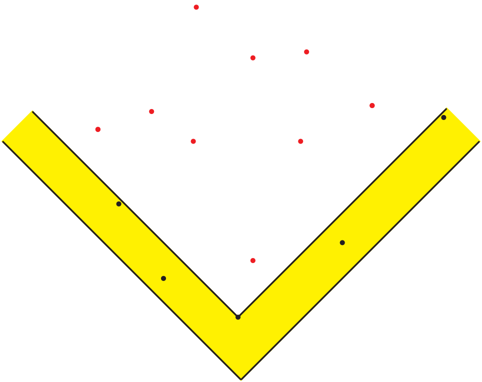

But a string cannot break where it has already broken

⇒ remove vertices in forward lightcone of another

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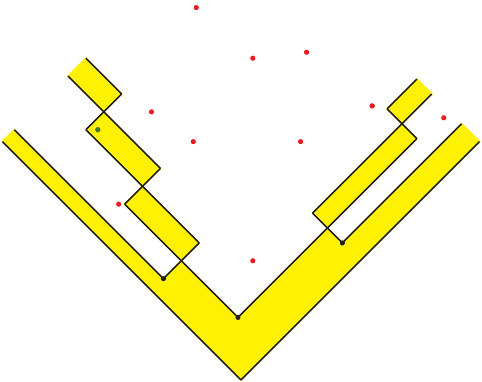


But a string cannot break where it has already broken

$\Rightarrow$ remove vertices in forward lightcone of another

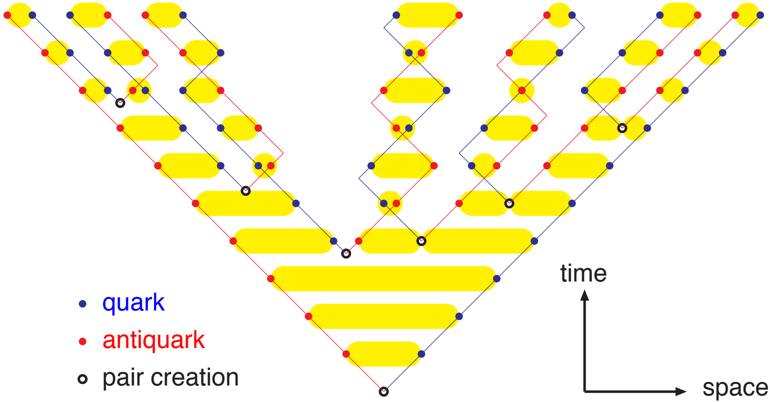
$\Rightarrow$ dampening factor $\exp(-\mathcal{P}\tilde{A})$, where $\tilde{A}$ is string area in the backwards lightcone

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:

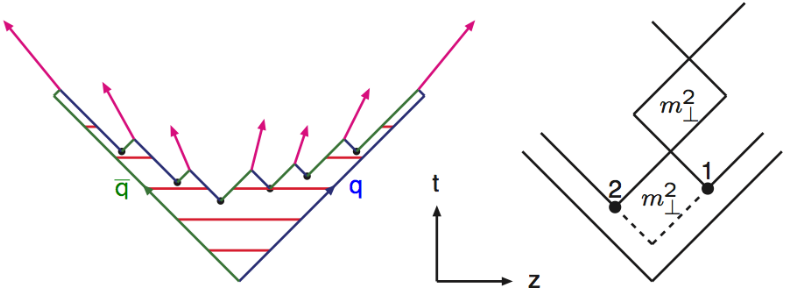



A $\mathrm{q}$ from one string break combines with a $\overline{\mathrm{q}}$ from an adjacent one.

Gives simple but powerful picture of hadron production.

# Where does the string break? – 1

Fragmentation starts in the middle and spreads outwards:



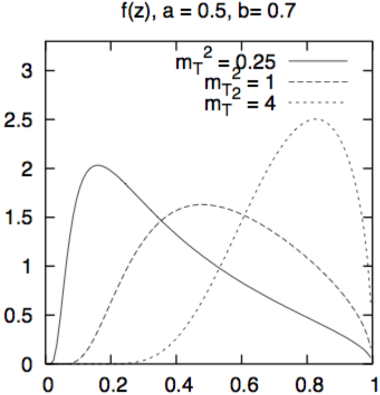

- Here $m_\perp^2$ fixed from hadron and $p_\perp$ selection (unlike AM).
- Lorentz covariant inside–out cascade.
- Breakup vertices causally disconnected
  $\Rightarrow$ iteration from ends inwards allowed!

# Where does the string break? – 2

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

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

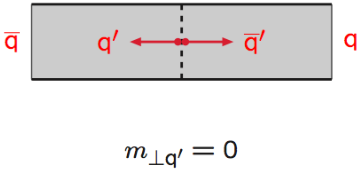
$\Rightarrow$ Lund symmetric fragmentation function:
$f(z) \propto (1-z)^a \exp(-bm_\perp^2/z)/z$

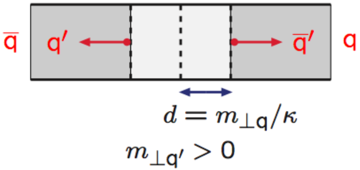



Lund–Bowler modified shape for heavy quarks:

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

# How does the string break?




String breaking modelled by tunneling:

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

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

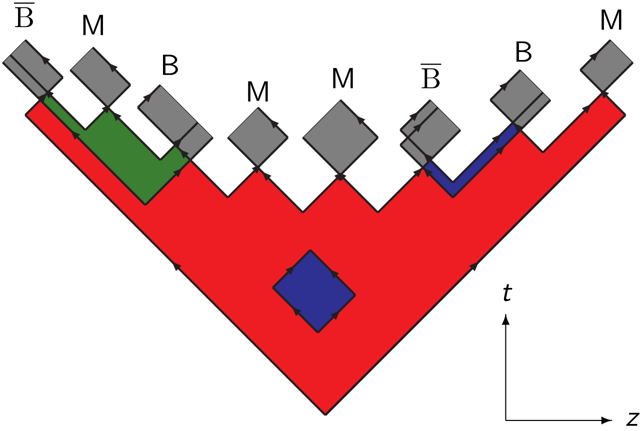
# Flavour composition

Combination of $\mathrm{q}$ from one break and $\overline{\mathrm{q}}$ $(\mathrm{qq})$ 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 $\mathrm{uds} \Rightarrow \Lambda^0$, $\Sigma^0$ or $\Sigma^{*0}$. 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
  $\Rightarrow$ strong suppression of multistrange and spin 3/2 baryons.
  $\Rightarrow$ effective parameters with less strangeness suppression.

# Heavy flavours: the dead cone

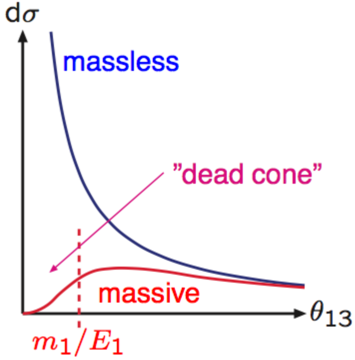
Consider eikonal expression for soft-gluon radiation

$$\frac{\mathrm{d}\sigma_{\mathrm{q\bar{q}g}}}{\sigma_{\mathrm{q\bar{q}}}} \propto (-1)\left(\frac{p_1}{p_1 p_3} - \frac{p_2}{p_2 p_3}\right)^2 \frac{\mathrm{d}^3 p_3}{E_3}$$
$$\propto \left(\frac{2 p_1 p_2}{(p_1 p_3)(p_2 p_3)} - \frac{m_1^2}{(p_1 p_3)^2} - \frac{m_2^2}{(p_2 p_3)^2}\right) E_3 \, \mathrm{d}E_3 \, d\cos\theta_{13}$$

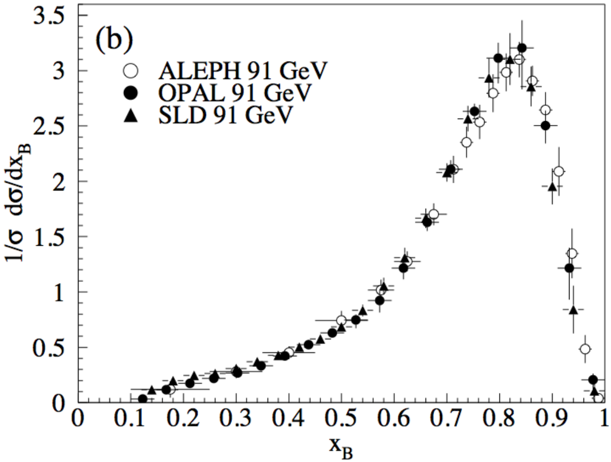
For $\theta_{13}$ small

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

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



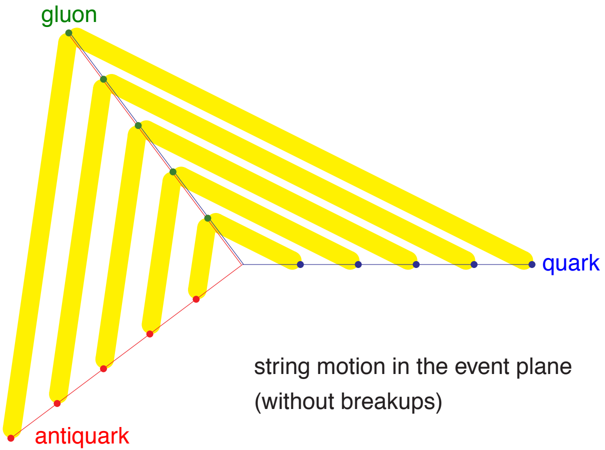
# Heavy flavours: fragmentation data




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

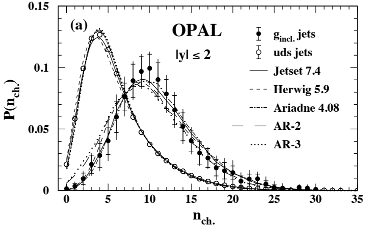
- Few parameters to describe energy-momentum structure!
- Many parameters to describe flavour composition!

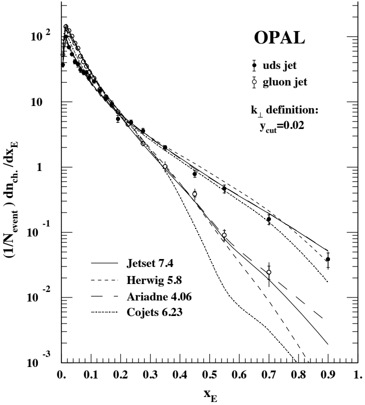
## String piece ≈ dipole

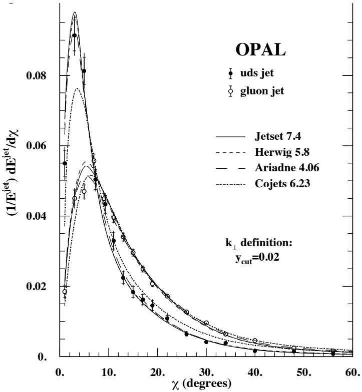
One-to-one correspondence between how strings and how colour dipoles are stretched between colour charges in $N_C \to \infty$ limit.
Dipole: emission in perturbative regime.
String: "emission" in nonperturbative regime.
String picture 5 years ahead. . .

# Gluon vs. quark jets

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

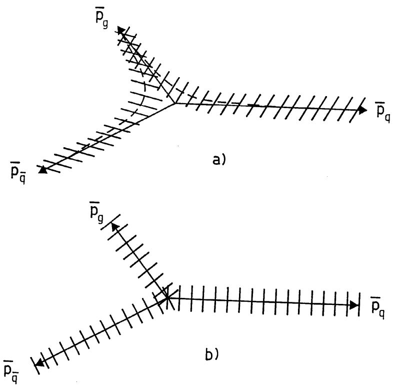


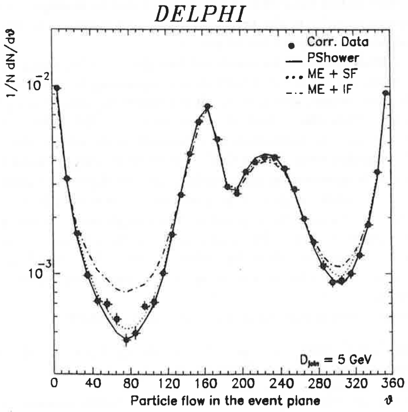



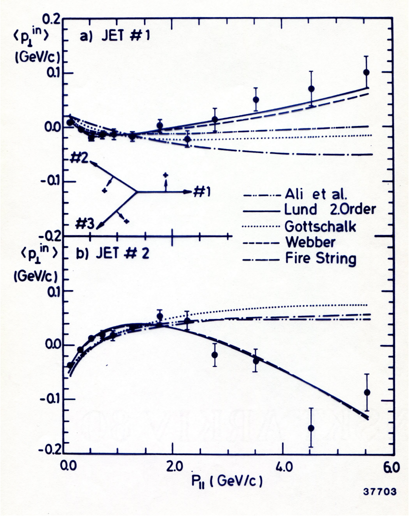
# The string effect - 1

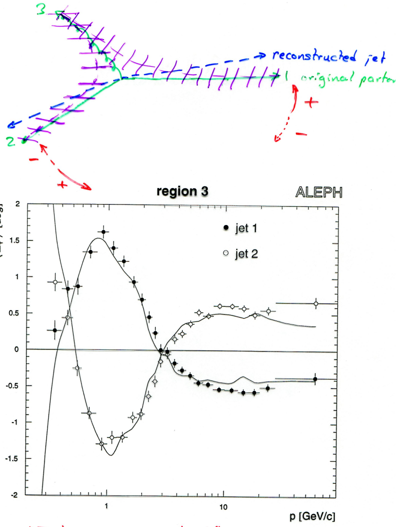
Particle flow in the $q\bar{q}g$ event plane depleted in $q$–$\bar{q}$ region owing to boost of string pieces in $q$–$g$ and $g$–$\bar{q}$ regions:



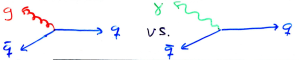

String fragmentation (SF) vs. independent fragmentation (IF), latter (nowadays) straw model of symmetric jet profile.

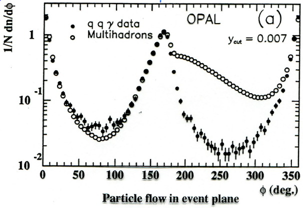



"Jets are crooked"

# Strings vs. perturbative dipoles

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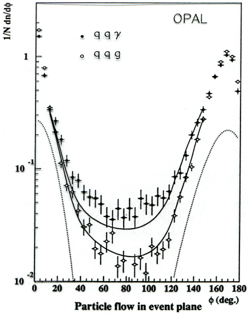
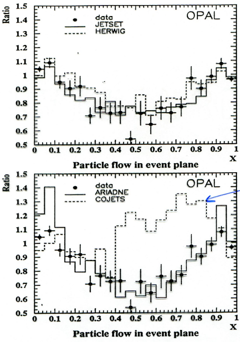



coherence + LPHD :
Azimov
Dokshitzer
Khoze
Troyan

$\frac{n(q\bar{q}g)}{n(q\bar{q}\gamma)}$




breakdown of model

x = scaled angle between jet 1 and 2

Figure 6: Ratio of charged particle flows in three-jet and two-jet radiative events with respect to the reduced angle $X$ for various Monte Carlo models: JETSET coherent parton shower with string fragmentation, HERWIG, ARIADNE and COJETS.

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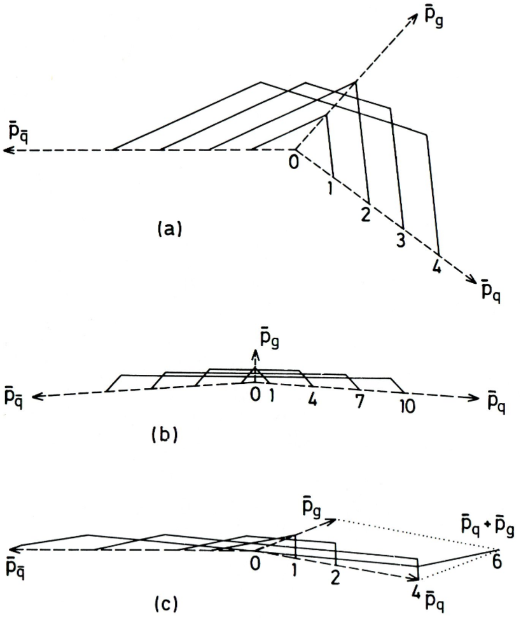
| | |
|---|---|
| **Reference value** Data | 0.71±0.03 |
| **Monte Carlo, with detector simulation** | |
| JETSET | 0.76±0.03 |
| ERT (Data $q\bar{q}\gamma$) | 0.71±0.03 |
| HERWIG | 0.82±0.02 |
| ARIADNE | 0.70±0.03 |
| COJETS | 1.08±0.03 |
| **JETSET, without detector simulation** | |
| coherent, SF | 0.73±0.03 |
| incoherent, SF | 0.91±0.03 |
| coherent, IF | 1.01±0.03 |
| incoherent, IF | 1.11±0.03 |

Table 2: Ratio $R$ of particle flows, compared to models

both pert. & nonpert. effects enter

# Infrared and collinear safety of string fragmentation

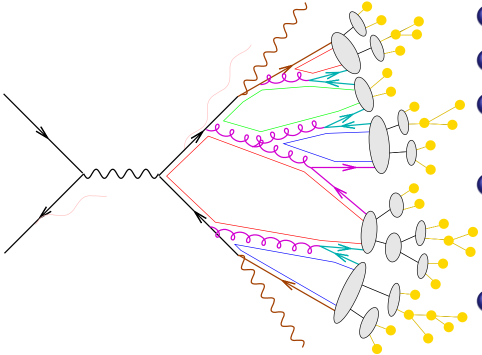


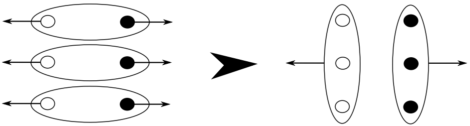

Emission of a soft or collinear gluon only negligibly perturbs string motion/evolution.

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 $\mathrm{g} \to \mathrm{q}\overline{\mathrm{q}}$ 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 $\mathrm{q}\overline{\mathrm{q}}$ clusters to reconnect to two clusters $\mathrm{q}_1\mathrm{q}_2\mathrm{q}_3$ and $\overline{\mathrm{q}}_1\overline{\mathrm{q}}_2\overline{\mathrm{q}}_3$.
6. New: allow nonperturbative $\mathrm{g} \to \mathrm{s}\overline{\mathrm{s}}$ in addition to $\mathrm{g} \to \mathrm{u}\overline{\mathrm{u}}$ and $\mathrm{g} \to \mathrm{d}\overline{\mathrm{d}}$.

# Cluster Model issues

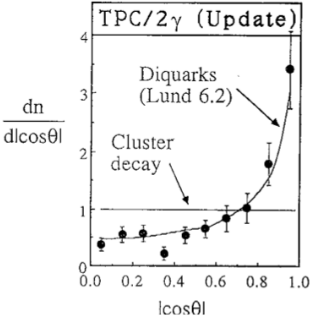
1 Tail to very large-mass clusters (e.g. if no emission in shower); if large-mass cluster $\to$ 2 hadrons then incorrect hadron momentum spectrum, crazy four-jet events
$\Longrightarrow$ split big cluster into 2 smaller along "string" direction; daughter-mass spectrum $\Rightarrow$ iterate if required;
$\sim$ 15% of primary clusters are split,
but give $\sim$ 50% of final hadrons

2 Isotropic baryon decay inside cluster
$\Longrightarrow$ splittings $\mathrm{g} \to \mathrm{qq} + \overline{\mathrm{qq}}$

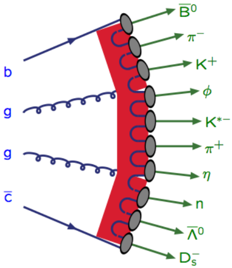
3 Too soft charm/bottom spectra
$\Longrightarrow$ anisotropic leading-cluster decay

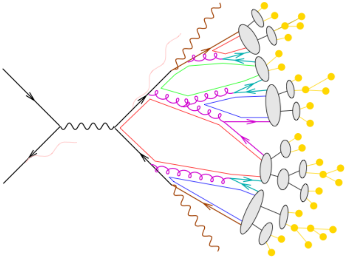
4 Charge correlations still problematic
$\Longrightarrow$ all clusters anisotropic (?)

5 Sensitivity to particle content
$\Longrightarrow$ only include complete multiplets



# String vs. Cluster



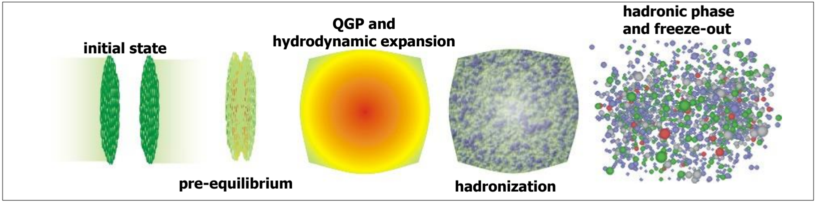



| program | PYTHIA | Herwig |
|---|---|---|
| model | string | cluster |
| energy–momentum picture | powerful | simple |
| | predictive | unpredictive |
| parameters | few | many |
| flavour composition | messy | simple |
| | unpredictive | in-between |
| parameters | many | few |

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

# Heavy Ion Collisions

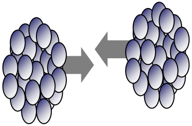
Conventional wisdom:

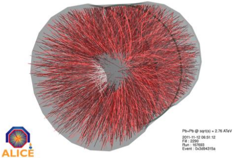



- The only way we can create the QGP in the laboratory!
- By colliding heavy ions it is possible to create a large (»1fm$^3$) zone of hot and dense QCD matter
- Goal is to create and study the properties of the Quark Gluon Plasma
- Experimentally mainly the final state particles are observed, so the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

# The three systems — understanding before 2012

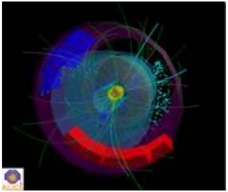
Pb-Pb





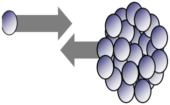

Hot QCD matter:
This is where we expect the QGP to be created in central collisions.

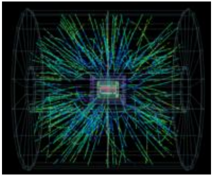
pp



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

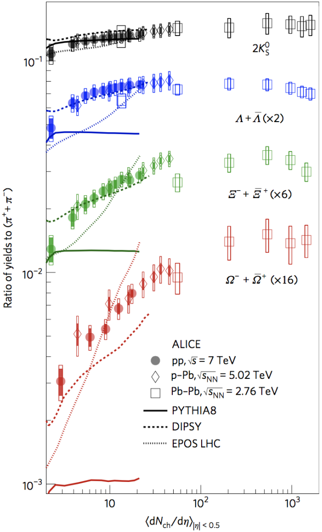
p-Pb

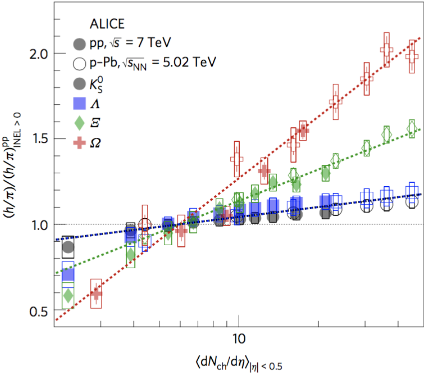




Cold QCD matter:
This is to isolate nuclear effects, e.g. nuclear pdfs.

# Strangeness enhancement

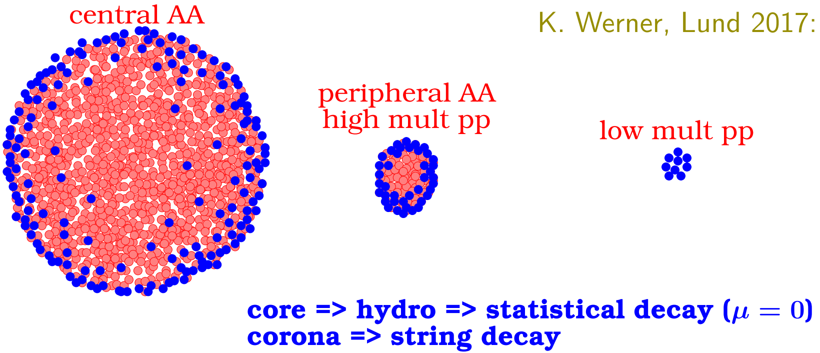



**Signs of QGP in high-multiplicity pp collisions? If not, what else? A whole new game!**

# The Core–Corona solution

Currently most realistic “complete” approach




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

Can conventional pp MCs be adjusted to cope?

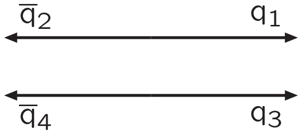
# Ropes (in Dipsy model)

Dense environment $\Rightarrow$ several intertwined strings $\Rightarrow$ **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 $\sim$parallel strings $\Rightarrow$ random walk in colour space.

Larger $\kappa_{\mathrm{eff}} \Rightarrow$ 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 $\mathrm{p}/\pi$ overestimated)

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

# Colour reconnection models

“Recent” PYTHIA option: QCD-inspired CR (QCDCR):

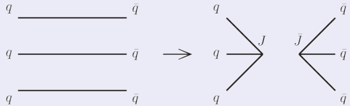
## Ordinary string reconnection


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

## Double junction reconnection

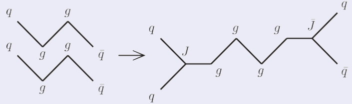

(qq: 1/3, gg: 10/64, model: 2/9)

## Triple junction reconnection

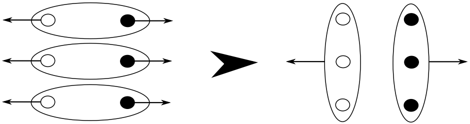



(q$\bar{\text{q}}$: 1/27, gg: 5/256, model: 2/81)

## Zipping reconnection



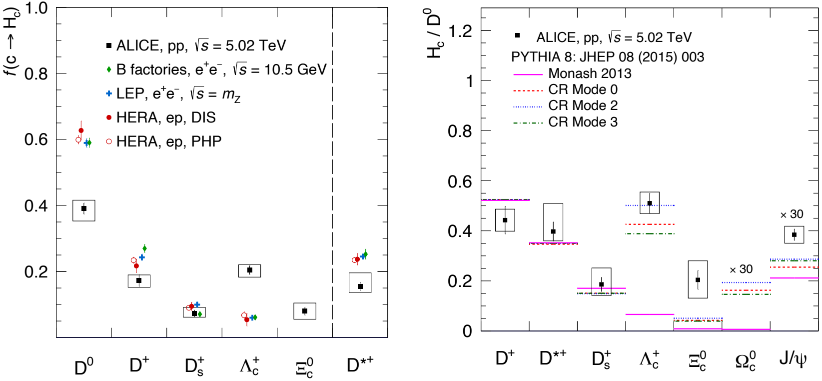

(Depends on number of gluons)



Triple-junction also in HERWIG cluster model.

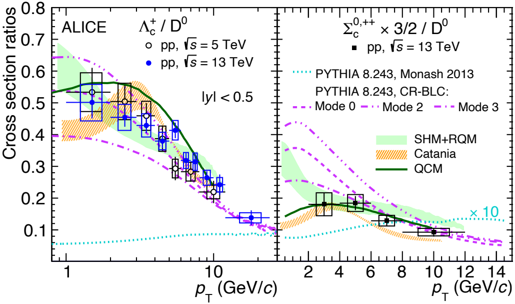
# The charm baryon enhancement

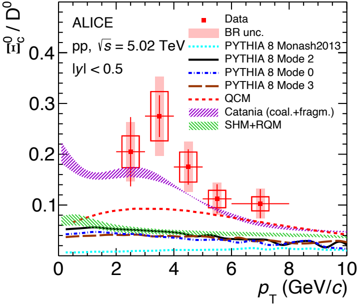
In 2017/21 ALICE found/confirmed strong enhancement of charm baryon production, relative to LEP, HERA and default PYTHIA.

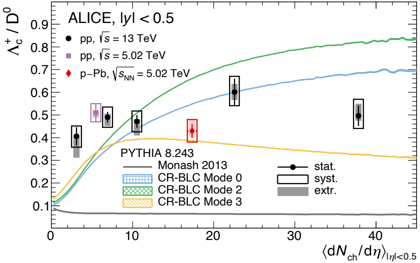



The QCDCR model does much better, with junctions ⇒ baryons.

# Charm baryon differential distributions



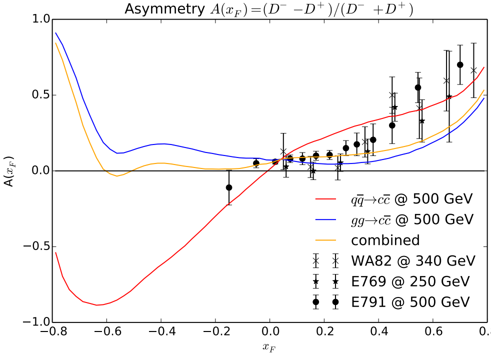



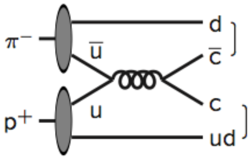

QCDCR does well
for some distributions,
less so for others.
Improvements needed,
but good starting point.

# Beam drag effects

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

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



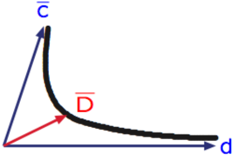




If low-mass string e.g.:

$\bar{\mathrm{c}}\mathrm{d} : \mathrm{D}^-, \mathrm{D}^{*-}$

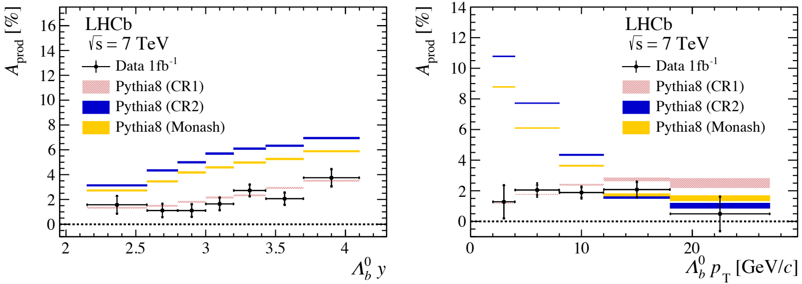
$\mathrm{cud} : \Lambda_\mathrm{c}^+, \Sigma_\mathrm{c}^+, \Sigma_\mathrm{c}^{*+}$

$\Rightarrow$ flavour asymmetries




Can give $D$ "drag" to larger $x_\mathrm{F}$ than $\mathrm{c}$ quark.

# Bottom asymmetries




$$A(y), A(p_\perp) = \frac{\sigma(\Lambda_{\mathrm{b}}^0) - \sigma(\overline{\Lambda}_{\mathrm{b}}^0)}{\sigma(\Lambda_{\mathrm{b}}^0) + \sigma(\overline{\Lambda}_{\mathrm{b}}^0)}$$

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

Enhanced $\Lambda_{\mathrm{b}}$ production at low $p_\perp$, like for $\Lambda_{\mathrm{c}}$, dilutes asymmetry?

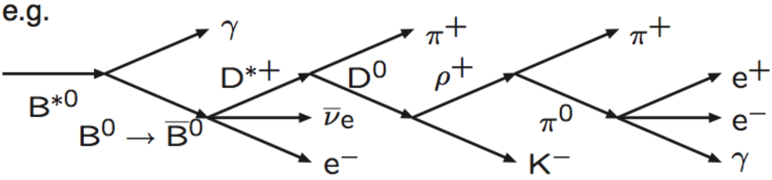
Asymmetries observed also for other charm and bottom hadrons.

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.




- $\mathrm{B}^{*0} \to \mathrm{B}^0\gamma$: 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, $\rho$ mass smeared
- $\rho^+ \to \pi^+\pi^0$: $\rho$ polarized, $|\mathcal{M}|^2 \propto \cos^2\theta$ in $\rho$ rest frame
- $\pi^0 \to \mathrm{e}^+\mathrm{e}^-\gamma$: Dalitz decay, $m(\mathrm{e}^+\mathrm{e}^-)$ peaked

# Problems with the Standard Model

- There are 25 free parameters.
- Unnaturally (?) large scale ratios:
  $m_e/m_\nu \sim 10^7$, $m_W/m_e \sim 10^5$, $m_{\mathrm{Pl}}/m_t \sim 10^{17}$
  where Planck mass $m_{\mathrm{Pl}} = \sqrt{\hbar c/G_N} = 1.22 \cdot 10^{19} \mathrm{GeV}/c^2$
  is the scale where gravitational strength is of $\mathcal{O}(1)$.
- Why are there three generations?
- Why do we have $\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$?
  Nature could have picked any symmetry!
- Why are the left-handed fermions in $\mathrm{SU}(2)$ doublets
  and the right-handed in singlets?
- Why is there charge quantization, so that $Q_p + Q_e \equiv 0$?
  In principle $Y$ in $\mathrm{U}(1)$ could be anything.
- Where is the antimatter?
- What is dark matter?
- Where does gravity fit in? What is dark energy?

# Fine-tuning

There is a problem with the Higgs mass!
Just as couplings are renormalized to be scale dependent, so are masses, e.g. fermions in QED:

$$m \to m_0 \left(1 + \frac{\alpha}{3\pi} \int_{m_0^2}^{\infty} \frac{dp^2}{p^2} + \ldots\right) \to m_0 \left(1 + \frac{\alpha}{3\pi} \ln \frac{\Lambda^2}{m_0^2} + \ldots\right)$$

where $\Lambda$ is some cutoff scale, like $m_{\mathrm{Pl}}$.
Assuming the Higgs mass at the scale $\Lambda$ is $m_H(\Lambda)$, considering only the top loop $H \to t\bar{t} \to H$ we have

$$m_H^2(m_Z) \sim m_H^2(\Lambda) - g_t^2(\Lambda^2 - m_t^2)$$

where $g_t \sim 1$.
If there is no physics below $m_{\mathrm{Pl}}$, that means $m_H(m_Z) \approx 125$ GeV comes from the subtraction between two huge numbers, requiring fine-tuning of order $(m_H/m_{\mathrm{Pl}})^2 \sim 10^{-34}$.

# Beyond the Standard Model

Consensus that there must be something beyond the Standard Model! But what?

Here consensus ends and countless suggestions begin, e.g.

- Grand Unification. Motivates gauge group structure.
- Supersymmetry. Stabilizes the Higgs potential and provides a Dark Matter candidate.
- Technicolor. Models $\mathrm{Z}^0$ and $\mathrm{W}^\pm$ as composite states under a strong force similar to QCD. These states would be the equivalents of $\pi^0$ and $\pi^\pm$, so-called pseudo-Goldstone-bosons.
- Extra Dimensions. Assume further curled-up dimensions on sub-mm scales, which can show up as new excited states.
- Superstrings. Extra dimensions on the Planck scale, unifying the SM with gravity. Allows for $\mathcal{O}(10^{500})$ different sub-models.
- Hidden Valleys. Assume that the dark matter can have a rich structure, like normal matter. Does not address SM problems.

# Grand Unified Theories

Symmetry breaking in the Standard Model:
$\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \to \mathrm{SU}(3)_C \times \mathrm{U}(1)_{em}$
Imagine that, at a high scale, all three forces are united into one, under a common larger symmety group $\mathcal{G}_{\mathrm{GUT}}$.
For some reason this group is then spontaneously broken

$$\mathcal{G}_{\mathrm{GUT}} \to \mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$$

by a Higgs mechanism.

SU(5) is

- the simplest possible group that can be broken to the SM,
- invented by Georgi and Glashow 1974, and
- excluded by data — but still instructive.

Other alternatives include SO(10).

# The basic multiplet

The basic multiplet is given by
a colour triplet and a weak doublet
in an (anti-) quintet.

Since the weak doublet is left-handed,
the quarks need to be left-handed and
weak singlets, so we use the $\bar{d}$.

$$U_{\overline{5}} = \begin{pmatrix} \begin{pmatrix} \overline{d}_r \\ \overline{d}_g \\ \overline{d}_b \end{pmatrix} \\ \begin{pmatrix} e^- \\ \nu_e \end{pmatrix} \end{pmatrix}_L$$

Other fermions in a $U_5$, a $U_{10}$ and a $U_{\overline{10}}$, times 3 generations.
Group generators are traceless $N \times N$ matrices,
where the diagonal generators will give the charges, and thus

$$\sum \mathrm{colour} = \sum I_3 = \sum Y = \sum Q_i = 0.$$

This gives us charge quantisation and $3Q_{\bar{d}} + Q_e = 0$,
and for the 10 e.g. $Q_u = Q_d + Q_{e^+}$, which explains why
$Q_p + Q_e \equiv 0$.

# The unification scale

The running of couplings suggest a unification scale $\sim 10^{16}$ GeV.

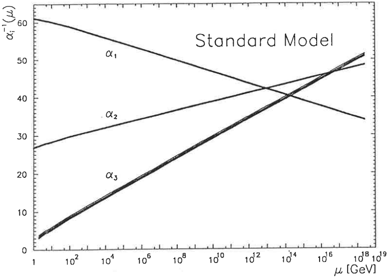



**Figure 7.1:** *Evolution of the coupling constants of the minimal standard model with three families and one Higgs doublet.*

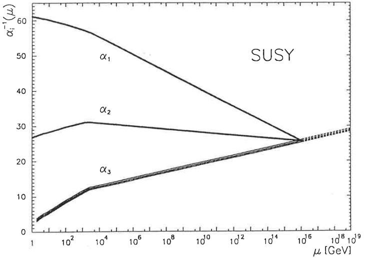



**Figure 7.2:** *Evolution of the coupling constants in the minimal supersymmetric standard model with three families and two Higgs doublets. The intermediate breaking scale is at* $M_{SUSY} = 1.2 \cdot 10^{3.0\pm0.8}$ *GeV. The dashed line shows an example of an evolution after the unification scale.*

But not perfect, hinting at more. . .

Big drawback: $5^2 - 1 = 24$ gauge bosons,
whereof the 12 new can violate baryon and lepton number,
notably $p = uud \to X^{+4/3}d \to e^+\overline{d}d = e^+\pi^0$.

Estimate $\tau_p \sim 10^{31\pm2}$ years, but data tell that
$\tau(p \to e^+\pi^0) > 10^{34}$ years. So SU(5) is dead!(?)

# Supersymmetry (SUSY)

Postulate a symmetry between fermions and bosons,
with an operator $Q$ changing one into the other

$$Q|b_i\rangle = |f_i\rangle \quad \text{and} \quad \bar{Q}|f_i\rangle = |b_i\rangle$$

but leaving any other quantum number unchanged.
The transformation is actually defined in terms of an algebra

$$\{Q, \bar{Q}\} = Q\bar{Q} + \bar{Q}Q = 2\sigma^{\mu} P_{\mu}$$
$$\{Q, Q\} = \{\bar{Q}, \bar{Q}\} = [Q, P] = [\bar{Q}, P] = 0$$

where $P_{\mu} = i\partial_{\mu}$ is a translation and the $\sigma^{\mu}$ Pauli matrices.
SUSY relates internal spin to external spatial translations!

# Partner particles

Need new particles that match existing ones except for spin,
so that # bosonic = # fermionic degrees of freedom.
MSSM = Minimal Supersymmetric extension to the SM.
Also includes an extra Higgs doublet = 4 further states.

Fermion partners, spin 0:

| normal | partner | |
|---|---|---|
| $q_L$ | $\tilde{q}_L$ | squark |
| $q_R$ | $\tilde{q}_R$ | (can mix) |
| $\ell_L$ | $\tilde{\ell}_L$ | slepton |
| $\ell_R$ | $\tilde{\ell}_R$ | (can mix) |
| $\nu_L$ | $\tilde{\nu}_L$ | sneutrino |

Boson partners, spin 1/2

| normal | partner | |
|---|---|---|
| $g$ | $\tilde{g}$ | gluino |
| $\gamma$ | $(\tilde{\gamma})$ | |
| $Z^0$ | $(\tilde{Z})$ | (photino zino higgsino) |
| $h^0$ | | all mix together into |
| $H^0$ | $(\tilde{H})$ | four neutralinos $\tilde{\chi}_i^0$ |
| $A^0$ | | |
| $W^\pm$ | $\tilde{W}^\pm$ | (wino higgsino) mix into |
| $H^\pm$ | $\tilde{H}^\pm$ | two chargino pairs $\tilde{\chi}_i^\pm$ |

# Desperately seeking SUSY

SUSY is a broken symmetry, since otherwise e.g. $m_{\tilde{q}} = m_q$.
The Higgs mass fine-tuning problem goes away for light sparticles, since $m_H^2(m_Z) \sim m_H^2(\Lambda) - g_t^2(m_{\tilde{t}}^2 - m_t^2)$.

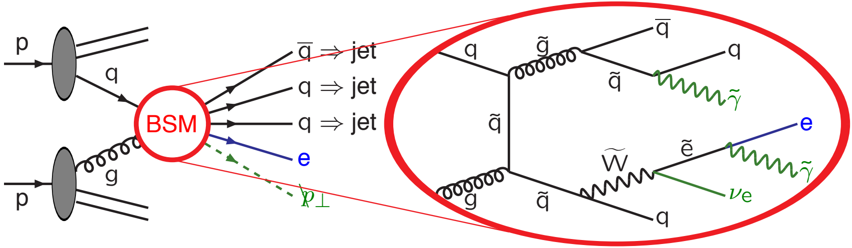
$R$-parity is defined as $R = (-1)^{L+3B+2S}$,
where $L$ is lepton number, $B$ is baryon number and $S$ is spin.
All ordinary particles have $R = +1$ and their spartners $R = -1$.
If $R$-parity is conserved, sparticles can only be produced in pairs.
A heavy sparticle can decay to a lighter one plus ordinary particles, giving a wide array of possible decay patterns.

The lightest super-symmetric particle (LSP) would be stable, and an excellent candidate for the Dark Matter particle.

No sign of SUSY, in spite of **many** searches over decades.
MSSM considered dead by many/most, but in total it involves $> 100$ parameters, so maybe still some wriggle room?
SUSY as such still possible, but then little predictive power.

# BSM at the LHC

BSM particles usually short-lived, or weakly interacting (like DM). Then visible final state consists of hadrons, leptons and photons, just like ordinary processes.

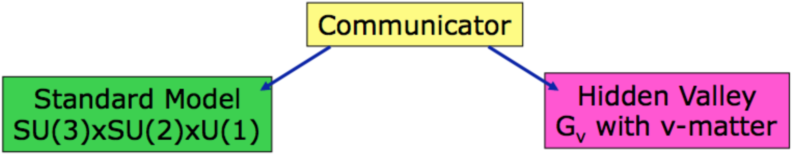


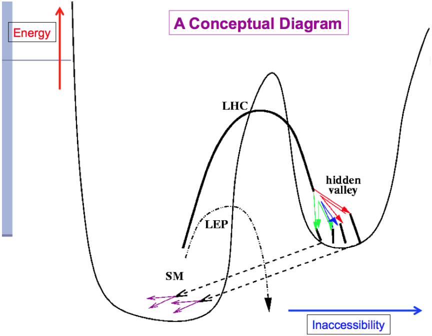

Can be as easy to model as SM processes.
Unfortunately, it may require detailed understanding of rare signals and huge backgrounds, limited by QCD modelling accuracy.

In addition, BSM physics can raise “new”, specific QCD aspects, for production, parton showers, decay, hadronization, . . . .

# 1. Hidden Valleys: motivation

M. Strassler, K. Zurek, Phys. Lett. B651 (2007) 374; . . .




Courtesy
M. Strassler

L. Carloni & TS, JHEP 1009, 105; L. Carloni, J. Rathsman & TS, JHEP 1104, 091

# Hidden Valleys setup

Hidden Valleys (secluded sectors) experimentally interesting
if they can give observable consequences at the LHC:

- coupling not-too-weakly to our sector, and
- containing not-too-heavy particles.

Here: no attempt to construct a specific model,
but to set up a reasonably generic framework.

# Hidden Valleys setup

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Either of two gauge groups,

1. Abelian $U(1)$, unbroken or broken (massless or massive $\gamma_v$),
2. non-Abelian $SU(N)$, unbroken ($N^2 - 1$ massless $\mathrm{g}_v$'s),

with matter $\mathrm{q}_v$'s in fundamental representation.

Times three alternative production mechanisms

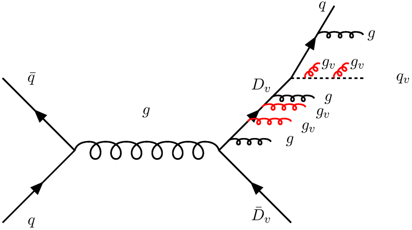
1. massive $\mathrm{Z}'$: $\mathrm{q}\overline{\mathrm{q}} \to \mathrm{Z}' \to \mathrm{q}_v\overline{\mathrm{q}}_v$,
2. kinetic mixing: $\mathrm{q}\overline{\mathrm{q}} \to \gamma \to \gamma_v \to \mathrm{q}_v\overline{\mathrm{q}}_v$,
3. massive $\mathrm{F}_v$ charged under both SM and hidden group, so e.g. $\mathrm{gg} \to \mathrm{F}_v\overline{\mathrm{F}}_v$. Subsequent decay $\mathrm{F}_v \to \mathrm{f}\mathrm{q}_v$.

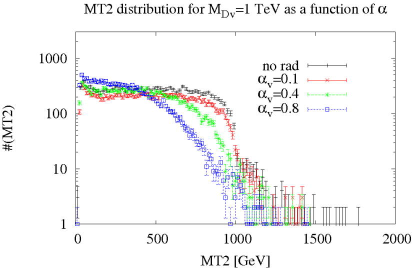
# Hidden Valleys showers

Interleaved shower in QCD, QED and HV sectors:
emissions arranged in one common sequence of decreasing emission $p_\perp$ scales.

HV $U(1)$: add $\mathrm{q}_v \to \mathrm{q}_v \gamma_v$ and $\mathrm{F}_v \to \mathrm{F}_v \gamma_v$.

HV $SU(N)$: add $\mathrm{q}_v \to \mathrm{q}_v \mathrm{g}_v$, $\mathrm{F}_v \to \mathrm{F}_v \mathrm{g}_v$ and $\mathrm{g}_v \to \mathrm{g}_v \mathrm{g}_v$.



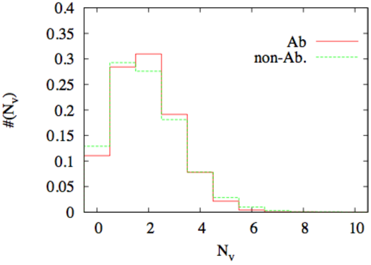

Recoil effects in visible sector also of invisible emissions!

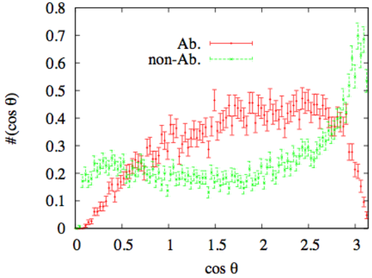
# Hidden Valleys decays

Hidden Valley particles may remain invisible, or

- Broken $U(1)$: $\gamma_v$ acquire mass, radiated $\gamma_v$s decay back, $\gamma_v \to \gamma \to \mathrm{f}\bar{\mathrm{f}}$ with BRs as photon ($\Rightarrow$ lepton pairs!)
- $SU(N)$: hadronization in hidden sector, with full string fragmentation setup, giving
  - off-diagonal "mesons", flavour-charged, stable & invisible
  - diagonal "mesons", can decay back $\mathrm{q}_v\bar{\mathrm{q}}_v \to \mathrm{f}\bar{\mathrm{f}}$

Even when tuned to same average activity, hope to separate



# 2. *R*-hadron motivation

Now different tack: *R*-parity conserved.

Conventional SUSY: LSP is neutralino, sneutrino, or gravitino.
Squarks and gluinos are unstable and decay to LSP,
e.g. $\tilde{\mathrm{g}} \to \tilde{\mathrm{q}}\overline{\mathrm{q}} \to \mathrm{q}\tilde{\chi}\overline{\mathrm{q}}$.

Alternative SUSY: gluino LSP, or long-lived for another reason.

E.g. Split SUSY (Dimopoulos & Arkani-Hamed):
scalars are heavy, including squarks $\Rightarrow$ gluinos long-lived.

# 2. *R*-hadron motivation

Now different tack: *R*-parity conserved.

Conventional SUSY: LSP is neutralino, sneutrino, or gravitino.
Squarks and gluinos are unstable and decay to LSP,
e.g. $\tilde{\mathrm{g}} \to \tilde{\mathrm{q}}\overline{\mathrm{q}} \to \mathrm{q}\tilde{\chi}\overline{\mathrm{q}}$.

Alternative SUSY: gluino LSP, or long-lived for another reason.

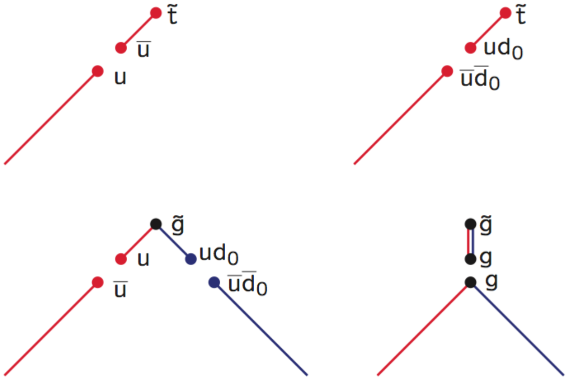
E.g. Split SUSY (Dimopoulos & Arkani-Hamed):
scalars are heavy, including squarks $\Rightarrow$ gluinos long-lived.

More generally, many BSM models contain colour triplet or octet particles that can be (pseudo)stable: extra-dimensional excitations with odd KK-parity, leptoquarks, excited quarks, . . . .

$\Rightarrow$ PYTHIA allows for hadronization of 3 generic states:

- colour octet uncharged, like $\tilde{\mathrm{g}}$, giving $\tilde{\mathrm{g}}\mathrm{u}\overline{\mathrm{d}}$, $\tilde{\mathrm{g}}\mathrm{uud}$, $\tilde{\mathrm{g}}\mathrm{g}$, . . . ,
- colour triplet charge $+2/3$, like $\tilde{\mathrm{t}}$, giving $\tilde{\mathrm{t}}\overline{\mathrm{u}}$, $\tilde{\mathrm{t}}\mathrm{ud}_0$, . . . ,
- colour triplet charge $-1/3$, like $\tilde{\mathrm{b}}$, giving $\tilde{\mathrm{b}}\overline{\mathrm{c}}$, $\tilde{\mathrm{b}}\mathrm{su}_1$, . . . .

# $R$-hadron formation




Squark fragmenting to meson or baryon

Gluino fragmenting to baryon or glueball

Most hadronization properties by analogy with normal string fragmentation, but glueball formation new aspect, assumed $\sim 10\%$ of time (or less).

# $R$-hadron interactions

$R$-hadron interactions with matter involve interesting aspects:

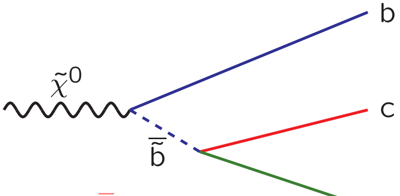
- $\tilde{\mathrm{b}}/\tilde{\mathrm{t}}/\tilde{\mathrm{g}}$ massive $\Rightarrow$ slow-moving, $v \sim 0.7c$.
- In $R$-hadron rest frame the detector has $v \sim 0.7c$
  $\Rightarrow E_{\mathrm{kin,p}} \sim 1$ GeV: low-energy (quasi)elastic processes.
- Cloud of light quarks and gluons interact with hadronic rate;
  sparticle is inert reservoir of kinetic energy.
- Charge-exchange reactions allowed, e.g.
  $R^+(\tilde{\mathrm{g}}\mathrm{u}\overline{\mathrm{d}}) + \mathrm{n} \to R^0(\tilde{\mathrm{g}}\mathrm{d}\overline{\mathrm{d}}) + \mathrm{p}$.
  Gives alternating track/no-track in detector.
- Baryon-exchange predominantly one way,
  $R^+(\tilde{\mathrm{g}}\mathrm{u}\overline{\mathrm{d}}) + \mathrm{n} \to R^0(\tilde{\mathrm{g}}\mathrm{udd}) + \pi^+$,
  since (a) kinematically disfavoured ($\pi$ exceptionally light)
  and (b) few pions in matter.

... but part of detector simulation (GEANT), not PYTHIA.

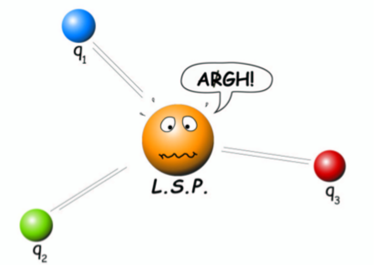
A.C. Kraan, Eur. Phys. J. C37 (2004) 91; M. Fairbairn et al., Phys. Rep. 438 (2007) 1

# 3. $R$-parity violation in SUSY

Baryon number violation (BNV) is allowed in SUSY superpotential.
Alternatively lepton number violation, but proton unstable if both.
BNV couplings should not be too big, or else large loop corrections
$\Rightarrow$ relevent for LSP (Lightest Supersymmetric Particle).




Note: $m(\overline{\tilde{\mathrm{b}}}) > m(\tilde{\chi}^0)$



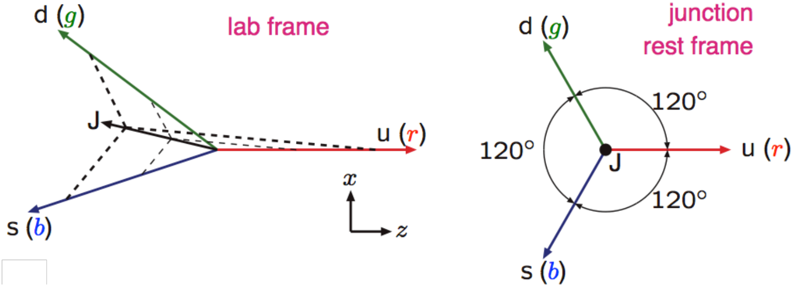

What about showers and hadronization in decays?

P. Skands & TS, Nucl. Phys. B659 (2003) 243;

N. Desai & P. Skands, arXiv:1109.5852 [hep-ph]

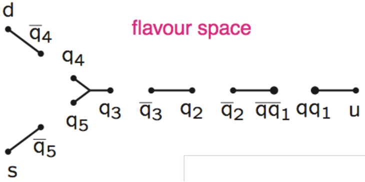
# The junction

What string topology for 3 quarks in overall colour singlet?
One possibility is to introduce a **junction** (Artru, 't Hooft, ...).

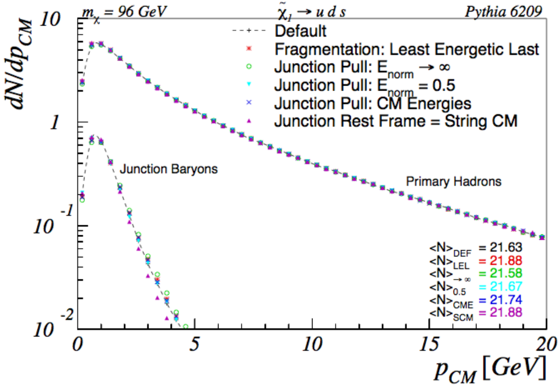



Junction rest frame = where string tensions $\mathbf{T}_i = \kappa\, \mathbf{p}_i / |\mathbf{p}_i|$ balance
$= 120^\circ$ separation between quark directions.
This is not the CM frame where momenta $\mathbf{p}_i$ balance,
but in BNV decay no collinear singularity between quarks,
so normally junction is slowly moving in LSP rest frame.

# Junction hadronization

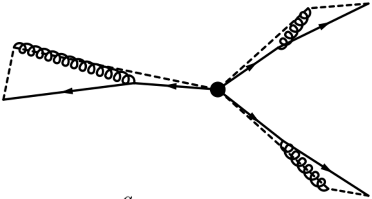



Each string piece can break, mainly to give mesons. Always one baryon around junction; junction “carries” baryon number.

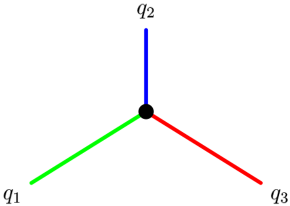



Junction baryon slow
$\Rightarrow$
"smoking-gun" signal.

# The junction and dipole showers



Normal showers:
each parton can radiate.




Dipole showers: each *pair* of partons, with matching colour–anticolour, can radiate, with recoil inside system.
But here no simply matching colours!

Solution: let each three possible dipoles radiate, but with half normal strength.
Gives correct answer collinear to each parton, and reasonable interpolation in between.

# Summary

- 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.
- Main alternative is cluster models.
- LHC data has revolutionized the picture of soft physics:
  **Goodbye jet universality!**
- This has led to a renewed phenomenology interest:
  **Welcome new mechanisms!**
- Many models for physics beyond the SM (GUT, SUSY, . . . ), with no consensus among theorists.
- No convincing signs of BSM so far, except for **Dark Matter**, but **Hope Springs Eternal**.