Baryon anomaly in heavy-ion collisions & colour correlations in QGP

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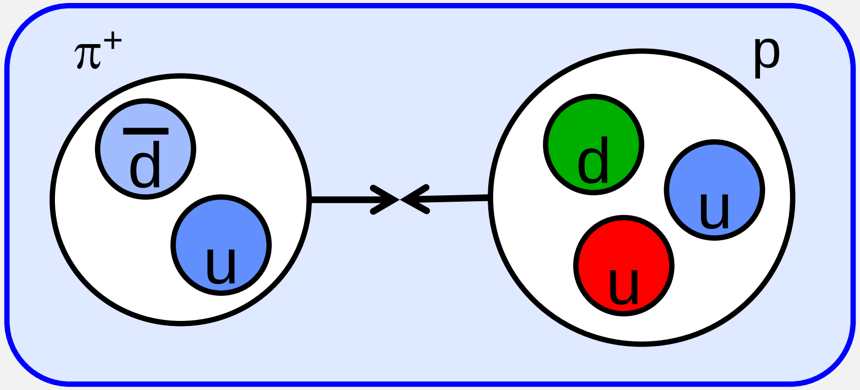
Constituent quark model

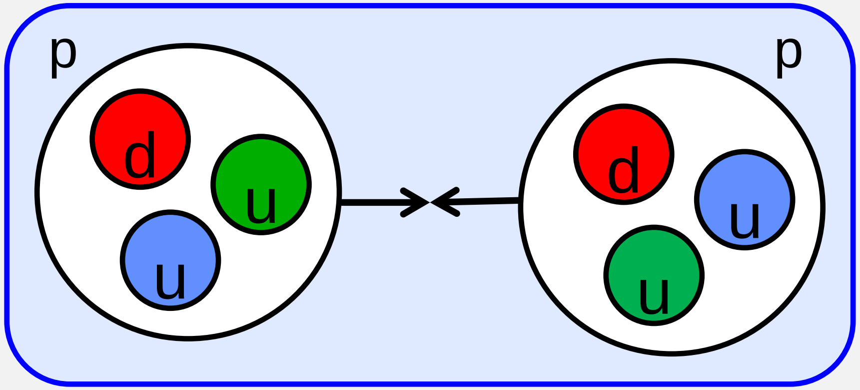
Constituent (additive) quark model:

Experimental observation $\frac{\sigma_{\pi p}}{\sigma_{pp}} \approx \frac{2}{3}$ value equal to the ratio of number of quarks in meson and baryon in naïve quark model !

Emerging picture: hardrons are made of loosely bounded (constituent) quarks

E.M.Levin, L.L.Frankfurt J. of Exp. and Theor. Phys. Lett. ***2*** *105 (1965)*





Baryon-to-meson ratio

If so, what would be the ratio of baryon to meson produced from a (symmetric) soup of quarks and antiquarks (*e.g.* at mid-rapidity of a hadron–hadron collision at infinite energy)? Starting from a quark:

$$
q \begin{cases} q\frac{1}{2} & \begin{cases} q\frac{1}{4} \rightarrow B \\ \bar{q}\frac{1}{4} \rightarrow M \end{cases} \\ \bar{q}\frac{1}{2} \rightarrow M & \end{cases}
$$

and starting from antiquark we obtain another ¾ of M and ¼ of $\bar{B}$

thus:

$$B : \bar{B} : M = 1 : 1 : 6$$

It was assumed that the first (closest) combination of quarks is *prepared* in colour-singlet state

V.V. Anisovitch, V.M. Schekhter Nucl. Phys. ***B55*** *455 (1973)*

… without colour correlations

Let's assume that colour states of quarks are completely random, then:

only 1/9 of $q\bar{q}$ pairs will bound into a meson $3 \otimes \bar{3} = 1 \oplus 8$

1/3 of qq pairs will became a di-quark $3 \otimes 3 = \bar{3} \oplus 6$

1/9 of diquark–q will bound into a baryon $3 \otimes 3 \otimes 3 = 1 \oplus 8 \oplus 8 \oplus 10$

- q
  - $q\frac{1}{2}$
    - $\frac{1}{6} \rightarrow qq$
      - $q\frac{1}{12}$
        - $\frac{1}{108} \rightarrow B$
        - $\frac{8}{108} \rightarrow$ qq …
      - $\bar{q}\frac{1}{12}$
        - $\frac{1}{108} \rightarrow M$
        - $\frac{8}{108} \rightarrow$ qq …
    - $\frac{2}{6} \rightarrow$ q …
  - $\bar{q}\frac{1}{2}$
    - $\frac{1}{18} \rightarrow M$
    - $\frac{8}{18} \rightarrow$ q …

Summing all that up…

Random colour:

$$B : \bar{B} : M = 3 : 3 : 10$$

Correlated colour:

$$B : \bar{B} : M = 1 : 1 : 6$$

Colour de-correlation favours baryon production up to a factor 9/5 (=1.8)

This would be hardly applicable for hadron–hadron collisions because:

average number of steps needed to find correct colour partner(s) is

for a meson 9.99 (exactly 899/90)

for a baryon 13.5

consequently we would get very high inv. masses, *e.g.* ≈ 30 GeV mesons for quarks with the mean distance in rapidity of $\Delta y \approx 0.5$

Proposed solution was:

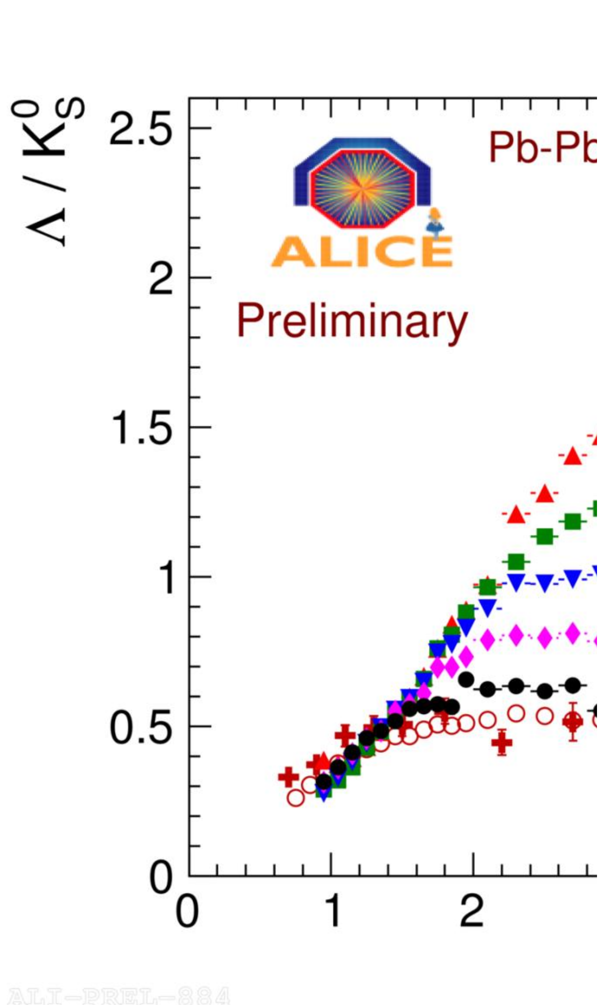
soft gluon exchange to adjust colours with probability ~ $\alpha_s^2 \approx O(0.1)$

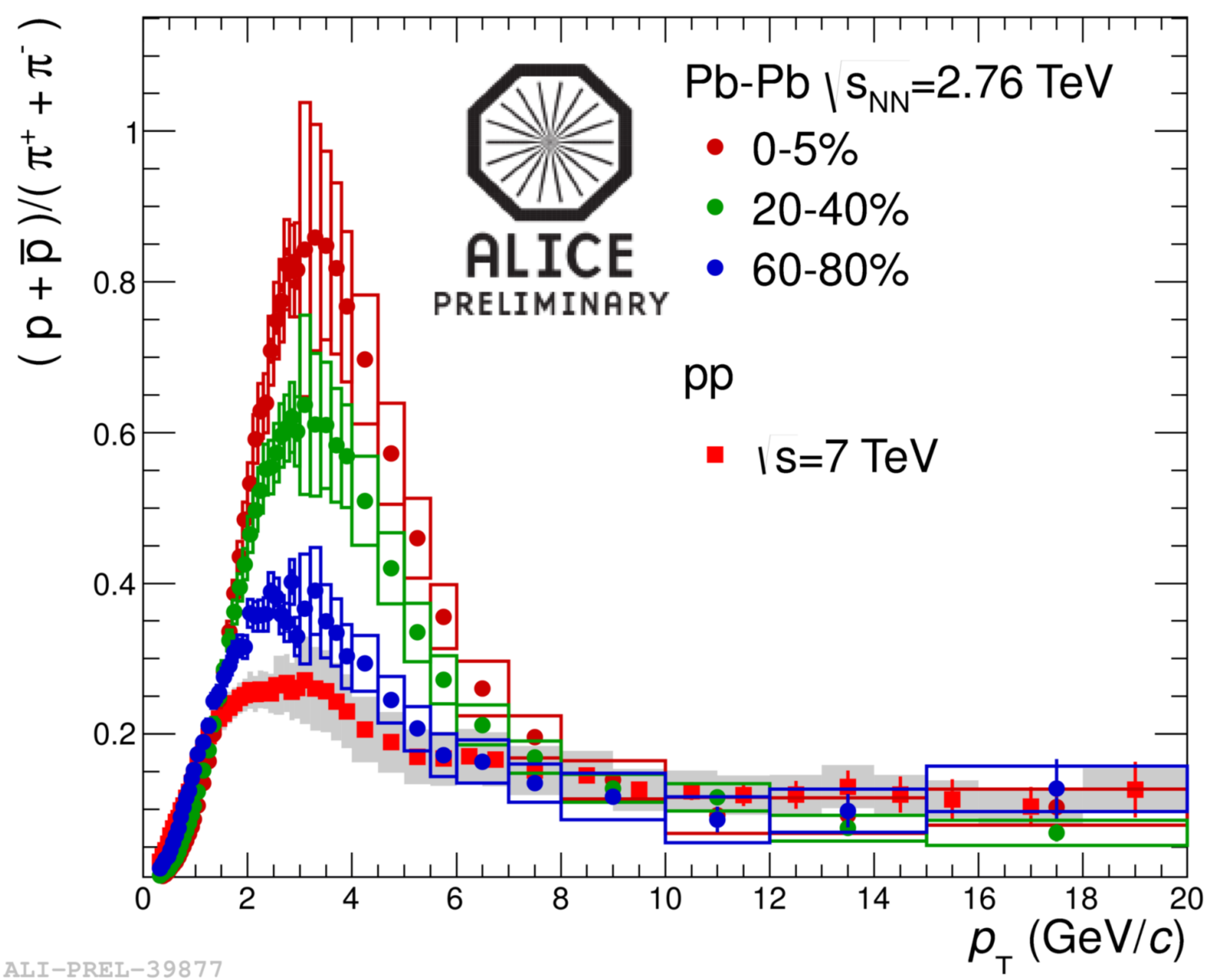
to penalize each step by factor ~ exp(-Δy) due to a quark (spin-½) t-channel exchange

This brings baryon-to-meson ratio practically back to 1 : 6 value…

E.M.Levin, M.G.Ryskin, K.Safarik 1979, unpublished

Heavy-ion collisions



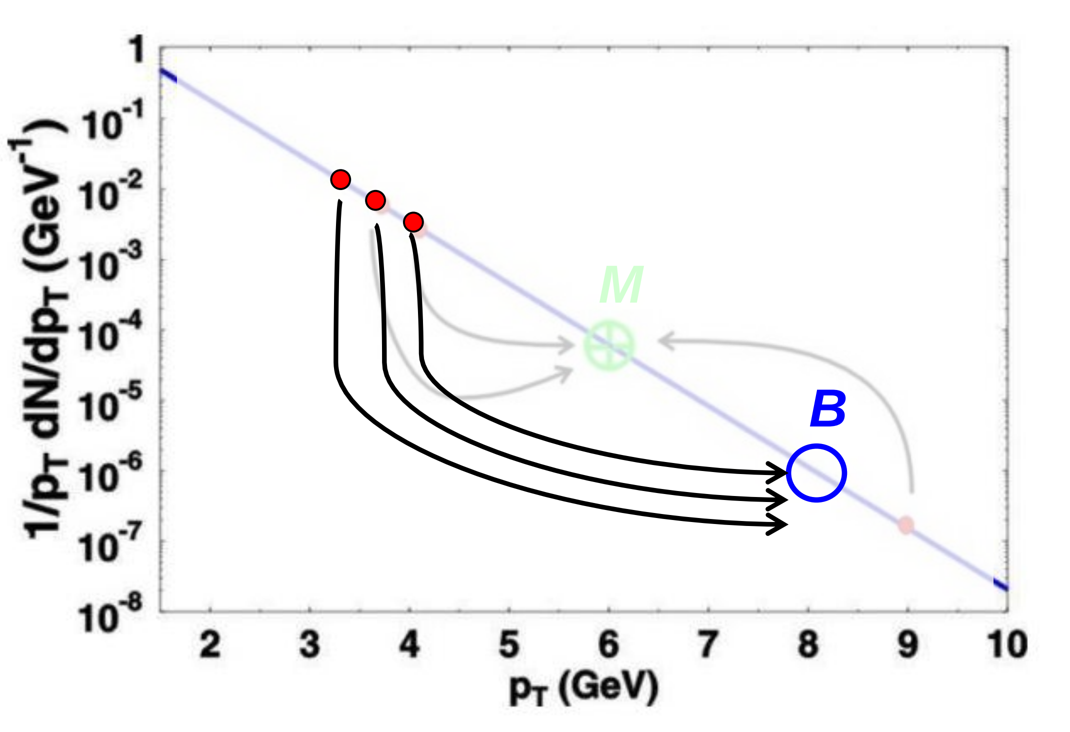


B/*M* ratio at $p_T \approx$ 2–3 GeV/c in central heavy-ion collisions is ~ 2–3 times higher than that in pp; at p_T above ~ 7–10 GeV/c back to the “normal” pp value

Recombination – coalescence

Up to some (intermediate) p_T [< O(10 GeV)] recombination will be favourable compared to fragmentation

This is even more true for baryons



Recombination explains the enhancement of baryons, *i.e.* baryon anomaly

However, colour de-correlation can enhance baryons even further, in the region where it is dominant production process

This is plausible for heavy-ion collisions, contrary to *h–h*, where in string fragmentation colours are naturally adjusted (*i.e.* correlated)

R.C.Hwa, C.B.Yang Phys. Rev. ***C67*** *064902, 2003*

R.J.Fries et al., Phys. Rev. Lett. ***90*** *202303; Phys. Rev.* ***C68*** *044902*

Baryon to meson from QGP

In previous study, when di-quark was created, we do not consider the possibility that the original quark can meet later another quark suited to be in di-quark combination and at the same time not to form a baryon

- di-quark was assumed to be a well-bounded state
- thus only the first di-quark combination was kept and should eventually end up in a baryon

For the recombination from QGP we search for the "closest" colour singlet combination to coalesce, thus we keep track of more than one di-quarks

This assumption favour baryons even more

- baryon-to-meson ratio become $B : \bar{B} : M = 29 : 29 : 82$
- compared to $B : \bar{B} : M = 3 : 3 : 10$ or $B : \bar{B} : M = 1 : 1 : 6$

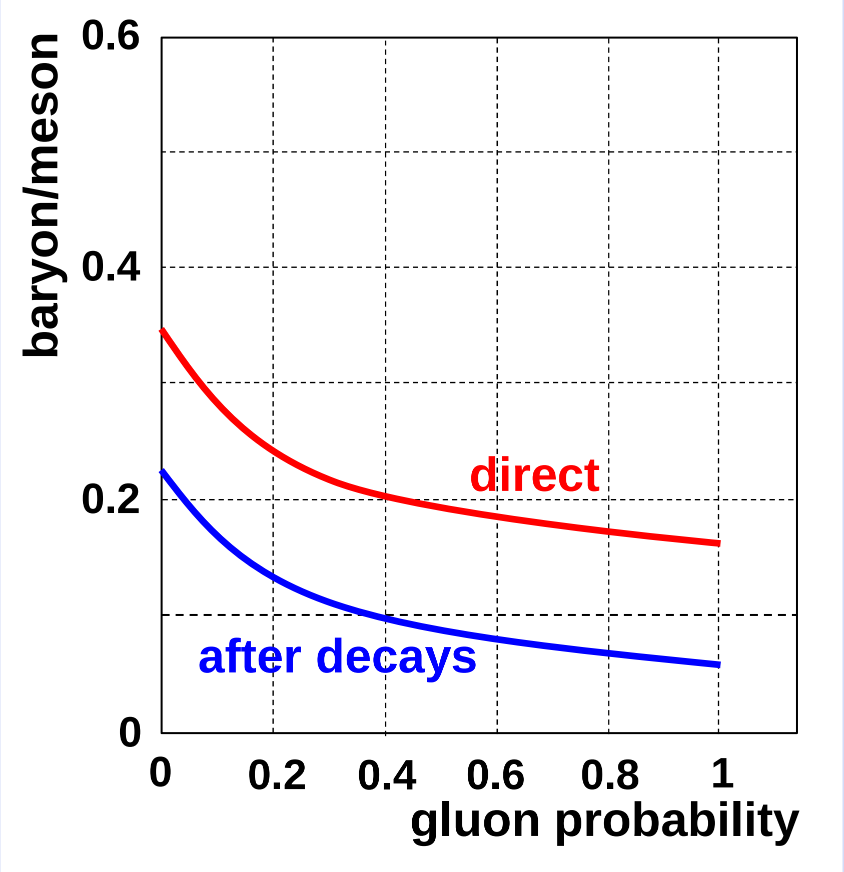
The relative increase of probability for baryons between the two extreme scenaria ("always adapted colours" and "completely random colours") is 87/41 (≈ 2.122)

G.Matulewicz, K.Safarik 2012, unpublished

Simple model

In our simple model at each step, when comes a quark with an unsuitable colour, we consider with some probability p_g (so called "gluon probability") that the colour is adjusted to the suitable one, by some sort of soft gluon emission

thus for $p_g = 0$ and $p_g = 1$ the two extreme cases are recovered



In order to calculate the final baryon-to-meson ratio we assign to quarks flavour (s quark being suppressed by factor 0.3)

Hadrons from lowest ($l = 0$) multiplets are constructed with weights according the number of spin states, and decayed

2-d model assuming thermal distribution for quark p_T is under construction, utilizing for quark ordering inv. mass

G.Matulewicz, K.Safarik 2012, unpublished

Conclusions

Colour correlations among nearby quarks and antiquarks in QGP can alter the baryon-to-meson ratio, resulting from their recombination, by a factor:

~ 2 (for directly produced particles)

~ 3 (taking into account decays)

Random distribution of colours in QGP favour baryon production

Contrary, when colours are adjusted to form white state with a neighbour, the baryon-to-meson ratio is lowered

Simple model is being prepared to calculate the p_T-dependence of baryon-to-meson ratio (and of different particle species) taking into account assumptions about degree of colour correlations in QGP