Modified string tensions

in the context of hadronization

Javira Altmann - Monash University

- ➢ Introduction to the **Lund String Model**
- ➢ Beyond Lund strings
    - ➢ Time dependent string tensions
    - ➢ Excitations

MONASH University

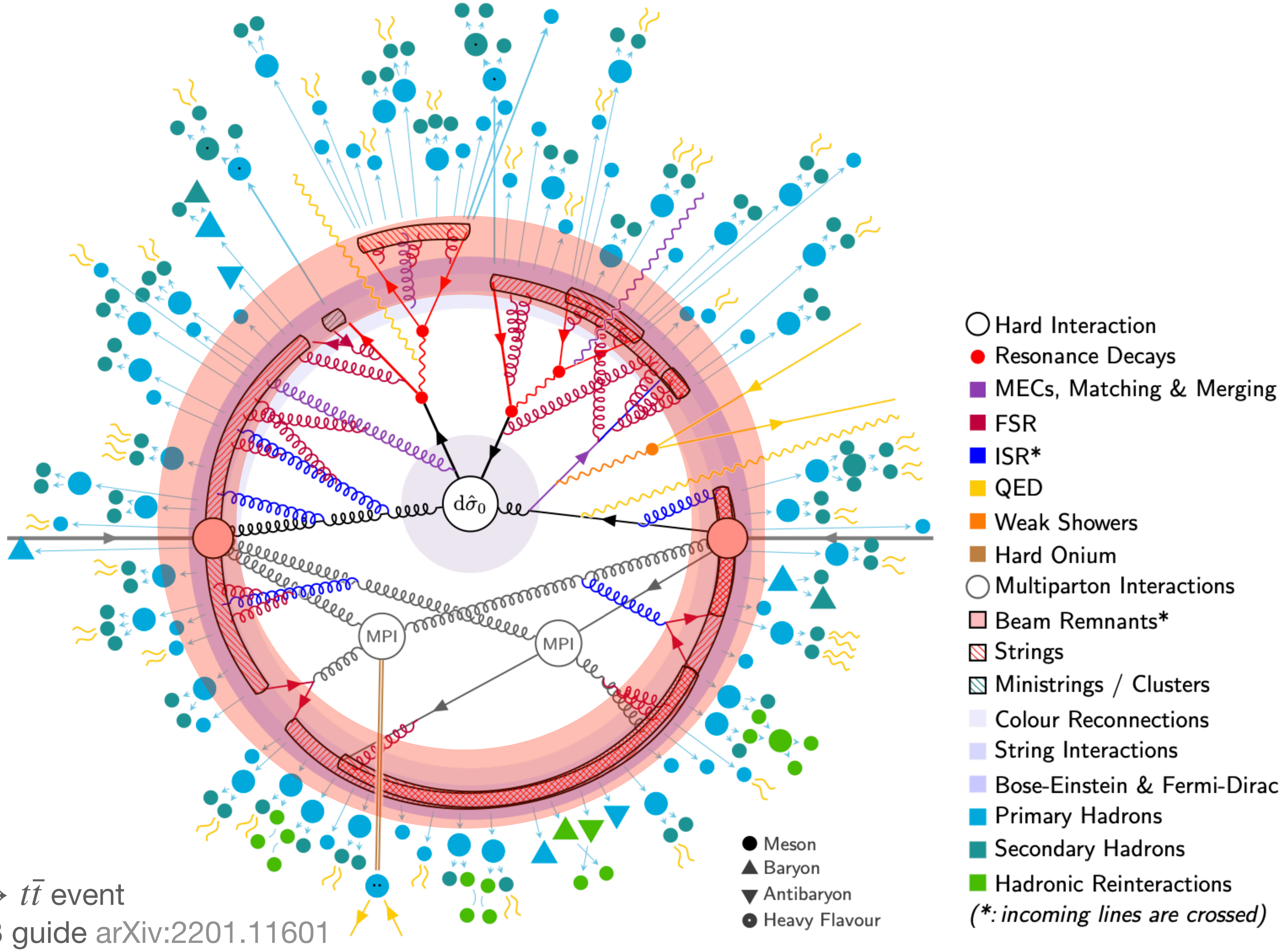
Confinement in high energy collisions

In high-energy collisions, such as proton-proton collisions at the LHC, need a dynamical process to ensure partons (**quarks and gluons**) become **confined** within hadrons

i.e. non-perturbative
parton → hadron map

Model requirements

- ➢ Confinement
- ➢ Dynamical mapping to on-shell hadrons



Example of $pp \to t\bar{t}$ event
From PYTHIA 8.3 guide arXiv:2201.11601

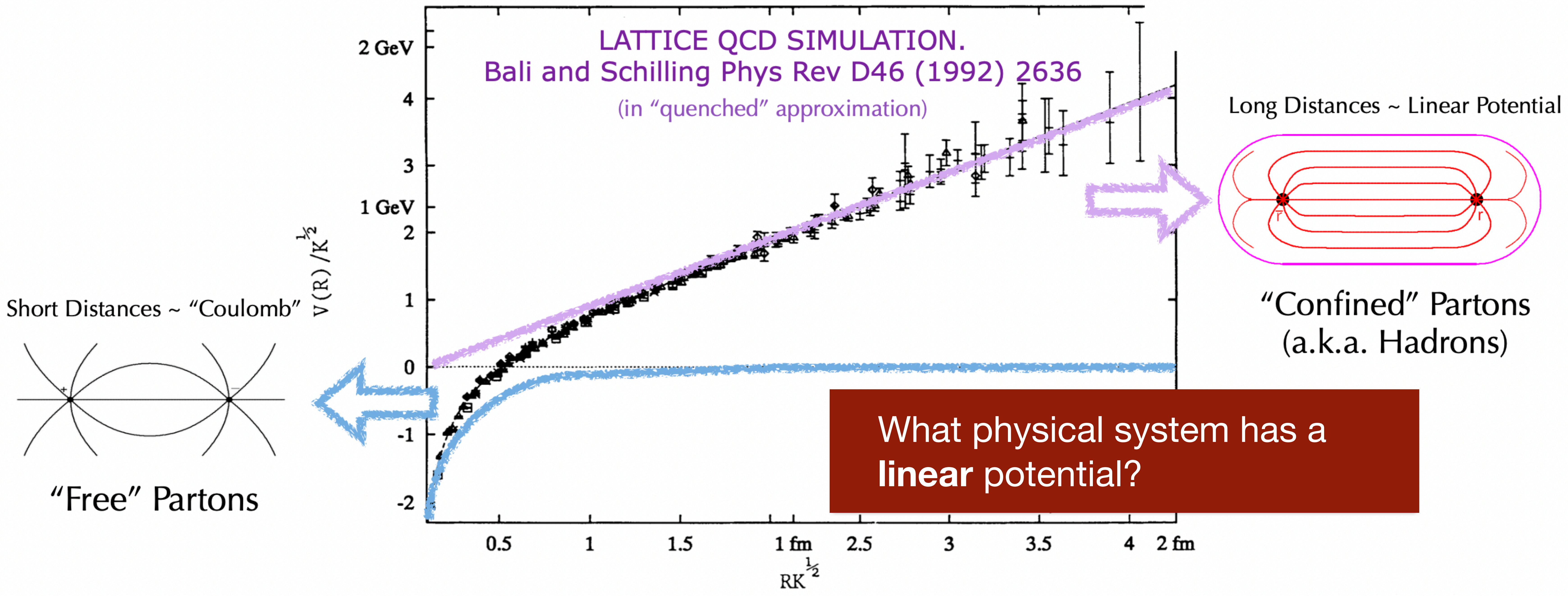
Confinement

Require colour neutralisation:

➢ The point of confinement is that partons are **coloured** → a physical model needs two or more partons to create **colour neutral** objects. Simplest example is a colour-anticolour $q\bar{q}$ pair

Lattice QCD **"Cornell potential"** $V(r) = -\frac{a}{r} + \kappa r$ with $\kappa \sim 1$ GeV/fm

shows us the potential energy of a **static** colour singlet $q\bar{q}$ at separation distance r



What physical system has a **linear** potential?

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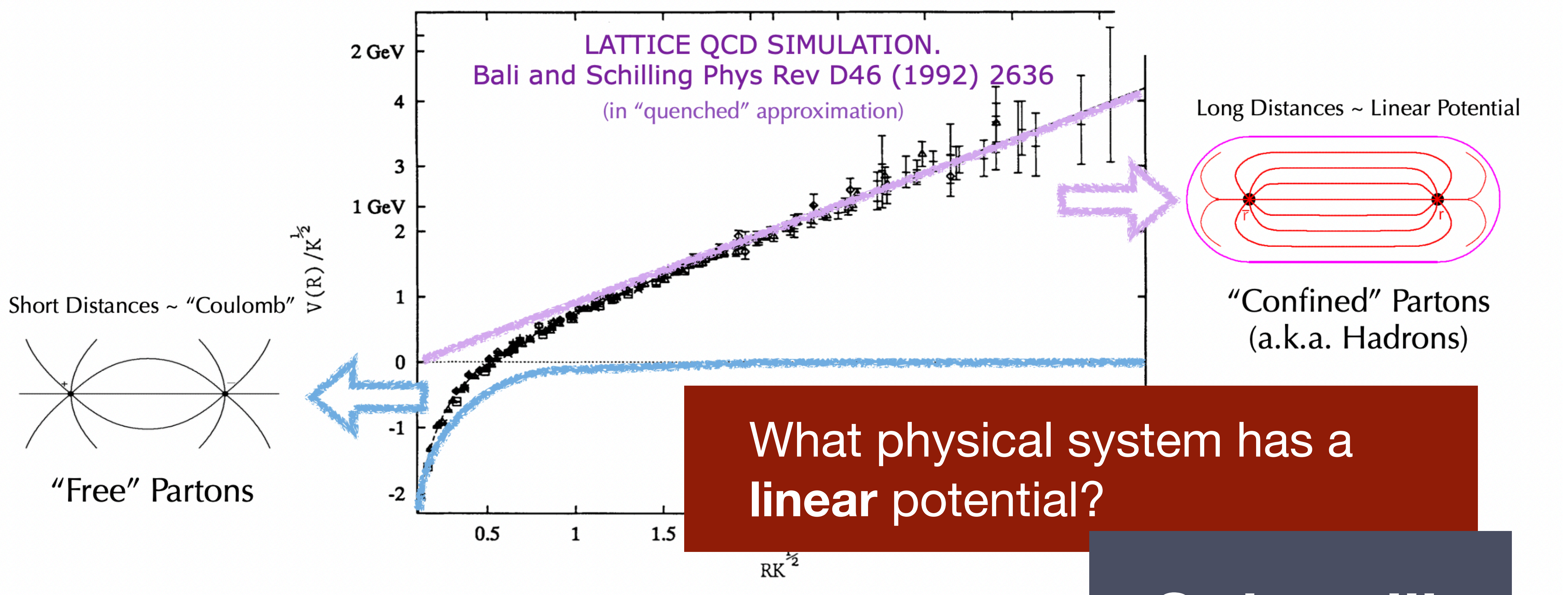

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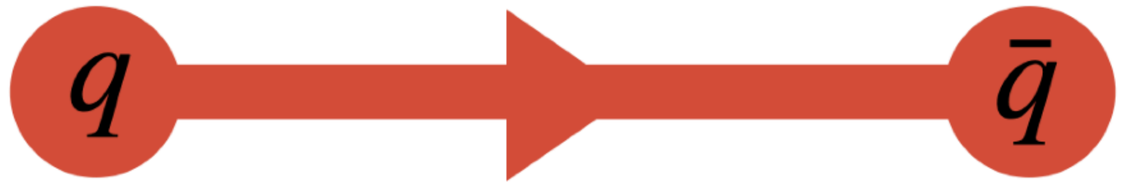
Strings !!!

Lund string model

model the **colour confinement field** as a **string**

with a characteristic **constant tension** κ_0

➢ Strings form between partons that form overall **colour-singlet** states



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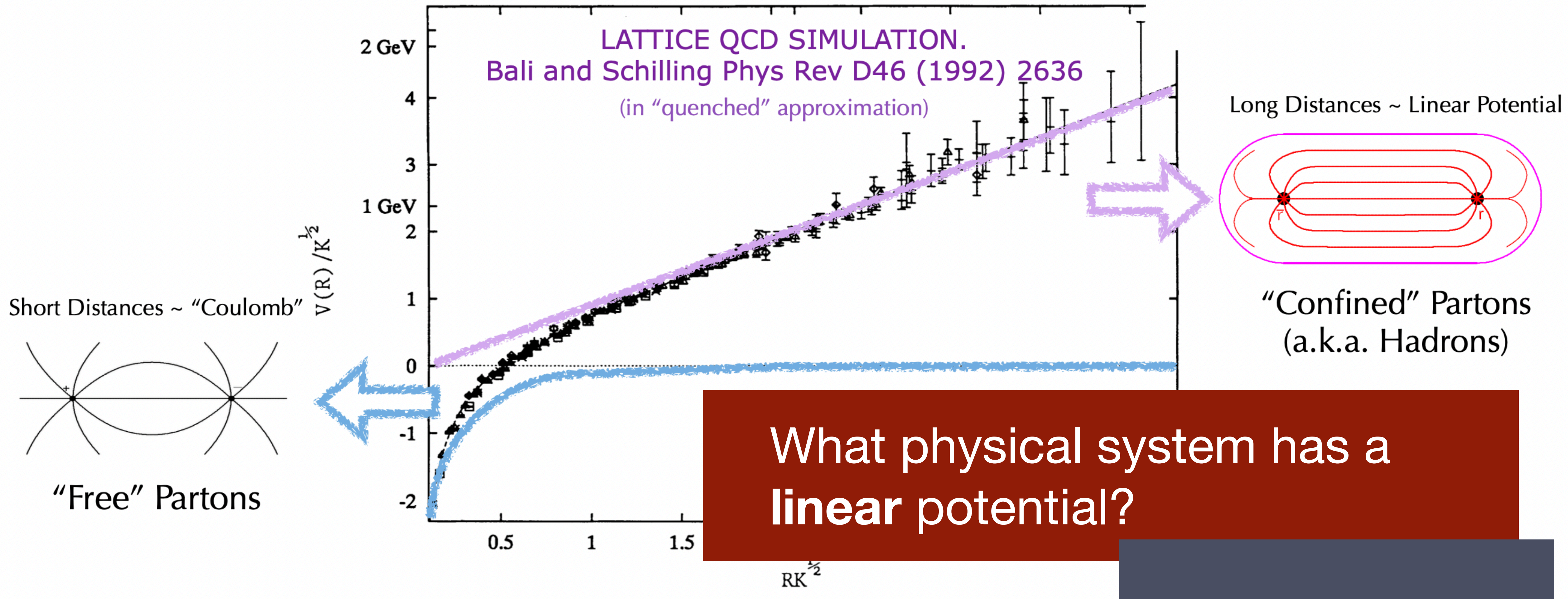

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High energy collisions → partons move apart at high energies

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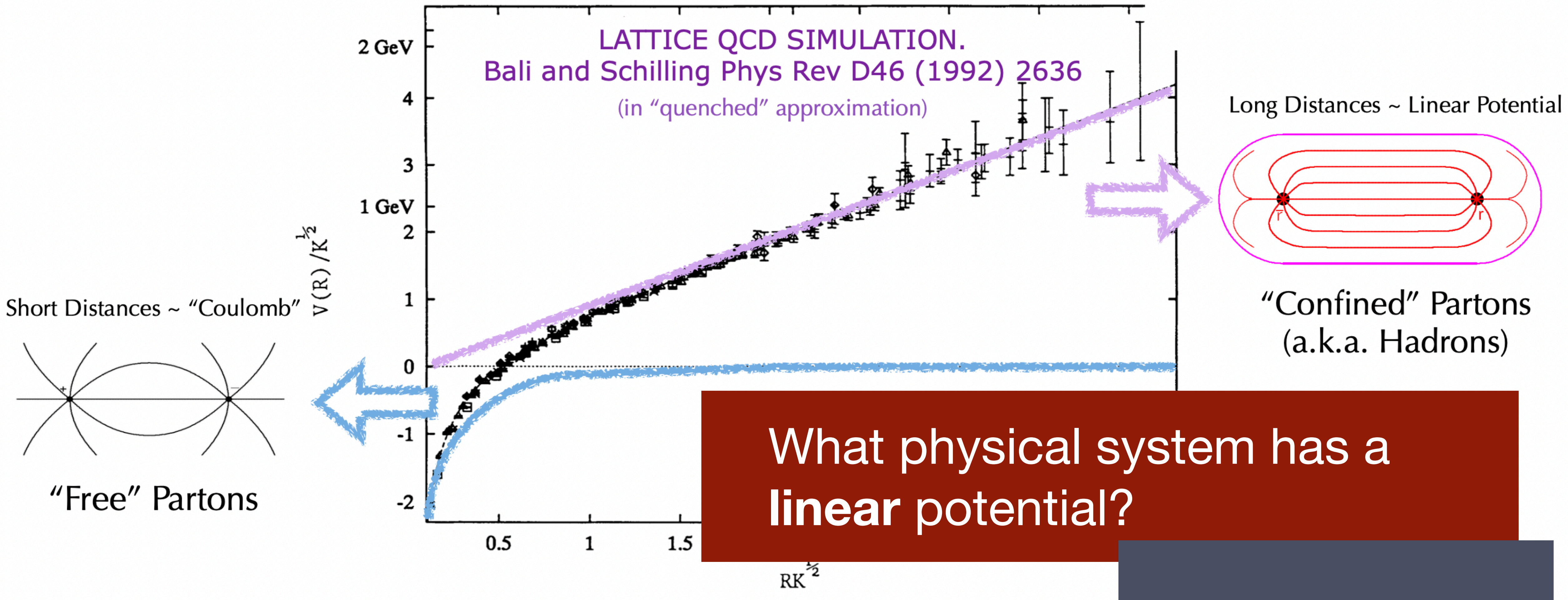

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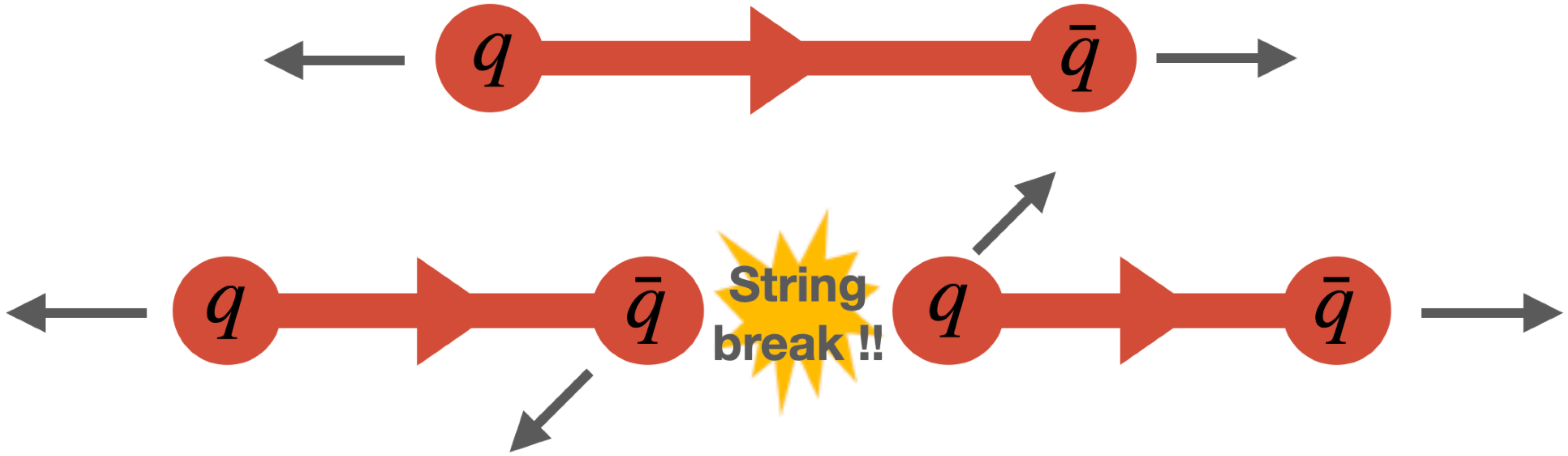
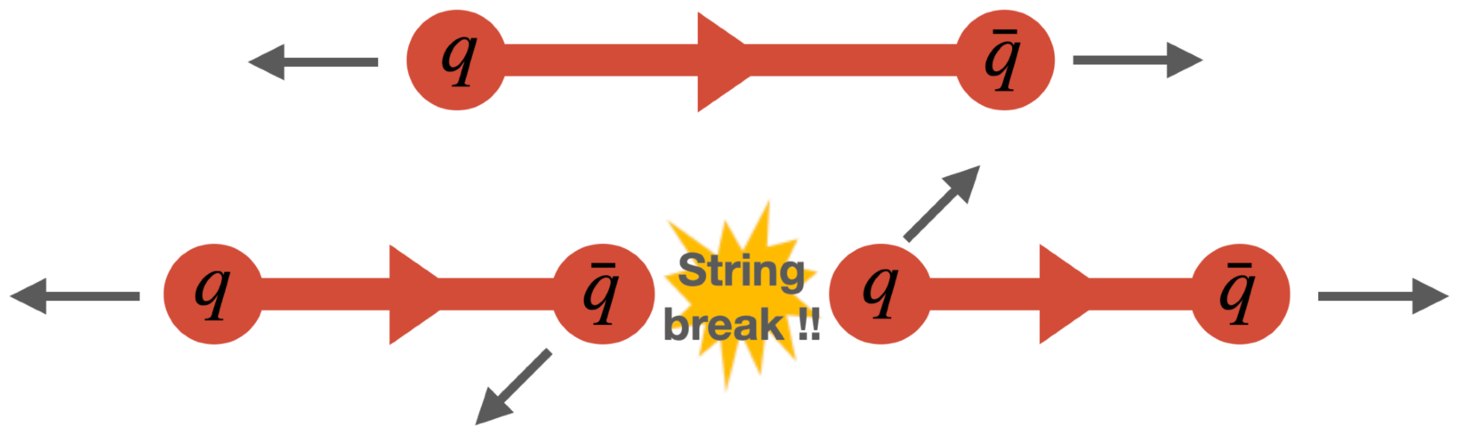


Partons → Hadrons

Hadronization:

Partons move apart and stretch the string → **string breaks**

→ creates **quark-antiquark pairs** with some momentum



Two things we need to describe the momentum of the produced hadrons

→ transverse component (quark $p_\perp$ and mass/flavour)

→ longitudinal component (fraction of the endpoint momenta)

Flavour and $p_\perp$ selection

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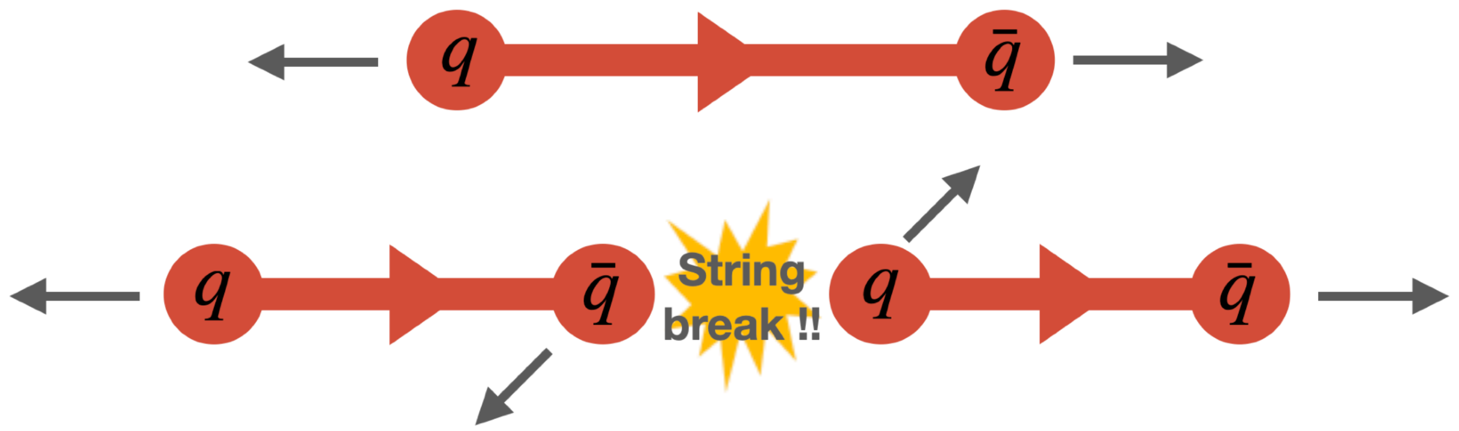

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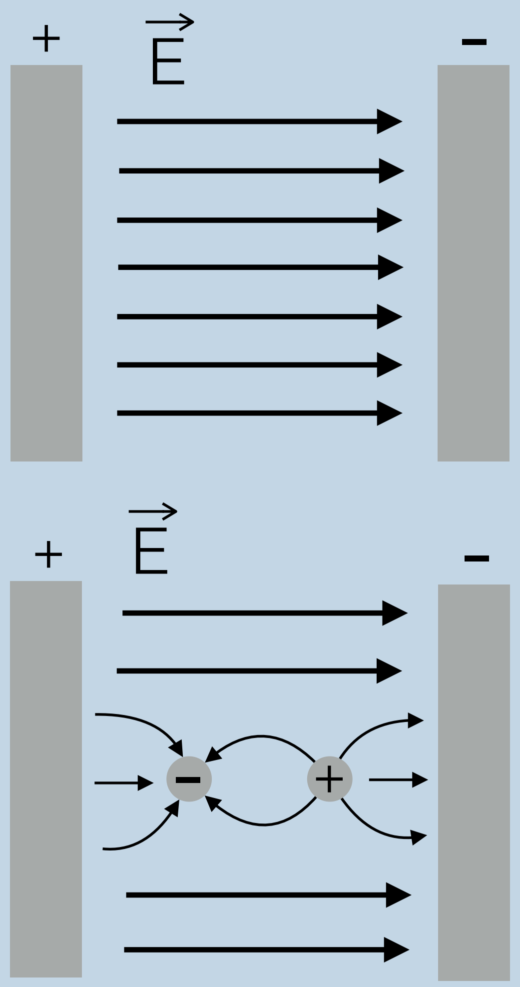

Non-perturbative creation of e^+e^- pairs in a strong electric field

Probability from tunnelling factor

$$\mathscr{P} \propto \exp\left(\frac{-m^2 - p_\perp^2}{\kappa/\pi}\right)$$

Gaussian suppression of high $m_\perp = \sqrt{m_q^2 + p_\perp^2}$

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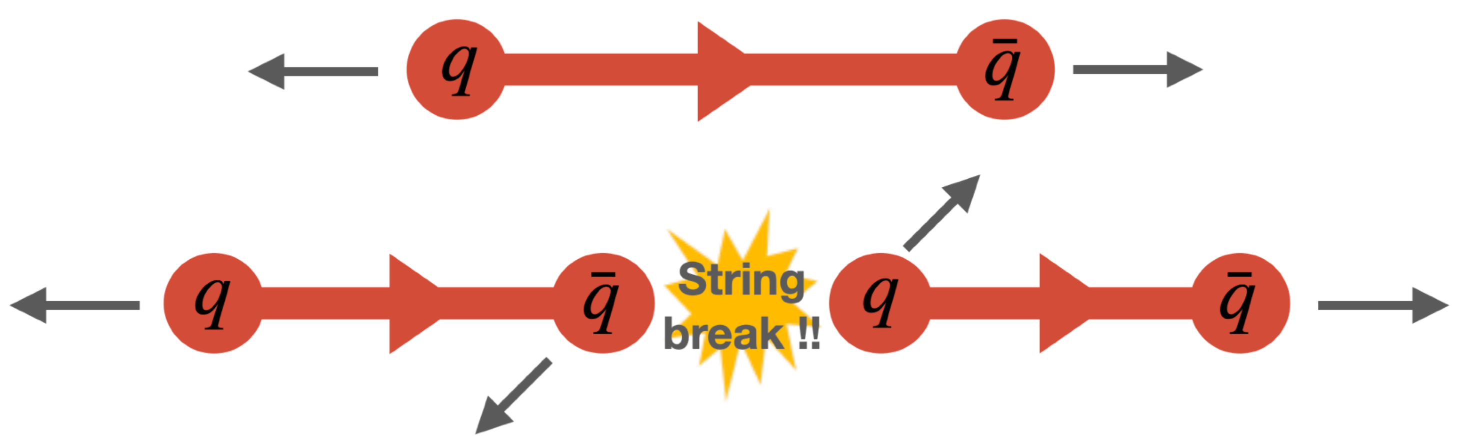

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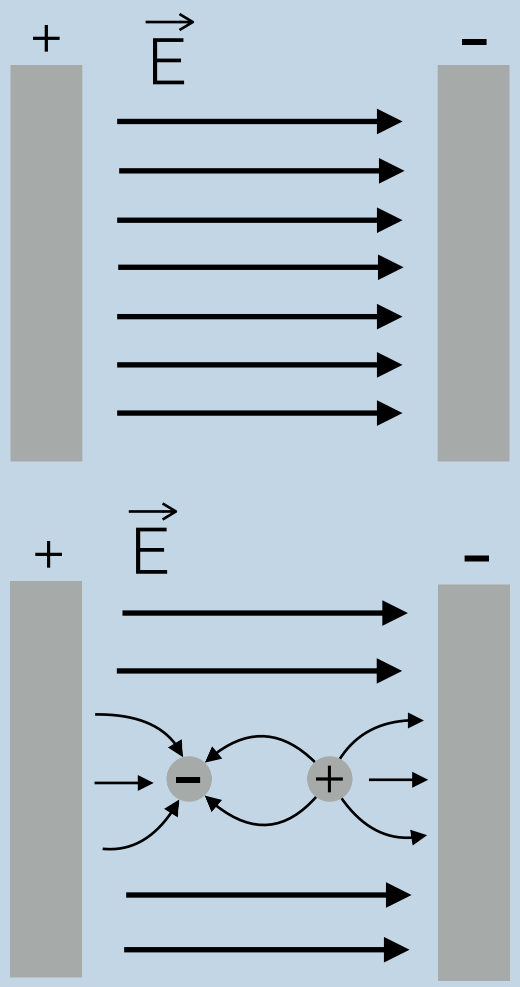

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Schwinger mechanism

→ Gaussian $p_\perp$ spectrum

→ Heavy flavour suppression

constant flavour probability along the string

Prob(u:d:s) ≈ 1 : 1 : 0.2

Prob(q:qq) ≈ 1 : 0.081

Baryon formation: **diquark-antidiquark** pair creation

Lund Symmetric Fragmentation Function

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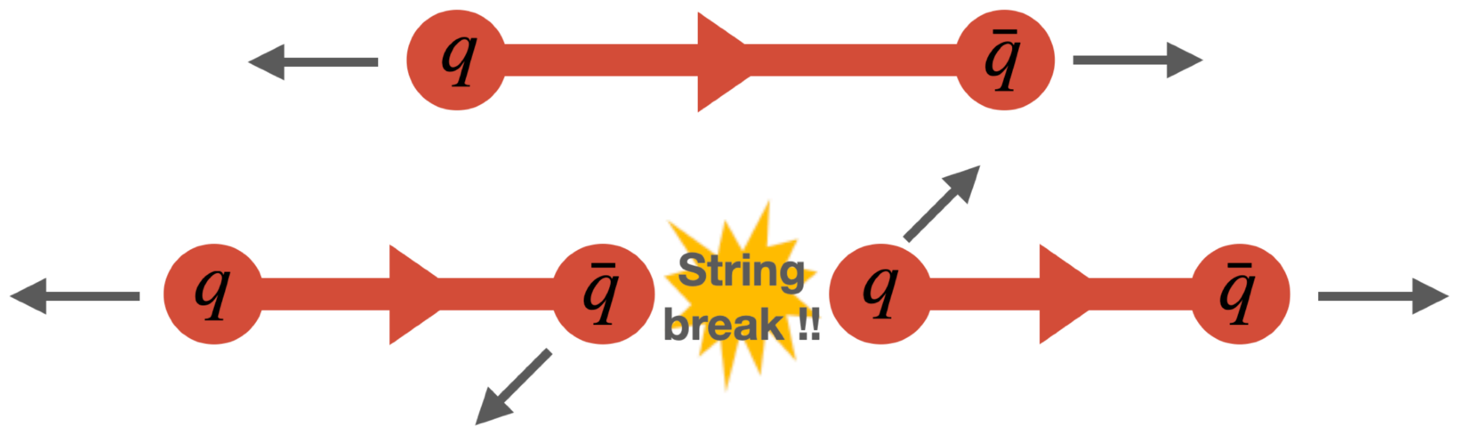

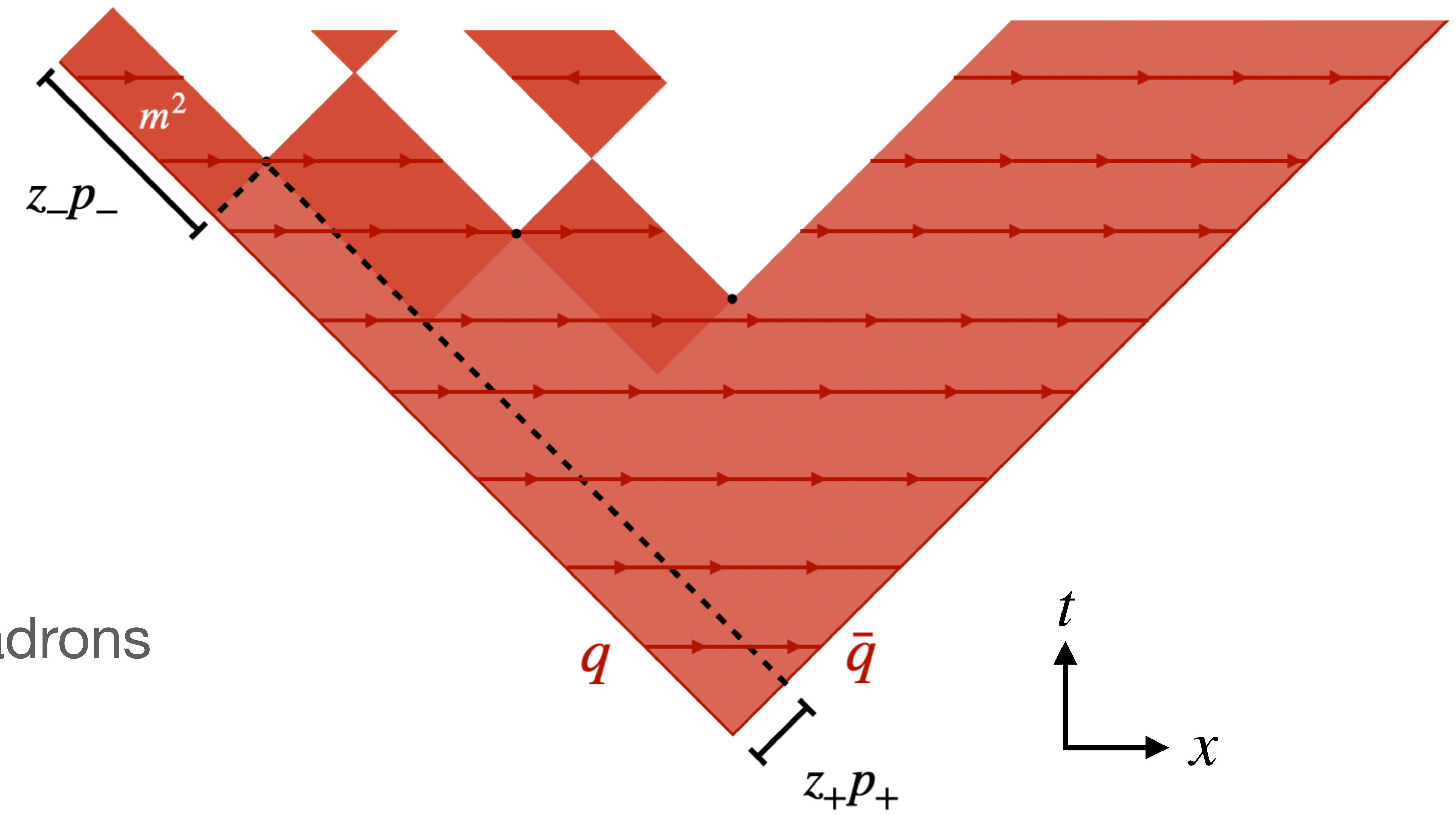

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$$f(z) \propto \frac{1}{z}(1-z)^a \exp\left(\frac{-b(m_h^2 + p_{\perp h}^2)}{z}\right)$$

Free tuneable parameters a and b

Fragment off hadrons from either **string end**

→ easier to obey hadronic mass constraints

Probability distribution for the **fraction of quark momenta, z,** the hadron will take

Lund string model assumptions

Assumptions made by the Lund string model

- String fragmentation in **dense string environment** is treated the same as vacuum string fragmentation

  → closepacking/ropes

- Treatment of **diquarks** as forming directly from Schwinger-type breaks

  → popcorn

- Beyond just colour-anticolour singlet states, what about **red-green-blue singlets**

  → junctions

- **Constant string tension** from motivated from the Cornell potential i.e. potential between **static** colour charges

  → beyond a constant string tension

  - time dependent string tensions
  - excitations on the string

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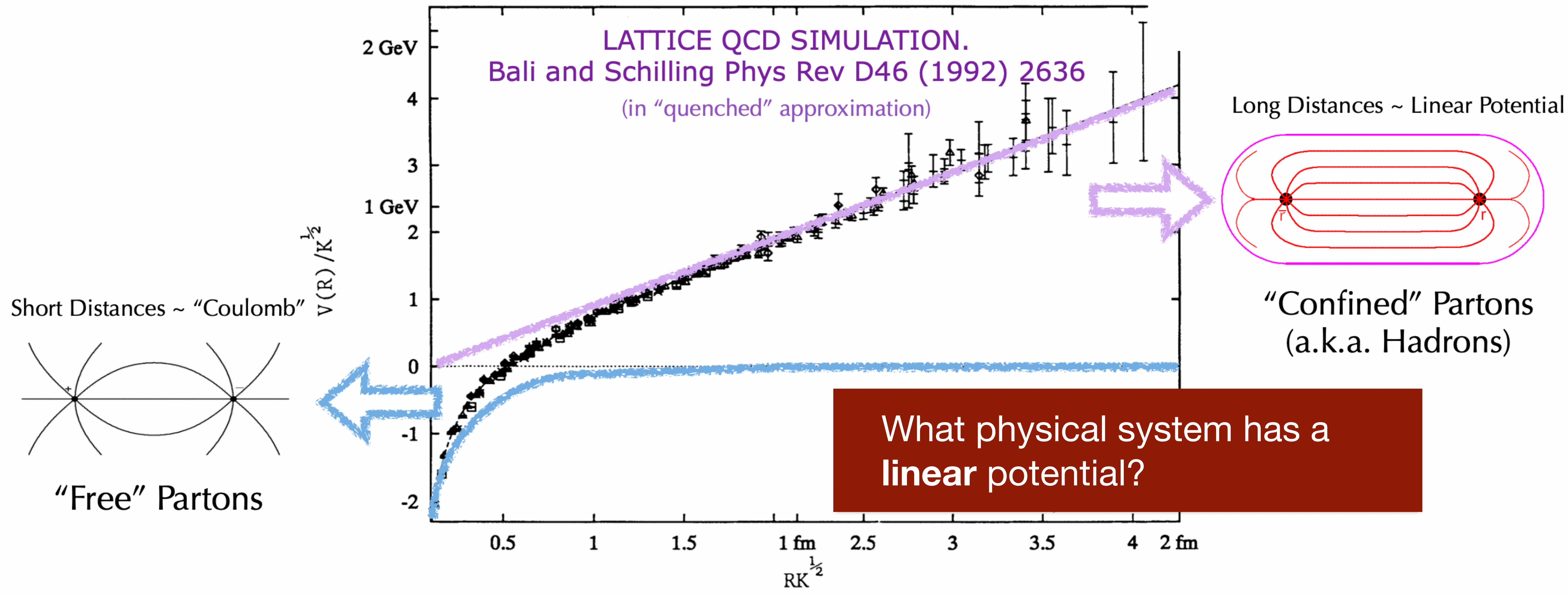

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- ➢ effect on Schwinger mechanism
- ➢ fragmentation procedure
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Schwinger Mechanism

Schwinger mechanism:

→ Gaussian **suppression of masses**

Parameterise flavour probabilities in Pythia as ratios e.g. $P_{s:u/d}$, $P_{qq:q}$, etc.

Here κ_0 is the constant string tension

$$P_{s:u/d} = \frac{P(m_s^2)}{P(m_{u/d}^2)} = \frac{\exp\left(\frac{-\pi m_s^2}{\kappa_0}\right)}{\exp\left(\frac{-\pi m_{u/d}^2}{\kappa_0}\right)} = \exp\left(\frac{-\pi\,(m_s^2 - m_{u/d}^2)}{\kappa_0}\right)$$

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which can be a function of coordinates on the string, or the surrounding environment, etc.

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Fragmentation procedure

How can we put a **non-constant tension,** κ_{eff} , on the string? e.g. $\kappa(\tau)$ or $\kappa(y)$

Standard fragmentation procedure

1) Select **flavour and** $p_\perp$
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→ need $m_\perp$ to sample $f(z, m^2_\perp)$, **BUT κ_{eff} is needed to calculate $m_\perp$**

Stuck in a loop !!!

Modified fragmentation procedure

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Solution: overestimate $m_\perp$ **distribution** and **accept/reject** string breaks to correct overestimation

Overestimate

$$\mathscr{P}_s(\kappa_{eff}) = P_{acc}(\kappa_{eff})\,\mathscr{P}_s(\kappa_{max})$$

Probability we need to reproduce

$$\mathscr{P}_s(\kappa_{eff}) = \frac{P_{s:u/d}(\kappa_{eff})}{2 + P_{s:u/d}(\kappa_{eff})}$$

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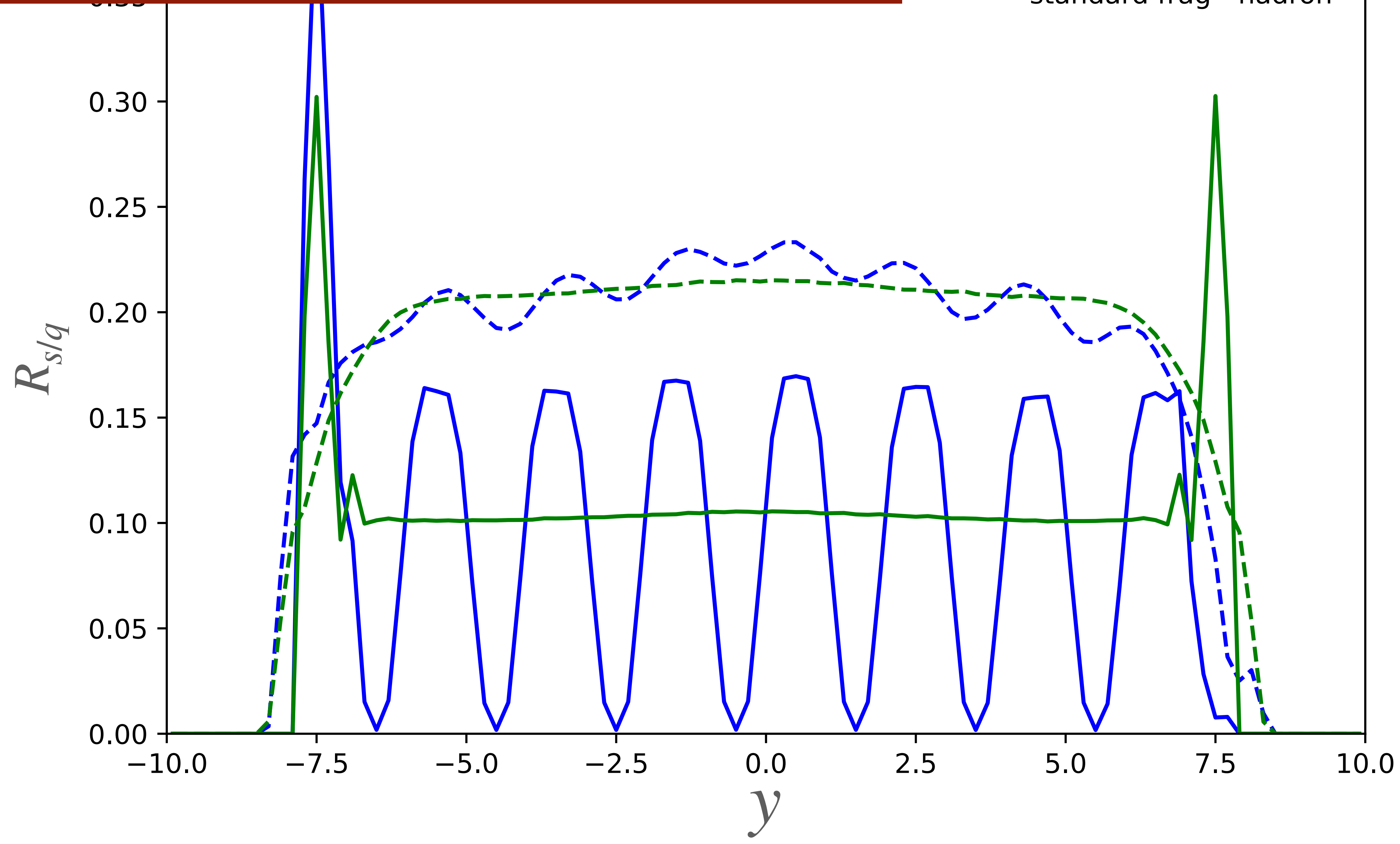
Proof of concept:

e.g. $\kappa(y) = (1 + \sin(\pi y))\kappa_0$



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Modified flavour selection

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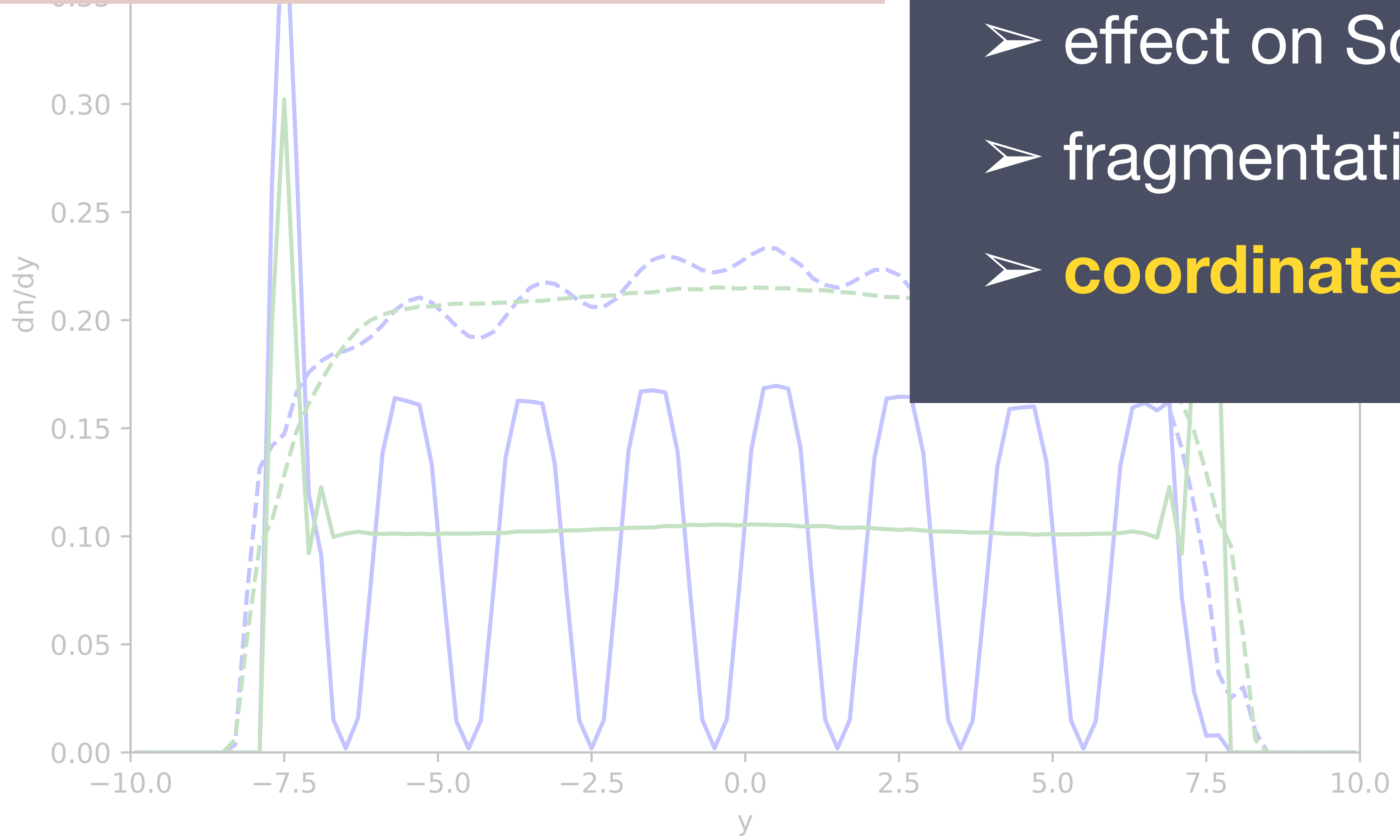

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➢ **coordinates along a string**

varying tension

eak **flavour with overestimate**

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What about space-time coordinates for e.g. $\kappa(\tau)$?

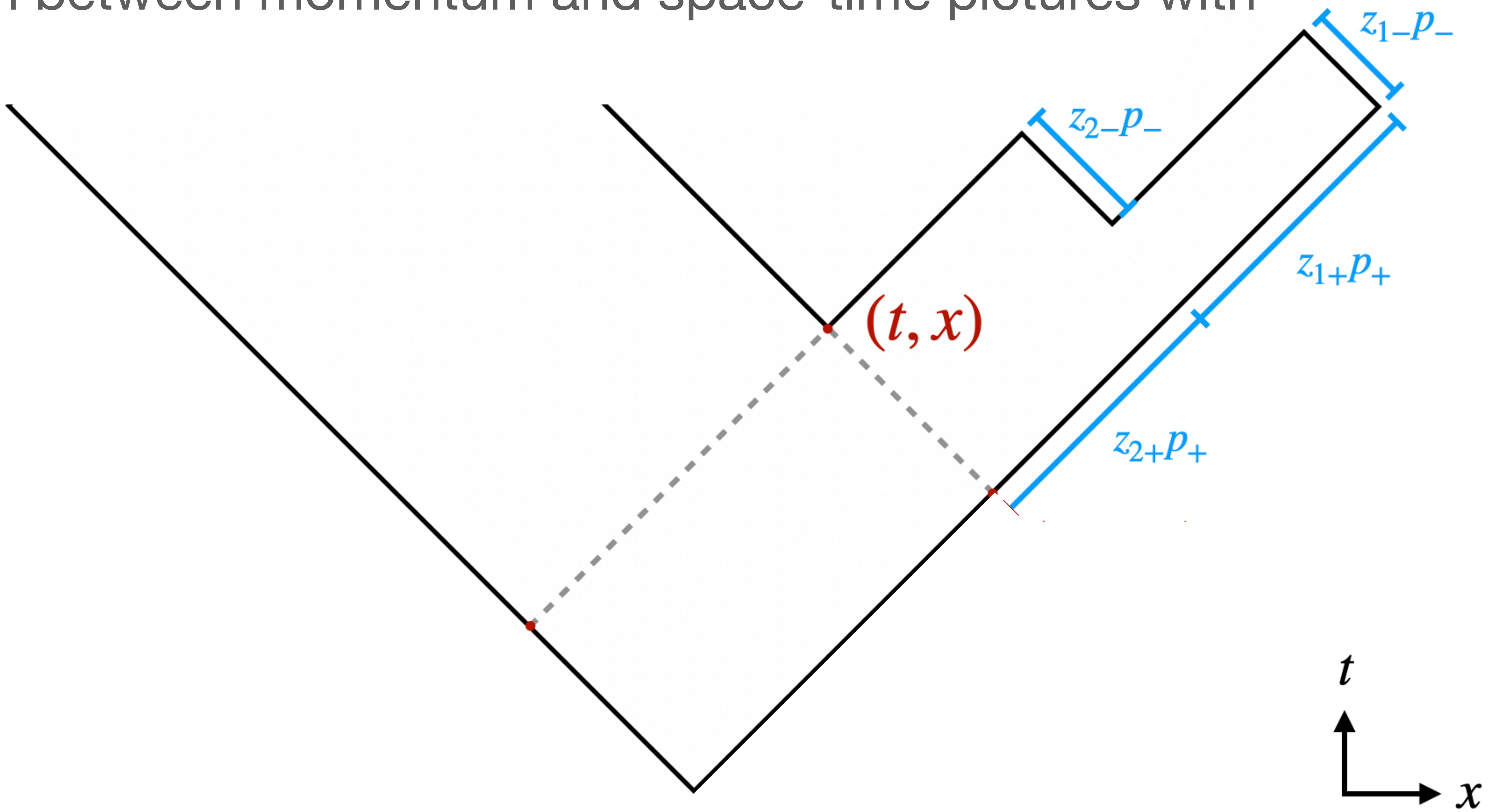
$P_{acc}(\kappa_{eff}) = \frac{\quad}{\mathscr{P}_s(\kappa_{max})}$

{t, x} coordinate calculation

Fragmentation procedure is a fully **momentum-space** picture

Constant string tension — conversion between momentum and space-time pictures with **factors of** κ, e.g. $\Gamma = \kappa_0^2\tau^2$

What if we have a $\kappa(\tau)$?



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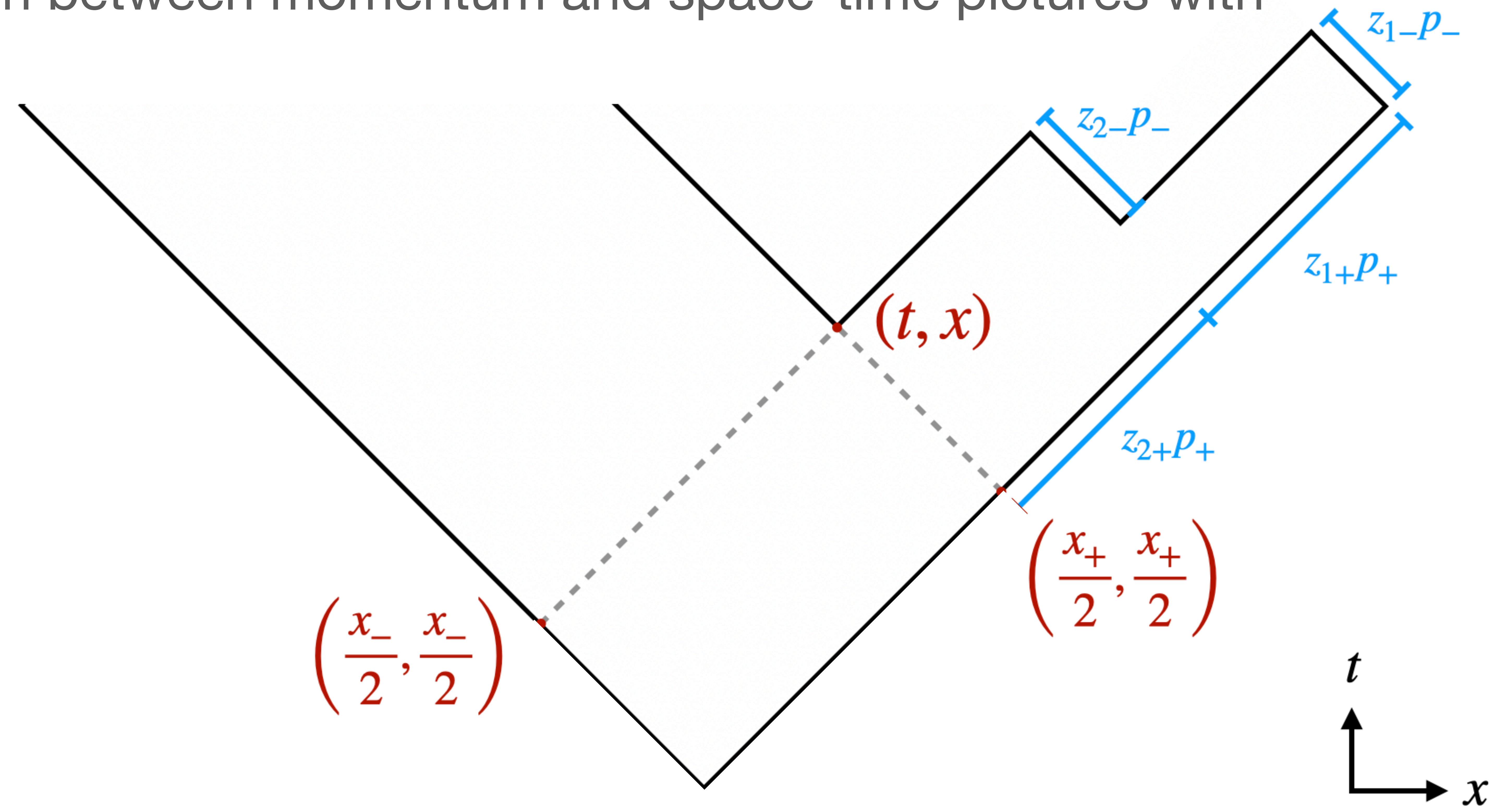

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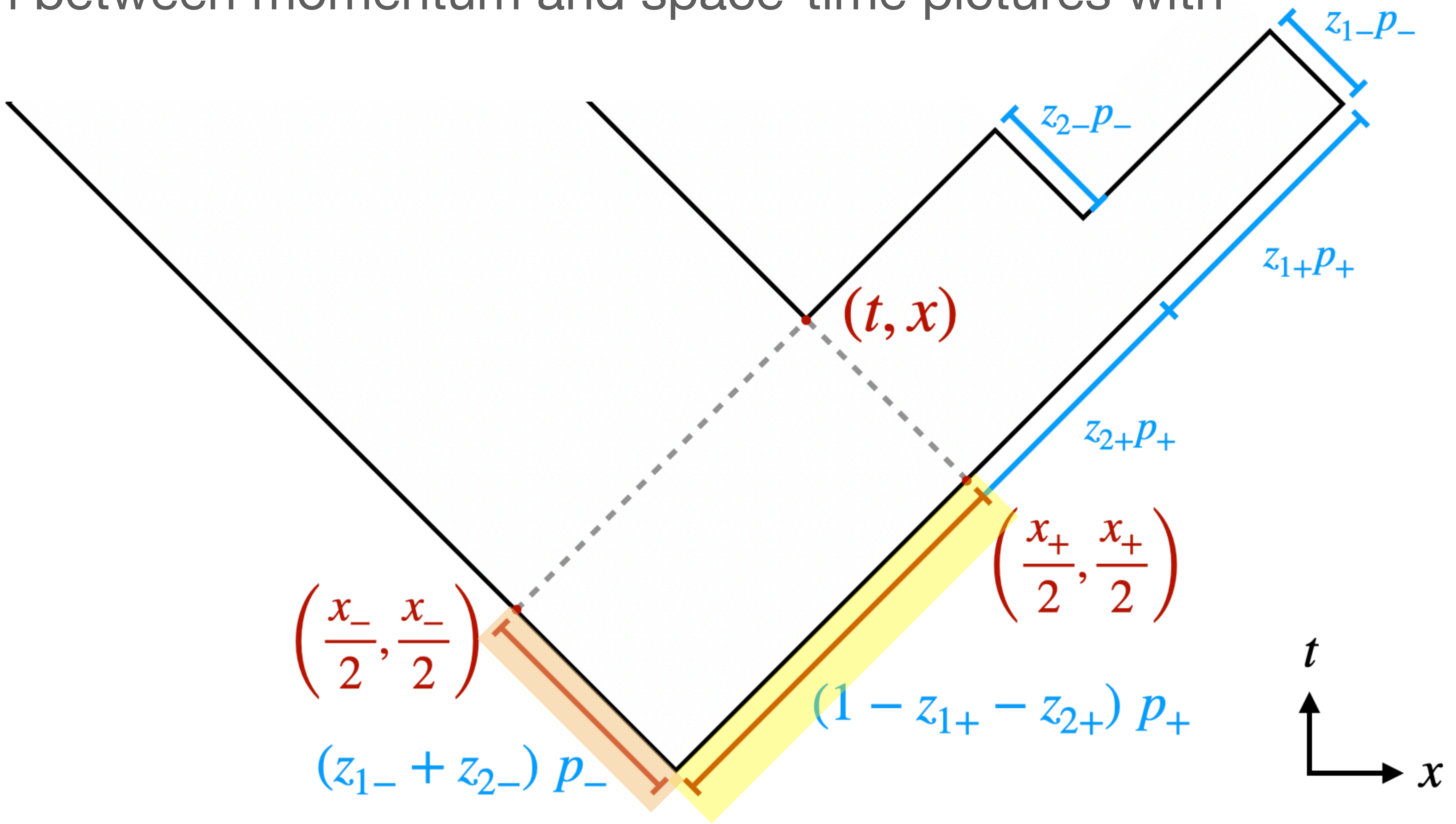

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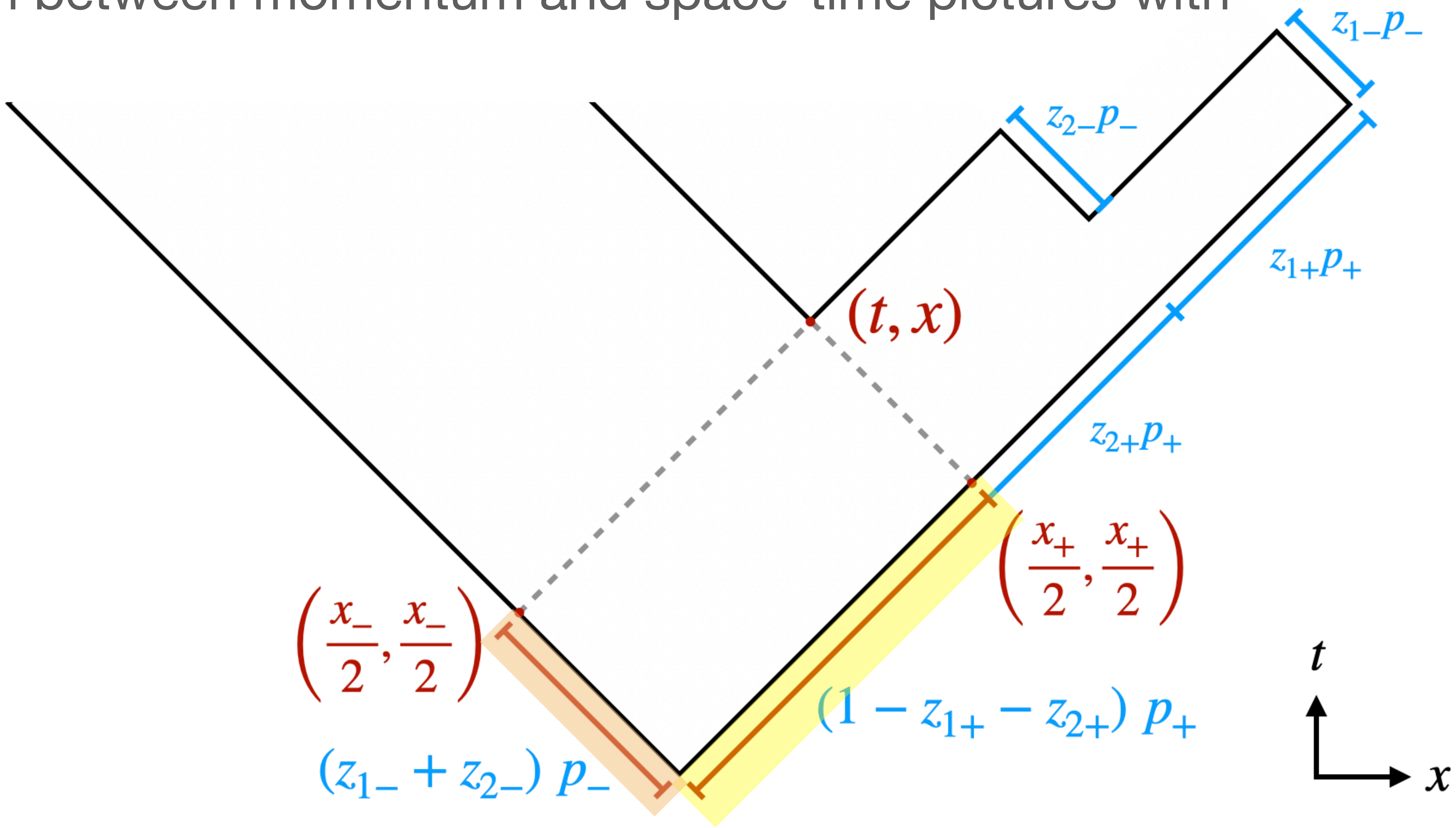

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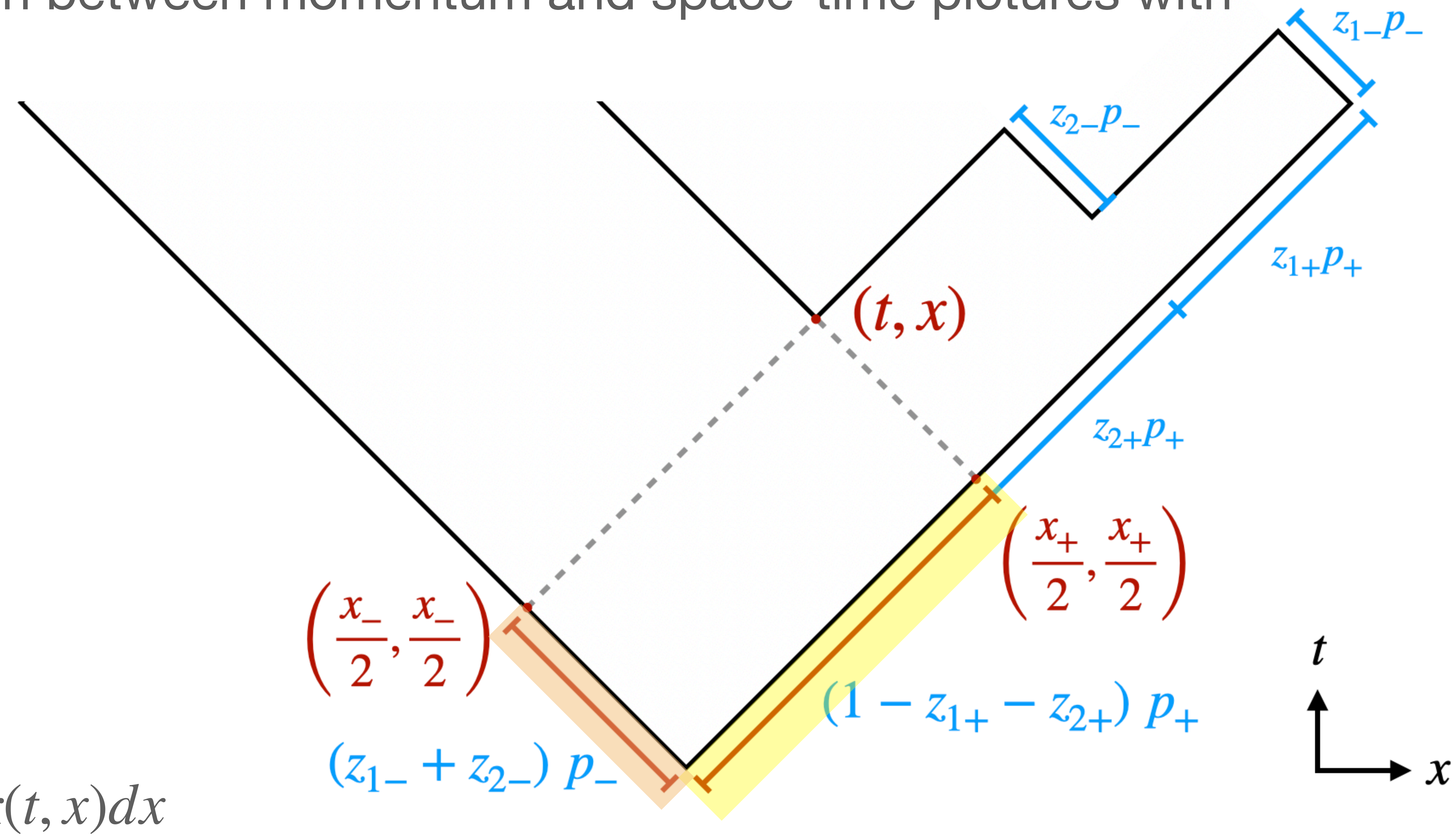
$$(\sum_{i=1}^{n} z_{i-}) p_- = -2 \int_0^{x_{n-}/2} \frac{dp}{dt} dt$$

$$\frac{dE_q}{dt} = \frac{dp_q}{dt} = -\frac{1}{2}\frac{dV(t)}{dt} = -\frac{1}{2}\frac{d}{dt}\int_{-t}^{t} \kappa(t,x) dx$$



Work in progress: generalisation to gluon kinks

{t, x} coordinate calculation

Fragmentation procedure is a fully **momentum-space** picture

Constant string tension — conversion between momentum and space-time pictures with **factors of** κ, e.g. $\Gamma = \kappa_0^2 \tau^2$

What if we have a $\kappa(\tau)$?

$$(1 - \sum_{i=1}^{n} z_{i+})p_+ = -2\int_0^{x_{n+}/2}$$

$$(\sum_{i=1}^{n} z_{i-})p_- = -2\int_0^{x_{n-}/2}$$

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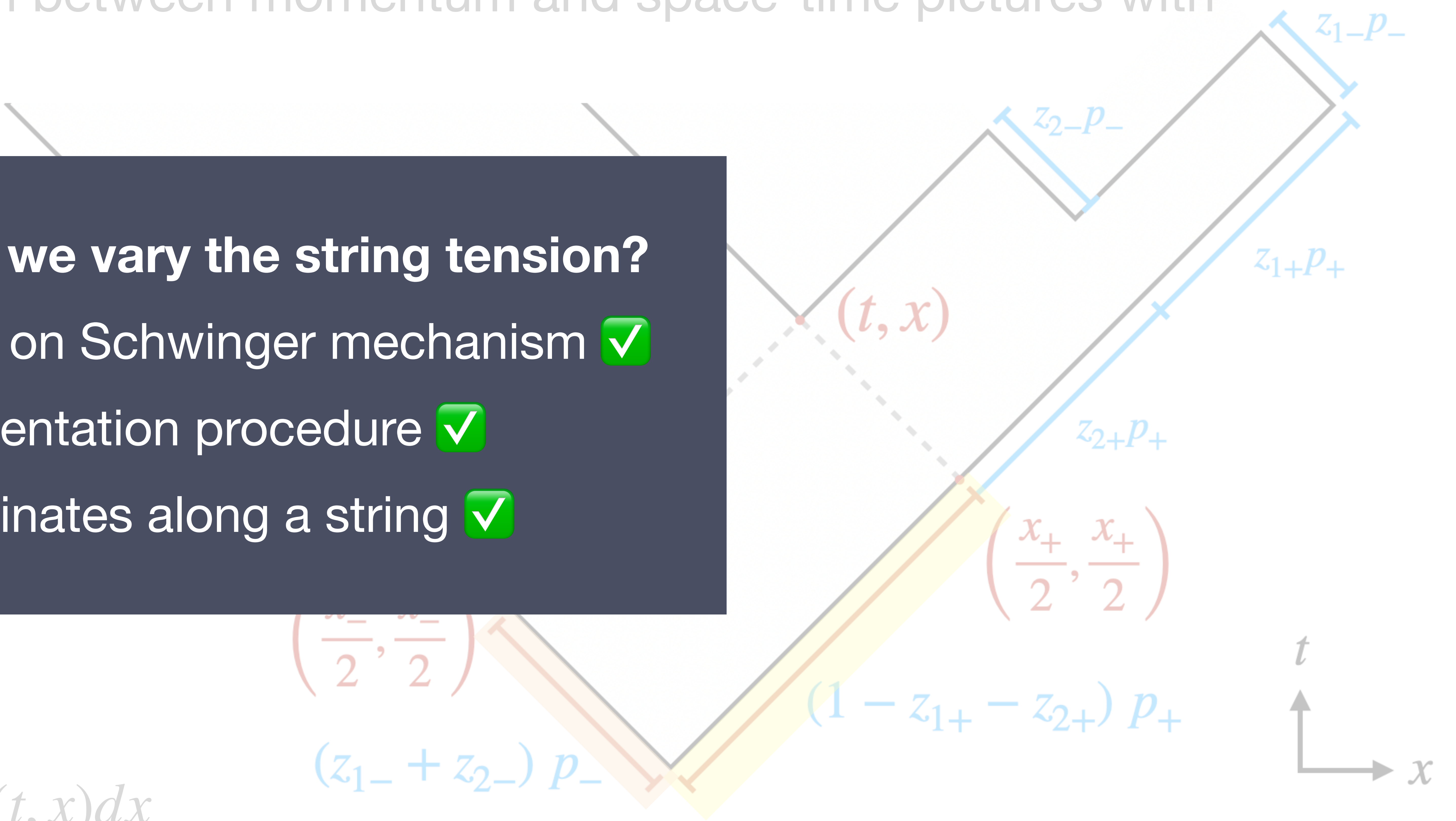


How do we vary the string tension?

- ➢ effect on Schwinger mechanism ✅
- ➢ fragmentation procedure ✅
- ➢ coordinates along a string ✅

Work in progress: generalisation to gluon kinks

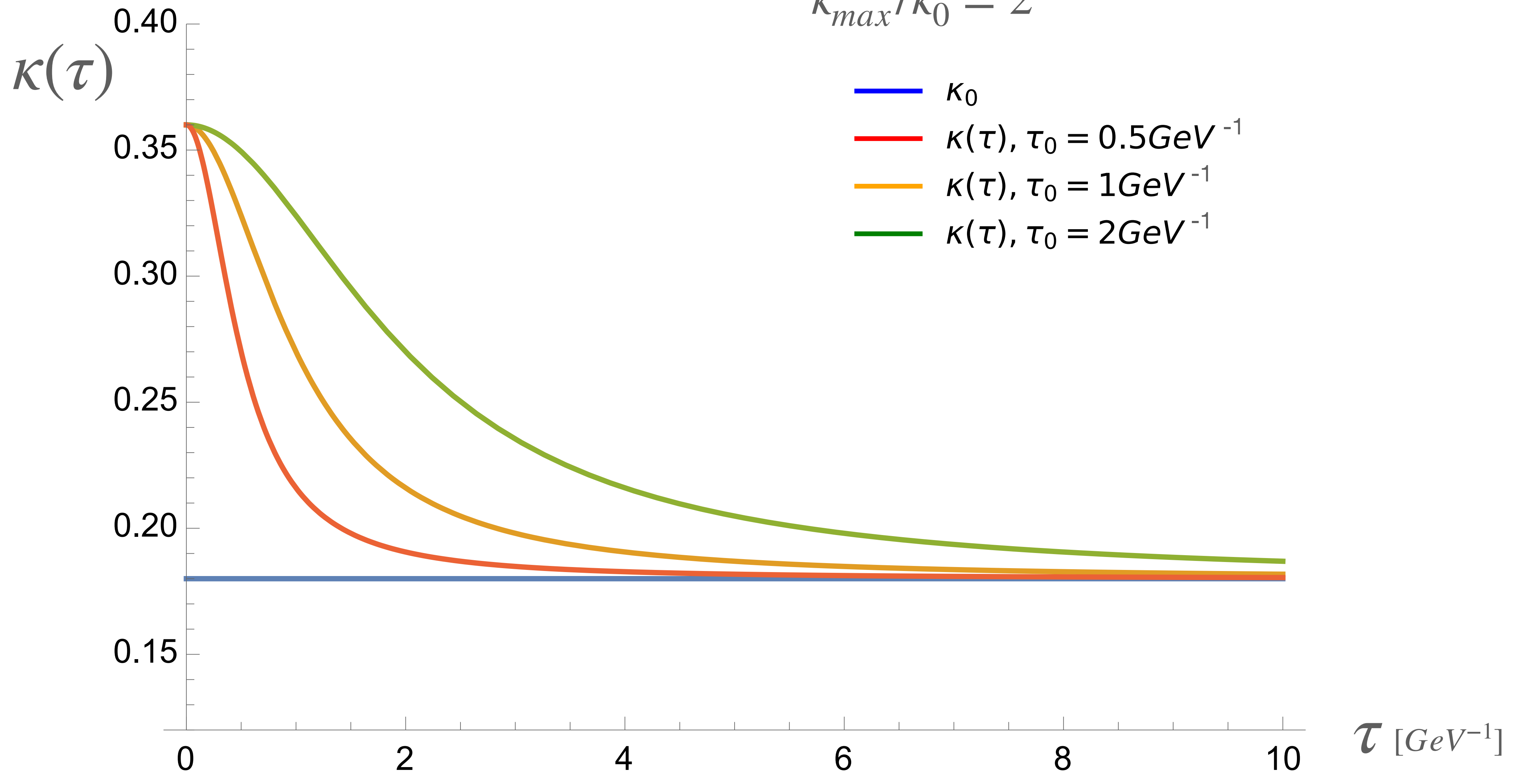
Tau-dependent example

e.g. higher tensions at early times

$$\kappa(\tau) = \kappa_0 \left(1 + \frac{\left(\frac{\kappa_{max}}{\kappa_0} - 1\right)}{1 + \frac{\tau^2}{\tau_0^2}} \right)$$

$$\tau^2 = t^2 - x^2$$

$$\kappa_{max}/\kappa_0 = 2$$



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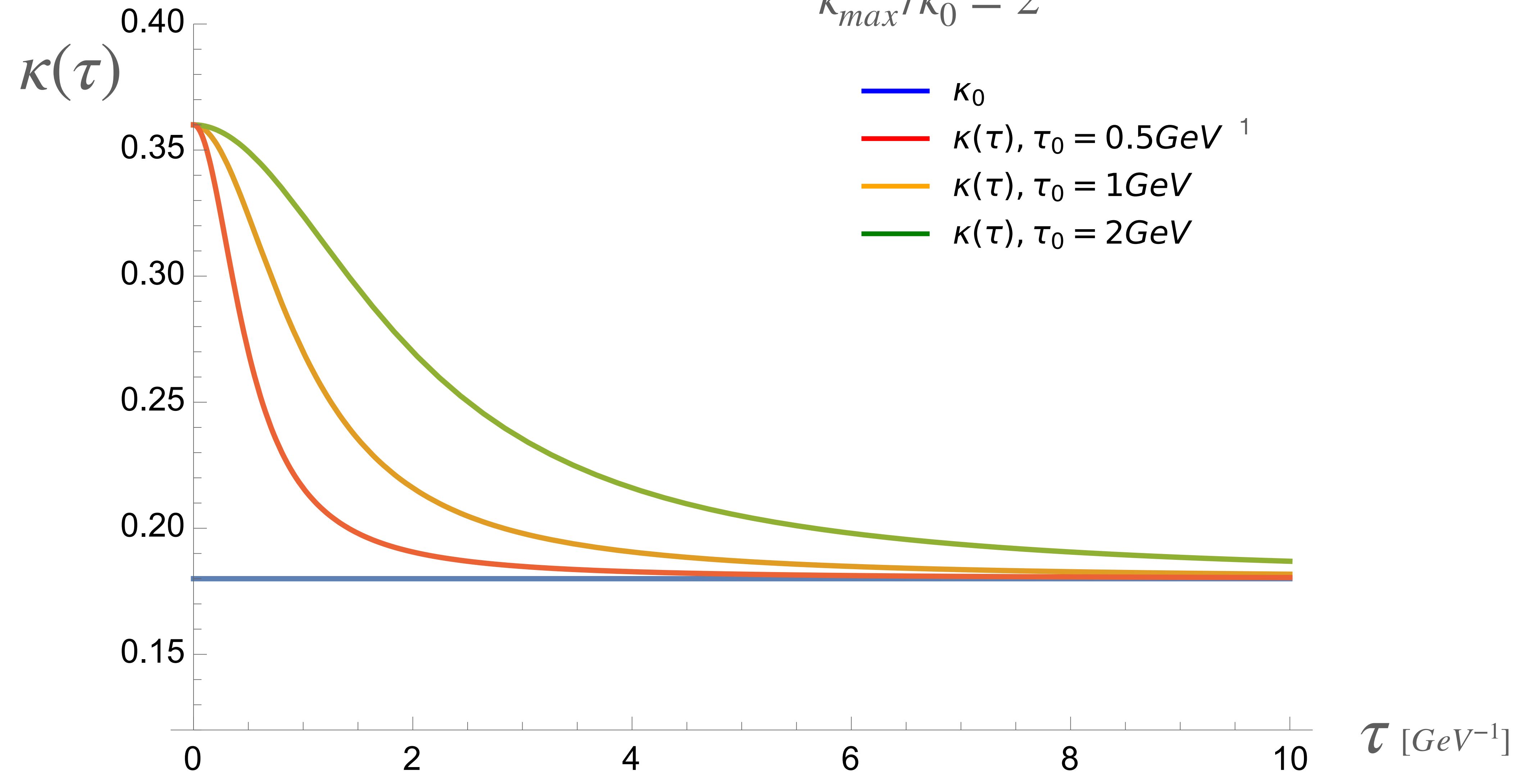
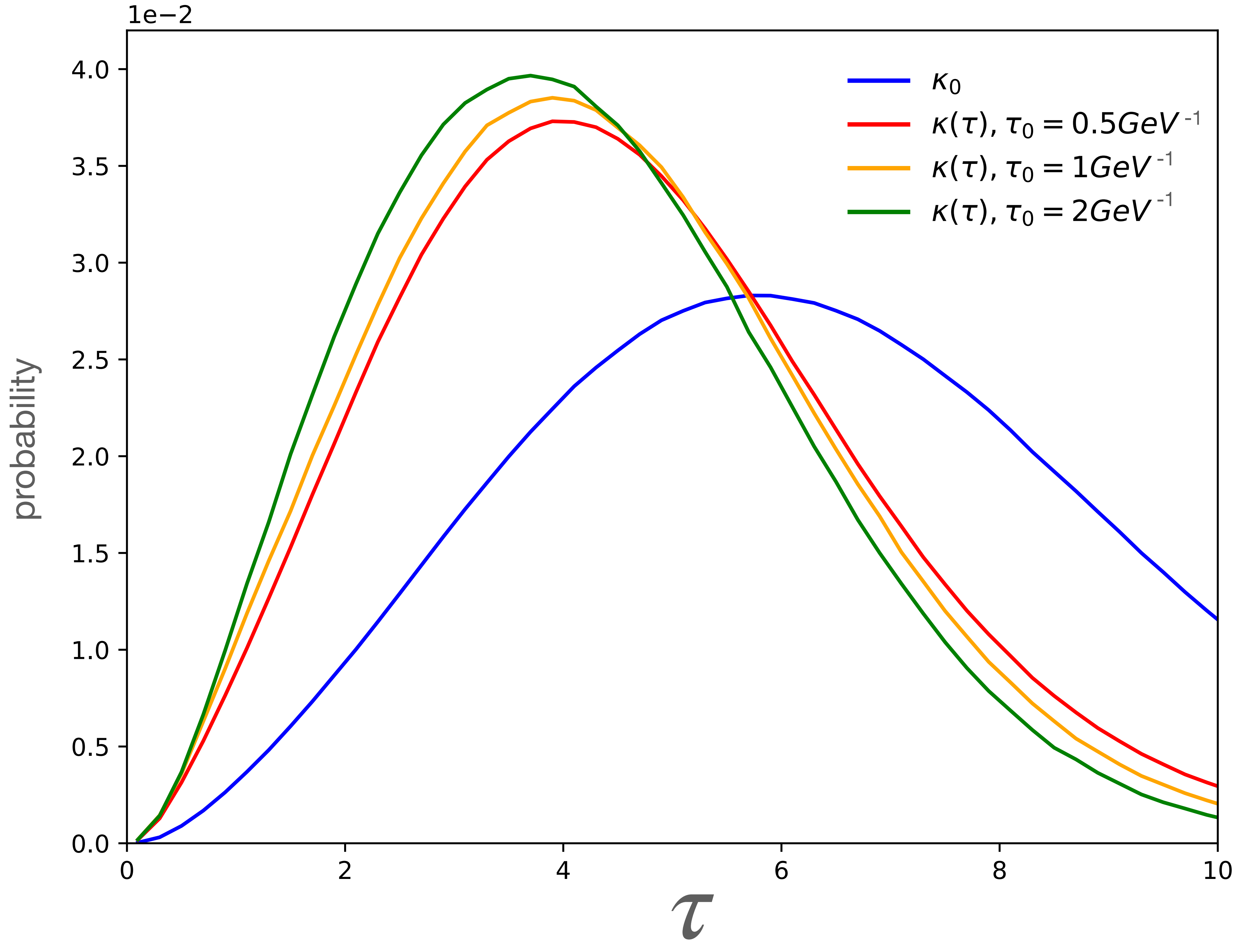


Expected consequences of an increased string tension

➢ **earlier** string breaks



Massless up quark endpoints on a $q\bar{q}$ string with 1000 GeV

Tau-dependent example

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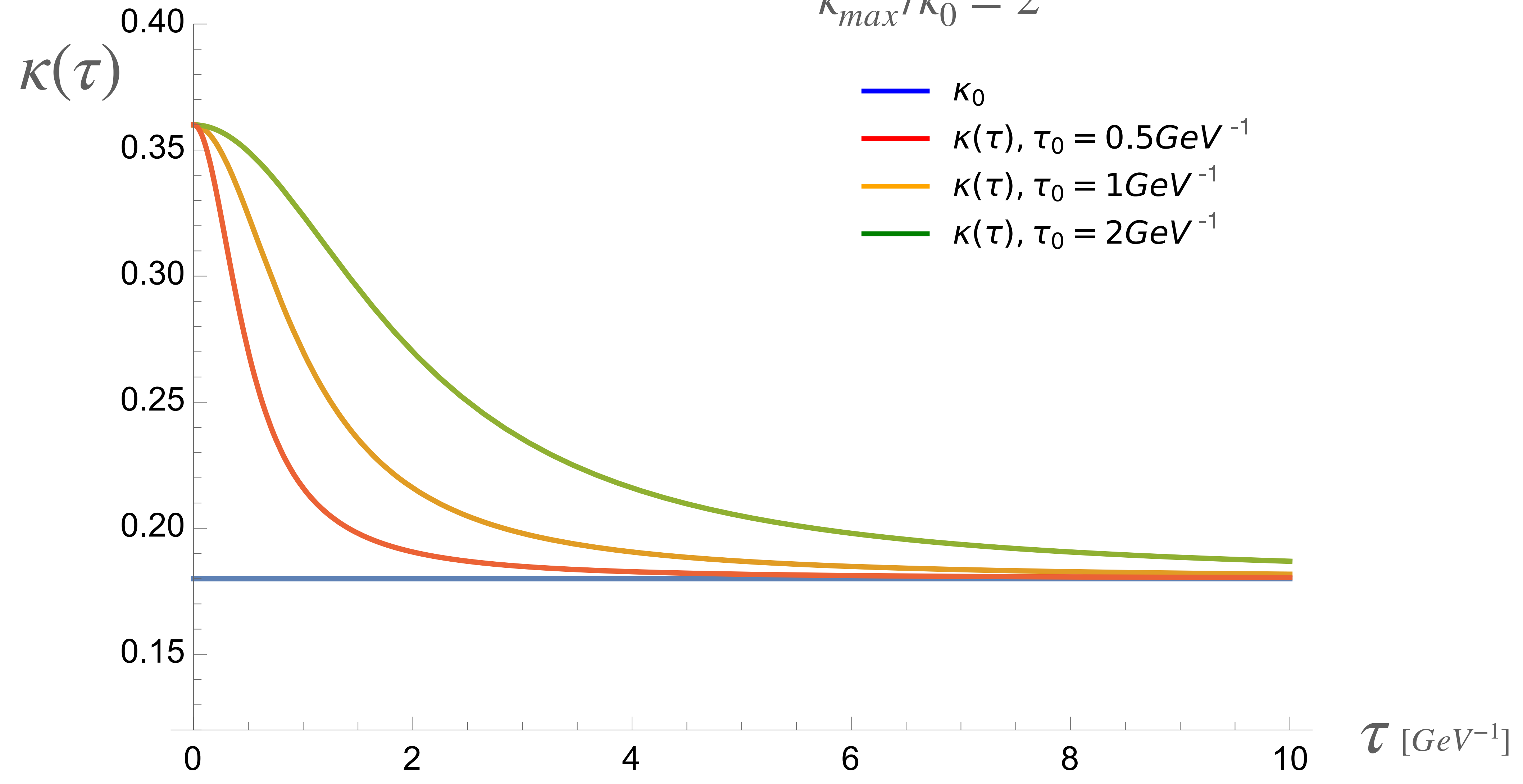
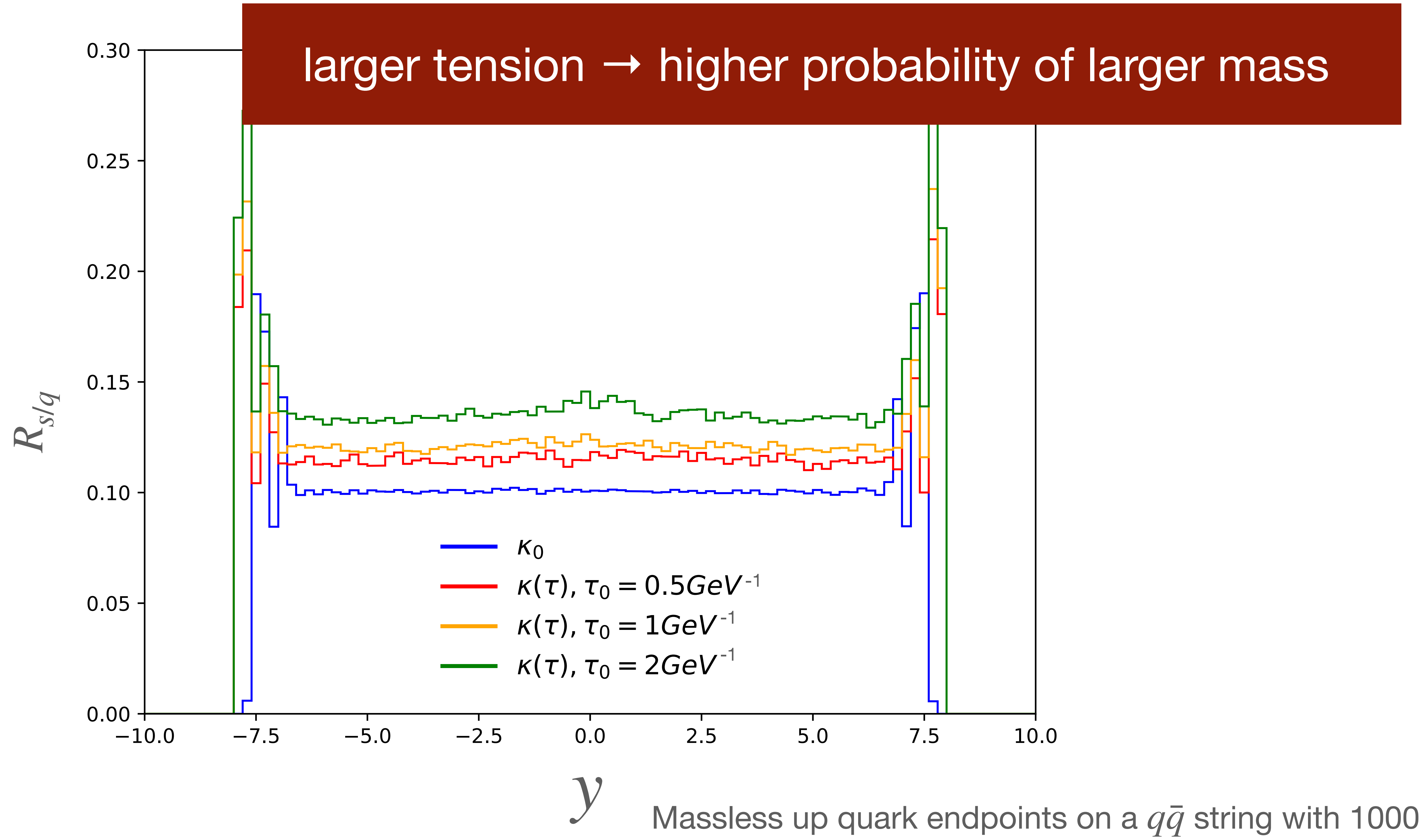


Expected consequences of an increased string tension

- ➢ **earlier** string breaks
- ➢ higher **strange** / diquark probabilities



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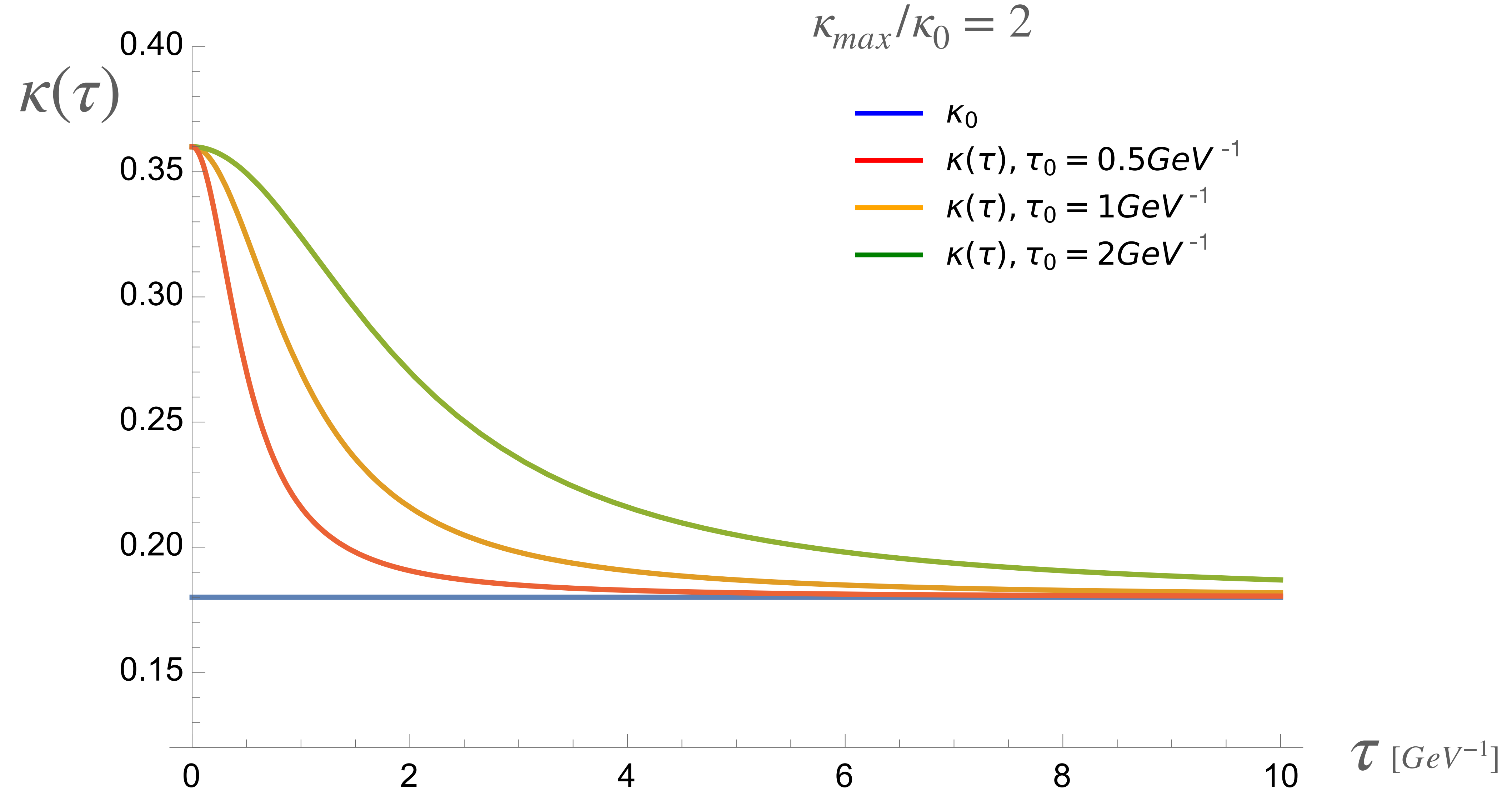
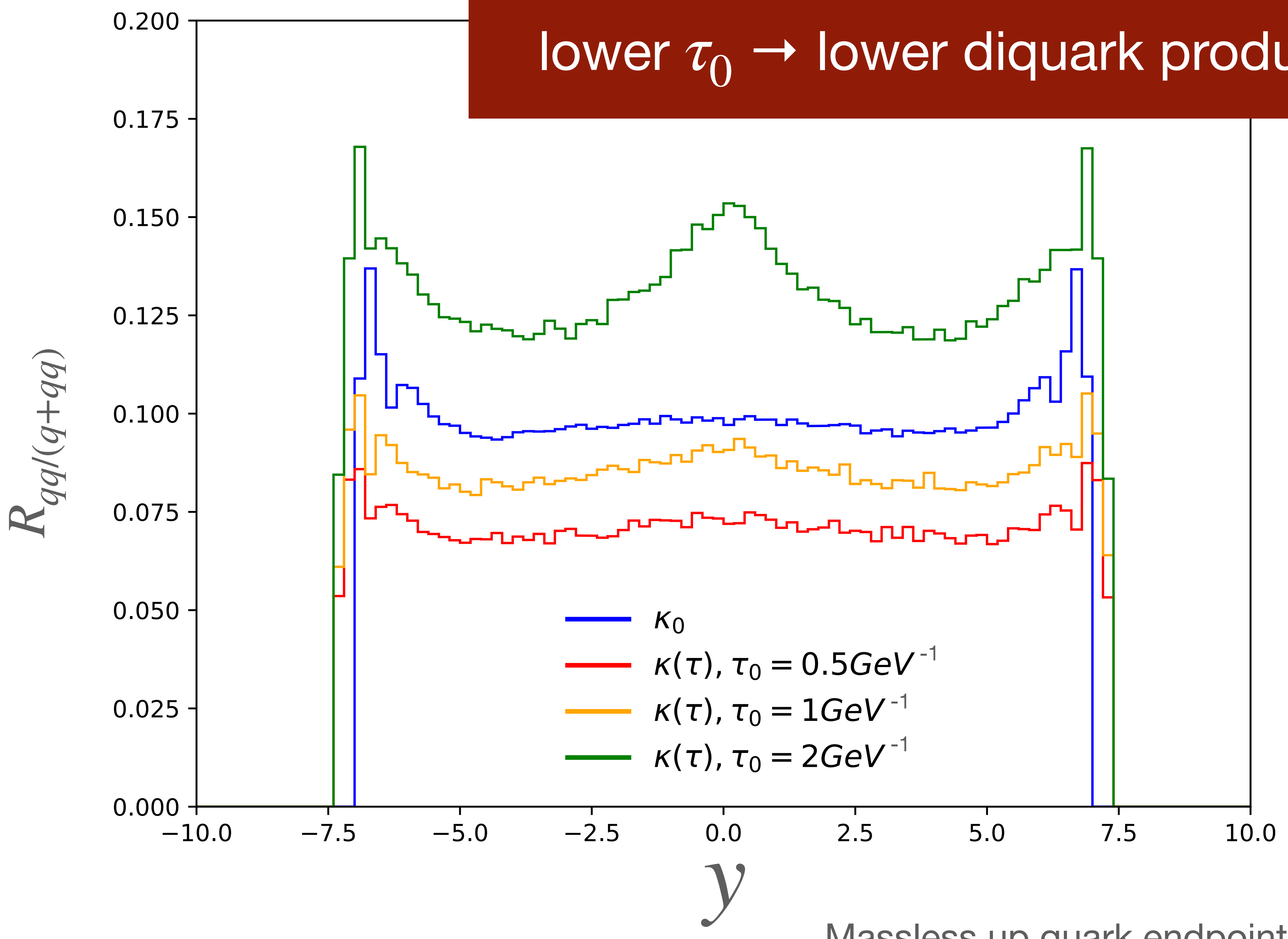


Expected consequences of an increased string tension

- ➢ **earlier** string breaks
- ➢ higher **strange** / **diquark** probabilities

lower τ_0 → lower diquark production ratios?



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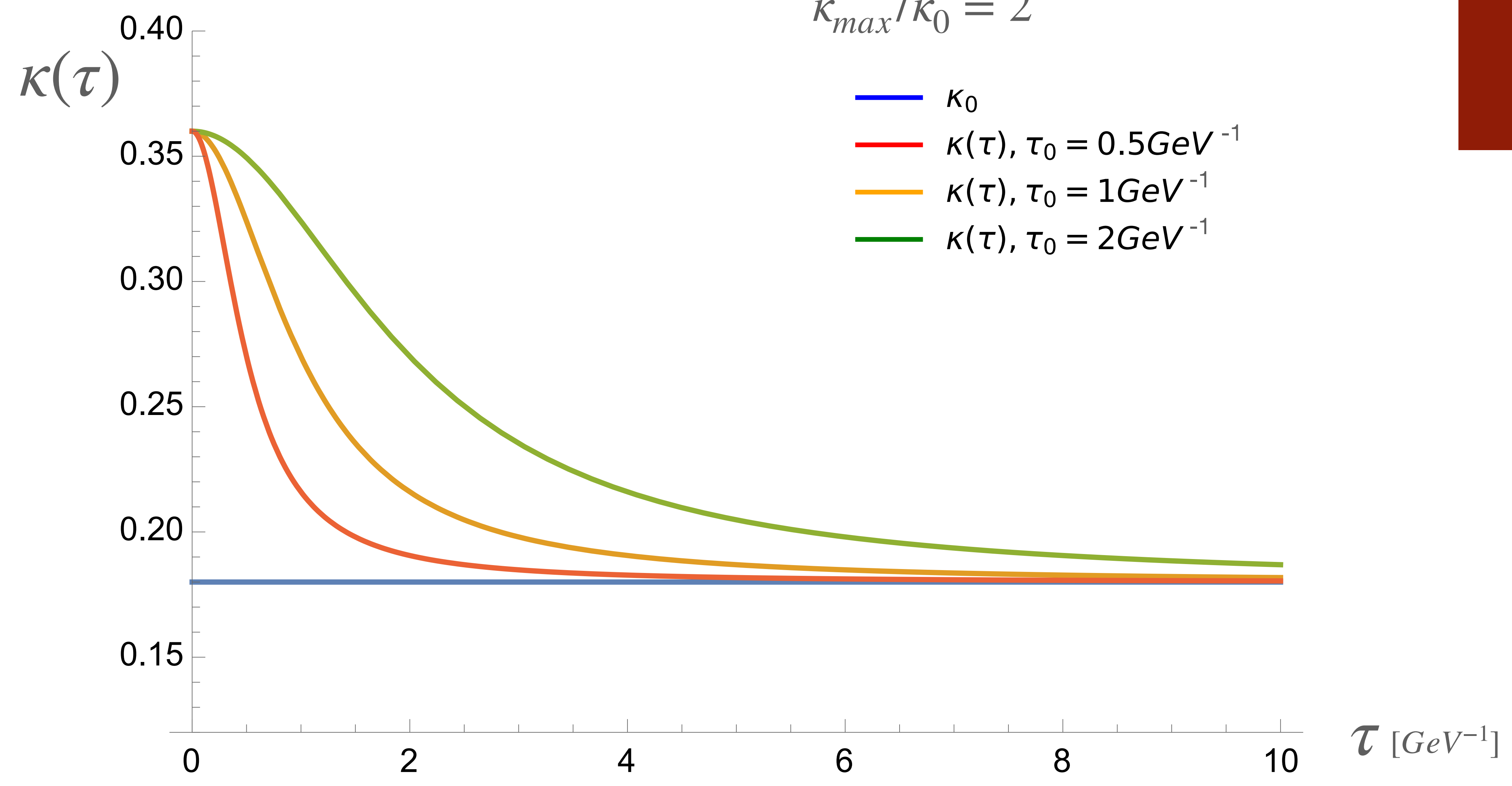


Expected consequences of an increased string tension

➢ **earlier** string breaks

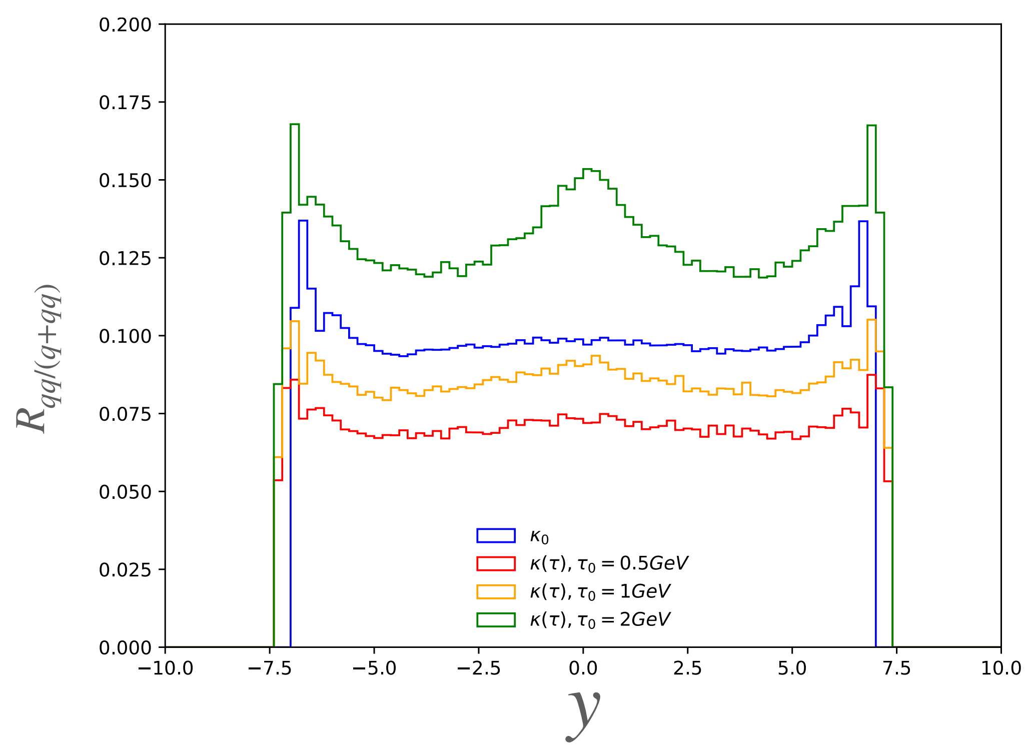
➢ higher **strange** / **diquark** probabilities

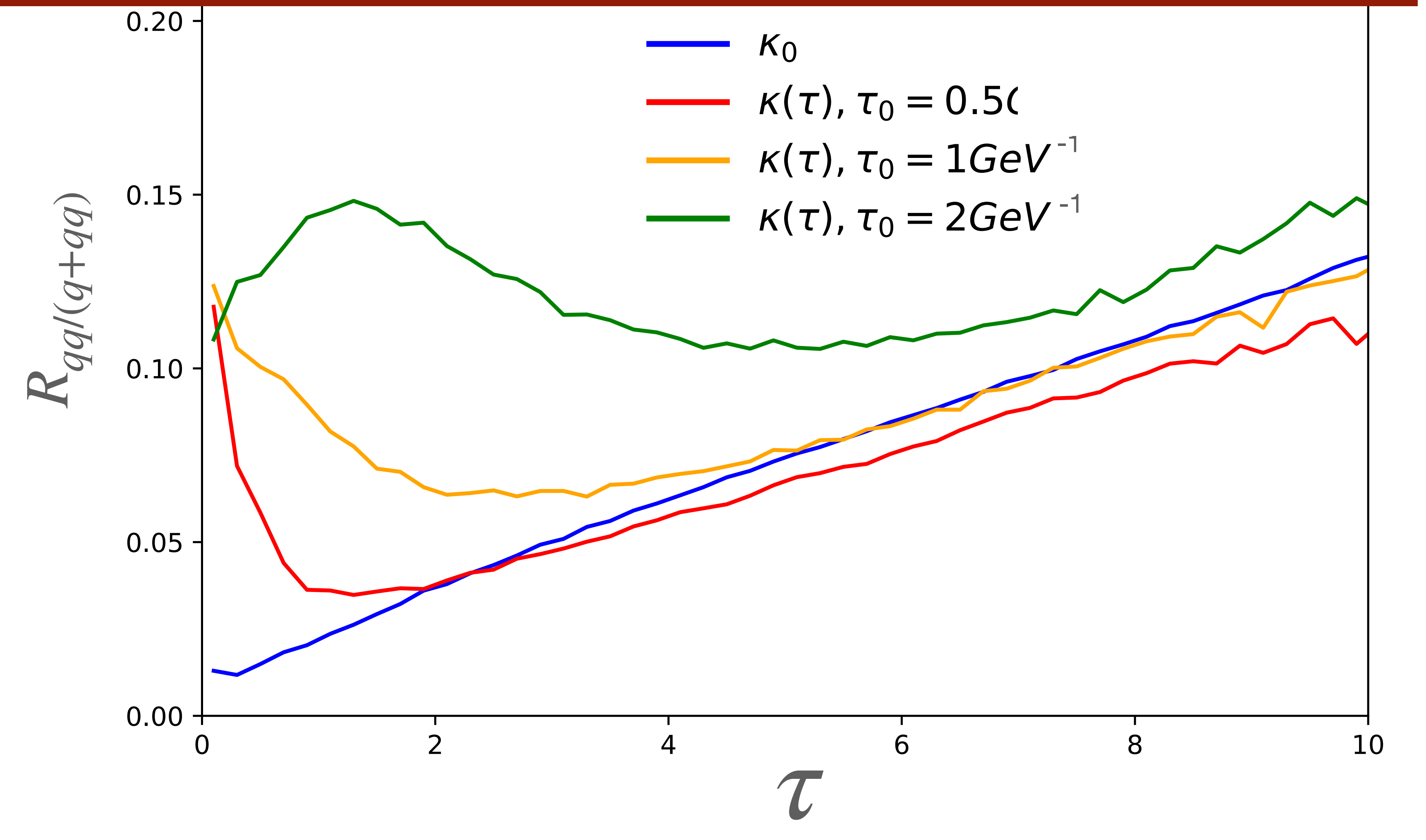
diquark mass → phase space constraints lead to typically larger z_+ and z_- values

→ later invariant times

BUT

larger tension → earlier string breaks → less diquark production overall





Beyond Lund Strings

Lund string model assumes **classical string dynamics** — using only first term of the Nambu-Goto action

Work from our Oxford collaborators:

Excitations on an expanding string by considering further terms in the action, i.e. **Nambu-Goldstone** degrees of freedom

$$S_{NG} = \int dt \int_{L_-(t)}^{L_+(t)} dx \left[-\kappa + \frac{1}{2}\partial_t X^i \partial_t X^i - \frac{1}{2}\partial_x X^i \partial_x X^i + \mathcal{O}\left(\frac{(\partial X)^4}{\kappa} \right) \right]$$

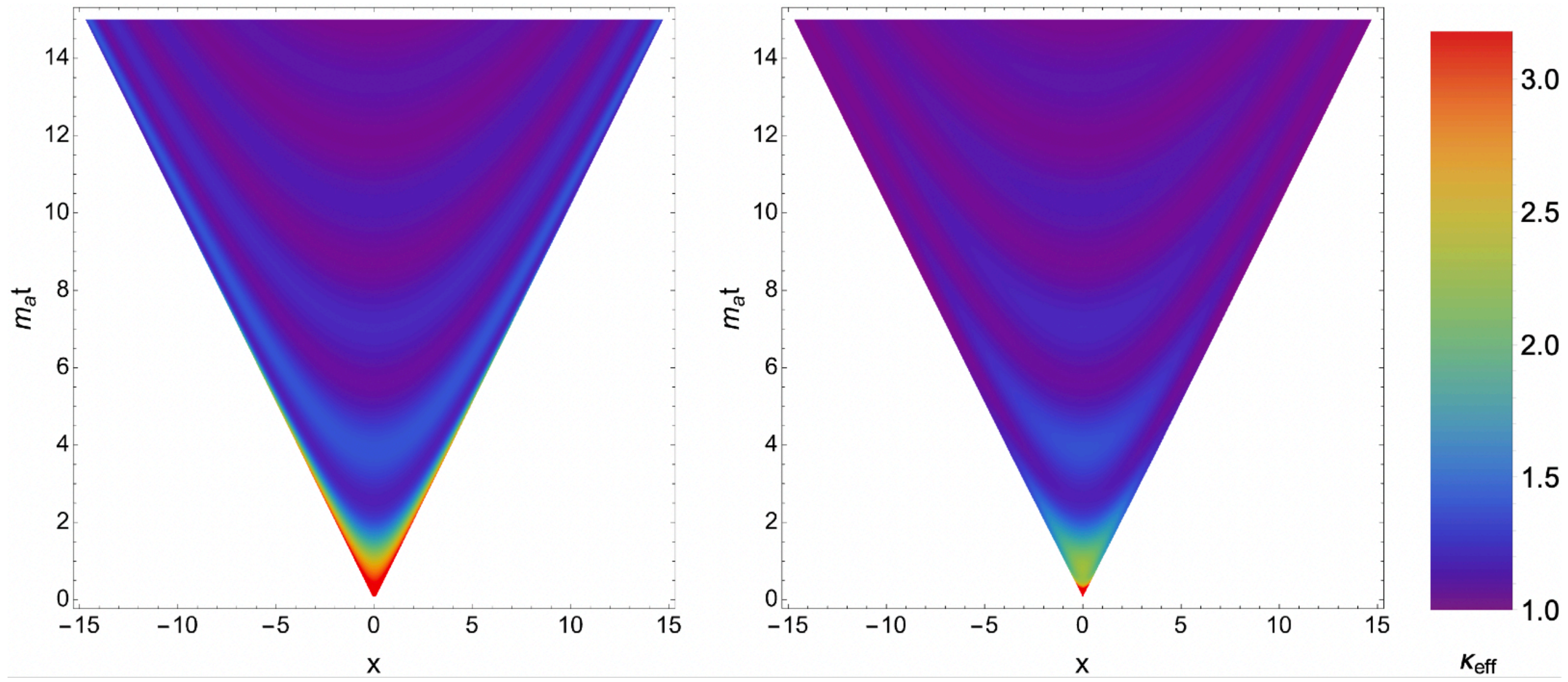
$x \in [L_-(t), L_+(t)]$

X^i are massless Nambu-Goldstone degrees of freedom

Axions

Lattice data strongly suggests that the lightest massive mode that exists on the worldsheet of a long static QCD string is the so-called ``worldsheet axion", a pseudoscalar particle of mass $m_a \approx 1.85\sqrt{\kappa}$

$$S_{eff} = \int dt d\sigma \sqrt{-\det(h)} \left(-\kappa + \frac{1}{2} h^{\alpha\beta} \partial_\alpha a \partial_\beta a - \frac{1}{2} m_a^2 a^2 \right) + S_q + S_a$$



(left) Neumann and (right) Dirichlet boundary conditions

Beyond Lund Strings

Lund string model assumes **classical string dynamics** — using only first term of the Nambu-Goto action

Work from our Oxford collaborators:

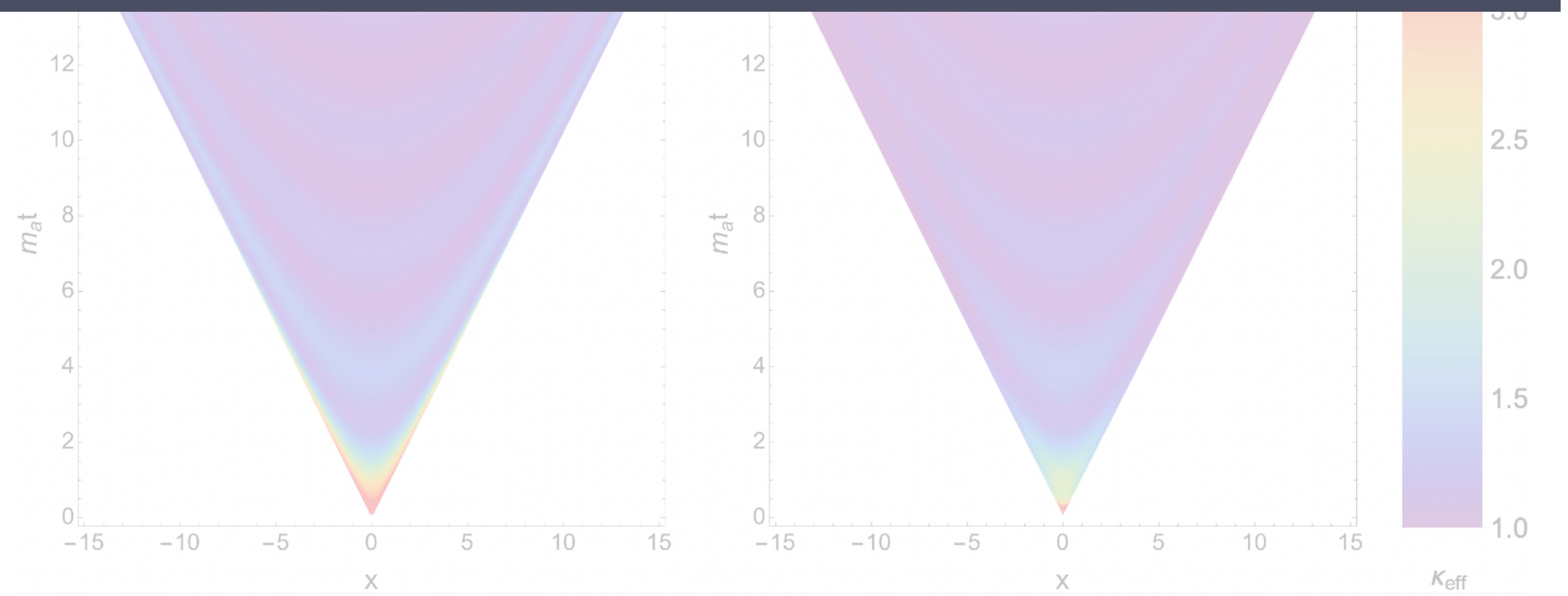
Excitations on an expanding string by considering further terms in the action, i.e. **Nambu-Goldstone** degrees of freedom

- ➢ Study effects on string tensions for **lowest lying NGB/axion modes**
- ➢ Look at **strange/diquark** production rates, **particle correlations**, etc. for string excitations and τ-dependent string tensions
- ➢ Study observables for e^+e^- **collision data**

Axions

Lattice data strongly suggests that the lightest massive mode that exists on the worldsheet of a long static QCD string is the so-called ``worldsheet axion", a pseudoscalar particle of mass $m_a \approx 1.85\sqrt{\kappa}$

$$S_{eff} = \int dt d\sigma \sqrt{-\det(h)} \left(-\kappa + \frac{1}{2} h^{\alpha\beta} \partial_\alpha a \partial_\beta a - \frac{1}{2} m_a^2 a^2 \right) + S_q + S_a$$



(left) Neumann and (right) Dirichlet boundary conditions

Future studies

Projects planned for my PhD

Sunshine

- Validation tests — 2→3 and power showers working, but interplay between 2→4 and 2→3 is yet to work

Closepacking tuning

- Theory side complete, awaiting tuning which has been delayed due to bug in fragmentation code in PYTHIA, but procedure is outlined and tested

Beyond Lund Strings

- Implementation of string excitations according to Nambu-Goldstone and axion modes

Future work / Aspirational projects

Colour reconnections

- New method to better describe colour algebra → better model for junction formation

Modified string tensions

- Extensions to gluon kinks on the string — for both tau-dependent tensions and string excitations

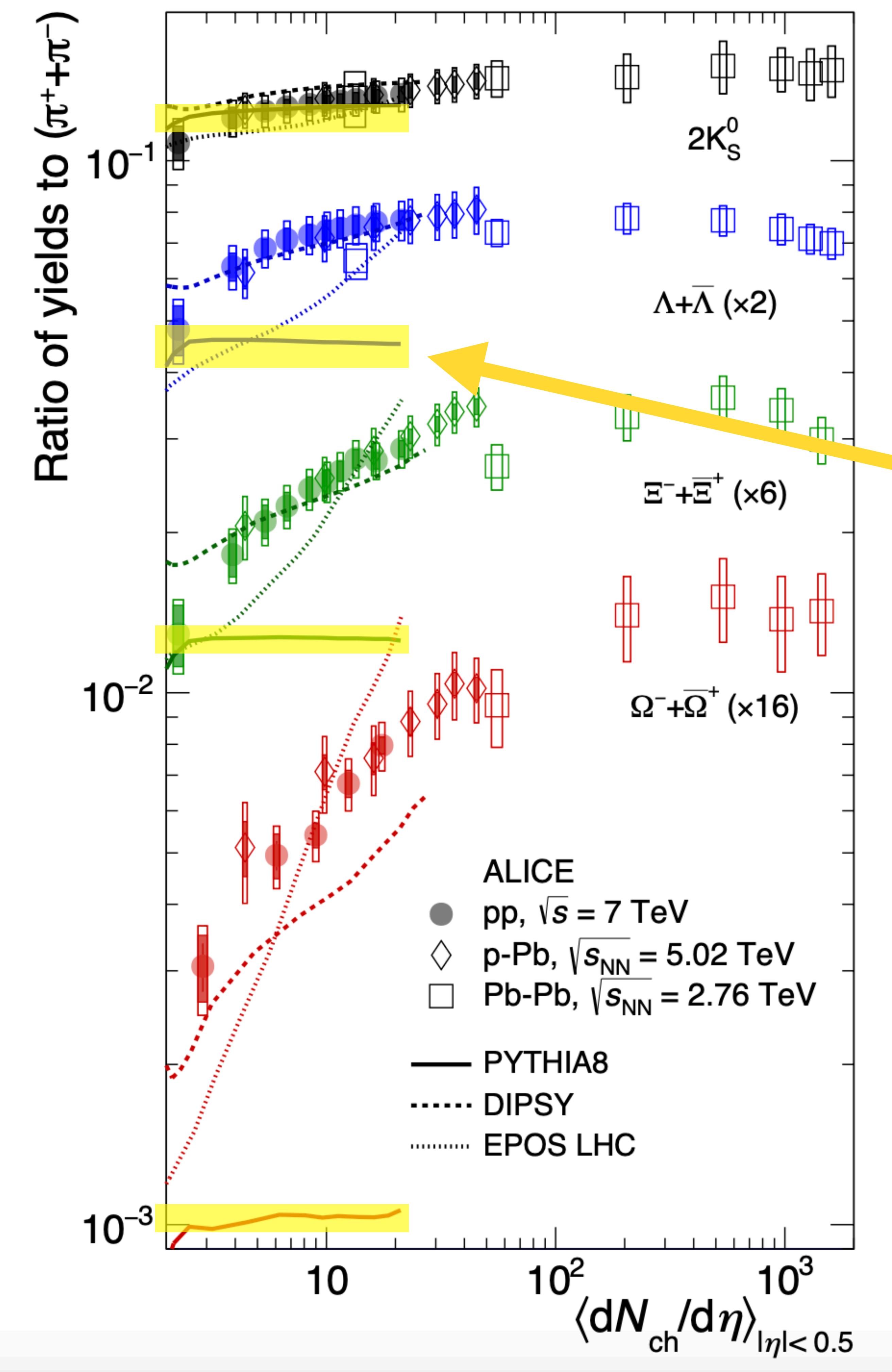
Strangeness

- Closepacking in jets (for e^+e^- studies)
- Ξ_c ratio under-predictions

Thank you for listening!

Backup slides

Dense string systems



Strange to non-strange hadron ratios

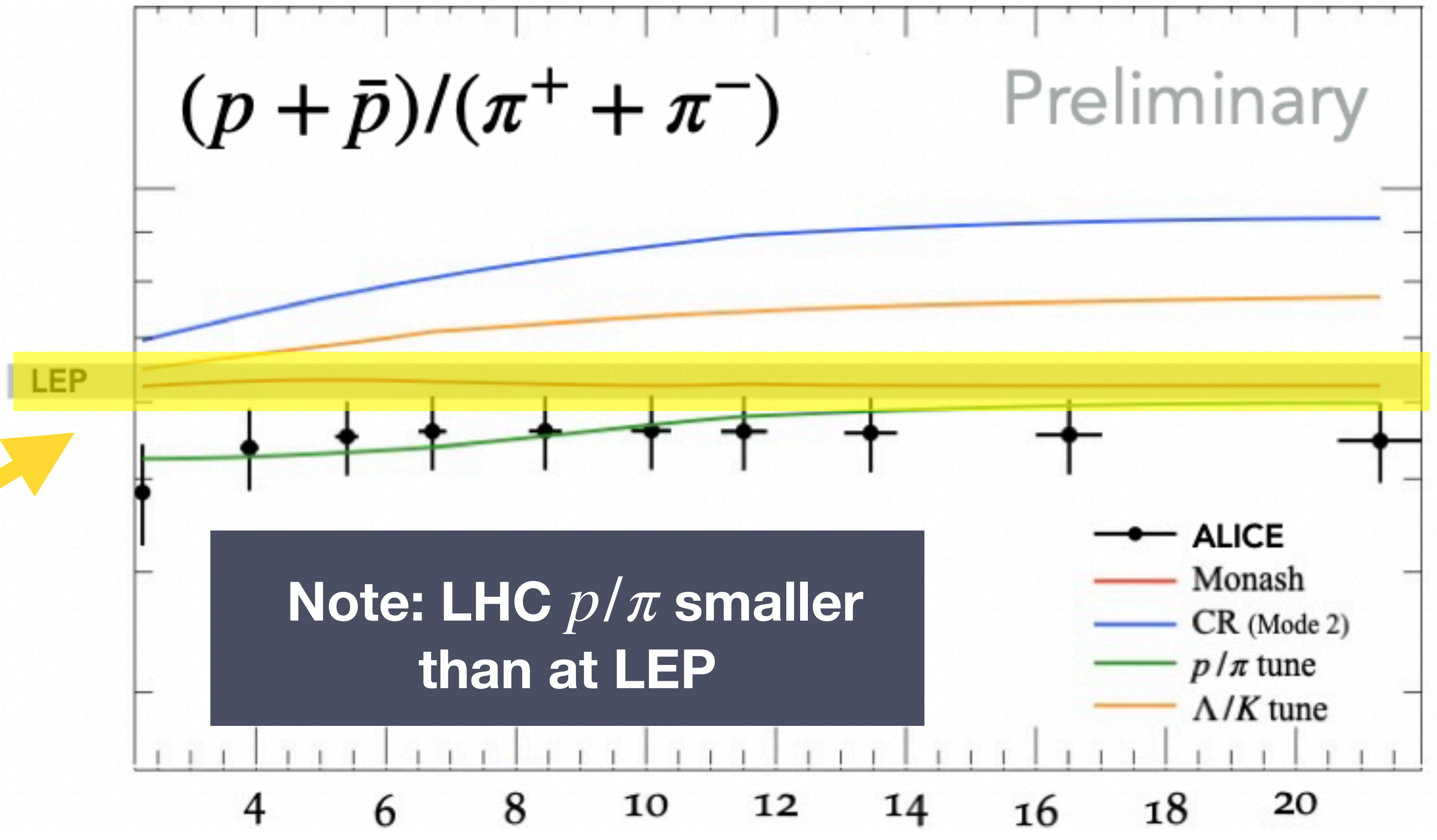
ALICE data shows increase in **strange hadron production** with **multiplicity**

high multiplicity is correlated with more partons

→ more dense string environments

Baseline Lund string model shows constant strange quark production along a string

Proton-to-pion ratio is overpredicted in *pp* **collisions** given diquark production rate value (StringFlav::ProbQQtoQ ($P_{qq:q}$)) tuned to e^+e^- data

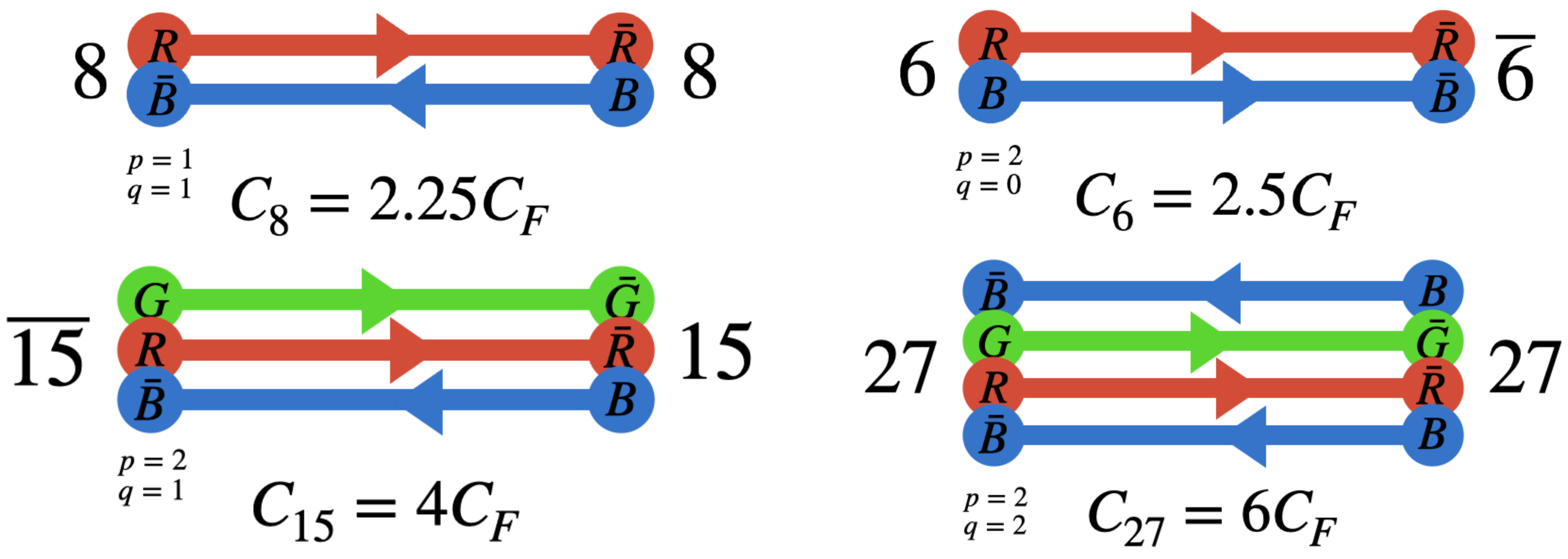


Overprediction of proton-to-pion ratio

Dense string systems

Closepacking

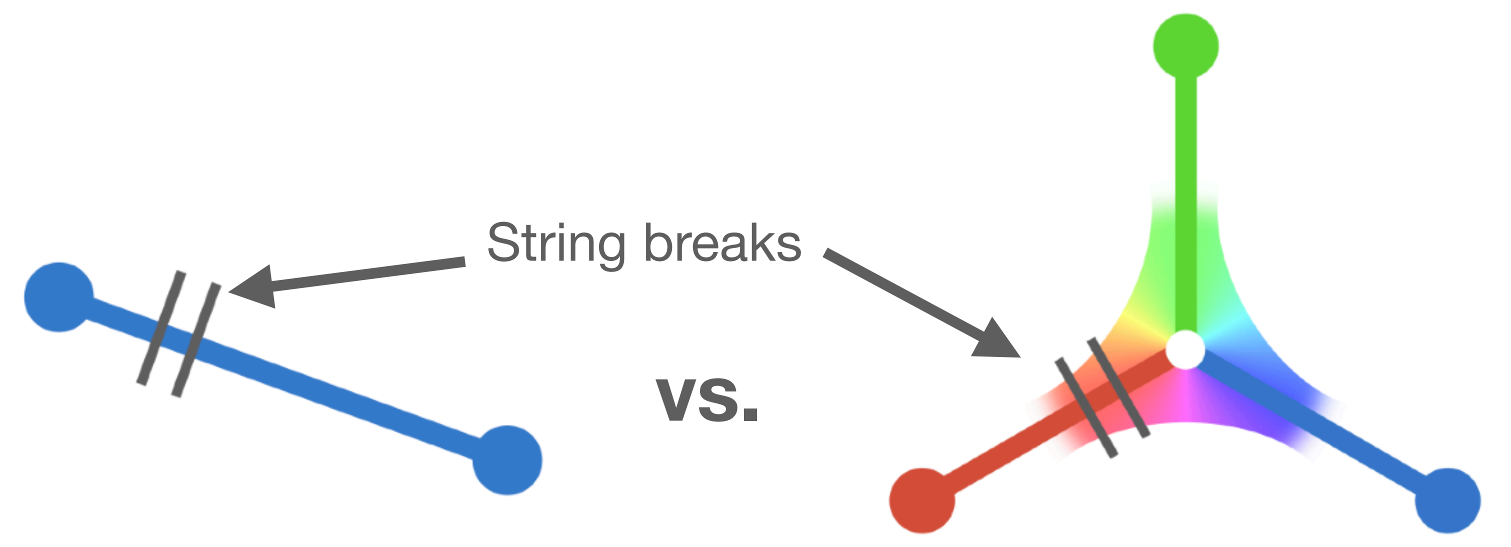
Enhance string tension for higher multiplets according to **Casimir scaling**



High multiplicity is correlated with more partons
→ more dense string environments

Strange Junctions

String tension could be different from the vacuum case compared to near a junction



Results in strangeness enhancement focused in baryon sector

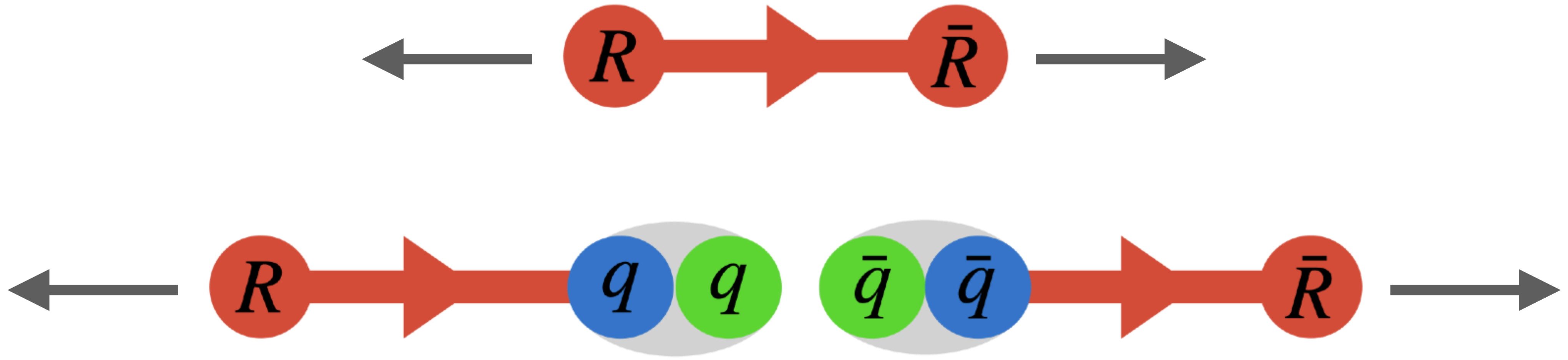
Junction formation is correlated with density of string systems

Diquark production

Proton-to-pion ratio is overpredicted in pp collisions given diquark production rates tuned to e^+e^- data

Junctions needed to describe other baryon-to-meson ratios → examine baryon formation via **diquark production**

Schwinger — direct tunnelling from vacuum



$$\mathscr{P} \propto \exp\left(\frac{-m_{qq}^2 - p_\perp^2}{\kappa/\pi}\right)$$

Diquark production

Proton-to-pion ratio is overpredicted in pp collisions given diquark production rates tuned to e^+e^- data

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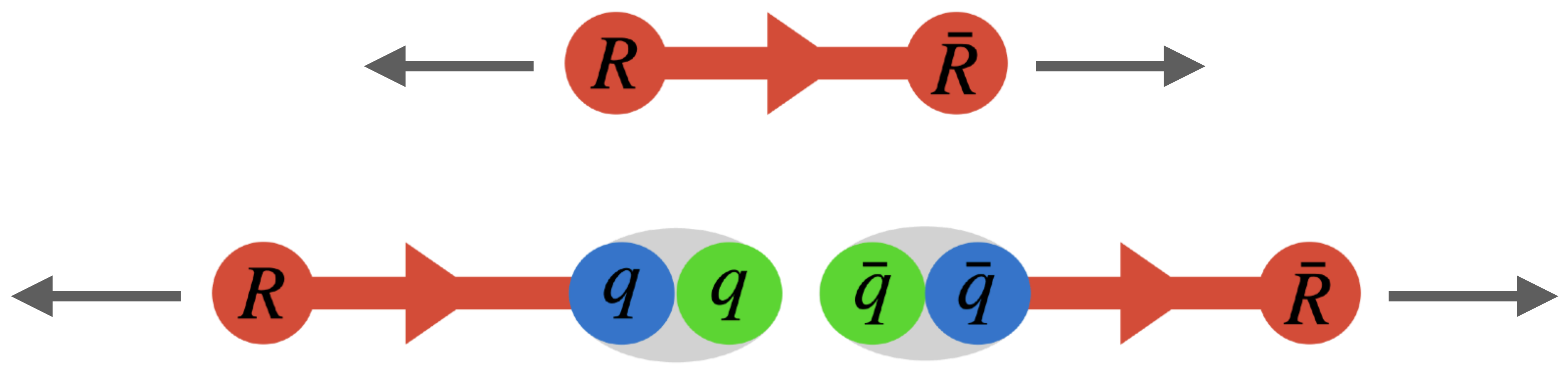
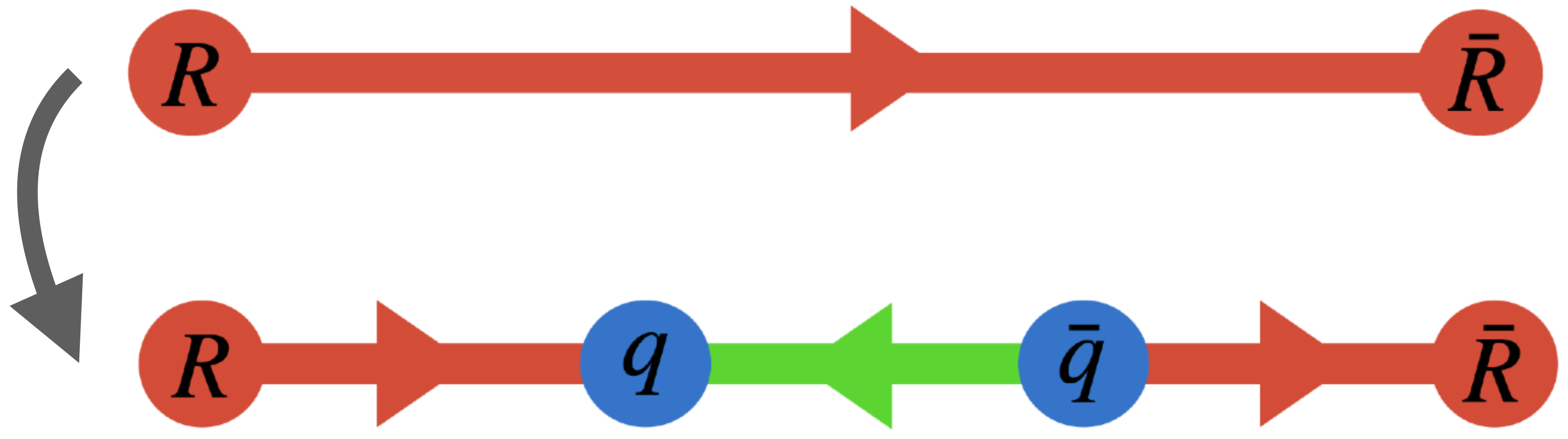


$$\mathscr{P} \propto \exp\left(\frac{-m_{qq}^2 - p_\perp^2}{\kappa/\pi}\right)$$

Popcorn mechanism for diquark production

Diquark formation via **successive colour fluctuations** — popcorn mechanism



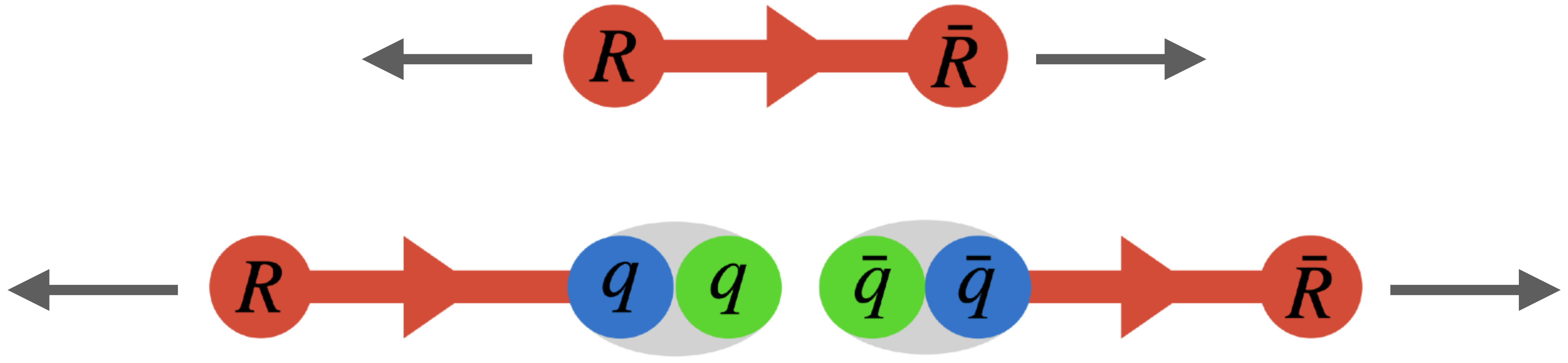
blue $q\bar{q}$ fluctuation on the string

Diquark production

Proton-to-pion ratio is overpredicted in pp collisions given diquark production rates tuned to e^+e^- data

Junctions needed to describe other baryon-to-meson ratios → examine baryon formation via **diquark production**

Schwinger — direct tunnelling from vacuum



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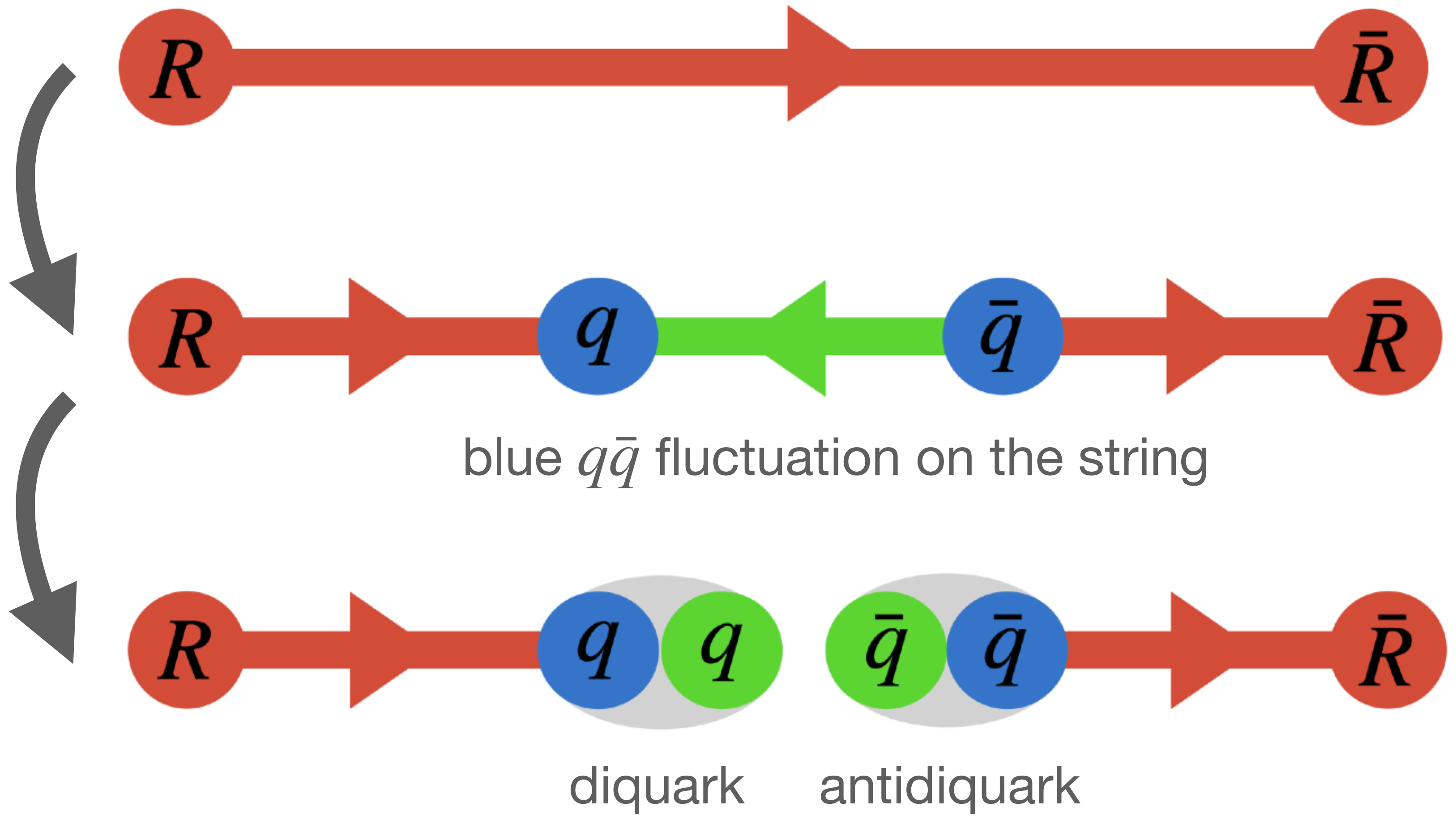


What would happen if we put this **red string** next to another string? e.g. a **blue string**

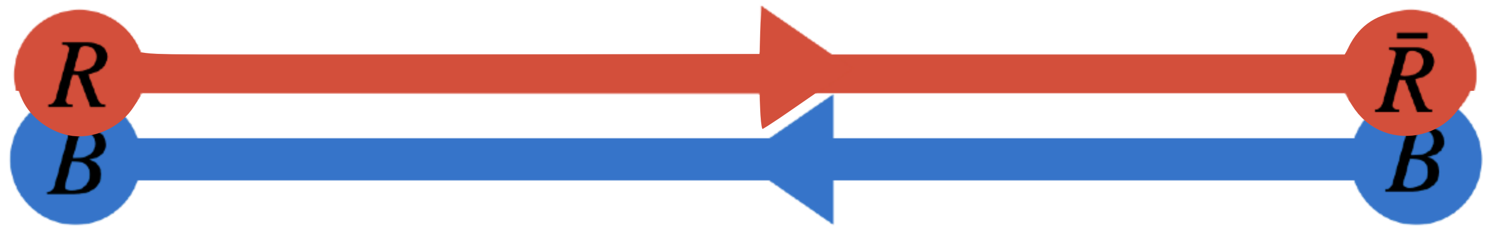
Popcorn destructive interference

Proton-to-pion ratio is overpredicted in pp collisions given diquark production rates tuned to e^+e^- data

Junctions needed to describe other baryon-to-meson ratios → examine baryon formation via **diquark production**

Popcorn mechanism for diquark production

Diquark formation via **successive colour fluctuations** — popcorn mechanism



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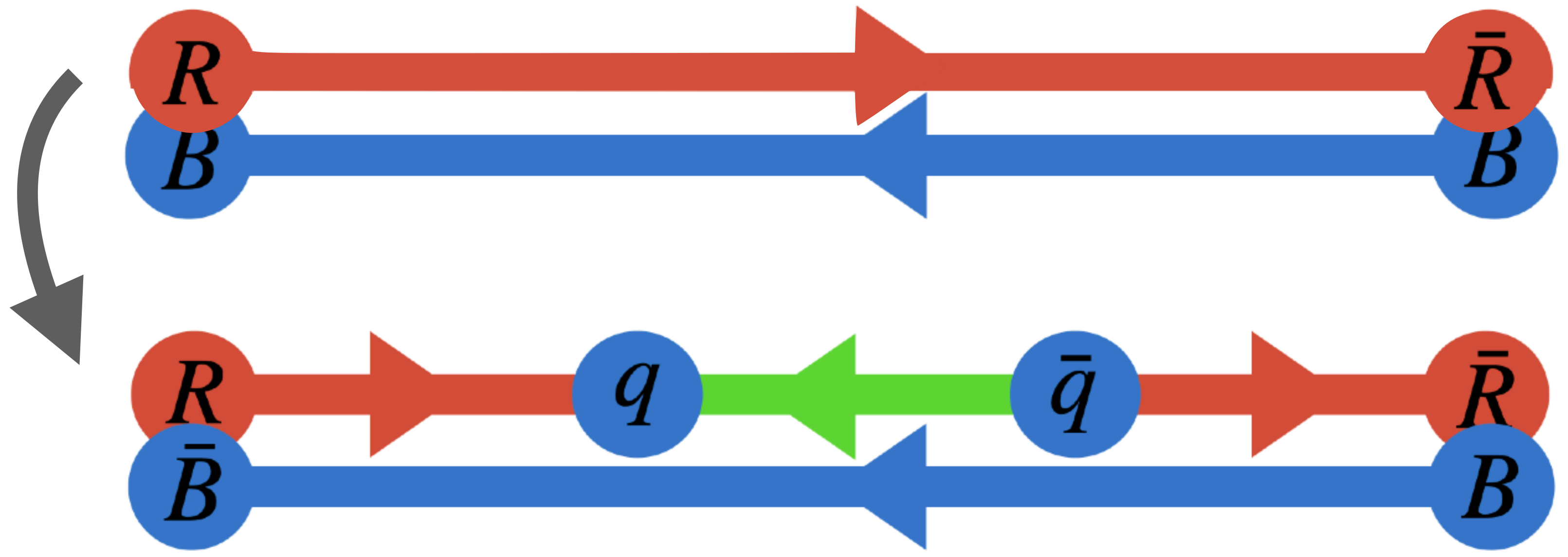
Popcorn mechanism for diquark production

Diquark formation via **successive colour fluctuations** — popcorn mechanism



blue $q\bar{q}$ fluctuation on the red string

What would happen if we put this **red string** next to another string? e.g. a **blue string**

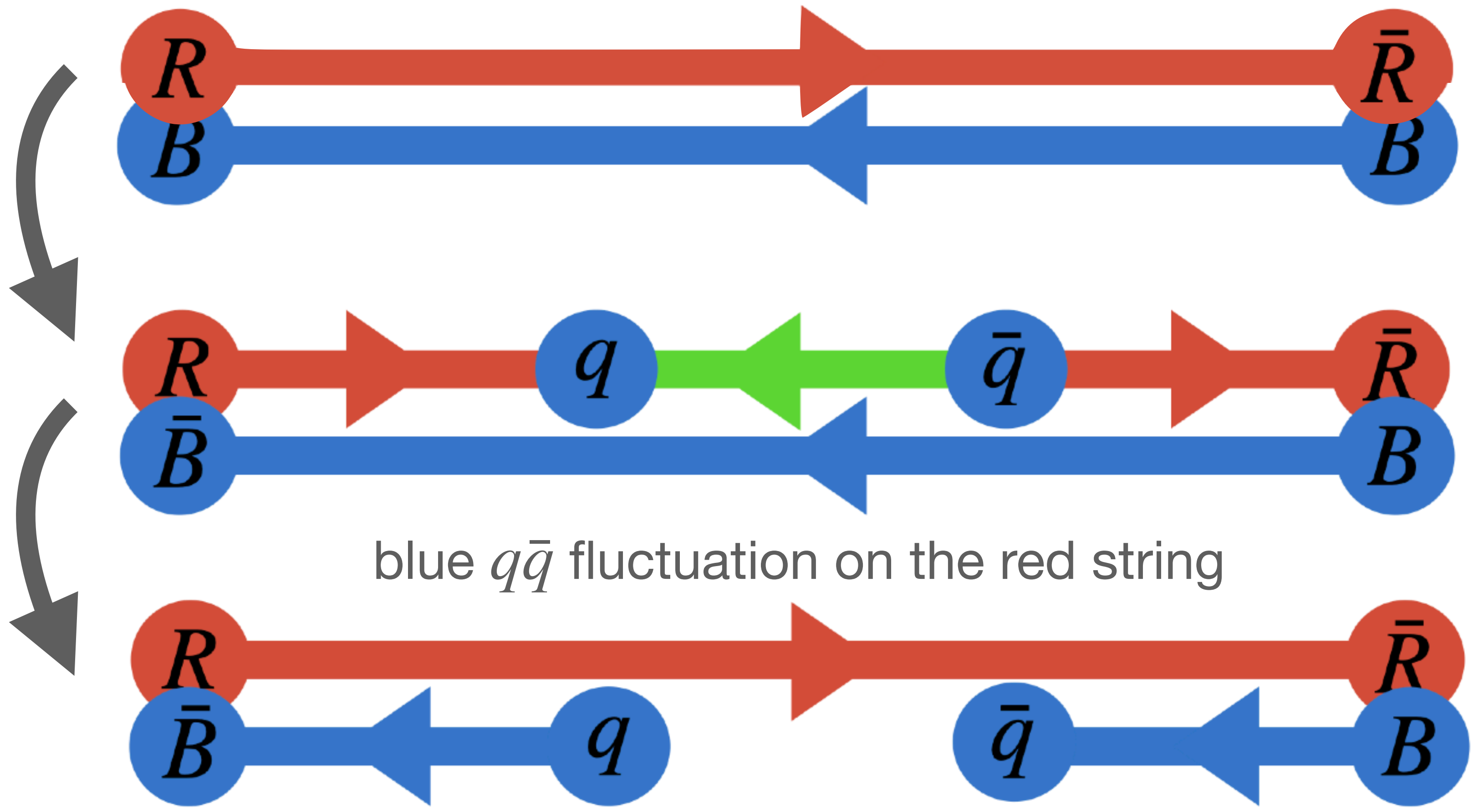
Popcorn destructive interference

Proton-to-pion ratio is overpredicted in pp collisions given diquark production rates tuned to e^+e^- data

Junctions needed to describe other baryon-to-meson ratios → examine baryon formation via **diquark production**

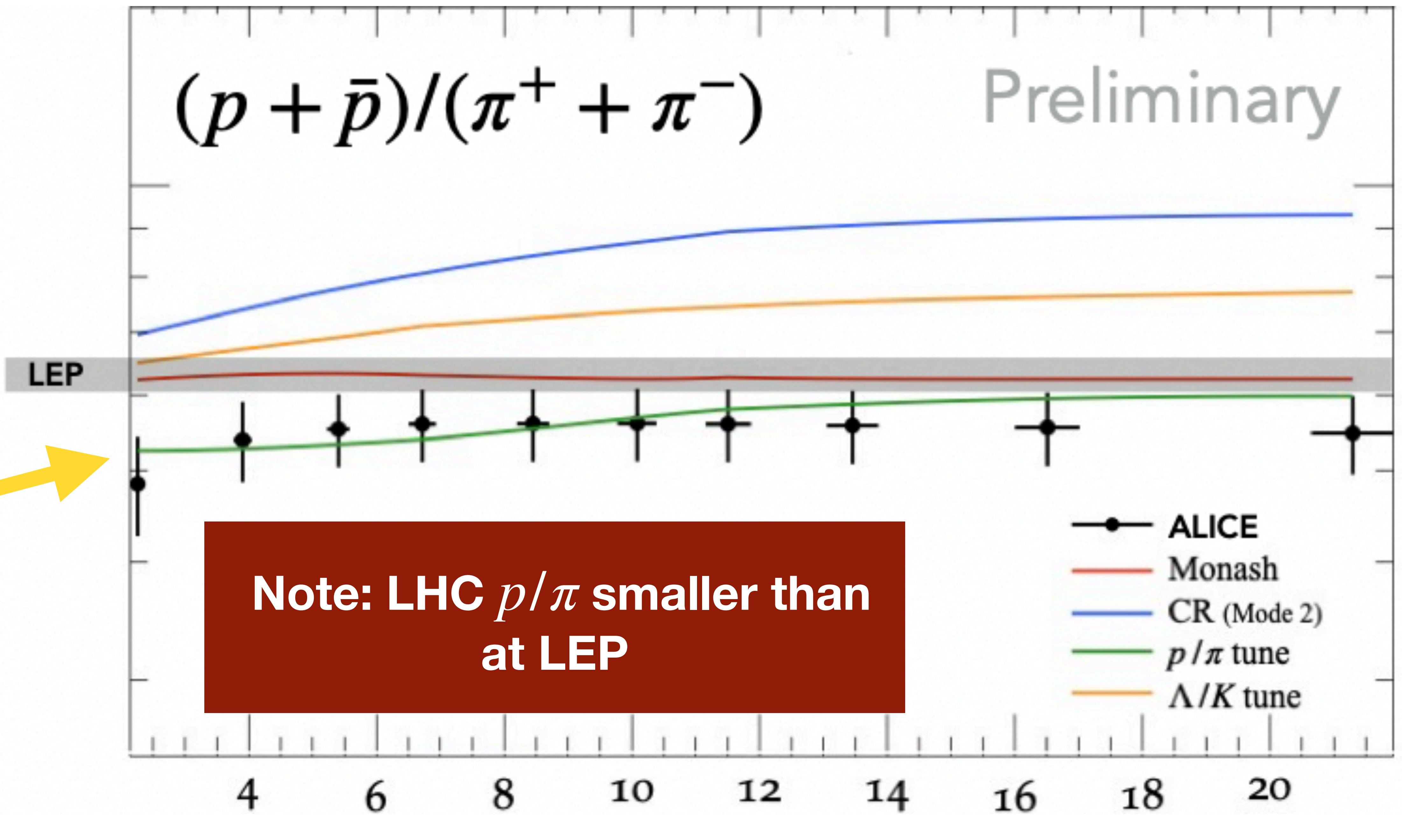
Popcorn mechanism for diquark production

Diquark formation via **successive colour fluctuations** — popcorn mechanism

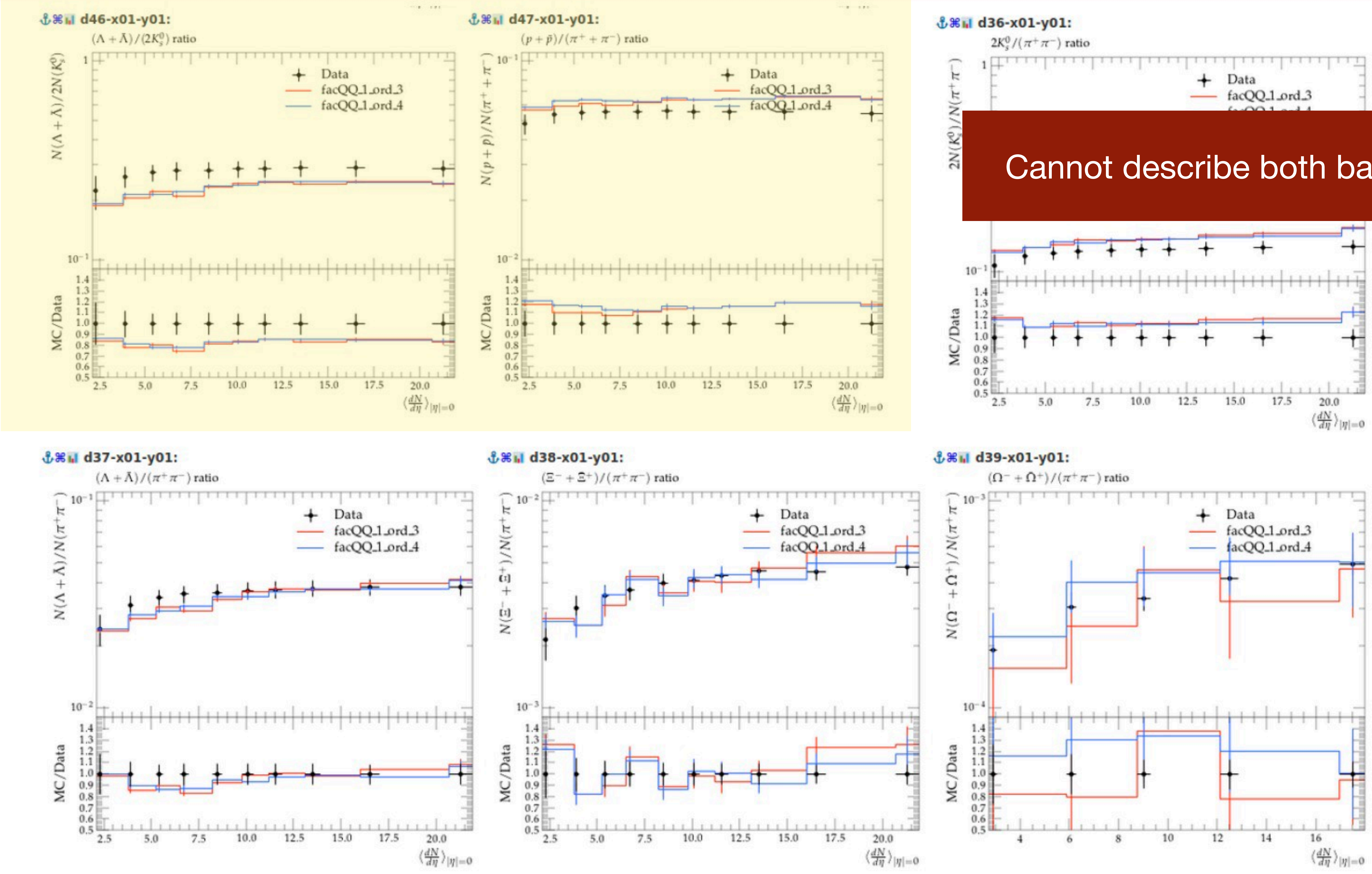


blue $q\bar{q}$ fluctuation breaks nearby blue string, preventing diquark formation

Popcorn destructive interference



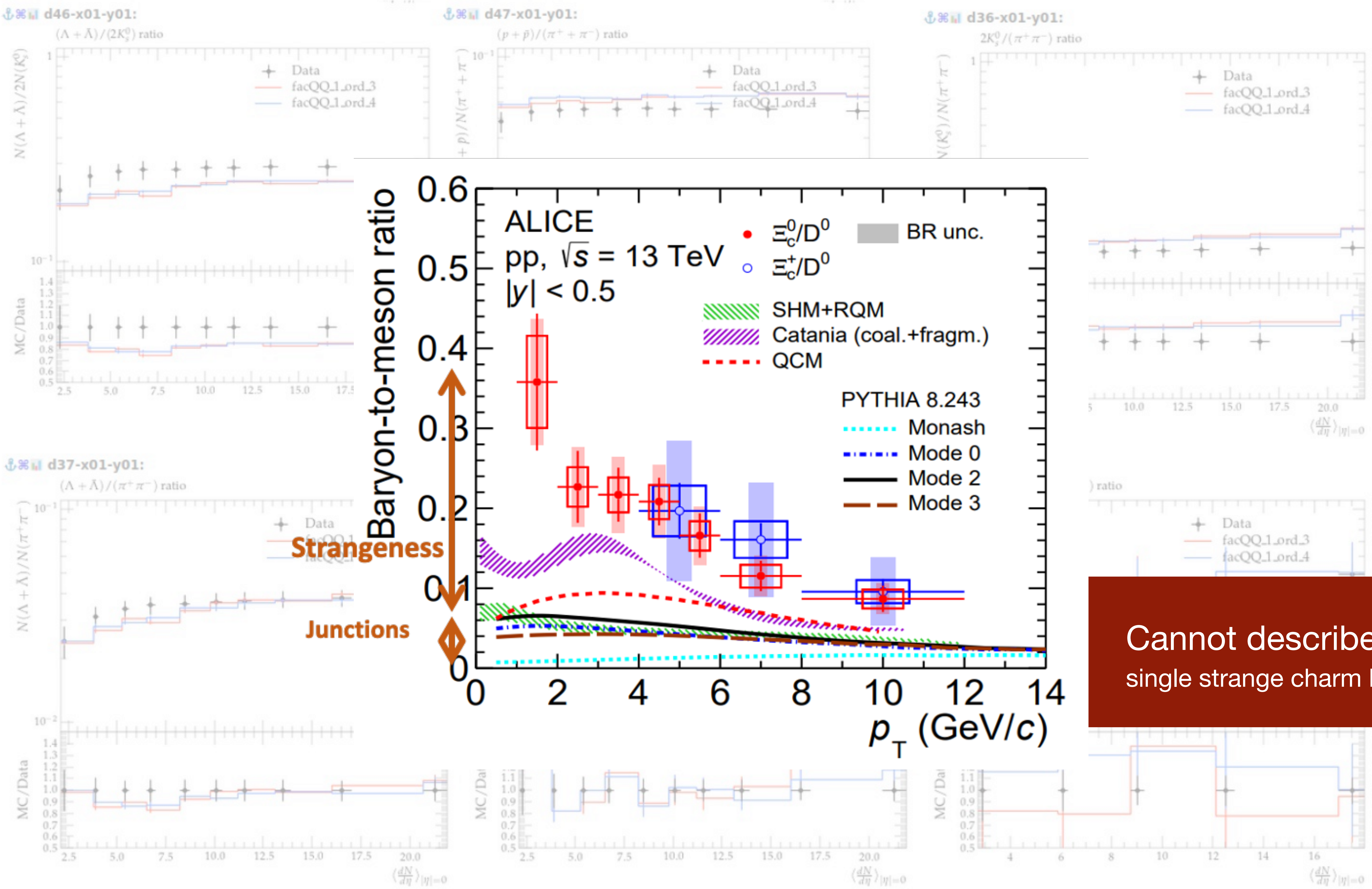
Results — ongoing



Cannot describe both baryon-to-meson ratios simultaneously

Taken from slide by Lorenzo Bernadinis: PhD student currently in Trieste undertaking tuning project with the model

Strange and heavy?



Cannot describe the Ξ_c/D^0 ratio nor the Ξ_c/Λ_c ratio

single strange charm baryon - to - charm meson/baryon ratio

String tension modifications

Diquark production:

$$P_{qq:q} = \frac{\sum_{qq_s} P_{qq_s}}{\sum_q P_q} = \alpha \frac{P_{ud0}}{P_u}$$

$$P_{qq:q}(\kappa_{eff}) = \tilde{\alpha} \left(\frac{P_{qq:q}}{\alpha} \right)^{\kappa_0/\kappa_{eff}}$$

$p_\perp$ spectrum:

$$\exp\left(\frac{-\pi p_\perp^2}{\kappa_0}\right) = \exp\left(\frac{-p_\perp^2}{\sigma^2}\right) \qquad \sigma^2 = \frac{\kappa_0}{\pi}$$

$$\sigma'^2 = \frac{\kappa_{eff}}{\pi} = \frac{\kappa_0}{\pi}\frac{\kappa_{eff}}{\kappa_0} = \sigma^2 \frac{\kappa_{eff}}{\kappa_0}$$

Increased width of $p_\perp$ spectrum
→ higher probability of higher $p_\perp$

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Lund string model assumes **classical string dynamics** — using only first term of the Nambu-Goto action

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$$X(t,\sigma) = \left(t, \frac{L_+(t)+L_-(t)}{2} + \sigma\frac{L_+(t)-L_-(t)}{2}, \frac{X^2(t,\sigma)}{\sqrt{\kappa}}, \frac{X^3(t,\sigma)}{\sqrt{\kappa}}\right) \quad \sigma \in [-1,1]$$

$x \in [L_-(t), L_+(t)]$

X^i are massless Nambu-Goldstone degrees of freedom

Axions

Lattice data strongly suggests that the lightest massive mode that exists on the worldsheet of a long static QCD string is the so-called ``worldsheet axion", a pseudoscalar particle of mass $m_a \approx 1.85\sqrt{\kappa}$

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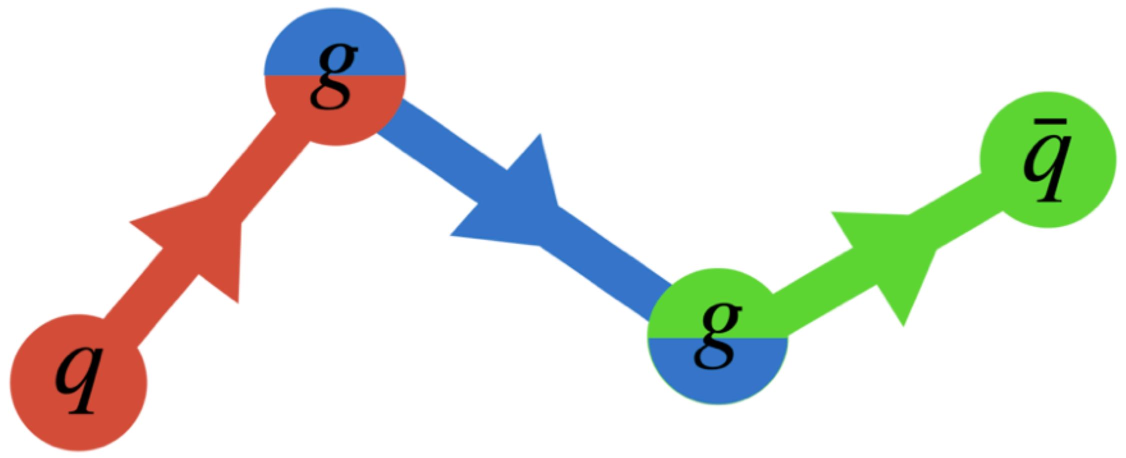
Modelling Colour

Leading Colour limit:

Starting point for Monte Carlo event generators $N_C \to \infty$

- ➢ Each **colour is unique** → only one way to make colour singlets
- ➢ Only **dipole** strings
- ➢ Used by PYTHIA in the default (Monash 2013) tune



e.g. a dipole string configuration which make use of the **colour-anticolour** singlet state

In e^+e^- collisions :

- ➢ Corrections suppressed by $1/N_C^2 \sim 10\,\%$
- ➢ Not much overlap in phase space

But high-energy pp collisions involve **very many** coloured partons with significant **phase space overlaps**

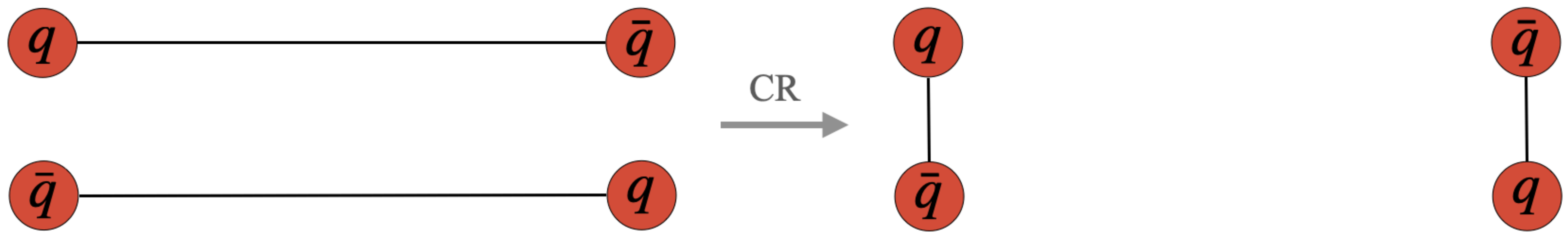
QCD Colour Reconnection (CR) model

QCD Colour Reconnections

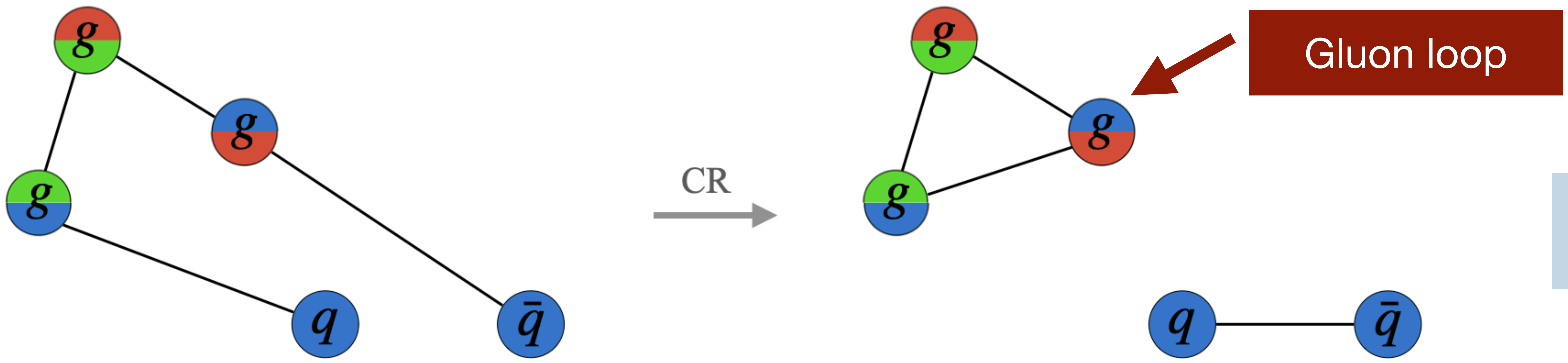
Stochastically restores colour-space ambiguities according to **SU(3) algebra**

➢ Allows for reconnections to **minimise string lengths**

Colour - anticolour singlet state



Dipole reconnection



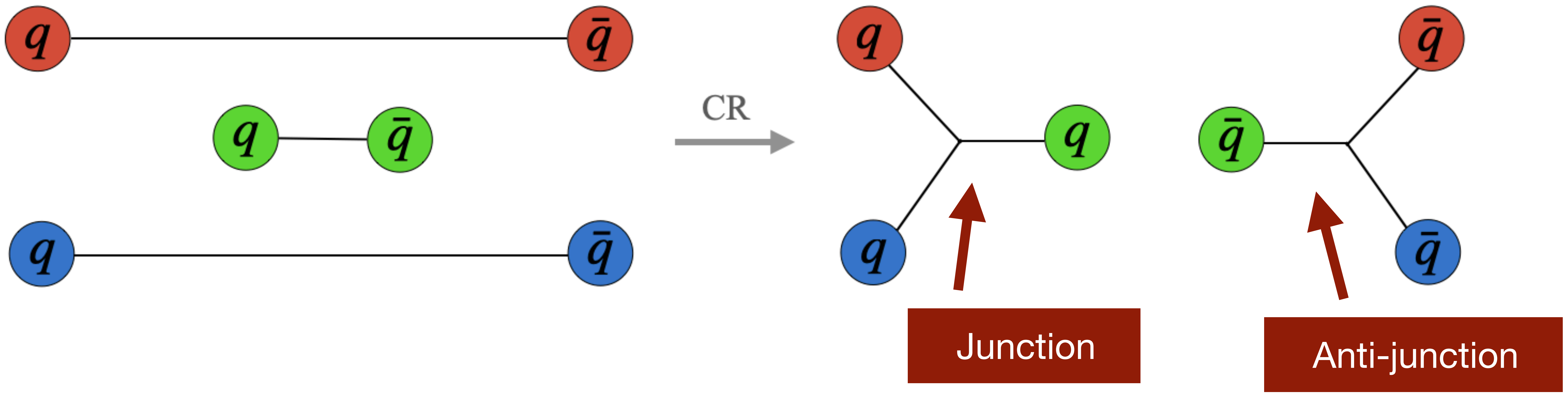
Gluon loop formation

QCD Colour Reconnections

Stochastically restores colour-space ambiguities according to **SU(3) algebra**

➢ Allows for reconnections to **minimise string lengths**

What about the red-green-blue colour singlet state?



Junction reconnection

Junction fragmentation

Junction fragmentation

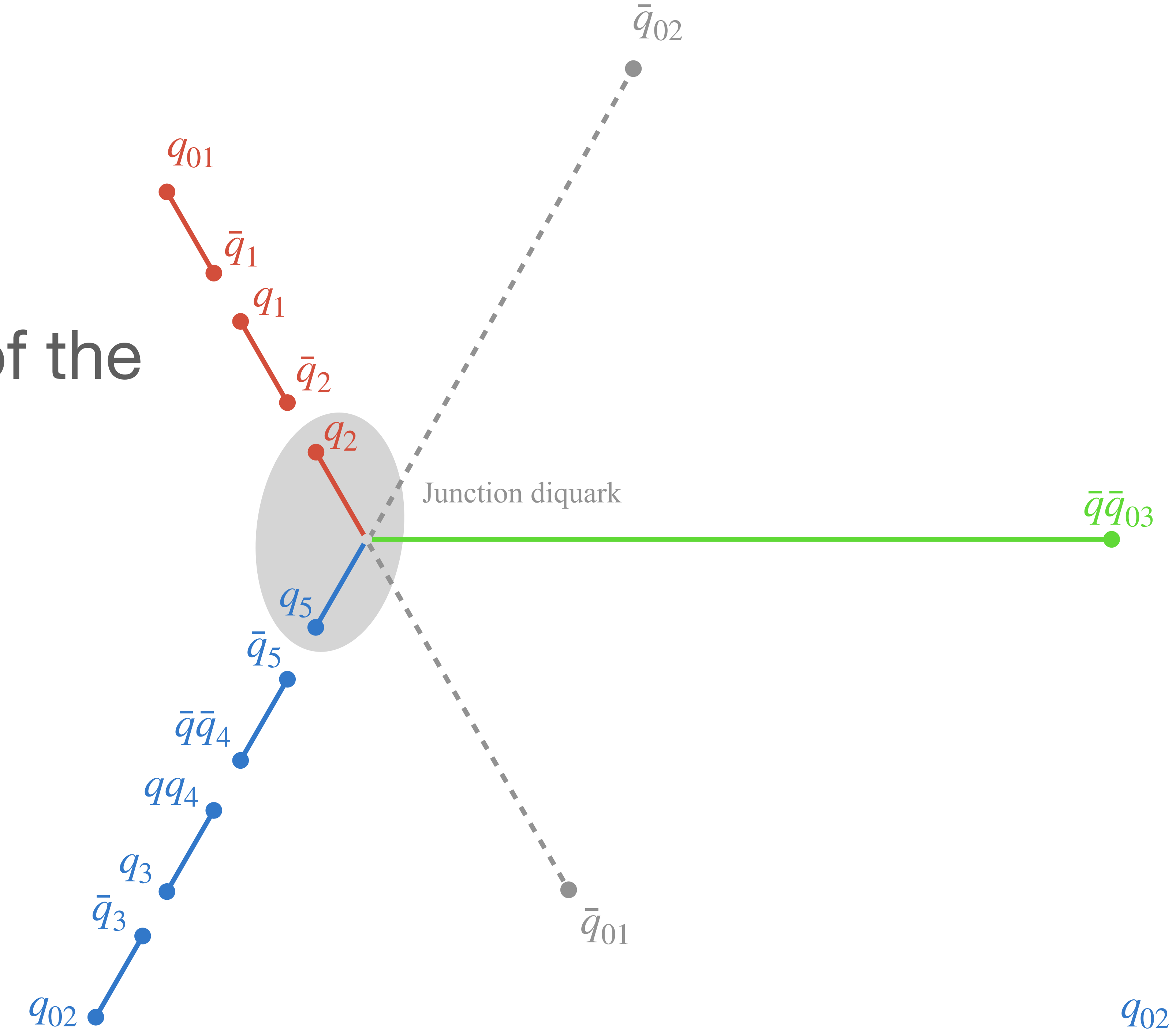
→ **Go to JRF**

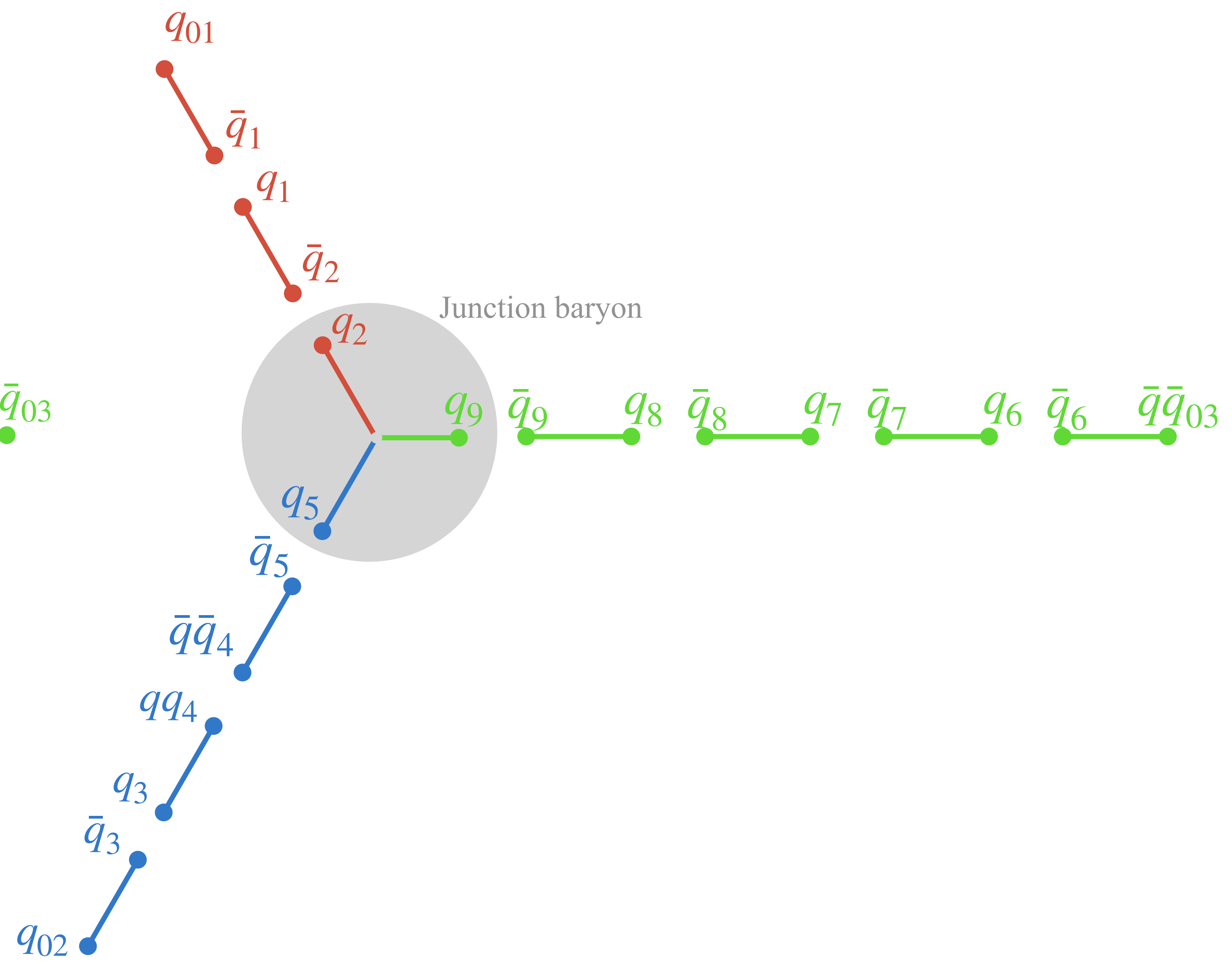
→ Fragment two softest strings first

→ Reflect each leg on the other side of the junction ("fictitious leg") to form a dipole string

→ Form junction diquark

→ Fragment last leg by fragmenting diquark — endpoint string





Partons → Hadrons

Baryon formation:

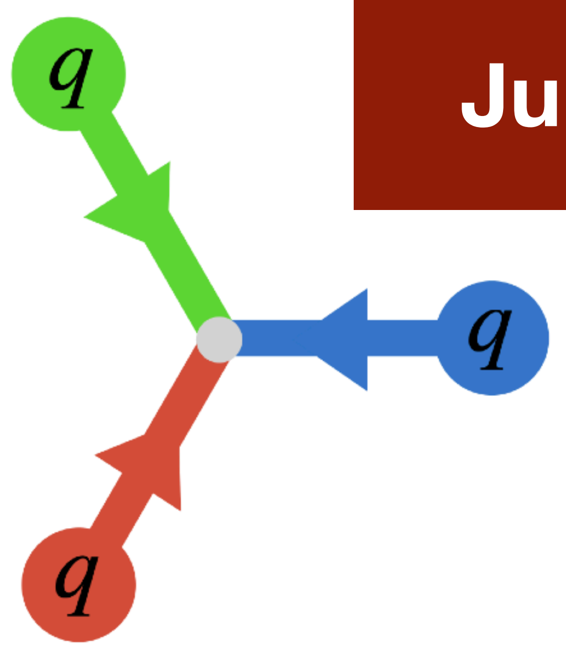
Diquark endpoints (e.g. beam remnants)

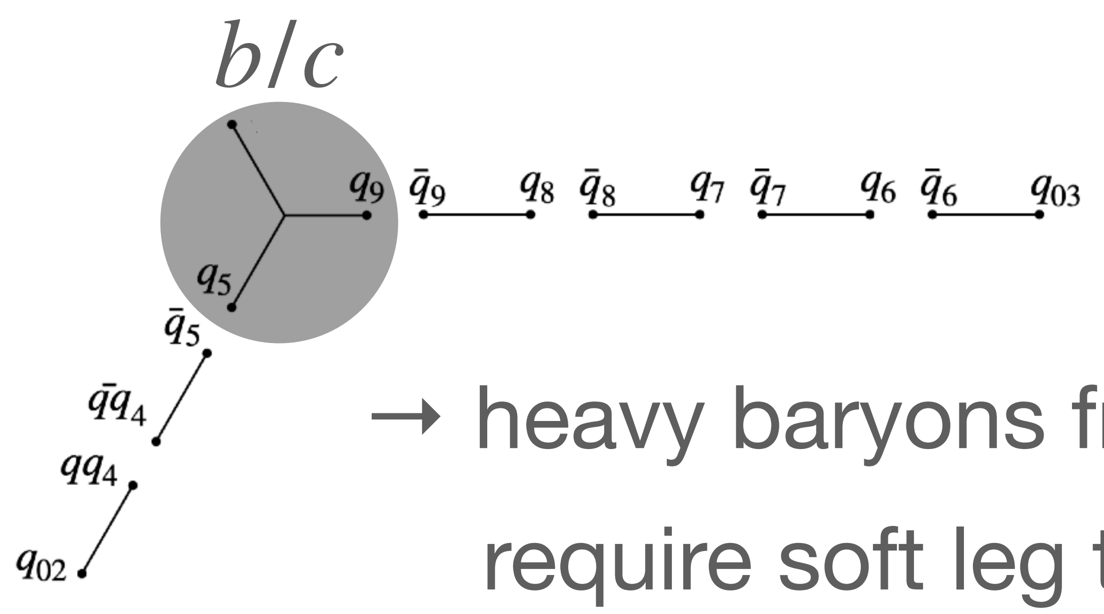
Diquark-antidiquark string breaks

➢ constant probability suppressed by Schwinger mechanism

What about the red-green-blue colour singlet state?

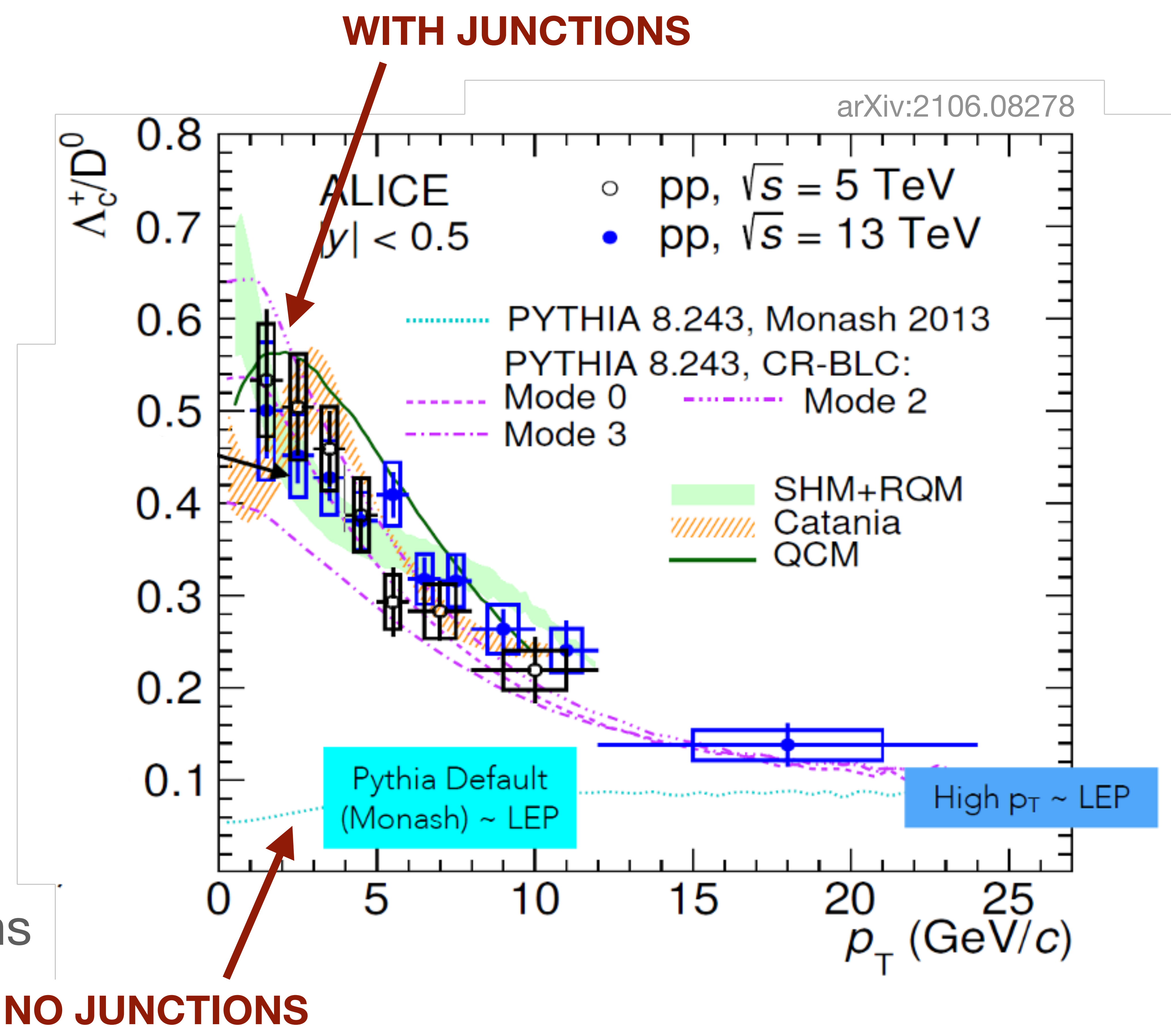
Junctions!





→ heavy baryons from junctions require soft leg treatment

Heavy baryon-to-meson ratio



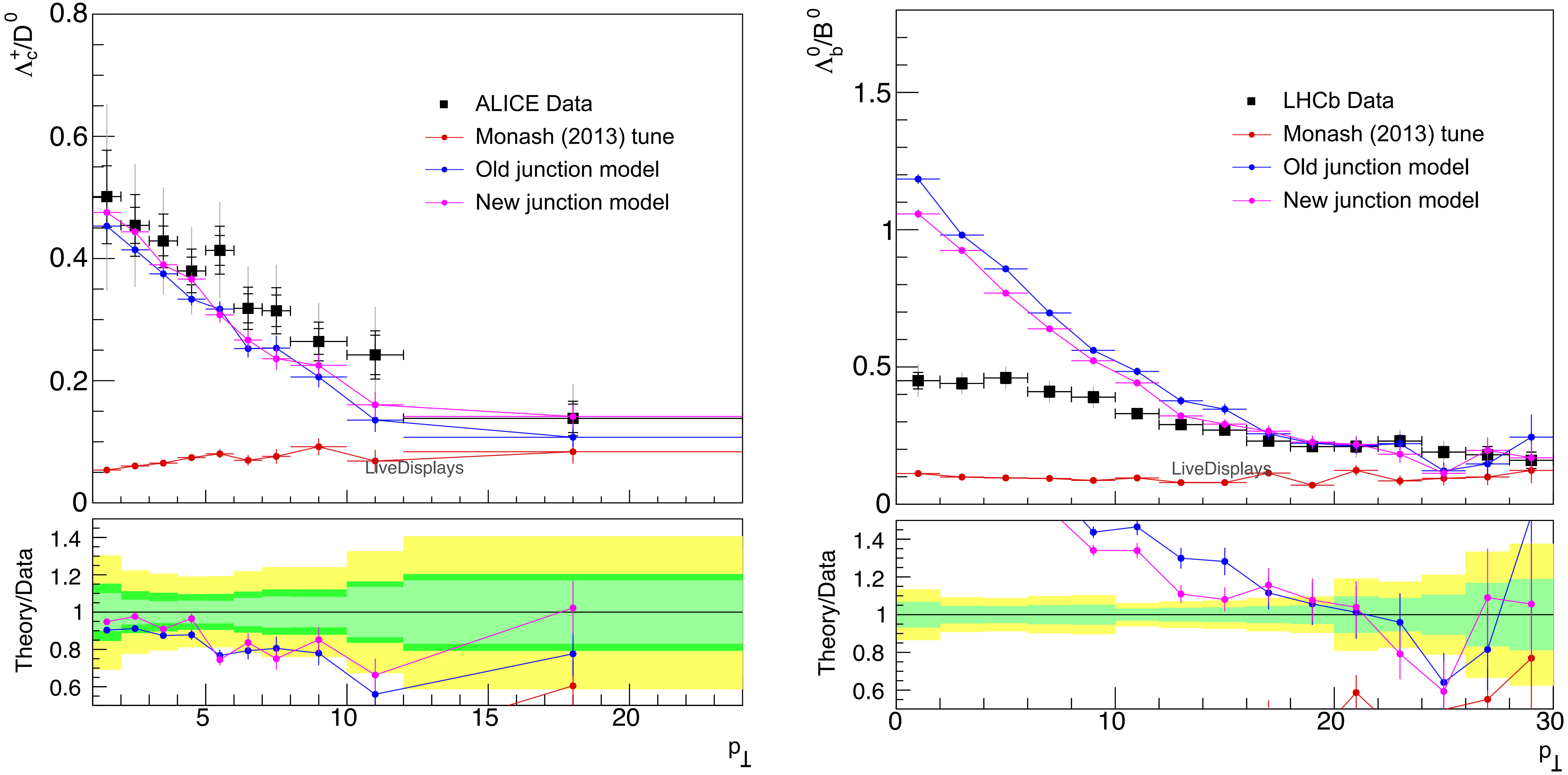
Heavy baryon ratios

Λ_b/B^0 **overprediction**

→ study of Λ_b **vs** Λ_c **production**

→ other heavy flavour ratios such as Λ_b/Λ_c and B^0/D^0

→ general study of what portion of each baryon comes from junctions



*Note Λ_c/D^0 is lower than typically as probQQ1toQQ0join was reverted to its default values and left untuned. Value should be slightly lower than default value and this ratio should increase