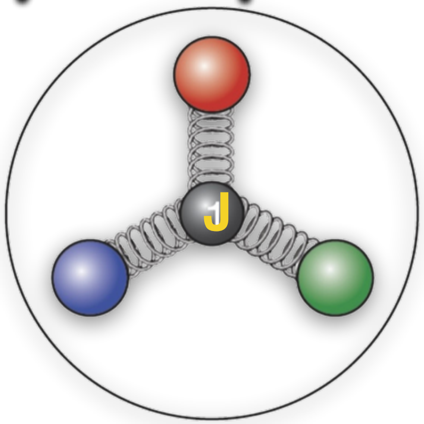
CFNS, Stony Brook, Jan 22-24, 2024

1st Workshop on Baryon Dynamics: from RHIC to EIC

The string-junction and its high-energy implications



Gabriele Veneziano

Based on work/discussions w/ Giancarlo Rossi for 45+ years

Outline

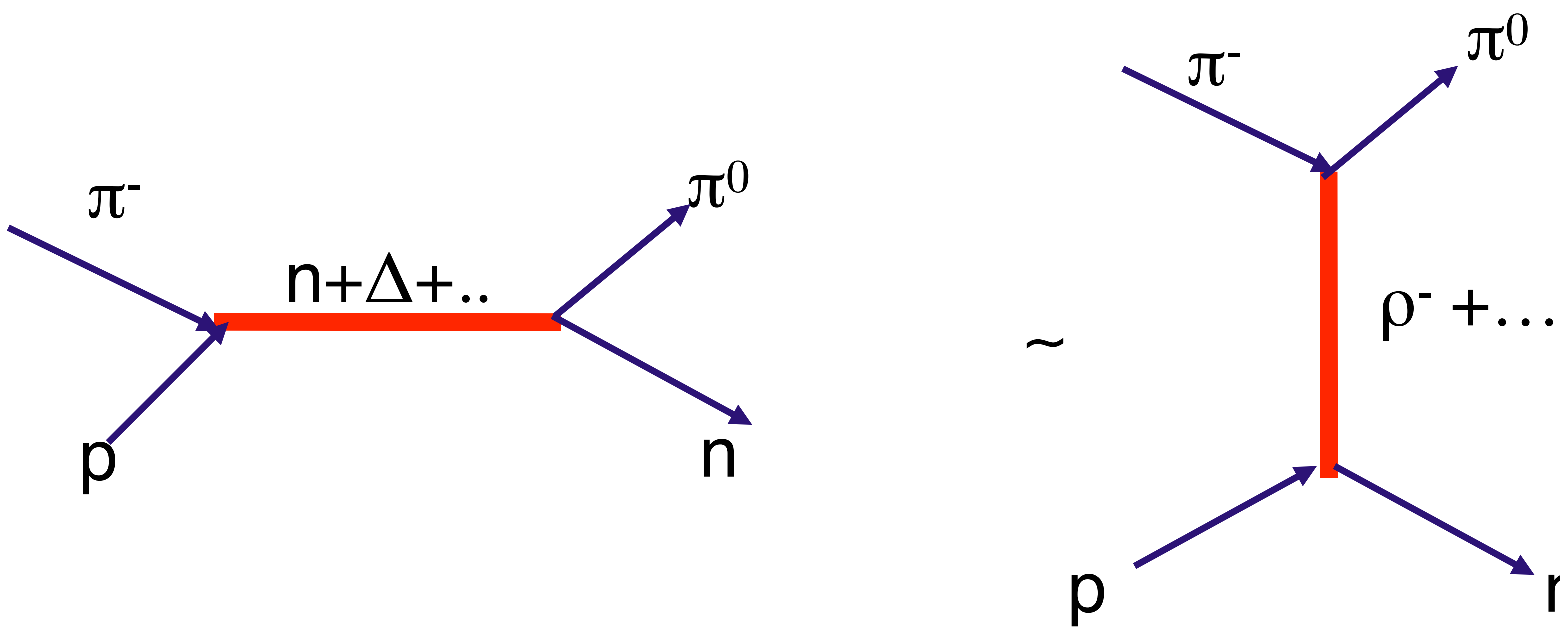
- Pre-QCD considerations
- Gauge-inv. QCD operators, baryons, junction
- QCD @ large-N_c (N_f, λ_t) and spectroscopy
  - -mesons, glueballs, baryons @ large N_c
  - -mesons & glueballs @ large N_c & N_f : OZI
  - –baryons & multiquarks @ large λ_t : JOZI
- Manifestations of J @ High Energy
  - - Flavor annihilation/transp. in MM/MB scatt.
  - - Baryon# transport in MB scattering
  - - B# annihilation/transport in BBbar, BB
- Conclusions

Pre-QCD

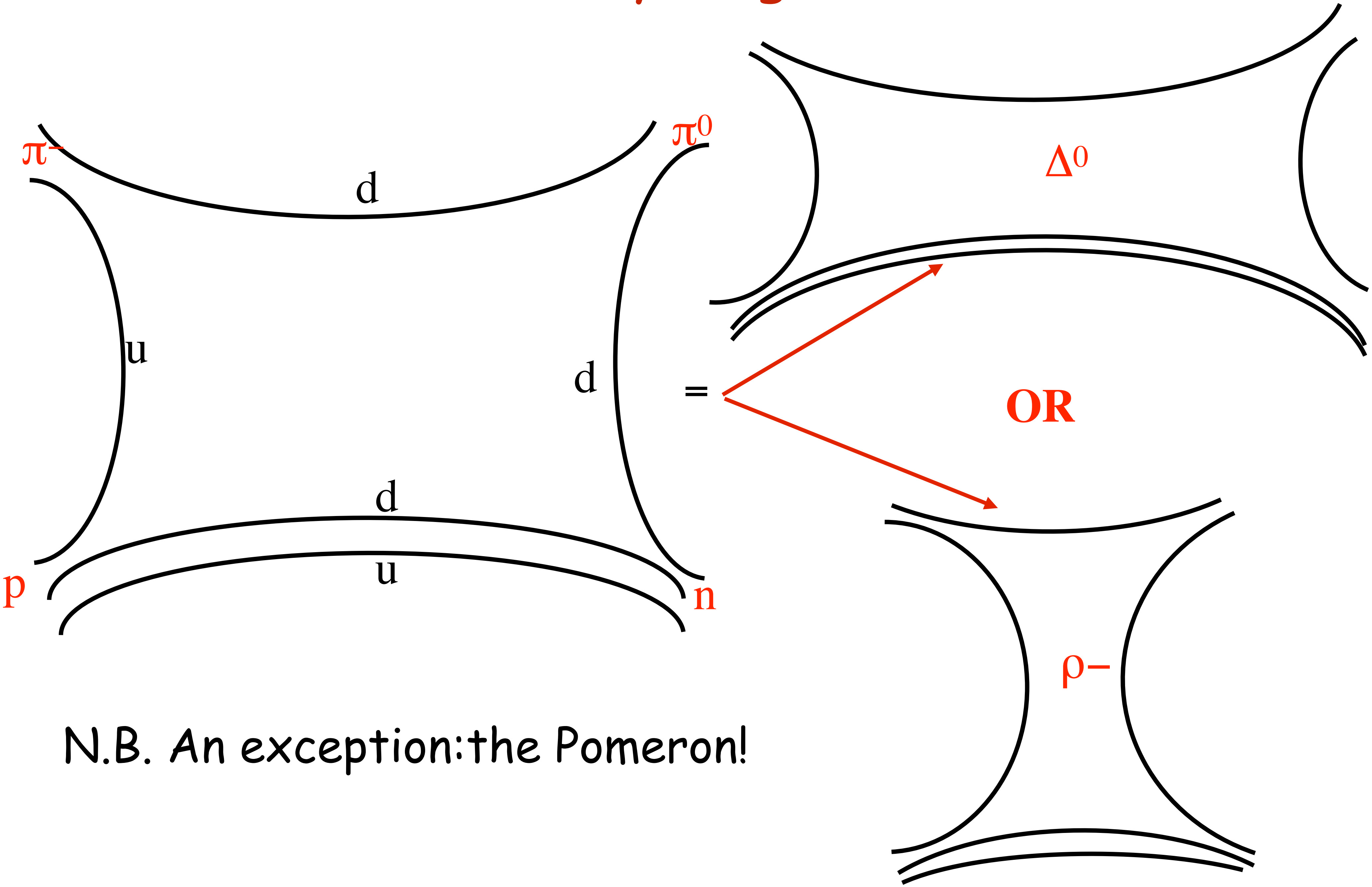
Dolen-Horn-Schmit duality (1967)

s-and t-channel descriptions of pion-nucleon charge exchange are, on average, equivalent, complementary,

DUAL

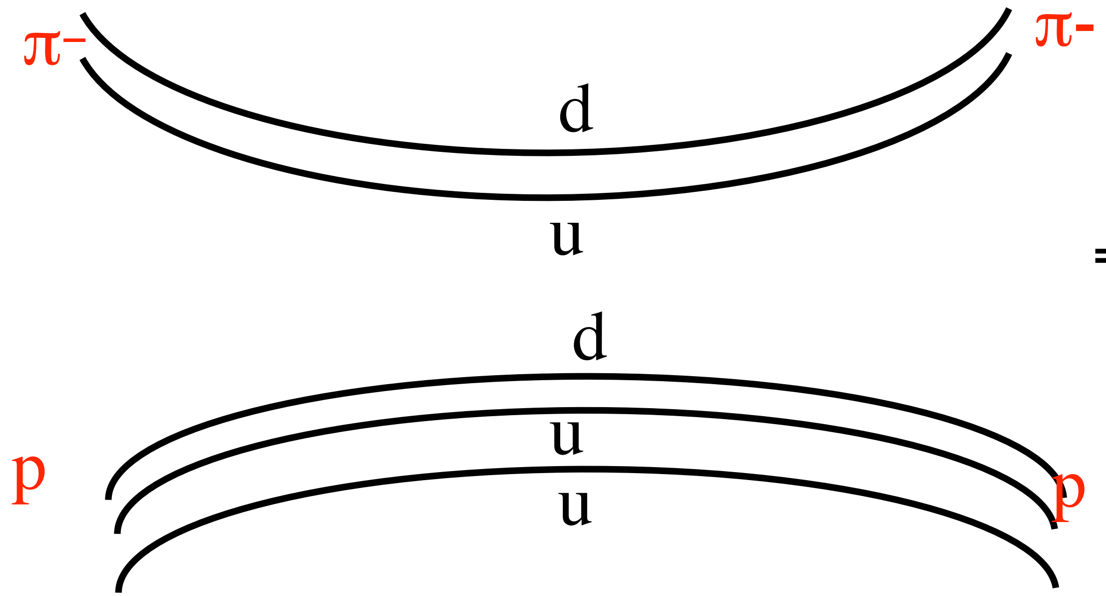


Harari-Rosner "duality diagrams"



N.B. An exception:the Pomeron!

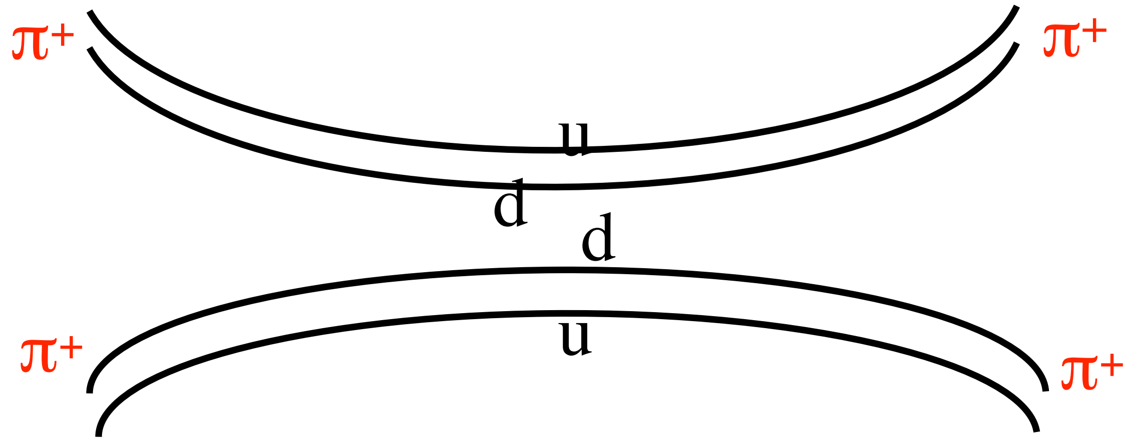
The Pomeron is dual to a non-resonating continuum (Harari-Freund, 1968). it's the only contribution for exotic channels…



= Pomeron exchange in t-channel

= 1 meson + 1 baryon in s-channel

****

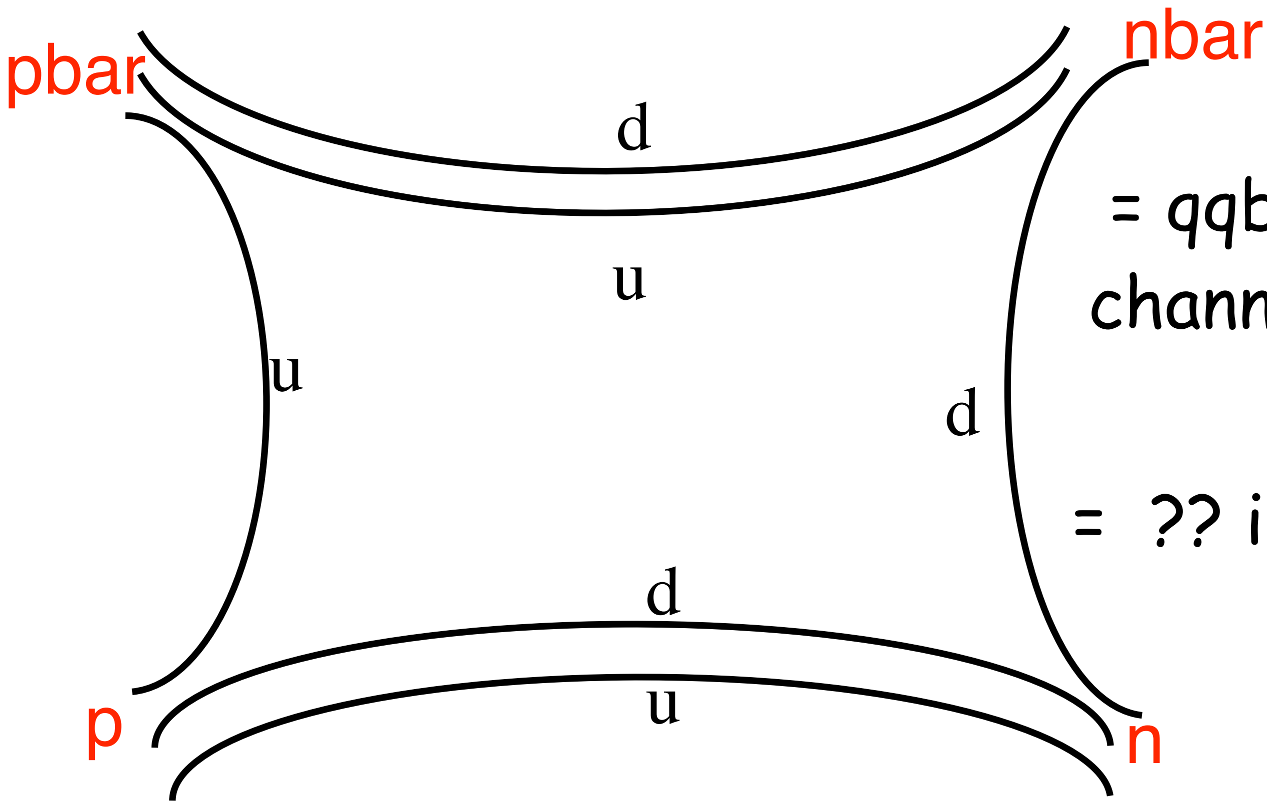


= Pomeron exchange in t-channel

= 2 mesons in s-channel

What about proton antiproton? A puzzle!

Rosner's diagram



= qqbar exchange in t channel

= ?? in s-channel

Q: What is dual to qqbar mesons? Could it be the same 2-meson state occurring in the $\pi\,\pi$ Pomeron diagram?

A: No! A new sector of (possibly exotic) 4q-bound states!

W/ the hadronic string but w/out QCD

X. Artru (1975) considered various possibilities for assigning strings to different hadrons.

For baryons he argued that a Y shape with a junction was the most interesting one phenomenologically.

It implied interpreting the Rosner diagram in terms of tetra-quarks with two junctions…

Within QCD

Hadrons as "irreducible" gauge-invariant operators

String junction and multiquark states

(G.C. Rossi and GV, 1977 + Phys. Rep. 1980)

- Basic idea: associate different "elementary" hadrons with irreducible (~"single trace") gauge invariant operators (as opposed to "molecules")
- For mesons and glueballs it's quite trivial in terms of Wilson lines, loops.
- For baryons one <u>needs</u> to introduce the notion of a "string junction"
- Recently made more precise in LQCD @ strong 'tHooft coupling λ_t (see below)

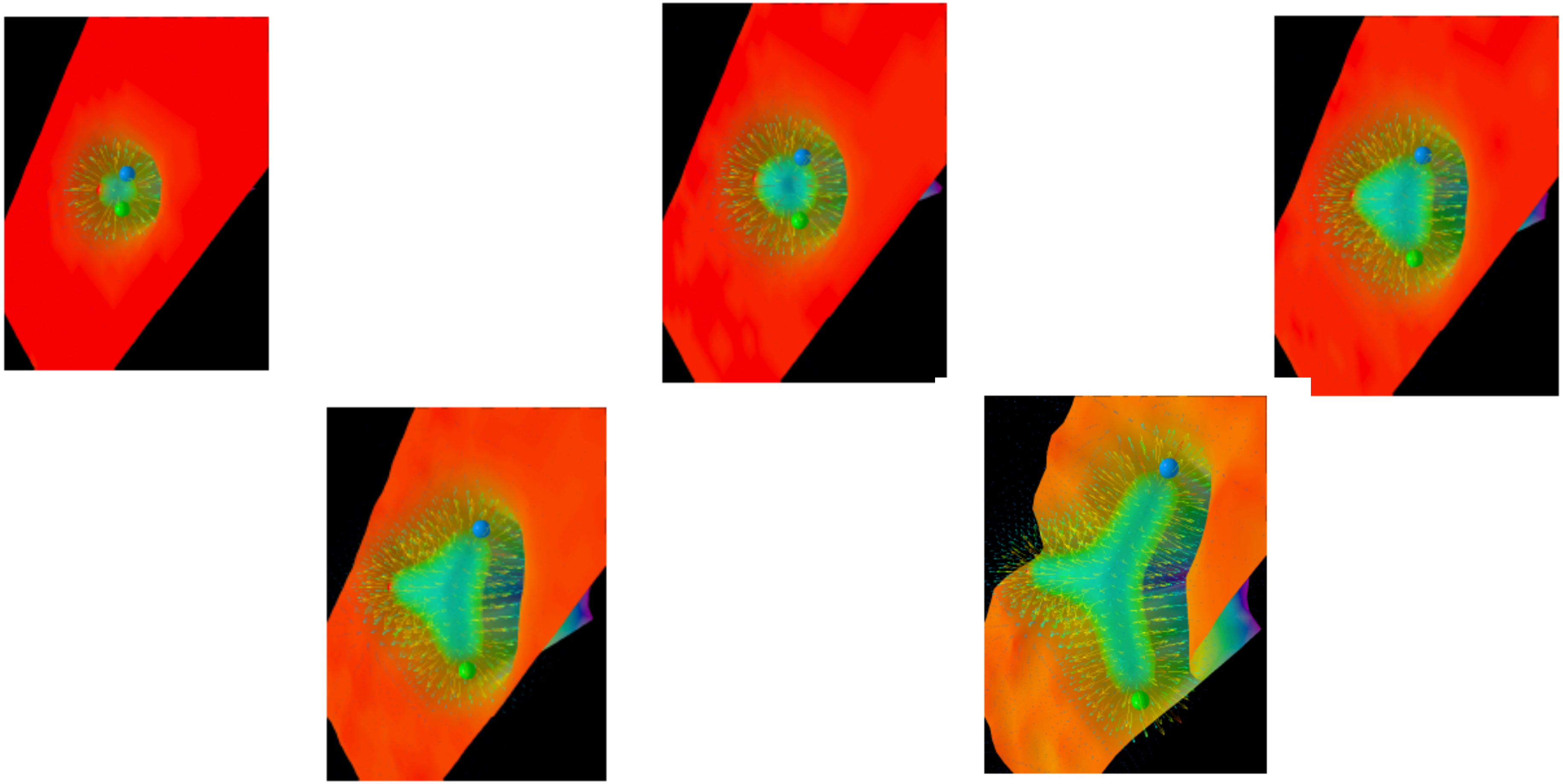
Table IIa

Simplest mesons and baryons : colour structure and string picture

HADRON	GAUGE INVARIANT OPERATOR	STRING PICTURE
$M_2 = q\bar{q}$ meson	$\bar{q}^{j_2}(x_2)\left[P\exp\left(ig\int_{x_1}^{x_2} A_\mu\, dx^\mu\right)\right]^{j_1}_{j_2} q_{j_1}(x_1)$	
M_0 = quarkless meson	$\mathrm{Tr}\left[P\exp\left(ig\oint A_\mu\, dx^\mu\right)\right]$	
$B_3 = qqq$ baryon	$\epsilon^{j_1 j_2 j_3}\left[P\exp\left(ig\int_{x_1}^{x} A_\mu\, dx^\mu\right) q(x_1)\right]_{j_1}$ $\left[P\exp\left(ig\int_{x_2}^{x} A_\mu\, dx^\mu\right) q(x_2)\right]_{j_2} \left[P\exp\left(ig\int_{x_3}^{x} A_\mu\, dx^\mu\right) q(x_3)\right]_{j_3}$	

G.C. Rossi and GV, 1977 + Phys. Rep. 1980

Junction clearly seen in lattice simulations when the three (static) quarks are pushed apart. J sits at the Fermat-Torricelli point! (Bissey et al. 2006)



Does the junction weigh?

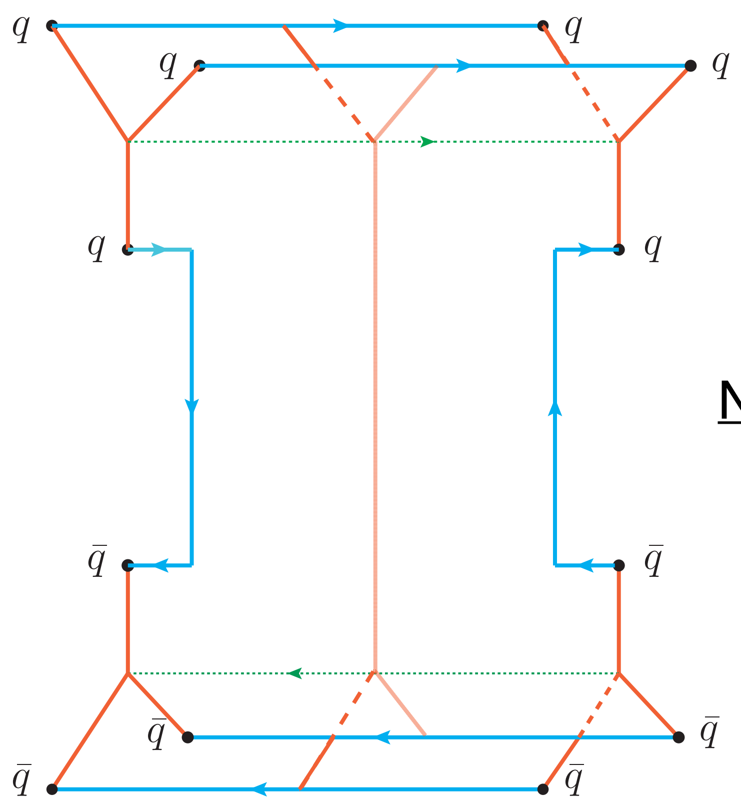
In order to fit hadron masses using only constituent quark masses one needs to introduce different masses for quarks in mesons and baryons (by about 55 MeV).

However, by adding an effective junction mass term (of ~165 MeV), one can recover universality of quark masses even for multiquark states.

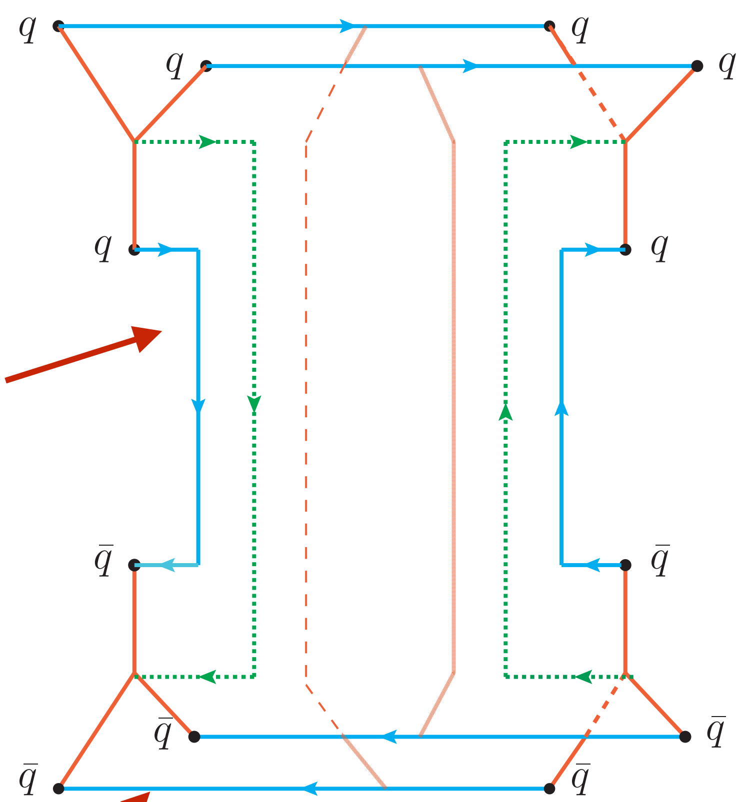
(Karliner-Nussinov-Rosner, 1611.00348)

Tracking junction's flow is crucial! Tracks B# flow!

Rosner's diagram & one w/ same valence-quark/flavor flow



Not Rosner!



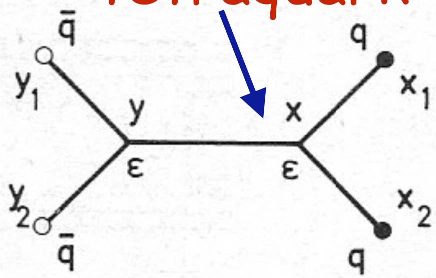
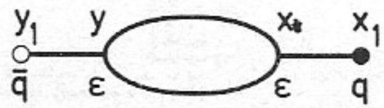
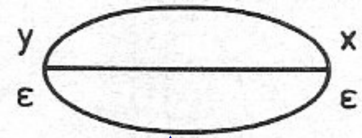
s-channel scattering thru tetraquark states, dual to qqbar meson exch.

s-channel BBbar annihilation into 2-meson states, dual to qqbar states w/ junctions

What's dual to what?

Table 2b

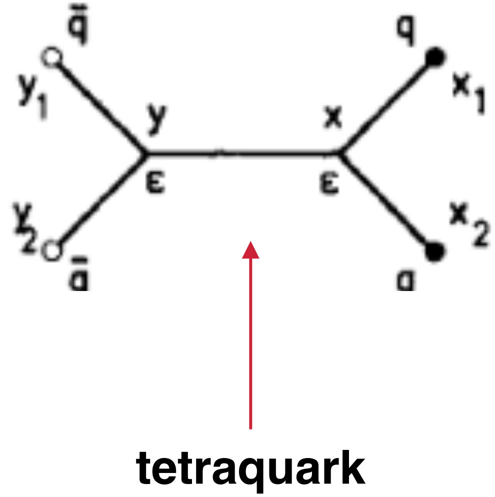
The three ($N_c = 3$) baryonium families: colour structure and string picture. The symbol $\exp\int_x^y$ is a shorthand for the path ordered exponential used in table 2a

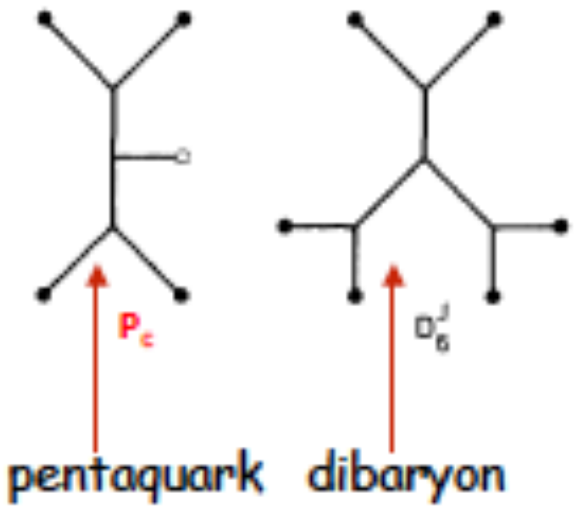
	Hadron	Gauge invariant operator	String picture	
to 1 meson	M_4^J = baryonium with $qq\bar{q}\bar{q}$ quantum numbers	$\varepsilon_{j_1j_2j_3}\varepsilon^{k_1k_2k_3}\left[\bar{q}(y_1)\exp\int_y^{y_1}\right]^{j_1}\left[\bar{q}(y_2)\exp\int_y^{y_2}\right]^{j_2} \times \left[\exp\int_x^{y}\right]^{j_3}_{k_1}\left[\exp\int_{x_1}^{x} q(x_1)\right]_{k_2}\left[\exp\int_{x_2}^{x} q(x_2)\right]_{k_3}$	tetraquark 	J_4
to 2 mesons	M_2^J = baryonium with $q\bar{q}$ quantum numbers	$\varepsilon_{j_1j_2j_3}\varepsilon^{k_1k_2k_3}\left[\bar{q}(y_1)\exp\int_y^{y_1}\right]^{j_1} \times \left[\exp\int_x^{y}\right]^{j_2}_{k_1}\left[\exp\int_x^{y}\right]^{j_3}_{k_2}\left[\exp\int_{x_1}^{x} q(x_1)\right]_{k_3}$	qqbar w/ JJbar 	J_2
to 3 mesons	M_0^J = quarkless baryonium	$\varepsilon_{j_1j_2j_3}\varepsilon^{k_1k_2k_3}\left[\exp\int_x^{y}\right]^{j_1}_{k_1}\left[\exp\int_x^{y}\right]^{j_2}_{k_2}\left[\exp\int_x^{y}\right]^{j_3}_{k_3}$	 JJbar glueball	J_0

J implies existence of exotic (multiquark) hadrons (Artru 1975, Rossi & GV 1977)

M_4^J = baryonium with $qq\bar q\bar q$ quantum numbers

$$\varepsilon_{j_1j_2j_3}\varepsilon^{k_1k_2k_3}\left[\bar q(y_1)\exp\int_y^{y_1}\right]^{j_1}\left[\bar q(y_2)\exp\int_y^{y_2}\right]^{j_2}$$
$$\times\left[\exp\int_y^{x}\right]^{j_3}_{k_1}\left[\exp\int^{x} q(x_1)\right]_{k_2}\left[\exp\int^{x} q(x_2)\right]_{k_3}$$





Main question for this talk: Are there manifestations of the junction for light (and fast moving) quarks/hadrons?

But first back to mesons as QCD strings.

Mesons & glueballs @ large N_c

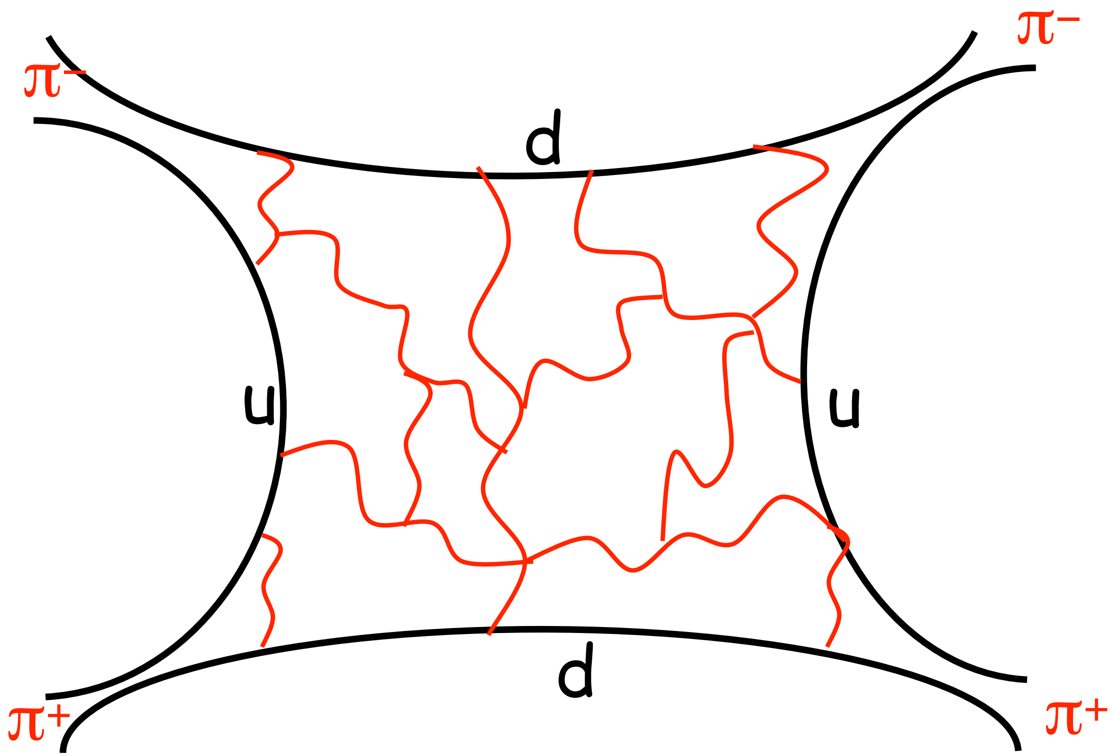
't Hooft 1974

(SU(N_c) QCD @ large N_c w/ N_f and $\lambda = \lambda_t = g^2 N_c$ fixed)

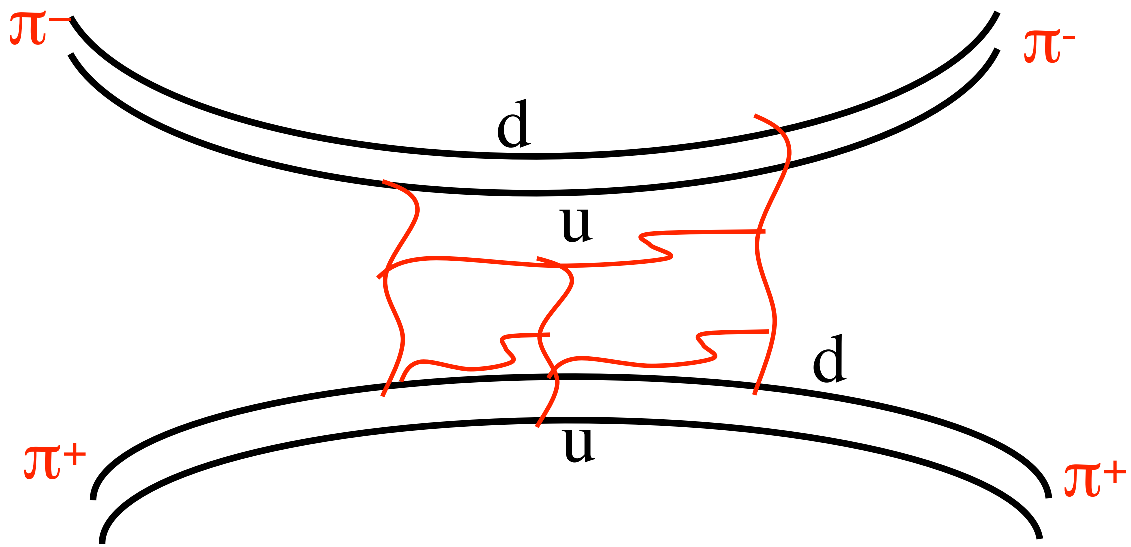
Duality diagrams correspond to the sum of planar diagrams

Both quark loops and non-planar diagrams are excluded.

Hadrons do not decay (tree approximation of **a** string theory)
Irreducible and reducible singlets do not talk to each other.



Similarly: Pomeron ~ glueballs



In 't Hooft's limit glueballs are also stable and do not mix w/ q-qbar states (GV 1976)

Baryons @ large N_c
(E. Witten NPB, 1979)

Baryons as solitons since

$M \sim N_c \sim g^{-2}$

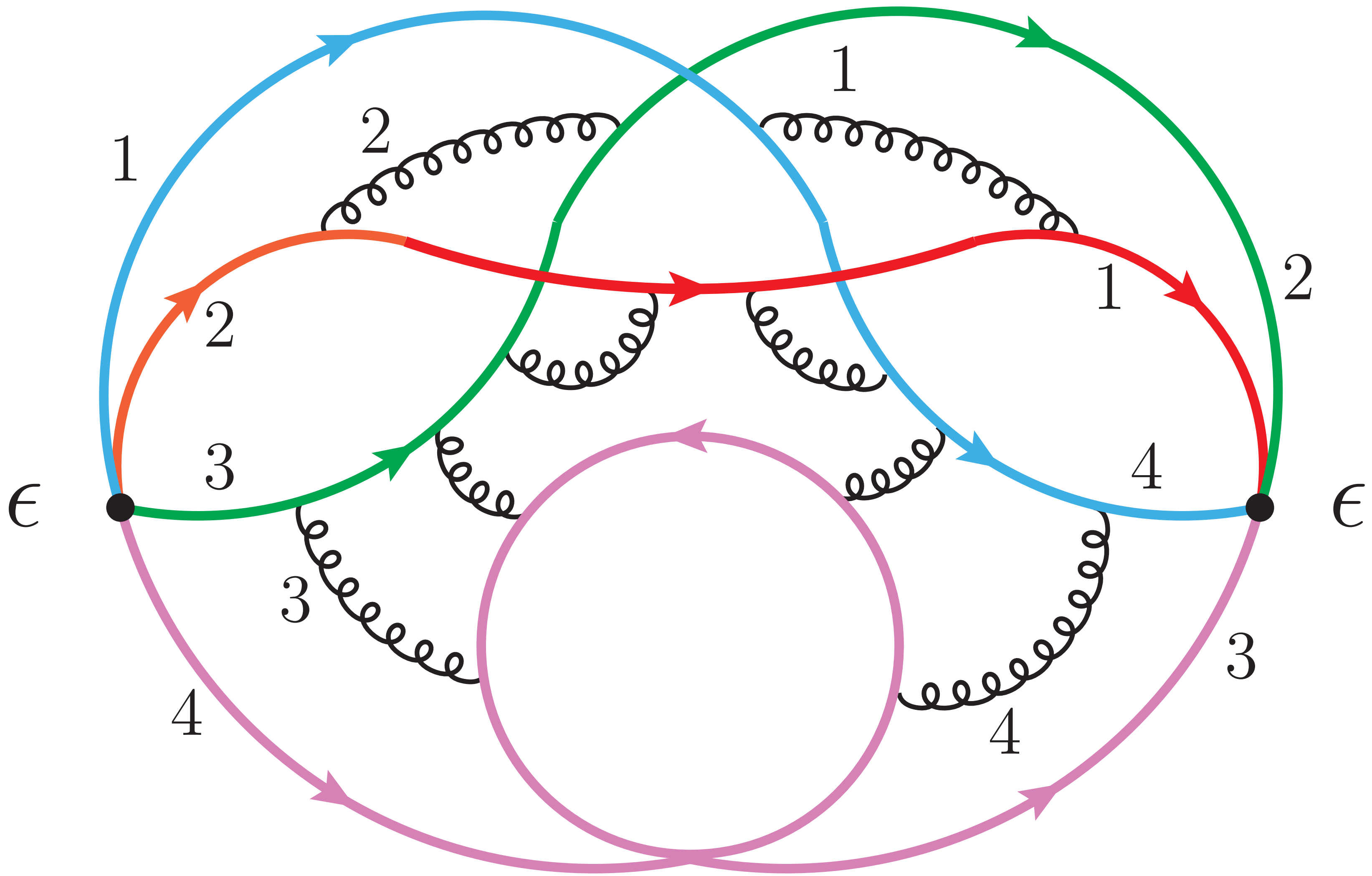
N_c-body bound state problem

through n-body inter.^{ns} ($n \leq N_c$)

Q: Can we define some analog of the large-N_c expansion for baryons?

A: Non-trivial but most likely yes through some new topological rules. (G.C.Rossi & GV, 1603.05830)

It can be done for the n-body potential if $n \ll N_c$.



Leading diagrams for n=4 potential @ large N_c
(colors denote flavor)

Mesons & glueballs @ large N_c & N_f: OZI rule

Irreducible and reducible singlets do talk to each other… but with restrictions

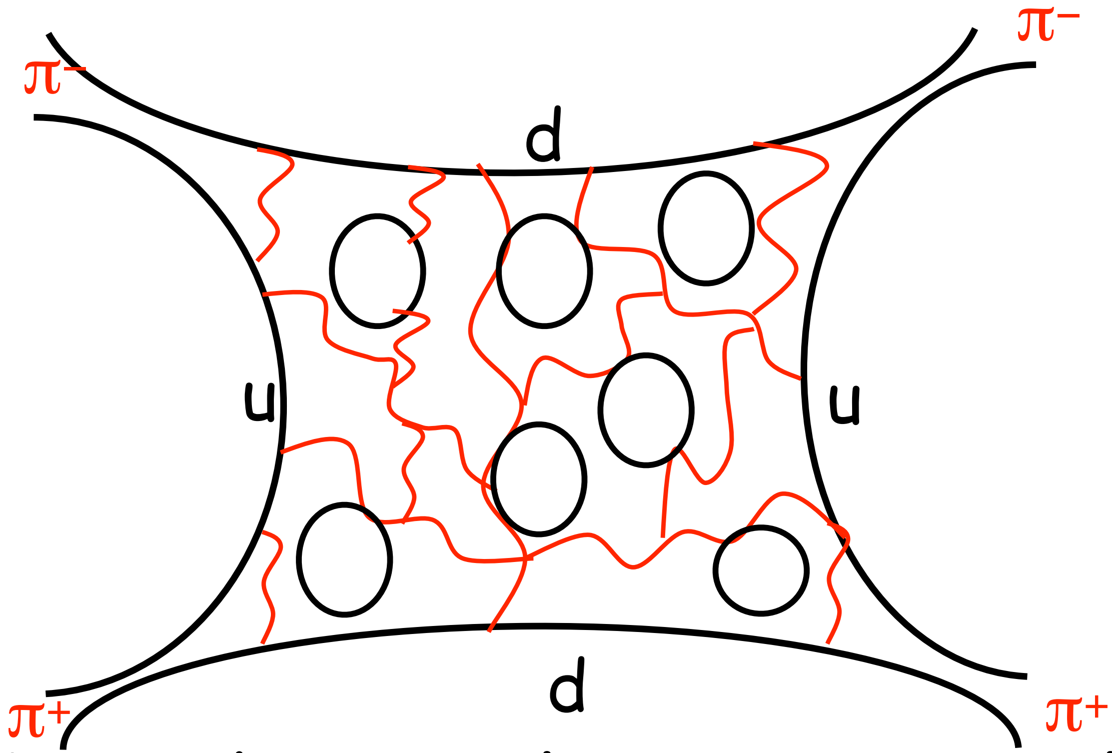
QCD Topological expansion, GV 1976

($SU(N_c)$ @ large N_c w/ N_f/N_c & $\lambda = g^2N$ fixed)

Planar diagrams w/ quark loops are now included (unquenched)

Hadrons get a finite width $O(N_f/N)$

Quarkonia decay via string breaking i.e. obey OZI (narrow!)



Glueballs & quarkonia only mix at non-planar/NL level

OZI rule

Large-N expansions support the usual OZI (Okubo-Zweig-Iizuka) rule suppressing decays that proceed via q-qbar annihilation wrt decays by string breaking (& creation of a q-qbar pair).

Well obeyed (also wrt mixing) in vector mesons; badly broken in light pseudoscalar sector. Reasons:

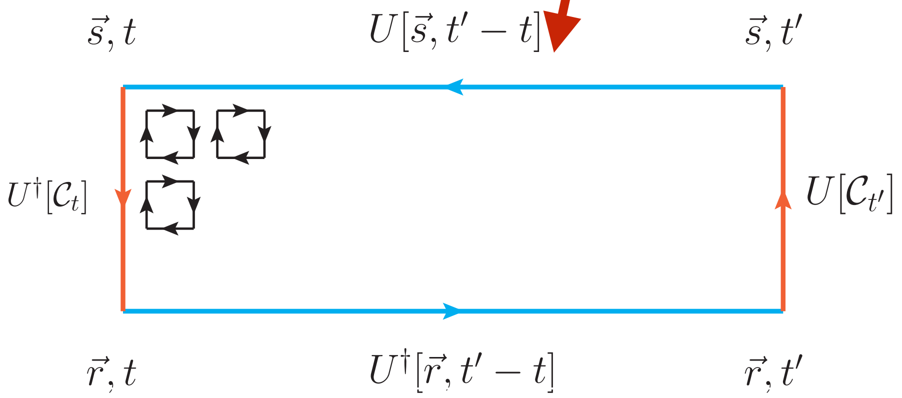
Light masses of PNG bosons

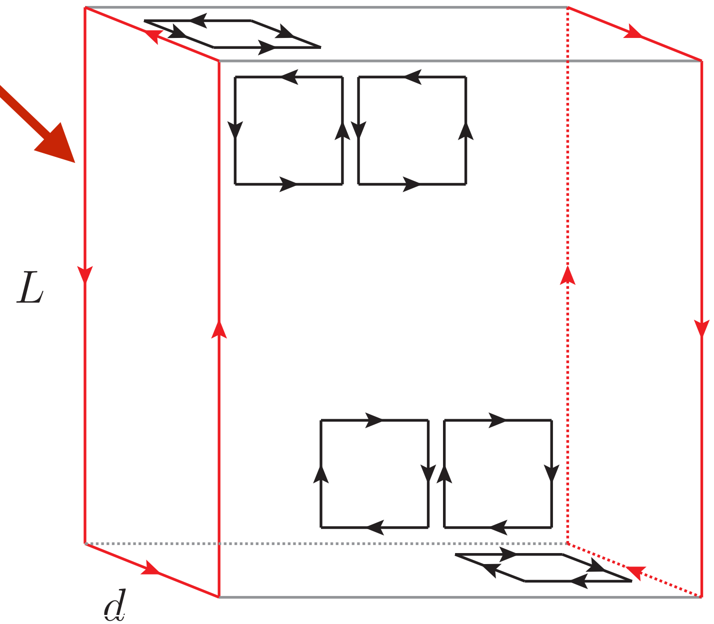
Large anomaly contribution in that channel (solution of U(1) problem, proton spin crisis)

LQCD @ strong λ

Mesons & glueballs

Meson/glueball propagators and corresponding Wilson loops show confining potential





with a string tension:

$$\kappa = \frac{1}{a^2} \log g^2 N$$

twice as large for glueballs

$$\kappa = \frac{1}{a^2} \log g^2 N$$

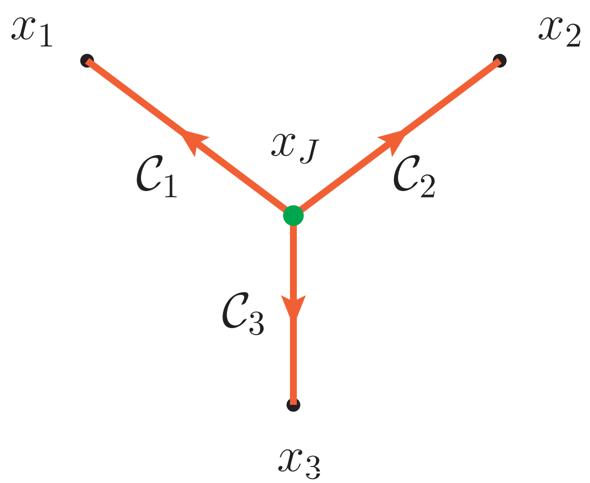
Note that the tension depends on the combination $\lambda = g^2N$, the 't Hooft coupling.

Indeed, one can argue (O' Brien-Zuber '85) that the strong-coupling expansion, at least for the meson sector, is actually a large-λ expansion*).

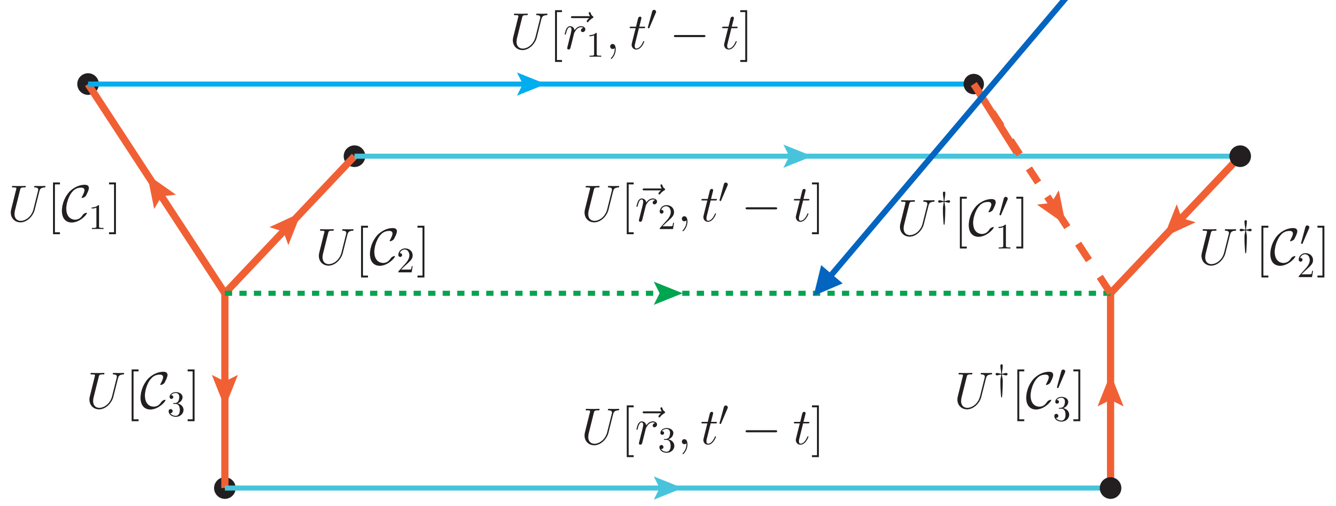
*) Also used in the AdS/CFT correspondence. Junction (renamed "baryon vertex") appears there as well!

Baryons & Multiquarks

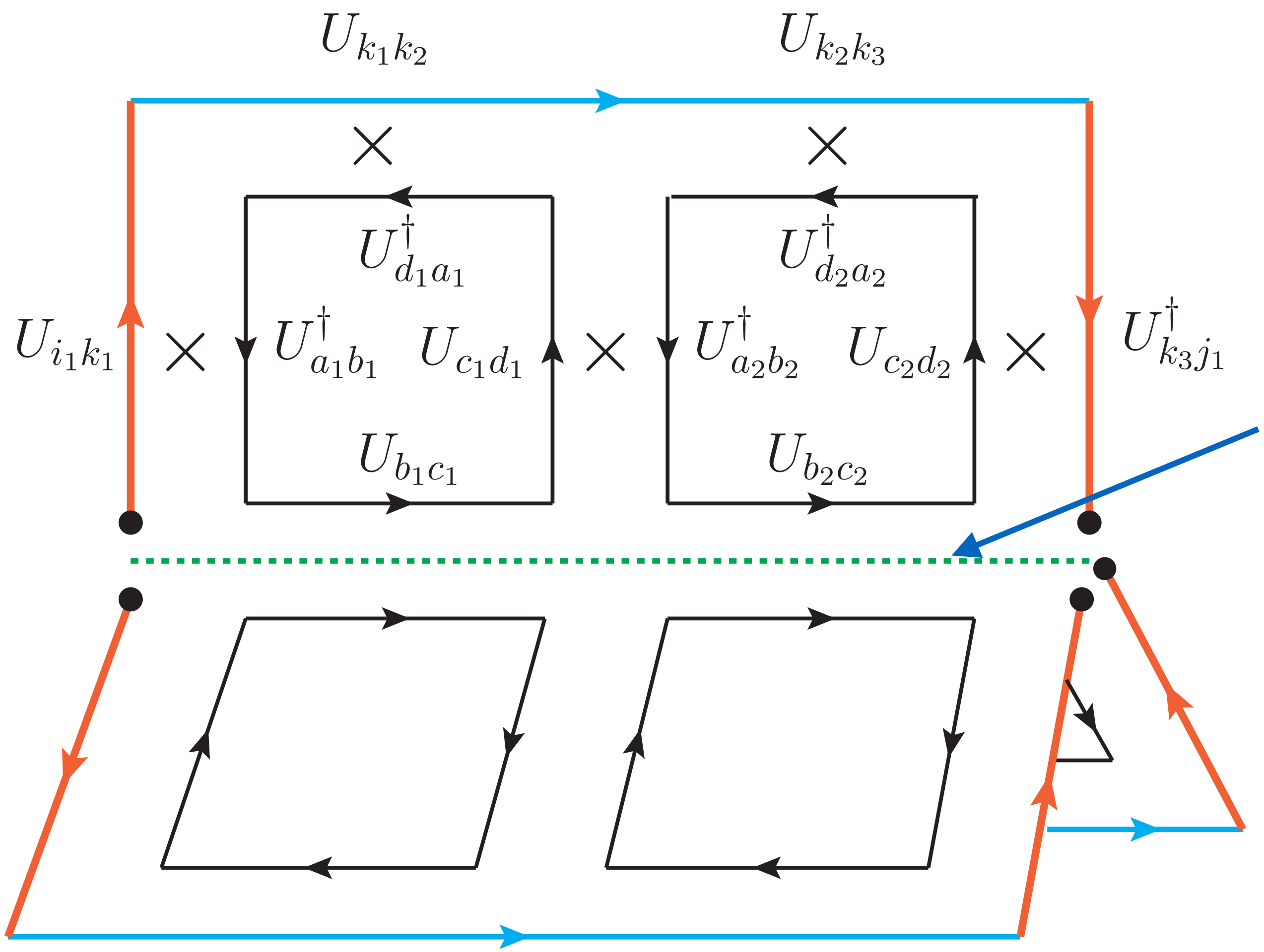
Baryon and its propagator as a baryonic Wilson loop (BWL)



junction line actually not there in BWL!



Baryonic Wilson loop in strong coupling LQCD



junction line emerges from tiling rules!

Tiling w/ minimum # of tiles gives same tension as for mesonic WL (wrt total area of the "book's pages")

JOZI rule (G.C. Rossi and GV, 1977)

Large-N expansions (Witten 1979, G.C.R. & GV 2016) and strong coupling expansions (G.C.R. & GV 2016) also support a junction OZI (JOZI) rule suppressing decays that proceed via JJbar annihilation (leading to mesonic decays) wrt decays by string breaking (leading to BBbar decays)

We thus expect (some) tetraquark states lying below threshold for baryonic decays to be unusually narrow.

Premature claim? Exp. "confirmation" had to wait for heavy quark discovery (LHCb..)... although some of them are probably "molecules" (Karliner & Rosner)

Manifestations of J @ HE in the TE of QCD

based on some slides from a 2007 talk @ CERN (Alice) & earlier work by D. Kharzeev (1996)

CERN, 19/01/07

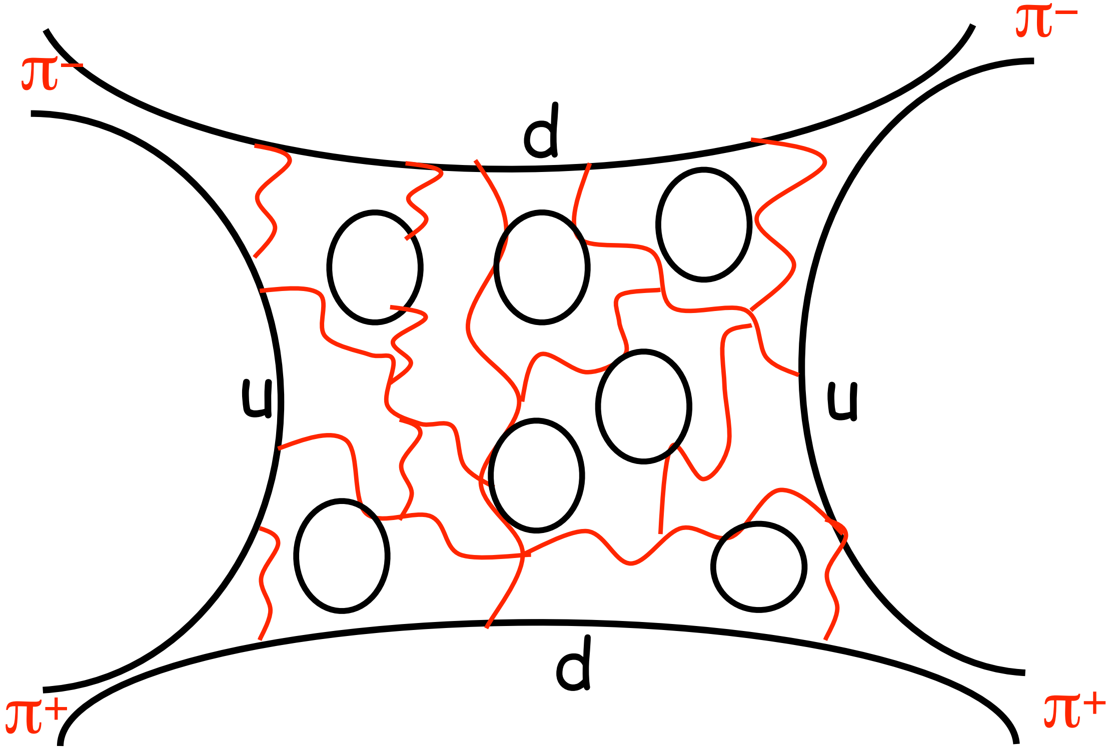
BARYON-NUMBER TRANSPORT AT LHC

(G. VENEZIANO PH/TH)

- HADRONS AS STRINGS IN QCD
- WHERE DOES FLAVOUR, BARYON# RESIDE?
- MESON-MESON SCATTERING
  - The cost of colour transport
  - The cost of $q\bar{q}$ annihilation
  - The cost of flavour transport
- MESON-BARYON SCATTERING
  - The cost of Baryon # transport
- BB, $B\bar{B}$ scattering
  - The cost of $J\bar{J}$ annihilation & B# transport
- BARYON # TRANSPORT AT LHC

Flavor annihilation/transport in MM and MB (forward) scattering

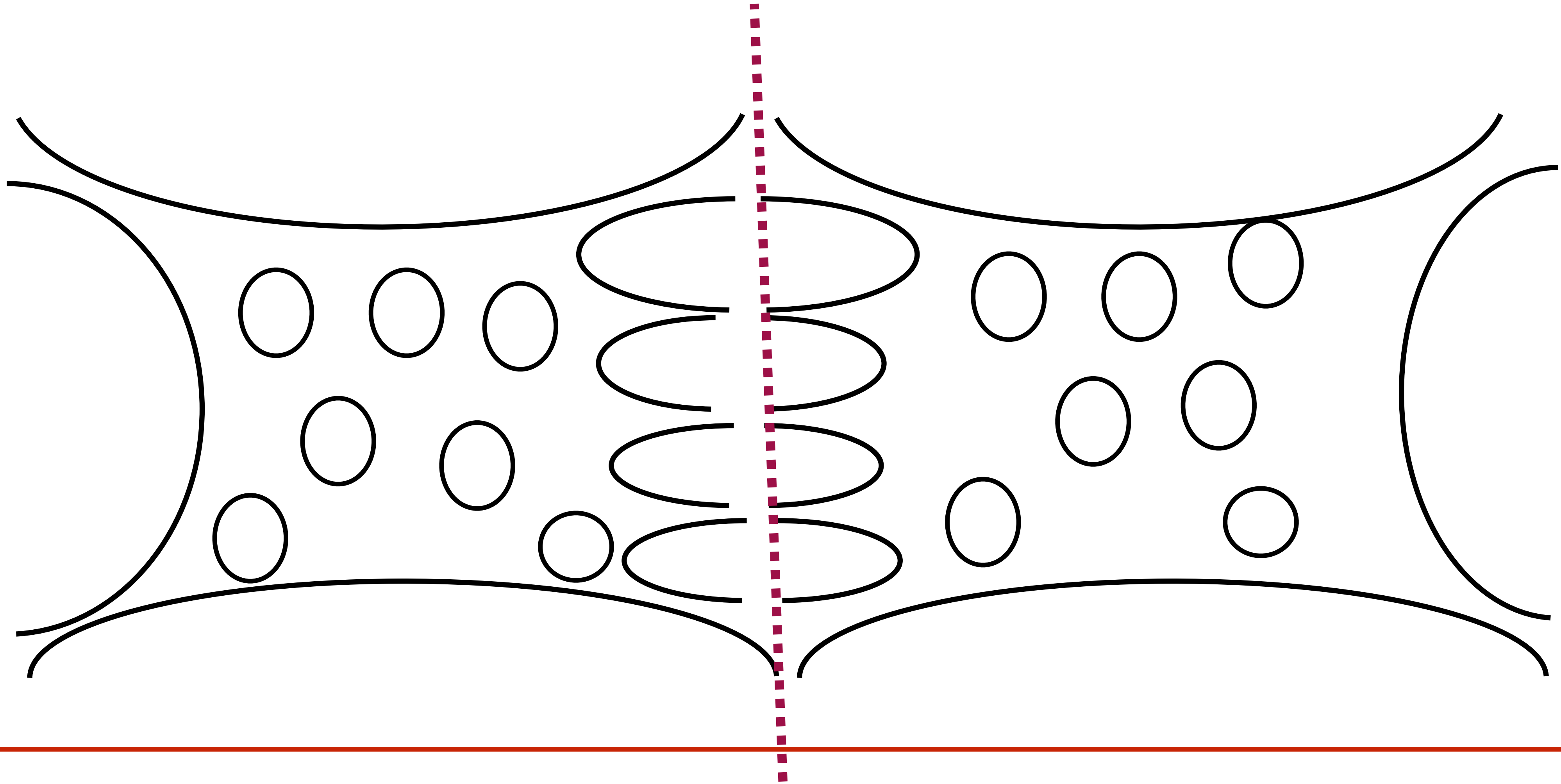
Meson-Meson scattering
(from previous slide)



Consider its s-clannel cuts

At leading order: planar unitarity/optical theorem

(gluons not shown)



$$2\ \mathrm{Im} A_{\mathrm{planar}}(2 \to 2) = \sum_n A_{\mathrm{planar}}(2 \to n) A^{\dagger}_{\mathrm{planar}}(n \to 2)$$

HE meson-meson scattering in the TE of QCD

At leading order in 1/N planar topology implies (via planar unitarity):

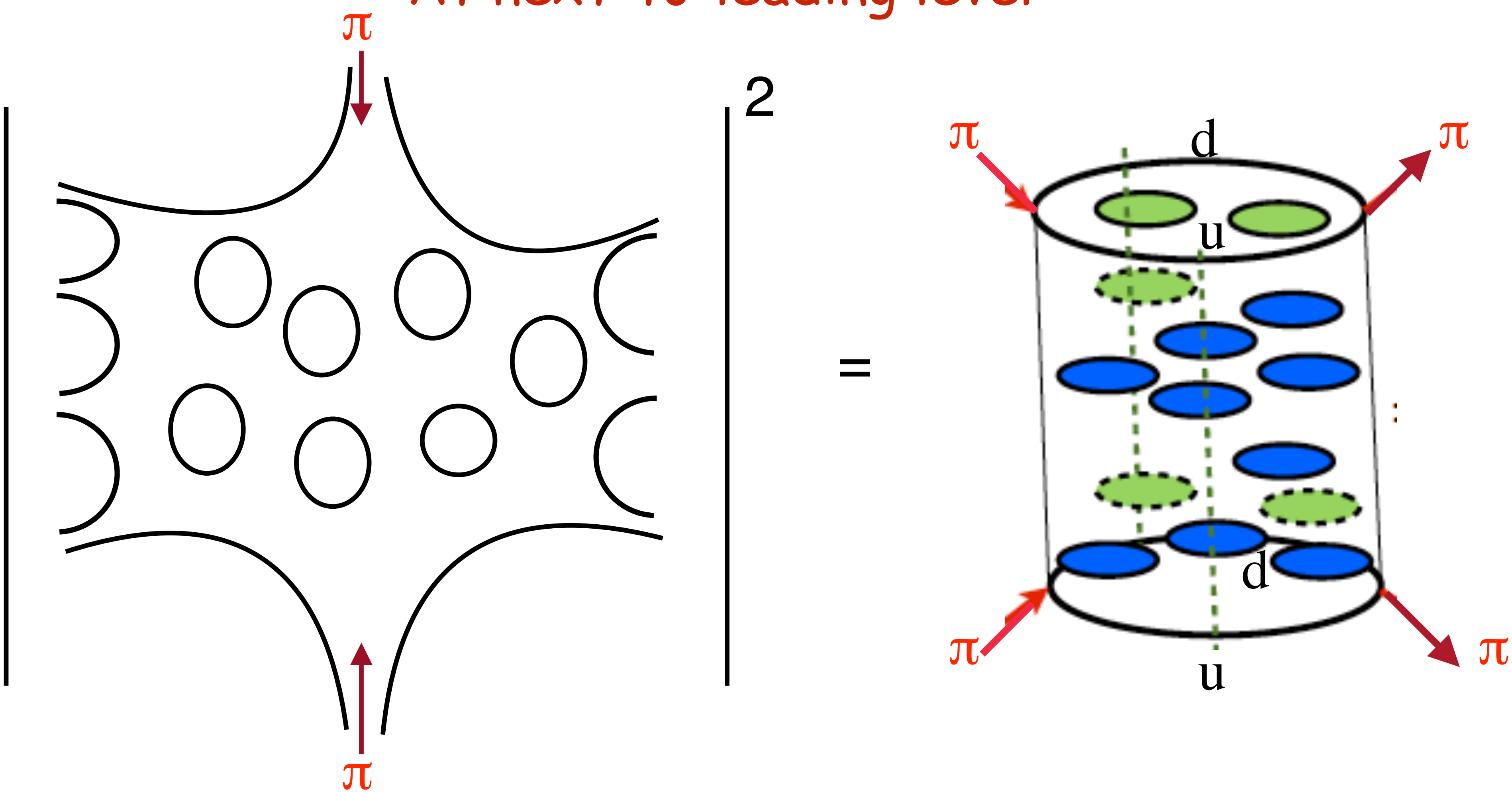
1. A 2->2 amplitude dominated by q-qbar exchange with an intercept $\alpha_R < 1$ (~ 0.5 for u,d mesons)

2. An elastic x-section going like $s^{2(\alpha_R-1)}$

3. A "total" x-section going like $s^{(\alpha_R-1)}$ via a planar optical theorem.

The price $s^{(\alpha_R-1)}$ comes from quark lines flowing uninterrupted from the forward to the backward region. Under x-ing they represent flavour annihilation or flavour flow between the two regions

At next-to-leading level



We can use Feynman's analog-gas model to argue that, if the two sets are weakly correlated, Dalton's law ($p = p_1+p_2$) guarantees that the totally inclusive x-section is roughly constant at high energy (GV 1973, Huan Lee 1973)

At next to leading order in 1/N the cylinder topology implies:

1. A 2->2 amplitude dominated by vacuum exchange with an intercept $\alpha_P \sim 1$ (bare Pomeron).

2. An elastic x-section going like $s^{2\alpha_P - 2}$

3. A total x-section going like $s^{\alpha_P - 1}$ via a non-planar optical theorem.

We are paying a 1/N price but we gain at high energy by not requiring flavour annihilation/ transport between the forward and backward regions.

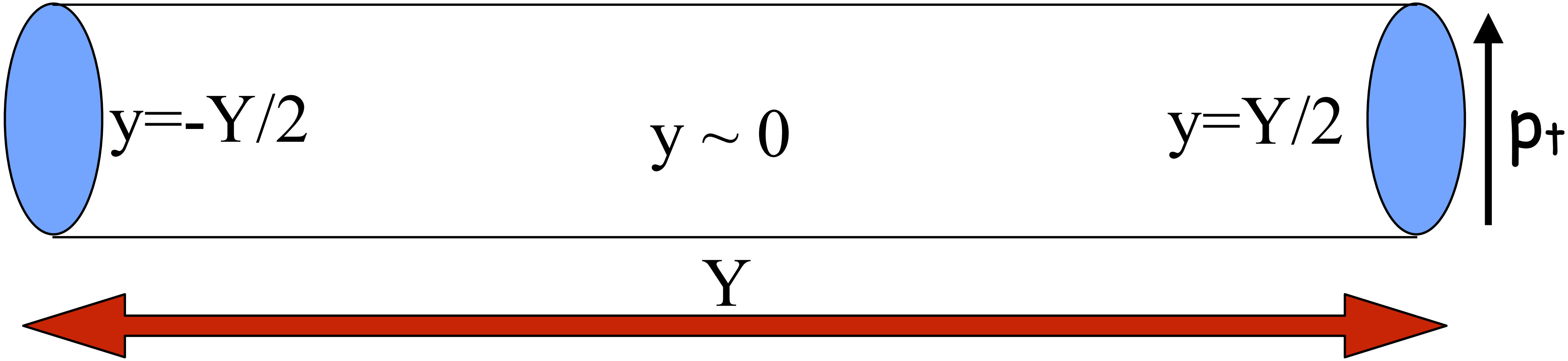
Color transport is free...

Feynman's analog gas model
(private comm. to Ken Wilson, 1970)

K.G. Wilson, Proc. 14th Scottish Universities Summer School in Physics (1973)

An analog gas/fluid living in momentum space: limited transverse momentum and an increasing (with E) longitudinal one.
After integrating over p_t it becomes one dimensional (rapidity y).

A very nice and intuitive description of soft high energy inclusive/exclusive x-sections. Final particles fill up this tube as gas molecules...



$$E \pm p_z = |p_t| e^{\pm y} \;\; ; \quad -\log(E/p_t) < y < +\log(E/p_t) \;\; ;$$

$$Y = \log(E^2/p_t^2) = \log(s/p_t^2)$$

RF introduced the concepts of a generating function Σ(z) from which one can get exclusive (inclusive) x-sections by expanding around z =0 (z=1). Assuming short-range correlations (as implied by Regge-pole dominance), log Σ can be expanded in terms of such correlations:

$$\Sigma(z) = \frac{1}{\sigma_t} \sum_n z^n \sigma_n = \exp\left(\sum_m \frac{(z-1)^m}{m!} C_m Y \right)$$

$$C_1 Y = \langle n \rangle \; ; \; C_2 Y = \langle n(n-1) \rangle - \langle n \rangle^2 \; ; \; \ldots$$

In analogy with Stat.Mech. Σ ~ part. function, log Σ~ free energy, Y~ volume.

Then thermodynamics gives the pressure as

$$\Sigma(z) = \exp(p(z)Y) \sim s^{p(z)} \;;\; p(z) \equiv \sum_m \frac{(z-1)^m}{m!} C_m$$

Therefore p(z) gets related to the Regge behavior of x-sections! Planar bootstrap gives:

$$p(1) - p(0) = (1 - \alpha_R(0))$$

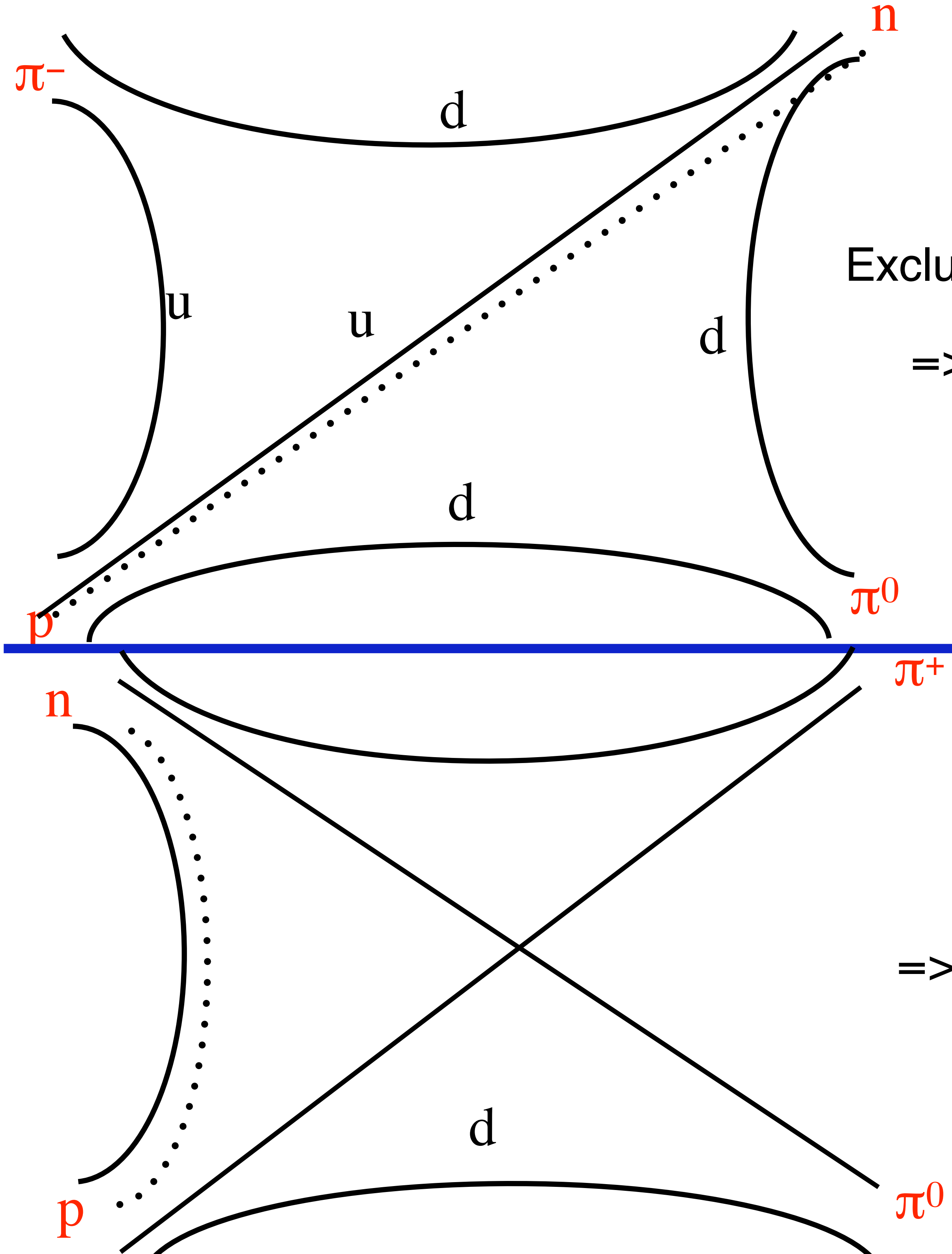
In the (cut) cylinder two species contribute to the pressure => $p(z_1,z_2) = Y^{-1} \log \Sigma(z_1,z_2)$. If the two species are weakly interacting, Dalton's law gives

$$p(1,1) - p(0,0) = 2(p(1,0) - p(0,0)) = 2\,(1 - \alpha_R(0))$$

and then $\alpha_P \sim 1$ (GV, PLB1973, see also H.Lee, PRL1973)

Baryon # transport in HE <u>backward</u> MB scattering

(HE M-B forward scattering
is copy and paste from M-M!)



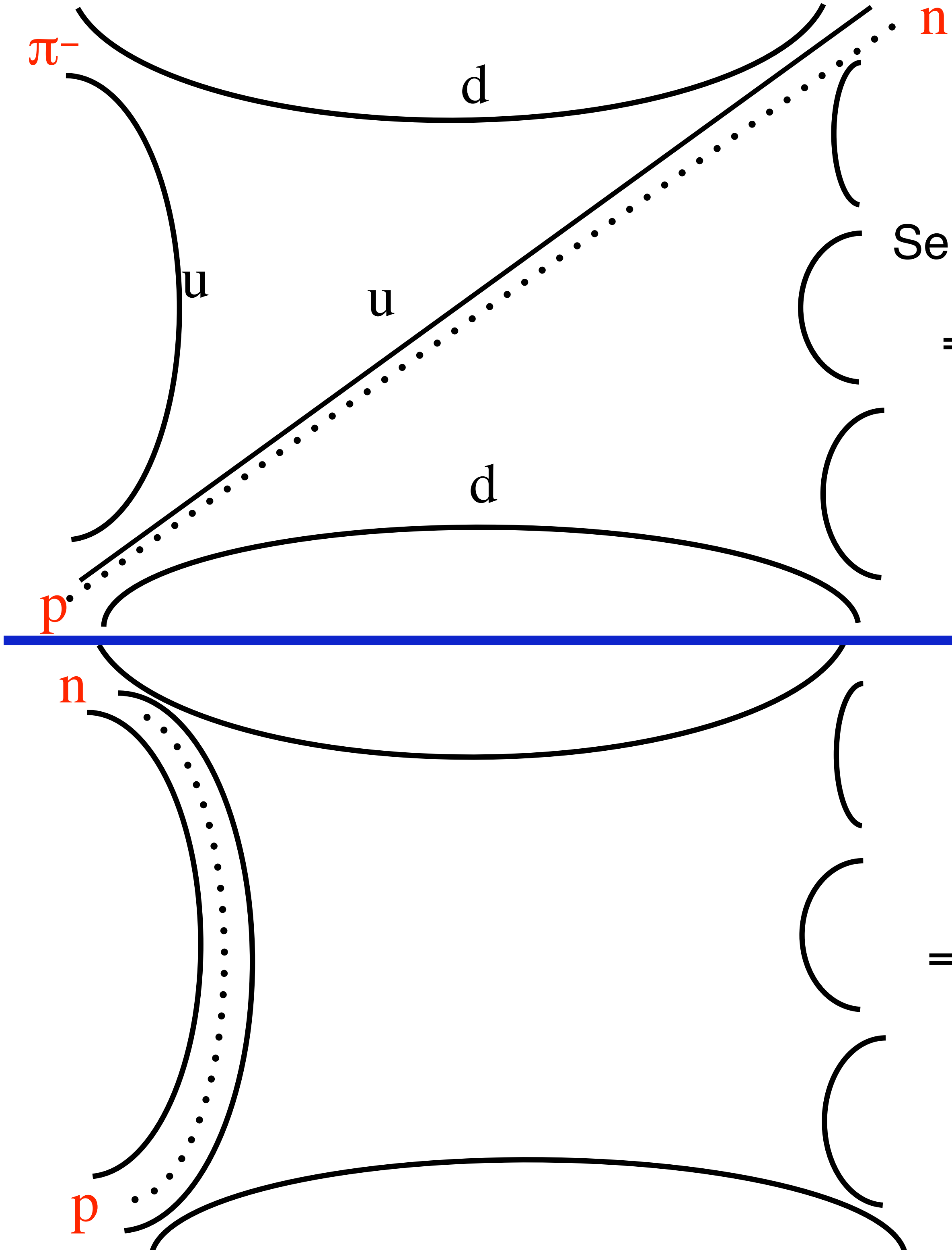
Exclusive backward scattering

=> $d\sigma/du \sim s^{2(\alpha B-1)}$

x-ing related

=> $d\sigma/dt \sim s^{2(\alpha B-1)}$

Exclusive annihilation



Semi-inclusive backward scattering

=> $d\sigma/du \sim s^{\alpha_T-1}$

T for tetraquark

=> $d\sigma/dt \sim s^{\alpha_T-1}$

Semi-inclusive annihilation

1. A 2->2 amplitude dominated by B exchange with an intercept α_B (exp.~ 0)

2. An exclusive x-section $d\sigma/du \sim s^{2(\alpha_B-1)}$

3. A partially inclusive x-section going like s^{α_T-1} via planar optical theorems.

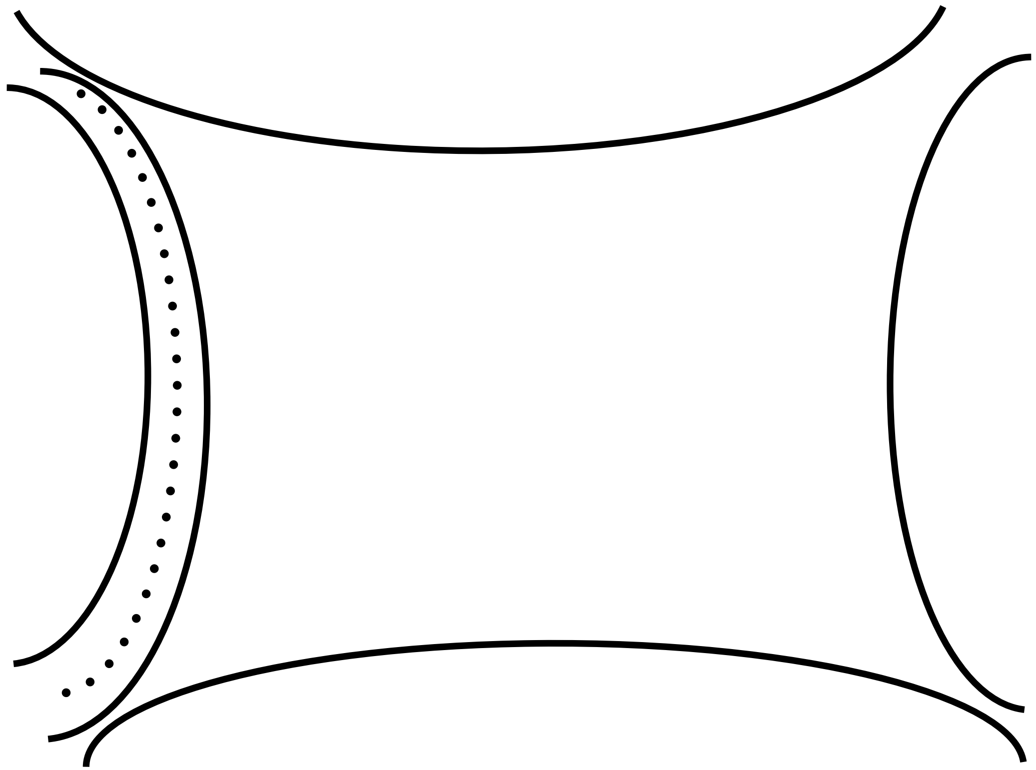
The price s^{α_T-1} comes from a junction line (plus two valence quark lines) flowing from the forward to the backward region.

Under x-ing it represents either B# annihilation or B# flow between the two hemispheres.

Clearly α_T represents a bosonic trajectory containing a J-Jbar pair plus 4 quarks. Estimate:

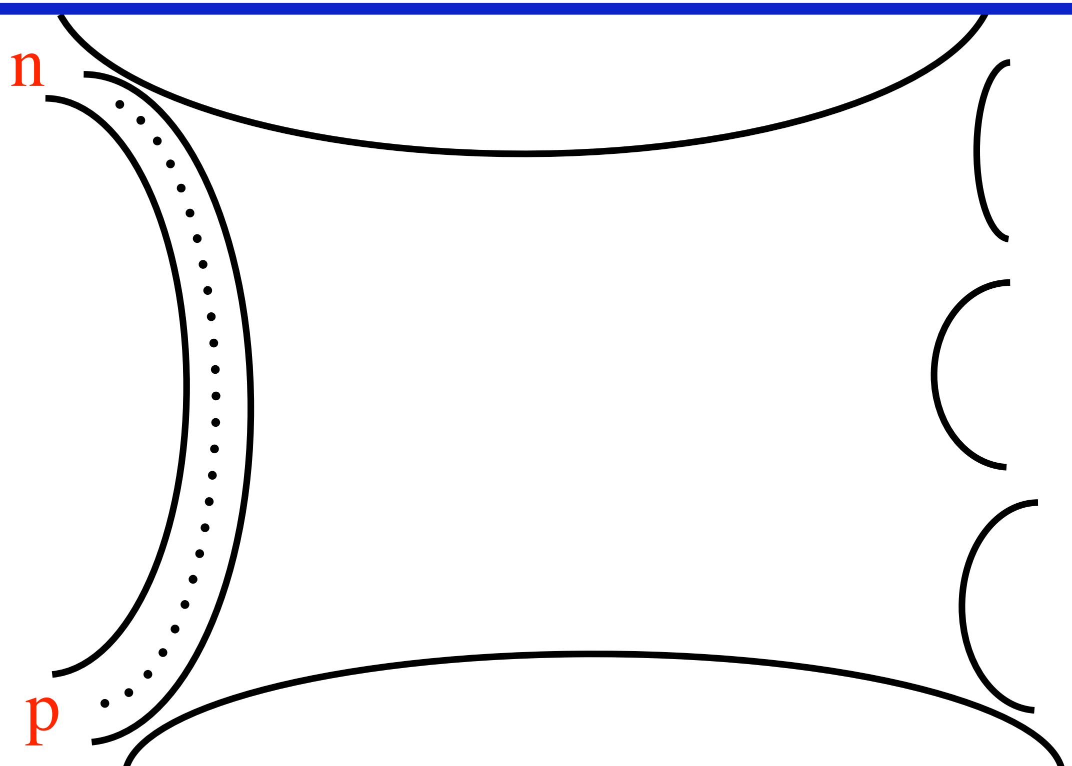
$$\boxed{(1-\alpha_T(0)) \sim 2(1-\alpha_B(0)) - (1-\alpha_R(0)) \Rightarrow \alpha_T(0) \sim -0.5}$$

Baryon # annihilation in HE BBbar scattering



=> $d\sigma/dt \sim s^{2(\alpha B-1)}$

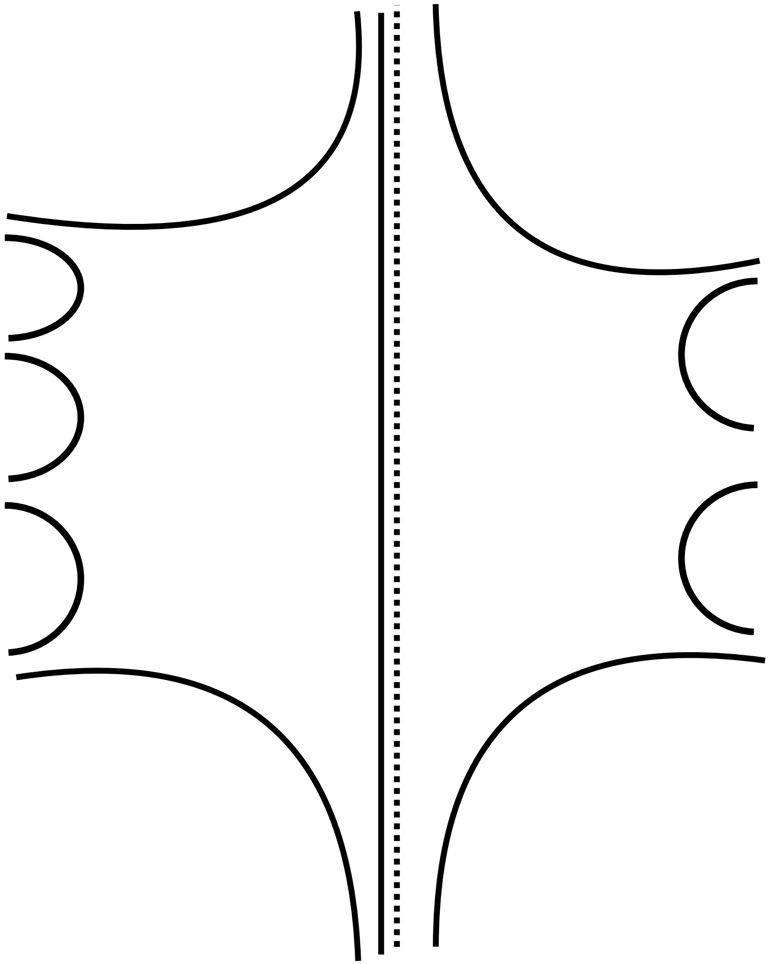
Exclusive annihilation



=> $d\sigma/dt \sim s^{\alpha_T-1}$

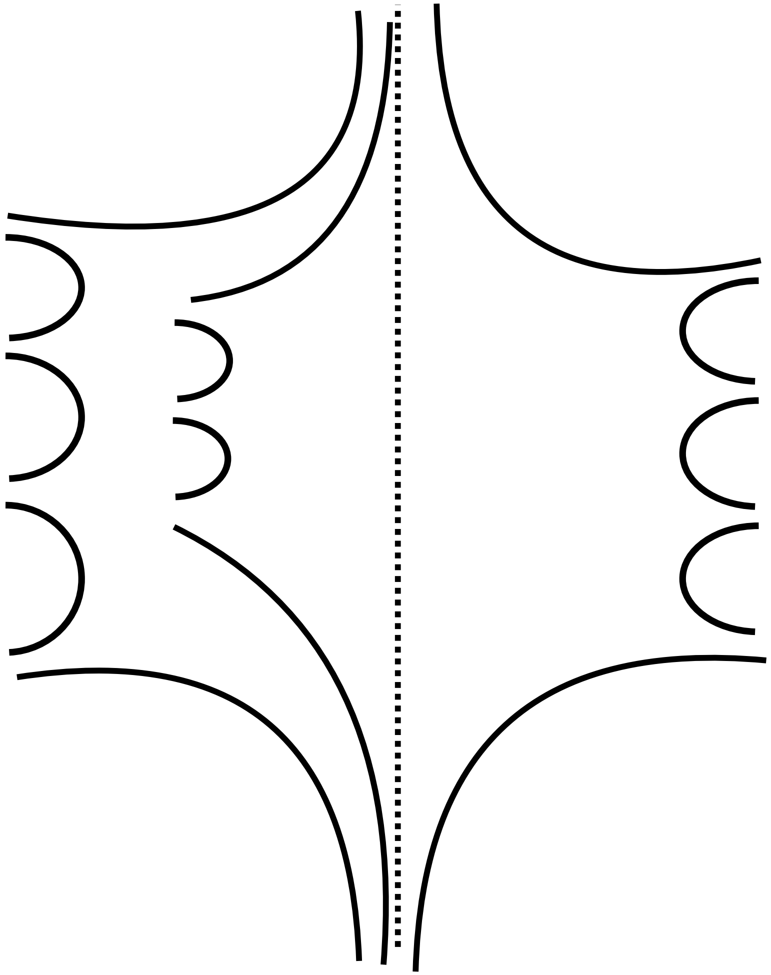
Semi^2-inclusive annihilation

Baryon # annihilation



Semi-inclusive annihilation

$d\sigma/du \sim s^{\alpha_{J2}-1}$



Fully-inclusive annihilation

$d\sigma/dt \sim s^{\alpha_{J0}-1}$

The price $s^{\alpha_T - 1}$ came from a junction line (plus two valence quark lines) flowing from the forward to the backward region. Similarly:

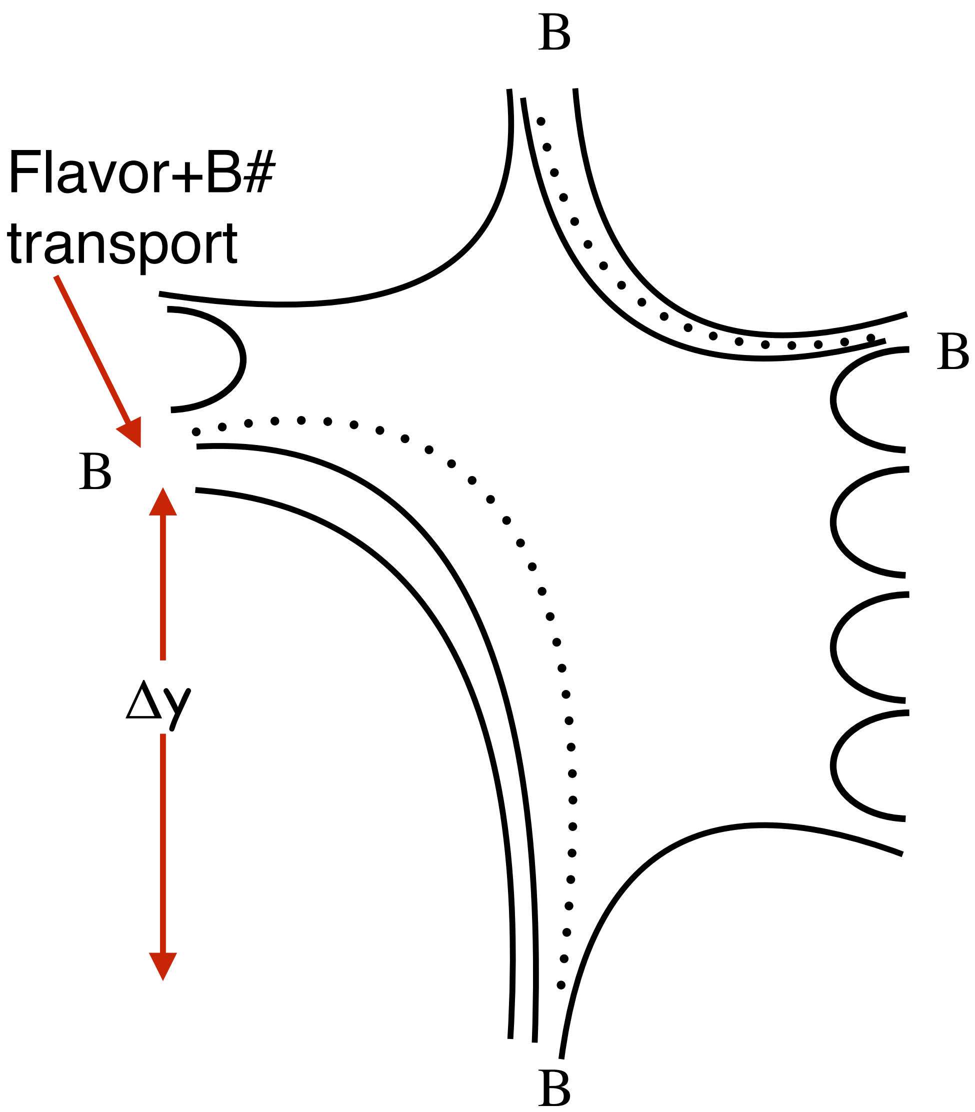
The price $s^{\alpha_{J2} - 1}$ comes from a junction line (plus one valence quark line) flowing from the forward to the backward region. α_{J2} represents a bosonic trajectory with two quarks and two junctions

The price $s^{\alpha_{J0} - 1}$ comes from a junction line flowing from the forward to the backward region. α_{J0} represents a bosonic trajectory with just two junctions. In this notation $T = J4$.

Feynman-gas estimates for α_{J2} and α_{J0} are simply:

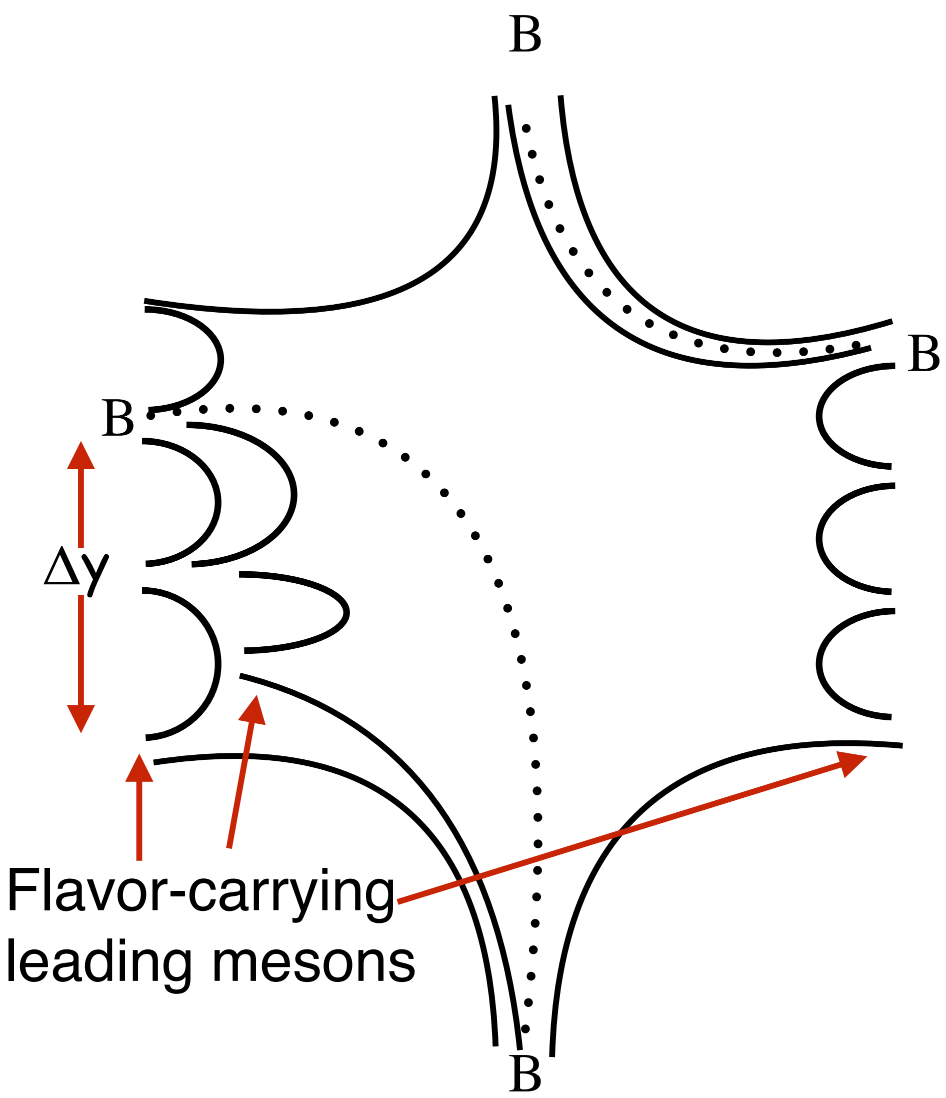
$$(1 - \alpha_{J2}(0)) \sim 2(1 - \alpha_B(0)) - 2(1 - \alpha_R(0)) \Rightarrow \alpha_{J2}(0) \sim 0$$
$$(1 - \alpha_{J0}(0)) \sim 2(1 - \alpha_B(0)) - 3(1 - \alpha_R(0)) \Rightarrow \alpha_{J0}(0) \sim 0.5$$

Baryon # transport in BB scattering



Semi-inclusive B# transport

$$d\sigma/dy \sim e^{-\Delta y(1-\alpha_T)}$$



Fully-inclusive B# transport

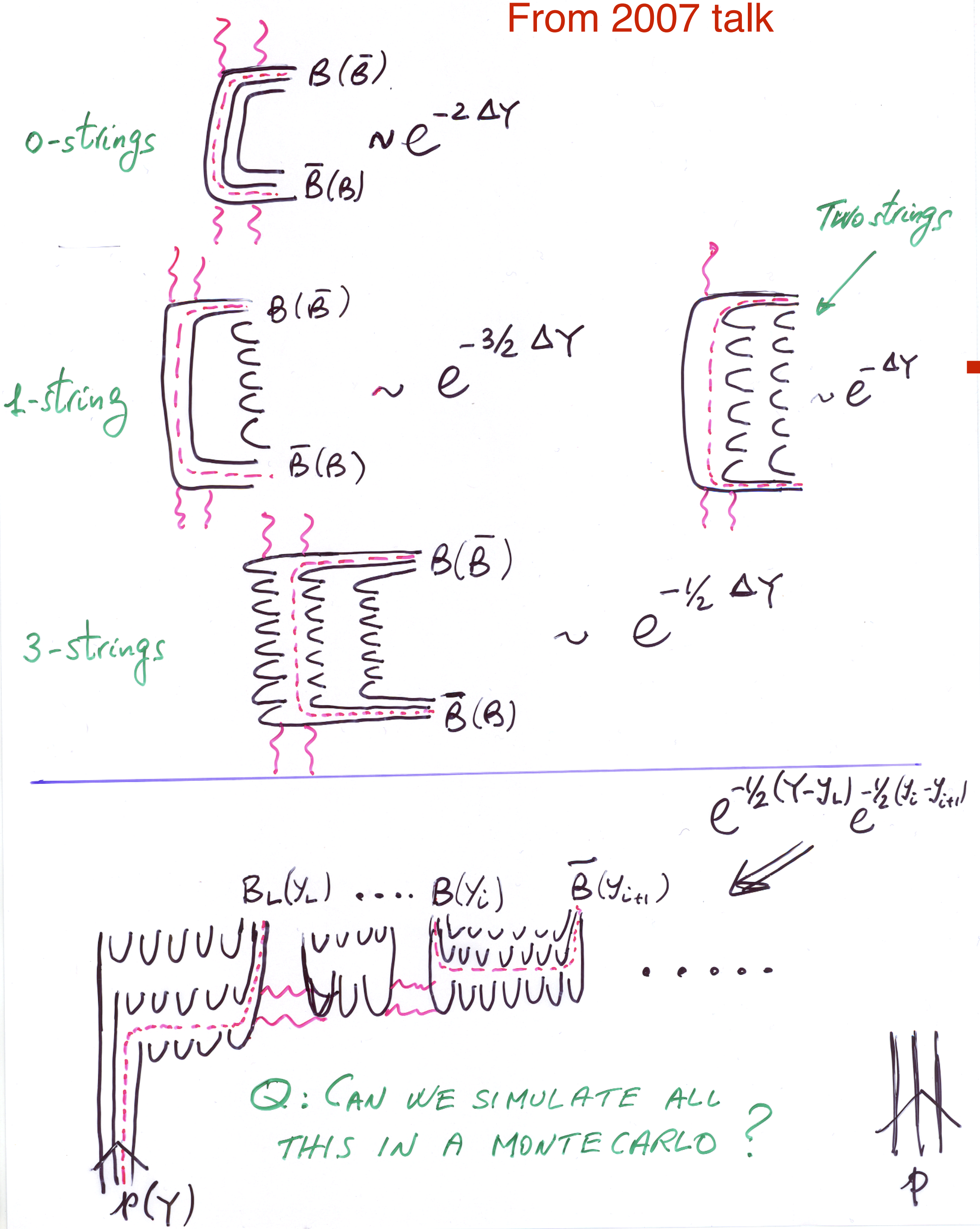
$$d\sigma/dy \sim e^{-\Delta y(1-\alpha_{J0})}$$

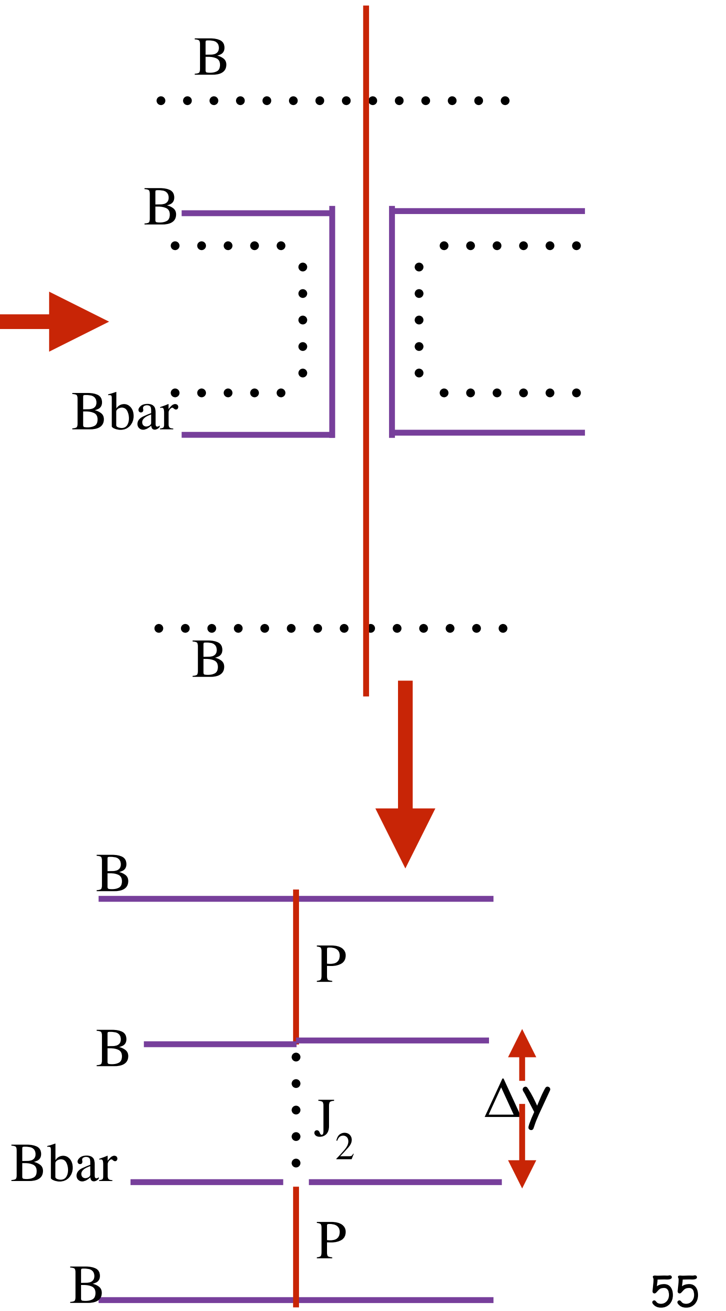
Similar considerations apply to BBbar rapidity distributions in central region

Better analyzed with Regge-Mueller diagrams?

2. $B\bar{B}$ pairs anywhere in rapidity

From 2007 talk



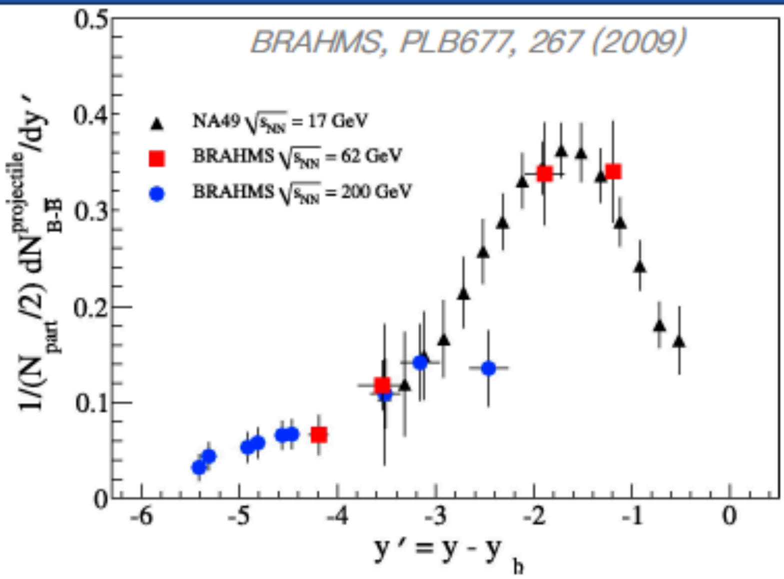


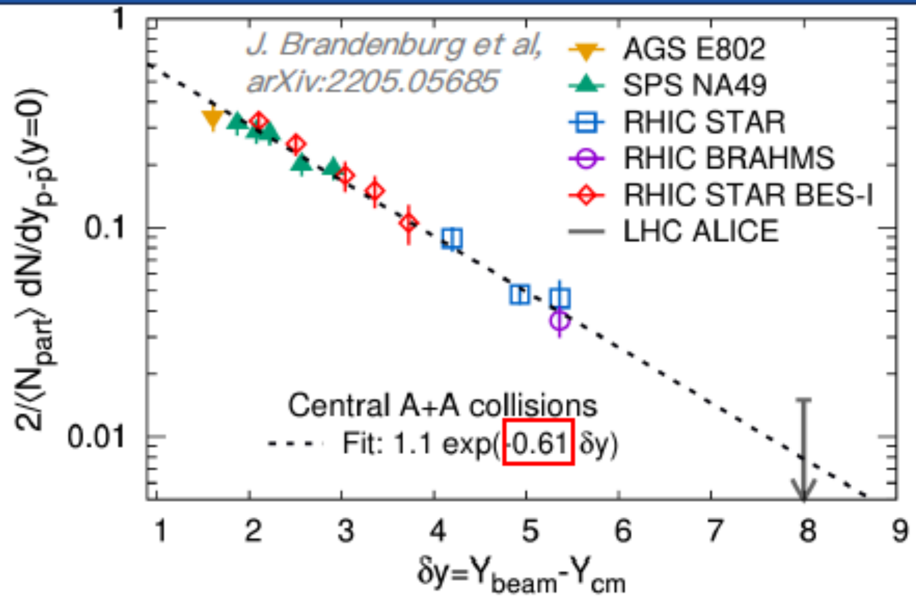
Evidence for weaker-than-expected B#-flavor correlations

(but rather see 2205.05685, 2312.15039, 2312.12376 & other talks!)

Higher than expected B-Bbar asymmetry in the central region (from talk by Z. Tang's)

Net–Baryon Rapidity Distribution





Regge theory predicts: $\frac{dN}{dy} \propto e^{-\alpha_B(y_{beam}-y)} + e^{-\alpha_B(y+y_{beam})} \xrightarrow{y=0} 2e^{-\alpha_B y_{beam}}$

$$\alpha_B = \begin{cases} 1 & double-baryon\ stopping \\ 0.42 & single-baryon\ stopping \end{cases}$$

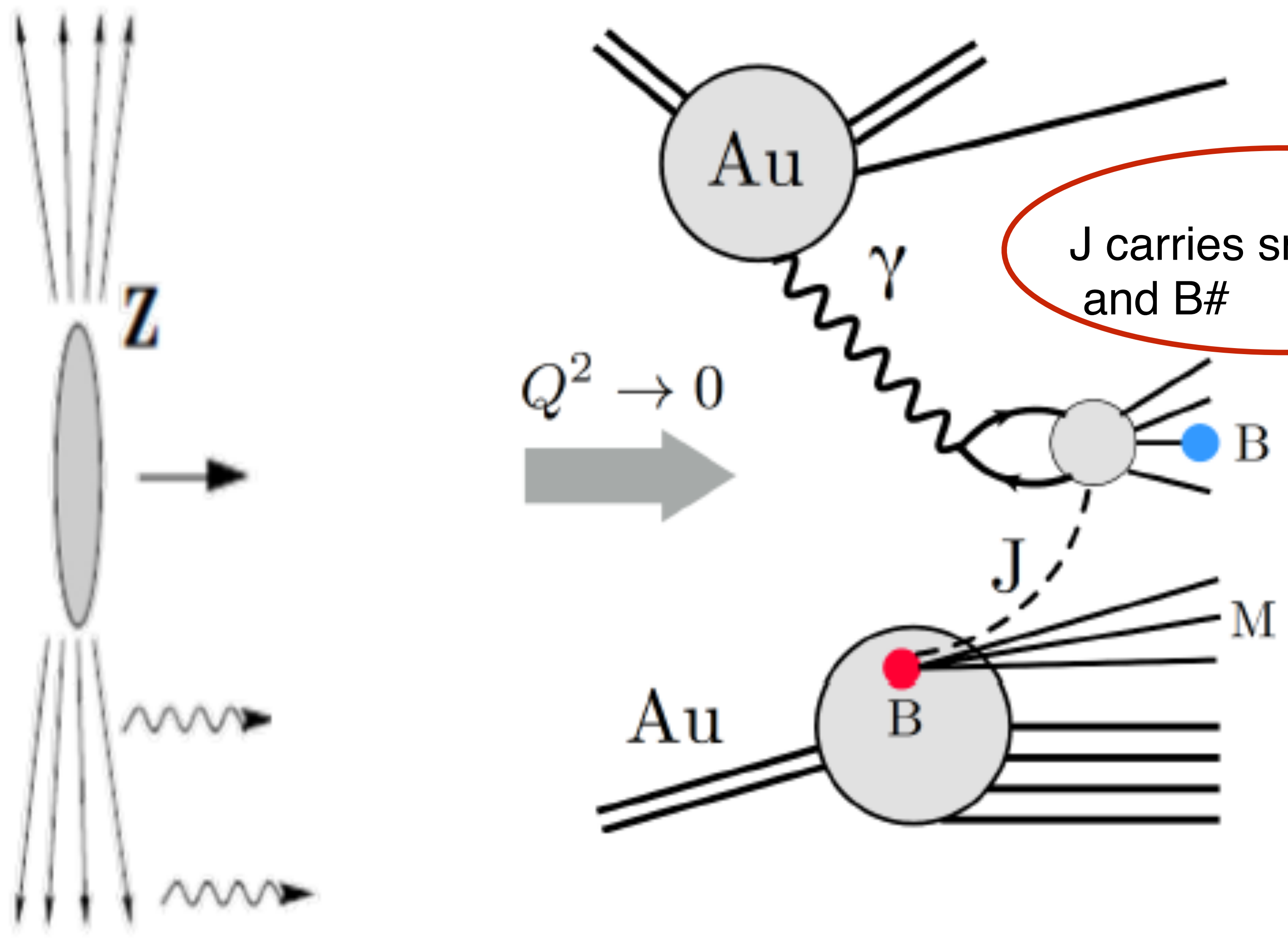
D. Kharzeev, PLB378, 238 (1996)

NB: α_B is our $(1-\alpha_{J0})$

Experiments observe: $\alpha_B = 0.61 \pm 0.03$

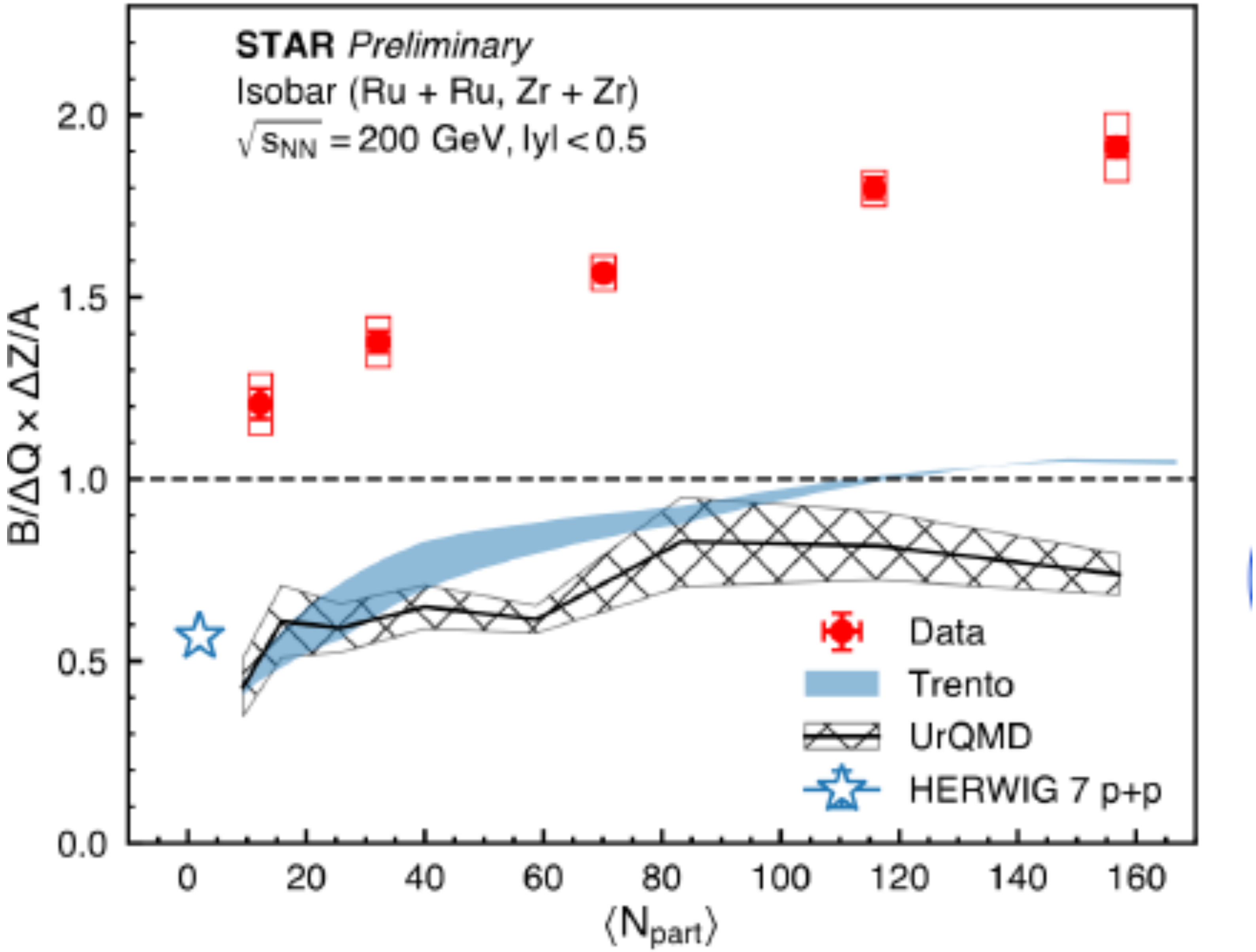
Consistent with baryon junction transport by gluons

Also, of course, DIS on heavy ions at EIC



From N. Lewis et al. 2205.05685v4

Comparing isobar ion collisions



Summarizing

- While the pre-QCD hadronic string allows for different baryonic-string configurations the QCD string points definitely towards the Y configuration with a string junction.
- That picture is further supported by numerical simulations and by large-N, large λ exps suggesting the validity of a JOZI rule
- The junction propagates like another valence constituent keeping track of B# flow independently of how flavor flows.

- The junction picture has phenomenological consequences in spectroscopy:
  - Makes easier to interpret baryon and multiquark masses in terms of universal (const.) quark masses
  - Predicts narrow exotics from the JOZI rule.
- More interestingly for this workshop, it also has high energy implications in particular for (partially) decoupling B# transport from flavor transport.
- Theoretically, it would be interesting to understand better the precise gluonic structure of the string junction (its color Q#, its topology, its possible role in solving the proton spin crisis…)
- Looking forward to the coming talks!

Thank You!